First observation of a New b-baryon Ξ_b at D0:

Celebrating 30 Years of Beauty @ Fermilab

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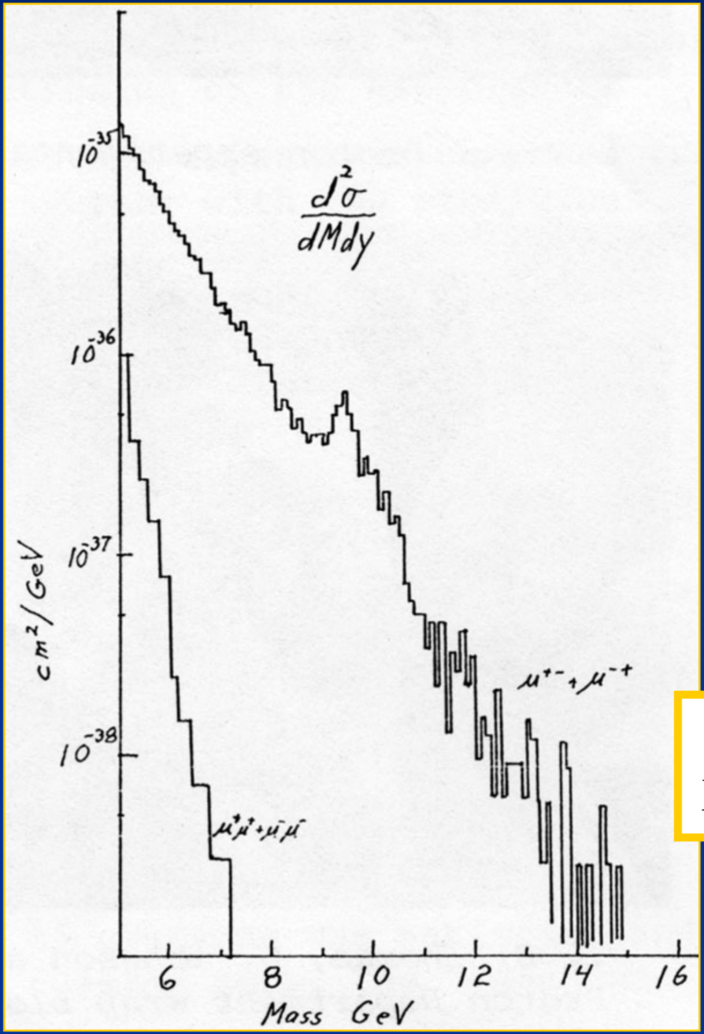
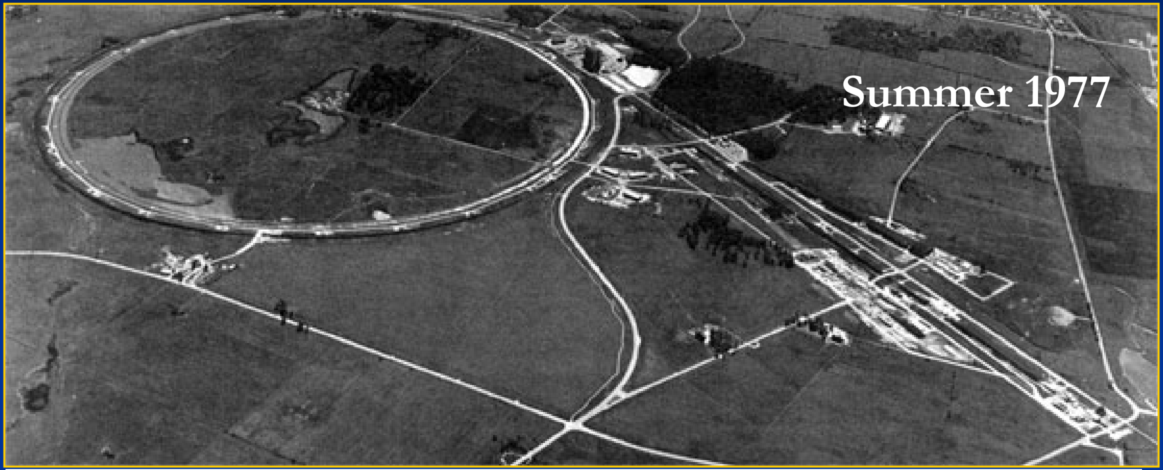
for the DØ Collaboration

The quest … a long journey

- Everything begins at … Fermilab
- The quest for B hadrons
- The quest for … the Ξ_b
  - Ξ_b signal
  - Mass measurement
  - Relative production ratio
- Summary

The quest begins 30 years ago at…





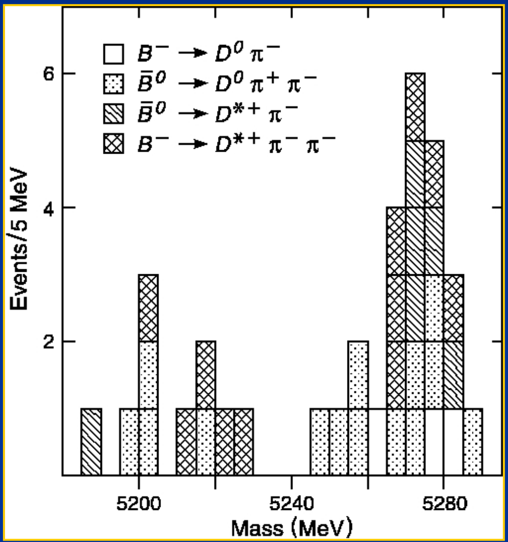
Fermilab's giant accelerator reveals another new sub-nuclear particle

!! EXTRA!! Fermilab Experiment Discovers New Particle "UPSILON"

B Physics, a whole field, was born on June 30 , 1977, here at Fermilab.

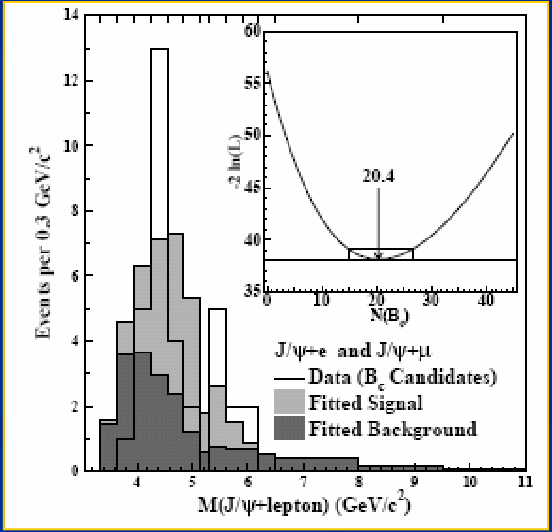
Since then …

Exclusive *B* decays
CLEO (1983)



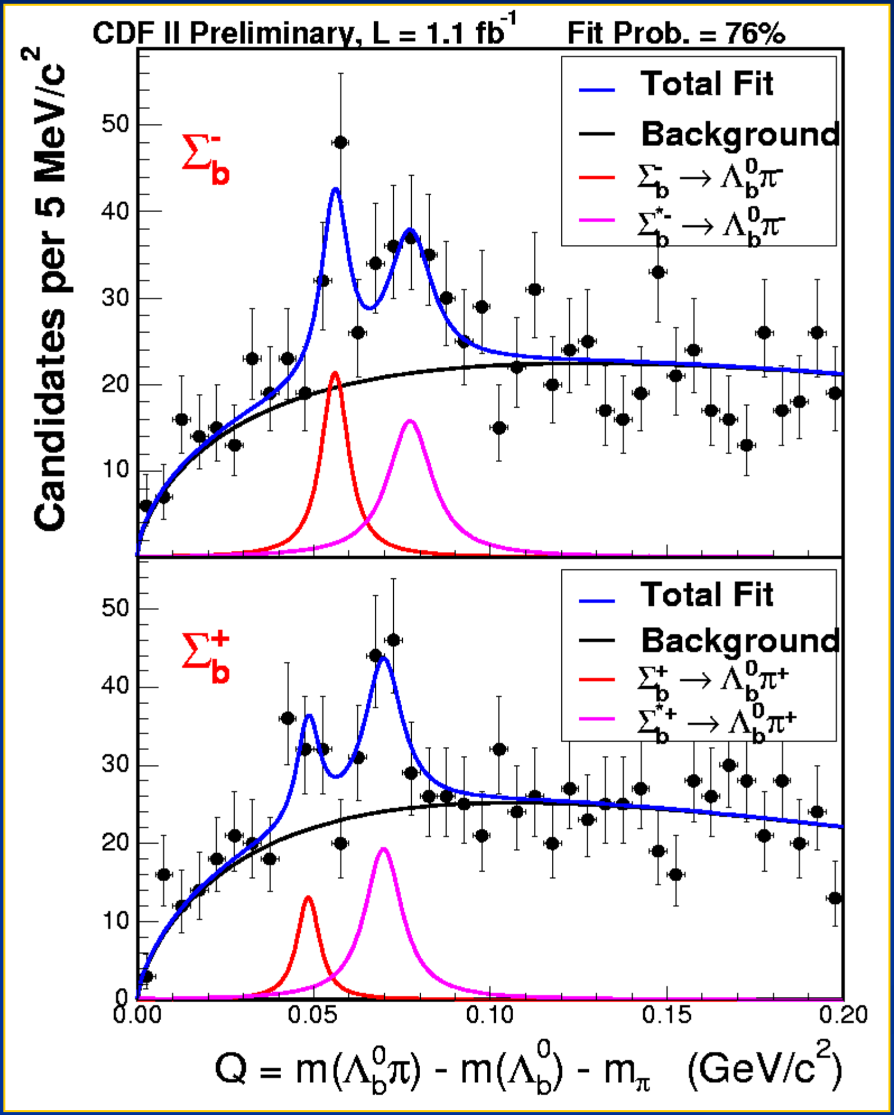
Main assumption to look for these particles: ½ of the mass of the upsilon!.

Bc by CDF (1998)



Last B meson in the ground 0^- state to be observed

Recently … October 2006

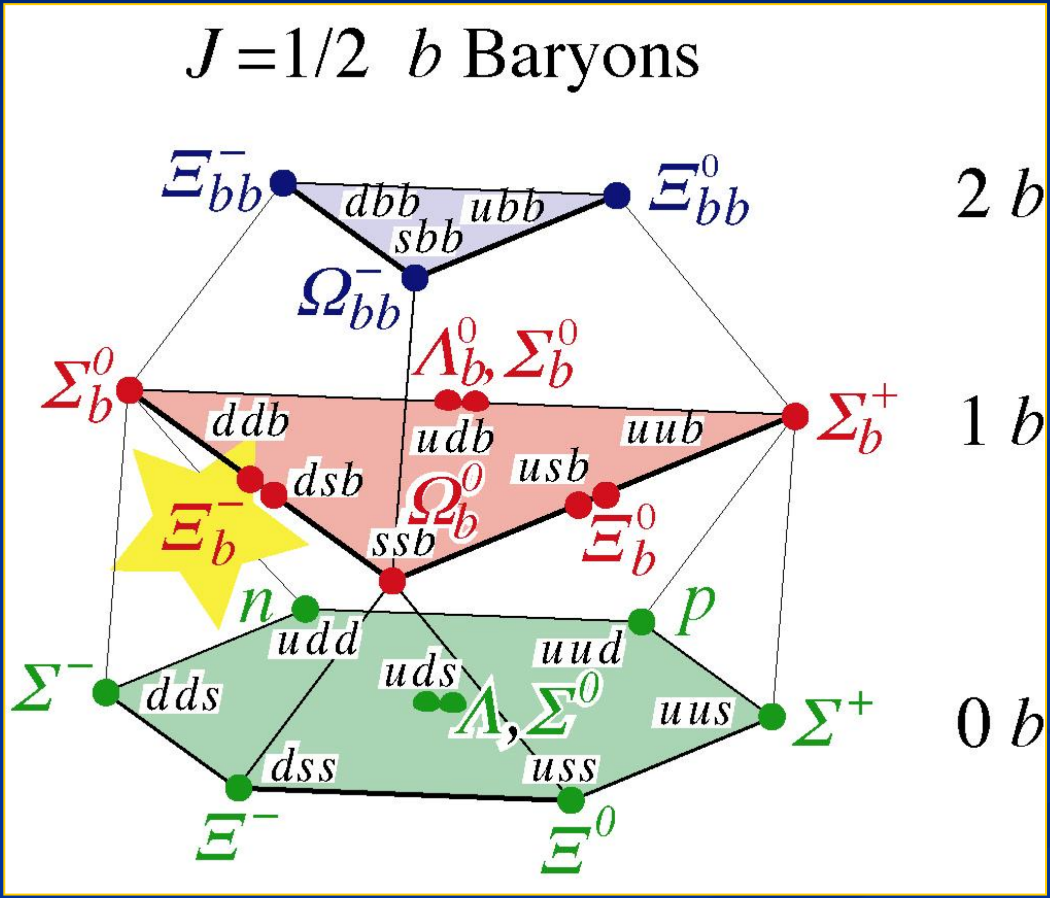


CDF announced a preliminary result using 1.1 fb^{-1} of the Σ_b's almost 8 months ago.

Status:

- Mesons:
  - B^+, B^0, B_s, B_c^+ (established)
  - B* (established),
  - B_d^{**}(submitted to PRL DØ, Preliminary CDF)
  - B_s^{**} (Preliminary DØ & CDF)
- Baryons:
  - Λ_b (established)
  - Σ_b^+, and Σ_b^{*+}(preliminary CDF)

The quest for b baryons

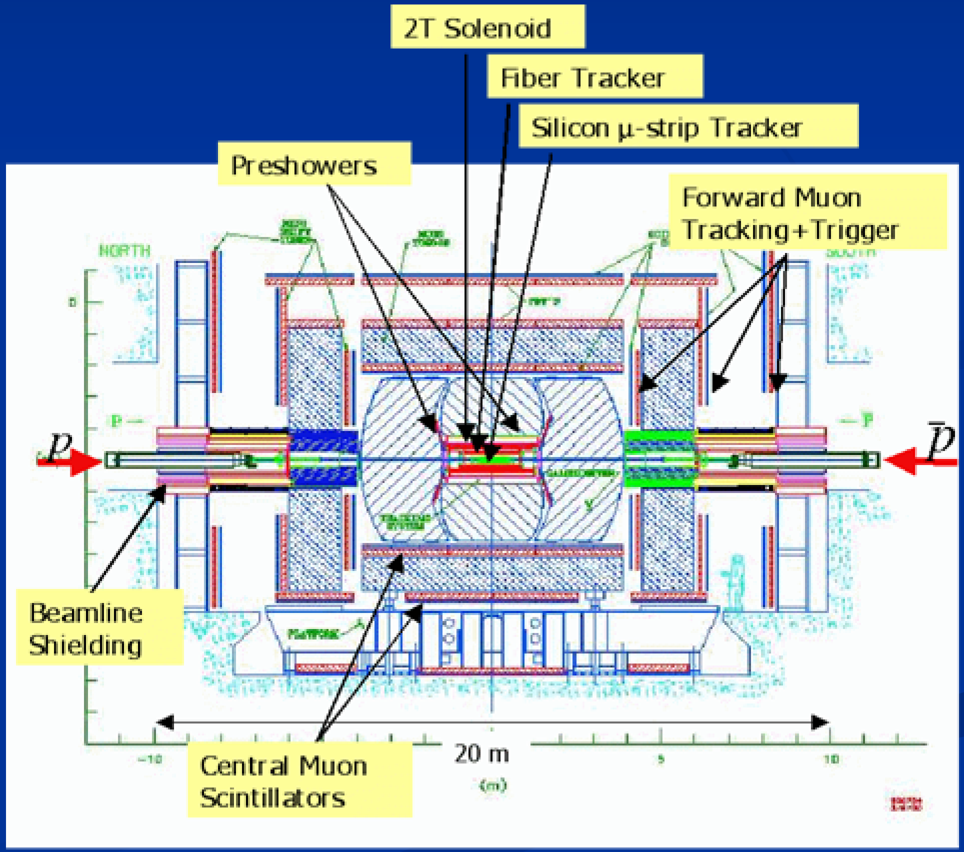


Plus there is a J = 3/2 baryon multiplet

Data we use …

In this analysis we use 1.3 fb^{-1} of data collected by DØ detector (RunIIa data).

Thanks to the Fermilab Accelerator division for doing wonderful work. Keep delivering, and we will keep collecting data and analyzing .

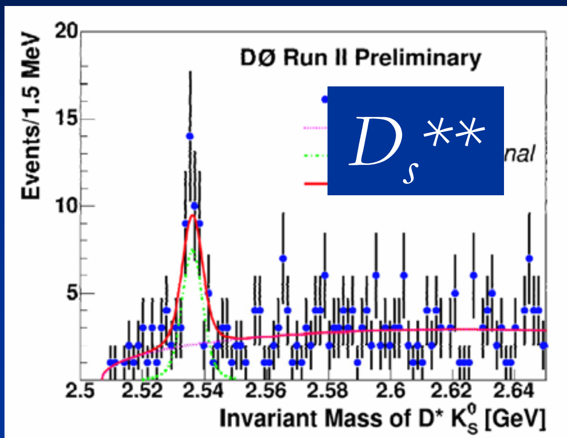


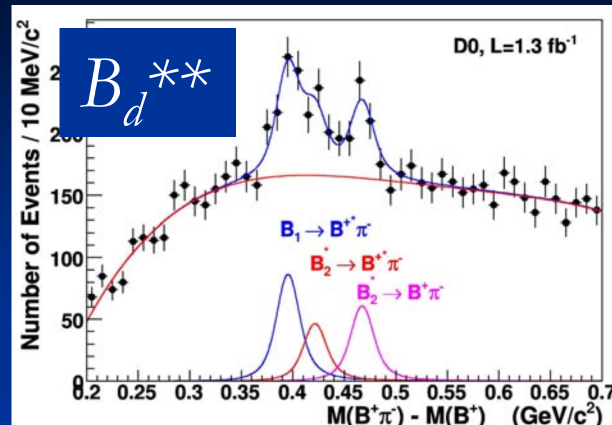
The entire D0 detector is important, but the muon and central
tracker subdetectors are particularly important in this analysis

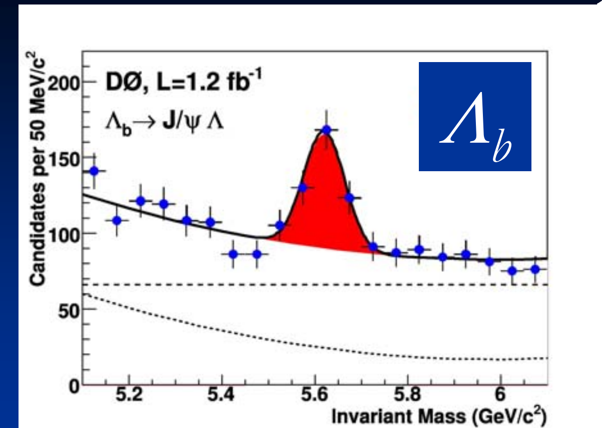
Motivation

- 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 BSM searches by finding undiscovered SM particles.

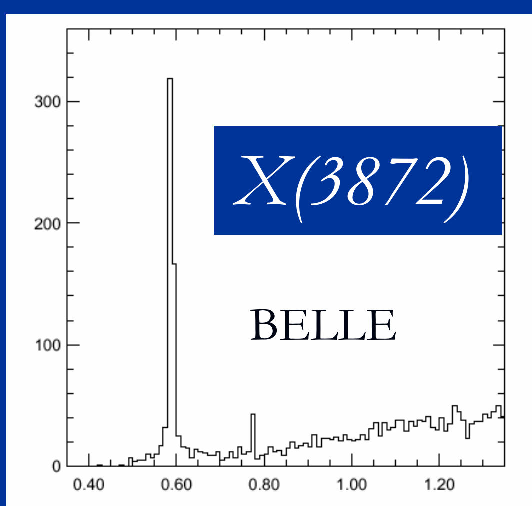
Understanding these:

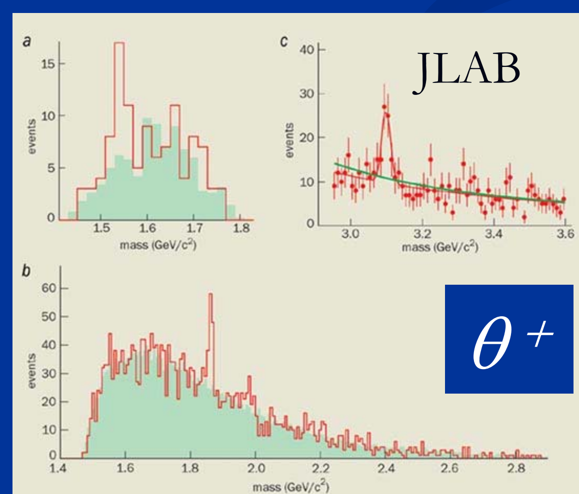


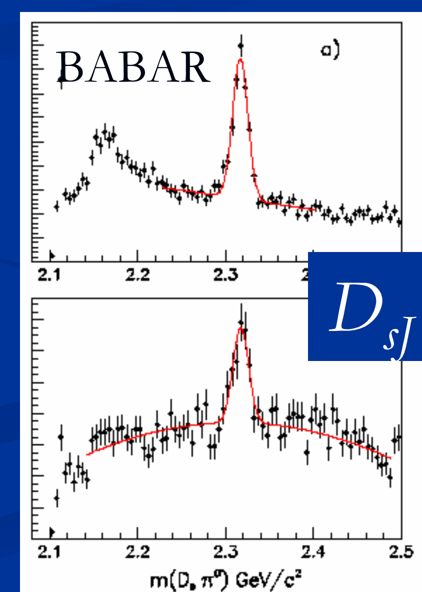




Helps us understand these:







Theoretical prediction of the masses

$$M(\Xi_b) = 5805.7 \pm 8.1\,\text{MeV}$$
$$M(\Sigma_b) = 5824.2 \pm 9.\,\text{MeV}$$
$$M(\Omega_b) = 6068.7 \pm 11.1\,\text{MeV}$$

Predicted mass hierarchy:

$M(\Lambda_b) < M(\Xi_b) < M(\Sigma_b)$

E. Jenkins, PRD 55 , R10-R12, (1997).

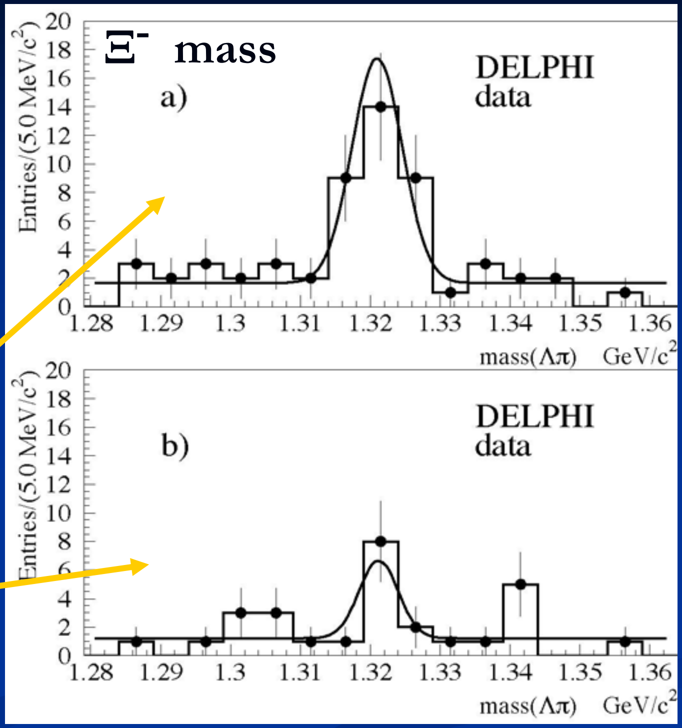
Just today, first citation …

Karliner et al., arXiv:0706.2163

LEP measurements:

LEP experiments only deduce the presence of the Ξ_b^- indirectly; they look for an excess of events in the right-sign combinations of $\Xi^-(\Lambda\pi^-)\ l^-$

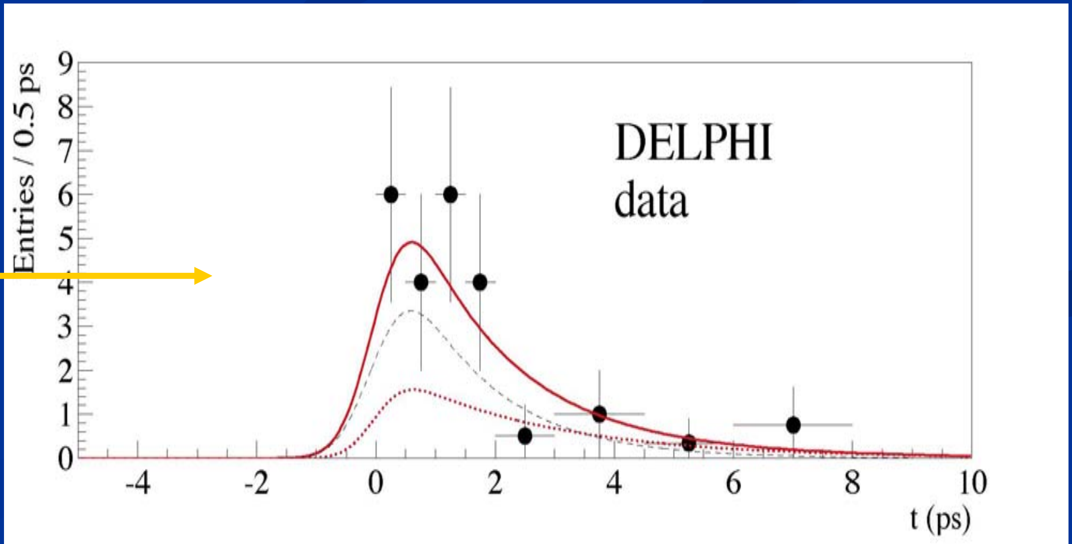
Wrong sign combination events



They measure the lifetime of this excess of events.

$1.45\ {+0.55}/{-0.43}$(stat.) $\pm$ 0.13(syst.) ps.

Eur. Phys. J. C 44, 299–309 (2005)



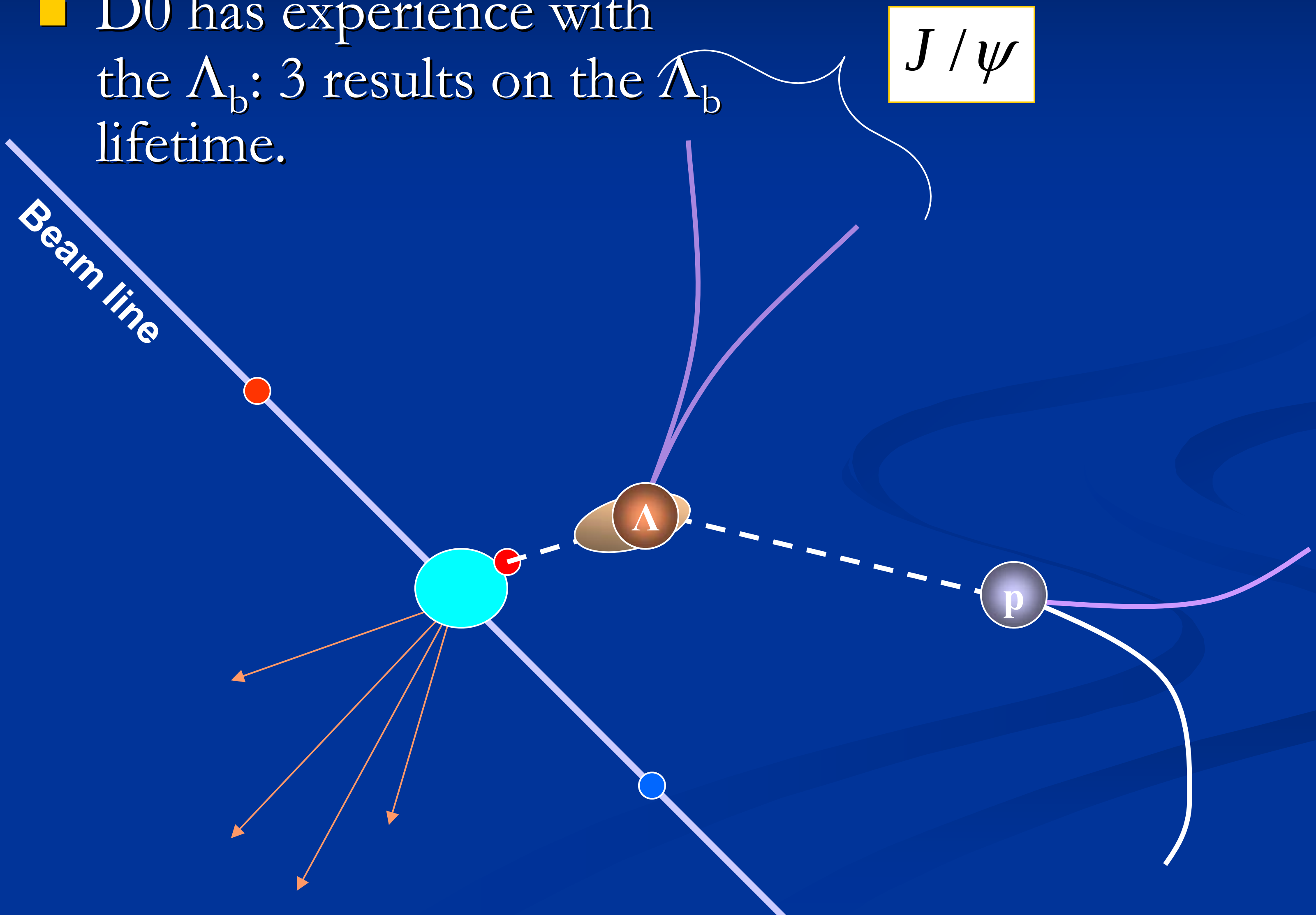
What do we know about the Ξ_b^-?

- Predicted mass: 5805.7 ± 8.1 MeV
- 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 GeV $< M(\Xi_b^-) <$ 5.808 GeV
- Ξ_b^- lifetime by LEP: 1.42 +0.28/-0.24 ps.*

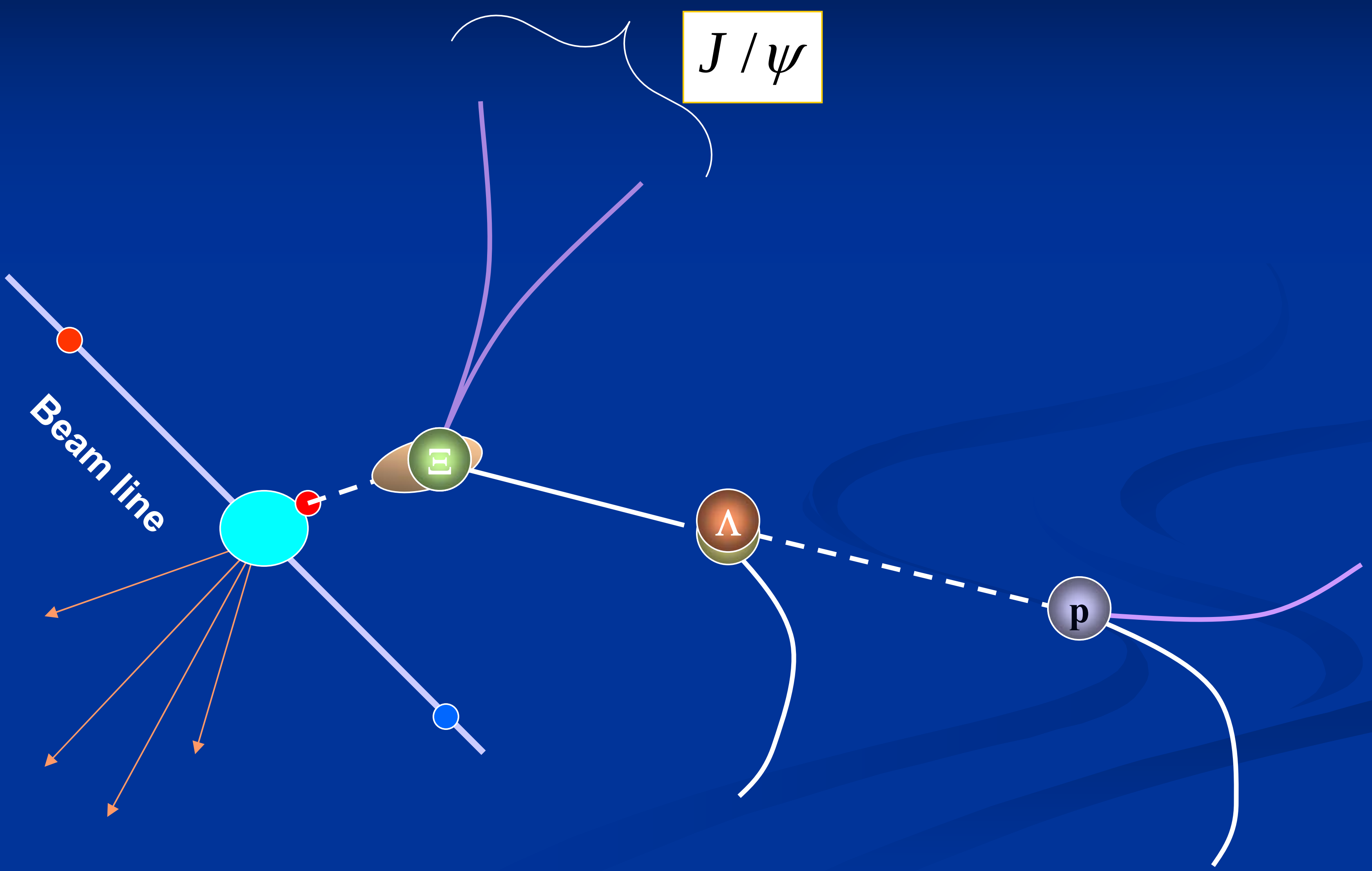
* This is the world average (ALEPH+DELPHI). HFAG: arXiv:0704.3575 [hep-ex]

Our knowledge about b-baryons

- D0 has experience with the Λ_b: 3 results on the Λ_b lifetime.

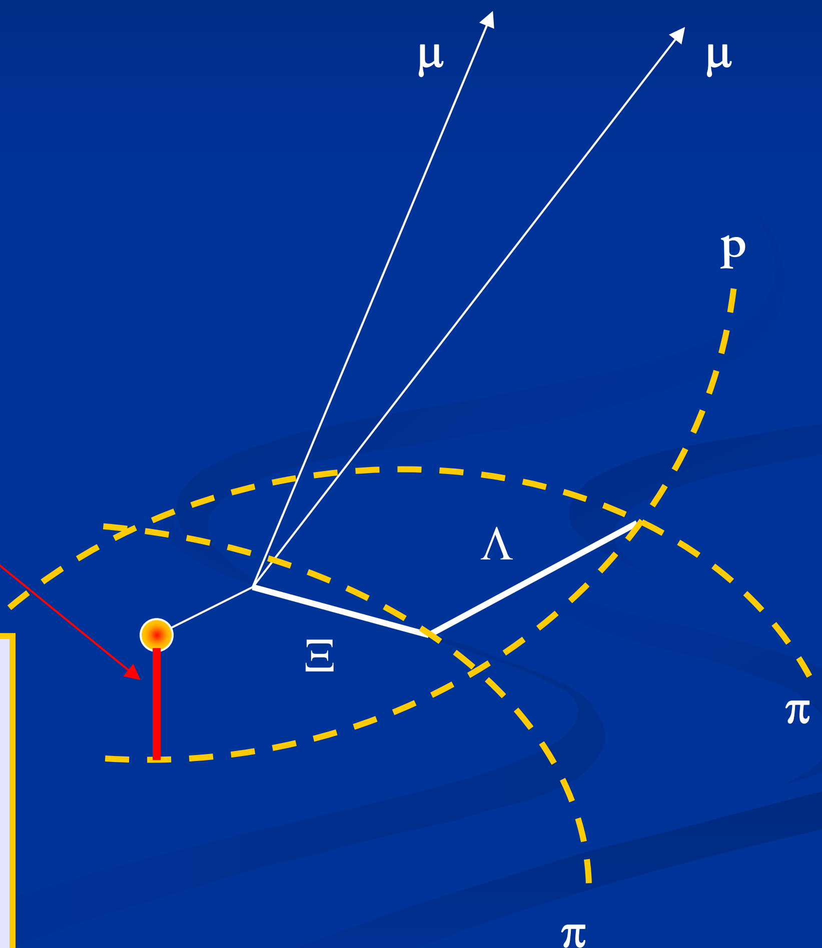


Searching for Ξ_b in $\Xi_b^- \rightarrow J/\psi + \Xi^-$



Impact parameter 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.

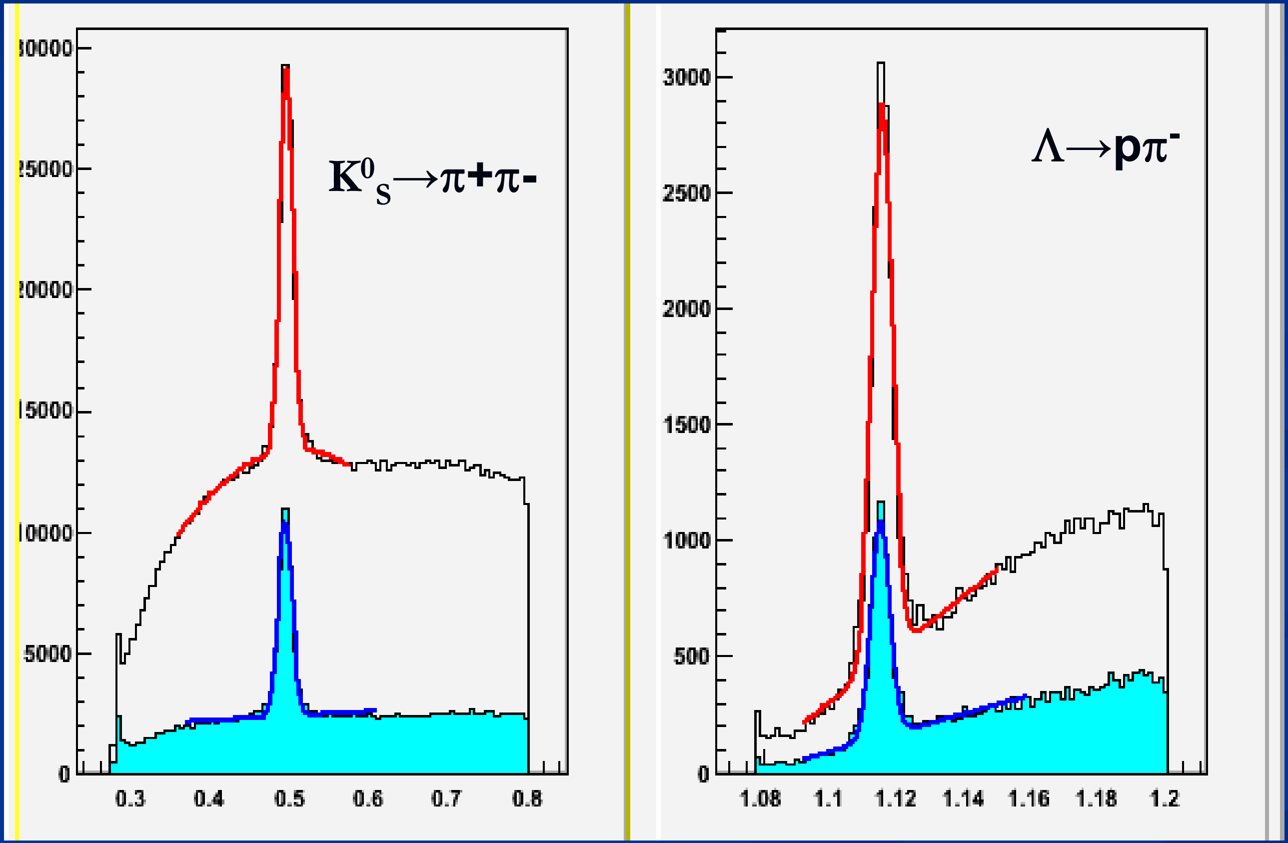


But for particles like the Ξ_b^-, this requirement could result in missing the π and proton tracks from the Λ and Ξ^- decays

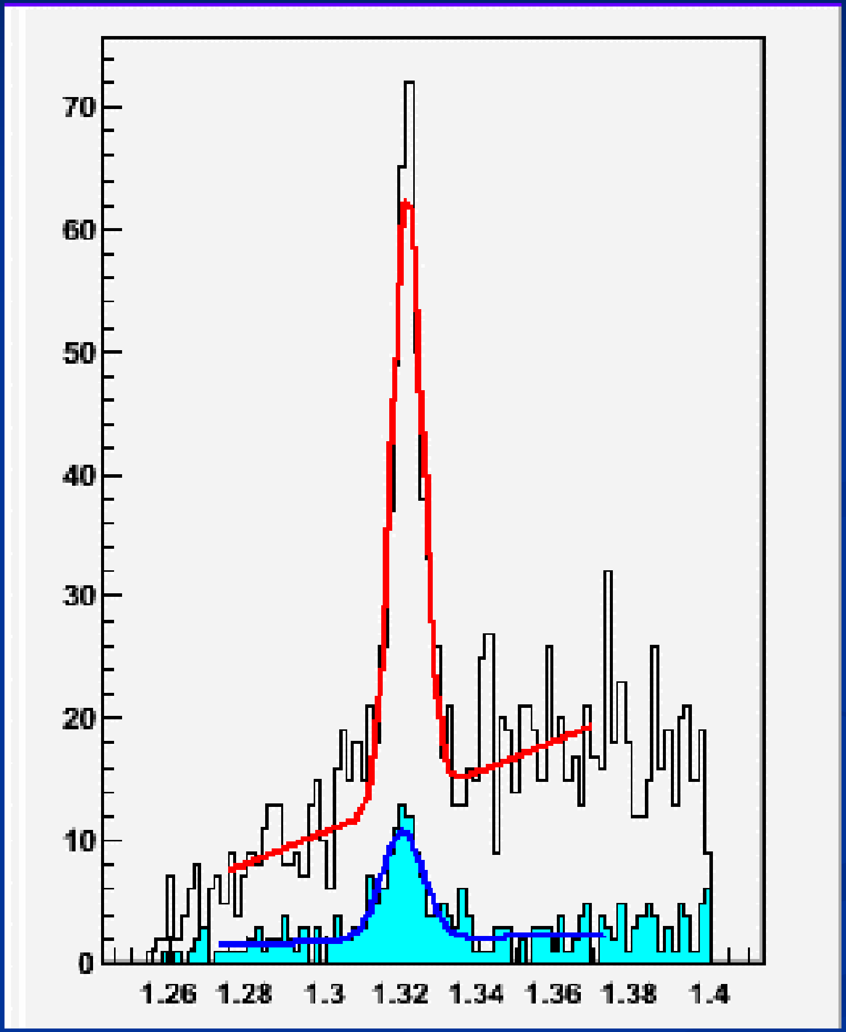
What did we do to solve this problem?

- 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. But …
- Thanks to our muon detector (and the guys from the muon team), $J/\psi \rightarrow \mu^+\mu^-$ is a golden channel.. Although B -> $J/\psi X$ is fairly rare, it is very clean channel for us 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,Λ^0 and Ξ^- signals for the "standard" (bottom histograms) and "extended" (opening up IP) tracks reconstruction.



Mass distribution for Ξ^- signal for the "standard" (bottom histograms) and "extended" (opening up IP) tracks reconstruction.

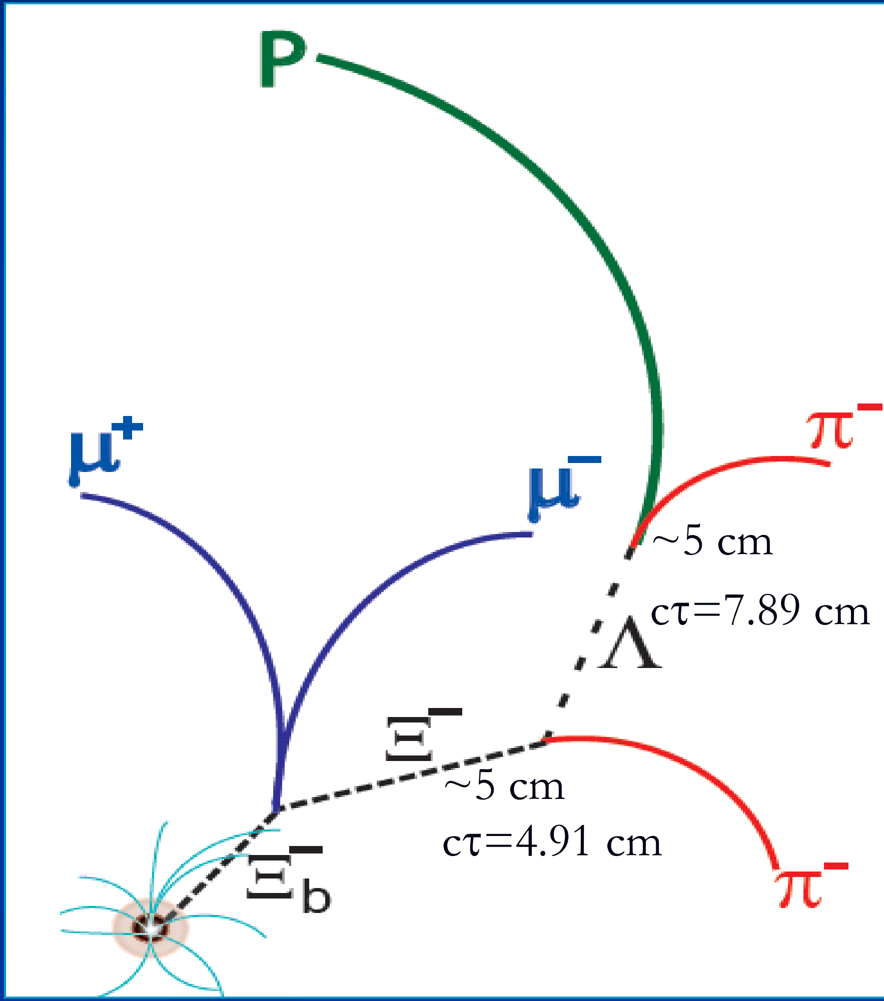


Reconstruction strategy for Ξ_b

- Reconstruct $J/\psi \to \mu + \mu -$
- Reconstruct $\Lambda \to p\pi$
- Reconstruct $\Xi \to \Lambda + \pi$
- Combine $J/\psi + \Xi$
- Improve mass resolution by using an event-by-event mass difference correction .
- The guides:
  - The sister: $\Lambda_b \to J/\psi\Lambda$ decays in data
  - The impostor: $J/\psi + \Xi$(fake from $\Lambda(p\pi^-)\pi^+$)
  - The clone: Monte Carlo simulation of $\Xi_b^- \to J/\psi + \Xi^-$

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

- Three daughter signal particles need to be reconstructed:
  - $\Lambda \rightarrow p + \pi$
  - $\Xi \rightarrow \Lambda + \pi$
  - $J/\psi \rightarrow \mu + \mu -$
- 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

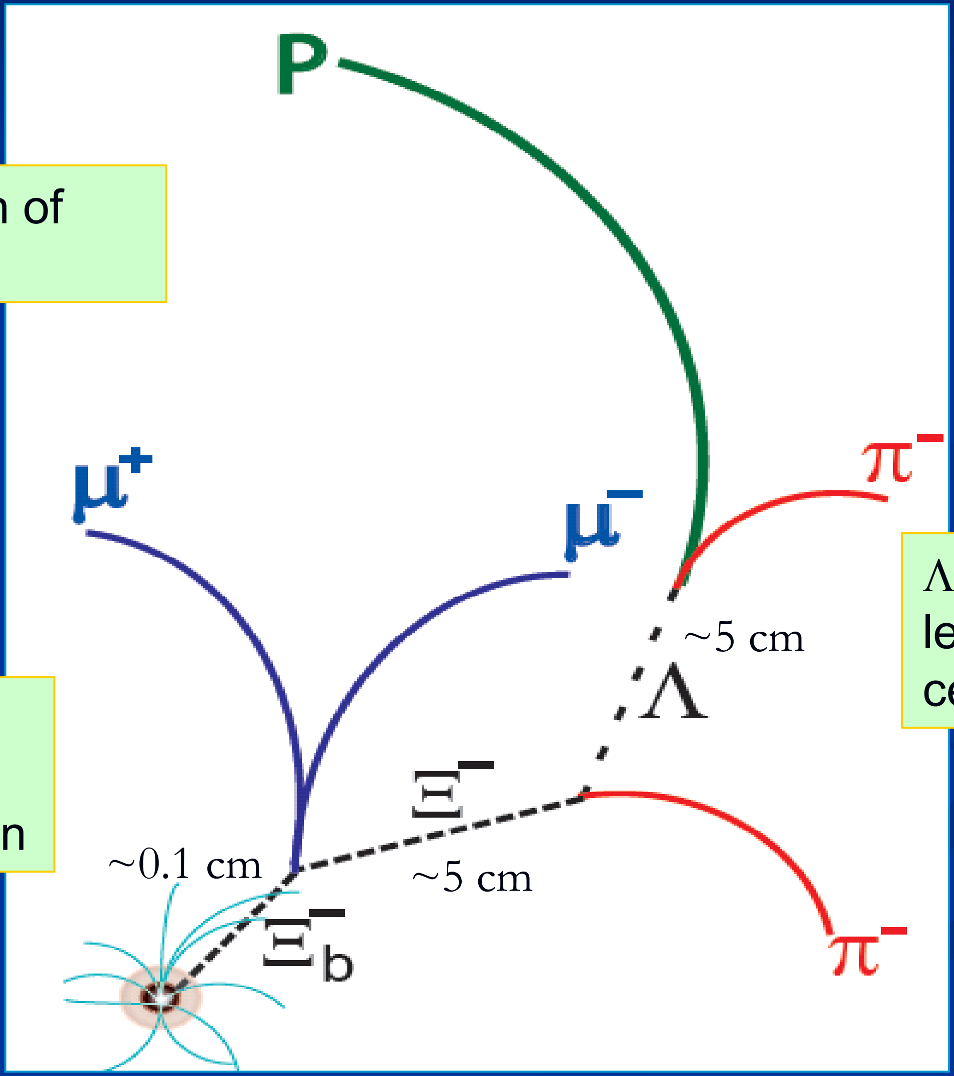


More features in $\Xi_b^- \rightarrow J/\psi + \Xi^-$

Ξ- has a decay length of few centimeters.

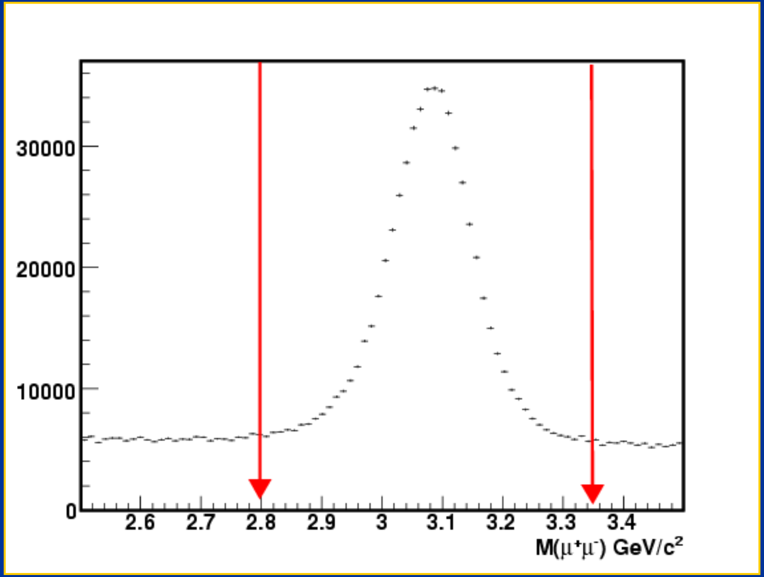
Ξ_b has a decay length of few hundred microns, PV separation

Λ has a decay length of few centimeters

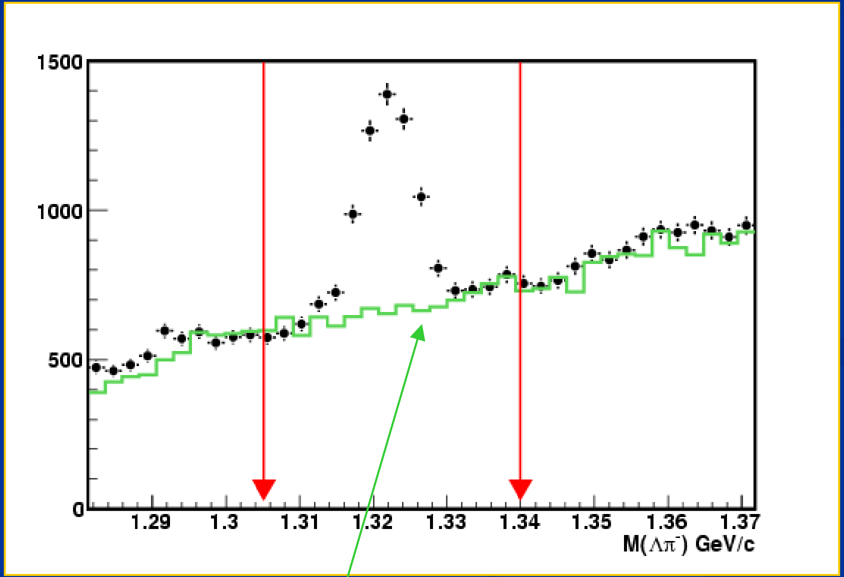


Reconstructing the daughters

J/ψ→μ+μ-



Ξ→Λπ



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

What background do we expect?

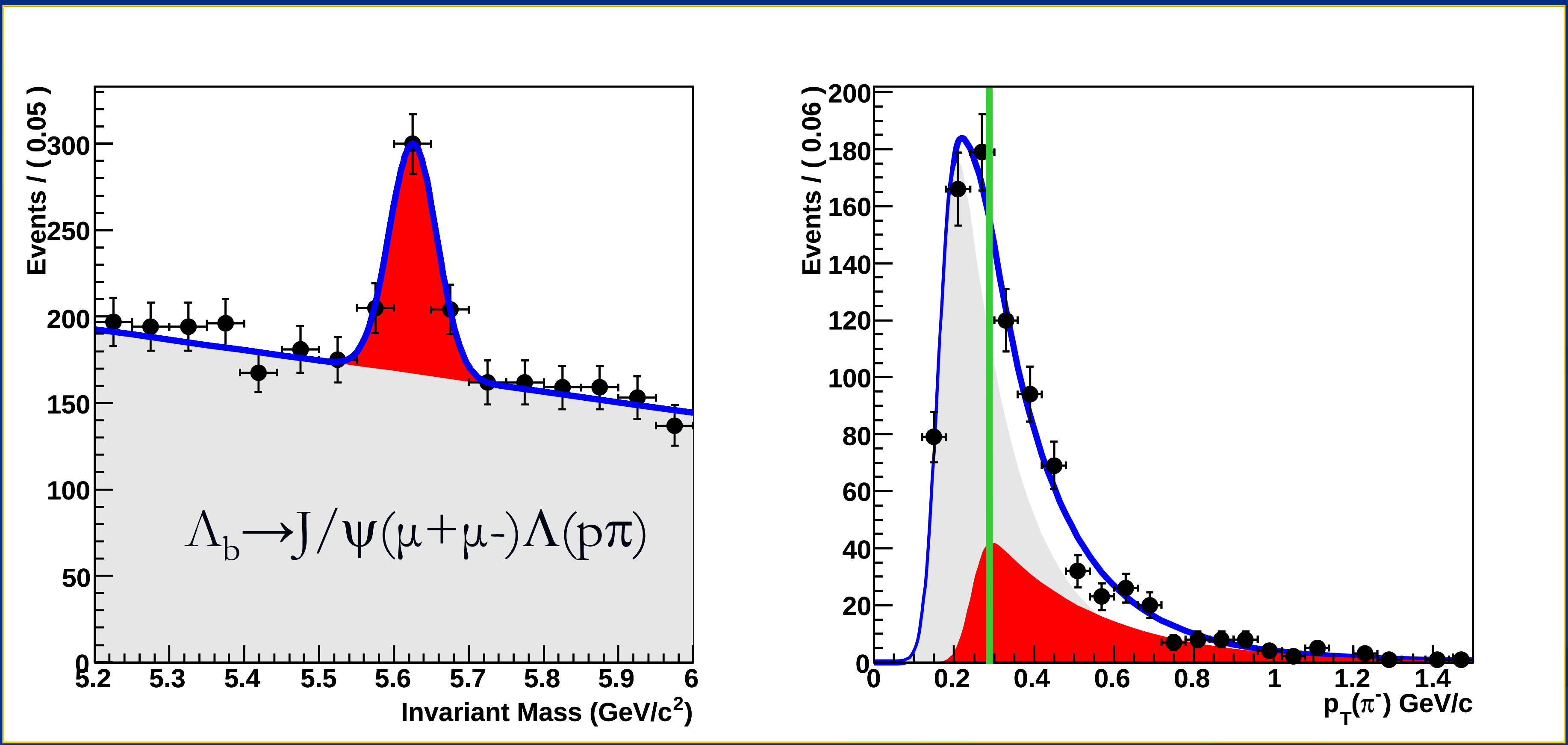
- Prompt background:
  - ~80% of the J/ψ are directly produced at the collision.
- Real B's:
  - The remaining ~20% of J/ψ come from B decays
- Combinatoric background:
  - Real J/ψ plus fake Ξ^-
  - Fake J/ψ plus fake Ξ^-
  - Fake J/ψ plus real Ξ^-
  - Real J/ψ plus real Ξ^- , but not from Ξ_b^-

Our wrong-sign combination events have these.

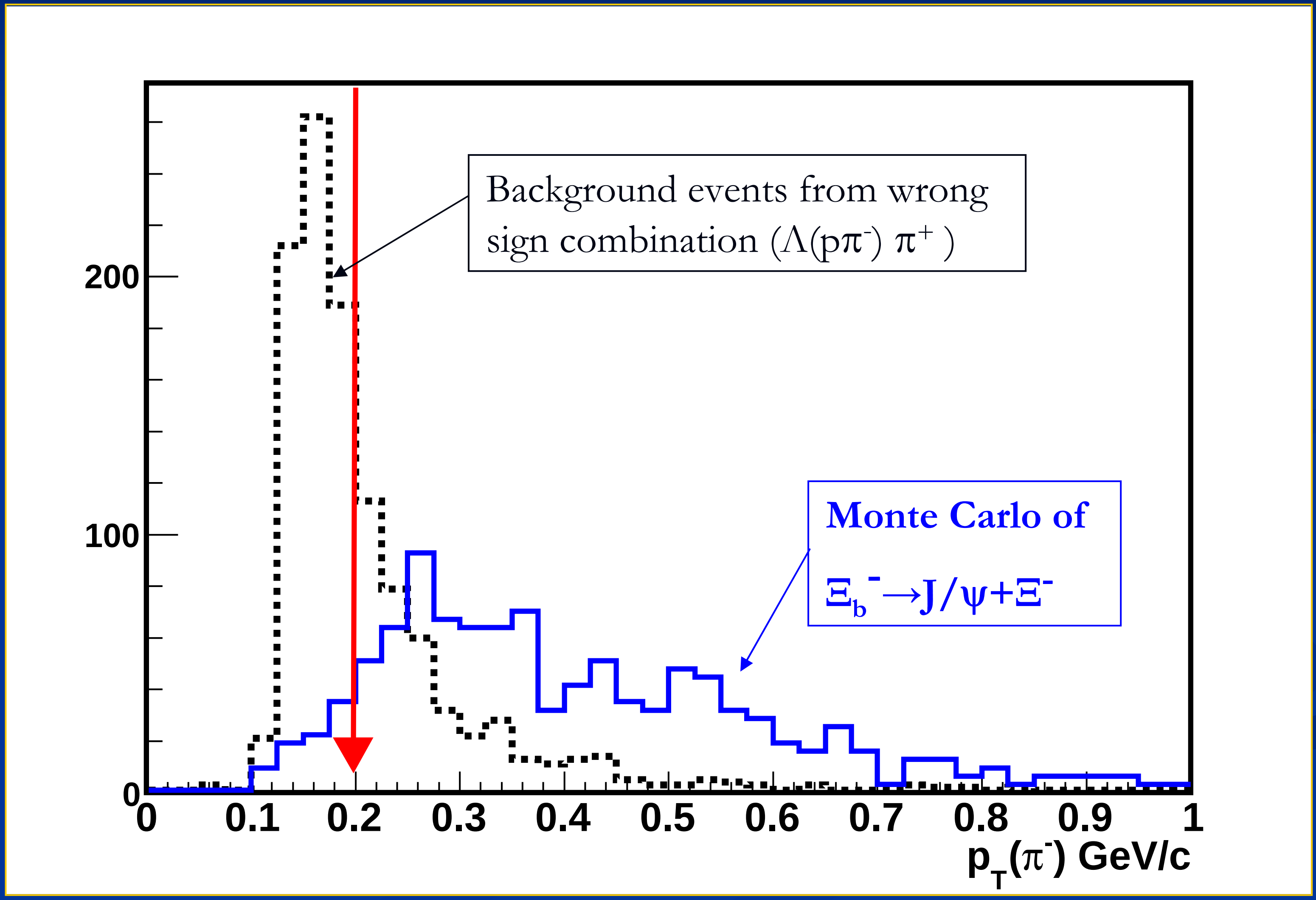
Determination of Selection Criteria

- To retain efficiency, try to keep cuts loose
- We use independent samples:
  - $\Lambda_b \rightarrow J/\psi\Lambda$ 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 Xi)

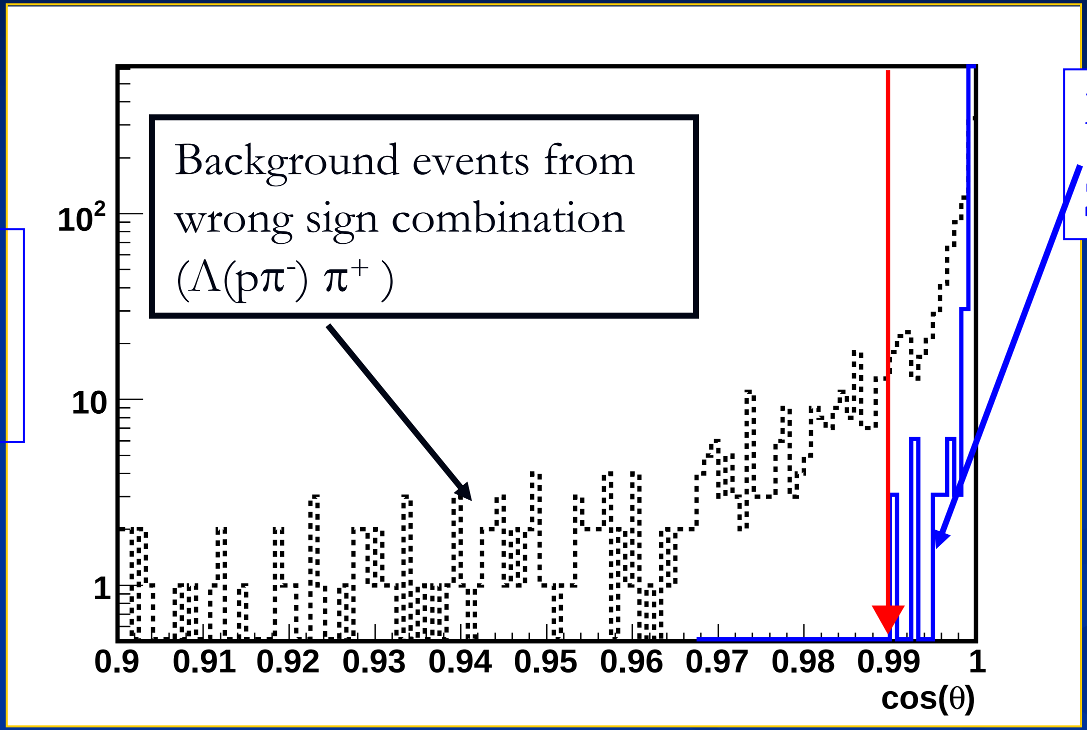
Example 1: pT(π⁻) from Λ



Example 2: pT(π^-) from Ξ^-



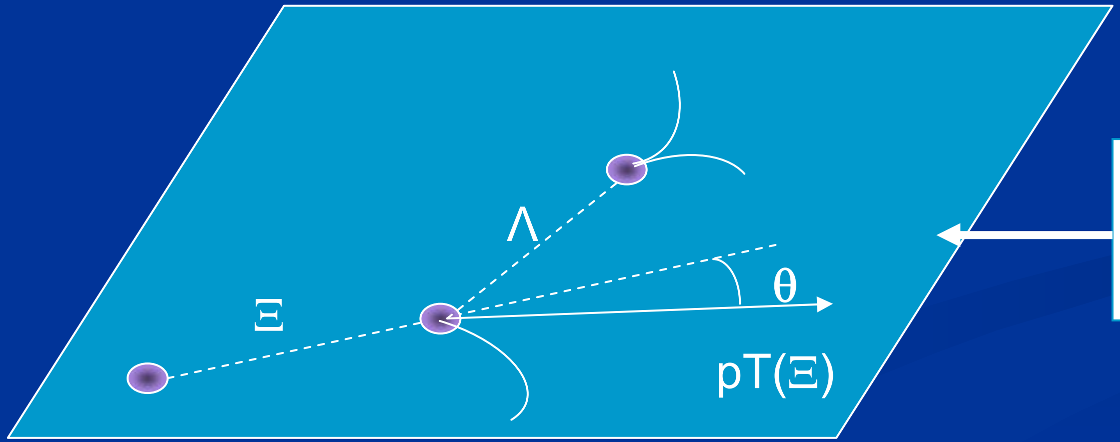
Example 3: topology cut



Monte Carlo of $\Xi_b^- \rightarrow J/\psi + \Xi^-$

Cos(θ)>0.99

100% efficiency



Collinearity in XY:

Cosine(θ)

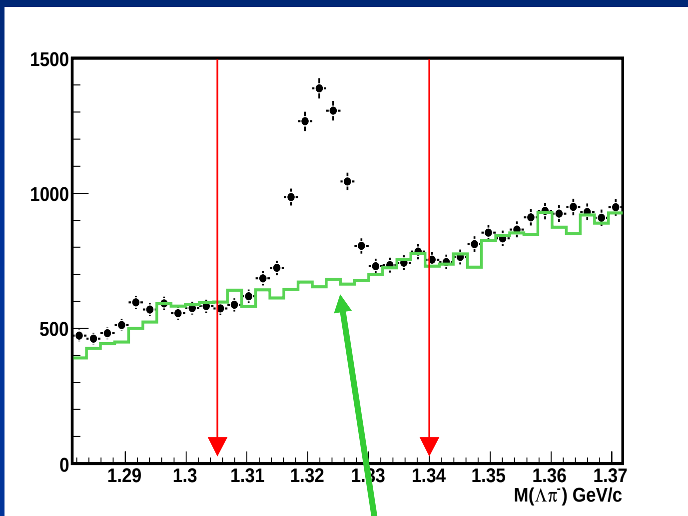
Finally we have: Ξ_b Selection

- $\Lambda \rightarrow p\pi$ decays:
  - pT(p)>0.7 GeV
  - pT(π)>0.3 GeV
- $\Xi^- \rightarrow \Lambda\pi$ 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

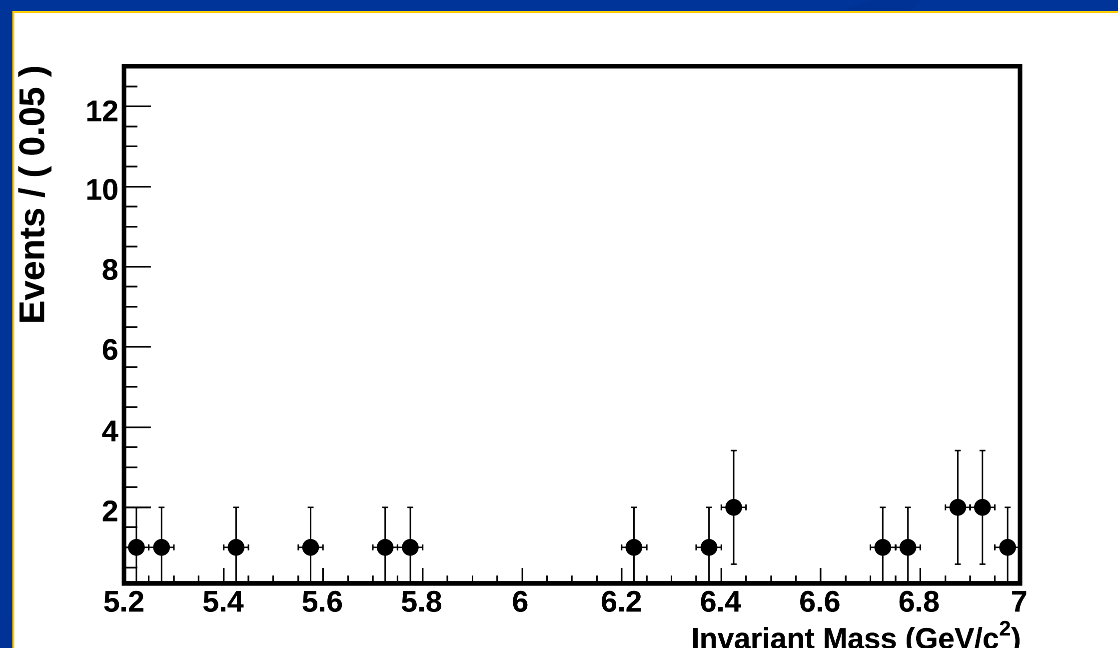
- We have three independent background samples:
  - Wrong sign combination (fake Ξ^-'s from $\Lambda(p\pi^-)\pi^+$)
  - J/ψ sideband events
  - Ξ^- sideband events.

Background: Wrong sign combinations

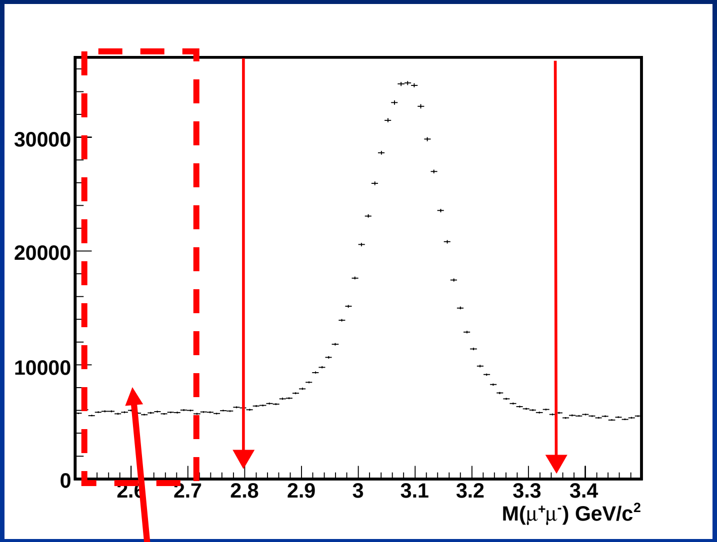


No peaking structure observed in this background control sample

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

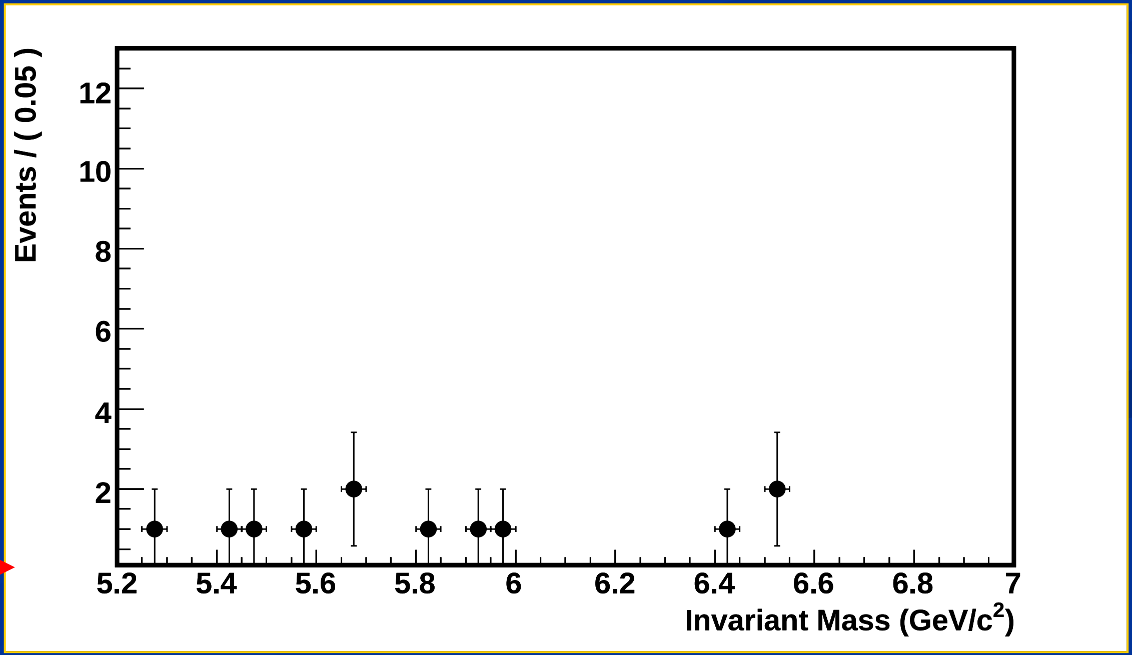


Background: J/ψ sideband events

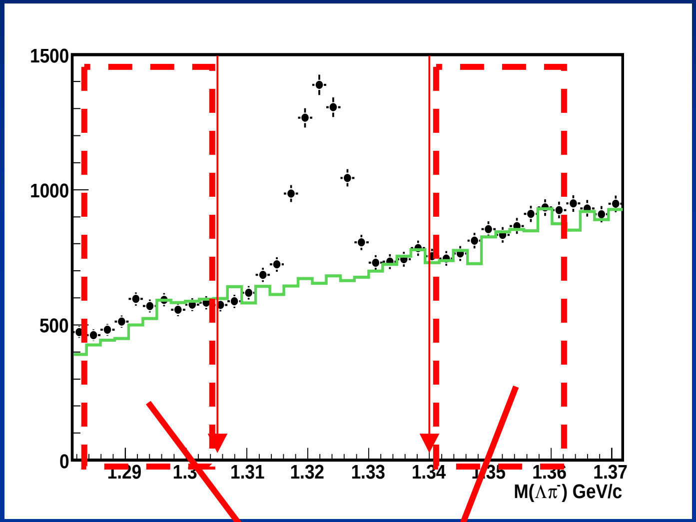


No peaking structure observed in this background control sample

J/ψ Λ(pπ-)π+

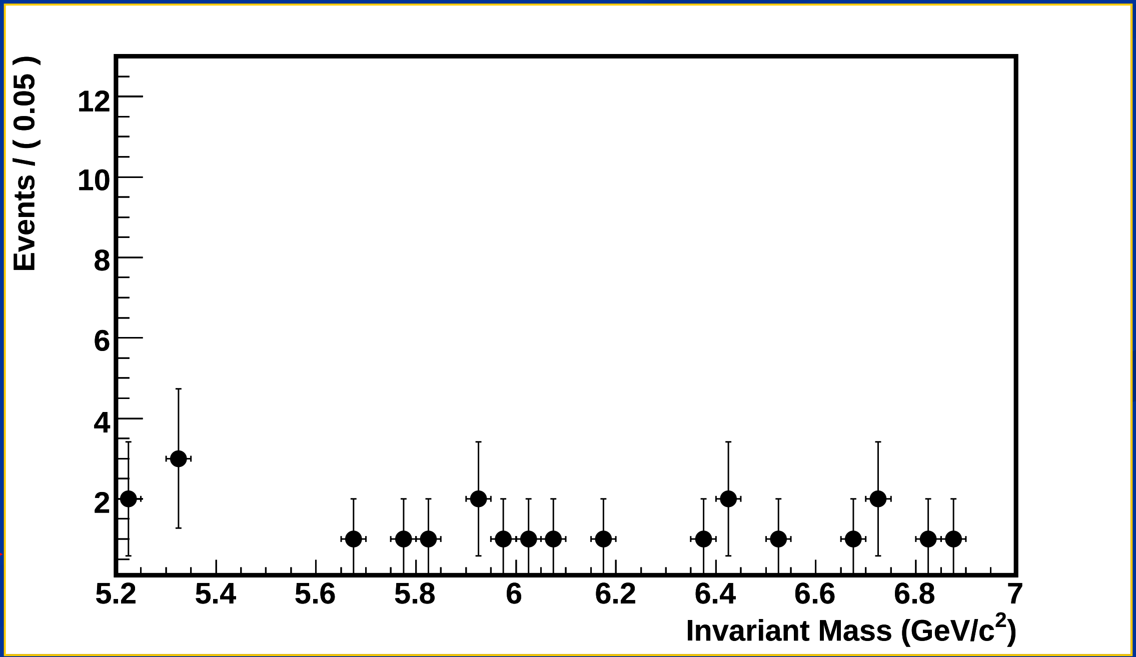


Background: Ξ^- sideband events



No peaking structure observed in this background control sample

J/ψ $\Lambda(p\pi^-)\pi^-$

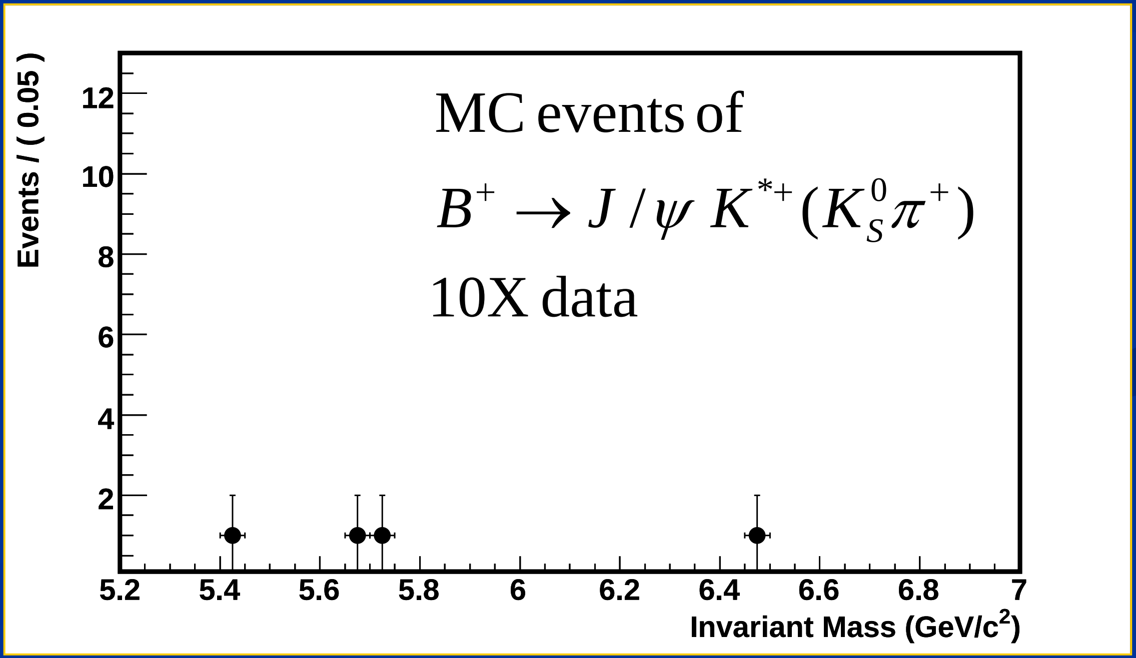


Now let's look at background MC

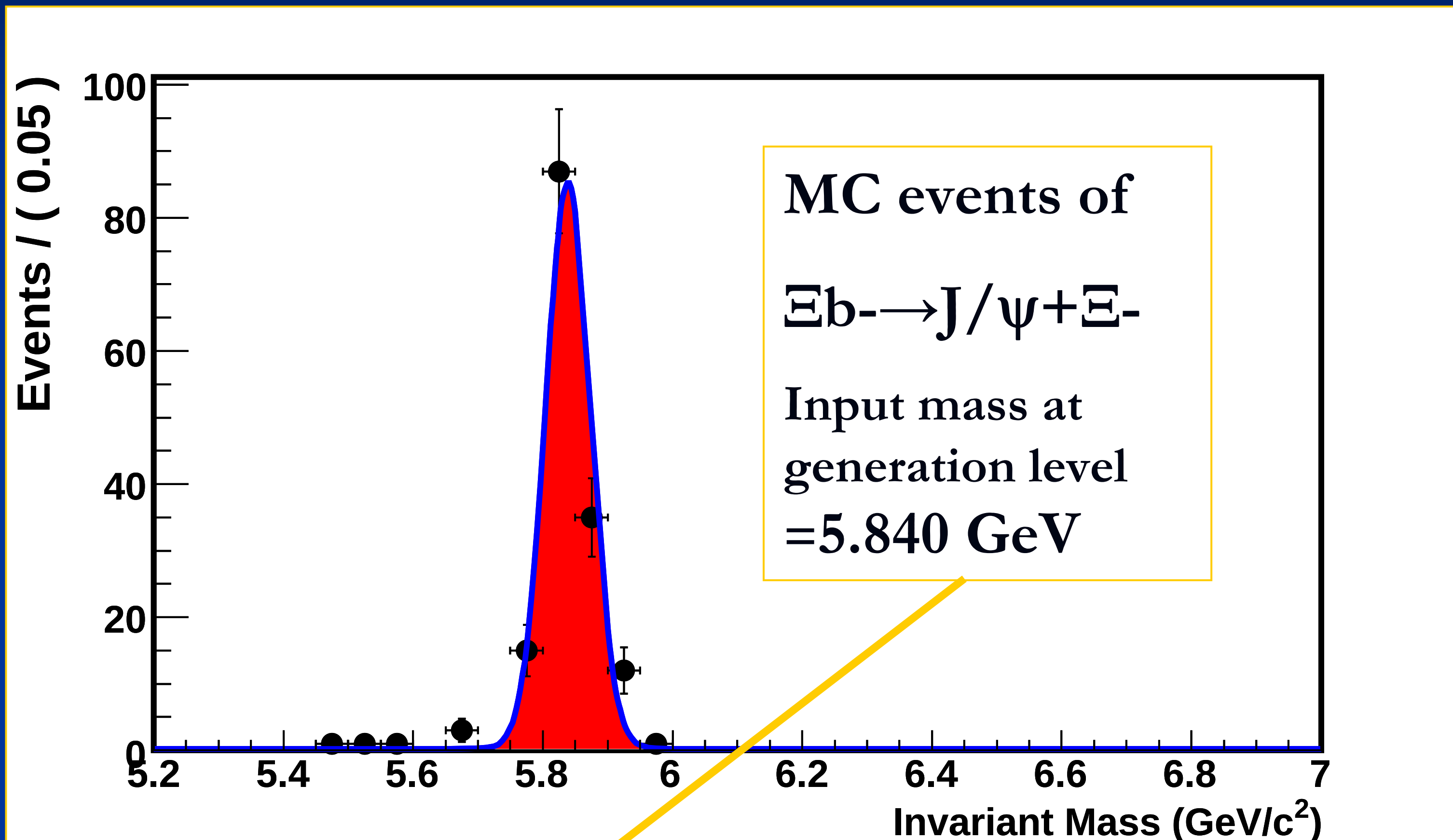
- We investigated with high MC statistics, B decay channels such as:

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

No peaking structure observed any these B decays MC samples



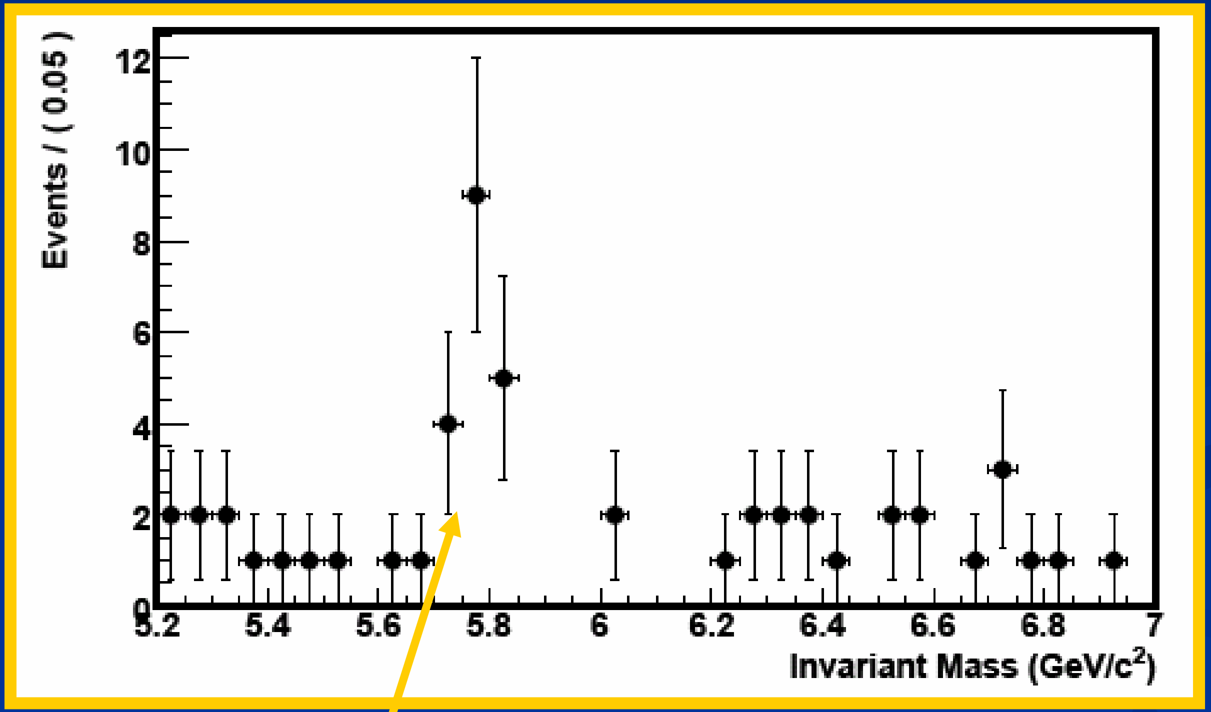
What we expect: signal MC



Mean of the Gaussian: 5.839 ± 0.003 GeV

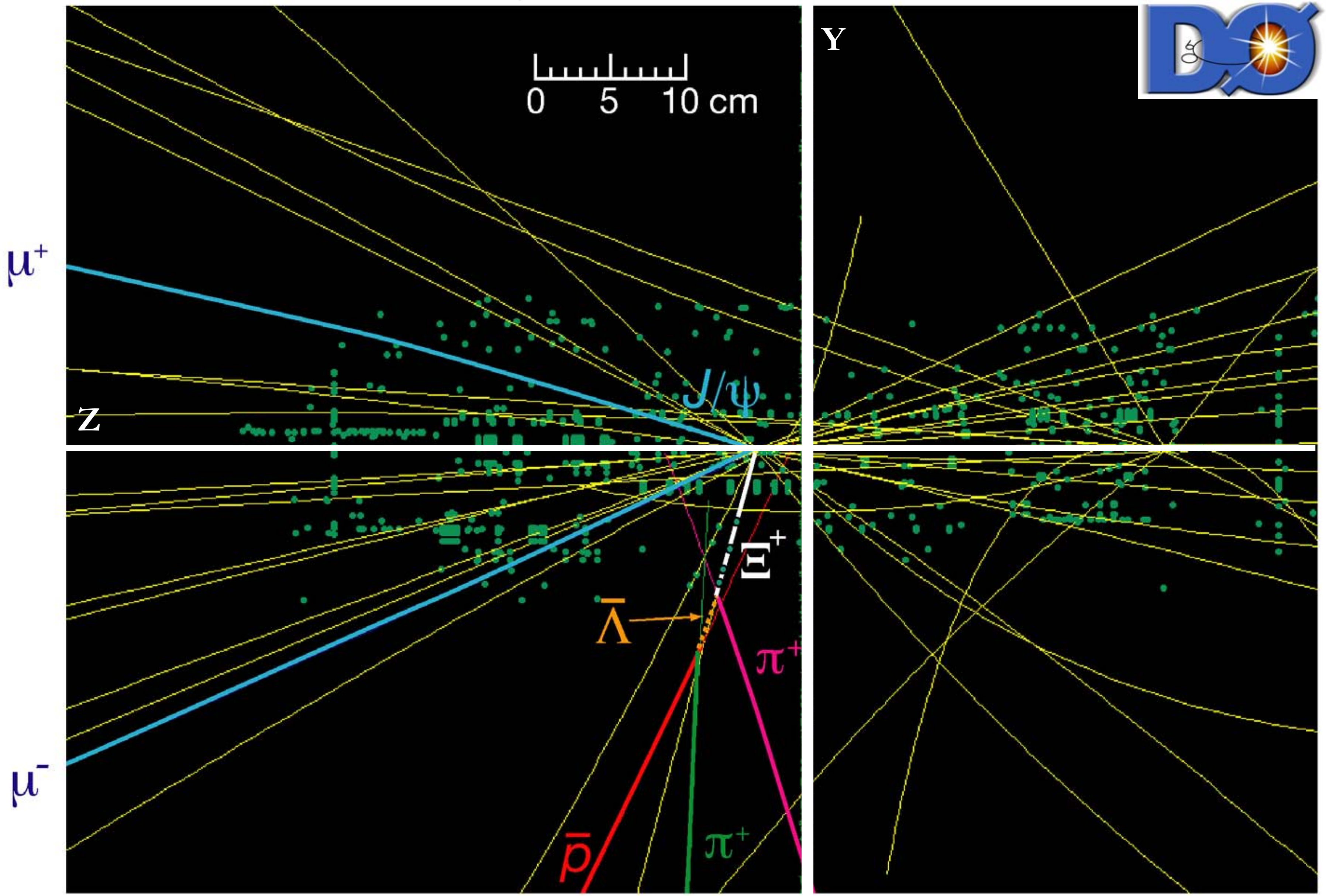
Width of the Gaussian: 0.035 ± 0.003 GeV

Looking at data



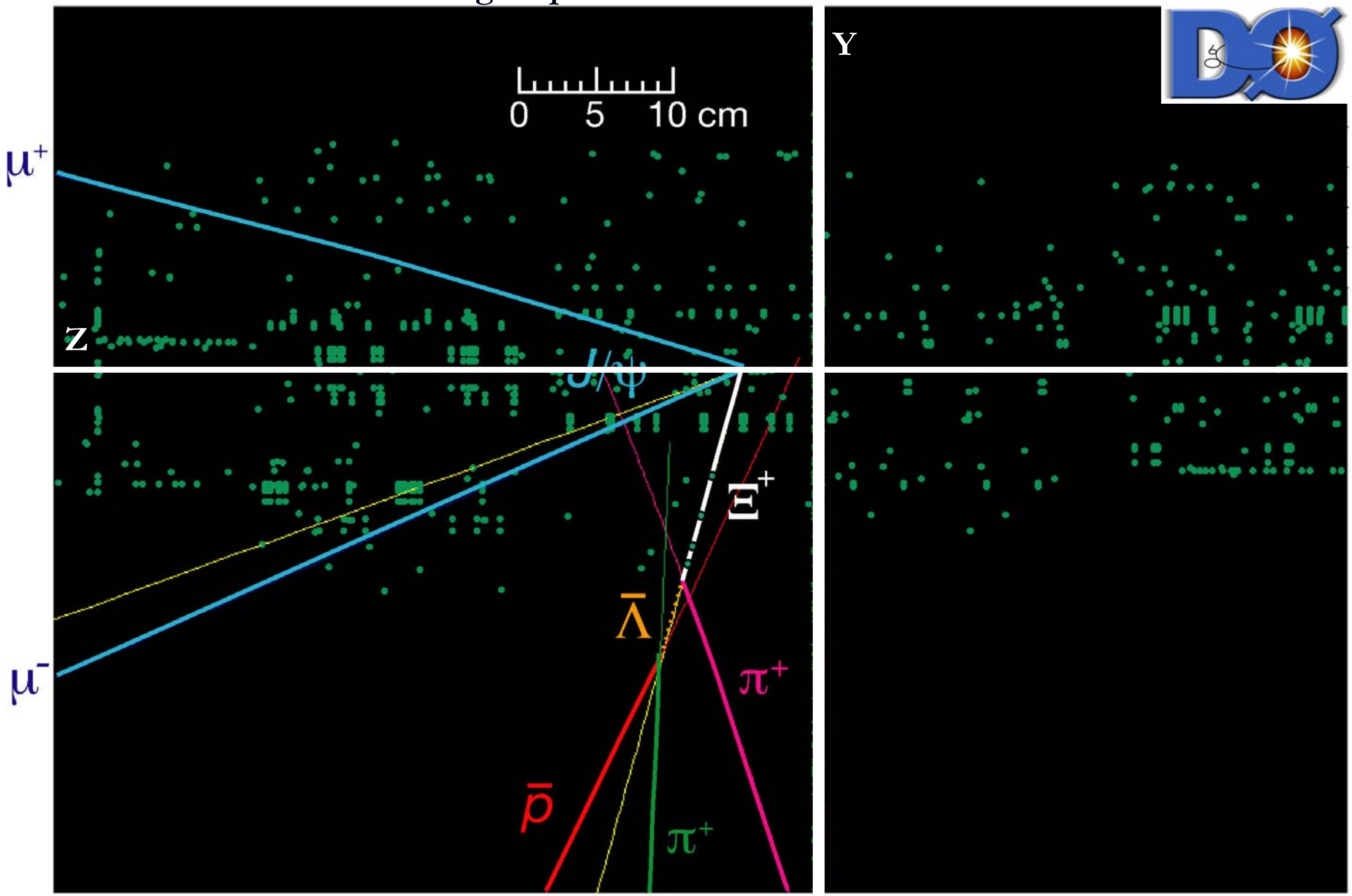
Clear excess of events just below 5.8 GeV

Event scan of event in the signal peak



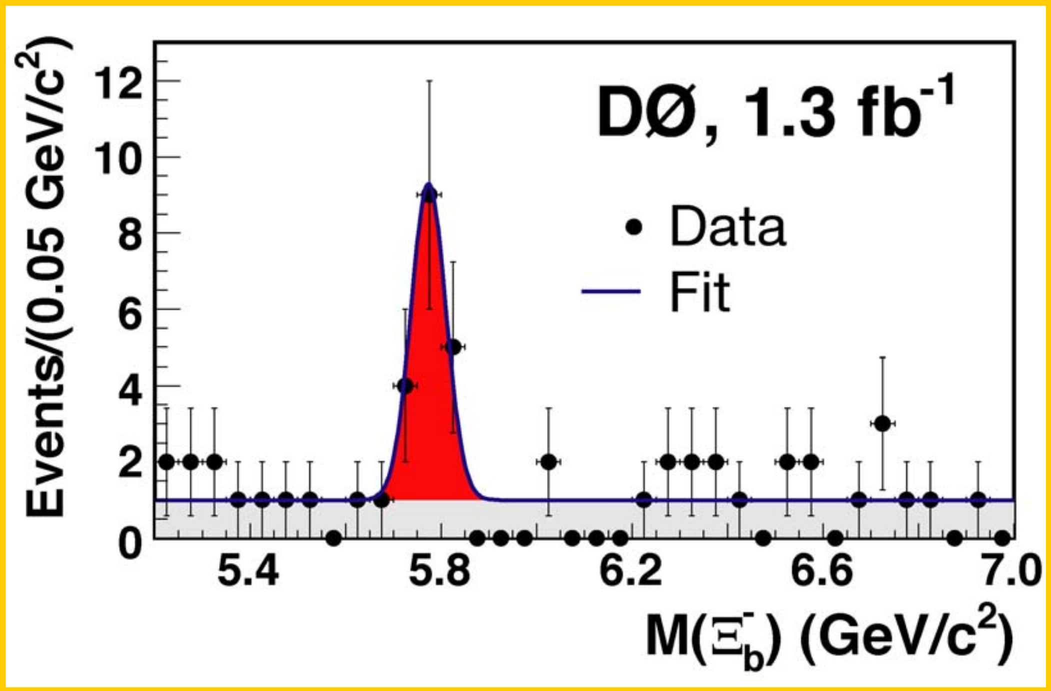
Run 179200, Event 55278820, $M(\Xi_b)$ = 5.788 GeV

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

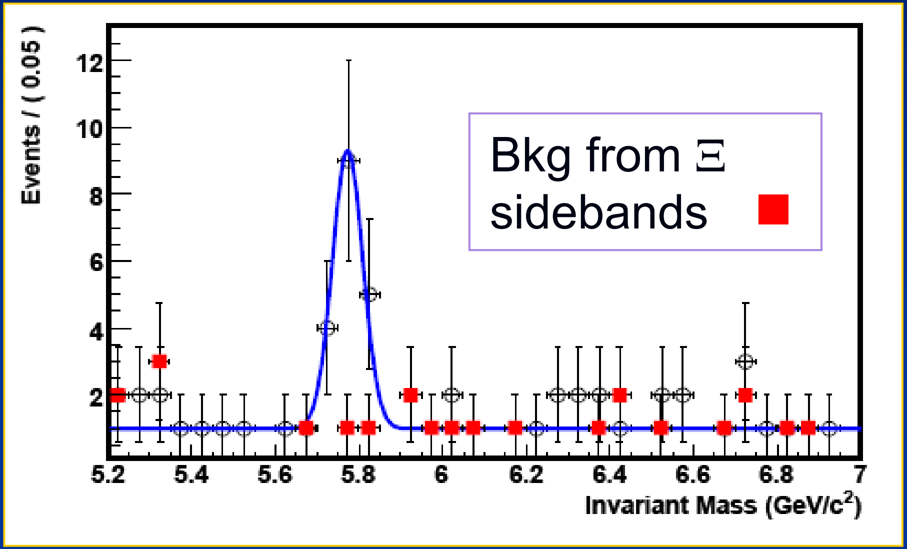
Mean of the Gaussian: 5.774 ± 0.011(stat) GeV

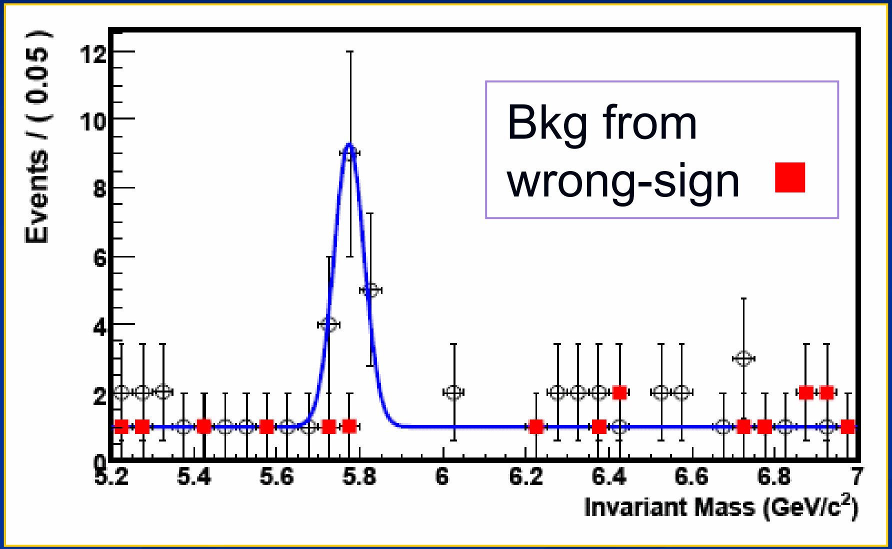
Width of the Gaussian: 0.037 ± 0.008 GeV

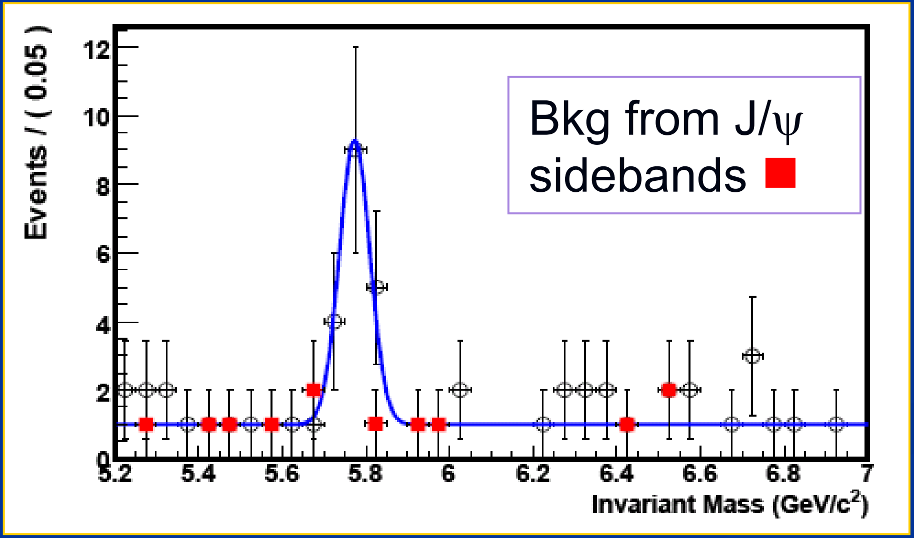
Compare to width measured in MC:

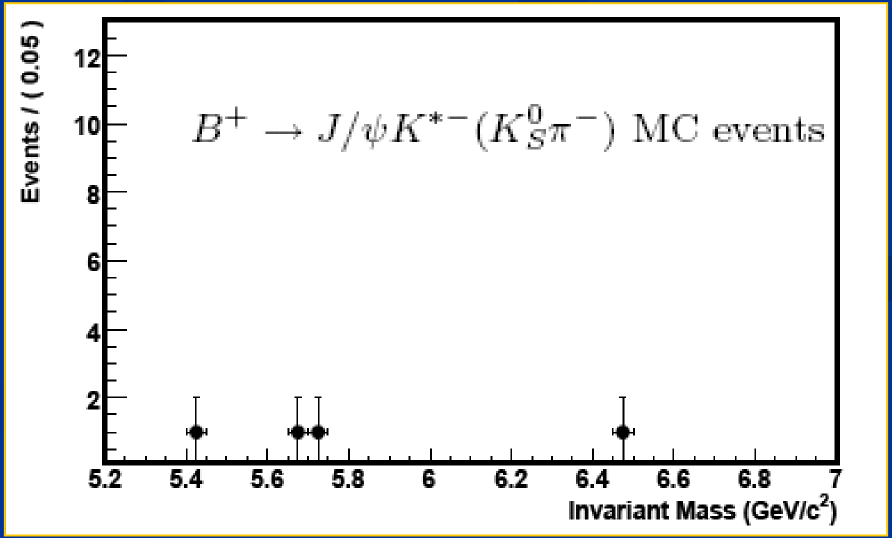
0.035 ± 0.003 GeV

Nothing in the background samples:









Significance of the peak

- Two likelihood fits are perform:
  1. Signal + background hypothesis (L_{S+B})
  2. Only background hypothesis (L_B)
- We evaluate the significance:

$$\sqrt{-2\Delta \ln L} = \sqrt{-2\ln\left(\frac{L_B}{L_{S+B}}\right)}$$

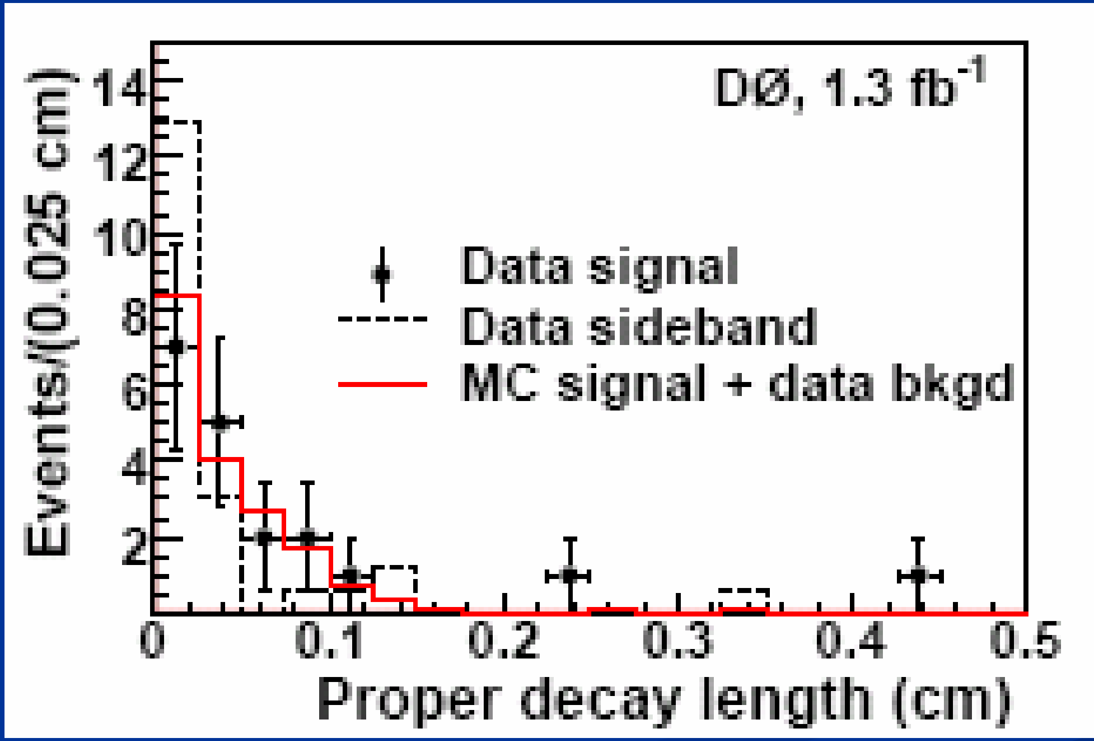
- Significance of the observed signal: 5.5σ

Alternative significance

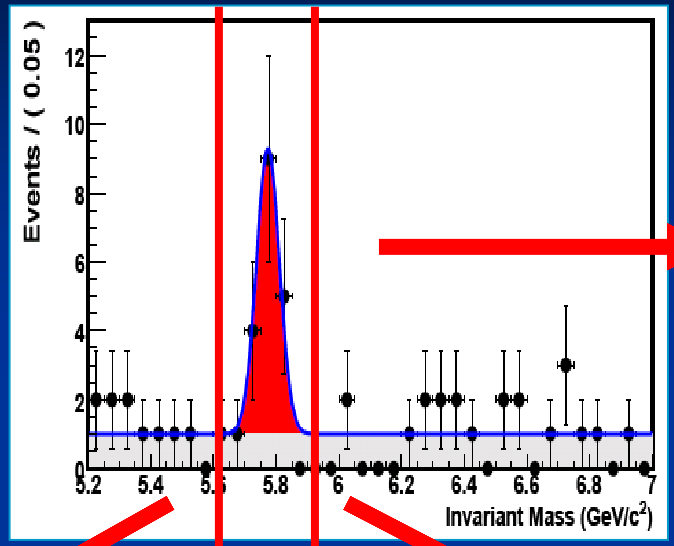
- In the mass region of 2.5 times the fitted width centered on the fitted mass, 19 candidate events are observed while 14.8 ± 4.3 (stat.)$+1.9/-0.4$ (syst.) signal and 3.6 ± 0.6 (stat.)$+0.4/-1.9$ (syst.) background events are estimated from the fit. The probability of backgrounds fluctuating to 19 or more events is **2.2×10^{-7}**, equivalent to a Gaussian significance of **5.2σ**

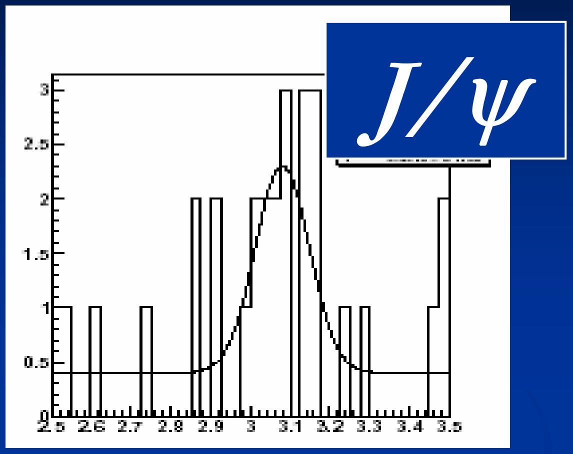
Consistency checks

- Decay length distribution

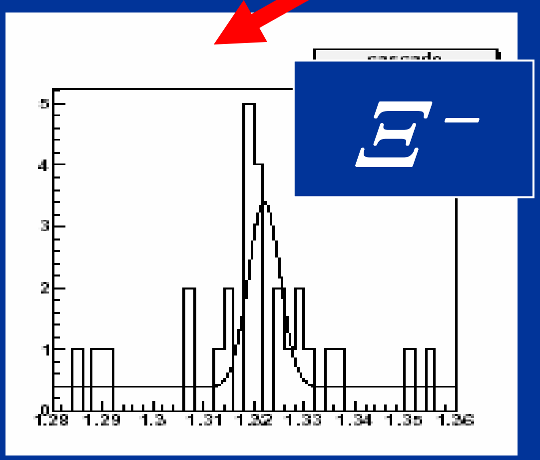


Intermediate Resonances



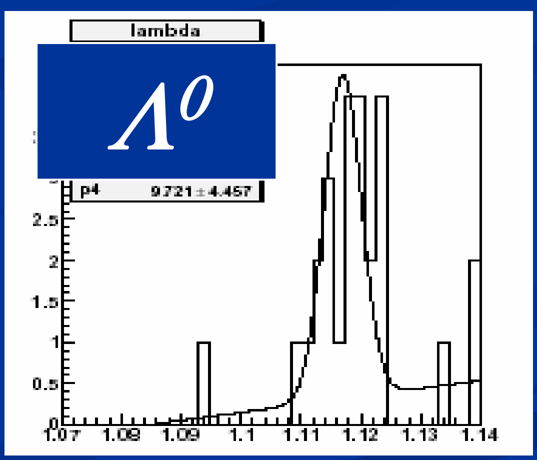


$m(\mu\mu)$



$m(\Lambda\pi)$

Signal visible in all intermediate resonances



$m(p\pi)$

A second analysis approach would be …

- A different approach is to rely heavily on Monte Carlo simulation.
- There are many multivariate techniques in the market:
  - Artificial Neural Networks,
  - Boosted Decision Trees,
  - Likelihood ratio,
  - etc.
- As a cross check we used Decision Trees

Example: Decision Trees (BDT)

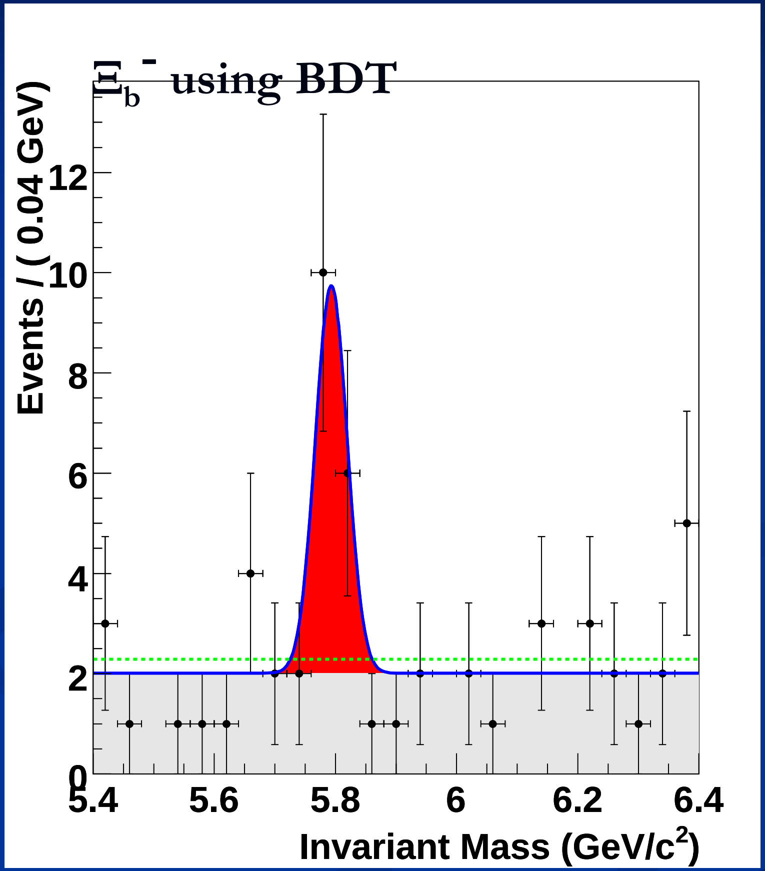
- In order to apply the same BDT to Λ_b in data, we use only J/ψ and Λ variables as input to the BDT.

Decision Tree Input Variables
Vertex quality:
χ^2 of $\mu^+\mu^-$ vertex
χ^2 of $p\pi^-$ vertex
χ^2 of $\mu^+\mu^-\Xi^\pm$ vertex
Kinematics variables:
p_T of μ^+
p_T of μ^-
p_T of p
p_T of π^-
p_T of Λ
Lifetime related variables:
Λ lifetime (w.r.t. primary vertex) significance
Λ transverse decay length (w.r.t. J/ψ vertex)
$\Xi_b^\pm$ lifetime uncertainty
Angular variables:
$\cos(\vec{v}_{xy}, p_T(\Xi_b))$, where $\vec{v}$ goes from the primary vertex to the $\Xi_b^\pm$ vertex.

Minimum overlap between BDT and cut-based variables

Decision Trees

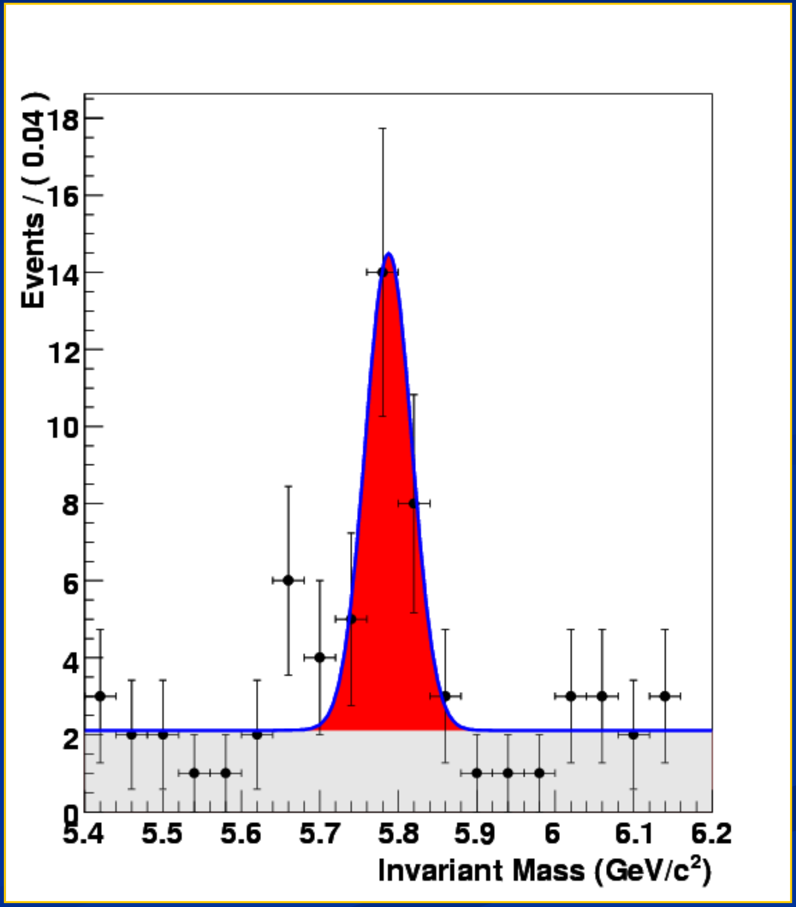
- We observe a signal consistent with that observed with cut-based analysis.
- Only ~50% overlap between selected events and the cut-based analysis.
- Width consistent with MC
- Background shape consistent with wrong-sign combination shape.



A multivariate technique with a simple set of input variables, not including Ξ^- variables, also results in a Ξ_b^- signal.

Combining: cuts+BDT

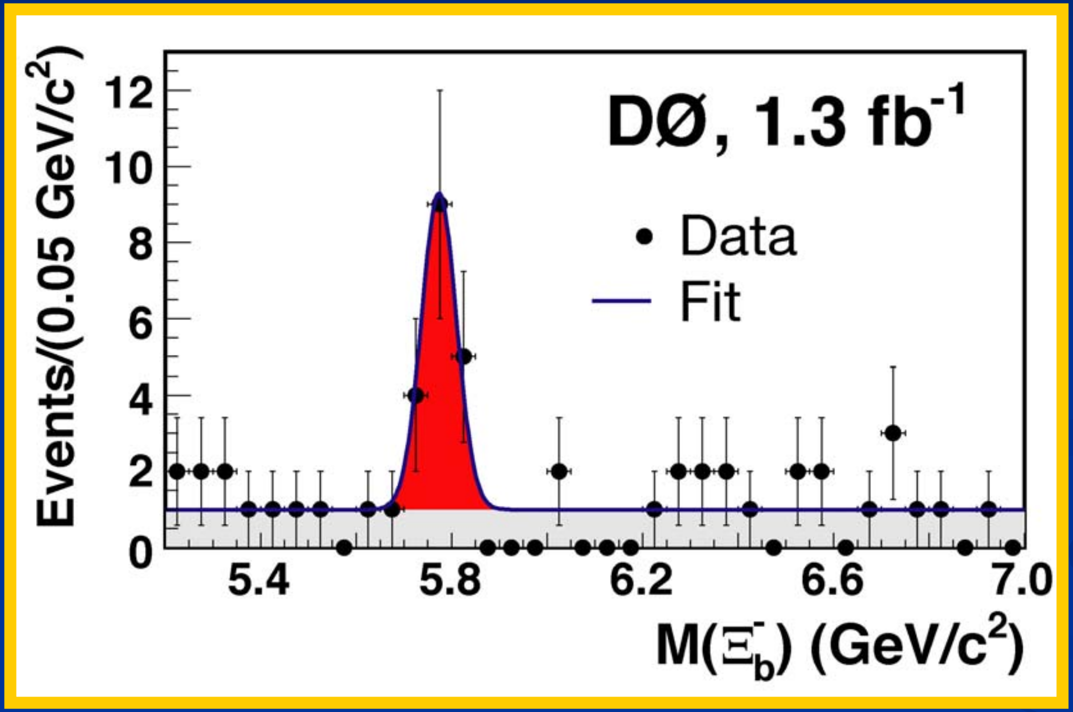
- After we remove duplicate events, we observe 22.8 ± 5.8 events.
- Significance:
  - Sqrt(-2ΔL) = 5.9



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!



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

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

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→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 use Monte Carlo samples of:
  - $\Xi_b^- \rightarrow J/\psi + \Xi^-$
  - $\Lambda_b \rightarrow J/\psi + \Lambda$
- 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

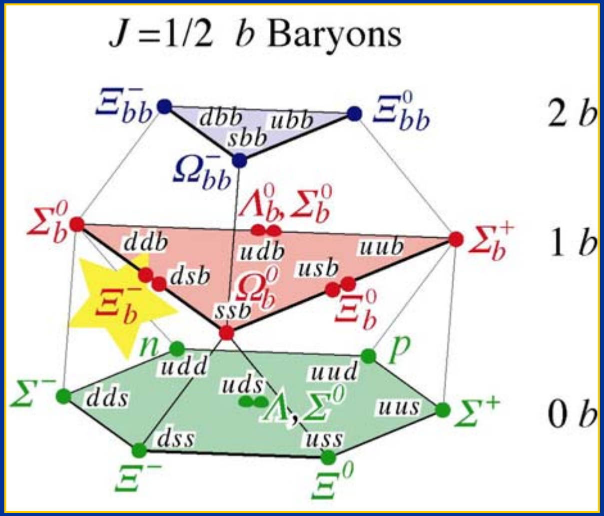
Conservatively take difference between reweighting result and no reweighting .

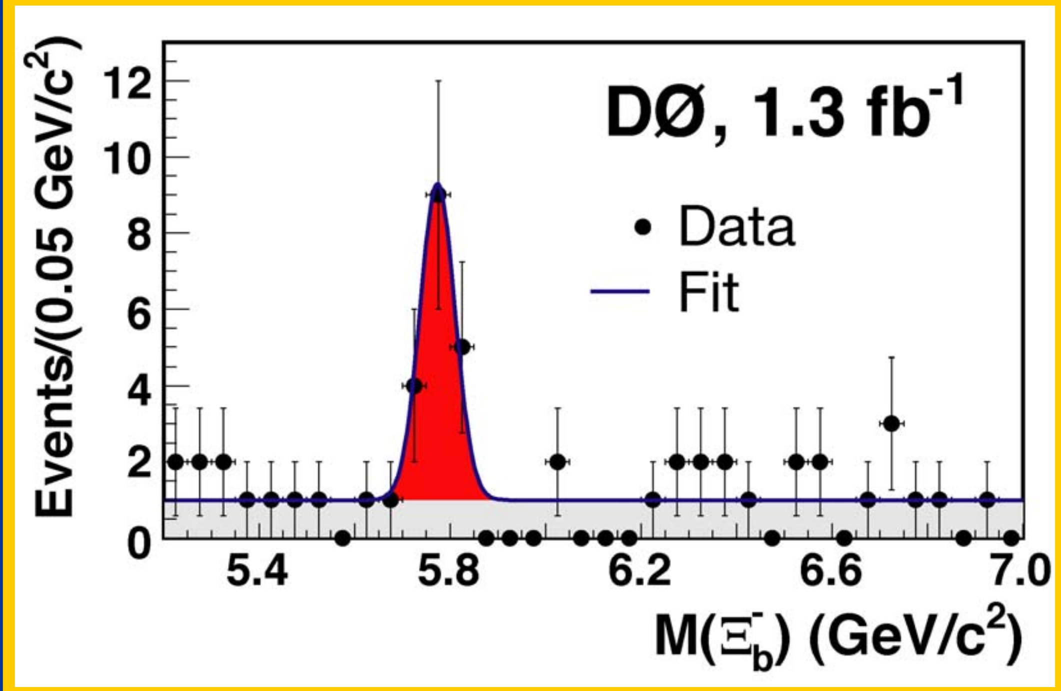
Production ratio

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

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

Last Tuesday June 12, DØ submitted a PRL article announcing the discovery a new b baryon: Ξ_b^-





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

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

Signal Significance

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

Production ratio

- We measure the relative production ratio to be:

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

Allows comparison between experiments

Submitted to PRL 6/12/07

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], S. Caron[33], W. Carvalho[3], B.C.K. Casey[77], N.M. Cason[55], H. Castilla-Valdez[32], S. Chakrabarti[17], D. Chakraborty[52], K.M. Chan[55], K. Chan[5], A. Chandra[48], F. Charles[18], E. Cheu[45], F. Chevallier[13], D.K. Cho[62], S. Choi[31], B. Choudhary[27], L. Christofek[77], T. Christoudias[43], S. Cihangir[50], D. Claes[67], C. Clément[40], B. Clément[18], Y. Coadou[5], M. Cooke[80], W.E. Cooper[50], M. Corcoran[80], F. Couderc[17], M.-C. Cousinou[14], S. Crépé-Renaudin[13], D. Cutts[77], M. Ćwiok[29], H. da Motta[2], A. Das[62], G. Davies[43], K. De[78], S.J. de Jong[34], P. de Jong[33], E. De La Cruz-Burelo[64], C. De Oliveira Martins[3], J.D. Degenhardt[64], F. Déliot[17], M. Demarteau[50]

arXiv:0706.1690, Fermilab-Pub-07/196-E

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Graphics and photos are available at:
http://www.fnal.gov/pub/presspass/images/DZero-cascade-b.html

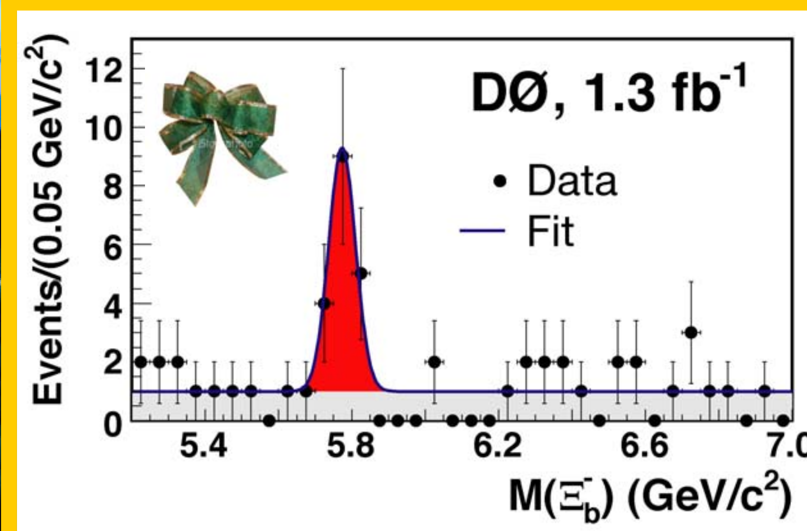
Fermilab physicists discover "triple-scoop" baryon

Three-quark particle contains one quark from each family.

Batavia, Ill. - Physicists of the DZero experiment at the Department of Energy's Fermi National Accelerator Laboratory have discovered a new heavy particle, the Ξ_b

The quest begins … and continues @ Fermilab

Celebrating 30 years of the b quark discovery @ Fermilab



A New b baryon:
an anniversary gift

Collaboration