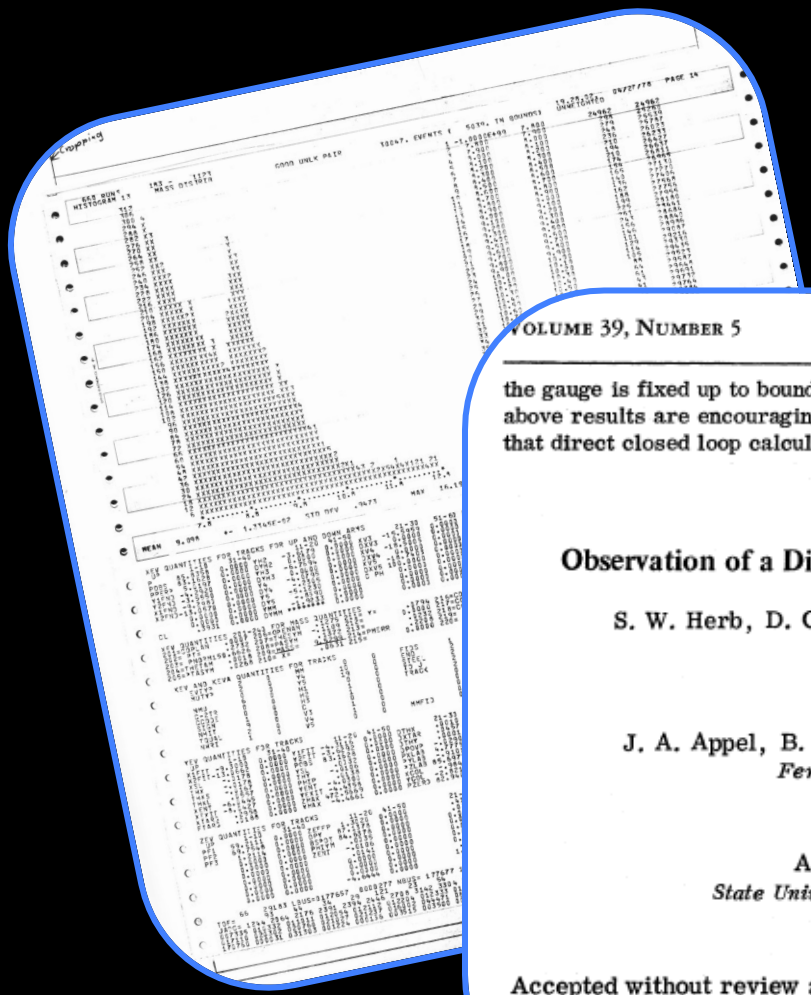
Spectroscopy results from the Tevatron

Heavy Quark and Leptons 2010 - Frascati, Oct 11,2010

Diego Tonelli - Fermilab

The beginning, 33 years ago…



VOLUME 39, NUMBER 5 1 AUGUST 1977

the gauge is fixed up to bounda… …her, simply because dimensional above results are encouraging. … respects the gauge invariances) that direct closed loop calculations … 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

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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.

The Physics

QCD – a pristine example of successful QFT

However low-energy regime far from being understood. One of the few SM soft-spots remaining.

Major show-stopper in precision CKM predictions. Also affects hadron spectroscopy, decay rates, lifetimes.

Heavy quarks help. Static source of color field for light-quark partners

Some quantities calculable with lattice. Powerful numerical technique, not truly illuminating on underlying physics.

Effective theories – work-around that decouples dynamic degrees of freedom and provide quantitative predictions. Still pretty much disconnected from general theory.

Experimental input crucial to adjust inputs/approximations and discriminate among models. One day will hopefully provide clear-cut link with high-Q perturbative regime.

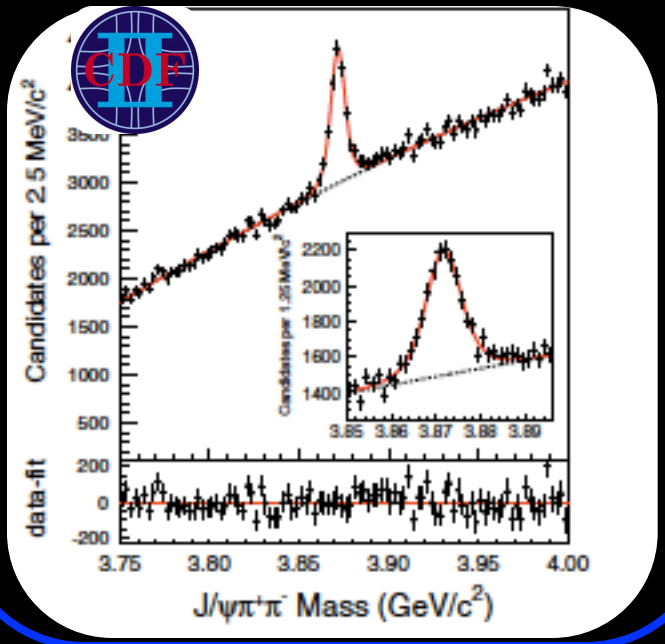
The ingredients

Large production x-sections of all HF in 1.96 TeV *ppbar* collisions.

Tracking

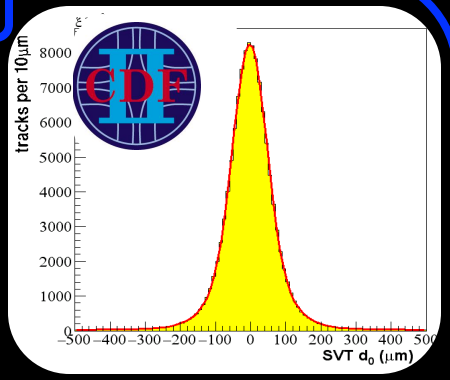
$\sigma_{pT} / p_T^2 \sim 0.1\%/$ GeV

30 microns vertex resolution



Trigger

Online silicon tracking exploits long-lived fully-hadronic HF decays by triggering on displaced tracks



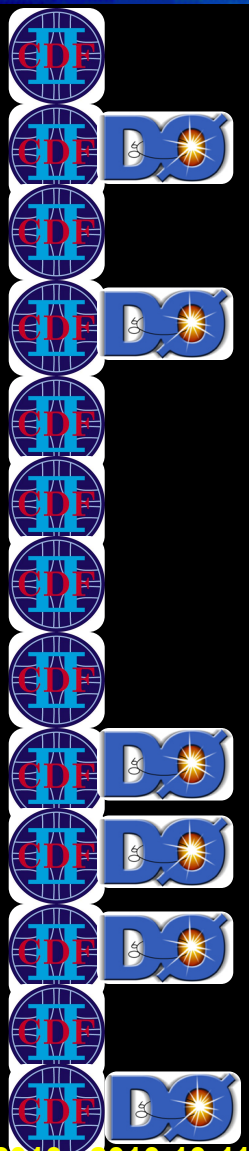
48 micron resolution impact par.

Mu acceptance

$|\eta|<3$, $p_T >$ 1.5-2.0 GeV

Tenths of millions J/ψ collected (20% from B)

The roadmap



D^+-D_s^+ mass difference	(2003)
X(3872) confirmation	(2004)
B hadron masses	(2006)
Mass of exclusive B_c	(2006 and 2008)
Orbitally excited D	(2006)
X(3872) quantum num.	(2006 and 2007)
Search for S=-2 pentaquarks	(2007)
Σ_b observation	(2007)
Cascade b observation	(2007)
Obitally excited B_s	(2008)
Orbitally excited B^0	(2009)
Observation of Y(4140)	(2009)
Observation of Ω_b	(2008 and 2009)

DØ: so far 6 papers published:
2 topcite50+ and 1 topcite100+

CDF: so far 17 papers published:
7 topcite50+ and 1 topcite100+

The impact

PRL 102, 242002 (2009) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2009

Evidence for a Narrow Near-Threshold Structure in the $J/\psi\phi$ Mass Spectrum in $B^+ \to J/\psi\phi K^+$ Decays

VOLUME 93, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 13 AUGUST 200

Observation of the Narrow State $X(3872) \to J/\psi\pi^+\pi^-$ in $\bar{p}p$ Collisions at $\sqrt{s} = 1.96$ TeV

VOLUME 93, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2004

Observation and Properties of the $X(3872)$ Decaying to $J/\psi\pi^+\pi^-$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

PRL 96, 082002 (2006) PHYSICAL REVIEW LETTERS week ending 3 MARCH 200

Evidence for the Exclusive Decay $B_c^\pm \to J/\psi\pi^\pm$ and Measurement of the Mass of the $B_c^\pm$ Meson

PRL 96, 102002 (2006) PHYSICAL REVIEW LETTERS week ending 17 MARCH 2006

Measurement of the Dipion Mass Spectrum in $X(3872) \to J/\psi\pi^+\pi^-$ Decays

PRL 96, 202001 (2006) PHYSICAL REVIEW LETTERS week ending 26 MAY 2006

PRL 98, 132002 (2007) PHYSICAL REVIEW LETTERS week ending 30 MARCH 200

Analysis of the Quantum Numbers J^{PC} of the $X(3872)$ Particle

PRL 99, 052001 (2007) PHYSICAL REVIEW LETTERS week endi 3 AUGUST

Direct Observation of the Strange b Baryon Ξ_b^-

PRL 99, 052002 (2007) PHYSICAL REVIEW LETTERS week ending 3 AUGUST 200

Observation and Mass Measurement of the Baryon Ξ_b^-

PRL 99, 172001 (2007) PHYSICAL REVIEW LETTERS week ending 26 OCTOBER 20

Properties of $L = 1$ B_1 and B_2^* Mesons

PRL 100, 082001 (2008) PHYSICAL REVIEW LETTERS week ending 29 FEBRUARY 2008

Observation of Orbitally Excited B_s Mesons

PRL 100, 082002 (2008) PHYSICAL REVIEW LETTERS week ending 29 FEBRUARY 2008

Observation and Properties of the Orbitally Excited B_{s2}^* Meson

PRL 100, 182002 (2008) PHYSICAL REVIEW LETTERS week ending 9 MAY 2008

Observation of the Decay $B_c^\pm \to J/\psi\pi^\pm$ and Measurement of the $B_c^\pm$ Mass

PRL 101, 012001 (2008) PHYSICAL REVIEW LETTERS week ending 4 JULY 2008

Observation of the B_c Meson in the Exclusive Decay $B_c \to J/\psi\pi$

PRL 101, 232002 (2008) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2008

Observation of the Doubly Strange b Baryon Ω_b^-

PRL 102, 102003 (2009) PHYSICAL REVIEW LETTERS week ending 13 MARCH 2009

Measurement of Resonance Parameters of Orbitally Excited Narrow B^0 Mesons

PRL 103, 152001 (2009) PHYSICAL REVIEW LETTERS week ending 9 OCTOBER 2009

Precision Measurement of the $X(3872)$ Mass in $J/\psi\pi^+\pi^-$ Decays

PHYSICAL REVIEW D 80, 072003 (2009)

Observation of the Ω_b^- baryon and measurement of the properties of the Ξ_b^- and Ω_b^- baryons

PRL 99, 202001 (2007) PHYSICAL REVIEW LETTERS week ending 16 NOVEMBER 2007

Observation of the Heavy Baryons Σ_b and Σ_b^*

PHYSICAL REVIEW D 73, 051104 (2006)

Measurement of mass and width of the excited charmed meson states D_1^0 and D_2^{*0} at CDF

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Improved determination of $\Sigma_b^{(*)}$ b-baryons resonance parameters

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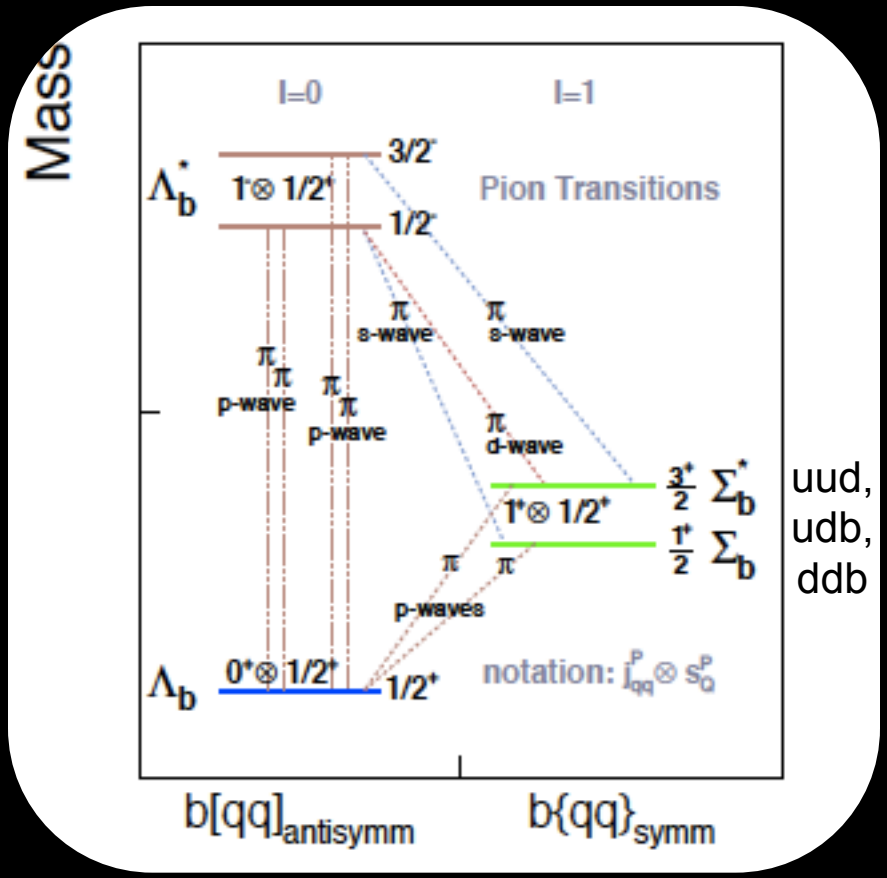
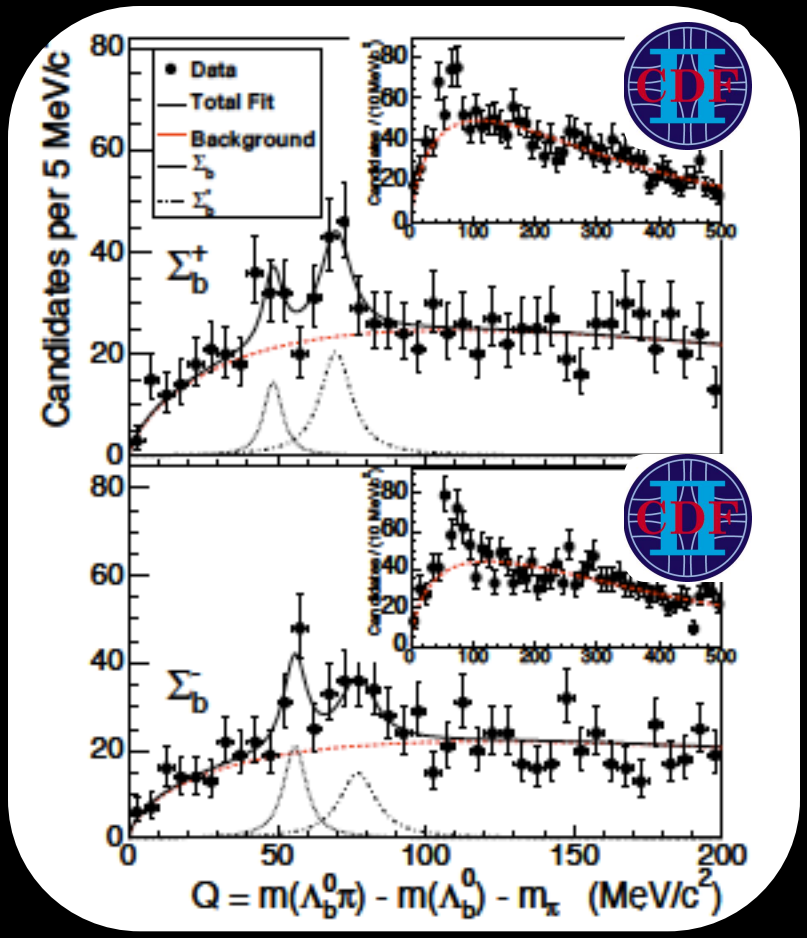
$\Sigma_b^{(*)}$ - Intro and status

2006 – Evidence for new bottom baryons using 1 fb^{-1}





Update to 6 fb^{-1}, provide independent determination of masses, widths and isospin splittings

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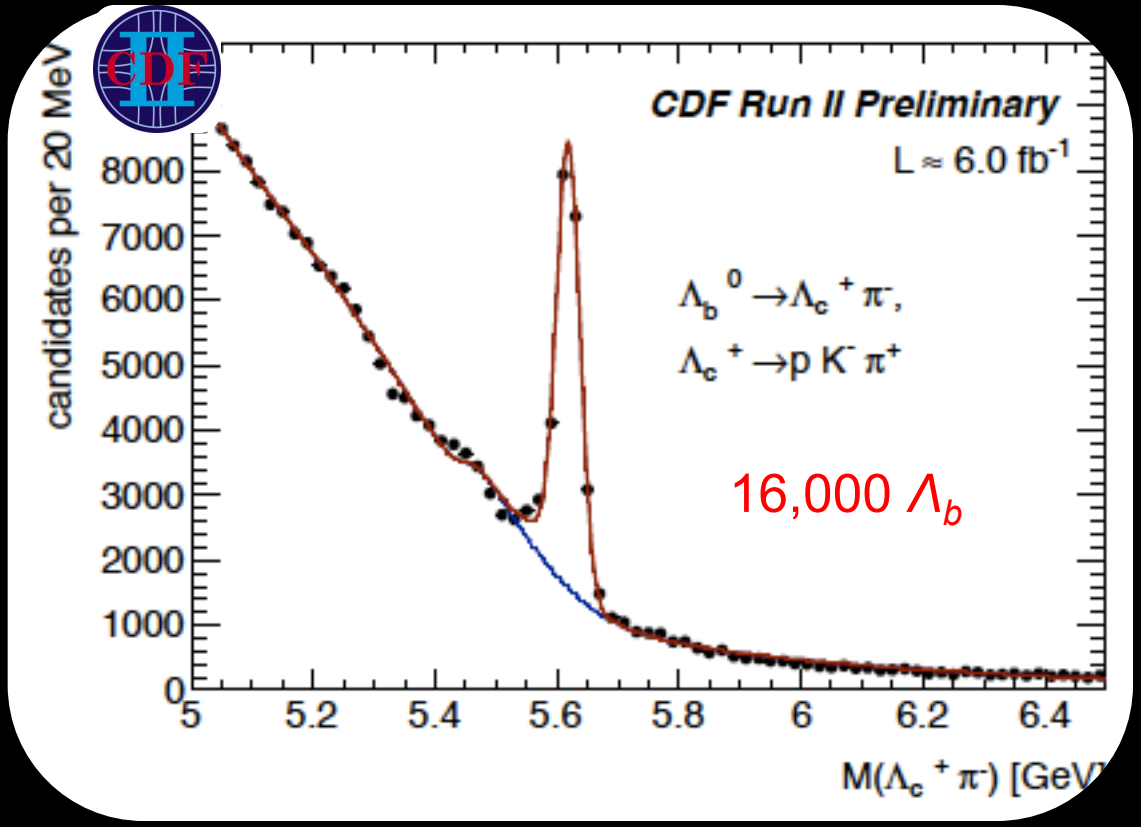
$\Sigma_b^{(*)}$ – selection & reconstruction

5-track final states.

Associate soft pion to large and clean signal of all-hadronic Λ_b decays:

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

Mass-difference to cancel Λ_b mass resolution and several systematic uncertainties.



$$Q = M(\Sigma_b^{(*)} \rightarrow \Lambda_b^0 \pi^{\pm}_{soft}) - M(\Lambda_b^0) - m(\pi^{\pm})_{PDG}$$

- Long Λ_b lifetime,
- Large momentum of Λ_b pion,
- Prompt production of pion from Σ

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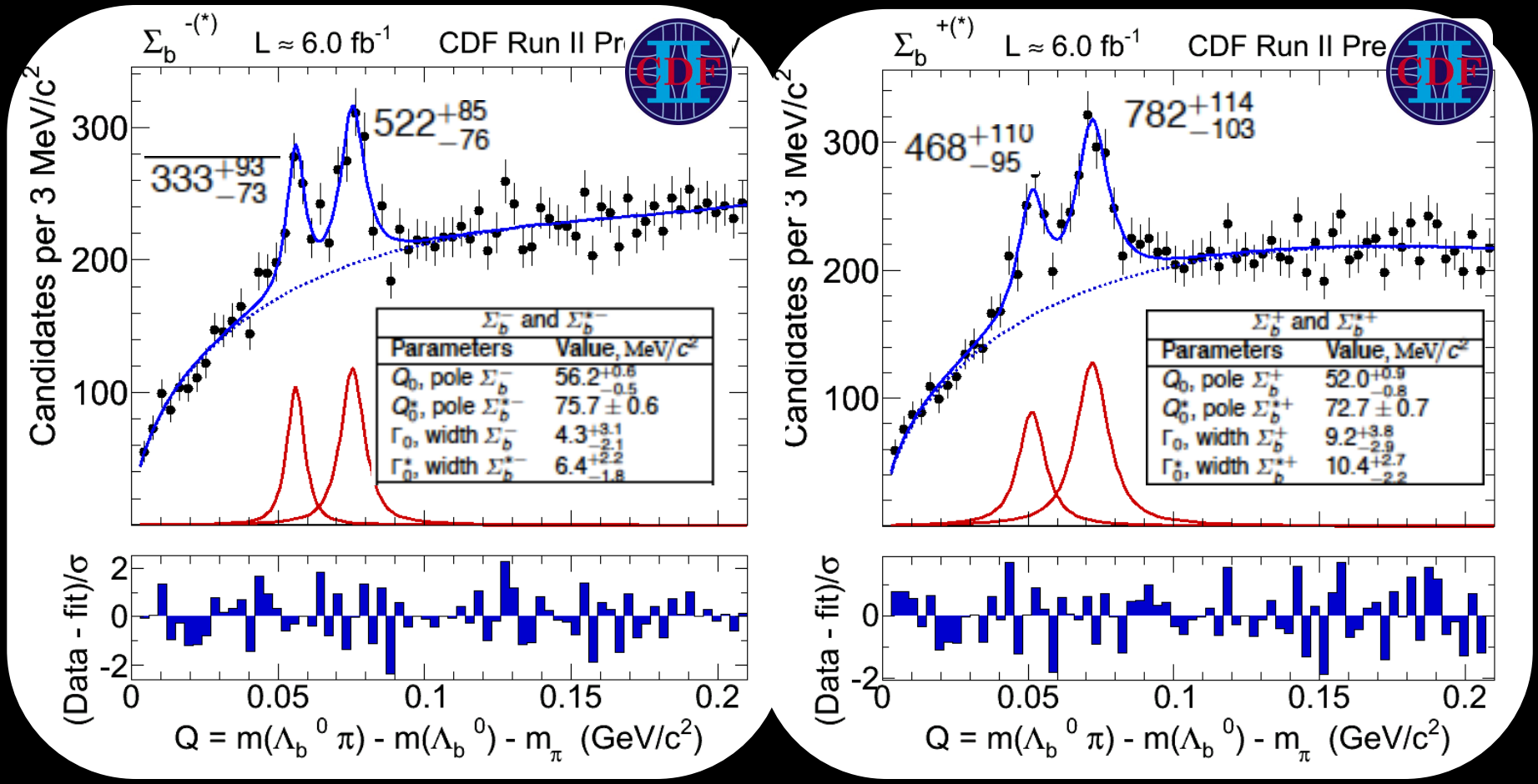
$\Sigma_b^{(*)}$ – mass difference fit



Non-relativistic P-wave BW convoluted with resolution for signal. Empirical background. All signals comfortably beyond 5σ significance

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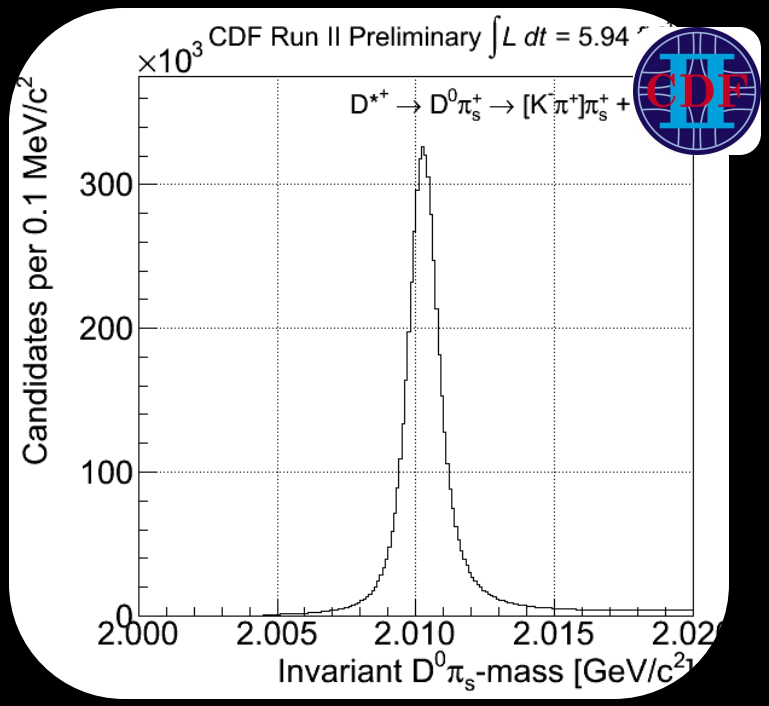
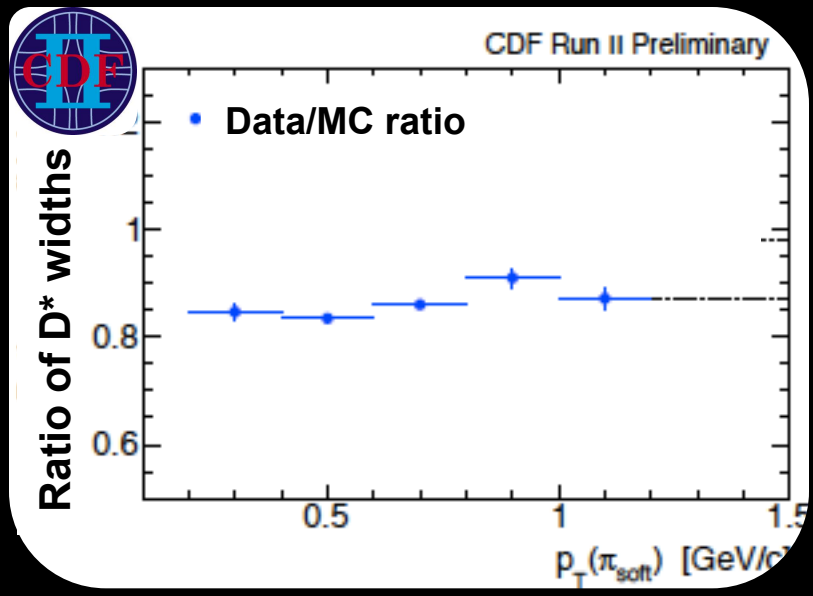
$\Sigma_b^{(*)}$ – Systematic uncertainties

Dominated by tracking resolution of soft pion from Σ_b. Compare data and simulation for large samples of $D^* \rightarrow D^0\pi$ *decays.*





25% relative uncertainty.

Minor contributions from magnetic field knowledge, Λ_b mass uncertainty, alternate background models.

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$\Sigma_b^{(*)}$ – final results

Using CDF measurement of 5619.7 ± 1.2 ± 1.2 MeV for the Λ_b mass

State	M, MeV/c^2	Γ_0, MeV/c^2
Σ_b^+	$5811.2^{+0.9}_{-0.8}\,(\text{stat}) \pm 1.7\,(\text{syst})$	$9.2^{+3.8}_{-2.9}(\text{stat})^{+1.0}_{-1.1}(\text{syst})$
Σ_b^{*+}	$5832.0 \pm 0.7\,(\text{stat}) \pm 1.8\,(\text{syst})$	$10.4^{+2.7}_{-2.2}(\text{stat})^{+0.8}_{-1.2}(\text{syst})$
Σ_b^-	$5815.5^{+0.6}_{-0.5}\,(\text{stat}) \pm 1.7\,(\text{syst})$	$4.3^{+3.1}_{-2.1}(\text{stat})^{+1.0}_{-1.1}(\text{syst})$
Σ_b^{*-}	$5835.0 \pm 0.6\,(\text{stat}) \pm 1.8\,(\text{syst})$	$6.4^{+2.2}_{-1.8}(\text{stat})^{+0.7}_{-1.1}(\text{syst})$

State	ΔM^{+-}, MeV/c^2
$\Sigma_b^+ - \Sigma_b^-$	$-4.2^{+1.1}_{-0.9}(\text{stat})^{+0.07}_{-0.09}(\text{syst})$
$\Sigma_b^{*+} - \Sigma_b^{*-}$	$-3.0 \pm 0.9\,(\text{stat})^{+0.12}_{-0.13}(\text{syst})$

CDF Public Note 10286

Established existence of these states. First measurements of widths and mass splittings

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Spectroscopy of charmed $\Lambda_c(2595)$, $\Lambda_c(2625)$, Σ_c (2455) and Σ_c (2520) baryons

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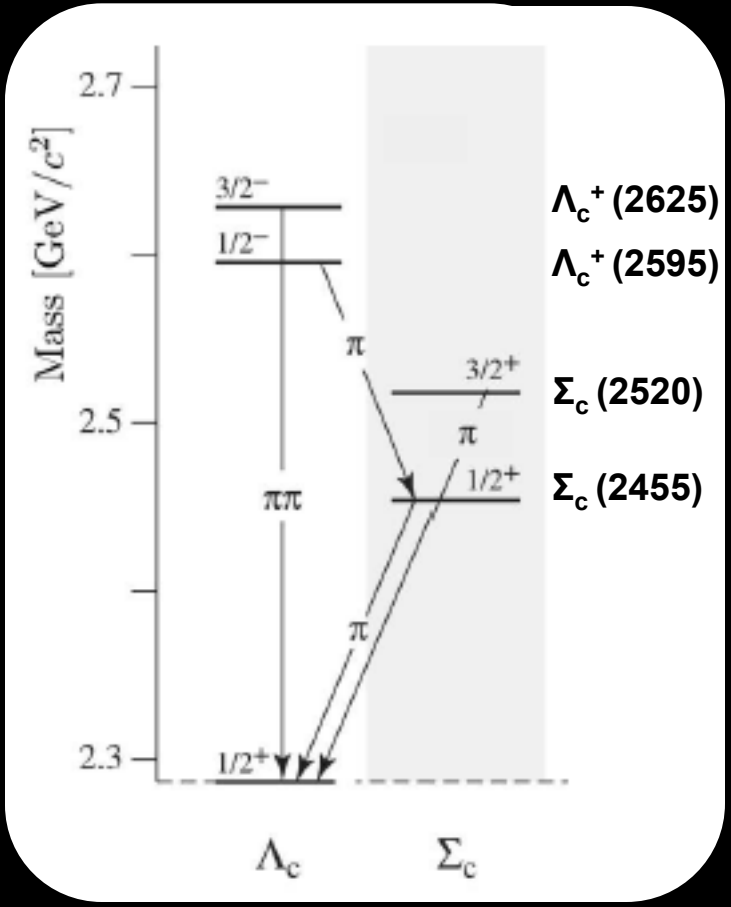
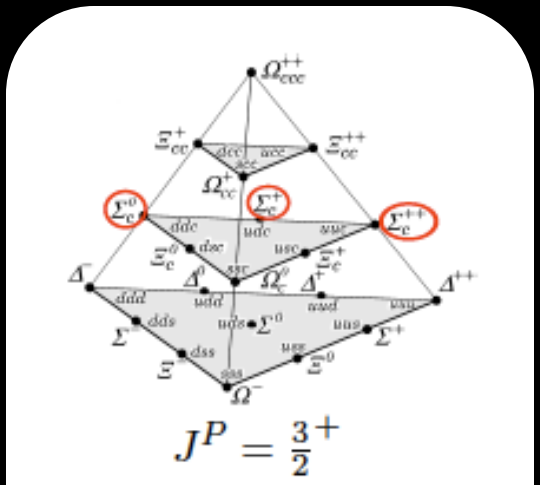
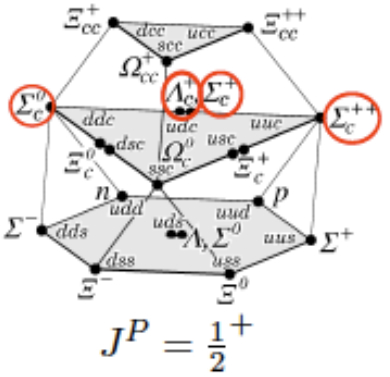
Charm baryons – introduction

- Λ_c^+ has $J^P = ½^+$ and is lightest *c*-baryon ➔ weak decay
- Λ_c^* are orbital excitations of Λ_c^+
- Σ_c are spin excitations of Λ_c^+ where light-diquark is spin-1
- Isospin triplet decays strongly to $\Lambda_c^+\pi$







First CDF analysis of these modes – 5.2 fb^{-1}
Previous work mostly by CLEO

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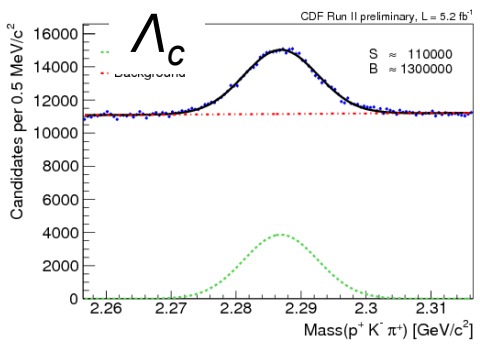
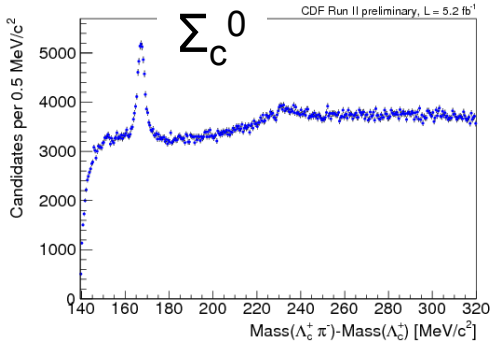
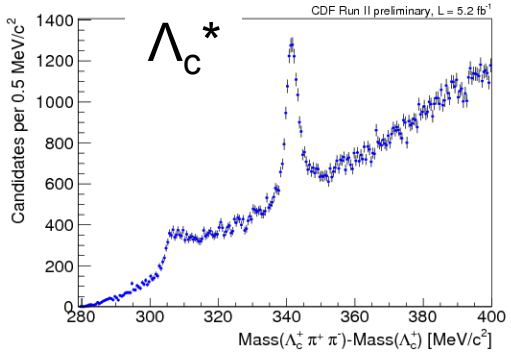
Charm baryons – reconstruction

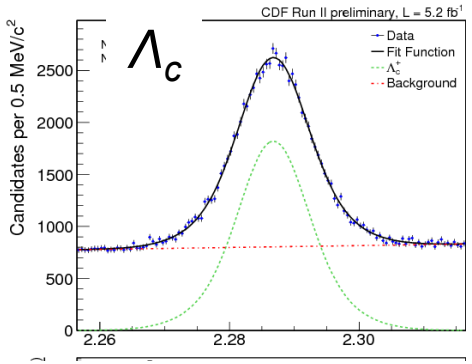
Displaced-track triggered $\Lambda_c \rightarrow pK\pi$. Attach 1 ($\Sigma_c$) or 2 ($\Lambda_c^*$) pions. Two-step NN optimization: on Λ_c and on Σ_c/Λ_c^* using fit quality, lifetime p_T.

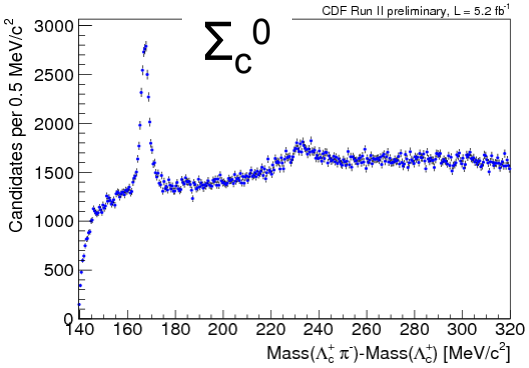


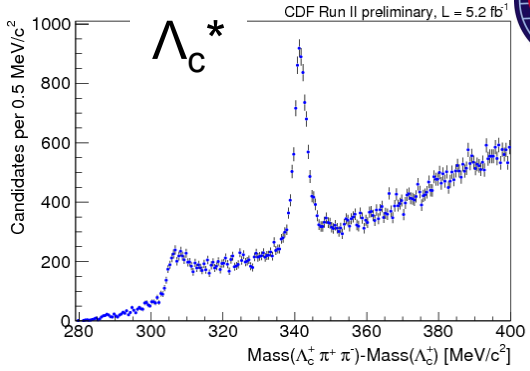




Neural Network







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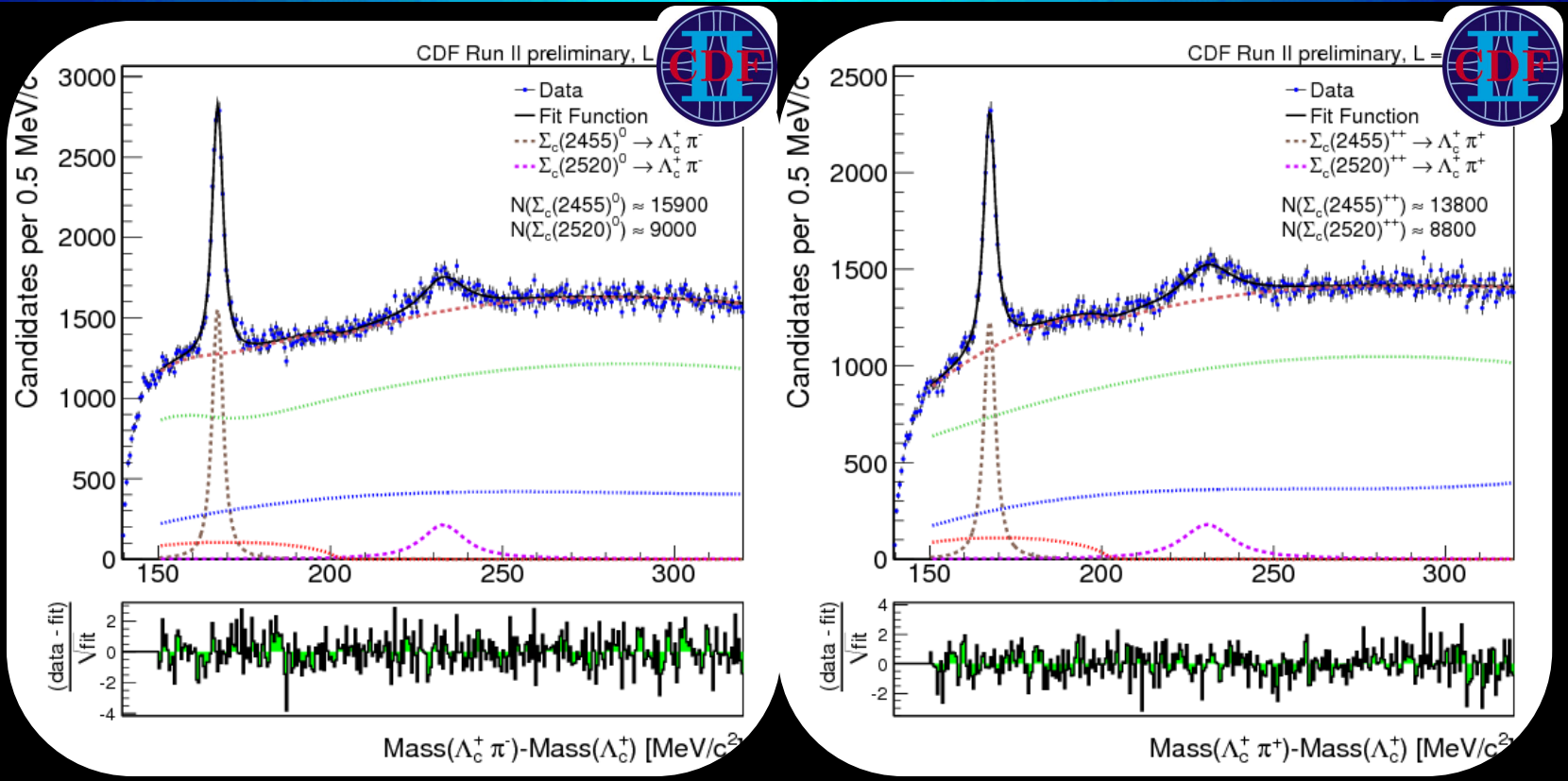
Charm baryons – Σ_c fits



Non-relativistic BW convoluted with detector resolution (from MC validated with $D^* \to D^0\pi$ data).

Backgrounds from fake Λ_c, real Λ_c, + track, feeddown from $\Lambda_c(2625)$

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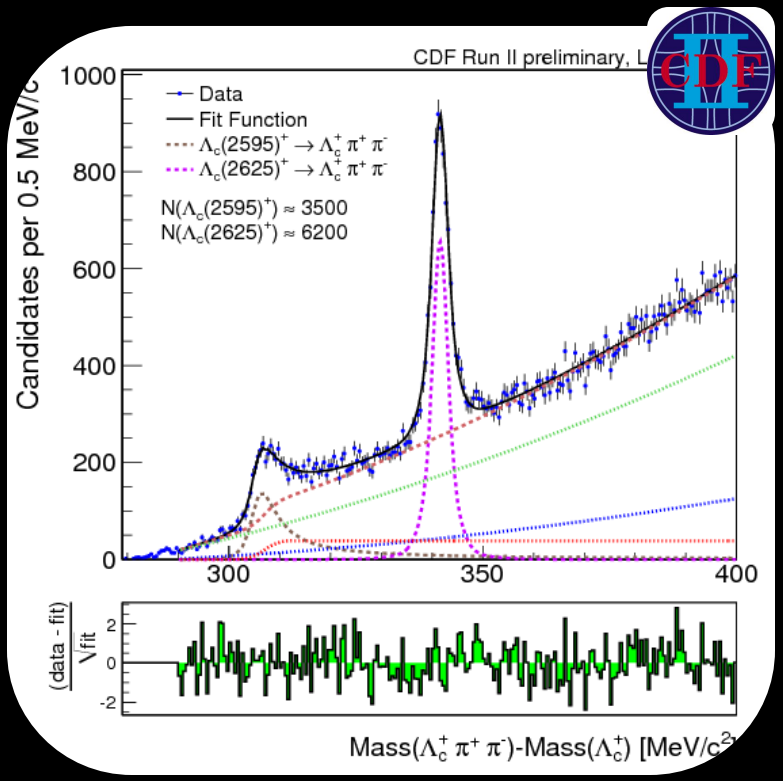
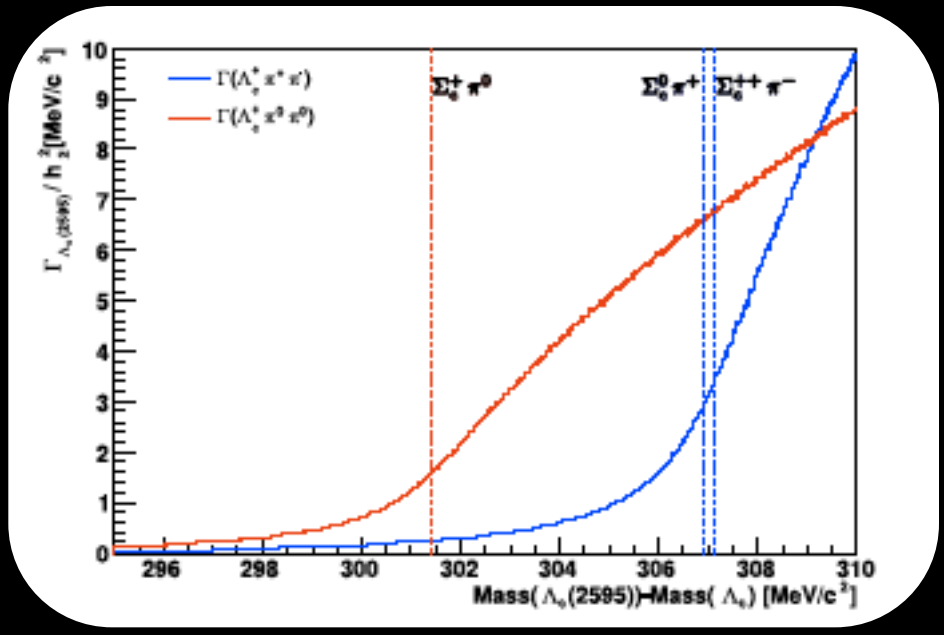
Charm baryons – Λ_c^* fits



Mass-dependent width at threshold

PRD 67, 074033



Hard because $\Lambda_c^*(2595)$ is right above threshold for $\to \Sigma_c(2455)\pi$

Non-relativistic BW convoluted with detector resolution (from MC validated with $D^* \to D^0\pi$ data).

Backgrounds from fake Λ_c, real Λ_c, + 2 tracks, $\Sigma_c(2455)$+track

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Charm baryons – results

Systematics: detector resolutions, mass scale (from ψ(2S) →*J/ψππ*). Fit model. External input for reference masses.

	$m - m(\Lambda_c^+)[\mathrm{MeV}/c^2]$	$\Gamma[\mathrm{MeV}/c^2]$
$\Sigma_c(2455)^0$	167.28 ± 0.12 (167.30 ± 0.11)	1.65 ± 0.50 (2.2 ± 0.4)
$\Sigma_c(2455)^{++}$	167.44 ± 0.13 (167.56 ± 0.11)	2.34 ± 0.47 (2.23 ± 0.30)
$\Sigma_c(2520)^0$	232.88 ± 0.46 (231.6 ± 0.5)	12.51 ± 2.28 (16.1 ± 2.1)
$\Sigma_c(2520)^{++}$	230.73 ± 0.58 (231.9 ± 0.6)	15.03 ± 2.52 (14.9 ± 1.9)
$\Lambda_c(2595)^+$	305.79 ± 0.24 (308.9 ± 0.6)	2.59 ± 0.56 $(3.6^{+2.0}_{-1.3})$
$\Lambda_c(2625)^+$	341.65 ± 0.13 (341.7 ± 0.6)	$< 0.97(90\%CL)$ $(< 1.9(90\%CL))$

- Comparable (Σ_c) or much better (Λ_c^*) than PDG. CDF Public Note 10260
- Difference in $\Lambda_c(2595)$ mass due to proper treatment of width at threshold. If not included get 3 MeV shift as seen in CLEO.
- Pion coupling constant determined from $\Lambda_c(2595)$: $h_2^2 = 0.36 \pm 0.08$

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Observation of Y(4140) exotic mesons

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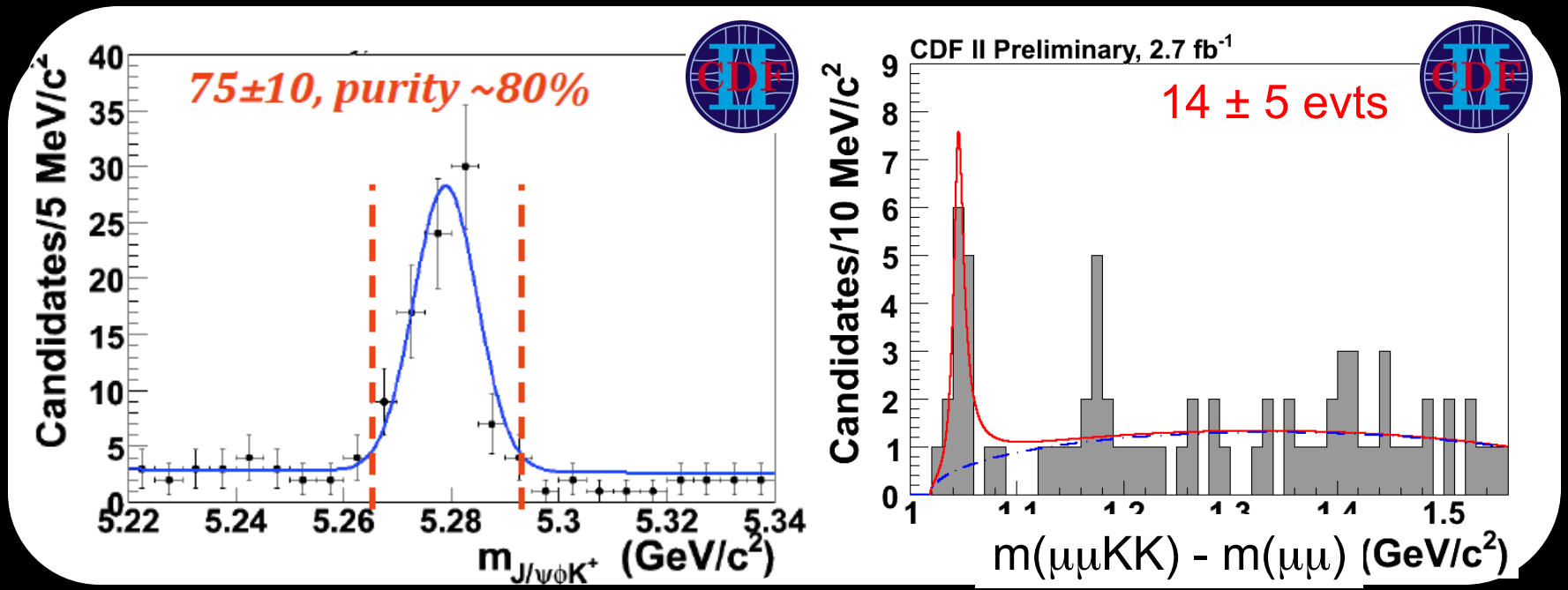
Y(4140) – recap

2009: evidence of $J/\psi\phi$ structure at 4140 MeV in exclusive $B^+ \rightarrow J/\psi\phi K^+$



M = 4143 ± 2.9 ± 1.2 MeV (above open charm)

$\Gamma = 11.7\ ^{+8.3}_{-\ 5.0} \pm 3.7$ MeV (probably a strong decay)

Many exotic interpretations proposed. No signal seen by Belle which sets product of Br $< 6\times 10^{-6}$ at 90%CL

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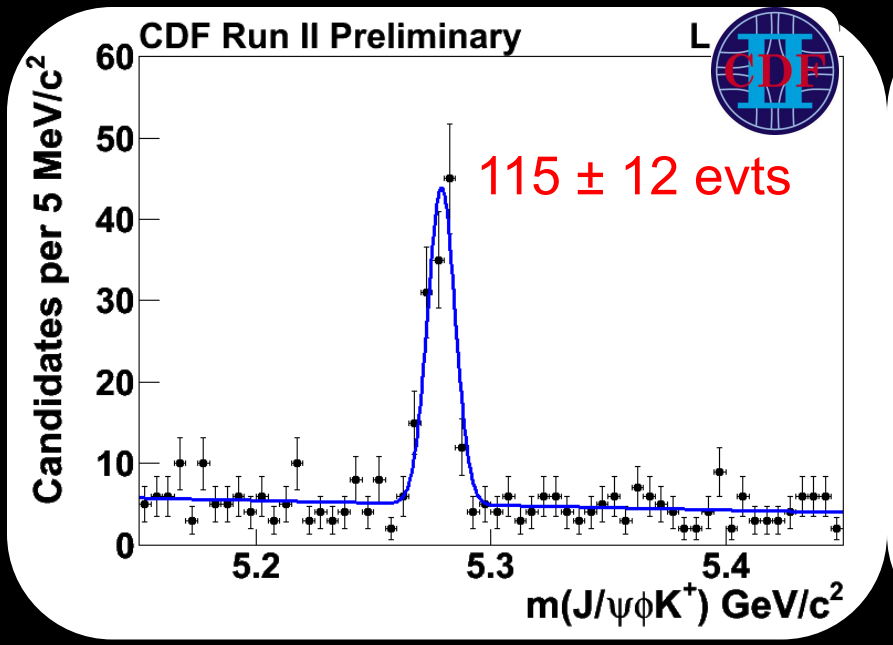
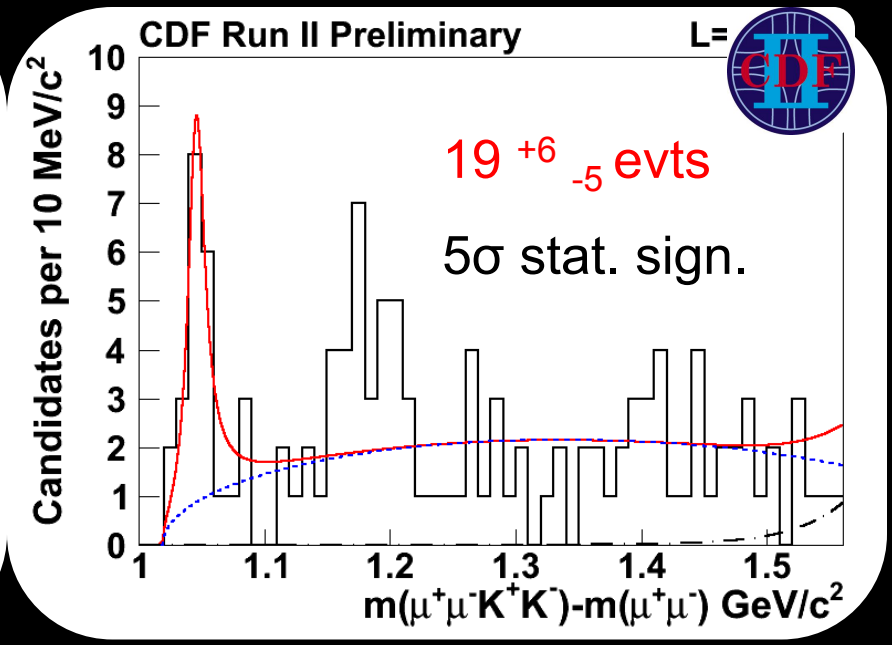
Y(4140) – 6 fb^{-1} analysis

Selection freezed to one used in 2009. Background shape changed.





S-wave BW convoluted with 1.7 MeV resolution + 3-body PS background

M = 4143.4 $^{+2.9}_{-3.0}$ ± 0.6 MeV Γ= 15.3 $^{+10.4}_{-6.1}$ ± 2.5 MeV

Rate relative to $B^+ \to J/\psi\phi K^+$ is (15 ± 5)% CDF Public Note 10244

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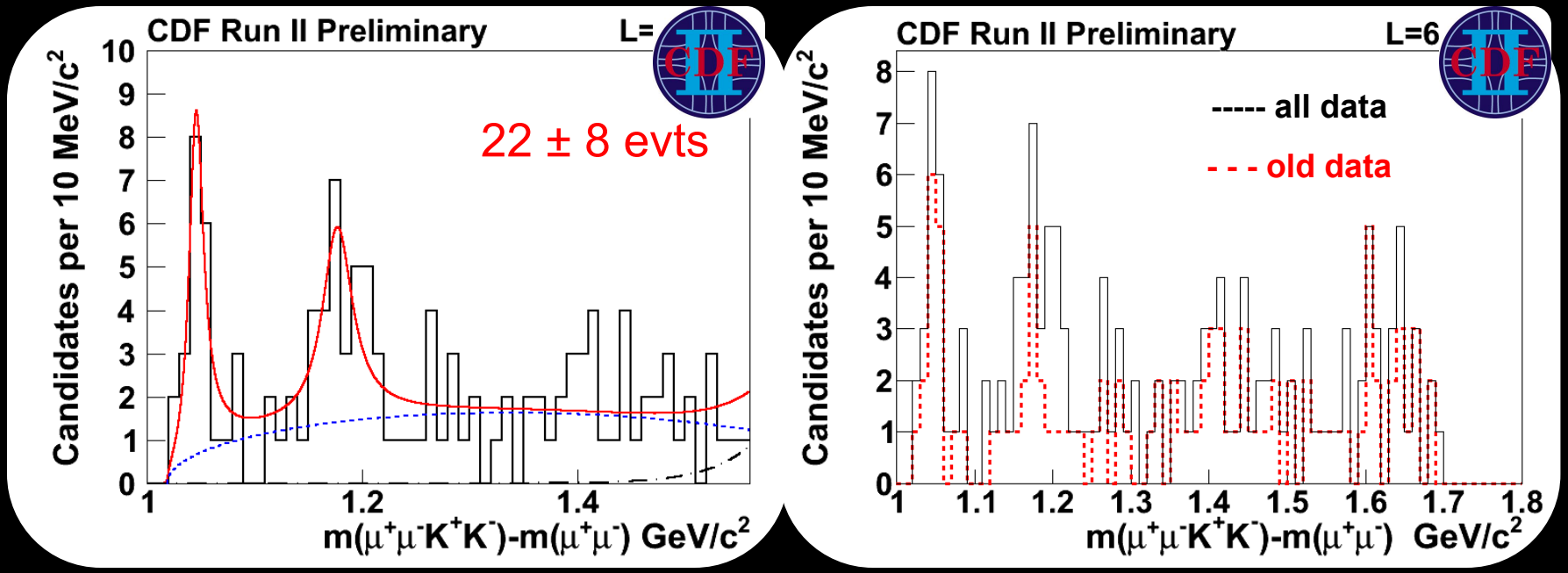
Y(4140) – 6 fb^{-1} analysis (cont'd)

Prominent cluster of events at 4275 MeV



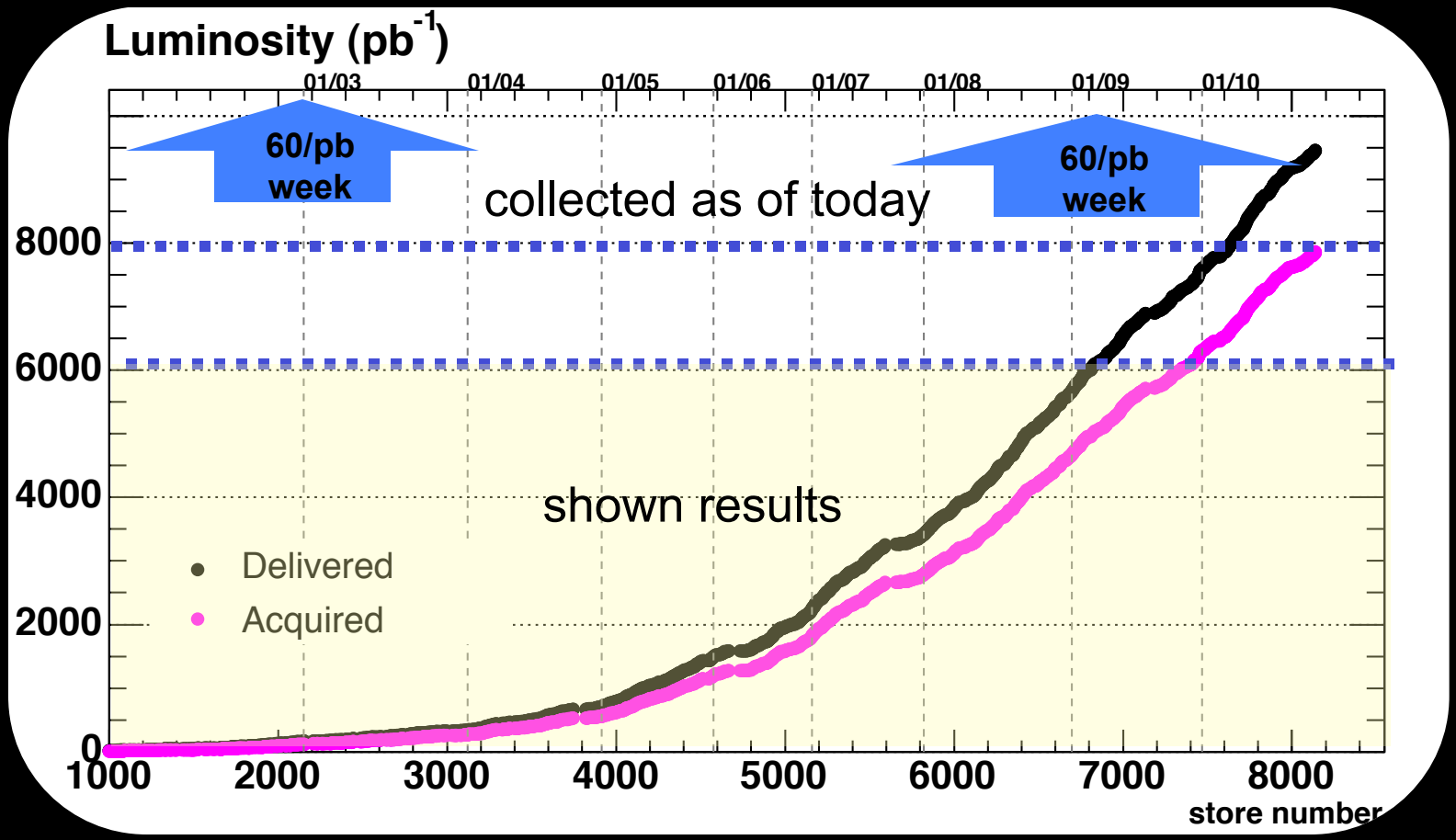
S-wave BW convoluted with 3.0 MeV resolution

M = 4274.4 $^{+8.4}_{-6.7}$ ± 1.9 MeV Γ= 32.3 $^{+21.9}_{-15.3}$ ± 7.6 MeV

3σ significance

CDF Public Note 10244

Not done, yet



More than 10 fb^{-1} of physics-quality data on tape by end of 2011 (3 yrs extension under discussion)

Concluding remarks

Impressive Tevatron spectroscopy program. Data, highly efficient triggers, excellent tracking and high muon acceptance.

- World-leading mass determination of B^+, B^0, B^0_s, Λ_b ground st. b-hadrons
- Pioneering studies of orbitally excited B^0 and B^0_s mesons
- Till 2001, Λ_b was only known *b*-baryon. CDF/DØ filled-in gaps with observations of Σ_b , strange Ξ_b , doubly-strange Ω_b.
- Key contributions to exotic XYZ: new states, confirm B-factories, unique determination of quantum numbers, leading mass measurements.

Program ongoing and exploiting new opportunities.

3 recent results: improved Σ_b properties, entered realm of charmed baryons, yet another particle added to the zoo of exotic XYZ.

Sitting on a goldmine of ever increasing data. A few exciting years of competition with LHCb upcoming.

Tevatron Run II

www.fnal.gov