Hunting for heavy b baryons from Ξ_b to Ω_b

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on behalf of the DØ Collaboration

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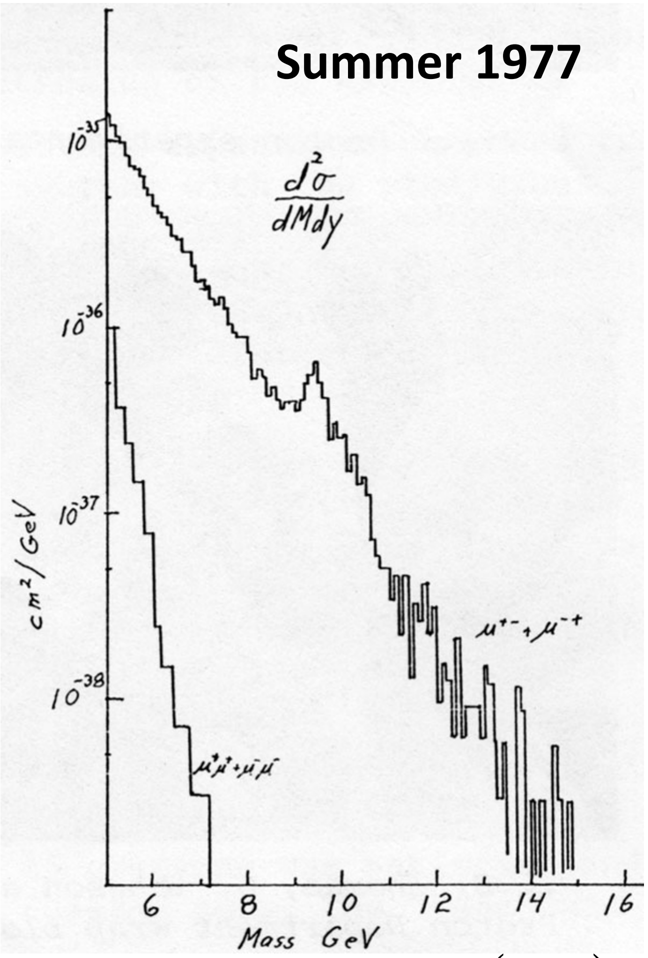
CPPM, Marseille

History of the Bottom…

$$p + (\mathrm{Cu},\ \mathrm{Pt}) \to \mu^+ \mu^- + X$$



$$M(\mu\mu)$$

It has been over 30 years since the discovery of the upsilon meson at Fermilab by Lederman et al.

Since then, we have come a long way in studying B mesons

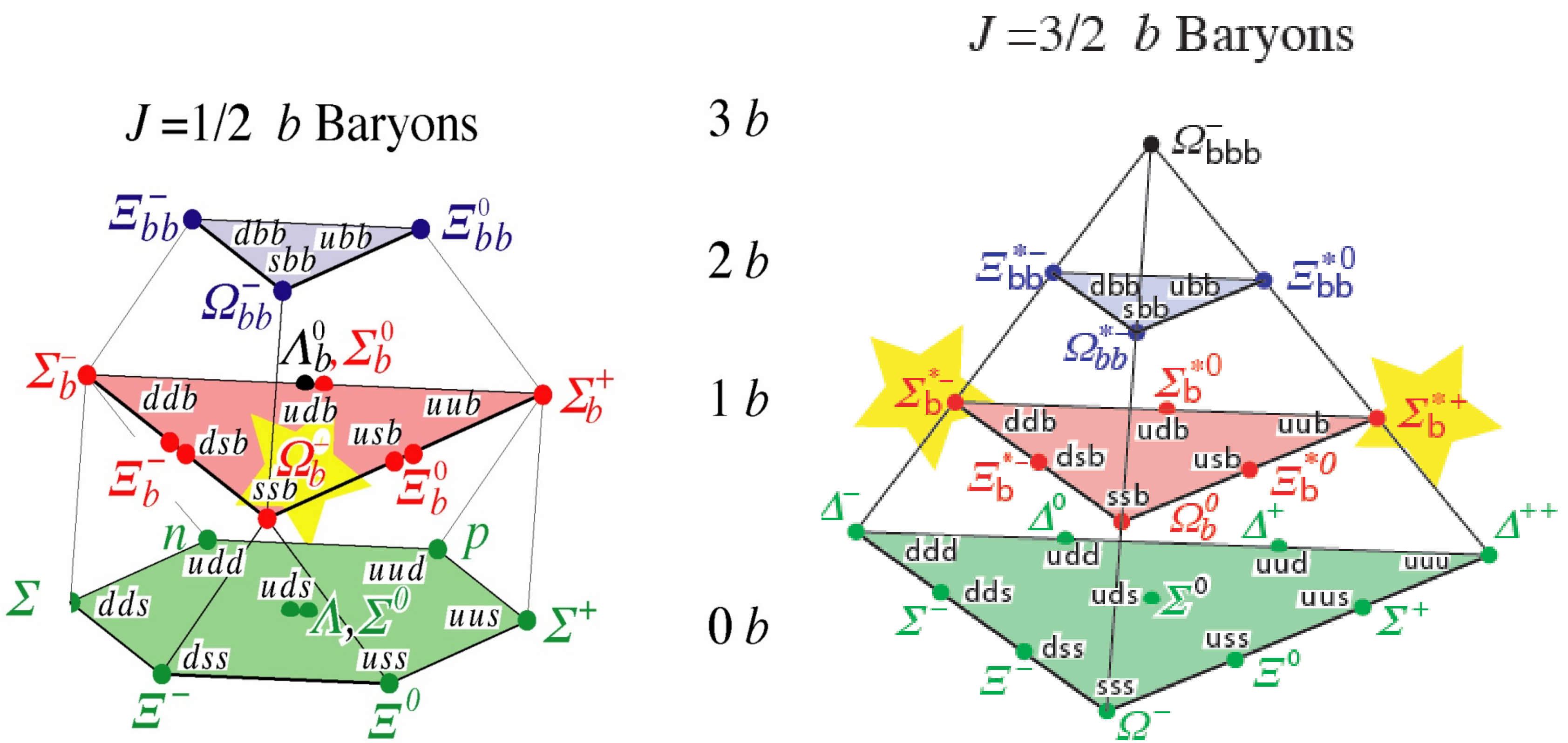
But not so much in understanding B baryons. Until two years ago, only one baryon was observed…

b Baryons

A total of 15 b baryons are predicted

(counting quark content only)

charmless b baryon (10 in total) multiplet



Observed b Baryons

Until recently, only one b baryon has been directly observed.

$$\Lambda_b\ (\mathrm{udb}):\ \Lambda_b \to J/\psi\ \Lambda$$

UA1: PL B273, 540 (1991)

However, four were discovered over the last two years:

$$\Sigma_b^+\ (\mathrm{uub})\ /\ \Sigma_b^-\ (\mathrm{ddb}):\ \Sigma_b^\pm \to \Lambda_b \pi^\pm \to \left(\Lambda_c^+ \pi^-\right)\pi^\pm$$

CDF: PRL 99, 202001 (2007)

$$\Xi_b^-\ (\mathrm{dsb}):\ \Xi_b^- \to J/\psi\ \Xi^-\ (\mathrm{D\O, CDF});\ \Xi_b^- \to \Xi_c^0 \pi^-\ (\mathrm{CDF})$$

DØ: PRL 99, 052001 (2007); CDF: PRL 99, 052002 (2007)

$$\Omega_b^-\ (\mathrm{ssb}):\ \Omega_b^- \to J/\psi\ \Omega^- \to J/\psi\ \left(\Lambda K^-\right)$$

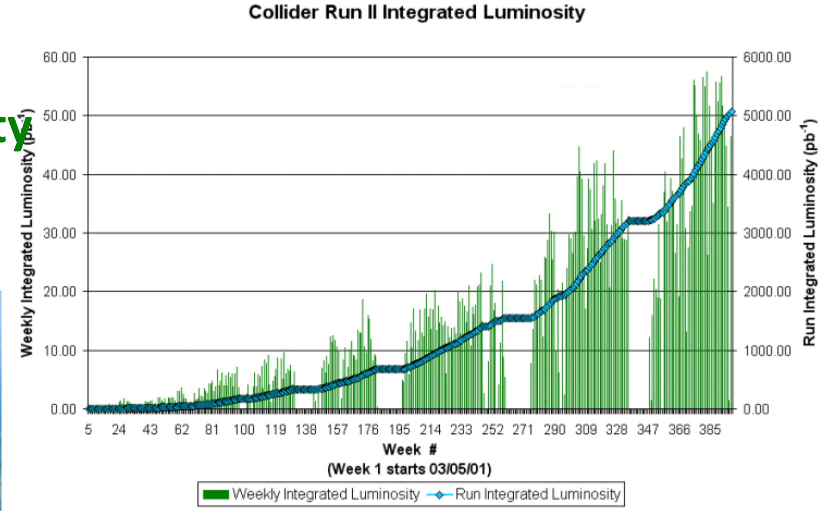
DØ: arXiv: 0808.4142 (2008), to be published in PRL

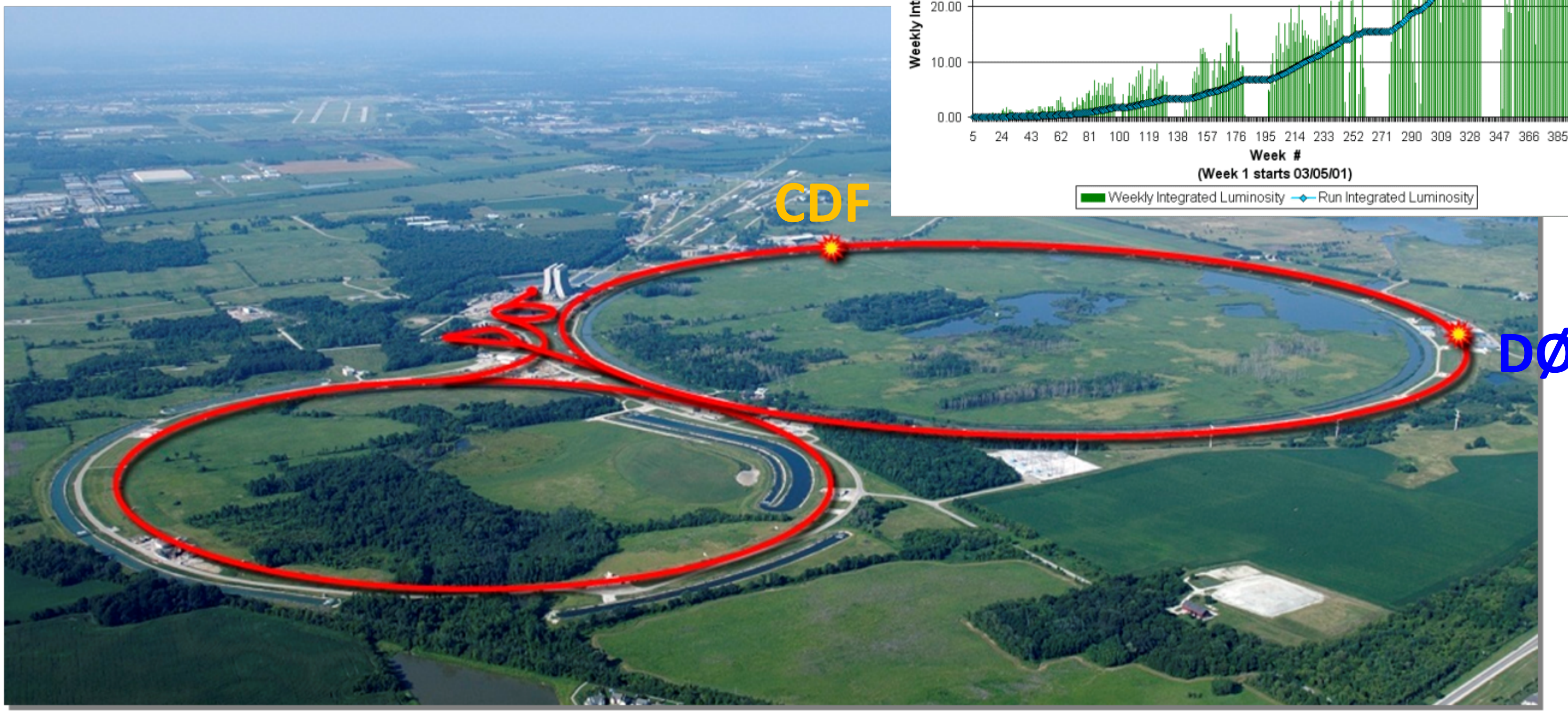
Tevatron Collider

$p\bar{p}$ collider with $\sqrt{s} = 1.96$ TeV

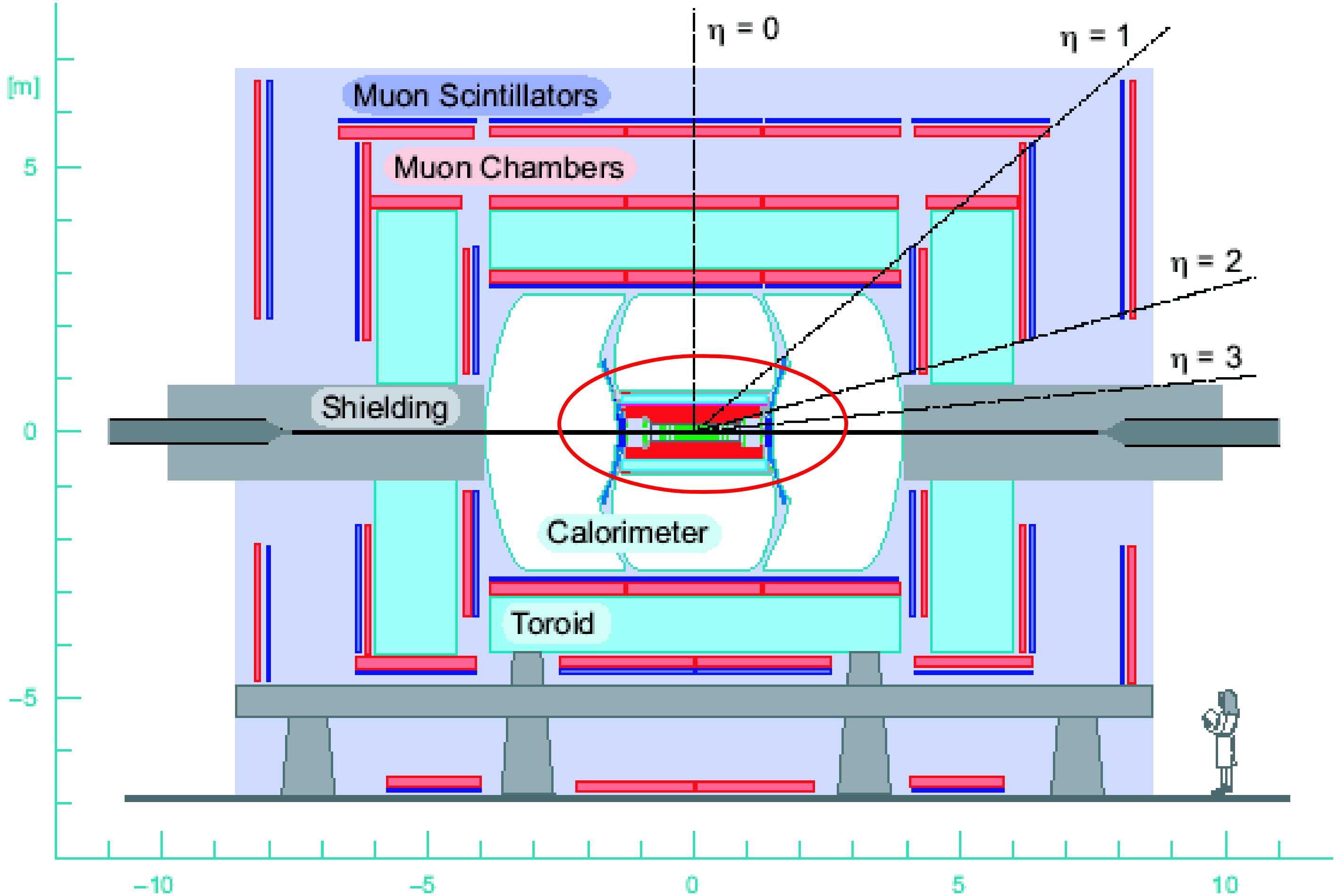
Running well…

- surpassed design instantaneous luminosity
- delivered ~ 5 fb^{-1} to each experiment





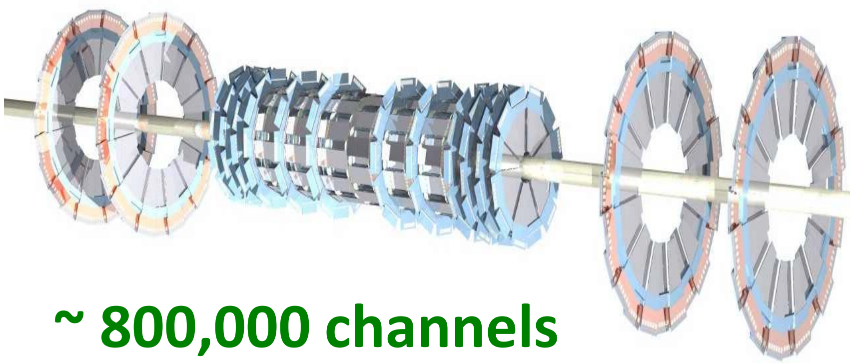
The DØ Detector



No particle ID, no large tracker, no displaced track trigger…

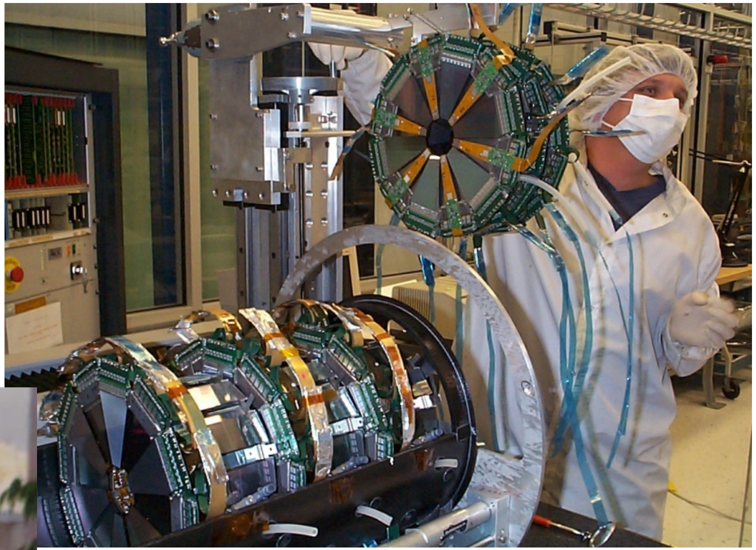
But many smart people ⇒ amazingly productive!

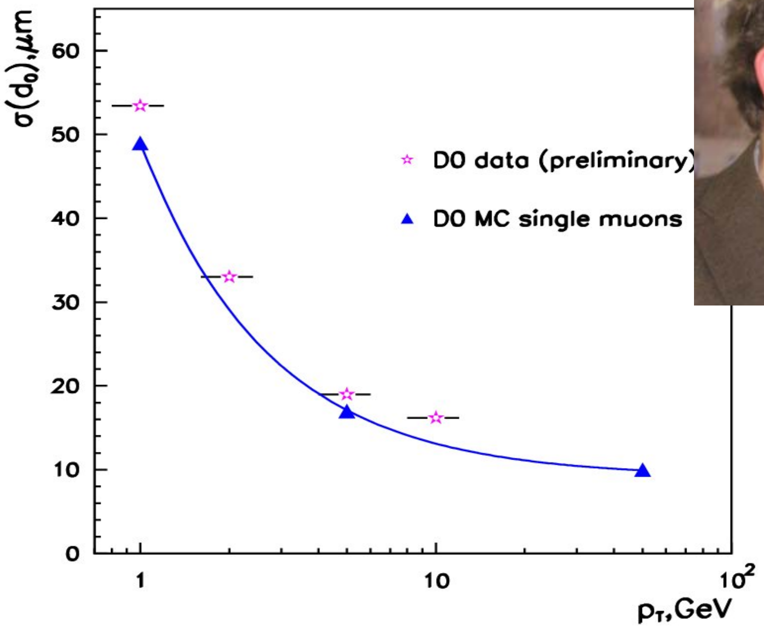
Silicon Detector

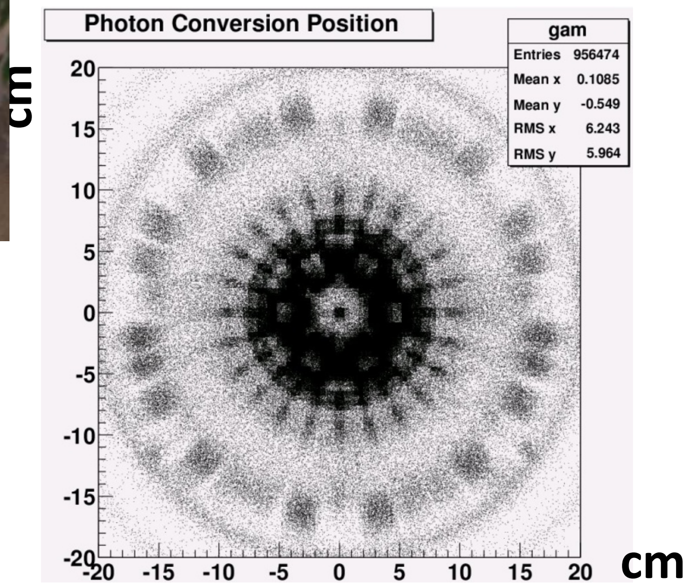


~ 800,000 channels

(1% of ATLAS pixel detector)

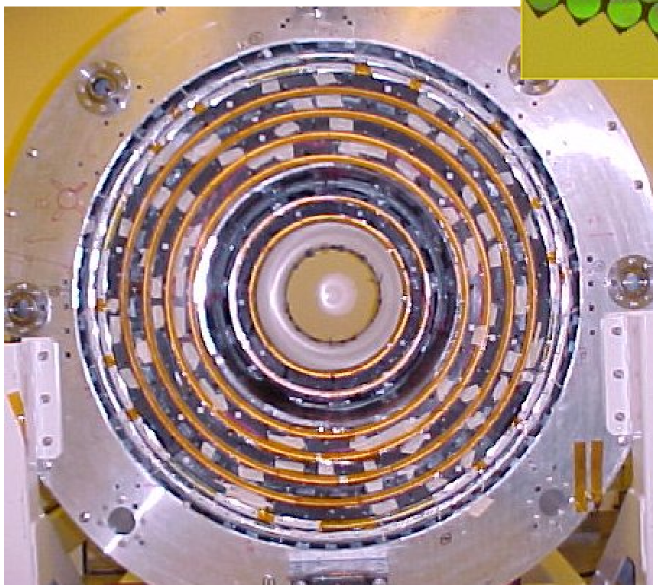


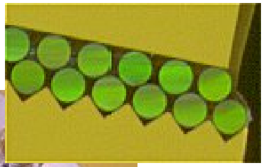




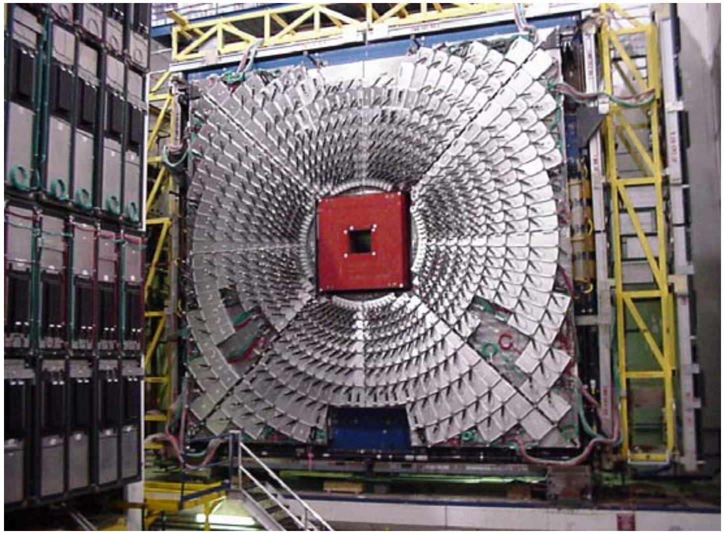
Tracking and Muon

Central Fiber Tracker





Muon Detector



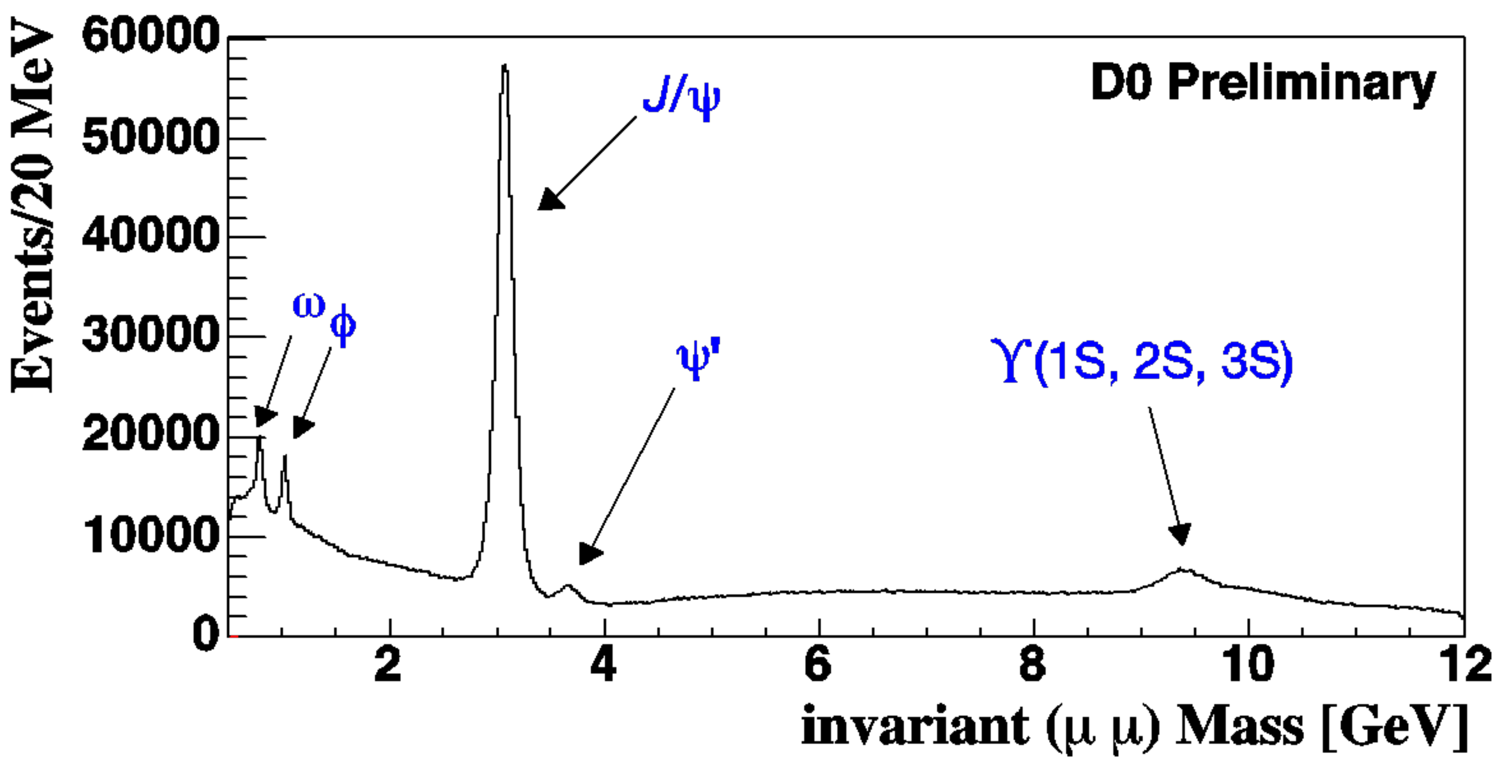
8 layers of ϕ=830 μm scintillating fibers with a total channel count of 76,800 and a radius span from 20 to 50 cm

$$B\ell^2 \sim 0.5\ \mathrm{Tm}^2 \Rightarrow \frac{\delta p_T}{p_T} \approx 1\% \times p_T$$

- **proportional drift tubes**
- **central and end toroidal magnets**
- **scintillator for triggers**

~ 20% standalone momentum resolution

Momentum Calibration



Calibrate the average momentum scale of tracks using well measured μμ resonances …

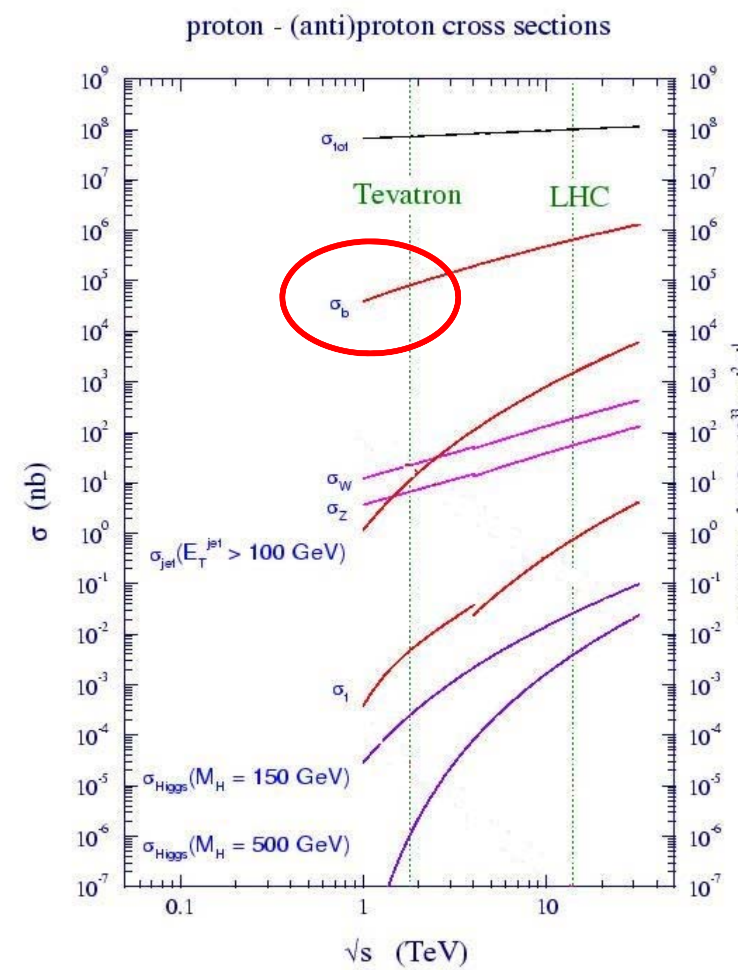
b Production

Huge production rate compared to lepton colliders:

$$\sigma\left(p\bar{p} \to b\bar{b}\right) \approx 150\ \mu\text{b} \ @ \ \sqrt{s}=2\ \text{TeV}$$

$$\sigma\left(e^+e^- \to b\bar{b}\right) \approx 7\ \text{nb} \ @ \ \sqrt{s}=M_Z$$

$$\sigma\left(e^+e^- \to B\bar{B}\right) \approx 1\ \text{nb} \ @ \ \sqrt{s}=M_{\Upsilon(4S)}$$



Campbell, Huston & Stirling, Rept. Prog. Phys. 70, 89 (2007)

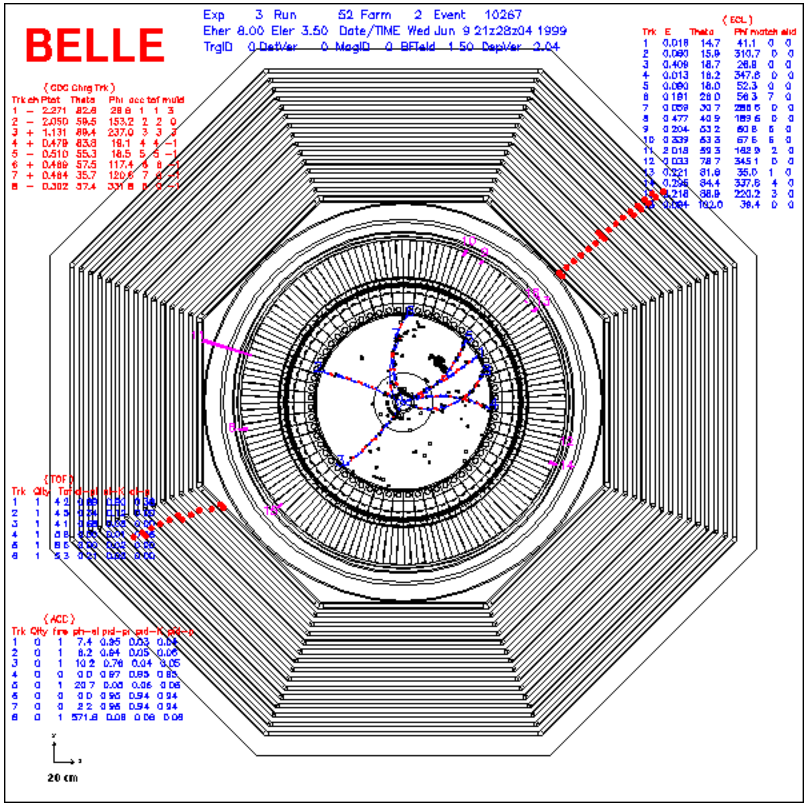
Production of heavy states often inaccessible elsewhere

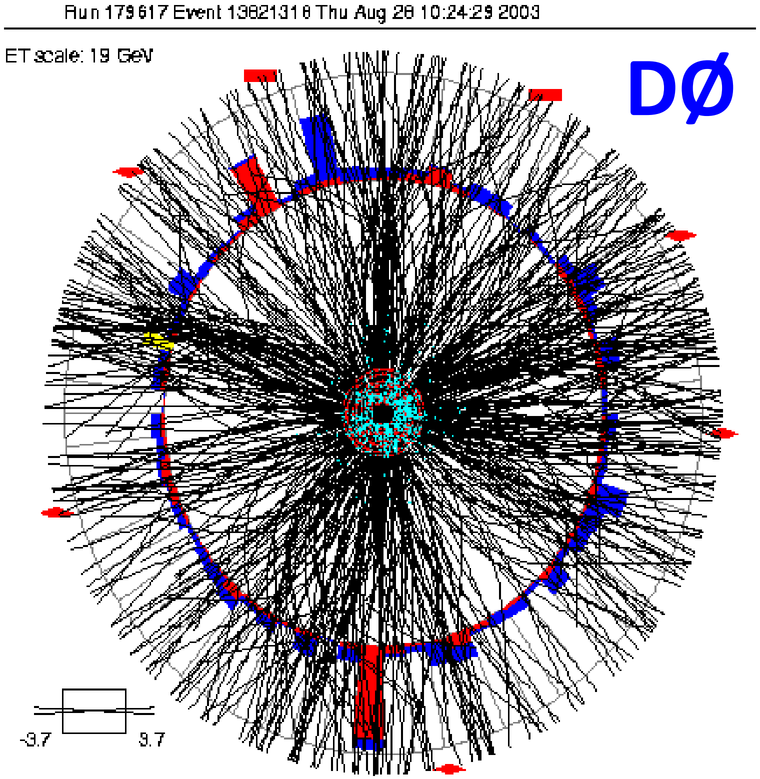
Mesons: B_s, B_c, B^{**}, B_s^{**}, …

Baryons: Λ_b, Σ_b, Ξ_b, Ω_b, …

But also huge backgrounds and messy events …

Environmental Challenges





~ 5 tracks / event

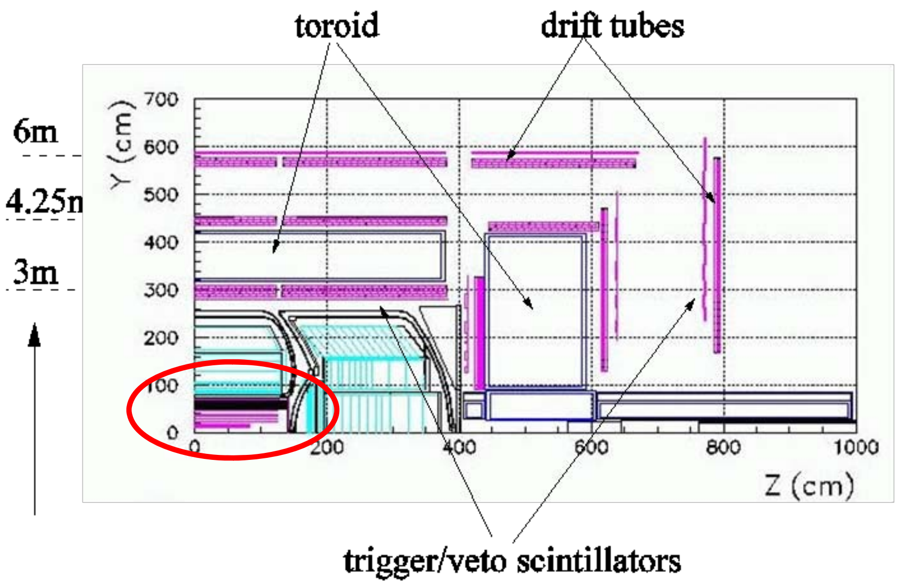
> 100 tracks / event

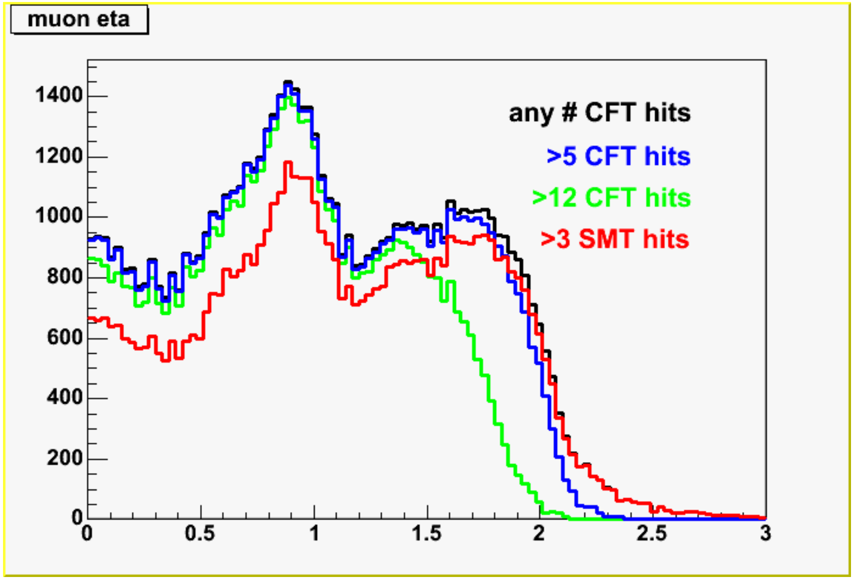
Tough environment to do B physics !

B Physics Triggers

The entire B physics program at DØ is based on muon triggers

- single and dimuon triggers
- large muon coverage ⇒ good acceptance for b events
- a few hertz final rate, limited by bandwidth capability





This analysis includes any event with a reconstructed $J/\psi \to \mu\mu$, no specific trigger is required.

B Physics at DØ

DØ has a diverse program in B physics, recent results include

- search for CP violation in semileptonic Bs decays;
- measurement of Br(Bs$\rightarrow$Ds*Ds*) and the lifetime difference in Bs system;
- measurement of the flavor oscillation frequency of Bs mesons;
- limit on the rare decay Bs $\rightarrow \mu\mu$;
- measurement of the angular and lifetime parameter of the the Bd $\rightarrow$ J/ψ Ks and Bs $\rightarrow$J/ψ ϕ decays;
- measurement of the lifetime and the mass of the Bc meson;
- measurement of the polarization of the Upsilon(1S) and Upsilon(2S);

……

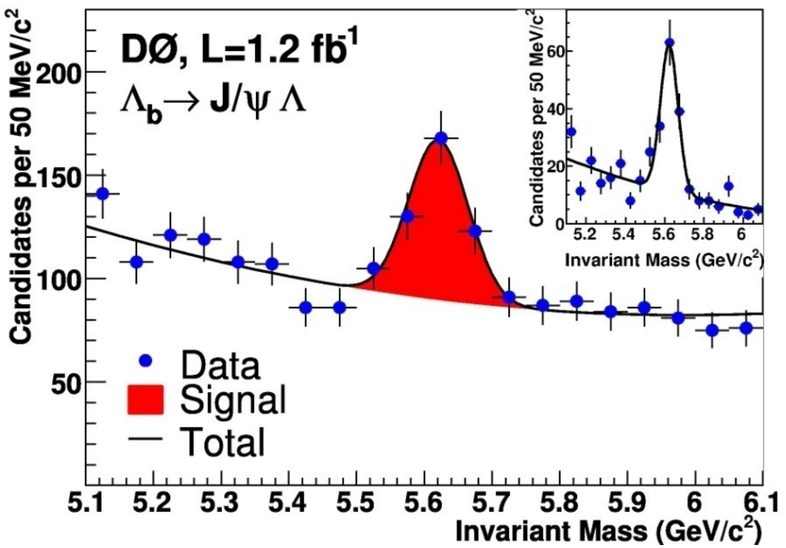
For the full list of the results, please refer to http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm

Λ_b Reconstruction

Our b baryon searches begin with the Λ_b lifetime measurement:

$$\Lambda_b \to J/\psi\ \Lambda, \quad J/\psi \to \mu^+\mu^-, \quad \Lambda \to p\pi^-$$

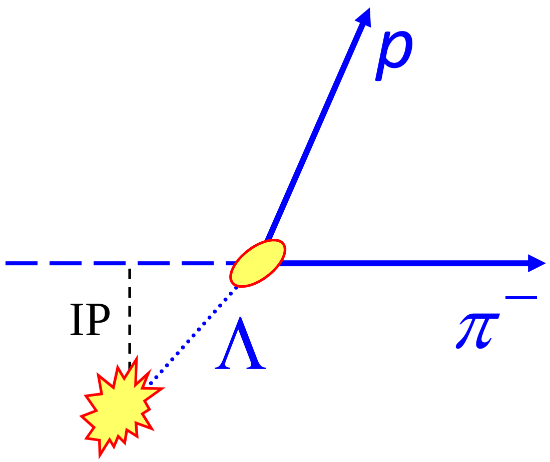
(charge conjugate states are assumed)



What we have learned:

the standard reconstruction algorithm is inefficient for long-lived particles due to its requirement that tracks originate close to the primary vertex

Λ is long-lived and has a soft pT spectrum. To improve efficiency, we have to relax the IP requirement in the reconstruction

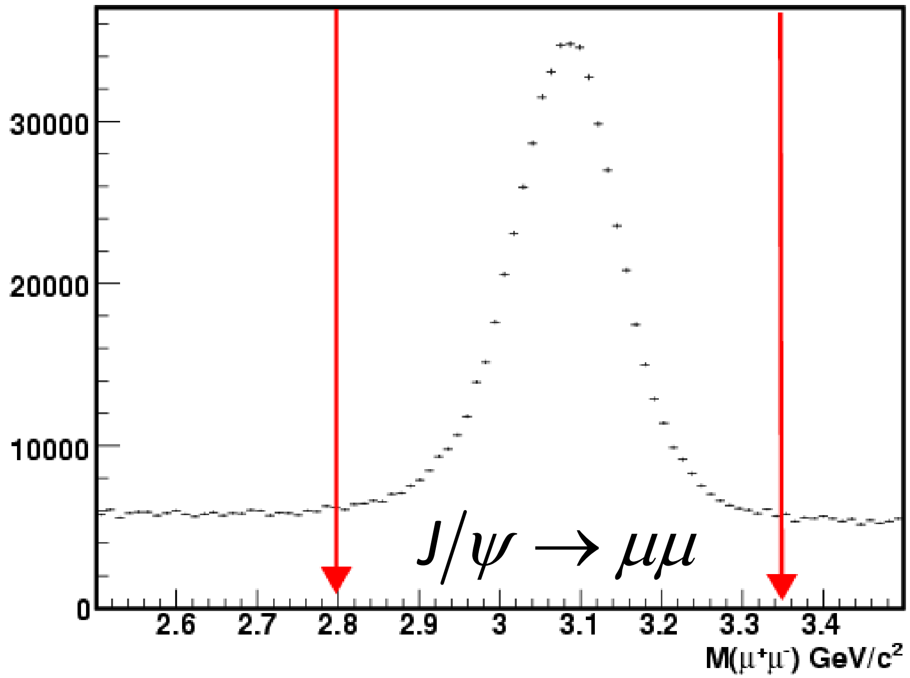


Special Reprocessing

Reprocessing with loose requirements is impractical, will bust our CPU budget

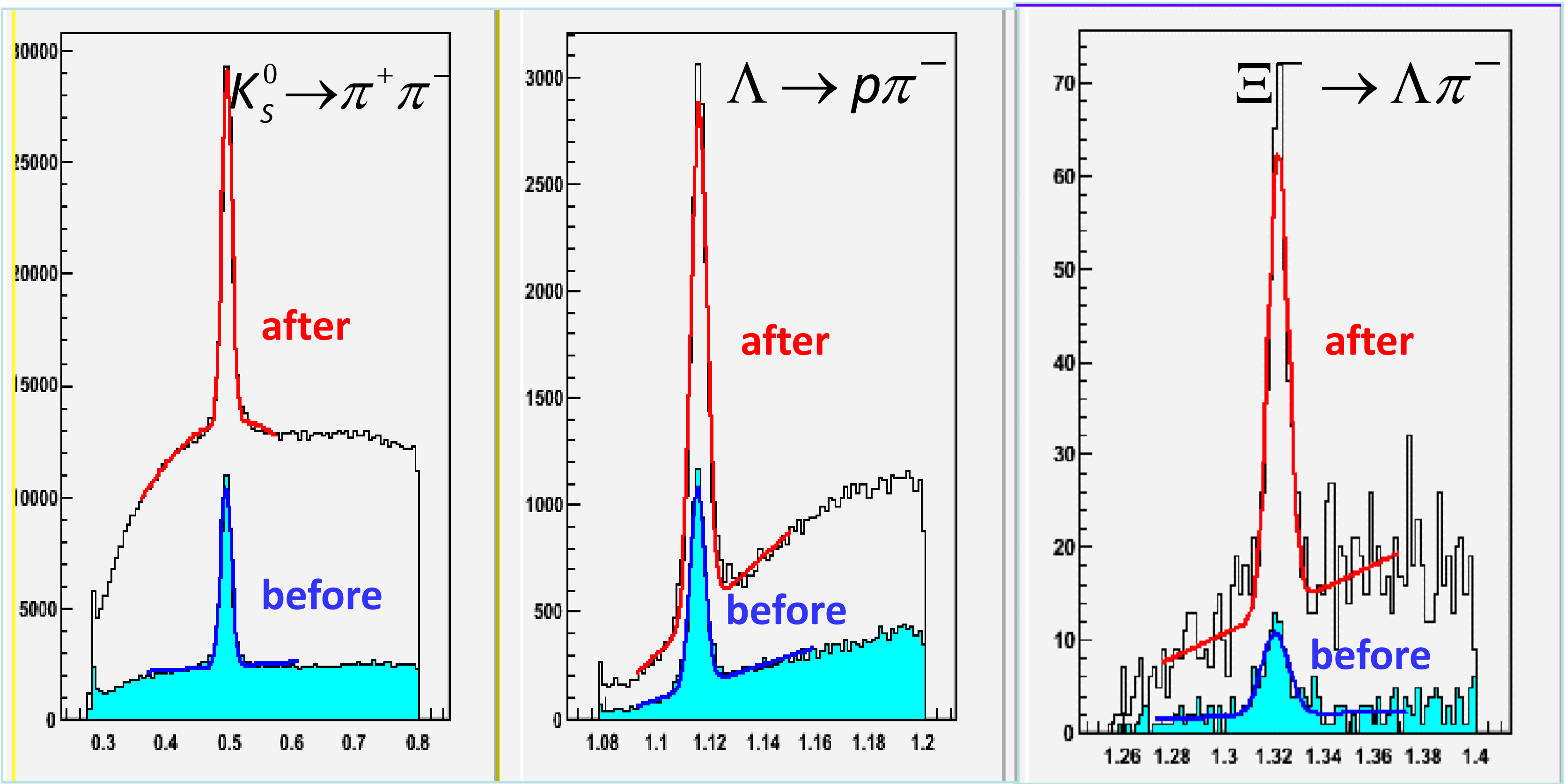
$\Rightarrow$ **Selective reprocessing**

- select $J/\psi \to \mu\mu$ events from the standard reconstruction
- reprocess these events with relaxed requirements such as the IP



Long-Lived Particles

The reprocessing significantly improved the yields of V particles



What can we do with this dataset ?

$\Rightarrow$ Look for Ξ_b and Ω_b

Search for Ξ_b

Ξ_b has a very similar decay chain as the $\Lambda_b \to J/\psi\ \Lambda$ decay:

$$\Lambda_b \to J/\psi\ \Lambda$$
$$J/\psi \to \mu^+\mu^-$$
$$\Lambda \to p\pi^-$$

$$\Xi_b^- \to J/\psi\ \Xi^-$$
$$J/\psi \to \mu^+\mu^-$$
$$\Xi^- \to \Lambda\pi^-$$
$$\Lambda \to p\pi^-$$

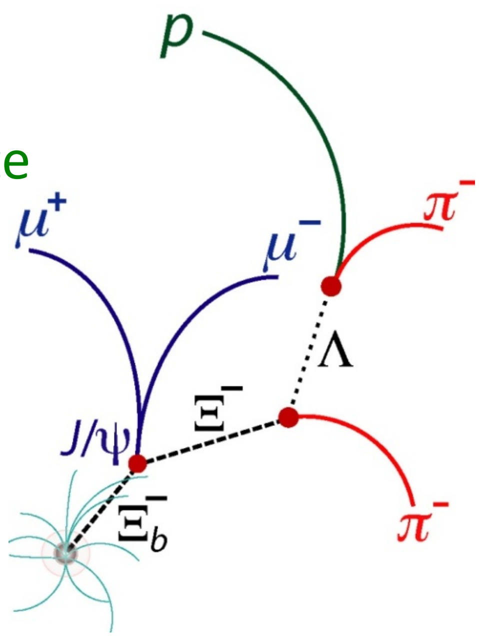
$$\Lambda_b \to \left(\mu^+\mu^-\right)\left(p\pi^-\right) \qquad \Xi_b^- \to \left(\mu^+\mu^-\right)\left(p\pi^-\right)\pi^-$$

- trigger on $J/\psi \to \mu\mu$,
- fully reconstructable, no neutral particles
- multiple intermediate resonances for background rejection

Ξ_b Reconstruction

Event Reconstruction:

- Reconstruct $J/\psi \to \mu^+\mu^-$ and $\Lambda \to p\pi^-$
- Combine Λ with another π^- to form Ξ^- candidate
- Combine J/ψ with Ξ^- to form Ξ_b^- candidate



Checks & Balances:

- validate with the known decays $\Lambda_b \to J/\psi\ \Lambda$
- wrong-sign $\Lambda(p\pi^-)\pi^+$ as background
- MC $\Xi_b^- \to J/\psi\ \Xi^-$ as the signal

Resonance mass constraints

$M(J/\psi \to \mu^+\mu^-) = 3.097$ GeV

$M(\Xi^- \to \Lambda\pi^-) = 1.321$ GeV

$M(\Lambda \to p\pi^-) = 1.115$ GeV

Lifetime information

$c\tau(\Xi_b^-) \approx 0.5$ mm

$c\tau(\Xi^-) = 4.9$ cm

$c\tau(\Lambda) = 7.9$ cm

Kinematic Variables

Decay length (DL)

the distance between the production and decay vertices in the transverse plane

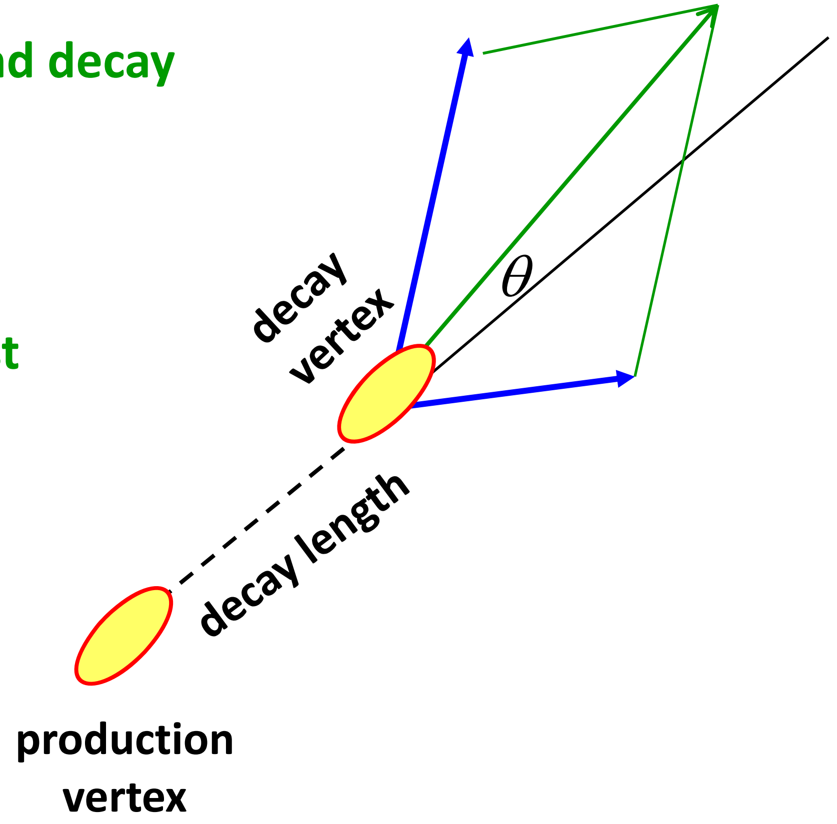
Proper decay length (pDL)

decay length corrected for Lorentz boost

$$\gamma_T = \frac{p_T}{M} \quad \Rightarrow \quad \mathrm{pDL} = \frac{\mathrm{DL}}{\gamma_T}$$

Collinearity $\cos\vartheta$

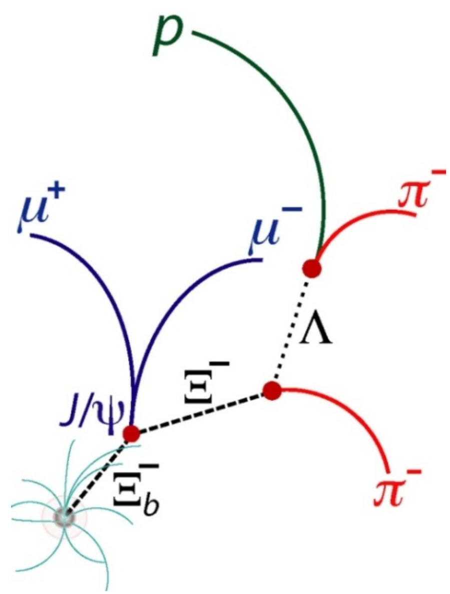
cosine of the angle in the transverse plane between the momentum vector of the mother and the vector pointing from the production to the decay vertex



Ξ_b Event Selection

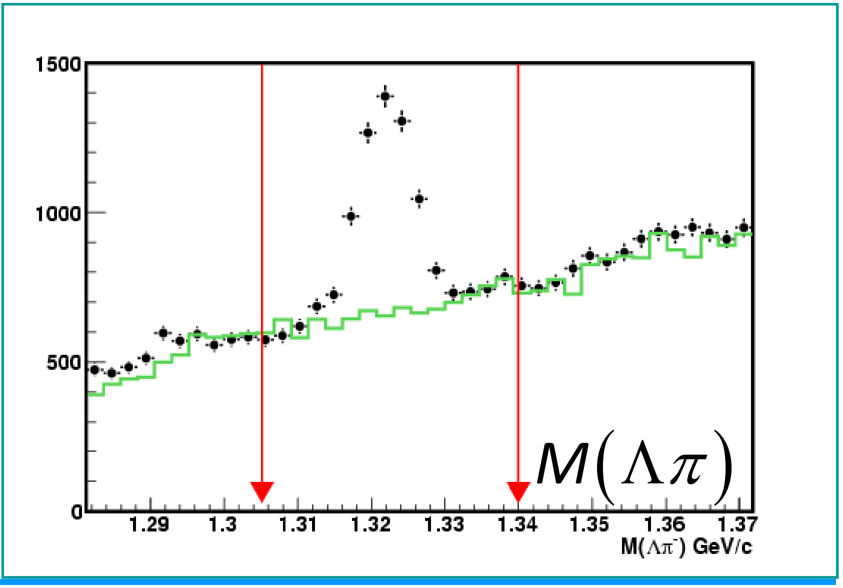
$\Lambda \to p\pi$ decays

- two tracks with large impact parameters;
- proton = the track with a higher momentum;
- $p_T(p) > 0.7$ GeV, $p_T(\pi) > 0.3$ GeV;
- Λ has a significant decay length ($>4\sigma$)



$\Xi \to \Lambda\pi$ decays

- π track has a large impact parameter;
- $pT(\pi) > 0.2$ GeV;
- uncertainty of Ξ decay length < 0.5 cm;
- Ξ has a significant decay length ($> 4\sigma$);
- collinearity > 0.99

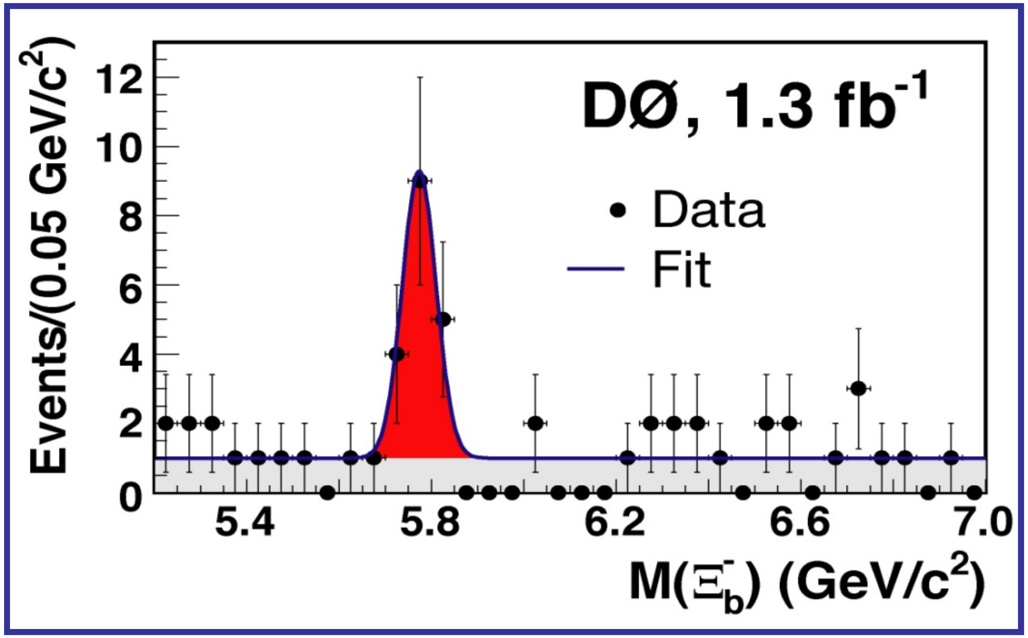


$\Xi_b \to J/\psi\ \Xi$ decays

- uncertainty on the proper decay distance < 0.05 cm;
- lifetime significance > 2

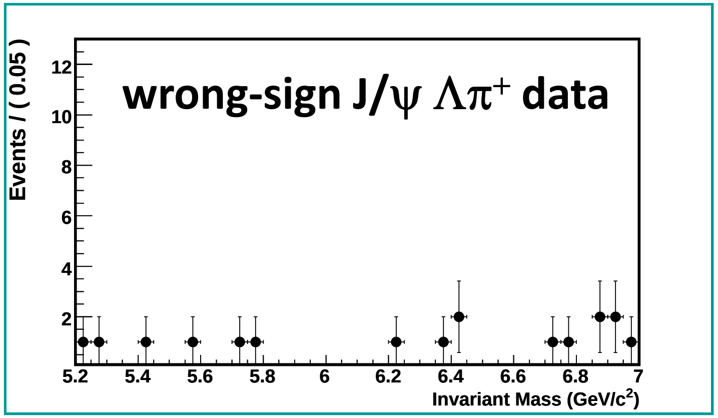
Ξ_b Observation

Mass distribution of $J/\psi\ \Xi^-$



$$M\left(\Xi_b^-\right) = 5.774 \pm 0.019\ \text{GeV}$$

$$N\left(\Xi_b^-\right) = 15.2 \pm 4.4$$



Likelihood fits w/o signal:

$$\sqrt{-2\ln\left(\frac{\pounds_b}{\pounds_{s+b}}\right)} = 5.5\sigma$$

PRL 99, 052001 (2007)

Search for the Ω_b

The Ω_b baryon has an almost identical decay mode as the Ξ_b

$$\Xi_b^- \to J/\psi\ \Xi^-,\quad J/\psi \to \mu^+\mu^-,\quad \Xi^- \to \Lambda\pi^-,\quad \Lambda \to p\pi^-$$

$$\Omega_b^- \to J/\psi\ \Omega^-,\quad J/\psi \to \mu^+\mu^-,\quad \Omega^- \to \Lambda K^-,\quad \Lambda \to p\pi^-$$

$$\Xi_b^- \to \left(\mu^+\mu^-\right)\ \left(p\pi^-\right)\ \pi^- \qquad \Omega_b^- \to \left(\mu^+\mu^-\right)\ \left(p\pi^-\right) K^-$$

what worked for the Ξ_b should work for the Ω_b

except it turns out the Ω identification is more difficult…

Decay Kinematics

$$\Omega_b^- \to J/\psi\ \Omega^- \to \left(\mu^+\mu^-\right)\left(\Lambda K^-\right) \to \left(\mu^+\mu^-\right)\left(p\pi^-\right)K^-$$

$c\tau\left(\Omega_b^-\right) \approx 0.5$ mm, $Q\left(\Omega_b^- \to J/\psi\ \Omega^-\right) > 1$ GeV

$M\left(\Omega^-\right)$ = 1672.45 MeV

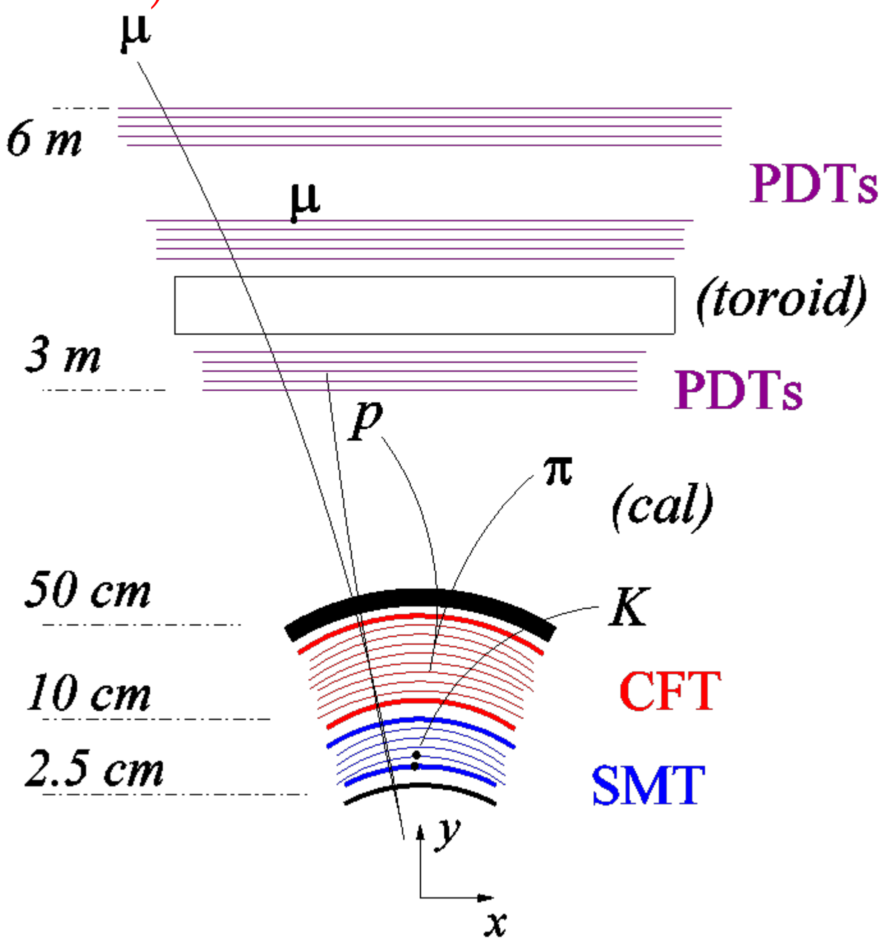
$c\tau\left(\Omega^-\right)$ = 2.46 cm

$Q\left(\Omega^- \to \Lambda K^-\right)$ = 63 MeV

$M\left(\Lambda\right)$ = 1115.68 MeV

$c\tau\left(\Lambda\right)$ = 7.89 cm

$Q\left(\Lambda \to p\pi^-\right)$ = 38 MeV



Search Strategy

- **use Ω_b Monte Carlo events as the signal model**

  produced with Pythia with M=6.052 GeV and τ=1.54 ps

- **use data wrong-sign events as the background model**

  Signal sample: $\left(\mu^+\mu^-\right)\left(p\pi^-\right)\boxed{K^-}$

  Control sample: $\left(\mu^+\mu^-\right)\left(p\pi^-\right)\boxed{K^+}$

- **optimize the selection of intermediate resonances**

  $\Lambda \to$ **p** π^- **and** $\Omega^- \to \Lambda$**K**$^-$

- **maximize selection efficiencies without exploring the details of Ω_b decay kinematics**

- **search in the mass window 5.6 – 7 GeV**

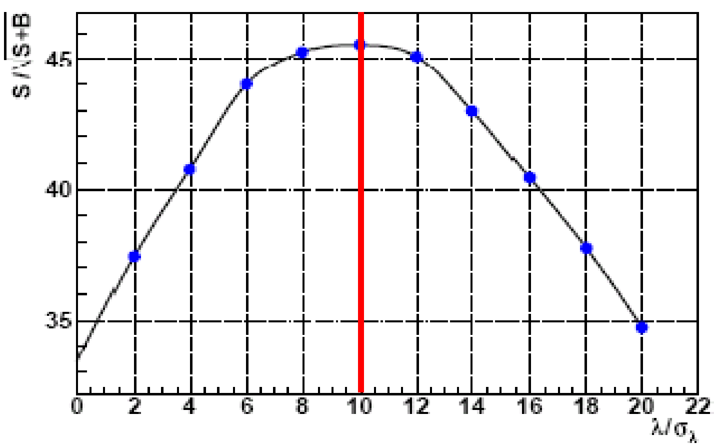
  $$\mathrm{M}\left(\Lambda_b\right) = 5.62\ \text{GeV},\ \ \mathrm{M}\left(\Omega_b^-\right) \sim 6\ \text{GeV}$$

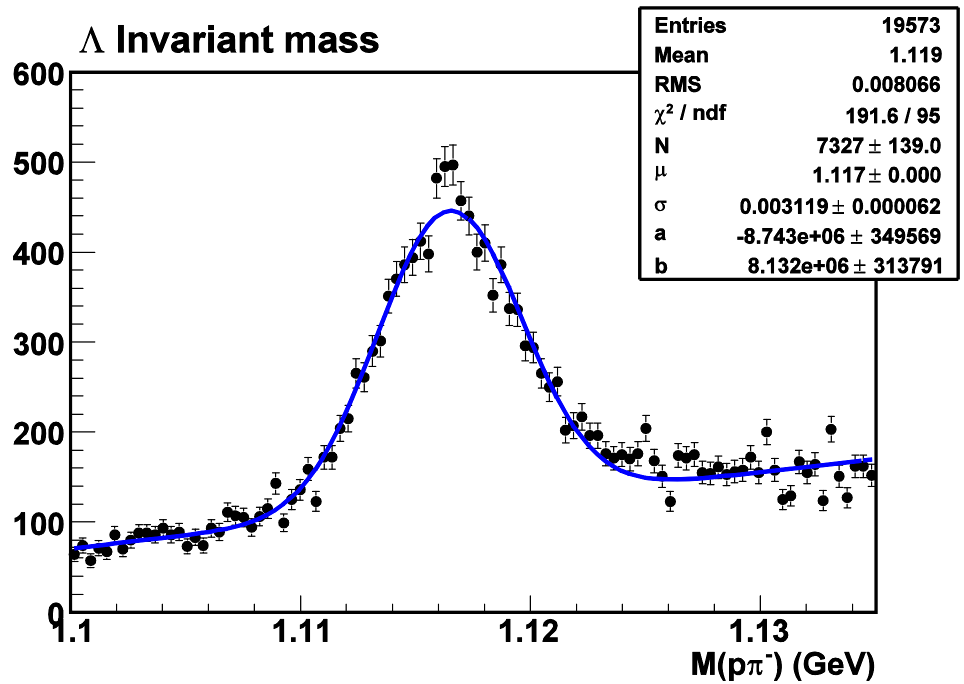
$\Lambda \to p\pi$ Reconstruction

- **two tracks with large impact parameters and consistent with being from a common vertex;**
- **transverse momentum greater than 0.2 GeV for both tracks;**
- **the track with the higher momentum assumed to be the proton;**
  - $\Rightarrow$ **almost always correct assignment according to Monte Carlo**
- **require the invariant mass of the tracks**

$$1.108 < M\left(p\pi^-\right) < 1.126 \text{ GeV}$$

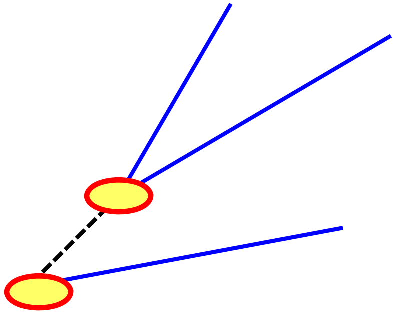
- **optimize the cut on the $\Lambda \to p\pi$ decay length significance**

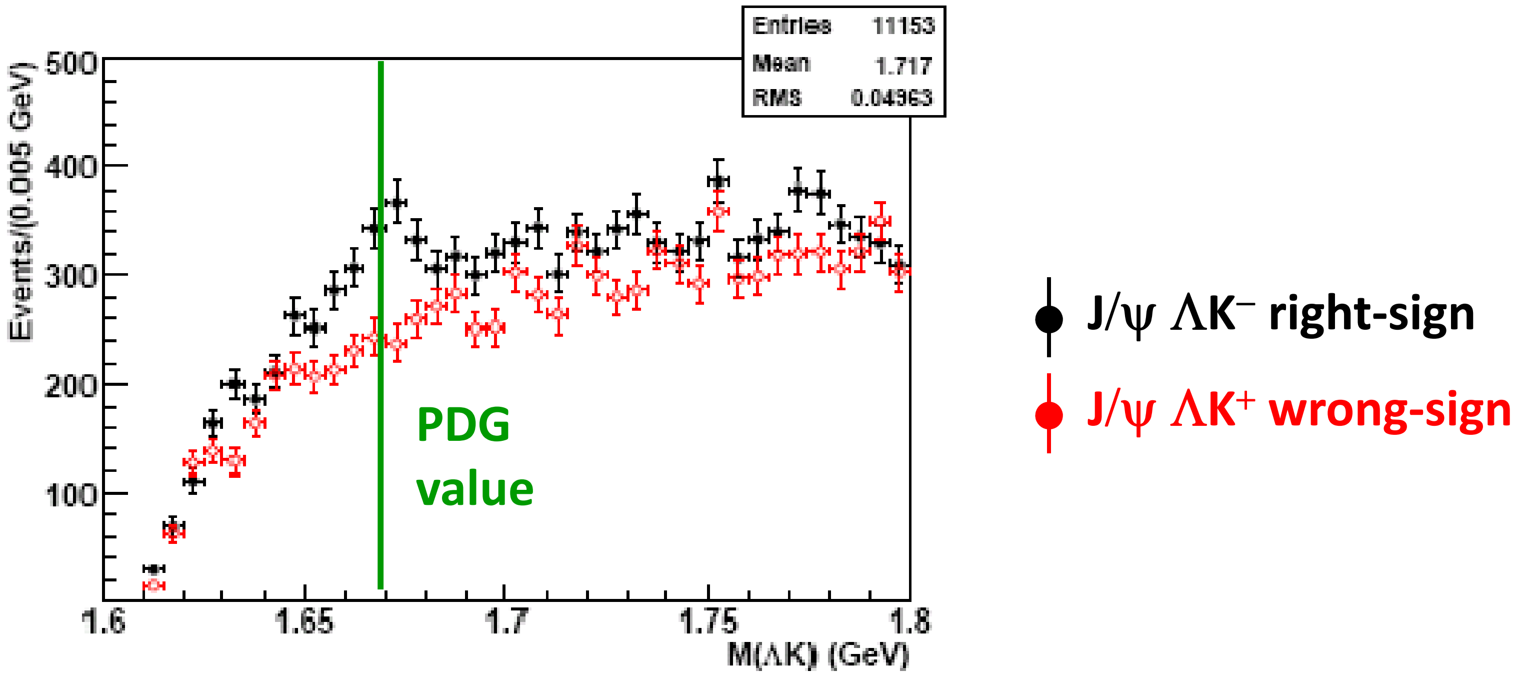




$\Omega \rightarrow \Lambda K$ Reconstruction

- $\Lambda(p\pi^-)$ and K^- form a good vertex
- uncertainty of the $\Omega^- \rightarrow \Lambda K^-$ proper decay length smaller than 0.5 cm;
- decay length significance greater than 4.





The Ω signal in the ΛK^- right-sign combination, but over a large combinatoric background

Ω Background

Boosted Decision Tree to reduce combinatoric background

20 input variables

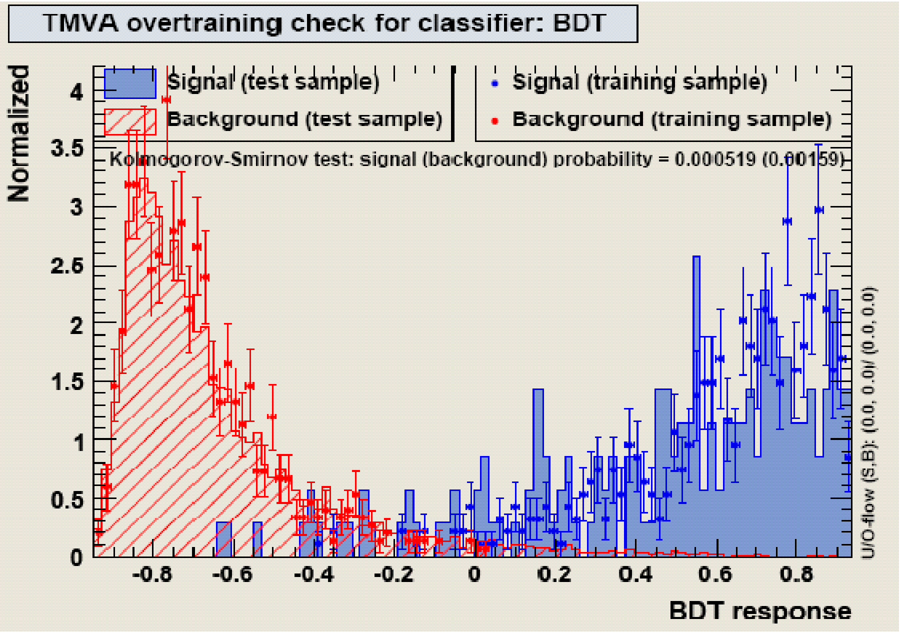
- Λ and Ω decay vertex quality variables and decay lengths;
- Λ and Ω decay kinematic information;
- *nothing on J/ψ Ω combination nor its vertex*

Training and optimization

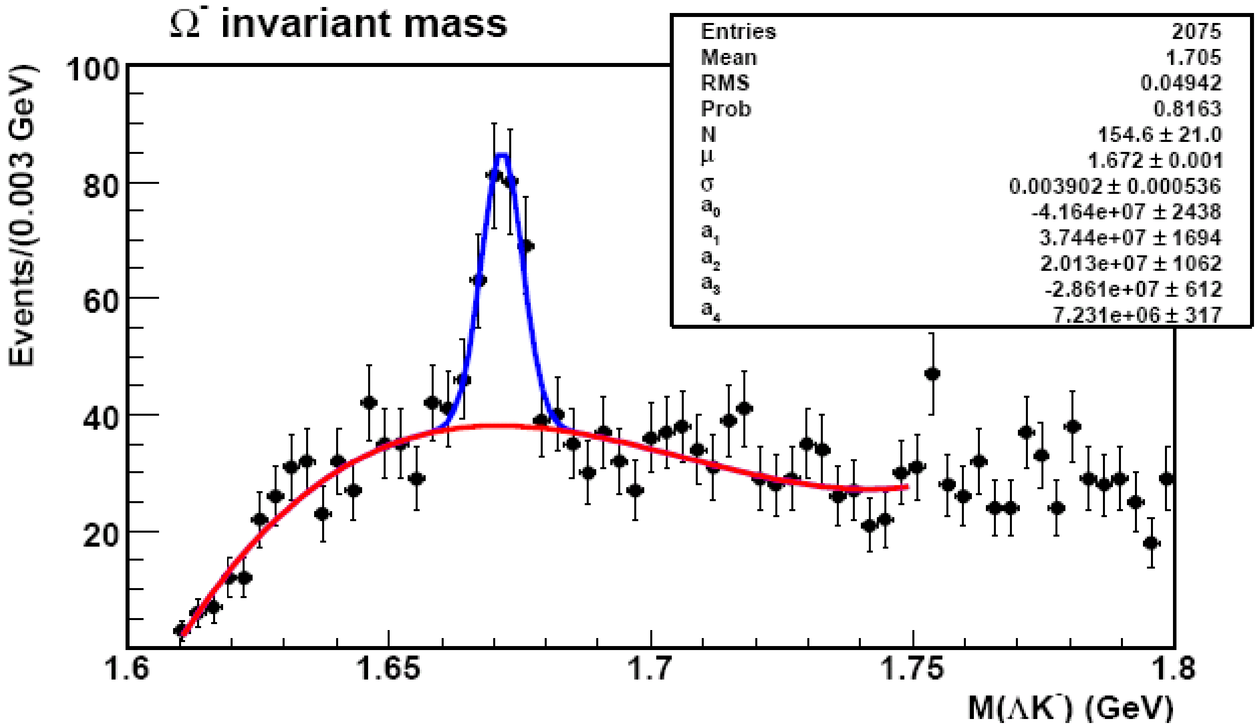
- Ω in the Ω_b MC events as the signal model;
- Data J/ψ ΛK^+ wrong-sign events as the background model

Most important variables

- pT of the kaon;
- pT of the proton;
- pT of the pion;
- Ω decay length



Ω after the BDT

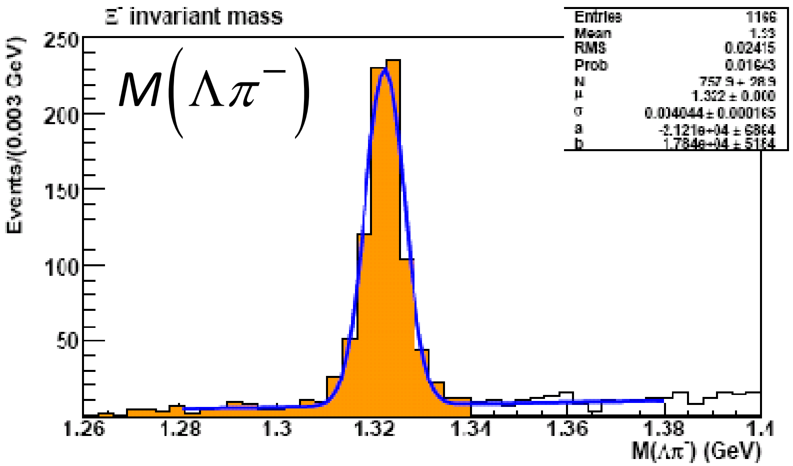


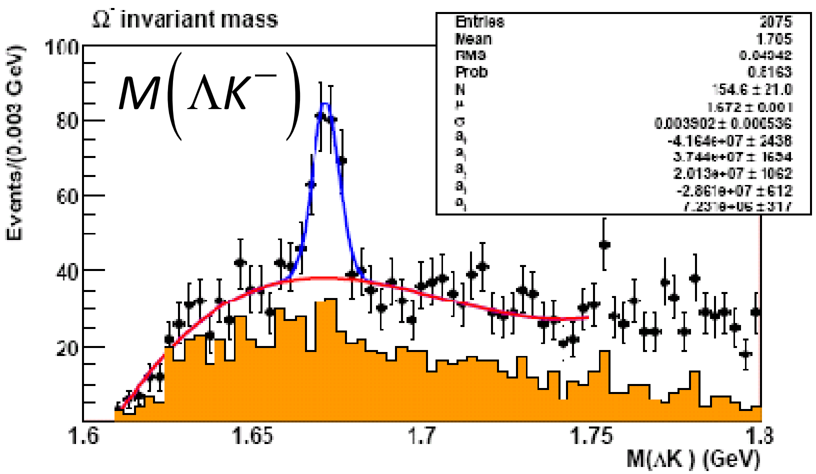
number of Ω candidates remain about the same, but the background is significantly reduced

We require $1.662 < M\left(\Lambda K^-\right) < 1.682$ GeV

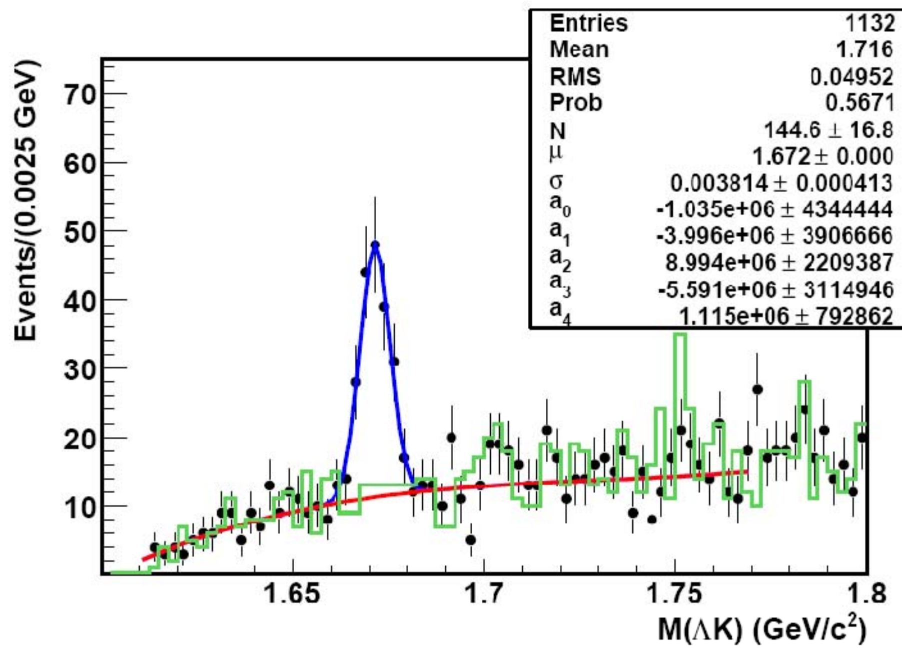
Contamination from Ξ

A significant fraction of the continuum background is from the $\Xi \to \Lambda\pi$ decays with a kaon mass assigned to the pion



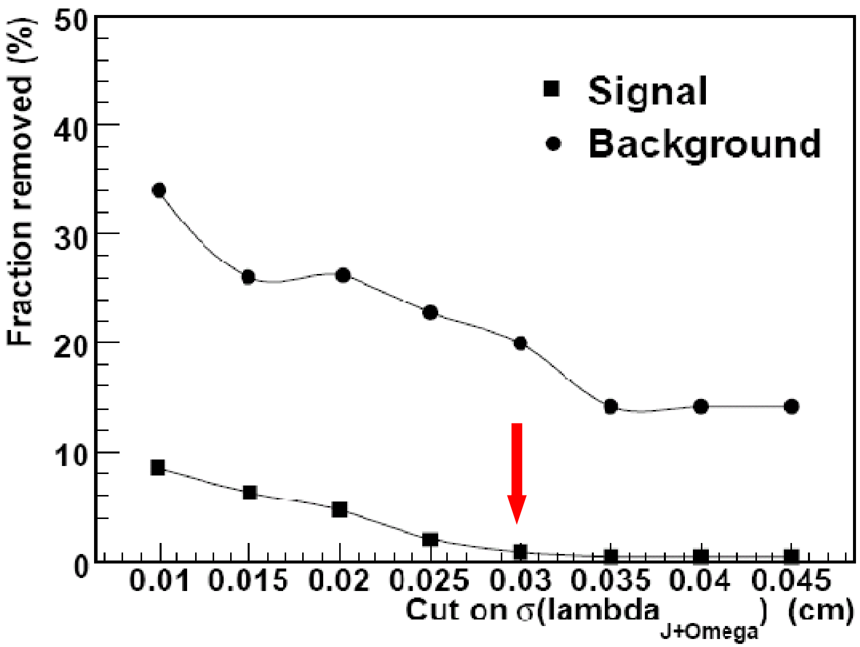


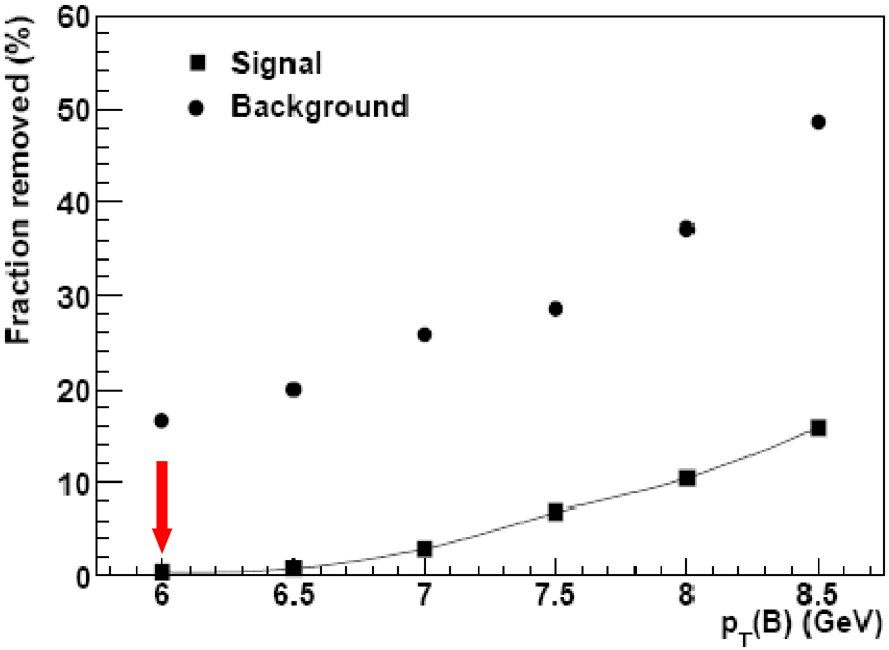
Vetoing events with M($\Lambda\pi$) < 1.34 GeV



Ω_b Selection

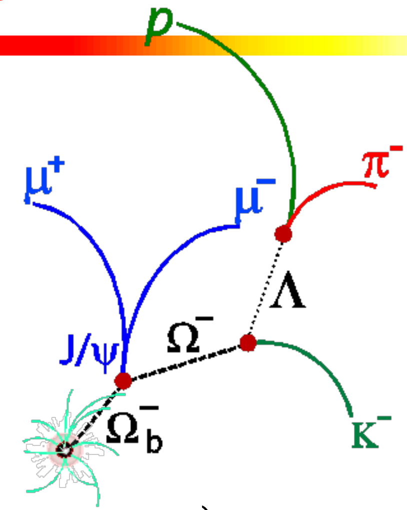
- J/ψ and Ω candidates are consistent with being from a common vertex;
- the uncertainty of the Ω_b proper decay length smaller than 0.03 cm;
- the Ω_b transverse momentum greater than 6 GeV;
- the J/ψ and Ω transverse opening angle less than 90 degree





optimized for high efficiency!

Mass Resolution

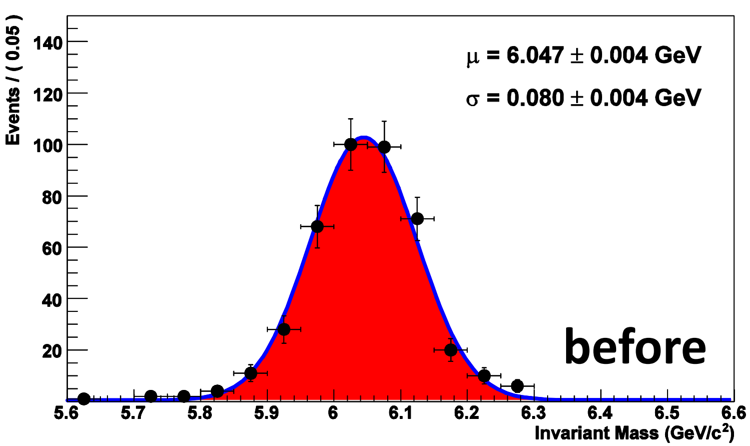


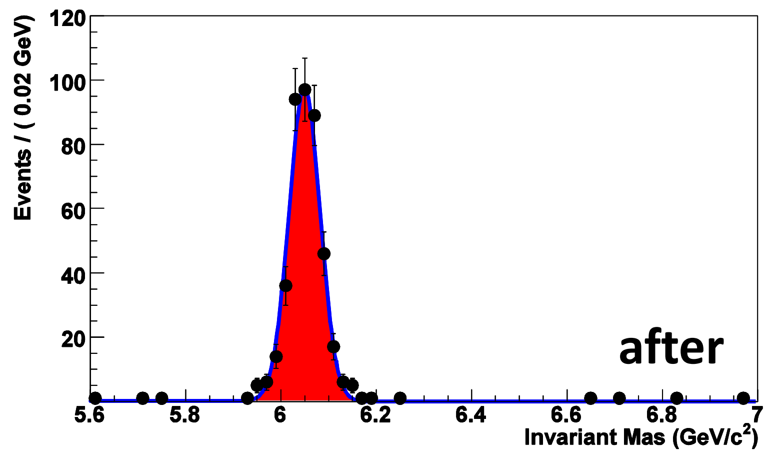
Poor-man's mass constraint to improve the Ω_b resolution

$$\boxed{M\left(\Omega_b^-\right) \equiv M\left(J/\psi\ \Omega^-\right) + \text{Corr.}}$$

Event-by-Event correction:

$$\text{Corr.} = \left\{M_{PDG}\left(J/\psi\right) - M\left(\mu^+\mu^-\right)\right\} + \left\{M_{PDG}\left(\Omega^-\right) - M\left(\Lambda K^-\right)\right\}$$



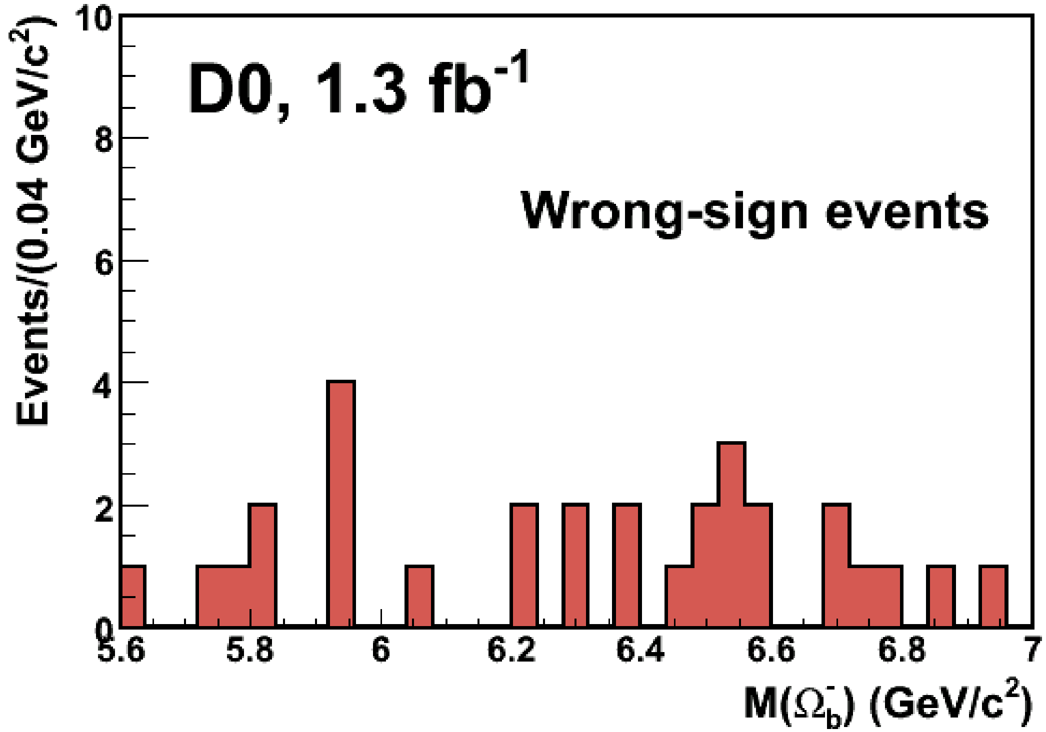


The Ω_b resolution is reduced from 80 MeV to 34 MeV in MC

Wrong-sign Events

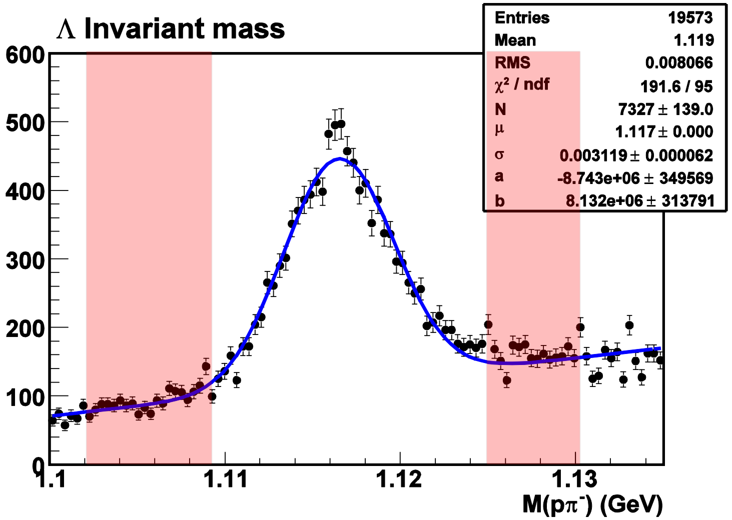
Mass distribution of $J/\psi\ \Lambda K^+$ events

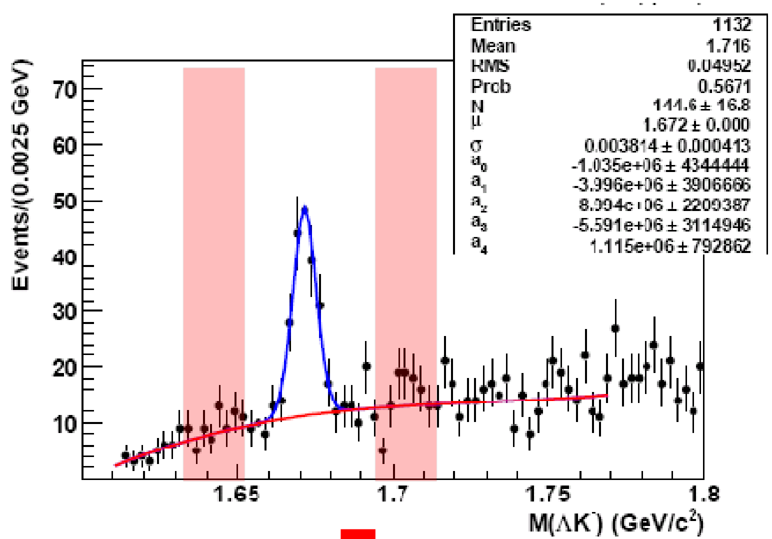
- require $M(\Lambda K^+)$ in the Ω^- mass window;
- Ω_b selection on $J/\psi\ \Lambda K^+$ combination;
- 30 events survived…

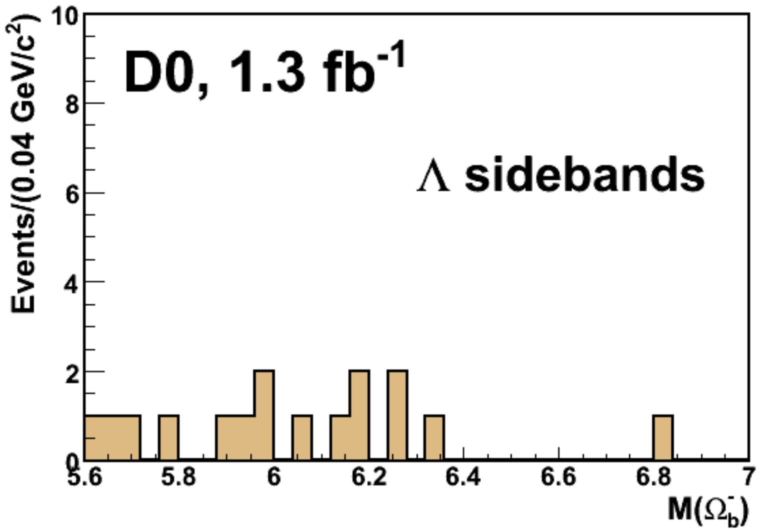


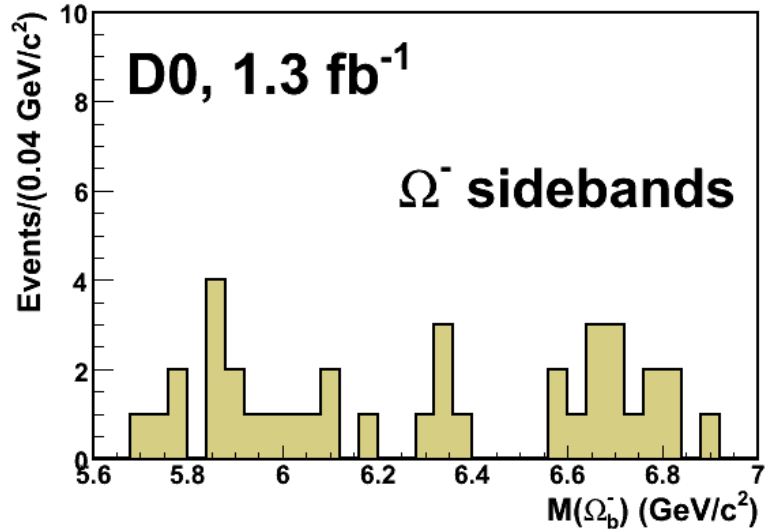
No apparent structure in the $M(J/\psi\ \Lambda K^+)$ distribution

Side-band Events



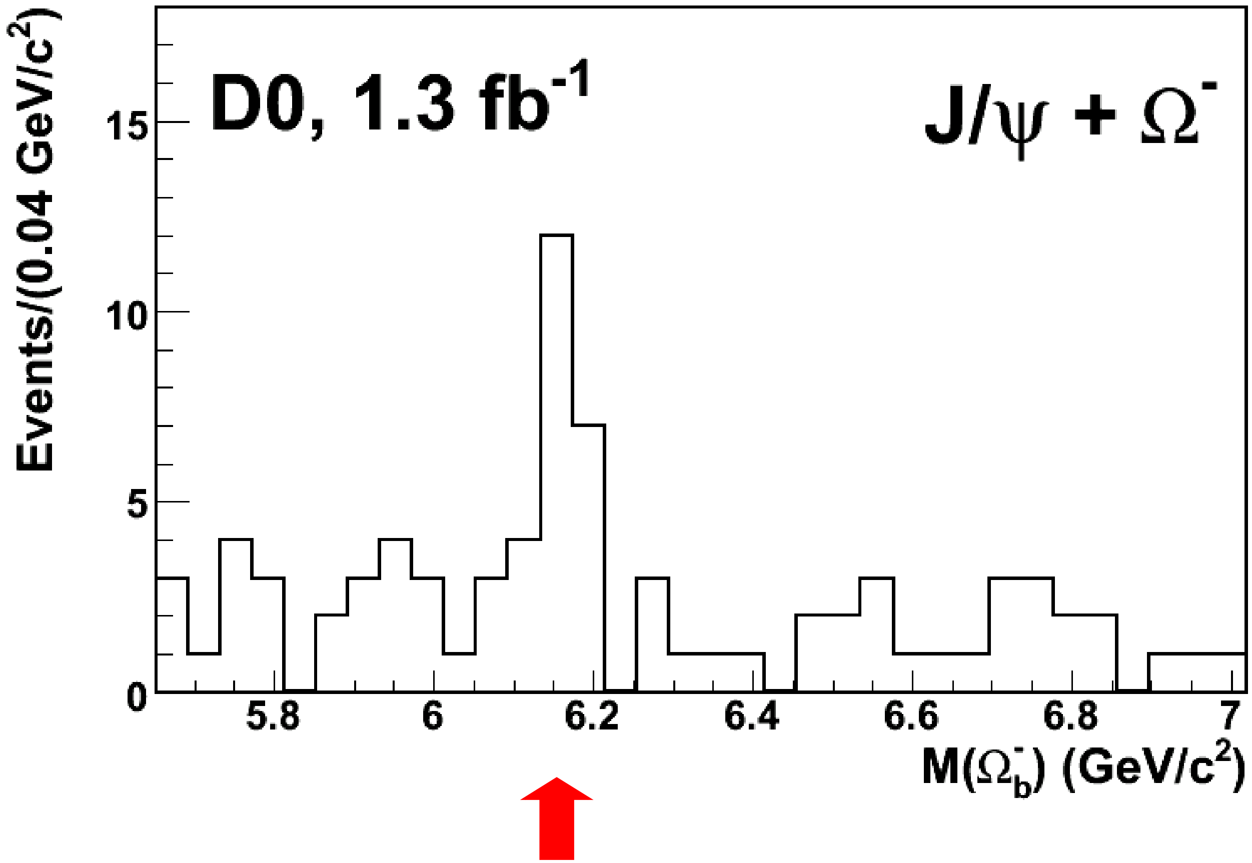






Open the Box

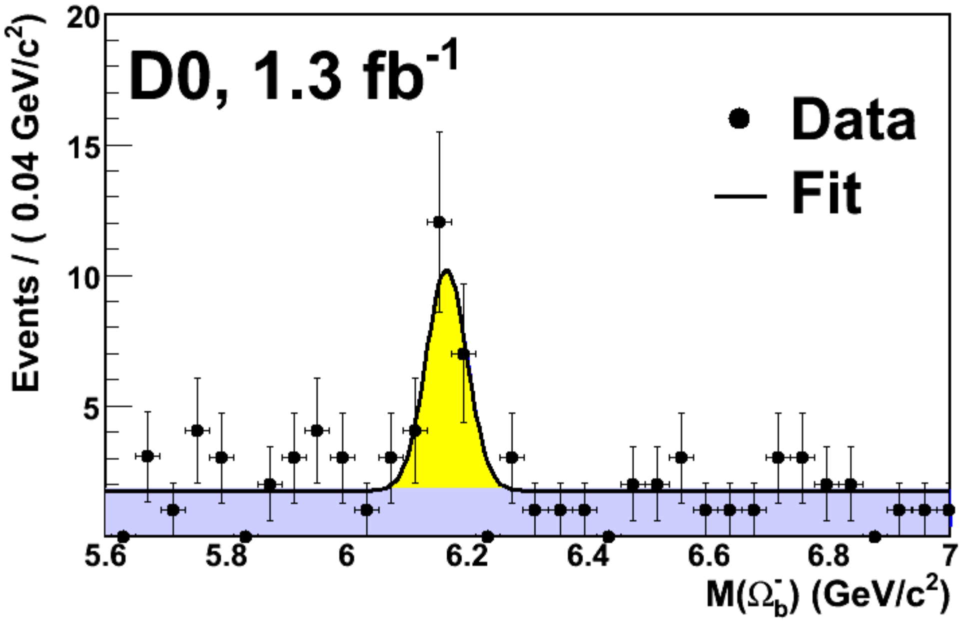
79 right-sign ($J/\psi\ \Lambda K^-$) events are selected



Something here !

Unbinned Likelihood Fit

- a flat background model;
- a Gaussian signal model with its width fixed to 0.034 GeV
- float numbers of signal and background events, signal mass



Results of the fit:

- number of signal events: 17.8 ± 4.9
- mean of the Gaussian signal: 6.165 ± 0.010 GeV

Signal Significance

To estimate the significance, two separate fits are performed

- **one with a background-only (flat) model;**
- **the other with a signal plus background model**

and calculate the difference in the likelihood values between the fits

$$\sqrt{-2\Delta \ln £} = \sqrt{-2\ln\left(\frac{£_b}{£_{s+b}}\right)} = 5.4\sigma$$

To study the robustness of this estimate, we vary

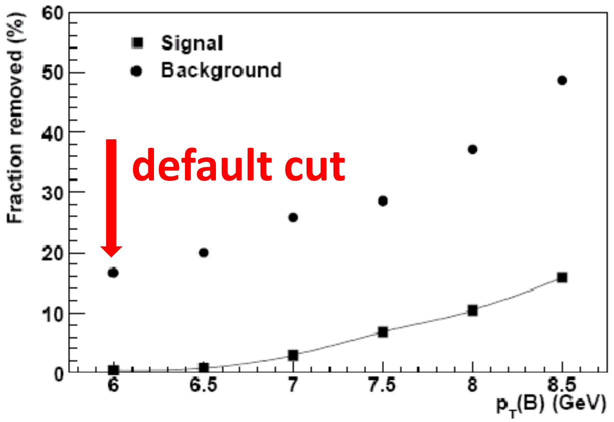
- **background model to a 1st order polynomial;**
- **the signal width between 0.028 and 0.040 GeV;**
- **the selection requirements such as Ω_b pT**

In all these cases, the significance remains above 5σ

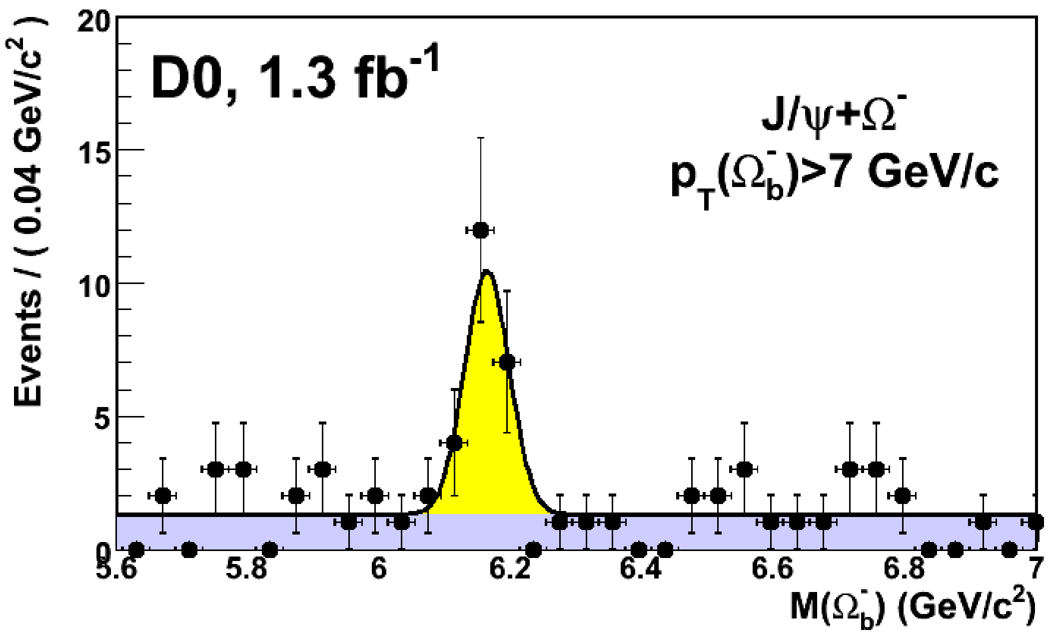
Consistency Check

The Ω_b pT cut impacts the signal significantly…

- optimized for high efficiency, not significance…



Background can be further reduced by raising the pT requirement



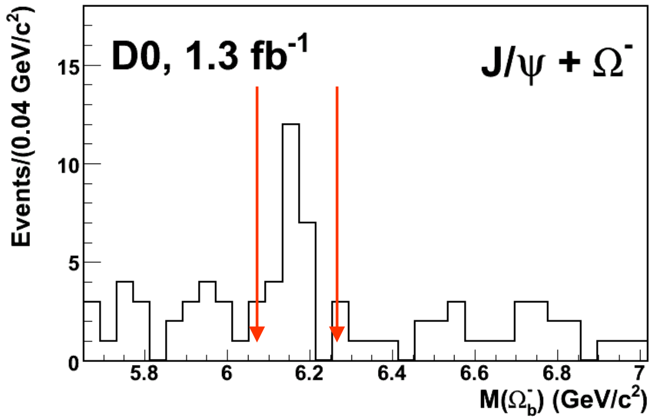
N_{signal}=19.3±5.0

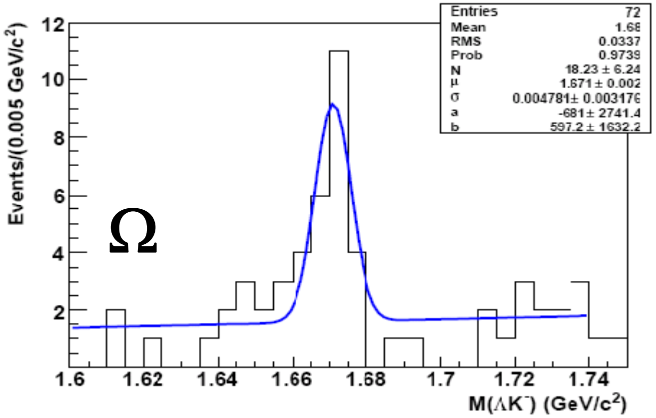
M_{signal}=6.164±0.009 GeV

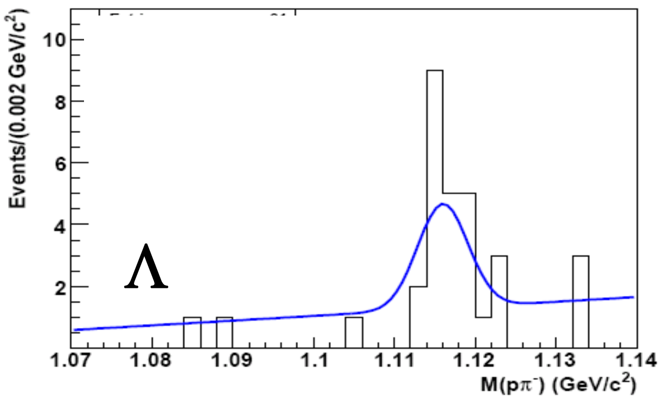
$\sqrt{-2\Delta \ln £} = 6.1\sigma$

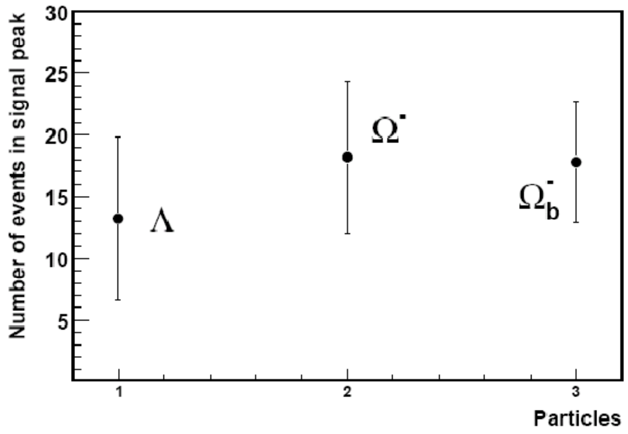
“Look back” Plots

We look back the Λ and Ω mass distributions of the Ω_b candidates and estimate the numbers of Λ and Ω candidates in these distributions









… and find consistent numbers of Λ, Ω and Ω_b candidates

Cuts instead of BDT

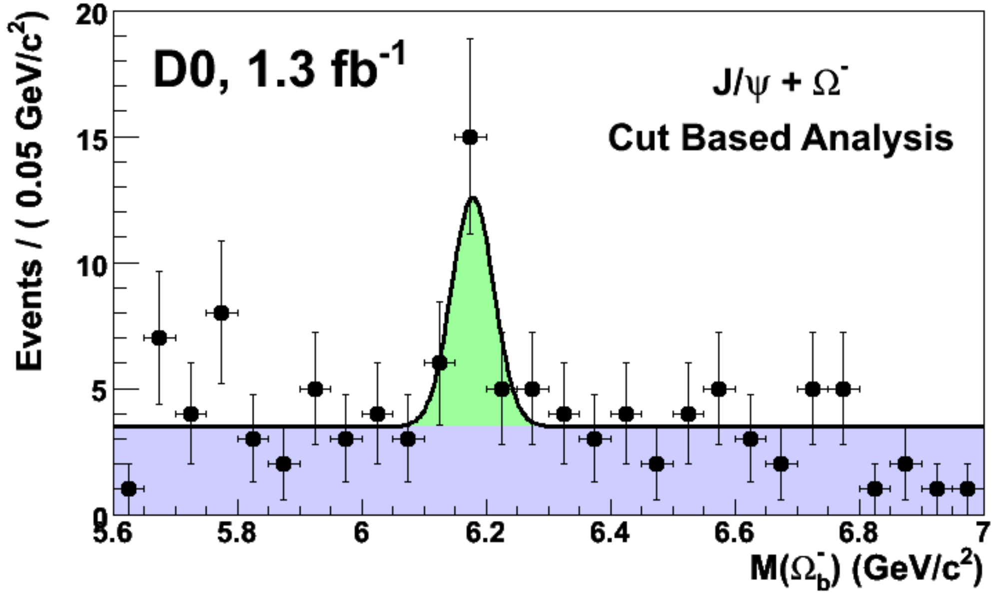
- Ξ_b was observed with simple cuts;
- can we see the Ω_b signal with a set of simple cuts as well?

(even though the BDT was trained to reduce the Ω background)

Variable	BDT	Cuts
$p_T(\pi)$ (GeV)	>0.2 and input to BDT	>0.2
$p_T(p)$ (GeV)	>0.2 and input to BDT	>0.7
$p_T(K)$ (GeV)	input to BDT	>0.3
Ω^- collinearity	input to BDT	>0.99
Ω^- decay length (cm)	input to BDT	>0.5
Ω_b^- proper decay length uncertainty (cm)	<0.03	<0.03

These variables were selected based on the relative importance in the BDT performance

Cut Based Analysis



Results of the fit:

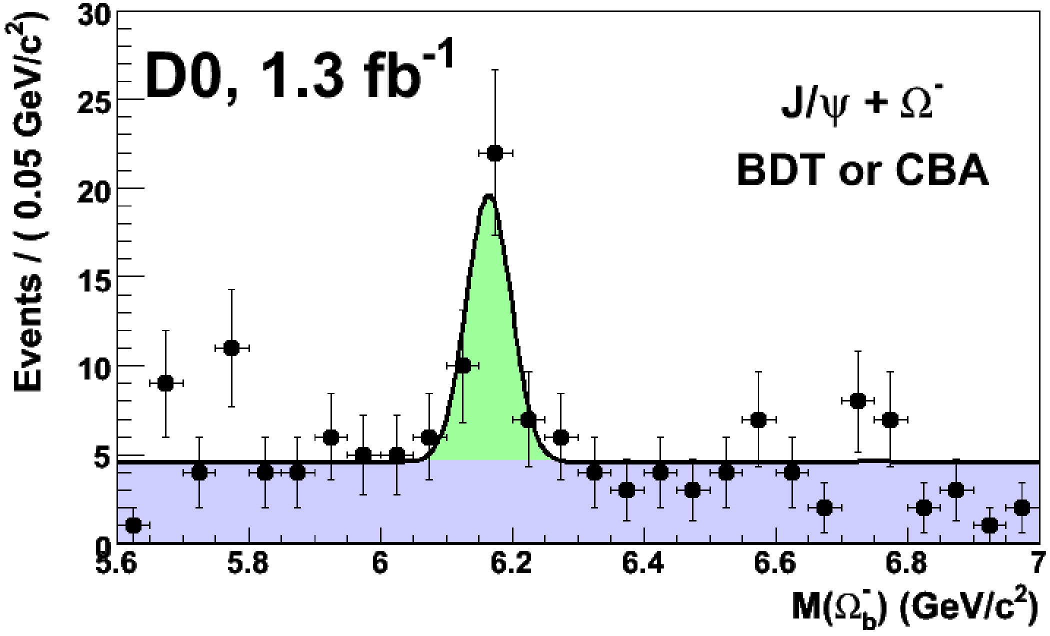
- number of signal events: 15.7 ± 5.3
- mean of the Gaussian signal: 6.177 ± 0.015 GeV

The significance is reduced to 3.9σ due to the increased background

BDT and Cuts

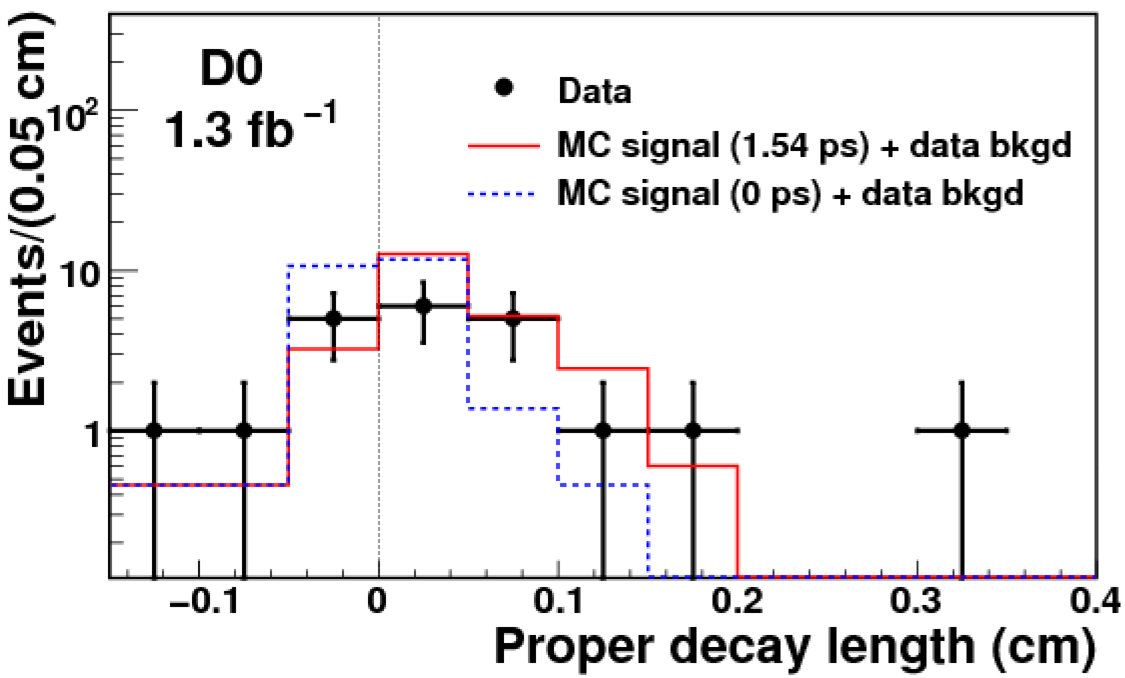
BDT and cut-based analyses often select different events, the overlap of the final candidates is only about 50%

If the two analyses are combined, we get 25.5 ± 6.5 signal events with a significance of 5.4σ



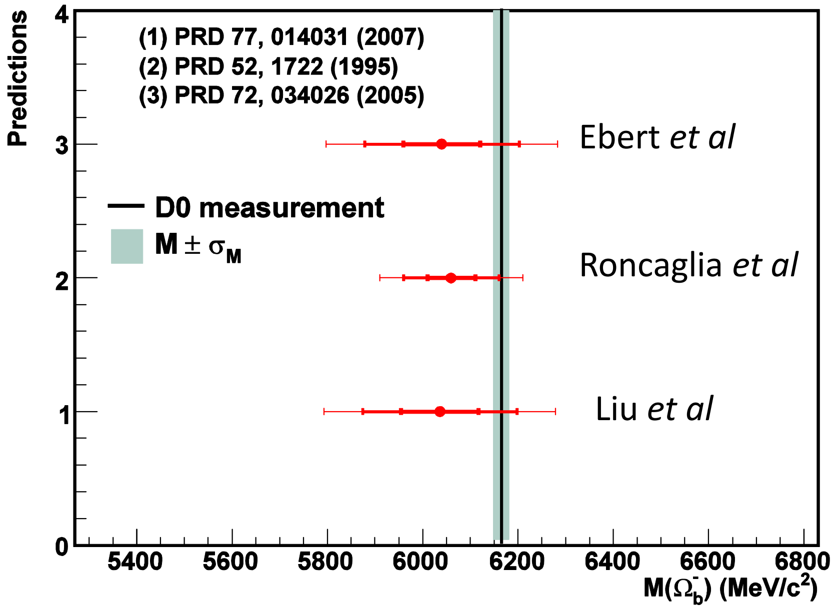
Signal Lifetime

Statistics is too small for a lifetime measurement, however the observed proper decay length distribution for candidates in ±3σ mass window is consistent with a lifetime of the order ~ 1 ps



Ω_b Mass

- **Fitting models**
  - Linear background instead of flat $\Rightarrow$ negligible change
  - Varying Gaussian width between 28 – 40 MeV $\Rightarrow$ 3 MeV
- **Momentum scale correction**
  - Fit to the Λ_b mass peak in data $\Rightarrow$ 4 MeV
- **Event selection**
  - The mass difference between the BDT and cut-based analyses $\Rightarrow$ 12 MeV



$$M\left(\Omega_b^-\right) = 6.165 \pm 0.010(\text{stat}) \pm 0.013(\text{syst})\ \text{GeV}$$

on the high side of the predicted mass…

Production Ratio

To get a ball-park production rate, we normalize to that of Ξ_b

$$\frac{f(b\to\Omega_b^-)\times Br(\Omega_b^-\to J/\psi\ \Omega^-)}{f(b\to\Xi_b^-)\times Br(\Xi_b^-\to J/\psi\ \Xi^-)}=\frac{\varepsilon(\Xi_b^-)}{\varepsilon(\Omega_b^-)}\frac{N(\Omega_b^-)}{N(\Xi_b^-)}$$

Using the efficiency ratio from MC

$$\frac{\varepsilon(\Omega_b^-)}{\varepsilon(\Xi_b^-)}=1.5\pm0.2\ \text{(stat)}$$

and the observed number of events, we obtain

$$\boxed{\frac{f(b\to\Omega_b^-)\times Br(\Omega_b^-\to J/\psi\ \Omega^-)}{f(b\to\Xi_b^-)\times Br(\Xi_b^-\to J/\psi\ \Xi^-)}=0.80\pm0.32(\text{stat})^{+0.14}_{-0.22}(\text{syst})}$$

Production Ratio

H.Y. Cheng, PRD 56, 2799 (1997)

$$\frac{\Gamma(\Omega_b^- \to J/\psi\ \Omega^-)}{\Gamma(\Xi_b^- \to J/\psi\ \Xi^-)} = 9.8 \qquad \left\{ \text{Spin}\left(\Xi^-\right) = 1/2,\ \ \text{Spin}\left(\Omega^-\right) = 3/2 \right\}$$

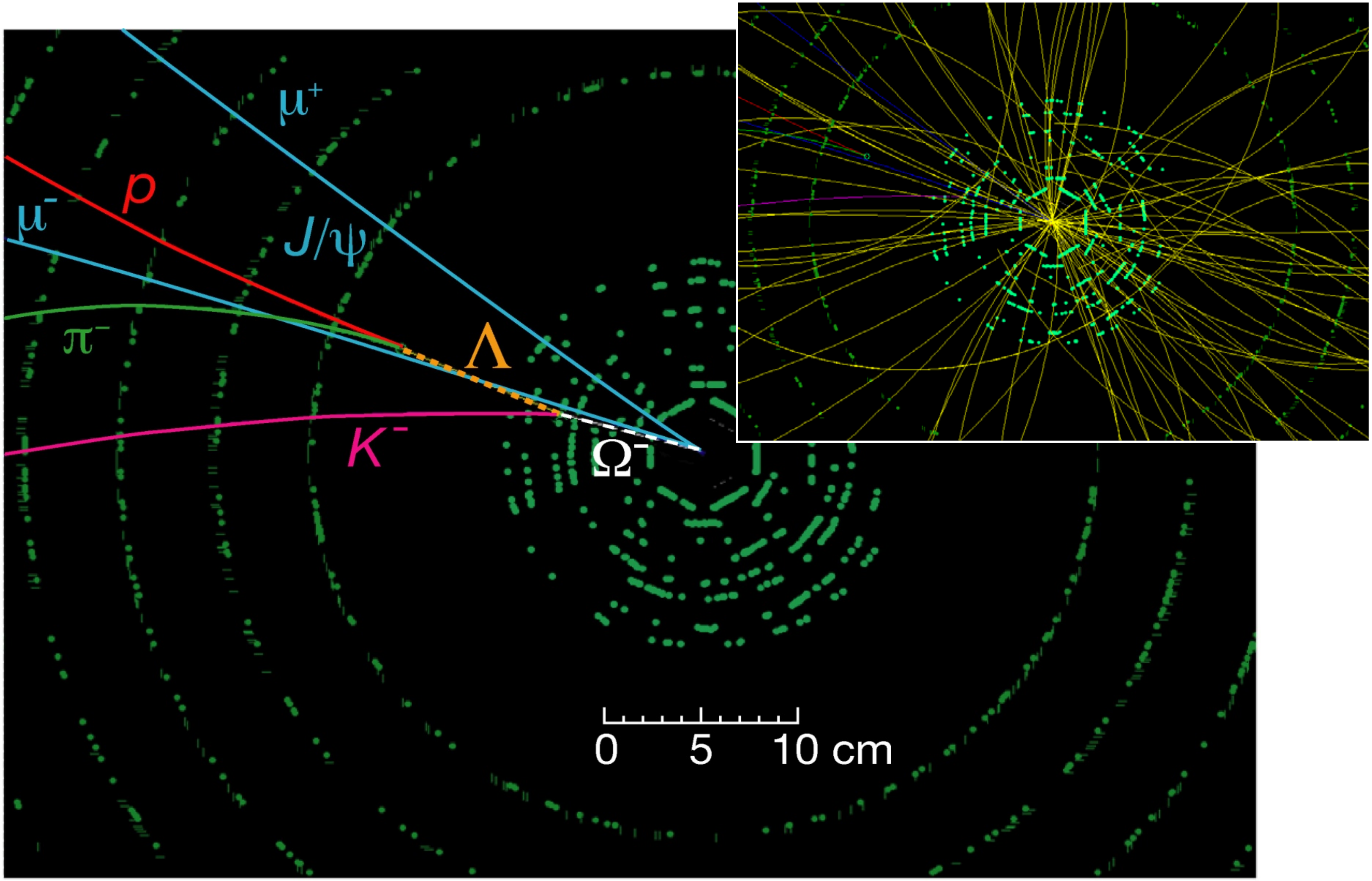
$$\tau(\Xi_b) = 1.42^{+0.28}_{-0.24}\ \text{ps}\ \left(\text{LEP, mixture of } \Xi^0 \text{ and } \Xi^-\right)$$

$$0.83 < \tau(\Omega_b^-) < 1.67\ \text{ps}\ \left(\text{prediction, very conservative}\right)$$

$$\frac{f(b \to \Omega_b^-)}{f(b \to \Xi_b^-)} \approx 0.07\text{-}0.14$$

(range of the central value)

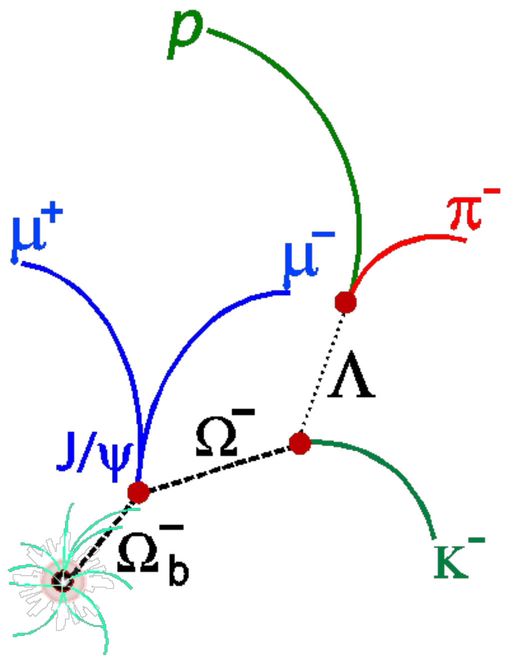
An Ω_b Candidate

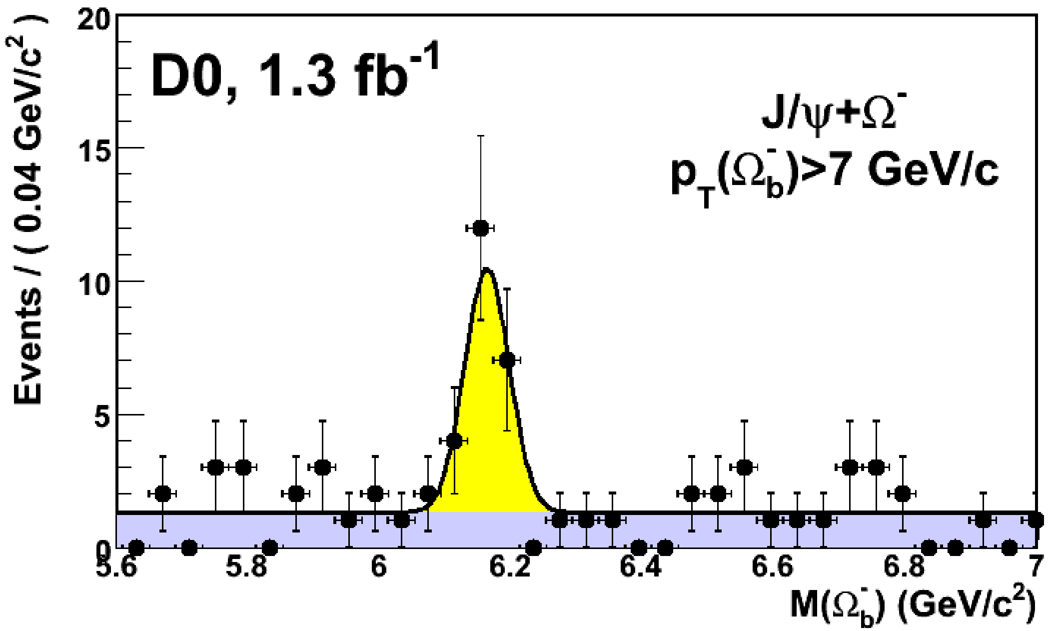


Run 203929, Event 22881065, $M(\Omega_b)$ = 6.158 GeV

Summary

We have observed Ω_b baryon with a significance > 5σ





$$M\left(\Omega_b^-\right) = 6.165 \pm 0.010(\text{stat}) \pm 0.013(\text{syst})\ \text{GeV}$$

$$N\left(\Omega_b^-\right) = 17.8 \pm 4.9(\text{stat}) \pm 0.8(\text{syst})$$

arXiv: 0808.4142 (2008)

BDT Variables

Variable description
Λ vertex χ^2
Λ collinearity
Λ lifetime significance
p track (from Λ) χ^2
p (from Λ) combined impact parameter significance
p track SMT hits
p track CFT hits
π track (from Λ) χ^2
π (from Λ) combined impact parameter significance
π track SMT hits
π track CFT hits
p (from Λ) p_T
π (from Λ) p_T
Λ transverse decay length
Error on Λ transverse decay length
Error on Ω^- transverse decay length
Ω^- transverse decay length
Ω^- collinearity
K^- (from Ω^-) p_T
K^- (from Ω^-) combined impact parameter significance