Heavy Hadron Spectroscopy at CDF

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Why study B hadrons ?

- Heavy quark hadrons are the hydrogen atom of QCD (we can use perturbative QCD to describe the potential quite well)

Properties: Focus on masses , lifetimes (decays)

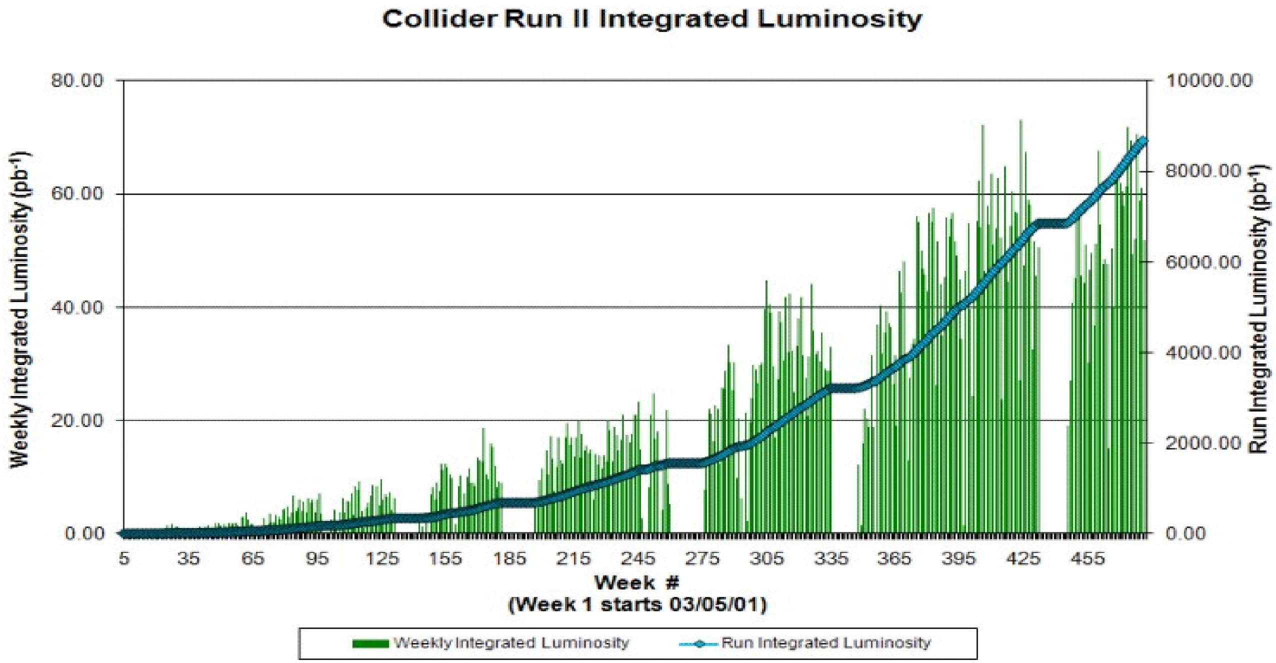
Why B Hadron masses ?

- B hadrons probe a unique region of parameter space (i.e., mass, energy, momentum, velocity) that can be studied using a wide range of tools (potential models, HQET, lattice gauge calculations)

Why B Hadron Lifetimes ?

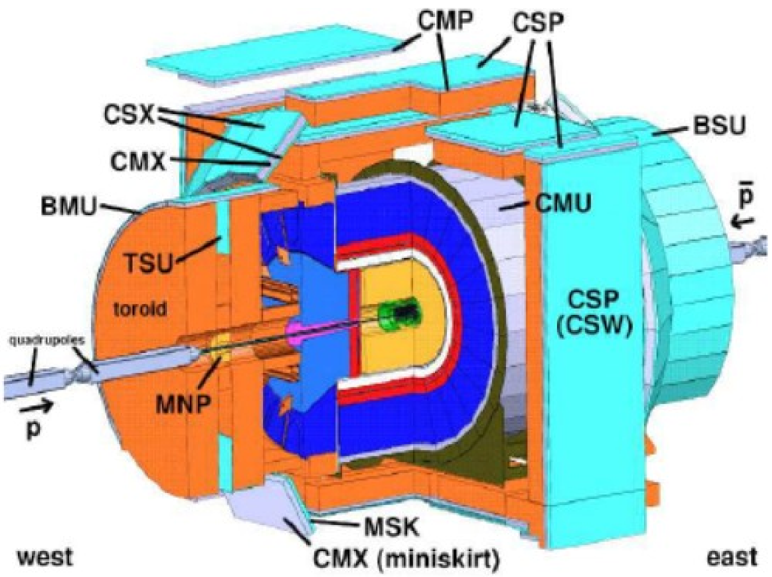
- The measurement of lifetimes (and ratios) can be used to evaluate deviations from the naive spectator quark model : b quark decays like free “particle” => all B hadron lifetimes are equal
- In reality QCD => lifetimes of B hadrons study the interplay between strong and weak interaction

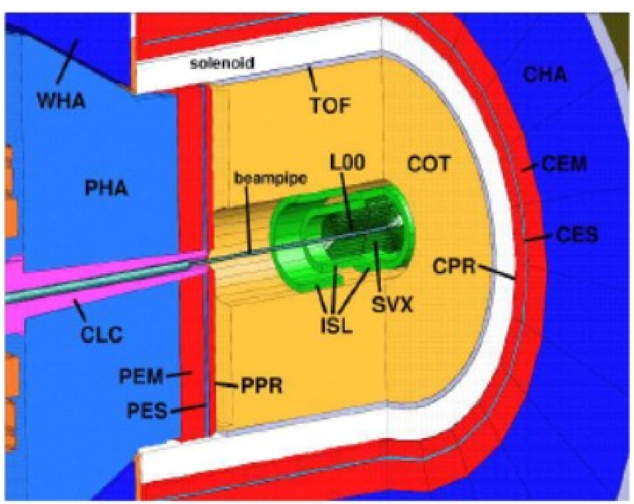
Introduction to the Tevatron



- ppbar collisions at 1.96 TeV
- Excellent performance of Tevatron accelerator
- Keep breaking record of peak Initial Luminosity after 9 years of running
- CDF has already > 7 **fb^{-1}** on tape. Rate is 50 pb^{-1}/week !!
- Expect ~10 fb^{-1} on tape by end 2011
- The analyses presented in this talk span from 1 to 5 fb^{-1}

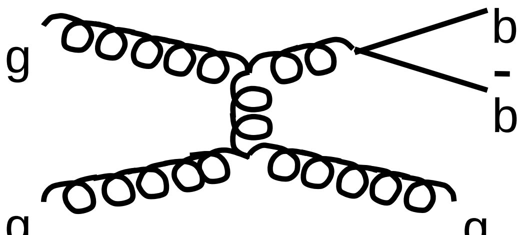
CDF detector



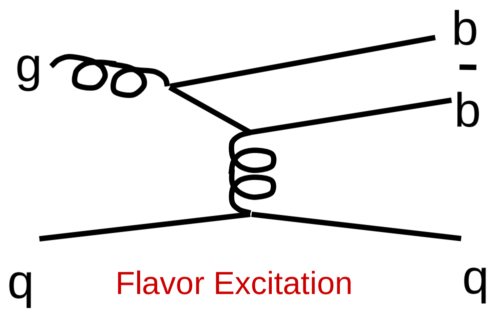


- Drift chamber (COT)
  $\Rightarrow$ Good tracking resolution
  $\sigma(p_T)/p_T \sim 0.07\ p_T\ \%\ GeV^{-1}$(for COT + silicon)
  $\Rightarrow$ Important for triggering
- Silicon vertex detector
  $\Rightarrow$ Good vertex resolution
  $\Rightarrow$ Important for triggering
- Muon System up to $|\eta| < 1.5$
  $\Rightarrow$ Important for triggering
- TOF detector and dE/dx from COT
  $\Rightarrow$ Good particle identification

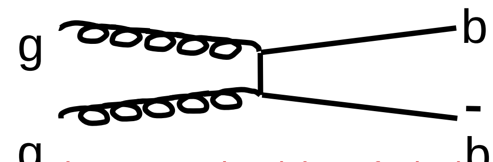
Basics of B Physics at the Tevatron



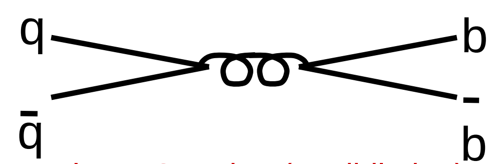
Gluon Splitting



Flavor Excitation



Flavor Creation (gluon fusion)

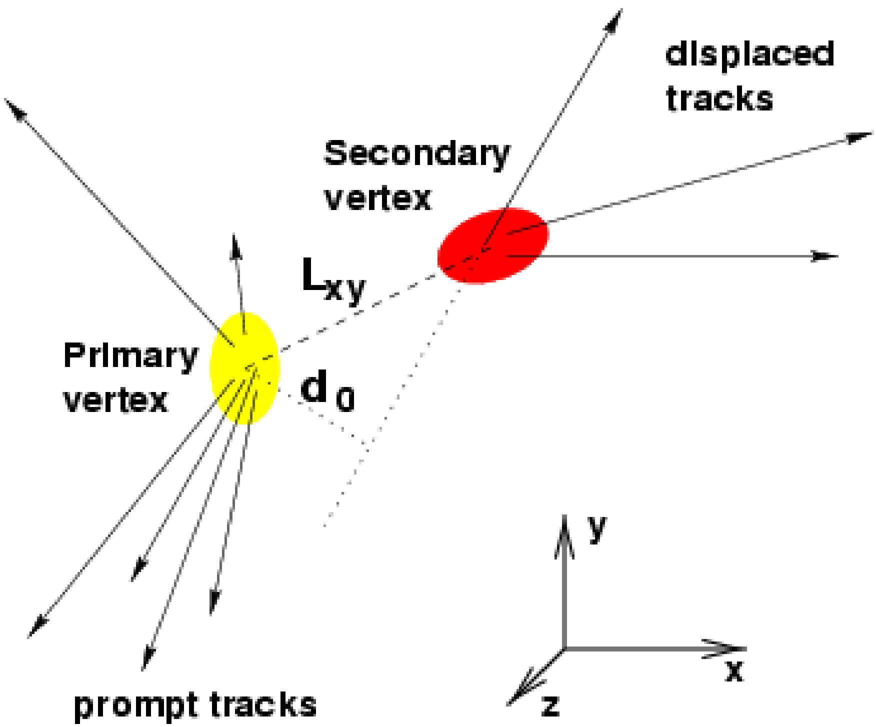


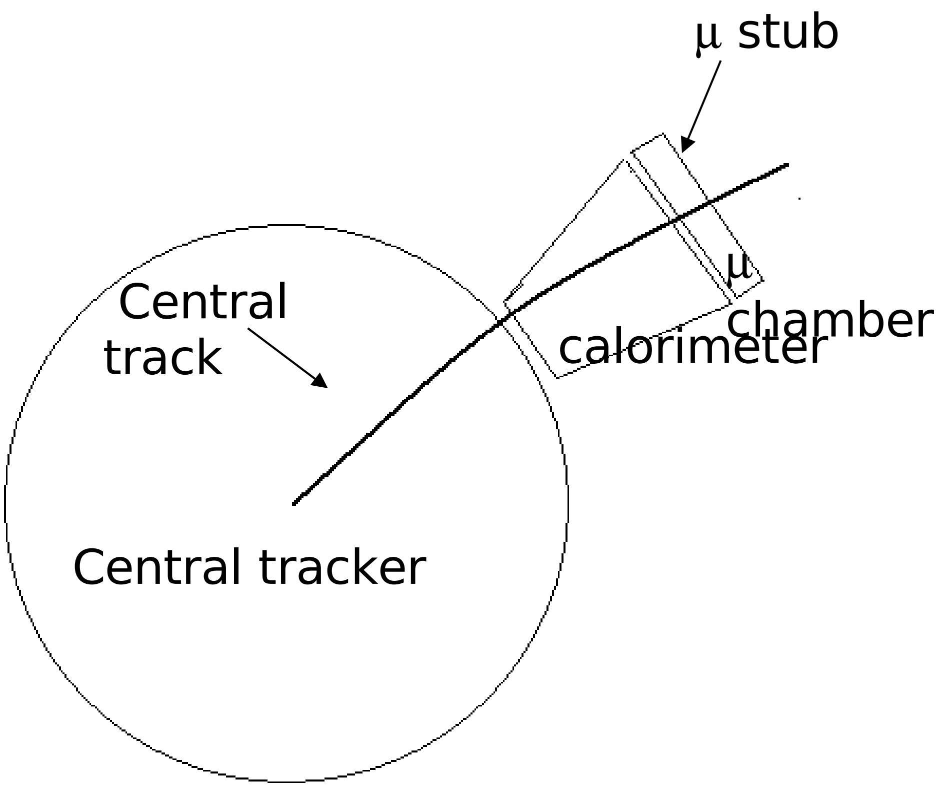
Flavor Creation (annihilation)

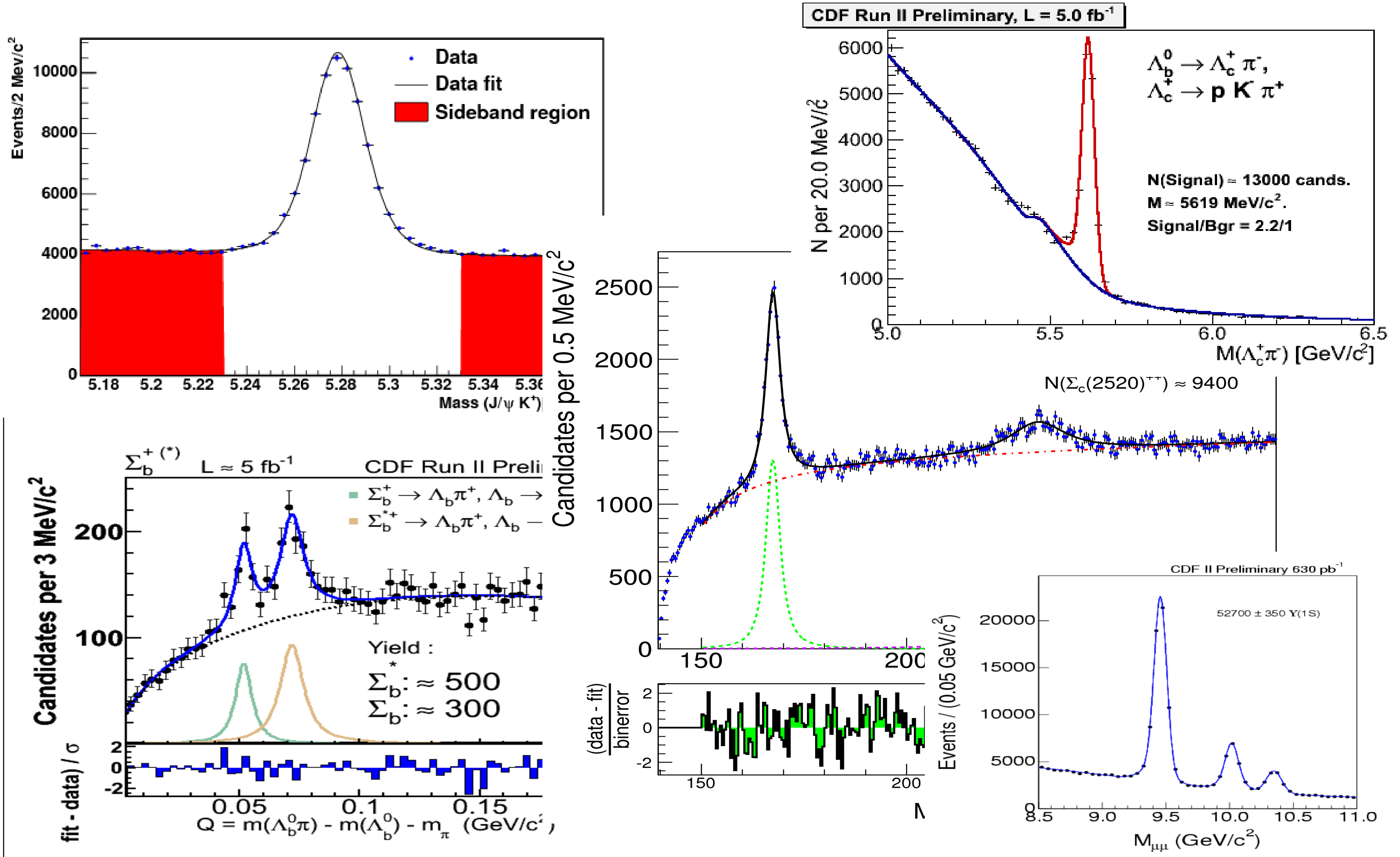
- High cross section σ (**$p\bar{p} \rightarrow b\bar{b}$**) ~ 40 μb at $\sqrt{s}$ = 2 TeV (vs 1 nb at the Υ(4s) resonance [B factories])
- Quarks fragment into hadrons: B_c^- ($b\bar{c}$), Λ_b(bdu), Σ_b^+ (buu), Σ_b^- (bdd), Ξ_b^-(bsd), Ω_b^-(bss) [Tevatron exclusive], B_s^0 ($\bar{b}s$), B_0($\bar{b}d$), B^-($b\bar{u}$), also B*, B**, etc
- $\rightarrow$ Tevatron can be considered as a B factory

Online B selection process

- Huge bkg to the process σ ($p\bar{p} \rightarrow b\bar{b}$)in Tevatron:O(0.05 b)
- To overcome the QCD background B hadrons filtered online using selective triggers based on clear signatures:
  - events selected by a $J/\psi \rightarrow \mu\mu$ oriented dimuon trigger
  - events selected by an impact parameter based trigger (SVT)







We have the largest beauty and charm samples ever collected!

Results :

- Σ_b mass
- Ω_b, Ξ_b mass and lifetime
- B_c mass and lifetime
- Exotic particles :
  $\chi(3872)$
  Y(4140)
- Charm baryon's masses
- B^+, B_0 & Λ_b lifetime and ratio of lifetimes

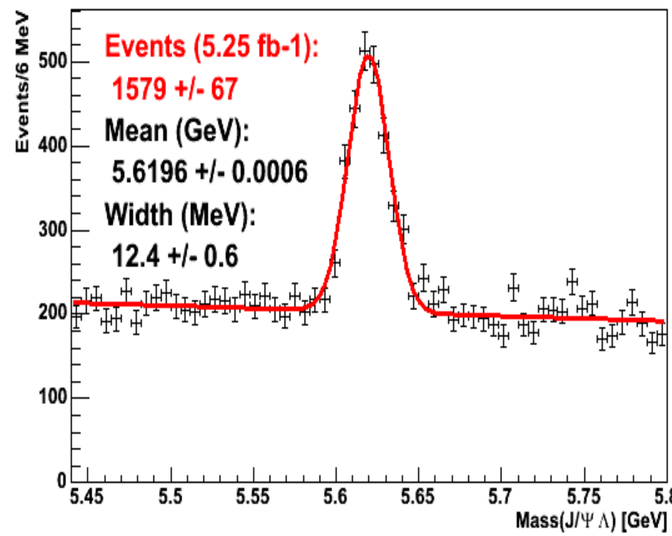
Σ_b , Σ_b^* Baryons

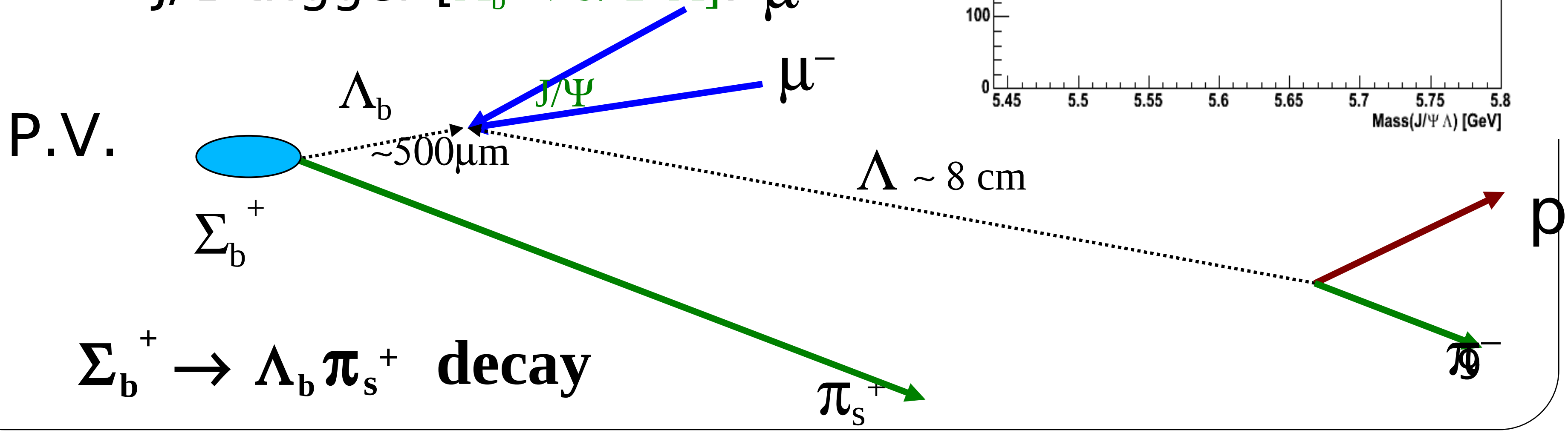
- Until 2006 Λ_b was only established B baryon

=> search for $\Sigma_b^+ = |buu\rangle$ $\Sigma_b^- = |bdd\rangle$

- $\Sigma_b^{*\pm}$ excited state of $\Sigma_b^\pm$ with s = 3/2
- Use two different triggers :
  - •displaced track [PRL 99, 202001 decay $\Lambda_b \to \Lambda_c^+\pi^-$ with $\Lambda_c^+ \to pK^-\pi^+$]
  - •J/Ψ trigger [$\Lambda_b \to J/\Psi\ \Lambda$]:

Reconstruct ~1600 Λ_b in J/Ψ Λ decay with 3.8 fb^{-1}.

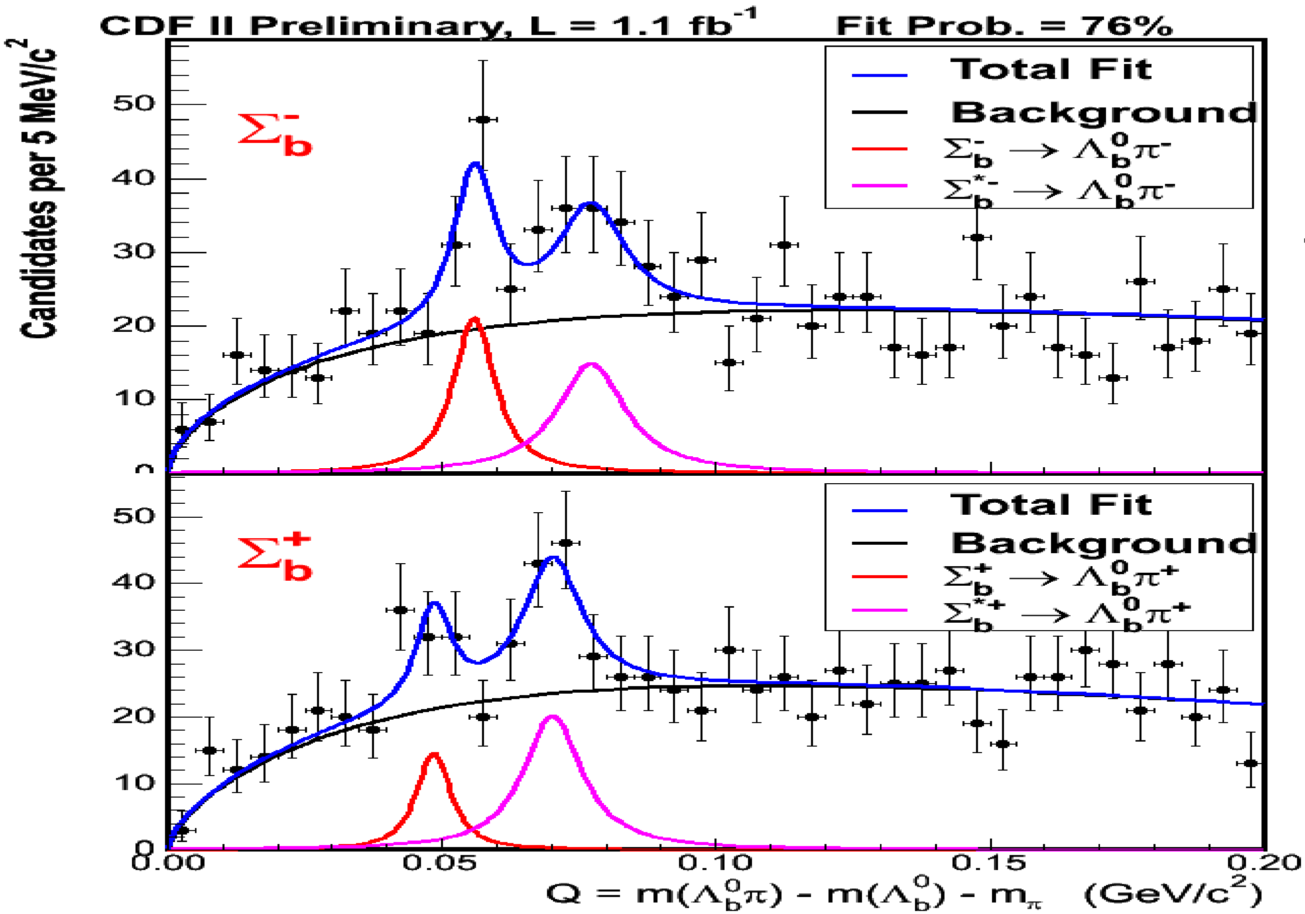




$\Sigma_b^+ \to \Lambda_b \pi_s^+$ **decay**

- $Q = M(\Sigma_b) - M(\Lambda_b) - m(\pi)$

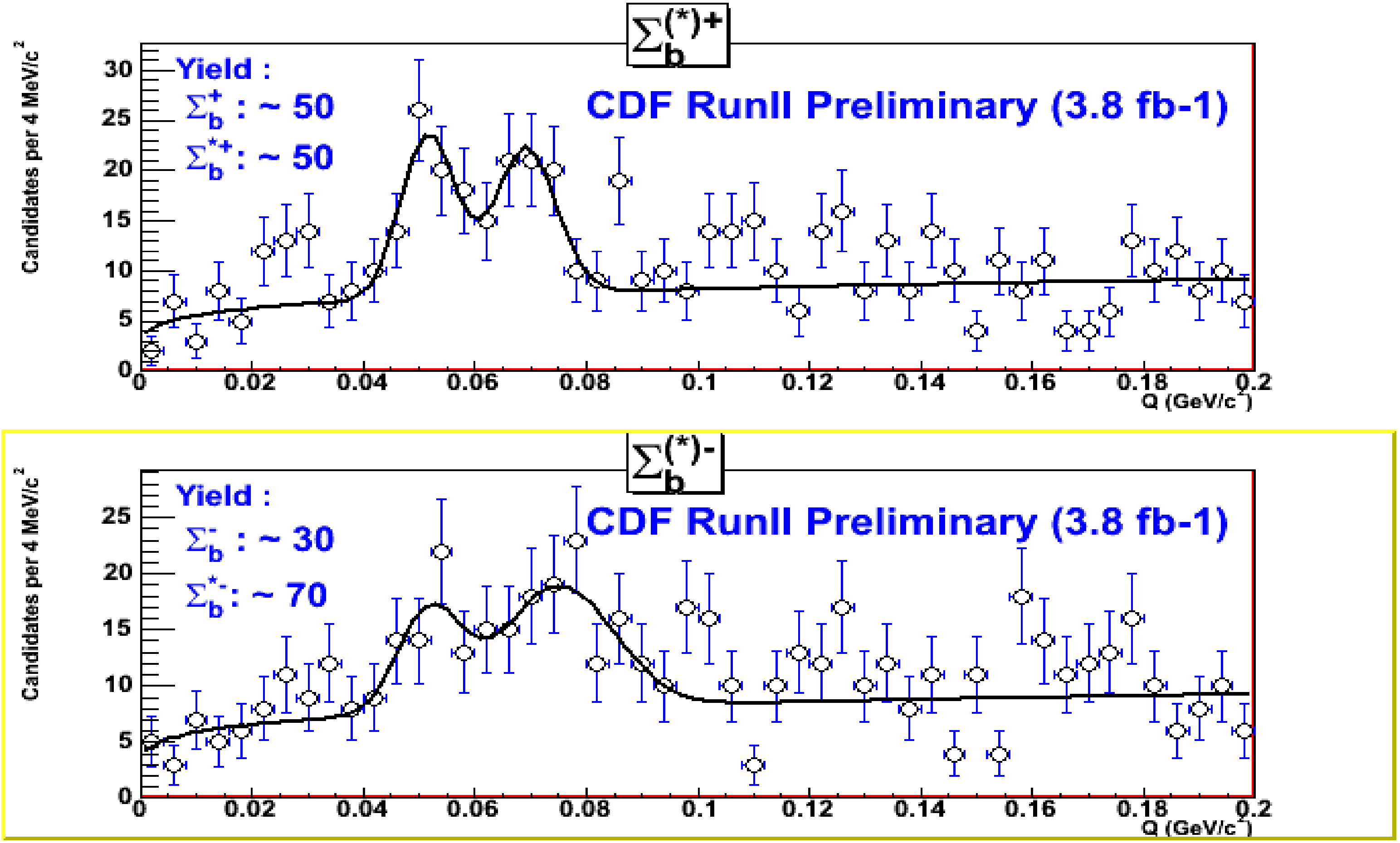
State	Yield	Q or $\Delta_{\Sigma_b^*}$ (MeV/c^2)	Mass (MeV/c^2)
Σ_b^+	32^{+13+5}_{-12-3}	$Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}$	$5807.8^{+2.0}_{-2.2} \pm 1.7$
Σ_b^-	59^{+15+9}_{-14-4}	$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2$	$5815.2 \pm 1.0 \pm 1.7$
Σ_b^{*+}	77^{+17+10}_{-16-6}	$\Delta_{\Sigma_b^*}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



- BW width from theory
- Fit constrain (Δ)

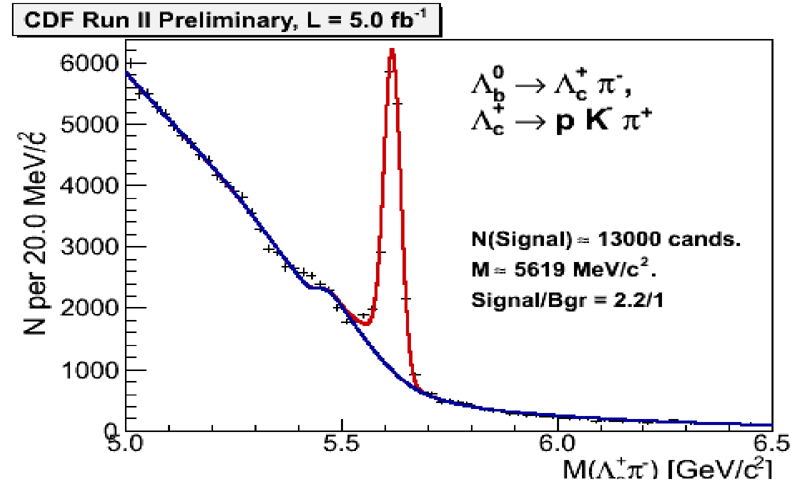
- Observe peaks with > 5σ w.r.t no signal

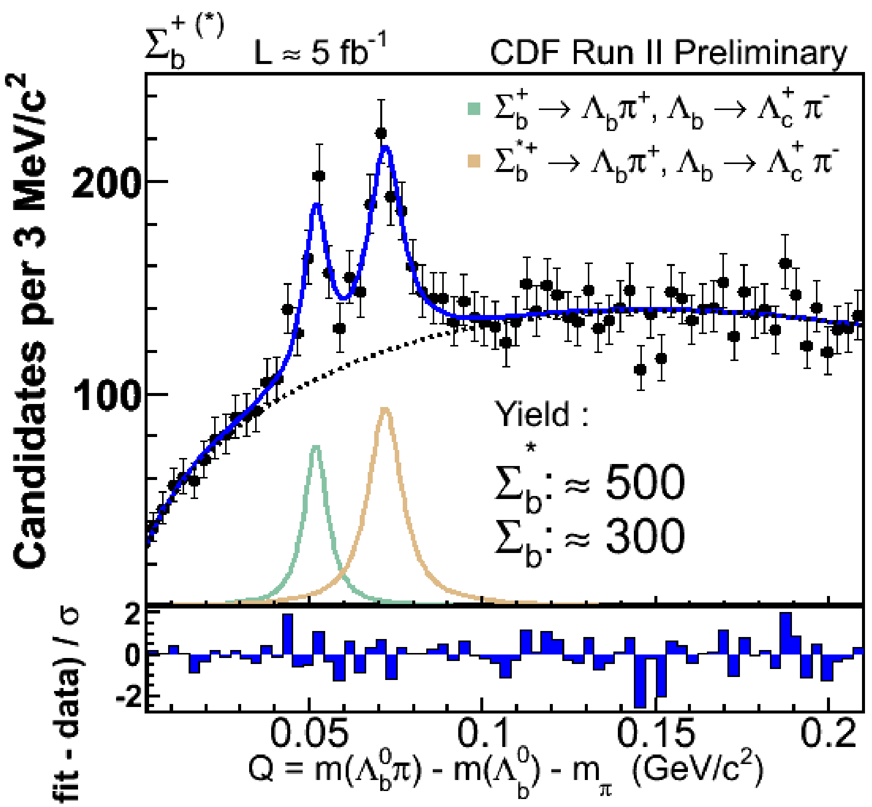
- $Q = M(\Sigma_b) - M(\Lambda_b) - m(\pi)$

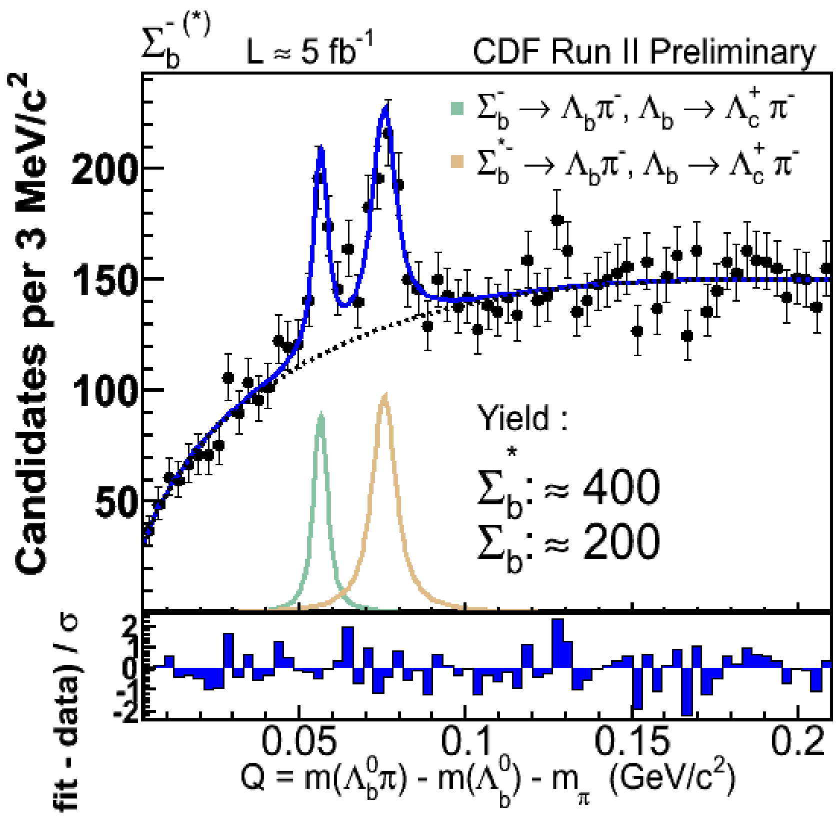


- Data suggest that in $\Lambda_b \to J/\Psi\ \Lambda$ decay mode there are consistent peaks

- High statistics (> 5 fb^{-1}) confirmation of discovered signals and measurement results coming soon
- Whole measurement of masses and widths (i.e., no constrains)





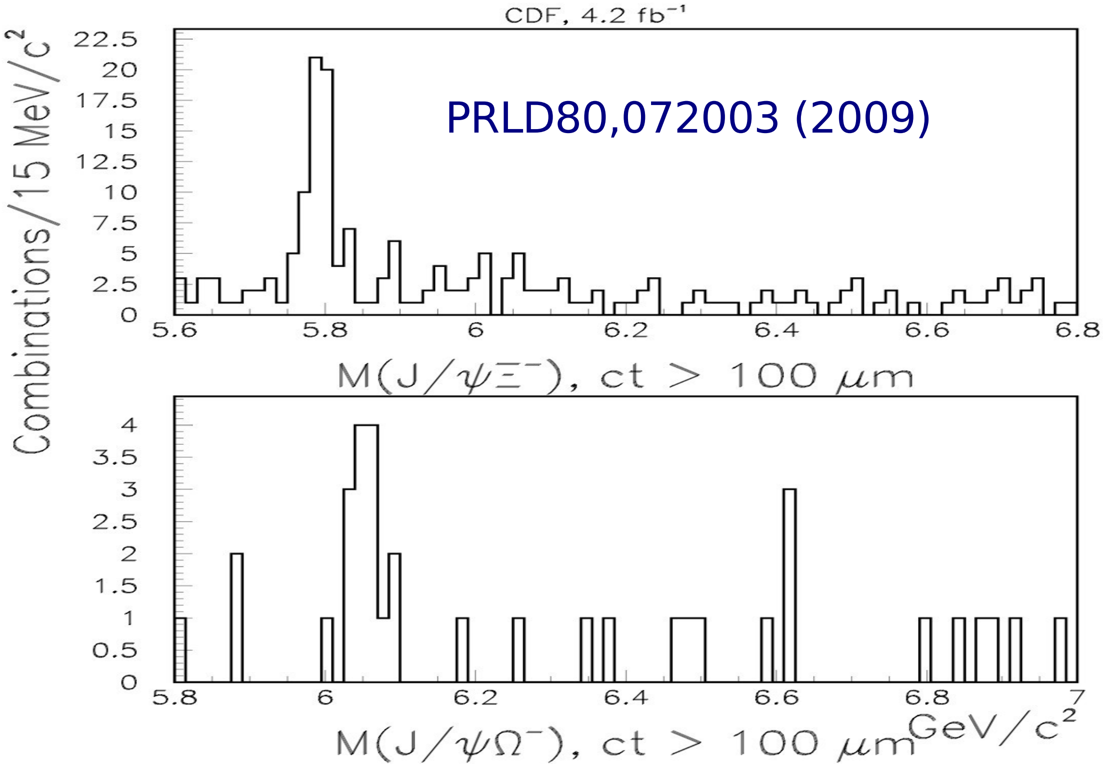


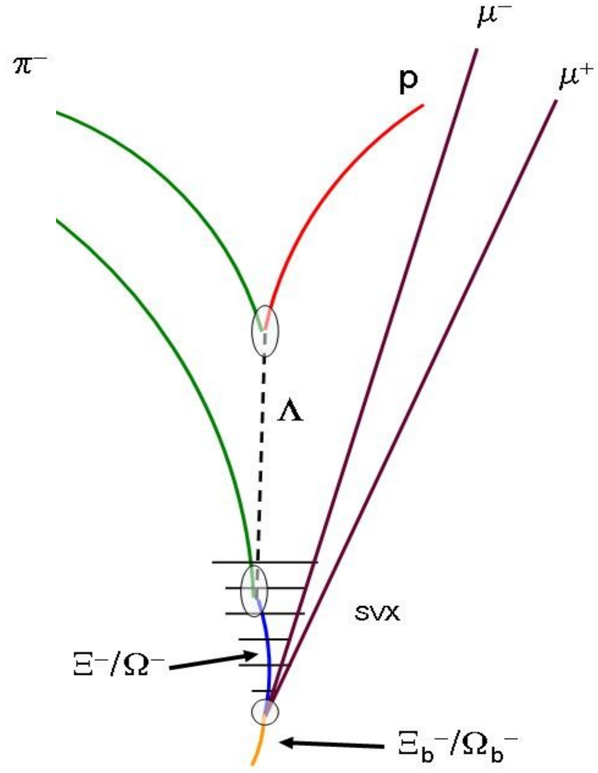
Ω_b & Ξ_b Baryons

$\Omega^-_b \rightarrow J/\psi\ \Omega^-$, $J/\psi \rightarrow \mu^+\mu^-$, $\Omega^- \rightarrow \Lambda K^-$, $\Lambda \rightarrow p\ \pi^-$ (in 4.2 fb^{-1}).

$\Xi_b^- \rightarrow J/\Psi\ \Xi^-$; $\Xi^- \rightarrow \Lambda\ \pi^-$, $\Lambda \rightarrow p\pi^-$

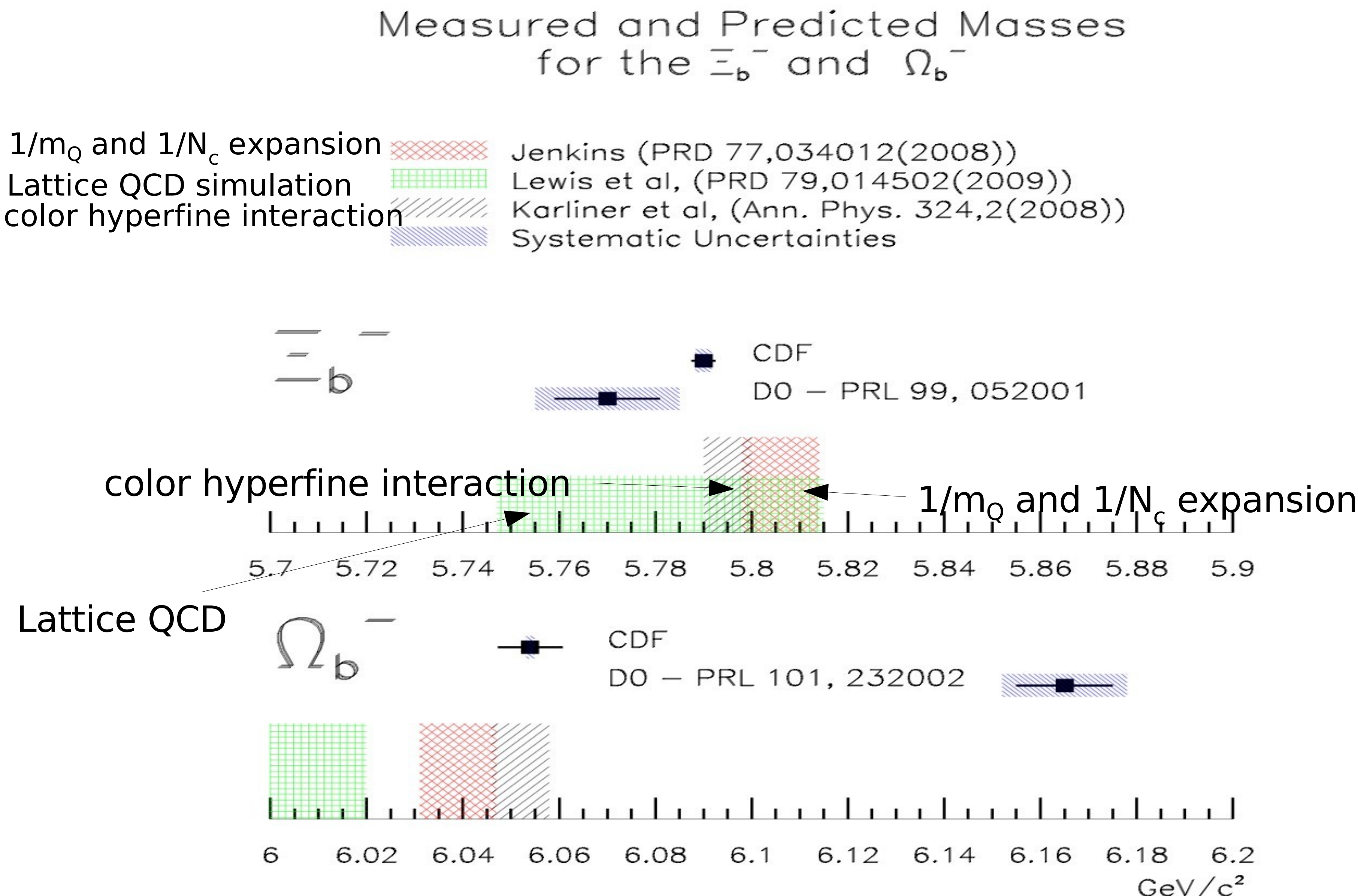
$N(\Omega_b) = 16^{+6}_{-4}$ significance 5.5σ





1st lifetime measurement!

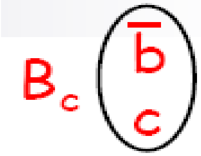
	Mass (MeV/c^2)	Lifetime (ps)
Ξ^-_b	5790.9 ± 2.6 ± 0.8	1.56+0.27-0.25 ± 0.02
Ω^-_b	6054.4 ± 6.8 ± 0.9	1.13+0.53-0.40 ± 0.02



The already small CDF uncertainties start to challenge the different predictions !

B_c mass

- B_c contains two heavy quarks: bottom and anti-charm



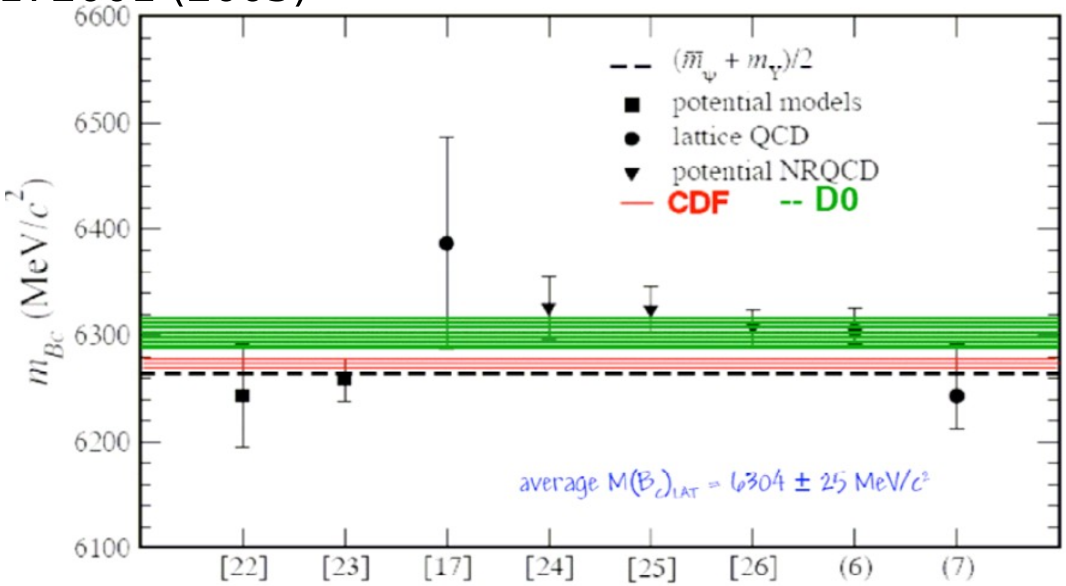
- Produced only at the Tevatron→ unique testing ground for QCD

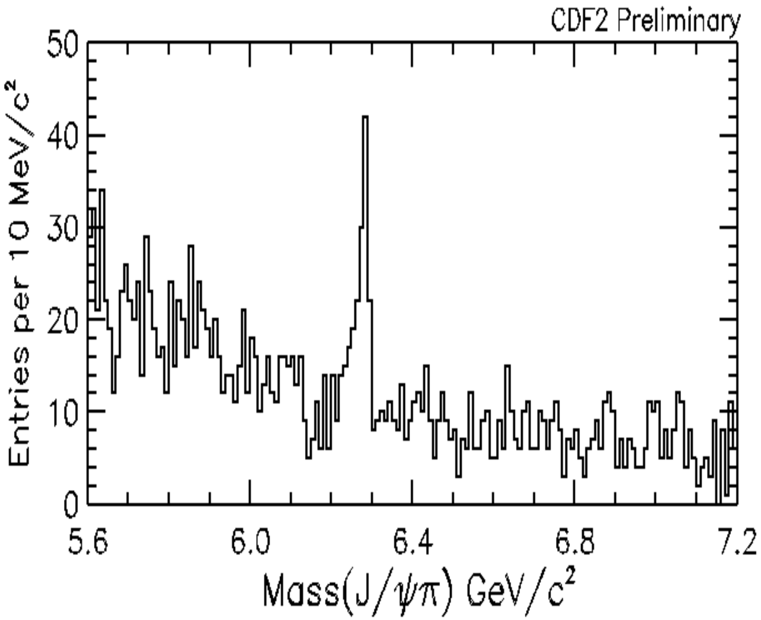
(until a few months ago)

- Best mass measurement from CDF in $B_c \to J/\Psi\pi$ decays (2.4 fb^{-1})

$$m(B_c) = 6275.6 \pm 2.9 \pm 2.5 \text{ MeV/c}$$ (PRL 100:182002,2008)

good agreement with theory (6304 ± 12+18-0) Phys. Rev. Lett. 94, 172001 (2005)





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

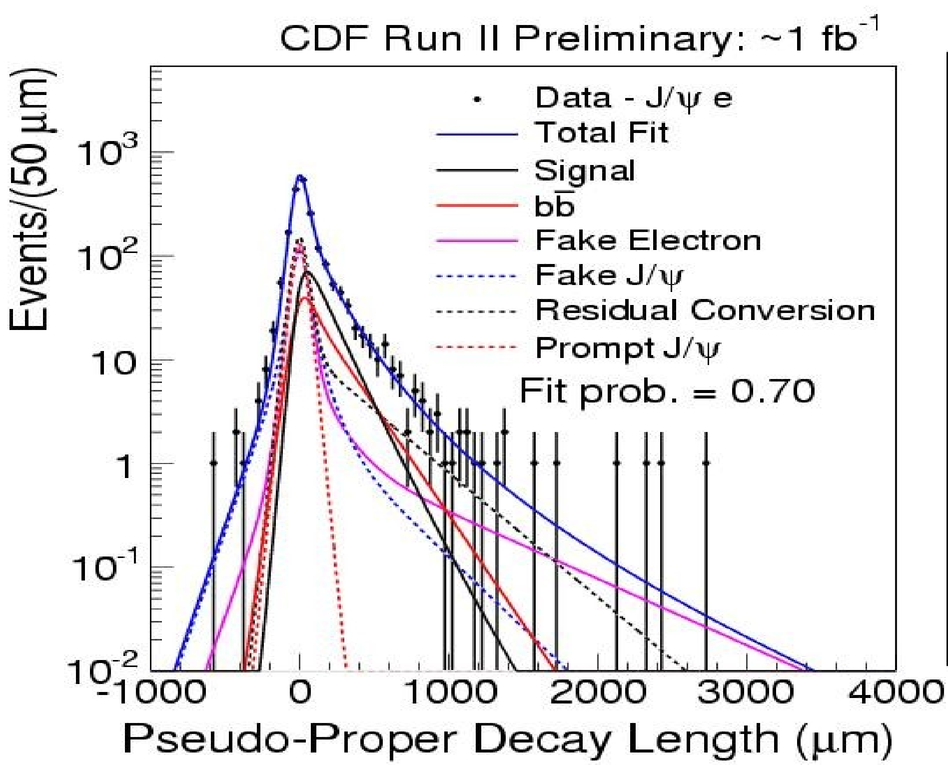
B_c lifetime

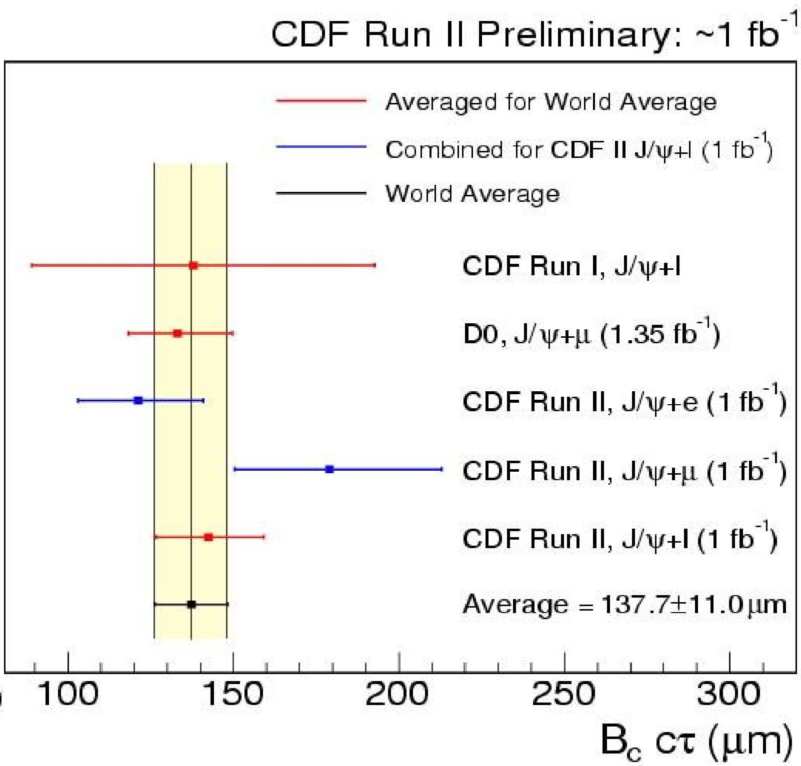
- Lifetime measurement in semileptonic decays $B_c \rightarrow J/\psi + l + X$
- Main issue control background

$c\tau(B_c) = 142.5\ ^{+15.8}_{-14.8}(\text{stat.}) \pm 5.5\ (\text{syst.})\ \mu m$

$= 0.475\ ^{+0.053}_{-0.049}(\text{stat.}) \pm 0.018\ (\text{syst.})\ ps$

Theoretical predictions:
0.47-0.59 ps





http://www-cdf.fnal.gov/physics/new/bottom/080327.blessed-BC_LT_SemiLeptonic/

Mass Measurement of the X(3872) State

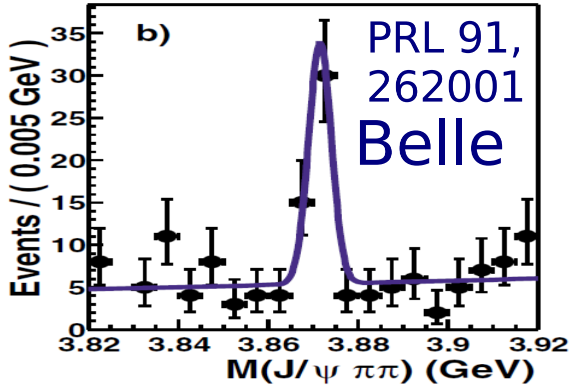
First observed by Belle(PRL 91, 262001 (2003)) :

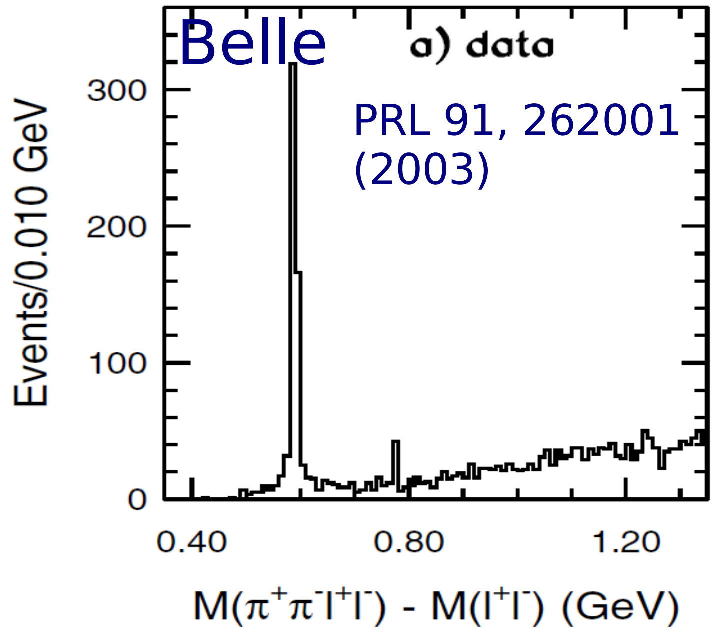
Belle reconstructed B^+ as: $B^+ \rightarrow J/\psi\pi\pi K^+$, $J/\psi \rightarrow l^+l^-$ ($l = e,\mu$)

Did a search for structure in $J/\psi\pi\pi$ mass spectrum inside B^+ mass window

Near threshold structure in

$\Delta M = m(l^+l^-\pi^+\pi^-) - m(\mu^+\mu^-) = 0.775$ GeV



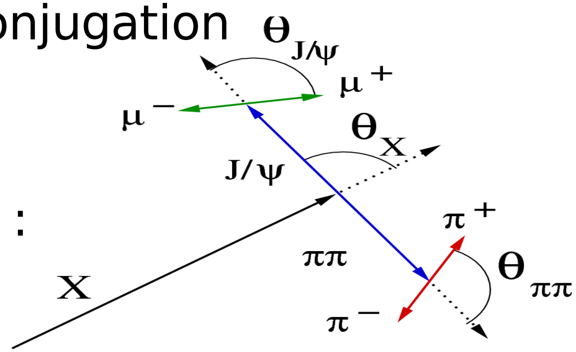


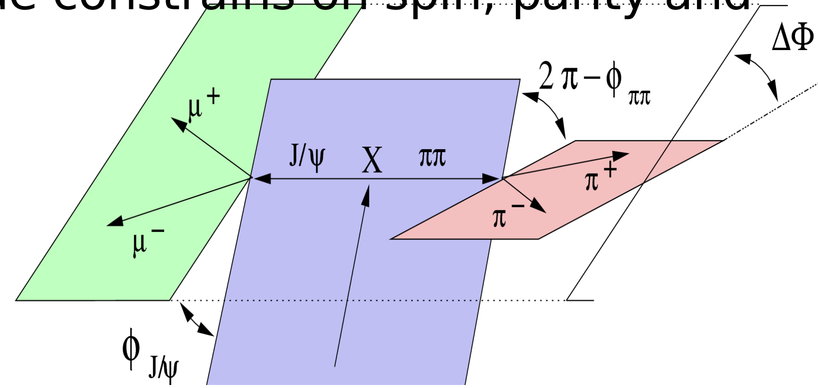
CDF (PRL 93, 072001 2004) was the first experiment to confirm X(3872) after Belle's observation

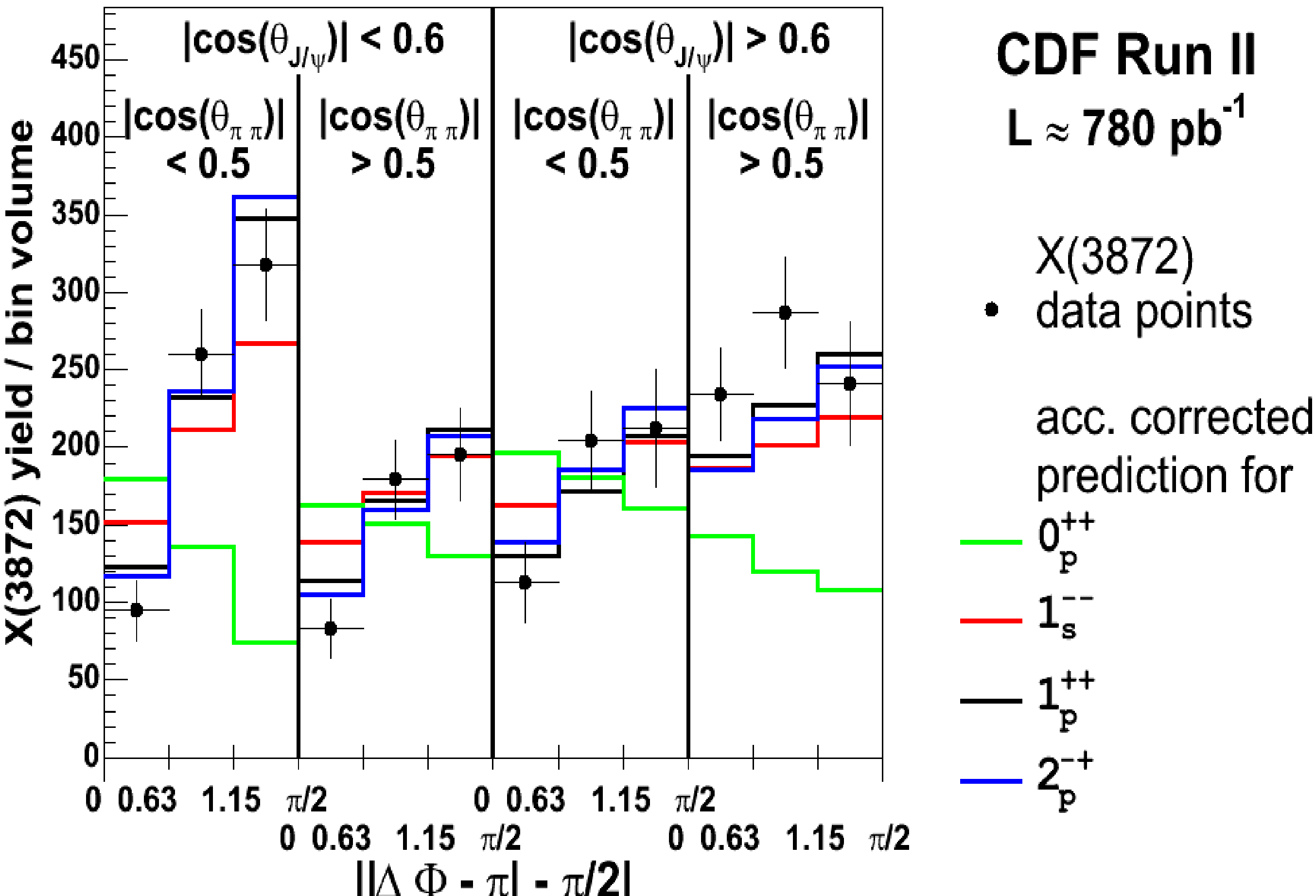
Tevatron continues to make contributions to understand the nature of X(3872)

Angular distribution of X(3872) provide constrains on spin, parity and charge conjugation

Angle definition :

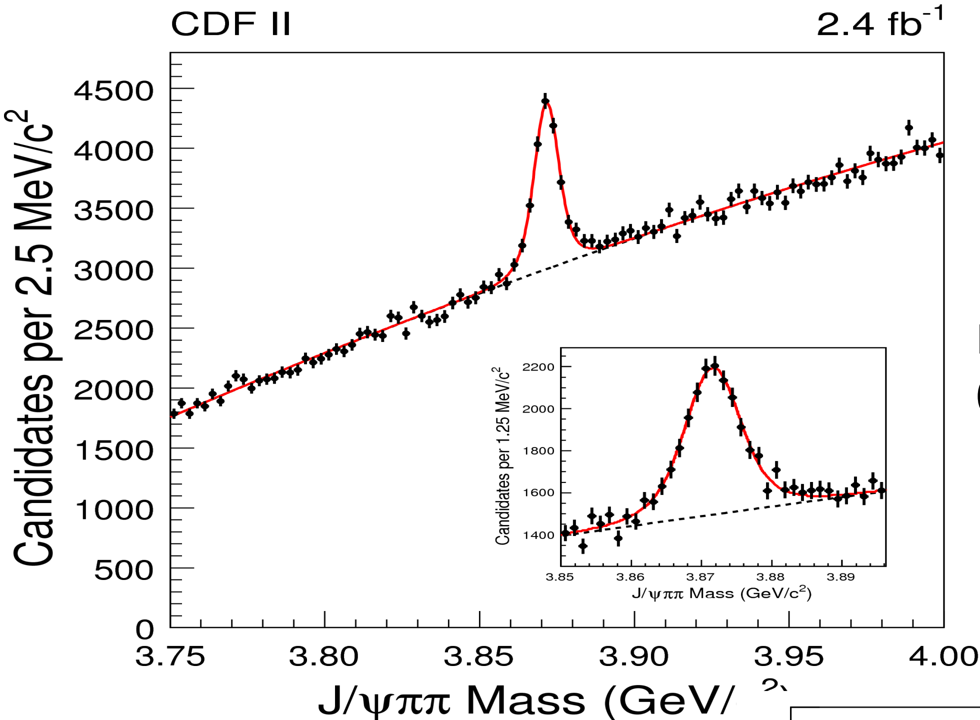






Quantum numbers J^{PC} = 1^{++} and 2^{-+} preferred, PRL 98,132002 (2007)

Latest update of X(3872) done with 2.4 fb^{-1} .

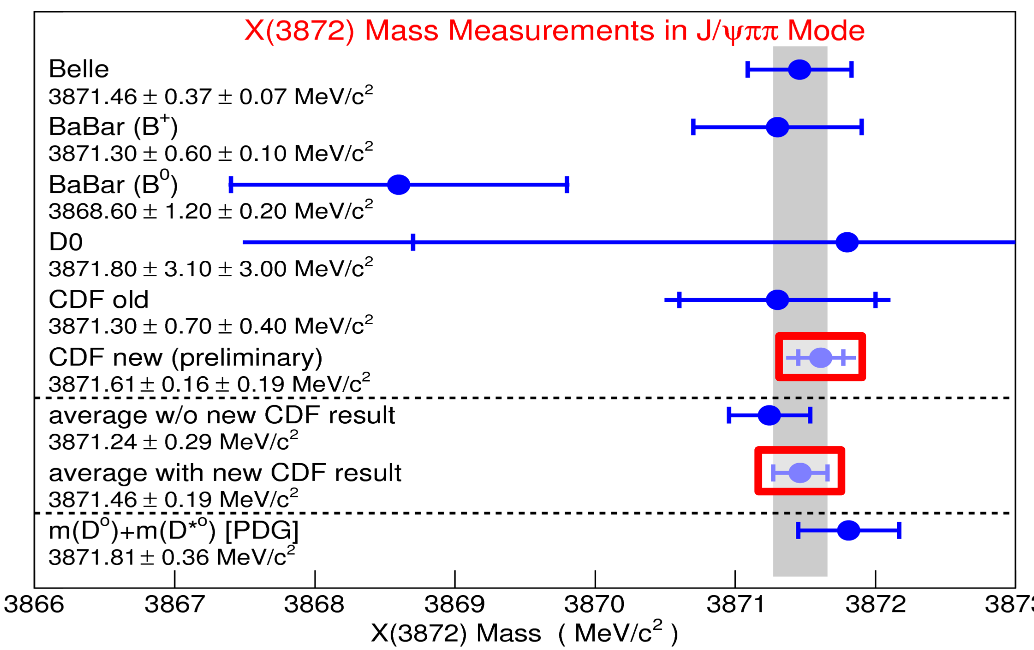


m(X(3872)) = 3871.61 +- 0.16 (stat) +- 0.19 (syst) MeV/c2.

PRL 103, 152001 (2009)

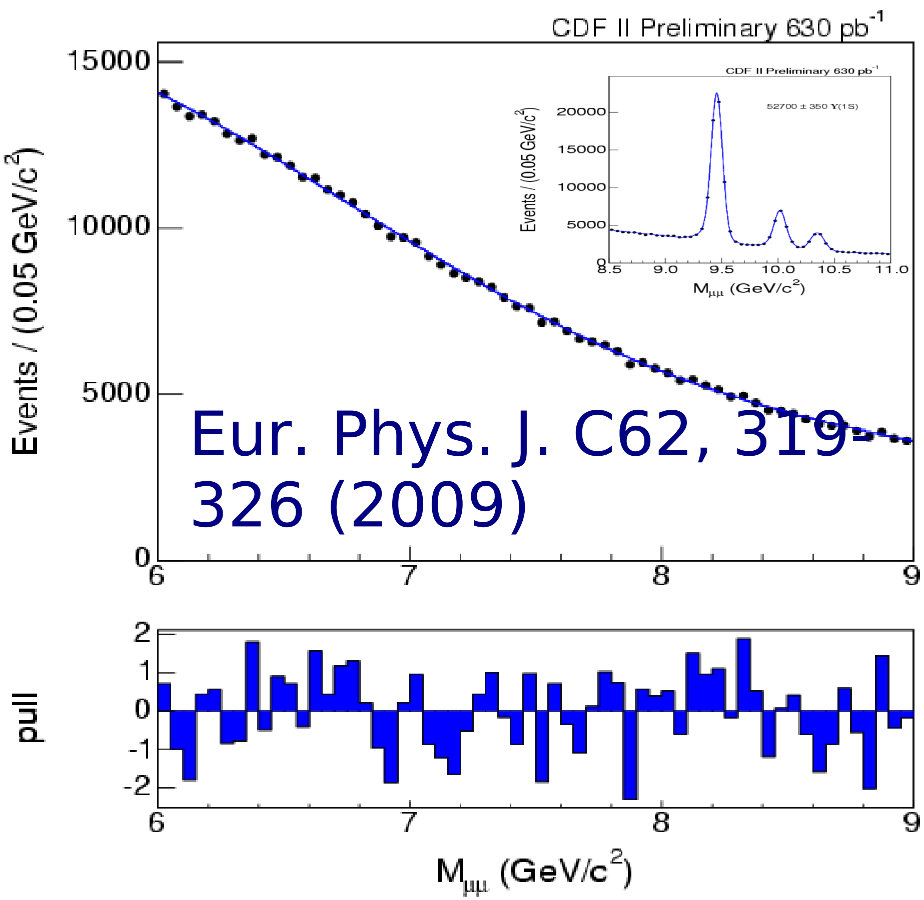
~6000 signal events
The largest sample to date

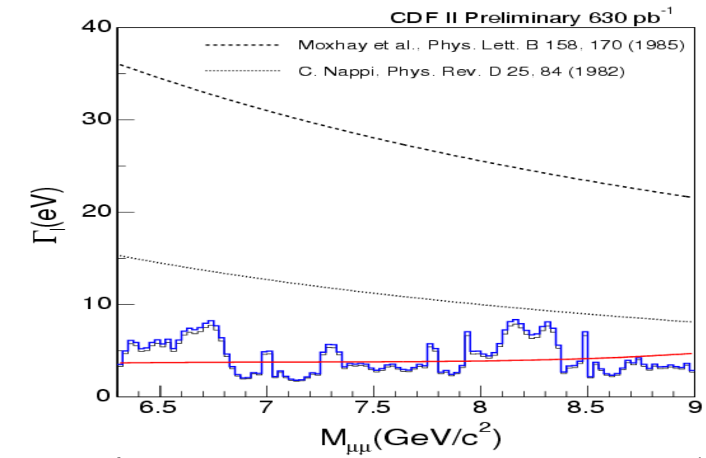
This is most precise mass measurement. Still within DD* threshold uncertainty (molecule hypothesis)
Test the hypothesis of: X(3872) composed of two states? Data consistent with 1

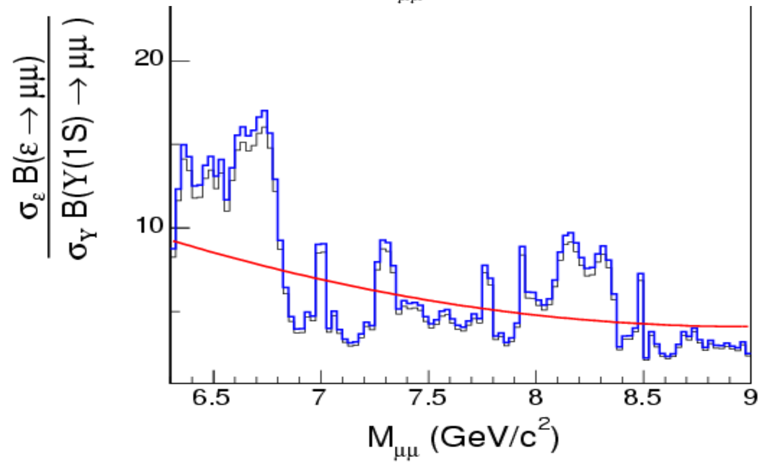


Search for Narrow Resonances

Narrow resonances decaying into $\mu^+\mu^-$ in 6.3-9.0 GeV/c^2 range





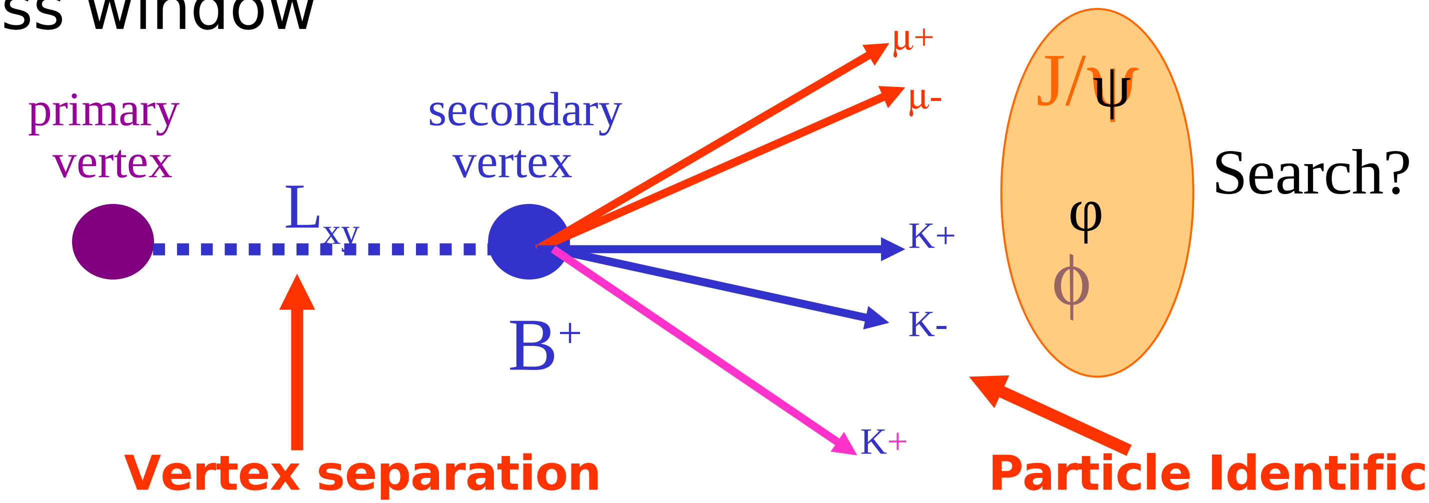


Eur. Phys. J. C62, 319-326 (2009)

Set 90% upper credible limits at about 1% on R, the ratio of the production cross section times muonic branching fraction of possible narrow resonances to that of the Υ(1S) meson. These limits correspond to an average 90% upper credible limit of < 10 eV to the leptonic with of possible resonances

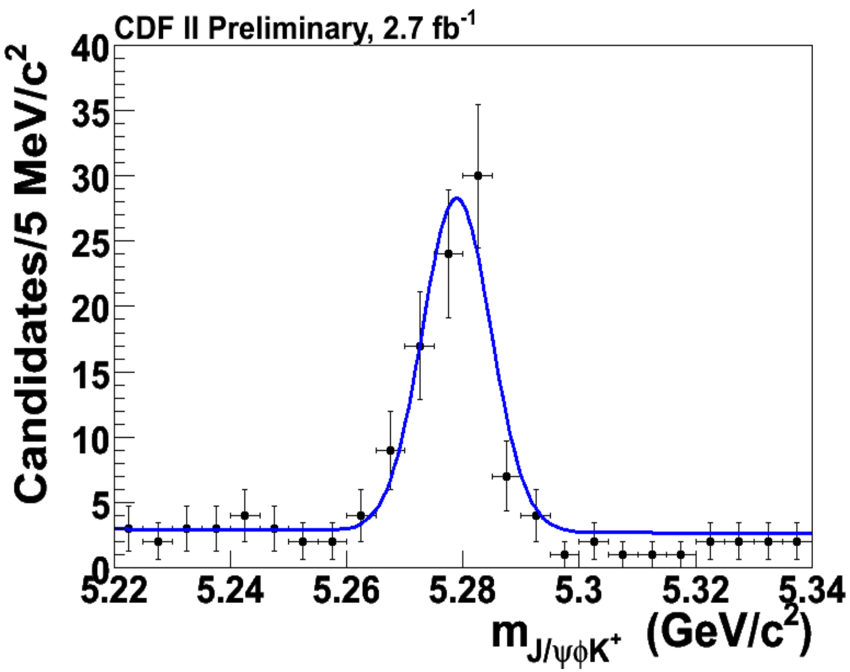
Evidence for a Near-Threshold Structure in the ***J/ψ φ*** from ***B+*** → ***J/ψ φ K+*** Decay

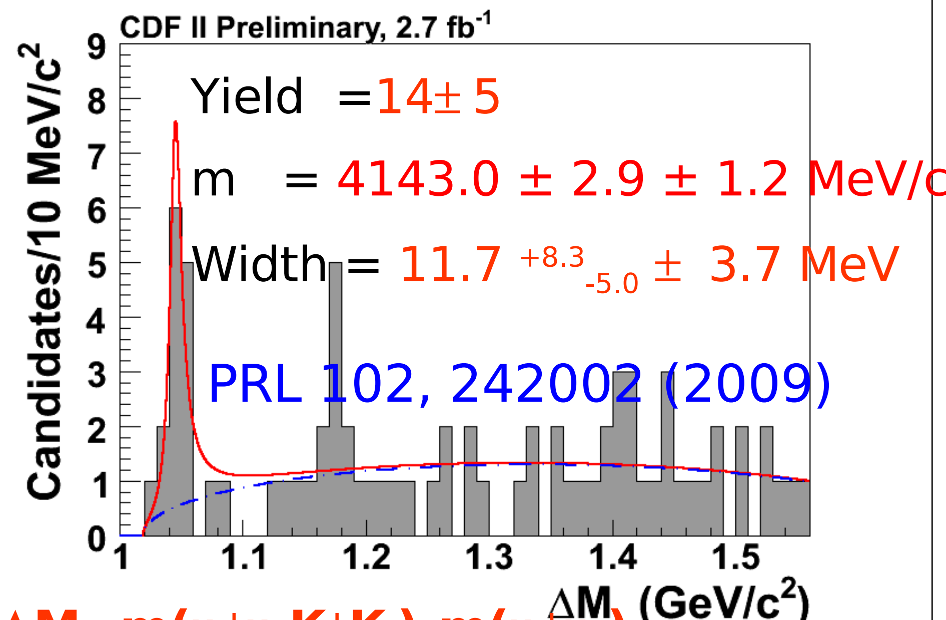
- Since ***X(3872)--2003*** many exotic mesons found
- QCD predictions : multiquark mesons molecule (qq`$\overline{qq}$`), hybrid mesons (q$\overline{g}$q), glueball (gg)
- Reconstruct B^+ as: $B^+ \rightarrow J/\psi\ \varphi\ K+$, $J/\psi \rightarrow \mu+\mu-$; $\varphi \rightarrow K+\ K-$
- Search for structure in $J/\psi\ \varphi$ mass spectrum inside B^+ mass window



- Mayor points : use L_{xy} to separate B vertex from P.V.
- Use kaon particle identification to reduce combinatorial bg.

$B^+ \to Y(4140)K^+$:near threshold structure





$\Delta M = m(\mu^+\mu^- K^+ K^-) - m(\mu^+\mu^-)$

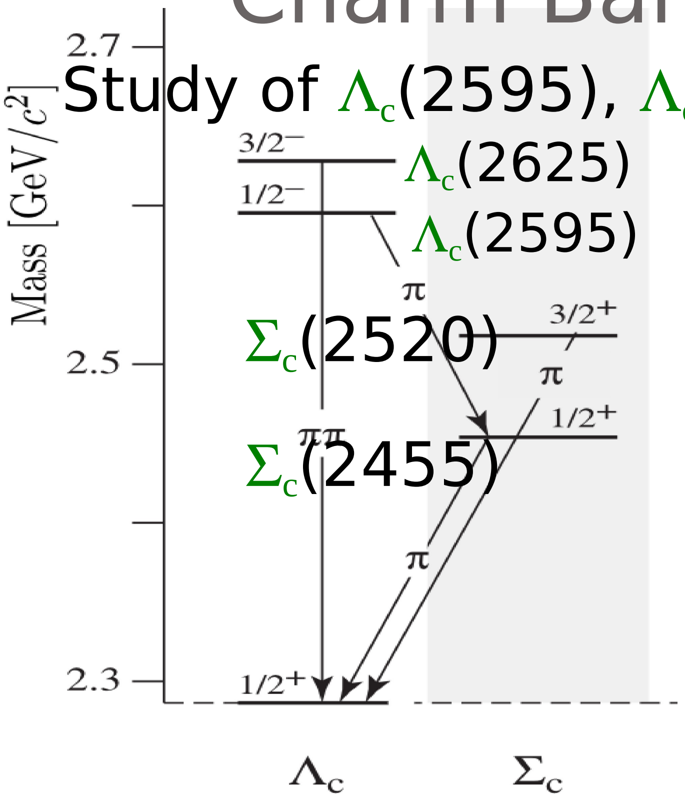
A near threshold enhancement is observed with 3.8σ significance

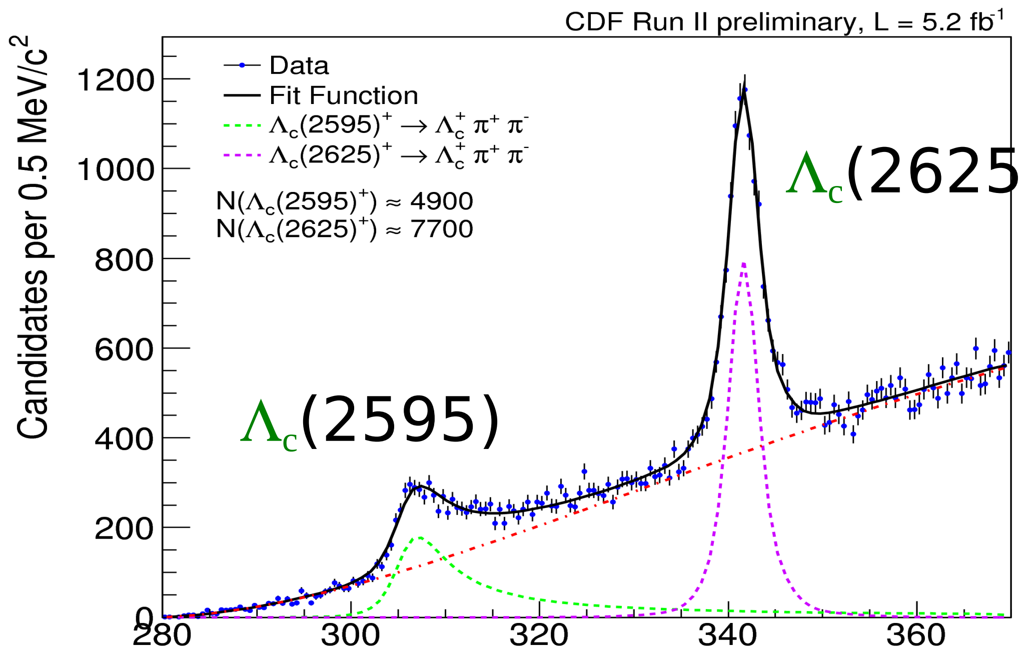
- Signal modelled with S-wave relativistic BW ⊗ resolution (1.7 MeV)
- Background : three-body decay phase space

What is it : does not fit into charmonium ; molecular?

Charm Baryon spectroscopy

Study of $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Sigma_c(2455)$ & $\Sigma_c(2520)$ Baryons



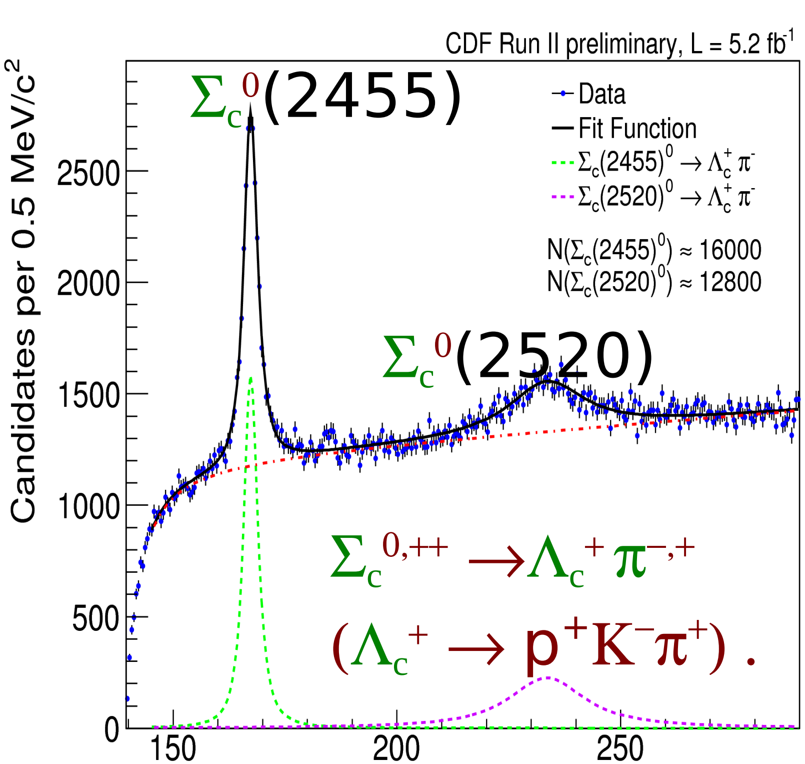


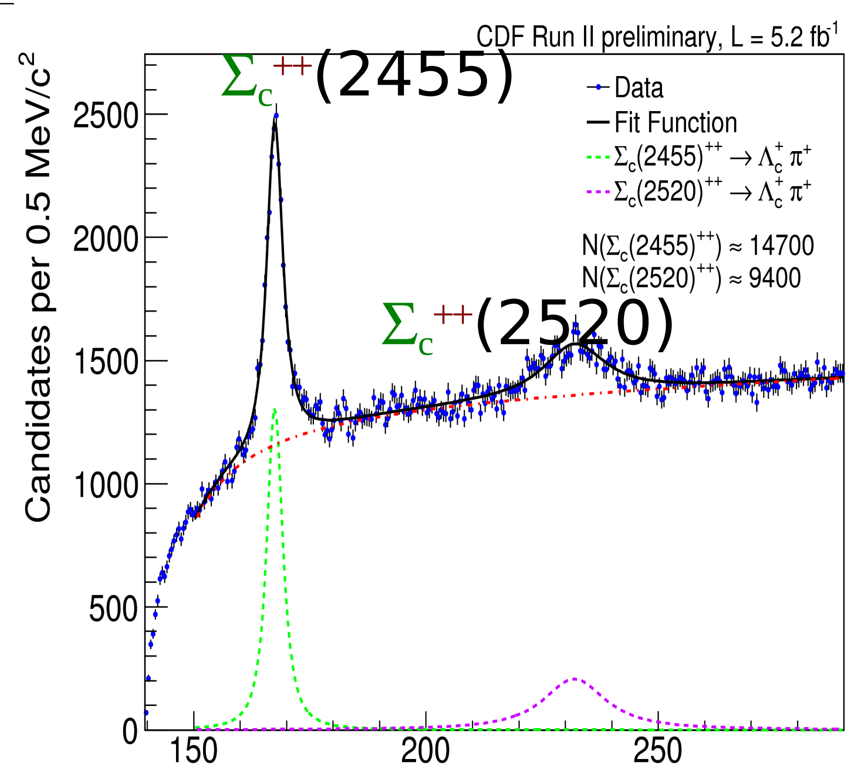
Charmed baryon system ideal for testing heavy quark symmetry

- rich mass spectrum
- relatively narrow widths of the resonances

Displaced track trigger for 2nd-ary vertex decays' selection
Lifetime, vertex fit, PID ,Dalitz used in a NN to extract signal

$\Lambda_c(2595,2625)^+ \rightarrow \Sigma_c(2455)^{0,++}\pi^{+,-}$, $\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^{-,+}$, $\Lambda_c^+ \rightarrow pK^-\pi^+$





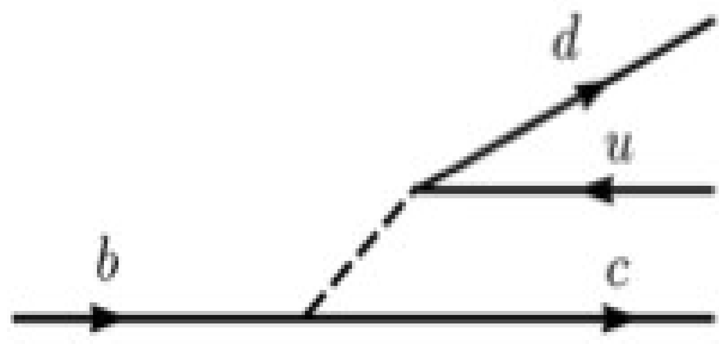
Signals modeled with convolution of Breit Wigner mass dependent width and detector resolution (from MC)
Phenomenological background functions

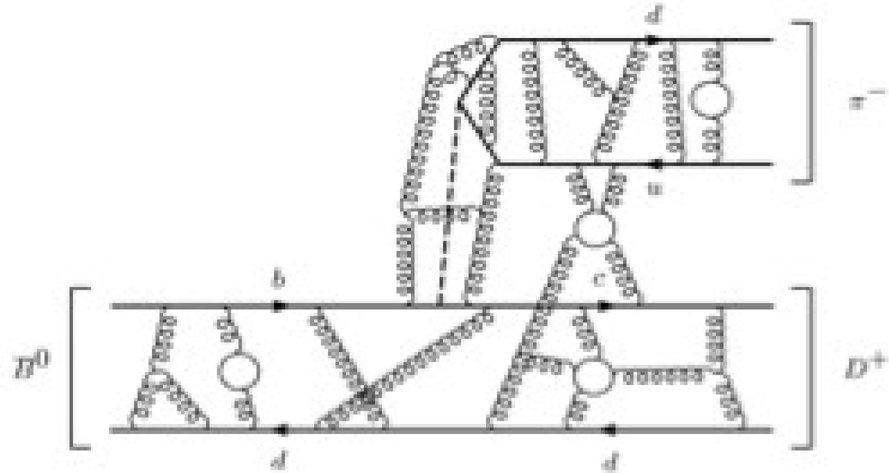
Analysis with by far highest number of signal events
$\rightarrow$ most accurate measurements of these quantities

$\Lambda_c(2595)^+$ mass ≈3 MeV/c^2 lower than previous measurements (CLEO) because of simplified assumption on BW shape

b-hadron lifetimes in decays to J/ψ

b-hadrons Lifetime: largely determined by charged weak decay of b quark
Interactions of quarks inside hadrons change these lifetimes by up to about 10%.



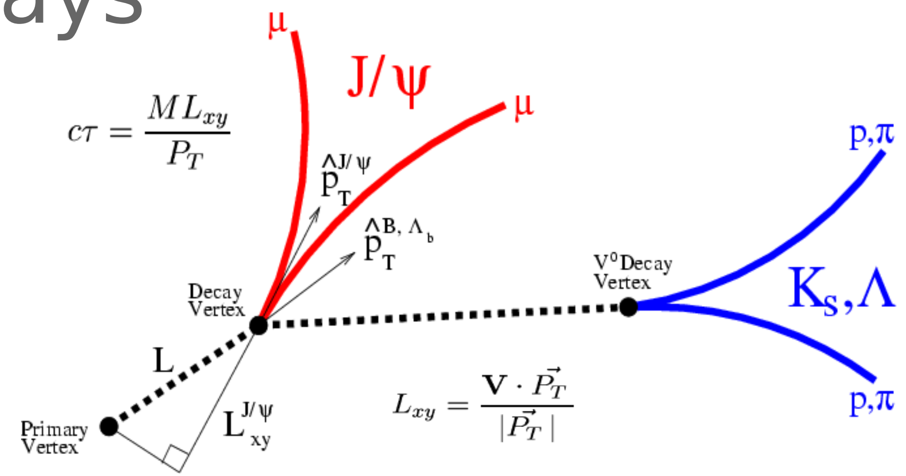


HQE predicts $\tau(B_u) > \tau(B_d) \sim \tau(B_s) > \tau(\Lambda_b) >> \tau(B_c) \rightarrow$ can be proved experimentally

Lifetime measurements allow a test of our capabilities to make precision measurements relevant for NP (oscillation, width differences)

J/ψ→μμ decays are used to find large samples of B decays

$B^+ \to J/\psi\ K^+$	45000 ± 230
$B^0 \to J/\psi\ K^*$	16860 ± 140
$B^0 \to J/\psi\ K_s$	12070 ± 120
$\Lambda_b \to J/\psi \Lambda$	1710+50



Displaced vertices and fully reconstructed decays used to measure some of the world's best lifetime measurements and ratios.

Careful and extensively-tested fitting model (developed on the decay modes with much higher statistics and then applied to Λ_b)

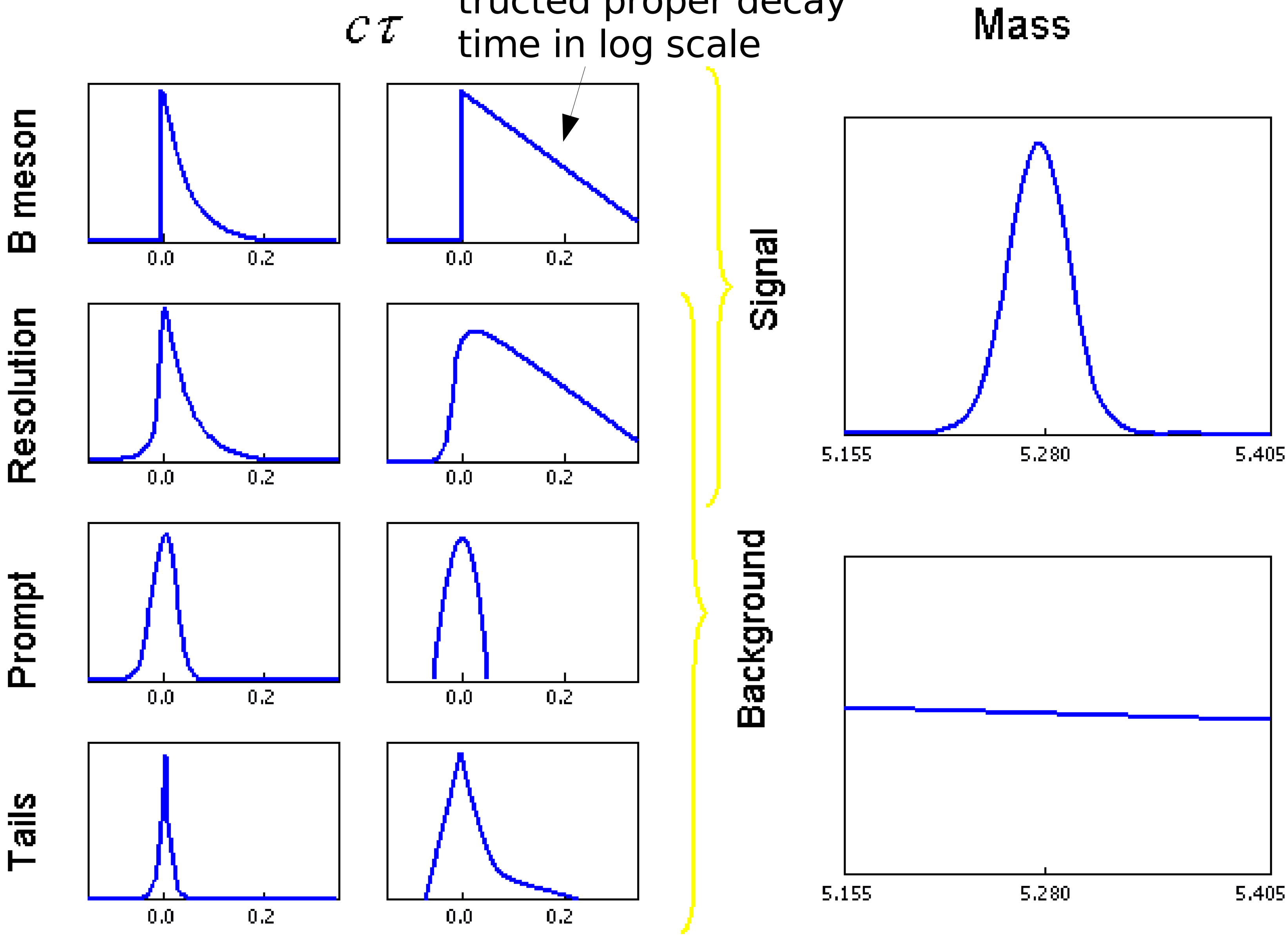
We can make precision measurements...

& HQE is a reliable framework...

How do we model this data?

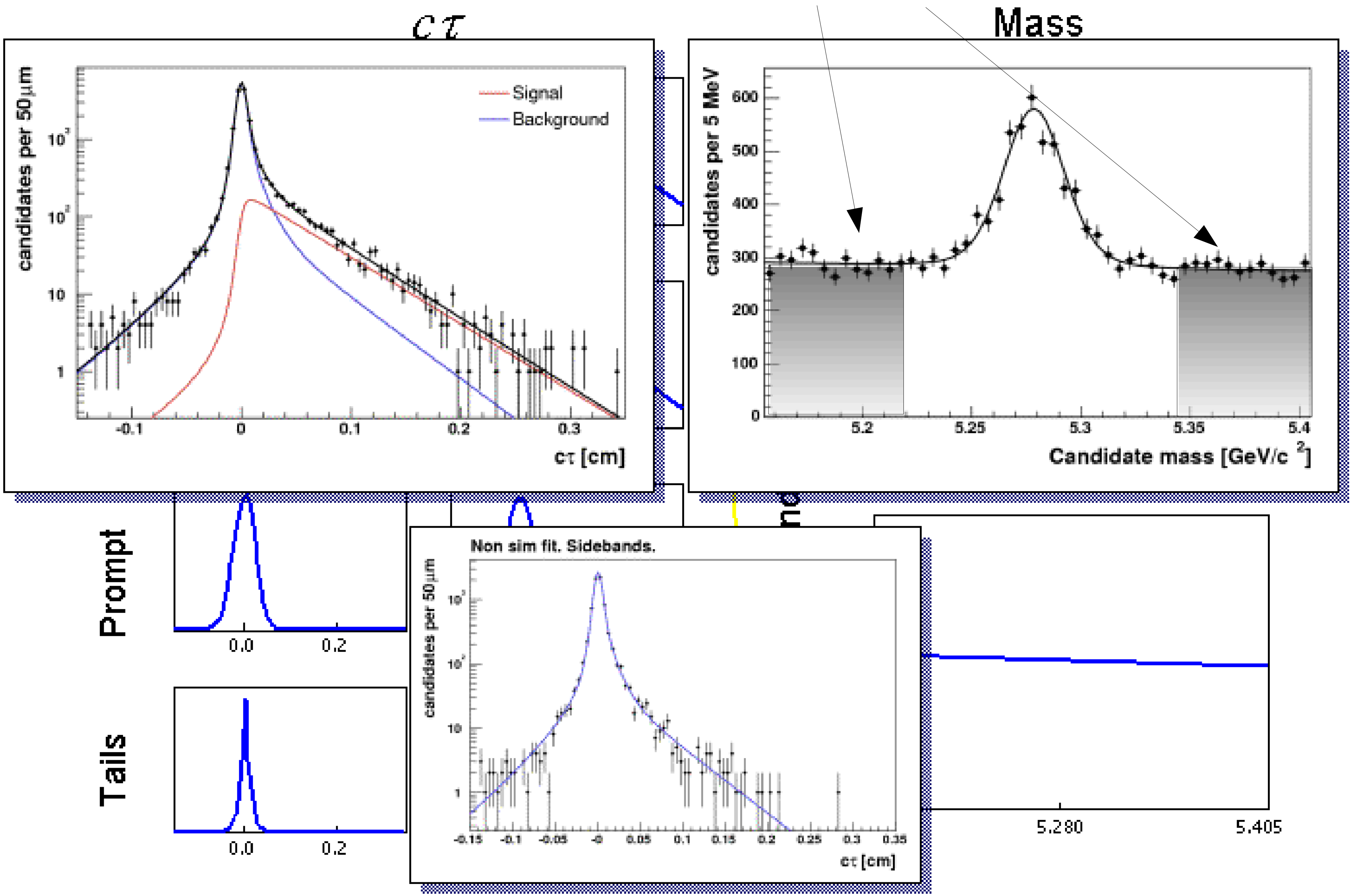
Fitting Model

Typically show reconstructed proper decay time in log scale



Fitting Model

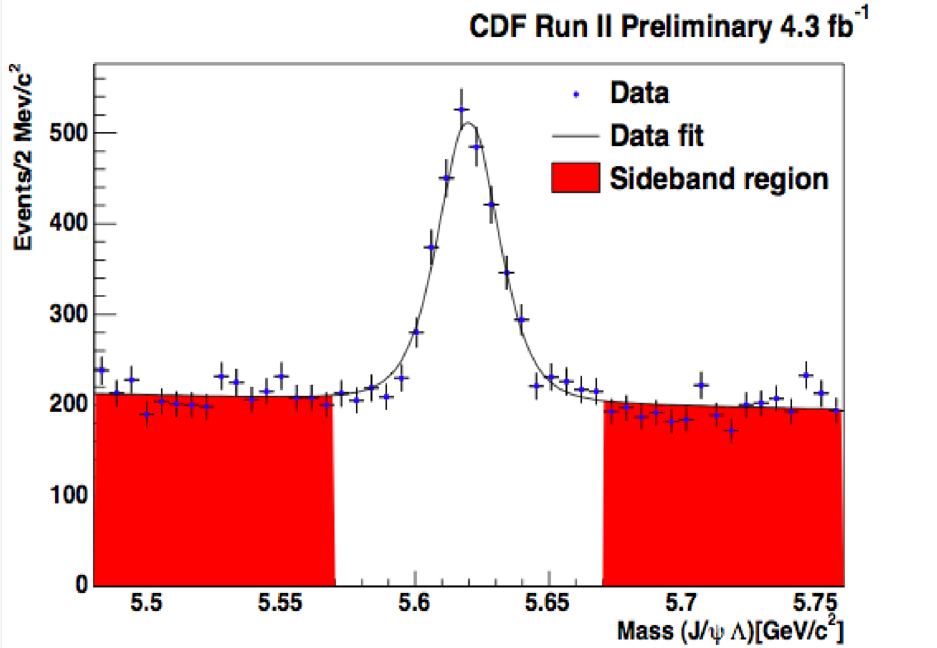
We get the resolution model from sideband events.

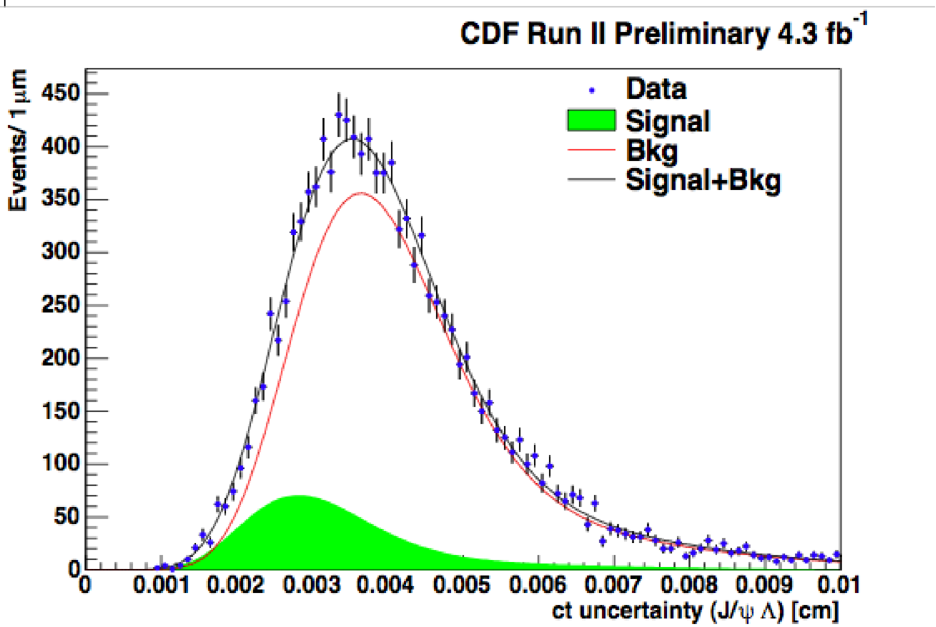


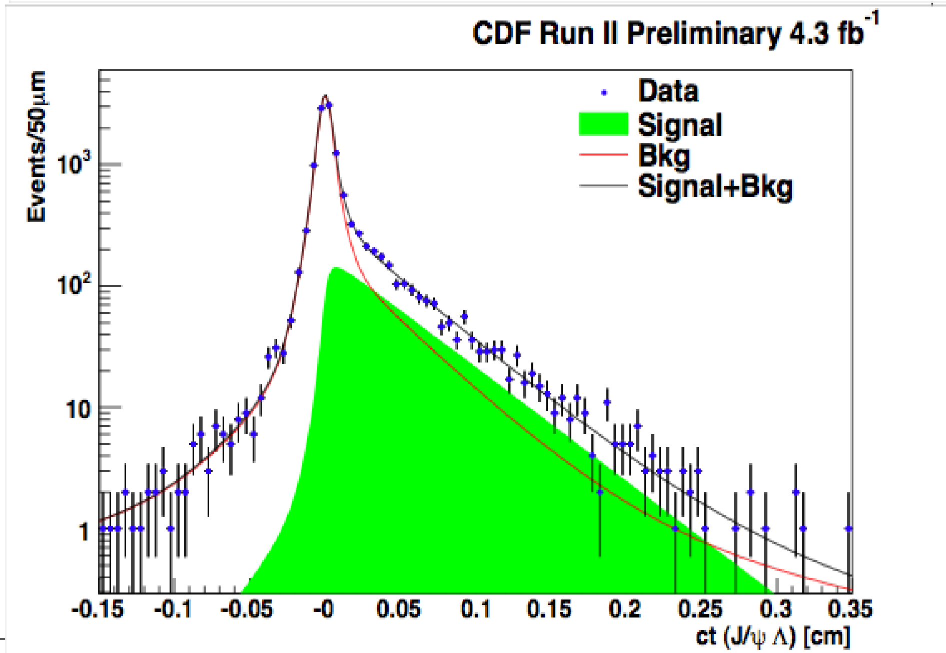
$\tau(\Lambda^0_b)$ = 1.537±0.045±0.014 ps

(first uncertainty is statistical second systematic)

This is the world's best measurement of the Λ_b lifetime







B hadron lifetime: All results

World's most precise Λ^0_b lifetime measurement

With 4.3 fb^{-1} the Λ^0_b lifetime remains higher than previous measurements.

Measured Ratio: $\tau(\Lambda^0_b)/\tau(B^0)$ =1.020± 0.030(stat)± 0.008(syst)

Theory: $\tau(\Lambda^0_b)/\tau(B^0)$ =0.88± 0.05 (A.Lenz, arXiv:0802.0977)

Some theories favour higher ratio 0.9-1.0 (I.I Bigi,hep-ph/0001003) [theory predictions for Λ^0_b less accurate than for mesons due to lack of NNLO corrections]

World's most precise measurement of $\tau(B^+)$, $\tau(B^0)$& $\tau(B^+)/\tau(B^0)$

$\tau(B^+)$= 1.639 ± 0.009(stat)± 0.009 (syst) ps

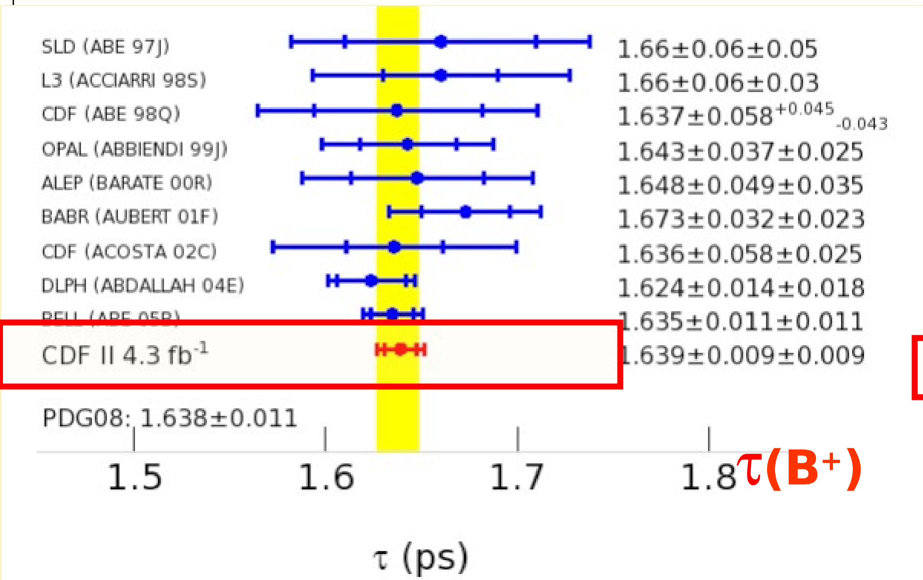
$\tau(B^0)$= 1.507 ± 0.010(stat)± 0.008 (syst) ps)

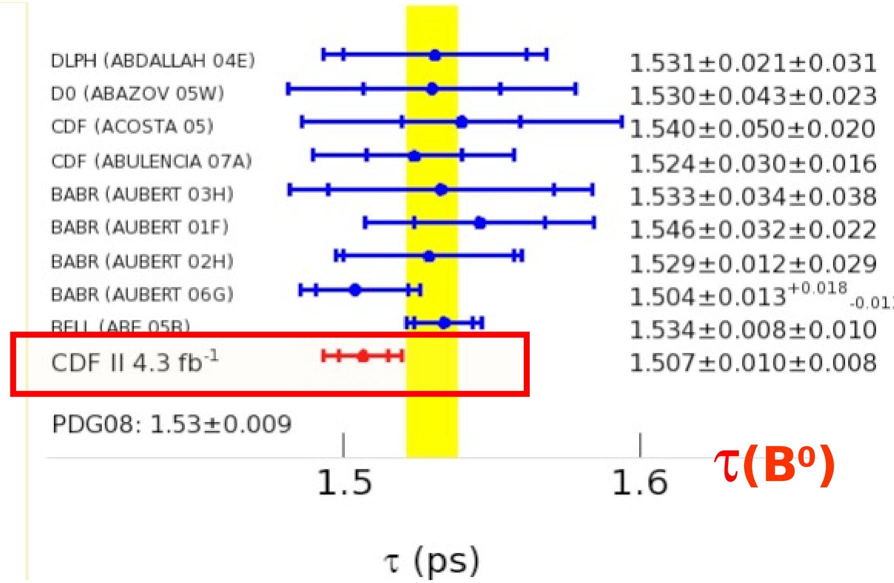
$\tau(B^+)/\tau(B^0)$= 1.088 ± 0.009(stat)± 0.004 (syst)

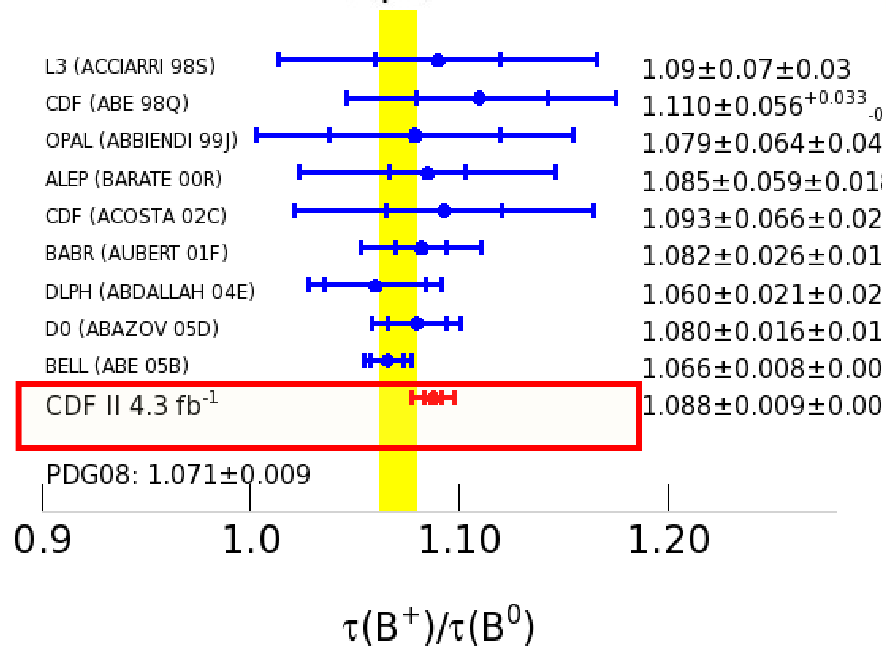
In agreement with theoretical prediction:

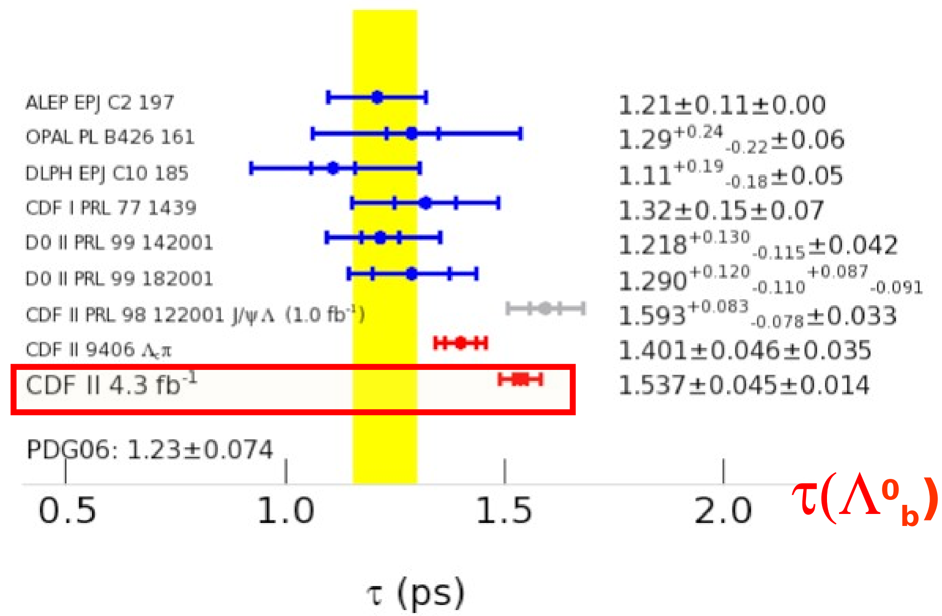
$\tau(B^+)/\tau(B^0)$ =(1.063± 0.027) (theory) [PLB667(20068),hep-ph/0310241(2004)]

B hadron lifetime: All results summary









Conclusions

Very rich heavy flavour program at CDF.
Unique to hadron colliders :
- heavy baryons
- high statistics exotic states
- precision lifetimes of all B hadrons

Large, well understood data sample.
Fantastic Tevatron performance.
Stay tuned for more...

A few exciting years of competition with LHC ahead!

Back up

How we model this data:

* The likelihood function is a sum of two terms: one for signal and one for the background.
* Each piece is probability density function (PDF) in three variables:
reconstructed mass (m)
reconstructed proper decay time (ct)
reconstructed proper decay time error (σ_{ct})
* The mass is described as:
A sum of two Gaussians, widths governed by event-per-event mass errors and collective scale factors, for the signal.
A linear background shape.
* The reconstructed proper decay time error distribution is modeled in an ad-hoc way using Gamma Distributions.

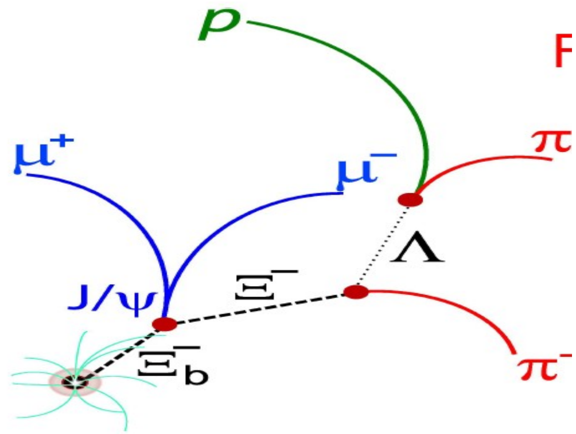
The biggest challenge is modeling the data in the very highest statistics channel.
* The reconstructed proper decay time distribution is described as:
For the signal: an exponential convolved with a model of the resolution.
For the background:
Two smeared positive exponentials models long-lived backgronds.
One smeared negative exponential models background from “other” B
A delta function convolved with the resolution-model models a background of prompt J/ψ events

We get the resolution model from sideband events.

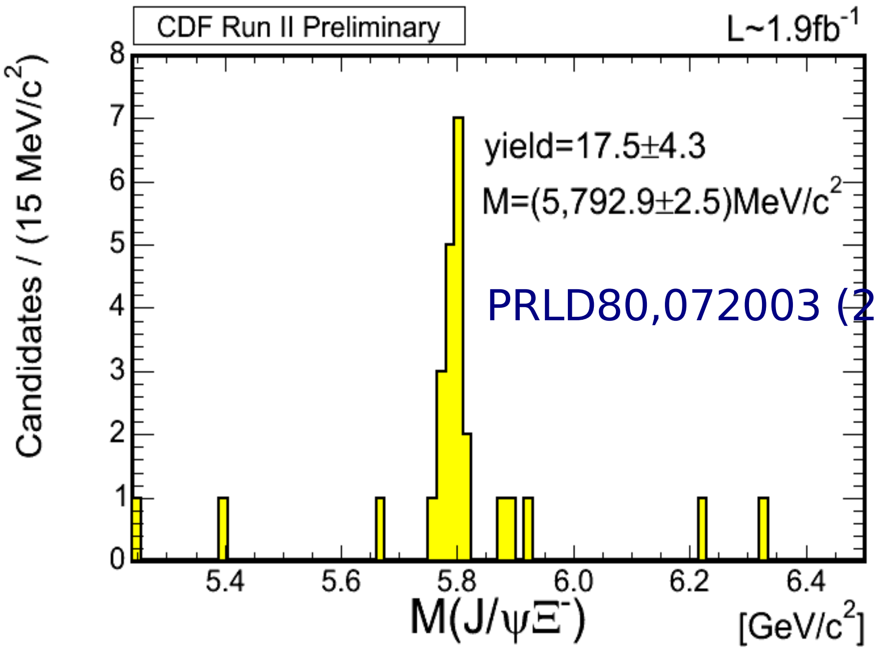
Baryon

$\Xi_b^- \rightarrow J/\Psi\ \Xi^-;\ \Xi^- \rightarrow \Lambda\ \pi^-,\ \Lambda \rightarrow p\pi^-$

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



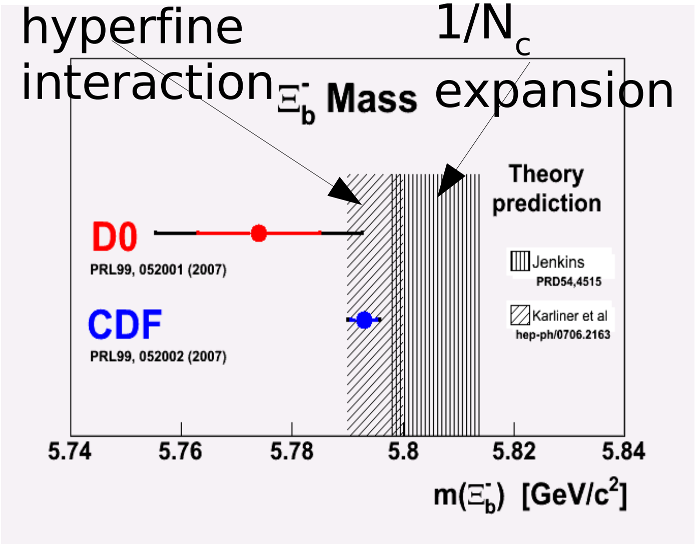
Phys. Rev. Lett. 99, 052002 (2007)



PRLD80,072003 (2009)

color hyperfine interaction

1/m_Q and 1/N_c expansion



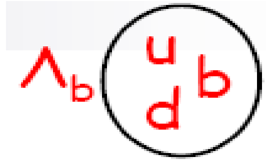
The statistical significance of the Ξ_b^- signal is over 7 σ

M(Ξ_b)=5,790.9 ± 2.6 (stat.) ± 0.9 (syst.) MeV/c2

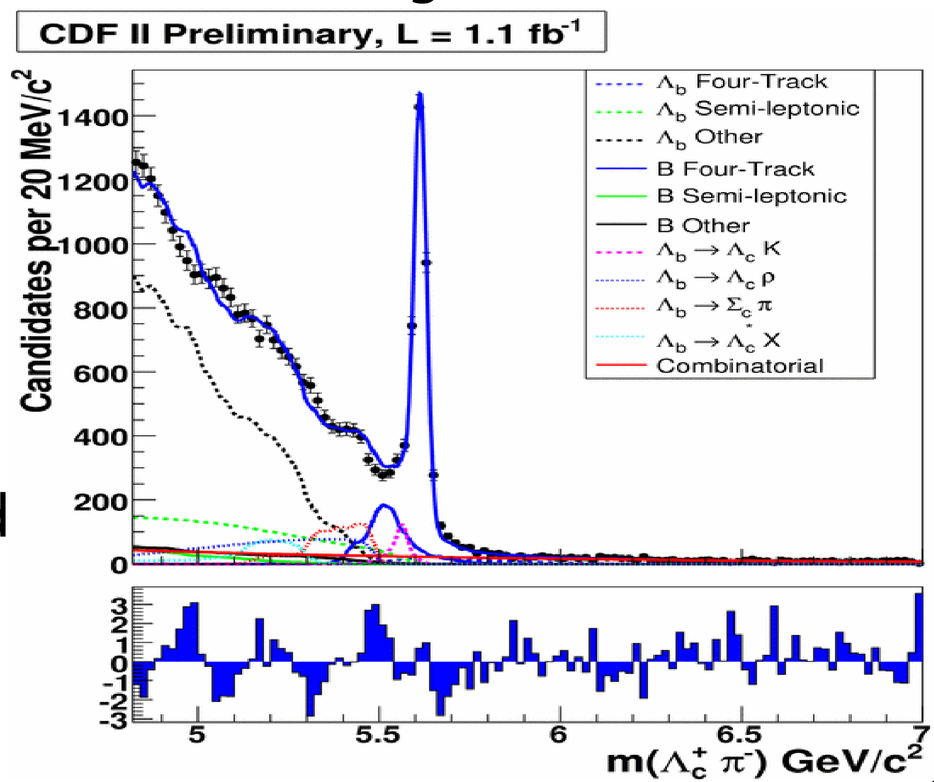
Lifetime (ps) 1.56+0.27-0.25 ± 0.02

What is our resolution model and where does it come from?
This has evolved since the first measurements:
195 pb^{-1} Use a single Gaussian, with one collective “scale” factor to describe misestimation of errors.
Use inclusive J/ψ events to derive an independent estimate of resolution fcn; take difference as a systematic error.
1 fb^{-1} Use the inclusive J/ψ events to actually determine the resolution function.
Carry out a Monte Carlo study to determine the systematic error due to the effect of selection cuts on the resolution model (particularly χ^2 cut).
4.3 fb^{-1} The inclusive J/ψ events can no longer be used to determine
the resolution model with sufficient accuracy.
We get the resolution model from sideband events. Systematic Errors now come from variations in the resolution model.

Λ_b lifetime in $\Lambda_b \to \Lambda_c \pi$

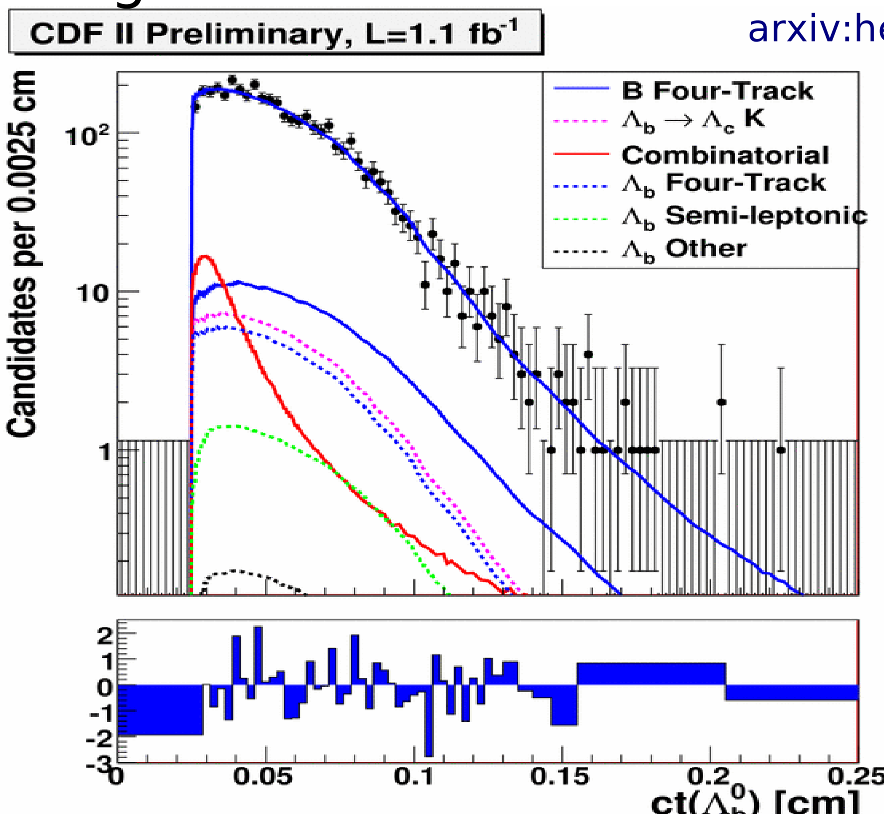


- Important test of models that describe interaction between heavy and light quarks within bound states
- Precise theoretical predictions difficult due to QCD effects
- OPE/HQET predicts lifetime hierarchy of the b-hadrons
- CDF analysis with large sample of ~3000 signal events in 1.1 fb^{-1}
- Displaced track trigger requirements : 120 μm< IP < 1 mm
- Trigger bias corrected using simulation
- Sample composition obtained from mas distribution

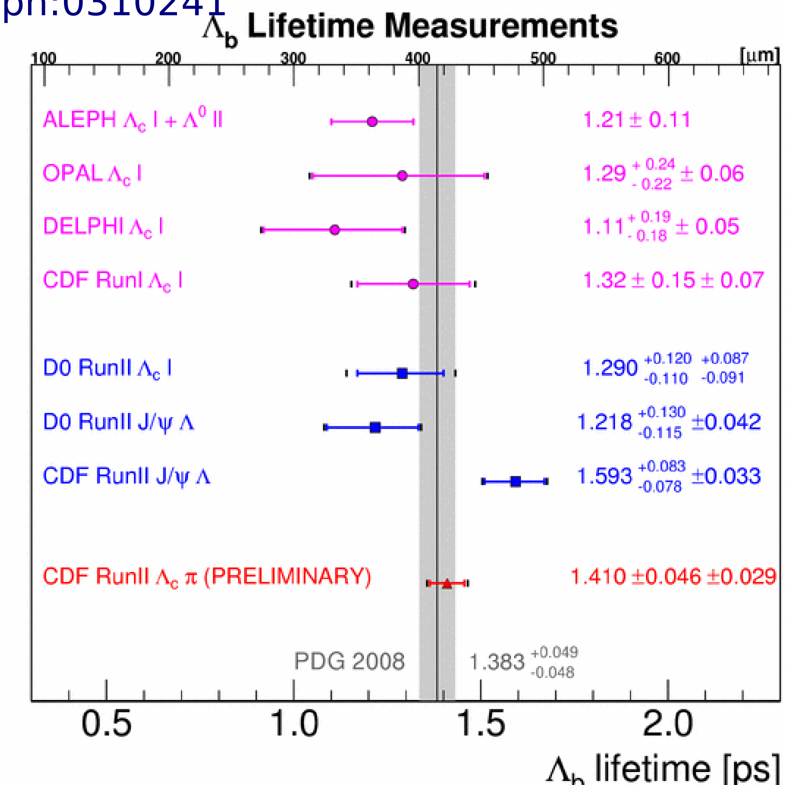


Λ_b lifetime result

- PDF is convolution of exponential, $c\tau$ resolution PDF, trigger eff.
- Precise measurement: $\tau c(\Lambda_b)=422.8 \pm 13.8(\text{stat.}) \pm 8.8(\text{syst.})\mu m$
- $\tau(\Lambda_b)/\tau(B_0) = 0.922 \pm 0.039$
- Good agreement with theory (0.88 ± 0.05) and previous world average



arxiv:hep-ph:0310241



http://www-cdf.fnal.gov/physics/new/bottom/080703.blessed-lblcpi-ct/

m(Σb+) = 5807.8+2.0-2.2(stat.) ± 1.7(syst.

m(Σb¯) = 5815.2 ± 1.0(stat.) ± 1.7(syst.) MeV

m(Σb*+) = 5829.0+1.6-1.8(stat.) +1.7-1.8(sy

m(Σb*¯) = 5836.4+2.0-1.8(stat.) +1.8-1.7(sys

- Predictions for masses come from non relativistic and relativistic potential quark models

- Baryons with a b quark and two light quarks described by HQET

π_s^+