Searches for Pentaquarks at CDF

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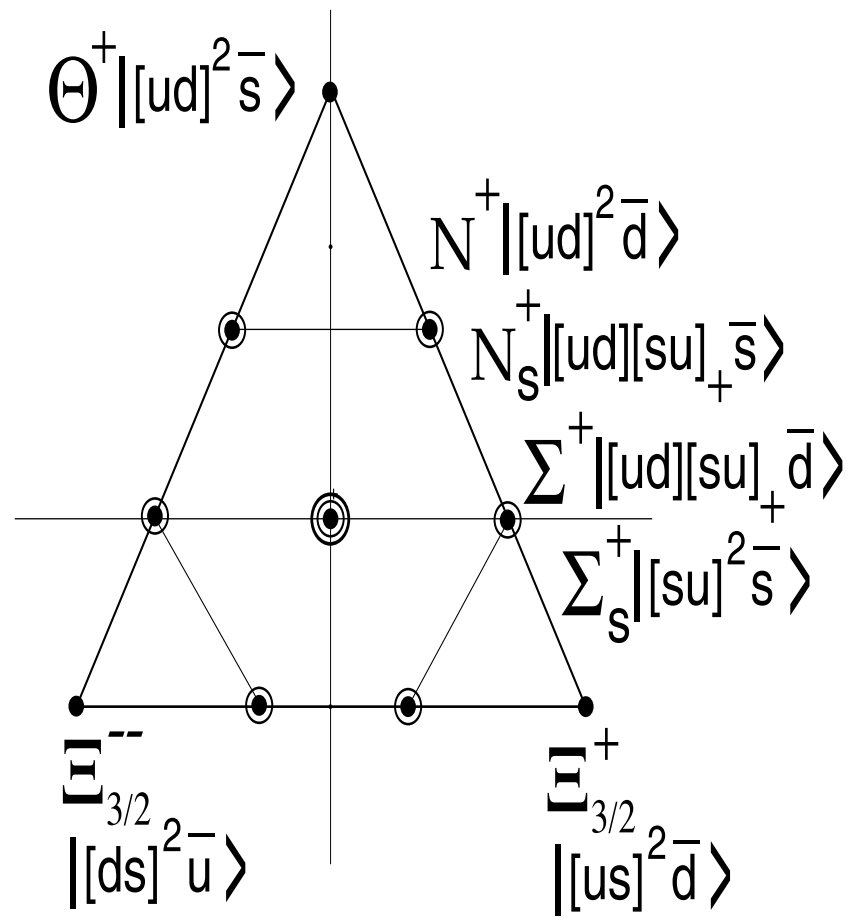
Motivation

- 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**, ($uudd\bar{s}$), consistent with Θ^+ predicted in chiral soliton model by by Diakonov, Petrov, Polyakov revived interest in baryon spectroscopy.
- In CQ picture:
  $[ud]^2\bar{s}$: $\underbrace{\bar{3}_f \otimes \bar{3}_f}_{\bar{6}_f} \otimes \bar{3}_f = 8_f \oplus \bar{10}_f$ (Jaffe/Wilczek)
  or $[ud](ud\bar{s})$ (Karliner/Lipkin)
- Followed by observation of $\Xi^{--}_{3/2}, \Xi^0_{3/2}$, $M \sim 1860\ \mathrm{MeV/c^2}$, decaying to $\Xi^-\pi^-, \Xi^-\pi^+$, by NA49 Experiment. Members of $S = -2$ ($qqss\bar{q}, q = u, d$) quadruplet of the SU(3) $\bar{10}$ of pentaquarks.
  need independent confirmation
- H1 Experiment reported anti-charmed analogue ($uudd\bar{c}$) of the Θ^+ state decaying to $D^{*+}\bar{p}$.
  $M(\Theta^0_c) = (3,099 \pm 3 \pm 5)\ \mathrm{MeV/c^2}$
  need independent confirmation

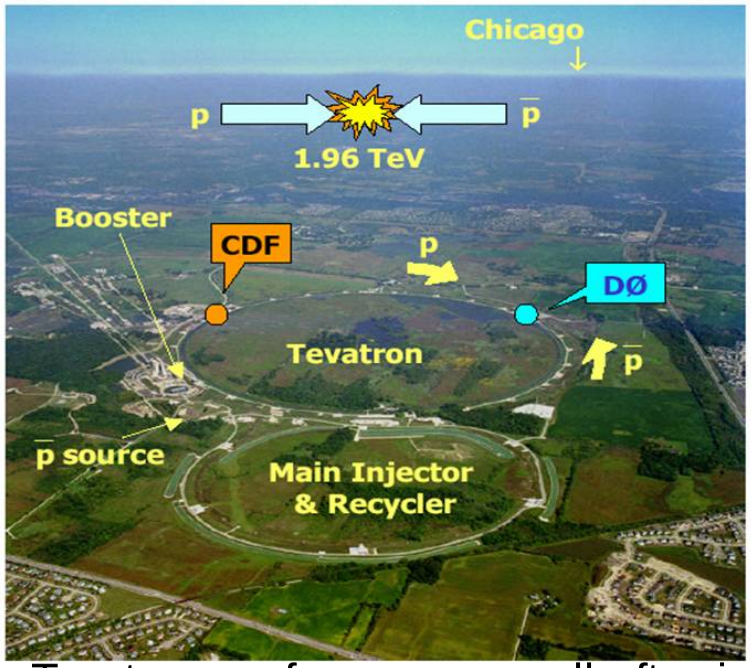


(from hep-ph/0307341)

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.

Tevatron at Fermilab

World's largest collider



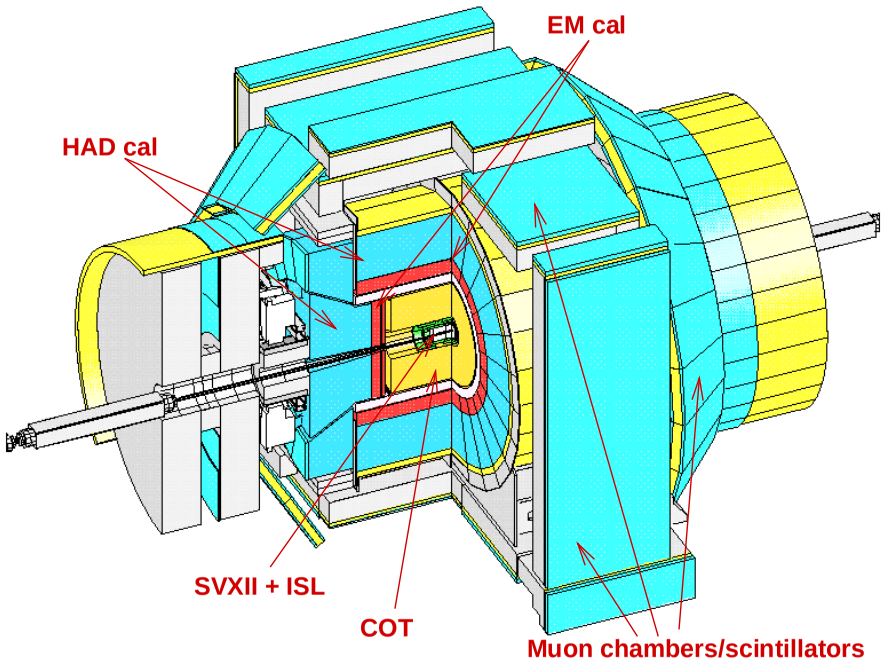
- Tevatron performs very well after initially slow start
- $\int \mathscr{L} dt \sim 700 pb^{-1}$ ($\sim 550 pb^{-1}$ on tape)
- CDF & D0 efficiency $\sim 80\%$
- expect $2\ fb^{-1}$ for Run IIa
- $4-8\ fb^{-1}$ by 2009

- 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
  - $\mathscr{L}_{inst} = 10.2 \times 10^{31} cm^{-2} s^{-1}$(record) (goal $8.1 \times 10^{31} cm^{-2} s^{-1}$)
  - high beam-beam crossing (inter-bunch spacing 396 ns), low pileup

Run II CDF Detector

Upgraded CDF Detector

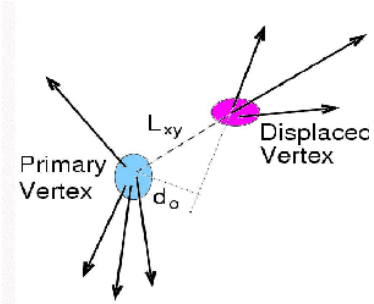
- **tracking**
  - L00 + 5 layers of SVX + 2/1 outer layers of ISL ($1.5 < \mathrm{R} < 30\mathrm{cm}$, $|\mathrm{Z}| < 45\mathrm{cm}$). $\mathrm{r}\phi$, rz, stereo strips. 720,000 channels. Si tracking up to $|\eta| < 2$.
  - Central Outer Tracker (COT), 30,240 sense wires, 96 layer drift wire chamber. $\sigma(1/\mathrm{p_T}) \sim 0.1\%/(\mathrm{GeV/c})$, $\sigma(\mathrm{hit}) \sim 150\mu\mathrm{m}$. 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
  - 4000/300/70 Hz
  - COT Tracks @ Level 1
  - Si Tracks @ Level 2
  - Full analysis @ Level 3
  - First hadronic B-trigger

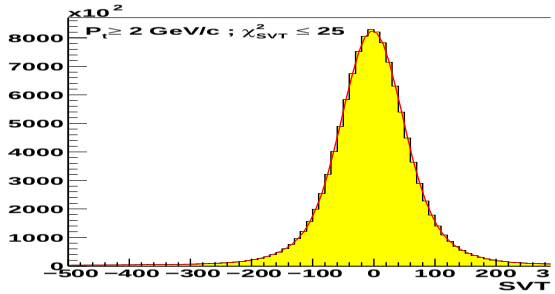


Hadronic Trigger

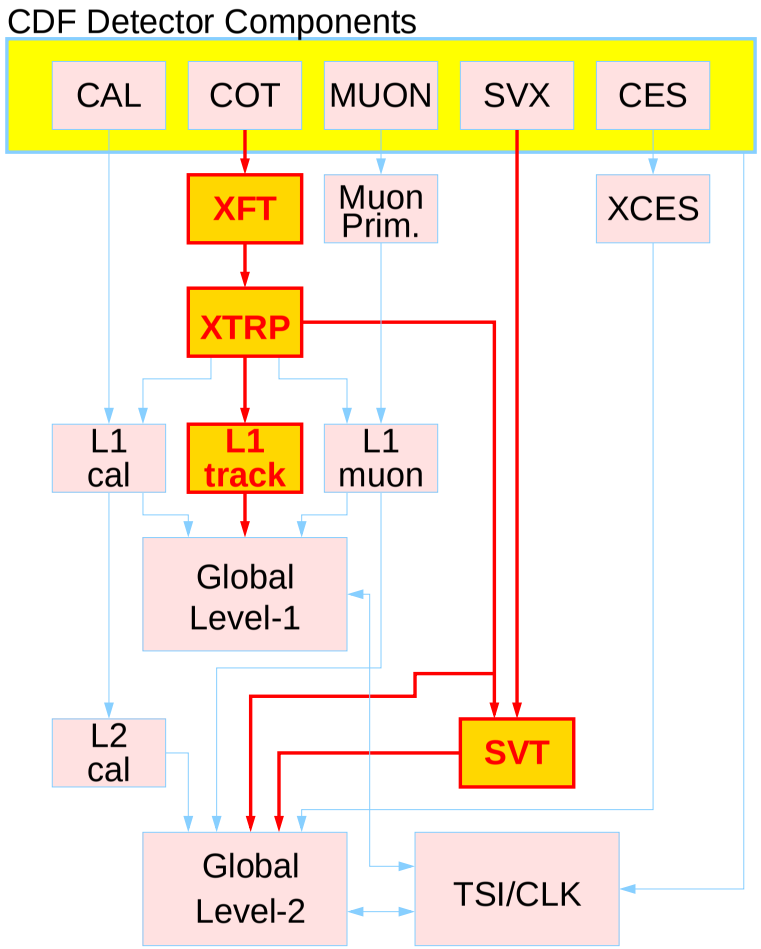
- **New displaced track triggers (two track and ℓ+track):**
  - **Level 1**
    - ✓ **XFT tracking in COT ($r-\phi$)**
    - ✓ **opposite charged track pair with** $p_T > 2\ \mathrm{GeV/c}$ **each**
    - ✓ $\Sigma p_T > 5.5\ \mathrm{GeV/c}$
    - ✓ $\Delta\phi < 135^\circ$
  - **Level 2**
    - ✓ **XFT 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 different cuts.





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



Search strategy at CDF

- 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	$\bar{c}uudu$	$\bar{D}^0p$	$D^{**} \to D^0\pi^+$
R^+_s	$\bar{b}uuds$	$J/\psi p$	$B^+ \to J/\psi K^+$

- 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)

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.

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 events has at least one jet with 20 GeV/c, generic QCD
  - prescaled trigger – lower statistics
- Min-bias and zero-bias trigger
  - soft inelastic scattering
- Dimuon data (J/ψ)

CDF reconstructs tracks in central rapidity region probing PQ produced in quark fragmentation or in b and c-hadron decays

Particle identification

- combine ToF and dE/dx information for a given track into common χ_i^2 :

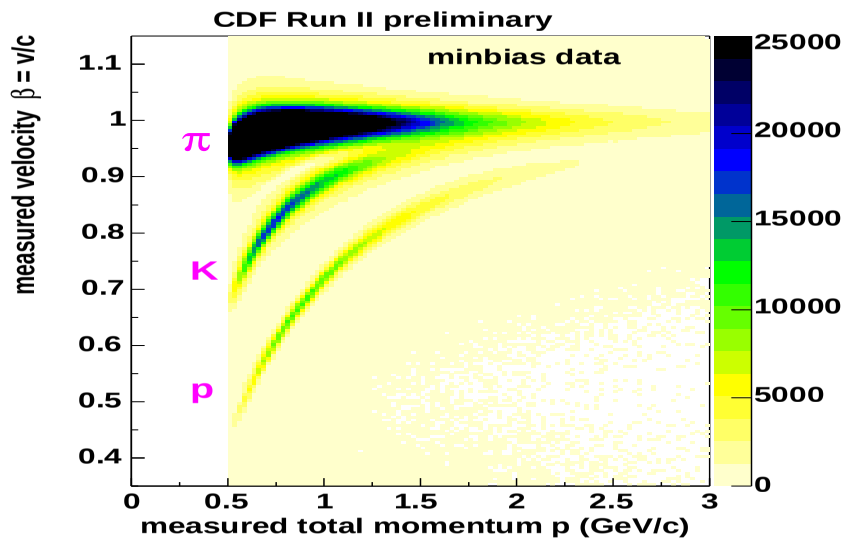
$$\chi_i^2 = \chi_i^2(\mathrm{ToF}) + \chi_i^2(\mathrm{dE/dx})(\mathrm{COT}),$$

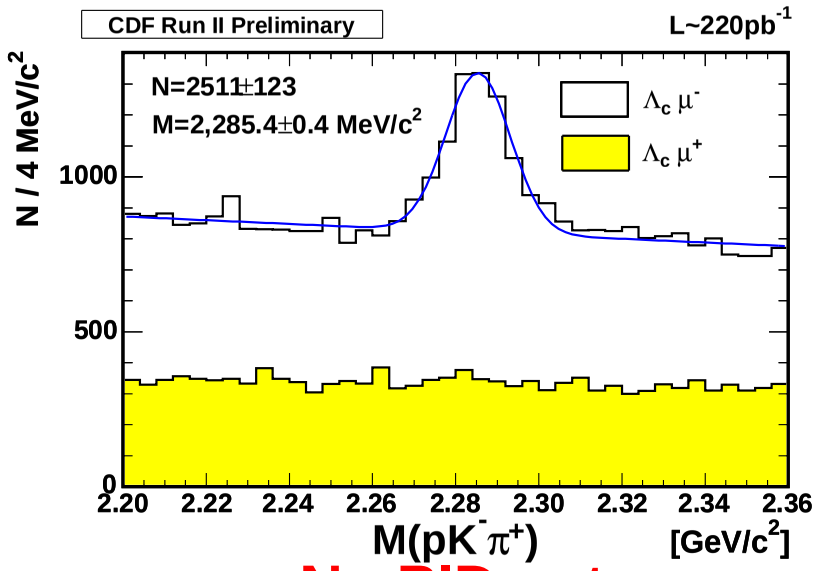
where $\mathrm{i} = \mathrm{p}, \mathrm{K}, \pi, \mathrm{e}, \mu$

- form normalized likelihood ratio:

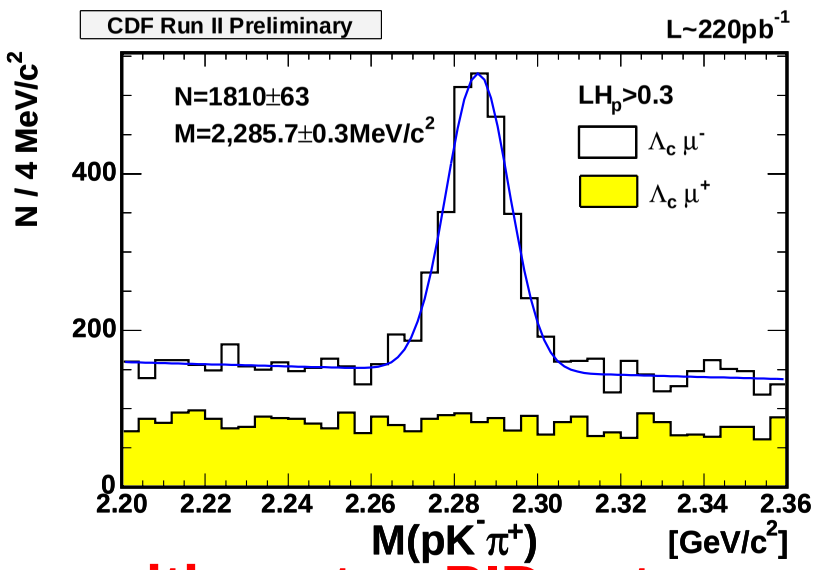
$$\mathrm{LH_i} = \frac{\mathrm{lh(i)}}{\mathrm{lh(p)} + \mathrm{lh(K)} + \mathrm{lh(e)} + \mathrm{lh}(\mu) + \mathrm{lh}(\pi)}$$

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





No PID cut

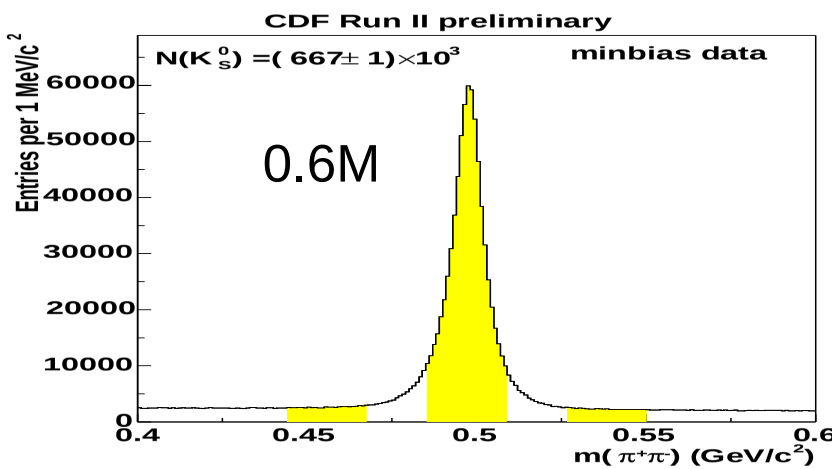


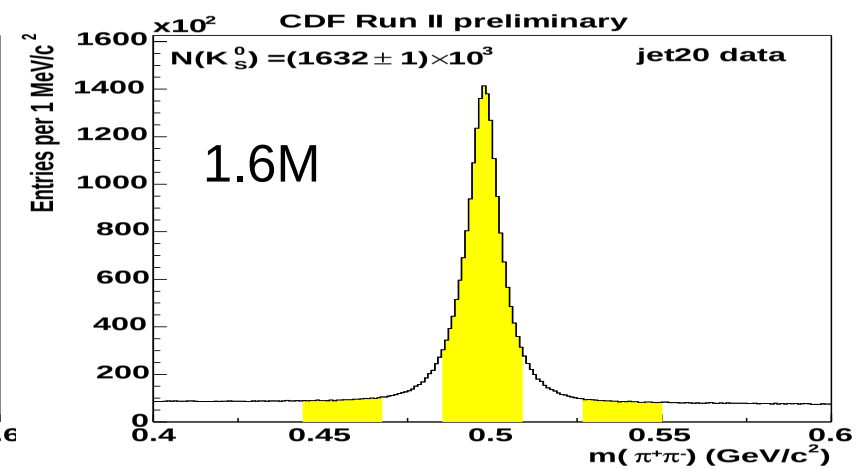
with proton PID cut

Search for Θ^+

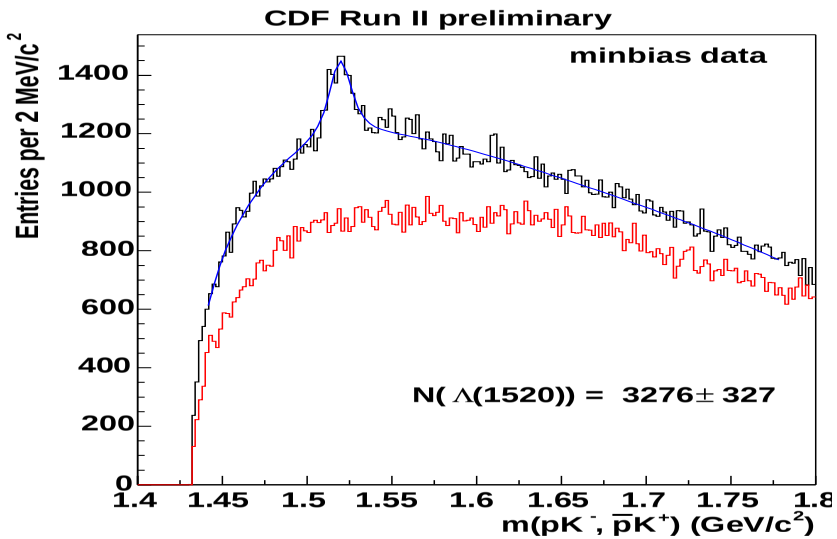
$$\Theta^+ \to K^0_S p$$
$$\hookrightarrow \pi^+\pi^-$$

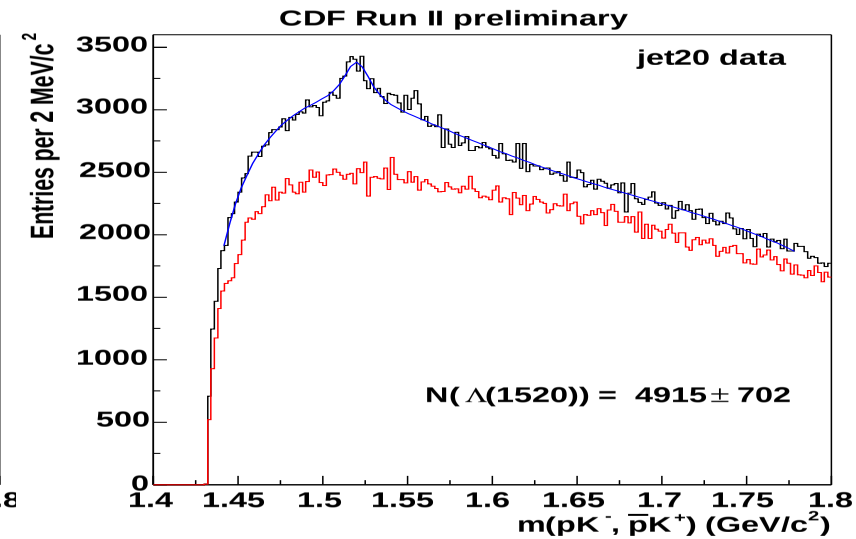
- use TOF to identify protons $0.5 < p_T < 2.1\ \mathrm{GeV}/c$
- Data samples used:
  - MINBIAS 12×10^6 events, ZEROBIAS 8×10^6 events
  - JET20 16×10^6 events

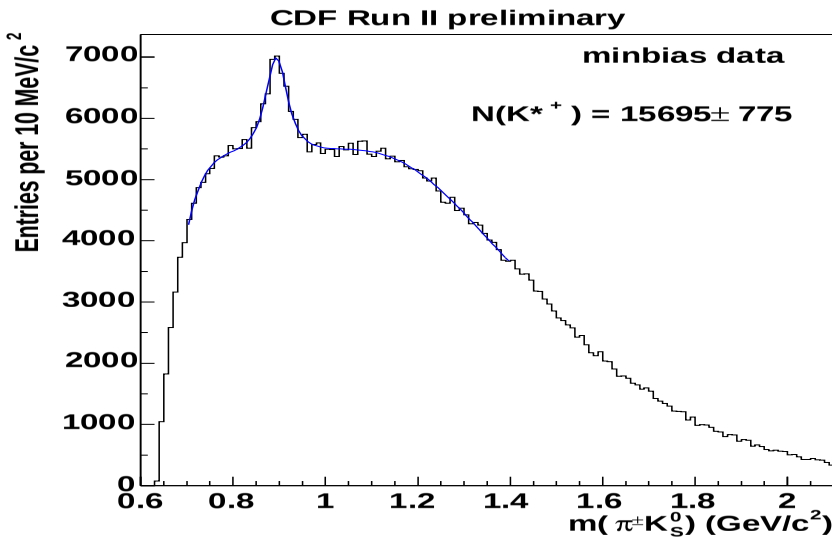


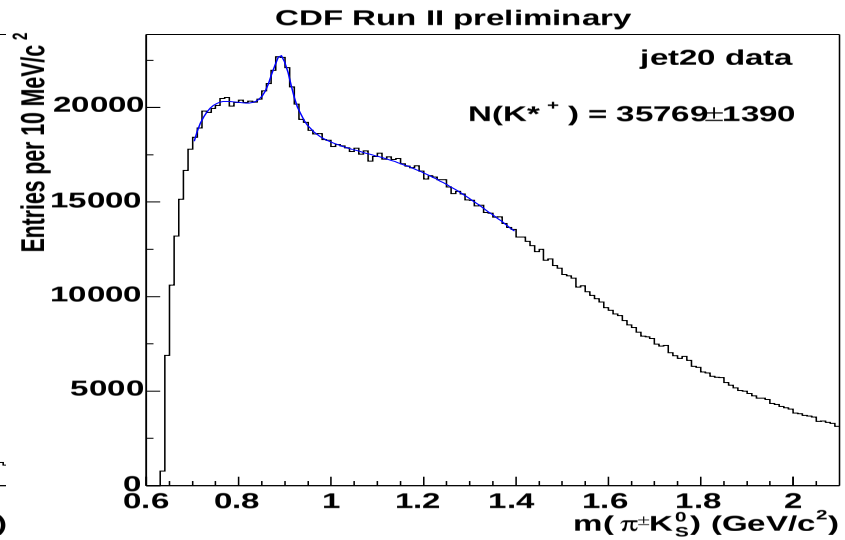


Known Resonances

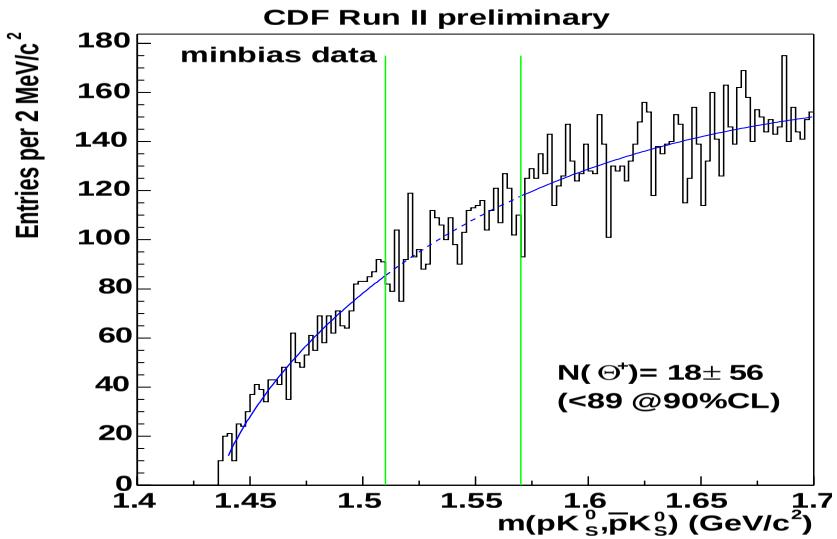


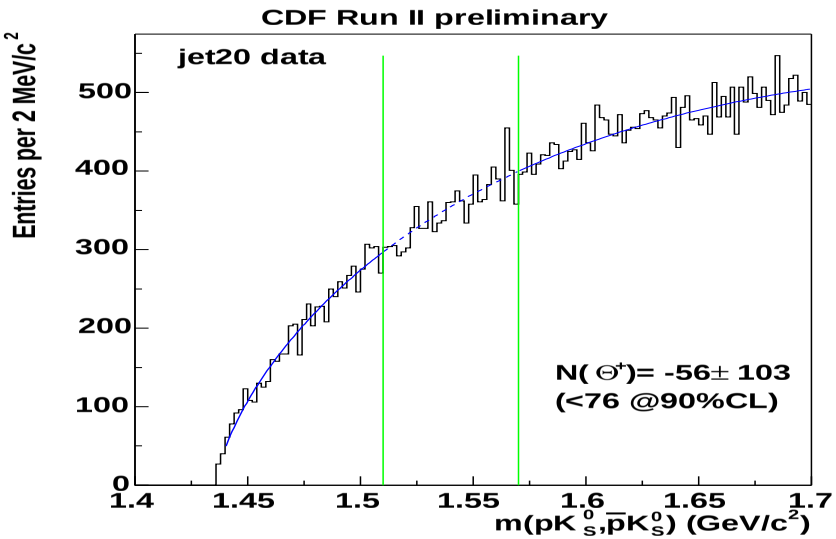






The pK^0_S spectrum





Resonance	Minbias data	Jet20 data
$\phi \to K^+K^-$	$19,721 \pm 273$	$26,658 \pm 385$
$\Lambda \to pK^-$	$3,276 \pm 327$	$4,915 \pm 702$
$K^{*+} \to K^0_S\pi^+$	$15,695 \pm 775$	$37,769 \pm 1,390$
$\Theta^+ \to pK^0_S$	18 ± 56	-56 ± 103
90% CL limit on Θ^+	**<89**	**< 76**

work on cross section continuing

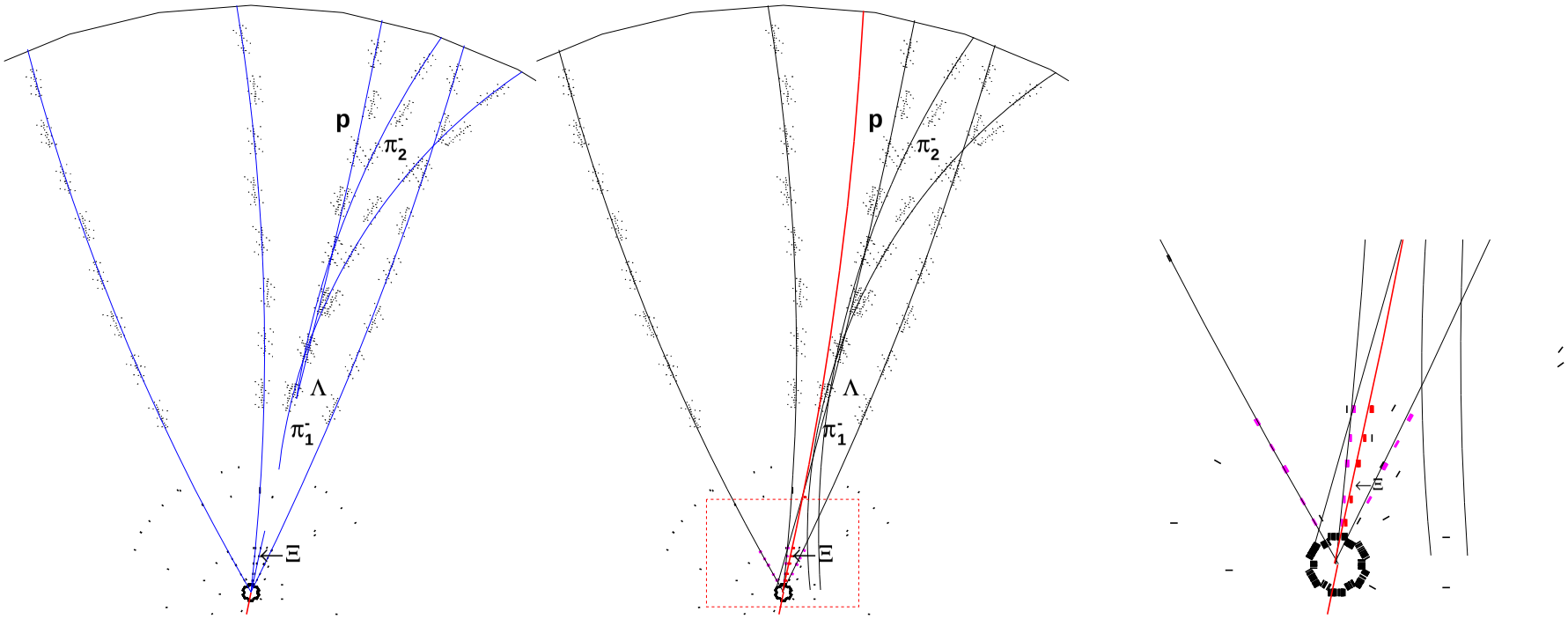
Exotic Cascade

$$\Phi^{0,--} \rightarrow \Xi^- + \pi^{+,-}$$
$$\hookrightarrow \Lambda\pi^-$$

Cascade tracking in SVX at CDF

Hyperon Are Tracked in Silicon

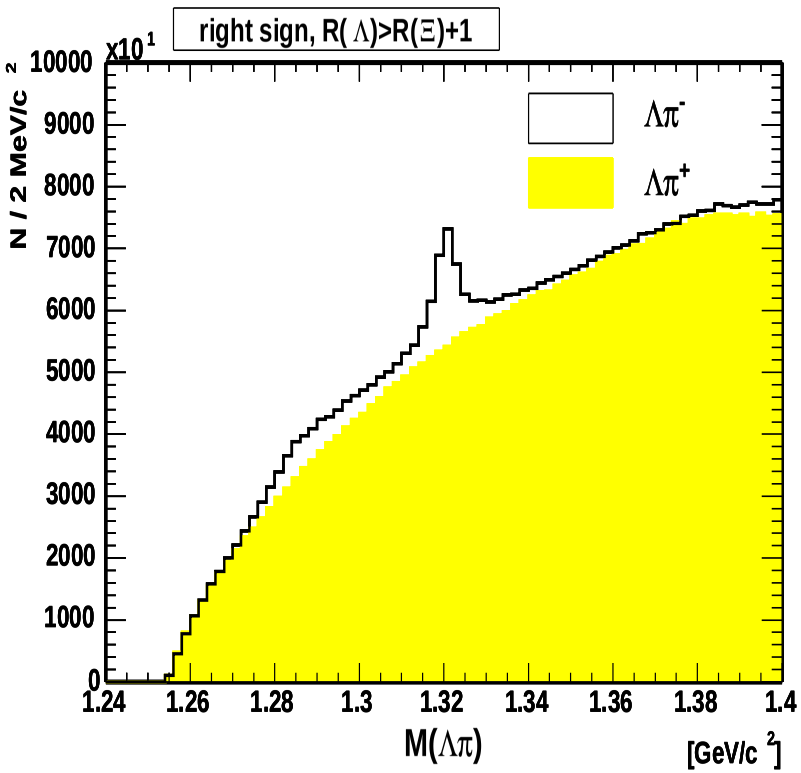
- $\Xi^- \to \Lambda^0 \pi^-$ is a long lived particle $c\tau = 4.91 cm$. It leaves hits in SVX detector. CDF developed dedicated tracking Ξ in Silicon. Momentum and vertex of $\Lambda\pi^-$ are used to seed silicon tracking algorithm.

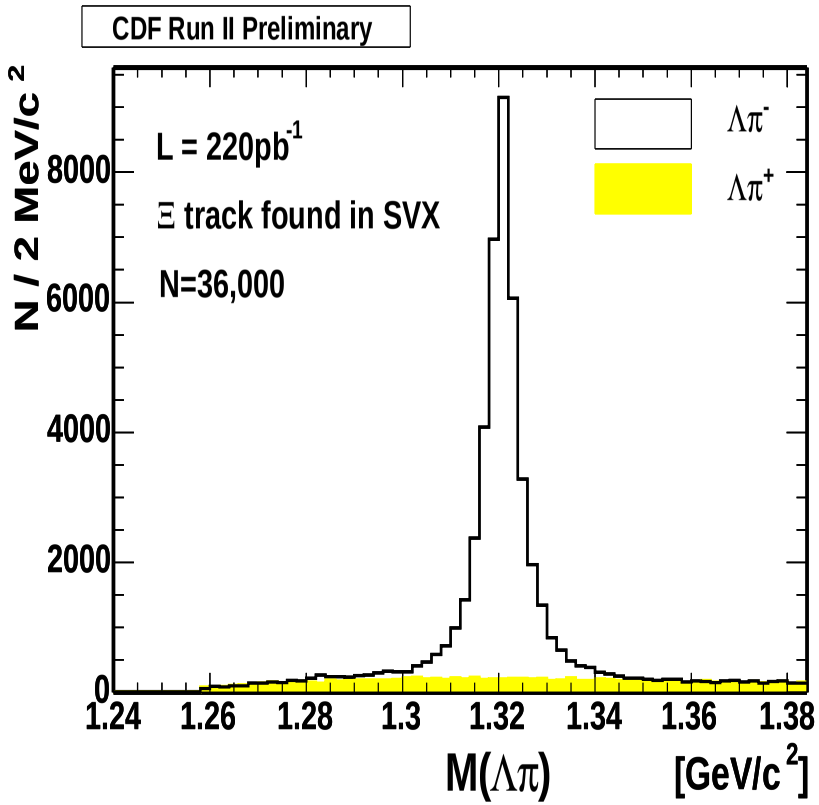


MC : $\Xi_b \to \Xi_c^+ \pi^- \quad \Xi_c^+ \to \Xi^- \pi^+ \pi^+ \quad \Xi^- \to \Lambda \pi_2^- \quad \Lambda \to p \pi_1^-$

Tracked Hyperon signals

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





Displaced Track trigger data

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

- **fit function:**

$$\mathscr{F} = BW \otimes Gauss + Gauss$$
$$= \left(\Sigma_{n=0}^{3} a_n \cdot x^n\right) \cdot \sqrt{x - M_\Xi - M_\pi}$$

- **fit yielded:**

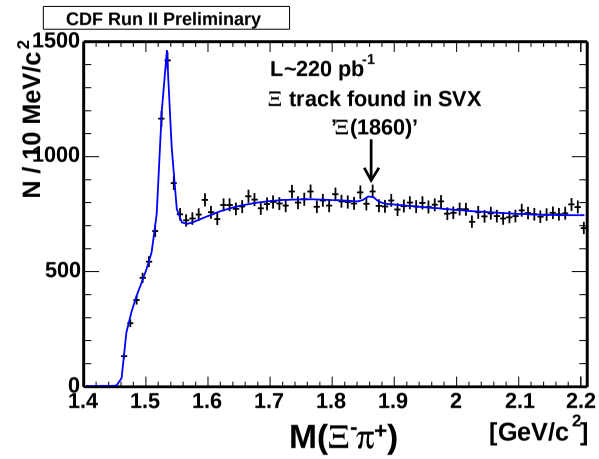
$$\mathrm{N}(\Xi(1530)) = 2,182 \pm 92$$
$$\mathrm{M} = (1,5320 \pm 0.4)\ \mathrm{MeV/c^2}$$

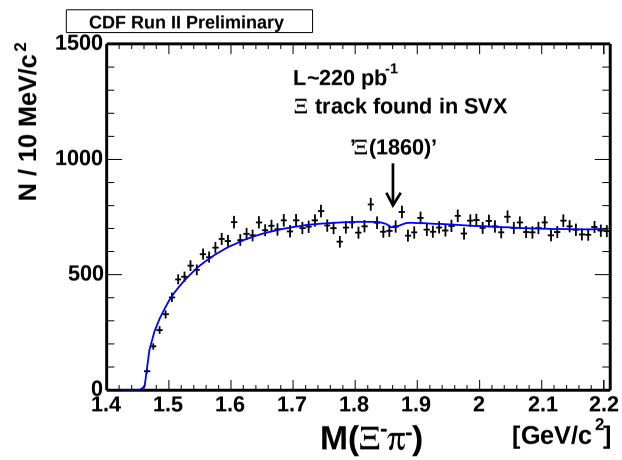
$$\frac{\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))}{\sigma(pp \to \Xi) \cdot a(\Xi)} \sim 0.061$$

Channel	# of events	90 % CL	relative yield
$\Xi^-\pi^+$	57±51	126	0.06
$\Xi^-\pi^-$	-54±47	51	0.03

(Relative yields of $\Xi(1860)/\Xi(1530)$ assuming equal detector efficiency)

hadronic trigger sample





no signal observed !

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

- $E_T > 20$ GeV **jet trigger data, SVX tracked** $\Xi^{\pm}$

$$N(\Xi(1530)) = 387 \pm 34$$
$$M(\Xi(1530)) = (1,532.3 \pm 0.8)\ \mathrm{MeV/c^2}$$

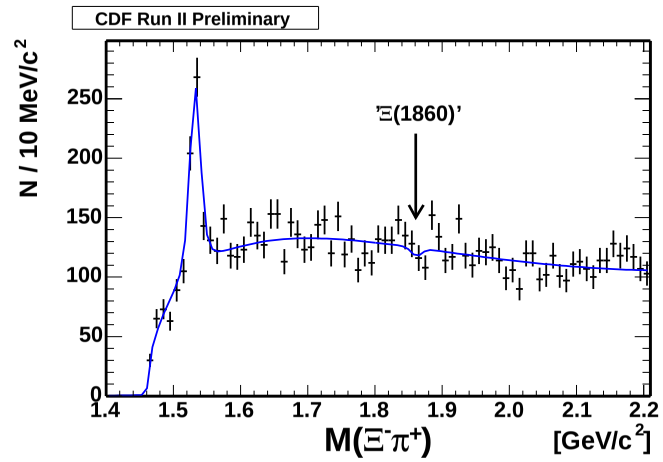
$$\frac{\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))}{\sigma(pp \to \Xi) \cdot a(\Xi)} \sim 0.08$$

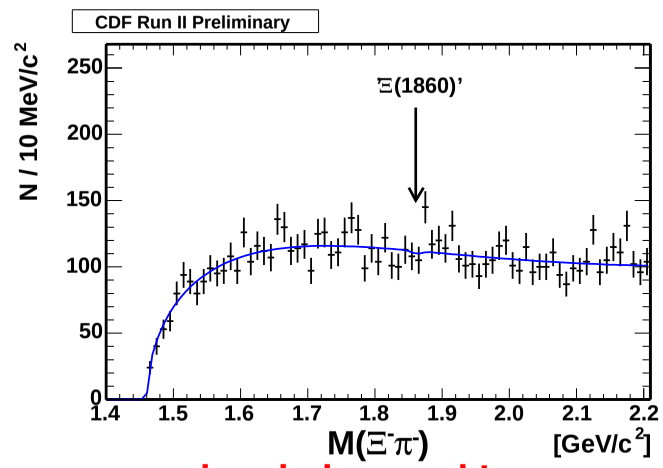
(similar to TTT sample and similar to NA49)

Channel	# of events	90 % CL	relative yield
$\Xi^-\pi^+$	-14±19	25	0.08
$\Xi^-\pi^-$	-4±18	28	0.09

(Relative yields of $\Xi(1860)/\Xi(1530)$ **assuming equal detector efficiency)**

Jet20 sample





no signal observed !

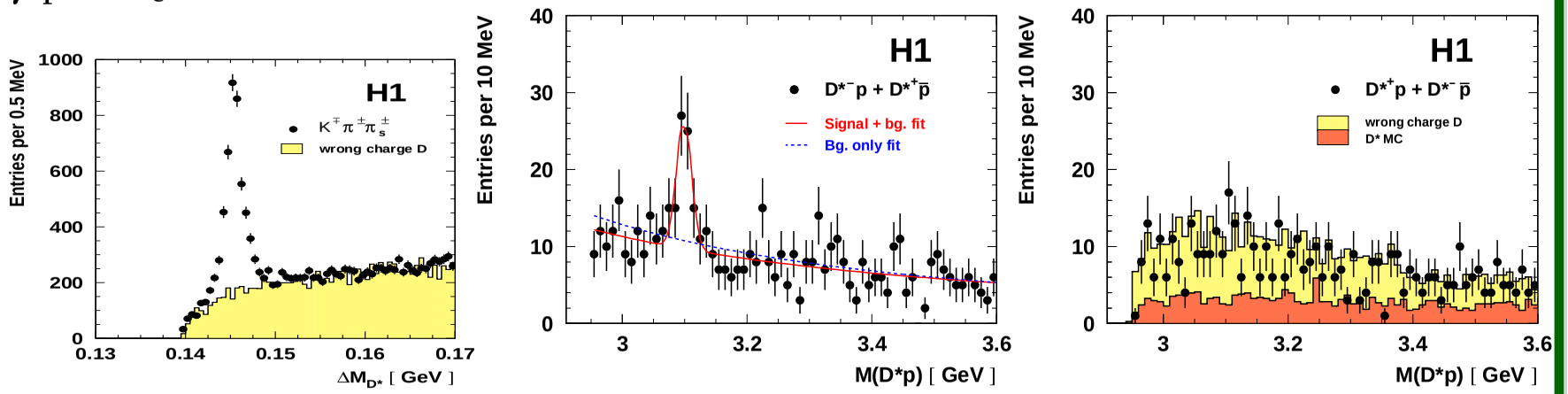
Θ_c signal

H1 Experiment @ HERA $\Theta_c \to D^{*-}p$

$\hookrightarrow \bar{D}^0\pi^-$

$\hookrightarrow K^+\pi^-$

- $\gamma^* p \to \Theta_c X$



Mass = $(3099 \pm 3(\text{stat.}) \pm 5(\text{syst.}))\ \text{MeV}/c^2$

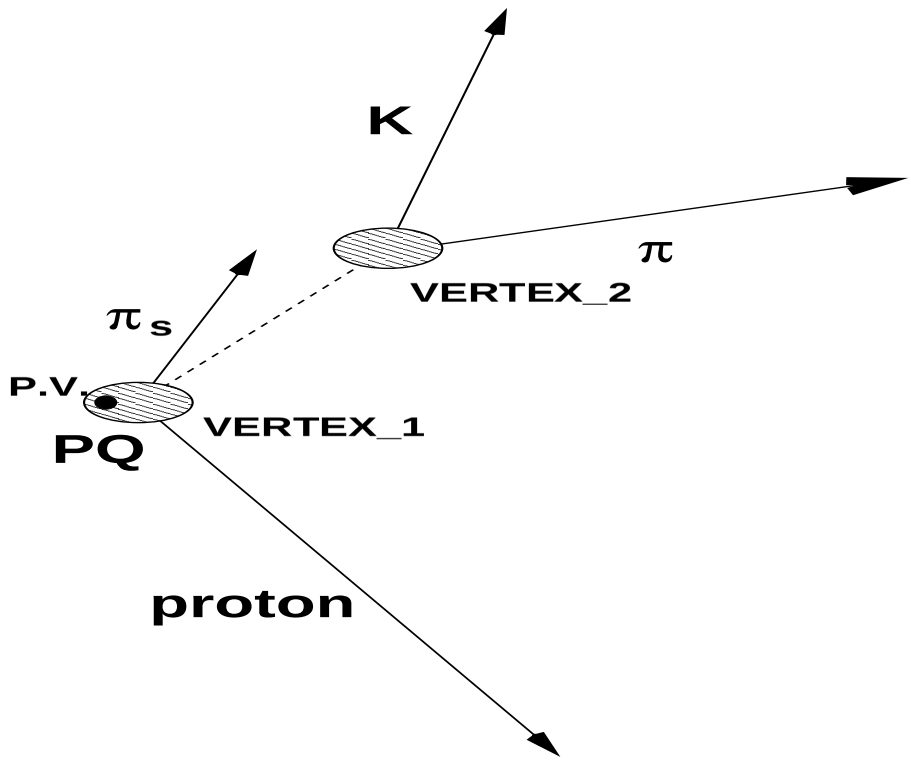
Gaussian width of the peak, $(12 \pm 3(\text{stat.}))\ \text{MeV}/c^2$**, is consistent with detector resolution**

$$\frac{\sigma(\gamma^* p \to \Theta_c) \cdot B(\Theta_c \to D^{*-}p)}{\sigma(\gamma^* p \to D^{*-})} \approx 1\%$$

- **also see** $\gamma p \to \Theta_c X$

- **ZEUS Experiment (also @ HERA) did not confirm** Θ_c^+

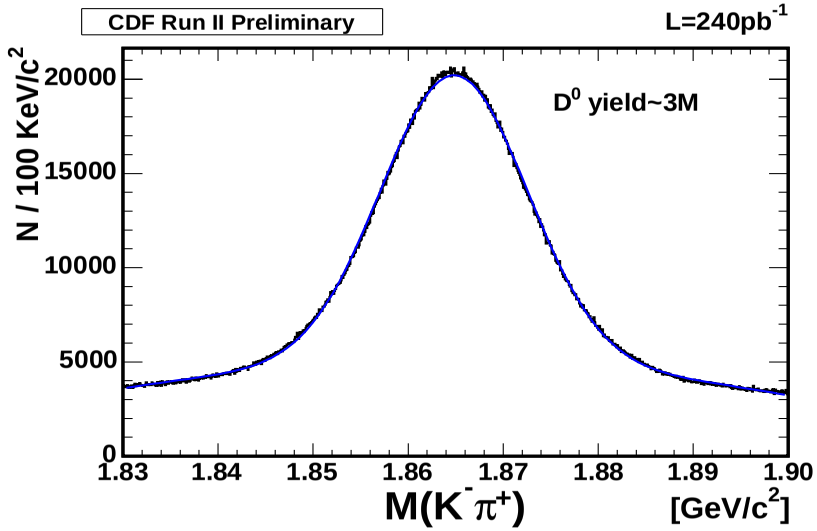
Θ_c decay topology

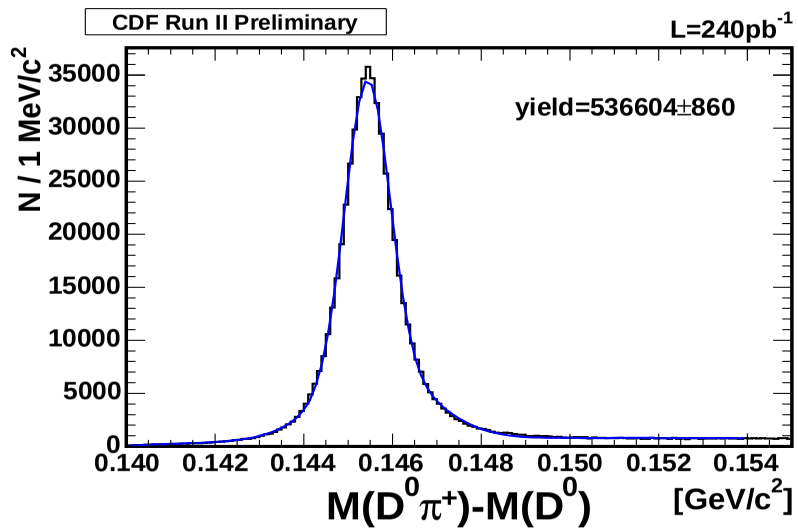


- prompt
- $|L_{xy}(PQ)| < 0.04$ cm
- $\left|L_{xy}(PQ)/\sigma_{L_{xy}}(PQ)\right| < 3$

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

Charm Signals in Hadronic Dataset





- 3M D^0 and 0.5M D^{*+}. 180x increase compared to H1 statistics.
- given 1% of D^* produced from Θ_c we expect
  - assuming fragmentation production (see hep-ph/0405281):

$$\sigma(\Theta_c) = (40 - 140)\ \mathrm{nb}$$

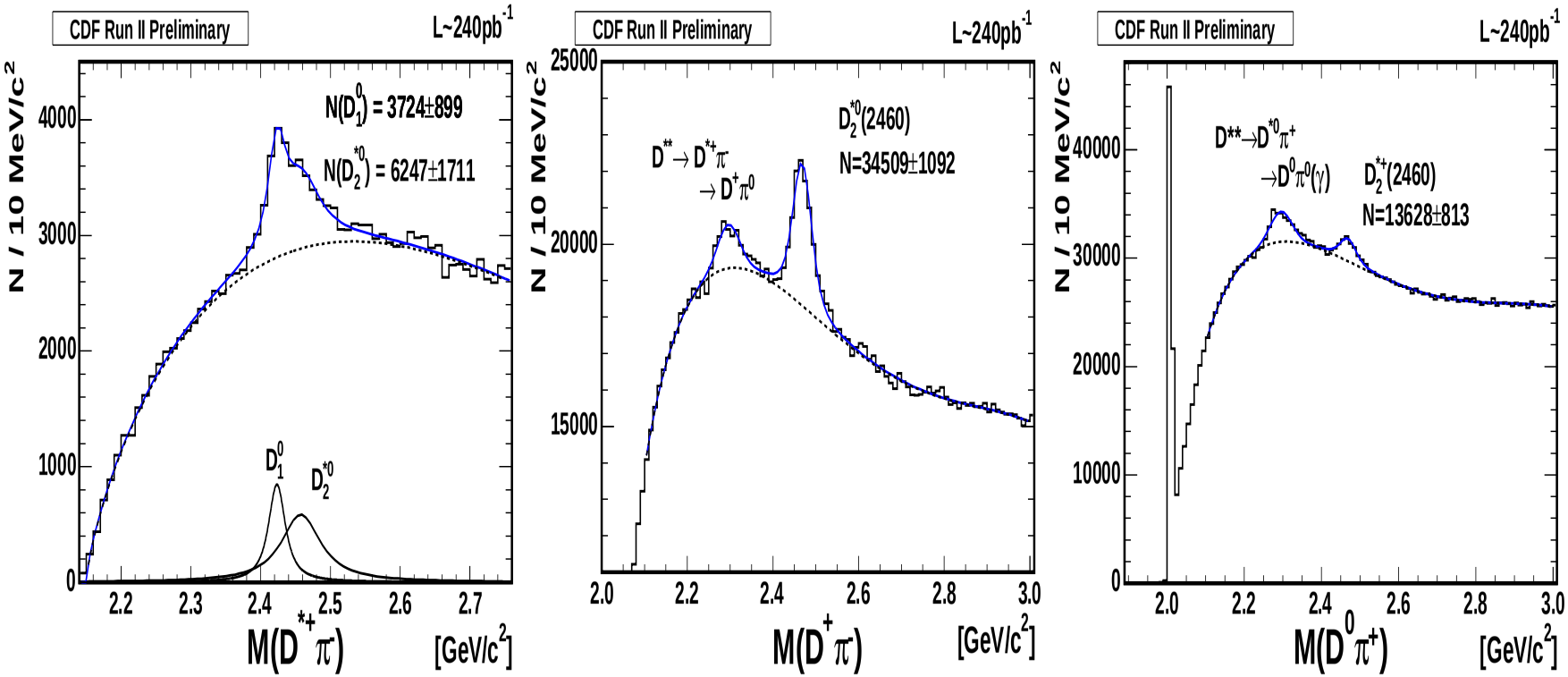
  - assuming coalescence production (see hep-ph/0409121):

$$\sigma(\Theta_c) = 240\ \mathrm{nb}$$

- so expect few thousand events per $100\mathrm{pb}^{-1}$

Reference Signals

Reference channels

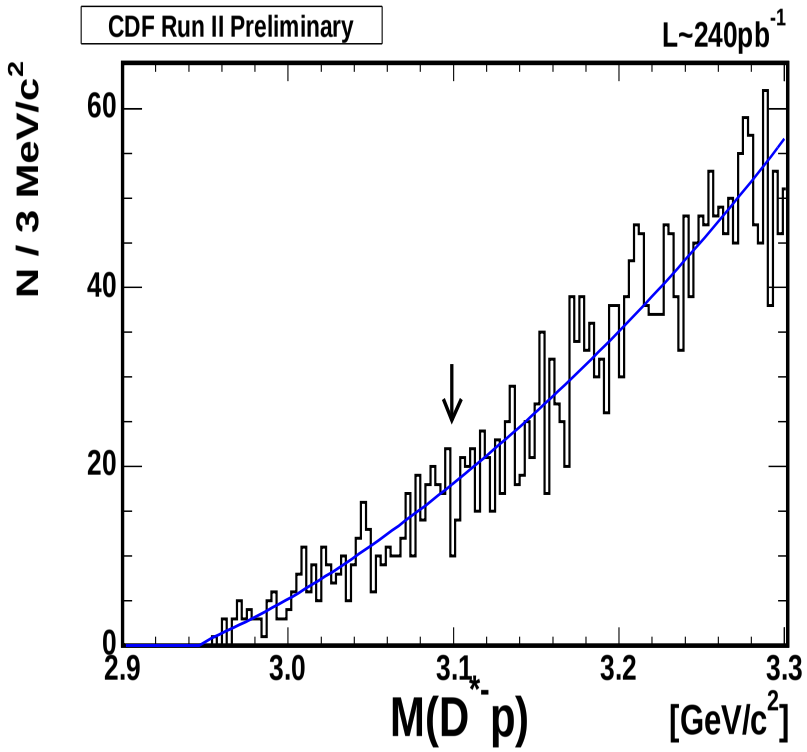


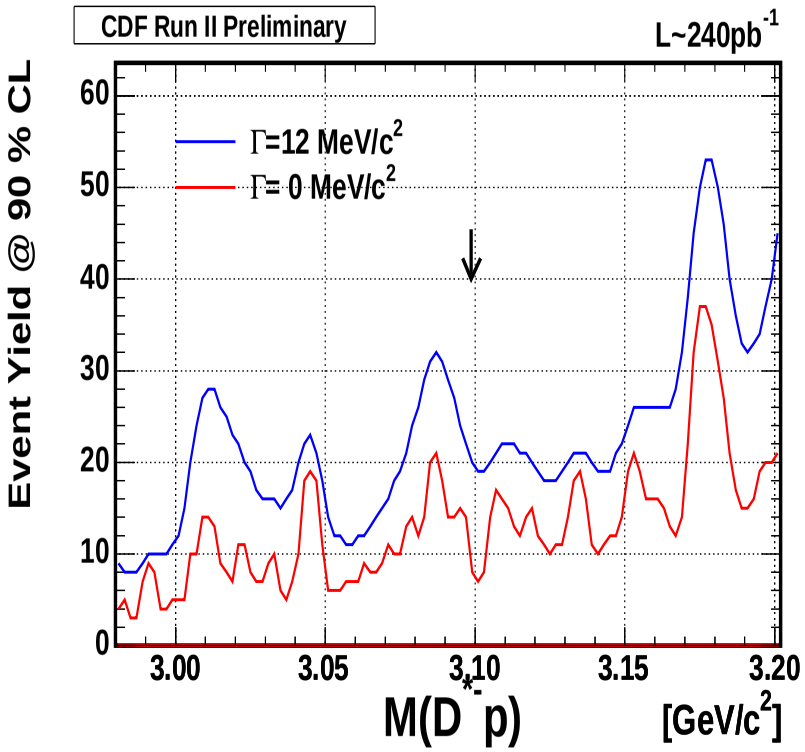
$$D^{**} \to D^{*+}\pi^- \hookrightarrow D^0\pi^+ \hookrightarrow K^-\pi^+$$

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

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

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

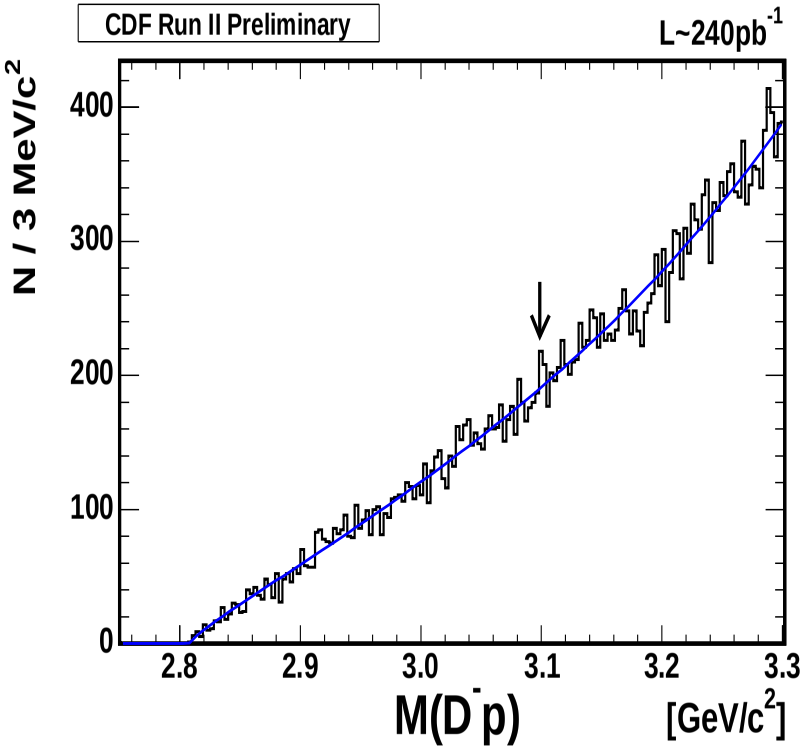


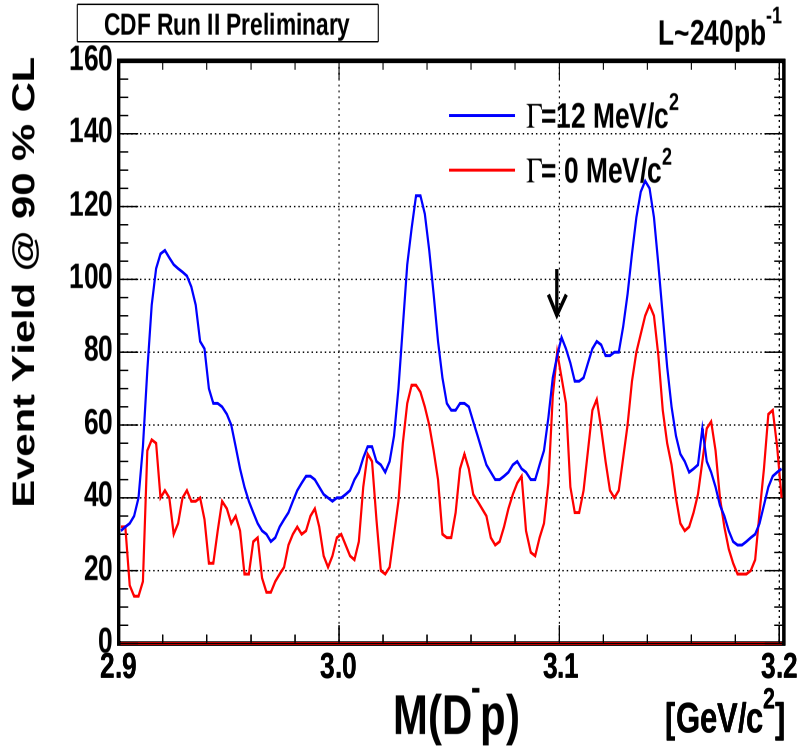


- $\Gamma = 0$ MeV/c^2:
  - 21@90%CL
- $\Gamma = 12$ MeV/c^2:
  - 32@90%CL

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

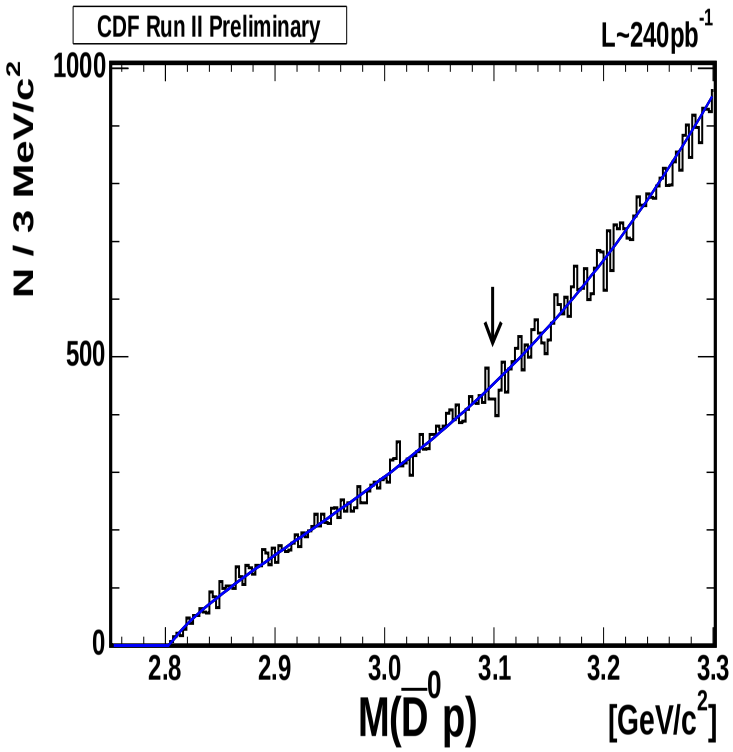
D^-p spectrum w/ proton PID

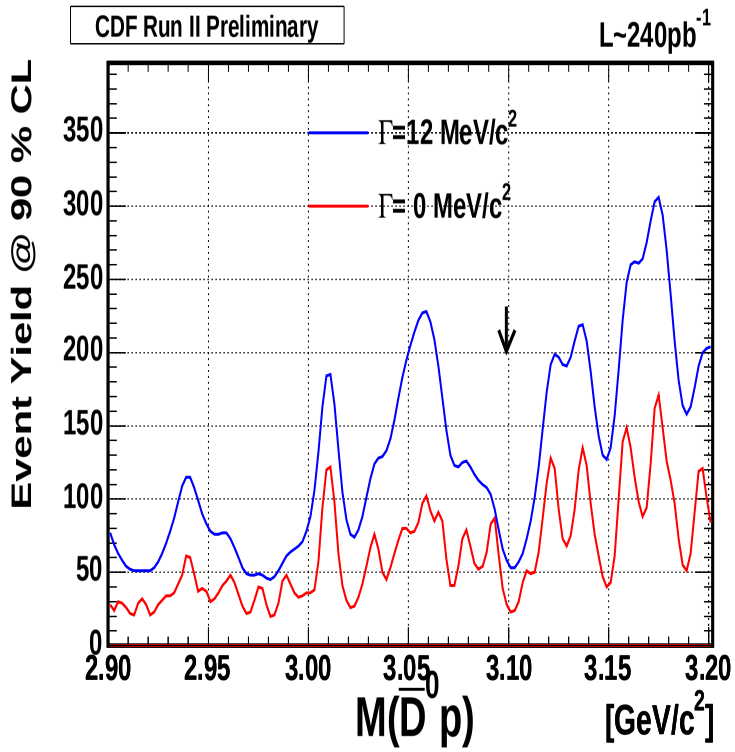




- $\Gamma = 0$ MeV/c^2:
  - 80@90%CL
- $\Gamma = 12$ MeV/c^2:
  - 84@90%CL

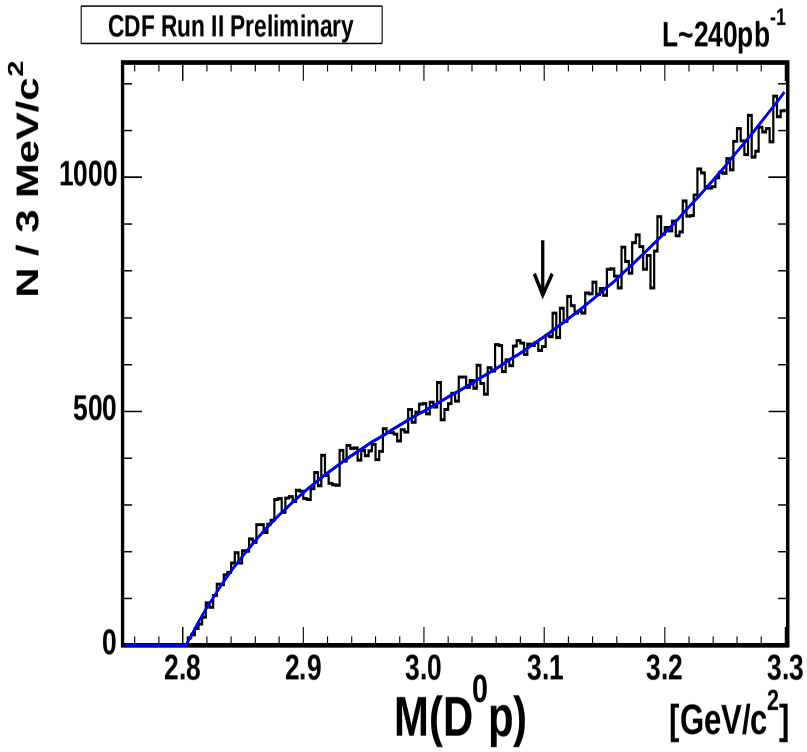
$\bar{D}^0 p$ spectrum w/ proton PID

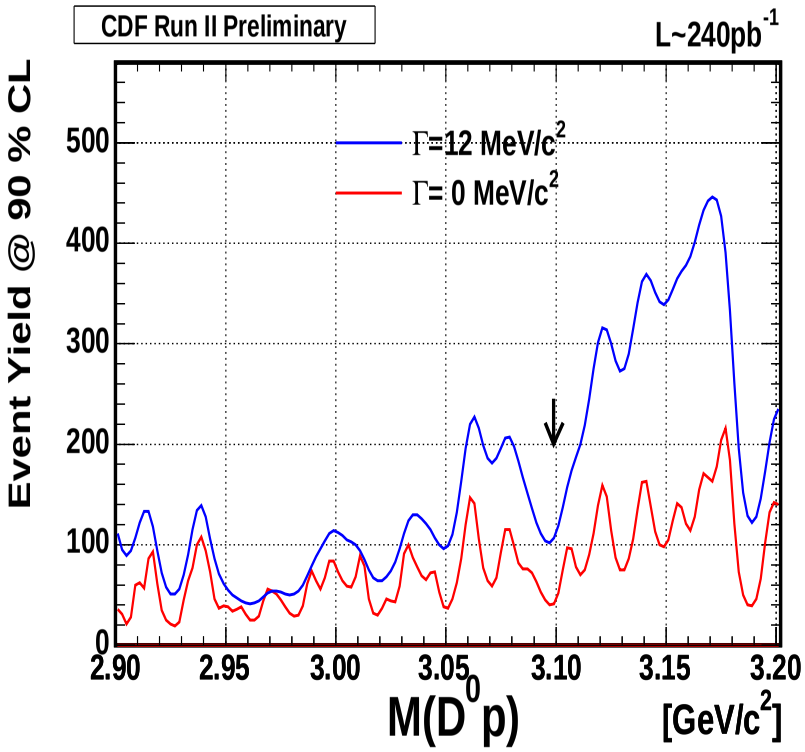




- $\Gamma = 0$ MeV/c^2:
  - 87@90%CL
- $\Gamma = 12$ MeV/c^2:
  - 122@90%CL

D^0p spectrum w/ proton PID





- $\Gamma = 0$ MeV/c^2:
  - 97@90%CL
- $\Gamma = 12$ MeV/c^2:
  - 245@90%CL

Limits on Θ_c

- search window $3.099 \pm 18\ \mathrm{MeV}/c^2$
- take worst point from the limit vs mass inside the window

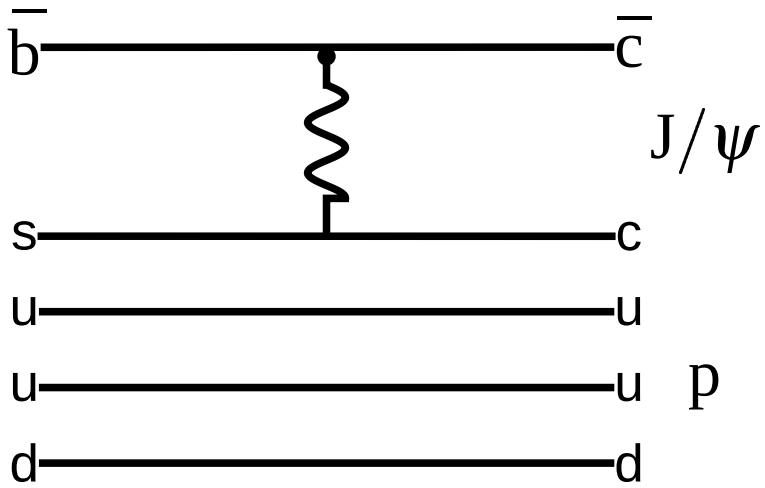
Reference channel		Search channel	
$D_2^{*0} \to D^+\pi^-$	6247 ± 1711	$\Theta_c^0 \to D^{*-}p$	< 21 @ 90% CL
$D_2^{*0} \to D^+\pi^-$	34509 ± 1092	$\Theta_c^0 \to D^-p$	< 89 @ 90% CL
$D_2^{*+} \to D^0\pi^+$	13628 ± 813	$\Theta_c^+ \to \bar{D}^0p$	< 87 @ 90% CL
		$\Theta_c^+ \to D^0p$	< 97 @ 90% CL

Search for Stable PQ

- Consider $R_s^+(\bar{b}uuds)$ (notation adopted from W. Stewart et al., hep-ph0402076) is stable against strong decay:

$$M_{R_s} \simeq M_\Theta + M_{\Lambda_b} - M_\Lambda + M_{\Xi_c} - M_{\Lambda_c'} = 5920\ \mathrm{MeV} < M(B_s p)$$

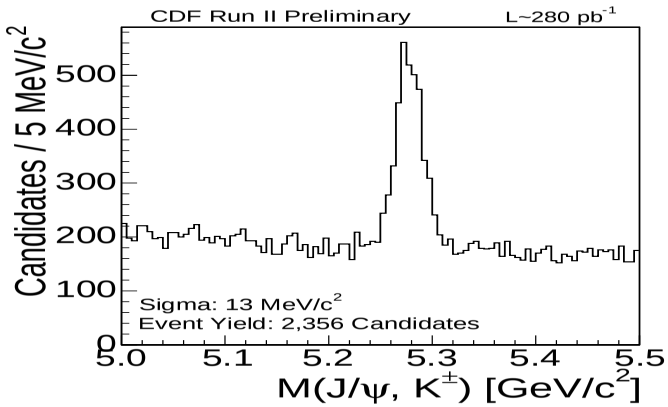
- Possible Weak decay:

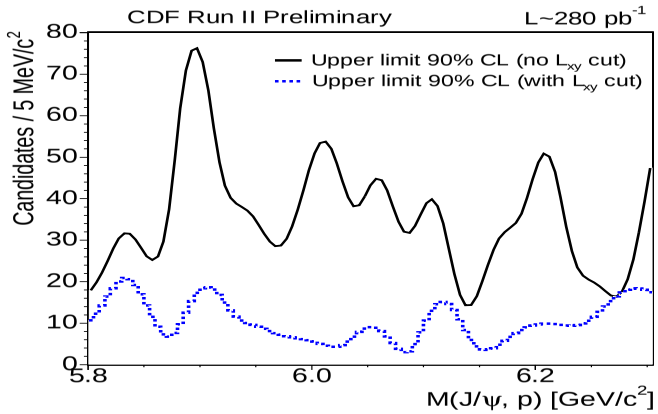


Search for R_s^+

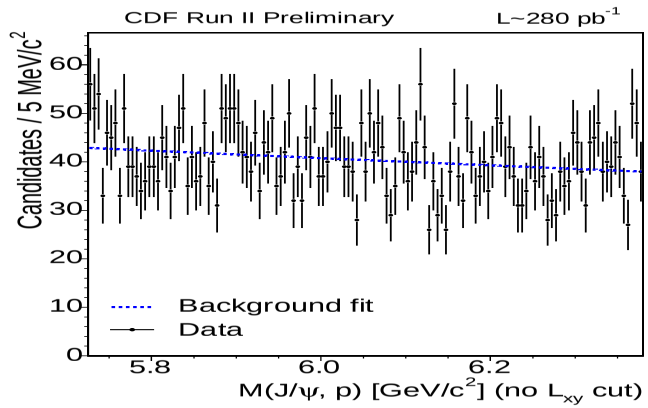
- $R_s^+ \to J/\psi p$ on dimuon data 282 pb^{-1} - ref. channel $B^+ \to J/\psi K^+$
- measurable R_s^+ lifetimes considered: $L_{xy} > 100\ \mu m$ and no L_{xy} cut
- unbinned likelihood fits varying mass in wide range => calculate mass dependent limits

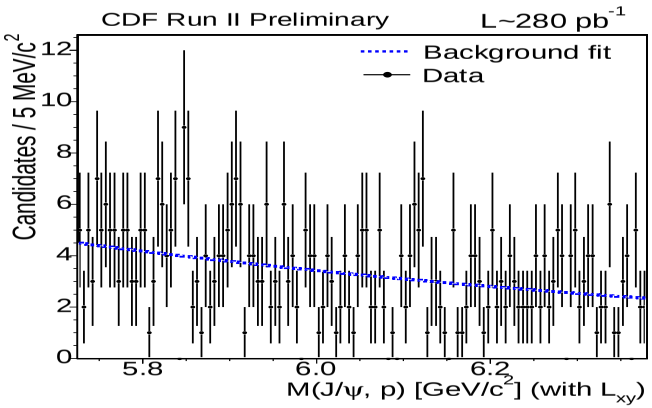
Ref. channel





$J/\psi p$





no signal found!

Conclusion

- Using detector with superior momentum resolution and good PID capabilities and high statistic clean samples of K^0_S, Ξ, D^{*+}, D^0, D^+, J/ψ we searched for recently reported pentaquark states: $\Phi^{--,0}, \Theta^+, \Theta_c, R_s$.
- No signals found, limits on relative yields with respect to known states established.
- Calculation of upper limits on production cross sections is in progress. Expect numbers by Winter
- Production of exotic baryons is severely suppressed with respect to normal baryon production calling for exotic production mechanisms to explain existing positive results.