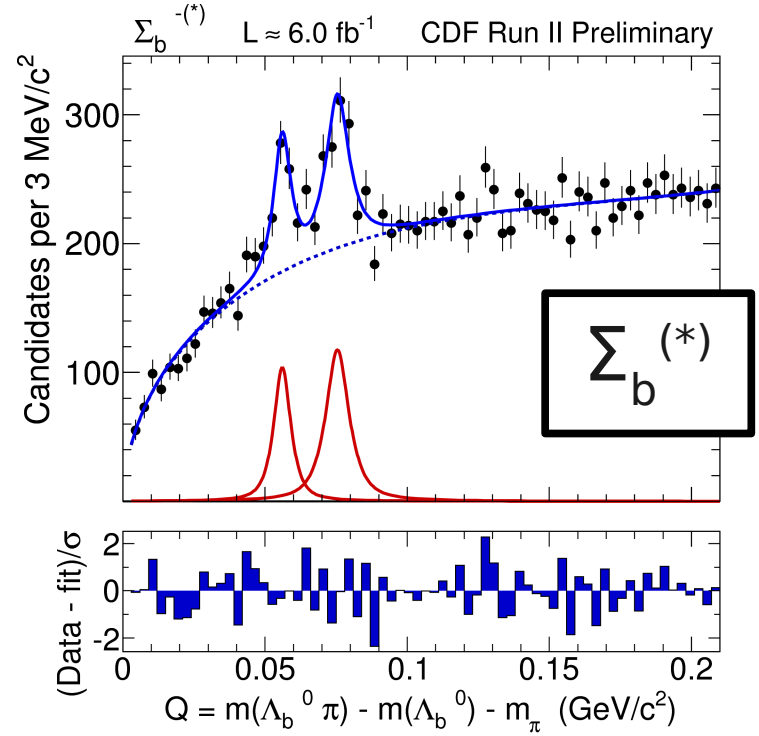
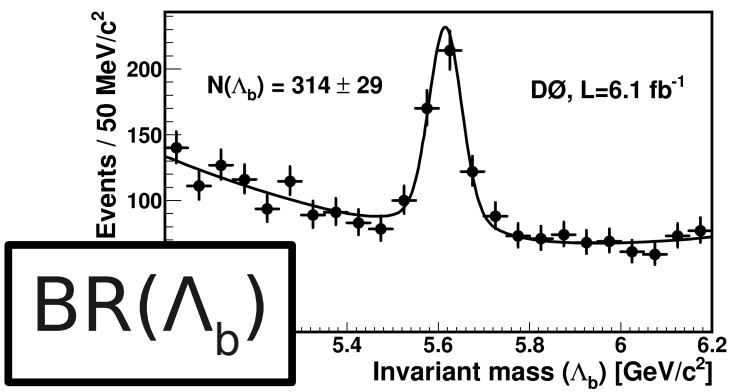
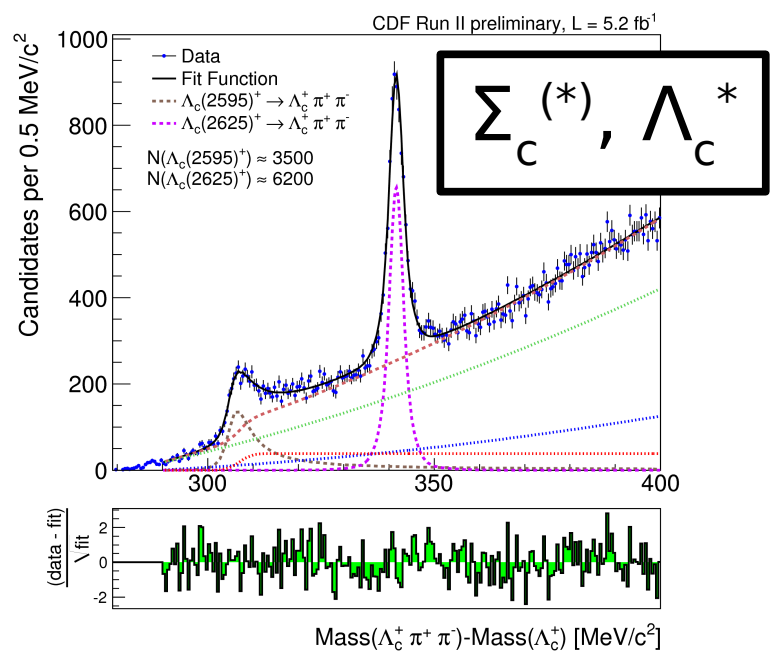
Heavy-Flavor Baryons (at the Tevatron)



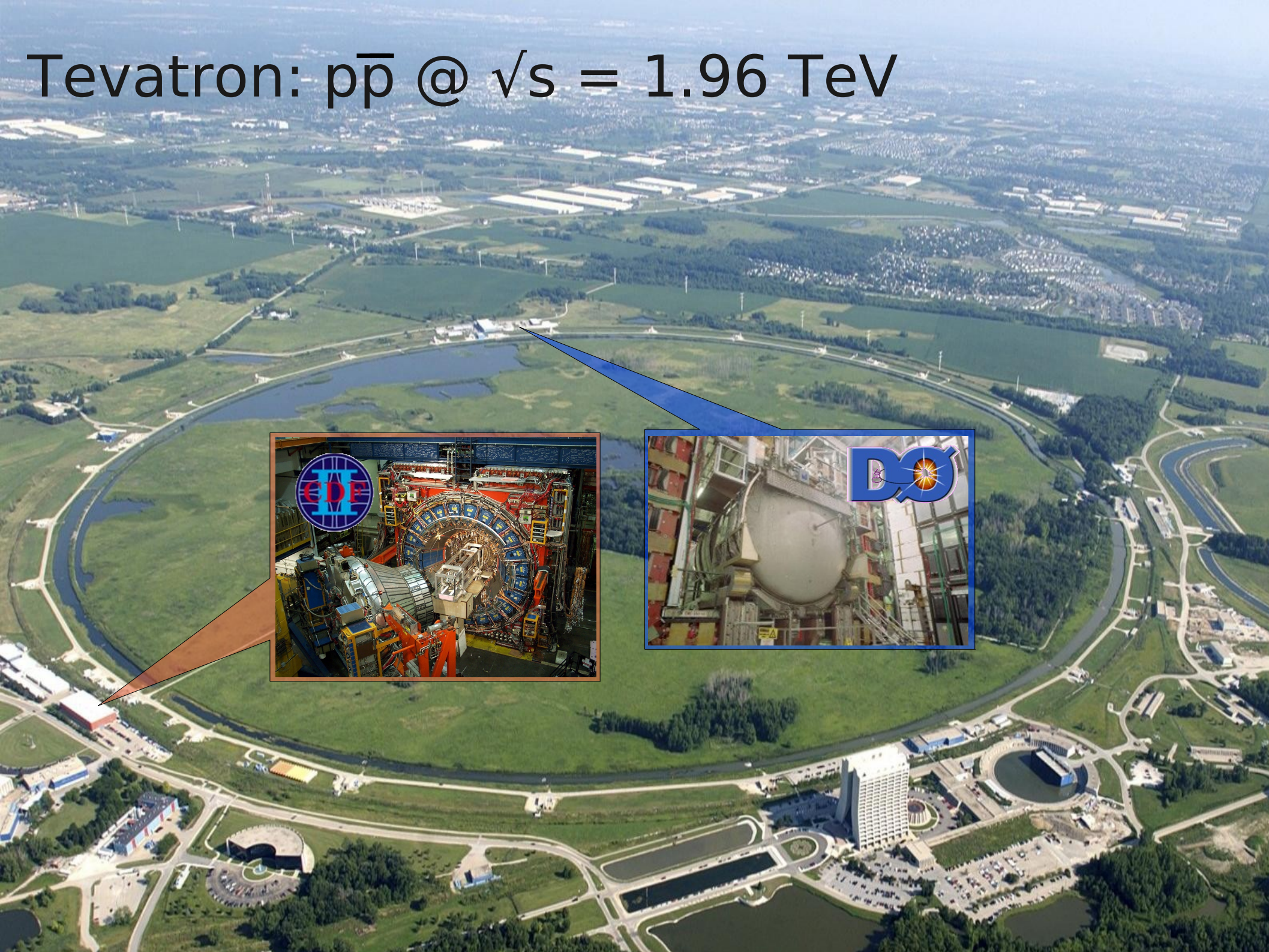




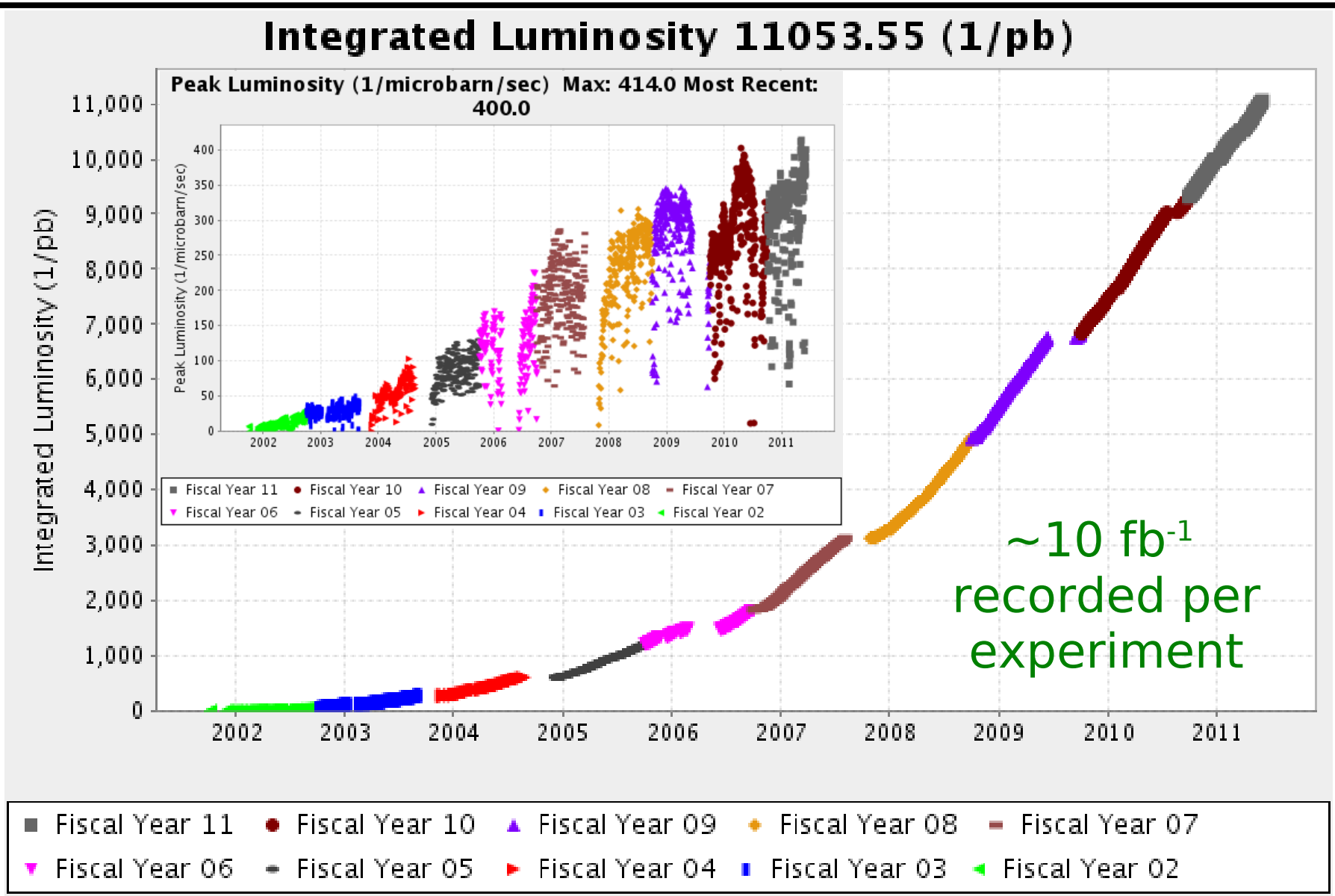
Thomas Kuhr

Hadron2011 16.06.2011

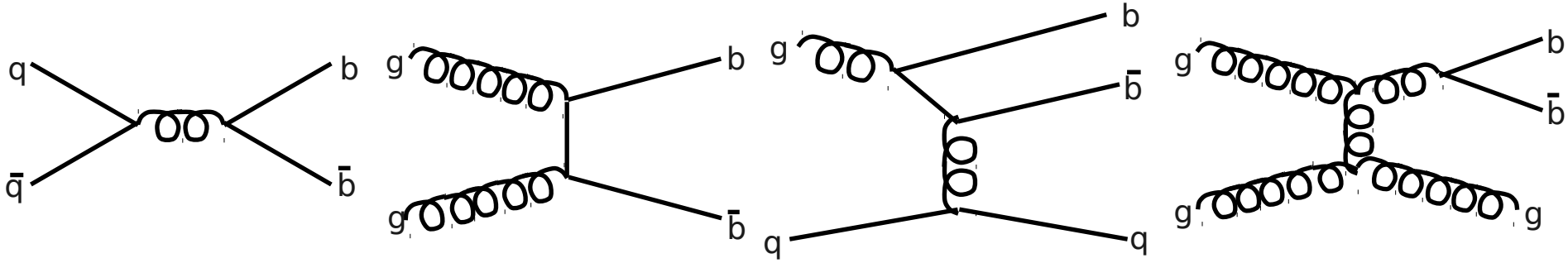
Tevatron: $p\bar{p}$ @ $\sqrt{s}$ = 1.96 TeV



Tevatron Performance



Heavy Flavor Production at the Tevatron

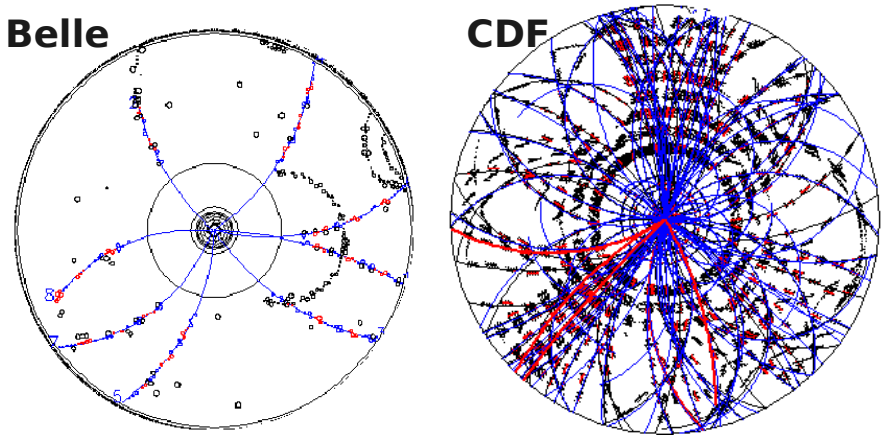


- ➔ Huge $b\bar{b}$ cross section
- ➔ Production of all heavy hadron species in fragmentation

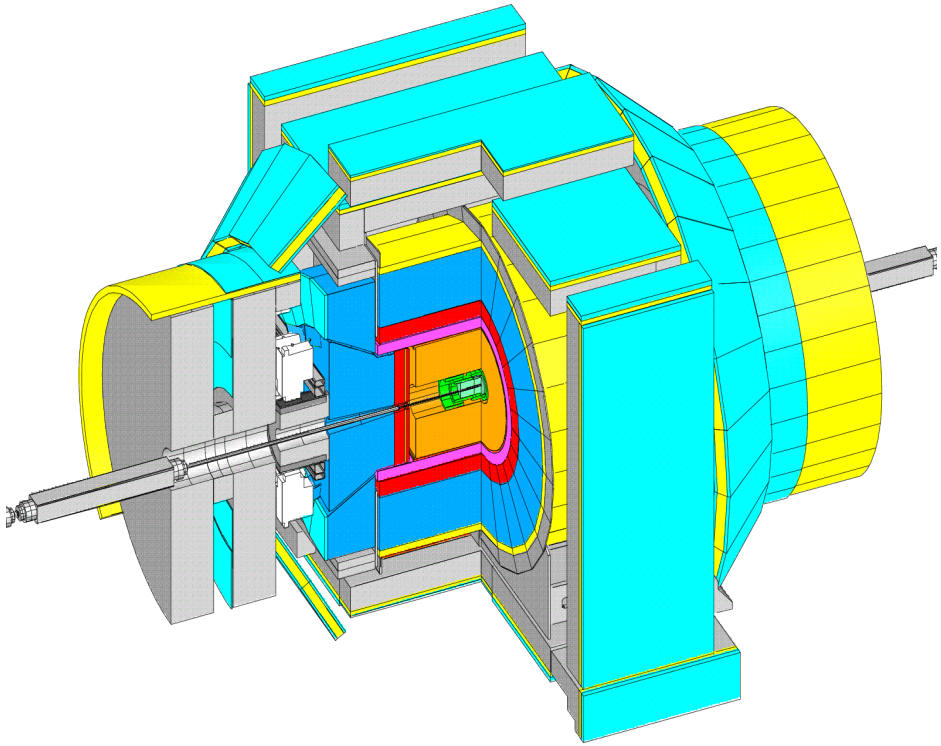
but

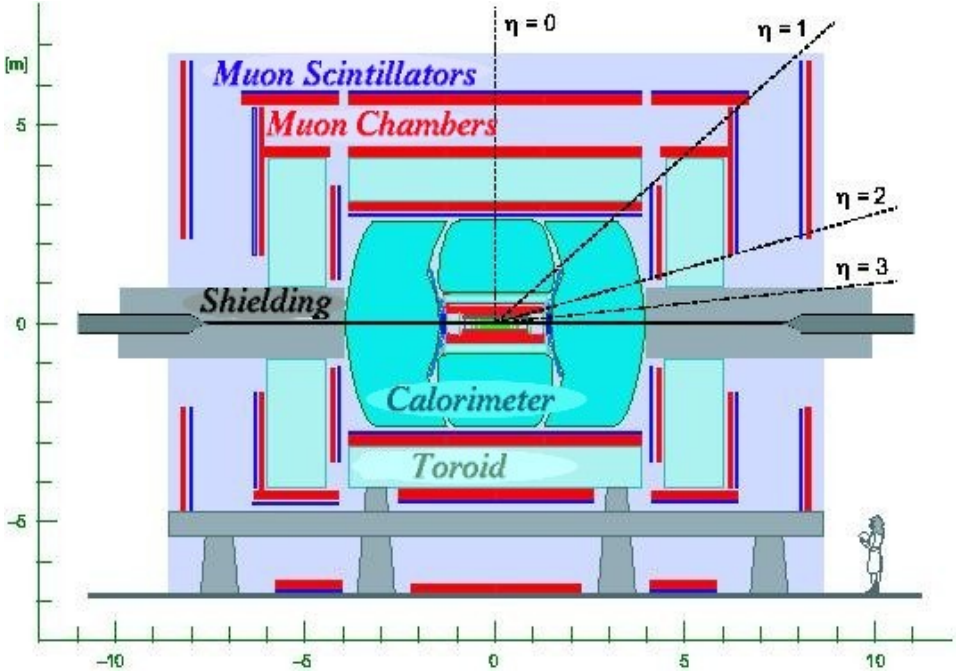
- ✗ inelastic cross section $\sim 10^3$ times larger than $\sigma(b\bar{b})$
  → Trigger

- ✗ Background tracks from fragmentation
  → High combinatorial background



CDF and D0 Detectors





CDF

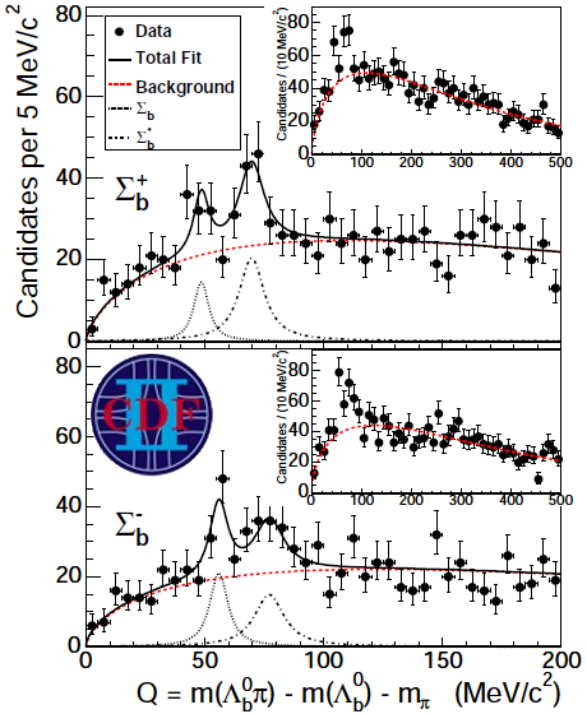
- Excellent mass resolution
- Displaced track and di-muon triggers

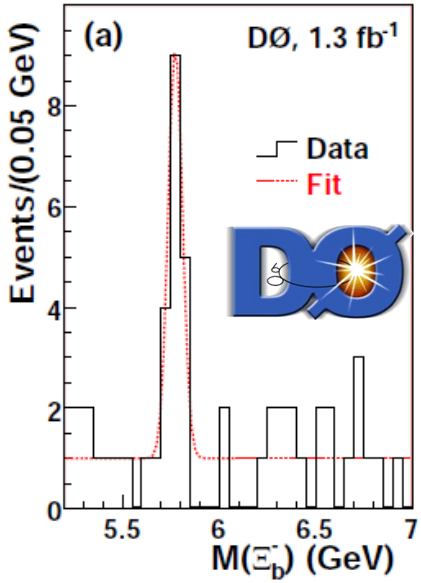
D0

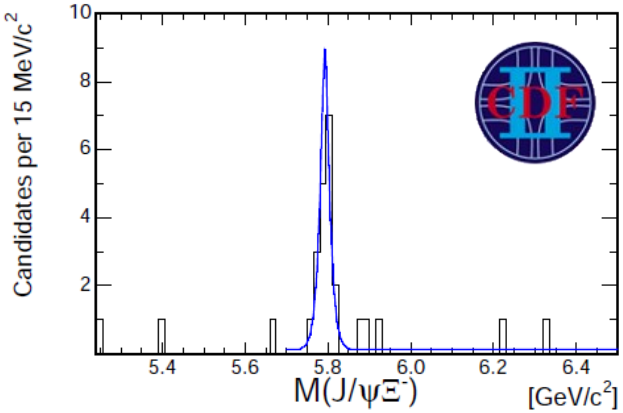
- Large tracking and muon coverage
- Single + di-muon triggers

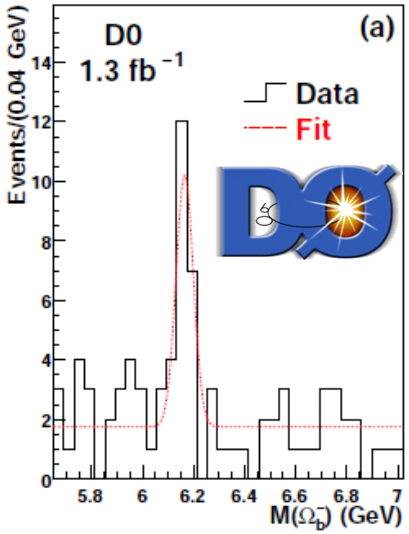
B Baryon History

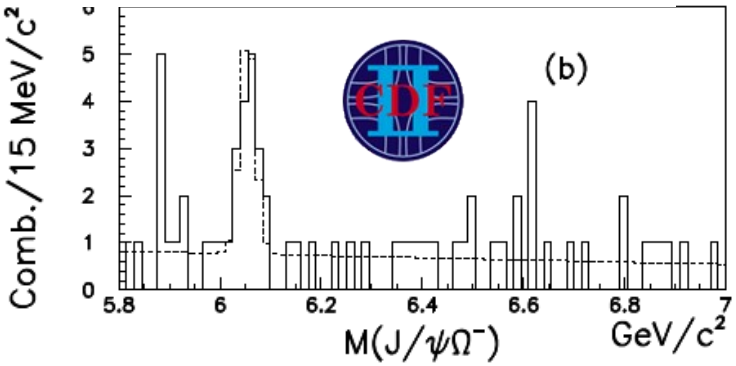
- ✔ Λ_b observation
  1991, UA1, PLB 273, 540
- ✔ $\Sigma_b^{(*)}$ observation
  2007, CDF, PRL 99, 202001
- ✔ Ξ_b observation (D0, CDF),
  2007, D0, PRL 99, 052001,
  2007, CDF, PRL 99, 052002
- ✔ Ω_b observation
  2008, D0,
  PRL 101, 232002
  2009, CDF,
  PRD 80, 072003











Current Knowledge

BOTTOM BARYONS ($B = -1$)

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$, $\Omega_b^- = ssb$

Λ_b^0

$I(J^P) = 0(\frac{1}{2}^+)$

$I(J^P)$ not yet measured; $0(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 5620.2 \pm 1.6$ MeV

$m_{\Lambda_b} - m_{B^0} = 339.2 \pm 1.4$ MeV

Mean life $\tau = (1.391^{+0.038}_{-0.037}) \times 10^{-12}$ s

$c\tau = 417\ \mu$m

The branching fractions B(b-baryon $\to \Lambda \ell^- \overline{\nu}_\ell$ anything) and B($\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell$ anything) are not pure measurements because the underlying measured products of these with B($b \to b$-baryon) were used to determine B($b \to b$-baryon), as described in the note "Production and Decay of b-Flavored Hadrons."

For inclusive branching fractions, *e.g.*, $\Lambda_b \to \overline{\Lambda}_c$ anything, the values usually are multiplicities, not branching fractions. They can be greater than one.

Λ_b^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$J/\psi(1S)\Lambda \times$ B($b \to \Lambda_b^0$)		$(4.7 \pm 2.3) \times 10^{-5}$		1741
$\Lambda_c^+ \pi^-$		$(8.8 \pm 3.2) \times 10^{-3}$		2343
$\Lambda_c^+ a_1(1260)^-$		seen		2153
$\Lambda_c^+ \ell^- \overline{\nu}_\ell$ anything	[v]	(10.7 ± 3.2) %		–
$\Lambda_c^+ \ell^- \overline{\nu}_\ell$		$(5.0^{+1.9}_{-1.4})$ %		2345
$\Lambda_c^+ \pi^+ \pi^- \ell^- \overline{\nu}_\ell$		(5.6 ± 3.1) %		2335
$\Lambda_c(2595)^+ \ell^- \overline{\nu}_\ell$		$(6.3^{+4.0}_{-3.1}) \times 10^{-3}$		2211
$\Lambda_c(2625)^+ \ell^- \overline{\nu}_\ell$		$(1.1^{+0.6}_{-0.4})$ %		2196
ph^-	[w]	$< 2.3 \times 10^{-5}$	90%	2730
$p\pi^-$		$(3.8 \pm 1.3) \times 10^{-6}$		2730
pK^-		$(6.0 \pm 1.9) \times 10^{-6}$		2709
$\Lambda\gamma$		$< 1.3 \times 10^{-3}$	90%	2699

Σ_b

$I(J^P) = 1(\frac{1}{2}^+)$

I, J, P need confirmation.

Mass $m(\Sigma_b^+) = 5807.8 \pm 2.7$ MeV

Mass $m(\Sigma_b^-) = 5815.2 \pm 2.0$ MeV

Σ_b DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda_b^0 \pi$	dominant	128

Σ_b^*

$I(J^P) = 1(\frac{3}{2}^+)$

I, J, P need confirmation.

Mass $m(\Sigma_b^{*+}) = 5829.0 \pm 3.4$ MeV

Mass $m(\Sigma_b^{*-}) = 5836.4 \pm 2.8$ MeV

$m_{\Sigma_b^*} - m_{\Sigma_b} = 21.2 \pm 2.0$ MeV

Σ_b^* DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Lambda_b^0 \pi$	dominant	156

Ξ_b^0, Ξ_b^-

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

I, J, P need confirmation.

Mass $m = 5790.5 \pm 2.7$ MeV

Mean life $\tau_{\Xi_b^-} = (1.56 \pm 0.26) \times 10^{-12}$ s

Mean life $\tau_{\Xi_b} = (1.49^{+0.19}_{-0.18}) \times 10^{-12}$ s

Ξ_b DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	p (MeV/c)
$\Xi_b \to \Xi^- \ell^- \overline{\nu}_\ell X \times$ B($\overline{b} \to \Xi_b$)	$(3.9 \pm 1.2) \times 10^{-4}$	1.4	–
$\Xi_b^- \to J/\psi \Xi^- \times$ B($b \to \Xi_b^-$)	$(8 \pm 4) \times 10^{-6}$		–

Ω_b^-

$I(J^P) = 0(\frac{1}{2}^+)$

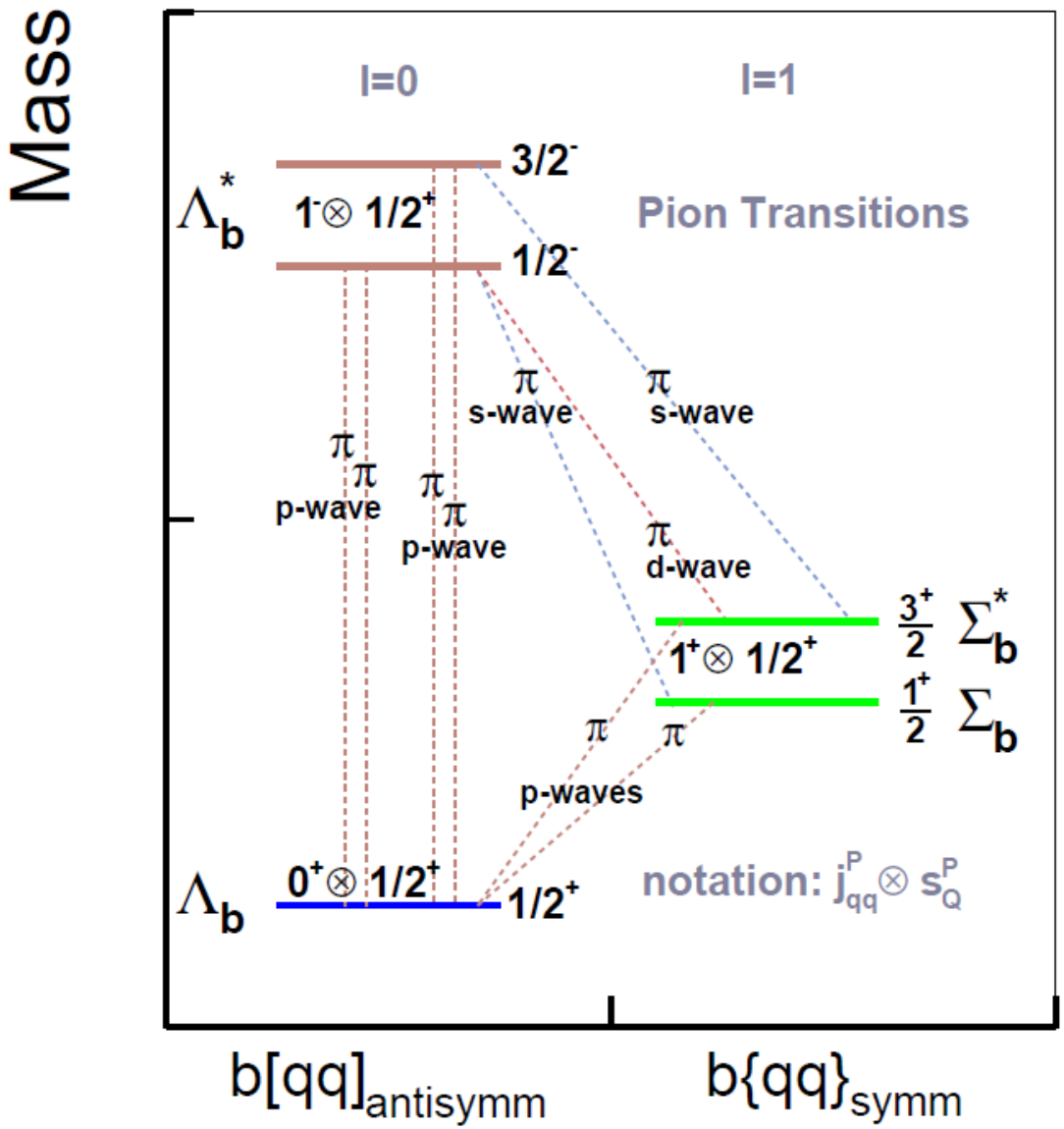
I, J, P need confirmation.

Mass $m = 6071 \pm 40$ MeV (S = 6.2)

Mean life $\tau = (1.1^{+0.5}_{-0.4}) \times 10^{-12}$ s

Ω_b^- DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$J/\psi \Omega^- \times$ B($b \to \Omega_b$)	$(2.4 \pm 1.2) \times 10^{-6}$	1826

$\Sigma_b^{(*)}$ States

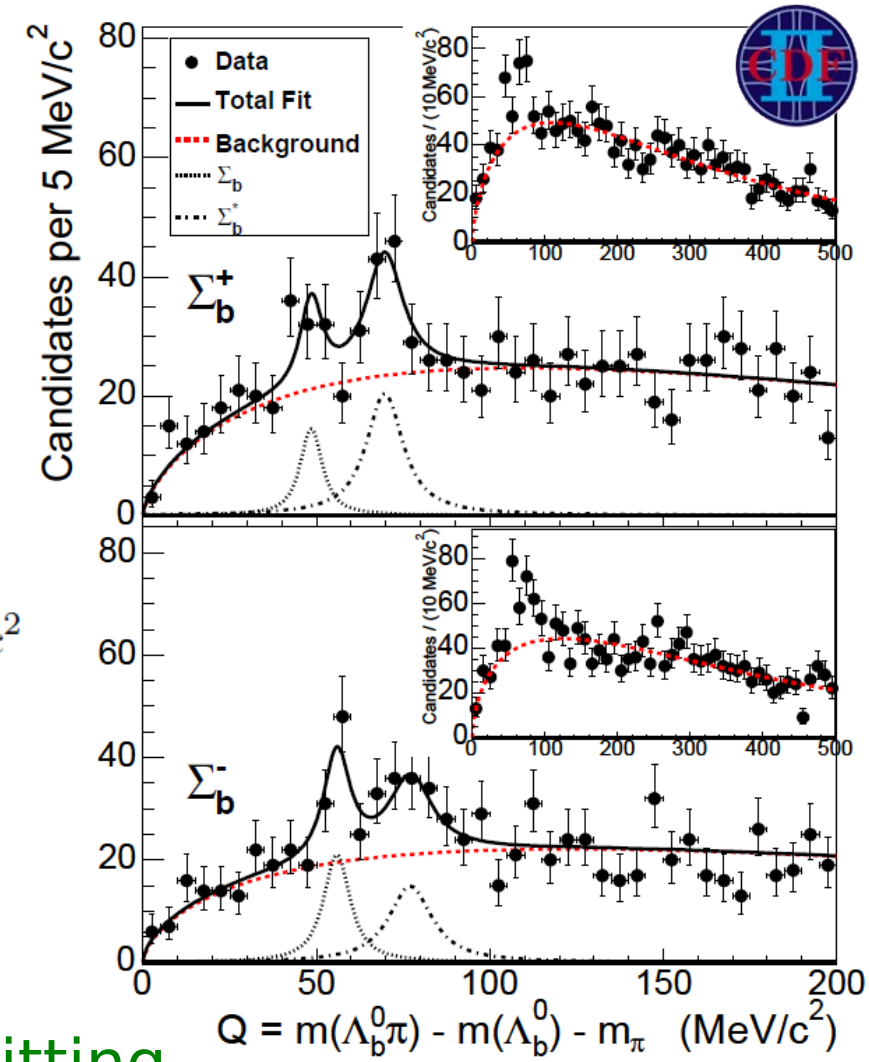


- Isospin triplets
- Strong decay to $\Lambda_b\pi$ via p-wave
- Charged states observable via decay chain:
  - $\Sigma_b^{(*)+} \rightarrow \Lambda_b^0 \pi^+$
  - $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$
  - $\Lambda_c^+ \rightarrow p K^- \pi^+$

$\Sigma_b^{(*)}$ Status

- First observed by CDF in 2007 with 1.1 fb^{-1}
- Significance of each peak ~ 3σ
- Measurement of masses and hyperfine splitting:

$$m_{\Sigma_b^+} = 5807.8^{+2.0}_{-2.2}\ (\text{stat.}) \pm 1.7\ (\text{syst.})\ \text{MeV}/c^2$$
$$m_{\Sigma_b^-} = 5815.2 \pm 1.0\ (\text{stat.}) \pm 1.7\ (\text{syst.})\ \text{MeV}/c^2$$
$$m(\Sigma_b^*) - m(\Sigma_b) = 21.2^{+2.0}_{-1.9}\ (\text{stat.})^{+0.4}_{-0.3}\ (\text{syst.})\ \text{MeV}/c^2$$

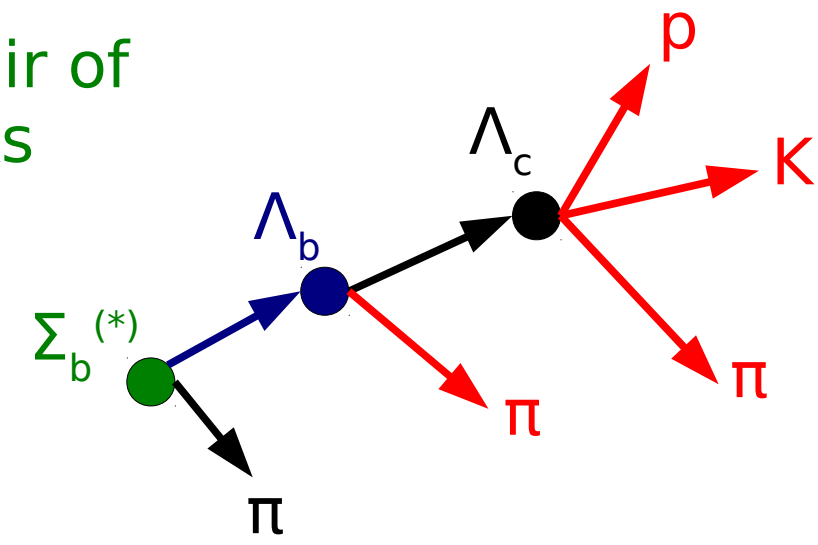


Motivation for update:

- Confirm observation
- Improve mass measurements
- Measure widths and isospin splitting

$\Sigma_b^{(*)}$ Trigger and Selection

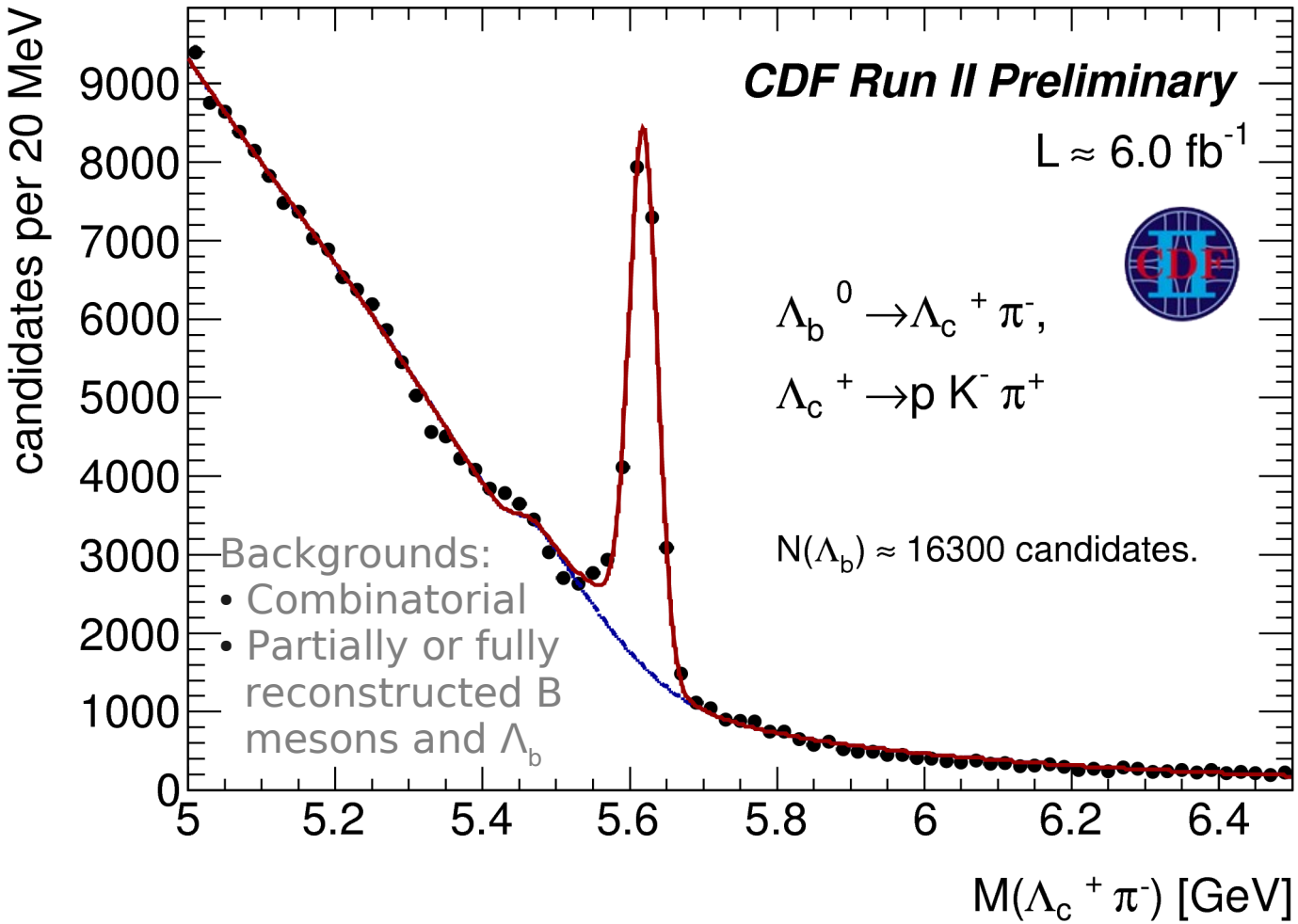
- Trigger on a pair of displaced tracks



- Vertex fit (with mass constraint) for Λ_c, Λ_b, and $\Sigma_b^{(*)}$
- Selection cuts on
  - Decay time, impact parameter, momentum

➔ Optimized on $S/\sqrt{(S+B)}$ of Λ_b signal

$\Sigma_b^{(*)}$ Data Sample



6 fb^{-1}

- ~16k Λ_b
- S/B ≈ 1.8

→ Real Λ_b with random π is dominant background for Σ_b

$\Sigma_b^{(*)}$ Fit

- Fit of $Q = M(\Lambda_b\pi) - M(\Lambda_b) - M(\pi)$

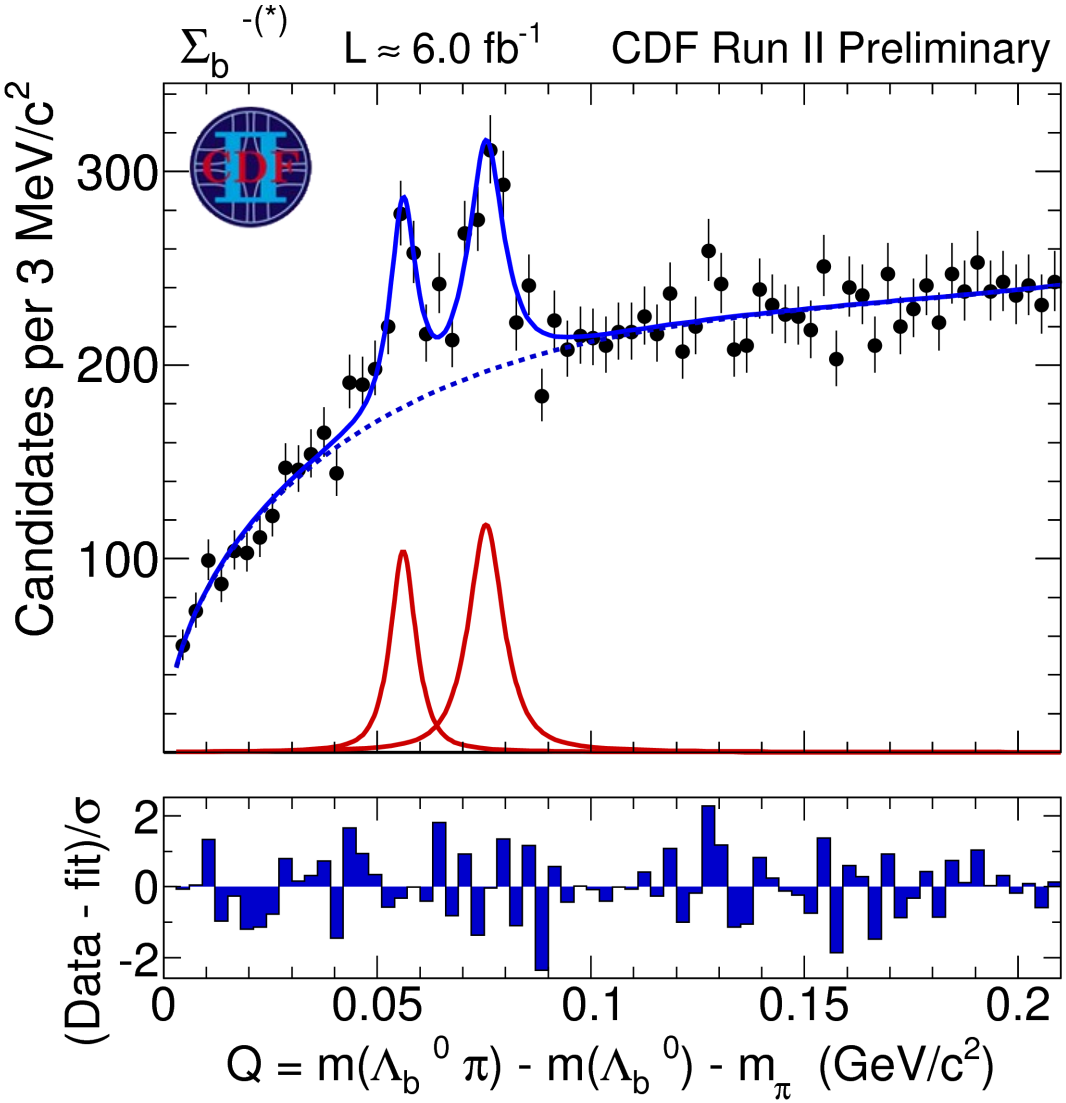
Background:

- Second order polynomial times
- Square root function (for threshold)

Signal:

- Non-relativistic Breit-Wigner
- With variable width $\Gamma = \Gamma_0 \, (p_\pi / p_{\pi,0})^3$ (for p-wave decay)
- Convolved with double-Gaussian resolution function determined from MC

$\Sigma_b^{(*)-}$ Mass Spectrum



Significance:

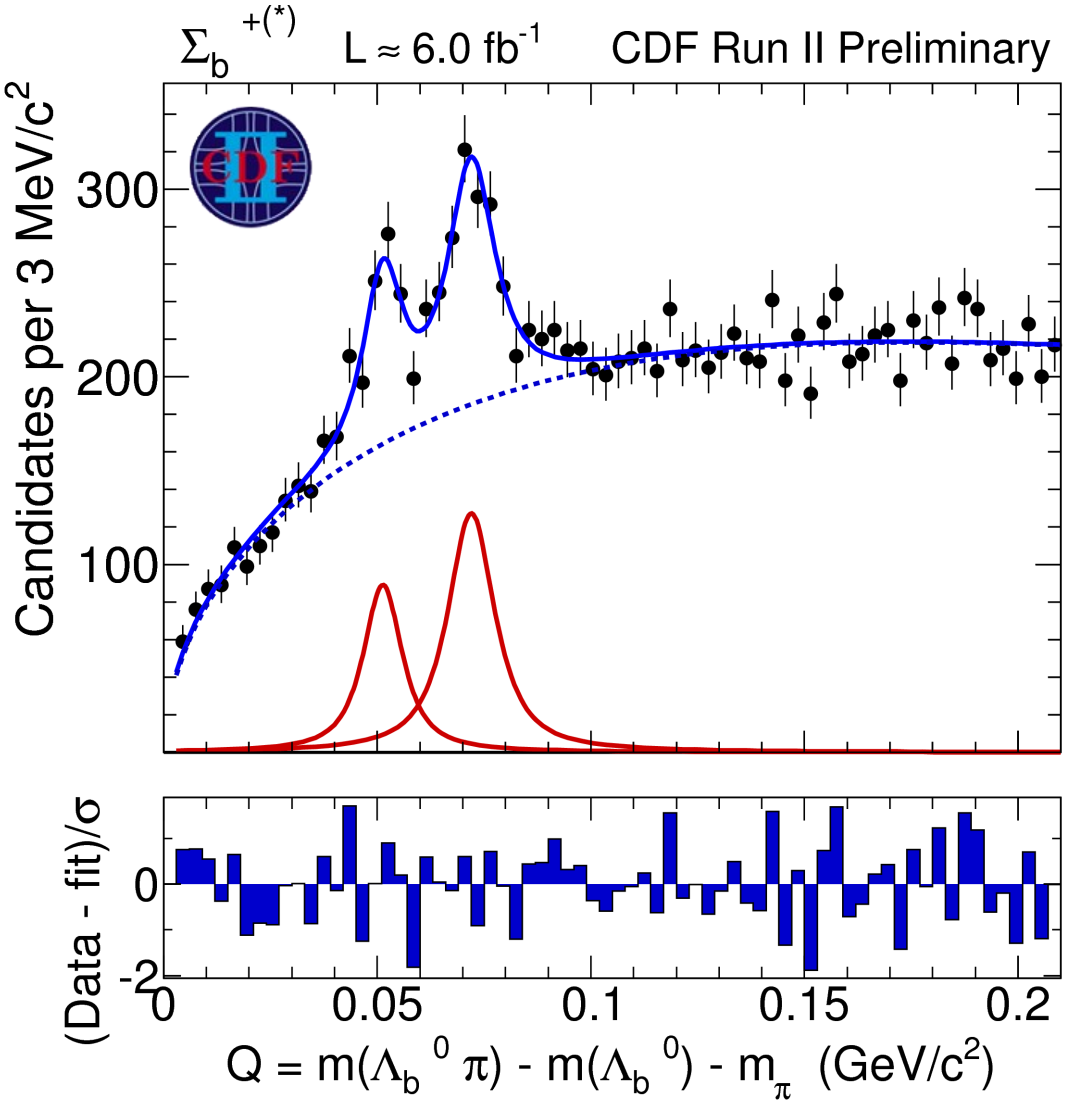
- Comparison of hypotheses for different numbers of peaks via Δlog(L)

➔ Two vs. one: 7.5σ

➔ One vs. none: 10.0σ

➔ Two vs. none: 12.3σ

$\Sigma_b^{(*)+}$ Mass Spectrum



Significance:

- Comparison of hypotheses for different numbers of peaks via Δlog(L)

➔ Two vs. one: 7.2σ

➔ One vs. none: 12.2σ

➔ Two vs. none: 14.0σ

$\Sigma_b^{(*)}$ Results

Talk by Igor Gorelov, tomorrow in Heavy Hadron session

- Systematics: momentum scale, resolution model, background model, fit bias, external input

State	Q-value, MeV/c^2	Absolute Mass, m, MeV/c^2	Natural Width, Γ, MeV/c^2	Yield, num. of cands.
Σ_b^+	$52.0^{+0.9}_{-0.8}{}^{+0.09}_{-0.4}$	$5811.2^{+0.9}_{-0.8} \pm 1.7$	$9.2^{+3.8}_{-2.9}{}^{+1.0}_{-1.1}$	$468^{+110}_{-95}{}^{+18}_{-15}$
Σ_b^-	$56.2^{+0.6}_{-0.5}{}^{+0.07}_{-0.4}$	$5815.5^{+0.6}_{-0.5} \pm 1.7$	$4.3^{+3.1}_{-2.1}{}^{+1.0}_{-1.1}$	$333^{+93}_{-73} \pm 35$
Σ_b^{*+}	$72.7 \pm 0.7^{+0.12}_{-0.6}$	$5832.0 \pm 0.7 \pm 1.8$	$10.4^{+2.7}_{-2.2}{}^{+0.8}_{-1.2}$	$782^{+114}_{-103}{}^{+25}_{-27}$
Σ_b^{*-}	$75.7 \pm 0.6^{+0.08}_{-0.6}$	$5835.0 \pm 0.6 \pm 1.8$	$6.4^{+2.2}_{-1.8}{}^{+0.7}_{-1.1}$	$522^{+85}_{-76} \pm 29$
	Isospin Mass Splitting, MeV/c^2			
m(Σ_b^+) - m(Σ_b^-)		$-4.2^{+1.1}_{-0.9}{}^{+0.07}_{-0.09}$		
m(Σ_b^{*+}) - m(Σ_b^{*-})		$-3.0 \pm 0.9^{+0.12}_{-0.13}$		

Improved by factor ≥2

First measurements

$\Lambda_b \to J/\psi\ \Lambda$

- Very little known about flavor physics processes in b baryons
  - For example $b \to s$ transitions are sensitive to new physics

- $\Lambda_b \to J/\psi\ \Lambda$

- CDF Run I measurement:

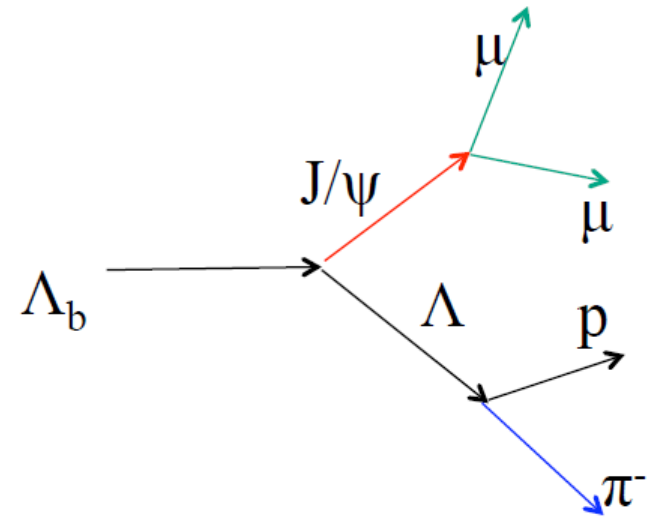
  $f(b \to \Lambda_b)\ BR(\Lambda_b \to J/\psi\ \Lambda) =$
  $(4.7 \pm 2.3 \pm 0.2) \times 10^{-5}$

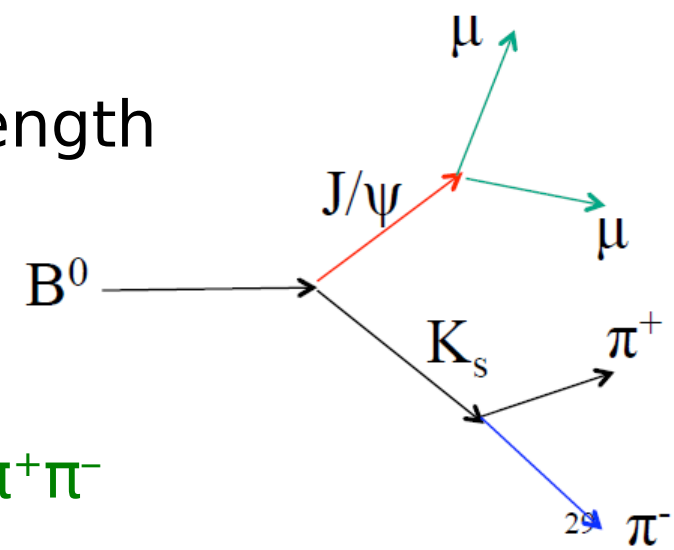
$\Lambda_b \to J/\psi\ \Lambda$ BR Measurement

- Trigger on muon pair or single muon
- Vertex fit for Λ, and Λ_b
- Cascade decays like $\Sigma \to \Lambda\gamma$ or $\Xi^0 \to \Lambda\pi^0$ suppressed by requiring Λ vertex in Λ momentum direction
- Selection cuts on
  - Momentum, impact par., decay length

➔ Optimized on $S/\sqrt{(S+B)}$ with S from MC and B from sidebands

➢ Normalized to $B^0 \to J/\psi\ K_S$ with $K_S \to \pi^+\pi^-$



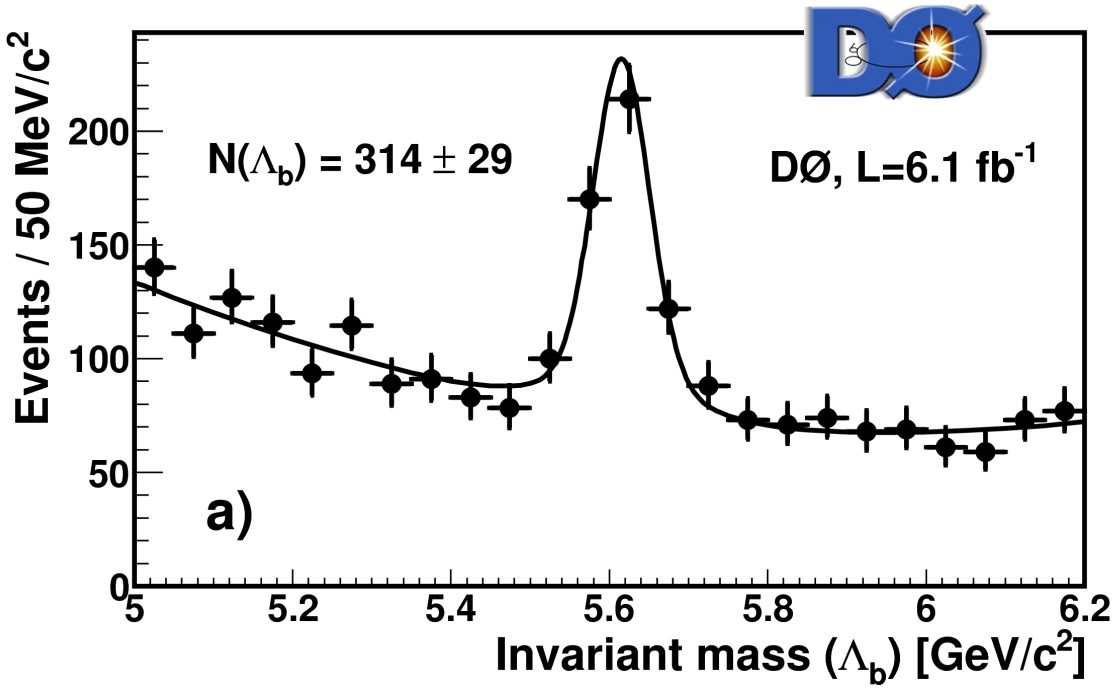


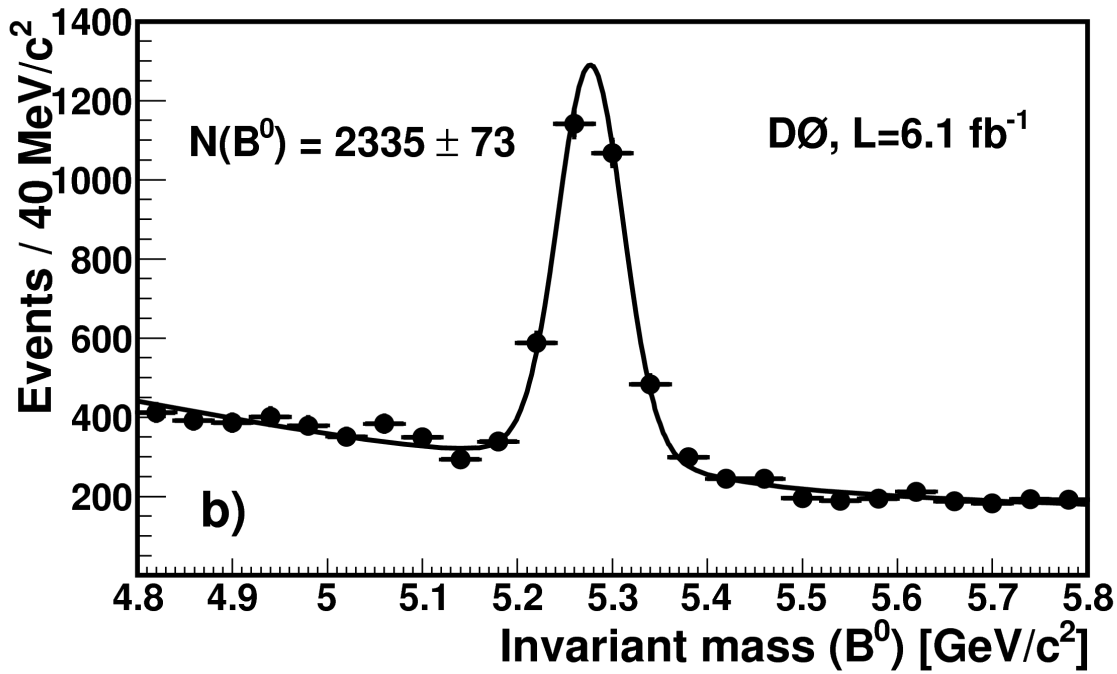
$\Lambda_b \rightarrow J/\psi\ \Lambda$ Fit

6.1 fb^{-1}

- Signal:
  double Gaussian
- Background:
  2nd order polynomial

- Relative efficiency
  from MC
- $\varepsilon = 2.37 \pm 0.05$ (stat.)





$\Lambda_b \to J/\psi\, \Lambda$ Result

$$\sigma_{rel} \equiv \frac{f(b \to \Lambda_b) \cdot B(\Lambda_b \to J/\psi\Lambda)}{f(b \to B^0) \cdot B(B^0 \to J/\psi K_s^0)} = \frac{N_{\Lambda_b \to J/\psi\Lambda}}{N_{B^0 \to J/\psi K_s^0}} \cdot \frac{B(K_s^0 \to \pi^+\pi^-)}{B(\Lambda \to p\pi^-)} \cdot \varepsilon$$

- Systematic uncertainties: Fit model (5.6%), relative efficiency [B^0 decay model] (2.0%), cross-feed (2.3%), Λ_b polarization (7.2%)

✔ Several cross-checks (sub-samples, data-MC comparisons)

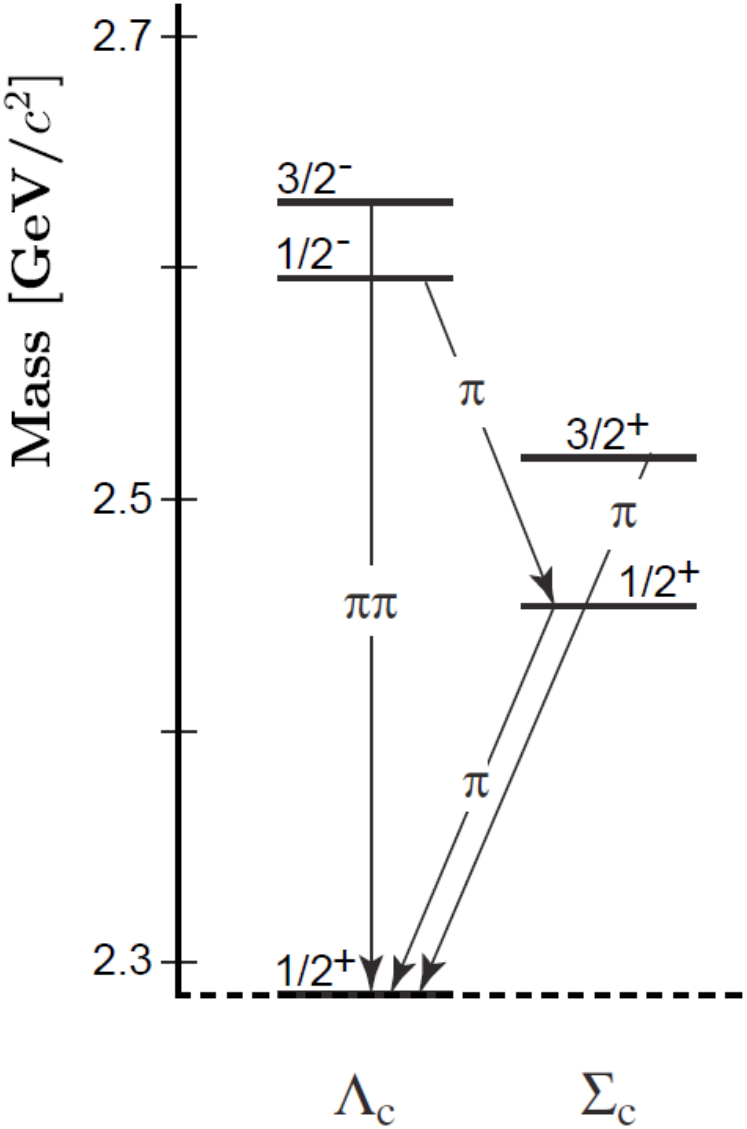
$$\sigma_{\rm rel} = 0.345 \pm 0.034\ (\text{stat.}) \pm 0.033\ (\text{syst.}) \pm 0.003\ (\text{PDG})$$

Factor ~3 improvement

$$f(b \to \Lambda_b) \cdot \mathcal{B}(\Lambda_b \to J/\psi\Lambda) = [6.01 \pm 0.60\ (\text{stat.}) \pm 0.58\ (\text{syst.}) \pm 0.28\ (\text{PDG})] \times 10^{-5} = (6.01 \pm 0.88) \times 10^{-5}$$

Submitted to PRD-RC
arXiv:1105.0690

Charm Baryons



- $\Sigma_c^{(*)}$: Isospin triplets
  $J^P=1/2^+$: $\Sigma_c(2455)$, $J^P=3/2^+$: $\Sigma_c(2520)$
- Λ_c^*: Λ_c orbital excitations
  $J^P=1/2^-$: $\Lambda_c(2595)$, $J^P=3/2^-$: $\Lambda_c(2625)$

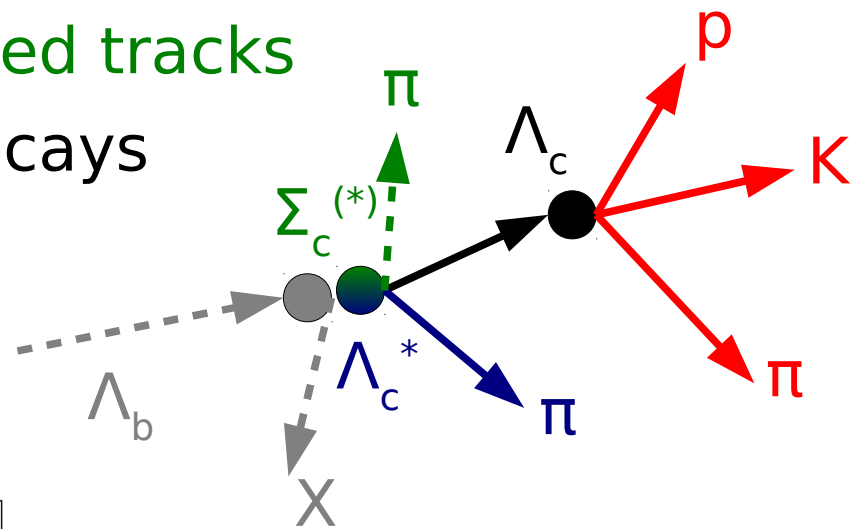
$\Lambda_c(2595)^+ - \Lambda_c^+$ MASS DIFFERENCE

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
308.9±0.6 OUR FIT Error includes scale factor of 1.1.					
308.9±0.6 OUR AVERAGE Error includes scale factor of 1.1.					
309.7±0.9±0.4	19	ALBRECHT	97	ARG	$e^+e^- \approx$ 10 GeV
309.2±0.7±0.3	14 ± 4.5	FRABETTI	96	E687	γBe, $\overline{E}_\gamma \approx$ 220 GeV
307.5±0.4±1.0	112 ± 17	EDWARDS	95	CLE2	$e^+e^- \approx$ 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
305.6±0.3		[1] BLECHMAN	03		Threshold shift

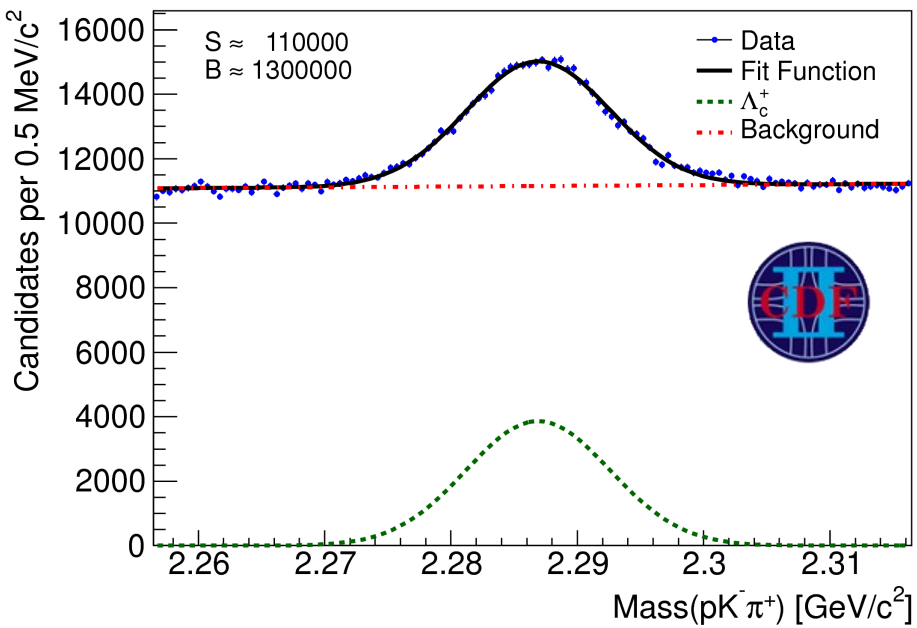
[1] BLECHMAN 03 finds that a more sophisticated treatment than a simple Breit-Wigner for the proximity of the threshold of the dominant decay, $\Sigma_c(2455)\pi$, lowers the $\Lambda_c(2595)^+ - \Lambda_c^+$ mass difference by 2 or 3 MeV.

Charm Baryons Trigger and Selection

- Trigger on a pair of displaced tracks
  - ➔ ~50% from b hadron decays



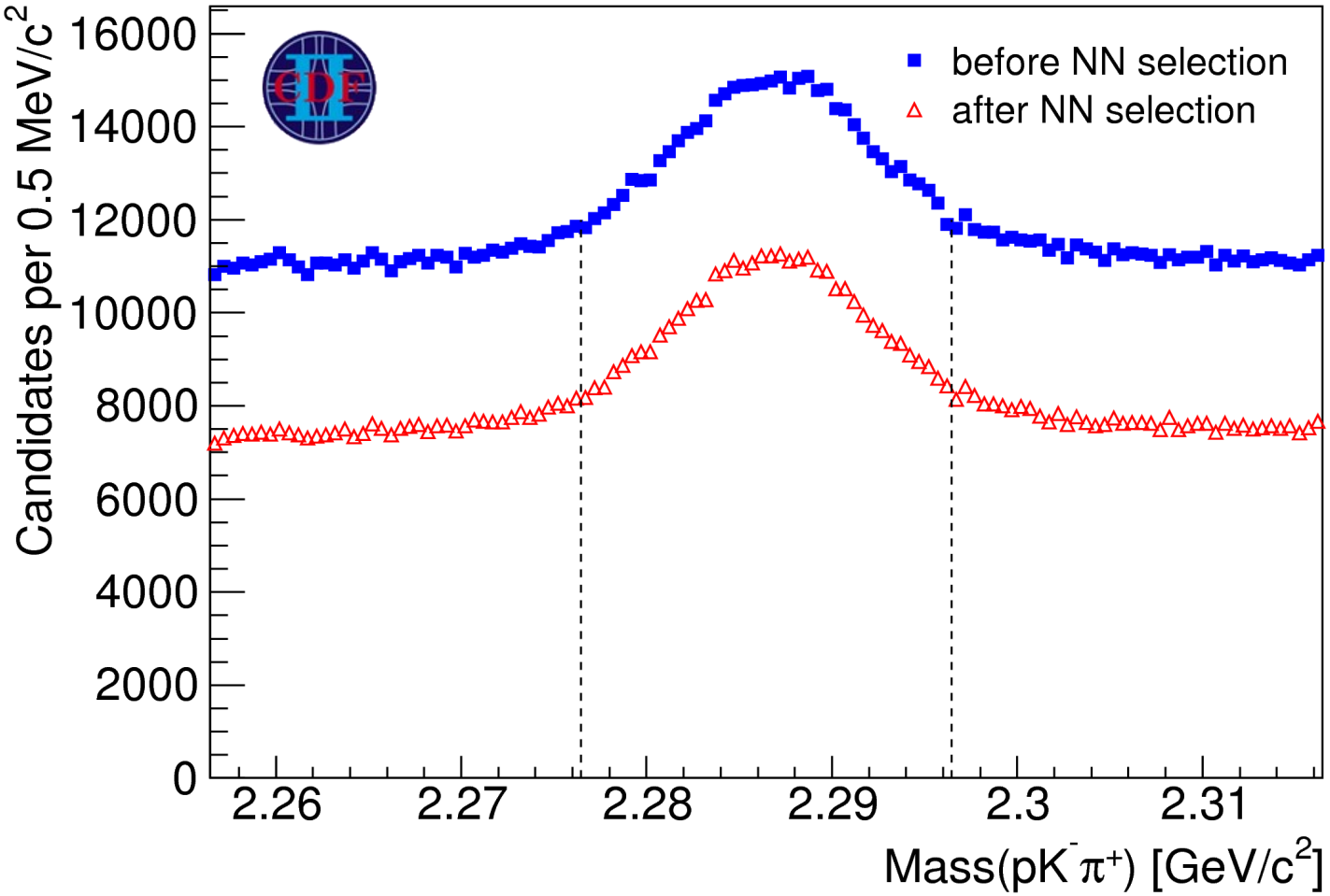
- Selection of $\Lambda_c^+ \rightarrow p\, K^-\, \pi^+$ with Neural Network (NN)



- Input variables: particle ID, decay time, decay angles, fit quality

➢ NN training on data only using sPlot technique

Charm Baryons Data Sample



5.2 fb^{-1}

$\Sigma_c^{(*)}$ candidates:

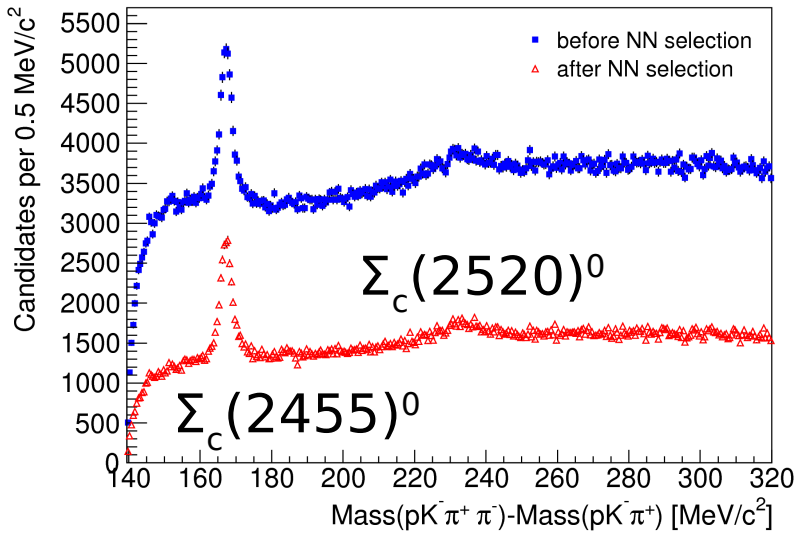
→ Λ_c + one π

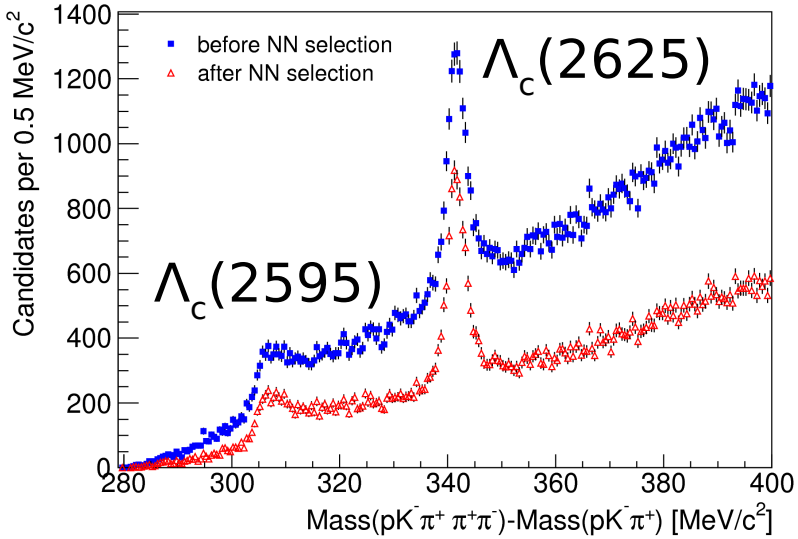
Λ_c^* candidates:

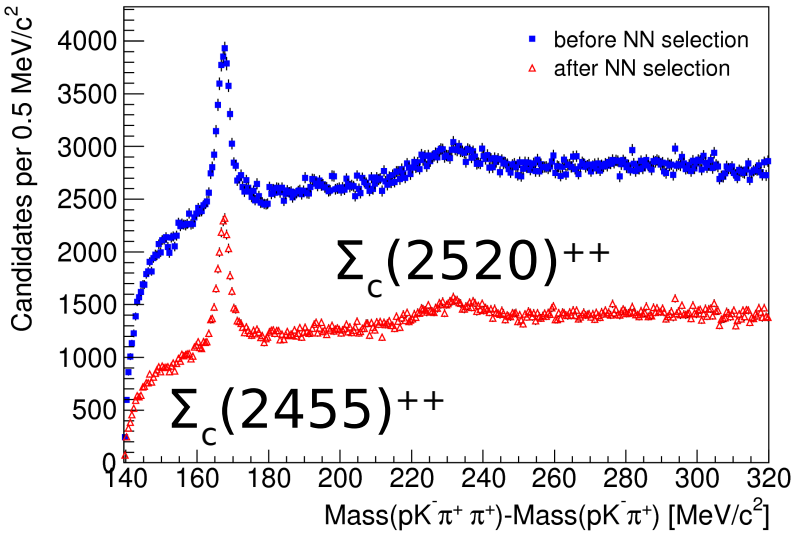
→ Λ_c + two π

- $\Sigma_c^{(*)}$ and Λ_c^* selection with NN trained on data (sPlot)

Charm Baryon Spectra



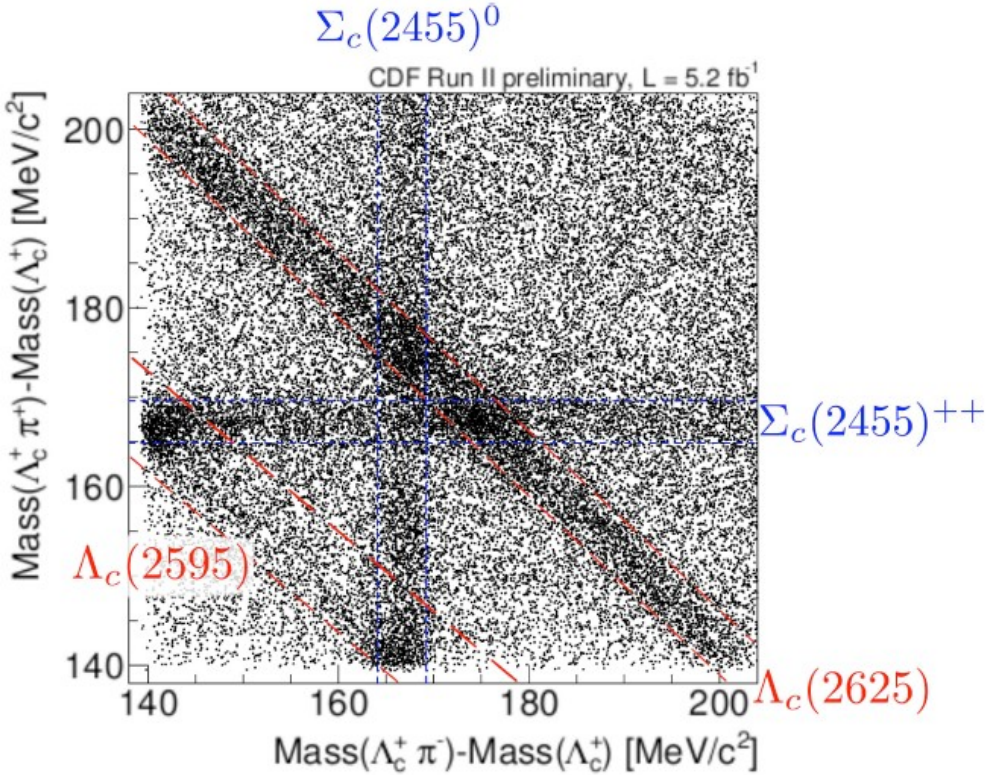




Fit of mass difference

- $\Sigma_c^{(*)}$: $\Delta M = M(\Lambda_c\pi) - M(\Lambda_c)$
- Λ_c^*: $\Delta M = M(\Lambda_c\pi\pi) - M(\Lambda_c)$

$\Sigma_c^{(*)}$ Fit

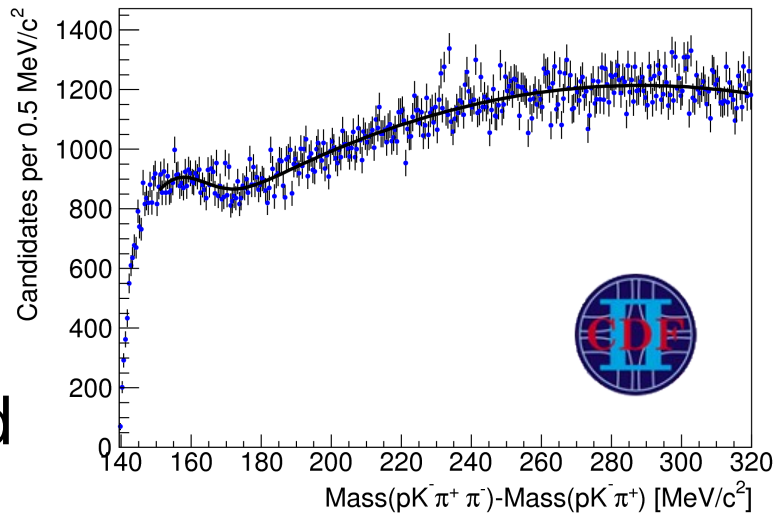


Signal:

- nonrelativistic Breit-Wigner convolved with triple Gaussian resolution function

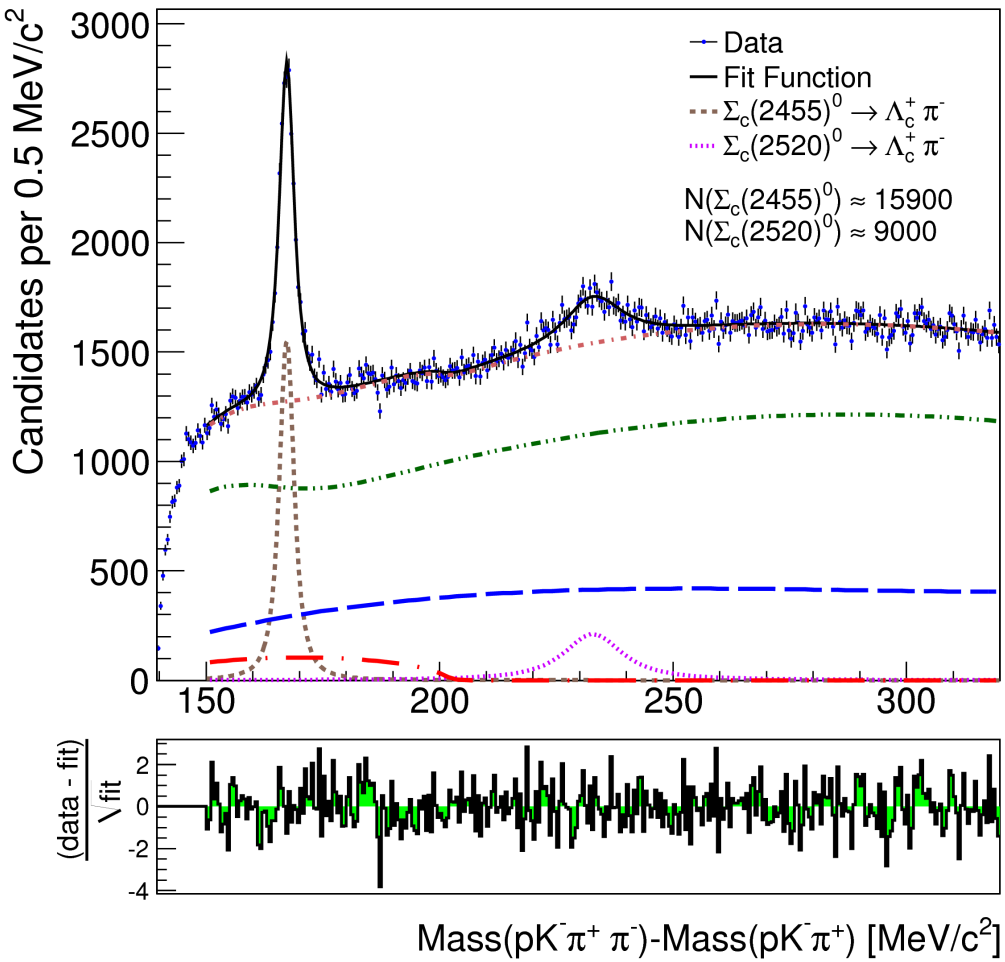
Background:

- Combinatorial:
  2nd order polynomial from Λ_c sideband, Gaussian for D^* reflection for $\Sigma_c^{(*)0}$ case
- Λ_c with random π: 3rd order pol.
- $\Lambda_c(2625) \rightarrow \Lambda_c\pi\pi$ feed down:
  derived from $\Lambda_c(2625) \rightarrow \Lambda_c\pi\pi$ yield

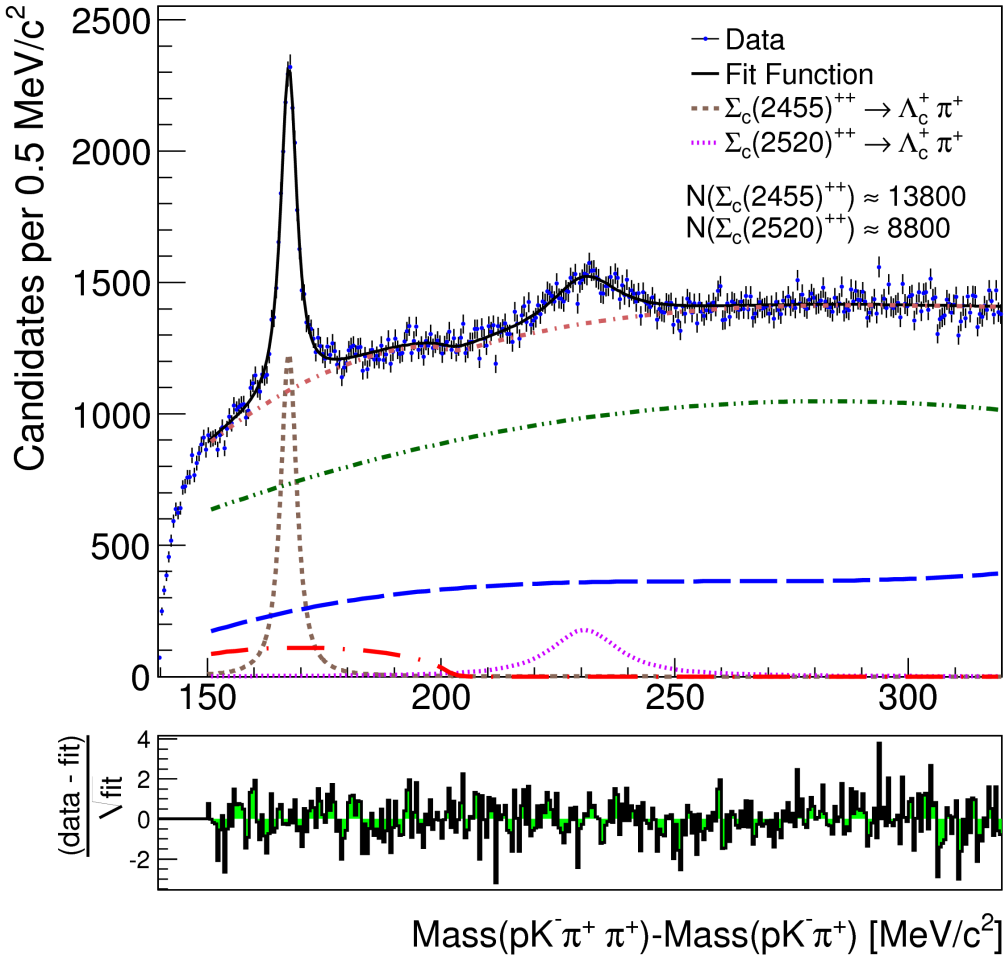


$\Sigma_c^{(*)}$ Fit Projections

$\Sigma_c^{(*)0} \rightarrow \Lambda_c^+\pi^-$



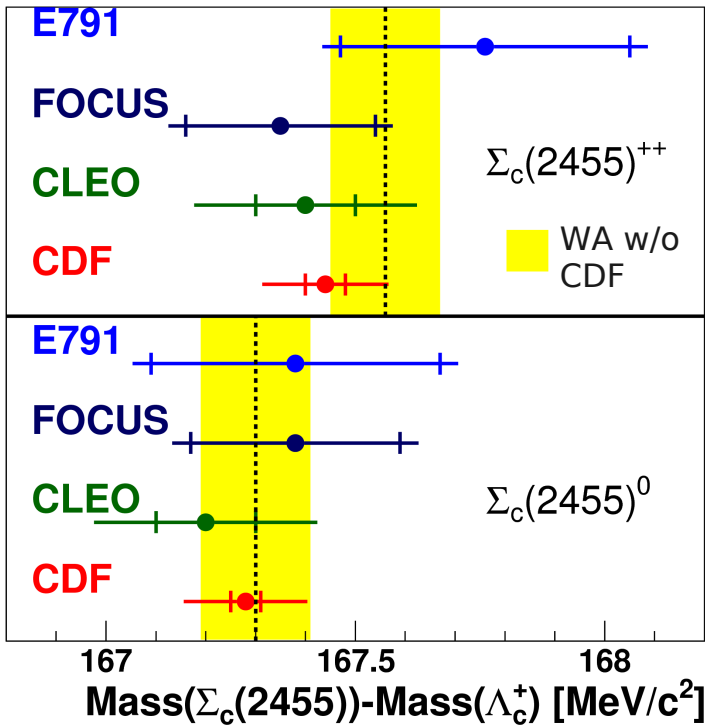
$\Sigma_c^{(*)++} \rightarrow \Lambda_c^+\pi^+$

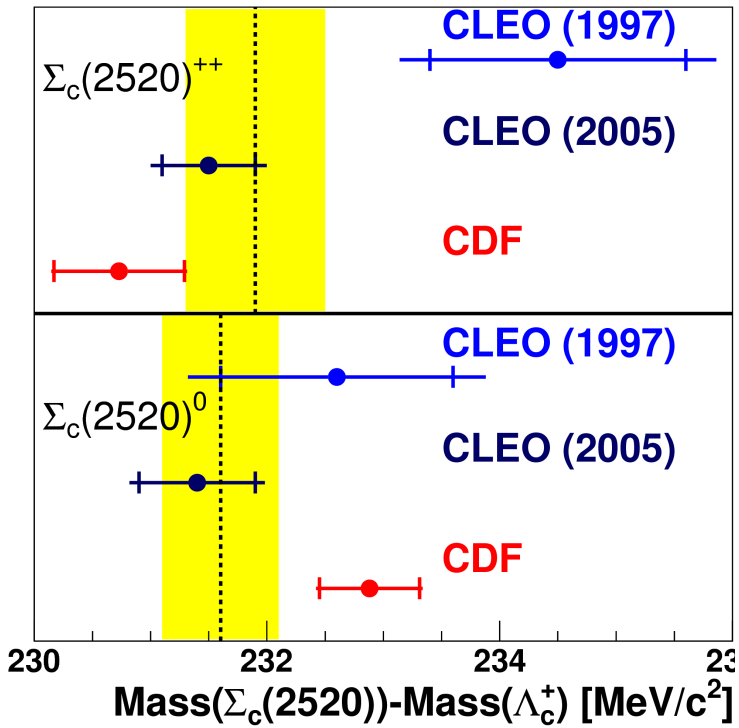


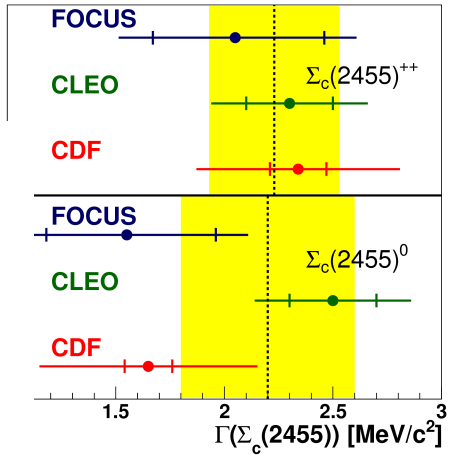
$\Sigma_c^{(*)}$ Results

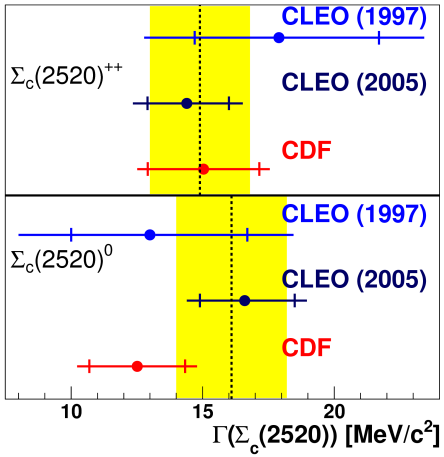
Hadron	ΔM [MeV/c^2]	Γ [MeV/c^2]
$\Sigma_c(2455)^{++}$	$167.44 \pm 0.04 \pm 0.12$	$2.34 \pm 0.13 \pm 0.45$
$\Sigma_c(2455)^{0}$	$167.28 \pm 0.03 \pm 0.12$	$1.65 \pm 0.11 \pm 0.49$
$\Sigma_c(2520)^{++}$	$230.73 \pm 0.56 \pm 0.16$	$15.03 \pm 2.12 \pm 1.36$
$\Sigma_c(2520)^{0}$	$232.88 \pm 0.43 \pm 0.16$	$12.51 \pm 1.82 \pm 1.37$

- Systematic uncertainties:
  resolution model, mass scale, fit model







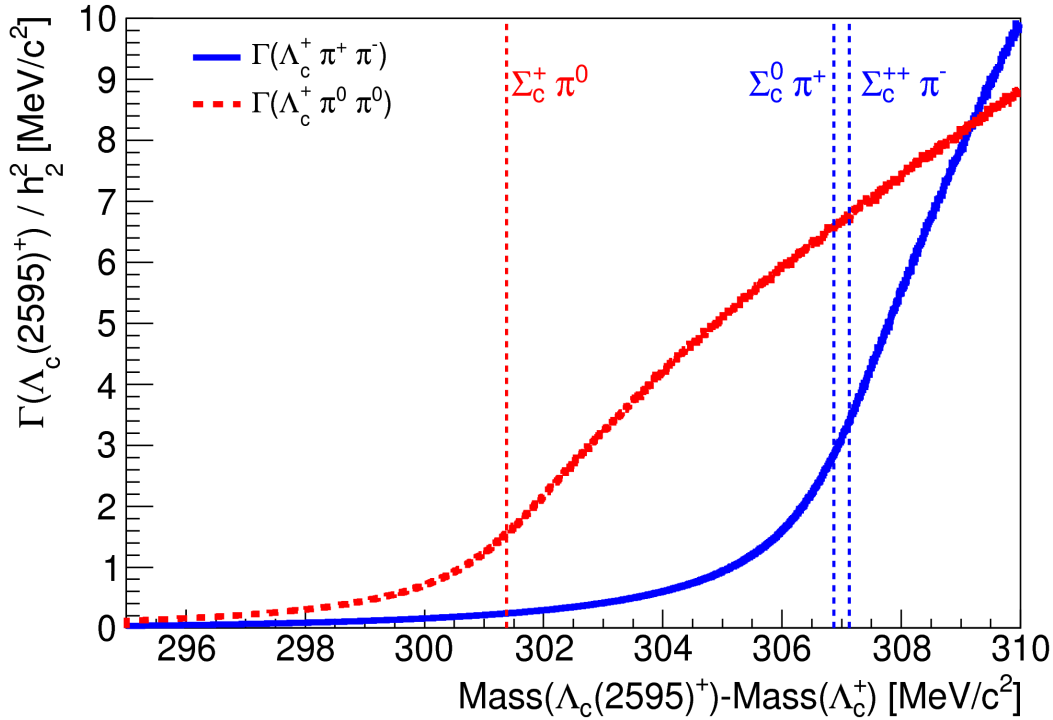


➢ Masses and widths consistent with world averages

Λ_c^* Fit

Signal:

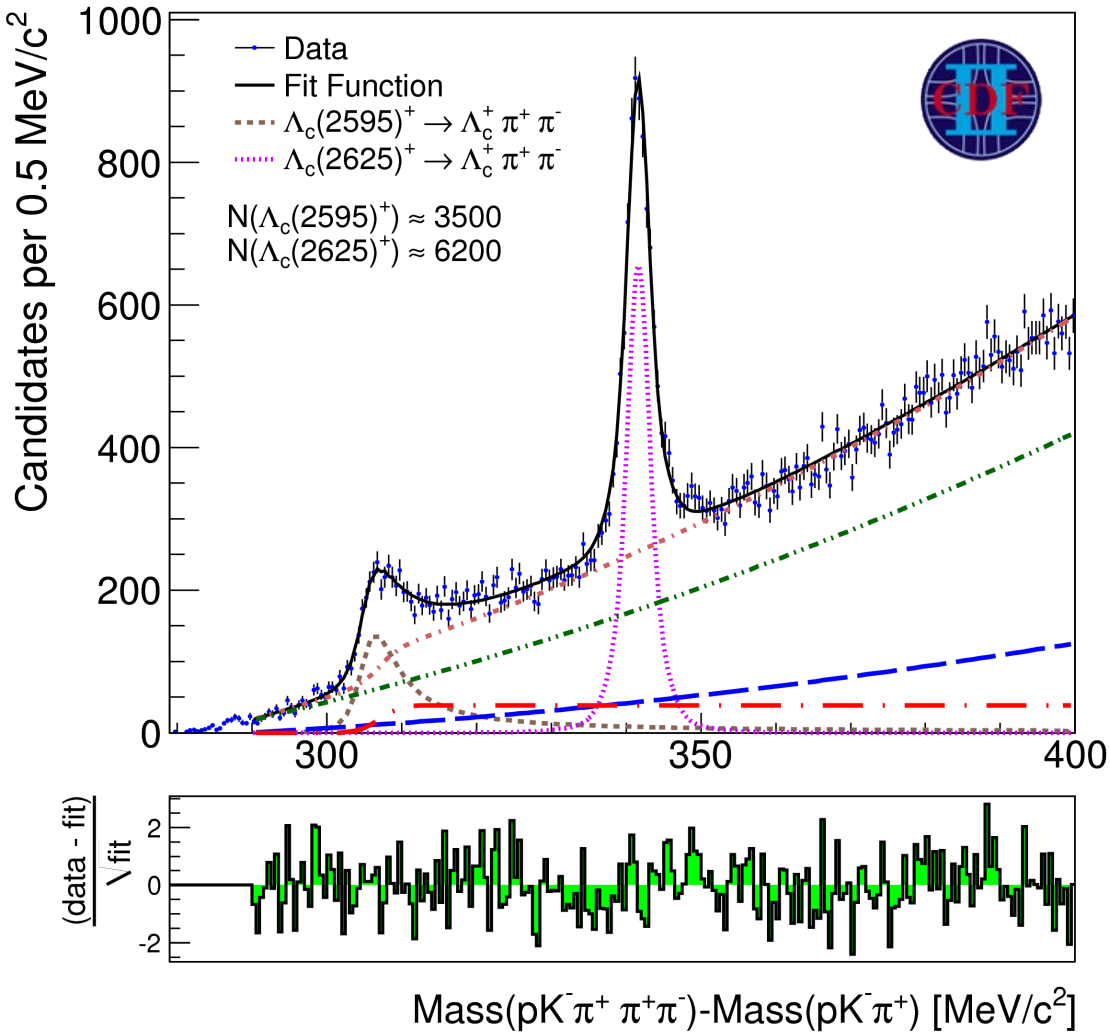
- Threshold effect in $\Lambda_c^{*+} \rightarrow \Sigma_c^{0,++} \pi^{+,-}$ taken into account by mass dependent width
- Pion coupling constant h_2

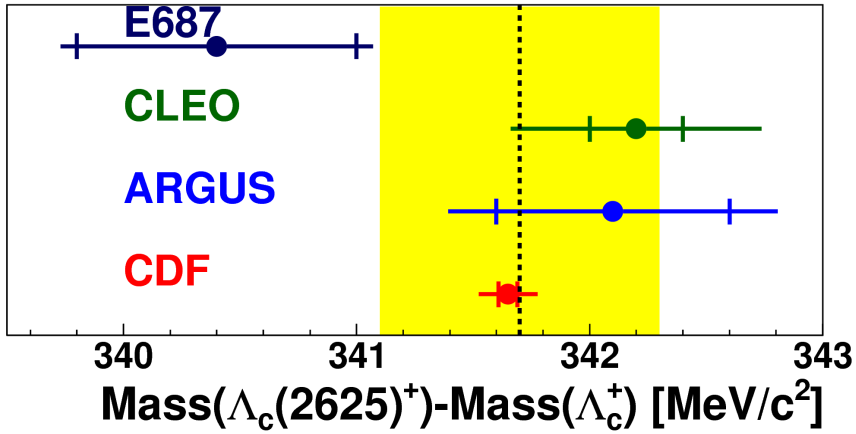


Background:

- Combinatorial: 2nd order polynomial from Λ_c sidebands
- Λ_c with random pions: 2nd order polynomial
- Σ_c with random pion: threshold function according to Σ_c line shape

$\Lambda_c(2625)$ Result

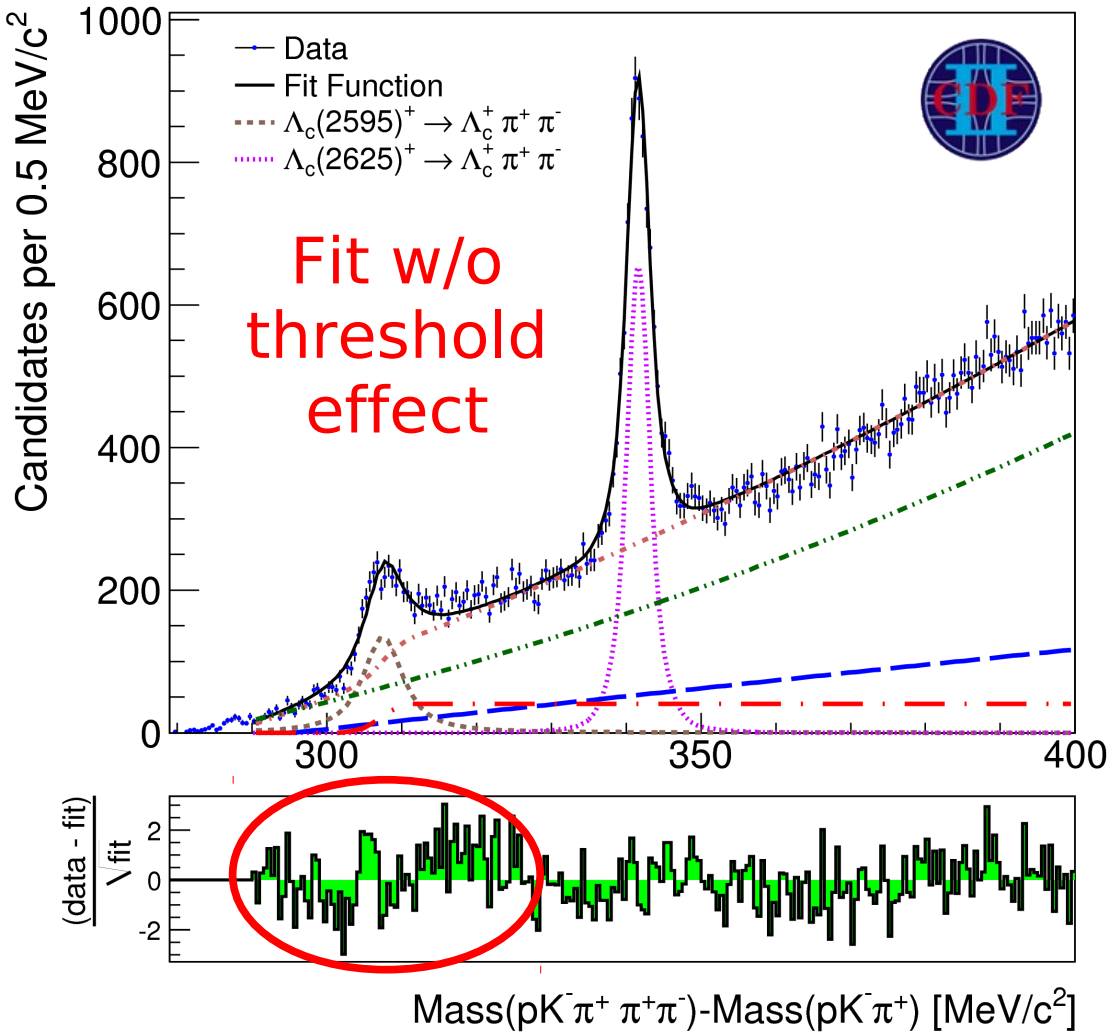




- ΔM (MeV/c^2) = 341.65 ± 0.04 ± 0.12
- Γ (MeV/c^2) < 0.97 @ 90% CL (PDG: < 1.9)

➢ Significantly improved precision

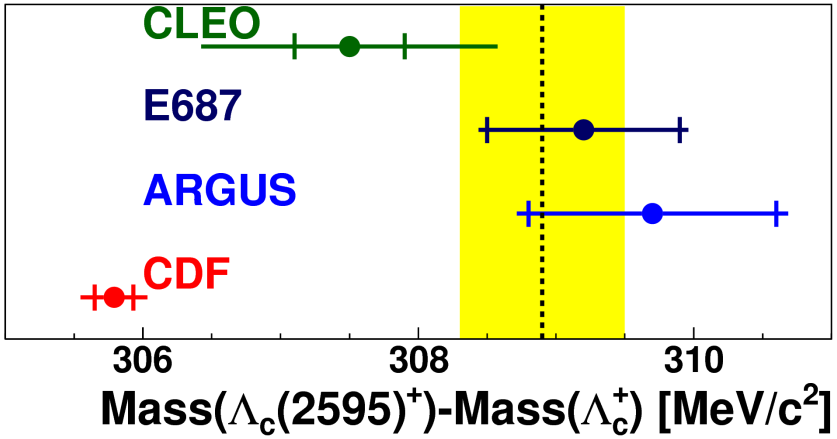
$\Lambda_c(2595)$ Threshold Effect

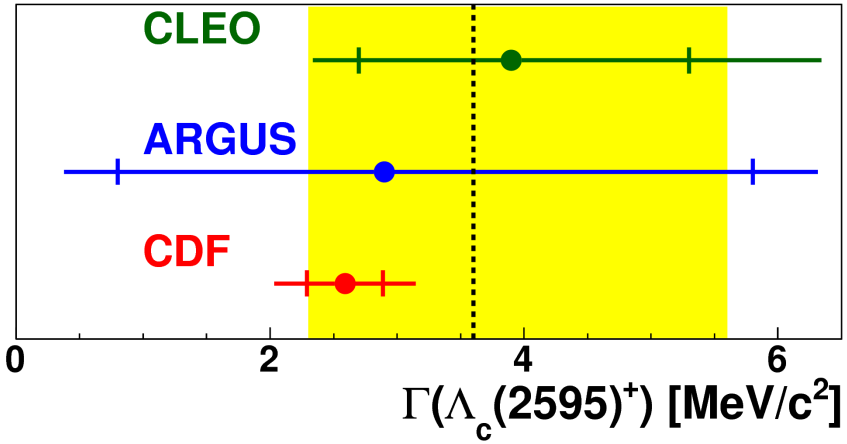


- Λ_c line shape not described by normal Breit-Wigner
  - Increase of χ^2 from 227 to 286 (for ndf=206)
- Discrepancy only observable because of high statistics
- Additional systematic uncertainty due to Σ_c parameters

$\Lambda_c(2595)$ Result

- $\Delta M = (305.79 \pm 0.14 \pm 0.20)$ MeV/c^2
- $h_2^2 = 0.36 \pm 0.04 \pm 0.07$





- Significantly improved precision
- Predicted threshold effect confirmed
  - **Leads to significantly smaller mass**

Submitted to PRD
arXiv:1105.5995

Summary

BOTTOM BARYONS ($B = -1$)

$\Lambda_b^0 = u\,d\,b$

Expected improvements in PDG tables

Λ_b^0

$I(J^P)$ not yet measur

Mass $m = 56$

$m_{\Lambda_b} - m_{B^0} = 339.2 \pm 1.4$ MeV

Mean life $\tau = (1.391^{+0.038}_{-0.037}) \times 10^{-12}$ s

$c\tau = 417\ \mu$m

The branching fractions B(b-baryon $\to$ $\Lambda \ell^- \overline{\nu}_\ell$ anything) and B($\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell$ anything) are not pure measurements because the underlying measured p re used to determine B($b \to$ b- uction and Decay of b-Flavored

For inclusiv anything, the values usually are multiplicities, not branc ons. They can be greater than one.

Factor ~3 improvement

Λ_b^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$J/\psi(1S)\Lambda \times$ B($b \to$ Λ_b^0)		$(4.7 \pm 2.3) \times 10^{-5}$		1741
$\Lambda_c^+ \pi^-$		$(8.8 \pm 3.2) \times 10^{-3}$		2343
$\Lambda_c^+ a_1(1260)^-$		seen		2153
$\Lambda_c^+ \ell^- \overline{\nu}_\ell$ anything	[v]	(10.7 ± 3.2) %		–

Σ_b

$I(J^P) = 1(\frac{1}{2}^+)$

I, J, P need confirmation.

Mass $m(\Sigma_b^+) = 5807.8 \pm 2.7$ MeV

Mass $m(\Sigma_b^-) = 5815.2 \pm 2.0$ Me

Σ_b DECAY MODES	Fraction (Γ_i/Γ)
$\Lambda_b^0 \pi$	dominant

Factor ~2 improvement

Σ_b^*

$I(J$ $1(\frac{3}{2}^+)$

I, J, P nfirmation.

Mass $m(\Sigma_b^{*+}) = 5829.0 \pm 3.4$

Mass $m(\Sigma_b^{*-}) = 5836.4 \pm 2.8$

$m_{\Sigma_b^*} - m_{\Sigma_b} = 21.2 \pm 2.0$ M

First measurement of width and isospin splitting

$\Lambda_c(2595)^+ - \Lambda_c^+$ MASS DIFFERENCE

VALUE (MeV)	EVTS				COMMENT
308.9±0.6 OUR FIT	Error incl				
308.9±0.6 OUR AVERAGE	Error inc				
309.7±0.9±	19				e^- ≈ 10 GeV
309.2±0.7±0.3	14 ± 4.5	FRABETTI	96	E687	γ Be, $\overline{E}_\gamma \approx$ 220 GeV
307.5±0.4±1.0	112 ±				e^- ≈ 10.5 GeV
• • • We do not use the followin					• •
305.6±0.3					eshold shift

[1] BLECHMAN 03 finds that a simple Breit-Wigner for the proximity of the threshold of the dominant decay, $\Sigma_c(2455)\pi$, lowers the $\Lambda_c(2595)^+ - \Lambda_c^+$ mas

Factor ~3 improvement

Mass shift by threshold effect

First direct h_2 measurement