Heavy Flavor spectroscopy at the Tevatron

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QCD 2010

Montpellier, 2-07-2010

In this talk:

- Tevatron detectors and B physics triggers
- b-Baryons observations and properties (Ξ_b , Ω_b)
- b-hadrons lifetimes (particularly Λ_b)
- Bottom-onium polarization
- Charm-onium–like resonances, X(3872) and Y(4140)
- Conclusions

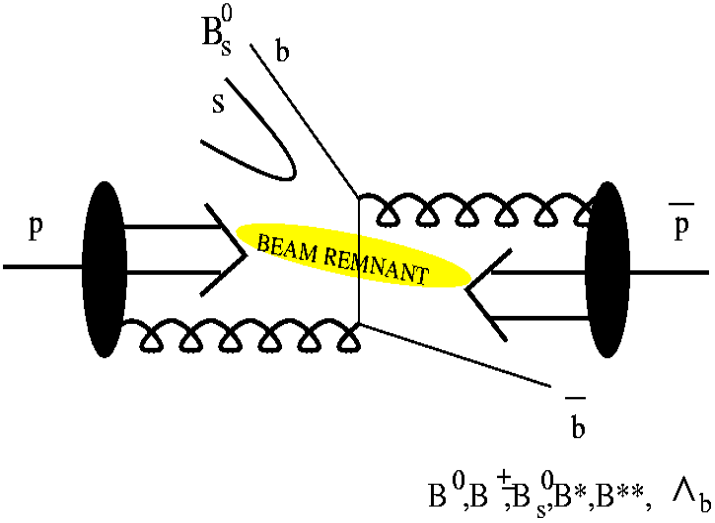
What is not in this talk:

CAVEAT: "*Heavy flavor properties*" is a huge and very rich field for Tevatron experiments, only CDF published 58 Run II papers till now !

→ *choose not to cover:*

- b-bbar and c-cbar production and correlations
- Charm physics (D^0 mixing and direct CPV)
- Charmed Baryons
- and … many other heavy hadron studied decay modes

B Physics at Collider



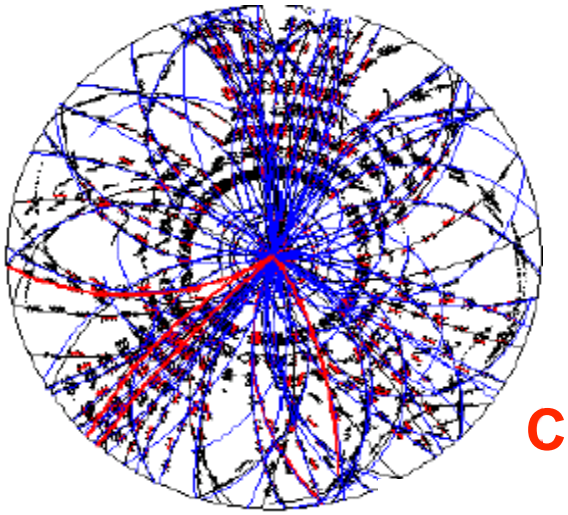
- All *B* species produced:

  $B_u, B_d, B_s, B_c, \Lambda_b, \Xi_b \ldots$

- With production fractions:

  $f_u : f_d : f_s : f_\Lambda \approx 4 : 4 : 1 : 1$

- Acceptance for other B is 20-40%

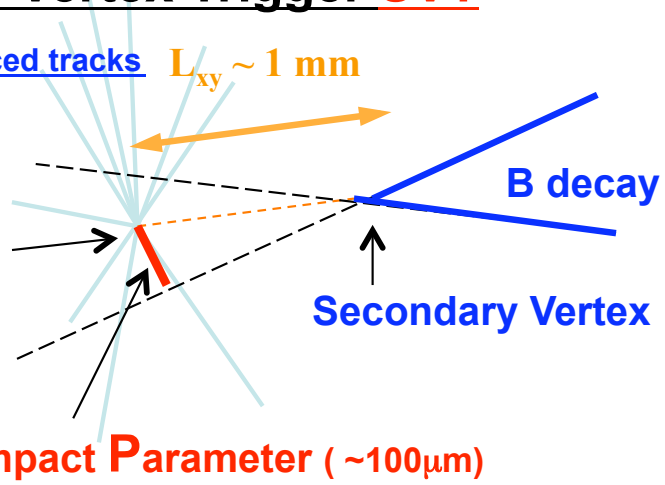


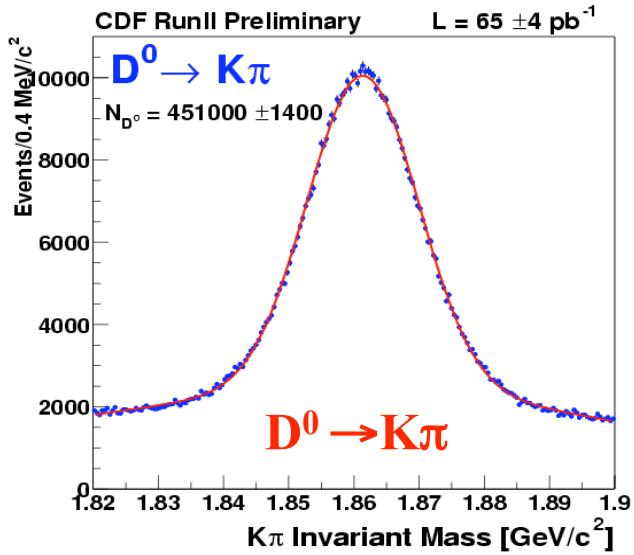
CDF

BUT: $\sigma(bb) << \sigma(pp)$ (~65 mb) ⇒ B have to be selected with specific Triggers

the CDF Secondary Vertex Trigger SVT

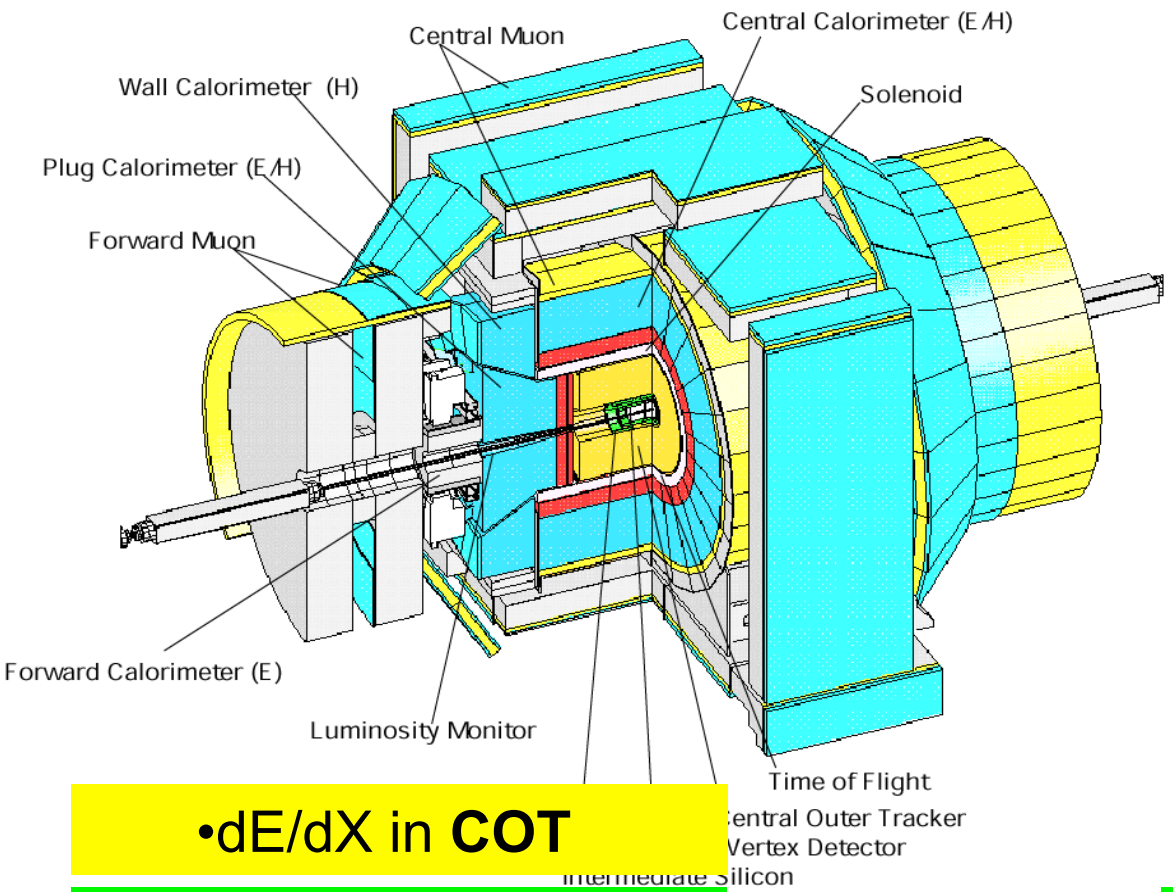
- **Online (L2) selection of displaced tracks based on Silicon detector hits.**

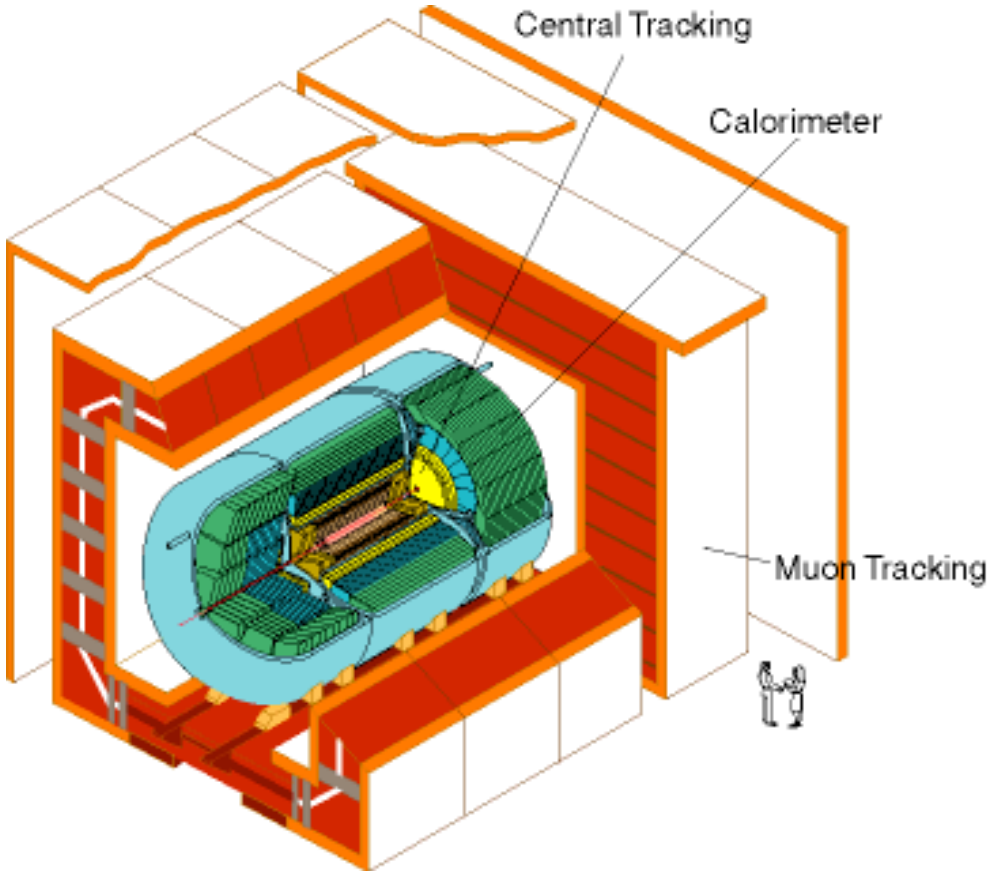




- b production is very large (~300 Hz @ 10^{32} cm^{-2} Hz) → trigger on specific decays

The run II detectors





- dE/dX in **COT**
- **Time Of Flight** detector

- **B-layer** to improve tracking resolution

Muons: CMU, CMP, CMX ($|\eta|<1.1$)

Muons: larger coverage ($|\eta|<1.8$)

Electrons: CEM (EM calorimeter)
CPR (pre-shower detector)

Electrons: liquid argon ECAL

B physics triggers at TeVatron

Conventional at colliders (Run I / D0)

Di-Muon (J/ψ)

Pt(μ) > 1.5 GeV

J/ψ modes down to low Pt(J/ψ)~0 (Run II)

+

With SVT trigger (at CDF)

1-Displaced track + *lepton* (*e*, *μ*)

120 μm < I.P.(trk) < 1mm

P_T(*lepton*) > 4 GeV

Semileptonic modes

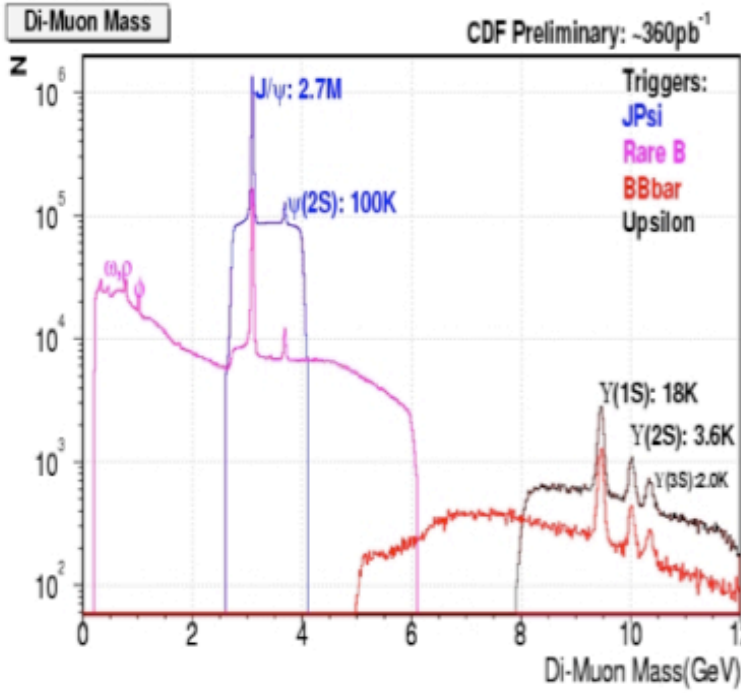
2-Displaced tracks

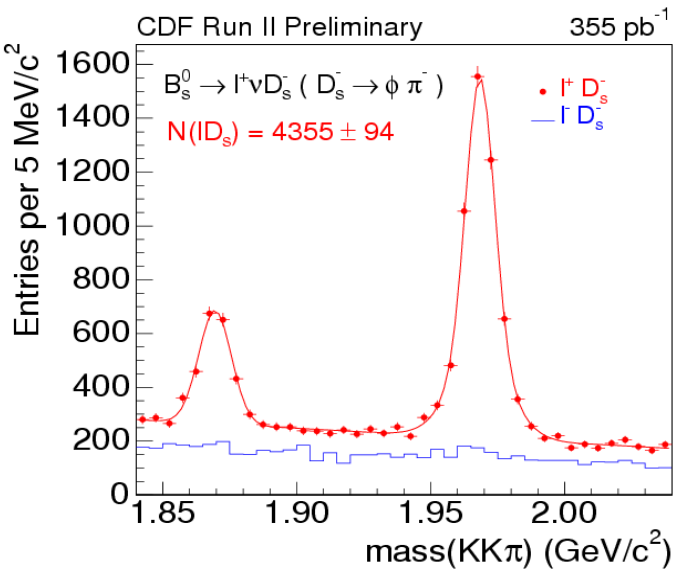
P_T(trk) > 2 GeV

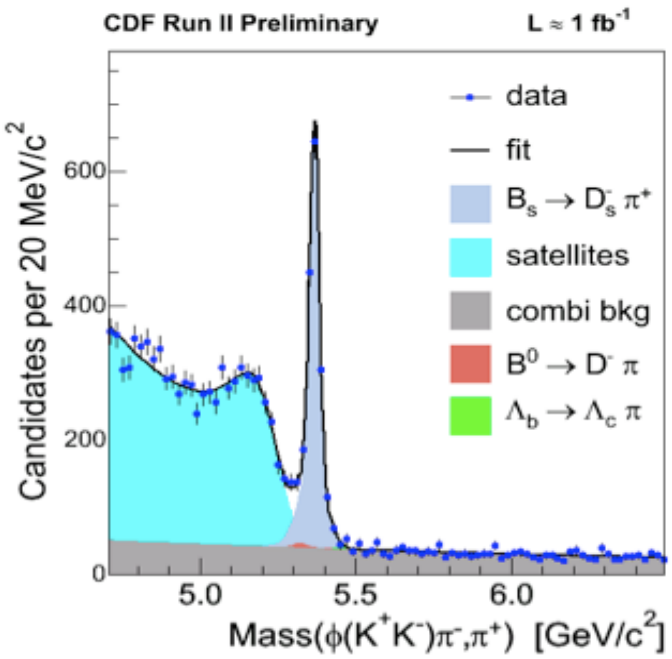
120 μm < I.P.(trk) < 1mm

Σp_T > 5.5 GeV

fully hadronic modes







b – Baryons

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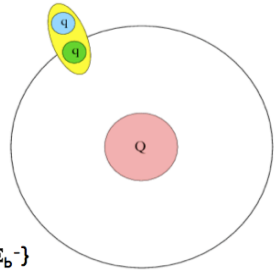
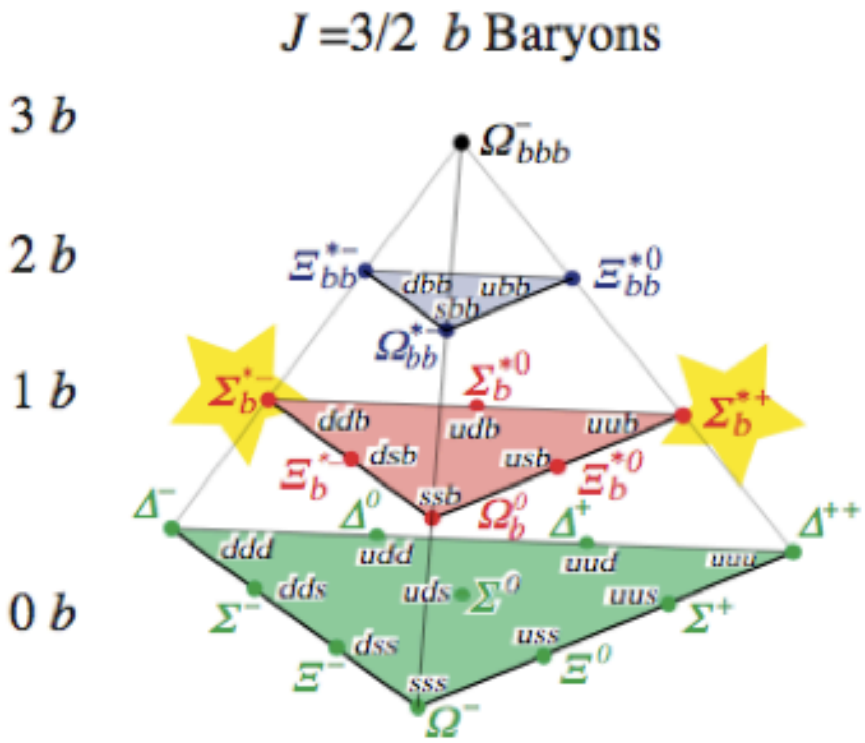
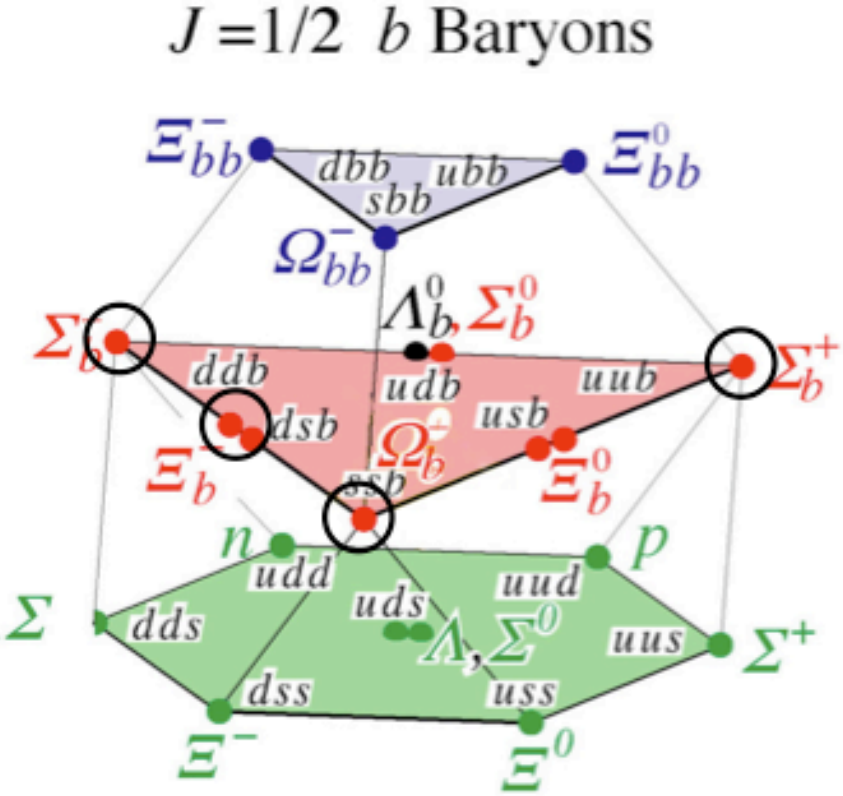


- This is totally a Tevatron field (b baryons copiously produced)

  - $\Sigma_b^{(*)+}$ and $\Sigma_b^{(*)-}$ observed in 2006 → updated with 5 fb^{-1}
  - Ξ_b^- observed by in 2007 → updated with 4.3 fb^{-1}
  - Ω_b^- observed in 2008
  - Several analyses involving Λ^0_b





Ξ_b and Ω_b reconstruction

Search for Ξ_b^- and Ω_b^- in the decays

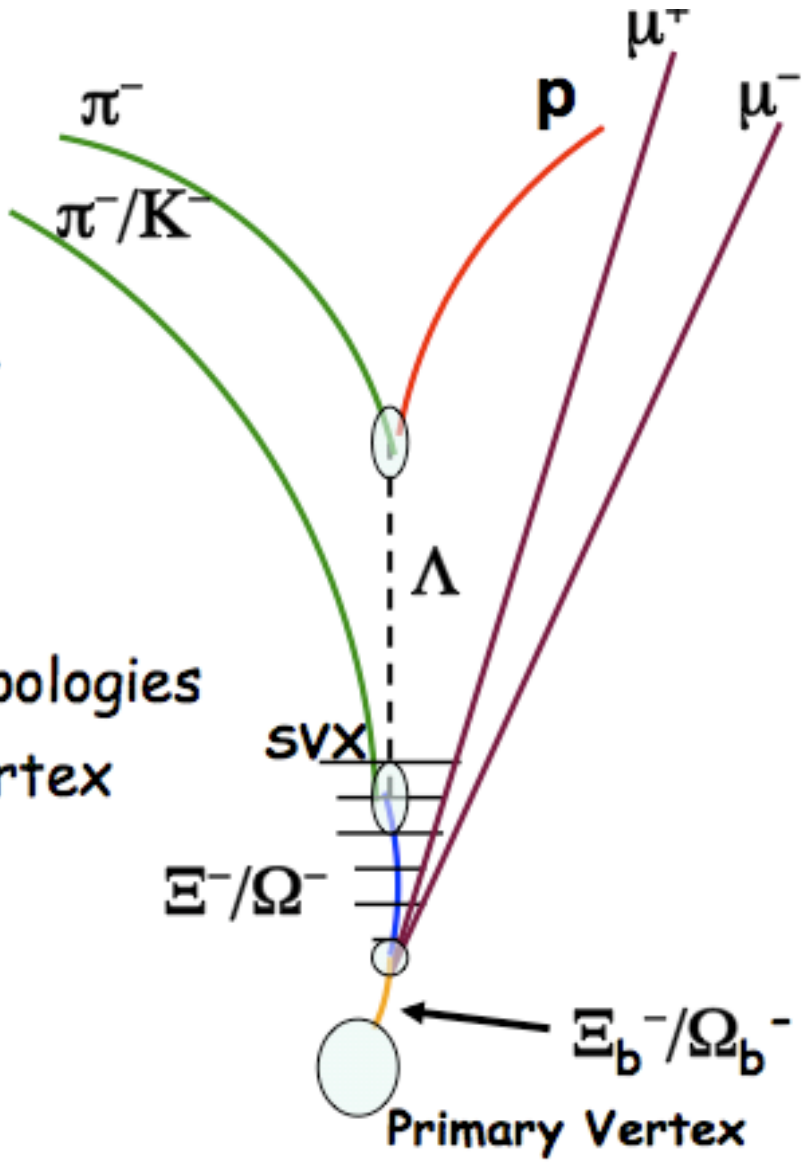
$\Xi_b^- \rightarrow J/\psi\ \Xi^-,\ J/\psi \rightarrow \mu^+\mu^-,\ \Xi^- \rightarrow \Lambda\pi^-$

$\Omega_b^- \rightarrow J/\psi\ \Omega^-,\ J/\psi \rightarrow \mu^+\mu^-,\ \Omega^- \rightarrow \Lambda K^-$

5-track, 3-vertex kinematic fit

- $\mu^+\mu^-$ constrained to J/ψ mass
- Trajectories constrained to appropriate topologies
- Reconstructed Ξ^-/Ω^- constrained to $\mu^+\mu^-$ vertex

Long life of the Ξ^- and Ω^- leaves hits in the silicon detector (unique to baryons)



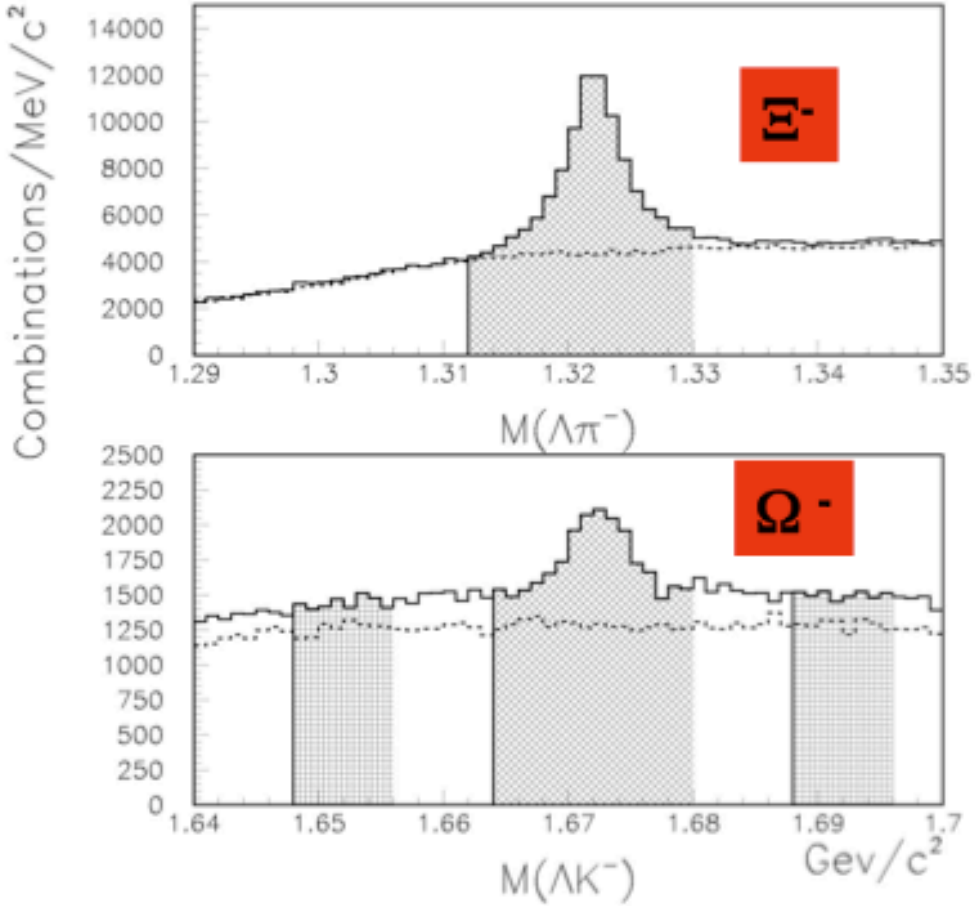
Inclusive Ξ^- and Ω^- samples

Base sample is given by

- $1.1077 < M(p\pi) < 1.1237$
- $P_T(\Xi/\Omega) > 2.0$
- $\text{Flight}(\Lambda/\Xi^-/\Omega^-) > 1$ cm
- $\text{Impact}(\Xi^-/\Omega^-) < 3\sigma$
- $P(\chi^2) > 10^{-4}$
- $P(\chi^2)_{used} > P(\chi^2)_{swapped}$
- Veto $1.311<M(\Lambda\pi)<1.331$ for ΛK sample (Ξ^- reflection)

Yields in the J/ψ sample:

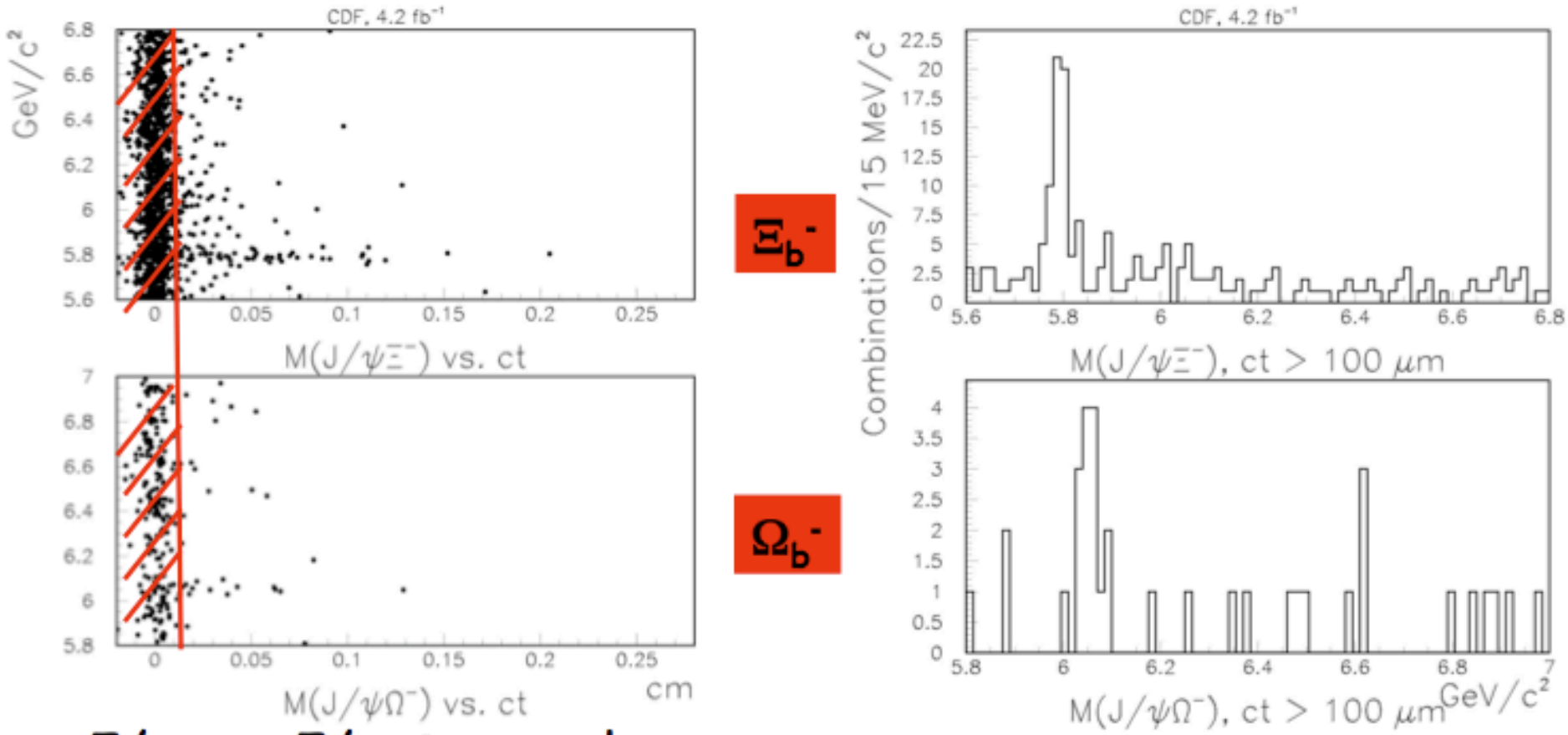
- Ξ^- : 41,000
- Ω^-: 3,500



Dashed histograms are WS $\Lambda\pi^+/K^+$

Shaded are selection and SB region

Ξ_b and Ω_b signals



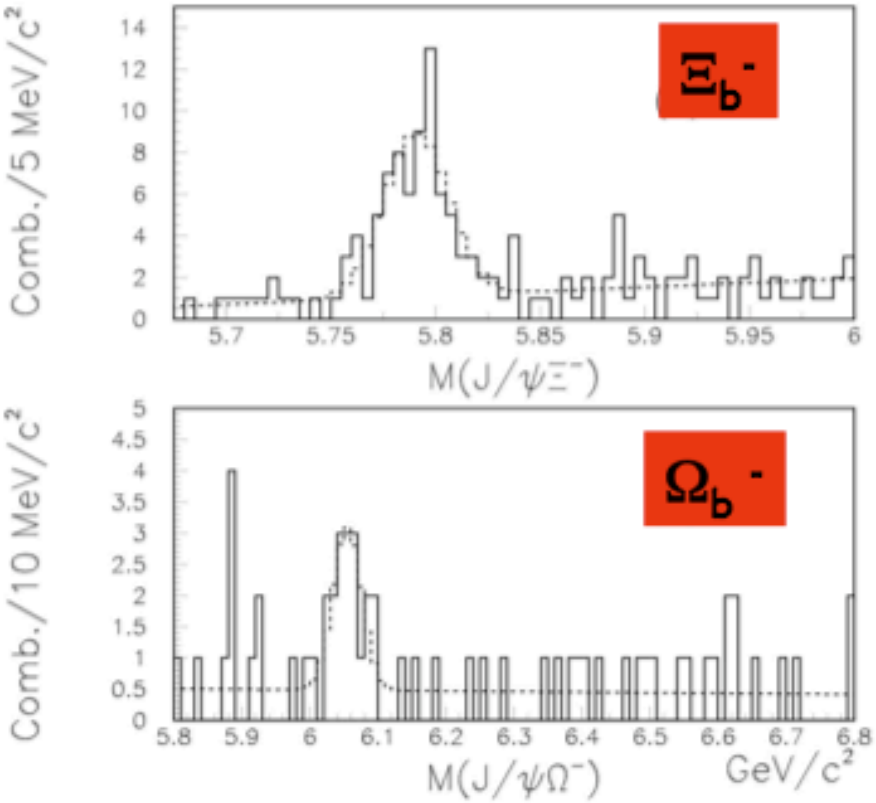
$J/\psi\Xi^-$, $J/\psi\ \Omega^-$ samples

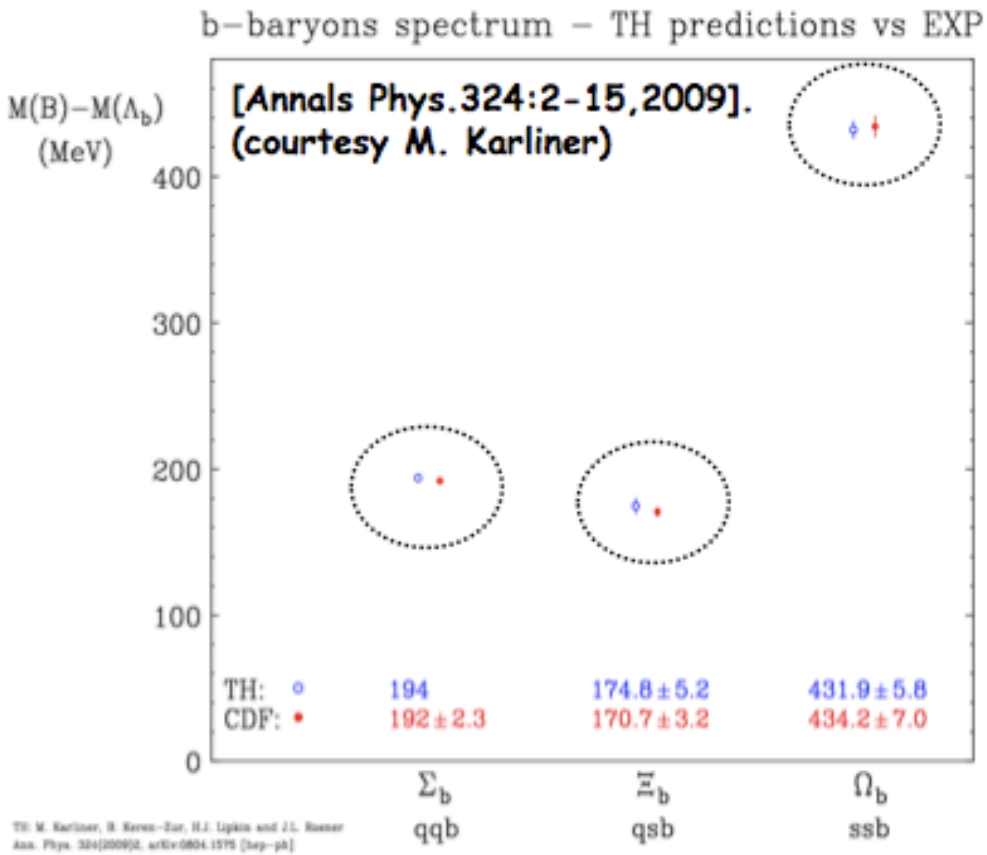
Obvious Ξ_b^- signal when **ct** > 100 μm

Cluster in the $J/\psi\ \Omega^-$ around 6.05 GeV/c^2

Test of Ω_b^- significance finds 5.5σ (with no ct cut)

Ξ_b and Ω_b mass measurements





$m(\Xi_b^-)$: 5790.9 ± 2.6(stat.) ± 0.8(syst.) MeV/c^2

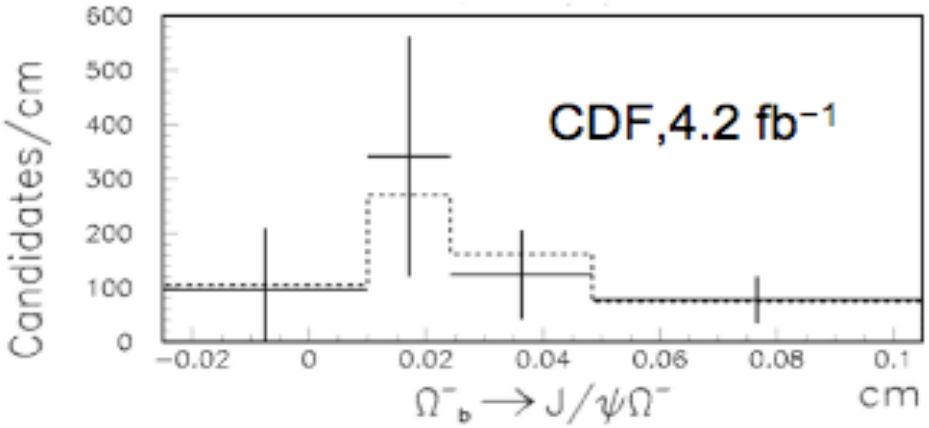
$m(\Omega_b^-)$: 6054.4 ± 6.8(stat.) ± 0.9(syst.) MeV/c^2

Systematic uncertainty

- 0.55 MeV from $B^0(K_s)$ error scale by 80% for kinetic energy in the decay
- 0.5 MeV from Λ_b resolution treatment (considered largest possible)
- 0.3 MeV from Ω^- mass

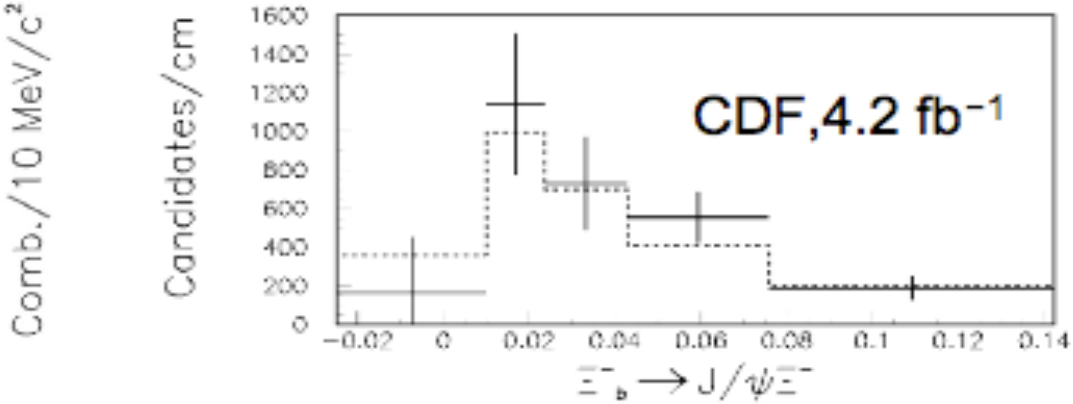
Ξ_b and Ω_b lifetimes and production rate

Ω_b^-



Lifetimes

Ξ_b^-



$$\tau(\Omega_b^-) = 1.13^{+0.53}_{-0.40}(\text{stat.}) \pm 0.02(\text{syst.})\ \text{ps}$$

$$\tau(\Xi_b^-) = 1.56^{+0.27}_{-0.25}(\text{stat.}) \pm 0.02(\text{syst.})\ \text{ps}$$

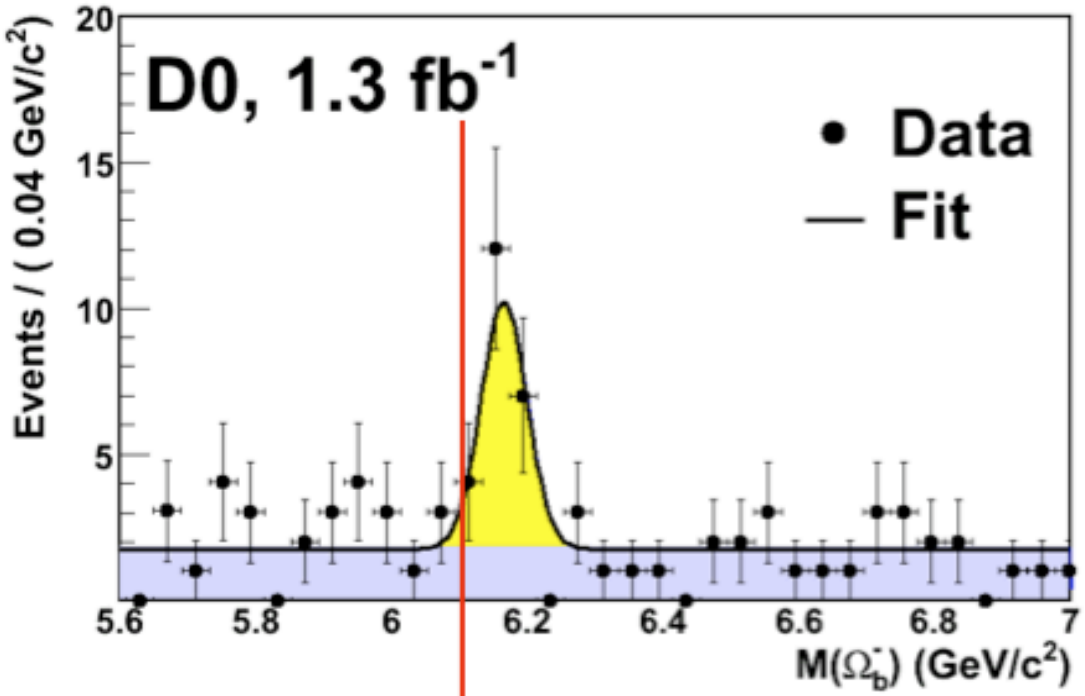
CDF: Phys. Rev. D80, 072003 (2009)

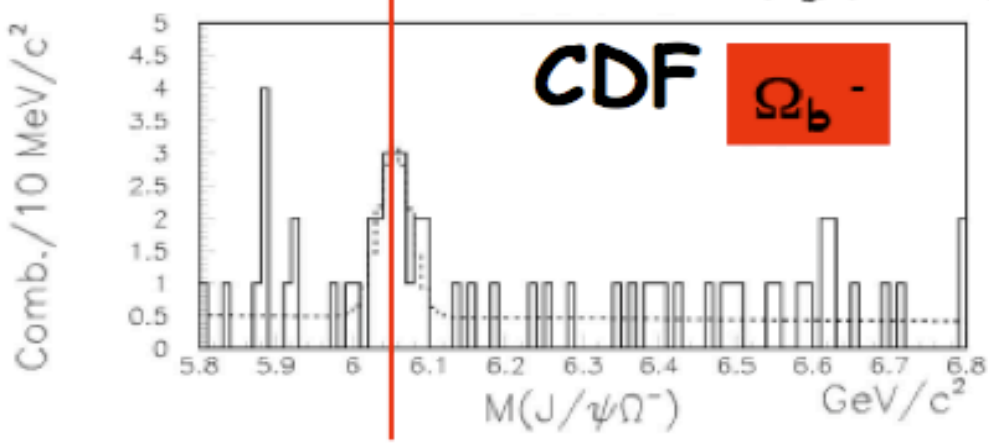
… and production rates relative to Λ_b

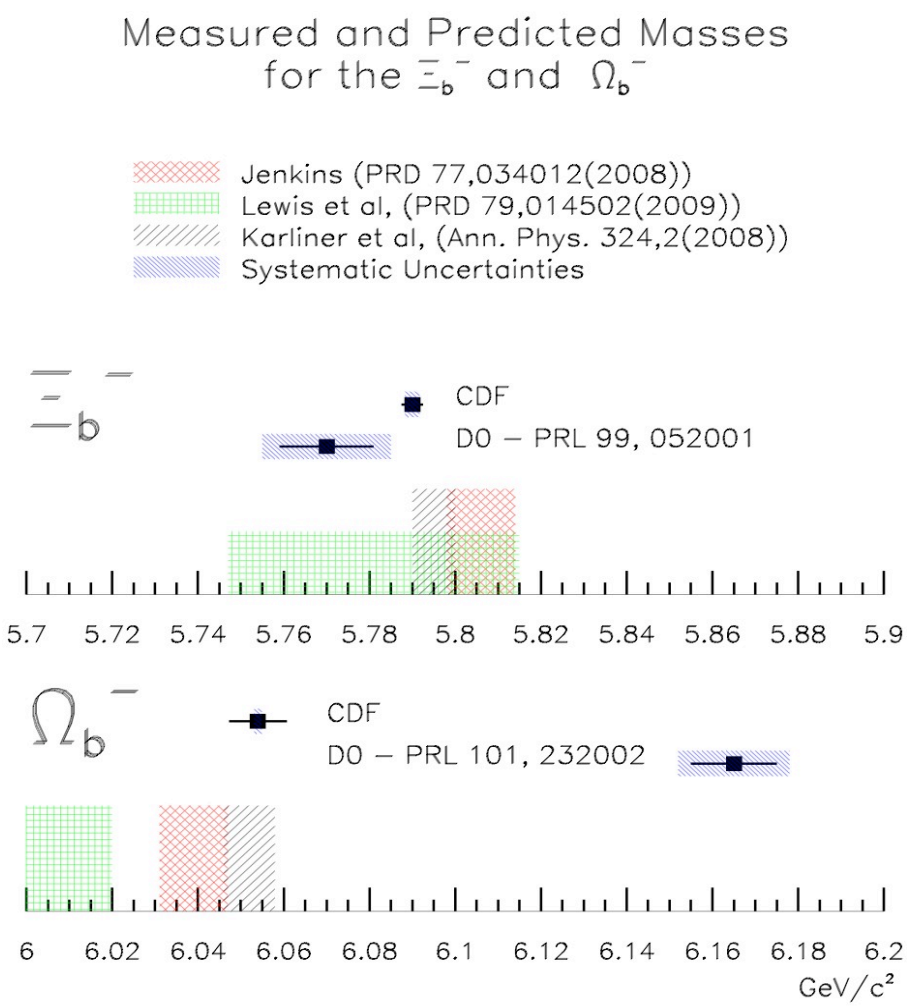
$$\frac{\sigma B(\Xi_b^- \to J/\psi\Xi^-)}{\sigma B(\Lambda_b \to J/\psi\Lambda)} = 0.167^{+0.037}_{-0.025} \pm 0.012$$

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

CDF - D0 comparison



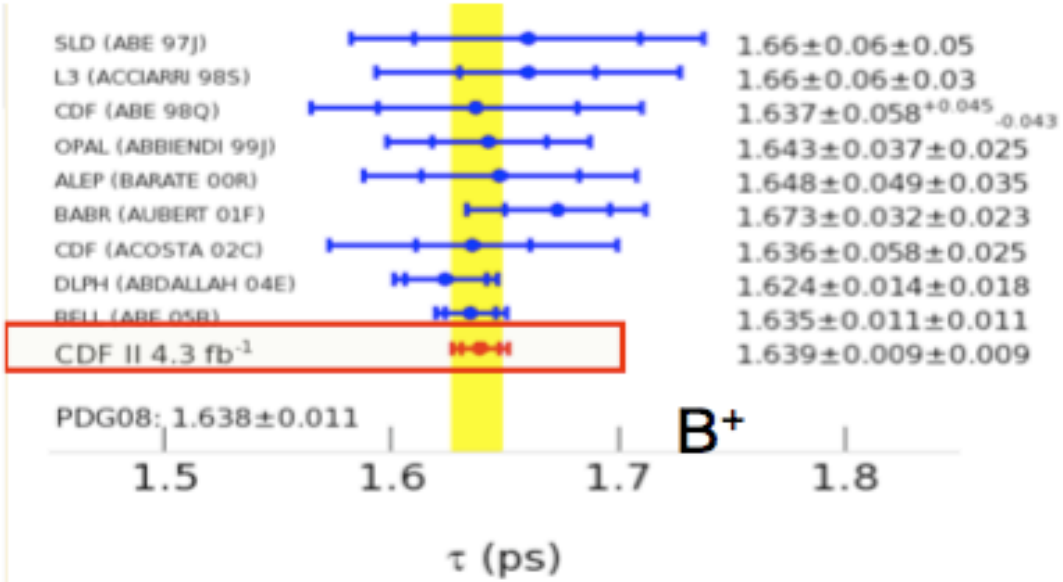


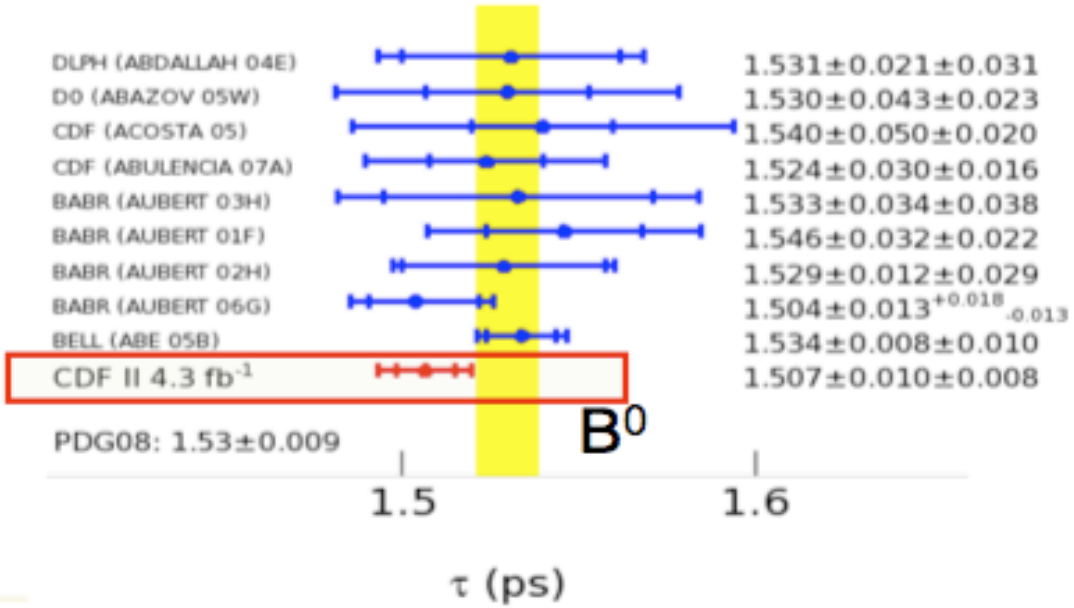


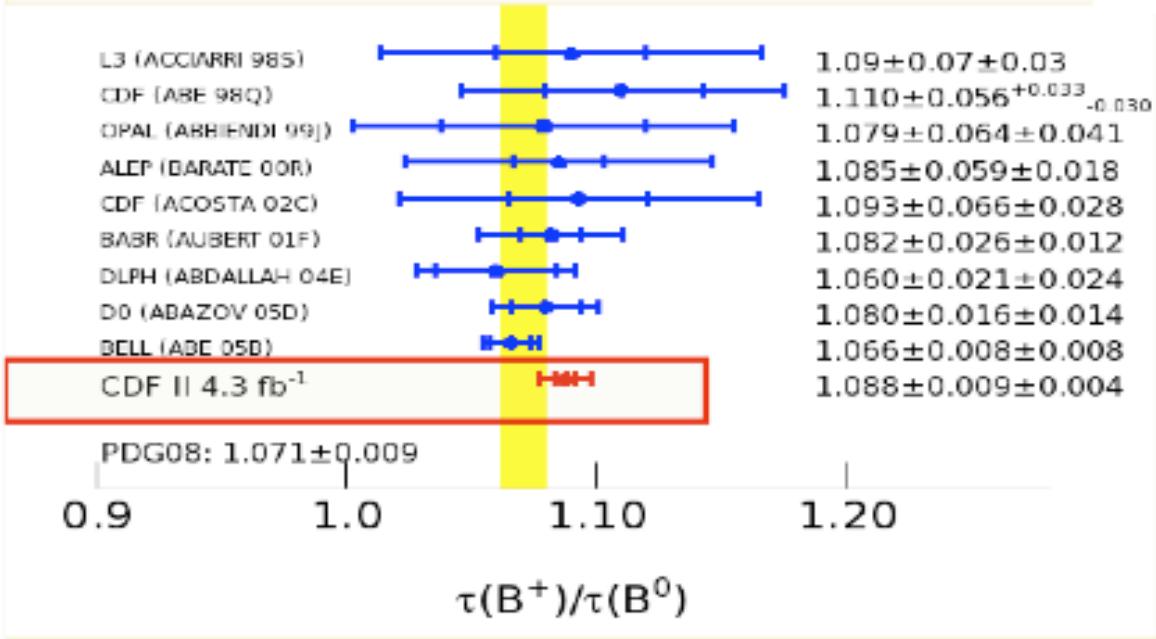
$m(\Omega_b^-)$: 6054.4 ± 6.8(stat.) ± 0.9(syst.) MeV/c^2

b – hadrons lifetimes

b – hadron Lifetimes at Tevatron







Results shown against PDG and other measurements

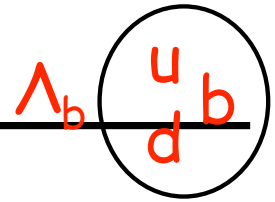
Most precise measurement of the B^+/B_0 ratio

In agreement with theoretical prediction:

$\tau(B^+)=(1.063\pm0.027)\tau(B_d)$ (theory)

$\tau(B^+)=(1.088\pm0.009\pm0.004)\tau(B_d)$ (exp)

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

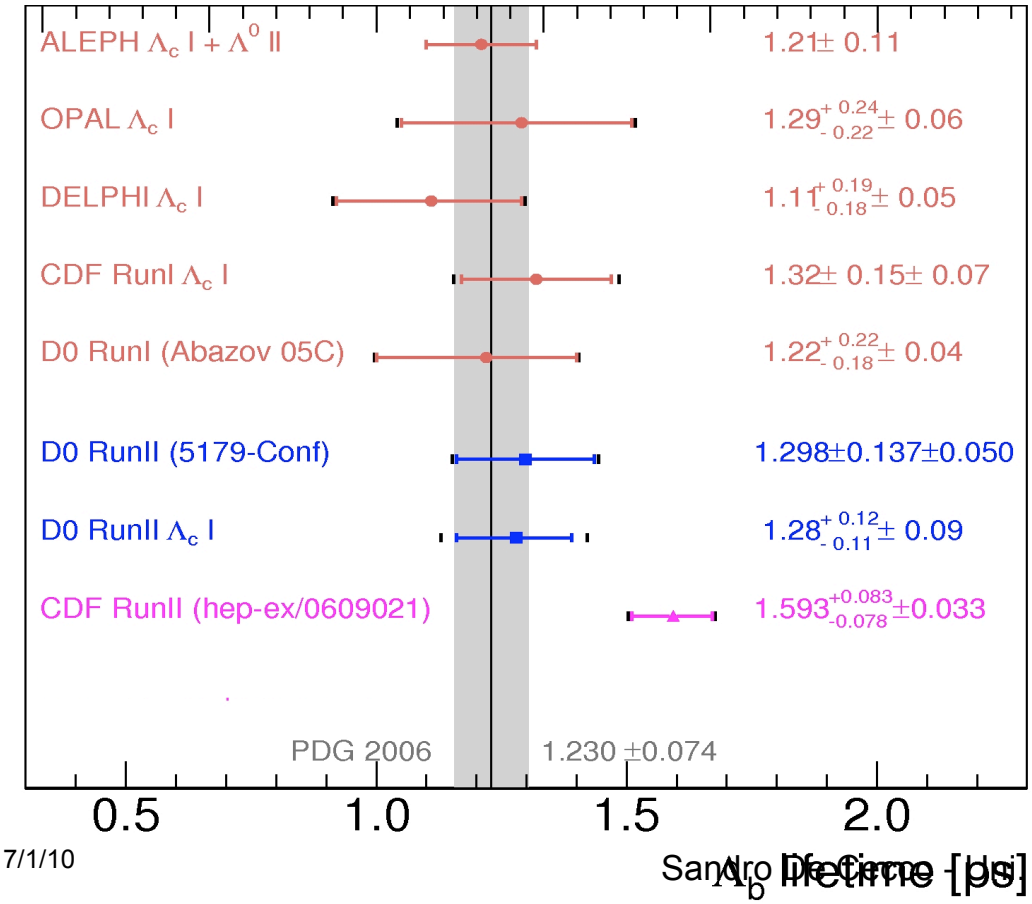


- Important test of models that describe interactions between heavy and light quarks within bound states
- In simple spectator model all b-hadrons have same lifetime
- Precise theoretical predictions difficult due to QCD effects
- OPE/HQET predicts lifetime hierarchy of b-hadrons:

$$\tau(B_c) < \tau(\Lambda_b) < \tau(B_s) \approx \tau(B^0) < \tau(B^+)$$

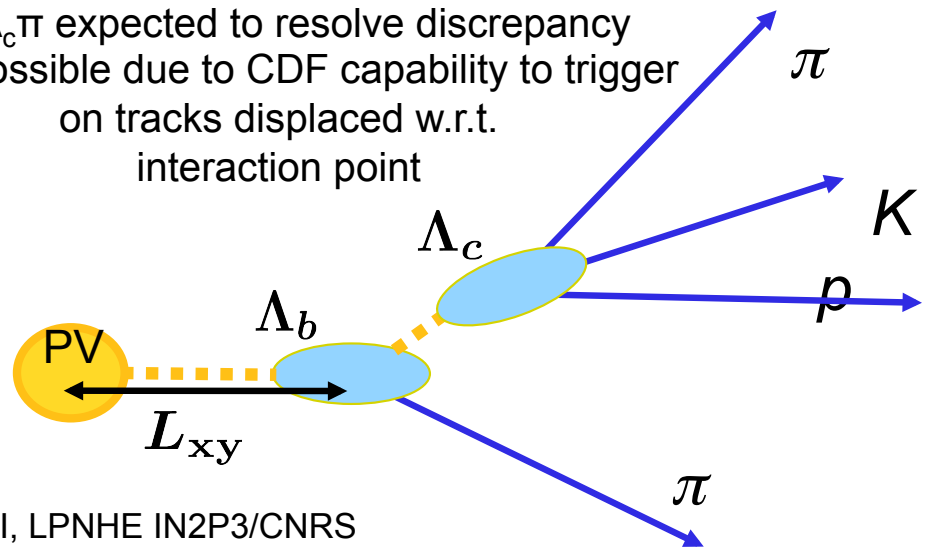
- Experimental status before this measuremer

	$\frac{\tau(\Lambda_b)}{\tau(B^0)}$
Theory	0.88±0.05
Exp.	0.921±0.036



- Possible disagreement between CDF measurement in $\Lambda_b \to J/\Psi\, \Lambda$ and other experiments

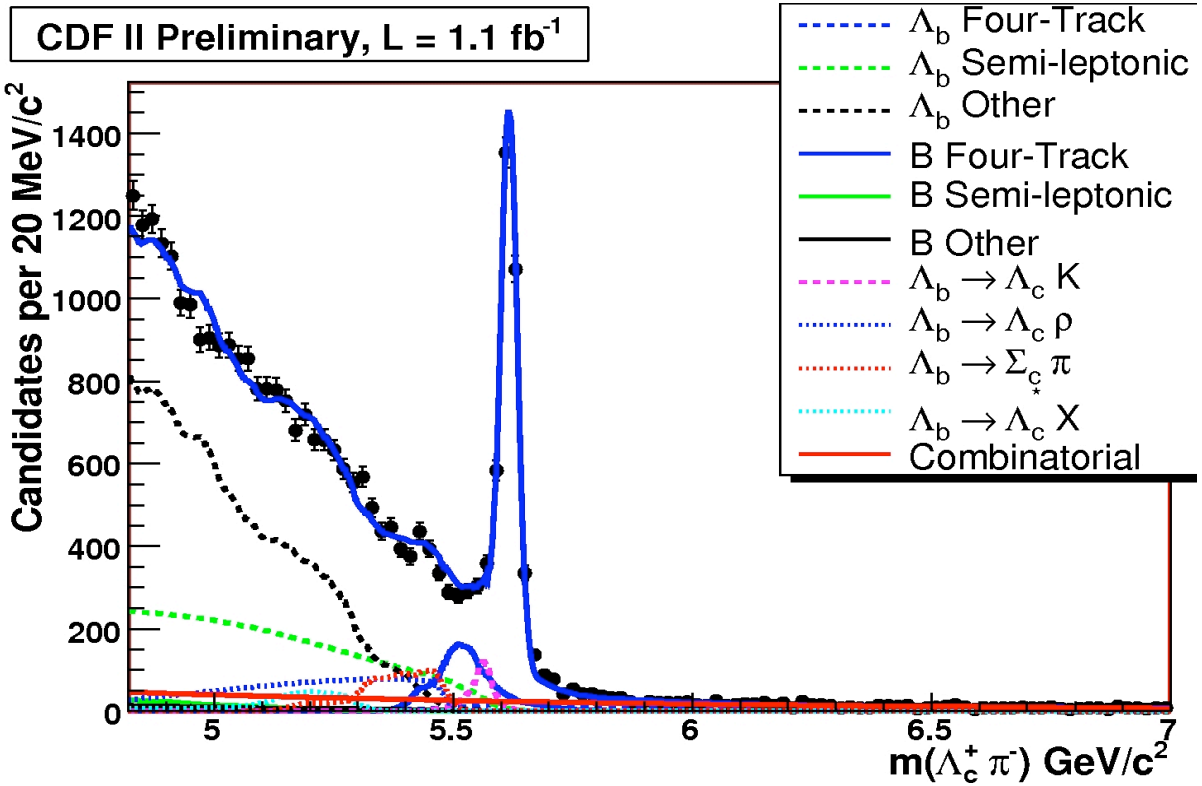
- New CDF measurement in fully hadronic Λ_b
  → $\Lambda_c \pi$ expected to resolve discrepancy
  → possible due to CDF capability to trigger on tracks displaced w.r.t. interaction point

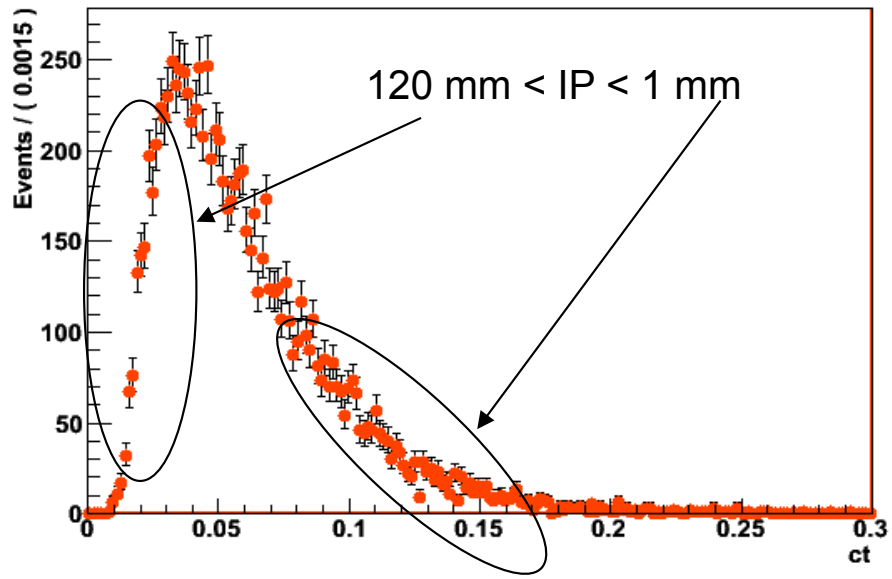


Λ_b Lifetime in $\Lambda_b \rightarrow \Lambda_c \pi$

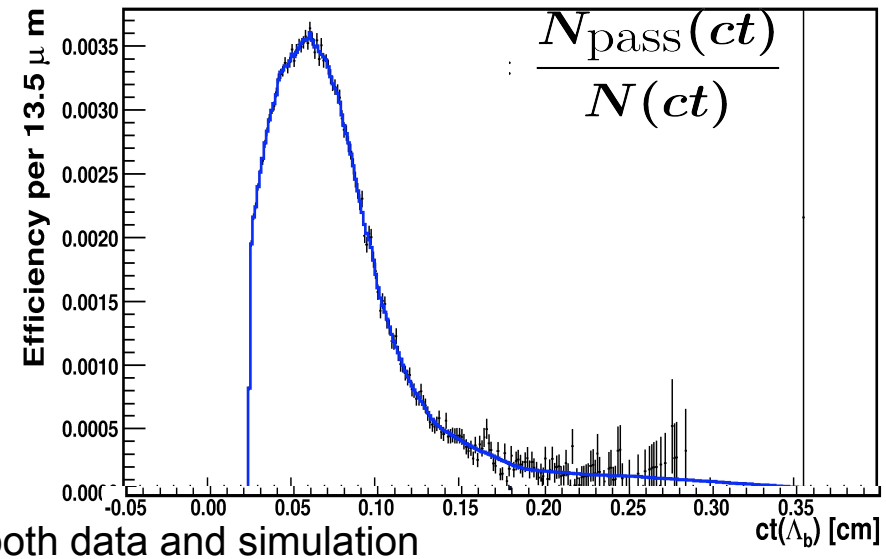
biased lifetime distribution

- Large sample of ~3000 signal events in ~1.1 fb^{-1}
- Displaced track trigger requirements: 120 μm < IP < 1 mm
  → biased lifetime distribution
- Trigger and analysis cuts bias determined from simulation





trigger efficiency from simulation



- Trigger efficiency in unbiased $J/\Psi \rightarrow \mu\mu$ sample determined in both data and simulation
  - find good agreement but still leads to largest systematic uncertainty of ~6 μm

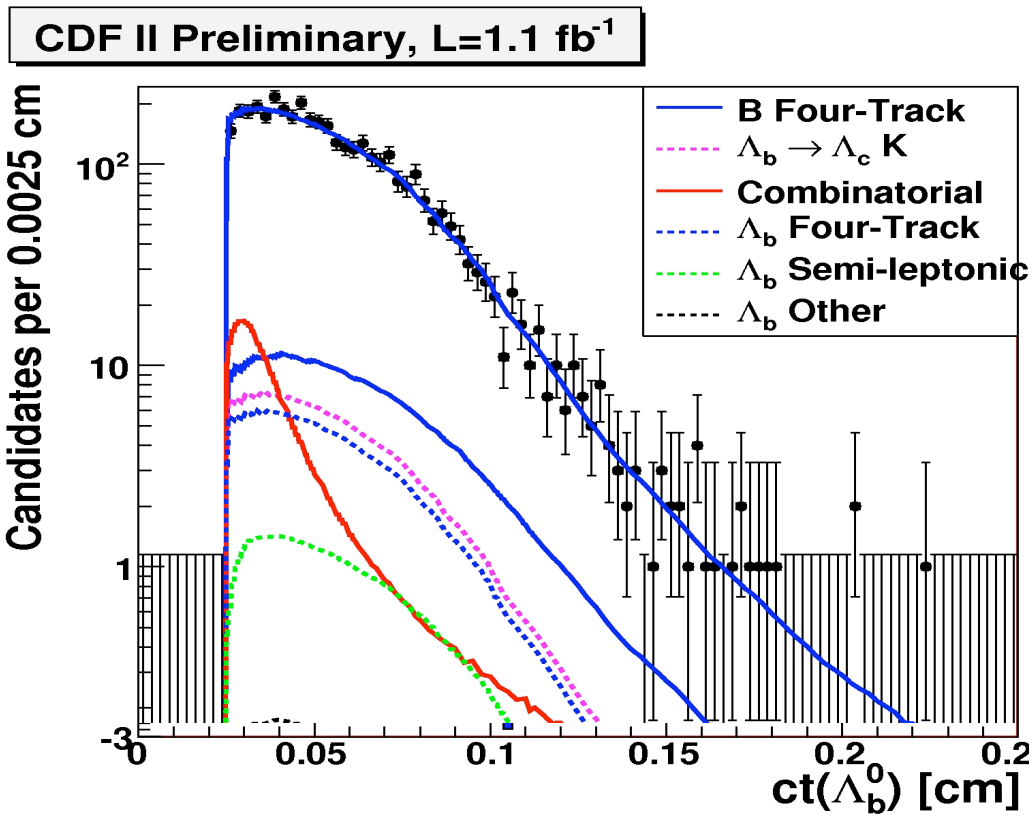
Λ_b Lifetime in $\Lambda_b \to \Lambda_c \pi$

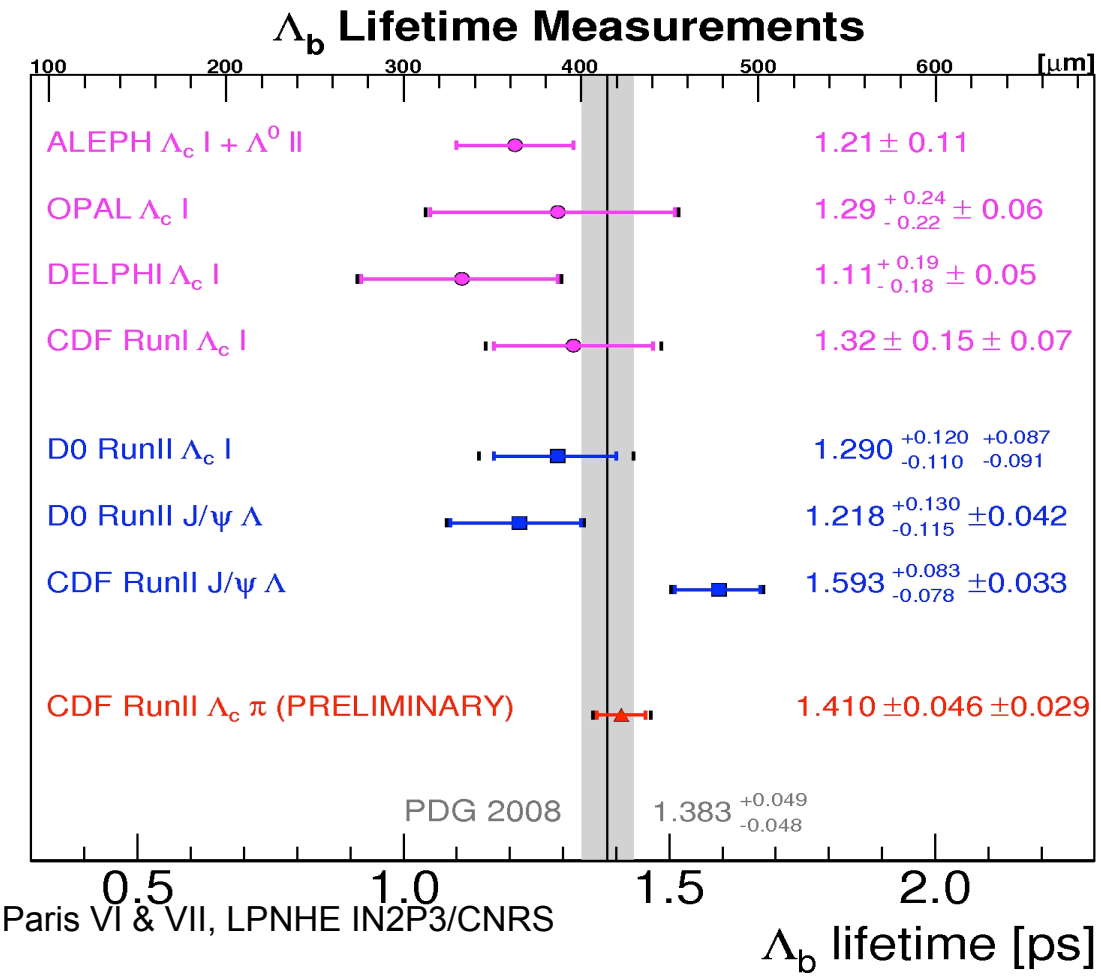
- Most precise Λ_b lifetime measurement: http://www-cdf.fnal.gov/physics/new/bottom/080703.blessed-lblcpi-ct/

$$c\tau(\Lambda_b) = 422.8 \pm 13.8\ \mu\mathrm{m}\ (\mathrm{stat.}) \pm 8.8\ \mu\mathrm{m}\ (\mathrm{syst.})$$

- Good agreement with theory prediction (0.88 ± 0.05 th ref…) $\dfrac{\tau(\Lambda_b)[\mathrm{this}]}{\tau(B^0)[\mathrm{PDG}]} = 0.922 \pm 0.039$

- and with previous world average





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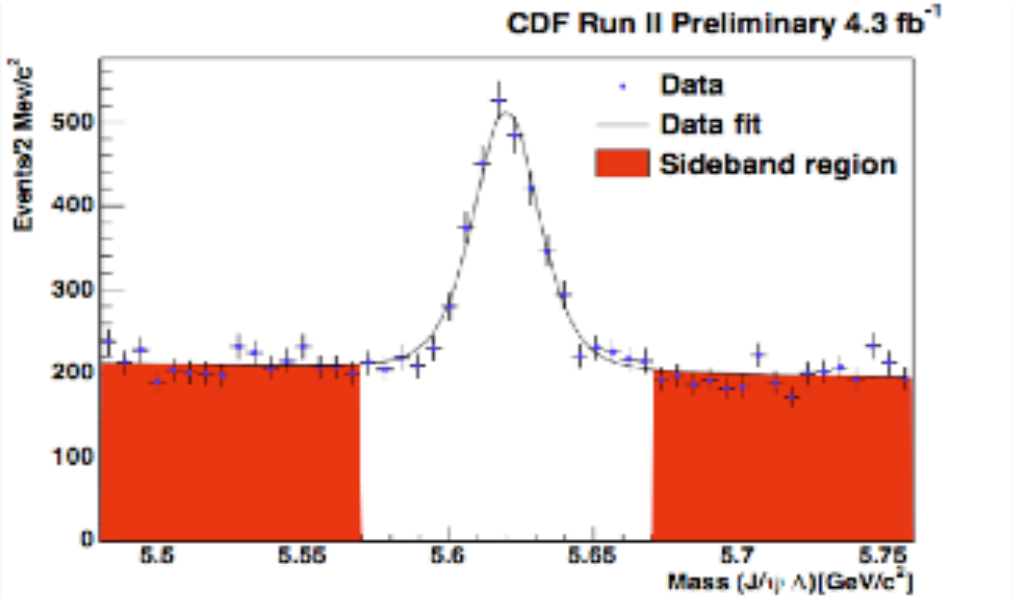
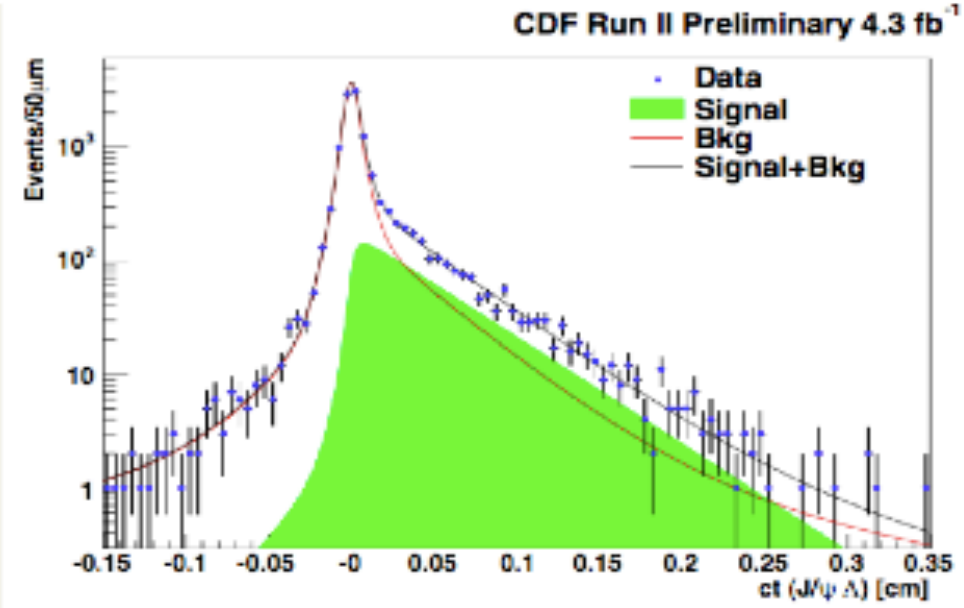
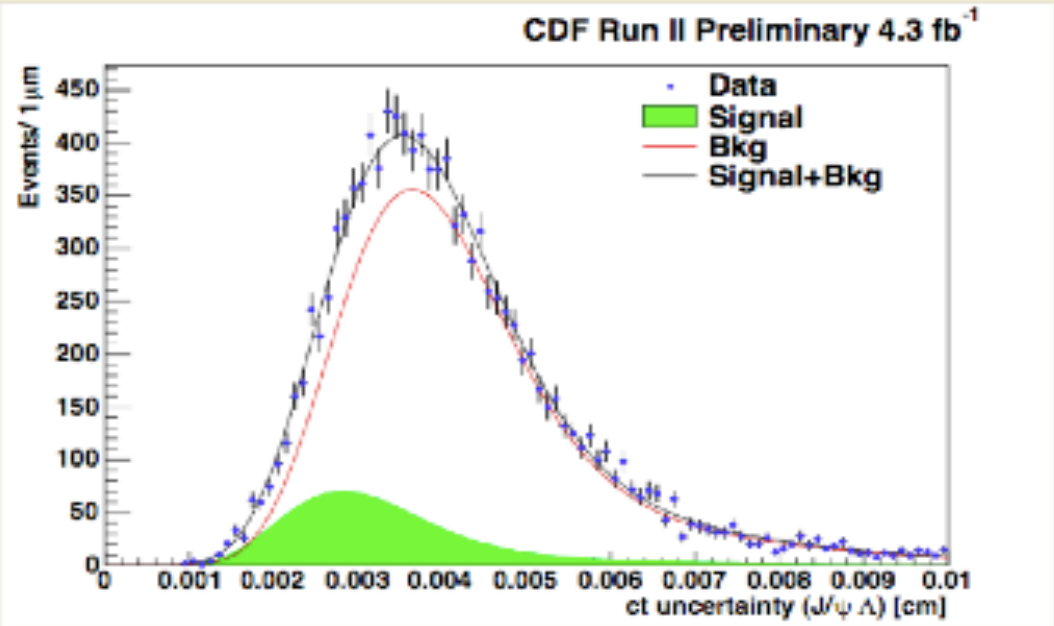
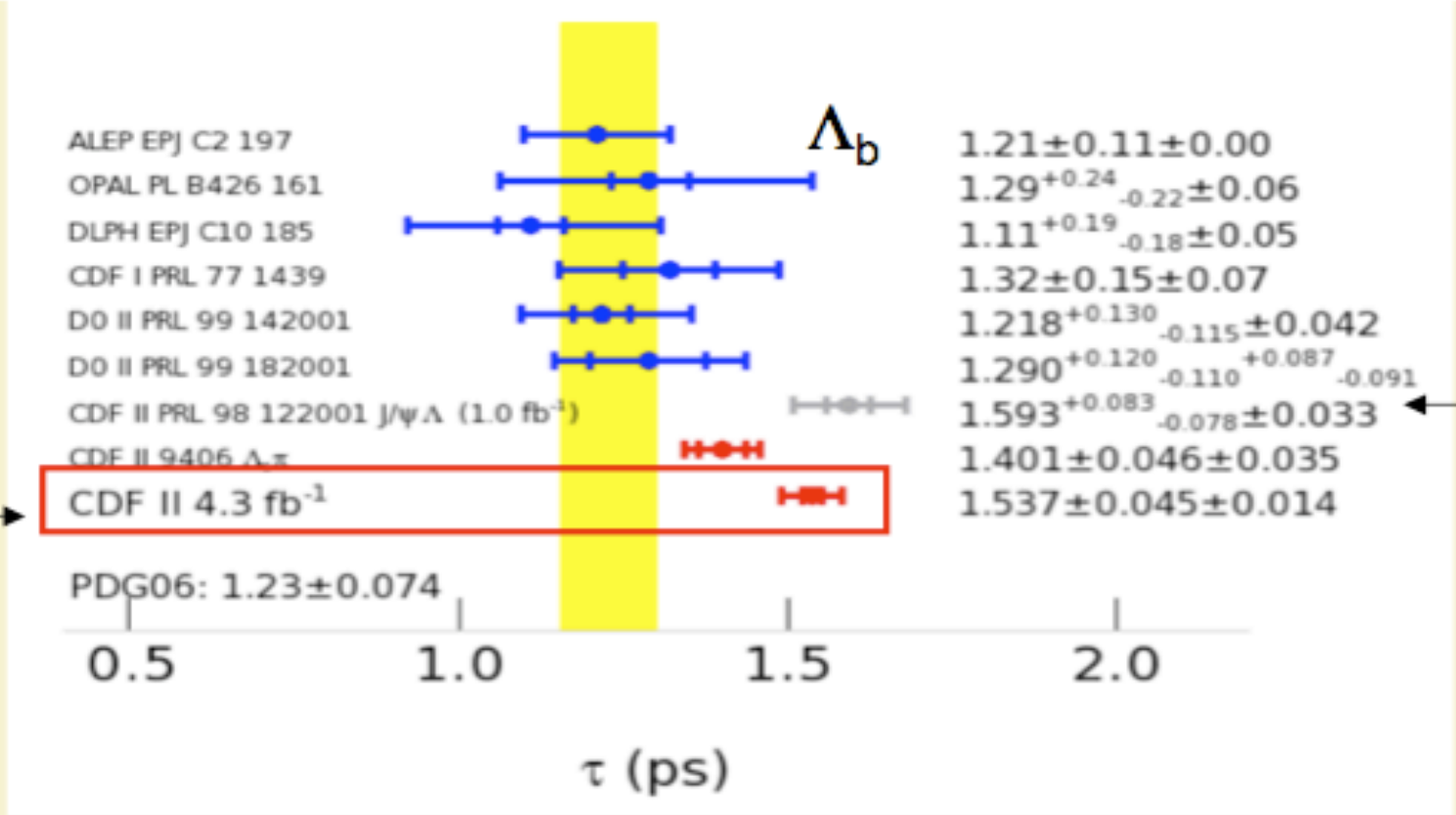
New $\Lambda_b \to J/\Psi\Lambda$ lifetime measurement







Λ_b lifetime results



New Result

Previous result in same channel

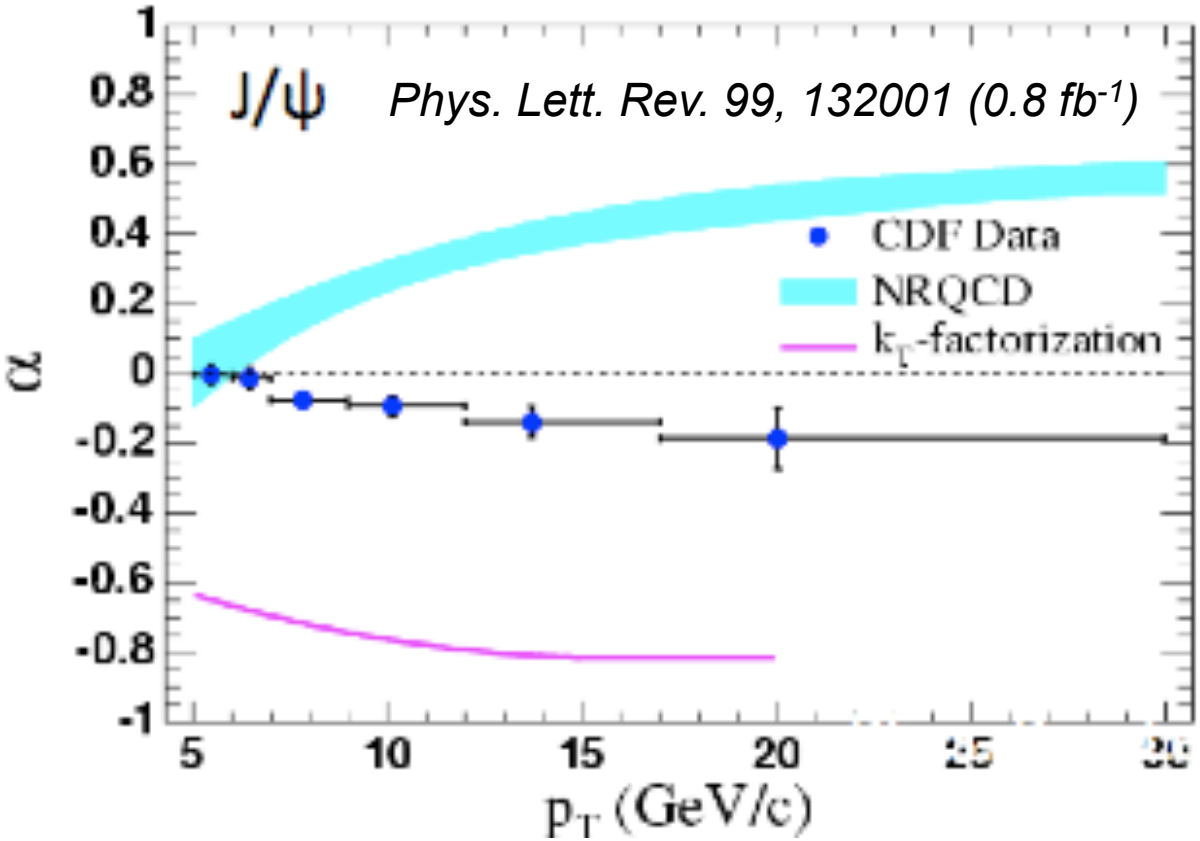
Most precise Λ_b lifetime measurement

With 4.3 fb^{-1} the Λ_b lifetime remains higher in comparison to other measurements.

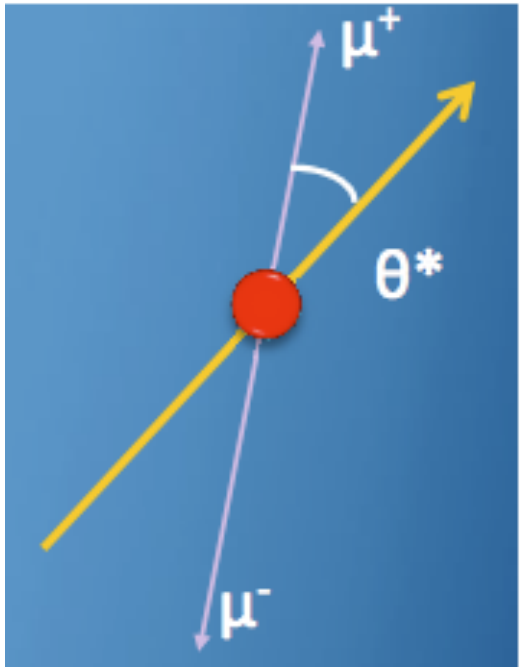
Measured Ratio: $\tau(\Lambda_b)/\tau(B_d)$ =1.020±0.030(stat)±0.008(syst)
Theory: $\tau(\Lambda_b)/\tau(B_d)$ =0.88±0.05, although there are theories that favor a higher ratio 0.9-1.0

O-onium production

J/Ψ polarization issue



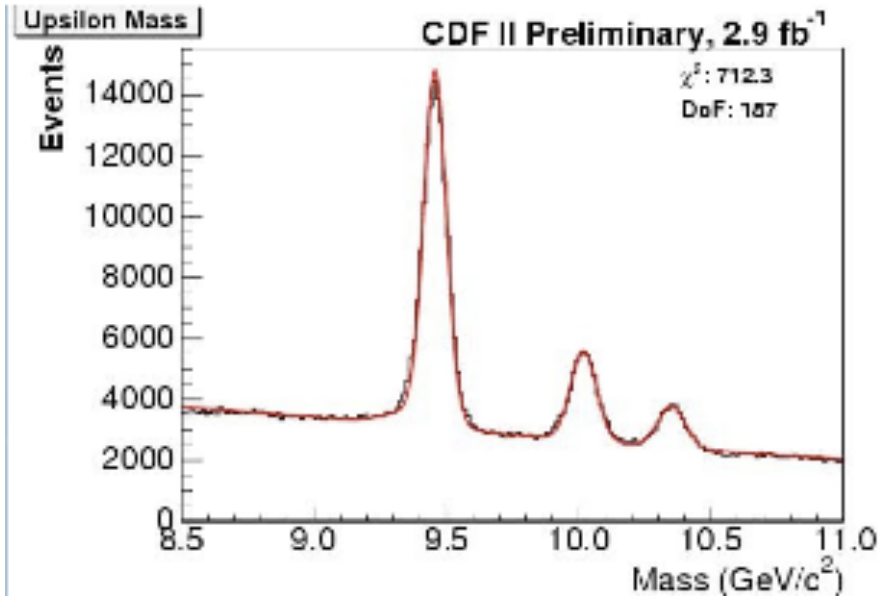
$dN/d(\cos\theta^*) \propto 1 + \alpha \cos^2\theta^*$

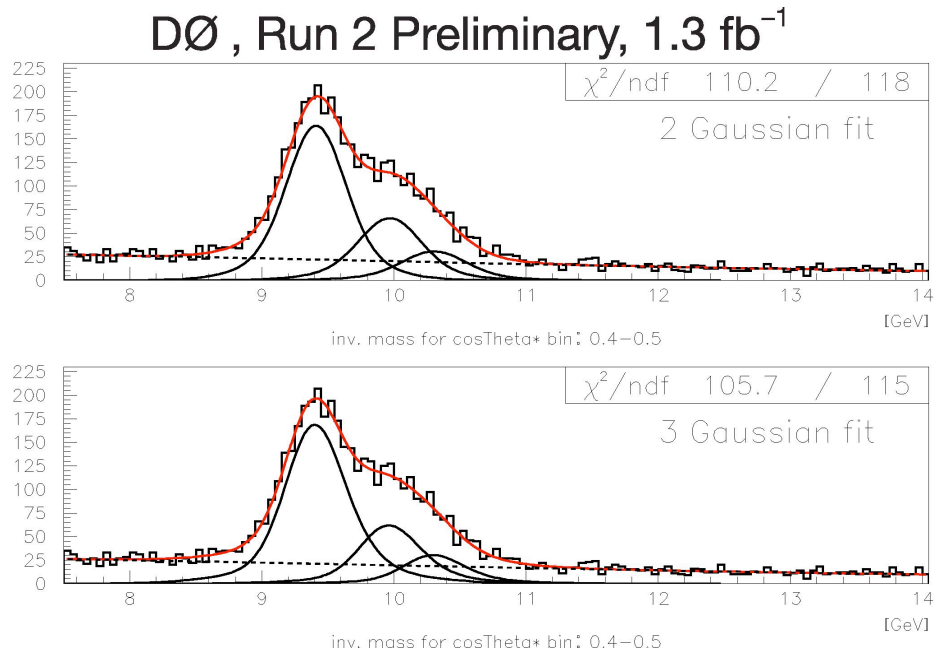


NNLO calculations predicts J/Y and Y cross sections but not J/Y polarization

Inconsistent with NRQCD prediction … charm quark mass is not infinite…
→ *test in the bottom-onium system* →

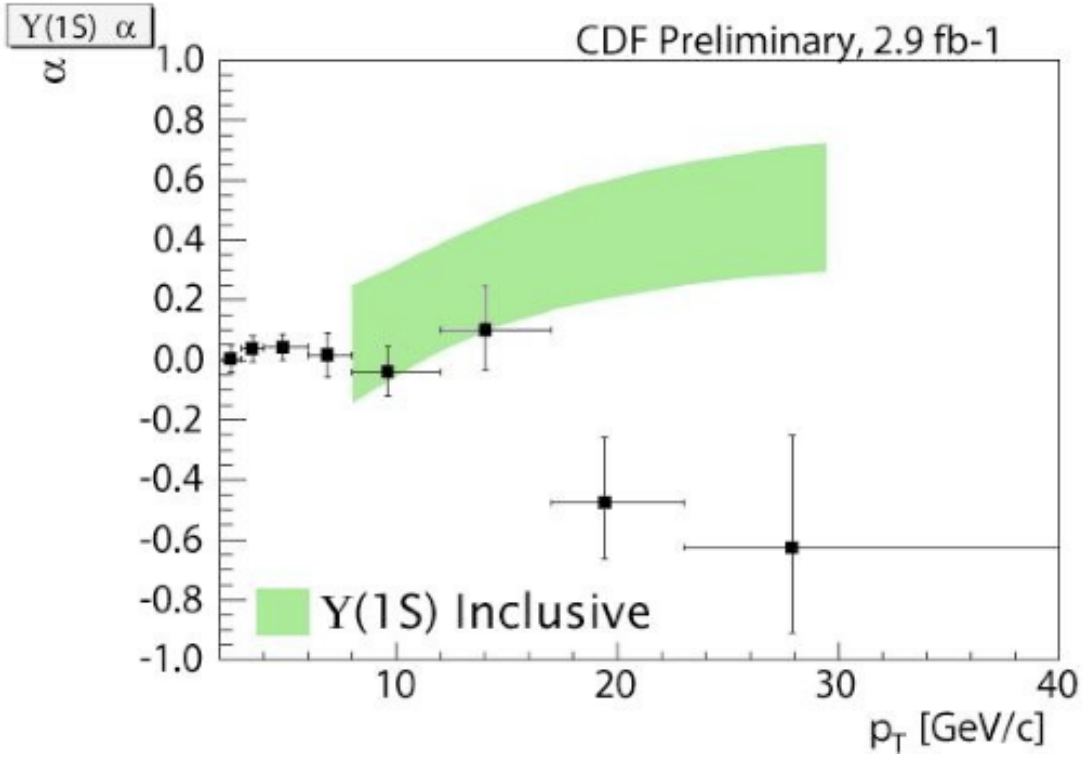
Y(1s,2s) production at Tevatron

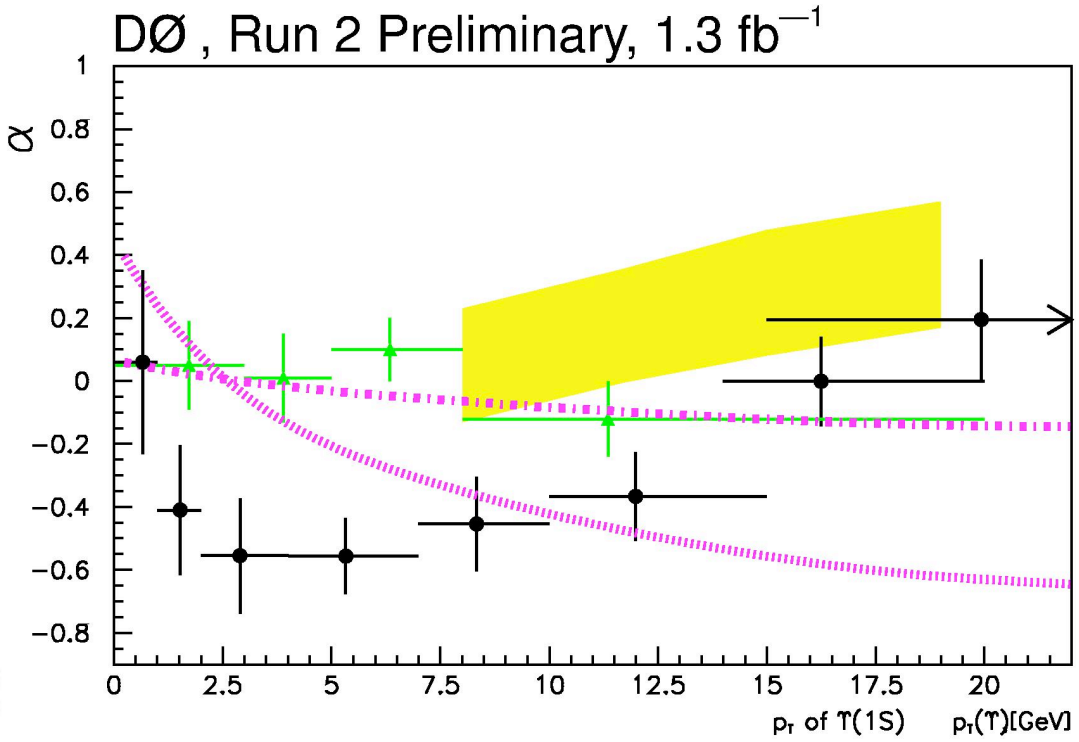




- CDF: ~83000 Y(1s) in 2.9 fb^{-1} with $|\eta|<0.6$, good mass resolution→resolve the 3 peaks
- D0: ~260000 Y(1,2,3s) in 1.3 fb^{-1} with $|\eta|<1.8$, higher yields, cross talks

Y(1s) polarization at Tevatron



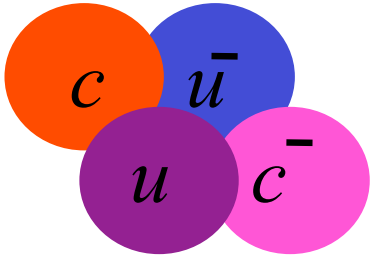


- NRQCD prediction has poor consistency with data
- CDF & D0 are largely inconsistent. New CDF measurement agrees with Run I result

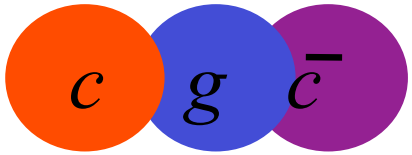
Charmonium-like resonances

Exotic Mesons(?) — QCD predictions

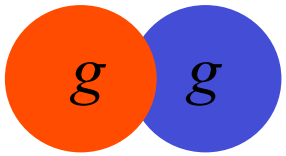
- *Multi-quark mesons*
  molecule, diquark-antidiquark



- *Hybrid mesons*
  quark-antiquark-gluon



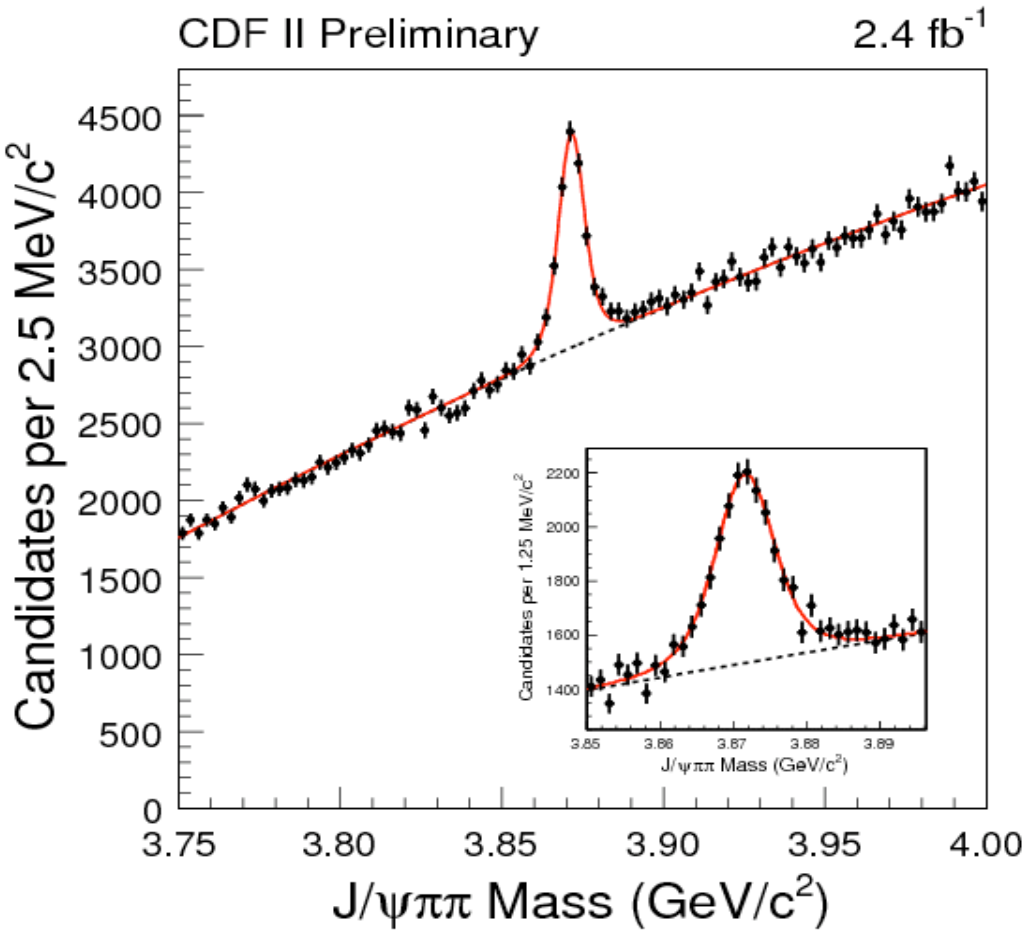
- *Glueball*
  gluonic color singlet states



Explore more channels to understand

How about **J/ψφ***? (threshold @4.116 GeV, VV, C=+)*
($c\bar{c}$) with a mass above 4.116 GeV, expect tiny branching fraction

X(3872) Mass Measurement at CDF (2008)



X → J/Ψ ππ

with J/Ψ → μμ/ee

~6000 signals

The largest sample to date

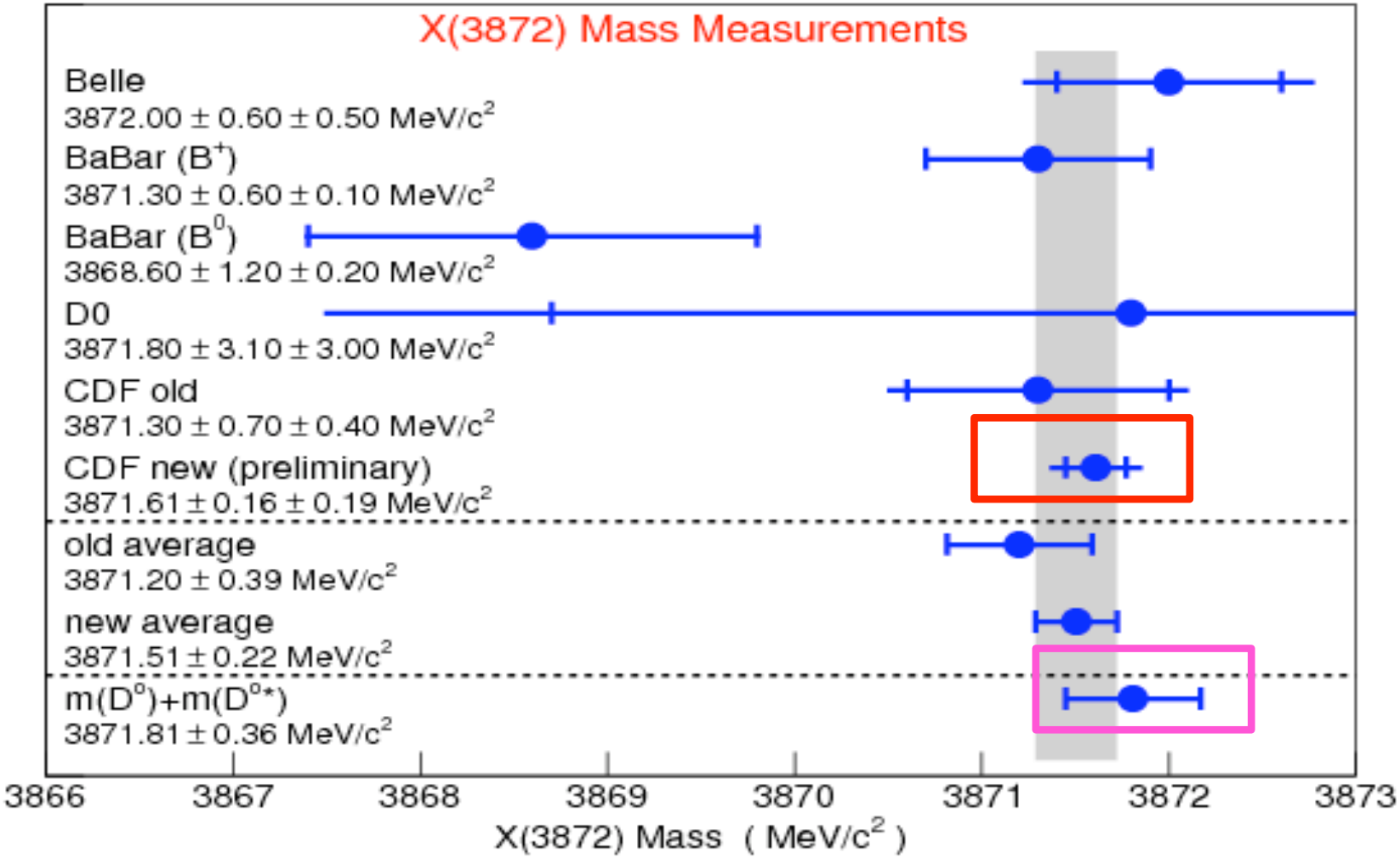
Use neural network to select

Testing the hypothesis of possible two states: $\Delta m < 3.2\ (3.6)$ MeV/c^2 at 90% (95%) C.L.

Consistent with one state hypothesis of mass:

$$m(X(3872)) = 3871.61 \pm 0.16\ (stat) \pm 0.19\ (syst)\ MeV/c^2$$

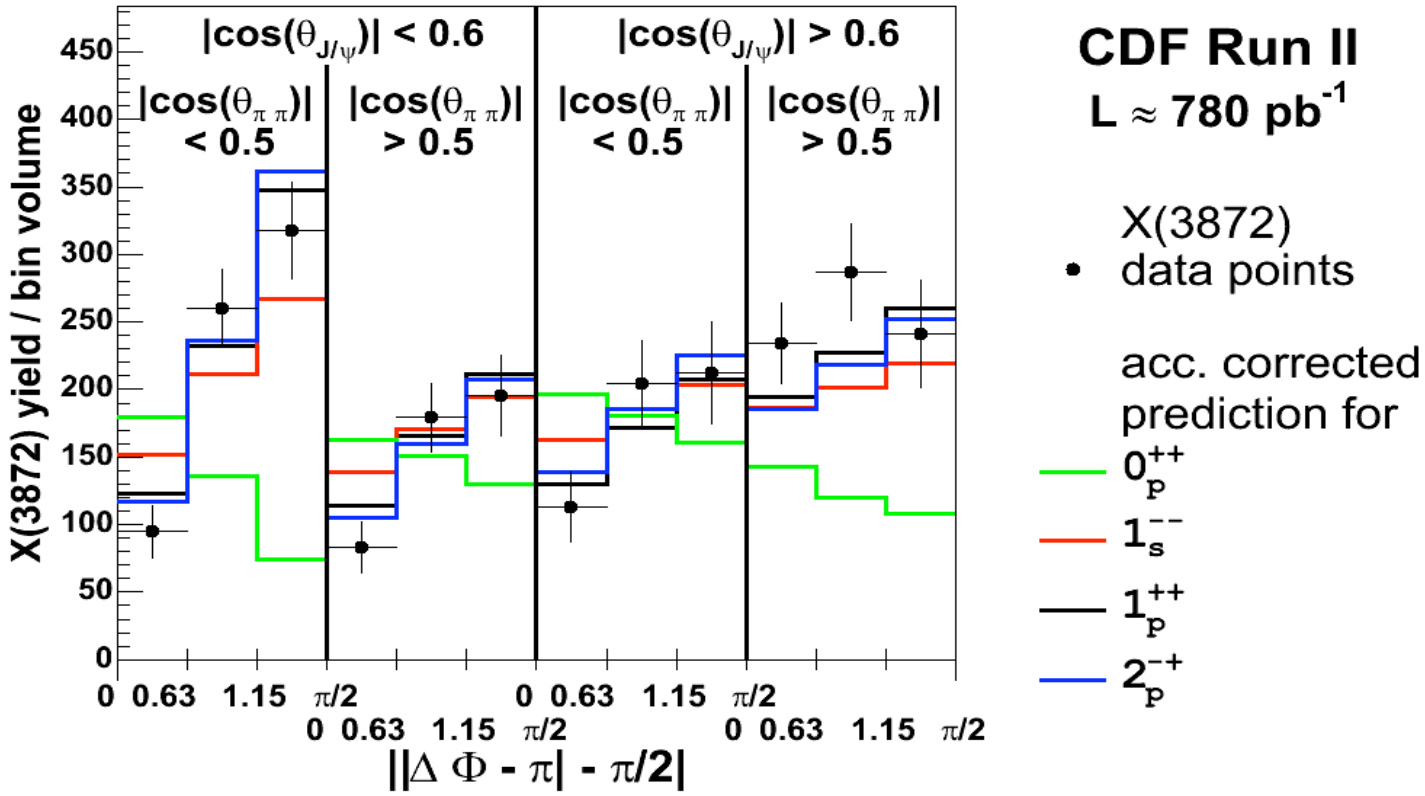
X(3872) Mass summary



the most precise measurement to date, still within the D*D threshold uncertainty

X(3872) properties

CDF studied performed angular analysis to disentangle s and p waves



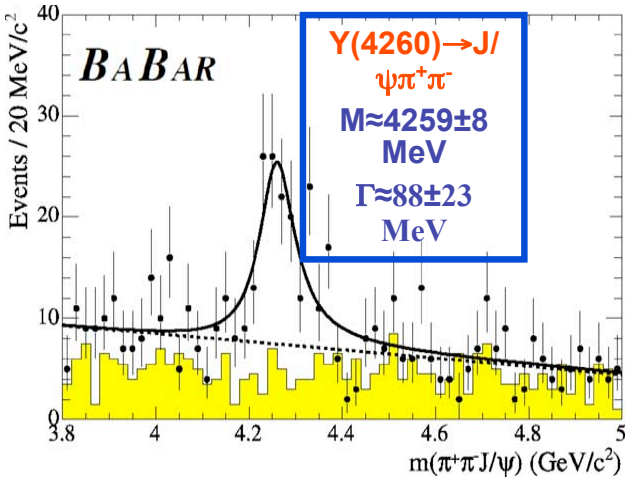
$J^{PC} = 1^{++}$ or 2^{-+} ? Not yet clear, to be updated with more stats

*Fraction of X produced from **b** was estimated to be ~ 16%*

Other states, charmonium hybrids →J/ψϕ ?

New states:

PRL 95, 142001



Well above DD && DD* threshold,
tiny Branching Fraction expected
$J^{PC}=1^{--}$, plus Y(4350), Y(4660)
too many 1^{--} ?

J^{PC}	Open charm	Hidden charm
0^{+-}	Quantum numbers forbid $D^{(*)}D^{(*)}$	$J/\psi\{f_{\{0,1,2\}},(\pi\pi)_S\}$ $h_c\eta;\ \eta_c h_1$ $\chi_{c0}\omega$ $\chi_{c\{1,2\}}\{\omega,h_1,\gamma\}$
0^{--}	D^*D	$h_c(\pi\pi)_S$ $J/\psi\{f_{\{1,2\}},\eta^{(\prime)}\}$ $\chi_{c0}h_1;\ \eta_c\{\omega,\phi\}$ $\chi_{c\{1,2\}}\{\omega,h_1,\gamma\}$
1^{-+}	$D^*D,\ D^*D^*$	$\chi_{c\{0,1,2\}}(\pi\pi)_S$ $\eta_c\{f_{\{1,2\}},\eta^{(\prime)}\}$ $\chi_{c\{1,2\}}\eta$ $\{h_c,J/\psi\}\{\omega,h_1,\phi,\gamma\}$ ← accessible at Tevatron
2^{+-}	$D^*D,\ D^*D^*$	$\{h_c,J/\psi\}\{f_{\{0,1,2\}},(\pi\pi)_S\}$ $\{h_c,J/\psi\}\eta^{(\prime)}$ $\{\eta_c,\chi_{c\{0,1,2\}}\}\{\omega,h_1,\phi,\gamma\}$

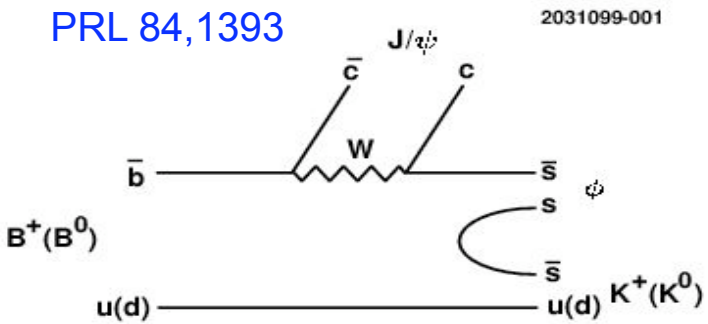
← PRD 57, 5653 (1998)
F. Close et al

J/ψϕ is also accessible to 0^{-+}, 2^{-+}
(0^{-+} ,1^{-+} ,2^{-+}) masses are expected near Y(4260), E. Eichten

Search structures → J/ψφ through B decays

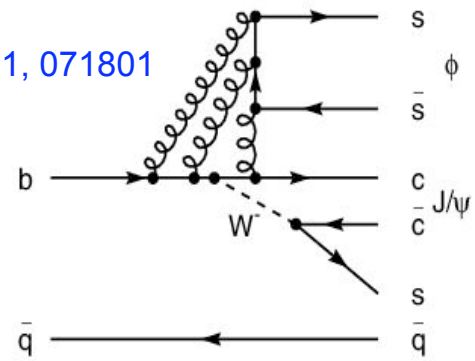
- Experimentally easy to search through clean B→J/ψφK channel
  - -- taking advantage of B lifetime and narrow B mass window
  - -- B➔J/ψφK is OZI suppressed, so low physics background

PRL 84,1393

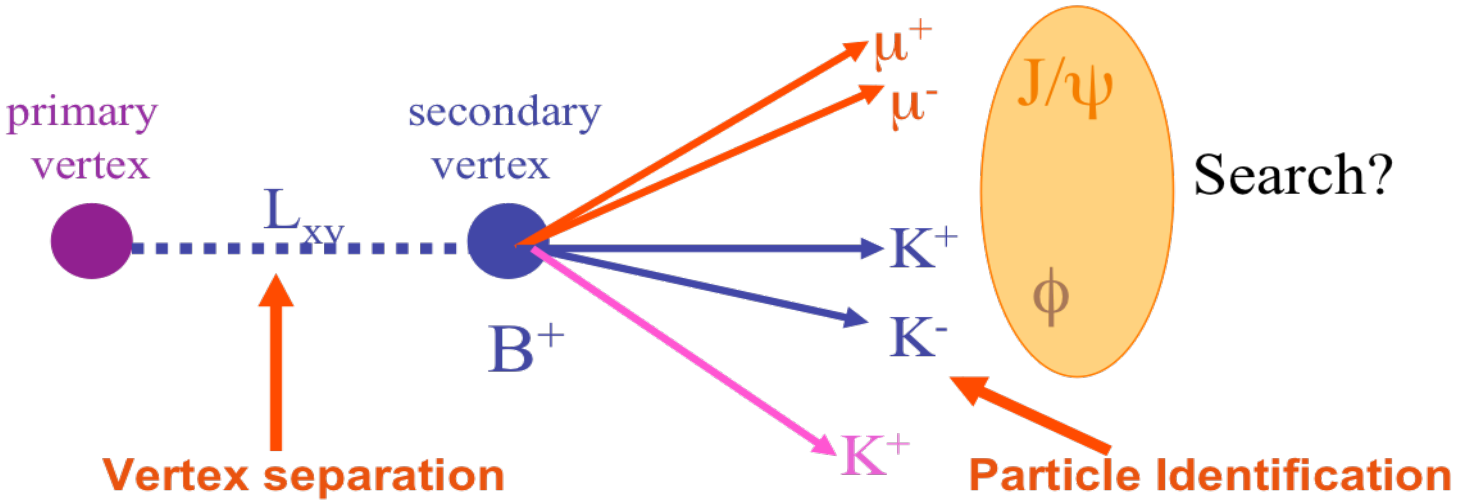


vacuum polarization

PRL 91, 071801

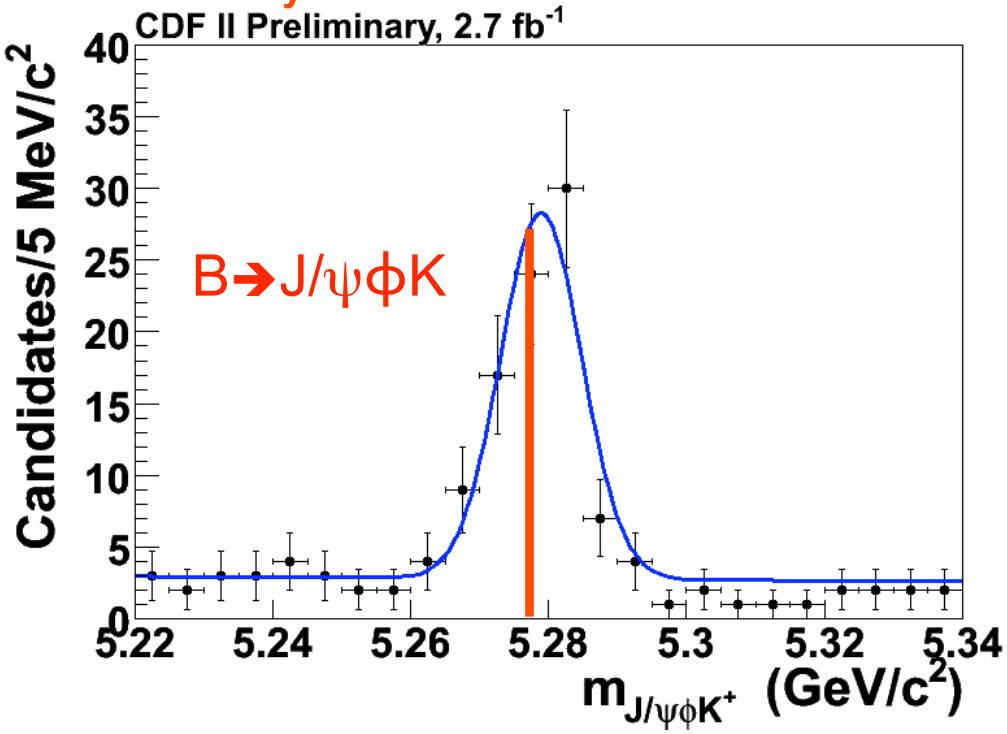


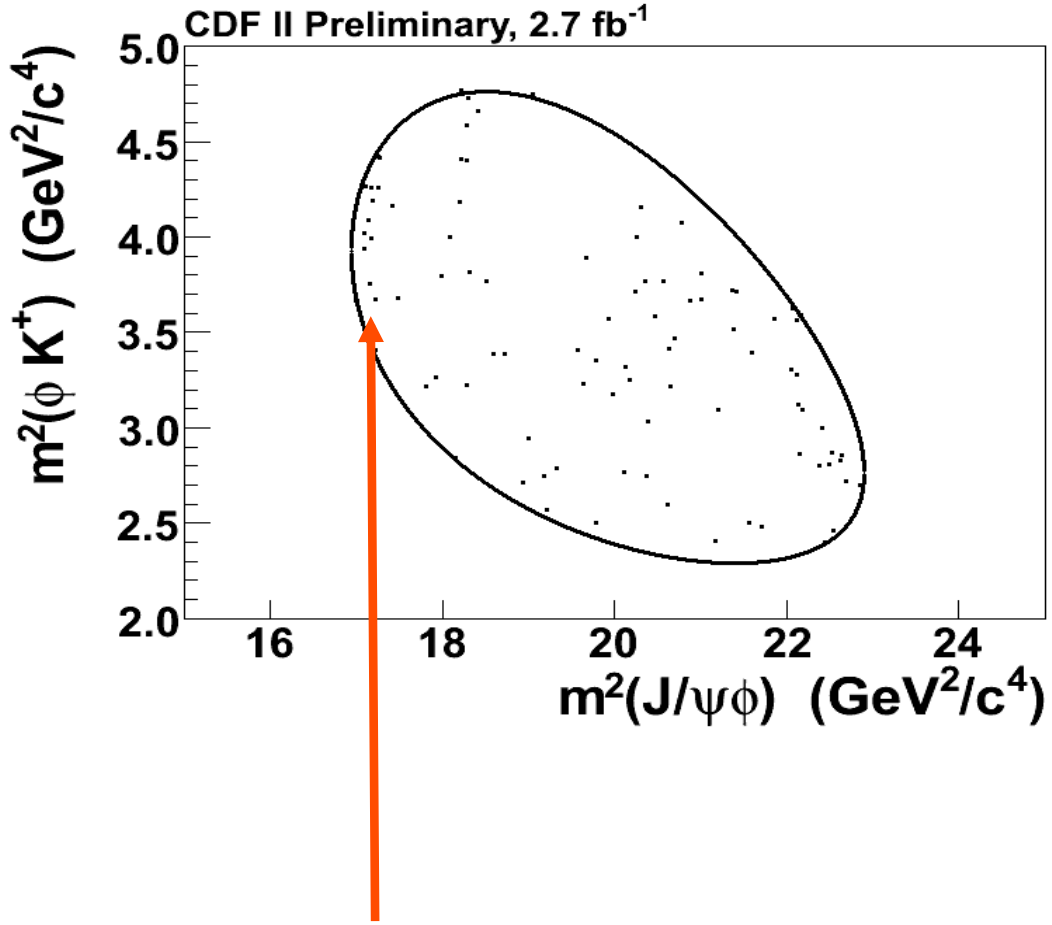
gluon coupling



Search for structures in J/ψφ mass--Data

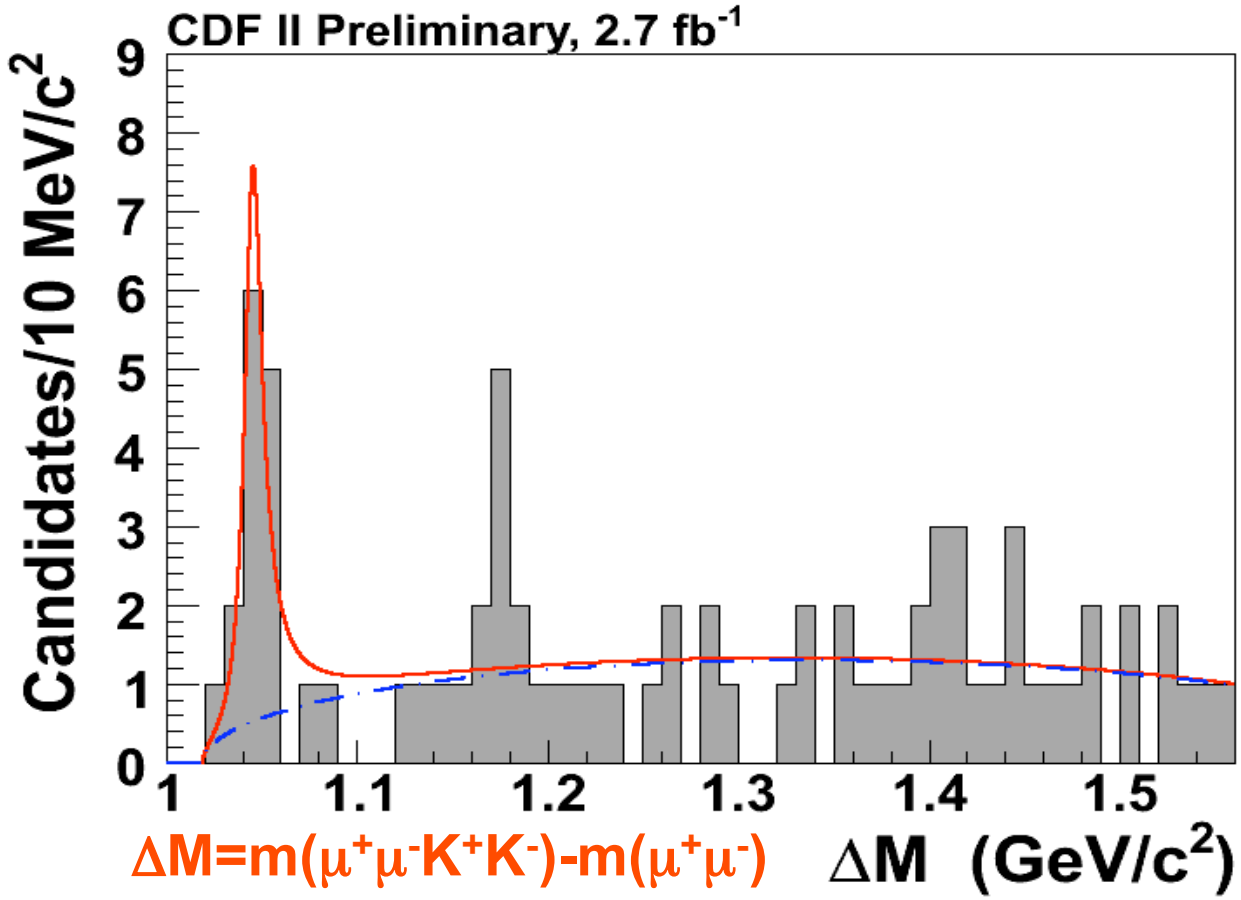
After L_{xy}>500 um, kaon LLR>0.2





a near threshold enhancement is observed in the Dalitz

Search for structures in $J/\psi\phi$ mass--Data



- **Results including systematics:**

  Yield =14±5

  Δm = 1046.3± 2.9 (stat)± 1.2 (syst) MeV/c^2

  Mass = 4143.0 ± 2.9 (stat)± 1.2 (syst) MeV/c^2

  Width = $11.7\ ^{+8.3}_{-5.0}$ (stat) ± 3.7(syst) MeV/c^2

(Convoluted with resolution of 1.7 MeV)

Three-body Phase Space Background shape is used

Width indicates a strong decay

Tentatively named: Y(4140)

$\sqrt{(-2\log(L_{max}/L_0))}=5.3$, need Toy MC to determine significance for low statistics

Significance: at least 3.8σ for most unphysical conservative background

Summary:

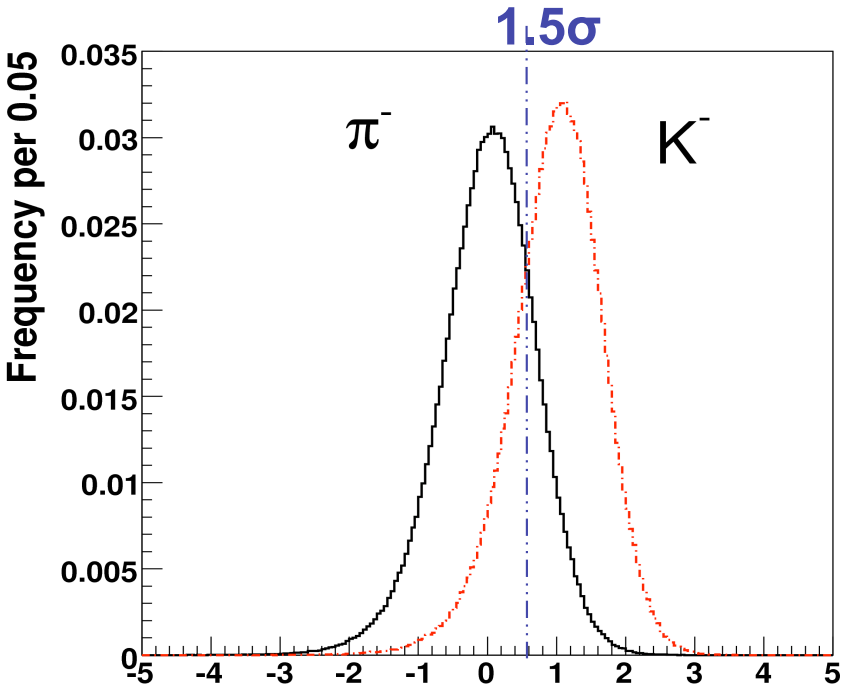
- Pioneering b-Baryons properties (Ξ_b , Ω_b) studies.
- Y polarization, a puzzling cross check for QCD predictions
- b-hadrons lifetimes toward very high precision measurement, constraining theory predictions. The Λ_b shows some discrepancy.
- Evidence for Y(4140) state, other states popping up? New charged state $Z(4430)^+ \rightarrow \psi(2S)\pi^+$ observed at Belle, CDF is searching.
- Many updates ongoing with 5 fb^{-1} data, coming soon.
- Still more (unexpected?) to come with full TeVatron statistics

Backup

CDF hadron PID

Main background: prompt pions, need PID to suppress

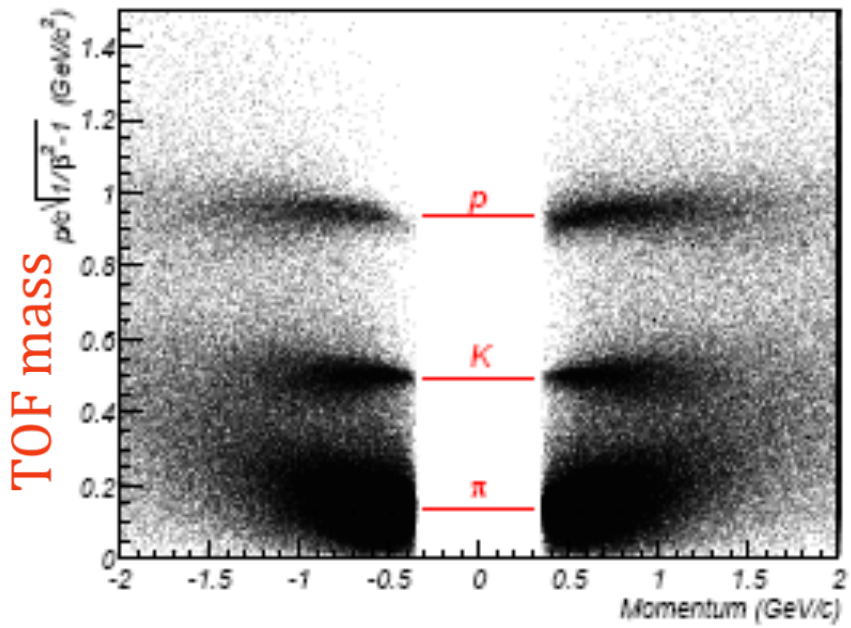
dEdx residual



dE/dx parameterized using $D^{*+(-)} \rightarrow D^0\pi^{+(-)}$ sample

dE/dx efficiency ~100%

CDF Time-of-flight: Tevatron store 860-12/23/2001



Excellent resolution

Time-of-Flight acceptance+efficiency ~60%

Make use of both dEdx and ToF for hadron PID
summarizing dEdx and ToF into a log-likelihood ratio

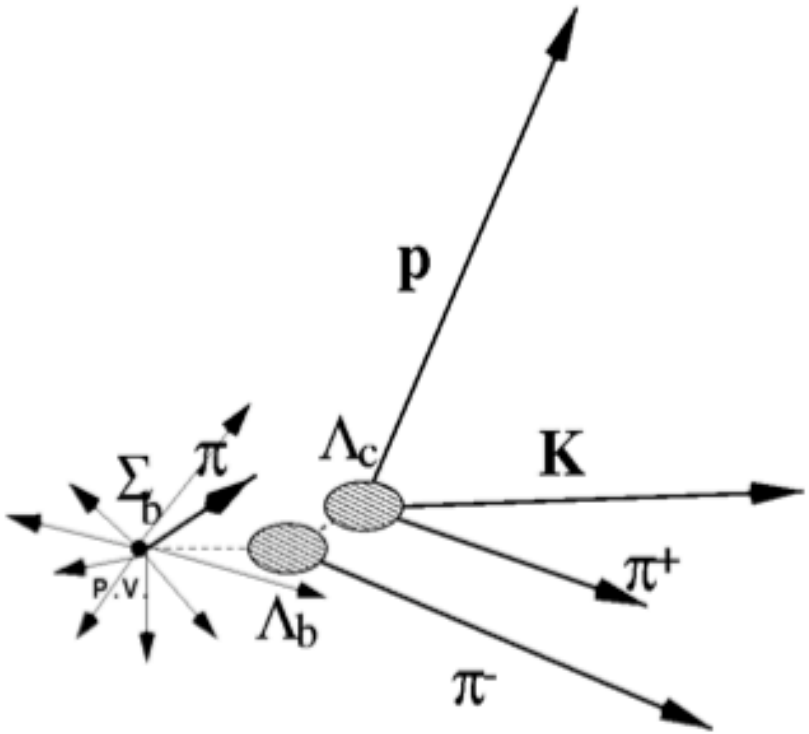
Updated analysis of $\Sigma_b^{\pm *}$ to 5 fb^{-1}

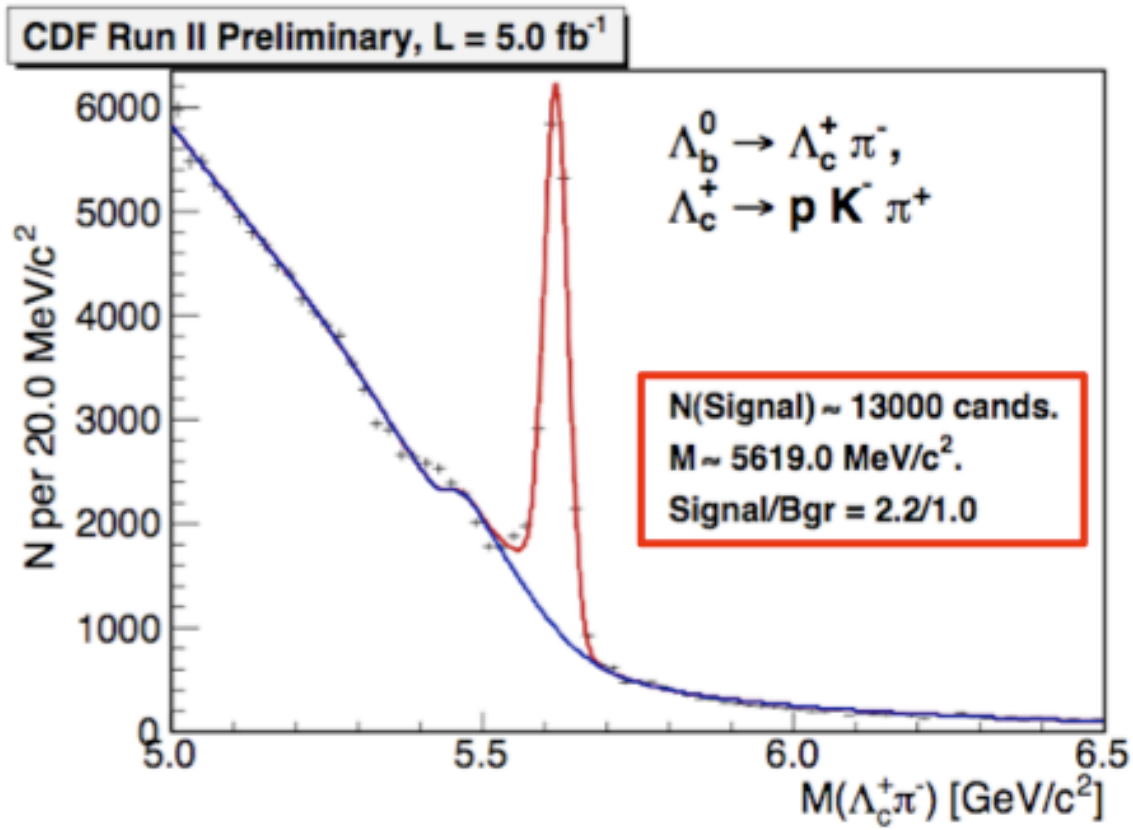
$\Sigma_b^{-(*)} \rightarrow \Lambda^0_b \pi^-$

$\Lambda^0_b \rightarrow \Lambda_c^+ \pi^-$

$\Lambda^+_c \rightarrow p K^- \pi^+$

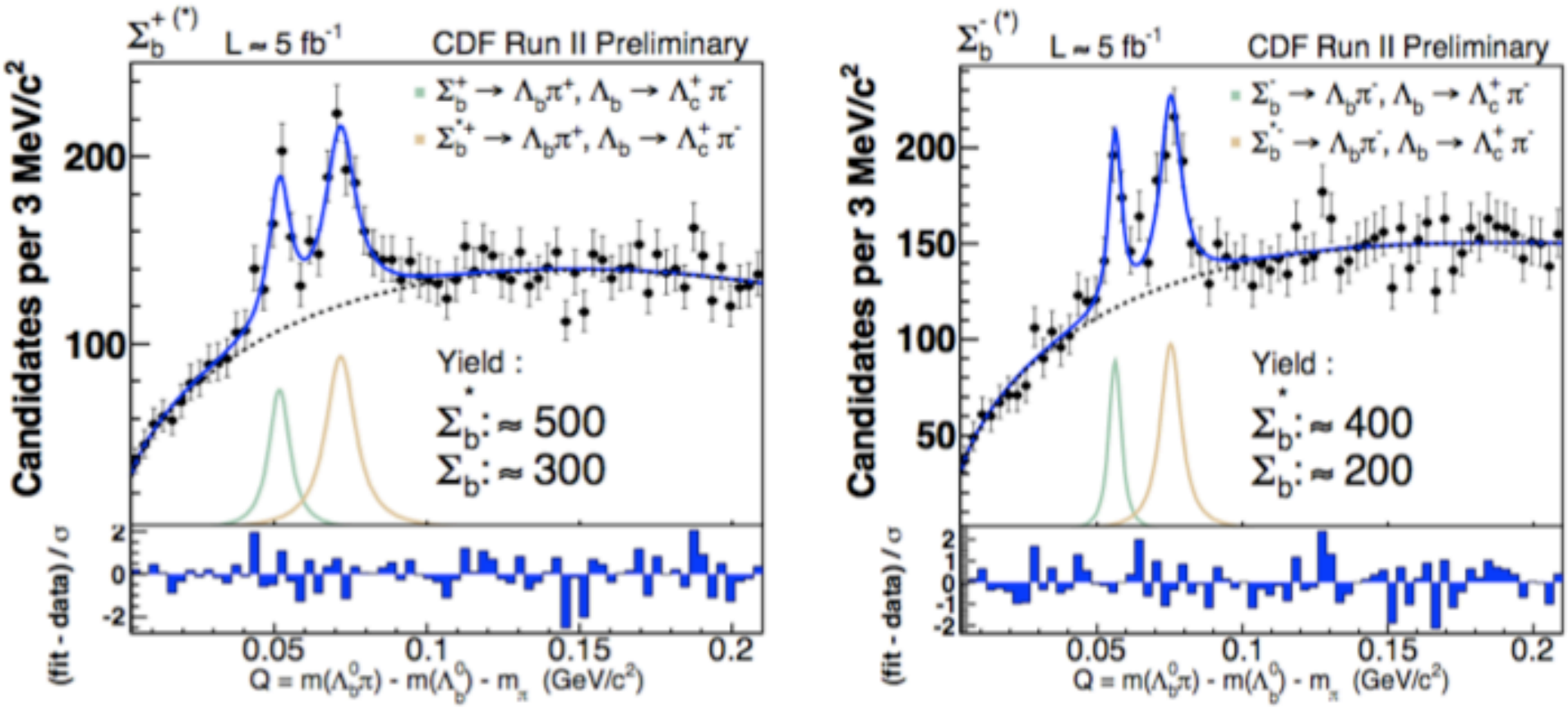
(Observation of Σ_b^+, Σ_b^-, Σ_b^{*+} and Σ_b^{*-} in 1.1 fb^{-1})
PRL 99, 202001 (2007)





≈4x increase of Λ^0_b sample wrt published analysis

Updated analysis of $\Sigma_b^{\pm *}$ to 5 fb^{-1}



Analysis Goals

- Improve mass measurements
- Measure natural widths of $(3/2)^+$ and $(1/2)^+$ states and mass splittings with no theoretical constraints

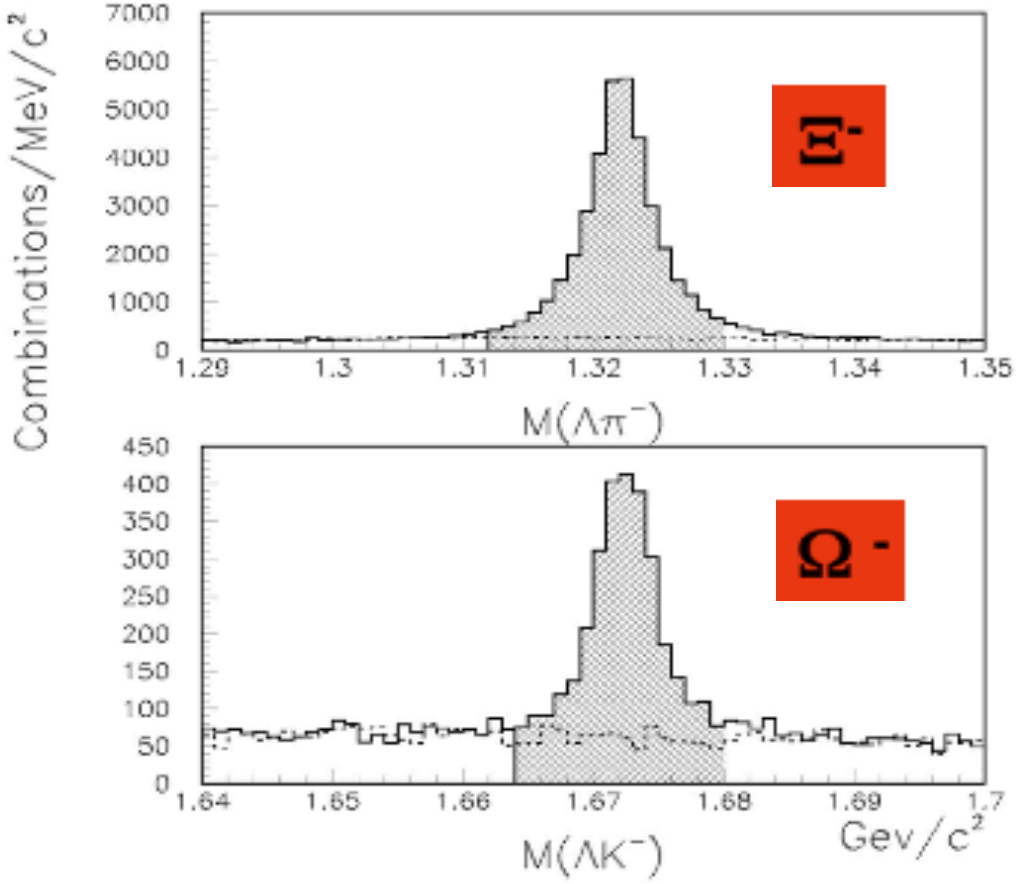
Ξ^- and Ω^- with silicon hits

Inclusive $\Lambda\pi$ and ΛK with previous selection and silicon on the Ξ^-/Ω^- track

- Ξ^- : 34,700
- Ω^-: 1,900

Shaded areas are our mass selection ranges.

- Shorter lifetime of the Ω^- (1" vs. 2") implies lower efficiency
- Many decay before reaching the silicon detector.

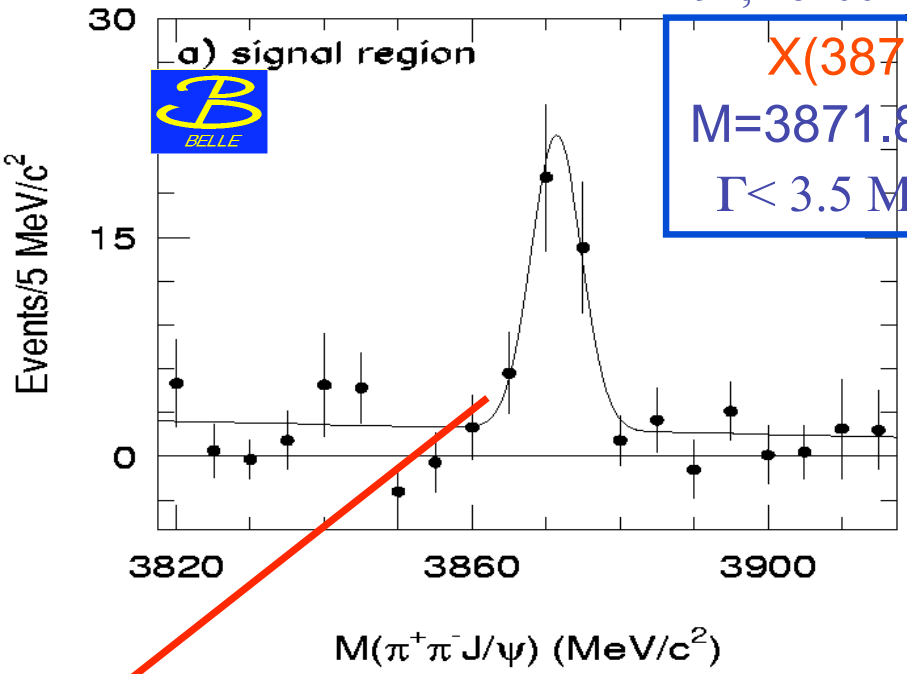


X(3872)--2003

PRL 91, 262001

$c\bar{c}$

$N\,^{2S+1}L_J$	J^{PC}	$u\bar{d}$, $u\bar{u}$, $d\bar{d}$ $I=1$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$ $I=0$	$c\bar{c}$ $I=0$
$1\,^1S_0$	0^{-+}	π	η, η'	$\eta_c(1S)$
$1\,^3S_1$	1^{--}	ρ	ω, ϕ	$J/\psi(1S)$
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$h_1(1170)$, $h_1(1380)$	$h_c(1P)$
$1\,^3P_0$	0^{++}	$a_0(1450)^*$	$f_0(1370)^*$, $f_0(1710)^*$	$\chi_{c0}(1P)$
$1\,^3P_1$	1^{++}	$a_1(1260)$	$f_1(1285)$, $f_1(1420)$	$\chi_{c1}(1P)$
$1\,^3P_2$	2^{++}	$a_2(1320)$	$f_2(1270)$, $f_2'(1525)$	$\chi_{c2}(1P)$
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$\eta_2(1645)$, $\eta_2(1870)$	
$1\,^3D_1$	1^{--}	$\rho(1700)$	$\omega(1650)$	$\psi(3770)$
$1\,^3D_2$	2^{--}			??
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$\omega_3(1670)$, $\phi_3(1850)$	
$1\,^3F_4$	4^{++}	$a_4(2040)$	$f_4(2050)$, $f_4(2220)$	
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$\eta(1295)$, $\eta(1440)$	$\eta_c(2S)$
$2\,^3S_1$	1^{--}	$\rho(1450)$	$\omega(1420)$, $\phi(1680)$	$\psi(2S)$
$2\,^3P_2$	2^{++}	$a_2(1700)$	$f_2(1950)$, $f_2(2010)$	
$3\,^1S_0$	0^{-+}	$\pi(1800)$	$\eta(1760)$	

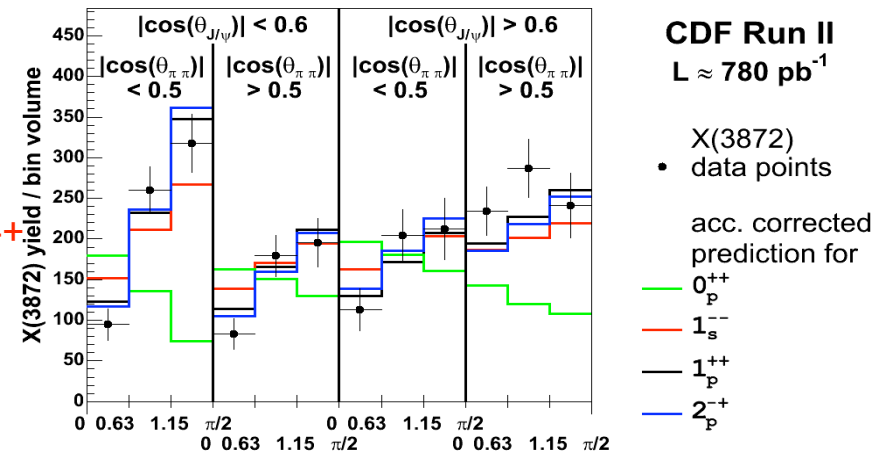


X(3872)→J/ψπ⁺π⁻
M=3871.8±0.7±0.4 MeV
Γ< 3.5 MeV @ 90% CL

mass ~70 MeV > predictions (2003)

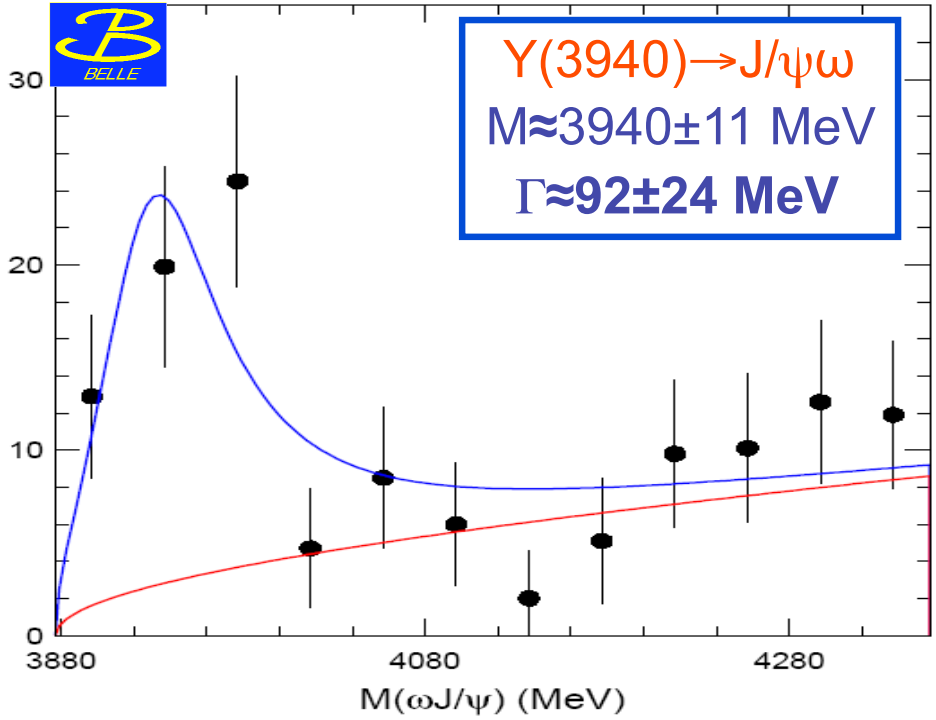
$\pi^+\pi^-$ peak at high value like a ρ (2003)

$J^{PC} = 1^{++}$ or 2^{-+}

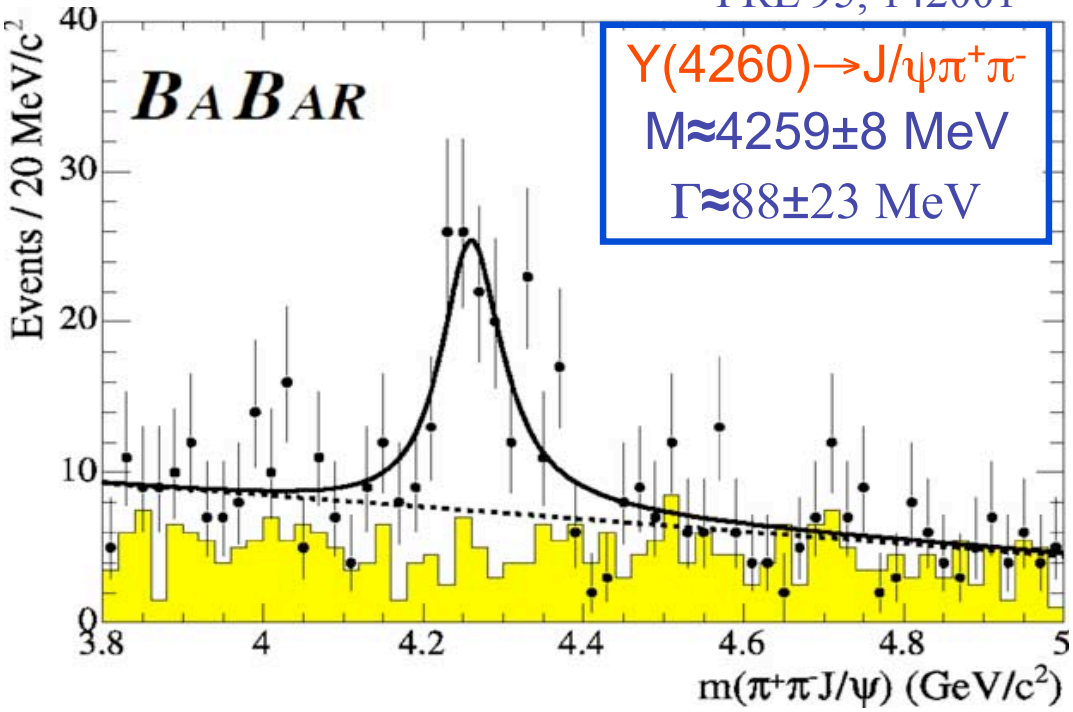


$Y(3940) \to J/\psi\omega$, $Y(4260) \to J\psi\pi^+\pi^-$--2005

PRL 94, 182002



PRL 95, 142001



Above $D\bar{D}$ && $D\bar{D}^*$ threshold,
tiny Branching Fraction expected
New mass and width from BaBar:
$M \approx 3914^{+3.8}_{-3.4} \pm 2.0$, $\Gamma \approx 34^{+12}_{-8} \pm 5$ MeV
at the $J/\psi\omega$ threshold ?

Well above $\bar{D}D$ && $\bar{D}D^*$ threshold,
tiny Branching Fraction expected
$J^{PC}=1^{--}$, plus Y(4350), Y(4660)
too many 1^{--} ?

Multi-quark states → $J/\psi\phi$?

J^{PC}	M(MeV)	Decay Channel
0^{++}	3834	-
0^{++}	3927	$J/\psi\ \omega$
0^{-+}	4277(+15)	$J/\psi\ \phi$, $J/\psi\ \omega$, $D_s^{*+}D_s^{*-}$
0^{-+}	4312(+30)	$J/\psi\ \phi$, $J/\psi\ \omega$, $D_s^{*+}D_s^{*-}$
0^{--}	4297(-5)	$\psi\ \eta(\eta')$, $D_s^{+}D_s^{*-}$
1^{++}	3890	$J/\psi\ \omega$
1^{+-}	3870	$J/\psi\ \eta$
1^{+-}	3905	$J/\psi\ \eta$
1^{-+}	4321(+15)	$J/\psi\ \omega$, $J/\psi\ \phi$
1^{-+}	4356 (+30)	$J/\psi\ \omega$, $J/\psi\ \phi$
1^{--}	4330	$\psi\ \eta(\eta')$, $D_s^{(*)+}D_s^{(*)-}$; $J/\psi\ f_0(980)$
1^{--}	4341(-5)	$\psi\ \eta(\eta')$, $D_s^{(*)+}\ D_s^{(*)-}$; $J/\psi\ f_0(980)$
1^{--}	4390(+40)	$\psi\ \eta(\eta')$, $D_s^{(*)+}D_s^{(*)-}$; $J/\psi\ f_0(980)$
1^{--}	4289(-41)	$\psi\ \eta(\eta')$, $D_s^{(*)+}D_s^{(*)-}$; $J/\psi\ f_0(980)$

arXiv:0902.2803 (new)
N. V. Drenska et al

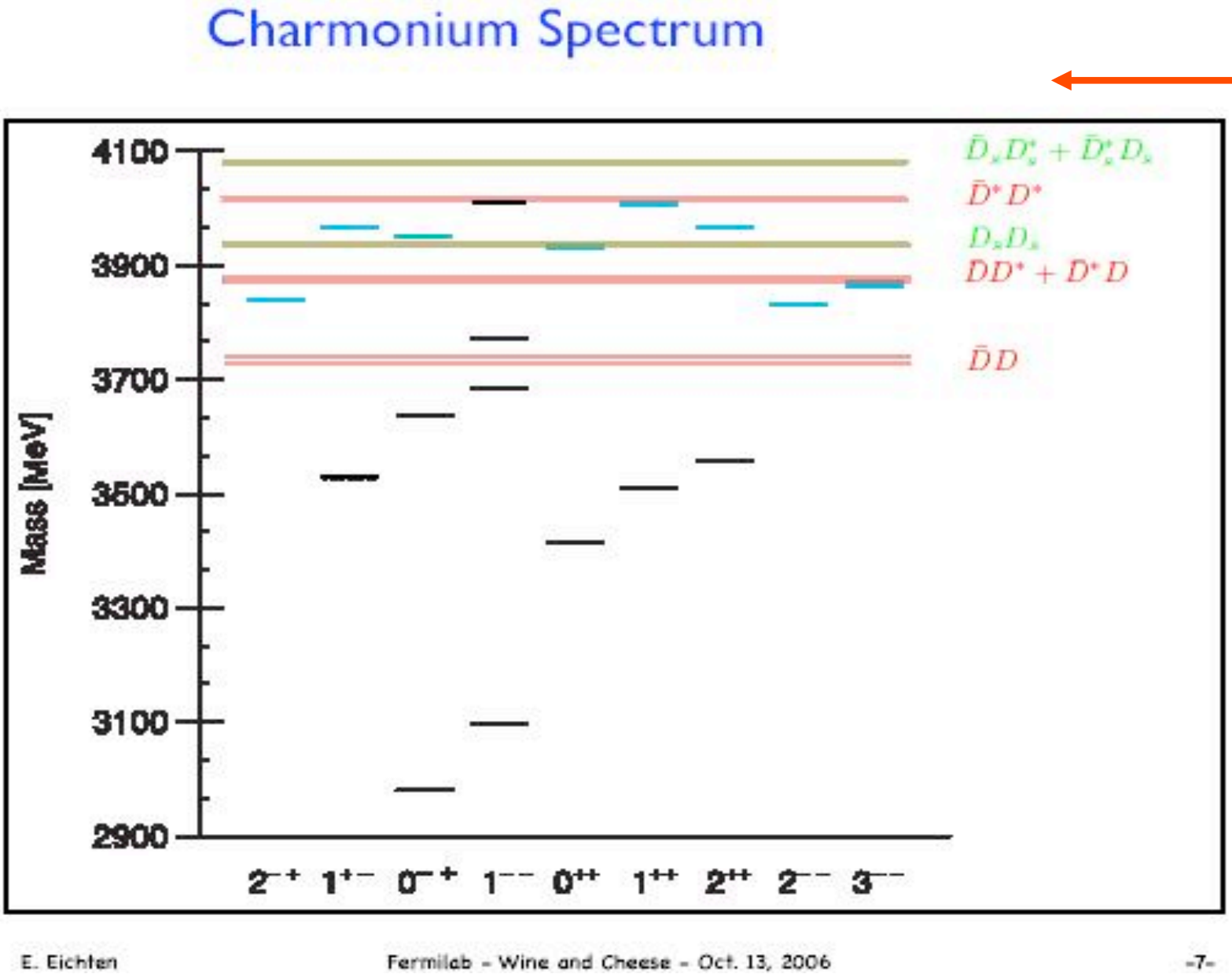
J/ψϕ is well motivated!

How to search?

Inclusive? Challenge!

Through B decays!

What is it?



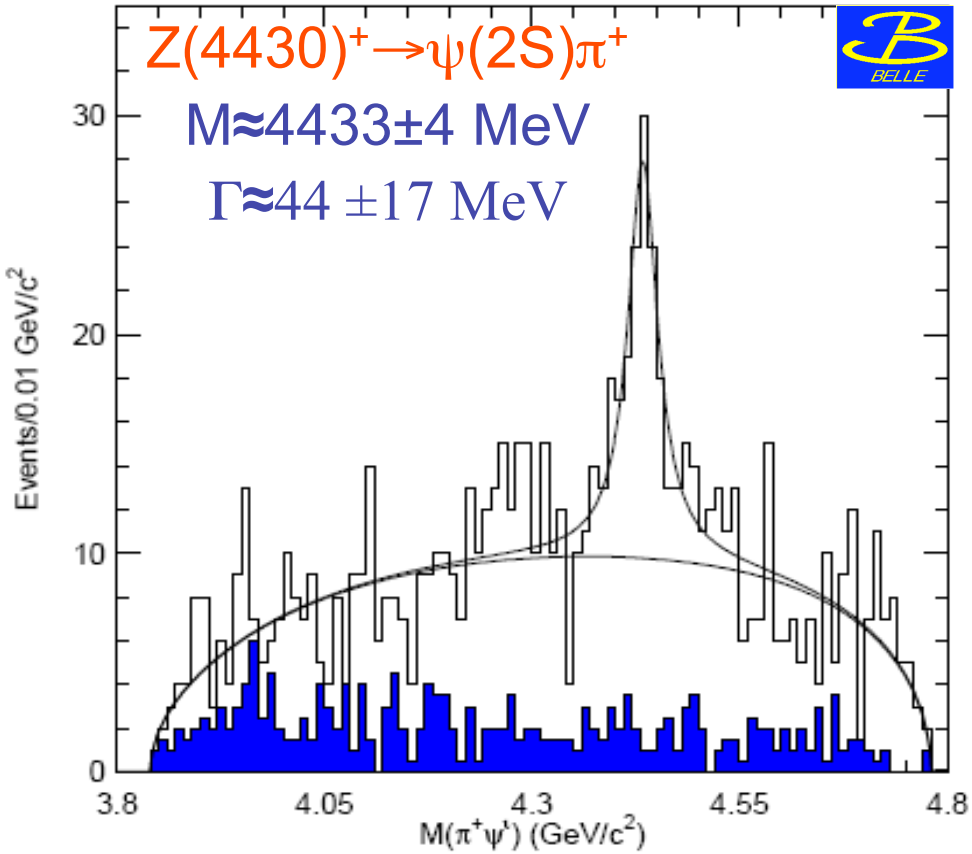
Y(4140)

- Well **above** charm pair threshold
- Expect **tiny** BF to J/ψφ
- Does **not** fit into charmonium
- Close J/ψφ threshold like Y(3940)

arXiv:0903.2529[hep-ph]
molecular?

$Z(4430)^+ \to \psi(2S)\pi^+$--2008

PRL 100, 142001



Needs confirmation

The first charged charmonium-like new state, if confirmed

Many more new states…

They do not (easily) fit into charmonium

Beyond ($q\bar{q}$) mesons: exotic mesons?