Heavy Quarks

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Hadron Collider Physics Summer School 2012
Fermilab, IL

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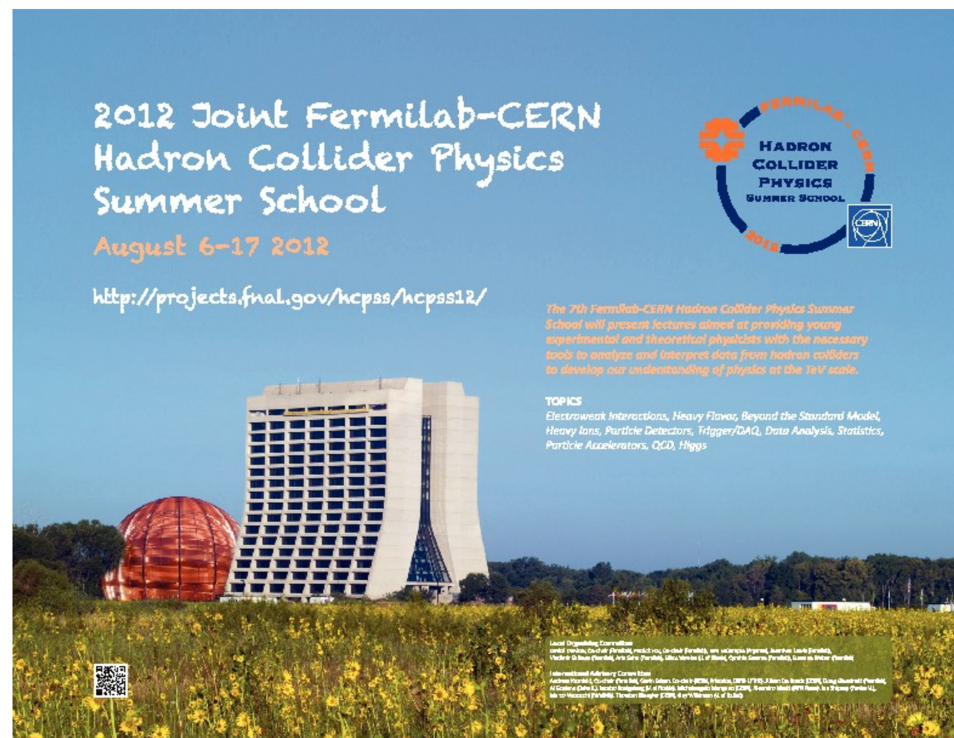
Lecture 1

Aug 14, 2012



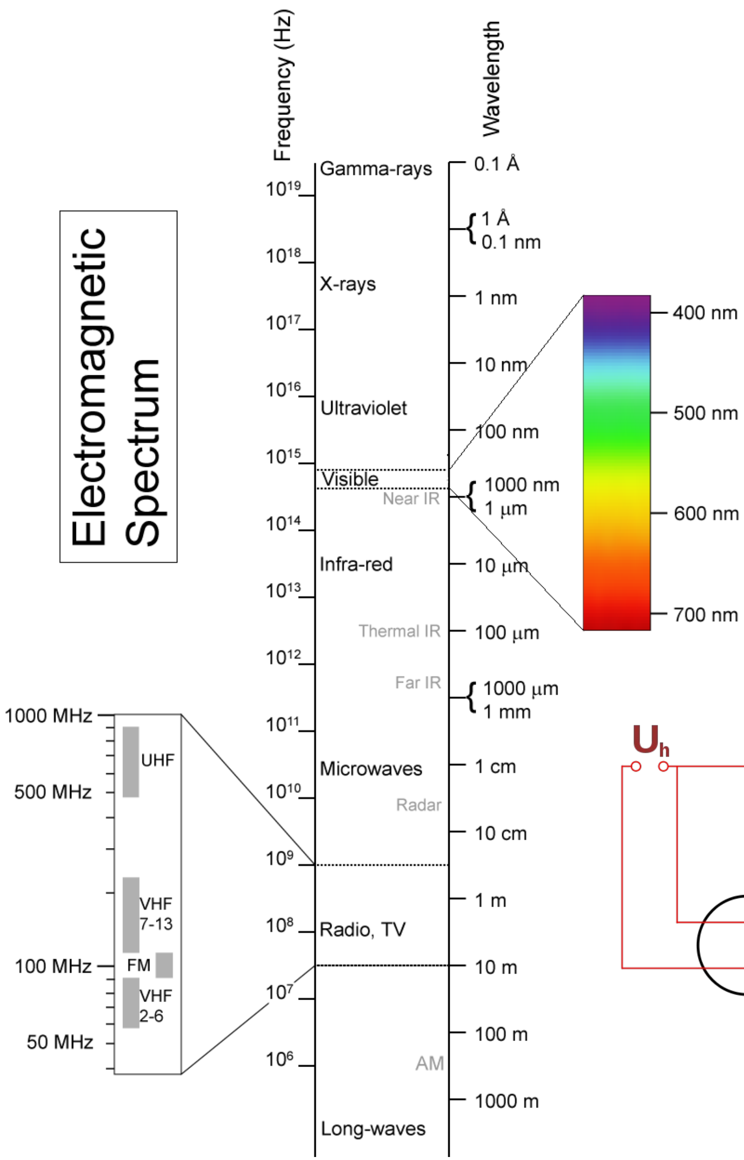
Lecture Outline

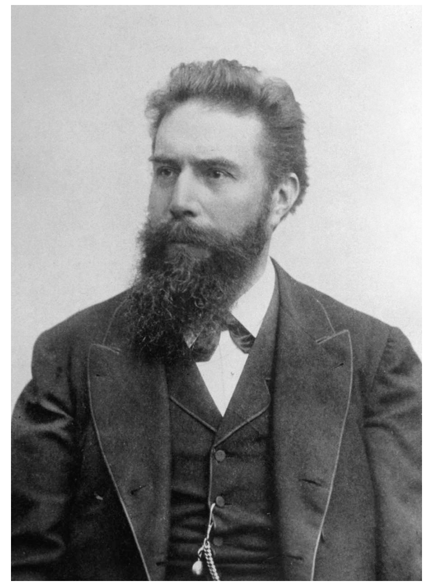
- **Lecture 1**
  - Introduction: Heavy Quarks
  - B Hadron Producers
  - Features of B Physics
  - B Hadron Properties
  - B Lifetimes
- **Lecture 2**
  - B_s^0 meson oscillations
  - CP Violation in B_s^0 system
  - Selected B Physics results

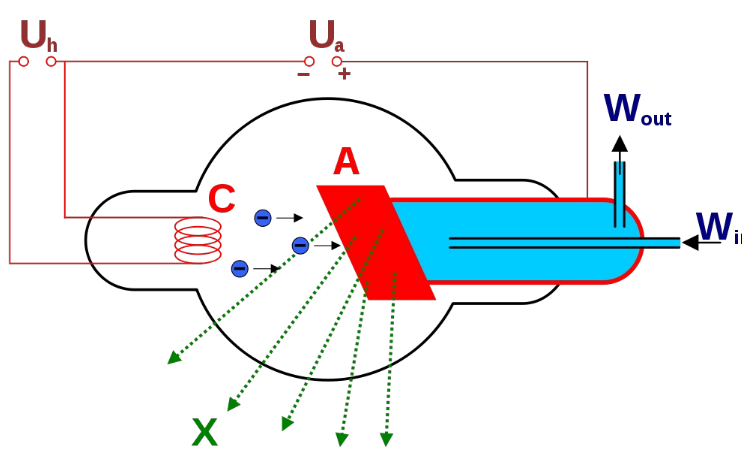
Introduction: Heavy Quarks

Discovery of 1st Elementary Particle

1895: X-ray (photon) by Wilhelm Röntgen

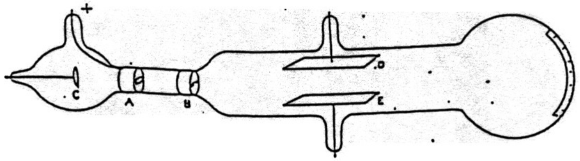


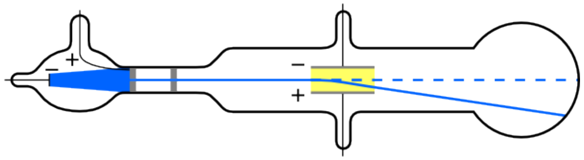


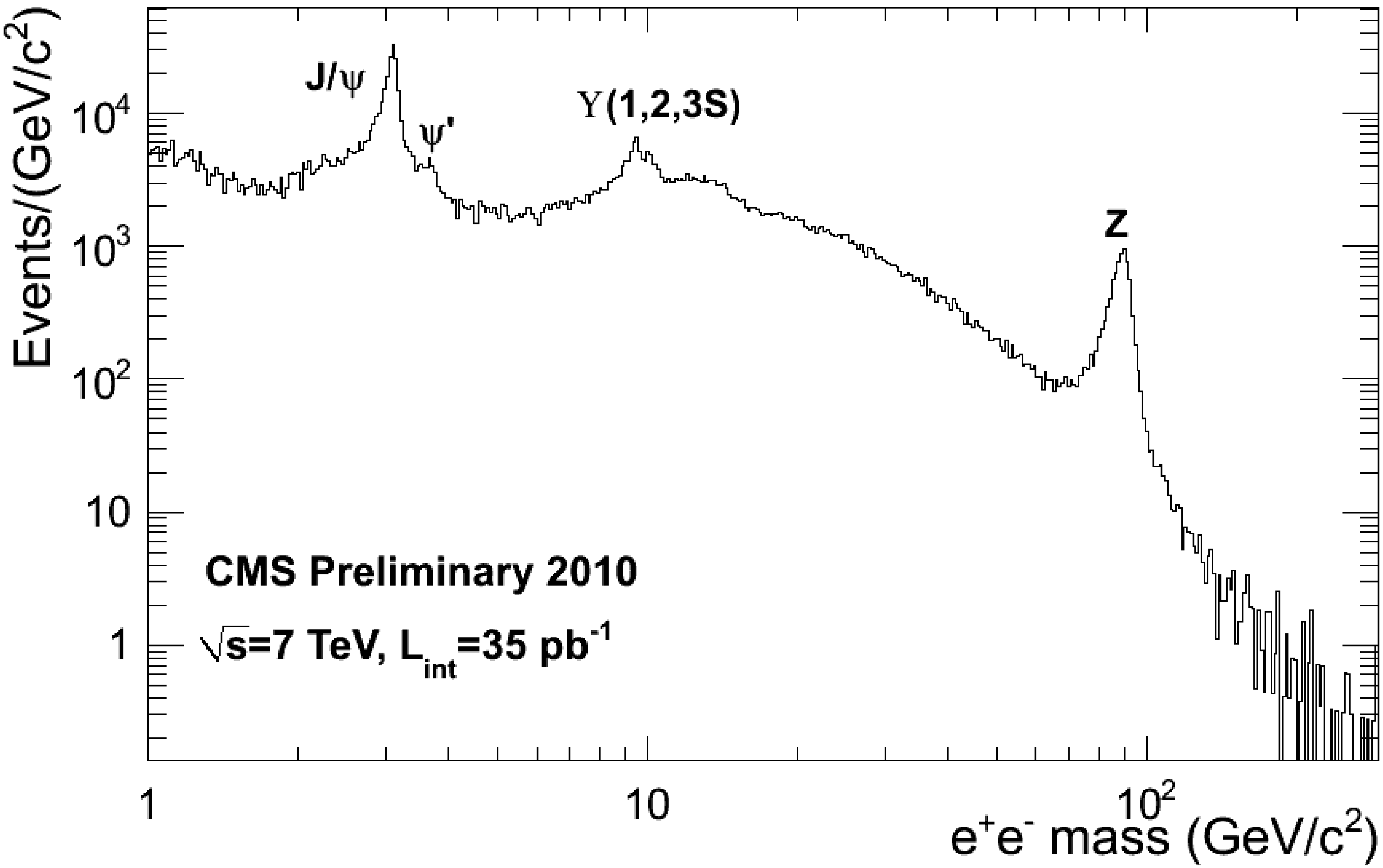


Electron

<u>1897:</u> **J.J. Thompson**

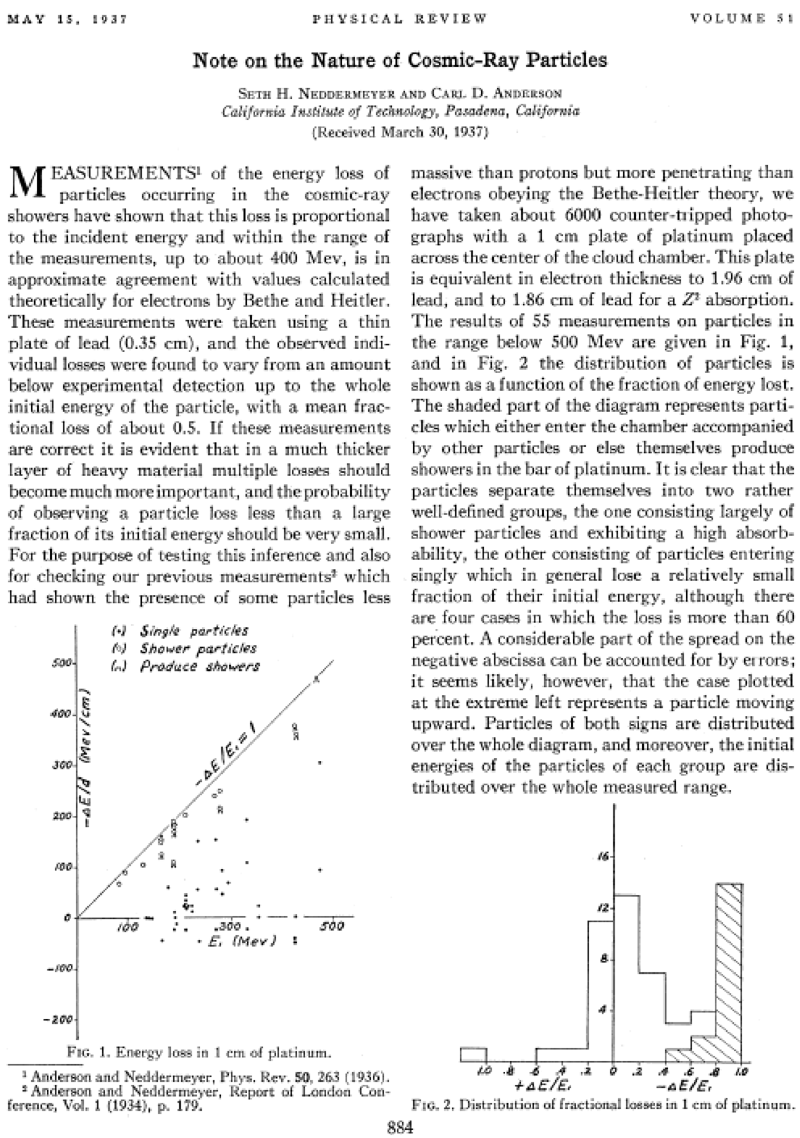






Muon

1937: Neddermeyer & Anderson



MAY 15, 1937 PHYSICAL REVIEW VOLUME 51

Note on the Nature of Cosmic-Ray Particles

SETH H. NEDDERMEYER AND CARL D. ANDERSON
California Institute of Technology, Pasadena, California
(Received March 30, 1937)

MEASUREMENTS[1] of the energy loss of particles occurring in the cosmic-ray showers have shown that this loss is proportional to the incident energy and within the range of the measurements, up to about 400 Mev, is in approximate agreement with values calculated theoretically for electrons by Bethe and Heitler. These measurements were taken using a thin plate of lead (0.35 cm), and the observed individual losses were found to vary from an amount below experimental detection up to the whole initial energy of the particle, with a mean fractional loss of about 0.5. If these measurements are correct it is evident that in a much thicker layer of heavy material multiple losses should become much more important, and the probability of observing a particle loss less than a large fraction of its initial energy should be very small. For the purpose of testing this inference and also for checking our previous measurements[2] which had shown the presence of some particles less massive than protons but more penetrating than electrons obeying the Bethe-Heitler theory, we have taken about 6000 counter-tripped photographs with a 1 cm plate of platinum placed across the center of the cloud chamber. This plate is equivalent in electron thickness to 1.96 cm of lead, and to 1.86 cm of lead for a Z^2 absorption. The results of 55 measurements on particles in the range below 500 Mev are given in Fig. 1, and in Fig. 2 the distribution of particles is shown as a function of the fraction of energy lost. The shaded part of the diagram represents particles which either enter the chamber accompanied by other particles or else themselves produce showers in the bar of platinum. It is clear that the particles separate themselves into two rather well-defined groups, the one consisting largely of shower particles and exhibiting a high absorbability, the other consisting of particles entering singly which in general lose a relatively small fraction of their initial energy, although there are four cases in which the loss is more than 60 percent. A considerable part of the spread on the negative abscissa can be accounted for by errors; it seems likely, however, that the case plotted at the extreme left represents a particle moving upward. Particles of both signs are distributed over the whole diagram, and moreover, the initial energies of the particles of each group are distributed over the whole measured range.

FIG. 1. Energy loss in 1 cm of platinum.

FIG. 2. Distribution of fractional losses in 1 cm of platinum.

[1] Anderson and Neddermeyer, Phys. Rev. 50, 263 (1936).
[2] Anderson and Neddermeyer, Report of London Conference, Vol. 1 (1934), p. 179.

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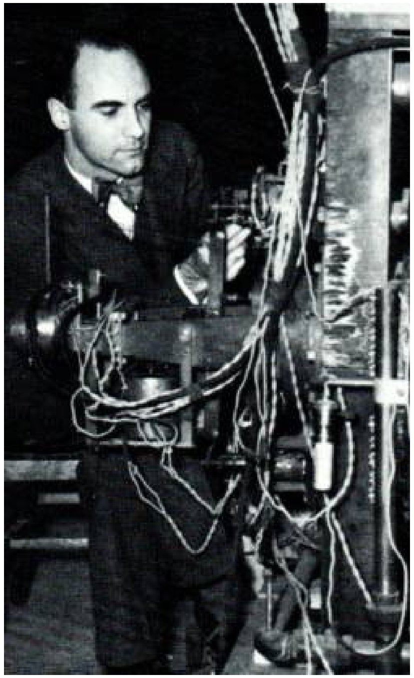
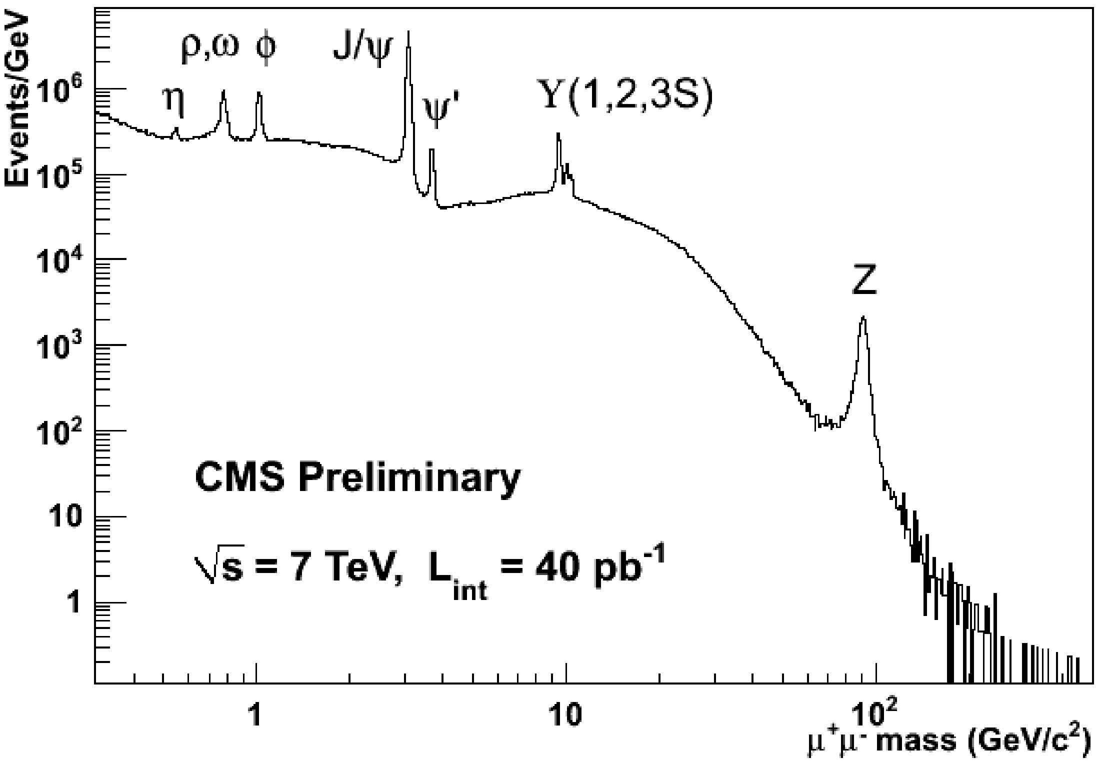




Pion & Kaon

1947: Pion: Powell, Kaon: Rochester & Butler

126 NATURE January 25, 1947 Vol. 159

Fig. 1 a. Photomicrograph of centre of star, showing track of meson producing disintegration. (Leitz 2 mm. oil-immersion objective. × 500)

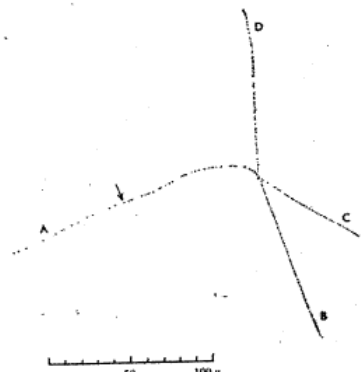


Fig. 1 b. Track of complete star on screen of projection microscope, showing projection of the tracks in the plane of the emulsion. Track A cannot be traced with certainty beyond the arrow

Nuclear Disintegration by Meson Capture

Recently, multiple nuclear disintegration 'stars', produced by cosmic radiation, have been investigated by the photographic emulsion technique. Plates coated with 50 μ Ilford B.1 emulsions[1] were exposed in aircraft for several hours at 30,000 ft. One of these disintegrations was of particular interest, for whereas all stars previously observed had been initiated by radiation not producing ionizing tracks in the emulsion, the one in question appears to be due to nuclear capture of a charged particle, presumably a slow meson.

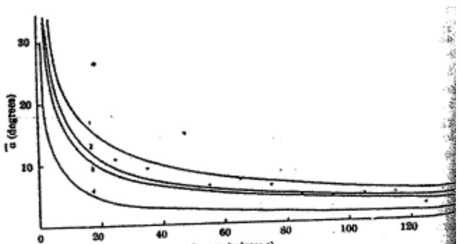
The star consists of four tracks *A*, *B*, *C* and *D* (Fig. 1). *A*, *B* and *D* lie almost in the plane of the emulsion, whereas *C* dips steeply (at about 40°) and ends in the glass. *D* is due to a proton of energy 3·7 MeV., and *C* also corresponds to a proton, of more than 3 MeV., and most likely about 5 MeV. Track *B* was most probably produced by a triton of 5·6 MeV. A short track, about 1 μ long, between *A* and *B* is apparently due to the residual recoil nucleus.

Track *A* appears to enter the emulsion surface about 150 μ from the star centre. On account of the relatively large distances between consecutive grains at this range, the track cannot be distinguished at all easily against the spontaneous background of grains, and only the last 100 μ of track (below arrow) can be traced with certainty. Assuming it to be singly charged, the mass of the particle producing track *A* has been roughly evaluated by the following methods.

(1) Both ionization and scattering increase towards the origin of the star, hence the particle was definitely travelling *towards* the disintegration point.

An electron is discounted because the observed ionization is far too high (an electron track of this range would, in fact, not be detected at all), and the scattering too small. On the other hand, a proton is discounted since the observed scattering is too great (Fig. 2). We must, therefore, conclude that the particle had a mass intermediate between that of electron and proton

The grain density along track *A* does, in fact, agree well with that to be expected of a meson of the observed range of about one tenth of the proton mass. The range-energy curve for mesons in the emulsion has been obtained from that for protons (kindly lent by Dr. C. F. Powell), using the ratio of the masses of the two particles.



Curve 1: $M = 100\ m_e$; curve 2: $M = 200\ m_e$; curve 3: $M = 300\ m_e$; curve 4: $M = 1{,}800\ m_e$

Fig. 2. Multiple scattering of mesons and proton in the emulsion. $\bar{\alpha}$ denotes the mean angle of scattering for a 10 μ layer of the emulsion. Curves calculated for particles of mass 100 m_e, 200 m_e, 300 m_e and 1,800 m_e (proton), m_e being the electron mass. Experimental points, from measurements of track *A*, indicated by dots

No. 4077 December 20, 1947 NATURE 855

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

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AND
Dr. C. C. BUTLER
Physical Laboratories, University, Manchester

Among some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character. These photographs have been selected from five thousand photographs taken in an effective time of operation of 1,500 hours. On the basis of the analysis given below we believe that one of the forked tracks, shown in Fig. 1 (tracks *a* and *b*), represents the spontaneous transformation in the gas of the chamber of a new type of uncharged elementary particle into lighter charged particles, and that the other, shown in Fig. 2 (tracks *a* and *b*), represents similarly the transformation of a new type of charged particle into two light particles, one of which is charged and the other uncharged.

The experimental data for the two forks are given in Table 1; *H* is the value of the magnetic field, α the angle between the tracks, *p* and Δ*p* the measured momentum and the estimated error. The signs of the particles are given in the last column of the table, a plus sign indicating that the particle is positive if moving down in the chamber. Careful re-projection of the stereoscopic photographs has shown that each pair of tracks is copunctal. Moreover, both tracks occur in the middle of the chamber in a region of uniform illumination, the presence of background fog surrounding the tracks indicating good condensation conditions.

Though the two forks differ in many important respects, they have at least two essential features in common: first, each consists of a two-pronged fork with the apex in the gas; and secondly, in neither

Table 1. Experimental data

Photograph	*H* (gauss)	α (deg.)	Track	*p* (eV./c.)	Δ*p* (eV./c.)	Sign
1	3500	66·6	*a* *b*	3·4 × 10⁸ 3·5 × 10⁸	1·0 × 10⁸ 1·5 × 10⁸	+ –
2	7200	161·1	*a* *b*	6·0 × 10⁸ 7·7 × 10⁸	3·0 × 10⁸ 1·0 × 10⁸	+ +

case is there any sign of a track due to a third ionizing particle. Further, [...] similar to these forks have [...] 3-cm. lead plate, whereas if [...] any type of collision process one [...] several hundred times as many [...] argument indicates, therefore, [...] be due to a collision process [...] some type of spontaneous pr[...] probability depends on the di[...] not on the amount of matter [...]

This conclusion can be su[...] arguments. For example, if [...] were due to the deflexion of a [...] collision with a nucleus, the tr[...] would be so large as to prod[...] recoil track. Then, again, the [...] for Fig. 2 by a collision pro[...] difficulty that the incident [...] through 19° in a single collision [...] 2·4° in traversing 3 cm. of lea[...] event. One specific collision pro[...] pair production by a high-energ[...] of the nucleus, can be excluded [...] observed angle between the tra[...] fraction of a degree, for examp[...] and a large amount of electroni[...] have accompanied the photon, a[...] plate is close above the fork.

We conclude, therefore, that th[...] do not represent collision process[...] spontaneous transformations. T[...] of process with which we are alr[...] decay of the meson into an elect[...] neutrino, and the presumed d[...] meson recently discovered by La[...] Powell[1].

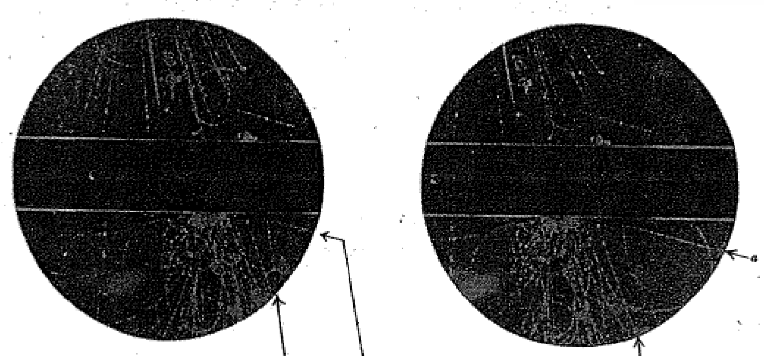
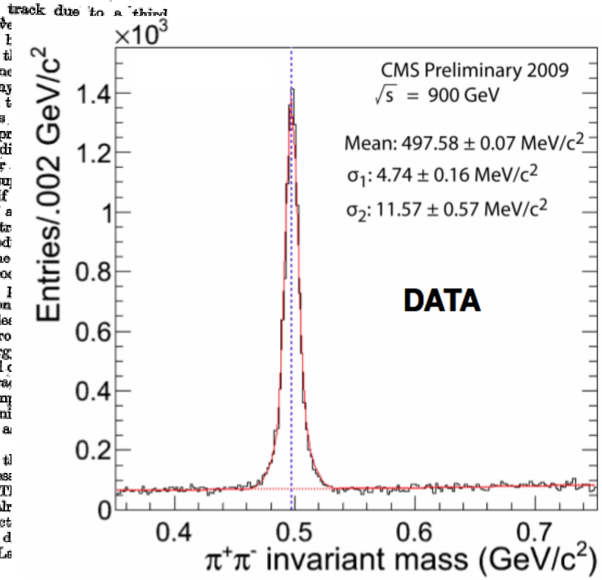


Fig. 1. Stereoscopic photographs showing an unusual fork (*a b*) in the gas. The direction of the magnetic field is such that a positive particle coming downwards is deviated in an anticlockwise direction



Charm Quark

1974: J/Ψ discovery by Ting and Richter

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

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Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

This experiment is part of a large program to study the behavior of timelike photons in $p + p \to e^+ + e^- + x$ reactions[1] and to search for new particles which decay into e^+e^- and $\mu^+\mu^-$ pairs.

We use a slow extracted beam from the Brookhaven National Laboratory's alternating-gradient synchrotron. The beam intensity varies from 10^{10} to 2×10^{12} p/pulse. The beam is guided onto an extended target, normally nine pieces of 70-mil Be, to enable us to reject the pair accidentals by requiring the two tracks to come from the same origin. The beam intensity is monitored with a secondary emission counter, calibrated daily with a thin Al foil. The beam spot size is 3×6 mm^2, and is monitored with closed-circuit television. Figure 1(a) shows the simplified side view of one arm of the spectrometer. The two arms are placed at 14.6° with respect to the incident beam; bending (by $M1$, $M2$) is done vertically to decouple the angle (θ) and the momentum (p) of the particle.

The Cherenkov counter C_0 is filled with one atmosphere and C_e with 0.8 atmosphere of H_2. The counters C_0 and C_e are decoupled by magnets $M1$ and $M2$. This enables us to reject knock-on electrons from C_0. Extensive and repeated calibra-

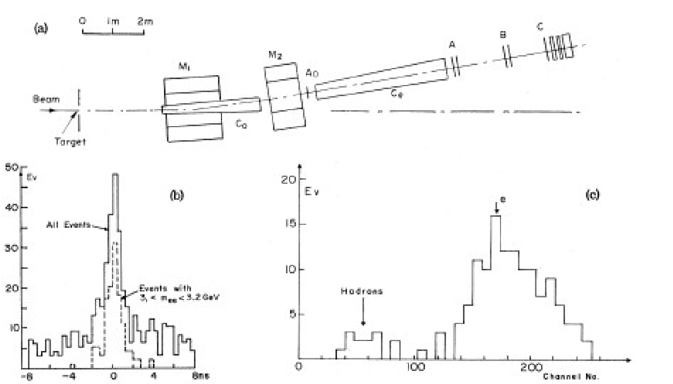


FIG. 1. (a) Simplified side view of one of the spectrometer arms. (b) Time-of-flight spectrum of e^+e^- pairs and of those events with $3.0 < m < 3.2$ GeV. (c) Pulse-height spectrum of e^- (same for e^+) of the e^+e^- pair.

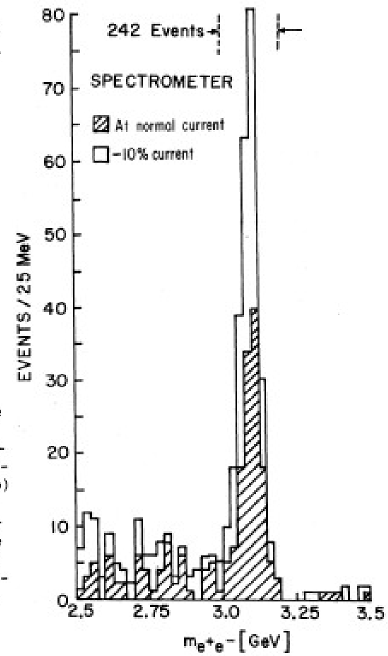


FIG. 2. Mass spectrum showing the existence of J. ...sults from two spectrometer settings are plotted ...wing that the peak is independent of spectrometer ...rents. The run at reduced current was taken two ...nths later than the normal run.

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

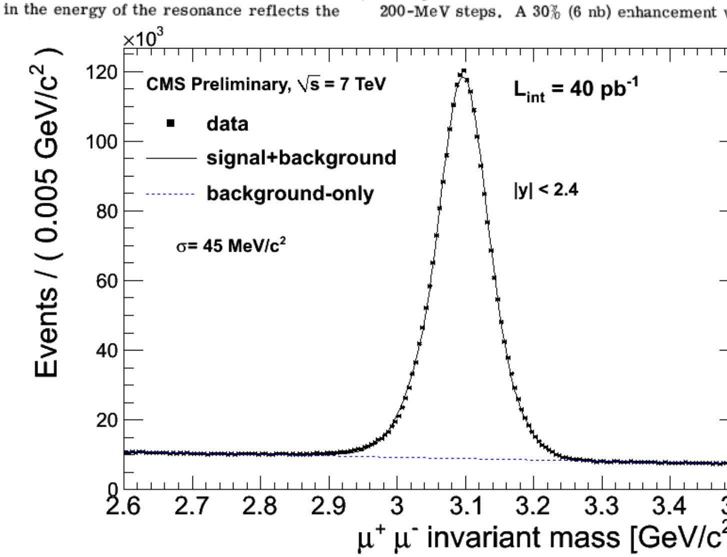
We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ in the Stanford Linear Accelerator Center (SLAC)–Lawrence Berkeley Laboratory magnetic detector[1] at the SLAC electron-positron storage ring SPEAR. The resonance has the parameters

$$E = 3.105 \pm 0.003 \text{ GeV},$$

$$\Gamma \leqslant 1.3 \text{ MeV}$$

(full width at half-maximum), where the uncertainty in the energy of the resonance reflects the uncertainty in the absolute energy calibration of the storage ring. [We suggest naming this structure $\psi(3105)$.] The cross section for hadron production at the peak of the resonance is $\geqslant 2300$ nb, an enhancement of about 100 times the cross section outside the resonance. The large mass, large cross section, and narrow width of this structure are entirely unexpected.

Our attention was first drawn to the possibility of structure in the $e^+e^- \to$ hadron cross section during a scan of the cross section carried out in 200-MeV steps. A 30% (6 nb) enhancement was



Bottom Quark

1977: Y discovery by Lederman

VOLUME 39, NUMBER 5 PHYSICAL REVIEW LETTERS 1 AUGUST 1977

the gauge is fixed up to boundary conditions, and the above results are encouraging. One may also argue that direct closed loop calculations will not produce a cosmological term either, simply because dimensional regularization (which respects the gauge invariances) leads to vanishing of tadpole diagrams.

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
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and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

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State University of New York at Stony Brook, Stony Brook, New York 11974

(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

We have observed a strong enhancement at 9.5 GeV in the mass spectrum of dimuons produced in 400-GeV proton-nucleus collisions. Our conclusions are based upon an analysis of 9000 dimuon events with a reconstructed mass $m_{\mu^+\mu^-}$ greater than 5 GeV corresponding to 1.6×10^{16} protons incident on Cu and Pt targets:

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

The produced muons are analyzed in a double-arm magnetic-spectrometer system with a mass resolution $\Delta m/m$ (rms) ≈ 2%.

The experimental configuration (Fig. 1) is a modification of an earlier dilepton experiment in the Fermilab Proton Center Laboratory.[1-3] Narrow targets (~0.7 mm) with lengths corresponding to 30% of an interaction length are employed.

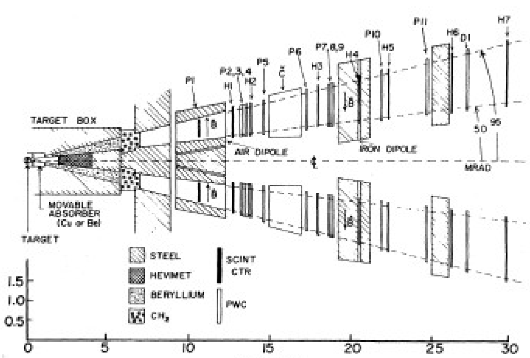
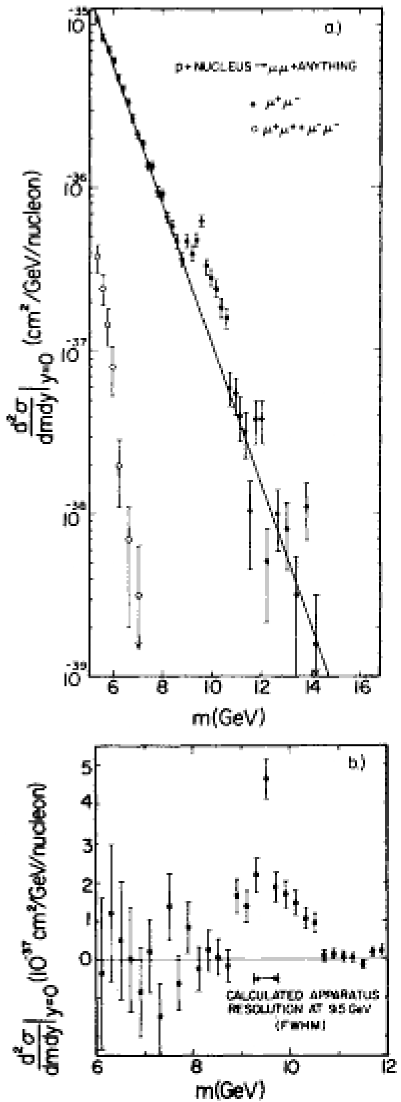
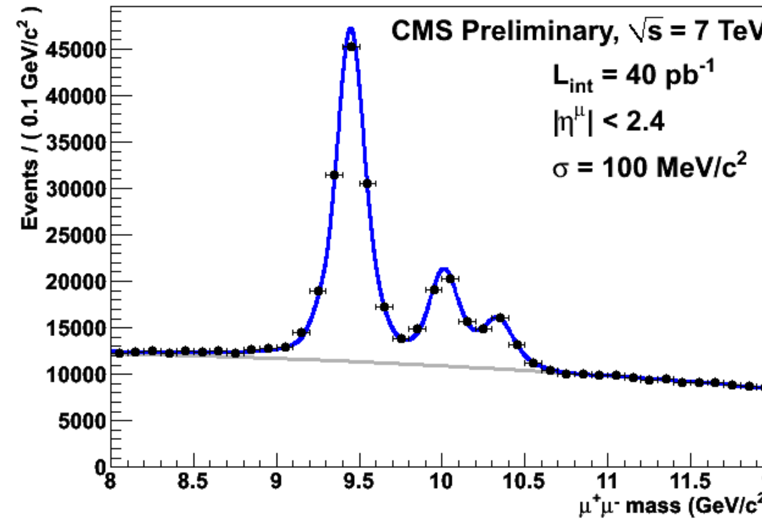
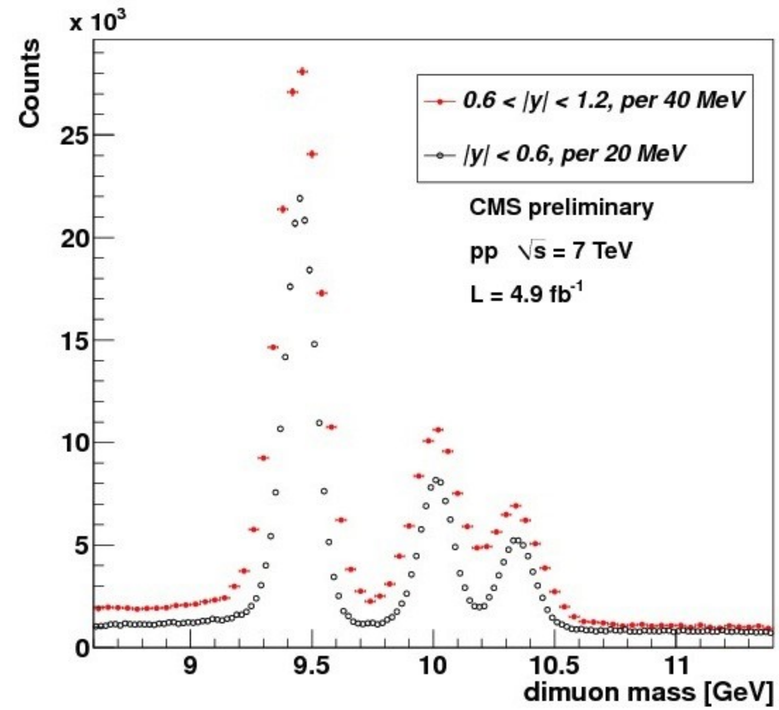


FIG. 1. Plan view of the apparatus. Each spectrometer arm includes eleven PWC's P1–P11, seven scintillation counter hodoscopes H1–H7, a drift chamber D1 and a gas-filled threshold Čerenkov counter Č. Each arm is up/down symmetric and hence accepts both positive and negative muons.





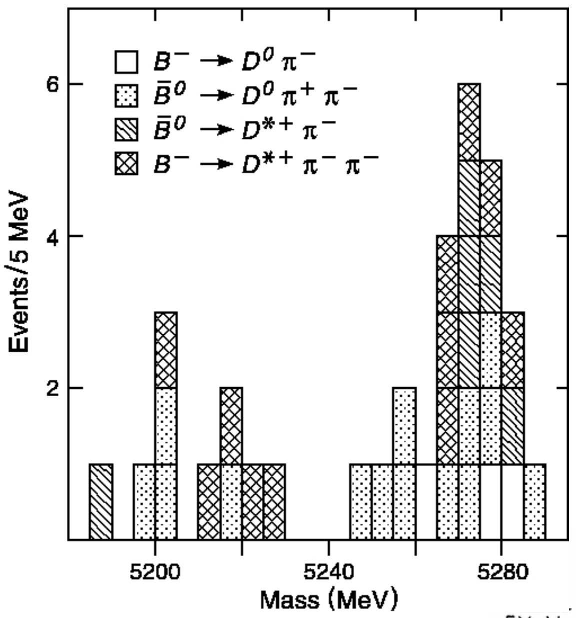


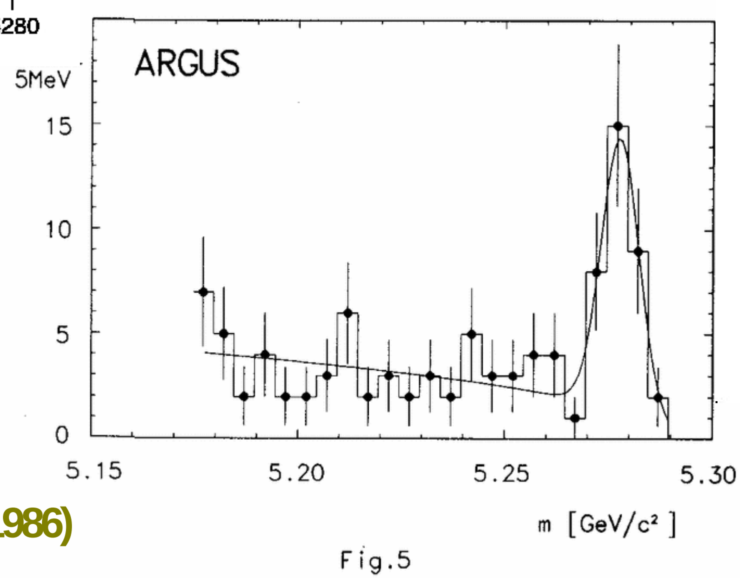
B Mesons

First fully reconstructed B mesons:

CLEO 1983

PRL 50, 881 (1983)





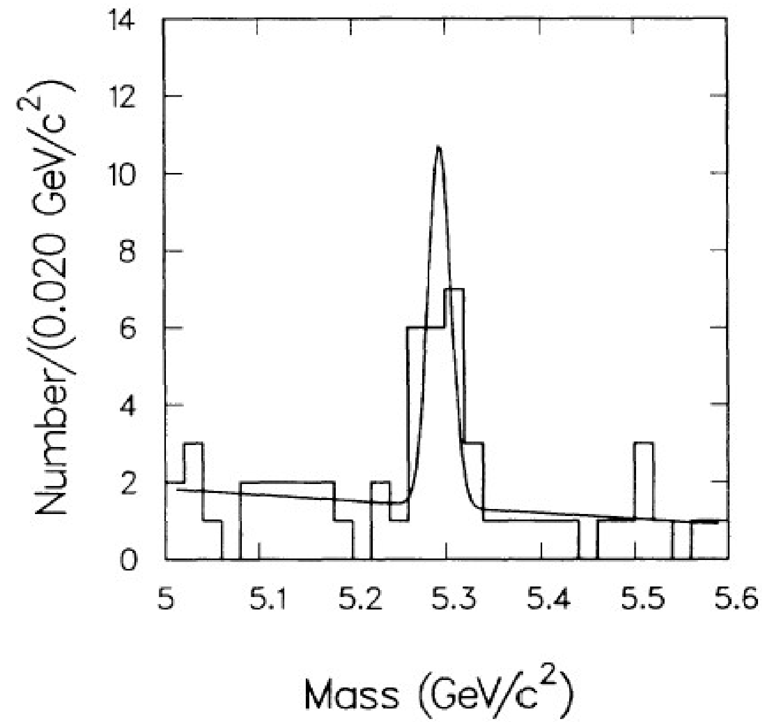
ARGUS 1986

Phys.Lett. B185, 218 (1986)

First fully reconstructed B mesons at a hadron collider

CDF 1992

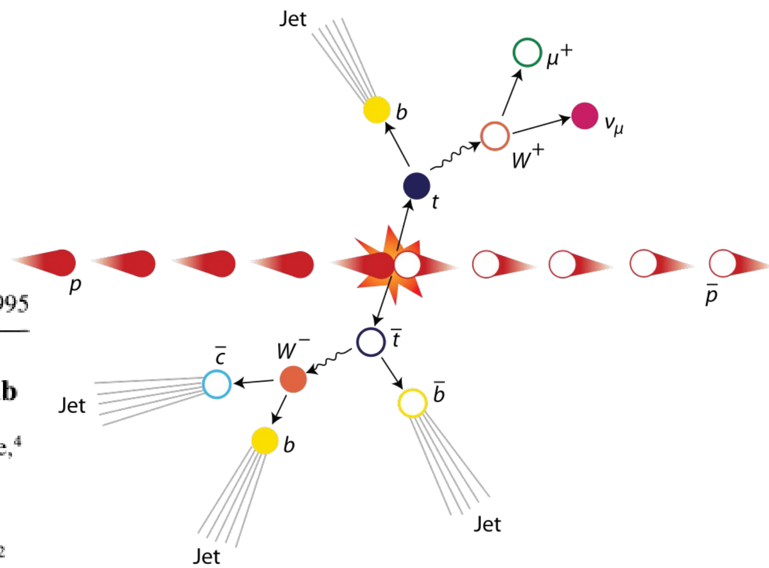
$B^+ \to J/\psi\ K^+$



PRL 68, 3403 (1992)

Top Quark

1995: Top discovery by CDF & D0



VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[24] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4] S. Aota,[32] G. Apollinari,[27] T. Asakawa,[32] W. Ashmanskas,[15] M. Atac,[7] P. Auchincloss,[26] F. Azfar,[22] P. Azzi-Bacchetta,[21] N. Bacchetta,[21] W. Badgett,[17] S. Bagdasarov,[27] M. W. Bailey,[19] J. Bao,[35] P. de Barbaro,[26] A. Barbaro-Galtieri,[15] V. E. Barnes,[25] B. A. Barnett,[13] P. Bartalini,[24] G. Bauer,[16] T. Baumann,[9] F. Bedeschi,[24] S. Behrends,[3] S. Belforte,[24] G. Bellettini,[24] J. Bellinger,[34] D. Benjamin,[31] J. Benlloch,[16] J. Bensinger,[3] D. Benton,[22] A. Beretvas,[7] J. P. Berge,[7] S. Bertolucci,[8] A. Bhatti,[27] K. Biery,[12] M. Binkley,[7] D. Bisello,[21] R. E. Blair,[1] C. Blocker,[3] A. Bodek,[26] W. Bokhari,[16] V. Bolognesi,[24] D. Bortoletto,[25] J. Boudreau,[23] G. Brandenburg,[9] L. Breccia,[2] C. Bromberg,[18] E. Buckley-Geer,[7] H. S. Budd,[26] K. Burkett,[17] G. Busetto,[21] A. Byon-Wagner,[7]

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of the Top Quark

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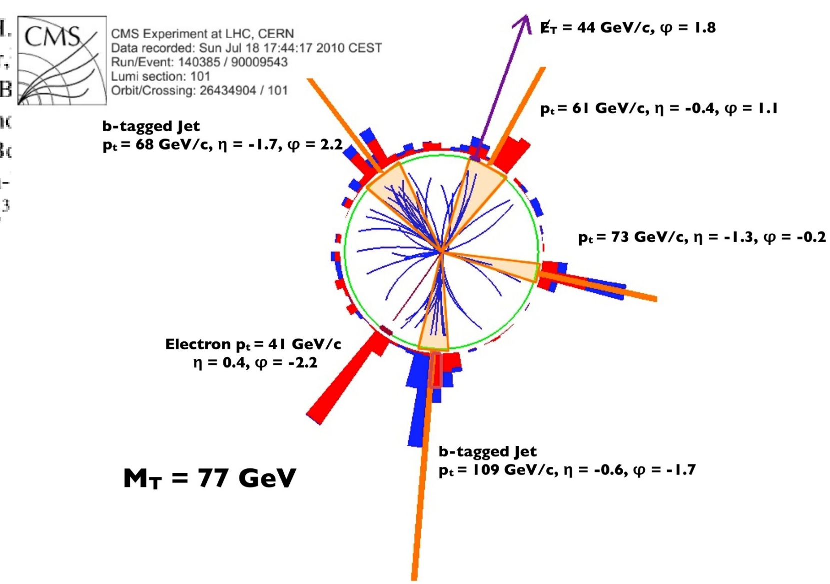
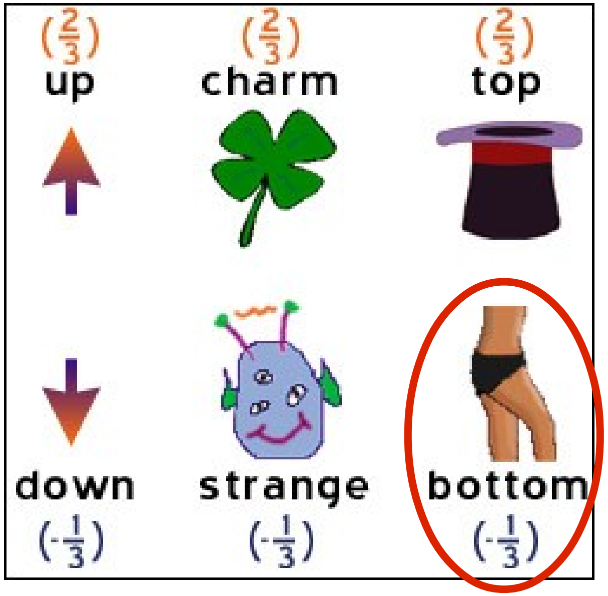
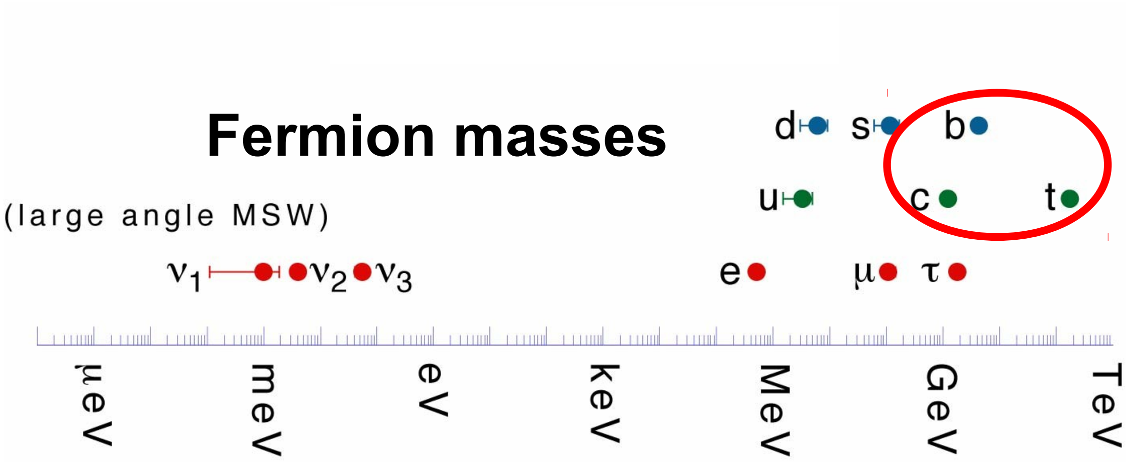


Heavy Quarks

Quarks





- Today established B meson states:

Mesons: $\bar{B}^0 = |b\bar{d}\rangle,\ B^- = |b\bar{u}\rangle,\ \bar{B}^0_S = |b\bar{s}\rangle$

$B_c^- = |b\bar{c}\rangle$

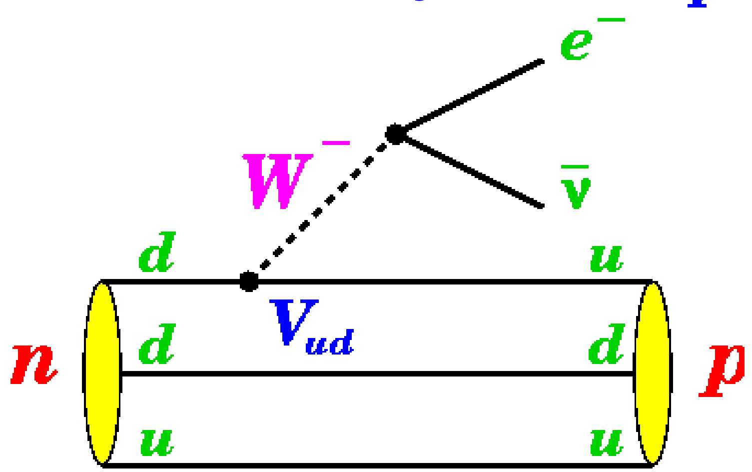
Baryons: $\Lambda_b^0 = |bdu\rangle$

- Rest mass: 5.3 - 6.5 GeV (~6 x mass of proton)
- All B hadrons decay via weak interaction

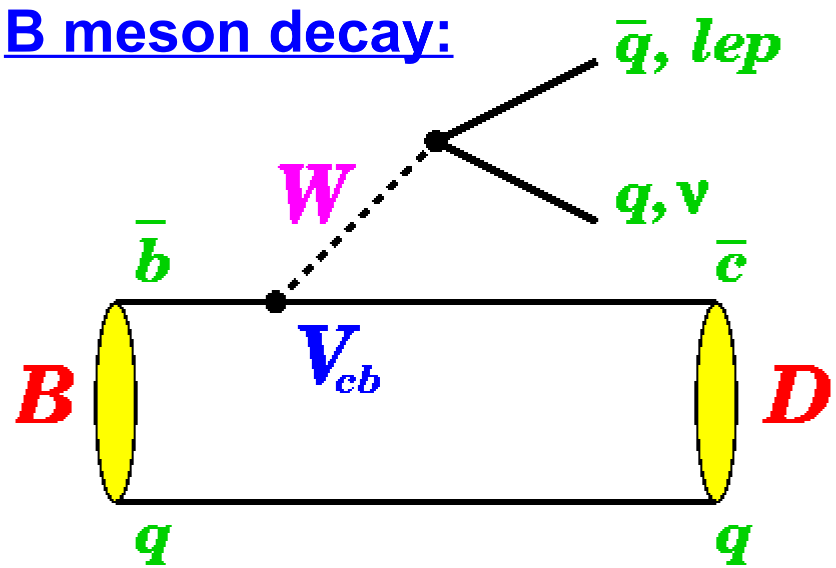
B Meson Decays

- All B hadrons decay via weak interaction

Neutron beta decay: $n \rightarrow p\, e^- \bar{\nu}_e$

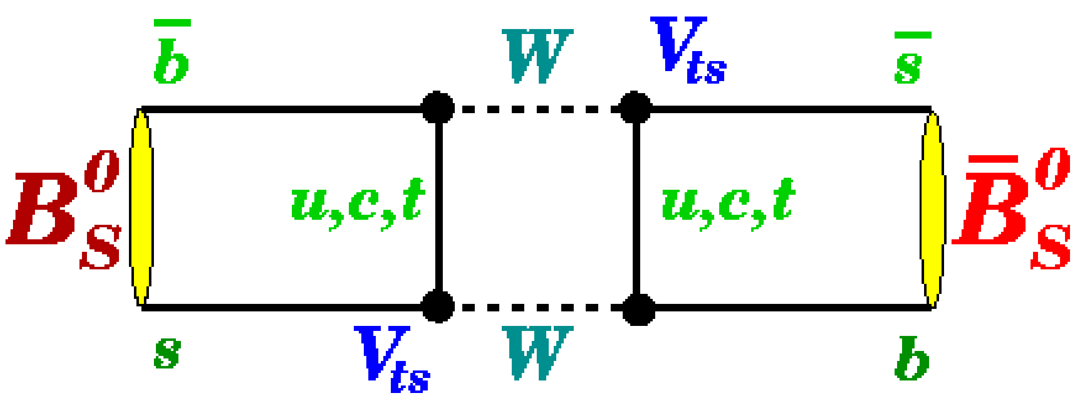


B meson decay:



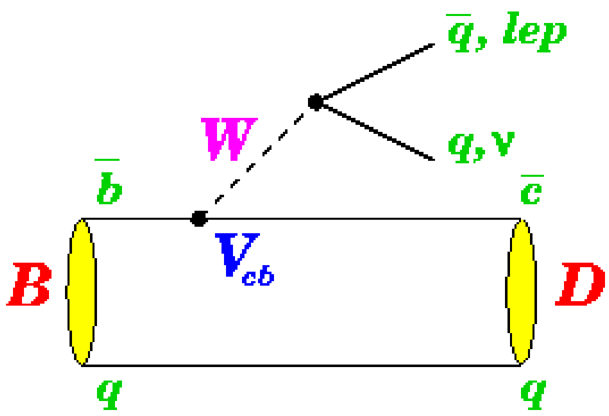
- Higher order diagrams describe e.g. particle oscillations:

Particle

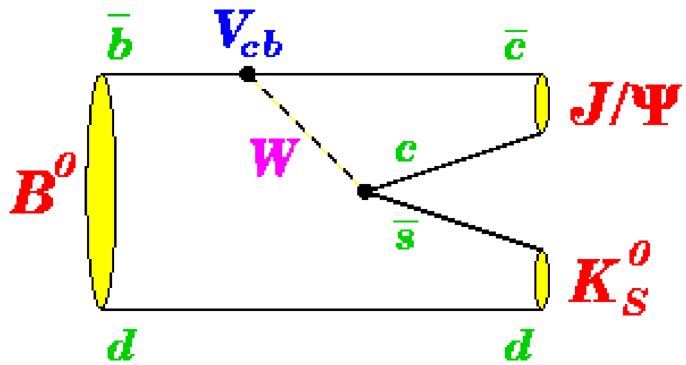


Anti-Particle

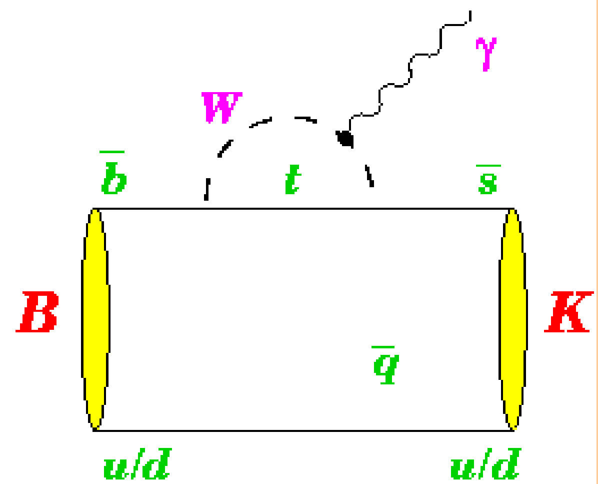
Overview of B Decay Diagrams



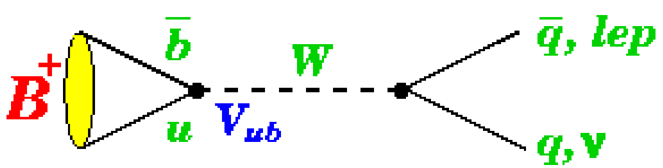
External spectator
(semileptonic, hadronic)



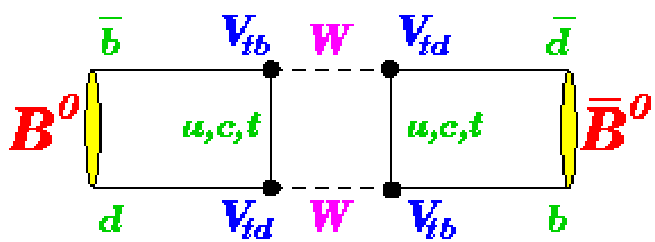
Internal spectator



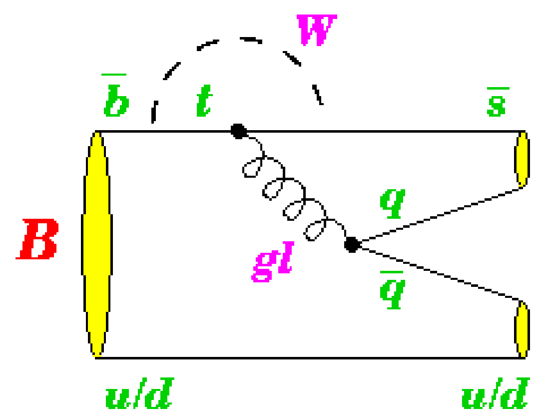
Penguin (radiative)



Annihilation



Oscillation



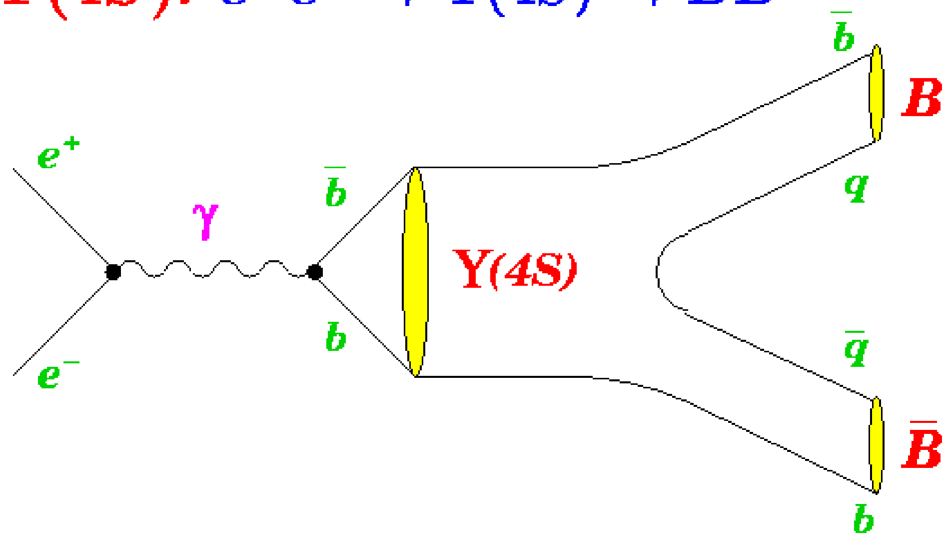
Penguin (gluonic)

B Hadron Producers

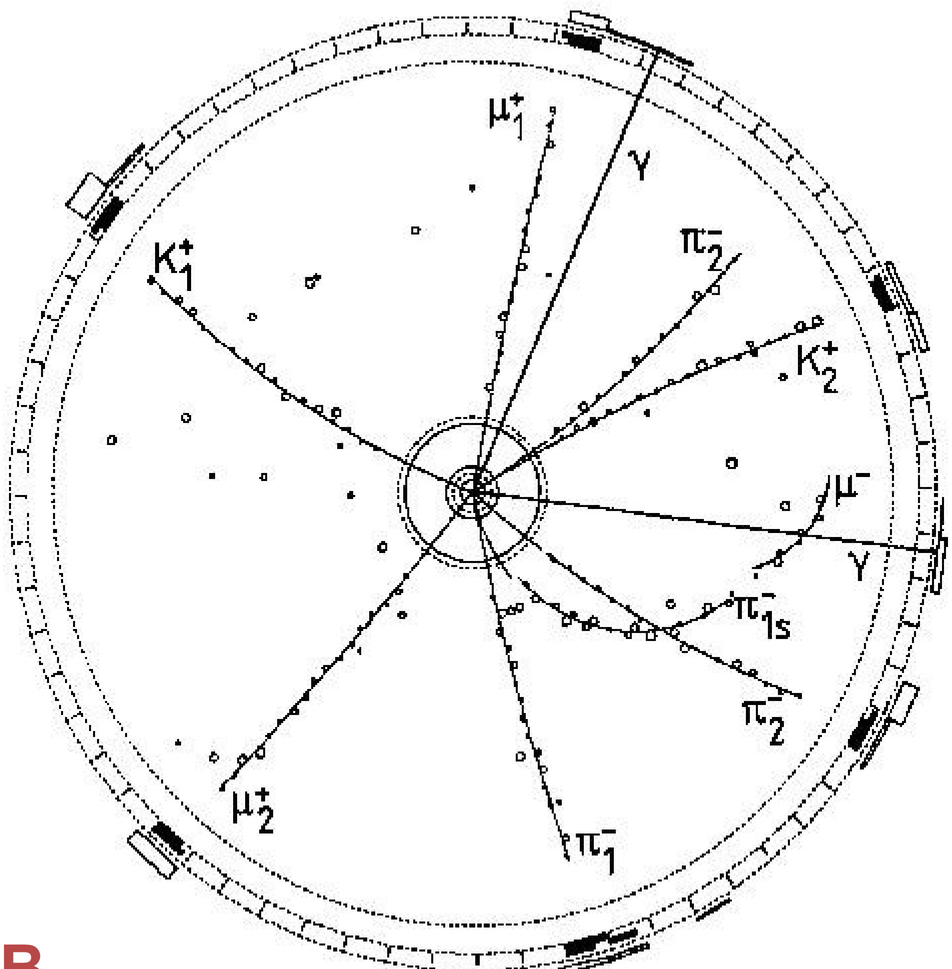
B Hadron Producers

Overview of B Hadron Producers:

$\Upsilon(4S)$: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



ARGUS:



The Players:

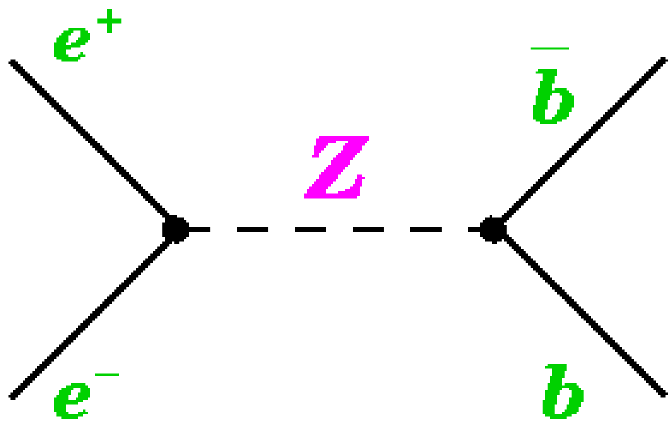
ARGUS & CLEO (Pioneers)

BaBar & Belle (B Factories)

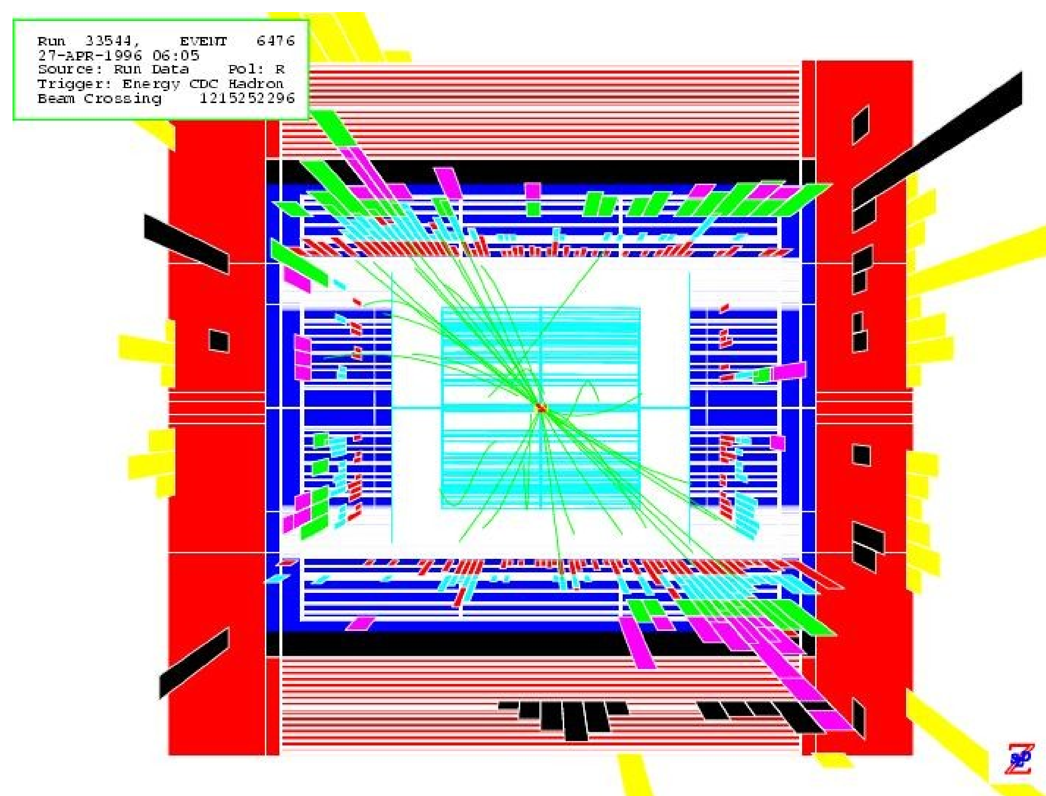
The Future: Super-Belle, Super-B

B Hadron Producers

Z^0: $e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}$



SLD:



The Players:

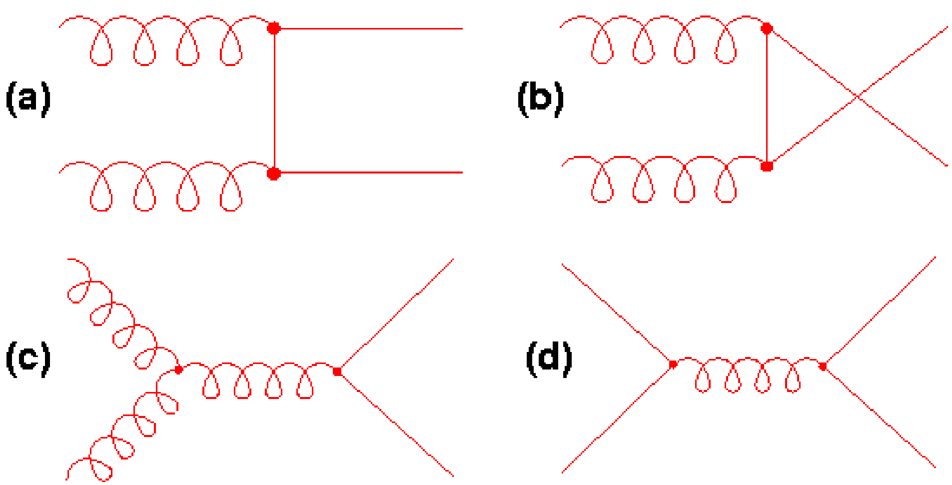
ALEPH, DELPHI, L3, OPAL

SLD

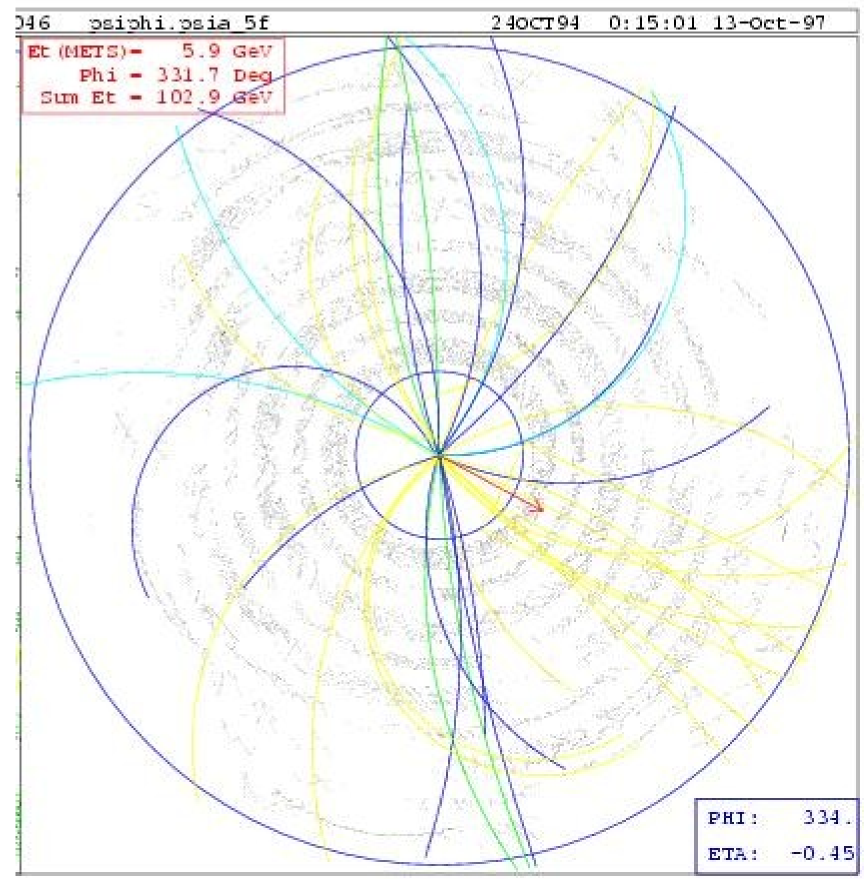
B Hadron Producers

Tevatron: $p\bar{p} \rightarrow b\bar{b}X$

- Lowest order $\mathcal{O}(\alpha_s^2)$ diagrams for $b\bar{b}$ production
  - (a)-(c) gluon-gluon fusion
  - (d) quark-antiquark annihilation



CDF:



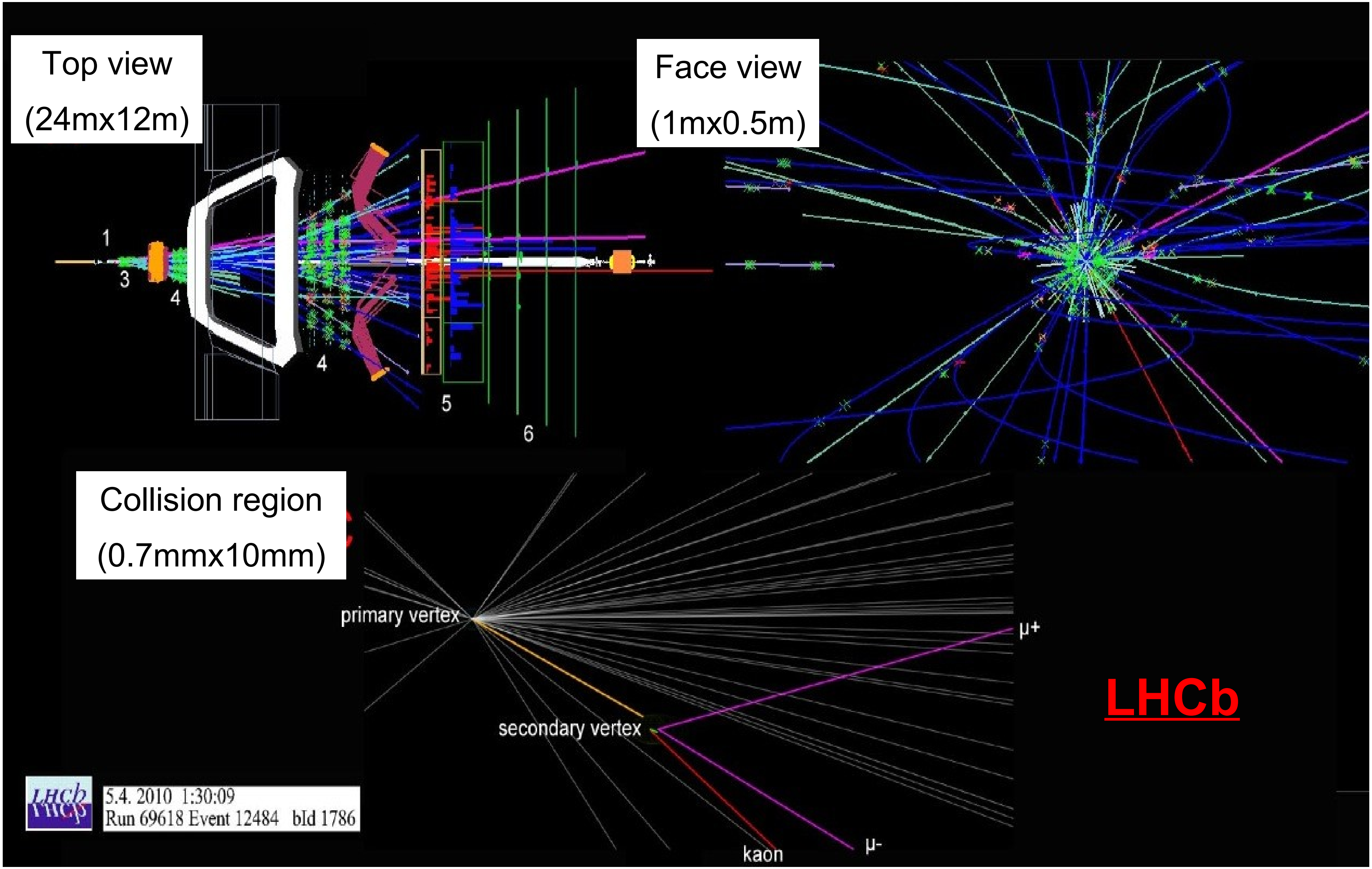
The Players:

LHCb, Atlas, CMS, CDF & D0

Other B producers:

Hera-B, FNAL fixed target

B Hadron Producers



LHCb

Features of B Physics

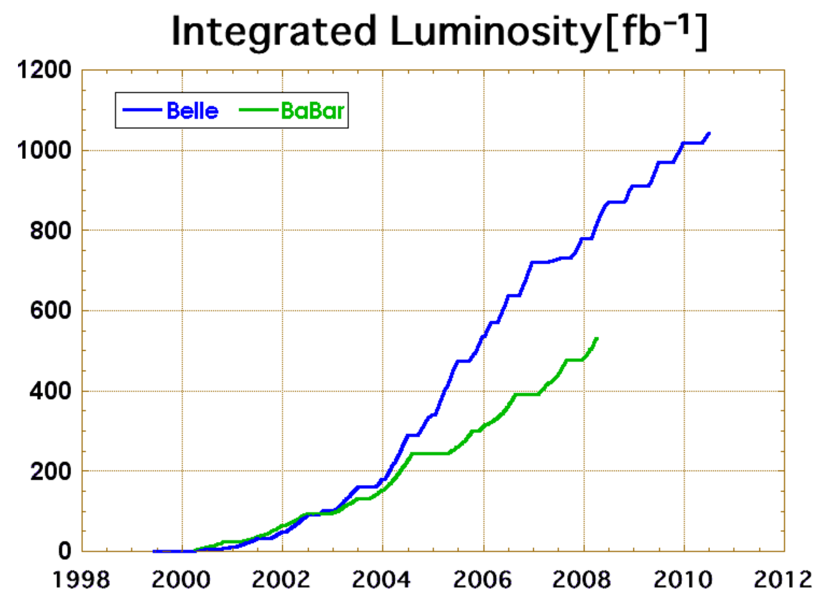
Features of B Physics

Elements for successful B physics:

1. High Rate B Production

- LEP: ~ 0.9×10^6 $b\bar{b}$ events per experiment (1991-1995)
- CLEO: ~10×10^6 $B\bar{B}$ events (9.3 fb^{-1} in 1993-1999)
- CDF: 5×10^{11} $b\bar{b}$ events produced (100 pb^{-1} in 1992-1995, Run I;
  Run II: ~10 fb^{-1} in 2001-2011)
- D0: no B physics in Run I, Run II similar to CDF
- BaBar: ~500 fb^{-1} (~500×10^6 $B\bar{B}$ events in 1999-2008)
- Belle: ~1000 fb^{-1} (~770×10^6 $B\bar{B}$ events in 1999-2010)
- LHCb: ~1 fb^{-1} @ 7 TeV in 2011;
  expect ~2 fb^{-1} @ 8 TeV
  in 2012

Belle & BaBar

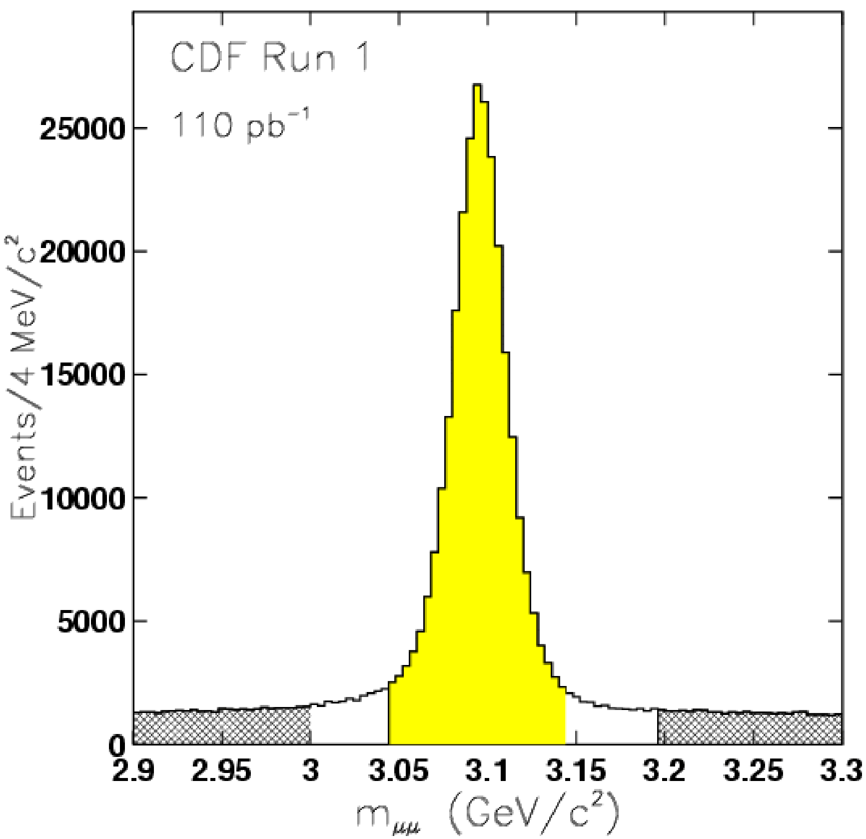


Features of B Physics

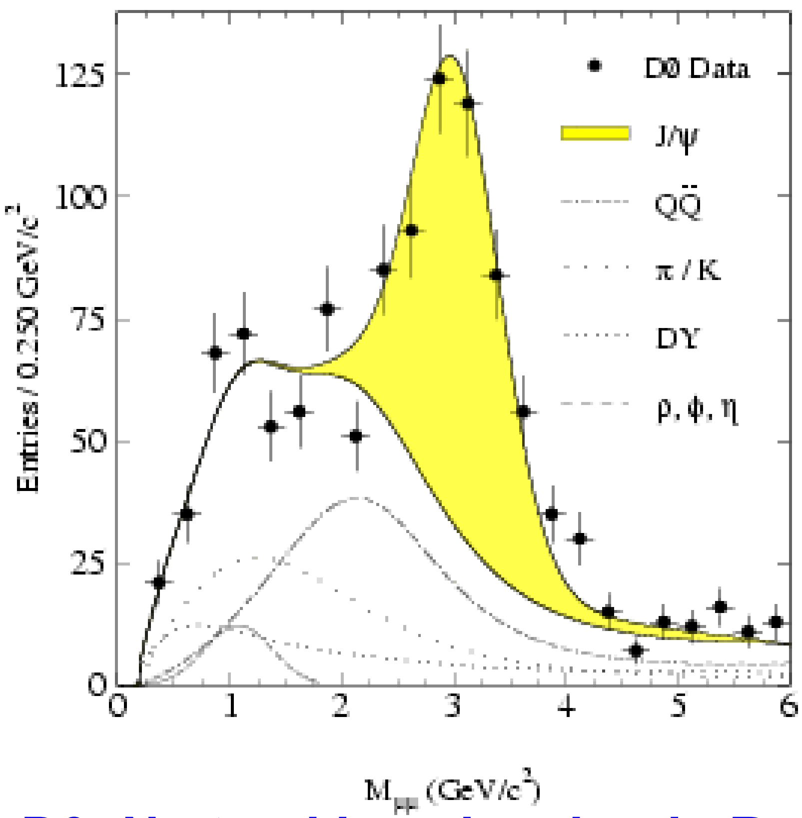
2. Excellent Track Reconstruction with Tracking Chamber

Excellent momentum resolution gives excellent invariant mass resolution

$$m^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 \quad (A \to a_1\, a_2)$$



CDF: dimuon mass resolution ~ 16 MeV



D0: No tracking chamber in Run I muon momentum from muon chambers

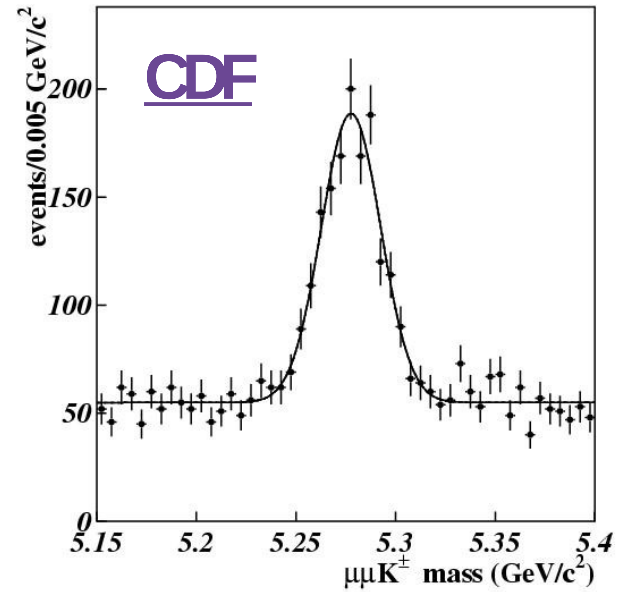
Features of B Physics

2. Excellent Track Reconstruction with Tracking Chamber

Reconstruction of B mesons:

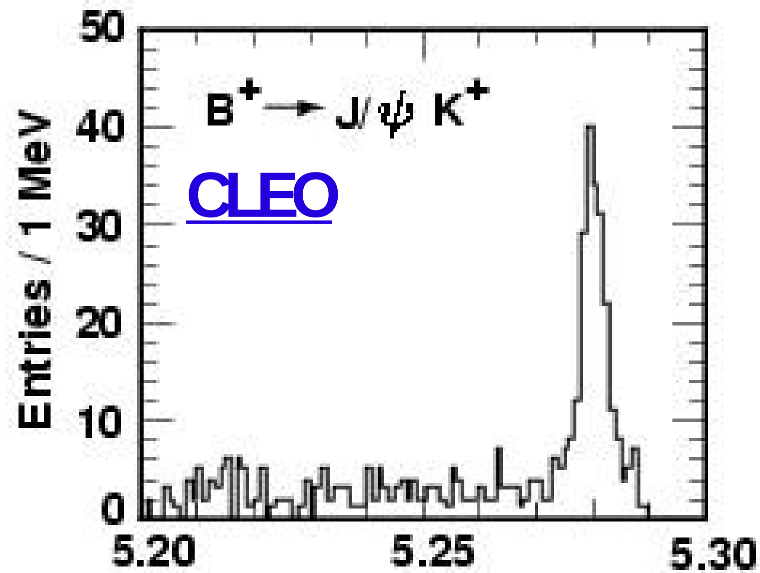
- CDF: $B^+ \rightarrow J/\psi\ K^+$
- Typical B mass resolution: ~20-30 MeV

  $\mathcal{L}$ = 110 pb^{-1} => N(B)=(998 ± 51)



- CLEO: $B^+ \rightarrow J/\psi\ K^+$
- Beam constraint: $m_B = \sqrt{E_{\rm beam}^2 - p_B^2}$
- Typical B mass resolution: ~2-3 MeV

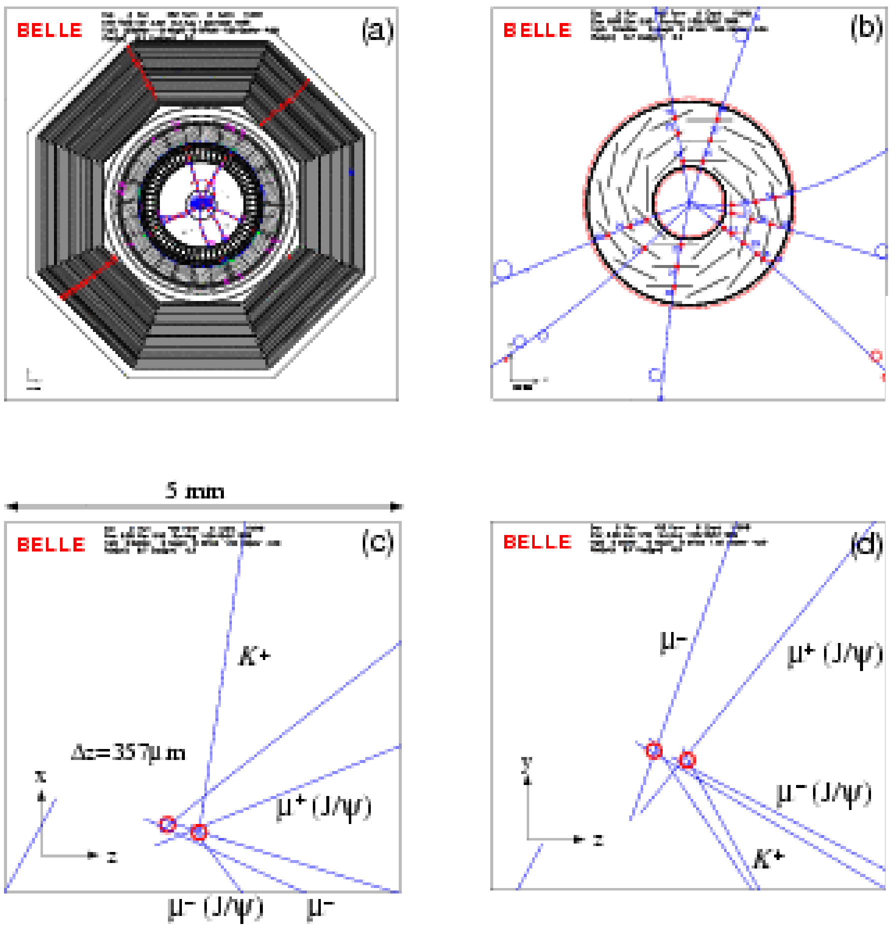
  $\mathcal{L}$ = 3100 pb^{-1} => N(B)=(198 ± 15)



Features of B Physics

3. Superb Vertexing with Silicon Vertex Detectors

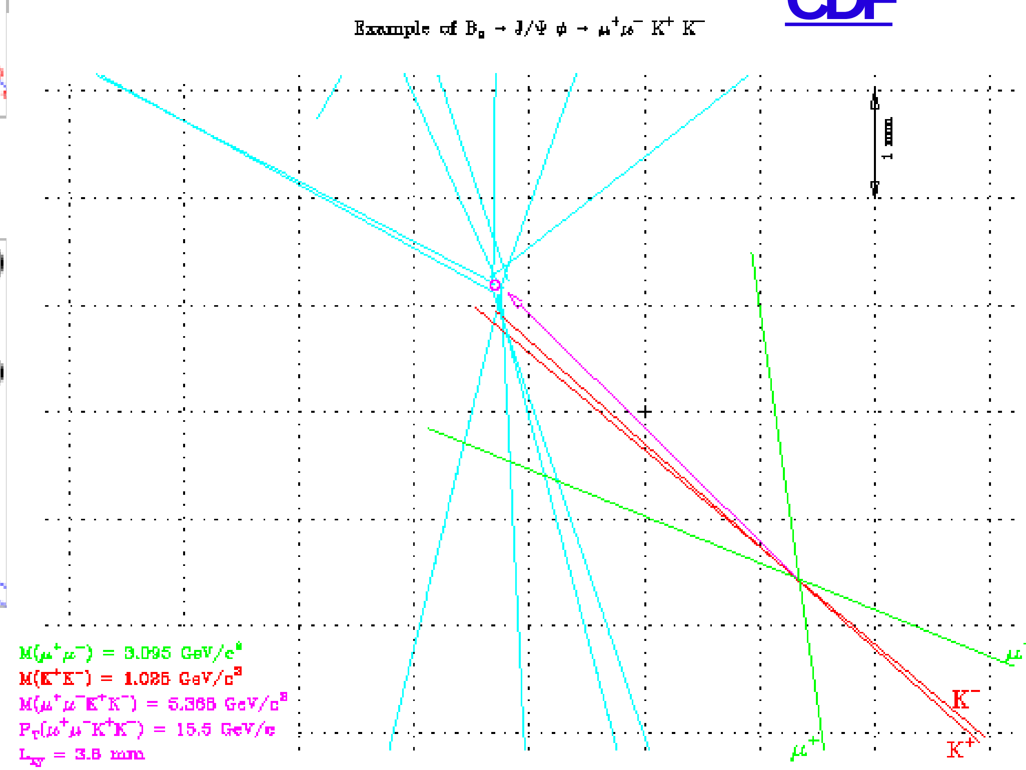
Exploit 'long' lifetime of B hadrons:



Belle

(Note: vertexing resolutions)

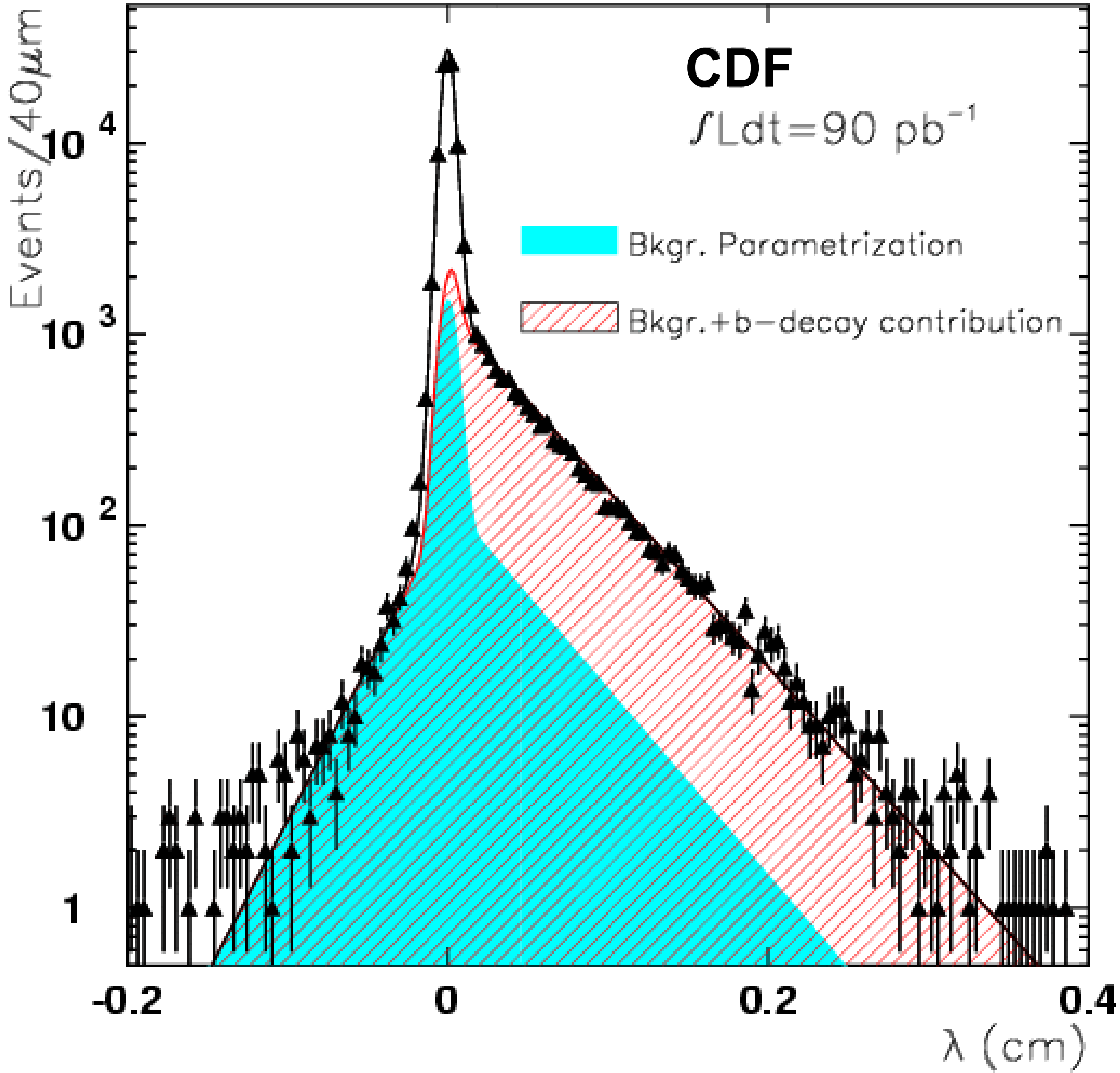
CDF



Features of B Physics

3. Superb Vertexing with Silicon Vertex Detectors

CDF: Decay length of J/Ψ mesons



Transverse decay length:

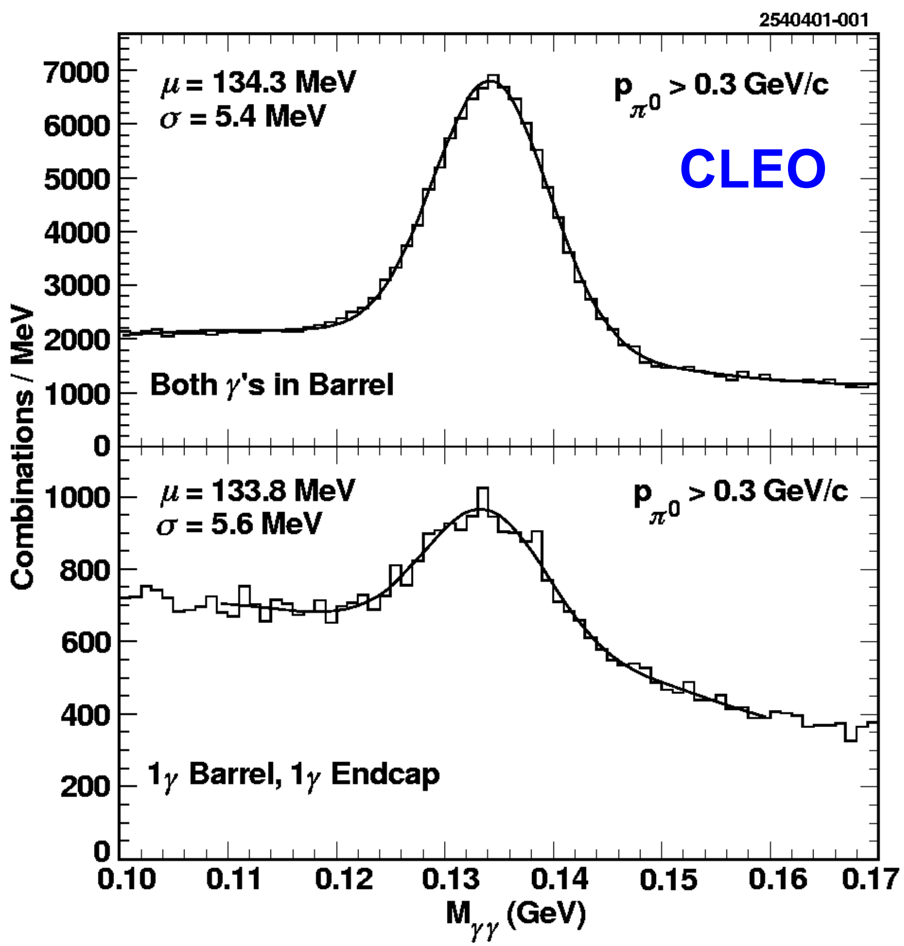
$$L_{xy}^{J/\psi} = \frac{\vec{X}\cdot \vec{p_T}^{J/\psi}}{|\vec{p_T}^{J/\psi}|}$$

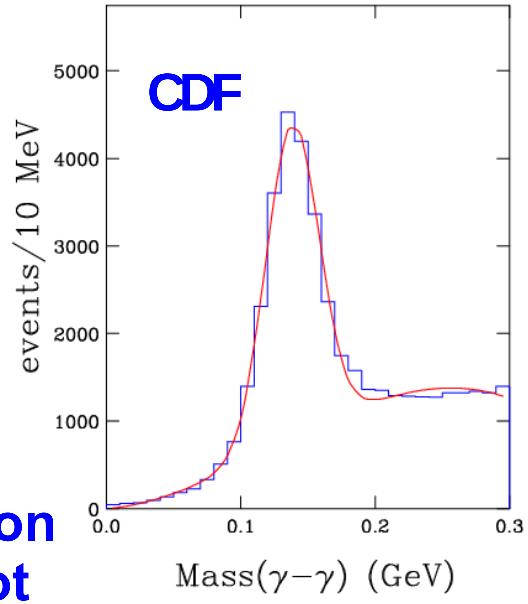
$$c\tau(J/\psi) = L_{xy}^{J/\psi}\cdot\frac{m(J/\psi)}{p_T(J/\psi)} = L_{xy}^{J/\psi}\cdot\frac{1}{(\beta\gamma)^{J/\psi}}$$

Features of B Physics

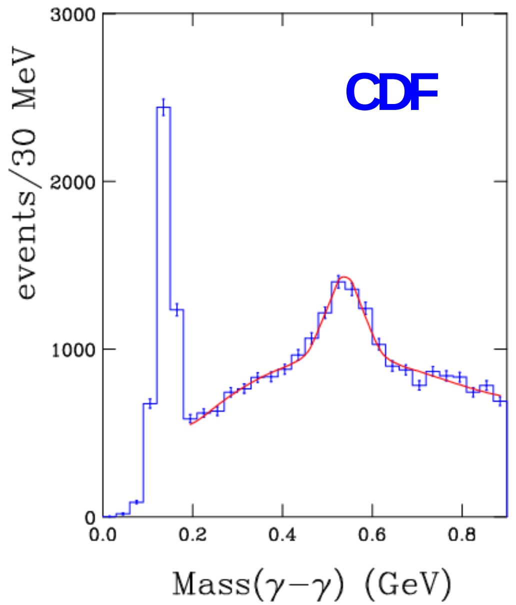
4. Good Calorimeter to Detect Low Energy Neutrals

Crystal calorimeters (CsI, BGO, ...)





CDF not well suited for detection of neutrals but not impossible



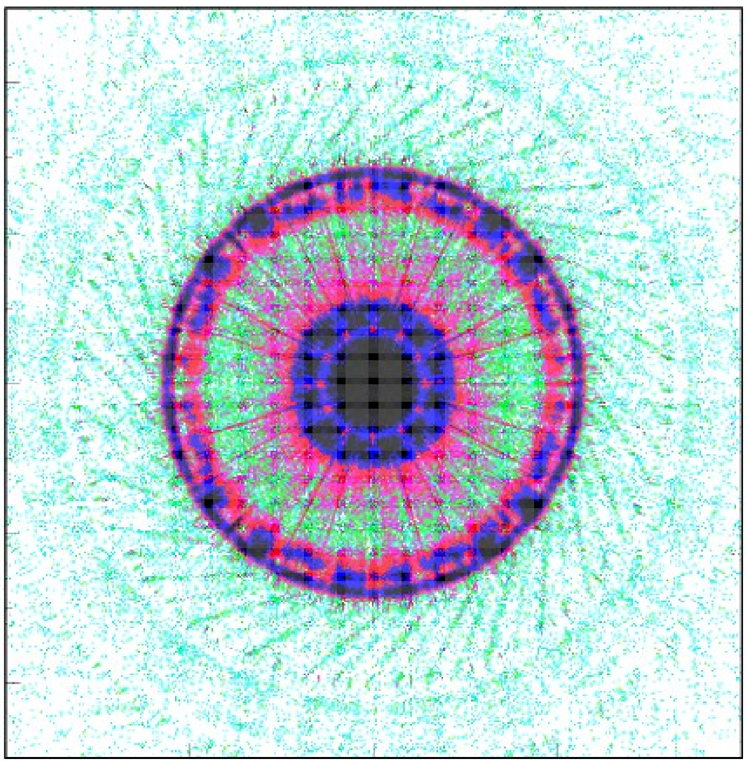
Excellent energy resolution translates into excellent di-photon invariant mass resolution

Features of B Physics

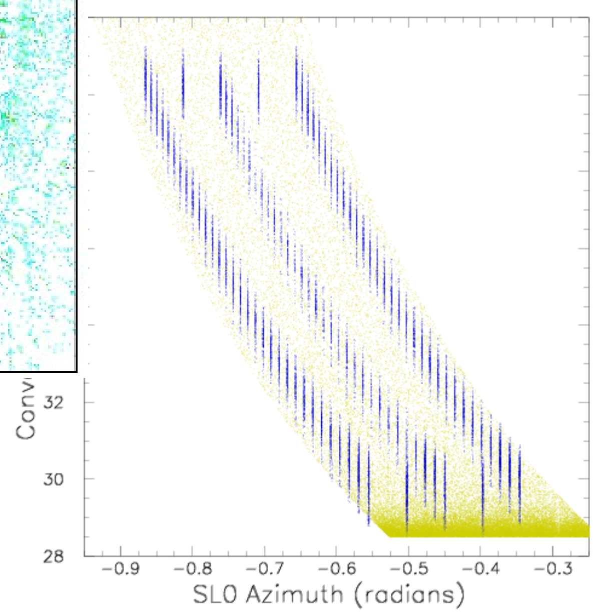
4. Good Calorimeter to Detect Low Energy Neutrals

If calorimeter not well suited for low energy photons

=> Photon conversion: $\gamma \rightarrow e^+e^-$ (low efficiency)

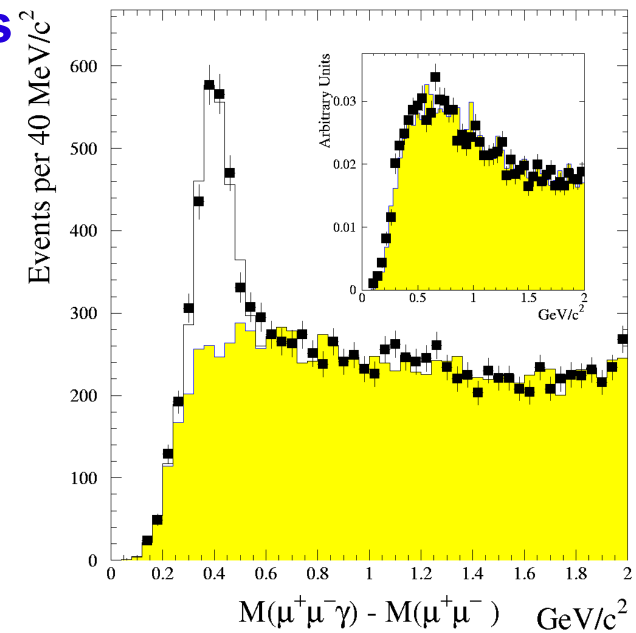


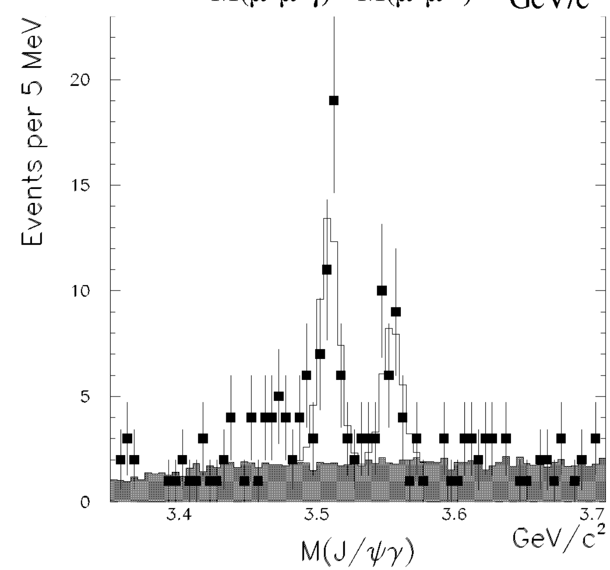
CDF: X-ray of inner detector



Example:

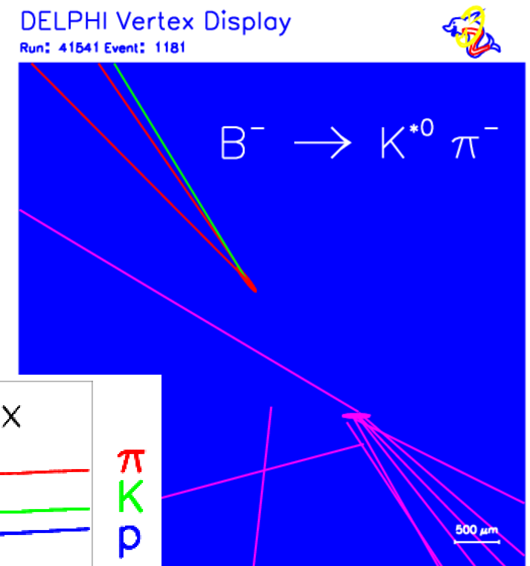
$\chi_c \rightarrow J/\psi\ \gamma$



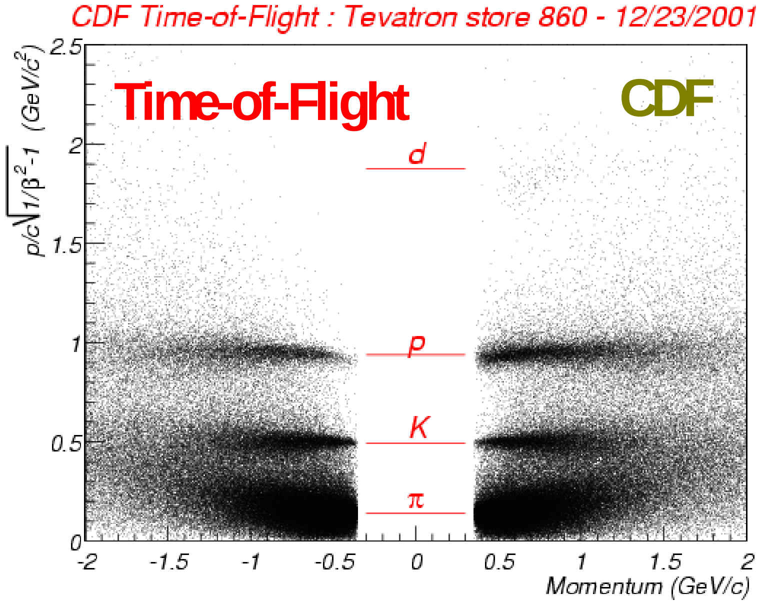


Features of B Physics

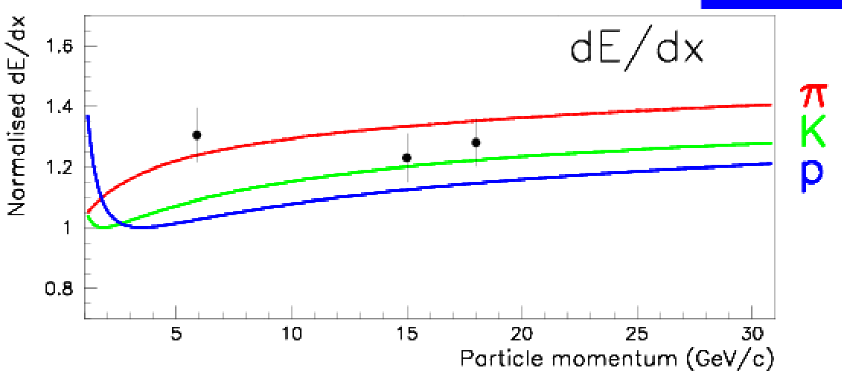
5. Good Particle identification

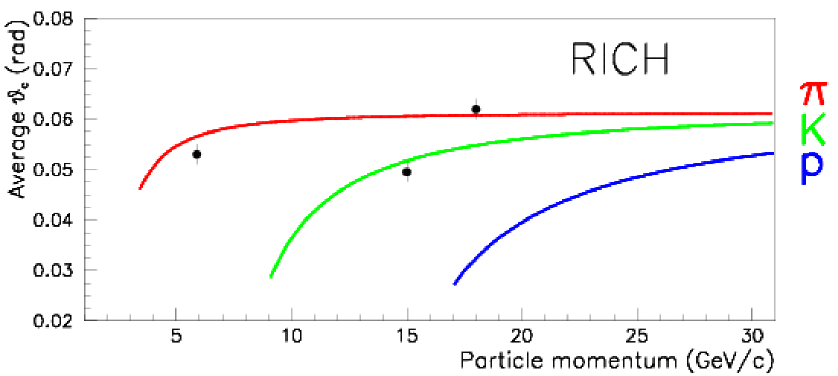


DELPHI

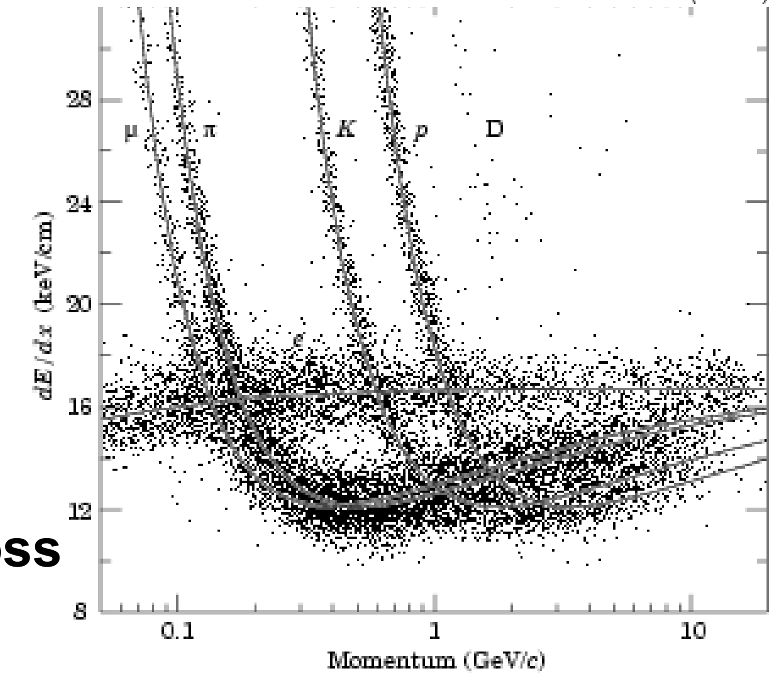


Cerenkov detector for pion-kaon separation





specific energy loss dE/dx



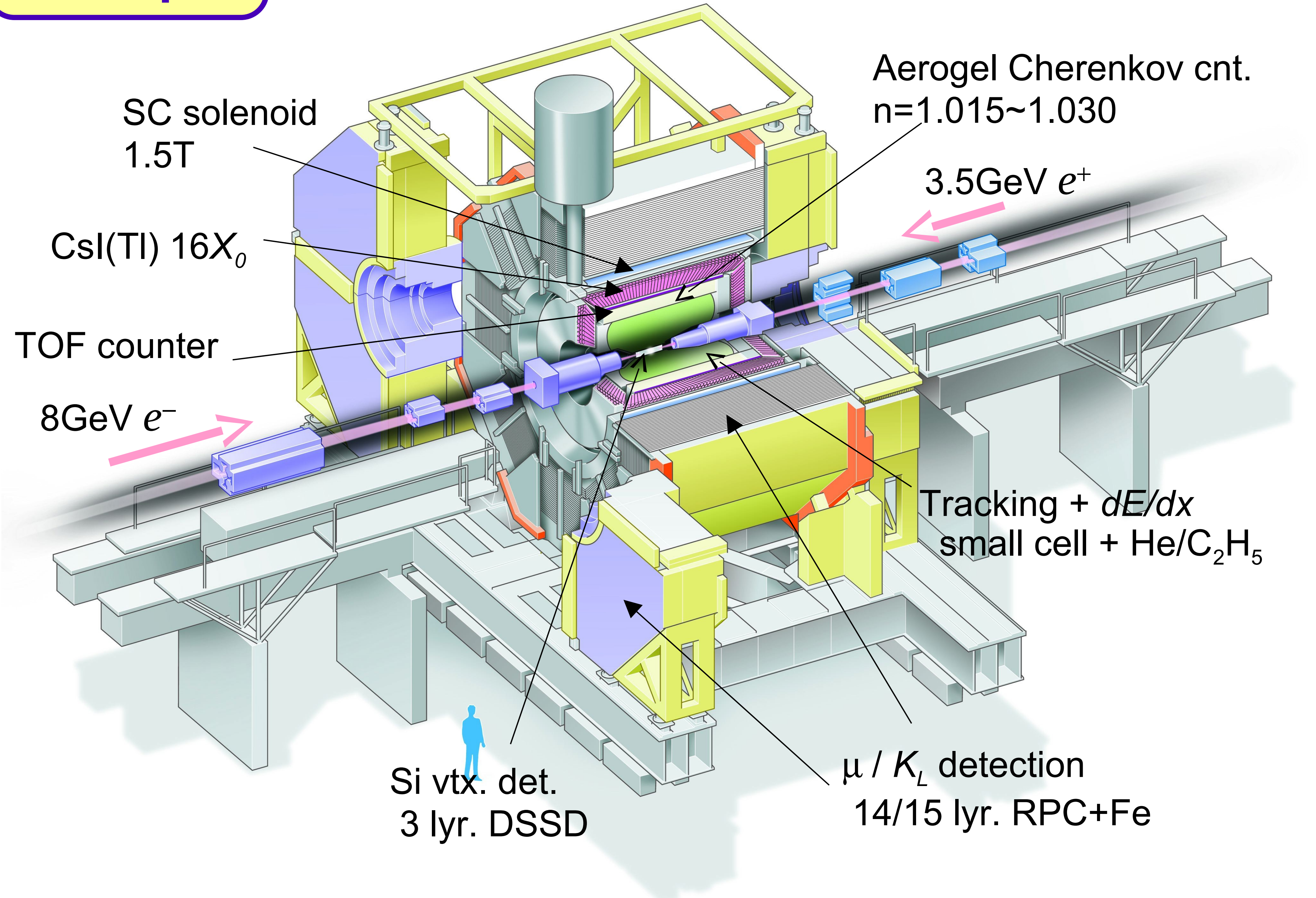
Features of B Physics

Summary of Elements for Successful B Physics:

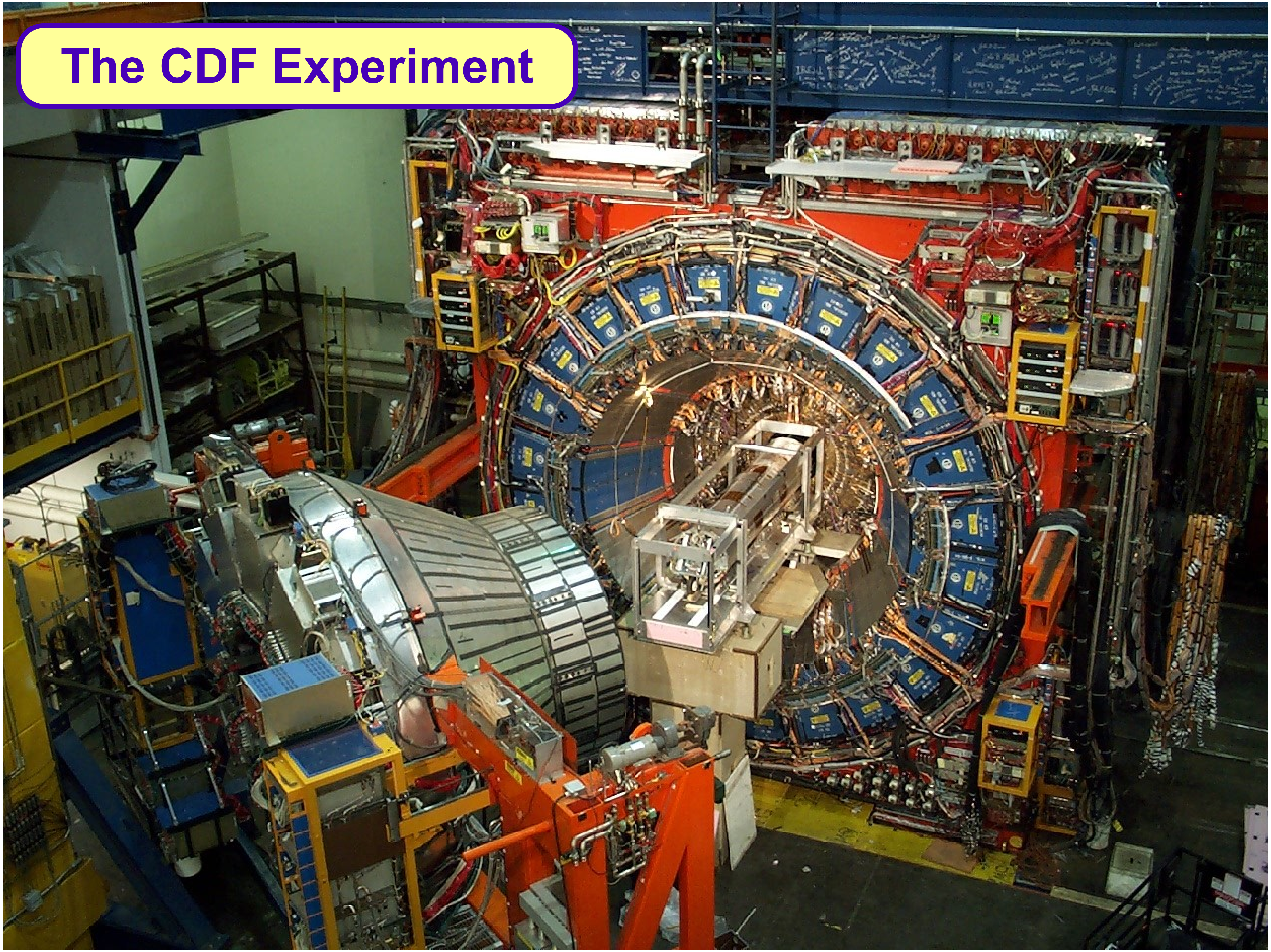
- High rate B production
- Excellent tracking in tracking chamber and silicon detector
- Superb vertexing with silicon vertex detector
- Good calorimeter to detect low energy neutral particles
- Particle identification (pion/kaon separation)
- Efficient identification of electrons and muons
- Large coverage of solid angle (4π coverage / hermiticity)

Example

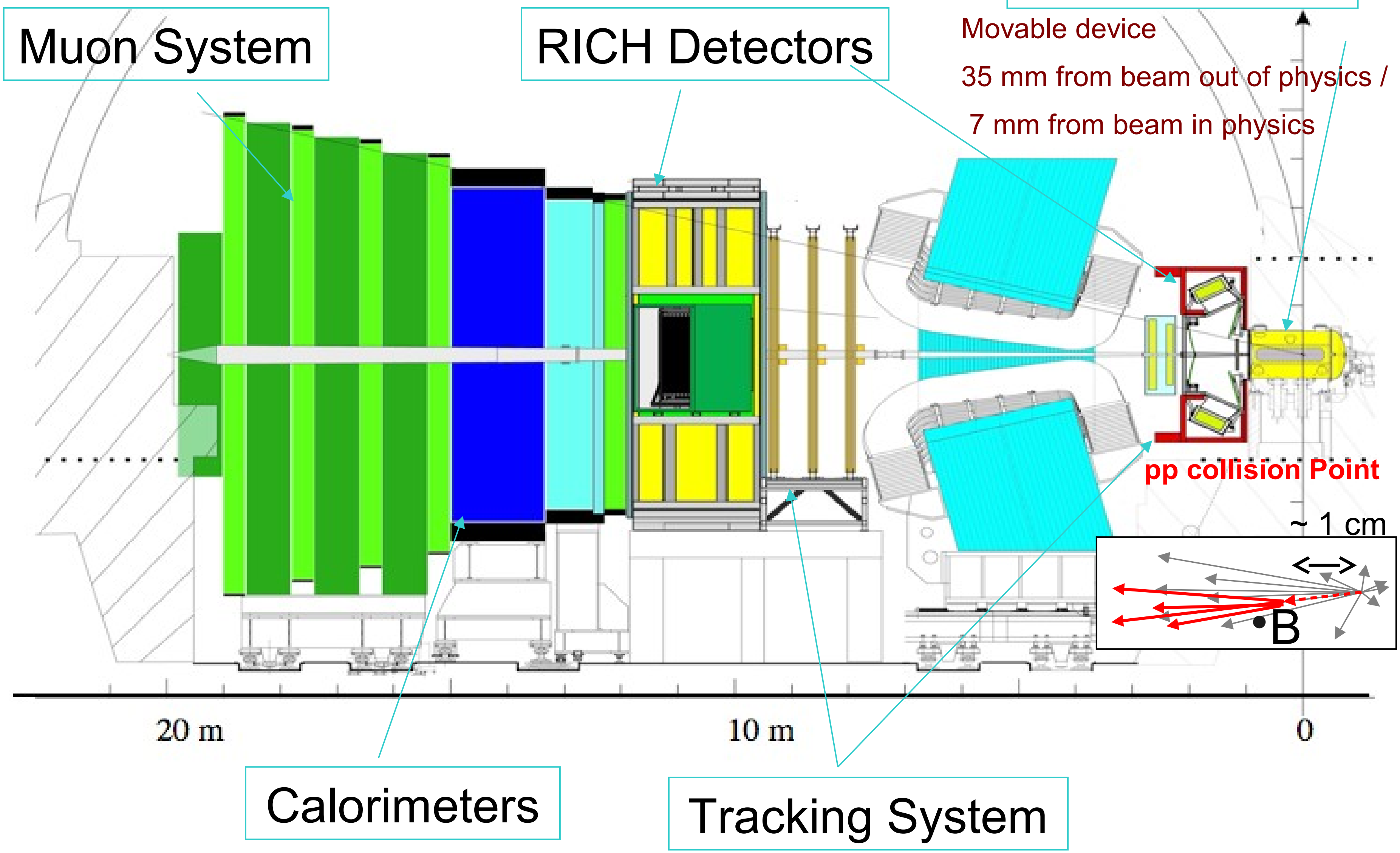
Belle Detector



The CDF Experiment

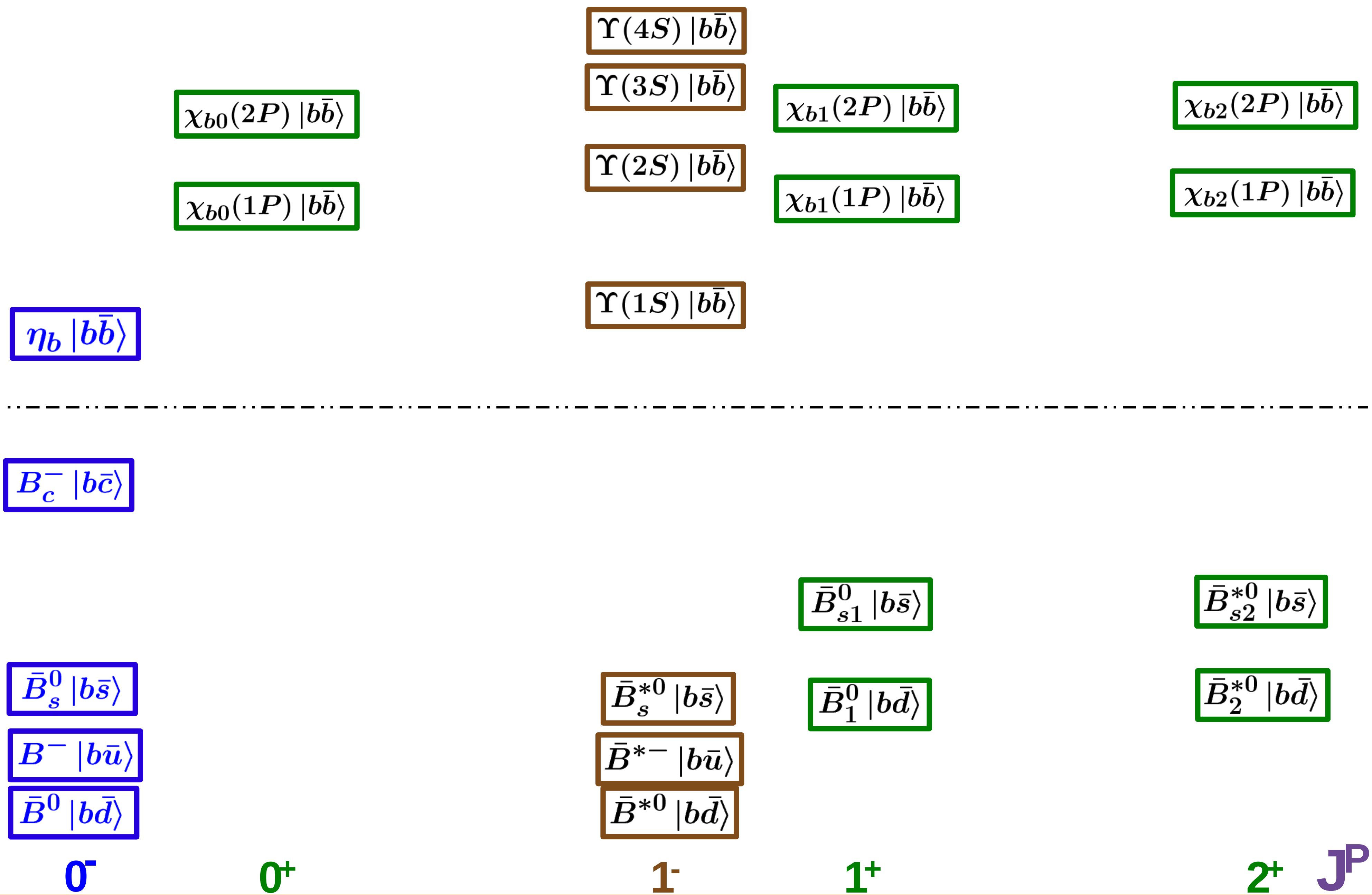


LHCb Experiment



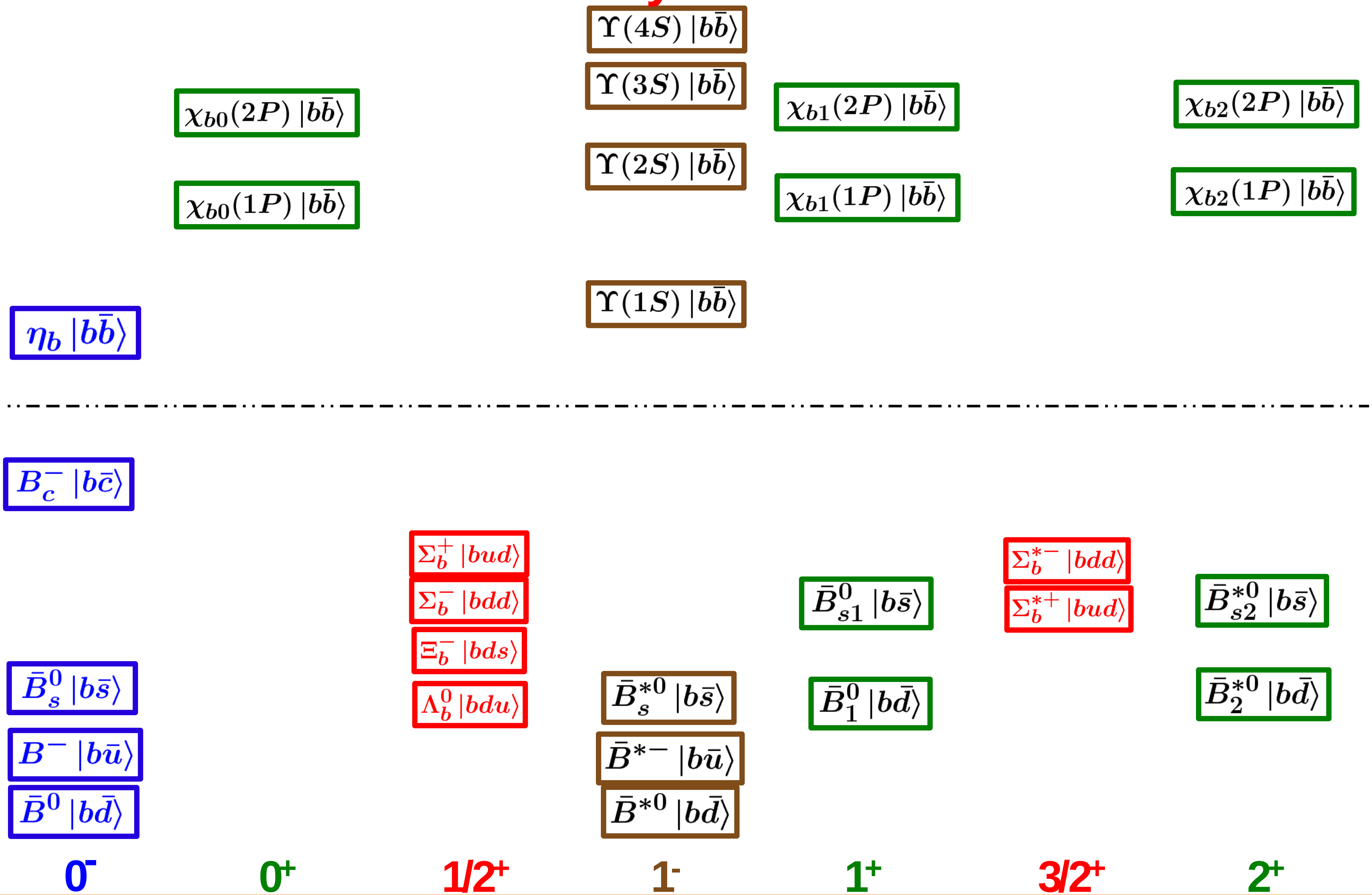
B Particle Properties

B Hadrons - Mesons



B Hadrons

- Mesons
- Baryons

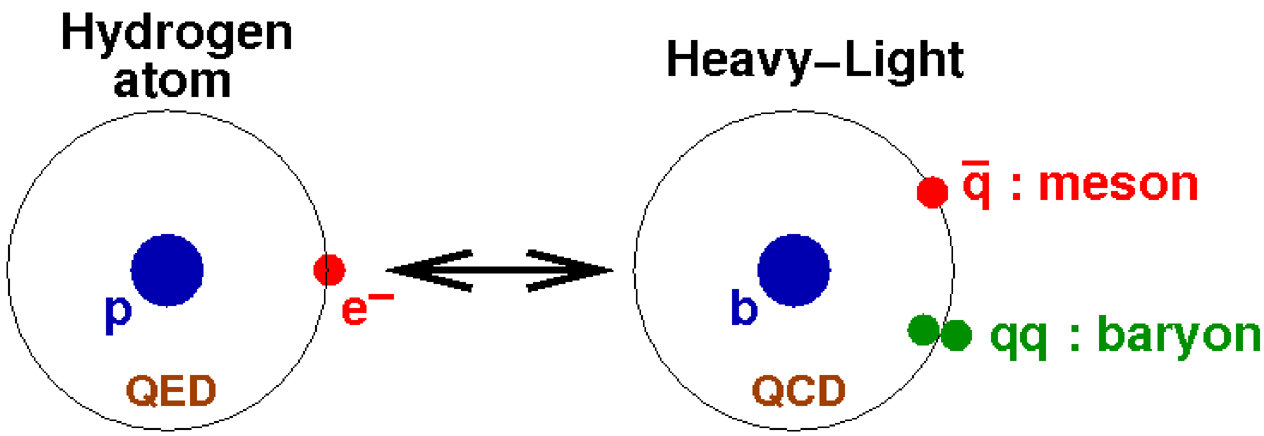


Properties

<u>Focus on:</u> **Masses, Lifetimes (Decays)**

Why study B hadrons?

From
hydrogen atom
to
B hadron
spectroscopy



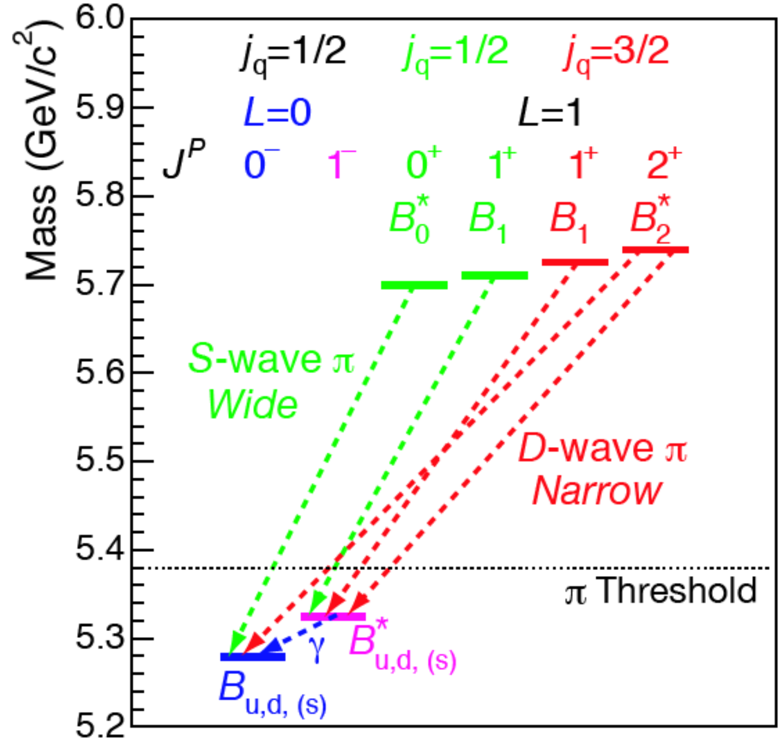
- Heavy quark hadrons are the hydrogen atom of QCD
  => study of B hadron states = study of (non-perturbative) QCD
- Measurements of B hadron masses provide sensitive tests of potential models, HQET and all aspects of QCD including lattice gauge calculations

B Meson States

- B^{**}, B_s^{**}
- B_c

B Excited States

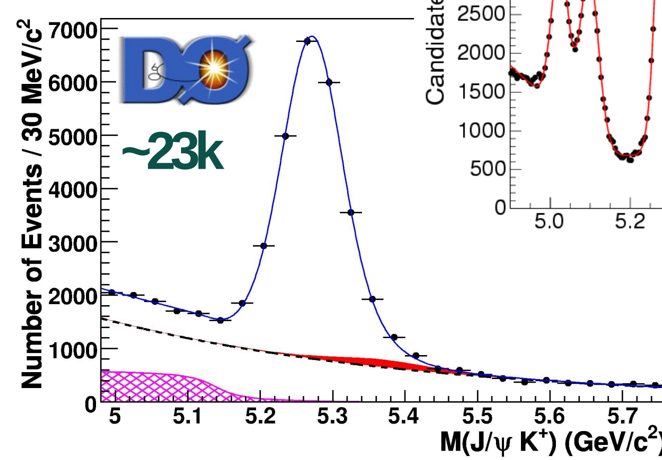
- Until ~2005 only ground states B^0, B^+, B_s or excited state B^* well established
- HQET predicts 4 P-wave states for the excited $B_{u/d}^{**}$ & B_s^{**}
  - Two decay via S-wave => wide (~100 MeV)
  - Two decay via D wave => narrow (~10 MeV)

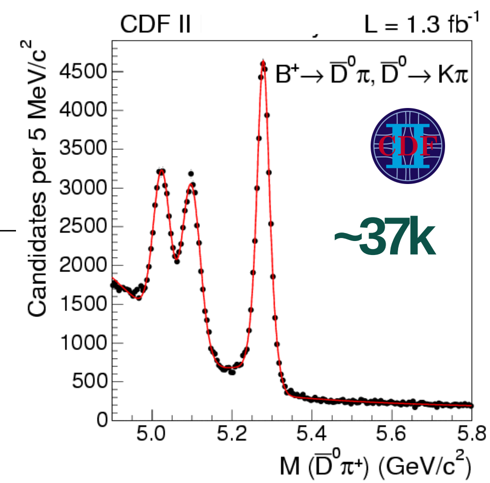


Reconstruct B in J/ψ and D^0 modes and add pion

not reconstructed

$$B_1^0 \to B^{*+}\pi^-;\ B^{*+} \to B^+\gamma$$
$$B_2^{*0} \to B^{*+}\pi^-;\ B^{*+} \to B^+\gamma$$
$$B_2^{*0} \to B^+\pi^-$$
$$B^+ \to J/\psi K^+ \qquad B^+ \to \bar{D}^0\pi^+$$
$$\hookrightarrow \mu^+\mu^-$$



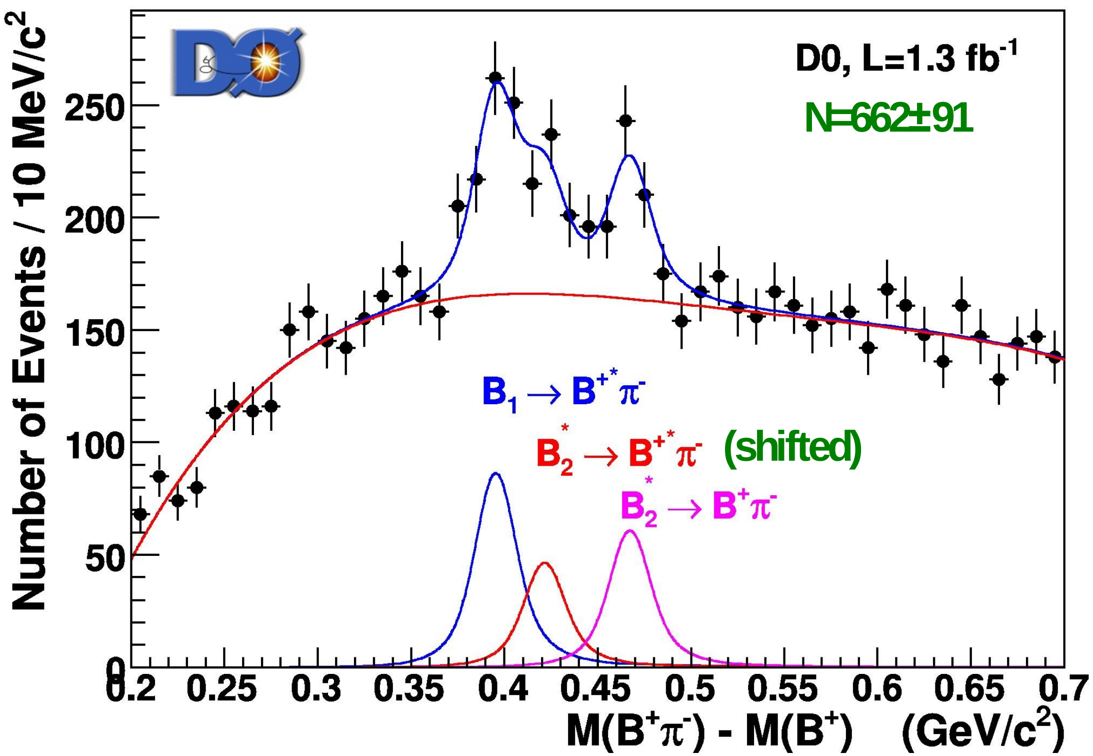


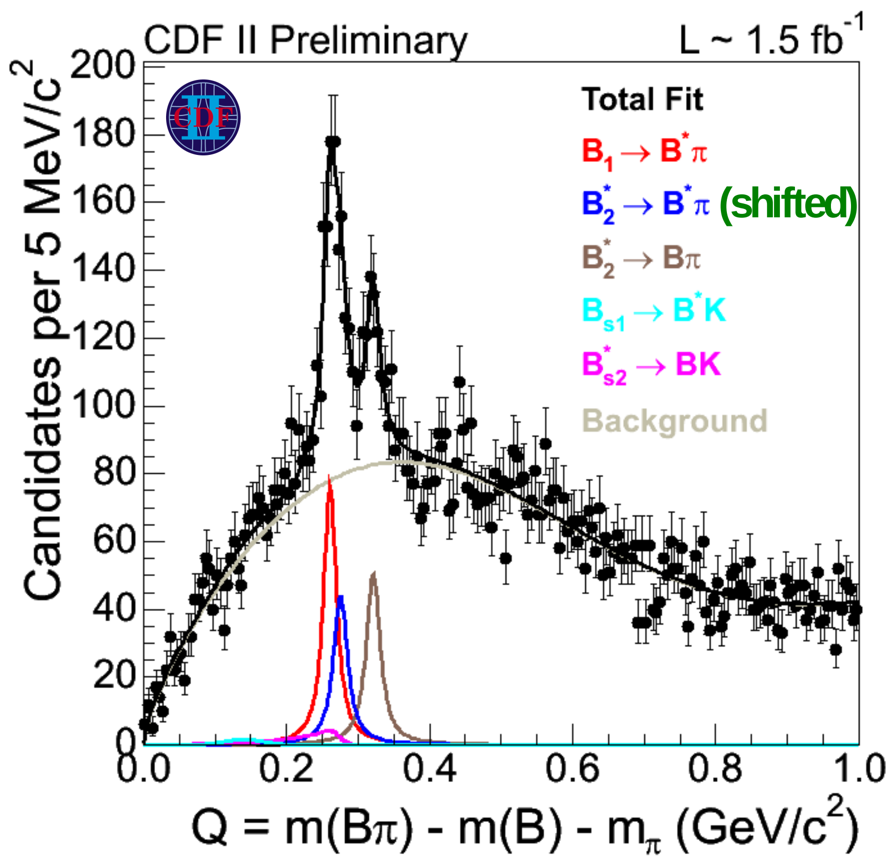
Fit mass difference

$$\Delta m(B^{**}) = m(B^{**}) - m(B) - m(\pi)$$

Narrow B_d** States

Results:





$$M(B_1) = 5720.6 \pm 2.4 \pm 1.4 \text{ MeV}$$

$$M(B_2^*) = 5746.8 \pm 2.4 \pm 1.7 \text{ MeV}$$

PRL 99, 172001 (2007)

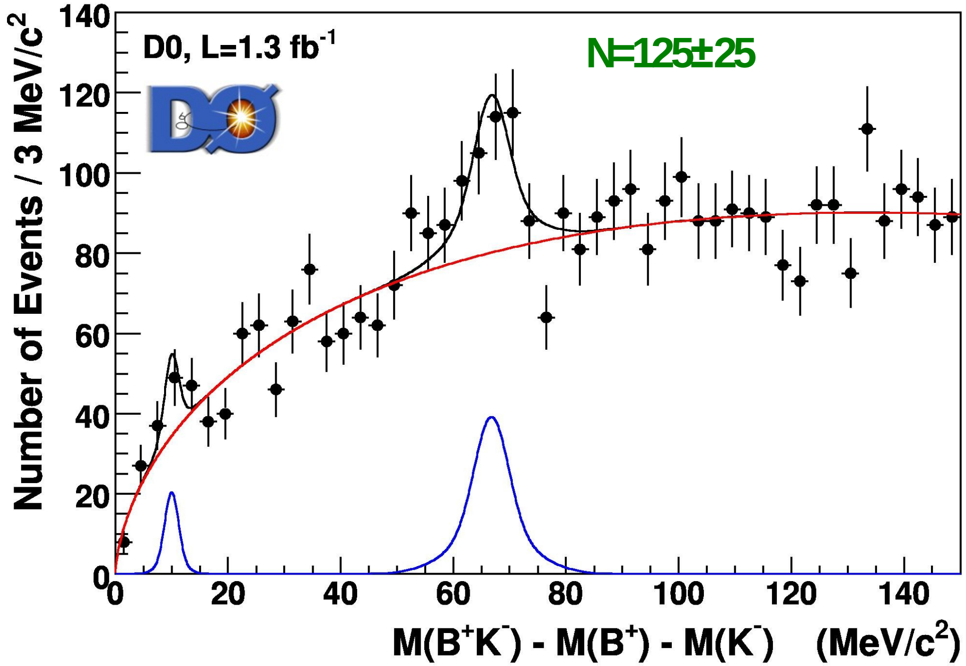
$$M(B_1^0) = 5725.3^{+1.6+0.8}_{-2.1-1.1} \text{ MeV}$$

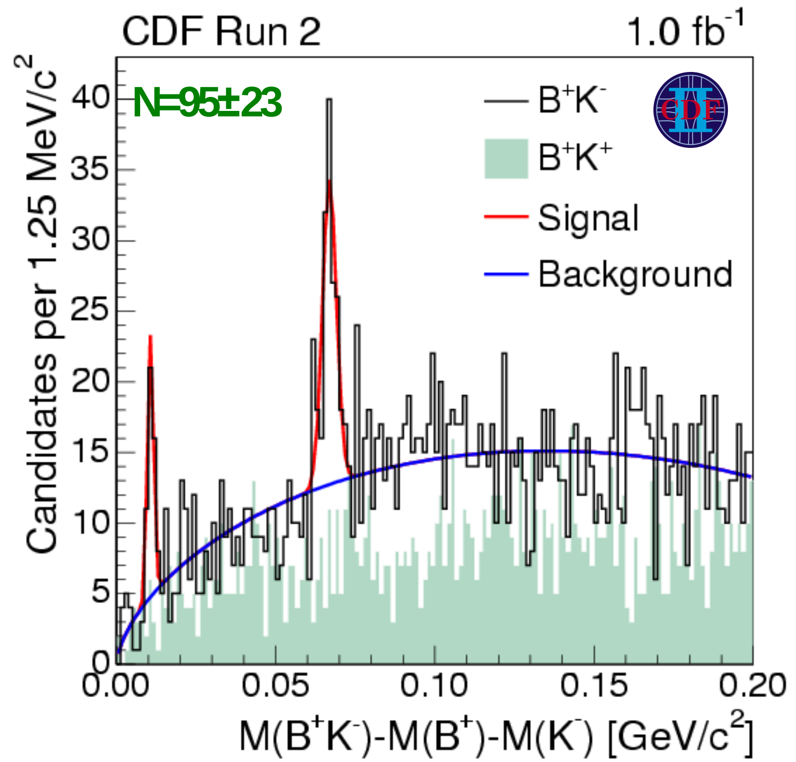
$$M(B_2^{*0}) = 5739.9^{+1.7+0.5}_{-1.8-0.6} \text{ MeV}$$

Measurements in agreement

Narrow B_s** States

- Decay B_s** to $B_s\pi$ isospin suppressed
- Reconstruct B_s** --> B^+K^- with B^+ --> $J/\psi K^+$ & B^+ --> $D^0\pi^+$





$$M(B_{s2}^*) = 5839.6 \pm 1.1 \pm 0.7\,\mathrm{MeV}$$

(B_{s1} not significant enough, < 3 σ)

PRL 100, 082002 (2008)

$$M(B_{s1}) = 5829.4 \pm 0.21 \pm 0.14 \pm 0.6\,(\mathrm{PDG})\,\mathrm{MeV}$$

$$M(B_{s2}^*) = 5839.6 \pm 0.39 \pm 0.14 \pm 0.5\,(\mathrm{PDG})\,\mathrm{MeV}$$

PRL 100, 082001 (2008)

B_c^+

B_c Meson

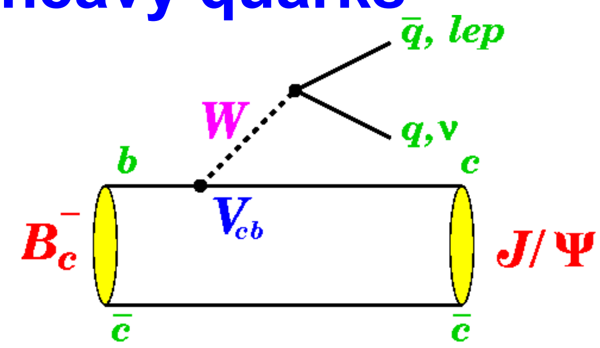
$$B_c^- = |b\,\bar{c}\rangle$$

- Weakly decaying particle which contains 2 heavy quarks
- Both quarks contribute to decay width

  - via b quark:

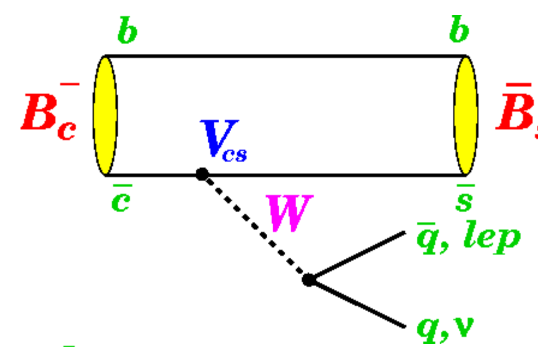
discovery mode

$$B_c^- \to J/\psi X \quad (J/\psi \pi^-, J/\psi \ell^- \nu)$$



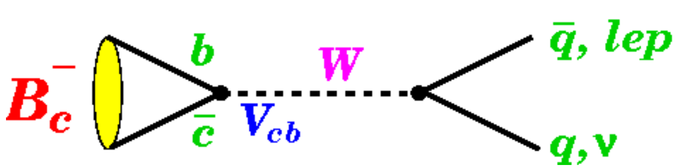
  - via c quark:

$$B_c^- \to \bar{B}_s^0 X \quad (\bar{B}_s^0 \pi^-, \ \bar{B}_s^0 \ell^- \nu)$$



  - via annihilation:

$$B_c^- \to \ell^- \nu / q\bar{q} X$$



- Theory predicts lifetime of ~0.5 ps

B_c Mass

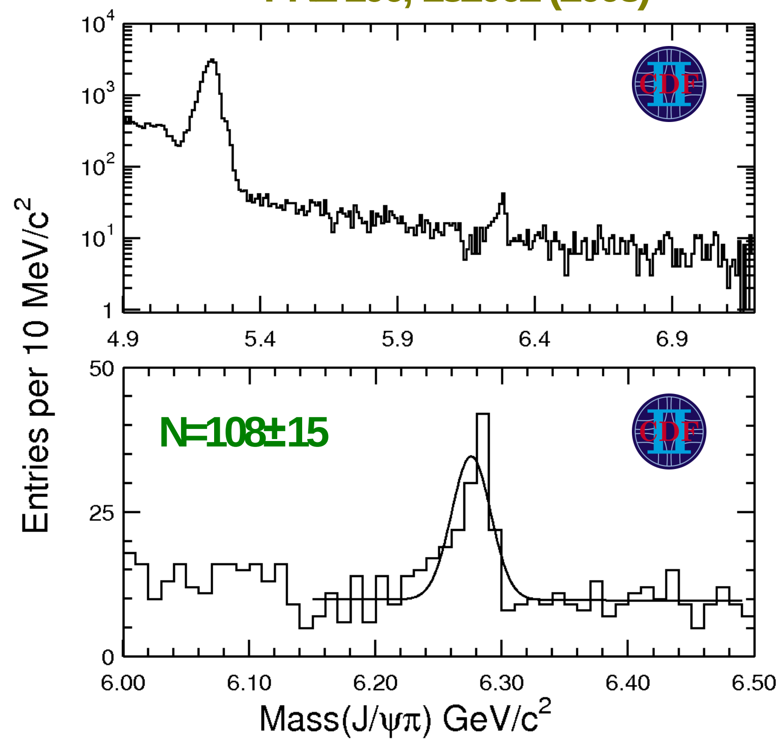
- **Use fully reconstructed**
  $$B_c^- \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\ \pi^-$$
  for precise mass measurement
- **2012 world average B_c mass:**

  $m(B_c) = (6277 \pm 6)\ \text{MeV}/c^2$

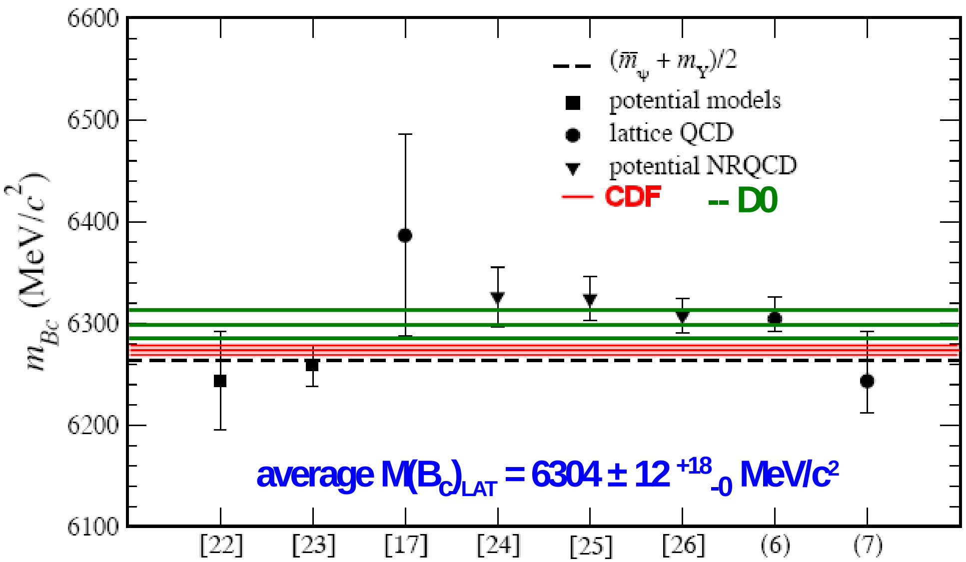
- **Comparison to predictions:**

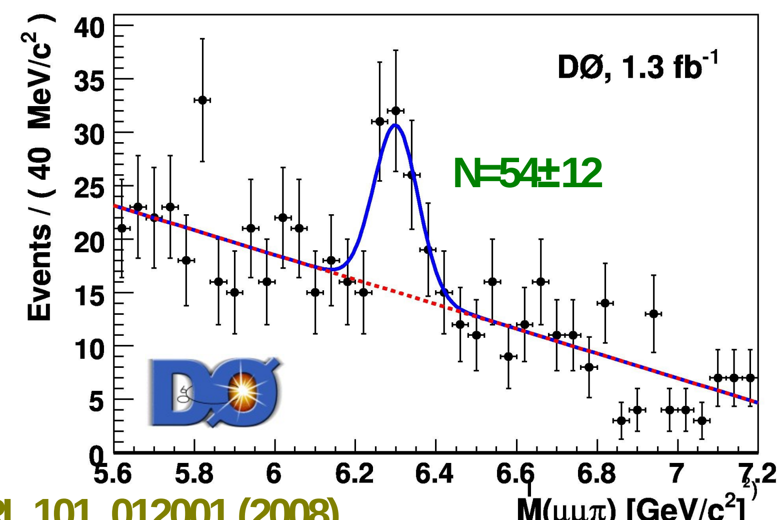
Experimental measurements with small uncertainties start to challenge theoretical models and lattice techniques

PRL 100, 182002 (2008)



$m(B_c) = (6275.6 \pm 2.9 \pm 2.5)\ \text{MeV}/c^2$





PRL 101, 012001 (2008)

$m(B_c) = (6300 \pm 14 \pm 5)\ \text{MeV}/c^2$

Bottom Baryons

Σ_b - Ξ_b - Ω_b

Heavy B Baryons

Motivation:

Until 2006 $\Lambda_b^0 = |b\,d\,u\rangle$

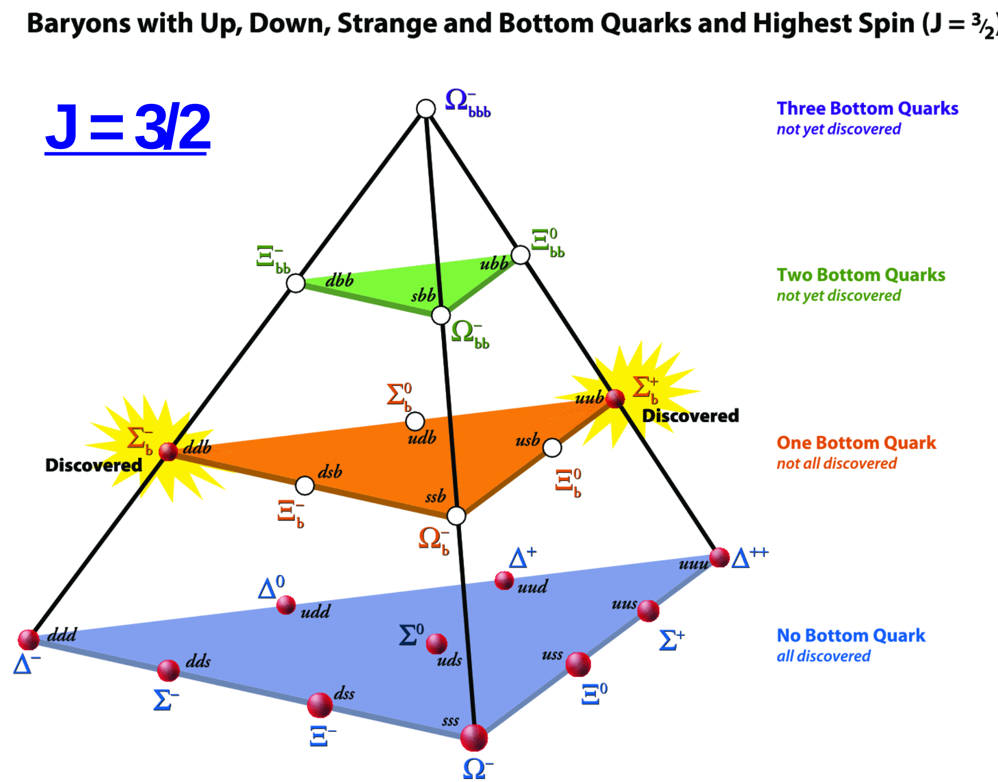
was only established *B* baryon

=> Search at Tevatron for

$$\Sigma_b^- = |b\,d\,d\rangle$$

$$\Xi_b^- = |b\,d\,s\rangle, \ \Omega_b^- = |b\,s\,s\rangle$$

J = 3/2



Example: Σ_b

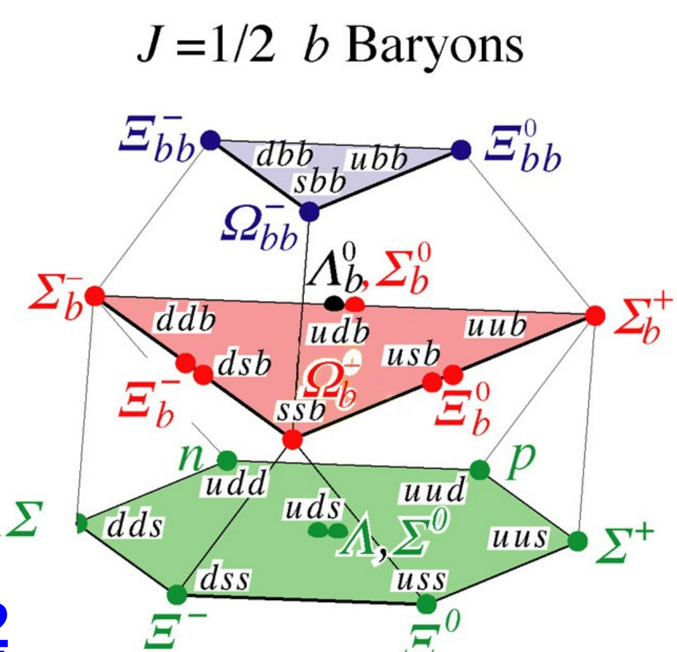
$$\Sigma_b: b\{qq\},\ q = u,d;\ J^P = S_Q + s_{qq}$$

$= 3/2^+$ (Σ_b^*)

$= 1/2^+$ (Σ_b)

H-atom: spin-spin interaction

= hyperfine splitting



J = 1/2

Σ_b Baryon

Searching for:

$$\Sigma_b^{(*)+} = |b\,u\,u\rangle \qquad \Sigma_b^{(*)-} = |b\,d\,d\rangle$$

$$\Sigma_b^{(*)0} = |b\,u\,d\rangle \qquad \Sigma_b^{(*)0} \rightarrow \Lambda_b^0\,\pi^0$$

← difficult for hadron collider

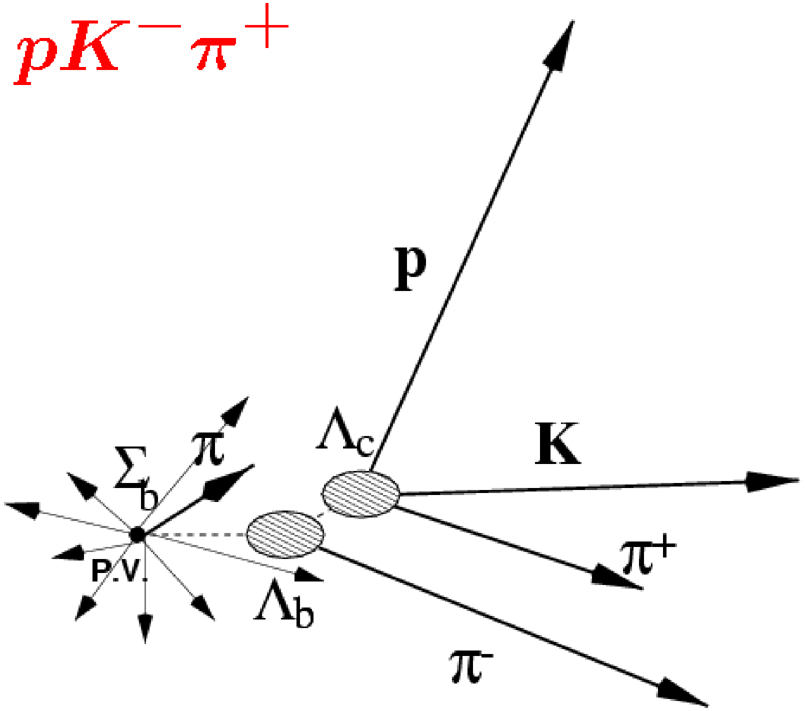
Search Strategy:

Use CDF two-track trigger to reconstruct:

$$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0\,\pi^\pm$$

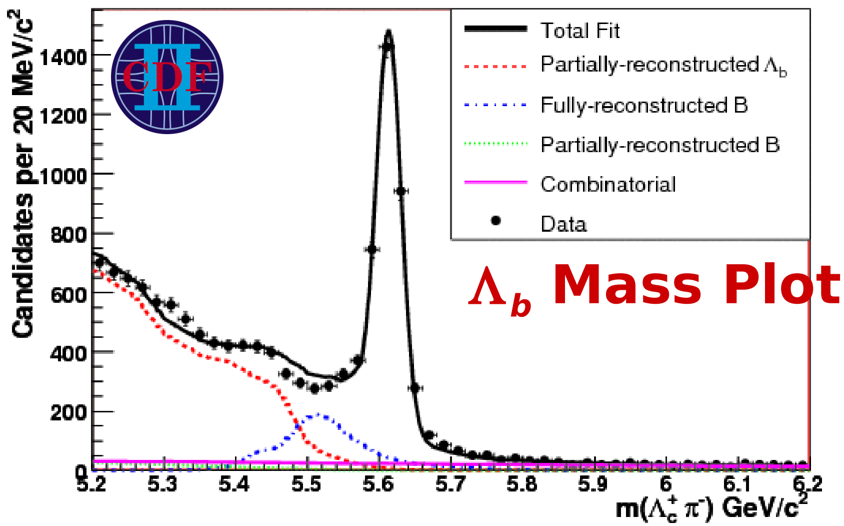
$$\hookrightarrow \Lambda_c^+\pi^-; \quad \Lambda_c^+ \rightarrow pK^-\pi^+$$

- Σ_b decays at primary vertex
- Combine Λ_b with a prompt track to form a Σ_b candidate
- **Separate Σ_b^- and Σ_b^+**

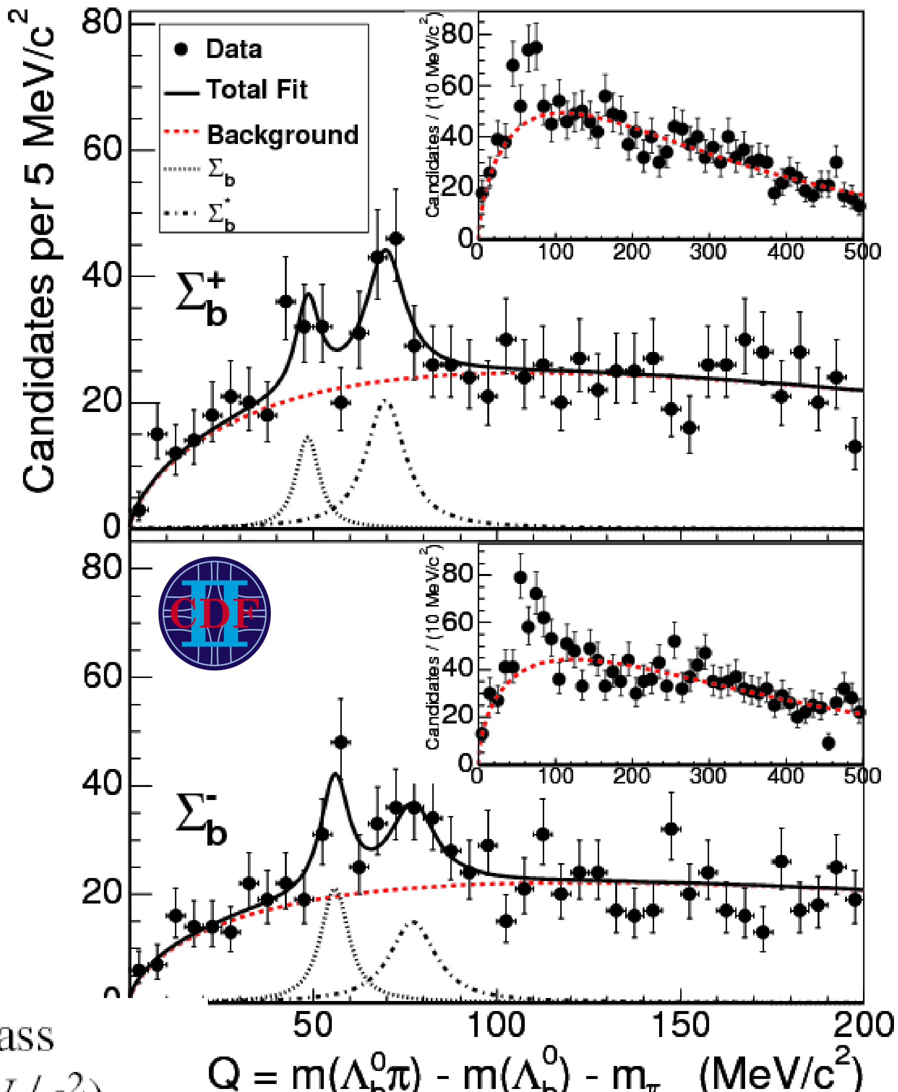


Σ_b Baryon

CDF uses large sample of Λ_b: ~3000



Λ_b Mass Plot



Observe peaks with >5σ w.r.t. no signal

PRL 99, 202001 (2007)

State	Yield	Q or $\Delta_{\Sigma_b^*}$ (MeV/c^2)	Mass (MeV/c^2)
Σ_b^+	32^{+13+5}_{-12-3}	$Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}$	$5807.8^{+2.0}_{-2.2} \pm 1.7$
Σ_b^-	59^{+15+9}_{-14-4}	$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2$	$5815.2 \pm 1.0 \pm 1.7$
Σ_b^{*+}	77^{+17+10}_{-16-6}	$\Delta_{\Sigma_b^*} = 21.2^{+2.0+0.4}_{-1.9-0.3}$	$5829.0^{+1.6+1.7}_{-1.8-1.8}$
Σ_b^{*-}	69^{+18+16}_{-17-5}		$5836.4 \pm 2.0^{+1.8}_{-1.7}$

Ξ_b^- Baryon

Possible decay modes:

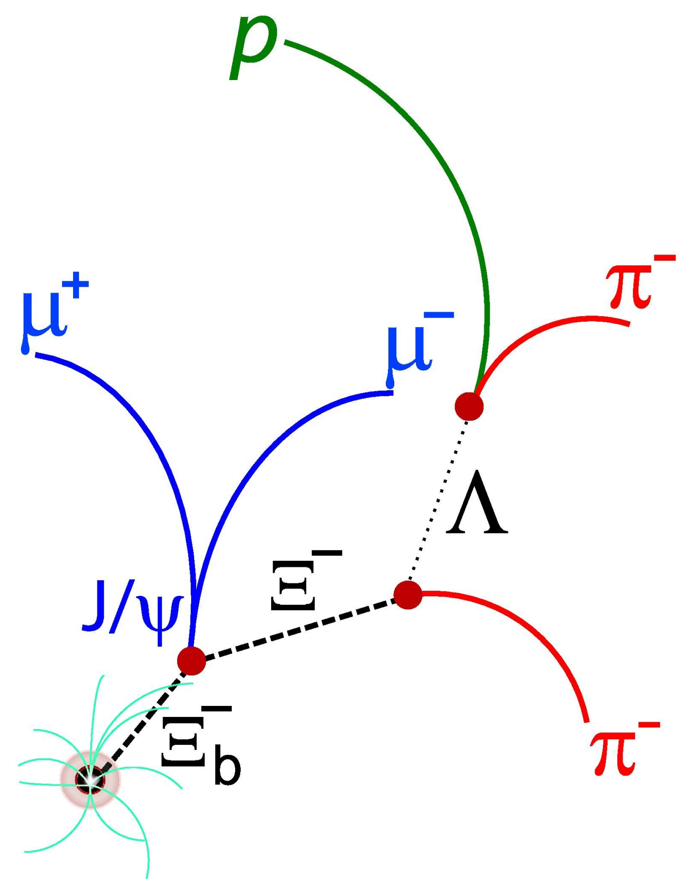
$$\Xi_b^- = |b\,d\,s\rangle \qquad \Xi_b^- \to J/\psi\Xi^-$$
$$\Xi_b^0 = |b\,u\,s\rangle \qquad \Xi_b^0 \to \Xi_c^0\pi^0,\quad J/\psi\Xi^0\,(\Lambda\pi^0)$$

difficult for hadron collider

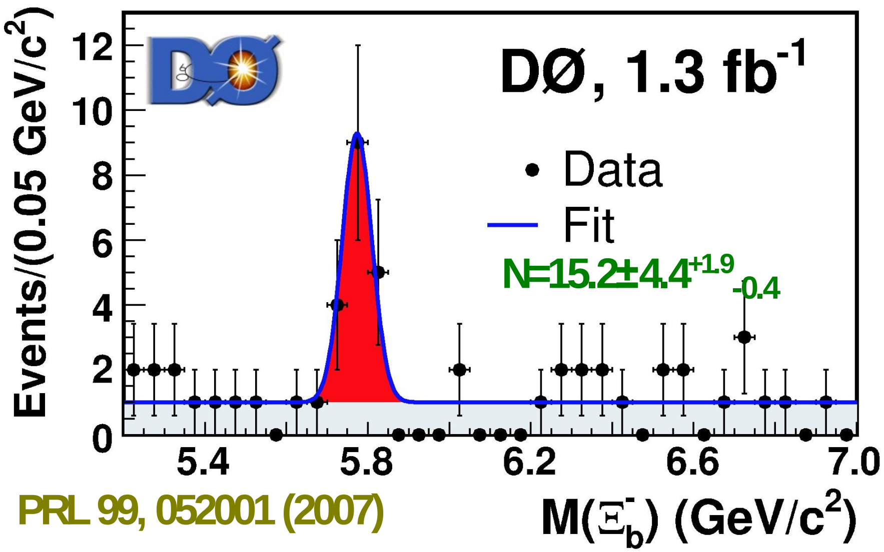
Search for Ξ_b:

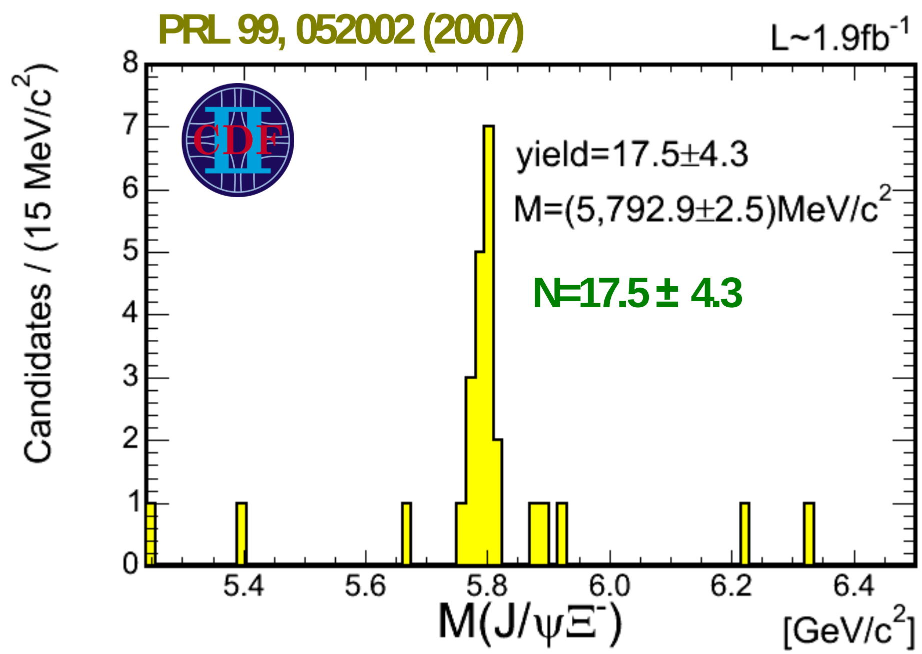
- Decays weakly through b-quark decay
  Expect lifetime similar to B lifetime
  (DELPHI: 1.4 ± 0.3 ps)
- Reconstruct at Tevatron

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



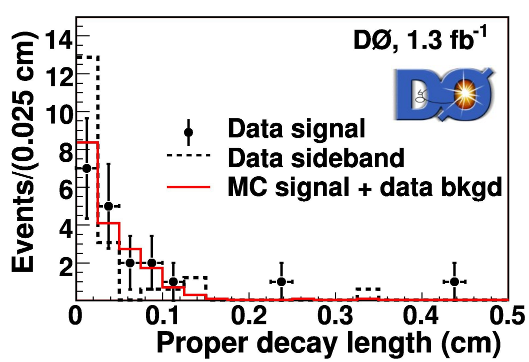
Ξ_b^- Baryon

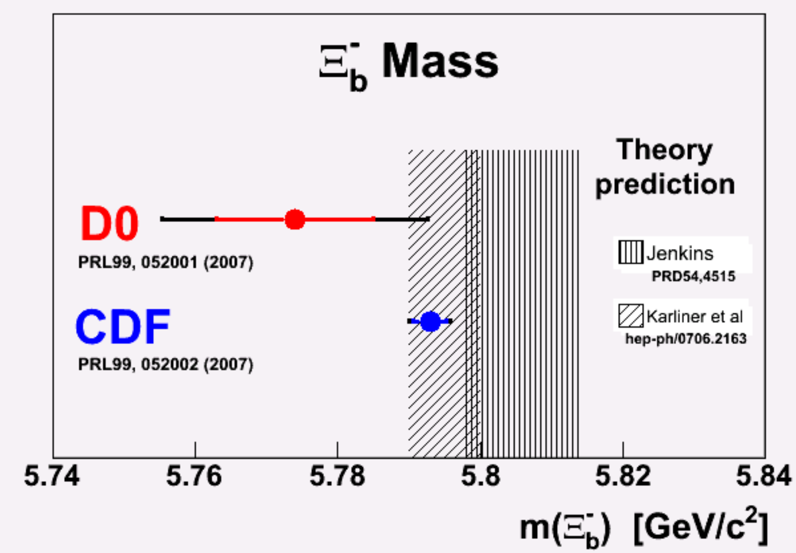




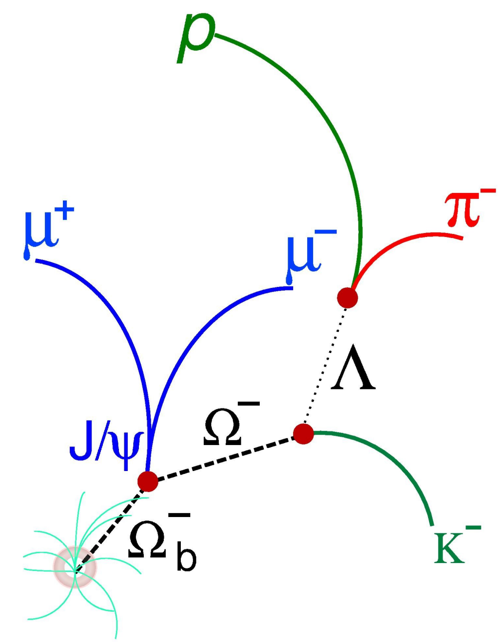
Both experiments see significant Ξ_b signals (D0: 5.5σ, CDF: 7.7σ)

- CDF: $m(\Xi_b) = (5792.9 \pm 2.5 \pm 1.7)$ MeV/c^2
- D0: $m(\Xi_b) = (5774 \pm 11 \pm 15)$ MeV/c^2
- 2011 World avg: $M(\Xi_b) = 5790.5 \pm 2.7$ MeV/c^2
- D0: Lifetime consistent with expectations



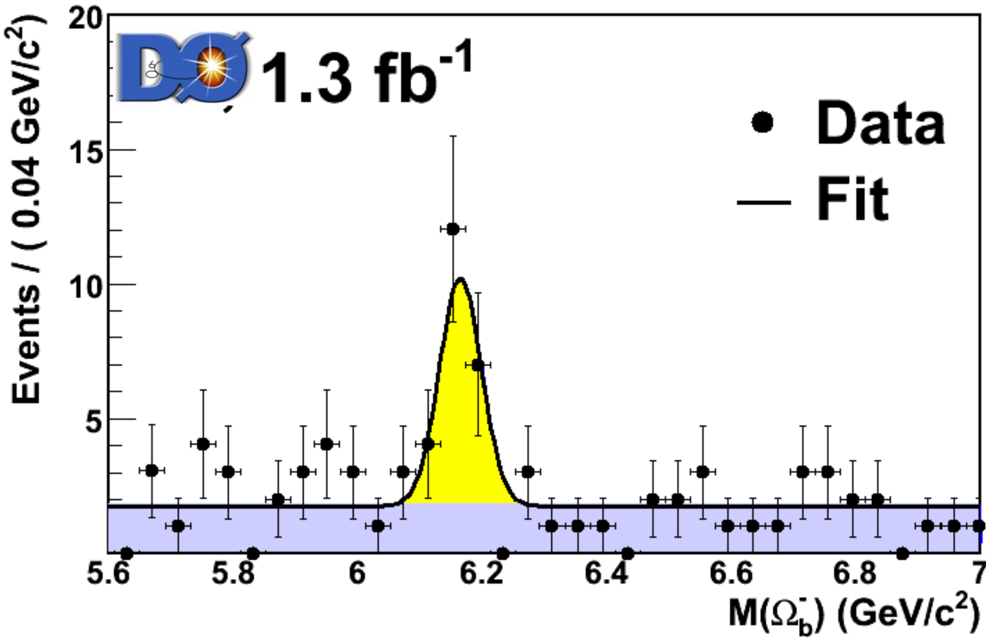


Ω_b Baryon

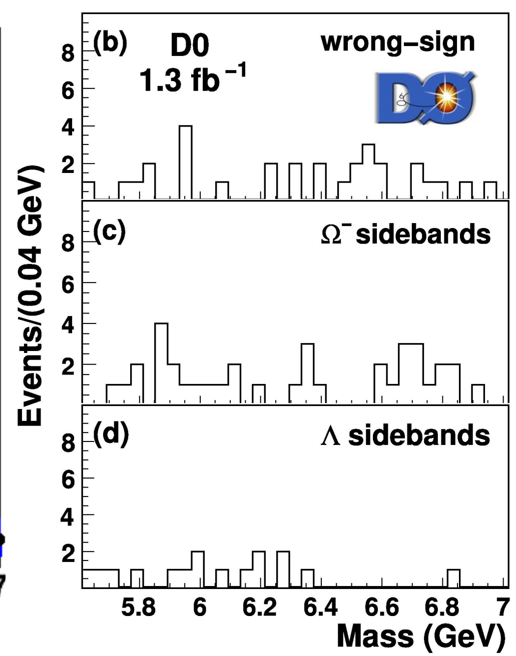


- Observation by D0 in Aug'08 with 1.3 fb^{-1} data
  (Builds on previous observation of Ξ_b)
- Observe 17.8 ± 4.9 ± 0.8 events
- Report signal significance: 5.4σ
- $m(\Omega_b) = (6165 \pm 10 \pm 13)$ MeV/c^2

  (expect 5.94-6.12 GeV/c^2)
- $$\frac{f(b \to \Omega_b^-)B(\Omega_b^- \to J/\psi\Omega^-)}{f(b \to \Xi_b^-)B(\Xi_b^- \to J/\psi\Xi^-)} = 0.80 \pm 0.32^{+0.14}_{-0.22}$$



PRL 99, 052001 (2007)



Ω_b Baryon

CDF 2009

- Comprehensive reconstruction of bottom baryons into J/ψ

$$\Lambda_b^0 \to J/\psi\,\Lambda; \quad \Lambda \to p\pi^-; \quad J/\psi \to \mu^+\mu^-$$

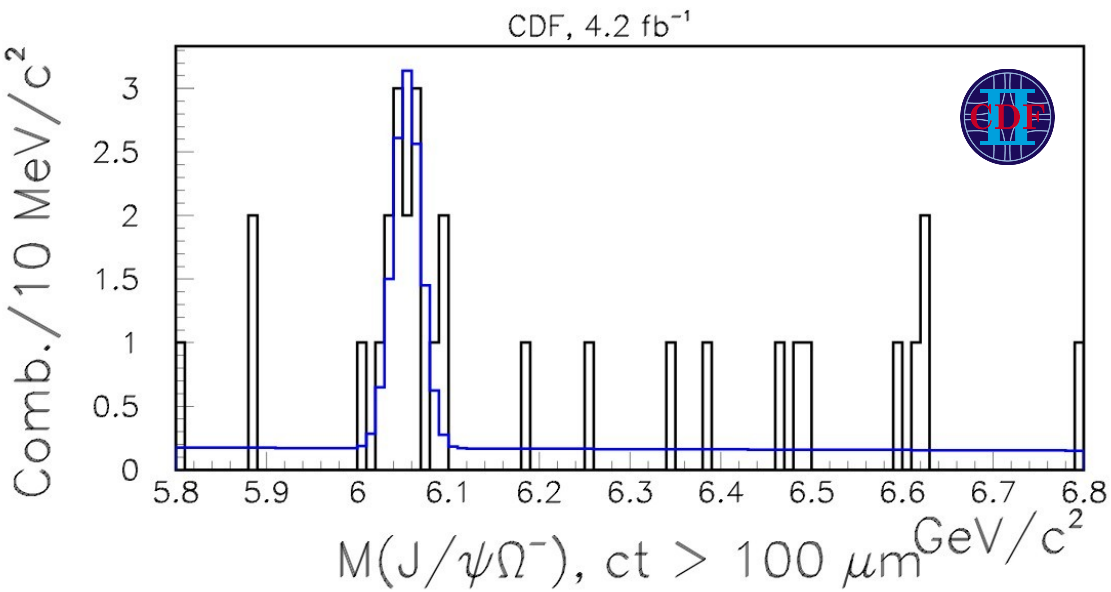
$$\Xi_b^- \to J/\psi\,\Xi^-; \quad \Xi^- \to \Lambda\pi^-$$

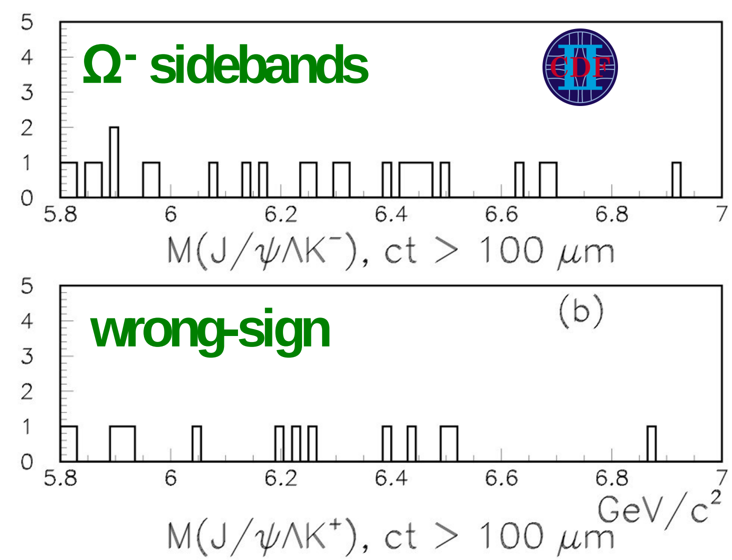
$$\Omega_b^- \to J/\psi\,\Omega^-; \quad \Omega^- \to \Lambda K^-$$

- Measurement of B^0 properties provides cross check:

$$B^0 \to J/\psi\,K^{*0} \quad \& \quad B^0 \to J/\psi\,K_S^0$$

- Observe structure of 16 signal events in J/ψ Ω with 5.5σ signif.





Ω_b Baryon

- CDF observes Ω_b Baryon
- Relative rate measurement (assume kinematics identical to Λ_b)

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

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

- Summary of mass measurement

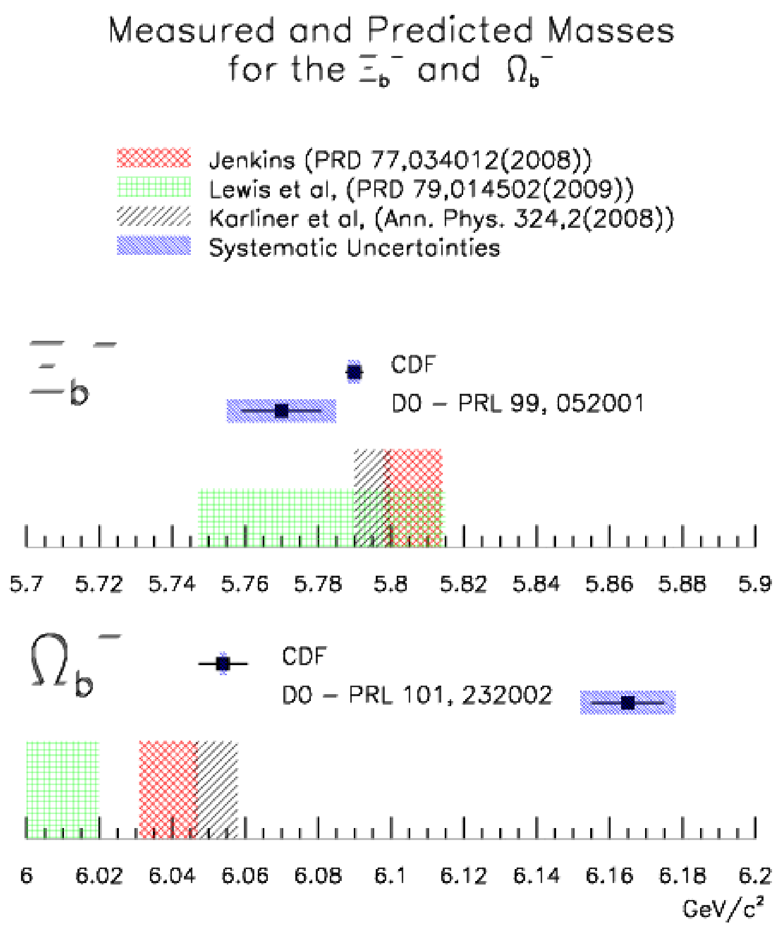
$$m(\Xi_b^-) = (5790.9 \pm 2.6 \pm 0.9)\ \mathrm{MeV}/c^2$$
$$m(\Omega_b^-) = (6054.4 \pm 6.8 \pm 0.9)\ \mathrm{MeV}/c^2$$

- Summary of lifetime measurement

$$\tau(\Xi_b^-) = (1.56^{+0.27}_{-0.25} \pm 0.02)\ \mathrm{ps}$$ <-- First fully rec.

$$\tau(\Omega_b^-) = (1.13^{+0.53}_{-0.40} \pm 0.02)\ \mathrm{ps}$$ <-- First !

Ω_b Baryon



Comparison with D0 result:

- D0: $m(\Omega_b) = (6165 \pm 10 \pm 13)$ MeV/c^2

  $\Rightarrow \Delta m = (111 \pm 12 \pm 14)$ MeV/c^2

Significant disagreement !

Rate measurements:

D0:
$$\frac{f(b \to \Omega_b^-) B(\Omega_b^- \to J/\psi \Omega^-)}{f(b \to \Xi_b^-) B(\Xi_b^- \to J/\psi \Xi^-)} = 0.80 \pm 0.32^{+0.14}_{-0.22}$$

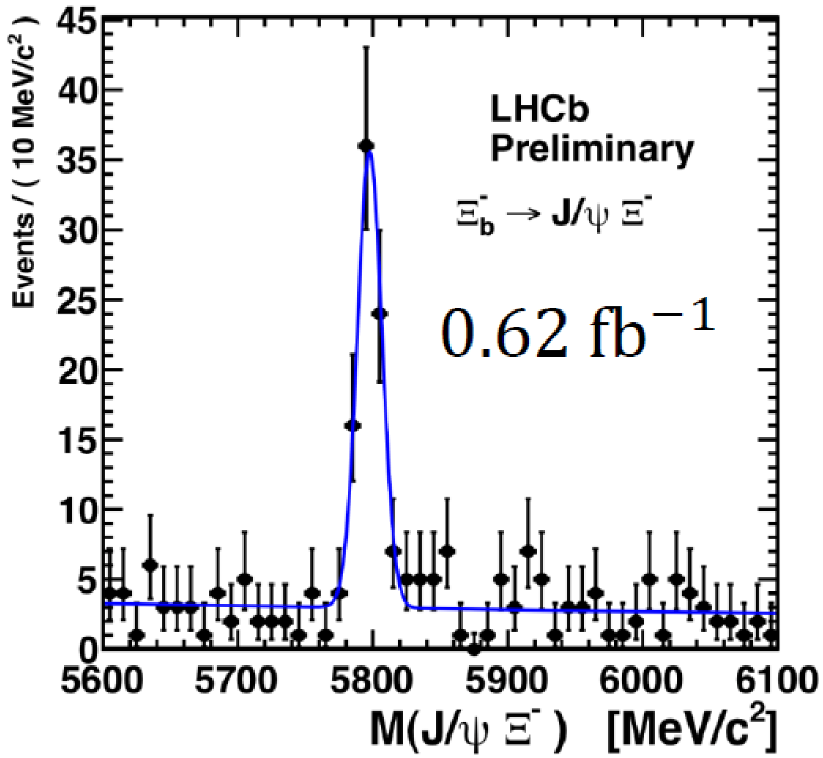
CDF:
$$\frac{\sigma B(\Omega_b^- \to J/\psi \Omega^-)}{\sigma B(\Xi_b^- \to J/\psi \Xi^-)} = 0.27 \pm 0.12 \pm 0.01$$

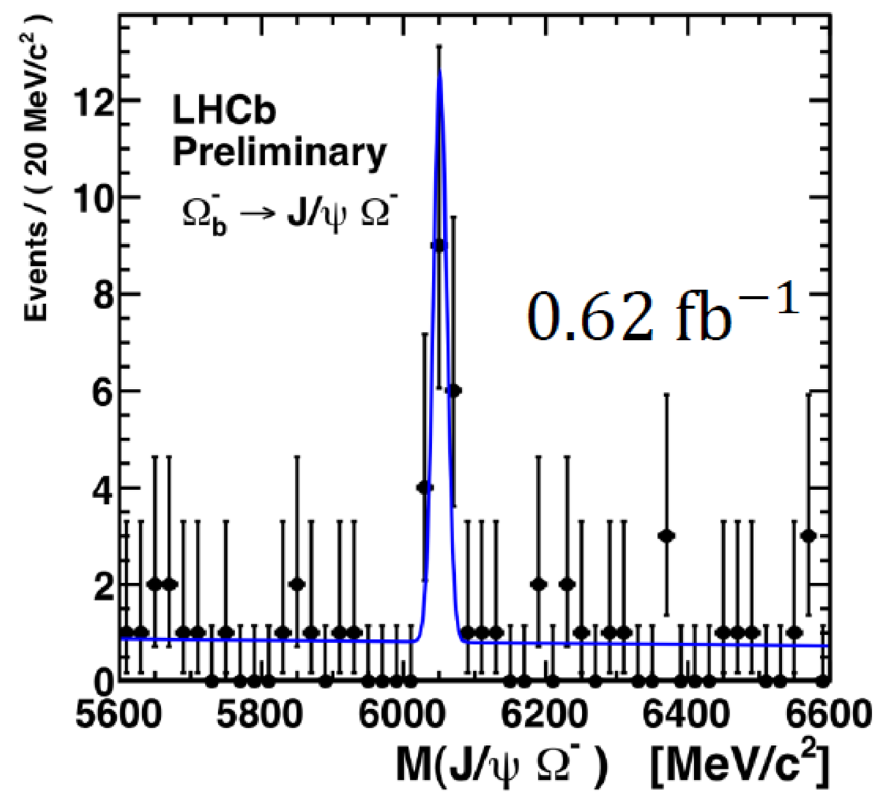
In agreement ?

Resolved by LHCb?

Ξ_b^- and Ω_b Baryons from LHCb

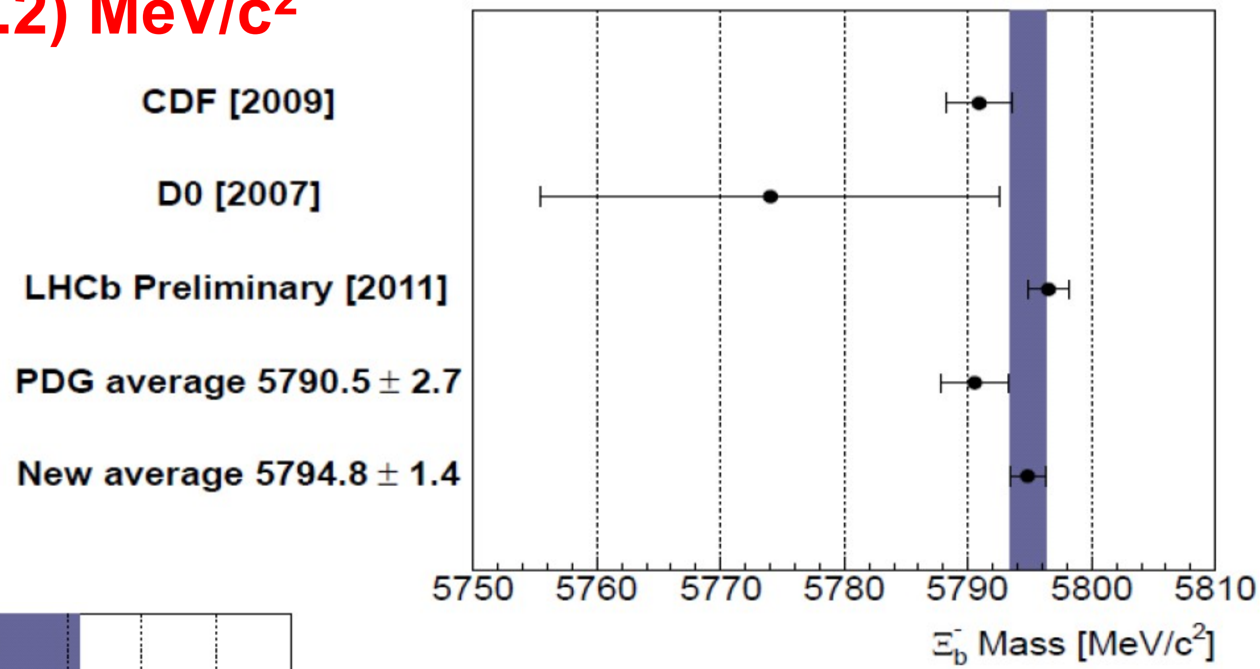
- Based on data of $0.62\ \text{fb}^{-1}$ collected in 2011
- Reconstructed modes
  - $\Xi_b^- \to J/\psi(\mu^+\mu^-)\Xi^-(\Lambda(p\pi^-)\pi^-)$ $\quad N_{\text{sig}} = 72.2 \pm 9.4$
  - $\Omega_b^- \to J/\psi(\mu^+\mu^-)\Omega^-(\Lambda(p\pi^-)K^-)$ $\quad N_{\text{sig}} = 13.9^{+4.5}_{-3.8}$
- Decay time cuts used to suppress background

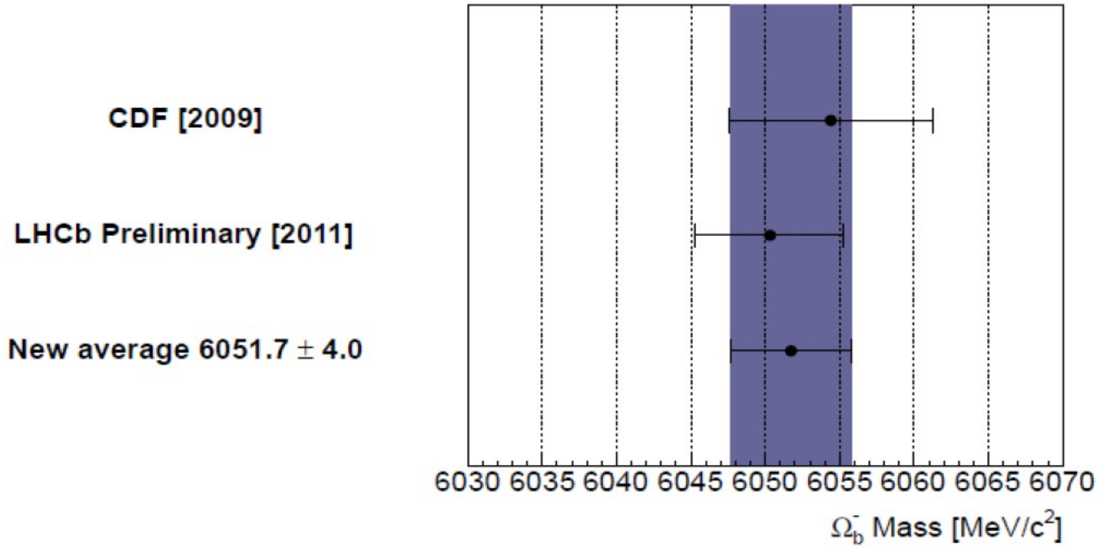




Ξ_b^- and Ω_b Baryons from LHCb

$m(\Xi_b) = (5796.5 \pm 1.2 \pm 1.2)$ MeV/c^2





LHCb:

$m(\Omega_b) = (6050 \pm 5 \pm 2)$ MeV/c^2

LHCb agrees with CDF

Ξ_b^0 Baryon

Observed by CDF in 2011:

- $\Xi_b^- = |b\,d\,s\rangle \qquad \Xi_b^- \to J/\psi\,\Xi^-$
  $\Xi_b^0 = |b\,u\,s\rangle \qquad \Xi_b^0 \to \Xi_c^0 \pi^0, \quad J/\psi\,\Xi^0\,(\Lambda\pi^0)$

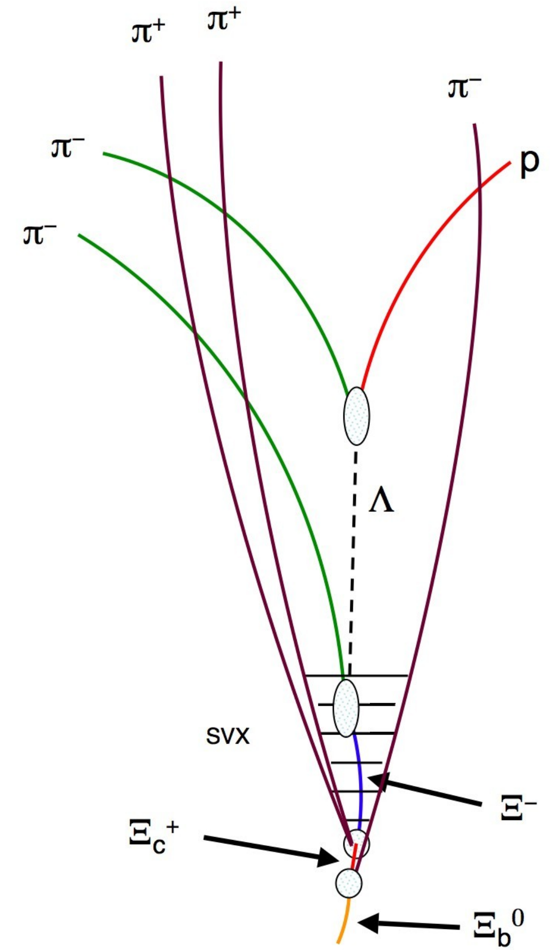
difficult for hadron collider

- CDF uses hadronic track trigger data (4.2/fb) to reconstruct:

$$\Xi_b^0 \to \Xi_c^+\pi^-, \quad \Xi_c^+ \to \Xi^-\pi^+\pi^+,$$
$$\Xi^- \to \Lambda^0\pi^+, \quad \Lambda^0 \to p\pi^-$$

- Also reconstruct as cross check:

$$\Xi_b^- \to \Xi_c^0\pi^-, \quad \Xi_c^0 \to \Xi^-\pi^+,$$
$$\Xi^- \to \Lambda^0\pi^+, \quad \Lambda^0 \to p\pi^-$$



$\Xi_b{}^0$ Baryon

Observed by CDF in 2011:

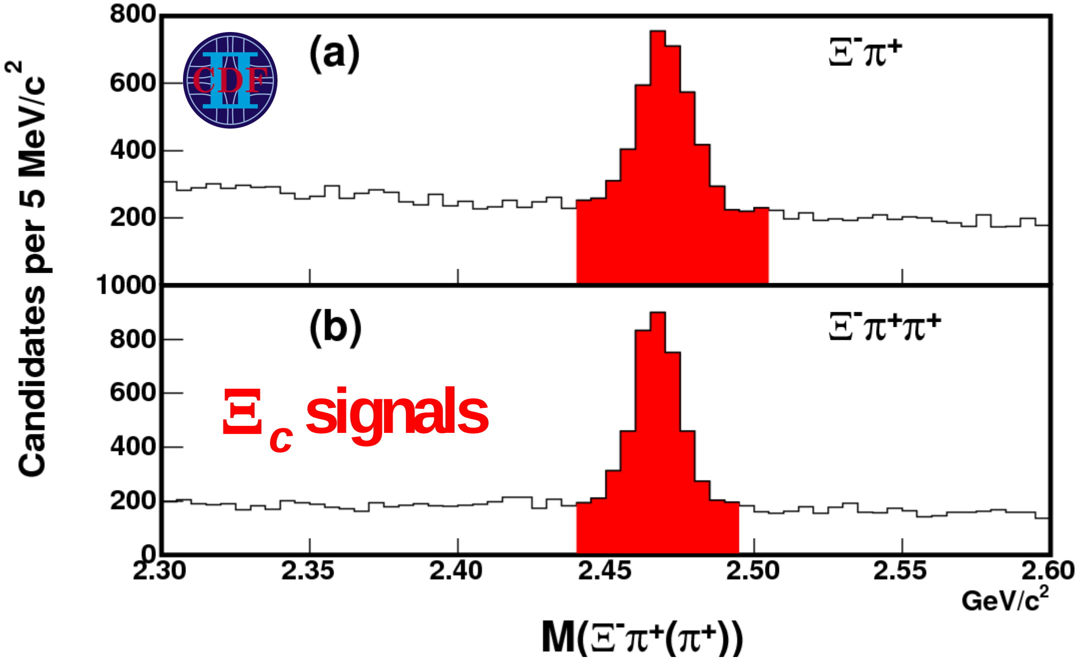
- Mass measurements:

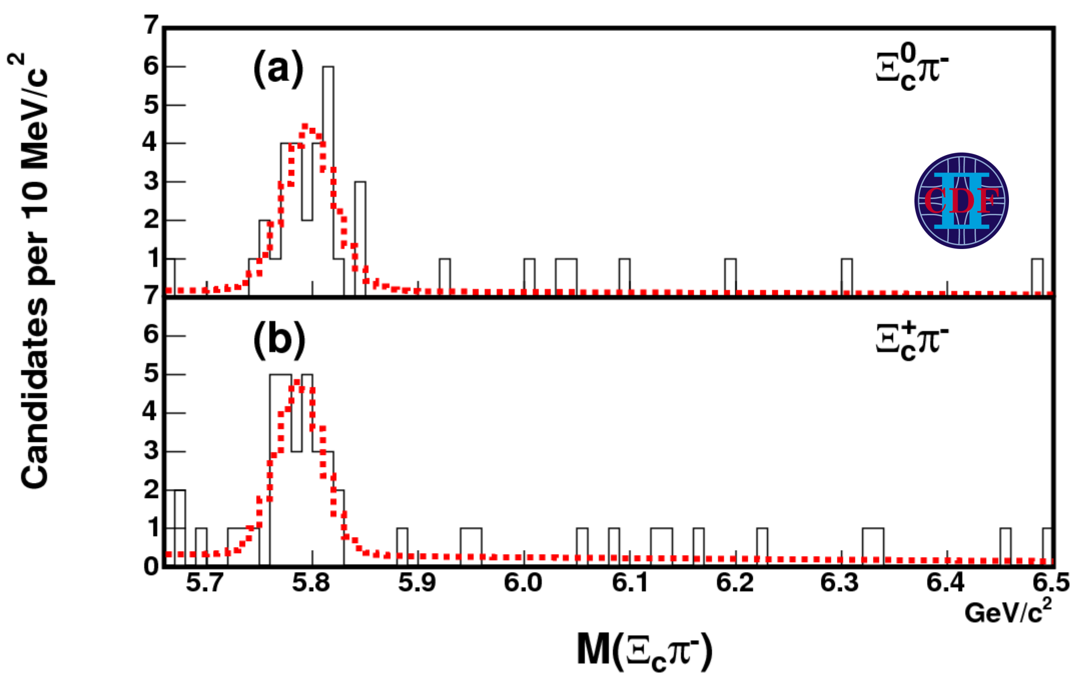
$$m(\Xi_b^0) = (5787.8 \pm 5.0 \pm 1.3)\ \mathrm{MeV}/c^2$$

$$m(\Xi_b^-) = (5796.7 \pm 5.1 \pm 1.4)\ \mathrm{MeV}/c^2$$

$$m(\Xi_b^-) - m(\Xi_b^0) = (3.1 \pm 5.6 \pm 1.3)\ \mathrm{MeV}/c^2$$

Using 2009 mass of Ξ_b^-

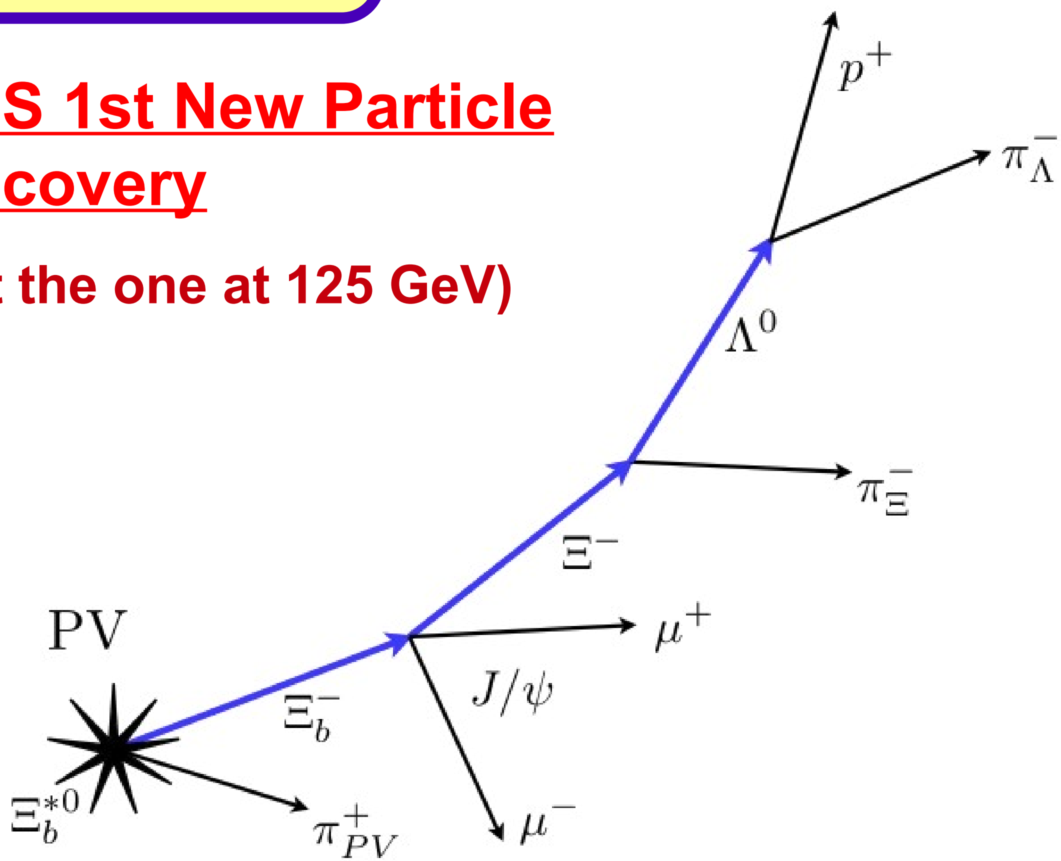


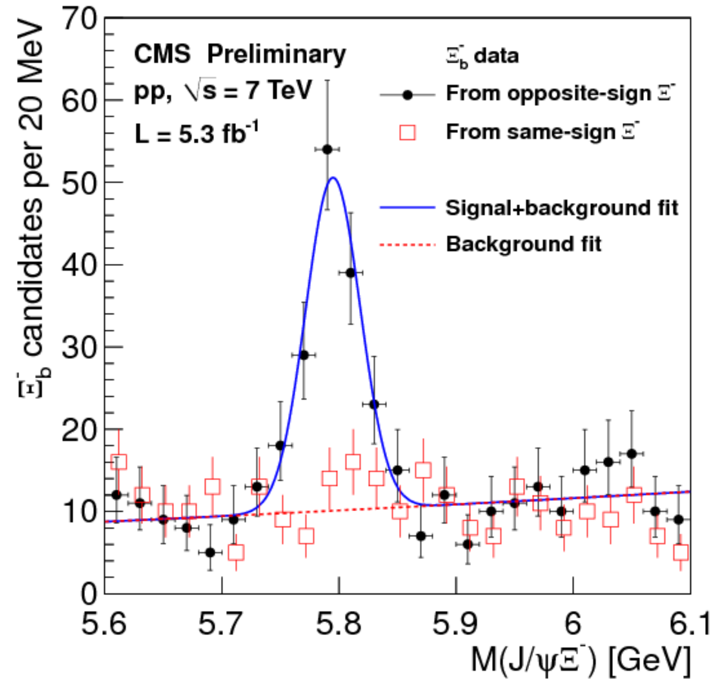


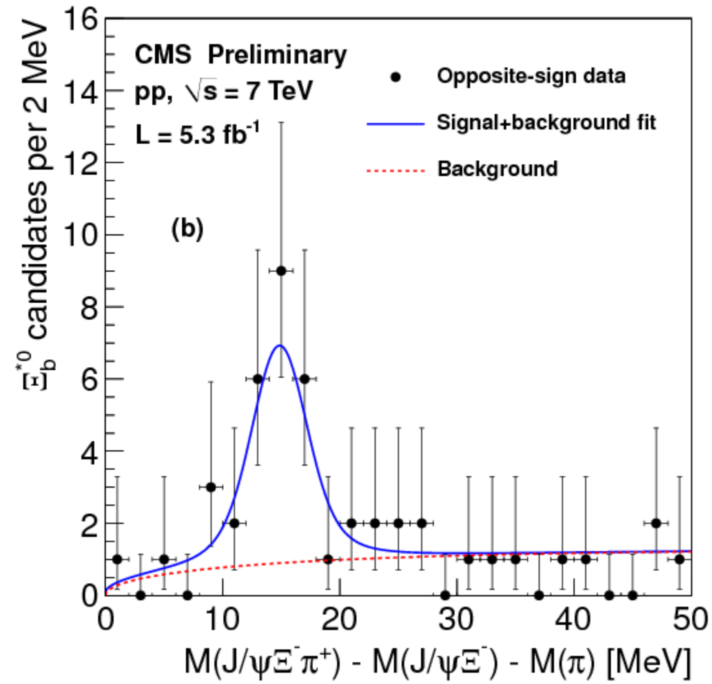
Ξ_b^{0*} Baryon

CMS 1st New Particle Discovery

(not the one at 125 GeV)



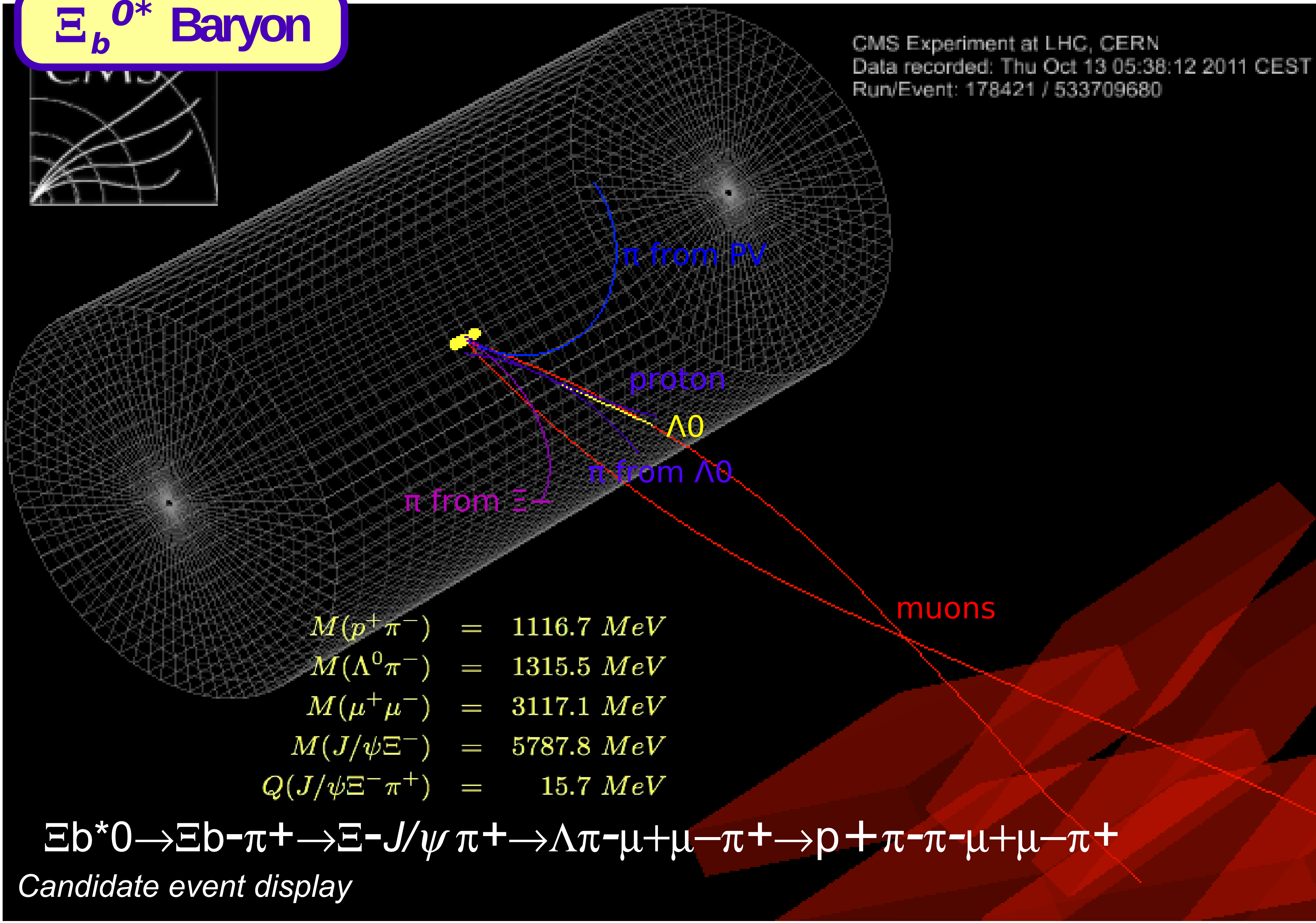




$\Xi b^{*}0 \rightarrow \Xi b^{-}\pi^{+} \rightarrow \Xi^{-} J/\psi\, \pi^{+}$

$\rightarrow \Lambda\pi^{-}\mu^{+}\mu^{-}\pi^{+} \rightarrow p+\pi^{-}\pi^{-}\mu^{+}\mu^{-}\pi^{+}$

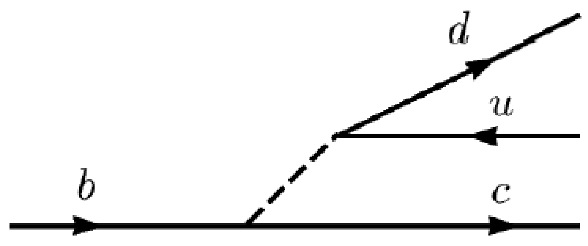
Ξ_b^{0*} Baryon



Candidate event display

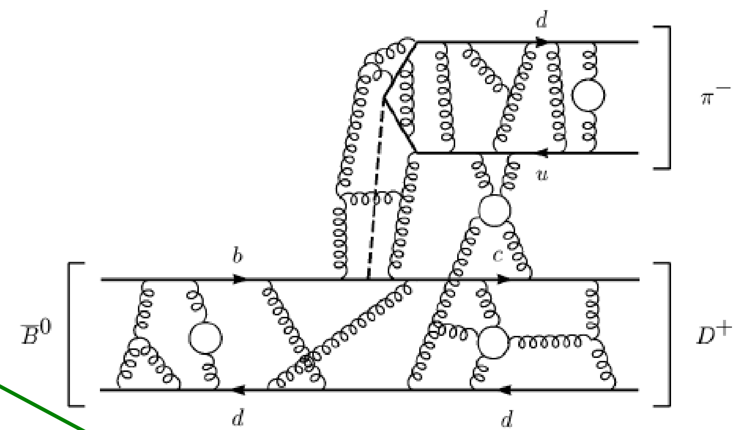
B Hadron Lifetimes

B Hadron Lifetimes



- Spectator model: *b* quark decays like free particle
  => All *B* hadron lifetimes are equal !
- In Reality: QCD => Lifetimes of *B* hadrons study interplay between strong and weak interaction
- Heavy quark expansion predicts *B* lifetimes:

$$\Gamma_B = |V_{CKM}|^2 \sum_n c_n^{(f)} \left(\frac{\Lambda_{QCD}}{m_b}\right)^n \langle H_b | O_n | H_b \rangle$$



$\mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)^2$ meson vs baryon

$\mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)^3$ spectator effects (B^0 vs B^+ vs B^0_s)

non-perturbative effects
(sum rules, OPE, lattice)

<u>Allow for precise predictions:</u>

(e.g. Bigi, Uraltsev; Tarantino;
Gabbiani, Onishchenko, Petrov; Lenz, Nierste)

$$\frac{\tau(B^+)}{\tau(B^0)} = 1.06 \pm 0.02 \qquad \frac{\tau(B^0_s)}{\tau(B^0)} = 1.00 \pm 0.01 \qquad \frac{\tau(\Lambda_b^0)}{\tau(B^0)} = [\,(0.88 \pm 0.05), 0.94\,]$$

=> Test validity of HQE => Supply input for extraction of CKM matrix elements

A Brief History of (Life)Time(s)

VOLUME 51, NUMBER 15 PHYSICAL REVIEW LETTERS 10 OCTOBER 1983

Measurement of the Lifetime of Bottom Hadrons

N. S. Lockyer, J. A. Jaros, M. E. Nelson, G. S. Abrams, D. Amidei, A. R. Baden, C. A. Blocker, A. M. Boyarski, M. Breidenbach, P. Burchat, D. L. Burke, J. M. Dorfan, G. J. Feldman, G. Gidal, L. Gladney, M. S. Gold, G. Goldhaber, L. Golding, G. Hanson, D. Herrup, R. J. Hollebeek, W. R. Innes, M. Jonker, I. Juricic, J. A. Kadyk, A. J. Lankford, R. R. Larsen, B. LeClaire, M. Levi, V. Lüth, C. Matteuzzi, R. A. Ong, M. L. Perl, B. Richter, M. C. Ross, P. C. Rowson, T. Schaad, H. Schellman, D. Schlatter,[a] P. D. Sheldon, J. Strait,[b] G. H. Trilling, C. de la Vaissiere,[c] J. M. Yelton, and C. Zaiser

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Department of Physics, Harvard University, Cambridge, Massachusetts 02138

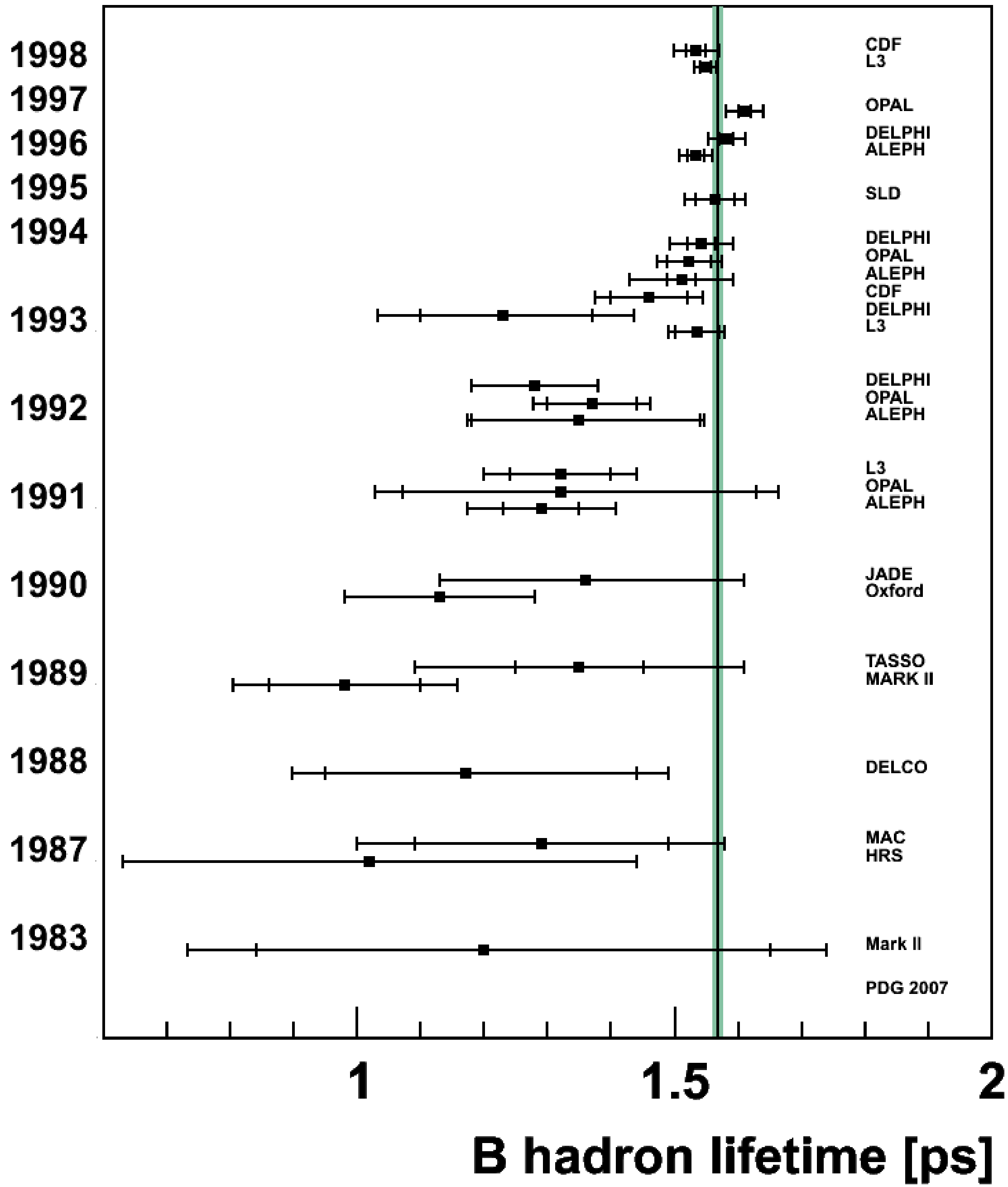
(Received 2 August 1983)

The average lifetime of bottom hadrons was measured with the Mark II vertex detector at the storage ring PEP. The lifetime was determined by measuring the impact parameters of leptons produced in bottom decays. $\tau_b = (12.0^{+4.5}_{-3.6} \pm 3.0) \times 10^{-13}$ sec was found.

MARK II at SLAC in 1983!

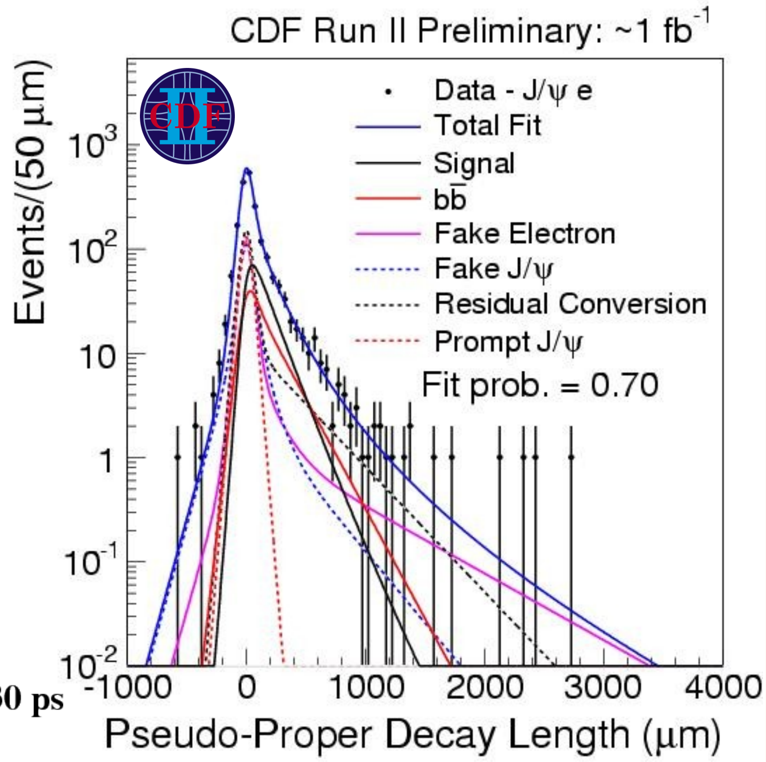
$\tau_b = (1.20^{+0.45}_{-0.36} \pm 0.30)$ ps

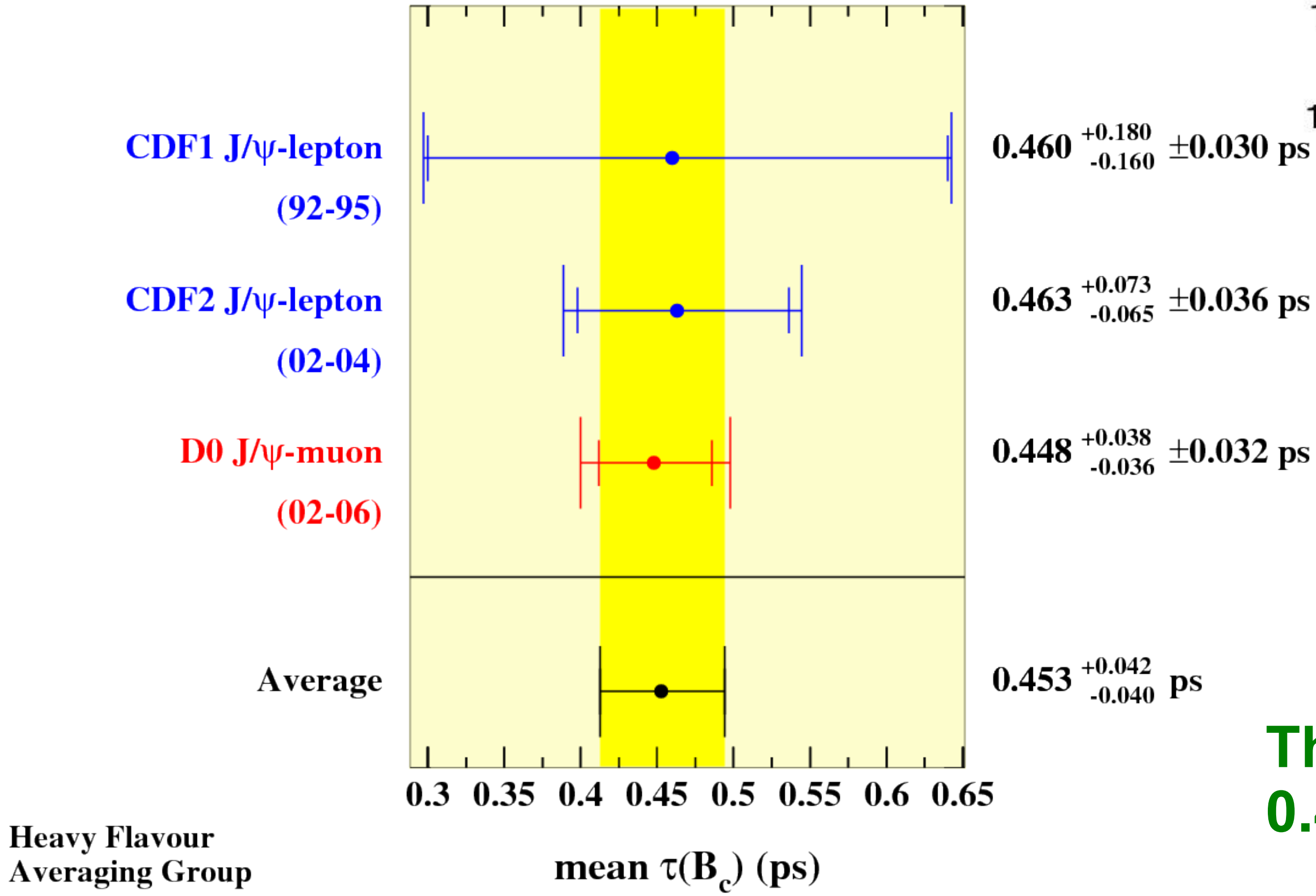
B Hadron Lifetime History



B_c Lifetime

- CDF/D0 use semilept. $B_c^\pm \rightarrow J/\psi \ell^\pm \nu X$
- Main issue: control backgrounds





Theory predictions:
0.47 - 0.59 ps

Λ_b Lifetime

Λ_b Lifetime in 2006:

- World average:

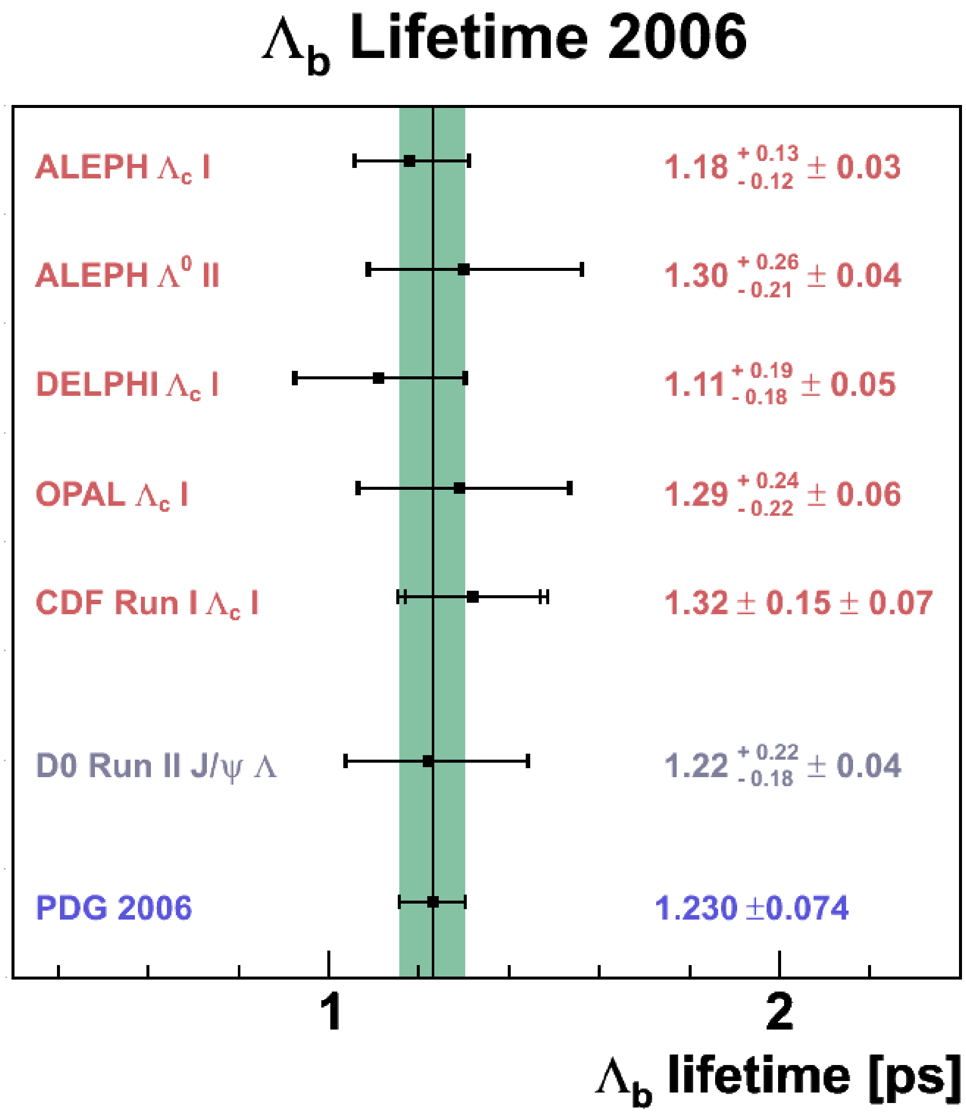
  $\tau(\Lambda_b) = (1.230 \pm 0.074)$ ps

  $\tau(\Lambda_b) / \tau(B^0) = (0.804 \pm 0.049)$

- Theory prediction:

  $\tau(\Lambda_b) / \tau(B^0) = [\,(0.88 \pm 0.05)\,,\ 0.94\,]$

- Long-standing puzzle of Λ_b lifetime being smaller than prediction



Λ_b Lifetime in 2007

Fully reconst. $\Lambda_b \to J/\psi\ \Lambda$

$\tau(\Lambda_b) = (1.218\ ^{+0.130}_{-0.115} \pm 0.042)$ ps

$\tau(\Lambda_b) / \tau(B^0) = (0.811\ ^{+0.096}_{-0.087} \pm 0.034)$

Semileptonic mode $\Lambda_b \to \Lambda_c \mu \nu X$

$\tau(\Lambda_b) = (1.290^{+0.119}_{-0.111}\ ^{+0.087}_{-0.091})$ ps

Results in agreement with PDG'06

Also fully rec. $\Lambda_b \to J/\psi\ \Lambda$

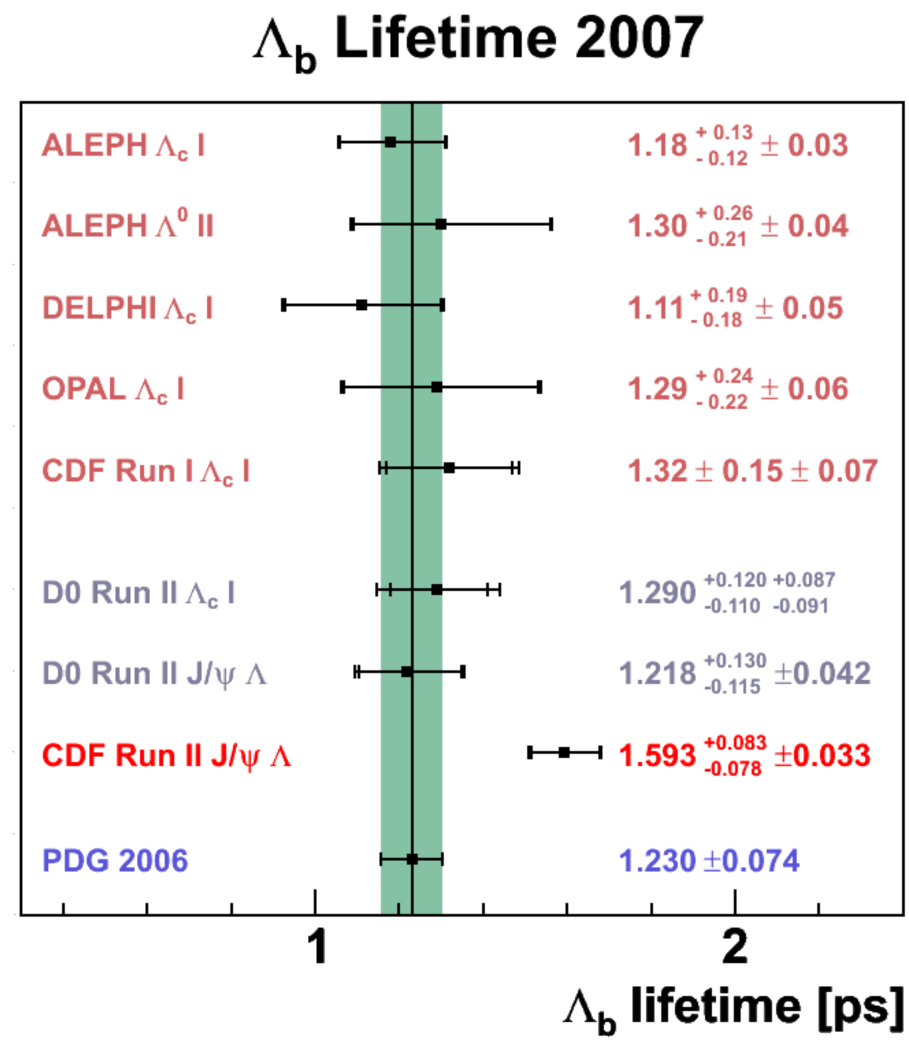
$\tau(\Lambda_b) = (1.580 \pm 0.077 \pm 0.012)$ ps

$\tau(\Lambda_b) / \tau(B^0) = (1.018 \pm 0.062 \pm 0.007)$

$\tau(B^0) = (1.551 \pm 0.019 \pm 0.011)$ ps

<u>BIG Surprise:</u> ~3σ above PDG'06

But: $\tau(B^0)$ comes out ok



Λ_b Lifetime in 2008

CDF: New precision measurement of Λ_b lifetime in hadronic mode $\Lambda_b \to \Lambda_c \pi$

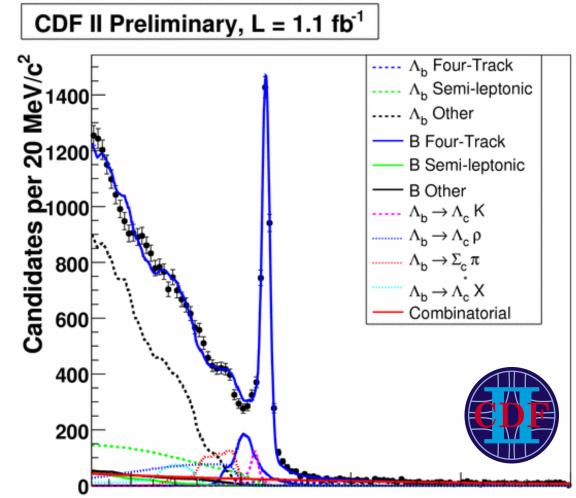
~2900 fully rec. $\Lambda_b \to \Lambda_c \pi$ signal events

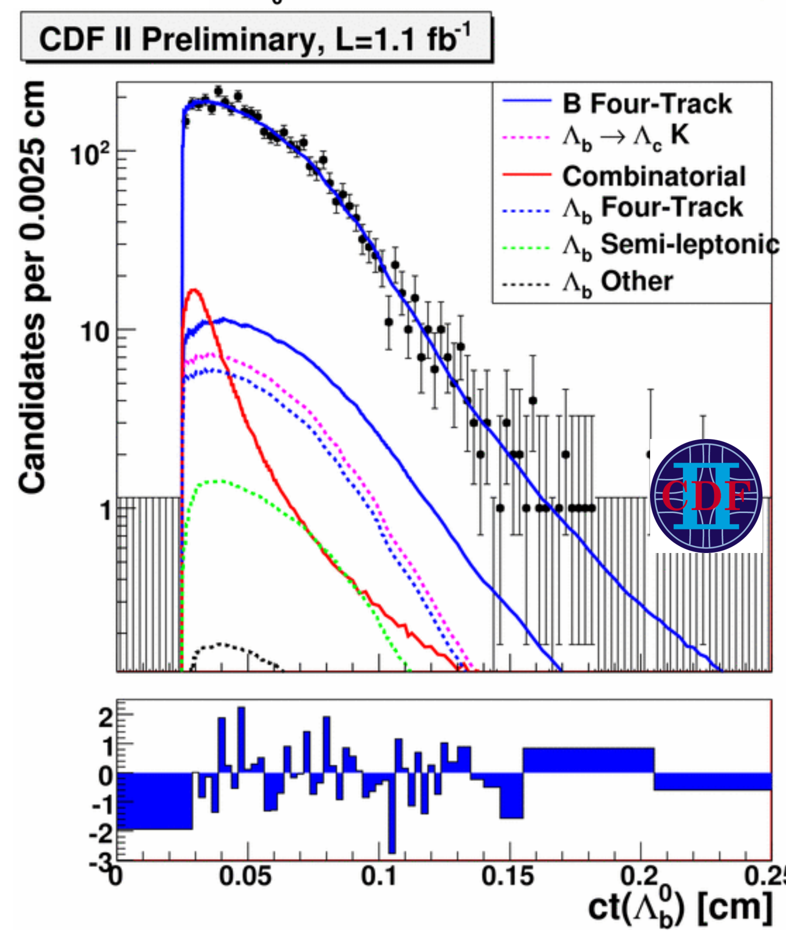
$\tau(\Lambda_b) = (1.401 \pm 0.046 \pm 0.035)$ ps

$\tau(\Lambda_b) / \tau(B^0) = (0.922 \pm 0.039)$

($\tau(B^0)$ from PDG'07)

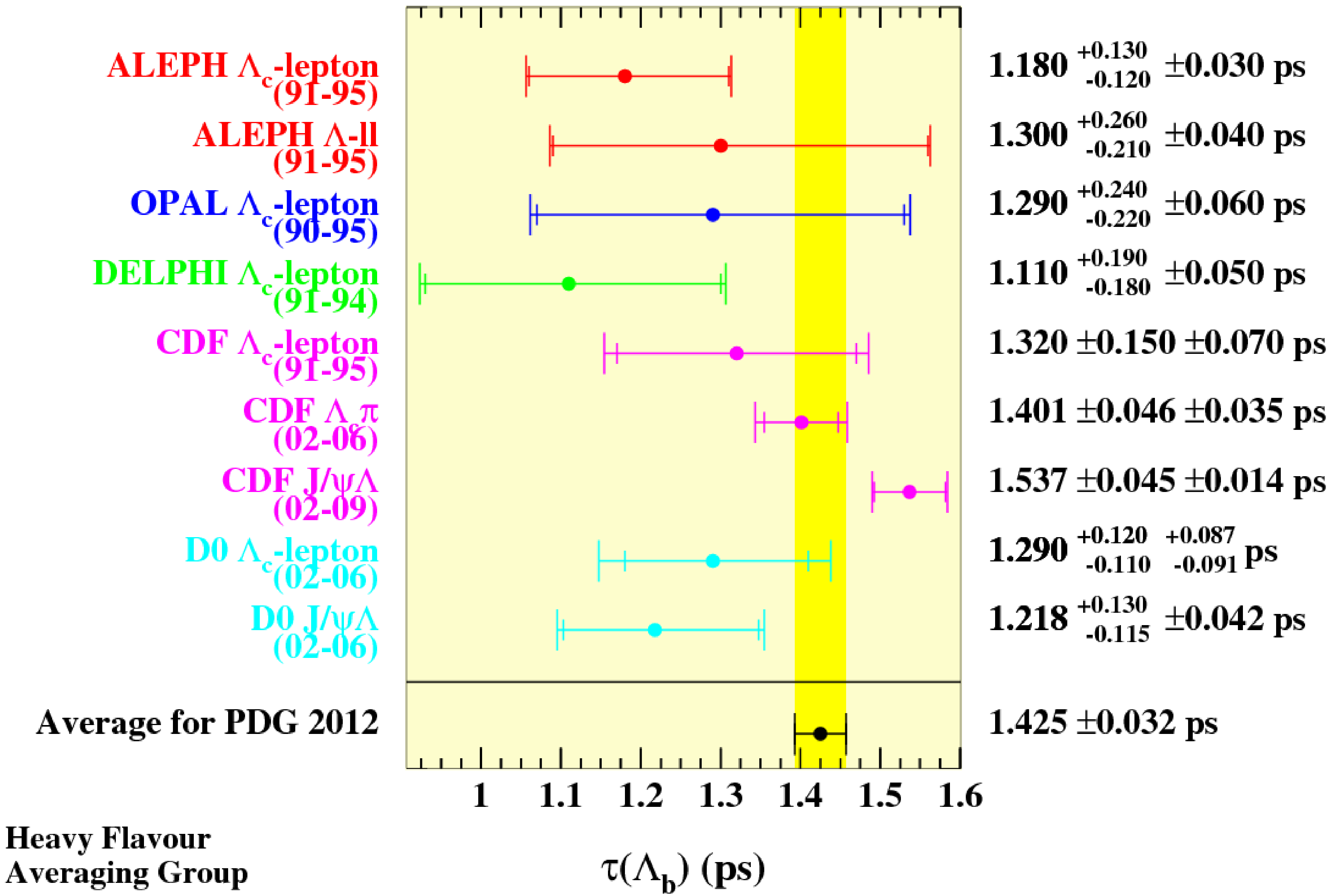
- World best measurement in 2008
  => as precise as 2008 world average



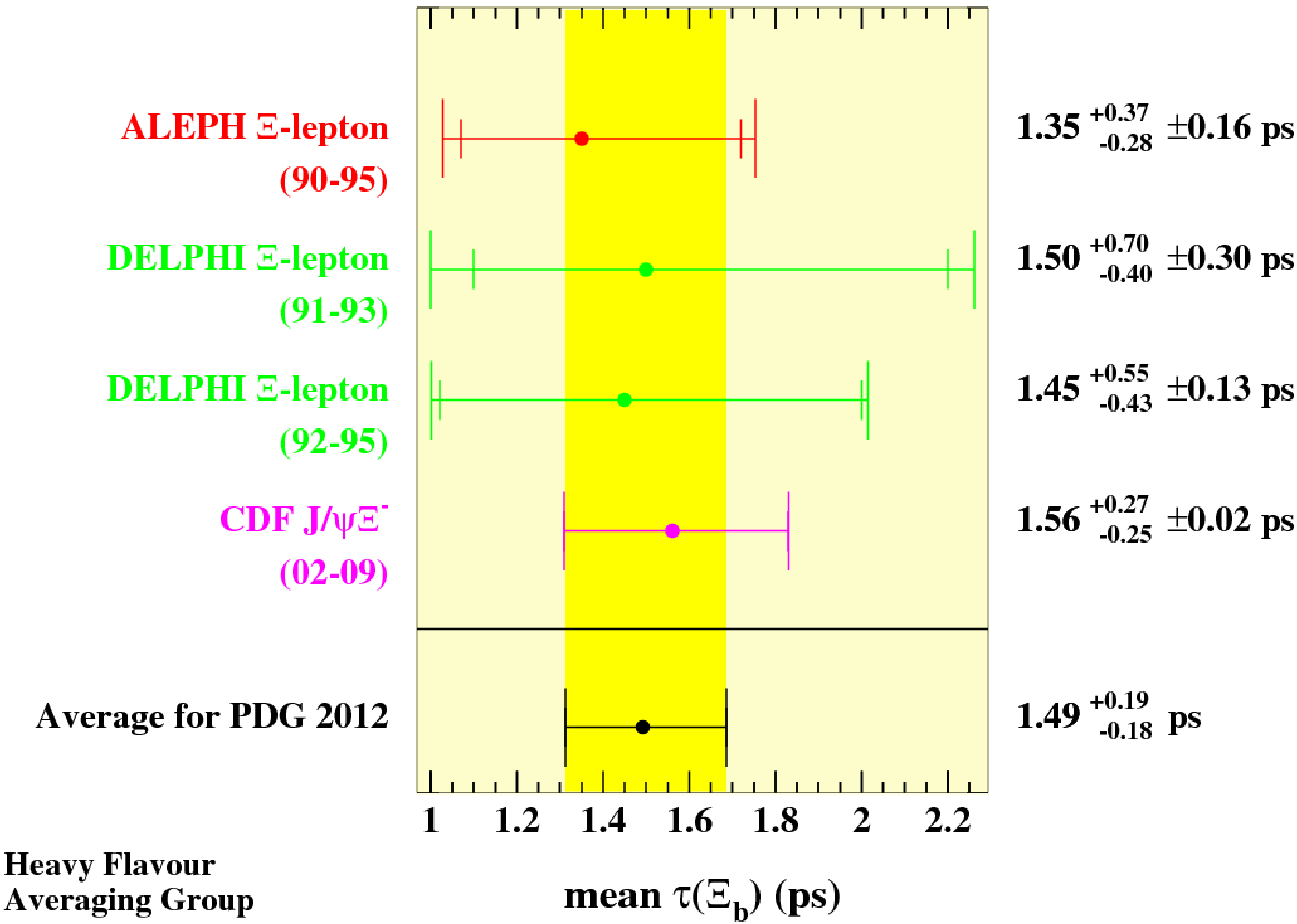


Λ_b Lifetime in 2012

- CDF result in good agreement with world average and theory prediction
- Longstanding puzzle resolved ?

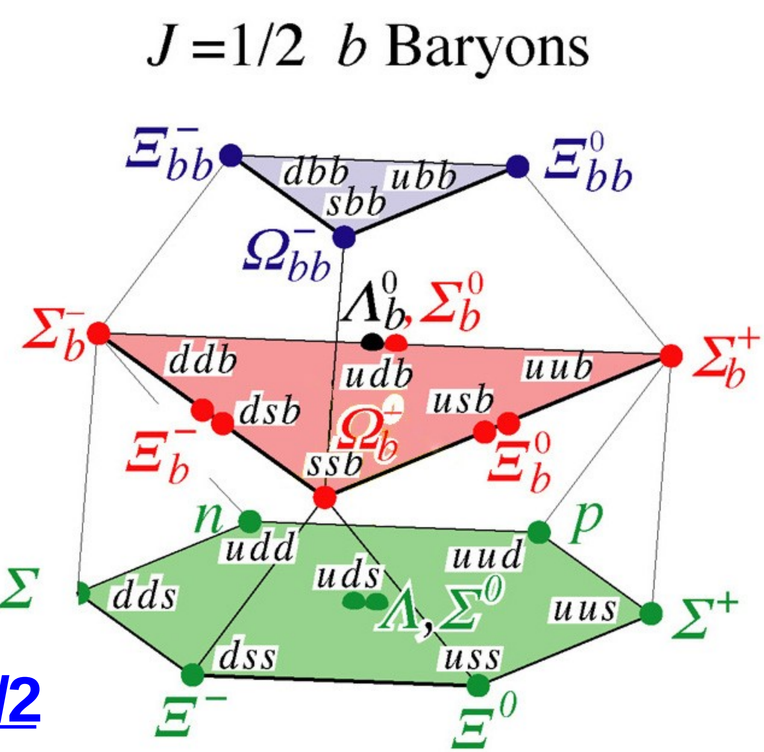


Ξ_b Lifetime in 2012



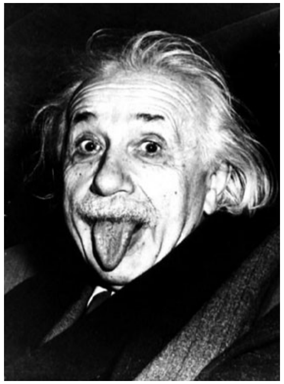
Summary of Lecture 1

- B hadron properties of old and new particles (Ξ_b^{0*})
- Measurements of properties of B hadrons not just bread & butter:
  - Precision B hadron mass measurements
  - Puzzle with Λ_b lifetime resolved?
  - Heavy baryons Σ_b, Ξ_b, Ω_b established
  - Next discoveries: Ξ_{bb} Ω_{bb} Ξ_{bc} Ξ_{cc} … ?
- Not everything revolves around Higgs



J = 1/2

Summary 2 of Lecture 1



"God doesn't play dice with the universe."
(Albert Einstein)

"If only god would give me some clear sign!
Like making a large deposit in my name at a Swiss bank."
(Woody Allen)