Observation of the Ω_b^- and Measurements of the Properties of the Ξ_b^- and Ω_b^-

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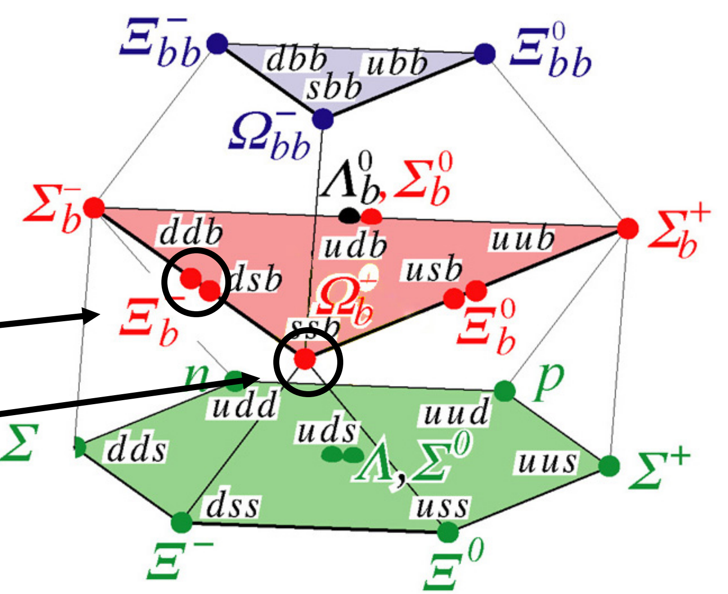
Baryon Ground States

- This is a report on *b*-baryon property measurements
  - Fully reconstructed states
- This analysis measures properties of two of the most recently observed *b*-baryons
  - Ξ_b^-, observed in 2007
  - Ω_b^-, observed by D0 in 2008

$J = 1/2\ \ b$ Baryons

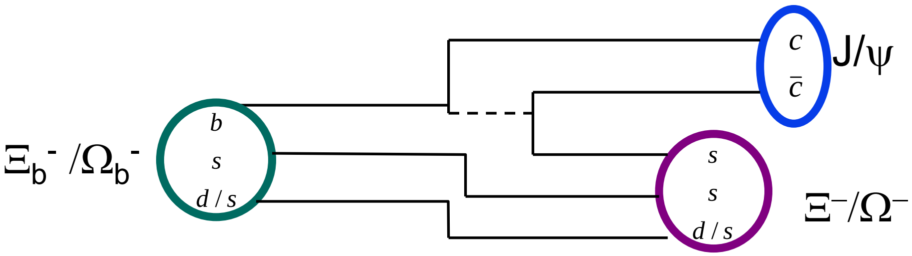


A Subject in its Infancy

- Little is known about the strange b-baryons
- The number of fully reconstructed events is small
  - Ξ_b^-: D0: 15, CDF: 18
  - Ω_b^-: D0: 18
- Only lifetime measurements of Ξ_b^- are semileptonic (LEP)
- Any information we can obtain is new
  - Of course the Tevatron owns this subject right now.

B Hadron Program

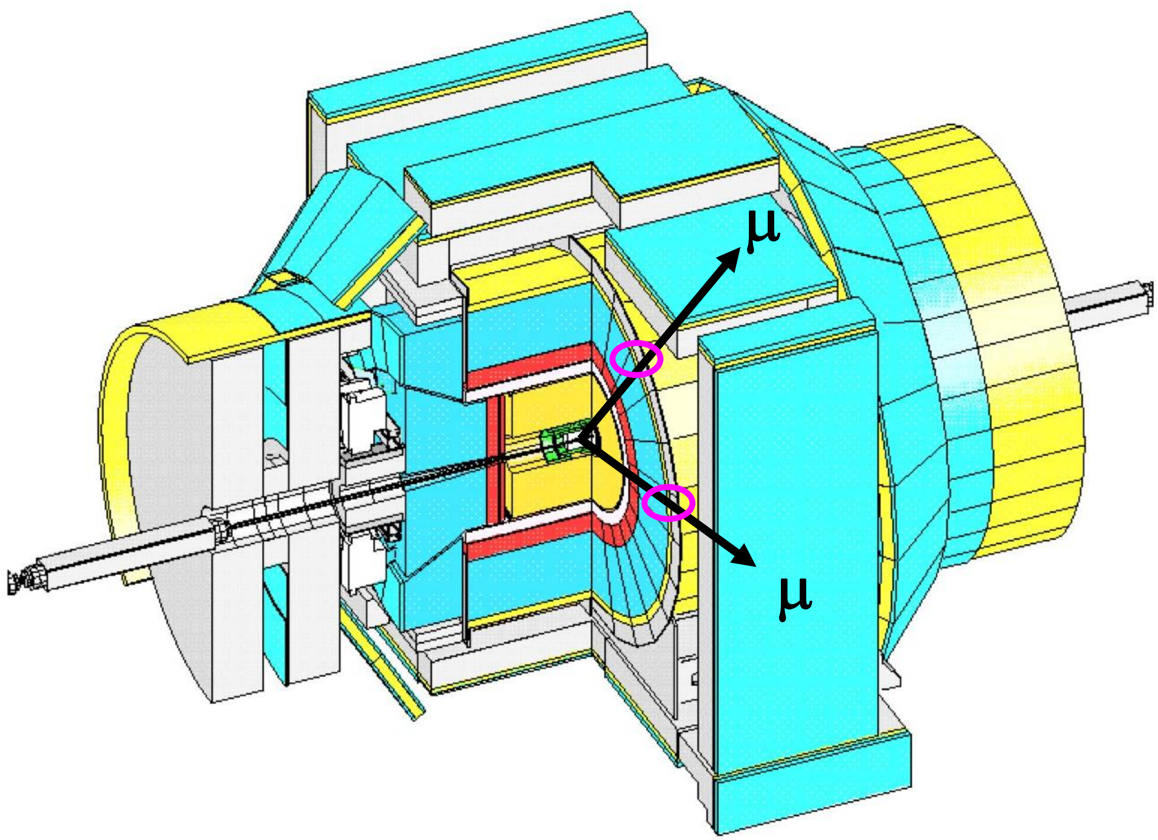
- The data set is from our di-muon trigger
  - $J/\psi \to \mu^+\mu^-$ in the final state
- We search for the Ξ_b^- and Ω_b^- through the processes
  - $\Xi_b^- \to J/\psi\, \Xi^-$, $J/\psi \to \mu^+\mu^-$, $\Xi^- \to \Lambda\pi^-$
  - $\Omega_b^- \to J/\psi\, \Omega^-$, $J/\psi \to \mu^+\mu^-$, $\Omega^- \to \Lambda K^-$



- This data set contains many *b*-meson candidates
- Therefore, the mesons are used throughout, to cross check the measurements.
- The baryon program is a natural extension of a larger *b*-meson program

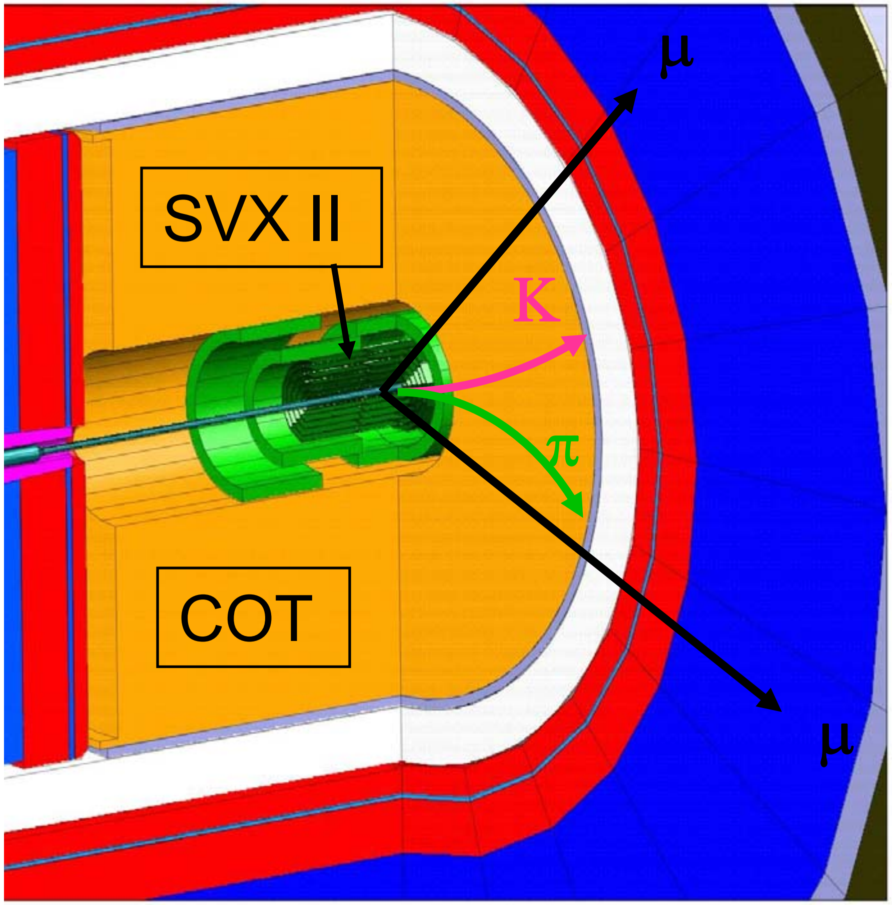
The CDF II Detector

- The data used in this analysis was collected with the CDF II Detector.
  - This analysis uses data from 4.2 fb^{-1}.
- The trigger requires
  - Tracks in muon chambers
  - Tracks in the central tracking chamber (COT) (p_T>1.5 GeV)
  - $2.7 < M(\mu^+\mu^-) < 4.0$ GeV/c^2
- Unbiased with respect to decay time for *b*-hadrons

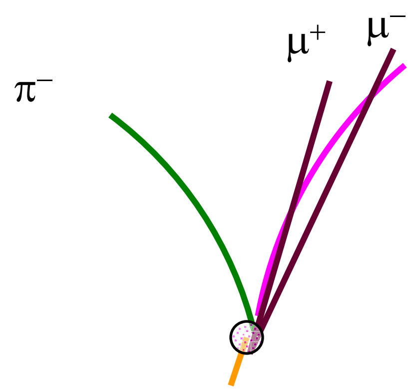


The CDF II Detector

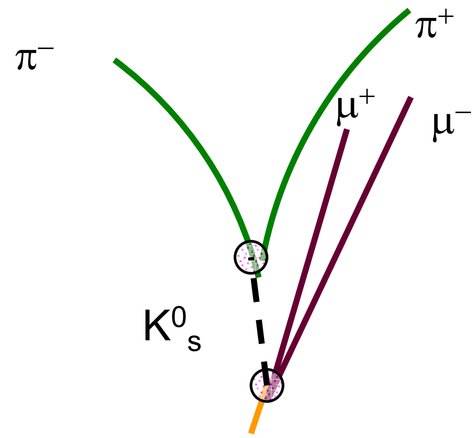
- Events that satisfy the trigger are fully analyzed.
- Track reconstruction identifies all tracks with p_T>0.4 GeV/c
- Three SVX II measurements are required for muon tracks.
  - Not used for p/K/π tracks



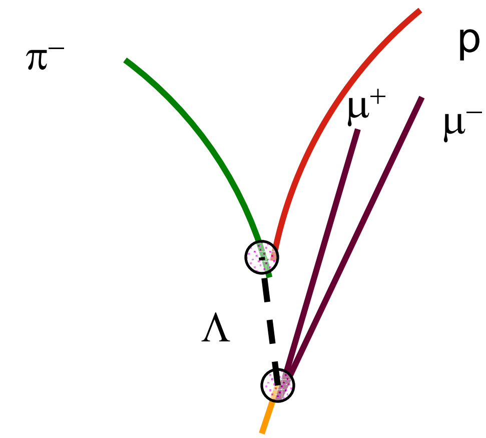
Reference Processes



$B^0 \rightarrow J/\psi\ K^{*0}$



$B^0 \rightarrow J/\psi\ K_s^0$

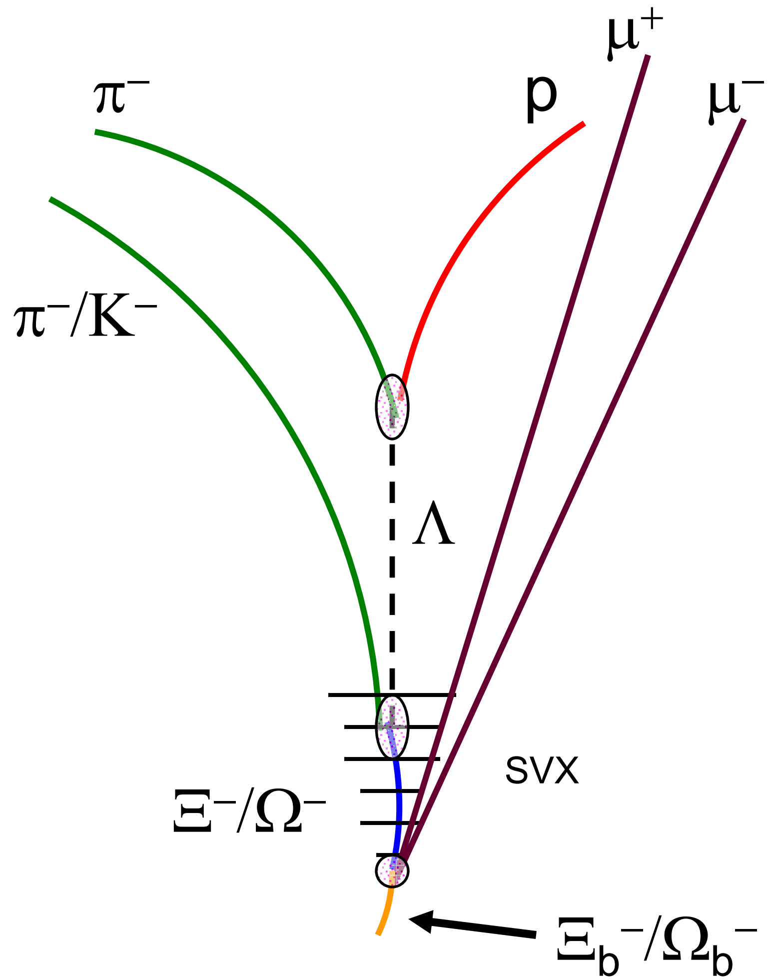


$\Lambda^0_b \rightarrow J/\psi\ \Lambda$

- Measurements of B^0 properties provide a cross check.
  - Also the Λ_b^0, the most plentiful *b*-baryon
- Reconstruction is very similar for these.
- Final state is fit with constraints
  - $\mu^+\mu^-$ are constrained to J/ψ mass
  - Hadron trajectories constrained to appropriate topologies

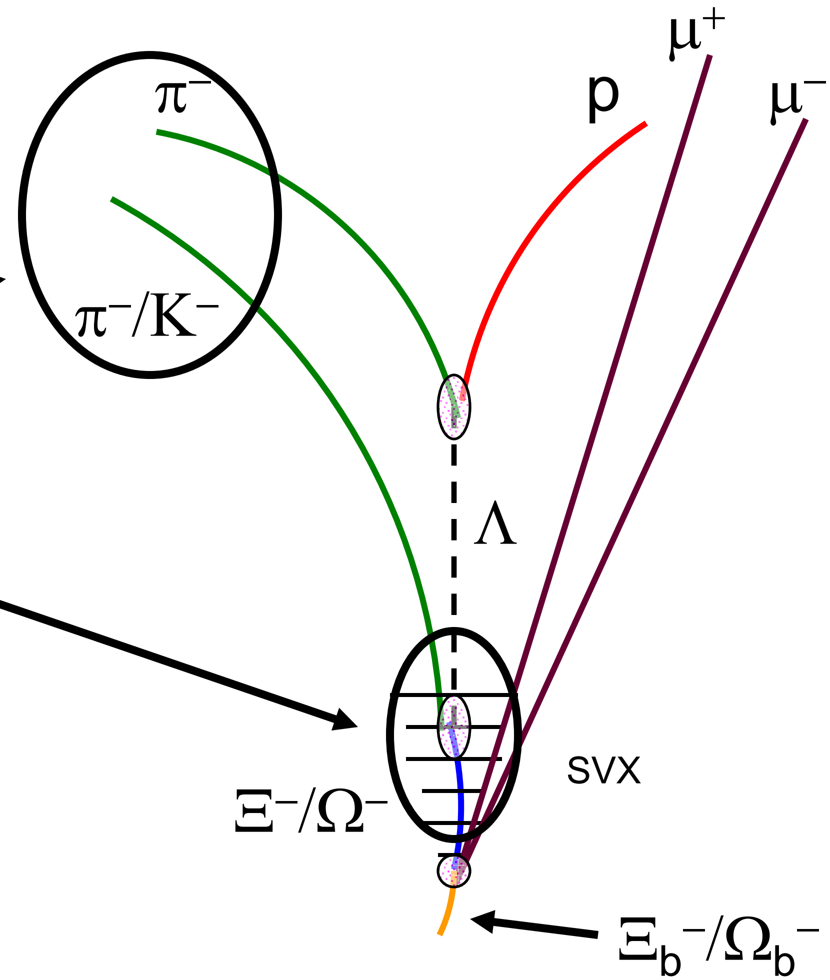
Ξ_b^-/Ω_b^- Reconstruction

- The Ξ^-/Ω^- reconstruction adds some complexity
  - 5^{th} track, 3^{rd} vertex
- Same techniques used for the neutrals can be applied
  - Decay Ξ^- or Ω^- is constrained to originate from the $\mu^+\mu^-$ intersection.
- The long life of the Ξ^- and Ω^- opens the possibility of using the silicon detector on the 6^{th} track in the process.
  - Impact resolution improvement



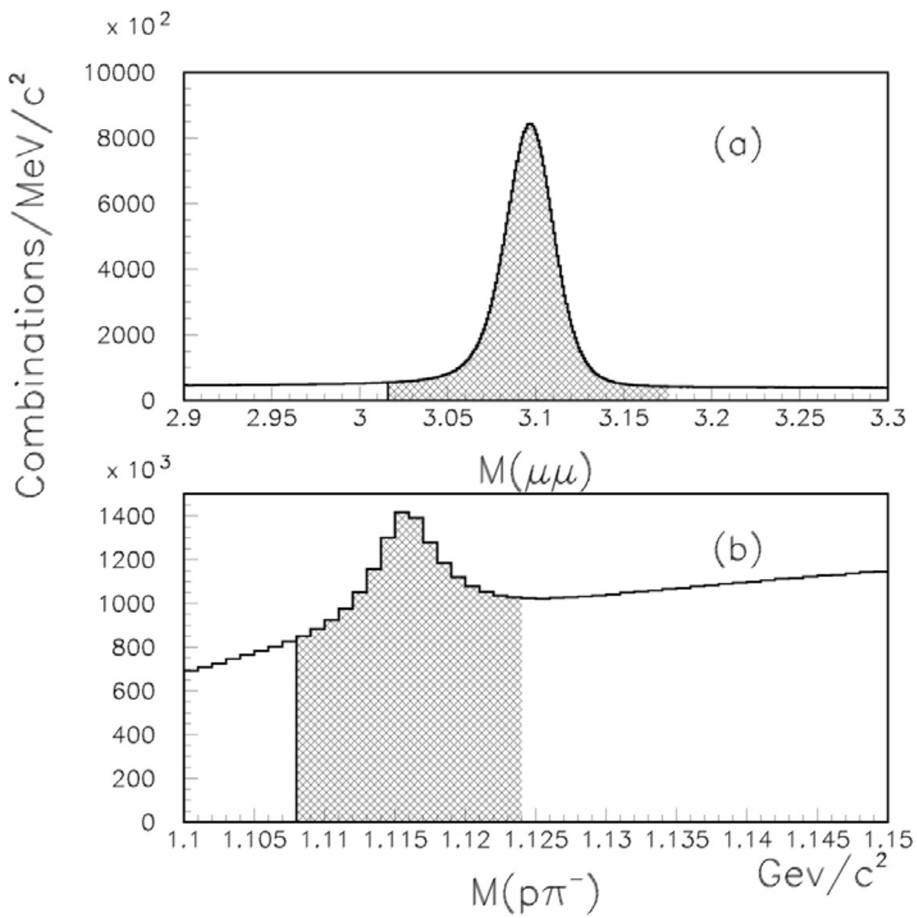
Ξ_b^-/Ω_b^- Reconstruction

- The third hadron track allows some occasional ambiguity
- Selection criteria may be satisfied by
  - Like sign pairs
    - p may form a Λ candidate with either
  - Both Λ – track intersections
- These are resolved by
  - Track measurements in the longitudinal (along beamline) view
  - Fully constrained 5-track fit
    - Helix constraint avoids "wrong" intersection



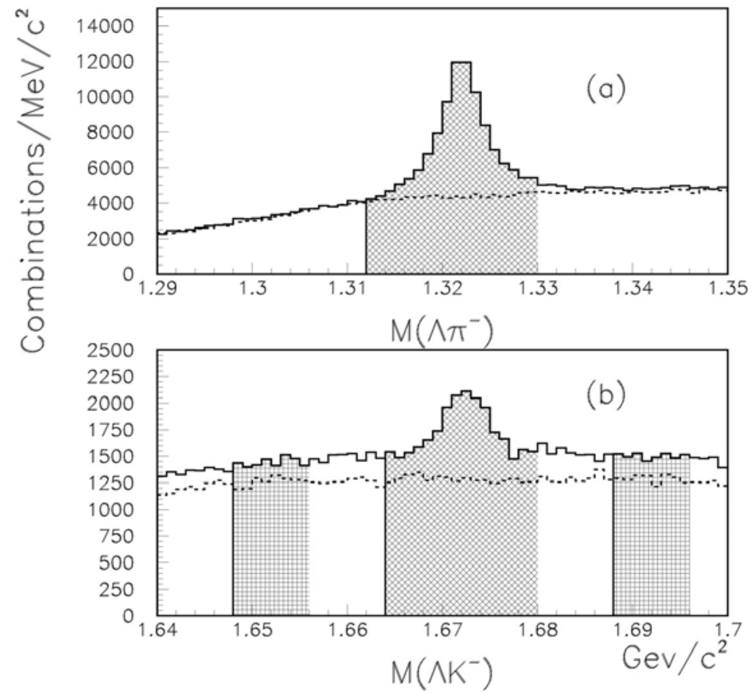
J/ψ and Λ Samples

- The analysis is based data collected from 4.2 fb^{-1} of collisions.
  - 2.9×10^7 J/ψ
- For Λ in the J/ψ sample,
  - Require decay position > 1 cm transverse from the collision.
  - $p_T > 2.0$ GeV/c
  - 3.6×10^6 Λ
- Shaded areas define the mass ranges used for *b*-hadron selection.



Inclusive Ξ^-/Ω^- Sample

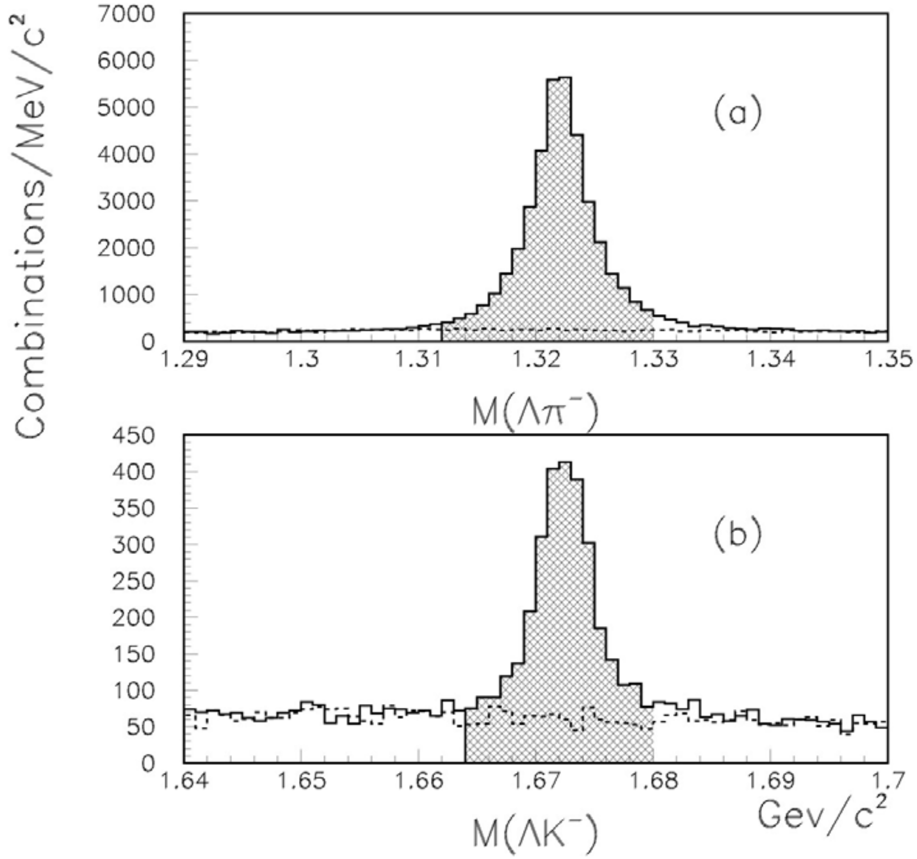
- The base sample is given by
  - $1.1077 < M(\pi p) < 1.1237$
  - $P_T(\Xi/\Omega) > 2.0$
  - Flight($\Lambda/\Xi^-/\Omega^-$) > 1 cm
  - Impact(Ξ^-/Ω^-) < 3σ
  - $P(\chi^2) > 10^{-4}$
  - $P(\chi^2)_{used} > P(\chi^2)_{swapped}$
  - Veto $1.311 < M(\Lambda\pi) < 1.331$ for ΛK sample (Ξ^- reflection)
- Yields in the full sample
  - Ξ^-: 41,000
  - Ω^-: 3,500



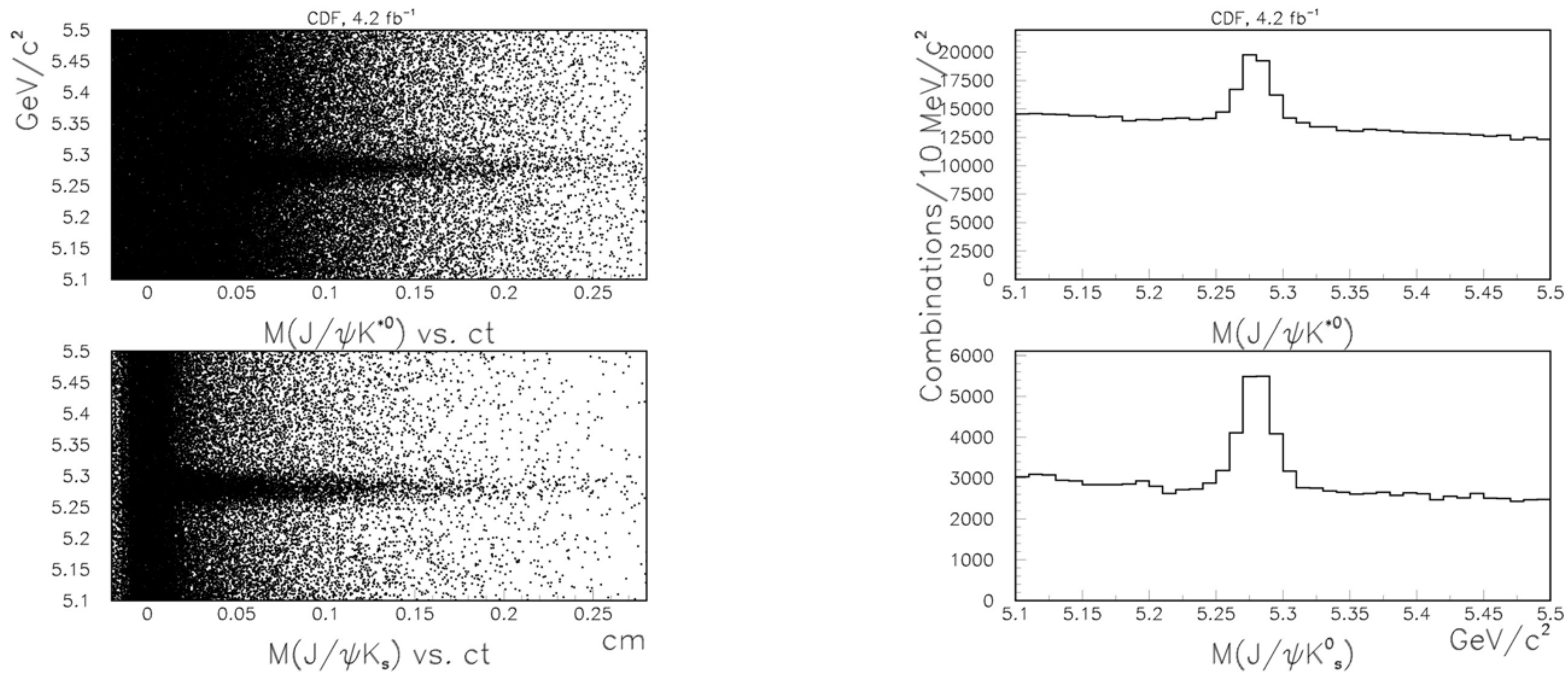
- Dashed histograms are $\Lambda\pi^+/K^+$
- Shaded are selection and sideband regions

Silicon on the Ξ^-/Ω^- Helices

- Inclusive $\Lambda\pi$ and ΛK with previous selection and silicon on the Ξ^-/Ω^- track
  - Ξ^-: 34,700
  - Ω^-: 1,900
- Shaded areas are our mass selection ranges.
  - Shorter lifetime of the Ω^- (1" vs. 2") implies lower efficiency
  - Many decay before reaching the silicon detector.



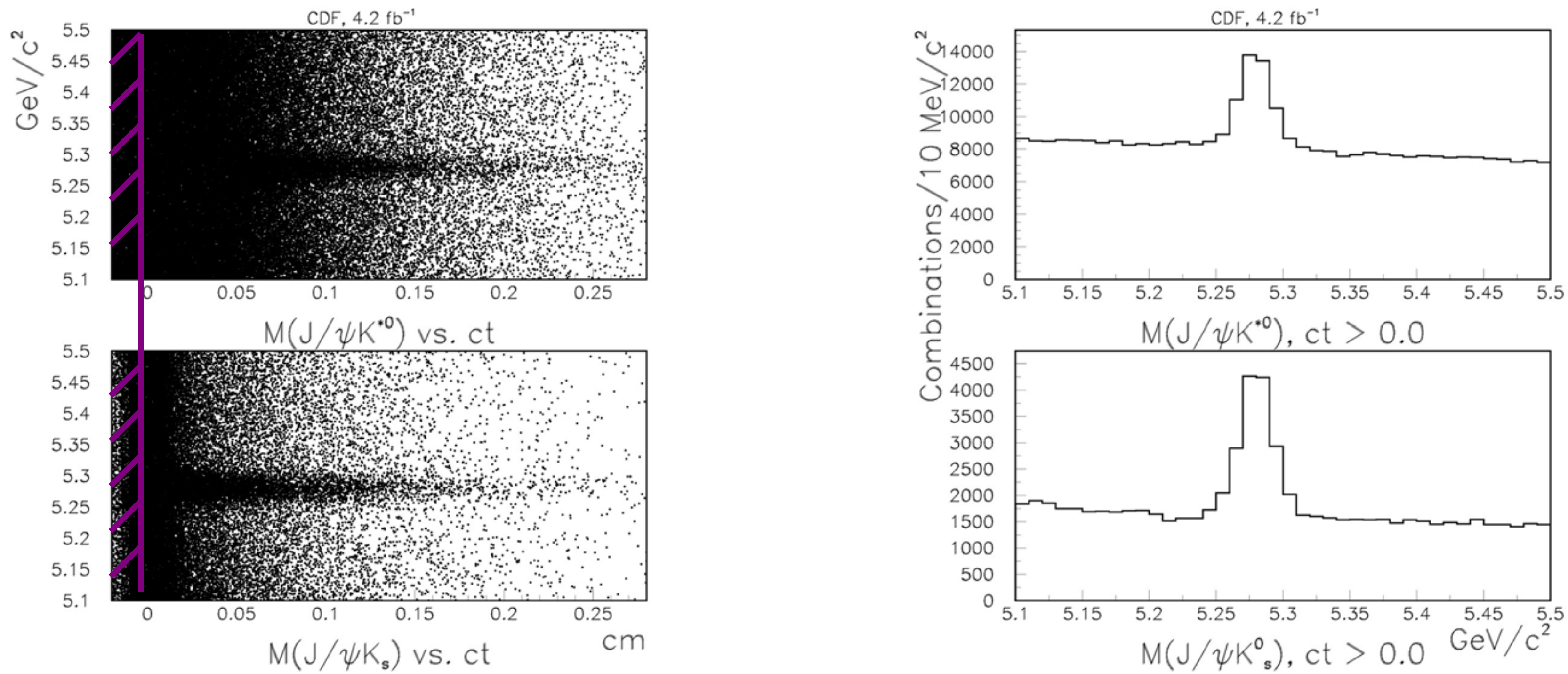
b-hadron signals at CDF



- B hadron signals are distinctive
  - Precisely measured mass
  - Characteristic lifetime

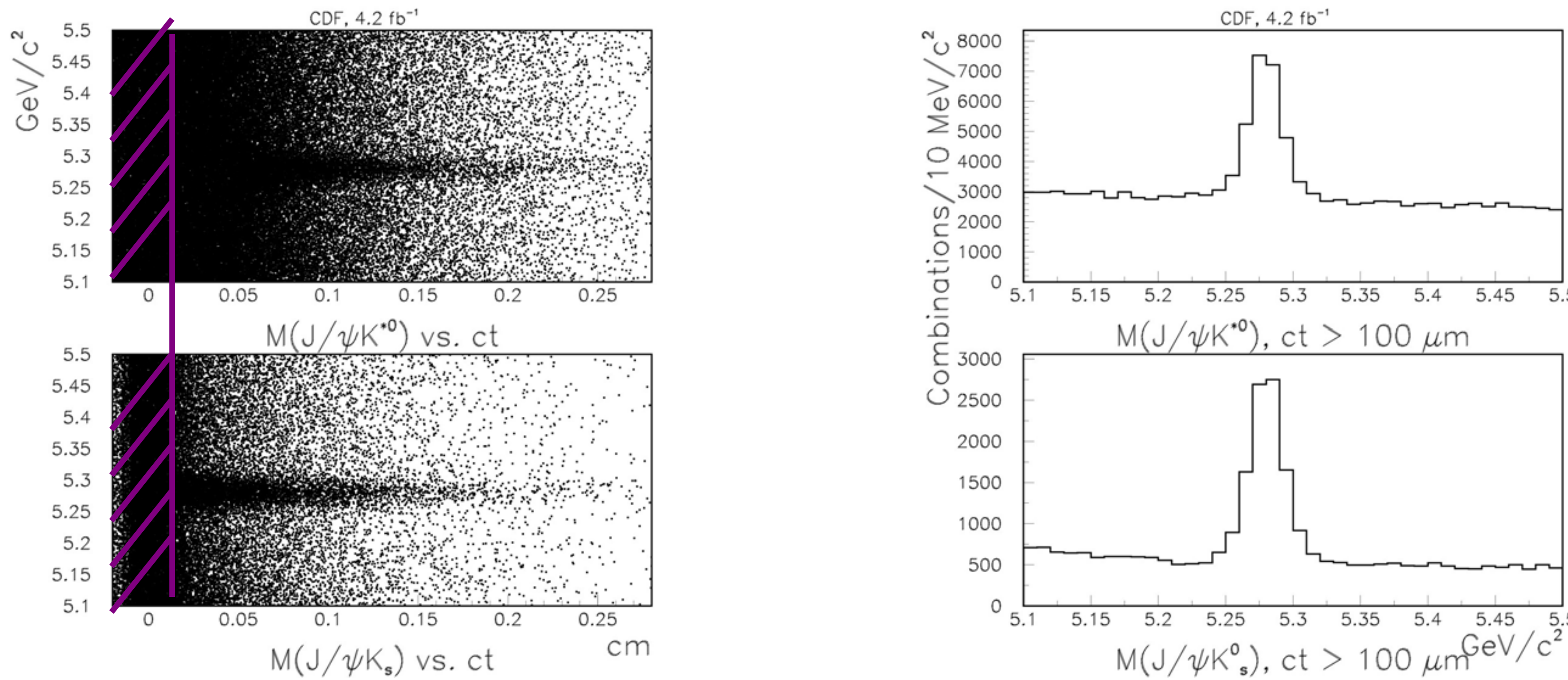
- $p_T(B^0) > 6$ GeV/c
- $p_T(K) > 2$ GeV/c
- Good fit with J/ψ mass constraint

b-hadron signals at CDF



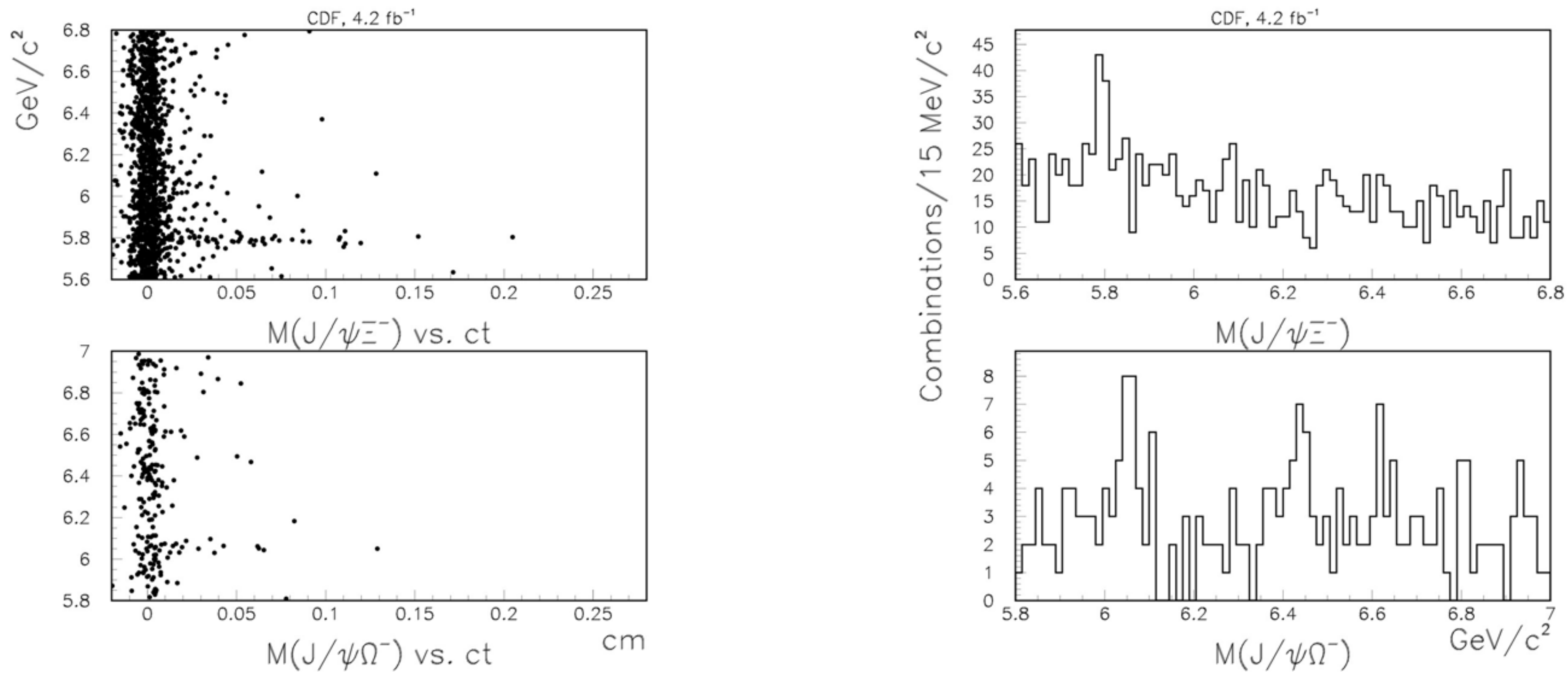
- Decay time selects B hadron signals from the prompt background
  - Here, *ct* > 0 requirement removes half the prompt background

b-hadron signals at CDF



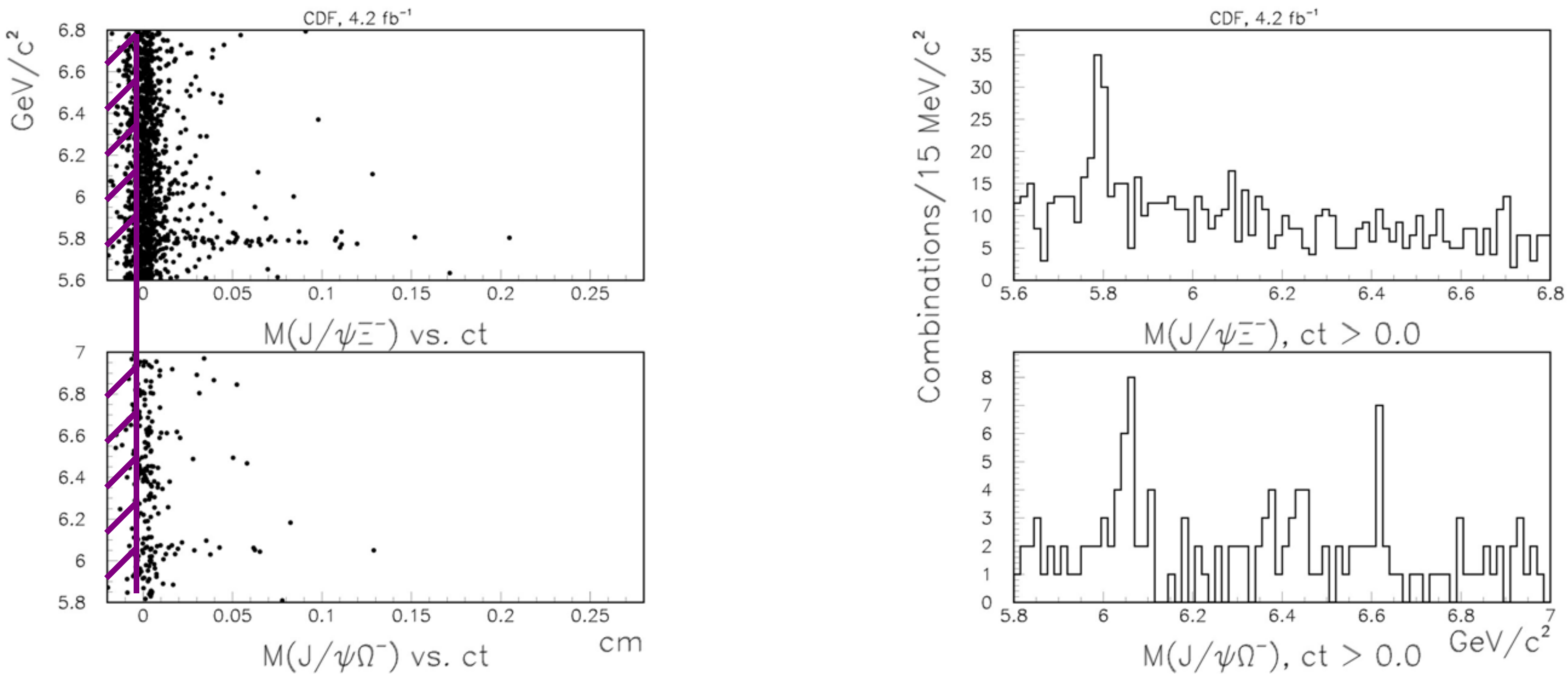
- Decay time selects B hadron signals from the prompt background
  - *ct* > 100 μm requirement removes most prompt background

b-baryon signals at CDF



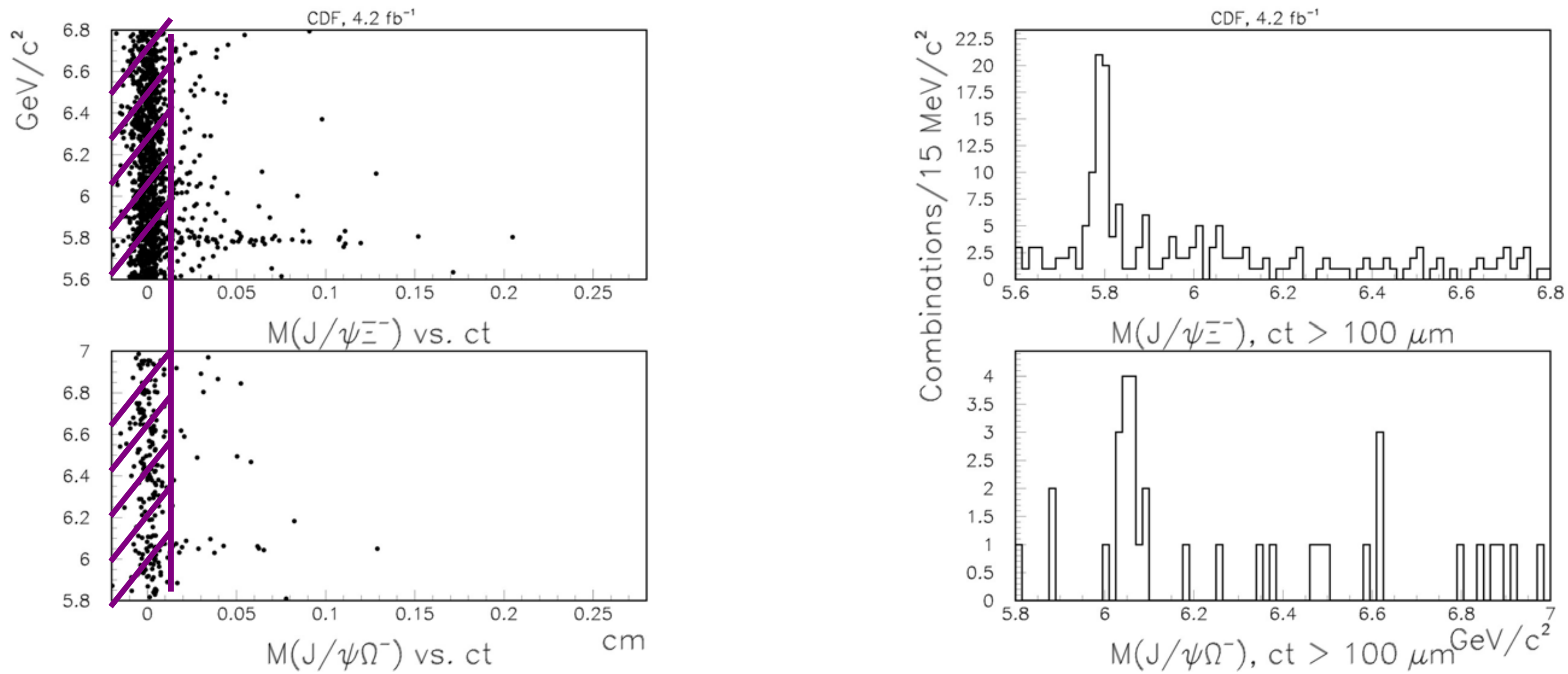
- J/ψ Ξ⁻ and J/ψ Ω⁻ samples
  - Same mass-decay time pattern appears
- p_T(B) > 6 GeV/c
- p_T(Ξ⁻/ Ω⁻) > 2 GeV/c
- Good fit with J/ψ mass constraint

b-baryon signals at CDF



- J/ψ Ξ^- and J/ψ Ω^- samples
  - As with the mesons, decay time requirements reduce the prompt background. Here ct > 0

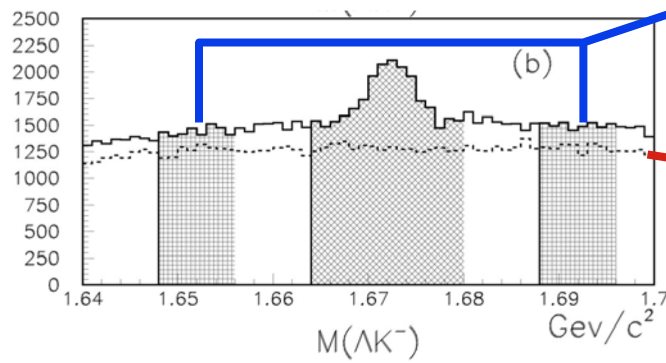
b-baryon signals at CDF

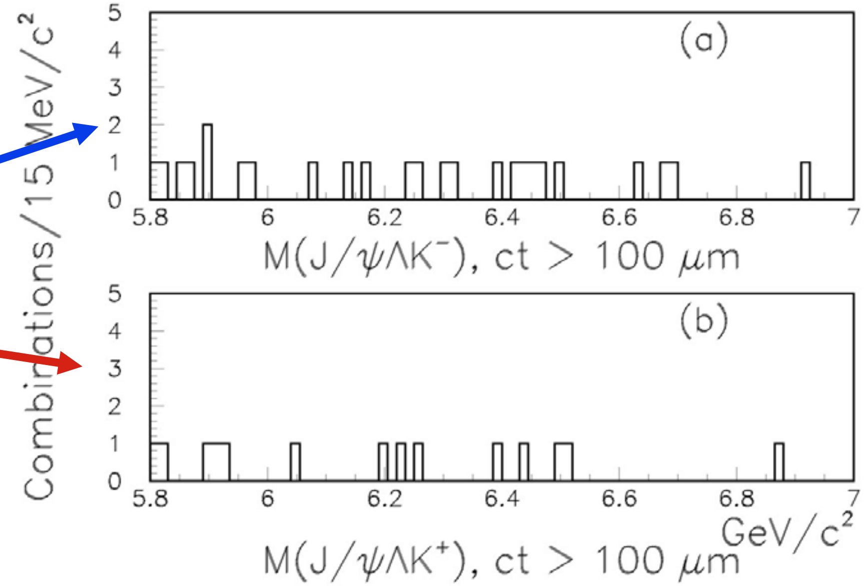


- J/ψ Ξ^- and J/ψ Ω^- samples
  - Obvious Ξ_b^- signal when *ct* > 100 μm
  - Cluster in the J/ψ Ω^- around 6.05 GeV/c^2 – test its significance

Where we expect nothing…

- For the same candidate selection, except for
  - The ΛK^- mass



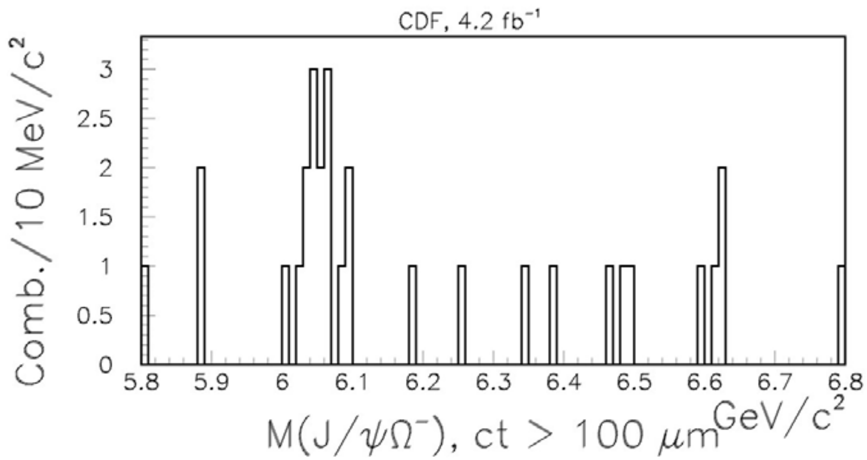


  - The “wrong sign” distribution

- Neither shows any features anywhere

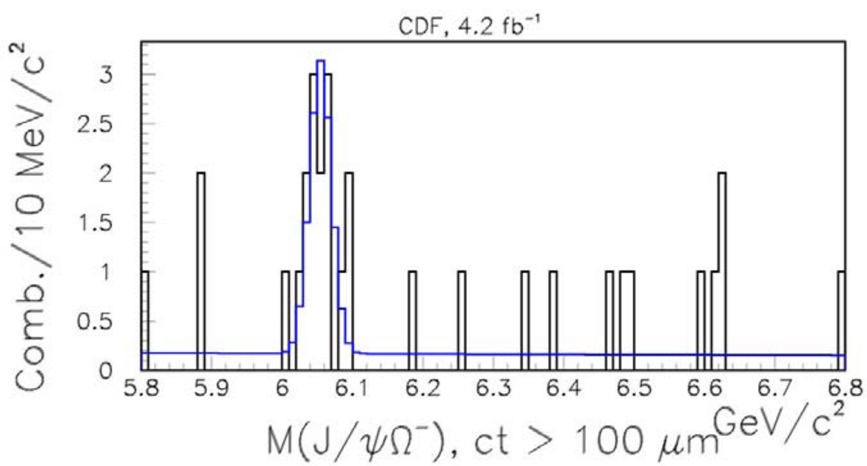
Ω_b^- Significance – Mass Distribution Test

- Two tests are used to determine the significance of the candidate signal in the $J/\psi\Omega^-$ sample.
- Ratio of likelihoods of the mass distribution with *ct* > 100 μm
  - P.D.F. is Gaussian signal and a flat background.
  - Fit freely, and with the null hypothesis



Ω_b^- Significance – Mass Distribution Test

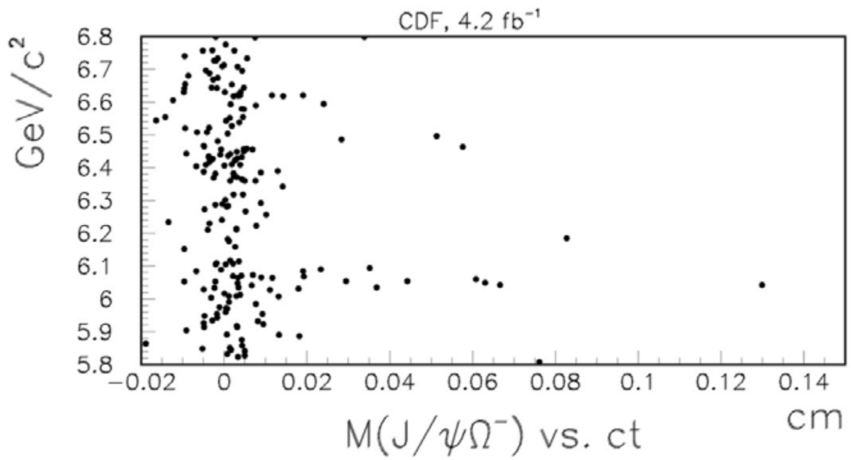
- Two tests are used to determine the significance of the candidate signal in the $J/\psi\Omega^-$ sample.
- Ratio of likelihoods of the mass distribution with ct > 100 μm
  - P.D.F is Gaussian signal and a flat background.
  - Fit freely, and with the null hypothesis
  - $\Delta 2\ln\mathcal{L} = 27.9$



- Interpreted as $P(\chi^2)$ with 2 d.o.f., = 8.7×10^{-7}, => 4.9σ
  - Confirmed by simulation
    - Similar prob. For random background
    - ± 200 MeV/c^2 search range

Ω_b^- Significance – Mass/Decay Time Distribution Test

- Second method - ratio of likelihoods of the mass-decay time distribution.
  - P.D.F in mass is Gaussian signal and a flat background.
  - P.D.F. in time is resolution smeared
    - Exponential(τ_0) for signal
    - Exponential(τ_b) for b-background
    - Delta function for prompt background
  - Fit freely, and with the null hypothesis



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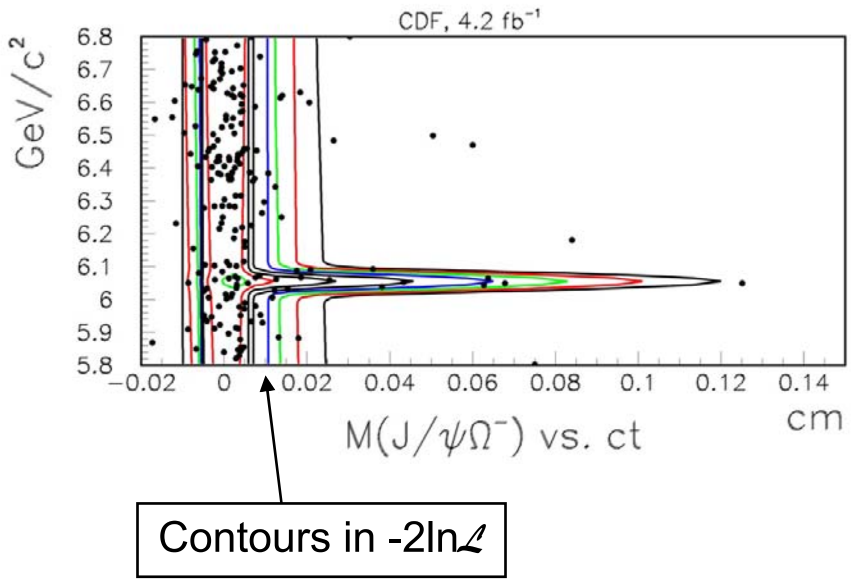
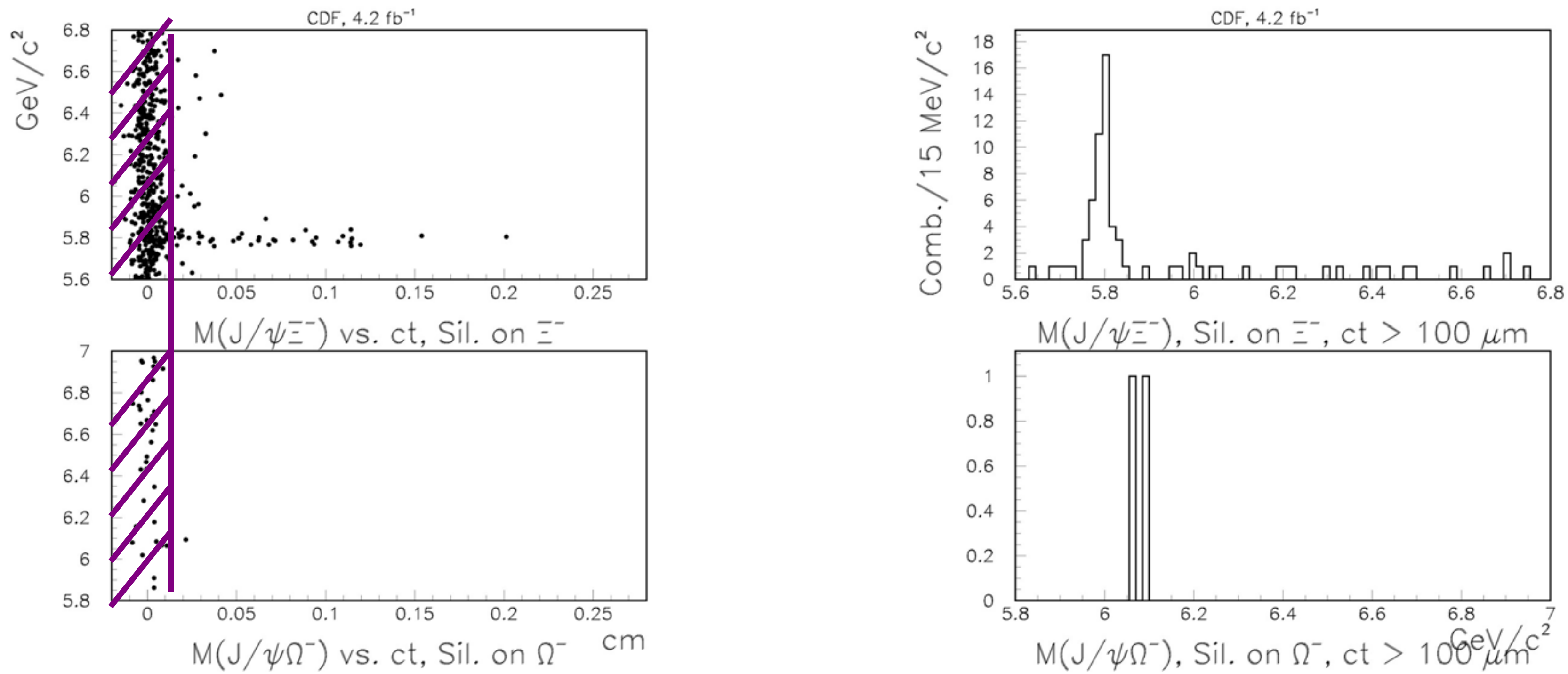
  - P.D.F in mass is Gaussian signal and a flat background.
  - P.D.F. in time is resolution smeared
    - Exponential(τ_0) for signal
    - Exponential(τ_b) for b-background
    - Delta function for prompt background
  - Fit freely, and with the null hypothesis
  - $\Delta 2\ln\mathcal{L} = 37.3$



- Interpreted as $P(\chi^2)$ with 3 d.o.f., = 4.0×10^{-8}, => 5.5σ

Can Silicon Help?

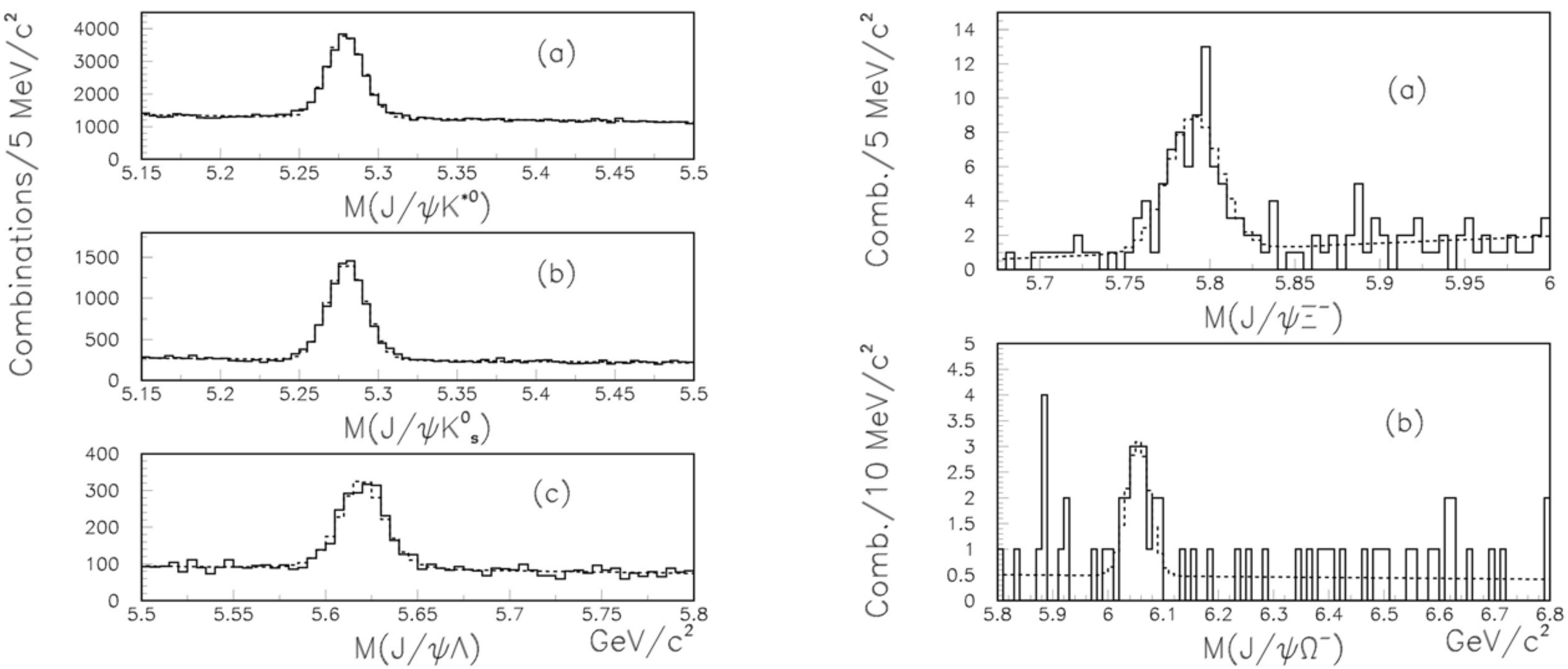


- J/ψ Ξ^- and J/ψ Ω^- samples, silicon on the Ξ^- or Ω^- track
  - Obvious Ξ_b^- signal, but few J/ψ Ω^- remain – acceptance is too low
- Next, move on to property measurements with a less restrictive sample

Mass and Lifetime Measurements

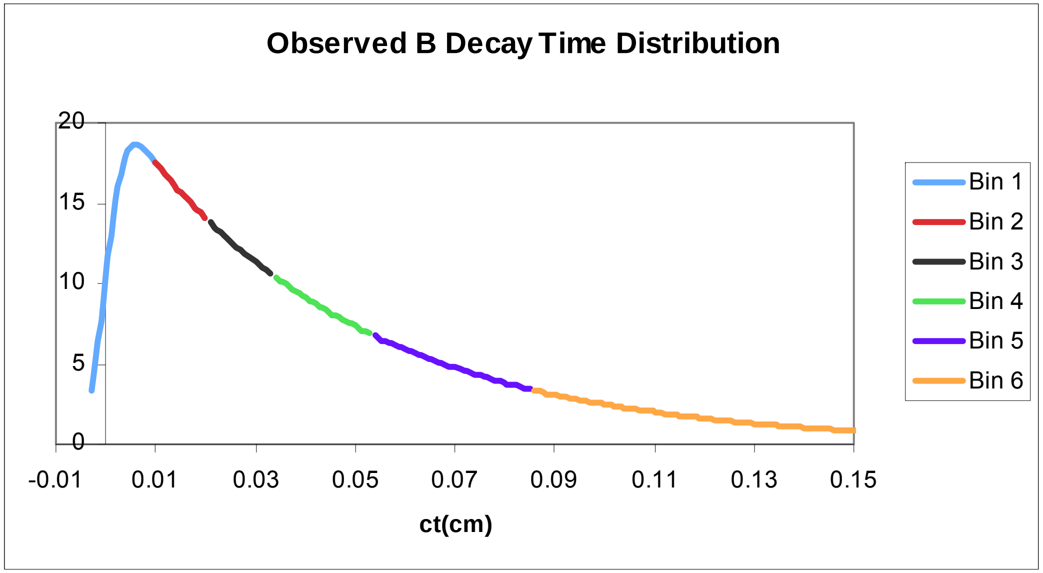
- Masses and lifetimes are calculated for 5 final states
  - 3 are references (B^0 in K^{*0} and K_s^0 final states and Λ_b^0)
  - 2 are results (Ξ_b^-, Ω_b^-)
- Similar selection is used for all final states
  - Same J/ψ selection, $p_T(B) > 6.0$, $p_T(K/\Lambda/\Xi/\Omega) > 2.0$
  - Drop impact requirements – various efficiency for this
  - Mass windows set for hadrons, full fit $P(\chi^2) > 10^{-4}$
- Unbinned mass fit applied to *ct* > 100 μm samples
- Unbinned mass, binned lifetime fit applied to whole samples.

Mass Measurements, Data and Fits



- Mass distributions for *ct* > 100 μm samples
  - Dashed lines are fit projections
  - Note, resolution is ~12-16 MeV/c^2 for all

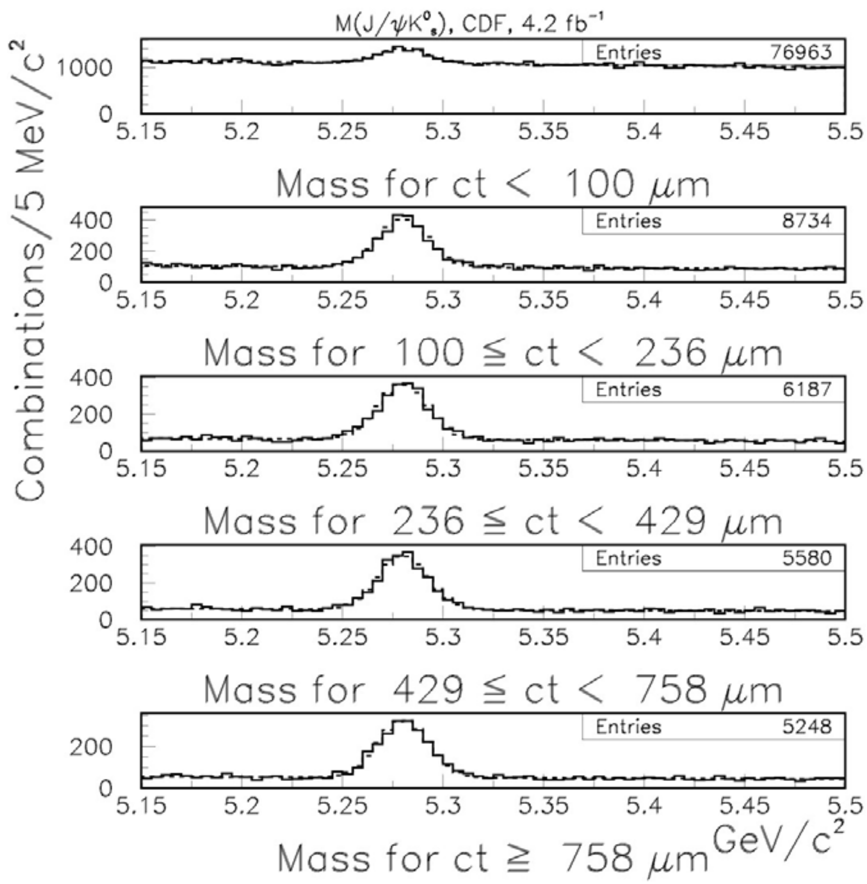
Binned Lifetime Calculation



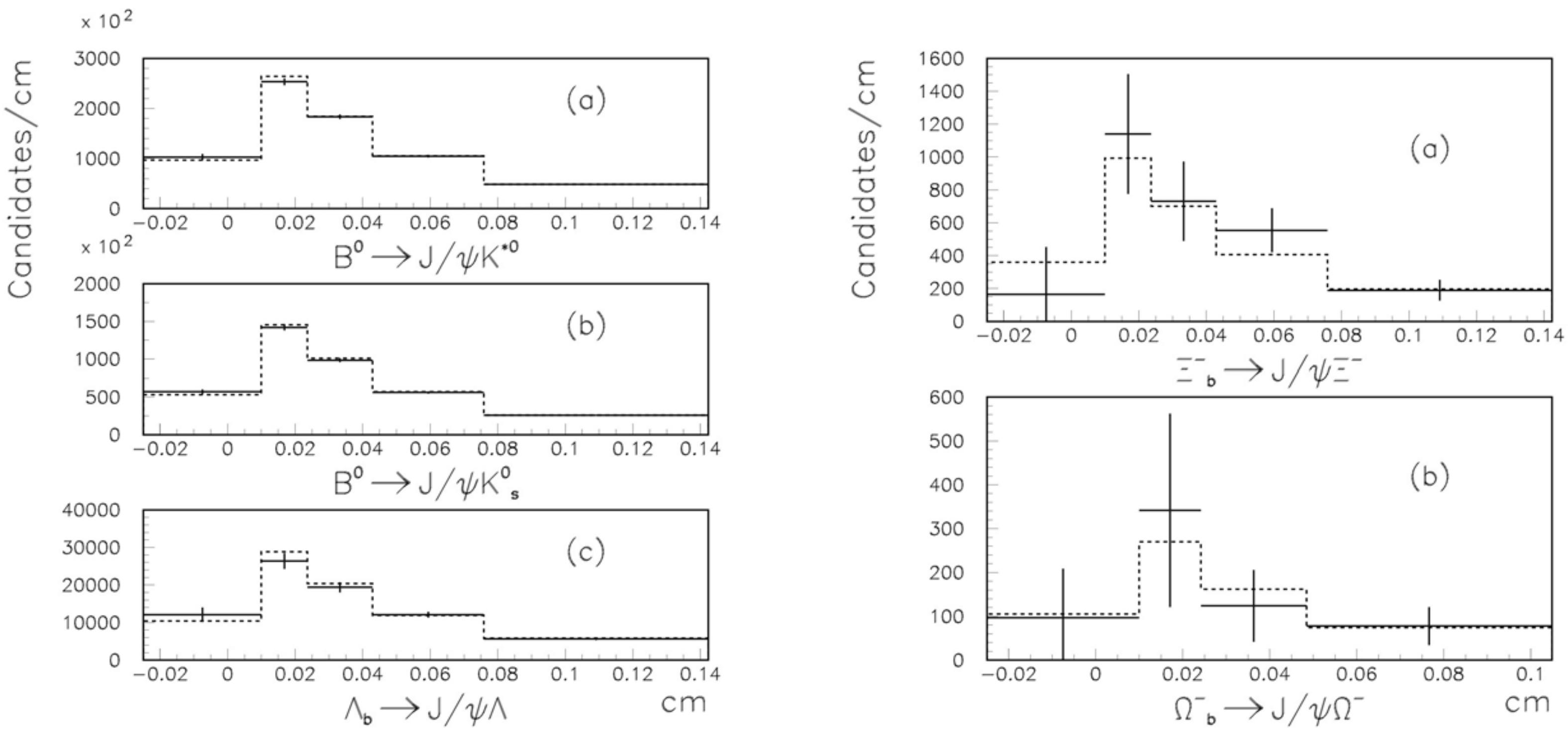
- Lifetime is calculated by binning the events in decay time.
  - Fit the mass distributions in each bin – count the candidates
  - Fit the lifetime to the distribution of candidates among the bins
- No need to model the background lifetime

A Binned Lifetime Demonstration

- Here is a demonstration on the full $B^0 \rightarrow J/\psi K^0_s$ sample.
  - Bin boundaries are indicated.
    - ~20% area in each time range
  - Projections of the mass fits are overlaid on the data.
- Fit results -
  - Yield: 9424 ± 167
  - Mass: 5280.2 ± 0.2 MeV/c^2
    - PDG: 5279.53 ± 0.33 MeV/c^2
  - $c\tau_0$: 448 ± 7 μm
    - PDG: 459 ± 3 μm



Lifetime Measurements, Data and Fits



- Binned lifetime fit distributions
  - Dashed lines are fit projections

Mass and Lifetime Results

	Mass (MeV)			Lifetime(μm)		
$B^0(K^{*0})$	5279.2	±	0.2	453	±	6
$B^0(K^0_s)$	5280.2	±	0.2	448	±	7
Λ_b	5620.3	±	0.5	472	±	17
Ξ_b	5790.9	±	2.6	468	+82	-74
Ω_b	6054.4	±	6.8	340	+160	-120

References: rows $B^0(K^{*0})$, $B^0(K^0_s)$, Λ_b

Results: rows Ξ_b, Ω_b

- 2.0 MeV/c^2 shift in Ξ_b^- from 1.9 fb^{-1} measurement - PRL 99,052002(2007)
- Systematic uncertainty on mass – 0.8 (Ξ_b^-) and 0.9(Ω_b^-) MeV/c^2
  - 0.55 MeV from $B^0(K_s)$ error – scale by 80% for kinetic energy in the decay
  - 0.5 MeV from Λ_b resolution treatment (considered largest possible)
  - 0.3 MeV from Ω^- mass
- Systematic uncertainty on lifetime – 1.3% overall
  - 2 μm from σ^{ct} treatment – range is 15-40 μm in B^0
  - 5 μm from binning

Production Rate Measurements

- We have access to the product of cross section times branching fraction.
  - We will measure ratios, with respect to the Λ_b^0:
    - Only other *b*-baryon with a large sample

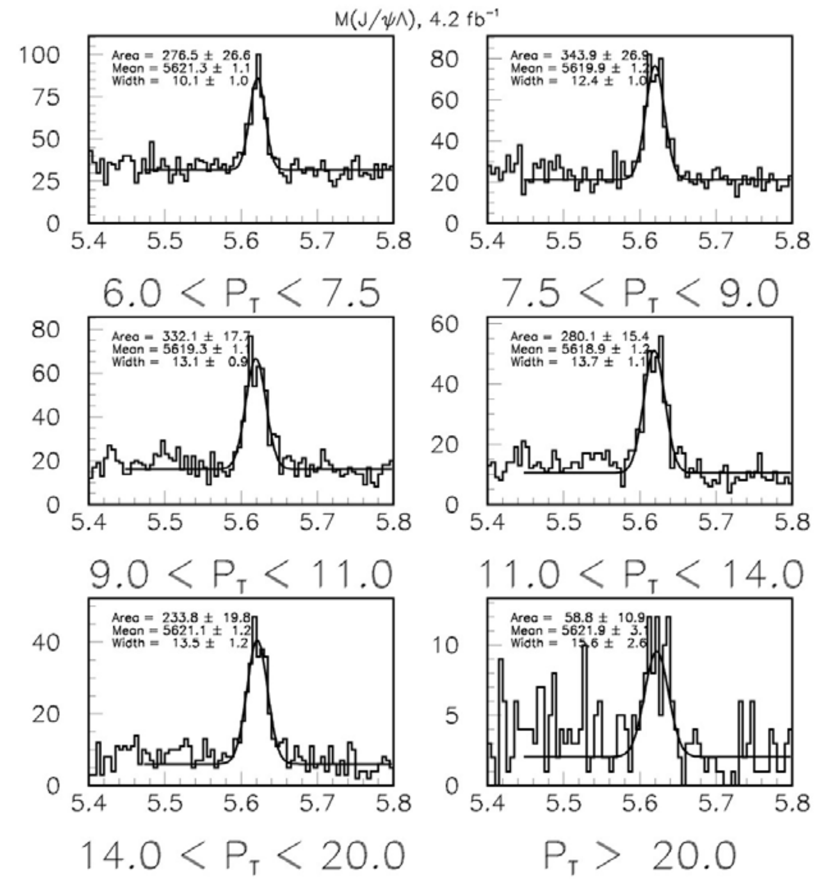
$$\frac{\sigma B(\Xi_b^- \to J/\psi \Xi^-)}{\sigma B(\Lambda_b \to J/\psi \Lambda)}$$

$$\frac{\sigma B(\Omega_b^- \to J/\psi \Omega^-)}{\sigma B(\Lambda_b \to J/\psi \Lambda)}$$

- Problem –
  - Experiment's acceptance is p_T dependent
    - This can be simulated
  - Cross section is p_T dependent
    - This is unknown in detail
  - Limited data sample requires integration over p_T
    - No Ξ_b^- or Ω_b^- candidates above 20 GeV/c

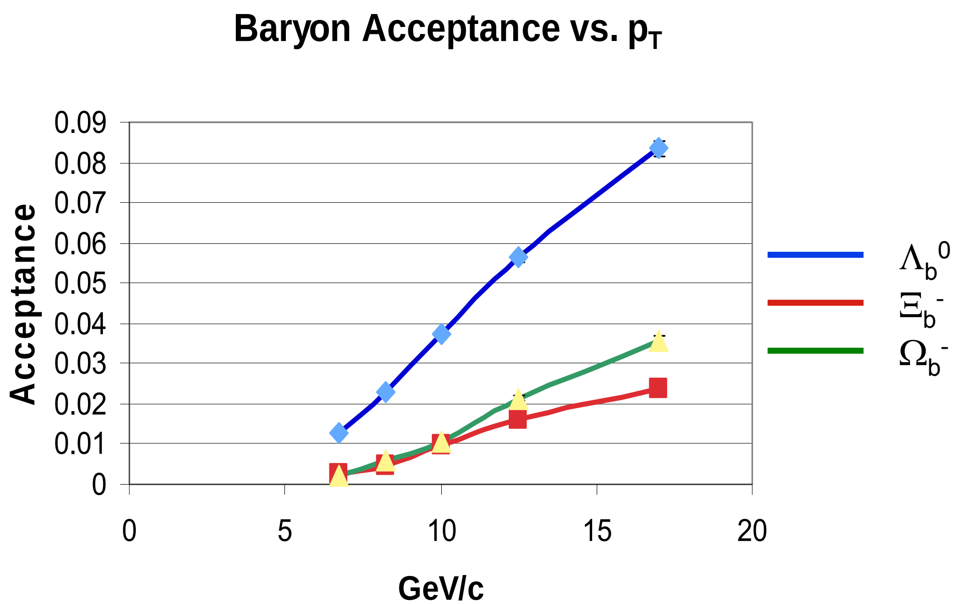
Λ_b Yield vs. p_T

- Use the data to perform the integration
  - We assume that production kinematics of the Ξ_b^- and Ω_b^- is the same as the Λ_b^0.
- The Λ_b^0 sample
  - ct > 100 μm requirement
- Gaussian fits give Λ_b^0 yield vs. p_T
  - Five bins over 6-20 GeV/c are used



Relative Rates

- Acceptance vs. p_T is obtained from simulation
  - Provides Λ_b^0 production vs. p_T
- Λ_b^0 production fractions are then used to obtain an integrated acceptance for the Ξ_b^- and Ω_b^- in a limited range of p_T (6-20 GeV/c).
  - Λ_b^0 : $3.1 \pm 0.2 \times 10^{-2}$
  - Ξ_b^- : $6.7 \pm 0.2 \times 10^{-3}$
  - Ω_b^- : $9.0 \pm 0.3 \times 10^{-3}$



Relative Rates

- The lifetime fits over 6.0 < p_T < 20 GeV/c also produce total yields
  - Λ_b^0: 1812 ± 61
  - Ξ_b^- : 66^{+14}_{-9}
  - Ω_b^- : 16^{+6}_{-4}
- These are combined with acceptances to give

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

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

Relative Rates

- Systematic uncertainties on the rates:
  - Simulation sample size plus Λ_b^0 sample gives ~6%
  - Tracking simulation – 3% (five tracks, no credit for the ratio)
  - K/π difference in tracking due to material - 0.3%
  - Ω- branching fraction – 1%
  - Λ_b^0 lifetime($\pm$50 μm) – 2.5%
  - Ω_b^- mass($\pm$100 MeV/c^2) - 5%
- Total systematic uncertainty of 7% for Ξ_b^-, 9% for Ω_b^-
- Final rate ratios
  - Ξ_b^-: $0.167^{+0.037}_{-0.025} \pm 0.012$
  - Ω_b^-: $0.045^{+0.017}_{-0.012} \pm 0.004$

Summary of Results

- CDF observes the Ω_b^-.
- CDF measures relative rates of production
  - Over the range $6.0 < p_T < 20$ GeV/c
  - Assume the kinematic distributions are identical for the Λ_b^0

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

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

Summary of Results

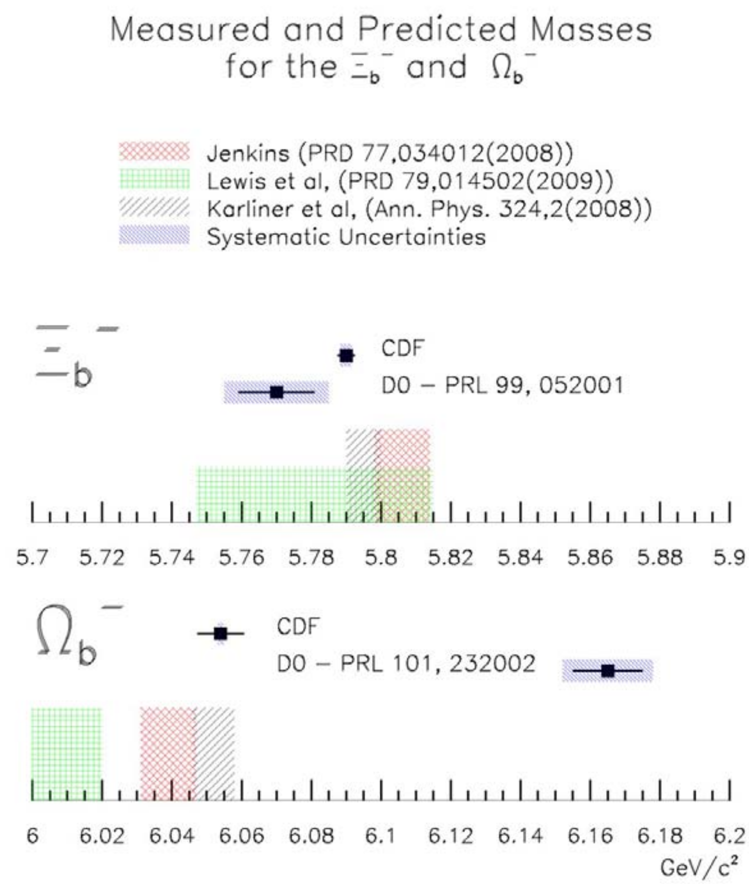
- CDF measures *b*-baryon masses:
  - Ξ_b^-: 5790.9 ± 2.6(stat.) ± 0.9(syst.) MeV/c^2
  - Ω_b^-: 6054.4 ± 6.8(stat.) ± 0.9(syst.) MeV/c^2
- CDF measures b-baryon lifetimes
  - Ξ_b^-: $1.56^{+0.27}_{-0.25}$(stat.) ± 0.02(syst.) ps
    - First in a fully reconstructed state.
  - Ω_b^-: $1.13^{+0.53}_{-0.40}$(stat.)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

Ω_b^- Measurements Compared to D0

- D0 finds $M(\Omega_b^-)$=6165±10(stat.)±13(syst.) MeV/c^2
  - PRL **101**, 232002(2008)
- We find $M(\Omega_b)_{D0} - M(\Omega_b)_{CDF}$ = 111±12(stat.)±14(syst.) MeV/c^2
  - Significant disagreement
- D0 finds $$\frac{f(b \to \Omega_b^-)B(\Omega_b^- \to J/\psi\Omega^-)}{f(b \to \Xi_b^-)B(\Xi_b^- \to J/\psi\Xi^-)} = 0.80 \pm 0.32^{+0.14}_{-0.22}$$
- CDF finds $$\frac{\sigma B(\Omega_b^- \to J/\psi\Omega^-)}{\sigma B(\Xi_b^- \to J/\psi\Xi^-)} = 0.27 \pm 0.12 \pm 0.01$$

b-Baryon Masses

- CDF results are from this work
- Two results by two groups are at odds
  - Consistency with the Ξ_b^-
  - Inconsistency with the Ω_b^-
- Resolution of this puzzle can only come with more measurements
  - CDF – other channels?
  - D0 – more J/ψ sample?

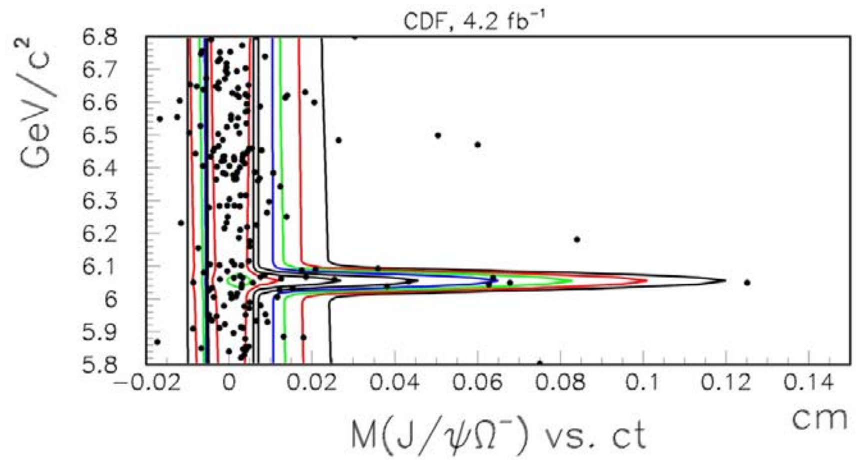


Conclusions

- CDF performs a "cut-based" selection on its J/ψ sample in 4.2 fb^{-1}.
  - Cut on p_T, mass ranges, track and constrained fit quality
- Samples of B^0, Λ_b^0, Ξ_b^- and Ω_b^- are isolated.
- Mass, lifetime, and relative production rate measurements are performed on the Ξ_b^- and Ω_b^-.
  - Plentiful B^0 and Λ_b^0 serve as cross checks and motivate systematics.
- These strange *b*-baryons are simply additional members of a rich program of fully reconstructed *b*-hadrons obtained in the CDF J/ψ sample.

Ω_b^- Significance – Mass/Decay Time Distribution Test

- Second method - ratio of likelihoods of the mass-decay time distribution.
  - P.D.F in mass is Gaussian signal and a flat background.
  - P.D.F. in time is resolution smeared
    - Exponential(τ_0) for signal
    - Exponential(τ_b) for b-background
    - Delta function for prompt background
  - Fit freely, and with the null hypothesis
  - $\Delta 2\ln\mathcal{L}$ = 37.3



- Interpreted as $P(\chi^2)$ with 3 d.o.f., = 4.0×10^{-8}, => 5.5σ
- Fit results:
  - Mass: 6055.5±6.6 MeV/c^2
  - $c\tau_0$: 338±100 μm
  - Yield: 18±5

Cross-check the Simulation with the B^0

p_T (Gev/c)	$B^0 \to J/\psi K^{*0}$			$B^0 \to J/\psi K_S^0$			$\mathcal{B}(K^0)/\mathcal{B}(K^{*0})$		
6.0-7.5	2640	±	74	1196	±	52	0.59	±	0.04
7.5-9.0	2687	±	52	1361	±	50	0.64	±	0.03
9-11	3189	±	49	1685	±	34	0.63	±	0.03
11-14	3243	±	54	1615	±	50	0.64	±	0.03
14-20	2787	±	56	1321	±	27	0.63	±	0.03
6-20	14546	±	129	7178	±	98	0.628	±	0.014

- We cross-check the simulation with the B^0 Branching Fraction Ratio
- From the data, and the simulated events, we get

$$\frac{\sigma(B^0)B(B^0 \to J/\psi K^0)}{\sigma(B^0)B(B^0 \to J/\psi K^{0*})} = \frac{4}{3}\frac{N_{data}(B^0 \to J/\psi K_s)}{N_{data}(B^0 \to J/\psi K^{0*})}\frac{N_{sim}(B^0 \to J/\psi K^{0*})}{N_{sim}(B^0 \to J/\psi K_s)}$$

- This is solved for several bins in p_T.
- Results are self consistent
- PDG value is 0.655±0.038.
  - We're consistent, and better (stat. only)