Heavy Baryon Physics at CDF

Dmitry Litvintsev

Fermilab CD/CDF

June 8, 2005

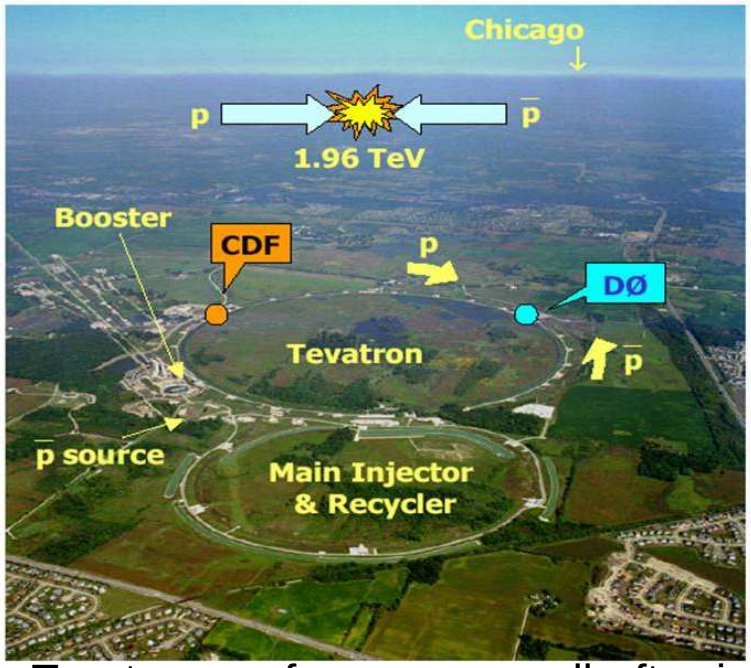
Seminar at TTU

Contents

- Introduction
- Heavy Baryons
- Searches for Pentaquarks
- Prospects
- Conclusion

Tevatron at Fermilab

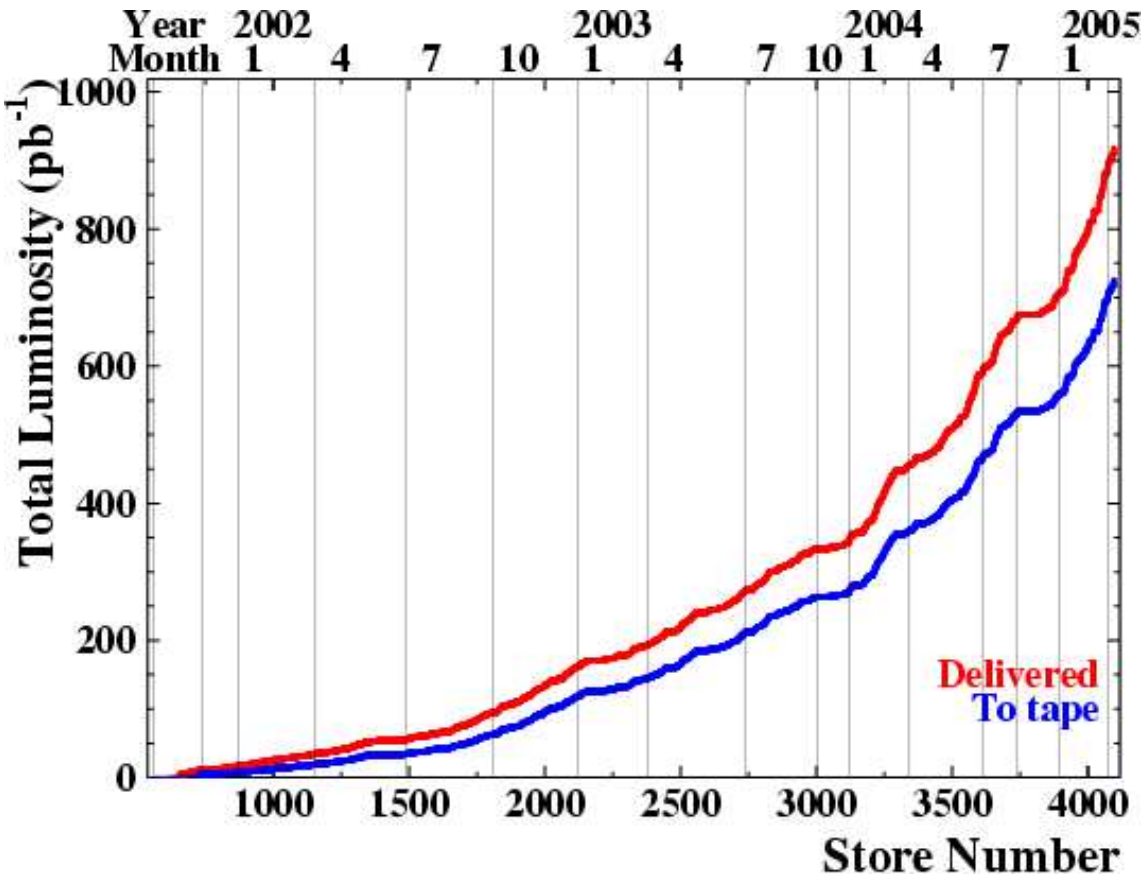
World's largest collider



- Tevatron performs very well after initially slow start
- $\int \mathscr{L} dt \sim 900 pb^{-1}$ ($\sim 700 pb^{-1}$ on tape)
- CDF & D0 efficiency $\sim 80\%$
- $4 - 8\ fb^{-1}$ by 2009

- 1 km ring radius; $p\bar{p}$ collisions, started 1984 $\sqrt{s} = 1.6$ TeV
- Run I (1992-1995) $\sqrt{s} = 1.8$ TeV, 6x6 bunches, $\mathscr{L}_{inst} = 1.6 \times 10^{31} cm^{-2} s^{-1}$, $\int \mathscr{L} dt = 110\ pb^{-1}$
- 1996-2000 major upgrade for Run II
  - main injector
  - $\bar{p}$ recycler
  - new synchrotron
  - upgraded $\bar{p}$ source
- Run II started 2001:
  - $\sqrt{s} \sim 1.96 TeV$.
  - 36x36 colliding $p\bar{p}$ bunches
  - $10^{11}(10^{10}) p(\bar{p})$ per bunch
  - $\mathscr{L}_{inst} = 11.7 \times 10^{31} cm^{-2} s^{-1}$(record) (goal $8.1 \times 10^{31} cm^{-2} s^{-1}$)
  - high beam-beam crossing (inter-bunch spacing 396 ns), low pileup

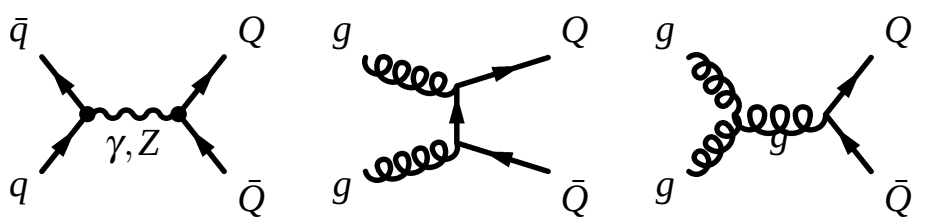
Collider Luminosity



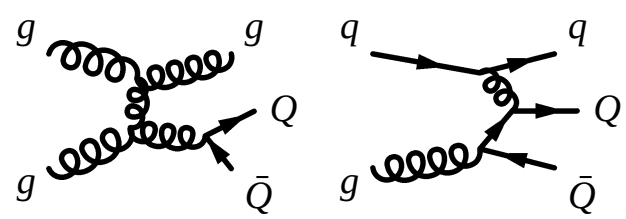
Results are based on $\int \mathscr{L} dt = 280 - 360 \mathrm{pb}^{-1}$

Heavy Flavor Production at Tevatron

LO Heavy quark production



NLO Heavy quark production



Accelerator	PEPII,KEK	Tevatron
$\sigma(b\bar{b})$	1 nb	100 μb
$\sigma(b\bar{b}) : \sigma(had)$	0.26	0.001
Production	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$	$p\bar{p} \to b\bar{b}X$
	coherent production	incoherent production
Environment	clean	messy
Hadrons produced	B^0, B^+	all
Boost	0.5	2-4
Kinematics	forward boost	$b\bar{b}$ not back-to-back, second b usually lost
pile-up	no	yes
Trigger	inclusive	selective
Beam energy constraint	yes	no

Q fragments into final states $\mathrm{B_u, B_d, B_s, Baryon_b}$ with the following fractions:

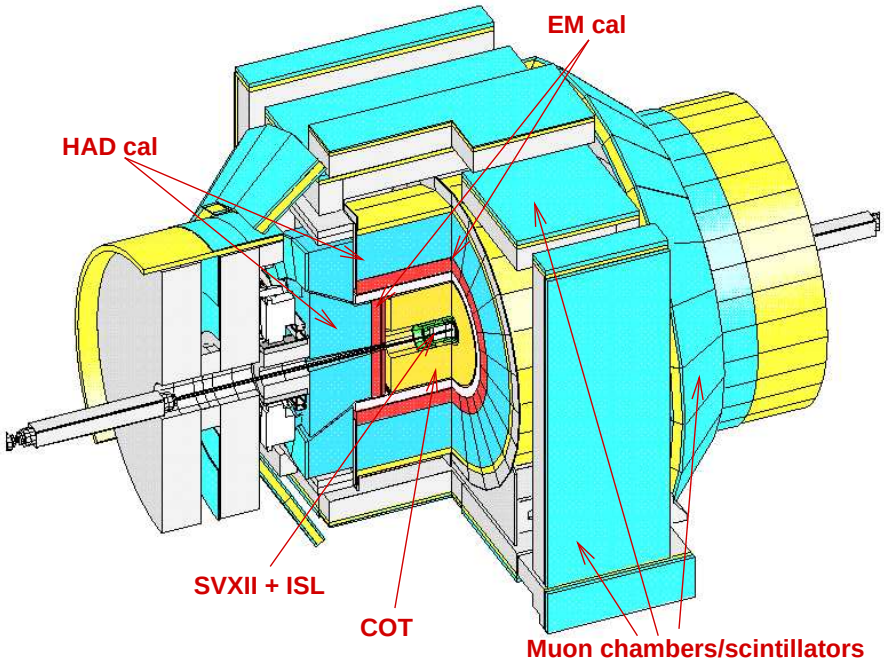
$$\mathrm{B_u : B_d : B_s : Baryon_b} = 0.388 : 0.388 : 0.106 : 0.118$$

production of $\mathrm{B_c}$ is suppressed by 2-3 orders of magnitude as hard gluon process is needed

Run II CDF Detector

Upgraded CDF Detector

- **tracking**
  - L00 + 5 layers of SVX + 2/1 outer layers of ISL ($1.5 < \mathrm{R} < 30\mathrm{cm}$, $|\mathrm{Z}| < 45\mathrm{cm}$). $\mathrm{r}\phi$, rz, stereo strips. 720,000 channels. Si tracking up to $|\eta| < 2$.
  - Central Outer Tracker (COT), 30,240 sense wires, 96 layer drift wire chamber. $\sigma(1/\mathrm{p_T}) \sim 0.1\%/(\mathrm{GeV/c})$, $\sigma(\mathrm{hit}) \sim 150\mu\mathrm{m}$. dE/dx PID.
- **new plug calorimeter**
- **extended muon coverage, $|\eta| < 1.5$**
- **ToF system, (120 ps @ 138 cm)**
- **improved DAQ and trigger systems**
  - new frontend electronics
  - Level 1 all digital, 132 ns pipeline
  - 40000/300/70 Hz
  - COT Tracks @ Level 1
  - Si Tracks @ Level 2
  - Full analysis @ Level 3
  - First hadronic B-trigger

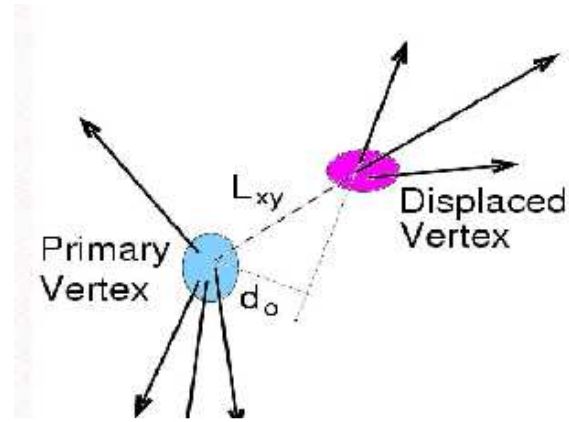


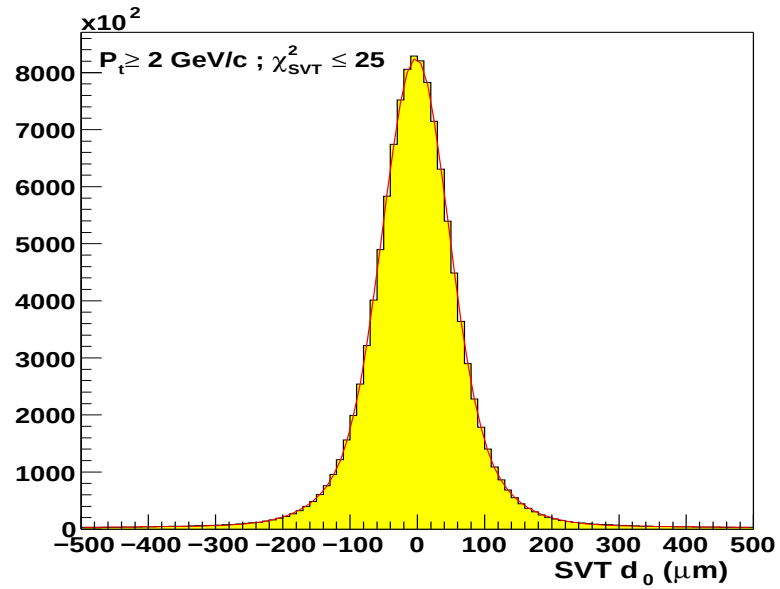
CDF Run II B-triggers

- di-lepton triggers (J/ψ and rare B decays)
- single lepton triggers $p_T > 4\ \mathrm{GeV/c}, \mathrm{p_T} > 8\ \mathrm{GeV/c}$
- New displaced track triggers (two track and ℓ+track):
  - Level 1
    - ✓ XFT tracking in COT ($r-\phi$)
    - ✓ opposite charged track pair with $p_T > 2\ \mathrm{GeV/c}$ each
    - ✓ $\Sigma p_T > 5.5\ \mathrm{GeV/c}$
    - ✓ $\Delta\phi < 135^\circ$
  - Level 2
    - ✓ XFT track seeds SVT boards, that perform fast ($r-\phi$) track fit
    - ✓ repeat Level 1 cuts
    - ✓ require tracks impact parameter to be $0.012 < |d_0| < 0.1\ \mathrm{cm}$

  ℓ+track uses slightly different set of cuts

Hadronic triggers improved B-physics sensitivity by 5 orders of magnitude (compared to Run I)





$\sigma(d_0)_{SVT} = 48\ \mu m$ (including $\sigma(beam) = 33\ \mu m$)

Motivation

- $\boxed{m_u, m_d, m_s \ll \Lambda_{QCD} \ll m_c, m_b, m_t}$
- **Heavy hadrons – heavy source of static color field in the center surrounded by the cloud of light degrees of freedom. As $m_Q \to \infty$ new Heavy Quark Symmetry arises:**
  - **Spin symmetry**
  - **Flavour symmetry (cloud and center communiucate via gluons which are flavor-blind)**
- **As the result QCD description of heavy-light systems simplifies in the HQS limit. Corrections to the limit are introduced as systematic (Λ_{QCD}/M_Q) expansion. The approach is called Heavy Quark Effective Theory (HQET).**
- **In heavy meason sector (bq) HQET predictions are known to work well and are tested with high statistics data from B-factories, LEP and Tevatron.**
- **Experimental data on Heavy Baryons remains scarce.**

Λ_b at CDF

- Λ_b – iso-singlet containing b and $S = 0$ $\bar{3}$ SU(3) di-quark $[ud]$. $\mathrm{M} = 5.620\ \mathrm{GeV/c^2}$. Discovered by ALEPH in $\Lambda_b \to \Lambda_c^+ 3\pi$ mode.
- Only two (PDG'2004) decays are established: $\Lambda_b \to J/\psi\Lambda$ and $\Lambda_b \to \Lambda_c^+ \ell \bar{\nu}_\ell \mathrm{X}$
- We set out to measure: $\dfrac{Br(\Lambda_b \to \Lambda_c^+ \mu \bar{\nu}_\mu)}{Br(\Lambda_b \to \Lambda_c^+ \pi^-)}$, where $\Lambda_c^+ \to pK^-\pi^+$.
- 4-track final states – systematics cancels

$$\frac{Br(\Lambda_b \to \Lambda_c^+ \mu \bar{\nu}_\mu)}{Br(\Lambda_b \to \Lambda_c^+ \pi^-)} = \left(\frac{N(\Lambda_c^+ \mu^-) - N_{\mathrm{physics}} - N_{\mathrm{fake}\mu} - N_{b\bar{b},c\bar{c}}}{N(\Lambda_c^+ \pi)} \right) \times \frac{\varepsilon(\Lambda_c^+ \pi)}{\varepsilon(\Lambda_c^+ \mu)}$$

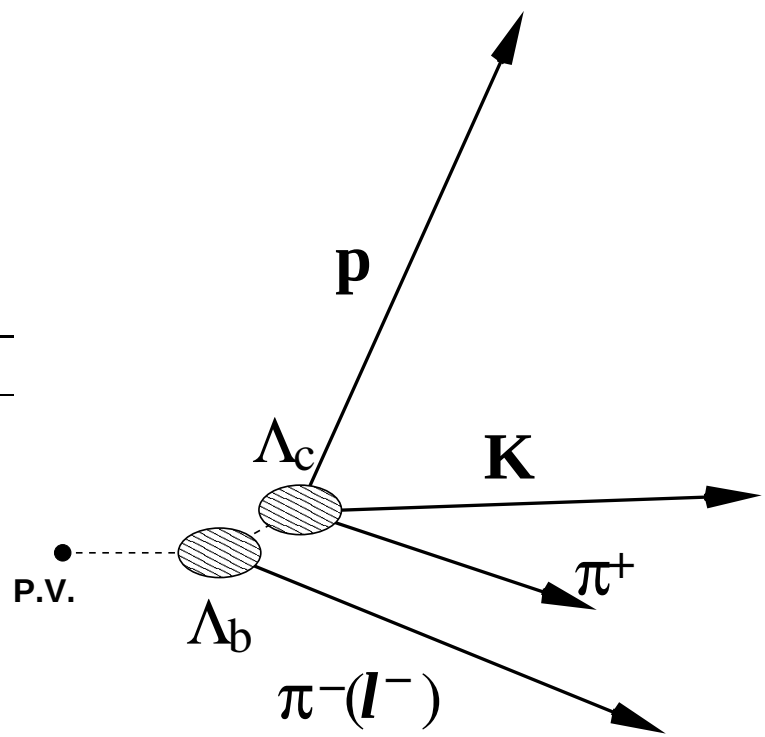
- use:
  - two-track hadronic trigger data
  - use decays similar decays $\bar{B}^0 \to D^{+,*+}$ as control samples
- Missing neutrino represents challenge as decay kinematics is not reconstucted fully, use:
  - Data to estimate fake rate
  - MC to estimate "physics" and $b\bar{b}, c\bar{c}$ backrounds. Use $\Lambda_c^+ \pi$ yield for normalization.

Event Selection

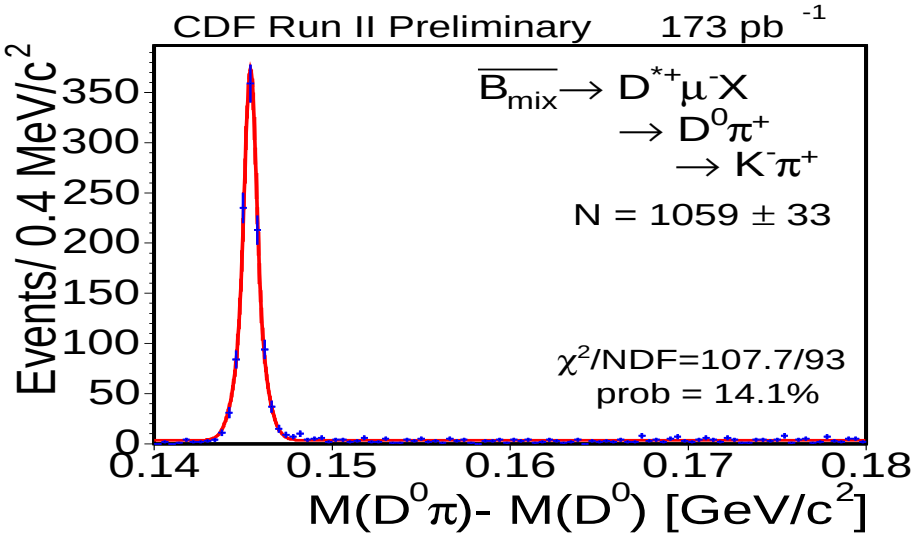
- $\int \mathscr{L} dt = 237\ \mathrm{pb}^{-1}$
- Two-Track trigger. Trigger confirmation on two out of four tracks:
  - $p_{T1} > 2\ \mathrm{GeV/c}, \mathrm{p_{T2}} > 2\ \mathrm{GeV/c}$
  - $\sum p_{T1} + p_{T2} > 5.5\ \mathrm{GeV/c}$
  - $2^\circ < |\Delta\phi_0| < 90^\circ$
  - $|\Delta z_0| < 5\ \mathrm{cm}$
  - $L_{xy}(\text{at track intersect}) > 200\ \mu\mathrm{m}$

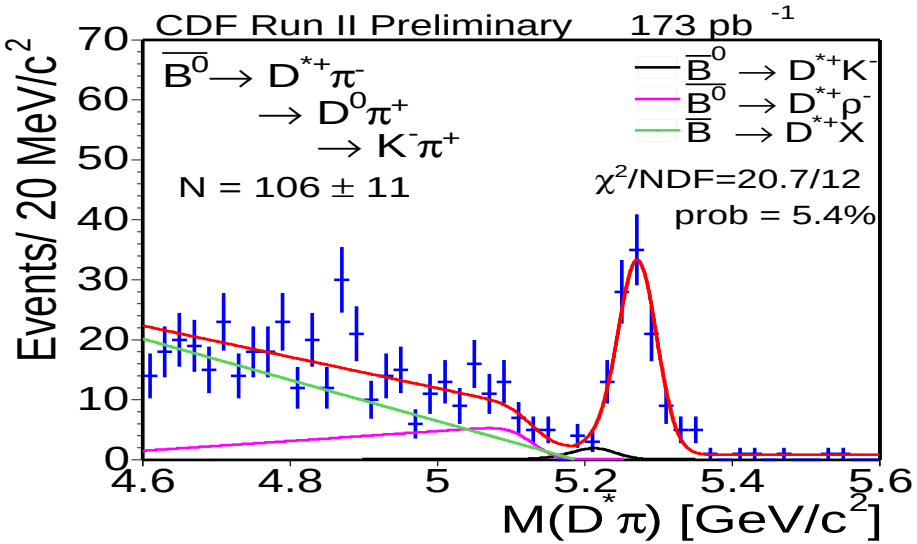
All modes	
p_T of all tracks	$> 0.5\ \mathrm{GeV/c}$
π_B, μ_B p_T	$> 2\ \mathrm{GeV/c}$
$p_T(4-\text{track})$	$> 6\ \mathrm{GeV/c}$
μ match χ^2	< 8
every track exits COT layer 95	
π_B is fiducial in muon system (CMU)	

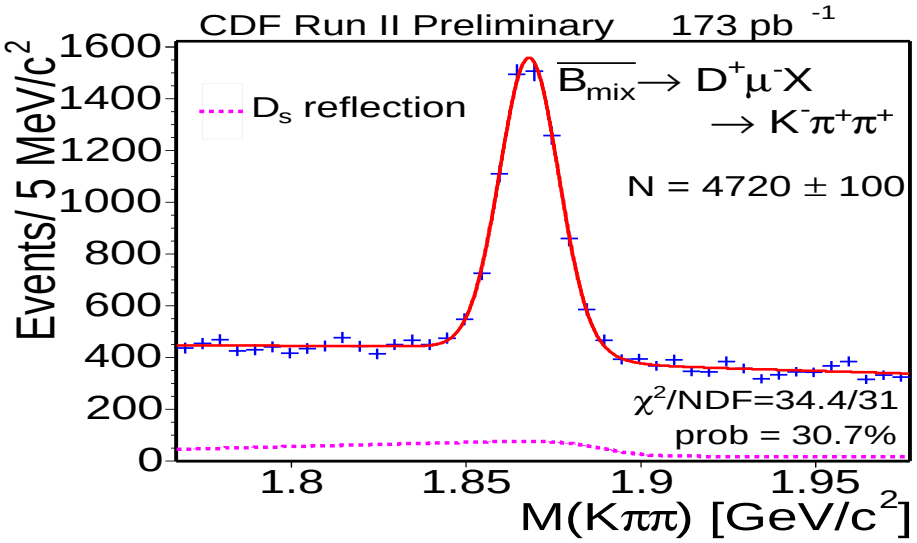
- $c\tau(B) > 200\ \mu\mathrm{m},\ c\tau(D^0 \to B) > -70\mu\mathrm{m},\ c\tau(D^+ \to B) > -30\mu\mathrm{m}$
- $c\tau(\Lambda_b) > 250\ \mu\mathrm{m}, c\tau(\Lambda_c^+ \to \Lambda_b) > -70\mu\mathrm{m}$

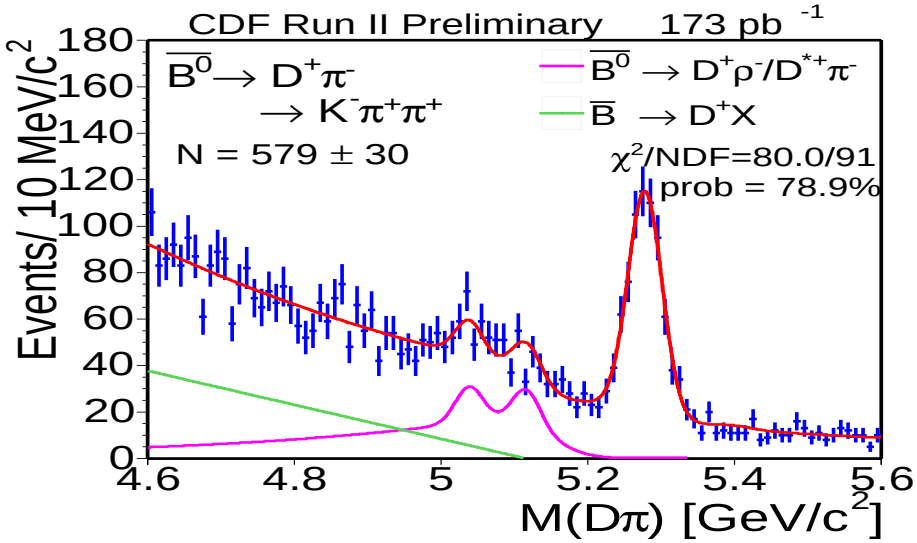


Control Samples

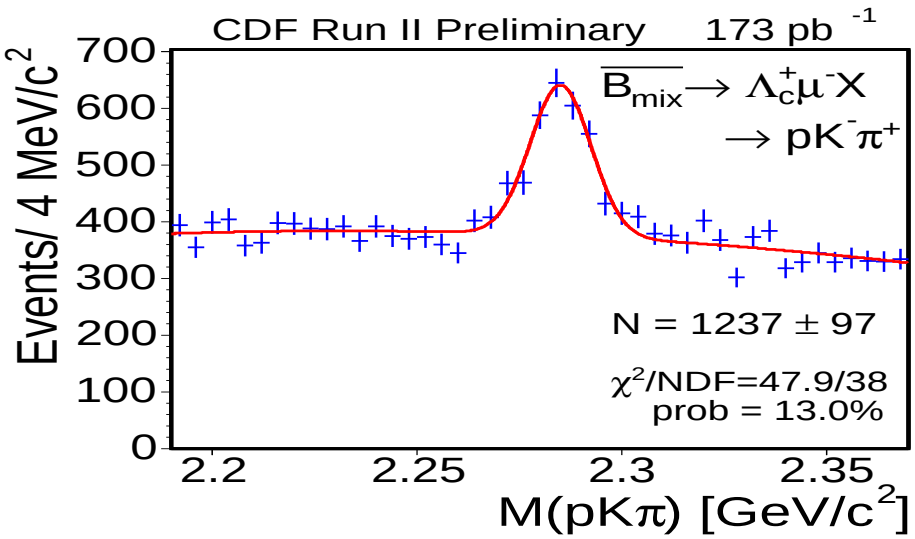


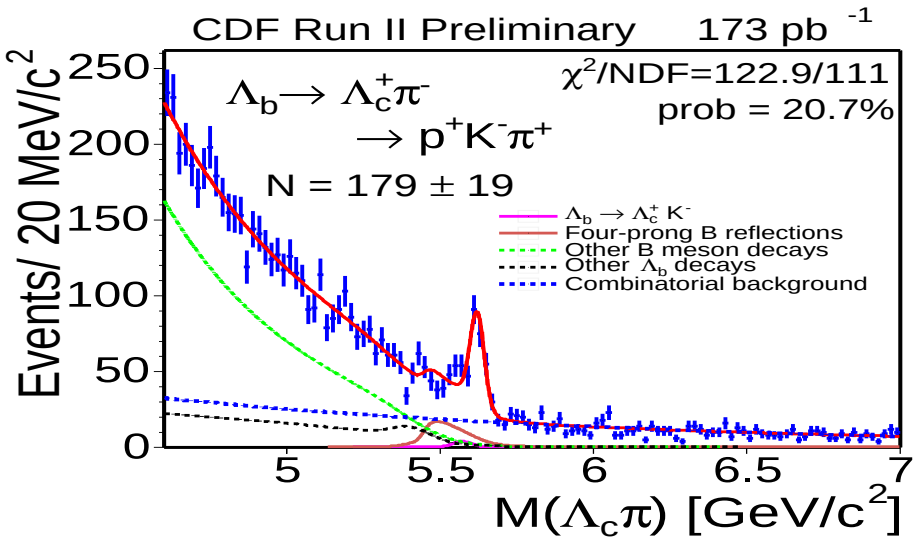






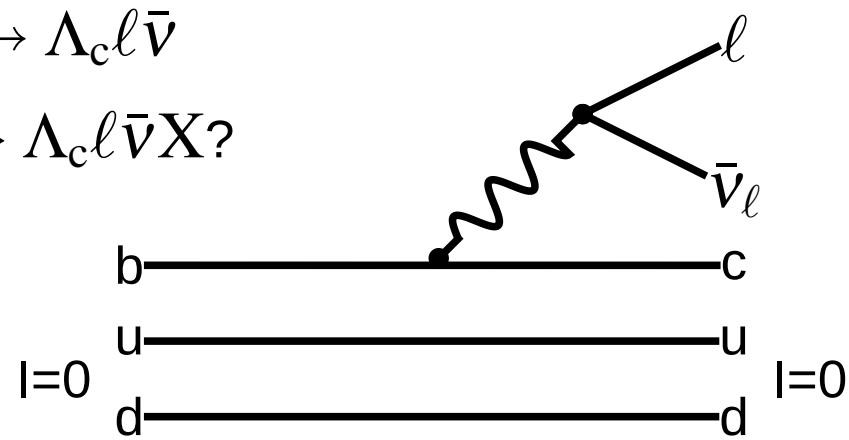
The Λ_b


CDF Run II Preliminary 173 pb -1
$\overline{B_{mix}} \to \Lambda_c^+ \mu^- X$
$\to pK^-\pi^+$
N = 1237 ± 97
χ^2/NDF=47.9/38
prob = 13.0%
Events/ 4 MeV/c^2
M(pKπ) [GeV/c^2]


CDF Run II Preliminary 173 pb -1
$\Lambda_b \to \Lambda_c^+ \pi^-$
$\to p^+K^-\pi^+$
χ^2/NDF=122.9/111
prob = 20.7%
N = 179 ± 19
$\Lambda_b \to \Lambda_c^+ K^-$
Four-prong B reflections
Other B meson decays
Other Λ_b decays
Combinatorial background
Events/ 20 MeV/c^2
M($\Lambda_c\pi$) [GeV/c^2]

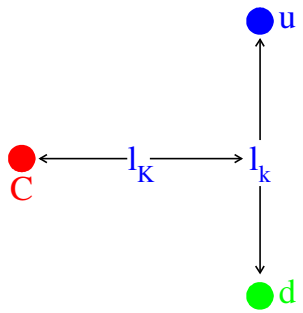
Nature of X

- We measure
  $\Lambda_b \to \Lambda_c \pi / \Lambda_b \to \Lambda_c \ell \bar{\nu}$
- what is X in $\Lambda_b \to \Lambda_c \ell \bar{\nu} X$?



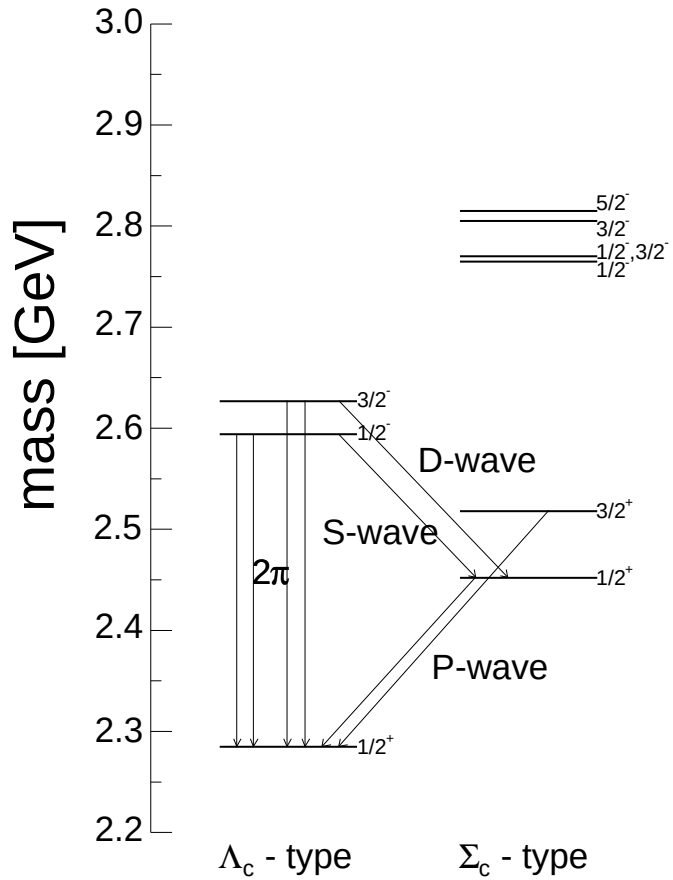
- I.d.f. conserve isospin, so:
  - decay $\Lambda_b \to \Sigma_c^+ \ell \bar{\nu}$ is suppressed
  - decays to I=0 states are OK, E.g.: $\Lambda_b \to \Lambda_c^* \ell \bar{\nu}$. Suppressed due to heavy b-quark.

What is Λ_c^* ?



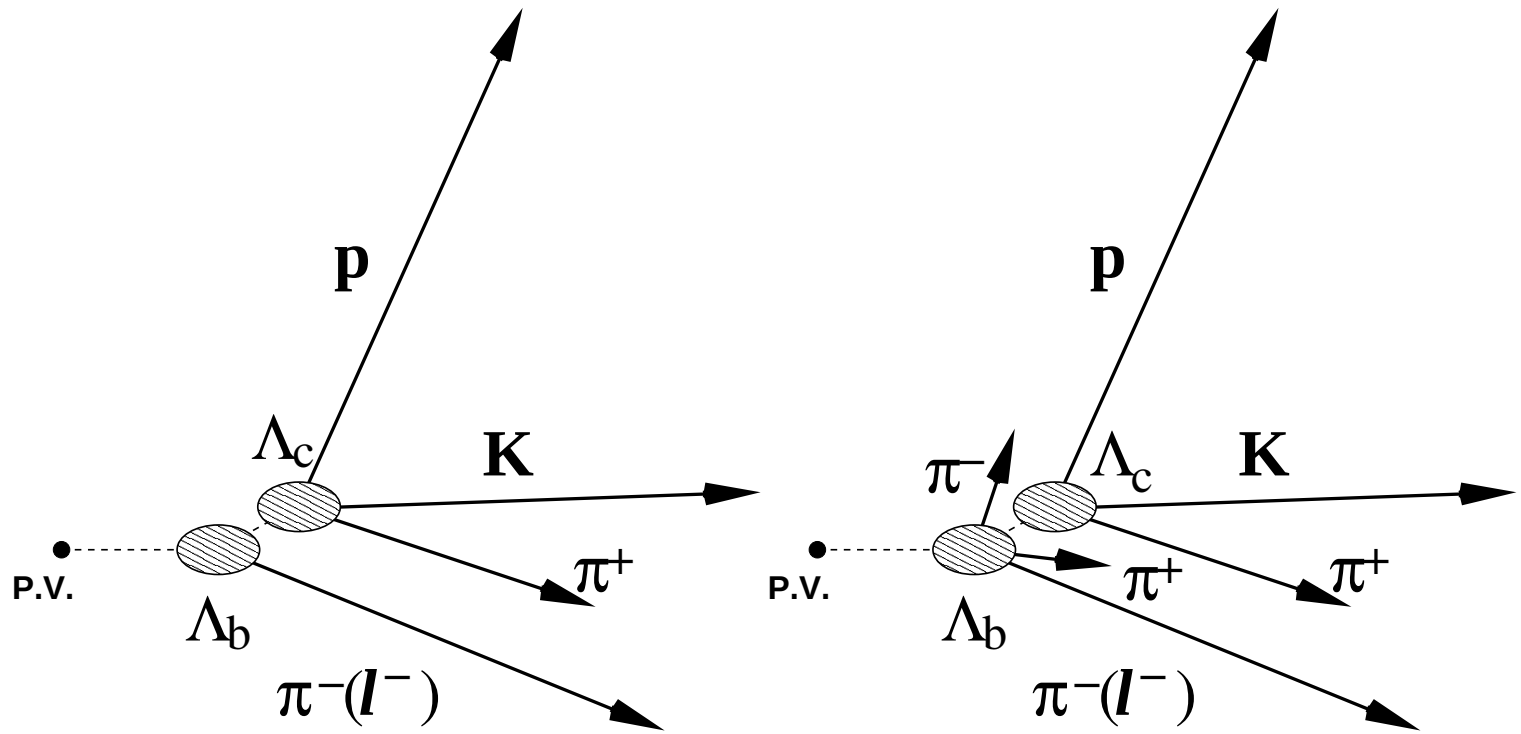
- lowest P-wave $l_k = 0, l_K = 1$:
- degenerate (in HQS limit) doublet:

$$J = j_l \pm s_Q \quad \begin{matrix} \nearrow \\ \searrow \end{matrix} \quad \begin{matrix} \frac{3}{2}^- \\ \frac{1}{2}^- \end{matrix} \quad \left\{ \begin{matrix} \Lambda_{c1}^* \\ \\ \Lambda_{c1} \end{matrix} \right\}$$



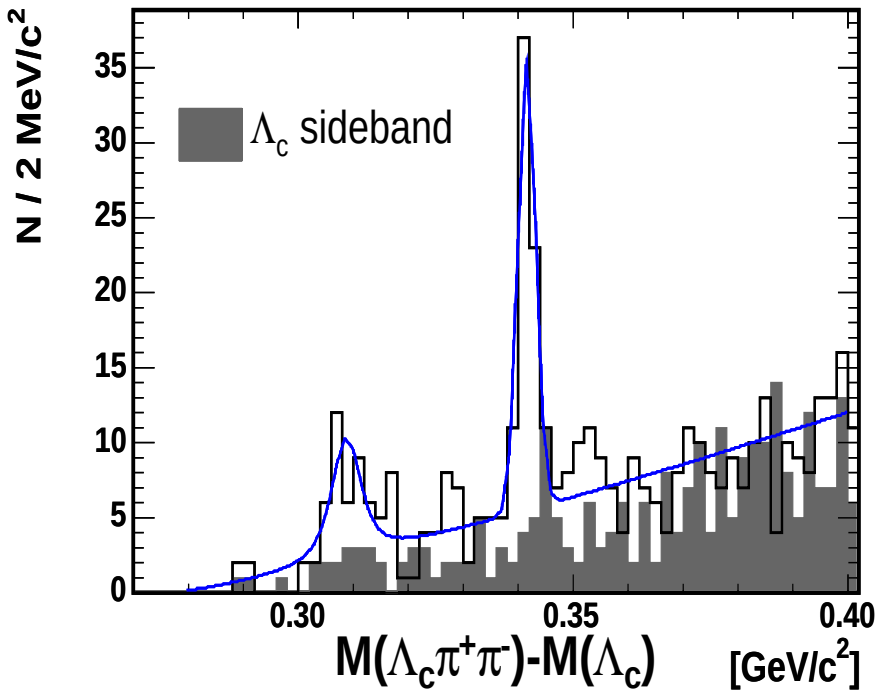
a

Search for $\Lambda_c^* \mu^-$



Add two soft pions to Λ_b decay vertex, keep all other cuts the same

Search for $\Lambda_c^* \mu^-$

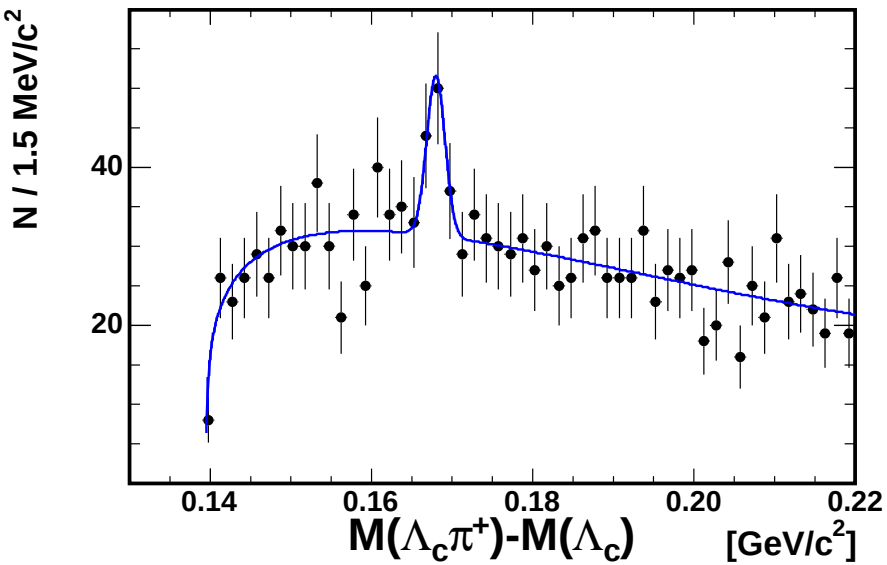


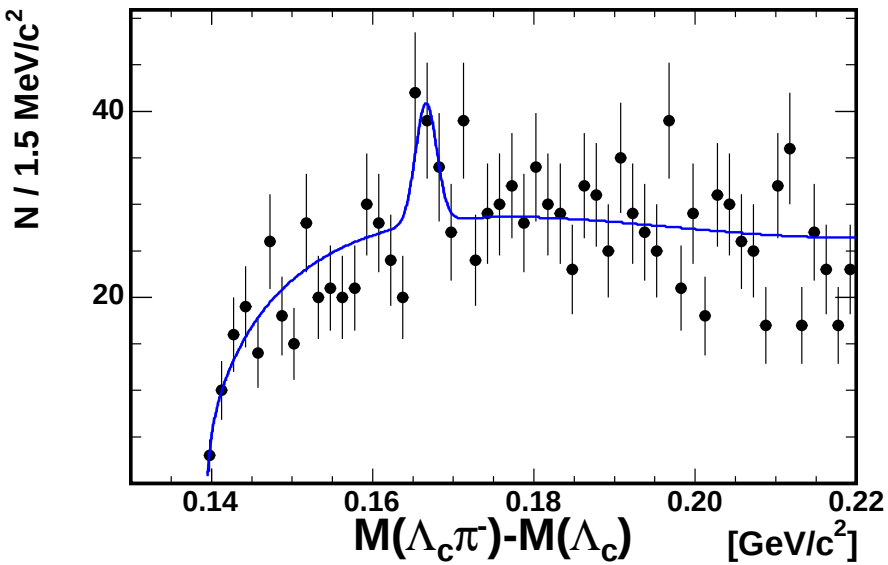
We see two significant peaks

$$\left|M(pK\pi) - M_{\Lambda_c^+}\right| < 18\ \mathrm{MeV/c^2}.$$

$$24\ \mathrm{MeV/c^2} < \left|\mathrm{M(pK\pi) - M_{\Lambda_c^+}}\right| < 42\ \mathrm{MeV/c^2}.$$

$\Sigma_c^{++,0}\mu^-$


N / 1.5 MeV/c^2
40
20
0.14
0.16
0.18
0.20
0.22
M($\Lambda_c\pi^+$)-M(Λ_c) [GeV/c^2]


N / 1.5 MeV/c^2
40
20
0.14
0.16
0.18
0.20
0.22
M($\Lambda_c\pi^-$)-M(Λ_c) [GeV/c^2]

Yields

Relevant Fit Parameter	no proton PID
$N(\Sigma_c^{++})$	$38 \pm 13 \pm 8$
$N(\Sigma_c^{0})$	$33 \pm 11 \pm 7$
$N(\Lambda_c^*(2593))$	$36 \pm 8 \pm 8$
$N(\Lambda_c^*(2625))$	$60 \pm 10 \pm 6$

What we want to measure

$$\frac{\mathscr{B}_1}{\mathscr{B}_0} = \frac{\mathscr{B}(\Lambda_b \to \Lambda_c^*(2593)\mu^-\bar{\nu}_\mu)}{\mathscr{B}(\Lambda_b \to \Lambda_c^+\mu^-\bar{\nu}_\mu)},$$

$$\frac{\mathscr{B}_2}{\mathscr{B}_0} = \frac{\mathscr{B}(\Lambda_b \to \Lambda_c^*(2625)\mu^-\bar{\nu}_\mu)}{\mathscr{B}(\Lambda_b \to \Lambda_c^+\mu^-\bar{\nu}_\mu)},$$

$$\frac{\mathscr{B}_3}{\mathscr{B}_0} = \frac{\mathscr{B}(\Lambda_b \to \Sigma_c\mu^-\bar{\nu}_\mu)}{\mathscr{B}(\Lambda_b \to \Lambda_c^+\mu^-\bar{\nu}_\mu)}.$$

Direct Σ_c yield

use measured properties of Λ_c^* baryons:

decay modes	$\Lambda_c^*(\frac{1}{2}^-)$	$\Lambda_c^*(\frac{3}{2}^-)$
$\Lambda_c^+\pi^+\pi^-$	$\approx 67\%$	$\approx 67\%$
$\Sigma_c^{++}\pi^-$	$24 \pm 7\%$	$< 5\%$
$\Sigma_c^0\pi^+$	$24 \pm 7\%$	$< 5\%$
$\Lambda_c^+\pi^+\pi^-$ 3-body	$18 \pm 10\%$	large

$$N(\Lambda_b \to \Sigma_c^{++}\mu\bar{\nu}_\mu) = N(\Sigma_c^{++}) - N(\Lambda_c^*(2593))/\varepsilon_3^\pi \cdot \mathscr{B}(\Lambda_c^*(2593) \to \Sigma_c^{++}\pi)$$

$$N(\Lambda_b \to \Sigma_c^0\mu\bar{\nu}_\mu) = N(\Sigma_c^0) - N(\Lambda_c^*(2593))/\varepsilon_3^\pi \cdot \mathscr{B}(\Lambda_c^*(2593) \to \Sigma_c^0\pi)$$

- $\varepsilon_3^\pi = 0.80 \pm 0.02 \pm 0.12$ – efficiency to find and "attach" π from Σ_c decay from $\Lambda_b \to \Lambda_c^*\mu\bar{\nu}_\mu$
- $N(\Lambda_b \to \Sigma_c^{++}\mu\bar{\nu}_\mu) = 27 \pm 13 \pm 9$
- $N(\Lambda_b \to \Sigma_c^0\mu\bar{\nu}_\mu) = 22.2 \pm 11 \pm 9$

Weighted average number of all three states $(\Sigma_c^0, \Sigma_c^+, \Sigma_c^{++})$ is $3 \times (24 \pm 8.4 \pm 6.3)$

Finally

$$\frac{\mathscr{B}_1}{\mathscr{B}_0} = (4.8 \pm 1.2 \pm 1.5) \times 10^{-2}$$

$$\frac{\mathscr{B}_2}{\mathscr{B}_0} = (7.8 \pm 1.5 \pm 2.0) \times 10^{-2}$$

$$\frac{\mathscr{B}_3}{\mathscr{B}_0} = (3.4 \pm 1.2 \pm 1.1) \times 10^{-2}$$

These numbers enter background estimate for $\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu}_\mu$

Numbers

	$\bar{B}^0 \to D^+X$	$\bar{B}^0 \to D^{*+}X$	$\Lambda_b \to \Lambda_c^+X$
yield (had)	106 ± 11	579 ± 30	179 ± 19
yield (sem)	1059 ± 33	4720 ± 100	1237 ± 97
physics	168 ± 8	477 ± 13	122 ± 6
fakes	44 ± 3	230 ± 19	40 ± 9
$N_{b\bar{b}}$	6 ± 0.6	34 ± 2	2.1 ± 0.2
$N_{c\bar{c}}$	4 ± 0.4	23 ± 1	0.20 ± 0.03

Results

$$\frac{B(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}{B(\bar{B}^0 \to D^{*+}\pi^-)} = 17.7 \pm 2.3(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.4(\text{Br}) \pm 1.1(\text{uknownBr})$$

$$19.7 \pm 1.7(\text{PDG})$$

$$\frac{B(\bar{B}^0 \to D^{+}\mu^-\bar{\nu}_\mu)}{B(\bar{B}^0 \to D^{+}\pi^-)} = 9.8 \pm 1.0(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.8(\text{Br}) \pm 0.9(\text{uknown Br}),$$

$$7.8 \pm 1.0(\text{PDG})$$

$$\frac{B(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)}{B(\Lambda_b \to \Lambda_c^+\pi^-)} = 20.0 \pm 3.0(\text{stat.}) \pm 1.2(\text{syst.})^{+0.7}_{-2.1}(\text{Br}) \pm 0.5(\text{uknown Br})$$

Other Ground states B=1, C=0

Weakly decaying ground state b-baryons

Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B	Mass
Λ_b	$b[ud]$	$1/2^+$	$\bar{\mathbf{3}}_A$	(0,0)	0	1	$5619.7 \pm 1.2 \pm 1.2\ \mathrm{MeV/c^2}$
Ξ_b^0	$b[su]$	$1/2^+$	$\bar{\mathbf{3}}_A$	(1/2,1/2)	-1	1	$5.80\ \mathrm{GeV/c^2}$
Ξ_b^-	$b[sd]$	$1/2^+$	$\bar{\mathbf{3}}_A$	(1/2,-1/2)	-1	1	$5.80\ \mathrm{GeV/c^2}$
Ω_b^-	bss	$1/2^+$	$\mathbf{6}_S$	(0,0)	-2	1	$6.04\ \mathrm{GeV/c^2}$

Quoted Λ_b mass is CDF measurement.

- Decays of bottom-strange baryon involve long lived hyperons as decay products.
- => start with reconstructing long lived hyperons

Decays with Hyperons

$$\Xi_b \to \boxed{J/\psi}\,\Xi^- + n\pi \quad , \Omega_b \to \boxed{J/\psi}\,\Omega^- + n\pi$$

$$\hookrightarrow \Lambda\pi^- \qquad\qquad \hookrightarrow \Lambda K^-$$

$$\Xi_b \to \Xi_c + n\boxed{\pi} \qquad , \Omega_b \to \Omega_c + n\boxed{\pi}$$

$$\hookrightarrow \Xi^- + n\boxed{\pi} \qquad\qquad \hookrightarrow \Omega^- + n\boxed{\pi}$$

$$\hookrightarrow \Lambda\pi^- \qquad\qquad \hookrightarrow \Lambda K^-$$

$$\Xi_b \to \Xi_c + \boxed{\ell^-}X \qquad , \Omega_b \to \Omega_c + \boxed{\ell^-}X$$

$$\hookrightarrow \Xi^- + n\boxed{\pi} \qquad\qquad \hookrightarrow \Omega^- + n\boxed{\pi}$$

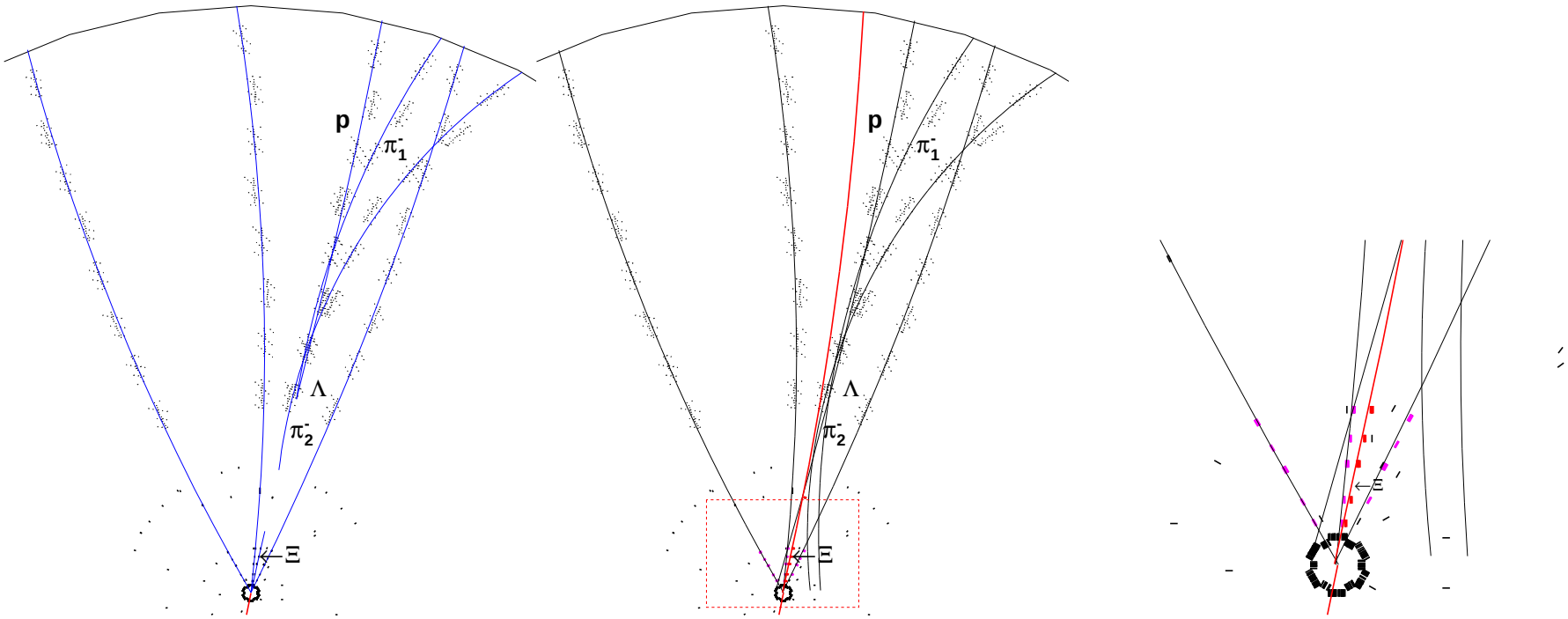
$$\hookrightarrow \Lambda\pi^- \qquad\qquad \hookrightarrow \Lambda K^-$$

$$\Xi_b \to D^0\Lambda \, , \Omega_b \to D^0\Xi^-$$

Cascade tracking in SVX at CDF

Hyperon Are Tracked in Silicon

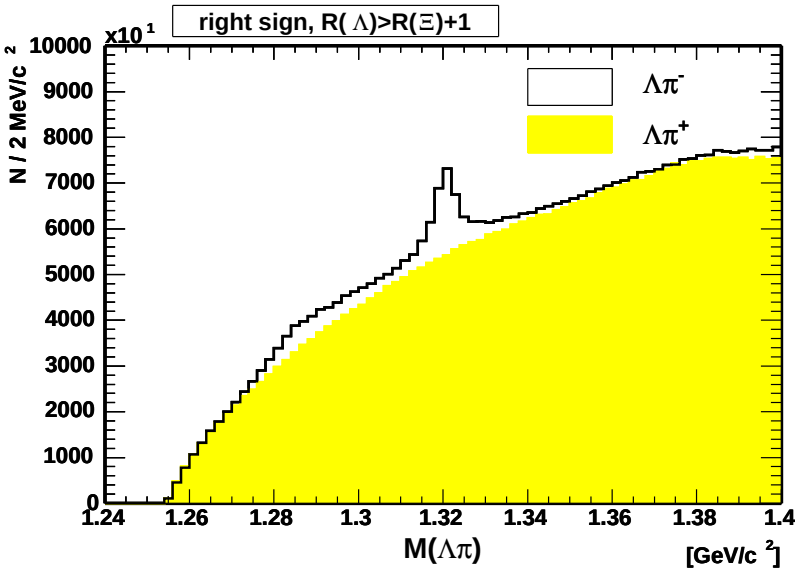
- $\Xi^- \to \Lambda^0 \pi^-$ is long lived $c\tau = 4.91 cm$. It leaves hits in SVX detector. Momentum and vertex of $\Lambda\pi^-$ are used to seed specialized tracking algorithm that finds Ξ tracks in silicon.

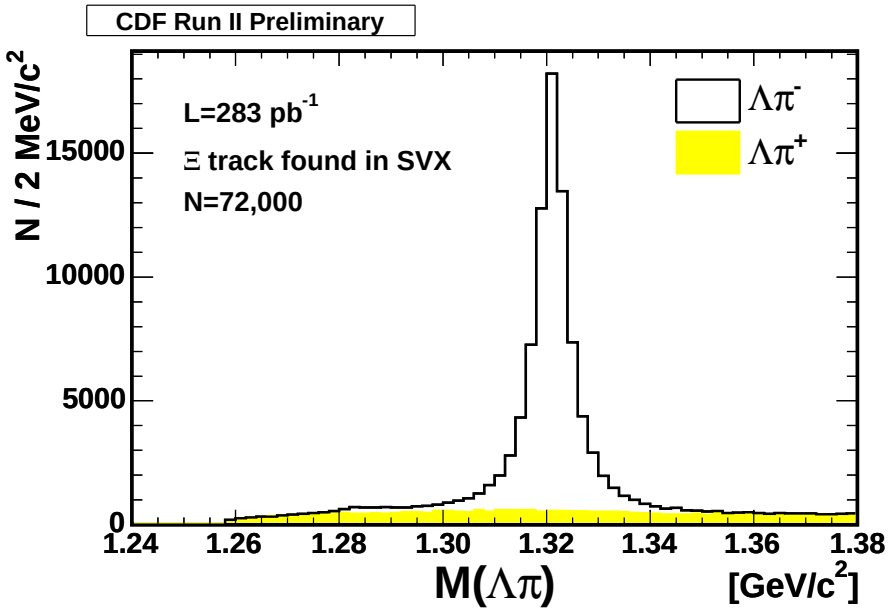


MC : $\Xi_b \longrightarrow \Xi_c^+ \pi^- \quad \Xi_c^+ \longrightarrow \Xi^- \pi^+ \pi^+ \quad \Xi^- \longrightarrow \Lambda \pi_2^- \quad \Lambda \longrightarrow p \pi_1^-$

Tracked Hyperon signals

- silicon tracking of hyperons improves momentum and impact parameter resolution as well as results in excellent background suppression



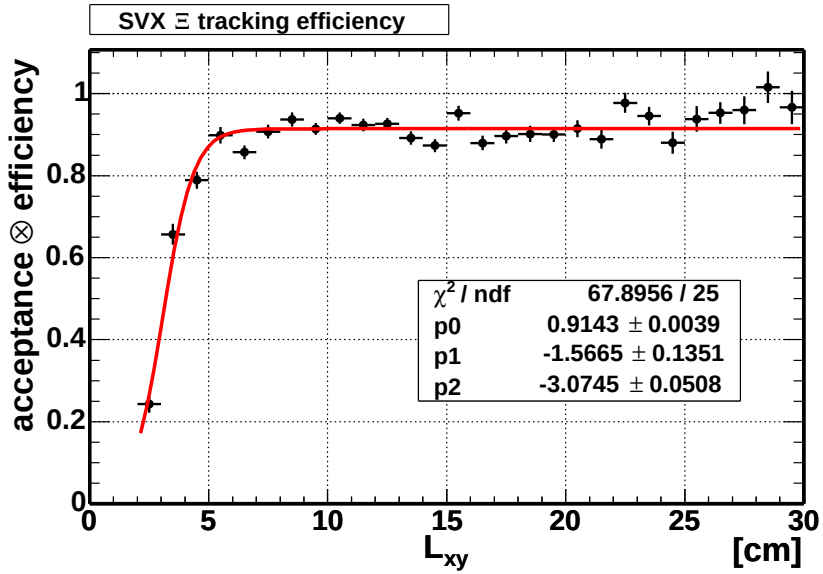


Hadron trigger data

- hyperon tracks reconstructed in SVX will be used to probe production of Ξ_b and Ω_b in decays accessible to CDF triggers (work in progress)

Relative Efficiency

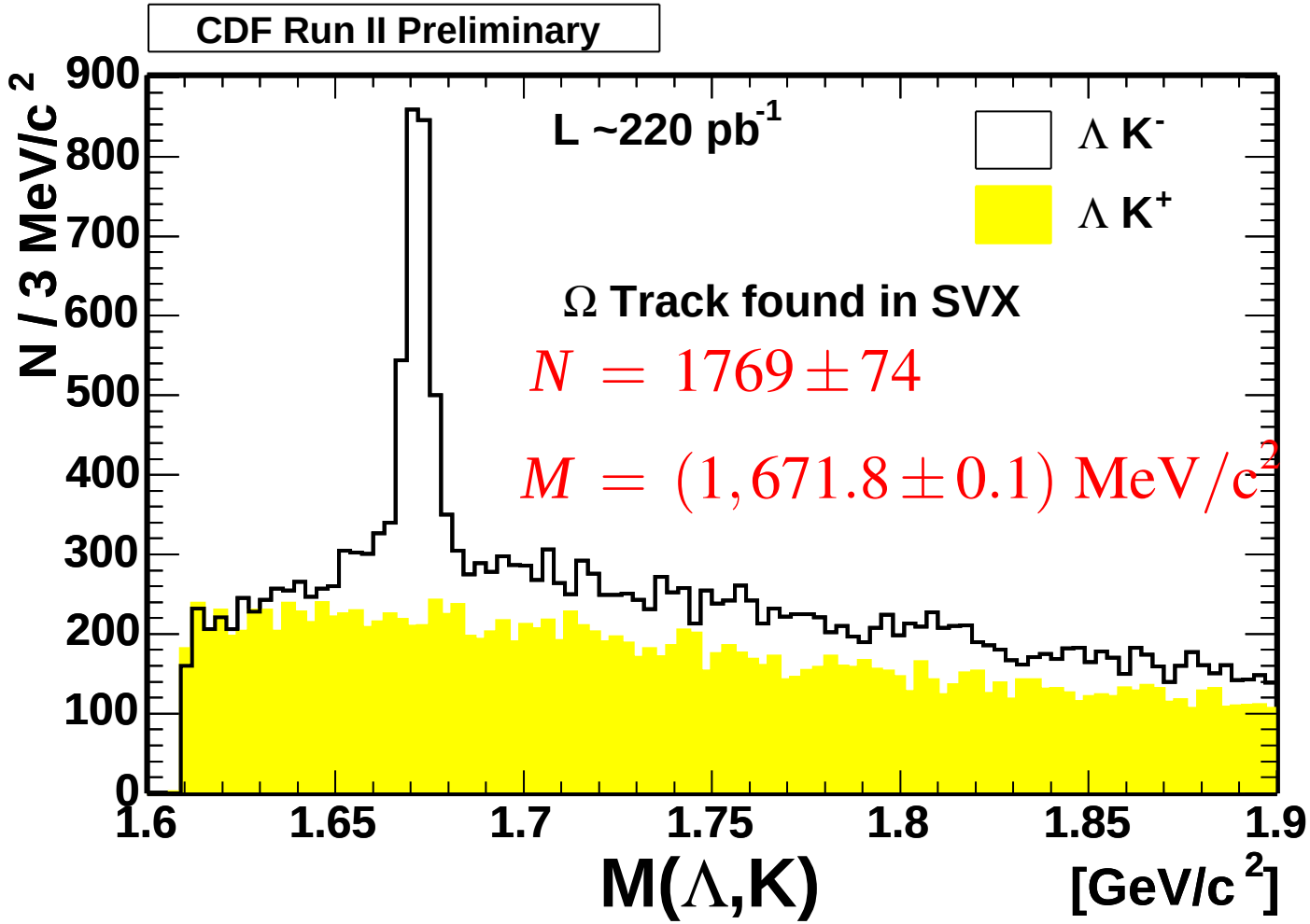
relative Ξ SVX tracking efficiency vs L_{xy}



- plateau at $(91 \pm 0.4)\%$ (including SVX fiducial)
- overall efficiency to find SVX Ξ track is 40%

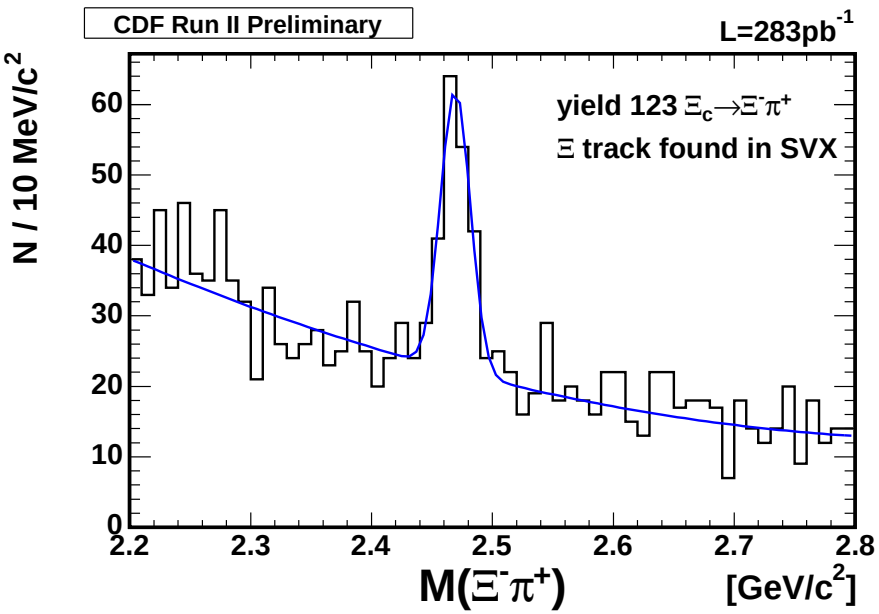
Omega

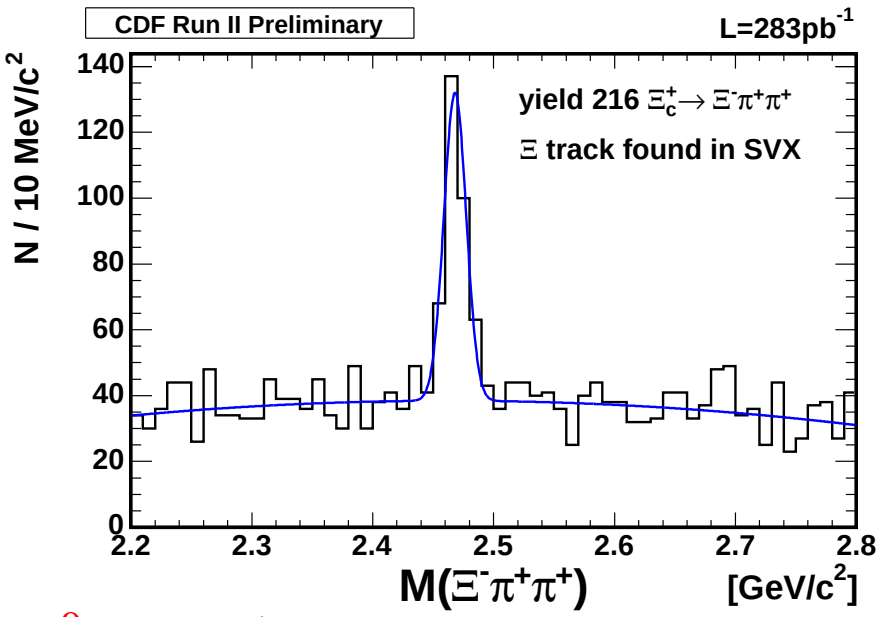
Ω reconstructed in SVX detector



Charmed-strange signals @ CDF

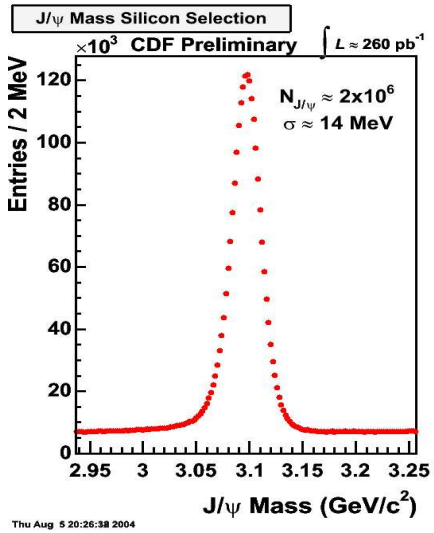
First observation in $p\bar{p}$ collisions

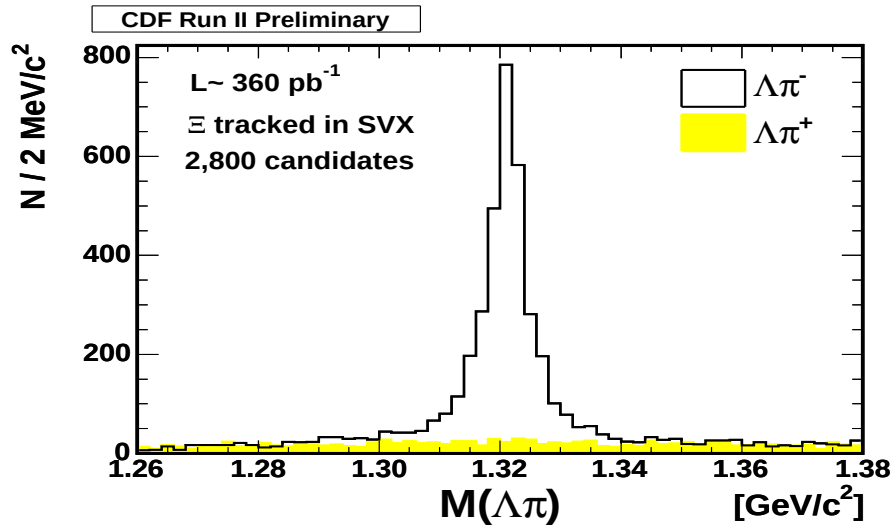


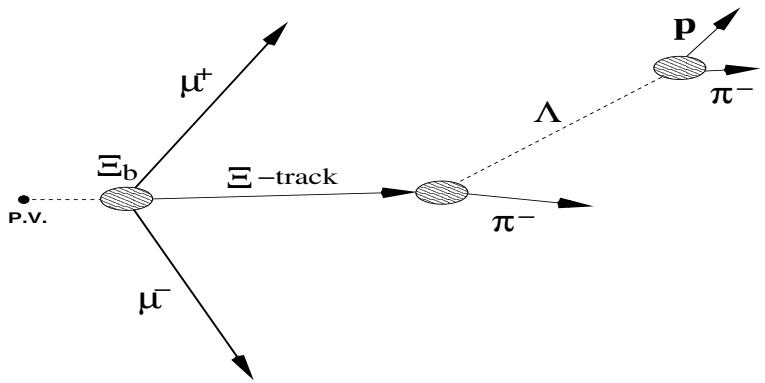


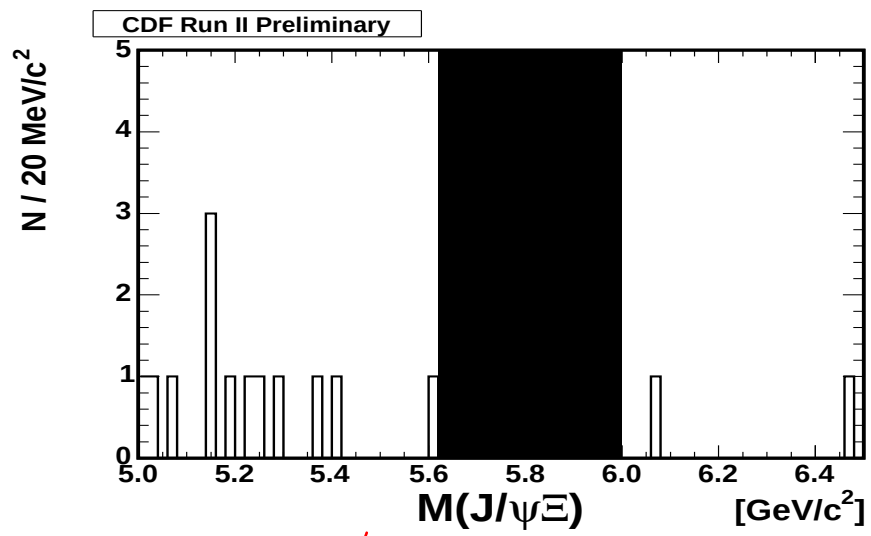
Signals from Ξ_c^0 and Ξ_c^+

$J/\psi\Xi$









Blinded mass spectrum of $J/\psi\Xi$

Expected Yield

- The expected yield in of Ξ_b^- is estimated from known yield of $\Lambda_b \to J/\psi\Lambda$ and measured b-quark fragmentation fractions into mesons and baryons:

$$\mathrm{bu} \ : \ \mathrm{bd} \ : \ \mathrm{bs} \ : \ \mathrm{b-baryon} = 0.388 : 0.388 : 0.106 : 0.118.$$

- Assuming that the probability of s-quark popping is the same for baryons and mesons one gets:

$$\mathrm{bud} \ : \ \mathrm{bsd} \ : \ \mathrm{bsu} \ : \ \mathrm{bss} = 0.78 : 0.098 : 0.098 : 0.024.$$

black

- Assuming $\mathrm{Br}(\Lambda_b \to J/\psi\Lambda) = \mathrm{Br}(\Xi_b^- \to J/\psi\Xi)$:

$$N(\Xi_b^- \to J/\psi\Xi) \sim \frac{N(\Lambda_b \to J/\psi\Lambda)}{8.3} \cdot \frac{A(\Xi_b^-)}{A(\Lambda_b)} \cdot \varepsilon_{SVX} \sim \frac{N(\Lambda_b \to J/\psi\Lambda)}{8.3} \cdot 0.9 \cdot \varepsilon_{kink-\pi} \cdot \varepsilon_{SVX},$$

$\frac{A(\Xi_b^-)}{A(\Lambda_b^-)}$ =0.9 is detector and trigger acceptance ratio obtained using PYTHIA
$\varepsilon_{kink-\pi}$ =0.6 estimate of pion efficiency from $\Xi \to \Lambda\pi$ decay
ε_{SVX} =0.4 known relative hyperon SVX track efficiency.

black

- $N(\Lambda_b \to J/\psi\Lambda)$ is 145 ± 24 in $240\ \mathrm{pb}^{-1}$ The current data sample at CDF is $360\ \mathrm{pb}^{-1}$, giving the number of expected $\Xi_b^- \to J/\psi\Xi$ events to be 6.3. By end of 2005, the Tevatron will have delivered $0.5\mathrm{fb}^{-1}$ of integrated luminosity which translates into the total of 14 signal events.

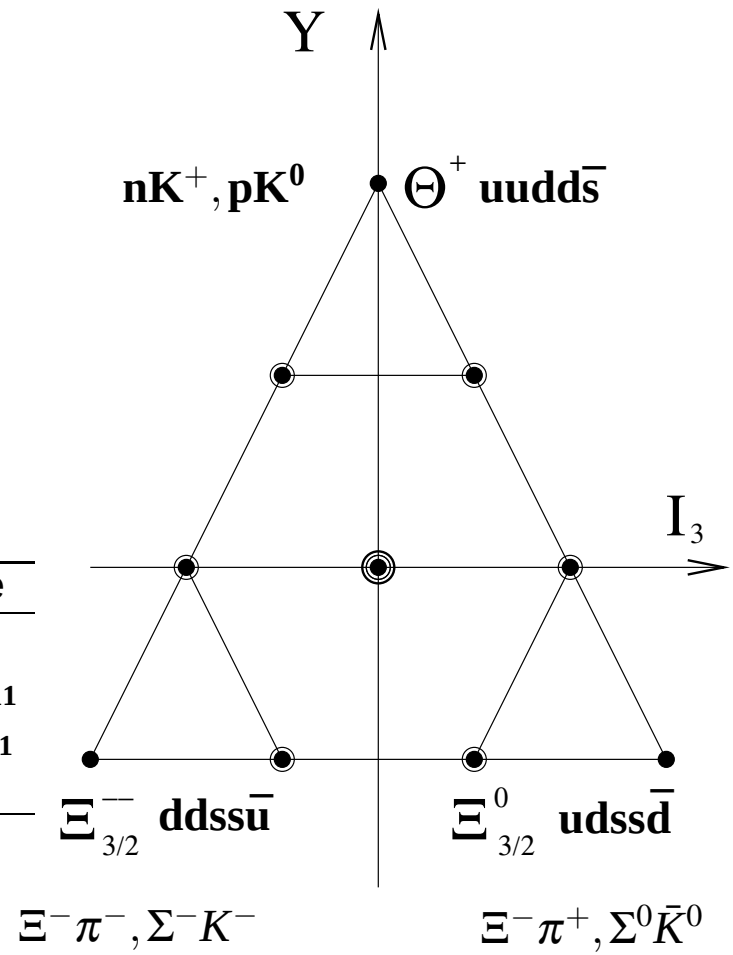
Exotic Baryons

Motivation

- Searches for states with exotic quantum numbers were made since the introduction of quark model. No convincing evidence was found.
- Recent flurry of reports of experimental evidences for a narrow exotic baryon state decaying to nK^+, pK^0_S at the mass of $\sim 1540\ \mathrm{MeV}/c^2$, interpreted as 5-quark, ($uudd\bar{s}$), Θ^+.
- Remarkable agreement with prediction made in chiral soliton model of baryons by Diakonov, Petrov, Polyakov in 1997. The state is believed to be lightest member of exotic $\mathbf{J^P} = \frac{1}{2}^+\ \mathbf{\bar{10}_f}$.

name	I	Y	Mass[MeV]	Γ[MeV]	candidate
Θ^+	0	2	1530	15	—
$N_{\bar{10}}$	1/2	1	1710 (input)	40	N(1710)$\mathbf{P_{11}}$
$\Sigma_{\bar{10}}$	1	0	1890	70	$\Sigma(1880)\mathbf{P_{11}}$
$\Xi_{3/2}$	3/2	-1	2070	>140	$\Xi(2030)$

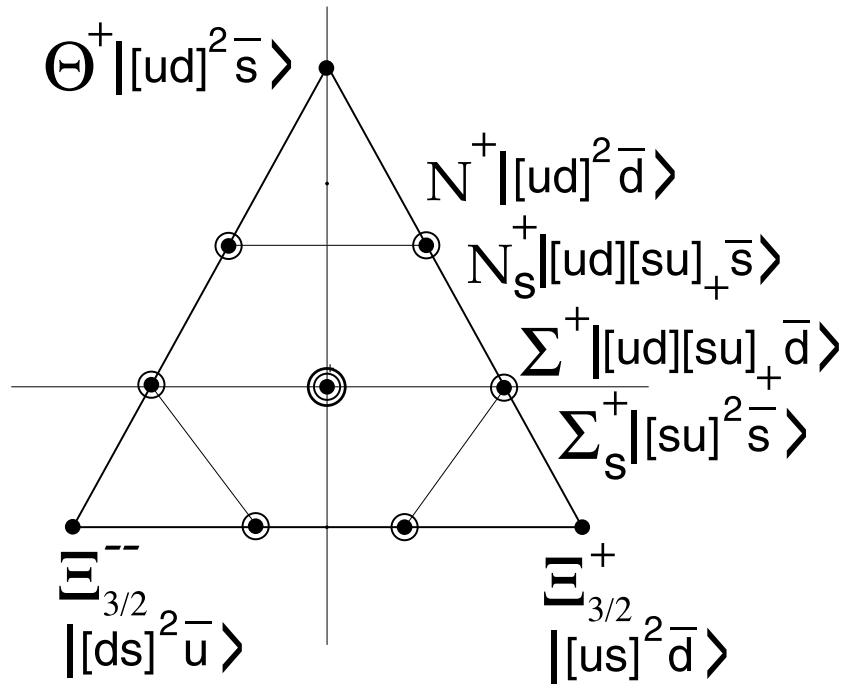
- $\mathbf{8_f} \oplus \mathbf{\bar{10}_f}$ of exotic baryons



Motivation

- In Correlated Quark approach:
  $[\mathrm{ud}]^2\bar{\mathrm{s}} : \underbrace{\bar{3}_\mathrm{f} \otimes \bar{3}_\mathrm{f}}_{\bar{6}_\mathrm{f}} \otimes \bar{3}_\mathrm{f} = 8_\mathrm{f} \oplus \bar{10}_\mathrm{f}$ (Jaffe/Wilczek)

  or
  $[\mathrm{ud}](\mathrm{ud}\bar{\mathrm{s}})$ (Karliner & Lipkin)
- Jaffe & Wilczek compute spectrum of $\overline{10}$ baryons using di-quark approach, predict $\Xi^{--}_{3/2}, \Xi^{0}_{3/2}$ with the mass 1750 and Θ_c Θ_b below strong decay thresholds.
- NA49 experiment observed $\Xi^{--}_{3/2}, \Xi^{0}_{3/2}$, $\mathrm{M} \sim 1860\ \mathrm{MeV/c^2}$, decaying to $\Xi^-\pi^-, \Xi^-\pi^+$
- H1 Experiment reported anti-charmed analogue ($uudd\bar{c}$) of the Θ^+ state decaying to $\mathrm{D}^{*+}\bar{\mathrm{p}}$. $\mathrm{M}(\Theta^0_c) = (3{,}099 \pm 3 \pm 5)\ \mathrm{MeV/c^2}$



(from hep-ph/0307341 (JW))

All results are of relatively low statistics with between 20 and 100 events in peaks, signal to background ratios ranging from 1:1 to 1:3, statistical significance 3-5 σ. Verification on high statistics samples is warranted => PQ task force at CDF.

PQ searches at CDF

Search strategy at CDF

CDF advantages

- high statistics samples
- excellent tracking:
  - good 3D vertexing reduces background
  - excellent mass resolution
  - ability to track long lived hyperons (Ξ^-, Ω^-) in SVX
- good PID capabilities based on ToF and dE/dx to identify protons, kaons.
- It may be difficult to connect results, especially for light PQ, w/ low energy experiments
- search for the following states:

Notation	Quark content	Decay channel	Reference Channel(s)
Θ^+	$\bar{s}uudd$	pK^0_S	$\Lambda(1520) \to pK^-$, $K^{*+} \to K^0_S\pi^+$
Φ^{--}	$\bar{u}ddss$	$\Xi^-\pi^-$	
Φ^0	$\bar{d}udss$	$\Xi^-\pi^+$	$\Xi^0(1530) \to \Xi^-\pi^+$
Θ^0_c	$\bar{c}dudu$	$D^{*-}p$	$D^{**} \to D^{*+}\pi^-$
Θ^0_c	$\bar{c}dudu$	D^-p	$D^{**} \to D^+\pi^-$
Θ^+_c	$\bar{c}uudu$	$\bar{D}^0p$	$D^{**} \to D^0\pi^+$

- calibrate/optimize cuts on reference channels, apply same cuts to PQ candidates, add proton PID cuts, obtain PID cut efficiencies from clean samples of protons (Λ)

Datasets

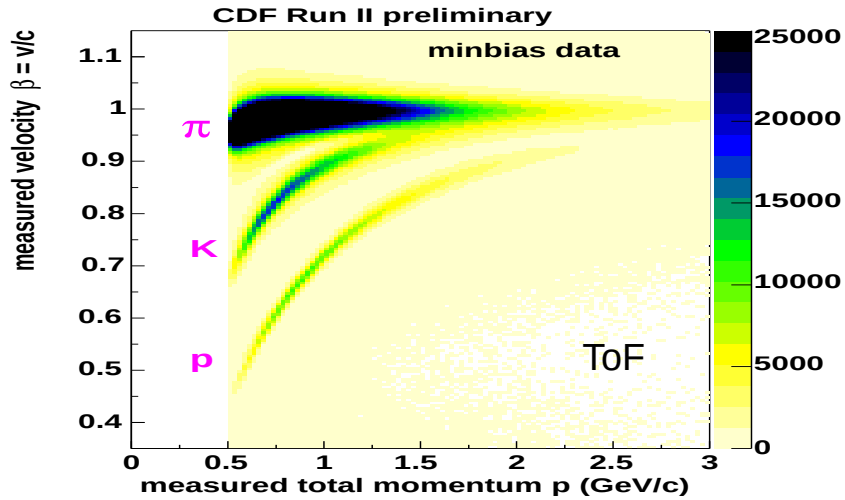
- hadronic trigger data
  - events with at least 2 displaced tracks
  - hard scattering events
  - sample enriched with decay products of charmed and bottom hadrons
- Jet20 trigger
  - each event has at least one jet with $\mathbf{E_T > 20\ GeV}$, generic QCD
  - prescaled trigger – lower statistics
- Min-bias and zero-bias trigger
  - soft inelastic scattering

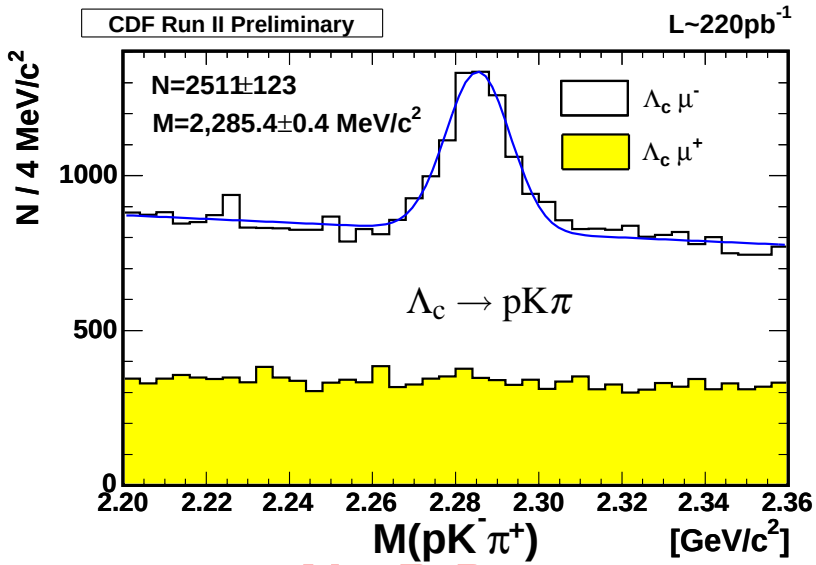
Particle identification

- combine ToF and dE/dx information for a given track into common χ_i^2 :
  $\chi_i^2 = \chi_i^2(\mathrm{ToF}) + \chi_i^2(\mathrm{dE/dx})(\mathrm{COT}),$
  where $\mathrm{i} = \mathrm{p}, \mathrm{K}, \pi, \mathrm{e}, \mu$
- form normalized likelihood ratio:

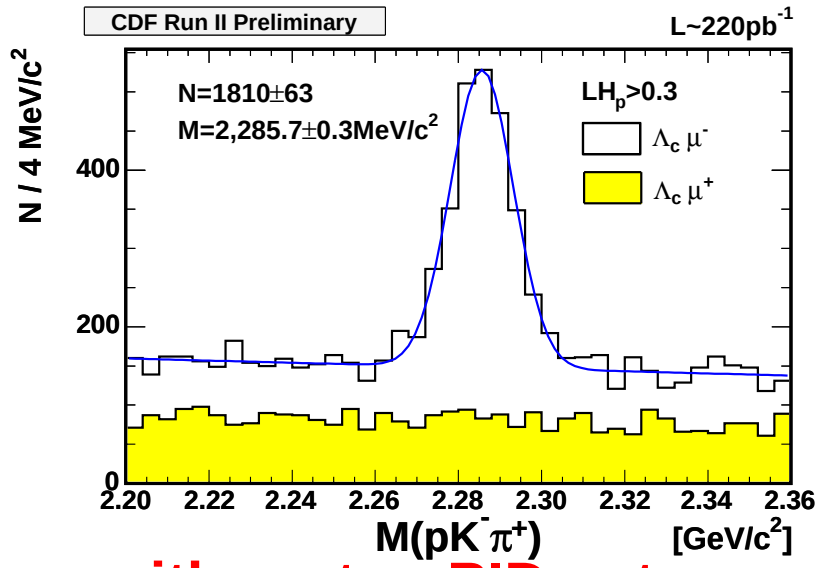
$$\mathrm{LH_i} = \frac{\mathrm{lh(i)}}{\mathrm{lh(p)} + \mathrm{lh(K)} + \mathrm{lh(e)} + \mathrm{lh}(\mu) + \mathrm{lh}(\pi)}$$

where $\mathrm{lh(i)} = \exp(-\chi_i^2/2),$





No PID cut

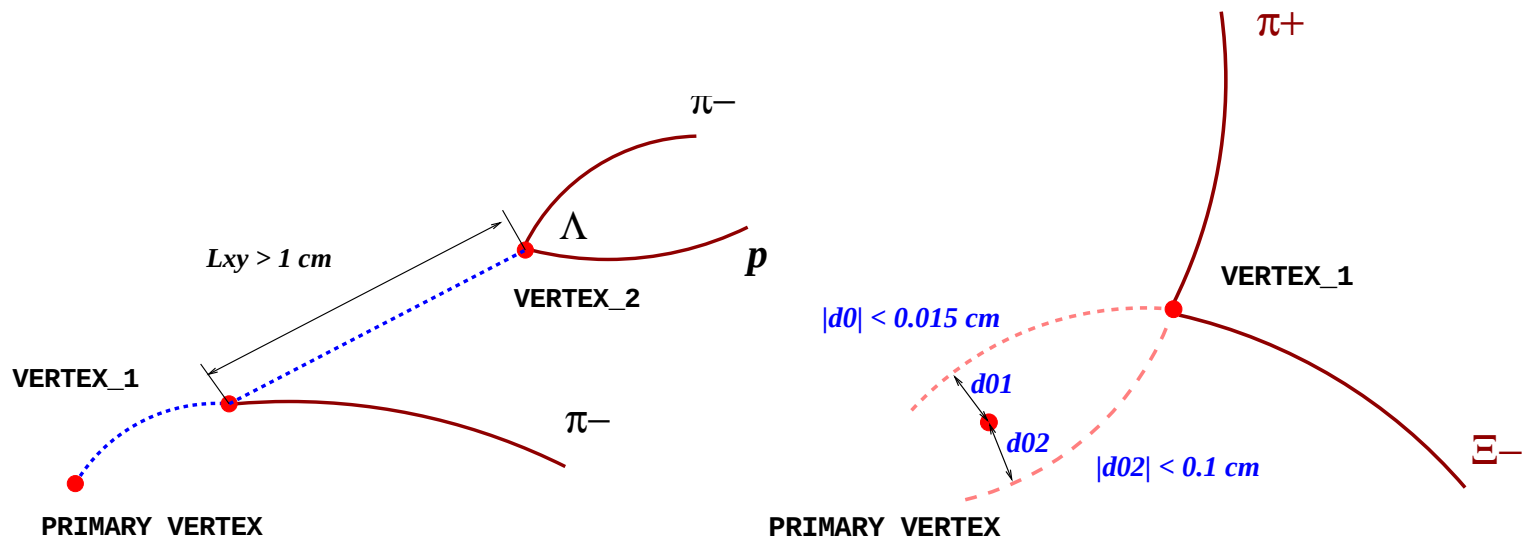


with proton PID cut

Exotic Cascade

$$\Phi^{0,--} \longrightarrow \Xi^- + \pi^{+,-}$$

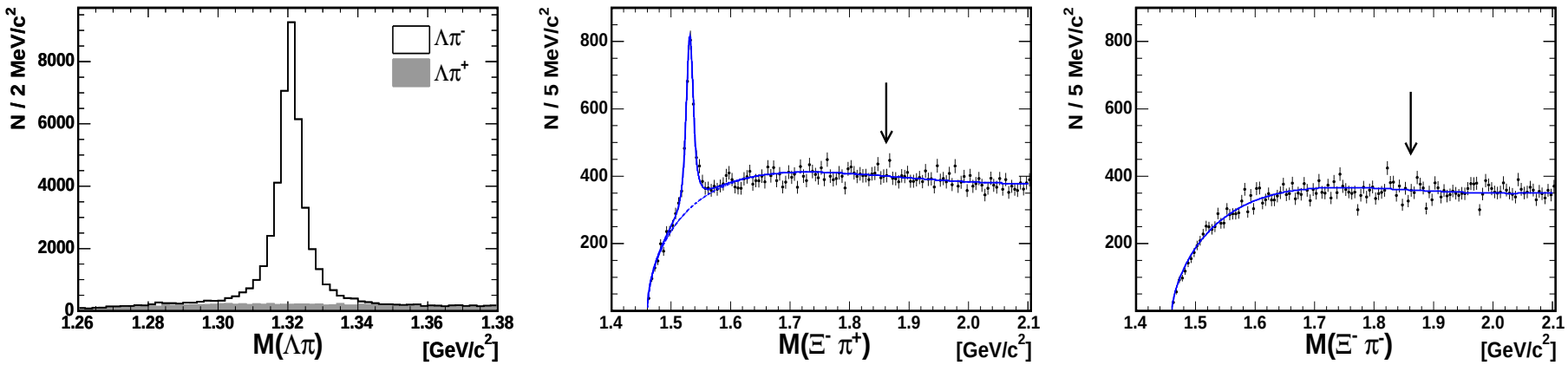
$$\hookrightarrow \Lambda\pi^-$$



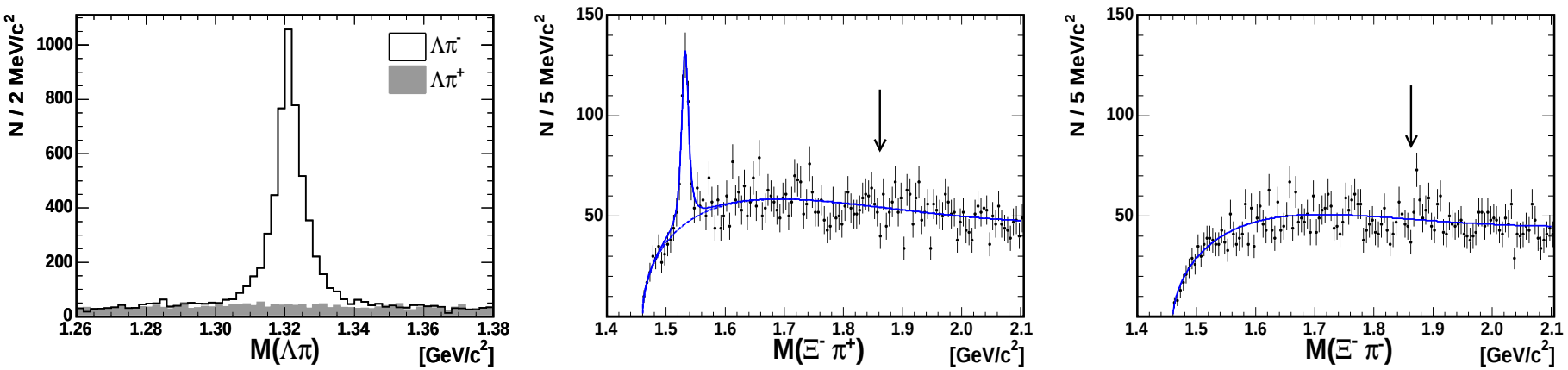
- find Ξ track in SVX.
- attach pion track to Ξ, fit the vertex, apply impact parameter cuts

CDF $\Xi\pi^{-,+}$ spectra

- SVT data, $\int \mathscr{L} dt = 220 pb^{-1}$



- Jet20 data, $\int \mathscr{L} dt = 0.36 pb^{-1}$



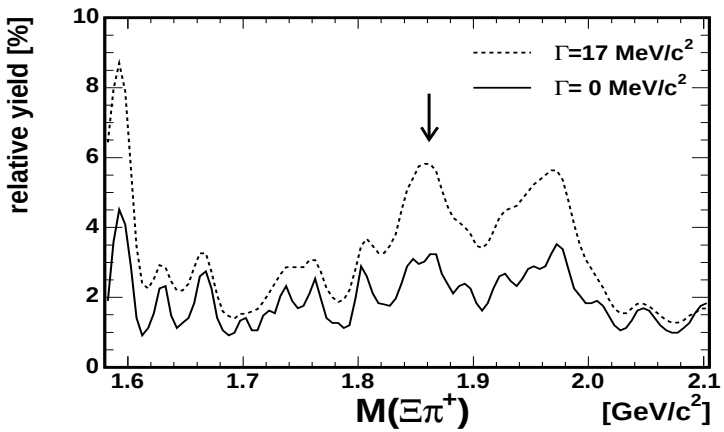
Results

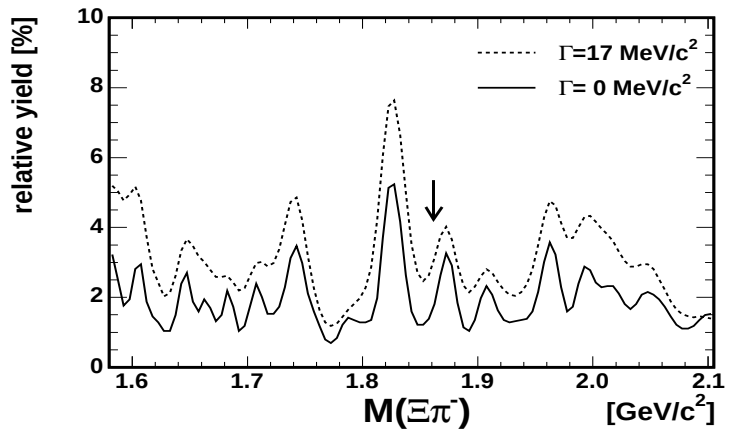
	SVT trigger($\Gamma = 17$ MeV/c^2)	Jet20 trigger($\Gamma = 17$ MeV/c^2)
N(Ξ)	35722 ± 326	4870 ± 122
N($\Xi(1530)$)	1923 ± 80	313 ± 28
$\frac{\sigma_{\Phi^{--}}(p_T>2\ \mathrm{GeV/c})\cdot\mathscr{B}(\Phi^{--}\to\Xi\pi^-)}{\sigma_{\Xi(1530)}(p_T>2\ \mathrm{GeV/c})}[\%]$	$< 1.7\ (3.1)$	$< 3.2\ (10.1)$
$\frac{\sigma_{\Phi^0}(p_T>2\ \mathrm{GeV/c})\cdot\mathscr{B}(\Phi^0\to\Xi\pi^+)}{\sigma_{\Xi(1530)}(p_T>2\ \mathrm{GeV/c})}[\%]$	$< 3.2\ (5.8)$	$< 3.0\ (9.2)$

Event yields of Ξ^-, $\Xi(1530)$ and upper limits on relative cross sections of $\Phi^{--,0}$ pentaquarks at the mass reported by NA49 and $\Xi(1530)$ at 90% Confidence Levels. The numbers in parentheses represent limits on relative cross section assuming natural width $\Gamma = 17$ MeV/c^2 for the pentaquarks.

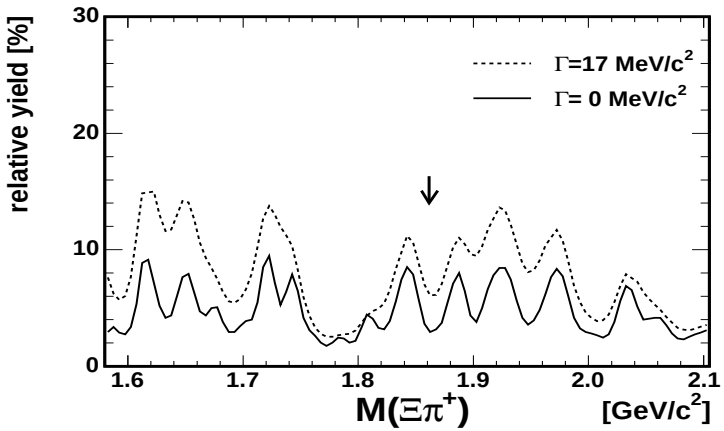
CDF $\Xi\pi^{-,+}$ spectra

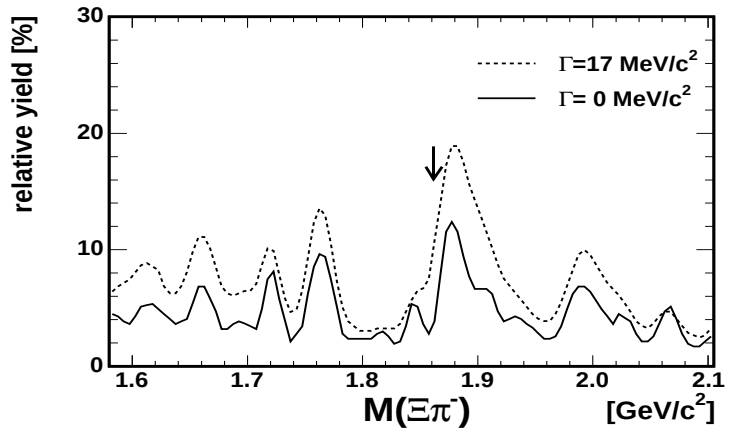
- SVT data:



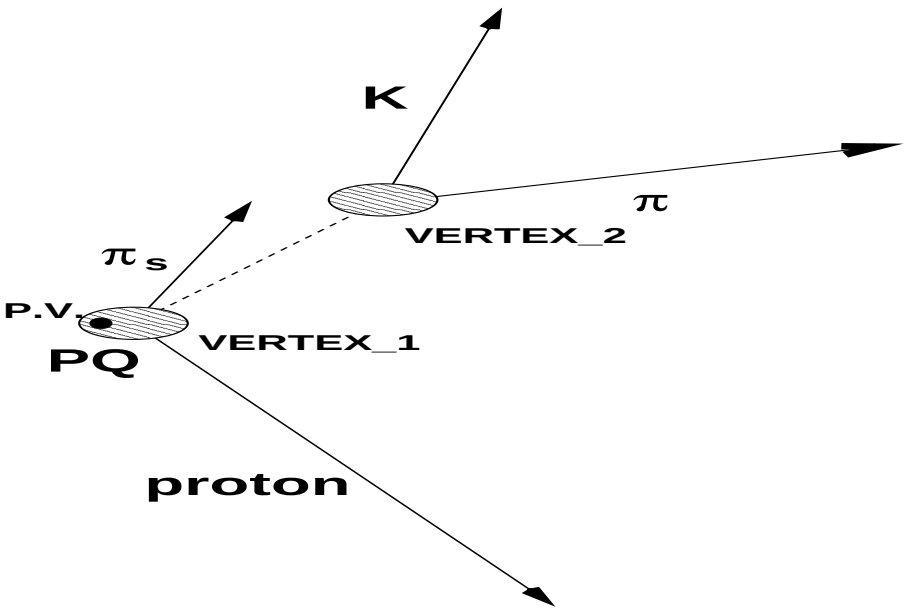


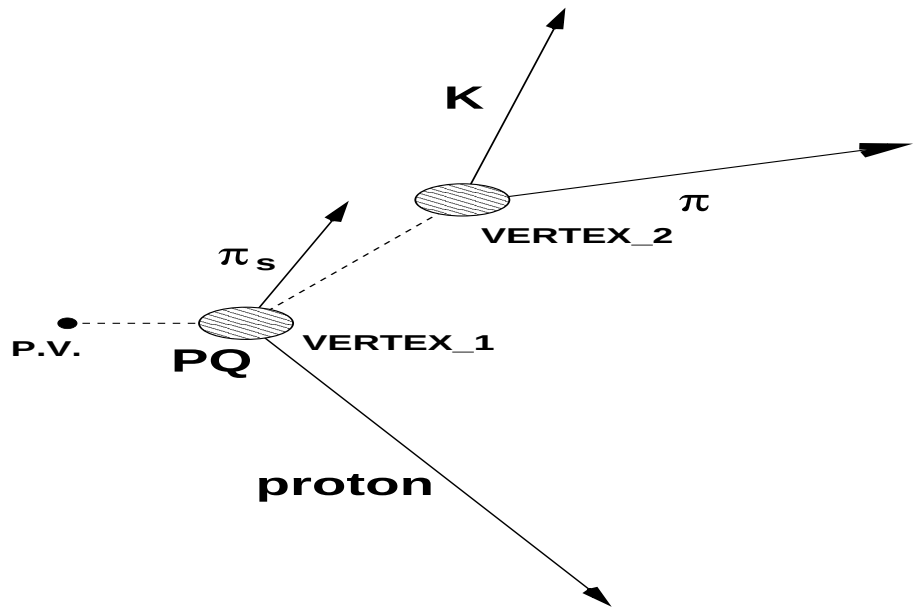
- Jet20 data:





Charmed PQ





Θ_c decays strongly, hence has no lifetime. It can be produced in fragmentation of direct c quark or in decays of $b-$ hadrons.

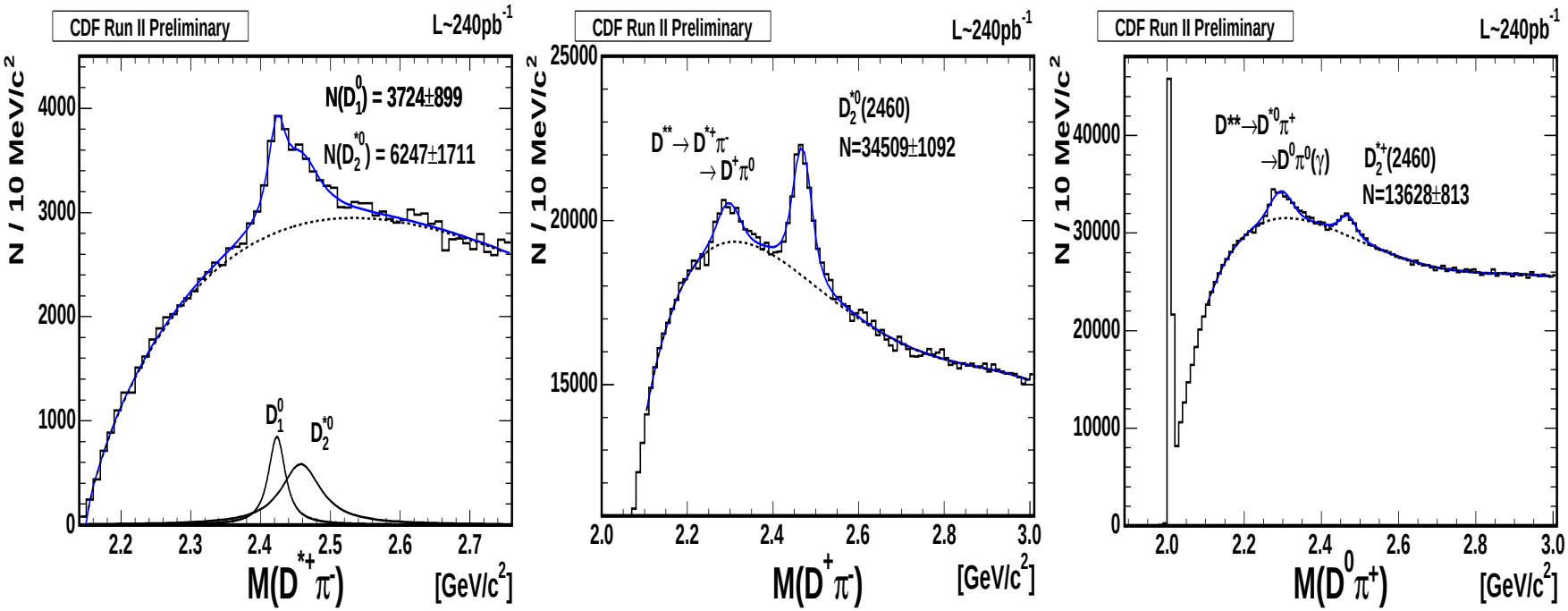
- prompt
- $|L_{xy}(PQ)| < 0.04$ cm
- $|L_{xy}(PQ)/\sigma_{L_{xy}}(PQ)| < 3$

- from B-decays or secondary production
- $L_{xy}(PQ) > 0.04$ cm
- $|L_{xy}(PQ)/\sigma_{L_{xy}}(PQ)| > 3$

CDF is especially sensitive to charmed/bottom PQ as displaced tracks from D-mesons come in on hadronic trigger

Reference Signals

Reference channels

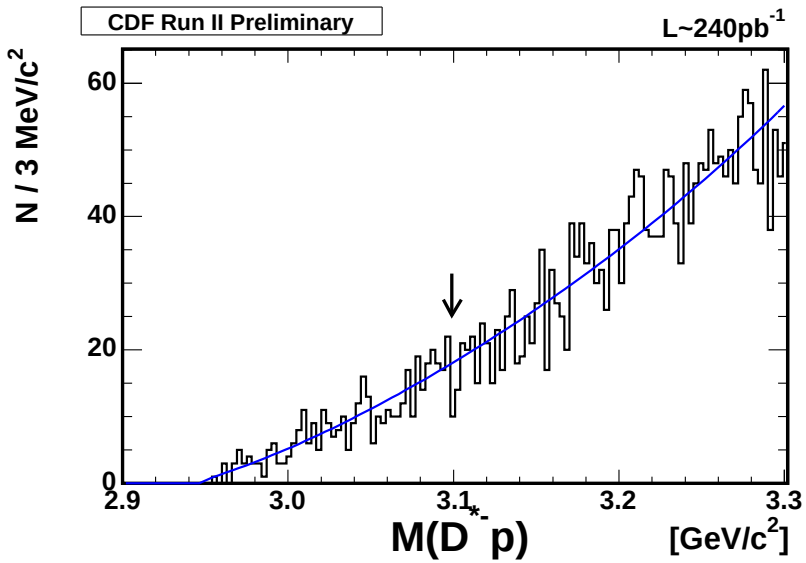


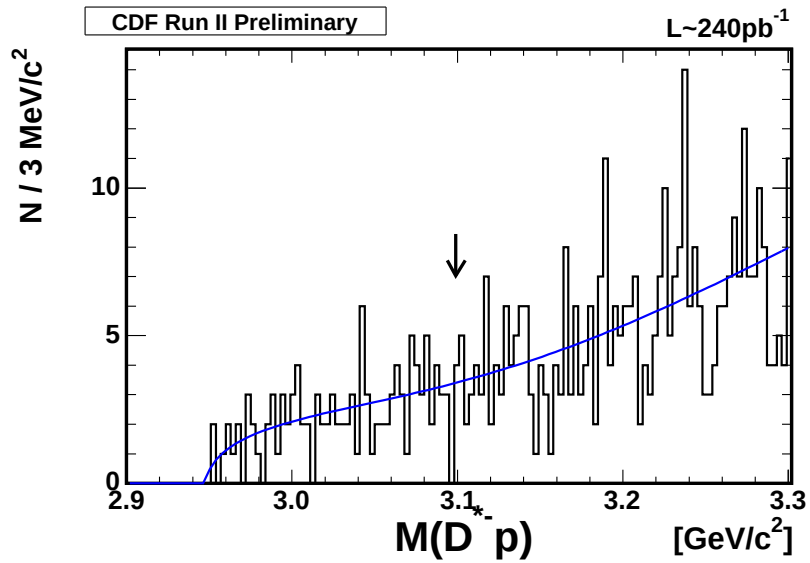
$D^{**} \to D^{*+}\pi^-$
$\hookrightarrow D^0\pi^+$
$\hookrightarrow K^-\pi^+$

$D^{**} \to D^+\pi^-$
$\hookrightarrow K^-\pi^+\pi^+$

$D^{**} \to D^0\pi^+$
$\hookrightarrow K^-\pi^+$

$D^{*-}p$ spectrum w/ proton PID



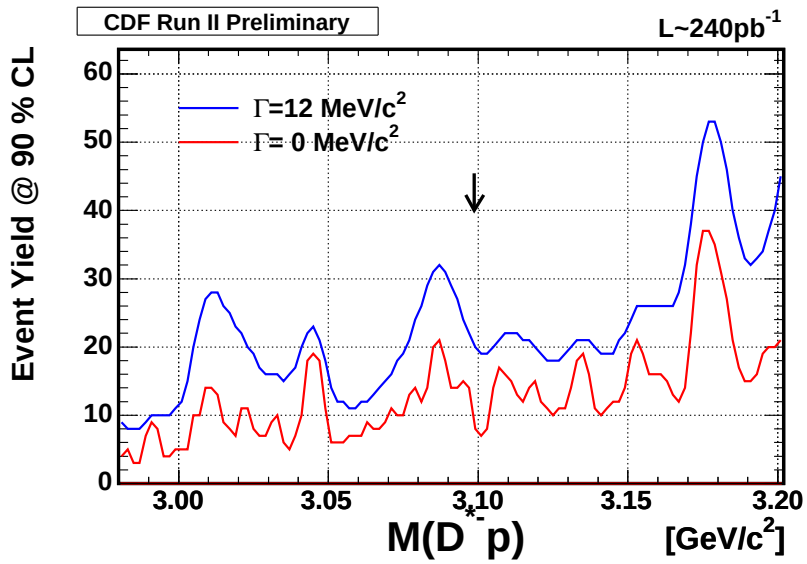


- prompt production
- $\Gamma = 0\ \mathrm{MeV/c^2}$: 21@90%CL
- $\Gamma = 12\ \mathrm{MeV/c^2}$: 32@90%CL

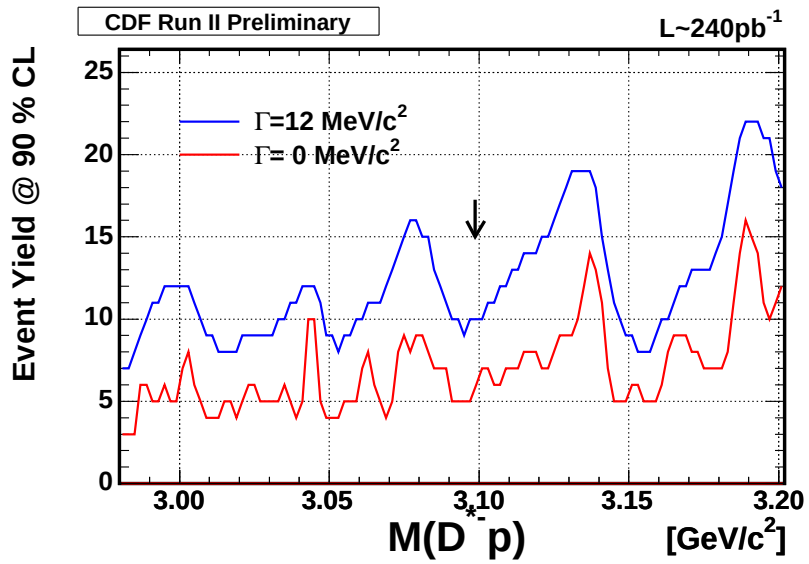
- secondary production
- $\Gamma = 0\ \mathrm{MeV/c^2}$: 8@90%CL
- $\Gamma = 12\ \mathrm{MeV/c^2}$: 15@90%CL

Event yield vs mass

- unbinned likelihood fits varying mass in wide range => calculate mass dependent limits

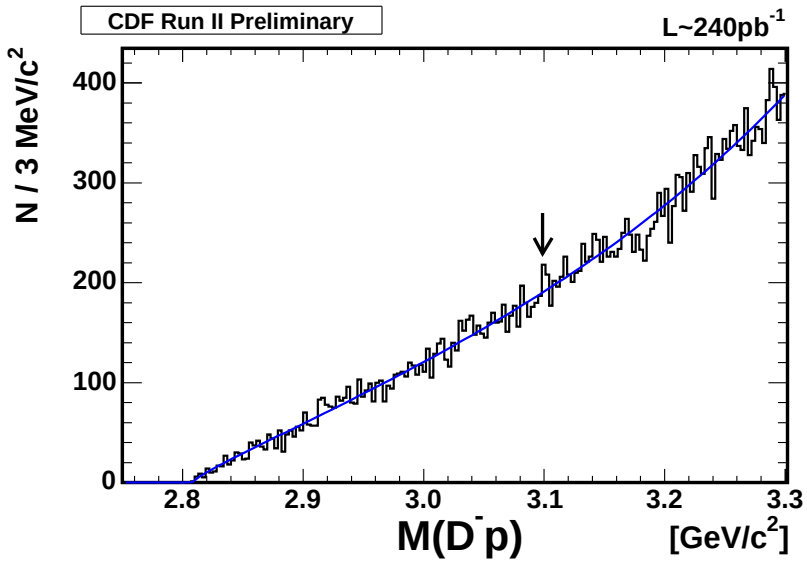


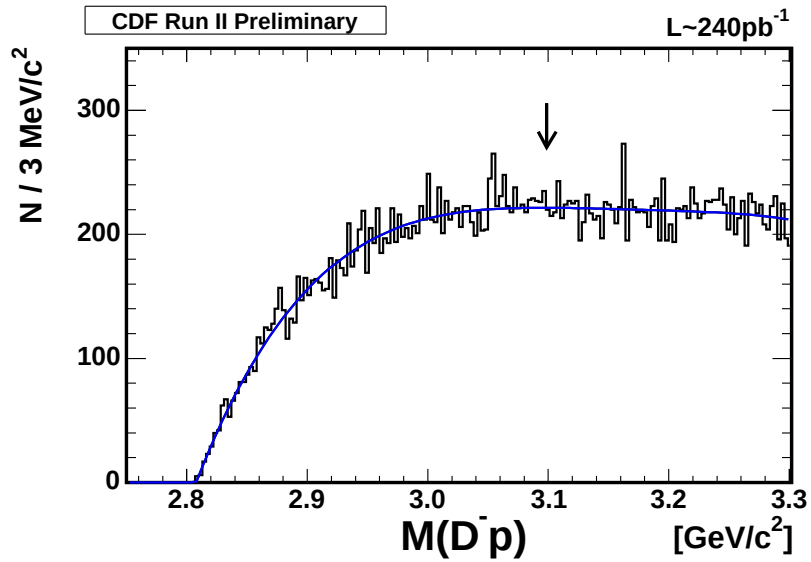
- prompt production



- secondary prouction

D^-p spectrum w/ proton PID



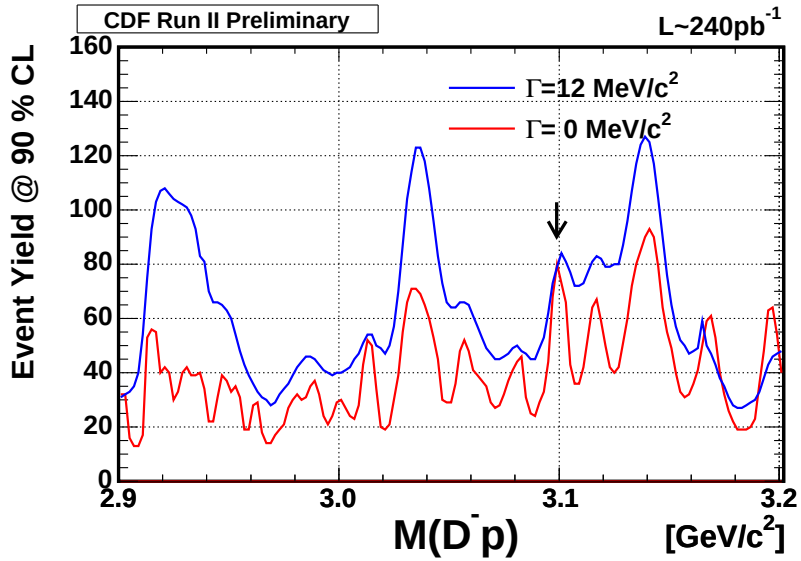


- prompt production
- $\Gamma = 0\ \mathrm{MeV/c^2}$: 80 @90%CL
- $\Gamma = 12\ \mathrm{MeV/c^2}$: 84 @90%CL

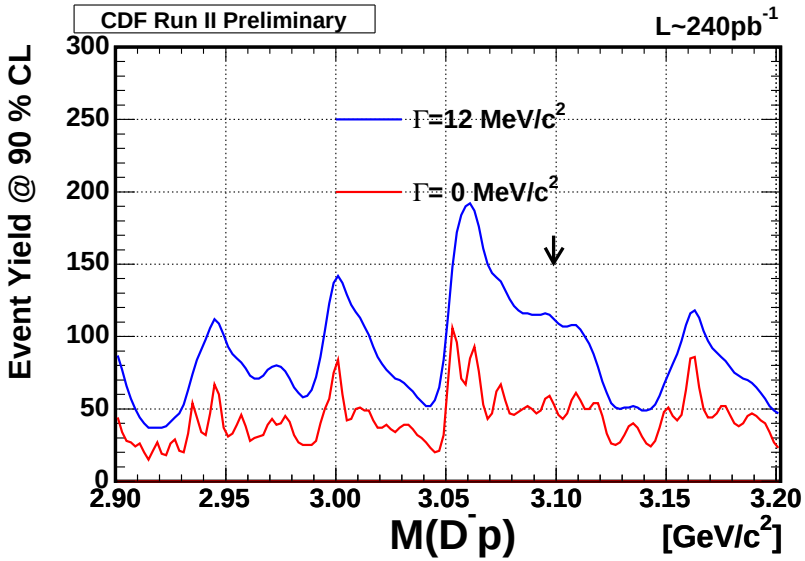
- secondary production
- $\Gamma = 0\ \mathrm{MeV/c^2}$: 61 @90%CL
- $\Gamma = 12\ \mathrm{MeV/c^2}$:
  - 118 @90%CL

UL vs mass

- unbinned likelihood fits varying mass in wide range => calculate mass dependent limits

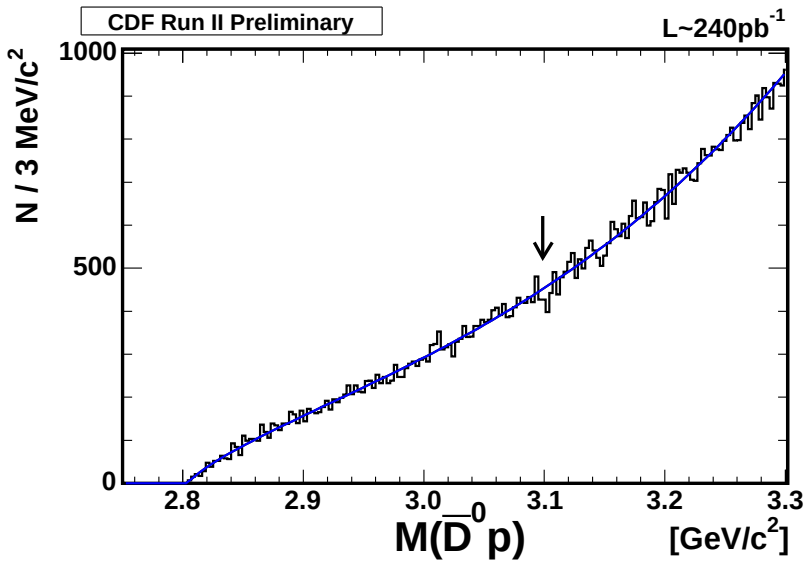


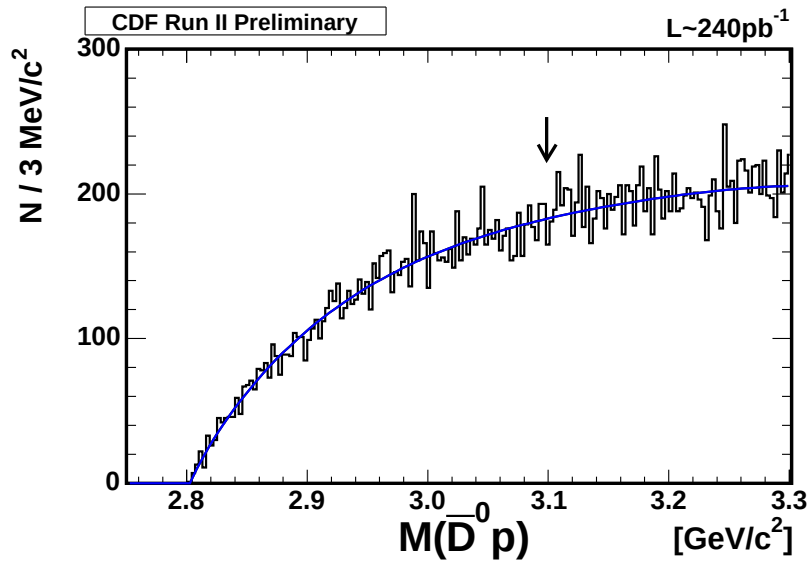
- prompt production



- secondary production

$\bar{D}^0 p$ spectrum w/ proton PID

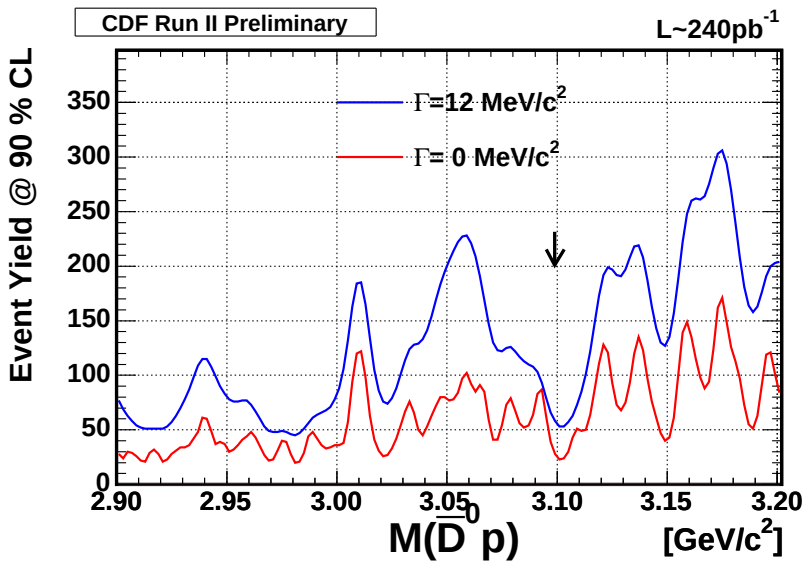




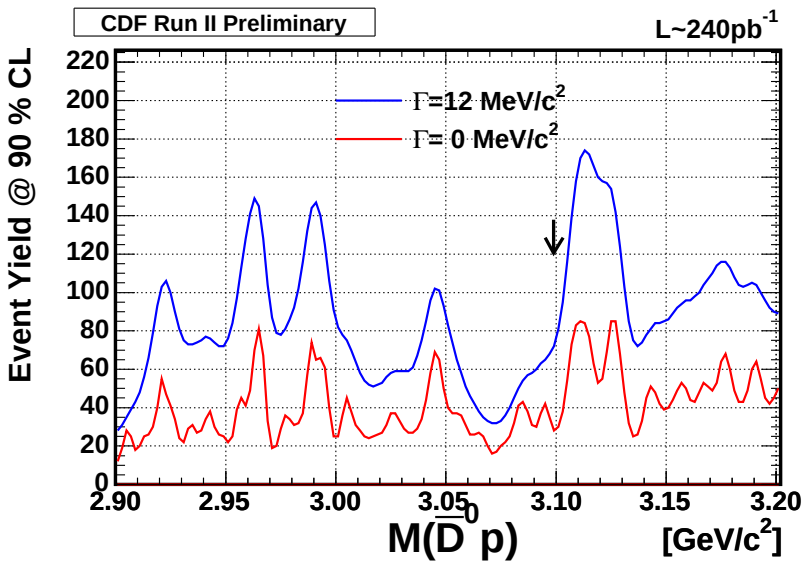
- prompt production
- $\Gamma = 0\ \mathrm{MeV/c^2}$: 87 @90%CL
- $\Gamma = 12\ \mathrm{MeV/c^2}$: 122 @90%CL

- secondary production
- $\Gamma = 0\ \mathrm{MeV/c^2}$: 107 @90%CL
- $\Gamma = 12\ \mathrm{MeV/c^2}$: 214 @90%CL

UL vs mass

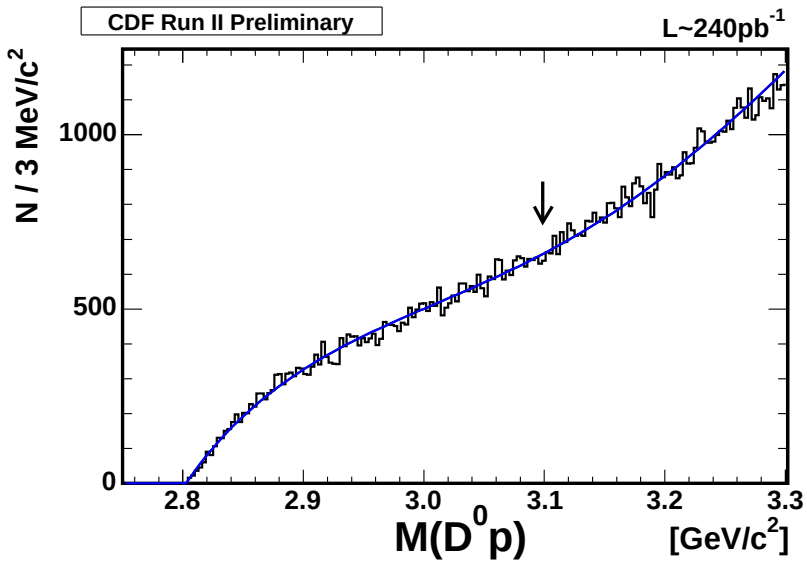


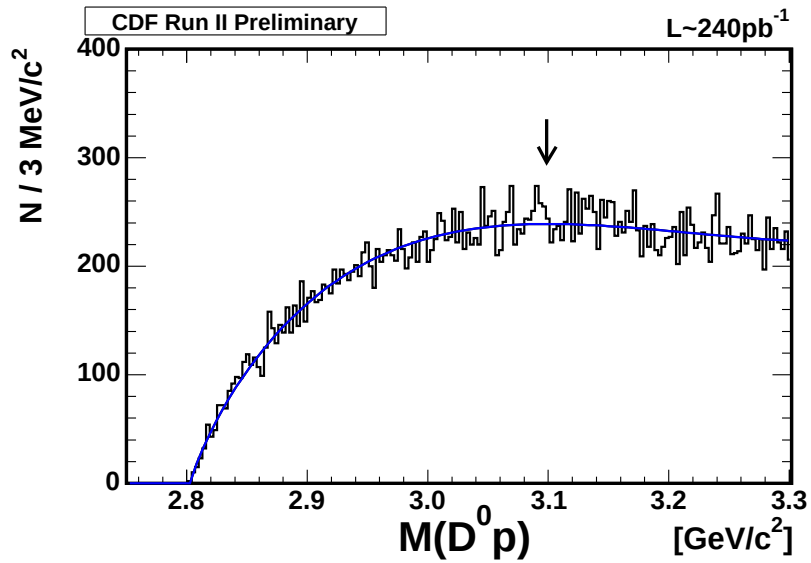
- prompt production



- secondary production

D^0p spectrum w/ proton PID

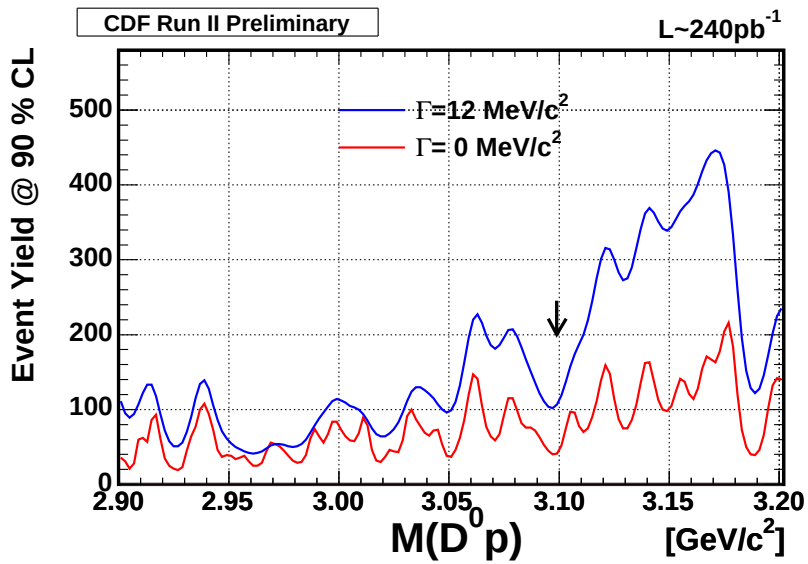




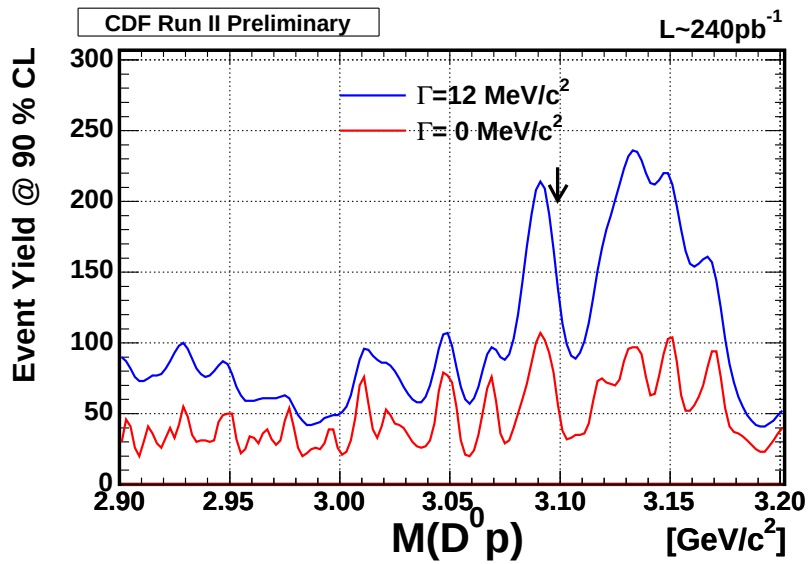
- prompt production
- $\Gamma = 0\ \mathrm{MeV/c^2}$: 97 @90%CL
- $\Gamma = 12\ \mathrm{MeV/c^2}$: 245 @90%CL

- secondary production
- $\Gamma = 0\ \mathrm{MeV/c^2}$: 85 @90%CL
- $\Gamma = 12\ \mathrm{MeV/c^2}$: 174 @90%CL

UL vs mass



- prompt production



- secondary production

Limits on Θ_c yields

- search window $3,099 \pm 18\ \mathrm{MeV}/c^2$
- take worst point from the limit vs mass inside the window

Reference channel		Search channel	
$D_2^{*0} \to D^+\pi^-$	6247 ± 1711	$\Theta_c^0 \to D^{*-}p$	< 21 @ 90% CL
$D_2^{*0} \to D^+\pi^-$	34509 ± 1092	$\Theta_c^0 \to D^-p$	< 89 @ 90% CL
$D_2^{*+} \to D^0\pi^+$	13628 ± 813	$\Theta_c^+ \to \bar{D}^0p$	< 87 @ 90% CL
		$\Theta_c^+ \to D^0p$	< 97 @ 90% CL

- conversion of event yields into $\sigma \times B$ limits is on the way.

Summary of non-sightings

Experiment	Reaction	Θ^+	$\Xi_{3/2}$	Θ_c	
ALEPH	$Z \to PX$	×	×	×	
DELPHI	$Z \to PX$	×	–	–	e^+e^- at Z pole
L3	$\gamma\gamma \to PX$	×	–	–	
BaBar	$ee \to \Upsilon(4S)$	×	×	–	
Belle	$KN \to PX, B \to PX$	×	×	–	e^+e^- at $\Upsilon(4S)$ or $c\bar{c}$ threshold
BES	$ee \to J/\psi(\psi(2S)) \to P\bar{P}$	×	–	×	
CDF	$p\bar{p} \to PX$	×	×	×	collider experiments
ZEUS	$ep \to PX$	✔	×	×	
COMPASS	$\mu(^6LiD) \to PX$	×	×	–	
E690	$pp \to PX$	×	×	–	
FOCUS	$\gamma p \to PX$	×	×	×	
HERA-B	$pp \to PX$	×	×	–	
HyperCP	$Kp \to PX$	×	–	–	
LASS	$K^+p \to K^+n\pi^+$	×	–	–	fixed target experiments
SELEX	$\pi, p, \Sigma \to PC(N)$	×	–	–	
SPHINX	$pC(N) \to PC(N)$	×	–	–	
WA89	$\Sigma^- - N \to PX$	×	–	–	
PHENIX	$AuAu \to PX$	×	–	–	heavy ion collider
score		13/16	1/9	1/6	

Discussion

- Θ^+:
  - low energy Photoproduction experiments (LEPS, CLAS, SAPHIR):
    - production of conventional mesons ϕ, a_2, f_2, ρ_3 decaying to K^+K^- could lead to broad structure in nK^+ spectrum at about 1540. Given small statistics and angular cuts a sharp peak may be generated by this contribution (see Dzierba et al. Phys Rev D69)
  - $KXe \to pK^0_S Xe$ (DIANA,ITEP)
    - charge exchange reaction $KXe \to pK^0_S$ yields peak at fixed mass $\sim$ 1540 if K momentum is fixed. The case in DIANA experiment ($400 MeV/c < p_{K^+} < 500 MeV/c$.
  - analysis of NK scattering data in the 1540 MeV region (Arnd et. al., Phys. Rev. C68) suggest only $\Gamma_{\Theta^+} < 1$ MeV.
    - HERMES and ZEUS contradict this by measuring $\Gamma_{\Theta+}$.
    - contradicts model prediction of 15 MeV
  - Non seeing of Θ^+ in high energy experiments typically leads to production mechanism argument. The reasoning – Θ^+ has a unique production mechanism characterized by low momentum transfers.
    - Observation of Θ^+ by ZEUS in high energy, central η DIS events plays against this argument.
- al low energy it would be nice to study exclusive reaction with pK^0_S which would rule some of the uncertainties related to missing neutron.

Conclusion

- Heavy Baryons
  - First Measurement: $\frac{Br(\Lambda_b \to \Lambda_c^+ \mu \bar{\nu}_\mu)}{Br(\Lambda_b \to \Lambda_c^+ \pi^-)}$, where $\Lambda_c^+ \to pK^-\pi^+$.
  - First observation of $\Lambda_b \to \Lambda_c^* \mu \bar{\nu}_\mu$
  - First observation of $\Lambda_b \to \Sigma^{++,0}\pi^{-,+}\mu\bar{\nu}_\mu$
  - Hyperon tracking allows to reconstruct $\Xi_c^{0,+}$ for the first time in $p\bar{p}$ collisions
  - CDF is close to discovering $\Xi_b \to \Xi J/\psi$
- Φ^{--} is not confirmed by any of the experiment with large Ξ samples.
- The Θ_c, observed by H1 in DIS, was the most promising, as it clearly indicated at Θ_c production in c-quark fragmentation. The result is not confirmed by other collider experiments including Zeus running in the same conditions.
- Experimental evidence for PQs is very weak
- On positive note. There are interesting diquark based models describing baryon properties.