The Ξ_b^-: Discovery of a strangely beautiful baryon

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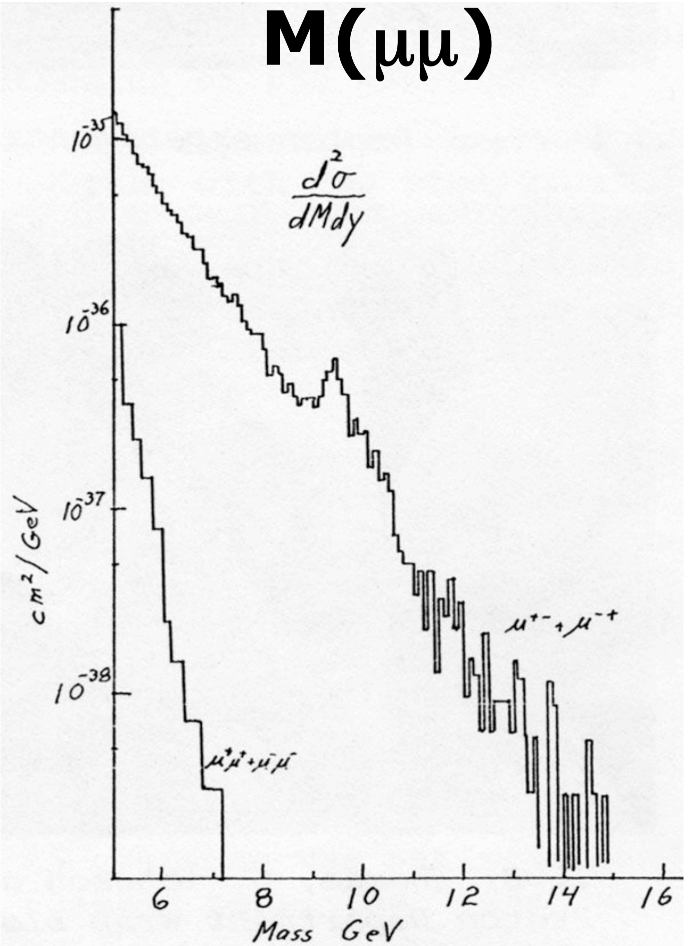
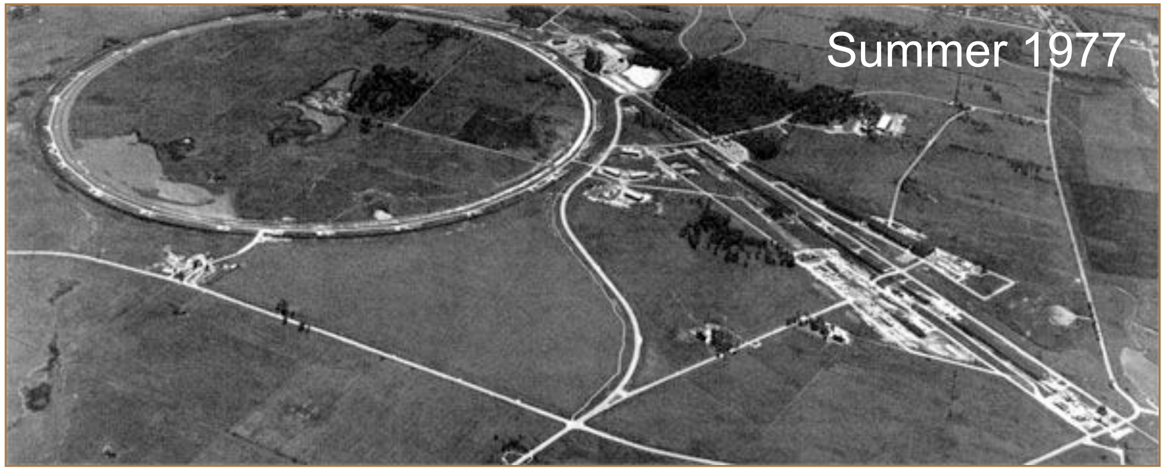
Outline

- B Physics and the observation status
- Fermilab & D0
- Search for the Ξ_b
  - Ξ_b signal
  - Mass measurement
  - Relative production ratio
- Summary

Birth of B Physics



The discovery of the upsilon meson in 1977 at Fermilab by Lederman et al.



Fermilab's giant accelerator reveals another new sub-nuclear particle

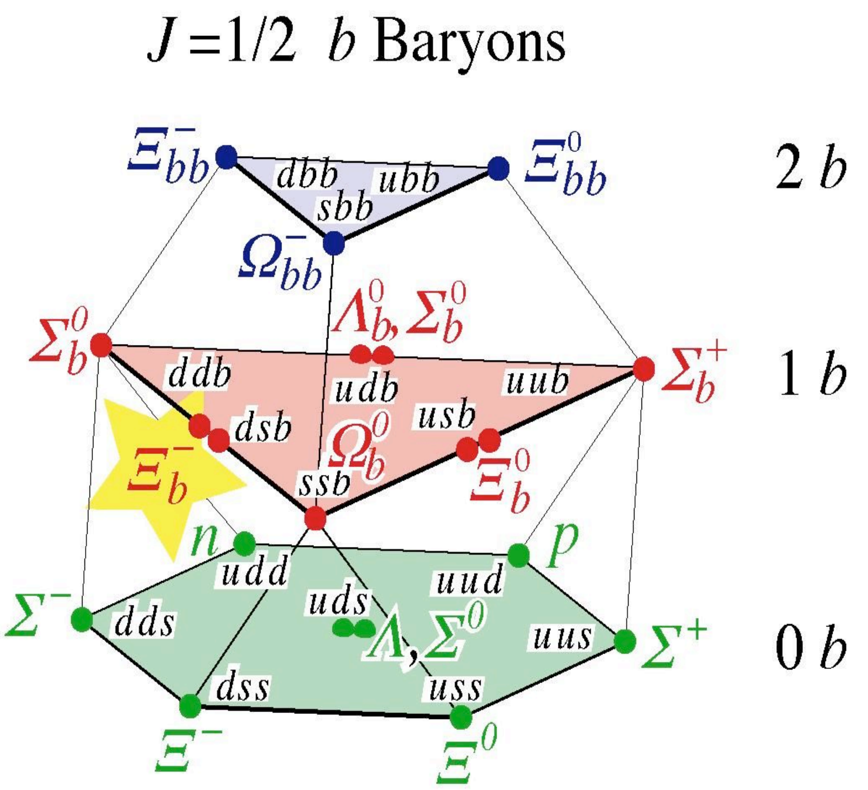
B Physics, a whole field, was born

Status of B hadrons:

- **Mesons:**
  - Established: $B^+(u\bar{b})$, $B^0(d\bar{b})$, $B_s(s\bar{b})$, $B_c^+(c\bar{b})$
  - Established: B^*
  - Preliminary: B_d^{**},B_s^{**} *(CDF & DØ)*

- **Baryons:**
  - Established: $\Lambda_b(udb)$
  - Preliminary (CDF): $\Sigma_b^+(uub)$,$\Sigma_b^-(ddb)$

The quest for b baryons



Plus there is a J = 3/2 baryon multiplet

Λ_b(udb)

discovered by UA1 in 1991

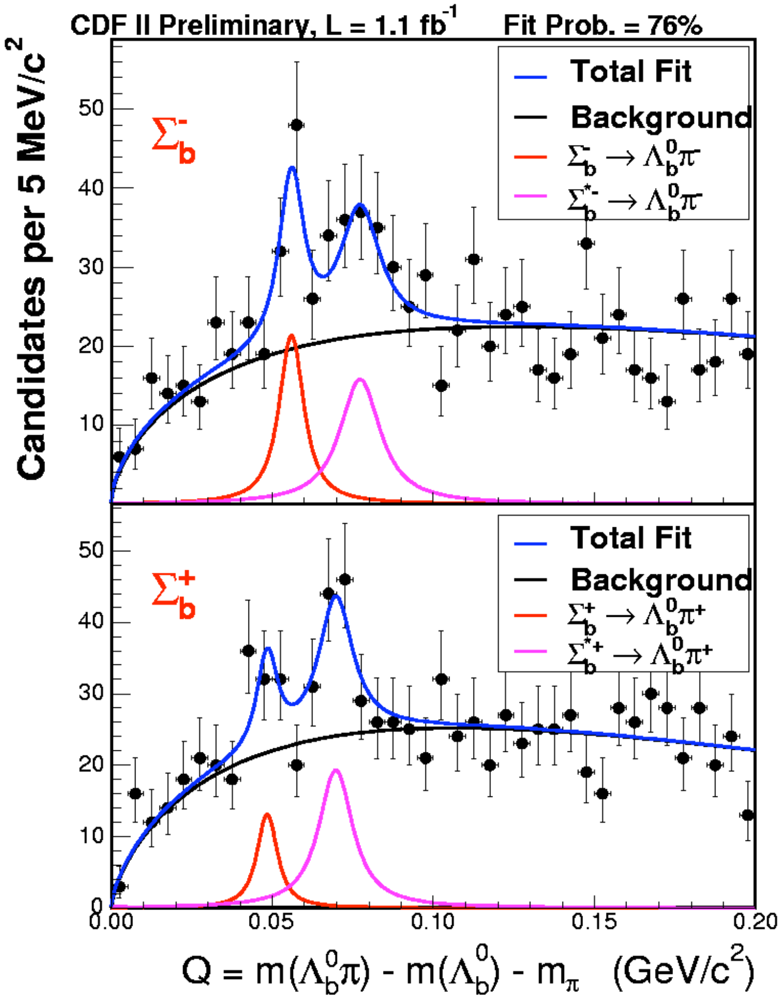
Σ_b(uub,ddb,udb)

discovered by CDF in 2006/2007

Ξ_b^-(dsb) ?

made of one quark from each generation

Σ_b^+, Σ_b^- observation



$\Sigma_b^+ = (uub)$

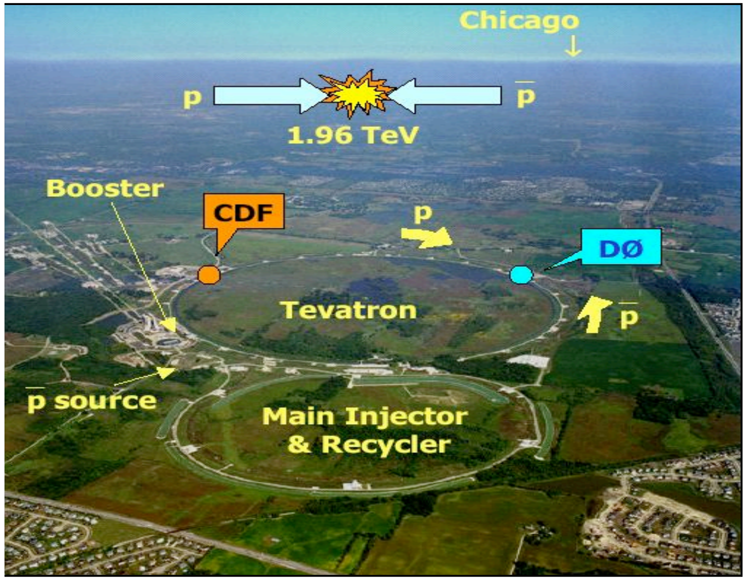
$\Sigma_b^- = (ddb)$

CDF analyzed

$\Sigma_b^\pm \to \Lambda_b \pi^\pm$

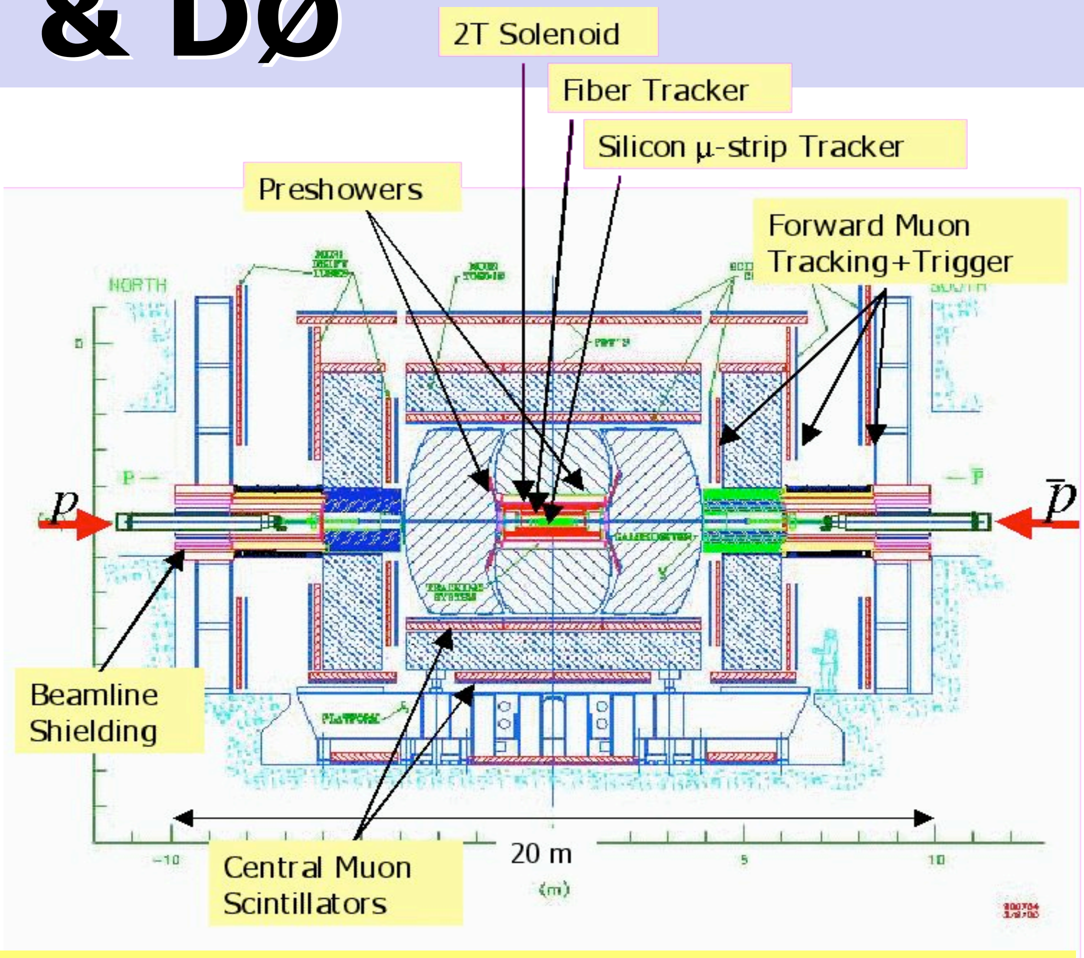
- October 2006 preliminary result
- June 2007, submitted for publication

The Tevatron & DØ



Tevatron is doing great:

Int. Lumi.	fb^{-1}
Delivered	>3
DØ Run IIa	1.3
D0 Run IIb	1.3

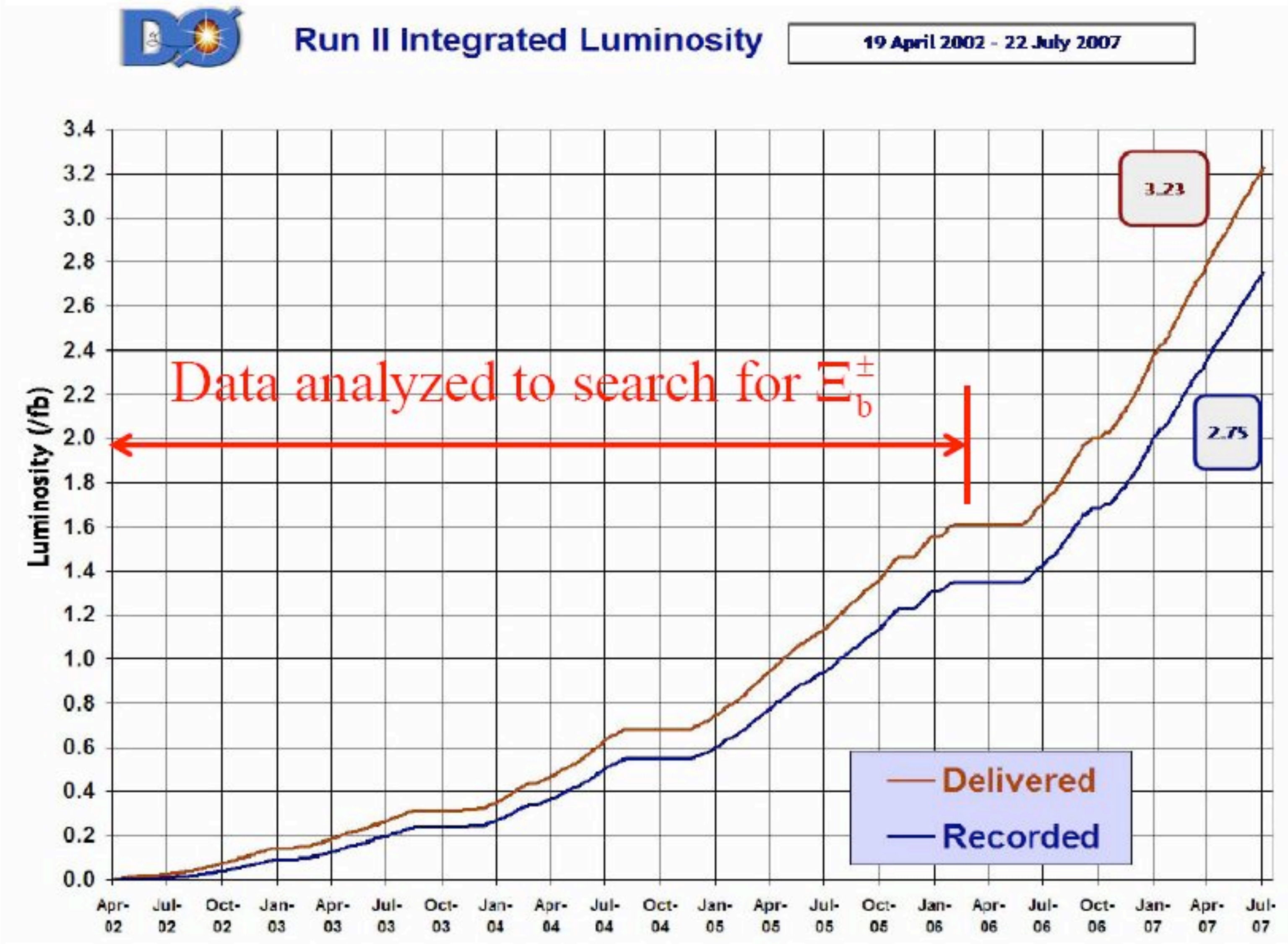


Excellent, large angle, muon spectrometer and trigger.
Large B→μ semileptonic and B→*J/ψ*+X samples

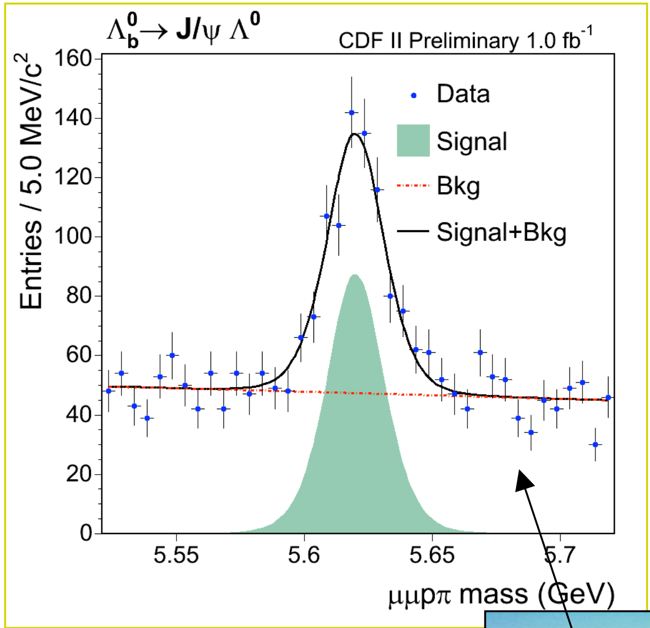
Run IIb addition:

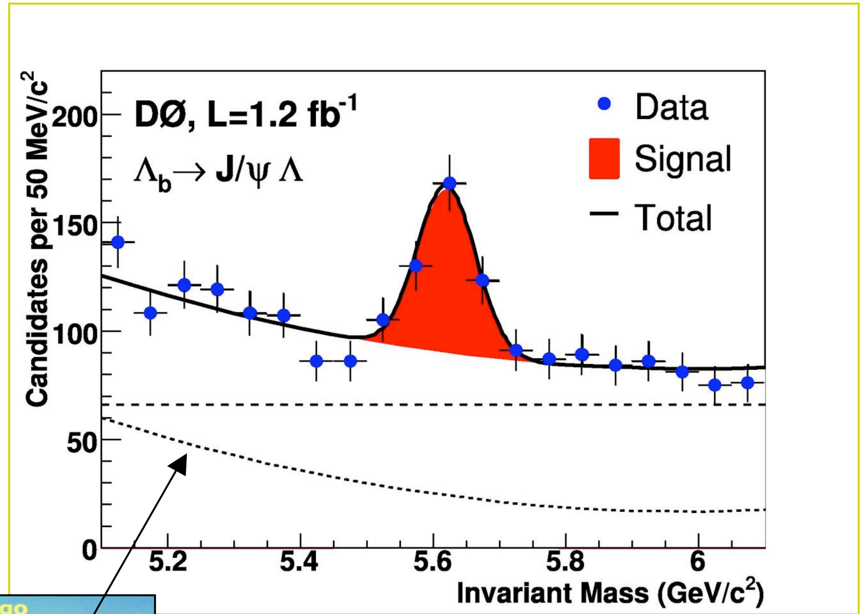
Silicon Layer Ø

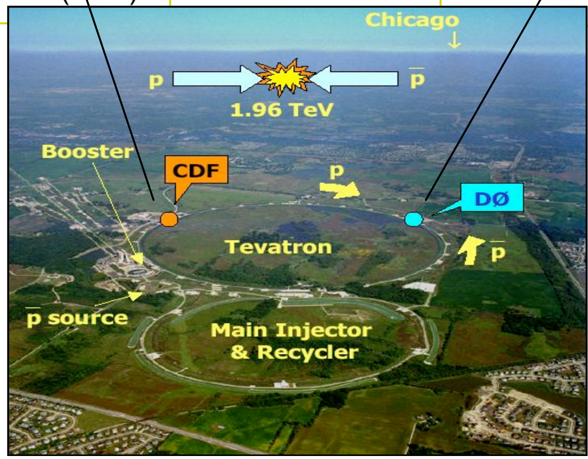
Data


Run II Integrated Luminosity
19 April 2002 - 22 July 2007
Luminosity (/fb)
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Apr-02 Jul-02 Oct-02 Jan-03 Apr-03 Jul-03 Oct-03 Jan-04 Apr-04 Jul-04 Oct-04 Jan-05 Apr-05 Jul-05 Oct-05 Jan-06 Apr-06 Jul-06 Oct-06 Jan-07 Apr-07 Jul-07
3.23
2.75
Data analyzed to search for $\Xi_b^\pm$
Delivered
Recorded

Triggering the Ξ_b search







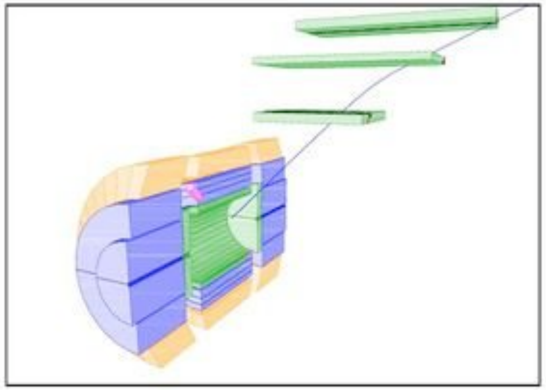
In approximately the same size of data sample, we have less (~1/3 only) $\Lambda_b \rightarrow J/\psi\Lambda$ events.

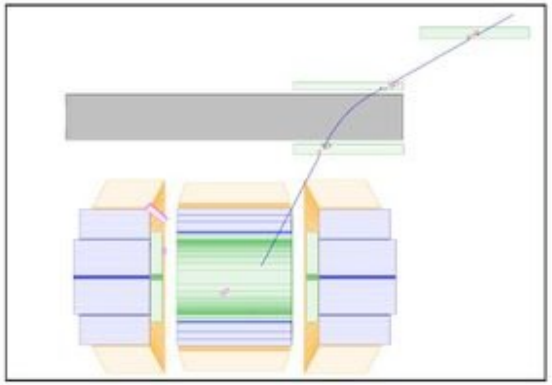
What do we know about the Ξ_b^-?

- Predicted mass: 5.7 - 5.8 GeV
- Predicted to follow the mass hierarchy
  - $M(\Lambda_b) < M(\Xi_b^-) < M(\Sigma_b)$
- By using preliminary Σ_b mass measurement from CDF and predicted mass hierarchy:
  - $5.624 \text{ GeV} < M(\Xi_b^-) < 5.8 \text{ GeV}$
- Ξ_b^- lifetime by LEP: 1.42 +0.28/-0.24 ps. (Indirect measurement) *

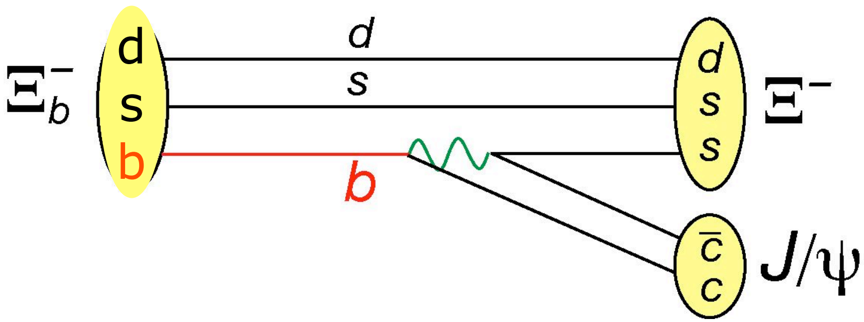
* This is the world average (ALEPH+DELPHI). HFAG: arXiv:0704.3575 [hep-ex]

How do we look for this particle?

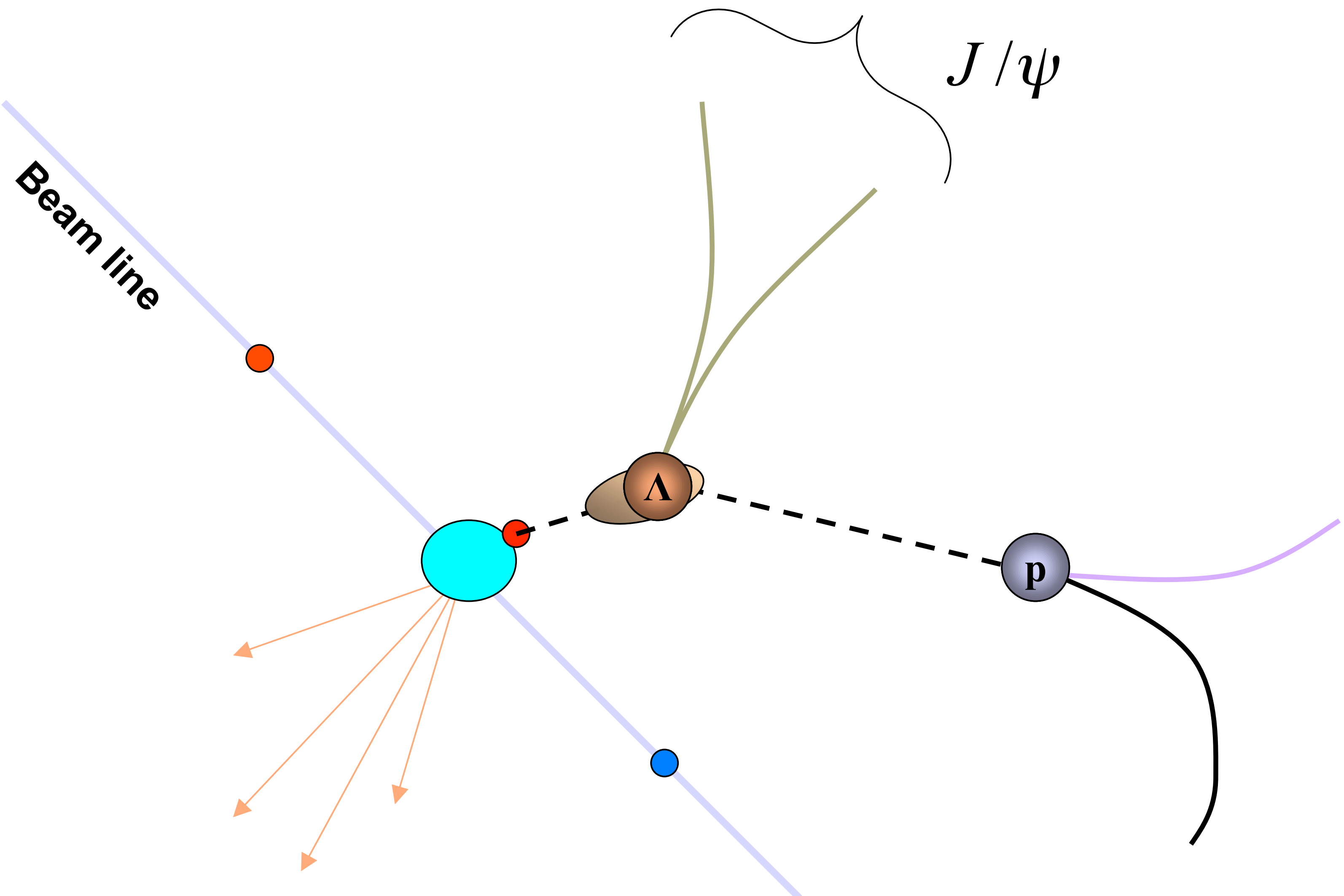




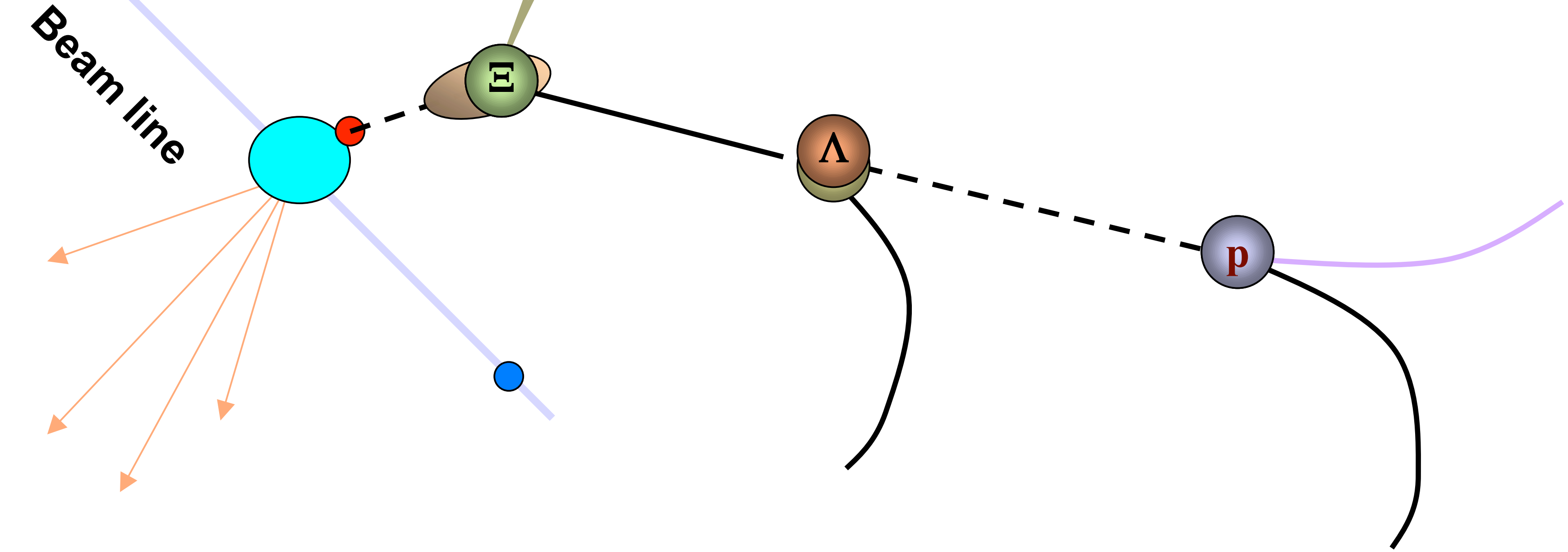
- We have an excellent dimuon sample.
- We have experience in $\Lambda_b \rightarrow J/\psi\Lambda$ (~170 events)
- Then we look in the decay $\Xi_b^- \rightarrow J/\psi + \Xi^-$ (This could be very rare!)

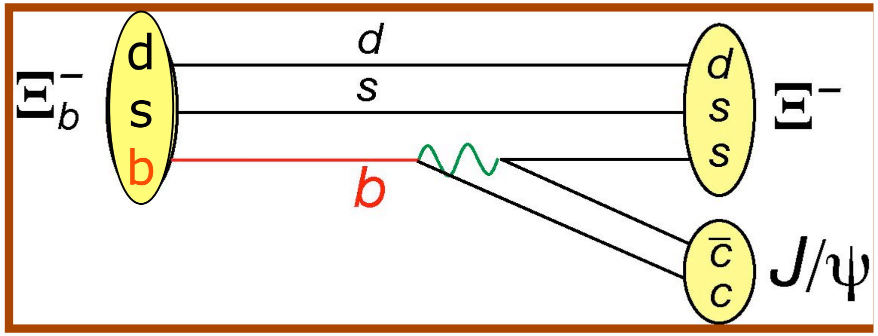


The sister ... $\Lambda_b \to J/\psi \Lambda$



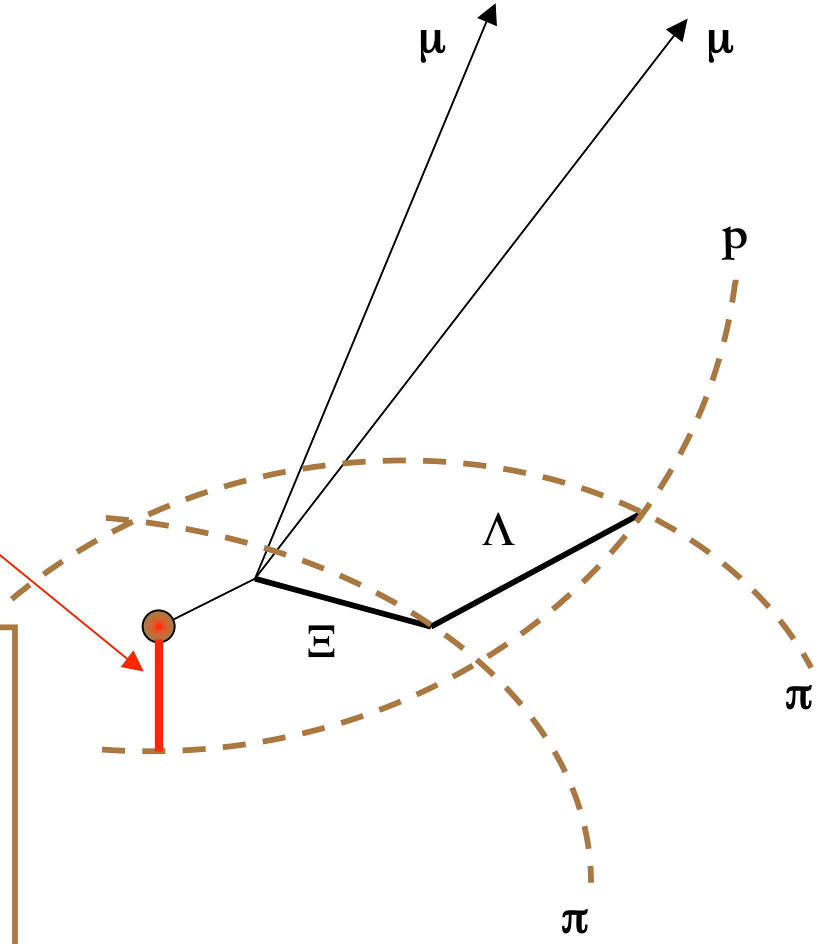
Searching for Ξ_b in $\Xi_b^- \rightarrow J/\psi + \Xi^-$





IP cut … a killer

When tracks are reconstructed, a maximum impact parameter is required to increase the reconstruction speed and lower the rate of fake tracks.

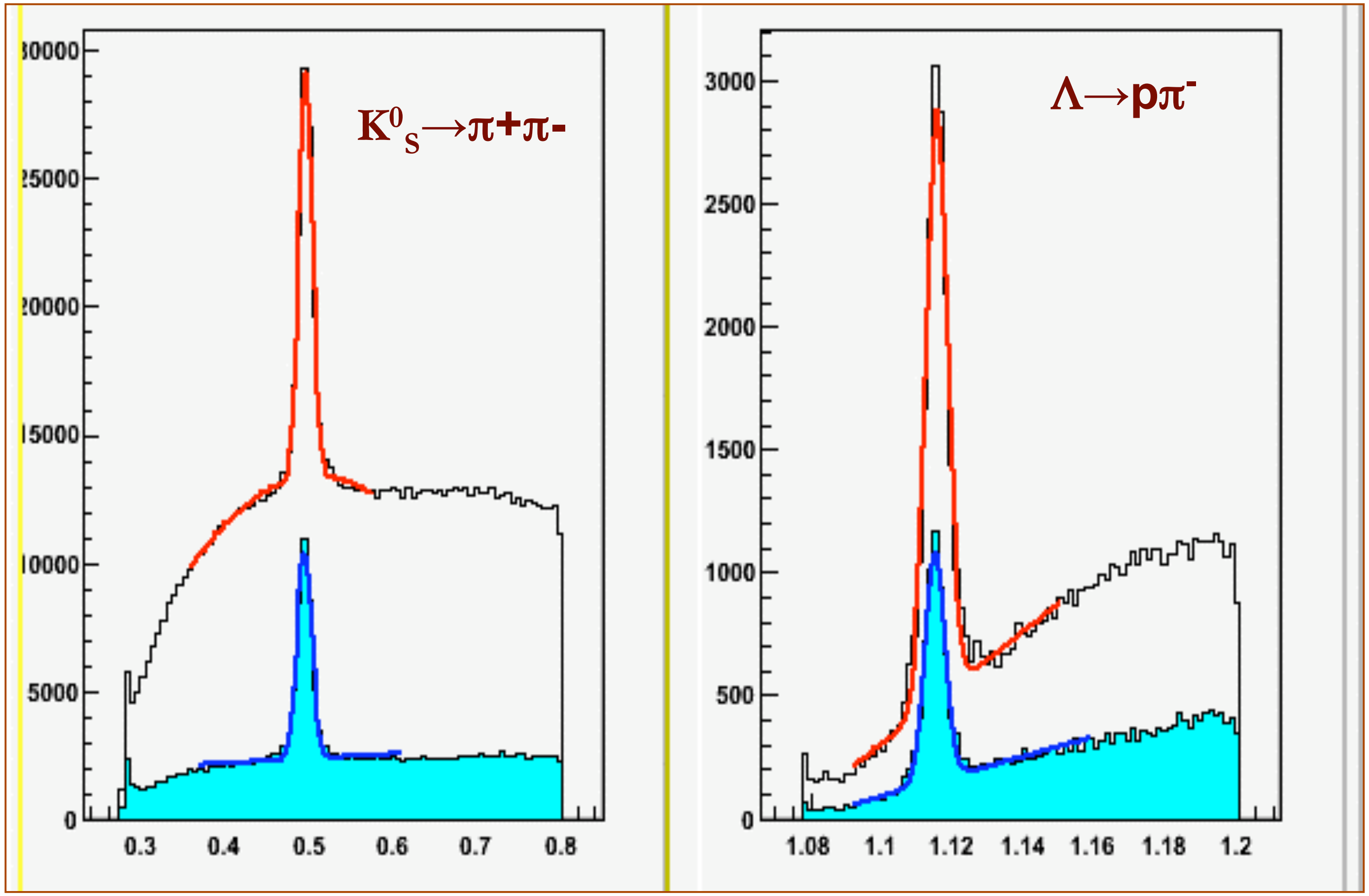


But for particles like the Ξ_b^-, this requirement could result in missing the π and proton tracks from the Λ and Ξ^- decays

What did we do to solve this problem?

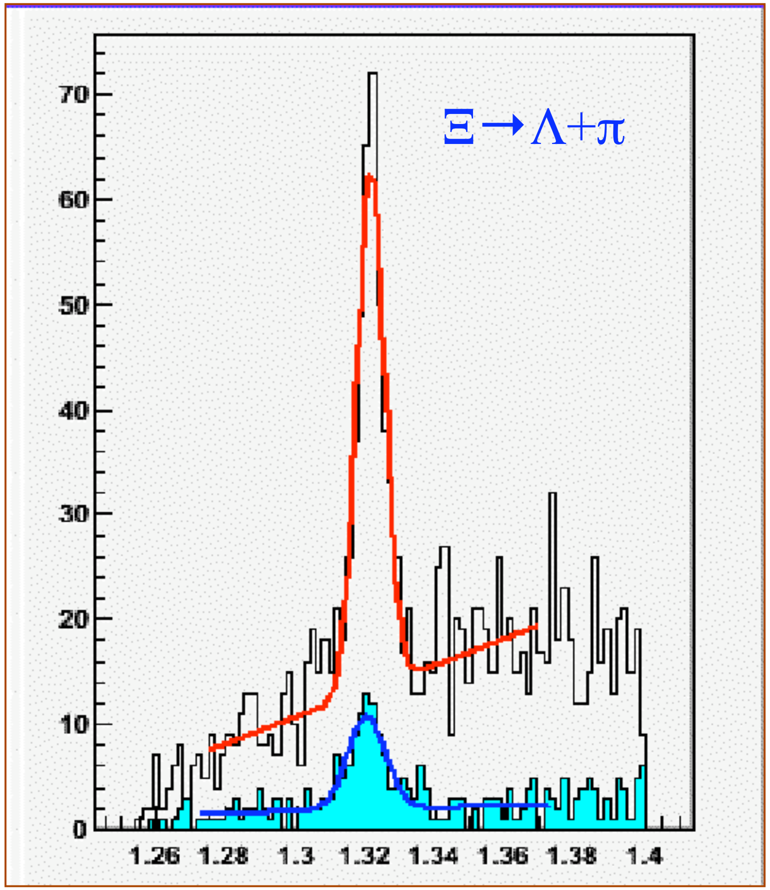
- We need to open up the IP at reconstruction
- To reprocesses all DØ data with a wider IP for track reconstruction is a very difficult task.
- The $J/\psi \to \mu^+\mu^-$ is a golden channel. Although $B \to J/\psi X$ is fairly rare, it is very clean channel and easy to trigger on.
- We therefore reprocessed DØ RunIIa data for events containing a J/ψ, which is ~35 million events.

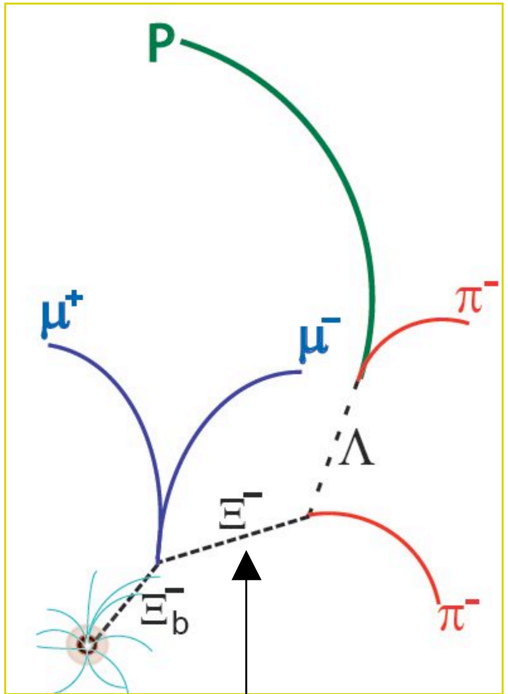
Mass distribution for K^0 and Λ signals for the "standard" (bottom histograms) and "extended" (opening up IP) tracks reconstruction.



Ξ^- Yield

The Ξ yield increased a factor of five from reprocessing



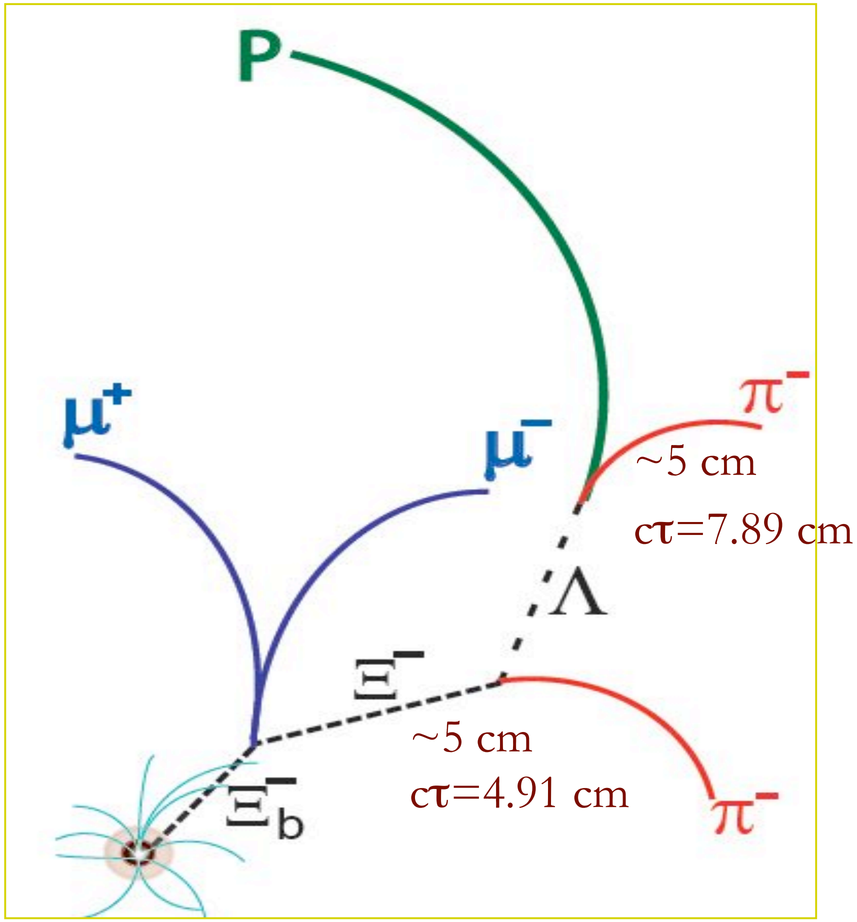


Reconstruction strategy for Ξ_b

- Reconstruct $J/\psi \rightarrow$ [illegible] μ-
- Reconstruct $\Lambda \rightarrow p\pi$
- Reconstruct $\Xi \rightarrow$ [illegible] π
- Combine $J/\psi + \Xi$
- Improve mass resolution by using an event-by-event mass difference correction .
- We need some guides to look for a particle:
  - The sister: $\Lambda_b \rightarrow J/\psi\Lambda$ decays in data
  - The impostor: $J/\psi + \Xi$(fake from $\Lambda(p\pi^-)\pi^+$)
  - The clone: Monte Carlo simulation of $\Xi_b^- \rightarrow J/\psi + \Xi^-$

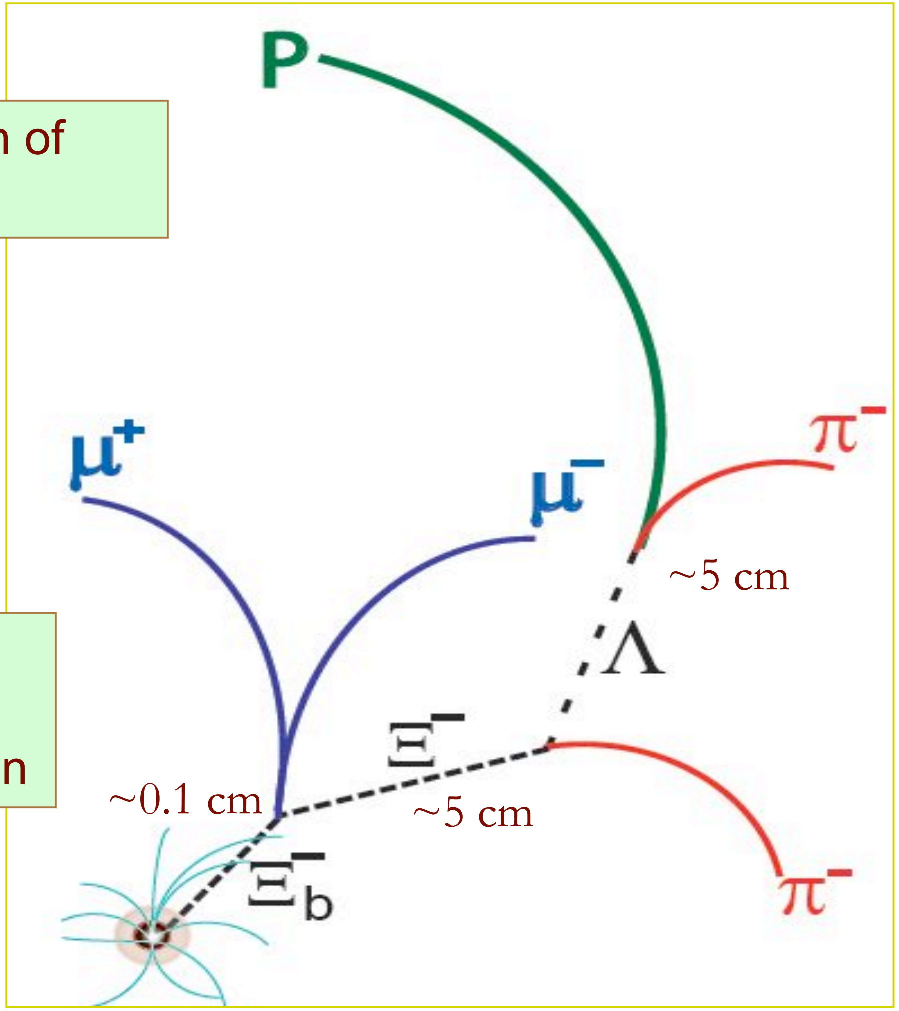
Natural constraints in $\Xi_b^- \rightarrow J/\psi + \Xi^-$

- Three daughter signal particles need to be reconstructed:
  - $\Lambda \rightarrow p + \pi$
  - $\Xi \rightarrow$ [illegible] π
  - $J/\psi \rightarrow$ [illegible] μ-
- The final state particles (p, π^-, π^-) have significant impact parameter with respect to the interaction point.
- Charge correlation: both pions must have the same charge



More features in $\Xi_b^- \rightarrow J/\psi + \Xi^-$

Ξ- has a decay length of few centimeters.

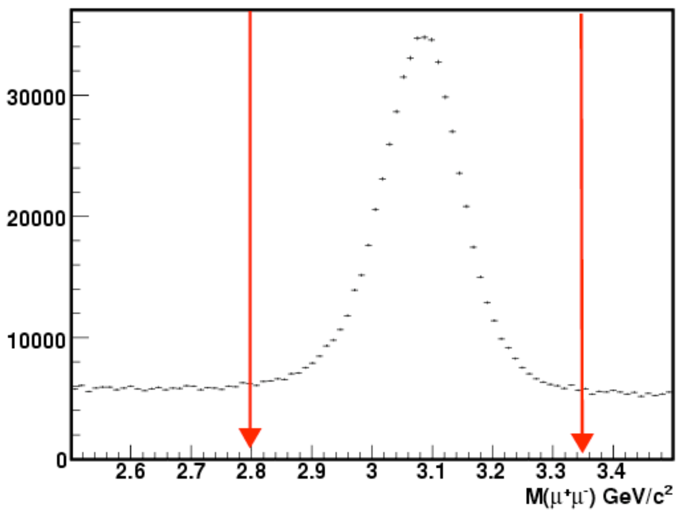


Λ has a decay length of few centimeters

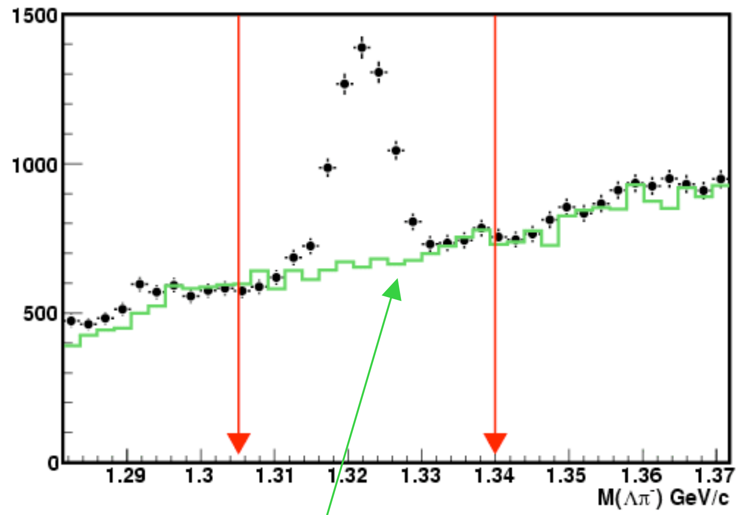
Ξ_b has a decay length of few hundred microns, PV separation

Reconstructing the daughters

$J/\psi \rightarrow$ [illegible] μ-



$\Xi \rightarrow$ [illegible]



Background events from wrong-sign combinations ($\Lambda(p\pi^-)\ \pi^+$)

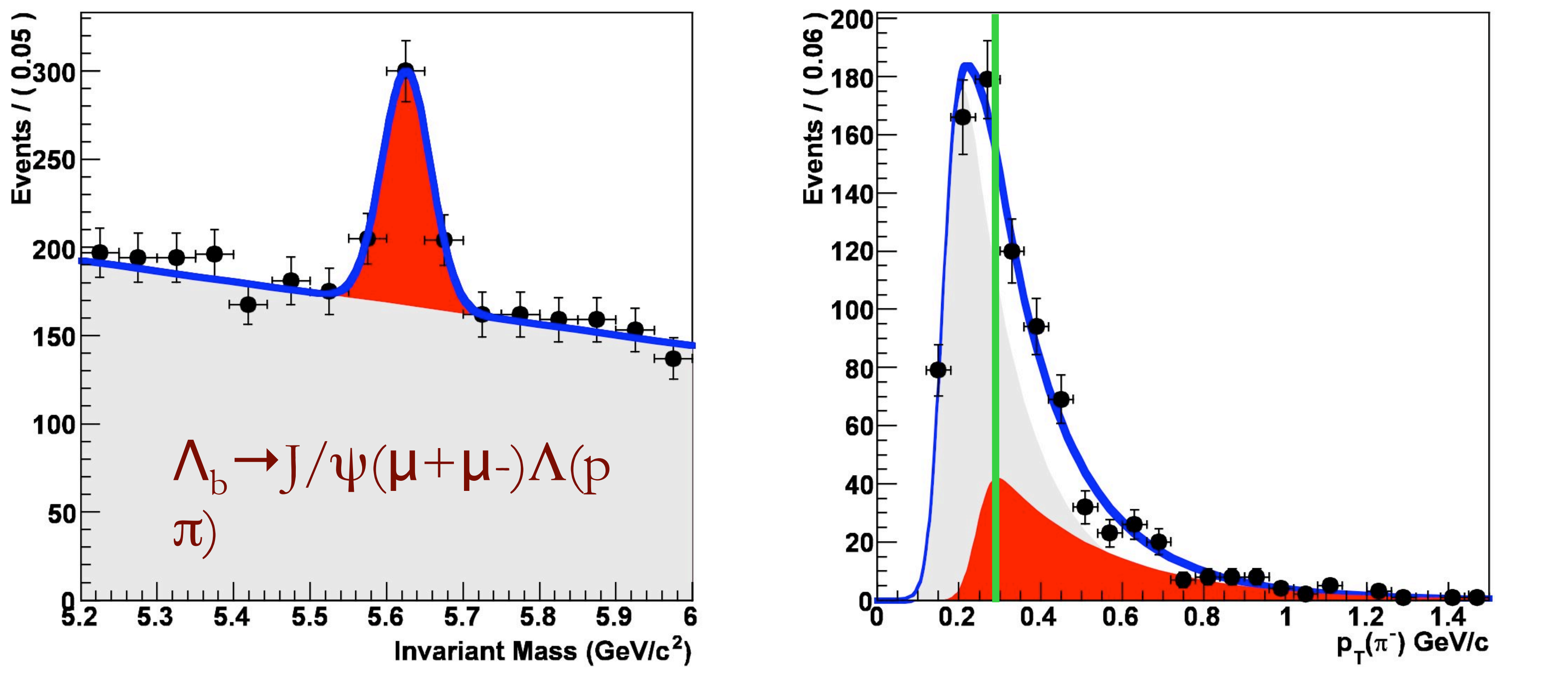
What background do we expect?

- Prompt background:
  - ~80% of the J/ψ are directly produced at the collision.
- Real B's:
  - The remaining ~20% of J/ψ come from B decays
- Combinatory background:
  - Real J/ψ plus fake Ξ^-
  - Fake J/ψ plus fake Ξ^-
  - Fake J/ψ plus real Ξ^-
  - Real J/ψ plus real Ξ^- , but not from Ξ_b^-

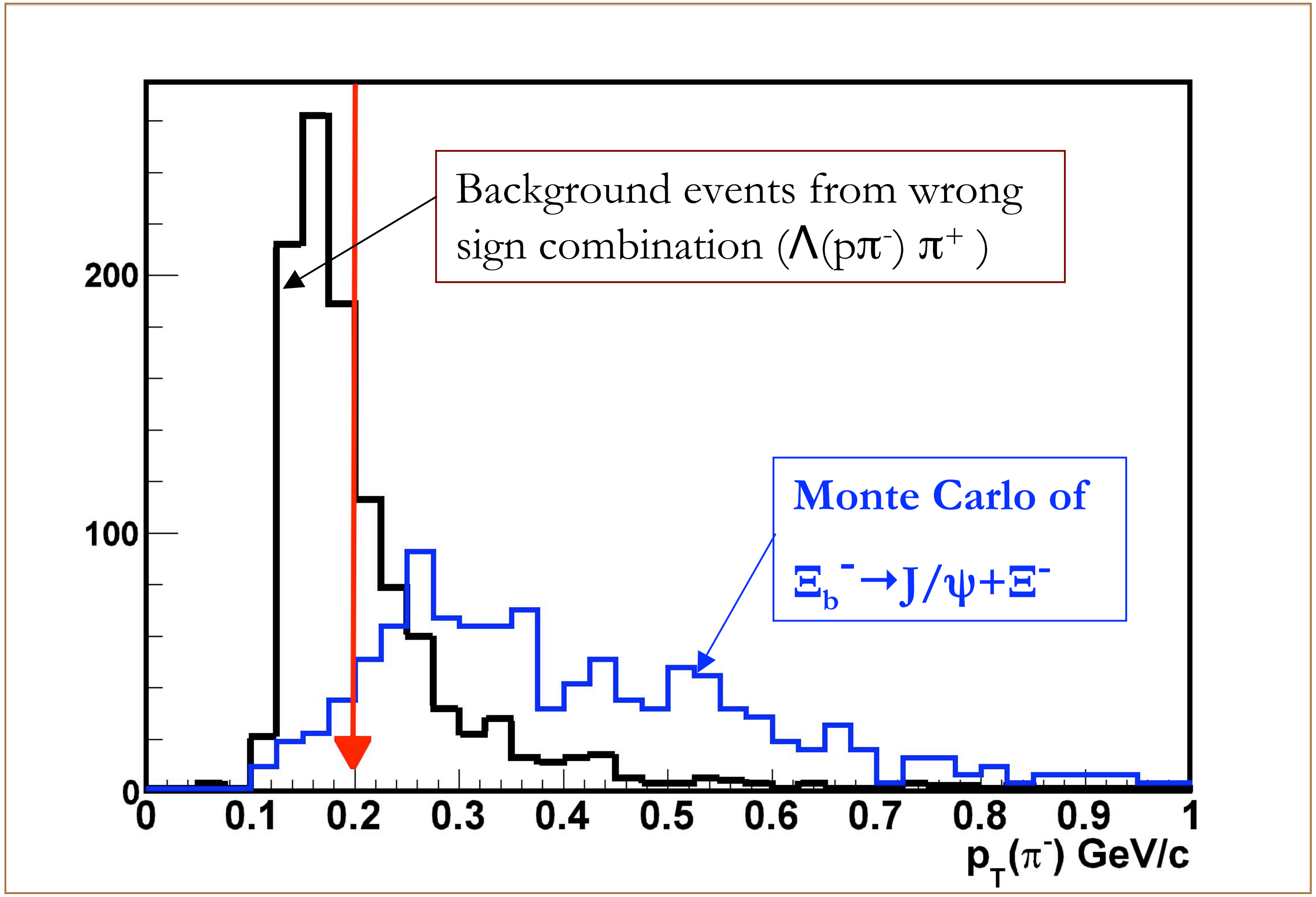
Determination of Selection Criteria

- To retain efficiency, try to keep cuts loose
- We use independent samples:
  - $\Lambda_b \to J/\psi\Lambda$ decays from data
  - Background from wrong-sign combination
  - Background from J/ψ sideband events
  - Background from Ξ^- sideband events
  - Use Ξ_b^- signal MC events only when no choice (e.g., pion from Ξ^-)

Example 1: pT(π^-) from Λ



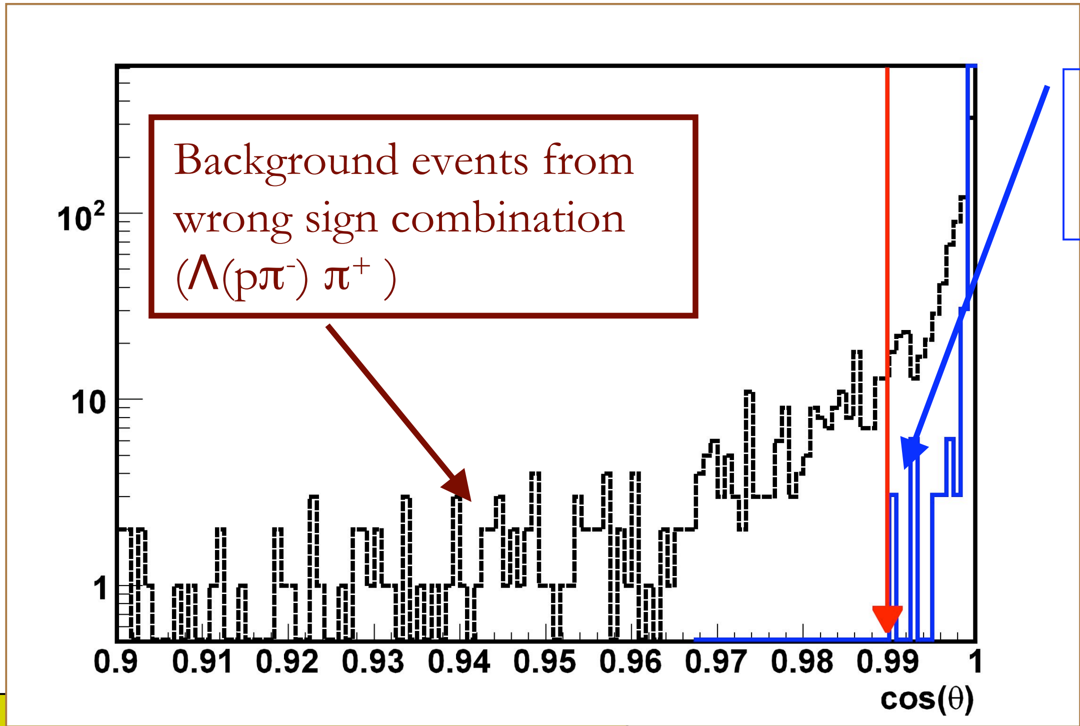
Example 2: pT(π^-) from Ξ^-



Example 3: topological cut

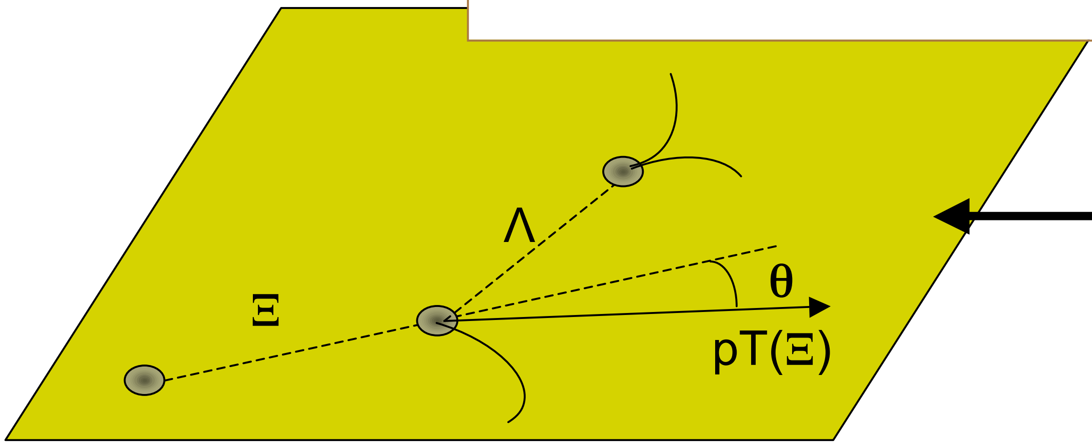
$\cos(\theta) > 0.99$

100% efficiency



Monte Carlo of

$\Xi_b^- \rightarrow J/\psi + \Xi^-$



Collinearity in XY:

Cosine(θ)

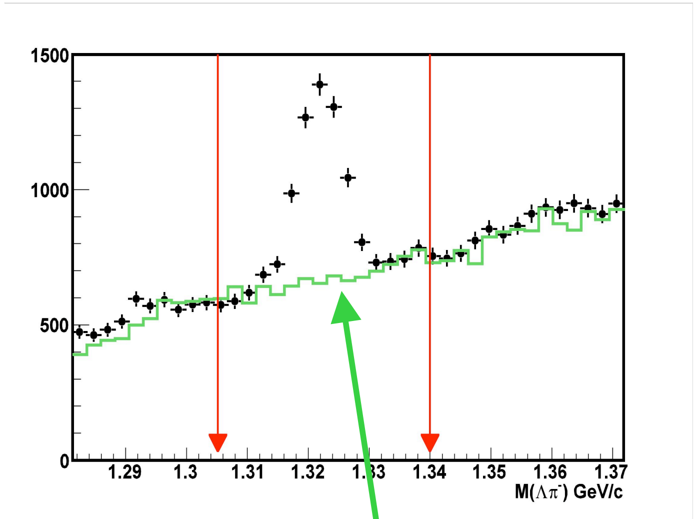
Ξ_b Selection

- $\Lambda \to p\pi$ decays:
  - pT(p)>0.7 GeV
  - pT(π)>0.3 GeV
- $\Xi^- \to \Lambda\pi$ decays:
  - pT(π)>0.2 GeV
  - Transverse decay length>0.5 cm
  - Collinearity>0.99
- Ξ^-_b particle:
  - Lifetime significance>2. (Lifetime divided by its error)

So now … let's first look at the background control samples after all cuts

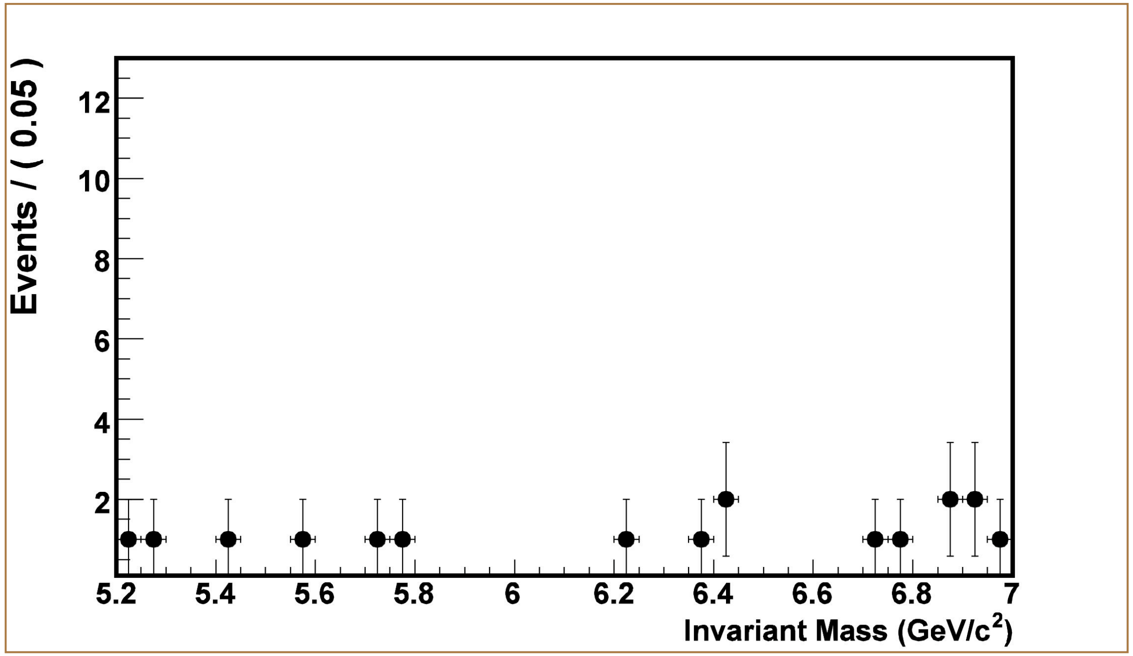
- We have three independent background samples:
  - Wrong sign combination (fake Ξ^-'s from $\Lambda(p\pi^-)\pi^+$)
  - J/ψ sideband events
  - Ξ^- sideband events.

Background: Wrong sign combinations

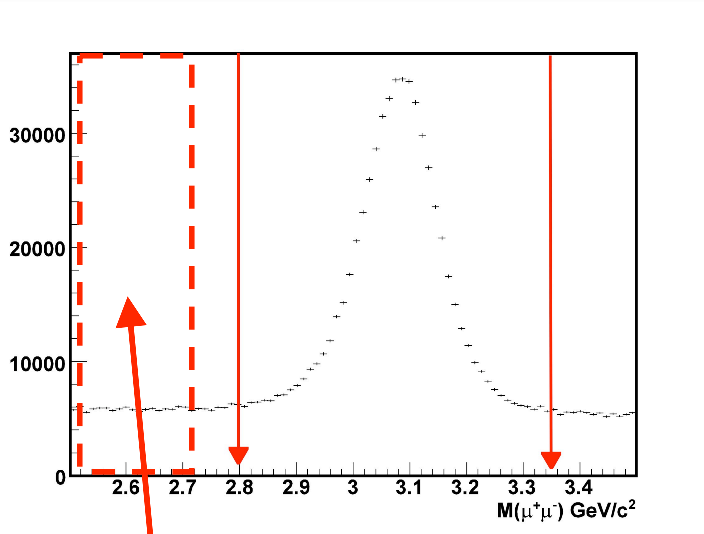


No peaking structure observed in this background control sample

$J/\psi\ \Lambda(p\pi^-)\pi^+$

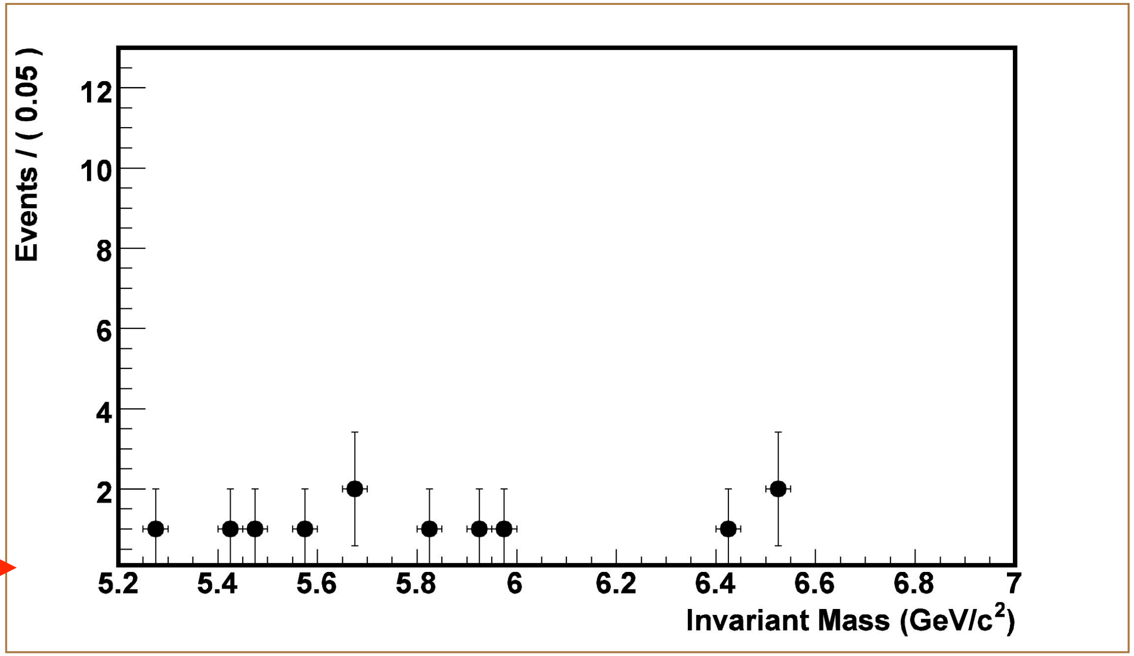


Background: J/ψ sideband events

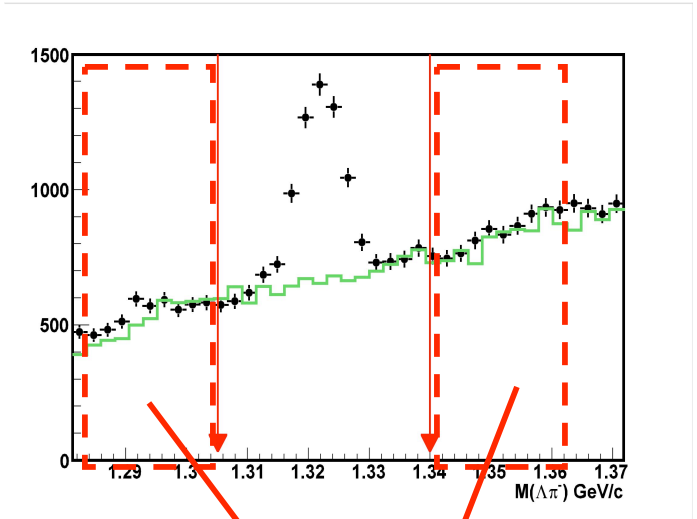


No peaking structure observed in this background control sample

$J/\psi\ \Lambda(p\pi^-)\pi^-$

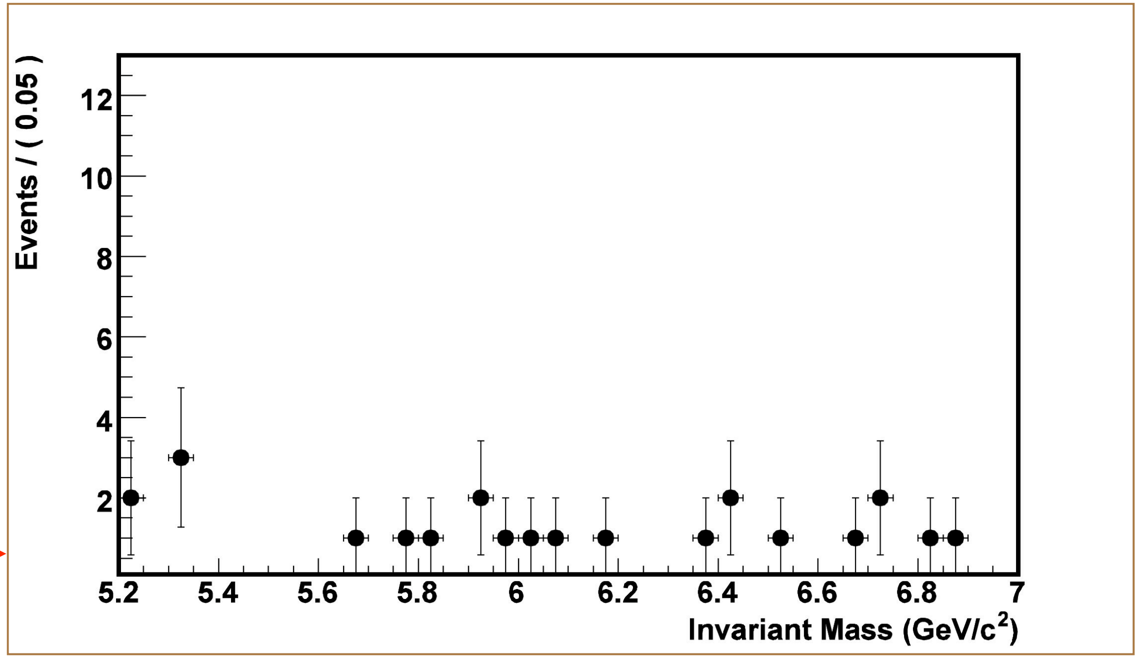


Background: Ξ^- sideband events



No peaking structure observed in this background control sample

$J/\psi\ \Lambda(p\pi^-)\pi^-$



Others backgrounds (MC)

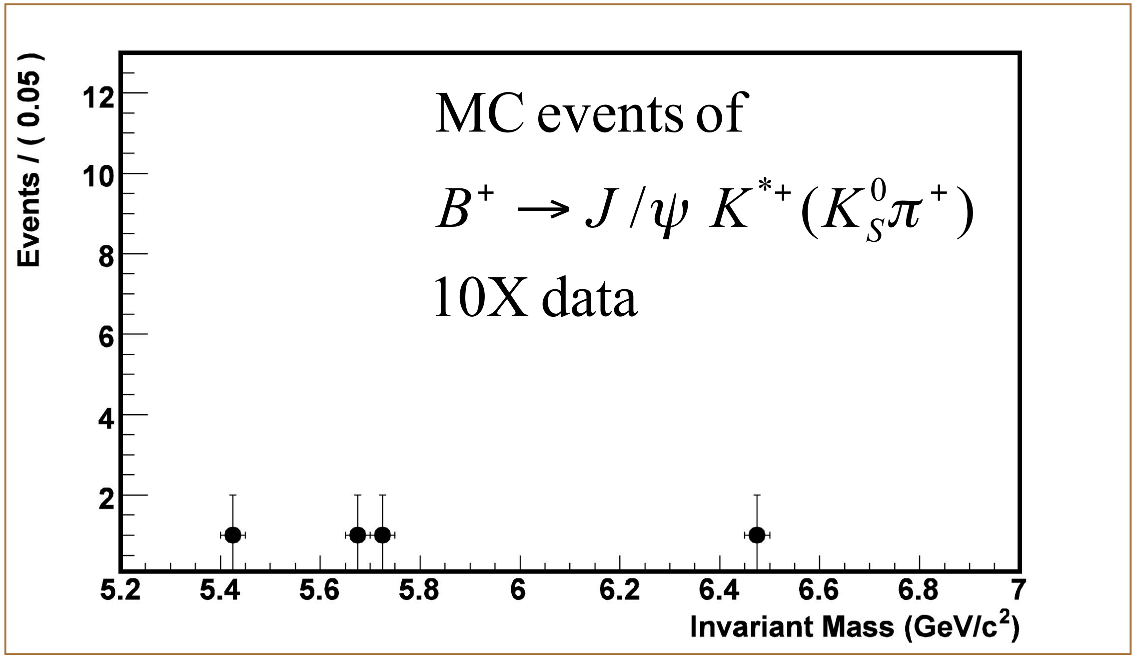
- We investigated with high MC statistics, B decay channels such as:

$$B^+ \to J/\psi\ K^{*+}(K_S^0\pi^+)$$

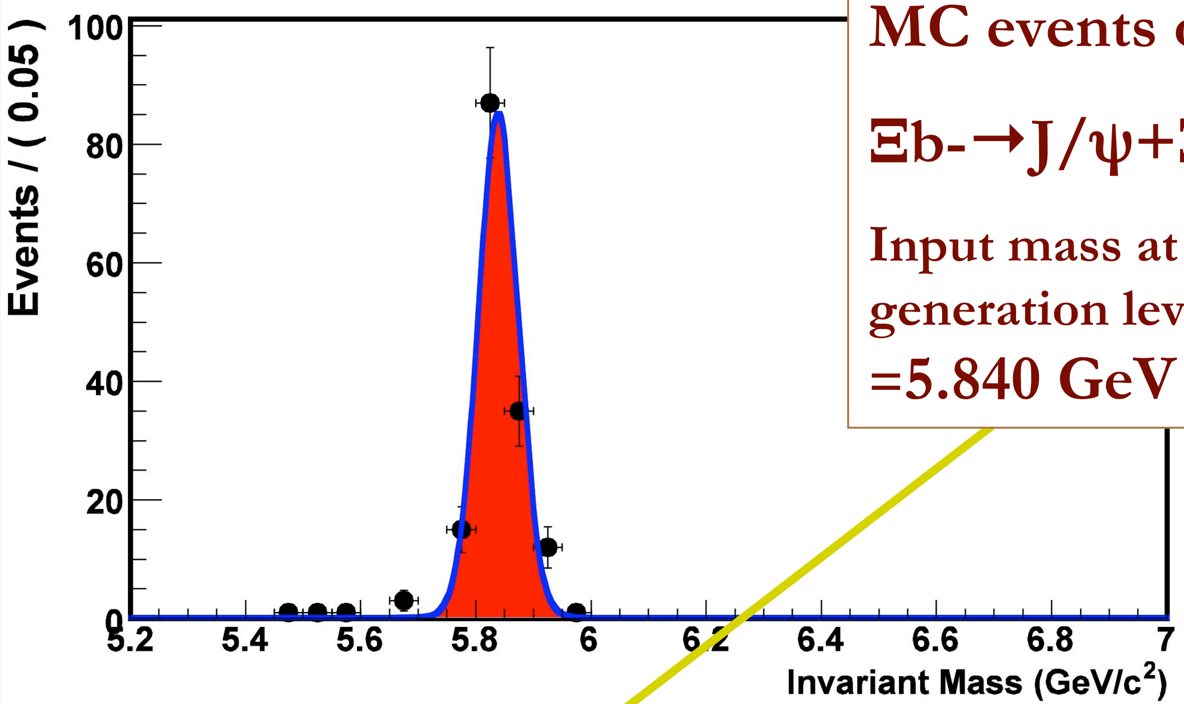
$$B^0 \to J/\psi\ K_S^0$$

$$\Lambda_b \to J/\psi\ \Lambda$$

No peaking structure observed any these B decays MC samples



What we expect: signal MC



MC events of

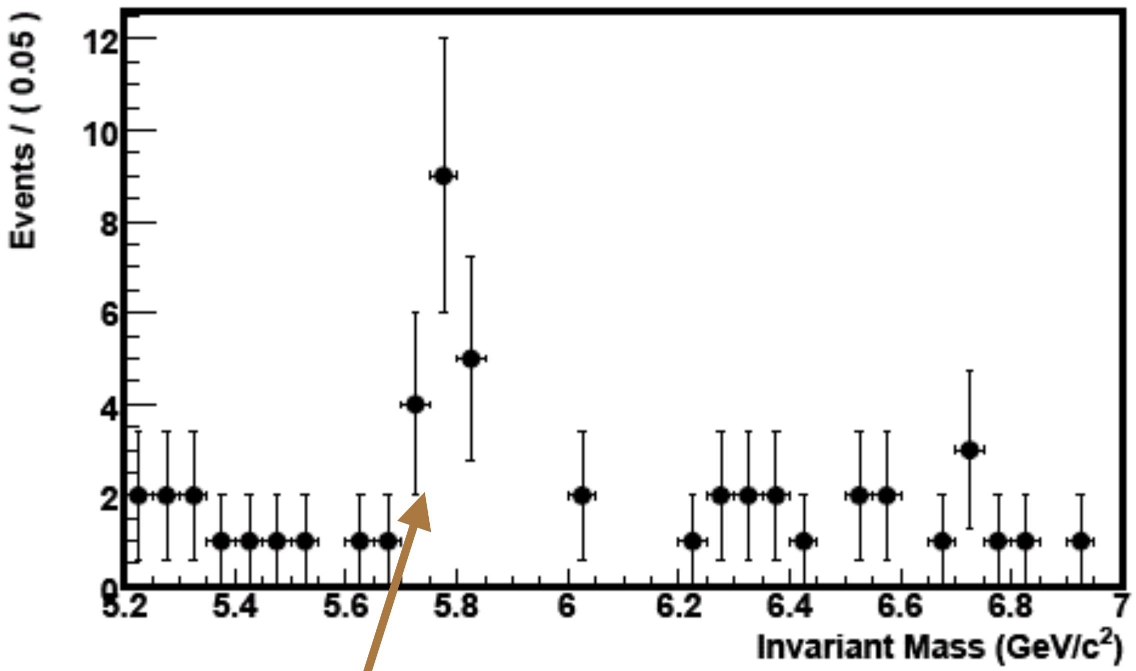
$\Xi b^- \rightarrow J/\psi + \Xi^-$

Input mass at generation level =5.840 GeV

Mean of the Gaussian: 5.839 ± 0.003 GeV

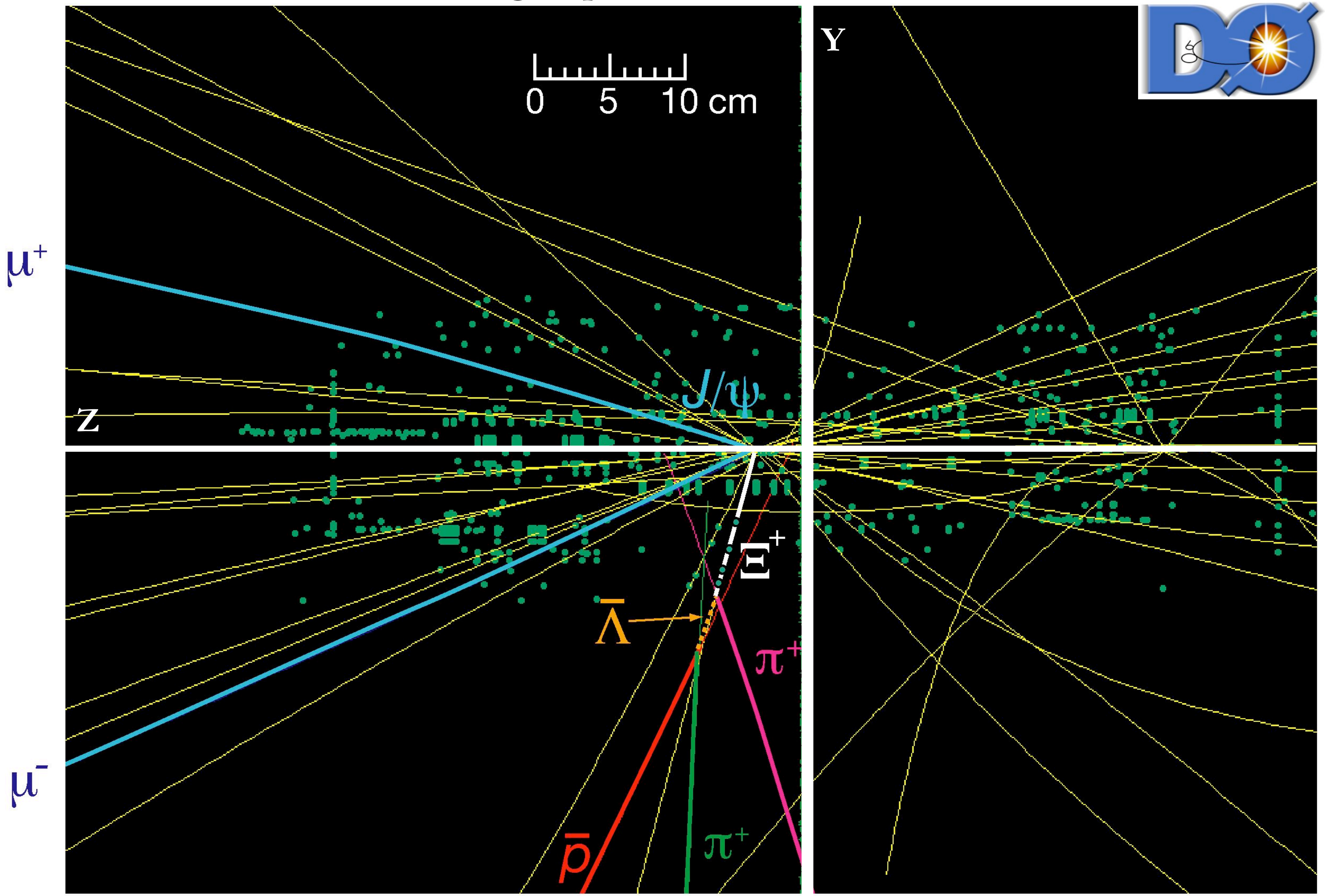
Width of the Gaussian: 0.035 ± 0.003 GeV

Looking at data



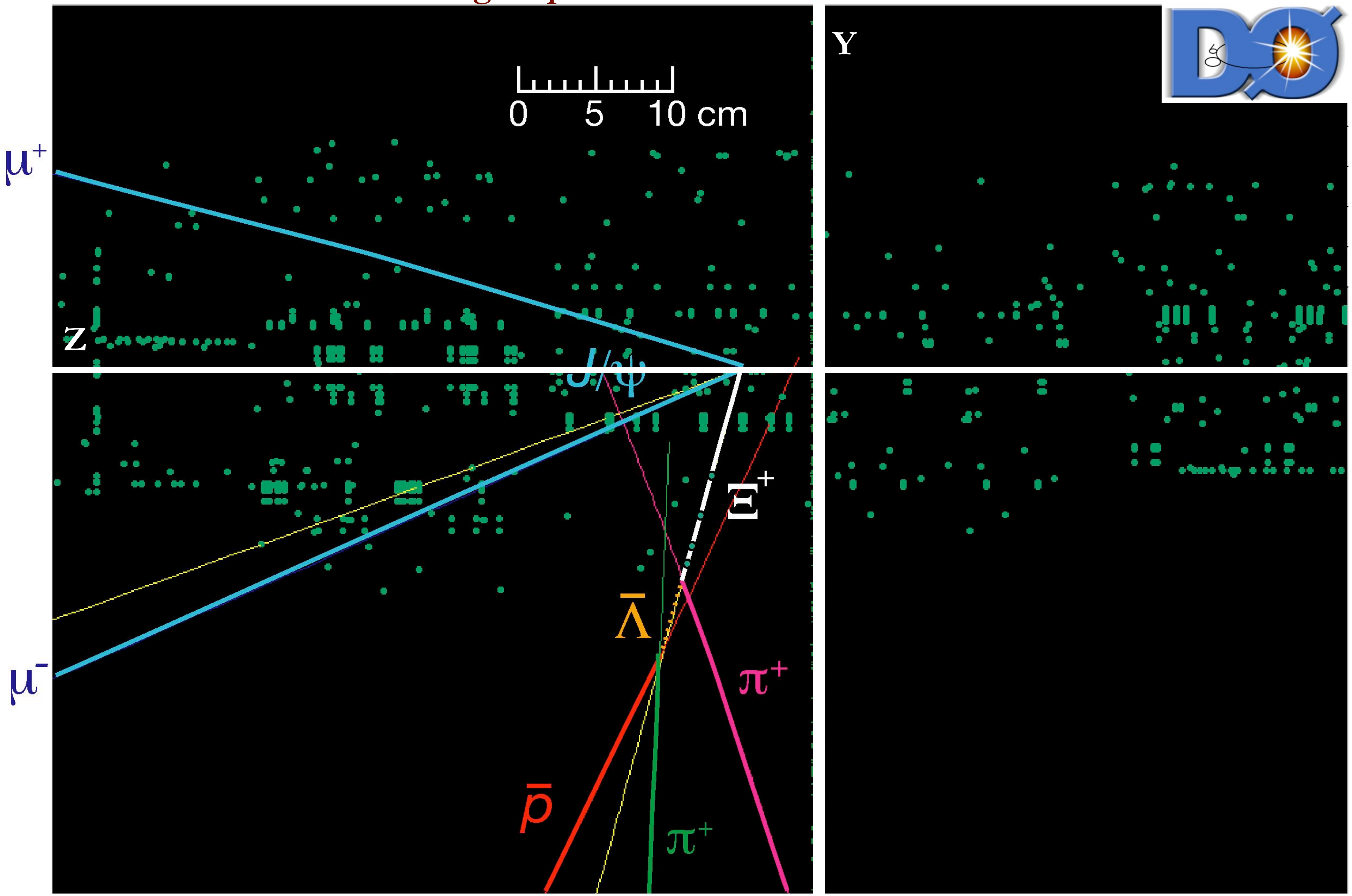
Clear excess of events just below 5.8 GeV

Event scan of event in the signal peak



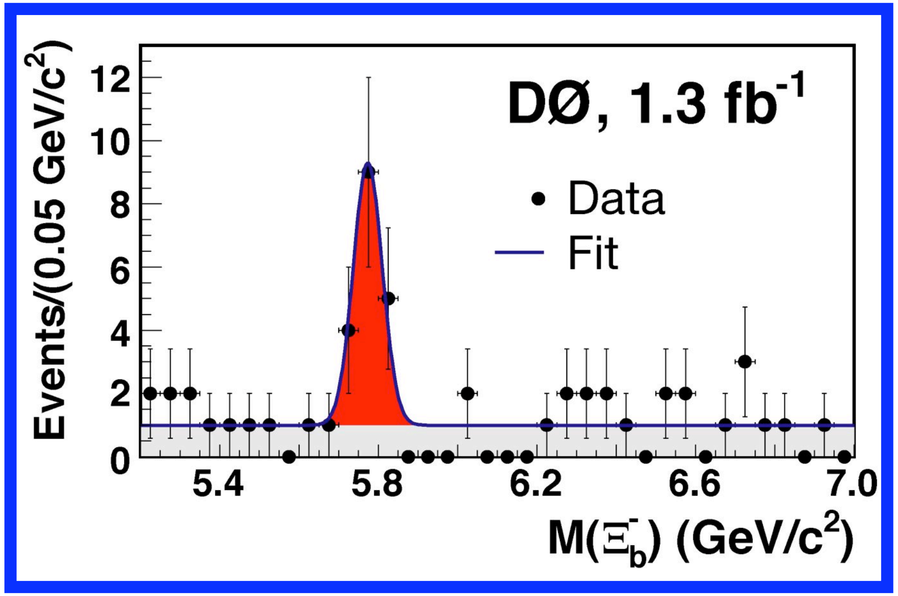
Run 179200, Event 55278820, $M(\Xi_b)$ = 5.788 GeV

Event scan of event in the signal peak



Run 179200, Event 55278820, $M(\Xi_b) = 5.788$ GeV

Mass measurement



- Fit:
  - Unbinned extended log-likelihood fit
  - Gaussian signal, flat background
  - Number of background/signal events are floating parameters

Number of signal events: 15.2 ± 4.4

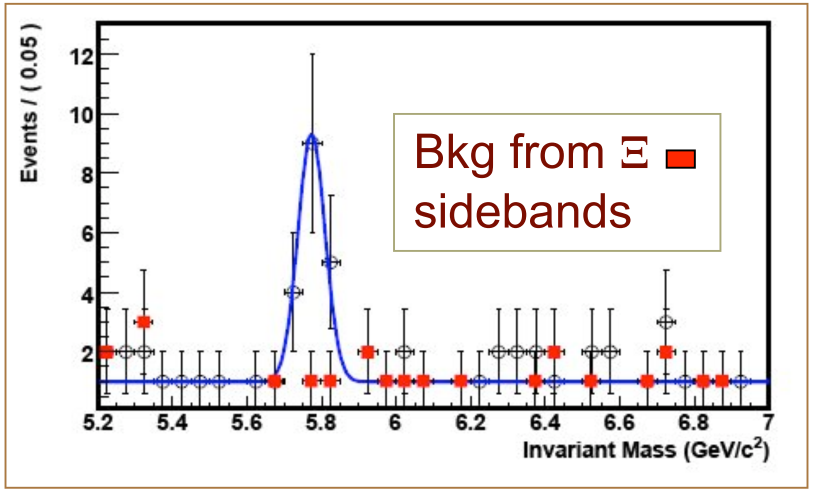
Mean of the Gaussian: 5.774 ± 0.011(stat) GeV

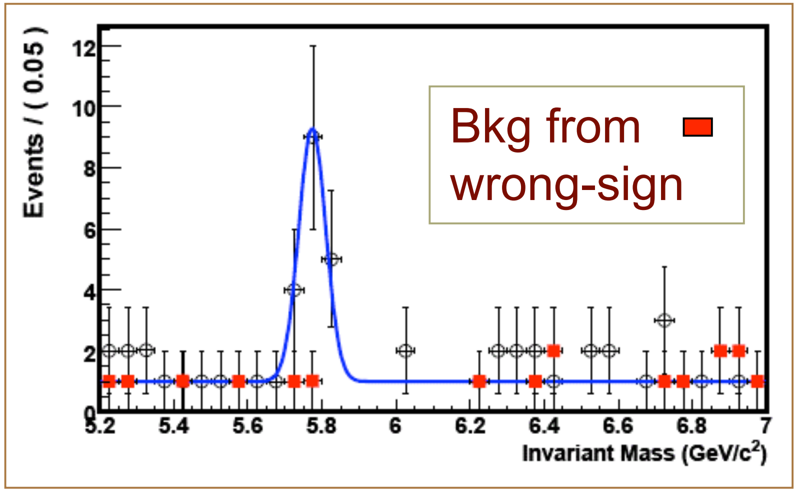
Width of the Gaussian: 0.037 ± 0.008 GeV

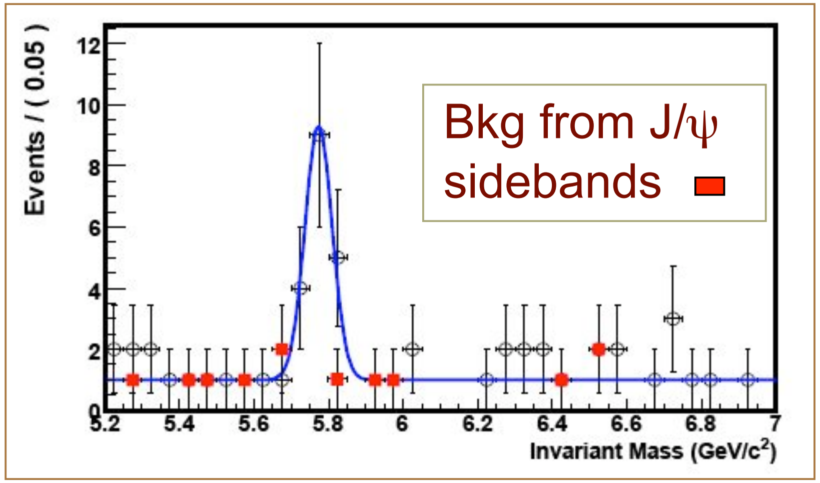
Compare to width measured in MC:

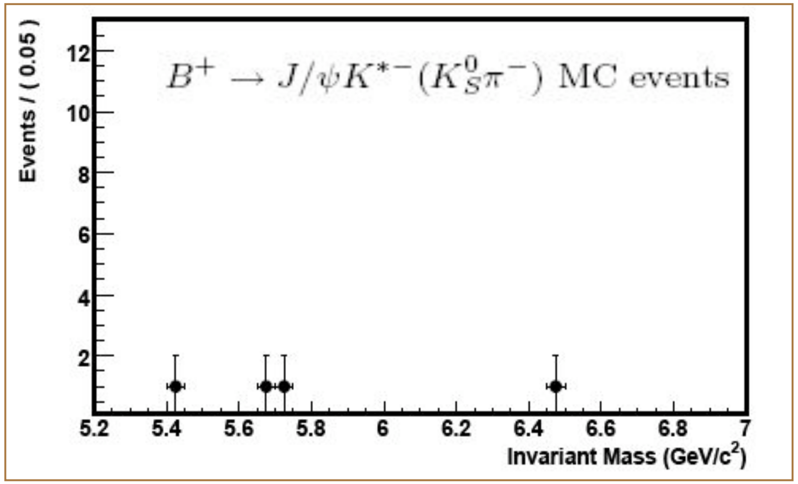
0.035 ± 0.003 GeV

Nothing in the background samples:





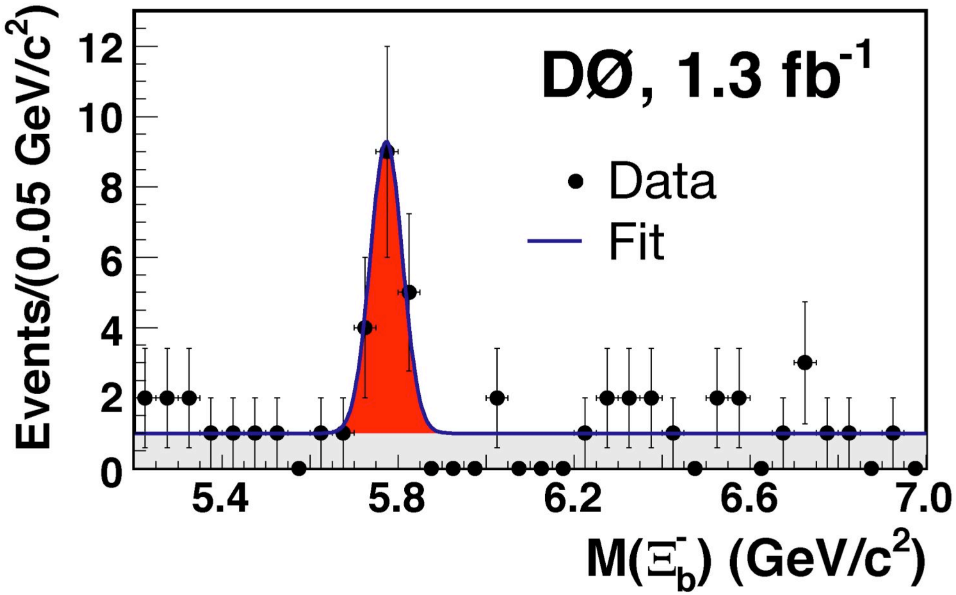




Signal significance:

- **Likelihood method, two fits:**
  - One with S+B
  - One with B only

$$\sqrt{-2\ln\left(L_{S+B}/L_B\right)} = 5.5$$



- **Simple counting in a ±2.5σ mass window:**

$$N_{obs} = 19$$

$$N_B = 3.6 \pm 0.6^{+0.6}_{-1.9}$$

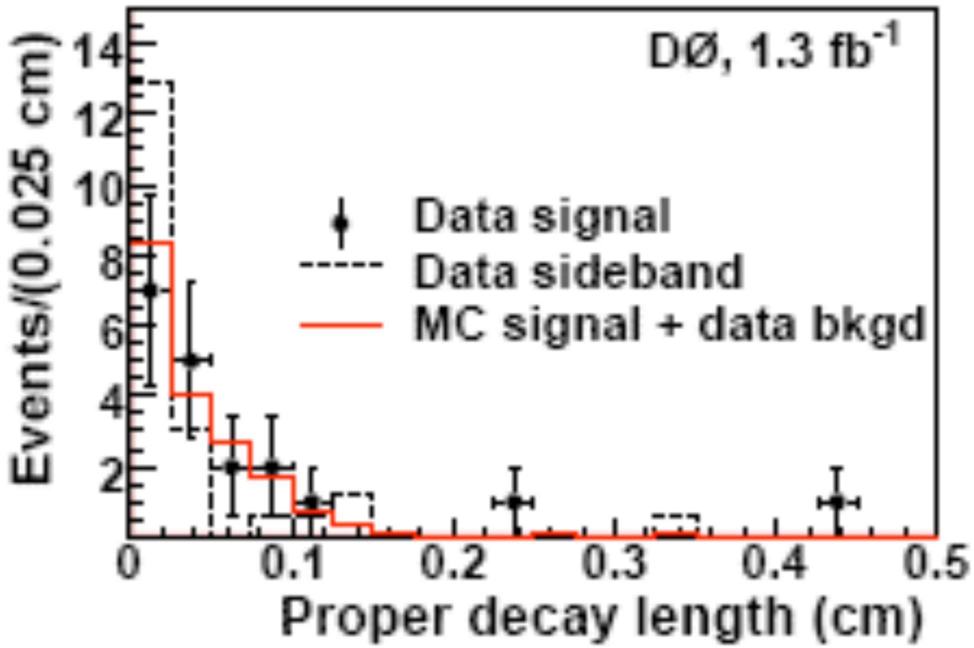
$$\Pr ob(3.6 \rightarrow 19) = 2.2\times10^{-7}$$

$$\text{or equivalently } 5.2\sigma$$

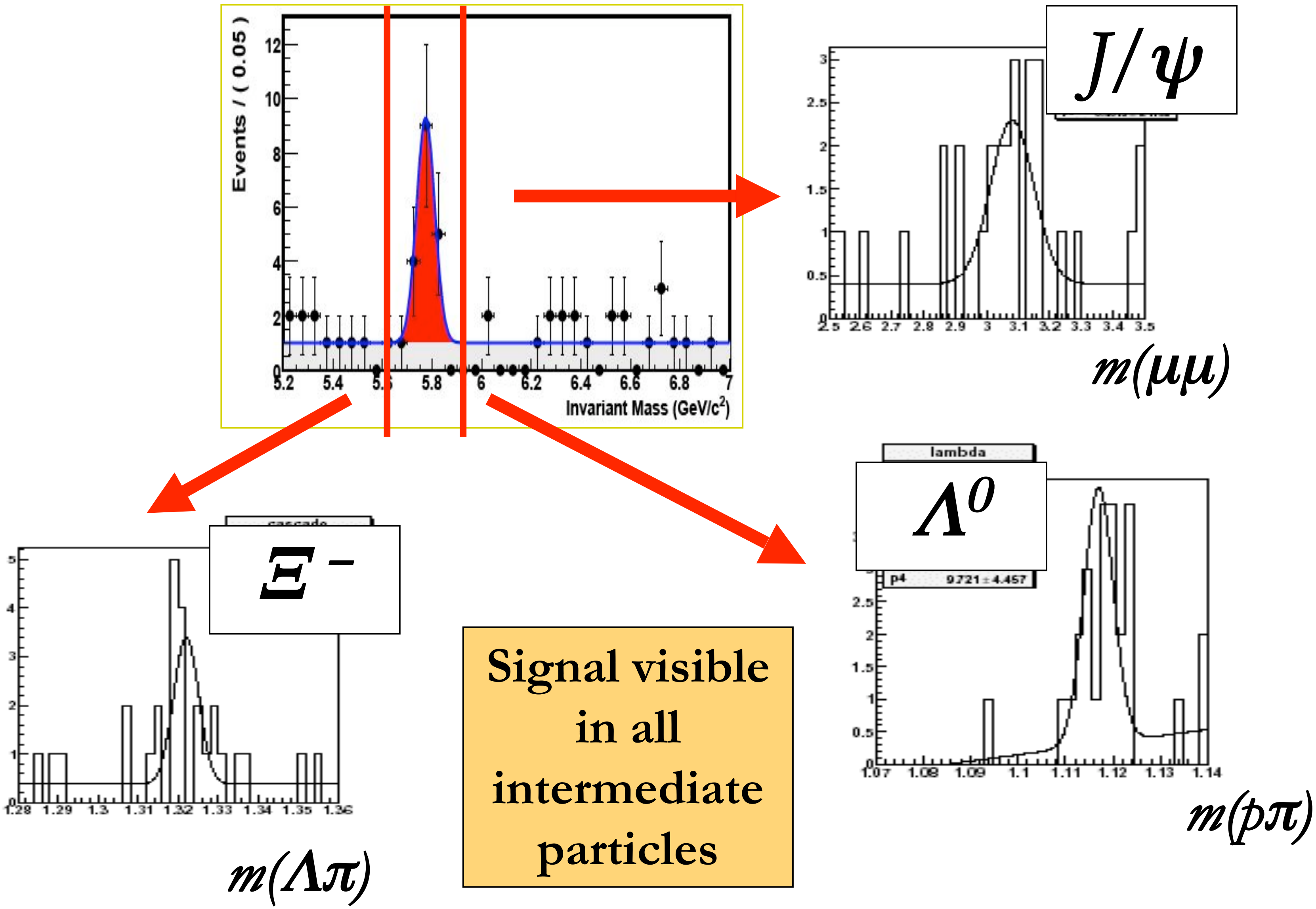
Ξ_b^- lifetime

Not enough statistics to measure lifetime,

but the decay length distribution favors signal over background by a ratio of 5 to 1



Intermediate particles



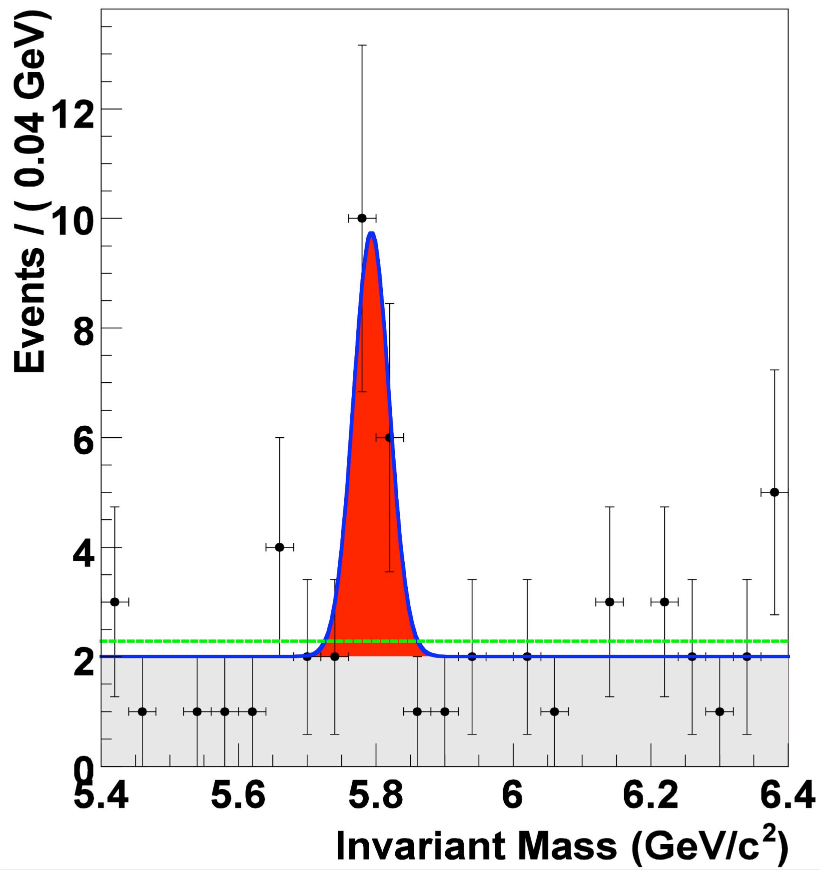
Signal visible in all intermediate particles

Decision Trees

We observed the signal using alternative decision tree based selection

- Minimum overlap between input variables of DT and cut based analysis
- Consistent with cut based analysis.
- Only ~50% overlap in the selected events between the two analysis.
- similar significance

Ξ_b^- using BDT

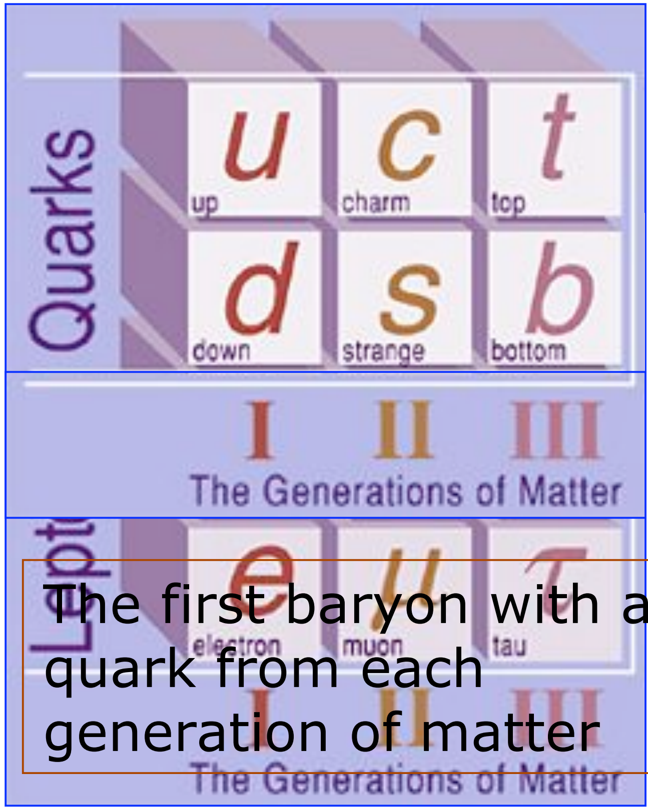


Combining two analyses → significance 0f 5.9σ

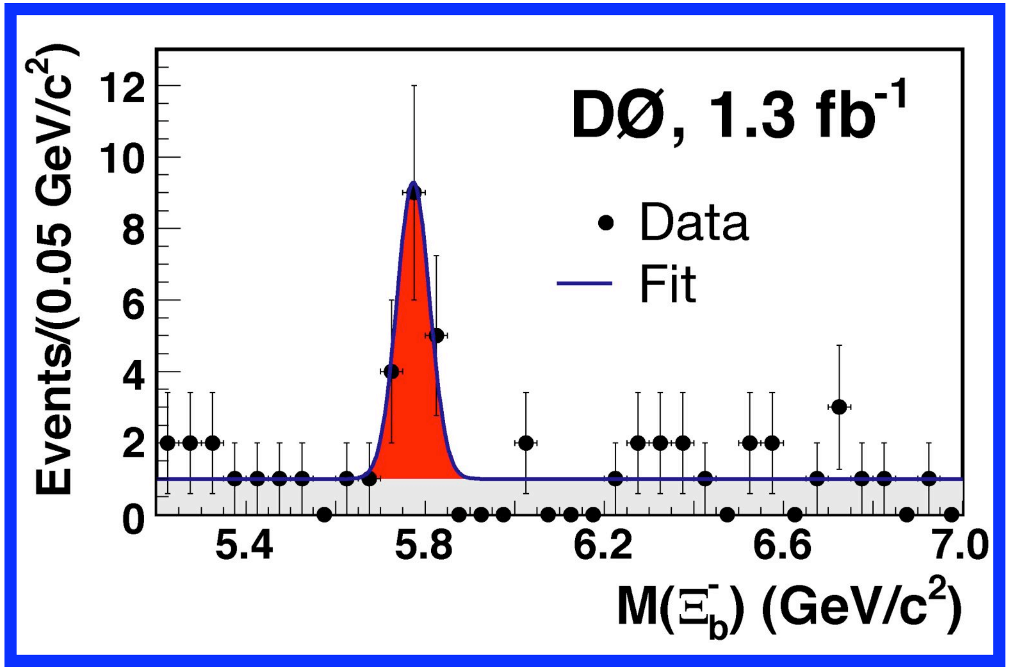
Systematic Uncertainties on Mass

- Fitting models
  - Two Gaussians instead of one for the peak. Negligible.
  - First order polynomial background instead of flat. Negligible.
- Momentum scale correction:
  - Fit to the Λ_b mass peak in data, < 1 MeV.
  - Fit to B^0 signal peak. Negligible effect < 1 MeV
  - Study of dE/dx corrections to the momentum of tracks finds a maximum deviation of 2 MeV from the measured mass .
- Event selection:
  - From the mass shift observed between the cut-based and BDT analysis, once removing the statistical correlation, a 15 MeV variation is estimated .

Discovery!



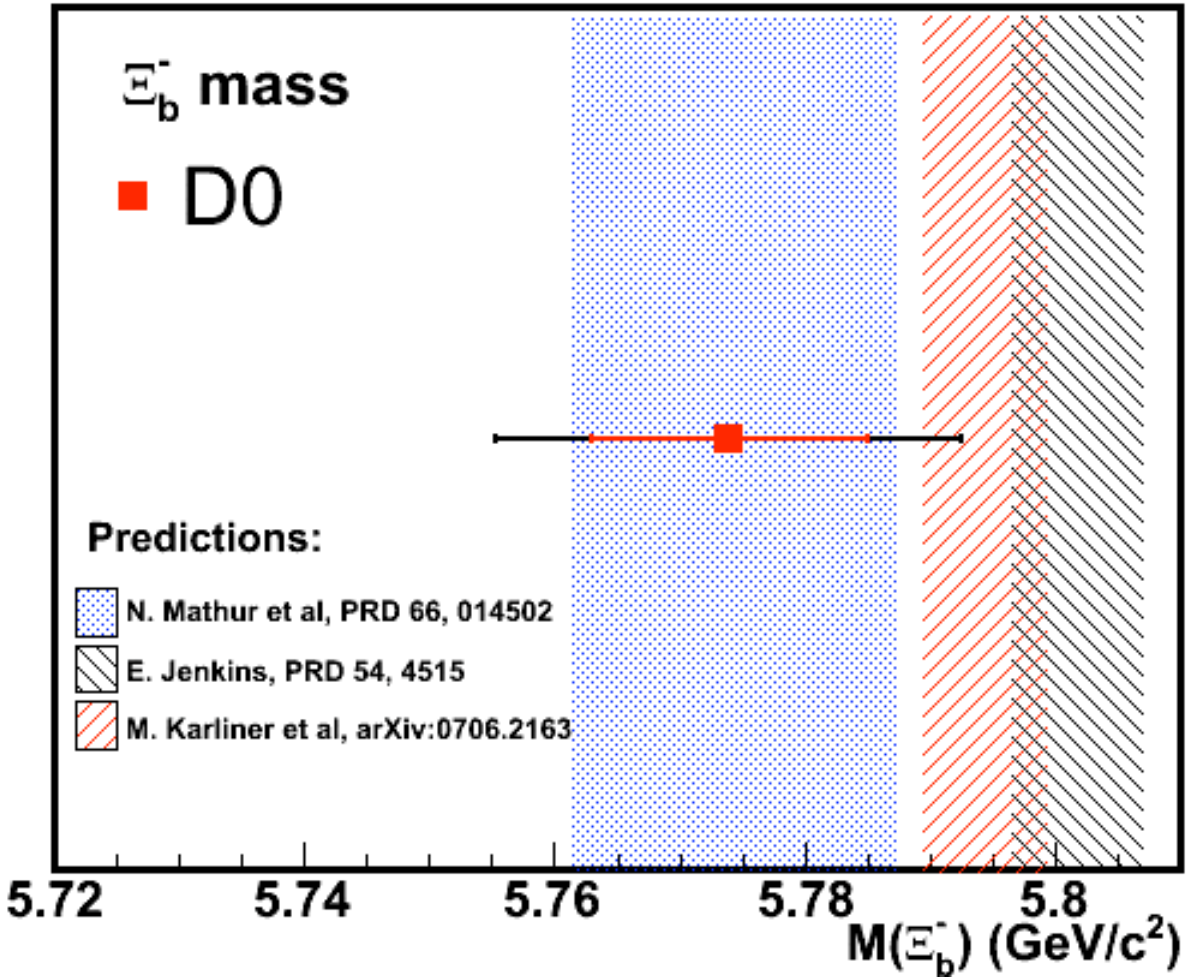
The first baryon with a quark from each generation of matter



$$M(\Xi_b^-) = 5.774 \pm 0.011\,(\text{stat}) \pm 0.015\,(\text{syst})$$

$$N_{\Xi_b^-} = 15.2 \pm 4.4\,(\text{stat}) + {}^{1.9}_{0.4}(\text{syst})$$

Predictions:

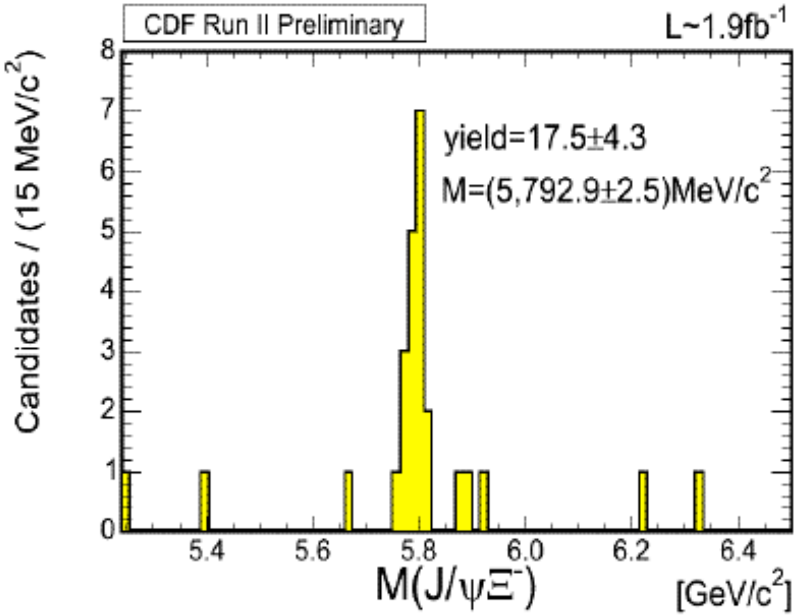


Predictions come from Lattice QCD, Heavy Quark Effective Theory, and potential models in NRQCD

CDF observation

Same decay channel

- **CDF signal has a significance greater than 7 sigma**

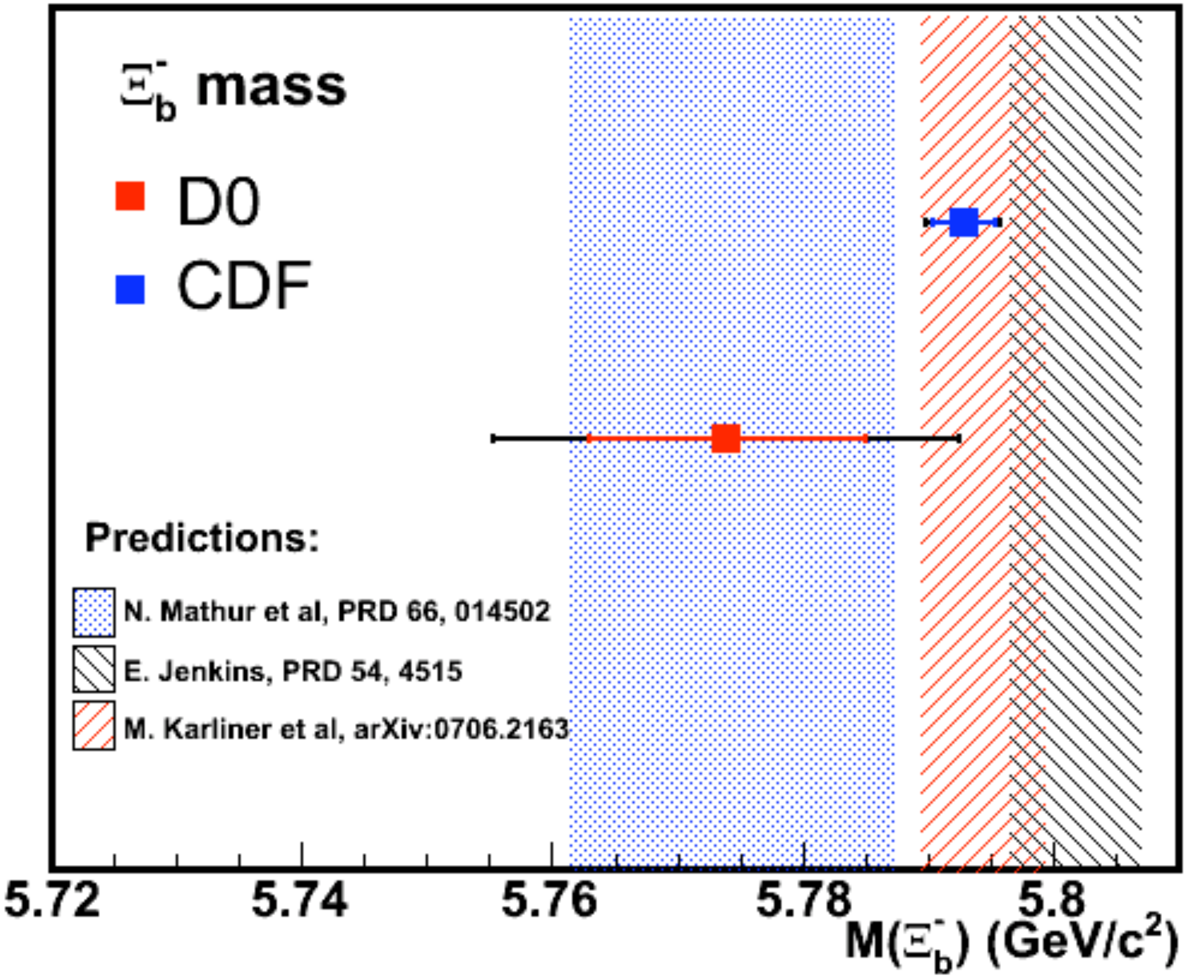


Excellent confirmation of DØ observation

Two weeks after D0 paper submission, CDF submitted a PRL reporting their Ξ_b observation.

Mass measurements in both observations are consistent.

CDF observation



Predictions come from Lattice QCD, Heavy Quark Effective Theory, and potential models in NRQCD

Production ratio

In addition to the observation, we also measure:

$$\frac{f(b \to \Xi_b^-) BR(\Xi_b^- \to J/\psi\, \Xi^-)}{f(b \to \Lambda_b) BR(\Lambda_b \to J/\psi \Lambda)}$$

$f(b \to X)$: fraction of times b quark hadronizes to X

This provides a measurement to allow other experiments to compare their production rate with this result.

Production ratio

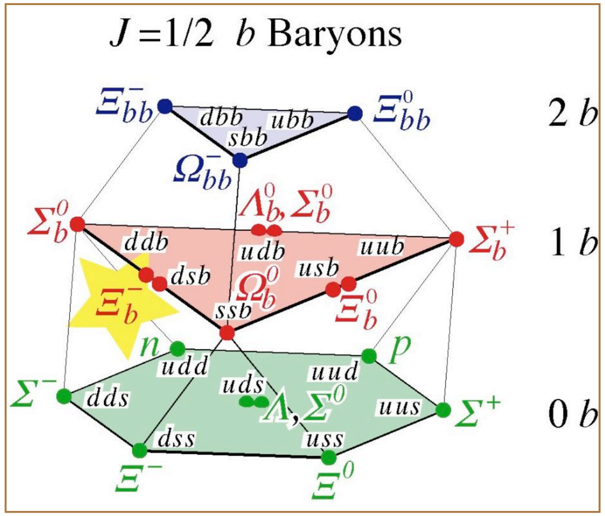
We find :

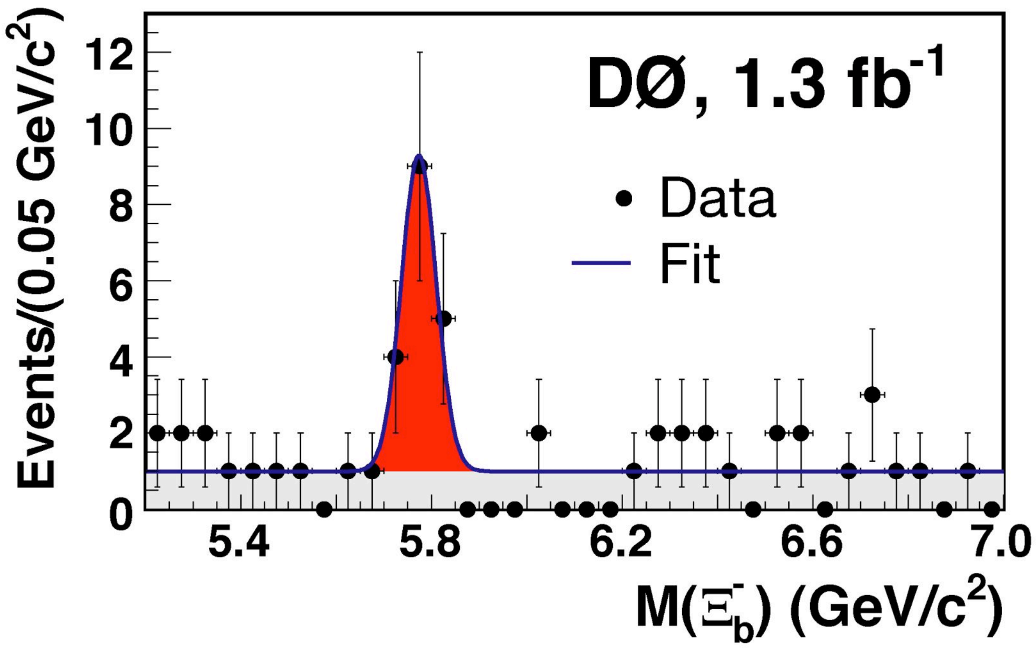
$$\frac{f(b \to \Xi_b^-) BR(\Xi_b^- \to J/\psi\ \Xi^-)}{f(b \to \Lambda_b) BR(\Lambda_b \to J/\psi \Lambda)} = 0.28 \pm 0.09\,(\mathrm{stat}) + {}^{+0.09}_{-0.08}\,(\mathrm{syst})$$

Ignoring the ratio of Br's, from ratio of hadronization fractions of B_s to B_d, expect ~1/4 or less

Summary

Ξ_b^- observation: Phys. Rev. Lett. 99, 1052001 (2007)





$$N_{\Xi_b^-} = 15.2 \pm 4.4\,(\text{stat}) + {}^{1.9}_{0.4}(\text{syst})$$

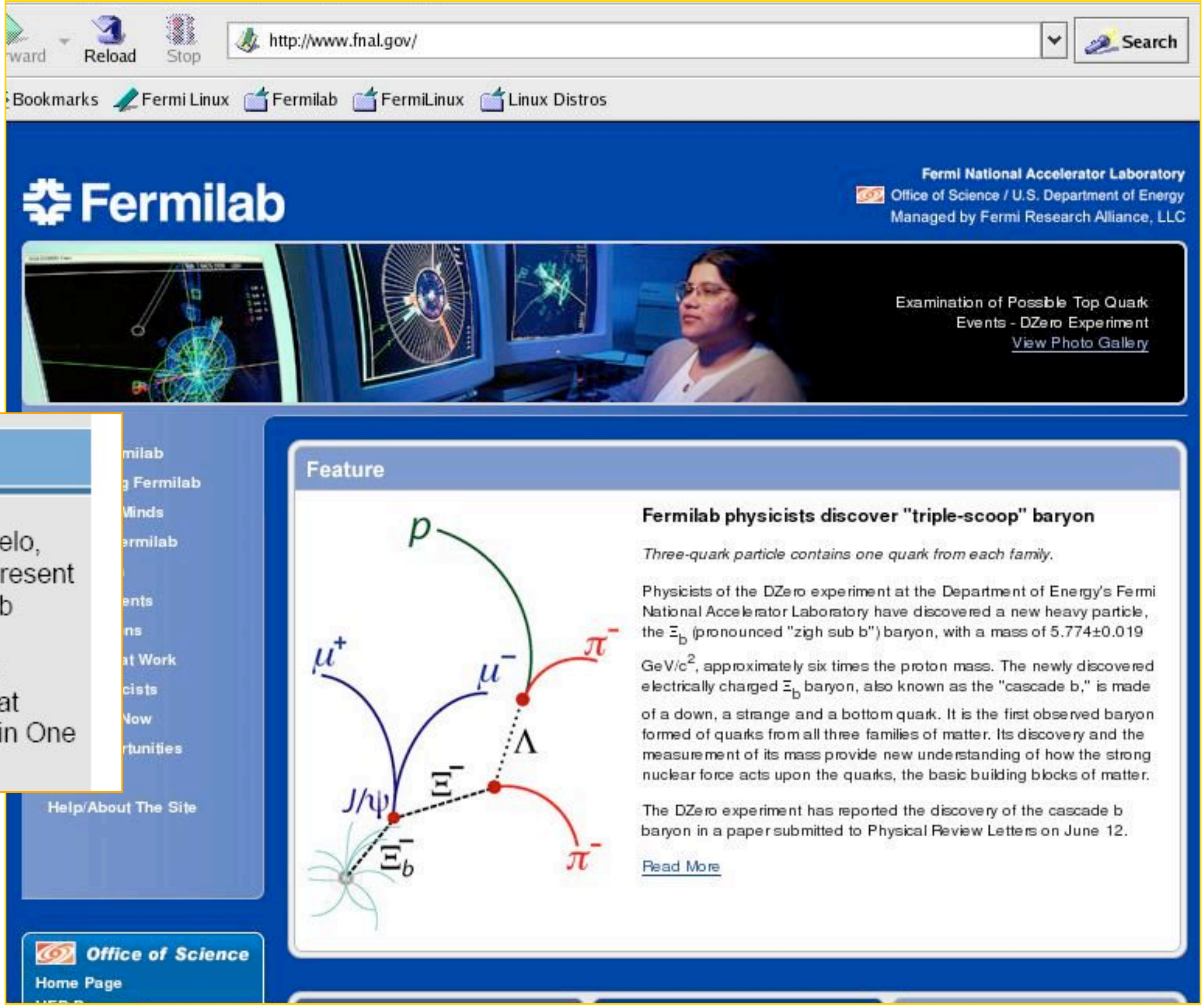
$$M(\Xi_b^-) = 5.774 \pm 0.011\,(\text{stat}) \pm 0.015\,(\text{syst})$$

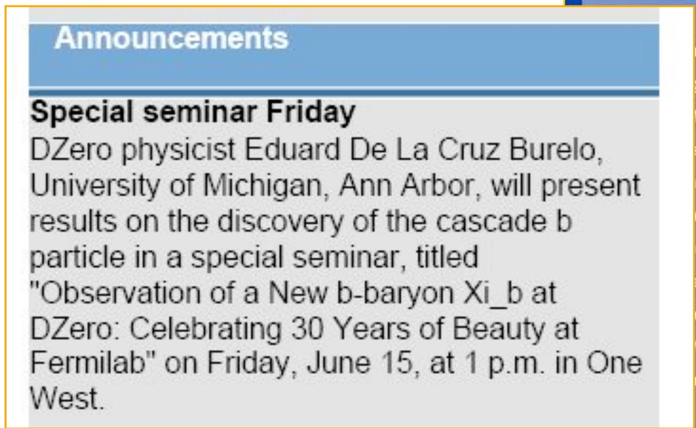
Signal Significance

$$\sqrt{-2\ln\Delta L} = 5.5\sigma$$

Backup slides

Celebrating @ Fermilab





Announcements

Special seminar Friday

DZero physicist Eduard De La Cruz Burelo, University of Michigan, Ann Arbor, will present results on the discovery of the cascade b particle in a special seminar, titled "Observation of a New b-baryon Xi_b at DZero: Celebrating 30 Years of Beauty at Fermilab" on Friday, June 15, at 1 p.m. in One West.

Timeline:

- **June 12, 2007: submitted to PRL and arXiv**
- **June 13, 2007: Fermilab press release**
- **June 14, 2007: Special Fermilab W&C seminar by Burelo**

Fermilab-Pub-07/196-E

Direct observation of the strange b baryon Ξ_b^-

V.M. Abazov[35], B. Abbott[75], M. Abolins[65], B.S. Acharya[28], M. Adams[51], T. Adams[49], E. Aguilo[5], S.H. Ahn[30], M. Ahsan[59], G.D. Alexeev[35], G. Alkhazov[39], A. Alton[64,*], G. Alverson[63], G.A. Alves[2], M. Anastasoaie[34], L.S. Ancu[34], T. Andeen[53], S. Anderson[45], B. Andrieu[16], M.S. Anzelc[53], Y. Arnoud[13], M. Arov[60], M. Arthaud[17], A. Askew[49], B. Åsman[40], A.C.S. Assis Jesus[3], O. Atramentov[49], C. Autermann[20], C. Avila[7], C. Ay[23], F. Badaud[12], A. Baden[61], L. Bagby[52], B. Baldin[50], D.V. Bandurin[59], S. Banerjee[28], P. Banerjee[28], E. Barberis[63], A.-F. Barfuss[14], P. Bargassa[80], P. Baringer[58], J. Barreto[2], J.F. Bartlett[50], U. Bassler[16], D. Bauer[43], S. Beale[5], A. Bean[58], M. Begalli[3], M. Begel[71], C. Belanger-Champagne[40], L. Bellantoni[50], A. Bellavance[50], J.A. Benitez[65], S.B. Beri[26], G. Bernardi[16], R. Bernhard[22], L. Berntzon[14], I. Bertram[42], M. Besançon[17], R. Beuselinck[43], V.A. Bezzubov[38], P.C. Bhat[50], V. Bhatnagar[26], C. Biscarat[19], G. Blazey[52], F. Blekman[43], S. Blessing[49], D. Bloch[18], K. Bloom[67], A. Boehnlein[50], D. Boline[62], T.A. Bolton[59], G. Borissov[42], K. Bos[33], T. Bose[77], A. Brandt[78], R. Brock[65], G. Brooijmans[70], A. Bross[50], D. Brown[78], N.J. Buchanan[49], D. Buchholz[53], M. Buehler[81], V. Buescher[21], S. Burdin[42,¶], S. Burke[45], T.H. Burnett[82], C.P. Buszello[43], J.M. Butler[62], P. Calfayan[24], S. Calvet[14], J. Cammin[71],

Phys. Rev. Lett. 99, 1052001 (2007)

Production ratio

- We use Monte Carlo samples of:
  - $\Xi_b^- \to J/\psi + \Xi^-$
  - $\Lambda_b \to J/\psi + \Lambda$
- MC passed through D0 detector simulation
- Same reconstruction and selection criteria as used on data is applied to Monte Carlo.
- Monte Carlo distributions need to be reweighted due to the Data/MC pT spectrum differences and to account for trigger effects.
- From comparison of Λ_b kinematic distributions in data and MC, determine further weighting factor, then apply to Ξ_b^-

Systematic uncertainties in the relative production ratio

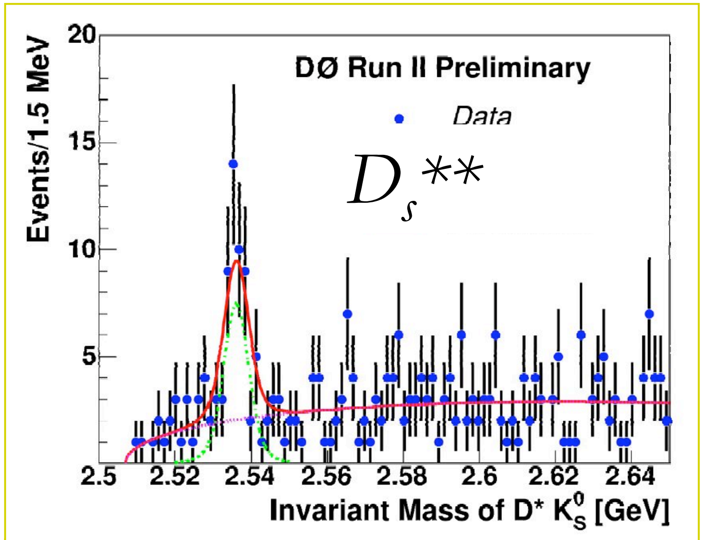
Source	Uncertainty (%)
Λ_b/Ξ_b hadronization models	Negligible
MC stat. on Λ_b /Ξ_b	10
pT(π) reconstruction	7
Effect of mass difference between data and MC	5
Λ_b/Ξ_b MC reweighting	**27**
Syst. uncertainties on the number of Ξ_b in data	+13, -3

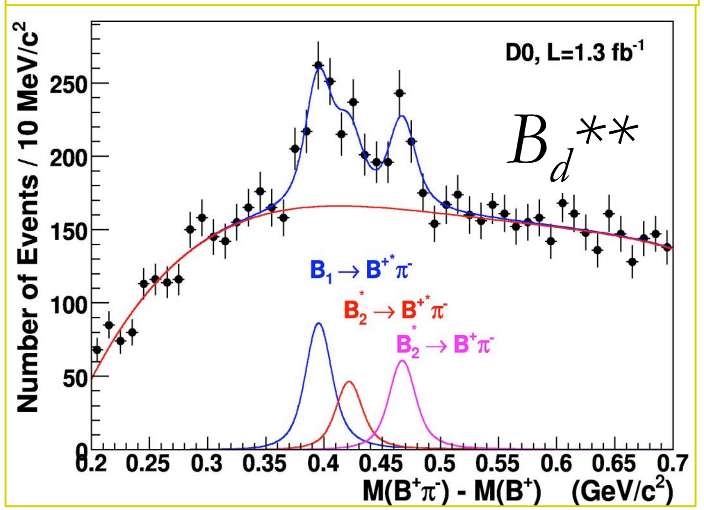
Conservatively take difference between reweighting result and no reweighting .

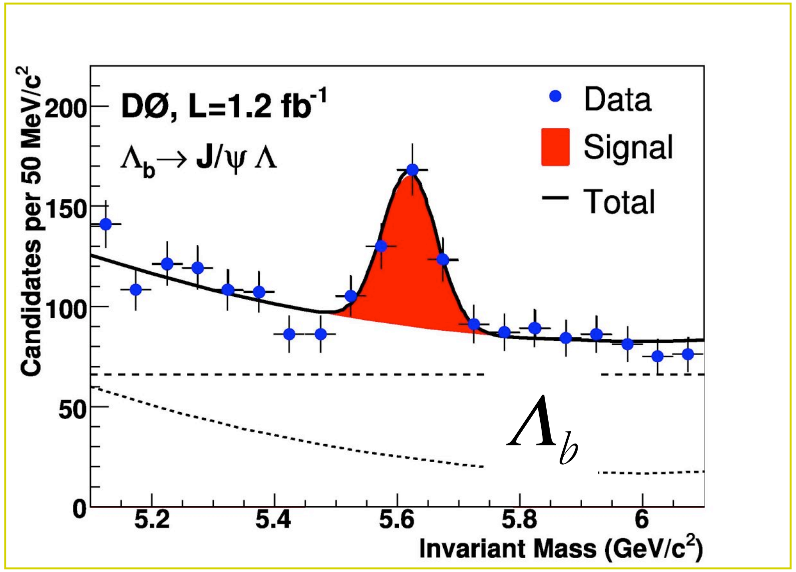
Why to look for particles?

- Spectroscopy:
  - One of the best ways to test our understanding of QCD and potential models
- Production and Fragmentation:
  - Major source of uncertainty in many measurements
- Discovery:
  - Practice techniques for beyond the Standard Model searches by finding undiscovered Standard Model predicted particles.

We try to understanding this

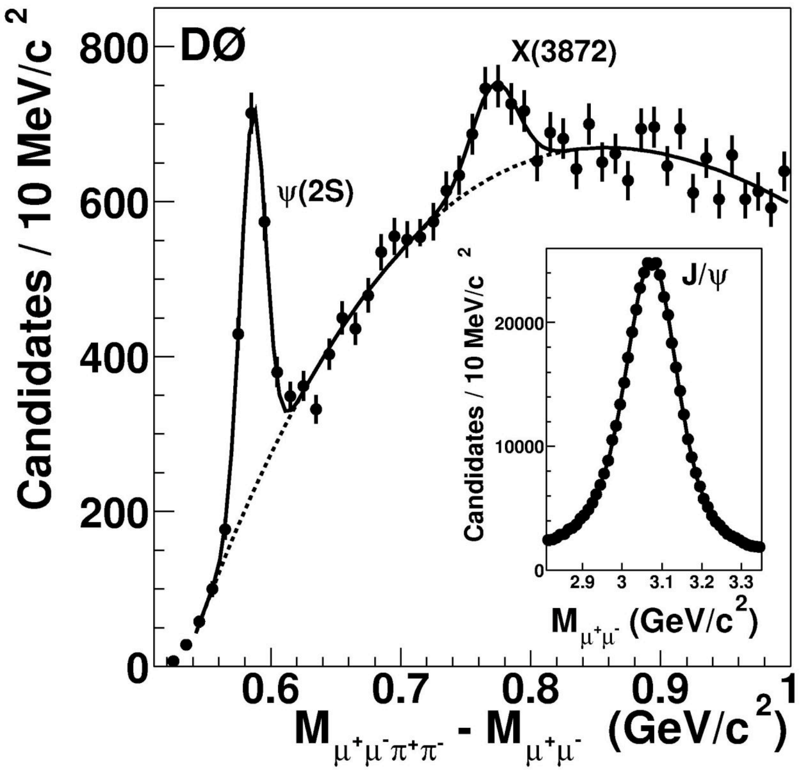






Particles which are predicted to exist

To then understand this …



What is this?

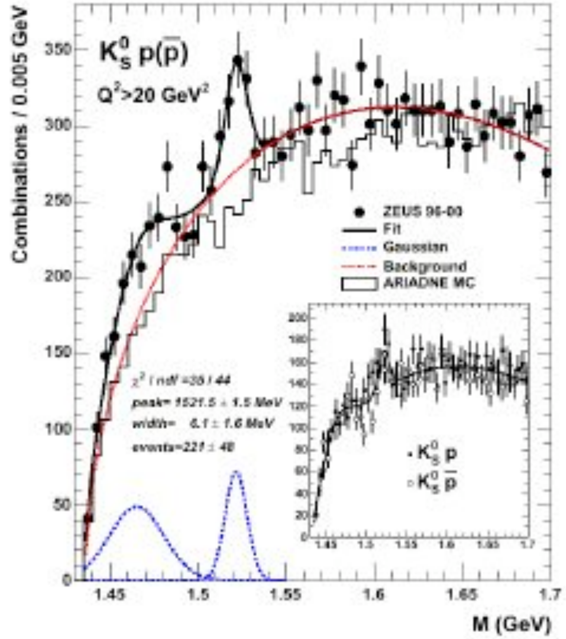


Figure 14: Data from ZEUS [8] for the reaction $e^+p \to K^0pX$ with a cut on the 4-momentum transfer $Q^2 > 20$ GeV^2. The solid line is a fit to a smooth background and two peaks: a known Σ^{*+} resonance and a possible Θ^+ peak at 1522 MeV. A Monte Carlo background is also shown by the histogram. The inset shows the two separate event sets added together in the main figure.

Pentaquarks?

Combining: cuts+BDT

- After we remove duplicate events, we observe 22.8 ± 5.8 events.
- Significance:
  - Sqrt(-2ΔL) = 5.9