Pentaquark Searches at CDF

International Workshop on Exotic Hadrons

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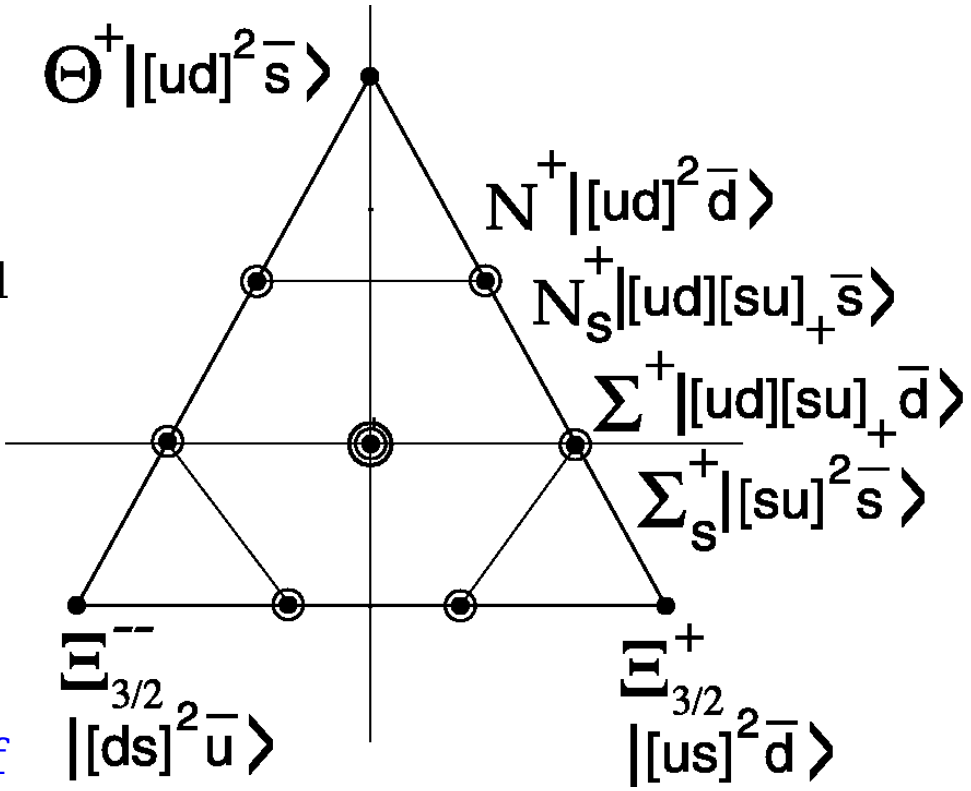
Overview - Motivation

Recent flurry of experimental evidence for a narrow exotic baryon state decaying to nK^+, pK_s with mass ~1540 MeV/c^2, interpreted as 5-quark ($uudd\bar{s}$) Θ^+ state in the $\bar{10}_f$ predicted by Diakonov, Petrov, Polyakov (1997) revived interest in baryon spectroscopy.

Observation by NA49 of $\Xi_{3/2}^{--}$, $\Xi_{3/2}^{0}$ decaying to $\Xi^-\pi^-$, $\Xi^-\pi^+$ with mass ~ 1860 MeV/c^2, interpreted as members of S=-2 ($qqss\bar{q}$, q=u,d) quadruplet of 10_f

H1 reports anti-charmed analogue ($uudd\bar{c}$) of the Θ^+ decaying to $D^{*-}p$ with mass = 3099 ± 6 MeV/c^2



Observations are all of relatively low statistics (20-100 signal events, S/B 1:1-1:3, significance ~3-5σ) with width consistent with detector resolutions

➔ Desire observations with higher statistics and better σ_{mass}

CDF and Pentaquarks

Why search for PQ's at the Fermilab Tevatron?

- Study PQ production in a different regime ($p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV) from other experiments
  - Important because PQ production is in general not understood
- CDF is a multi-purpose detector with demonstrated ability to study a wide variety of different physics

Our searches exploit strengths of CDF detector:

- High statistics samples from different types triggers
  - Hadronic trigger, Di-Muon, Jet20, Minimum-bias
- Precision tracking
  - Good 3D vertexing: Reduce backgrounds
  - Excellent momentum/mass resolution: Resolve states to ~few MeV
  - Able to track long-lived hyperons (Ξ^-, Ω^-) in Silicon detector (SVXII)
- Good particle identifcation
  - TOF and dE/dx to identify kaons and protons

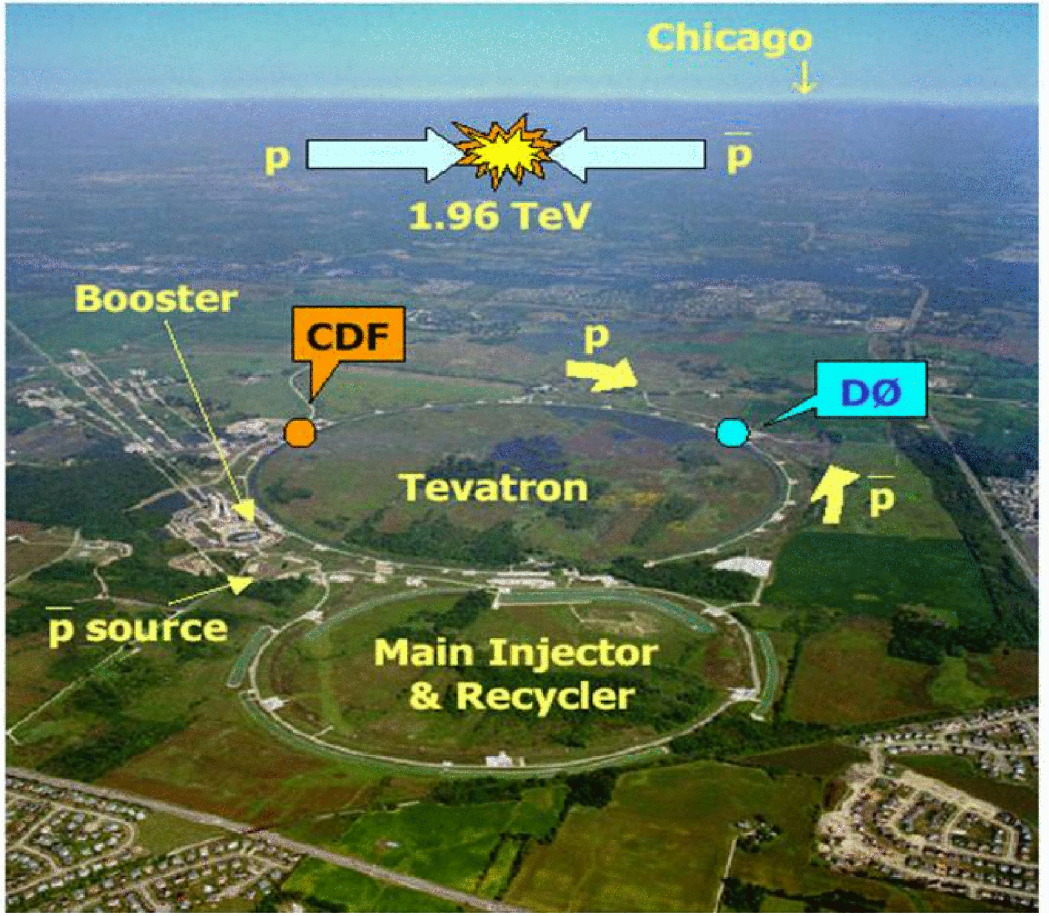
The Fermilab Tevatron

World's highest energy particle collider

Started 1984:
- 1km radius pp collisions at $\sqrt{s}$=1.6 TeV

Run I (1992-1995):
- $\sqrt{s}$=1.8 TeV
- 6×6 bunches, $\mathcal{L}_{inst} = 1.6\times10^{31}$ cm^{-2}s^{-1}
- $\int \mathcal{L}\, dt = 110$ pb^{-1}

1996-2000 Major Upgrade for Run II:
- Main Injector
- $\bar{p}$ Recycler
- new synchotron
- upgraded p source



Run II Started 2001:
- $\sqrt{s}$=1.96 TeV
- 36×36 Colliding $p\bar{p}$ bunches $10^{11}(10^{10})$ $p(\bar{p})$ per bunch
- $\mathcal{L}_{inst} = 10.7\times10^{31}$ cm^{-2}s^{-1} (record)
- $\int \mathcal{L}\, dt$ = ~780 pb^{-1} (~600 pb^{-1} to tape) with 4 – 8 fb^{-1} expected by 2009

The CDF Detector

Tracking systems:

- Silicon: L00 + 5 layers in SVXII + 2/1 layers in ISL
  rz, rϕ stereo strips. Si tracking for |n| < 2. 720, 000 channels
- Central Outer Tracker (COT): 96 layer drift wire chamber, 30,240 sense wires
  σ(1/pt)~0.1%/(GeV/c), σ(hit)~150um, PID via dE/dx

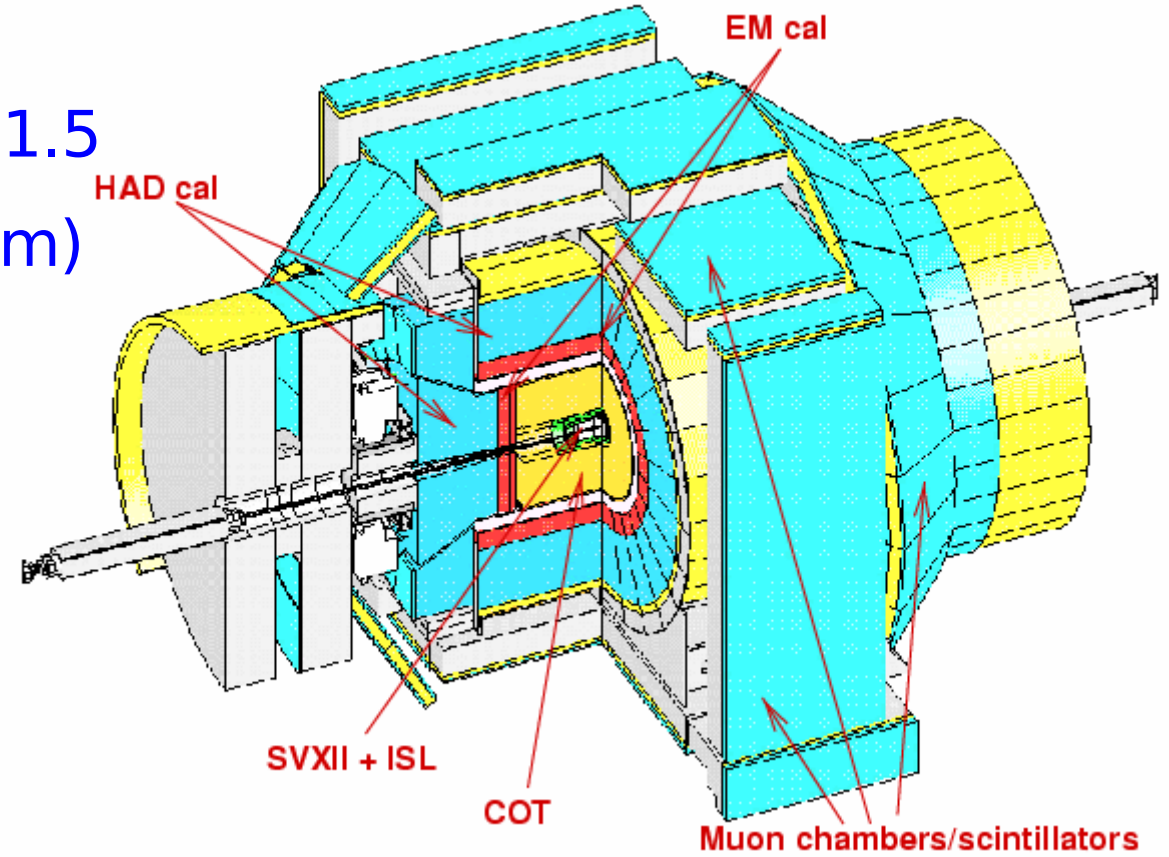
New Plug Calorimeter

Extended μ coverage to |n|<1.5

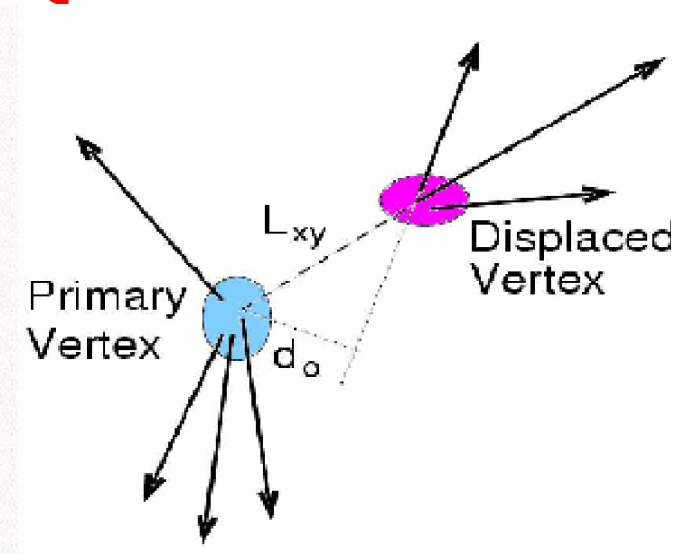
ToF System (120 ps @ 138 cm)

Improved DAQ and Trigger:

- New front-end electronics
- Level 1 all digital, 132 ns pipeline
- 4000/300/70 Hz L1/L2/L3 Rate
- COT tracks @ Level 1
- Si Tracks @ Level 2
- Full detector data @ Level 3
- First hadronic B trigger



Triggers/Datasets for PQ Searches



Hadronic Trigger:

- Events with at least 2 tracks displaced from primary interation
- → Hard scattering events rich in fragmentation products from $p\bar{p} \rightarrow c\bar{c}$ and $p\bar{p} \rightarrow b\bar{b}$

Di-Muon Trigger:

- Two tracks with matching stubs in muon chambers
- → Select invariant masses around J/ψ mass for $J/\psi \rightarrow \mu^+\mu^-$

Jet20 Trigger:

- Events with a least one jet with 20 GeV/c, heavily prescaled
- → Generic QCD events

Min-bias:

- → Soft inelastic scattering events

Use sizeable fraction of available Run II data:

- → ~250 pb^{-1} for pentaquark searches in this talk

Particle Identification

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

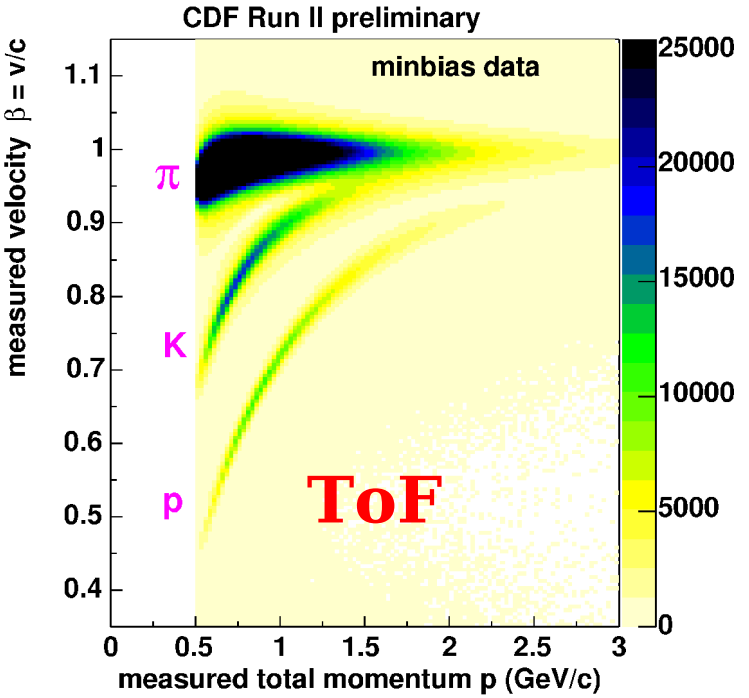
$$\chi_i^2 = \chi_i^2(\text{ToF}) + \chi_i^2(\text{dE/dx})(\text{COT})$$

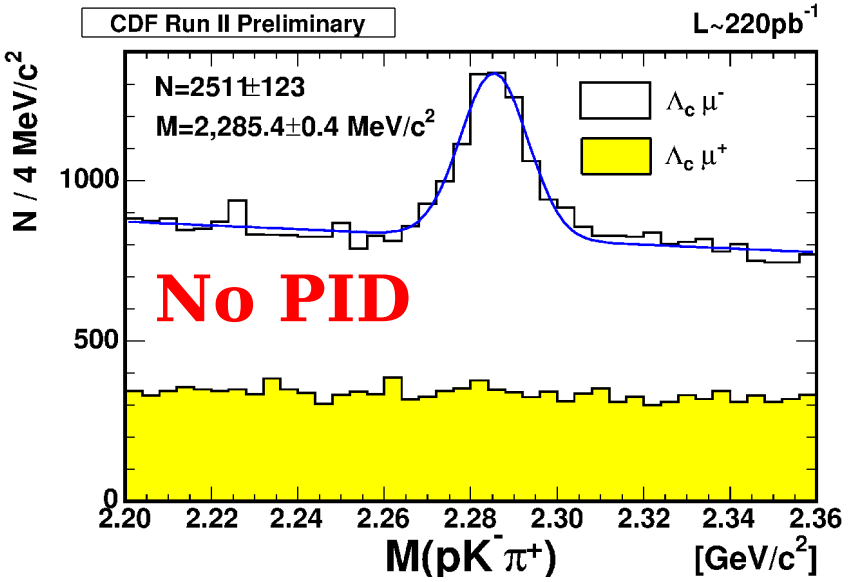
where i=p,K,π,e, or μ

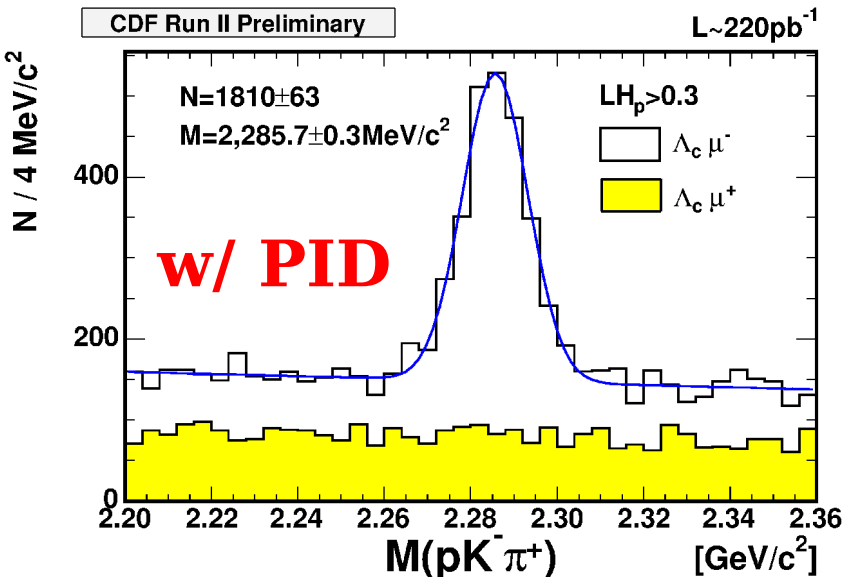
We form the normalized likelihood:

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

where lh(i) = exp(-χ_i^2/2)







PQ Search Strategy at CDF

Search for the following states:

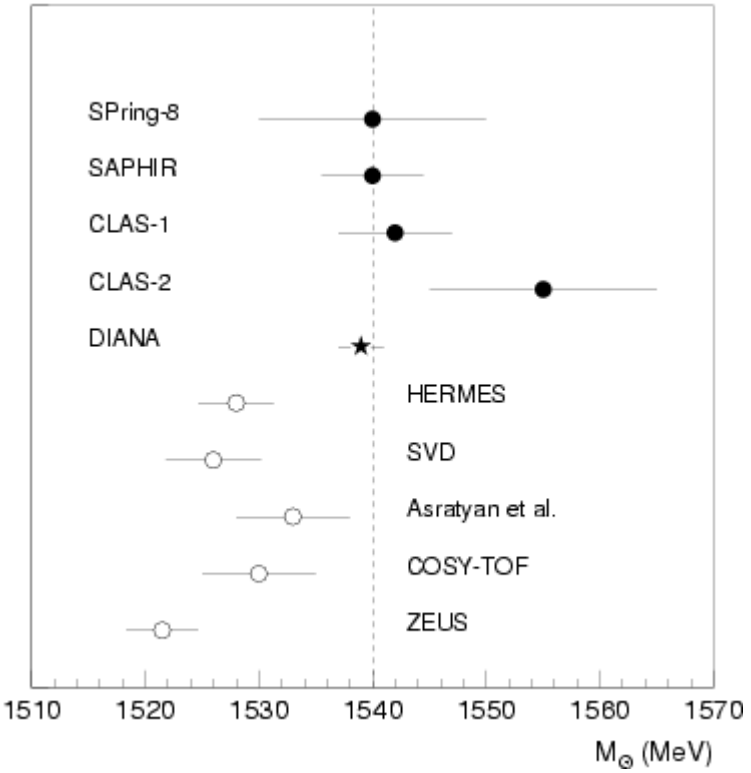
Observed by other exp's

Notation	Quark content	Decay channel	Reference Channel(s)
Θ^+	$\bar{s}uudd$	pK^0_S	$\Lambda(1520) \to pK^-$, $K^{*+} \to K^0_S\pi^+$
$\Xi^{--}_{3/2}$	$\bar{u}ddss$	$\Xi^-\pi^-$	
$\Xi^0_{3/2}$	$\bar{d}udss$	$\Xi^-\pi^+$	$\Xi^0(1530) \to \Xi^-\pi^+$
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	$\bar{b}uuds$	$J/\psi p$	$B^+ \to J/\psi K^+$

1) Optimize selection using reference modes
2) Apply same cuts to PQ modes
3) Add proton PID cut LH(p)>0.4 (when appropriate)
4) PID cut efficiencies from clean sample of protons (Λ)

Θ^+: Experimental Situation

Experiment	Mass MeV/c^2	Width	Reaction
LEPS	1540 ± 10	< 25	$\gamma n \to K^- \boxed{K^+ n}$
SAPHIR	$1540 \pm 4 \pm 2$	< 25	$\gamma p \to K^0_S \boxed{K^+ n}$
CLAS-1	1542 ± 5	< 21	$\gamma d \to K^- p \boxed{K^+ n}$
CLAS-2	1555 ± 10	< 26	$\gamma p \to K^- \pi^+ \boxed{K^+ n}$
DIANA	1539 ± 2	< 9	$K^+ Xe \to Xe' \boxed{K^0_S p}$
HERMES	$1528 \pm 2.6 \pm 2.1$	$17 \pm 9 \pm 3$	$\gamma d \to \boxed{K^0_S p} + X$
SVD	$1526 \pm 3 \pm 3$	< 24	$pA \to \boxed{K^0_S p} + X$
Asratyan *et al.*	1533 ± 5	< 20	$\nu A \to \boxed{K^0_S p} + X$
COSY-TOF	1530 ± 5	< 18	$pp \to \Sigma^+ \boxed{K^0_S p} + X$
ZEUS	$1521.5 \pm 1.5^{+2.8}_{-1.7}$	$6.1 \pm 1.6^{+2.0}_{-1.4}$	$\gamma^* p \to \boxed{K^0_S p} + X$



- $\Theta^+ \to pK^+$ not seen suggesting Θ^+ is indeed an isosinglet
- Widths consistent with detector resolutions
- Note systematic mass shift between pK_s and nK^+ final states

Θ^+ Search

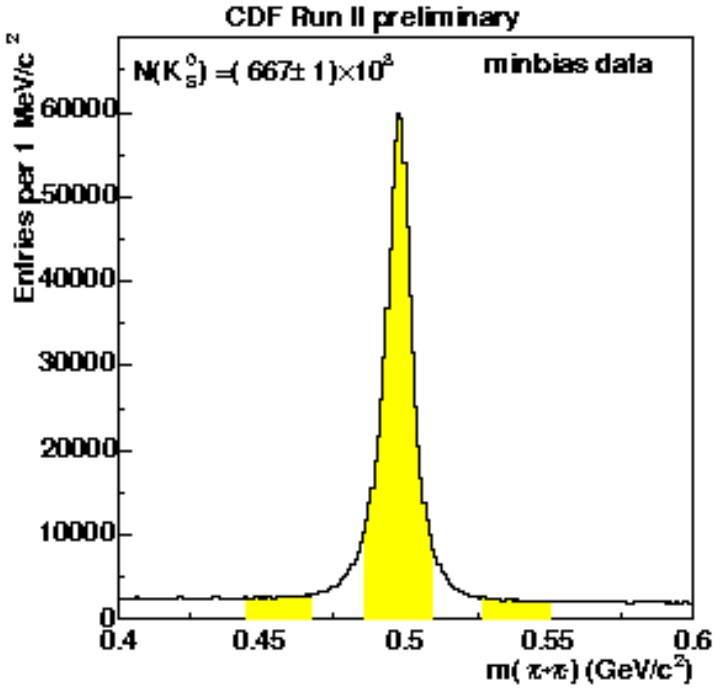
Search for $\Theta^+ \rightarrow pK_s$, with $K_s \rightarrow \pi\pi$

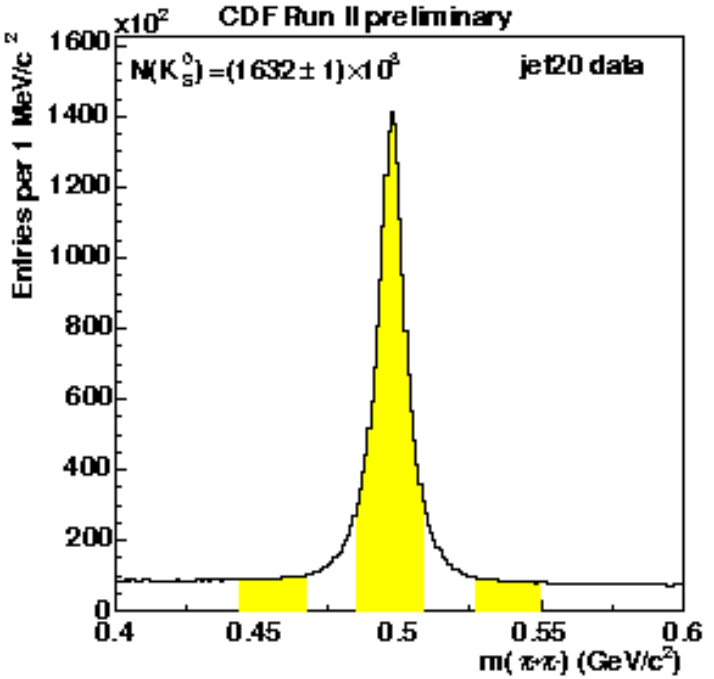
Data samples:

MINBIAS: 12×10^6 events

JET20: 16×10^6 events

Use ToF PID to identify protons with $0.5 < p_T < 2.1$ GeV/c



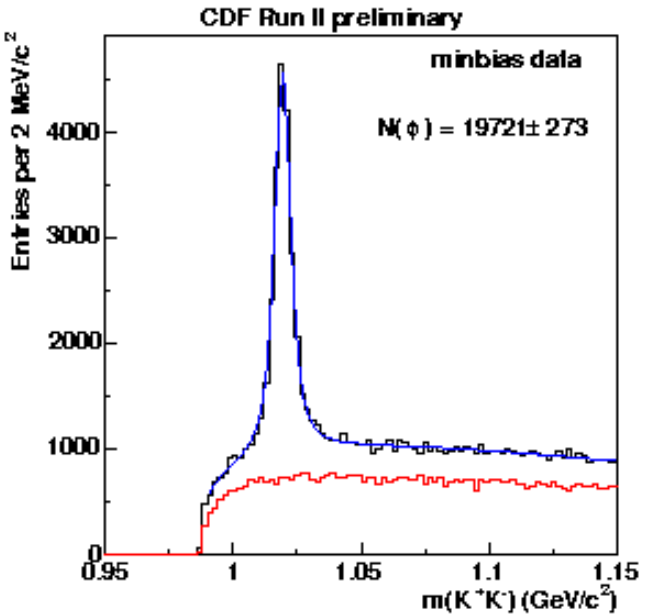


MINBIAS: 667×10^3 K_s candidates JET20: 1632×10^3 K_s candidates

Θ^+ Search: Known Resonances

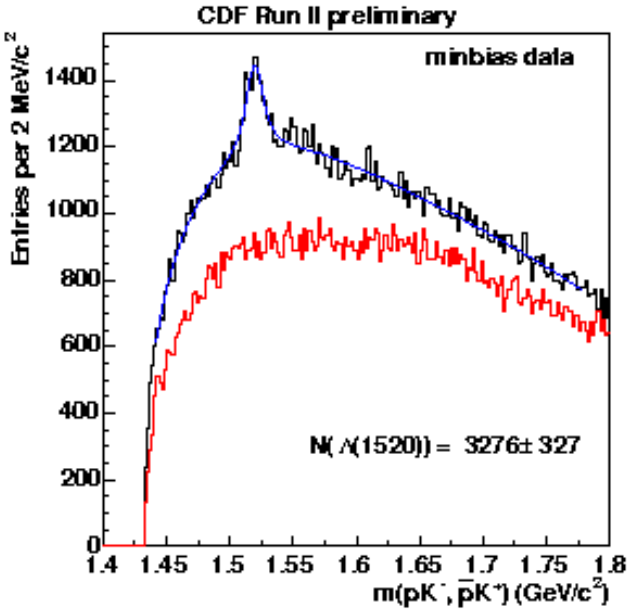
(in MINBIAS data)

$\phi \rightarrow K^+K^-$



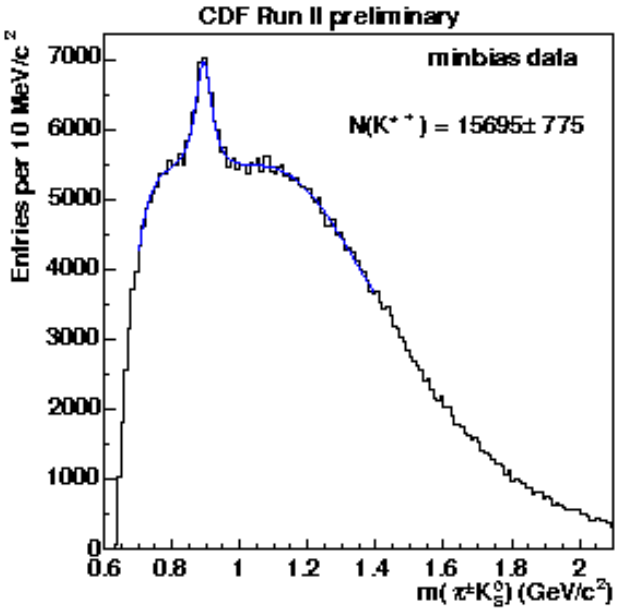
19721 ϕ candidates

$\Lambda(1520) \rightarrow pK^-$



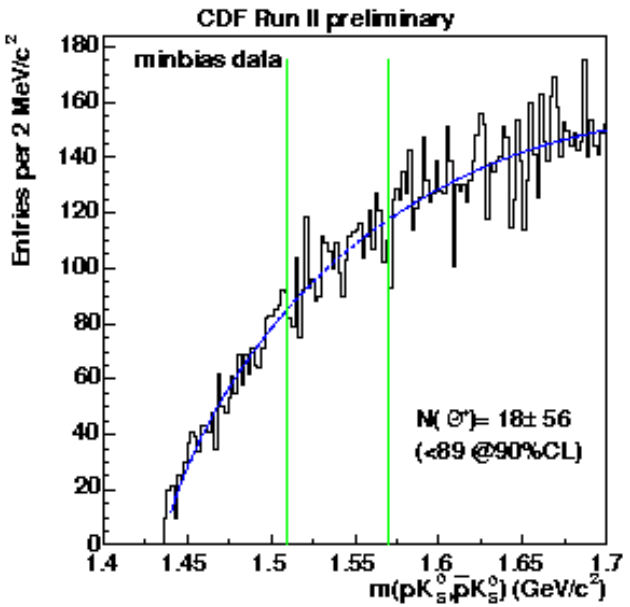
3276 $\Lambda(1520)$ candidates

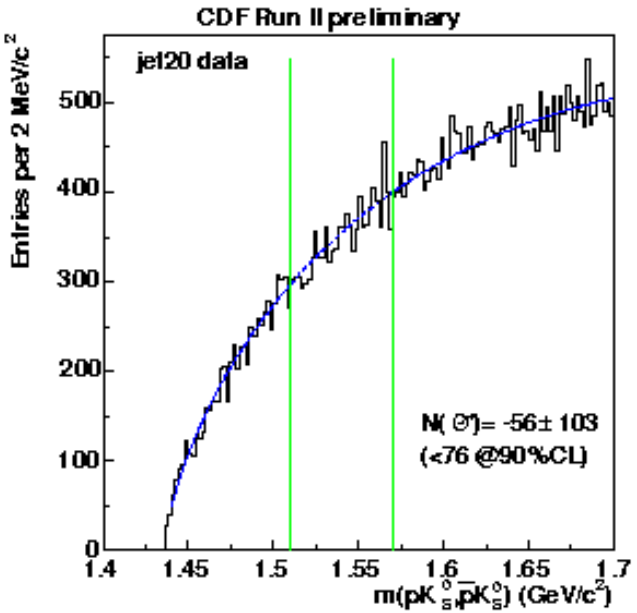
$K^{*+} \rightarrow \pi^+ K_s$

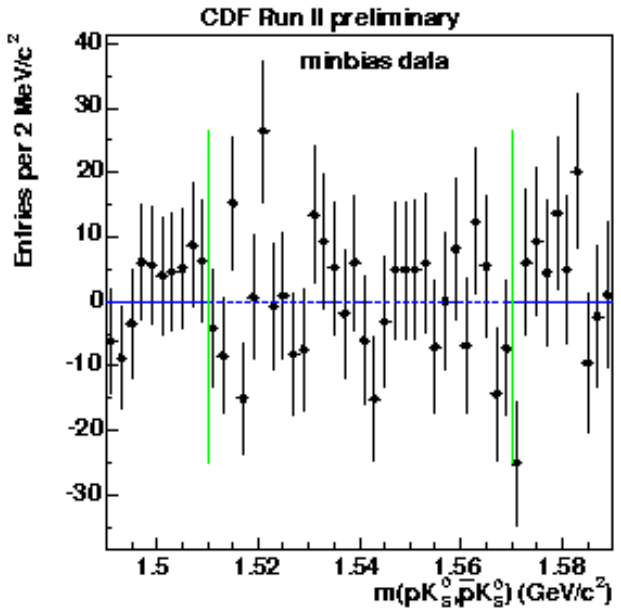


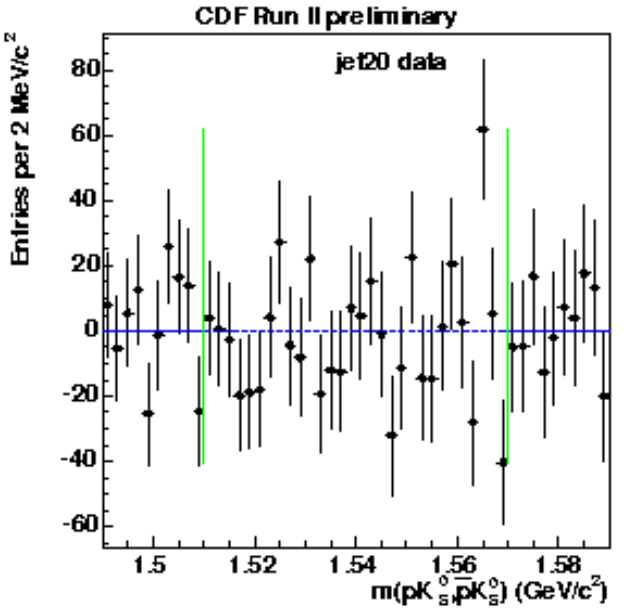
15695 K^{*+} candidates

Θ^+ Search: pK_s Invariant Mass









MINBIAS

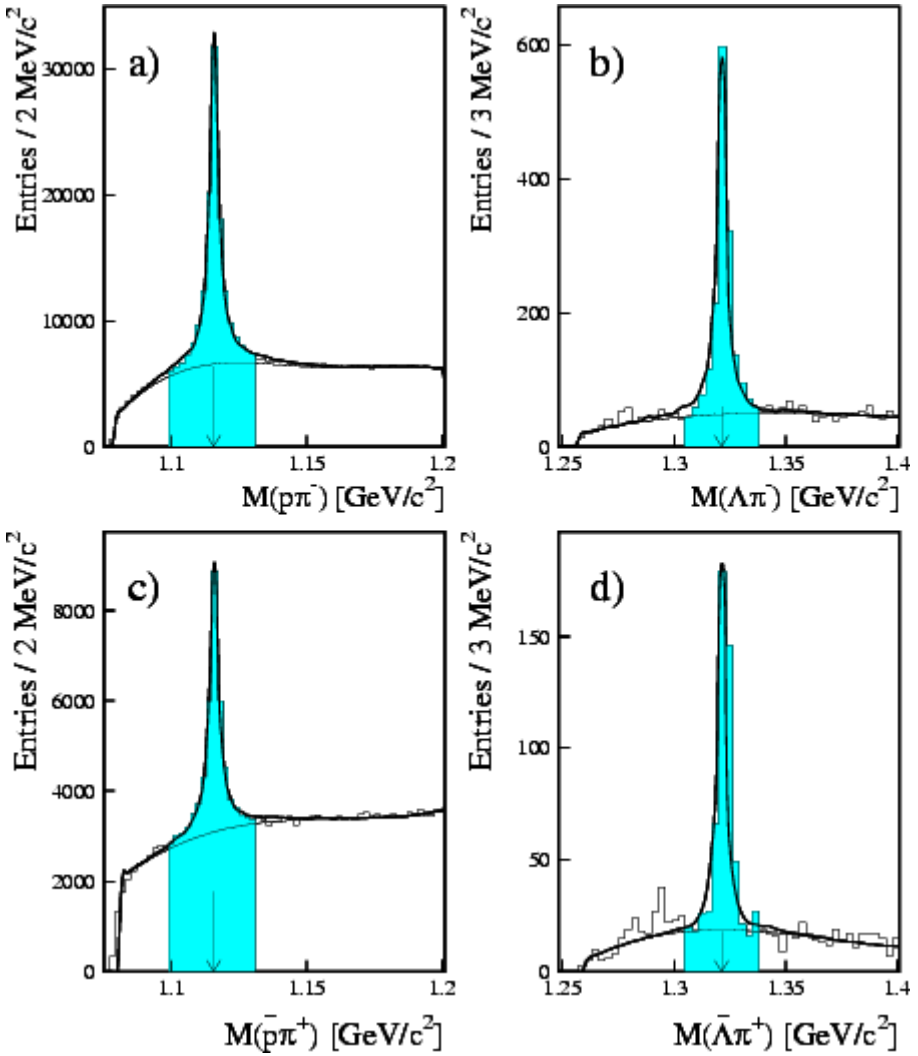
JET20

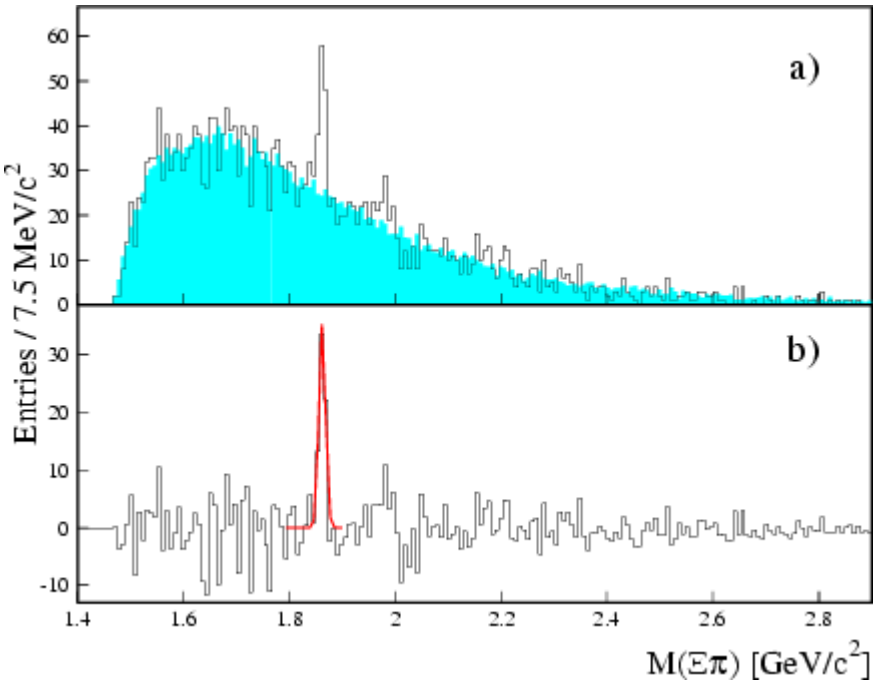
Θ^+ Search: Yields/Limits

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

$\Xi_{3/2}^{--,0}$ Evidence from NA49

$\Xi_{3/2}^{--,0} \rightarrow \Xi^-\pi^{-,+}$ with $\Xi^- \rightarrow \Lambda\pi^-$ and $\Lambda \rightarrow p\pi^-$





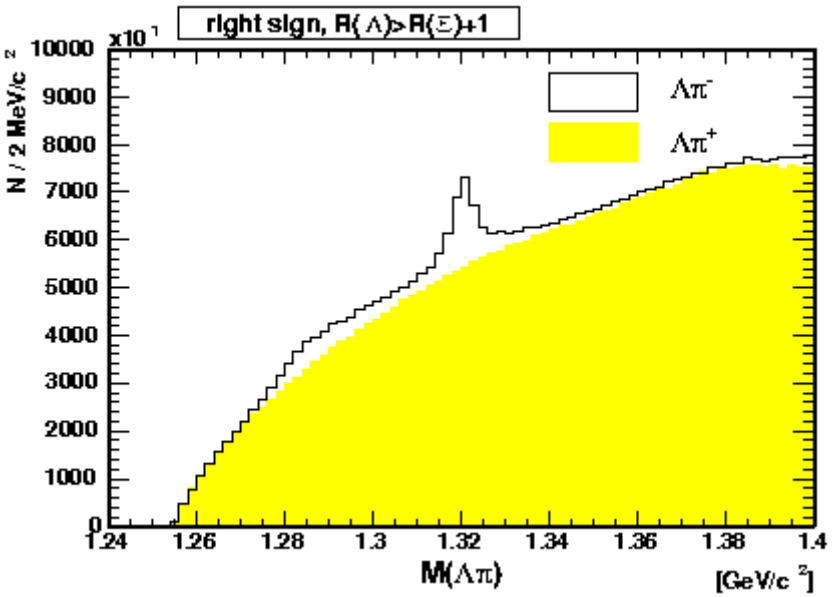
Mass = 1862 ± 2 MeV/c^2

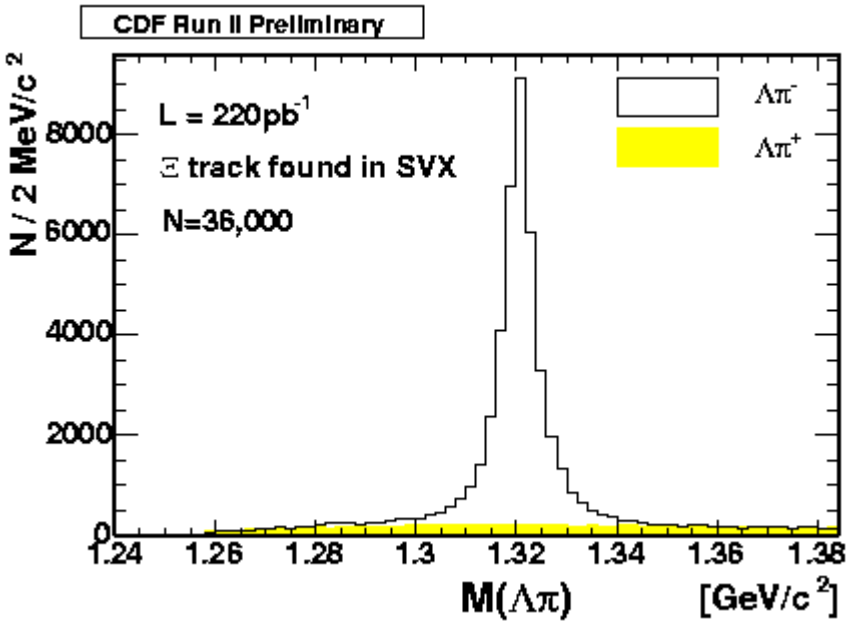
Width = 7.2 ± 1.2 MeV/c^2,
consistent with detector resolution

Silicon Tracked Hyperon Signals

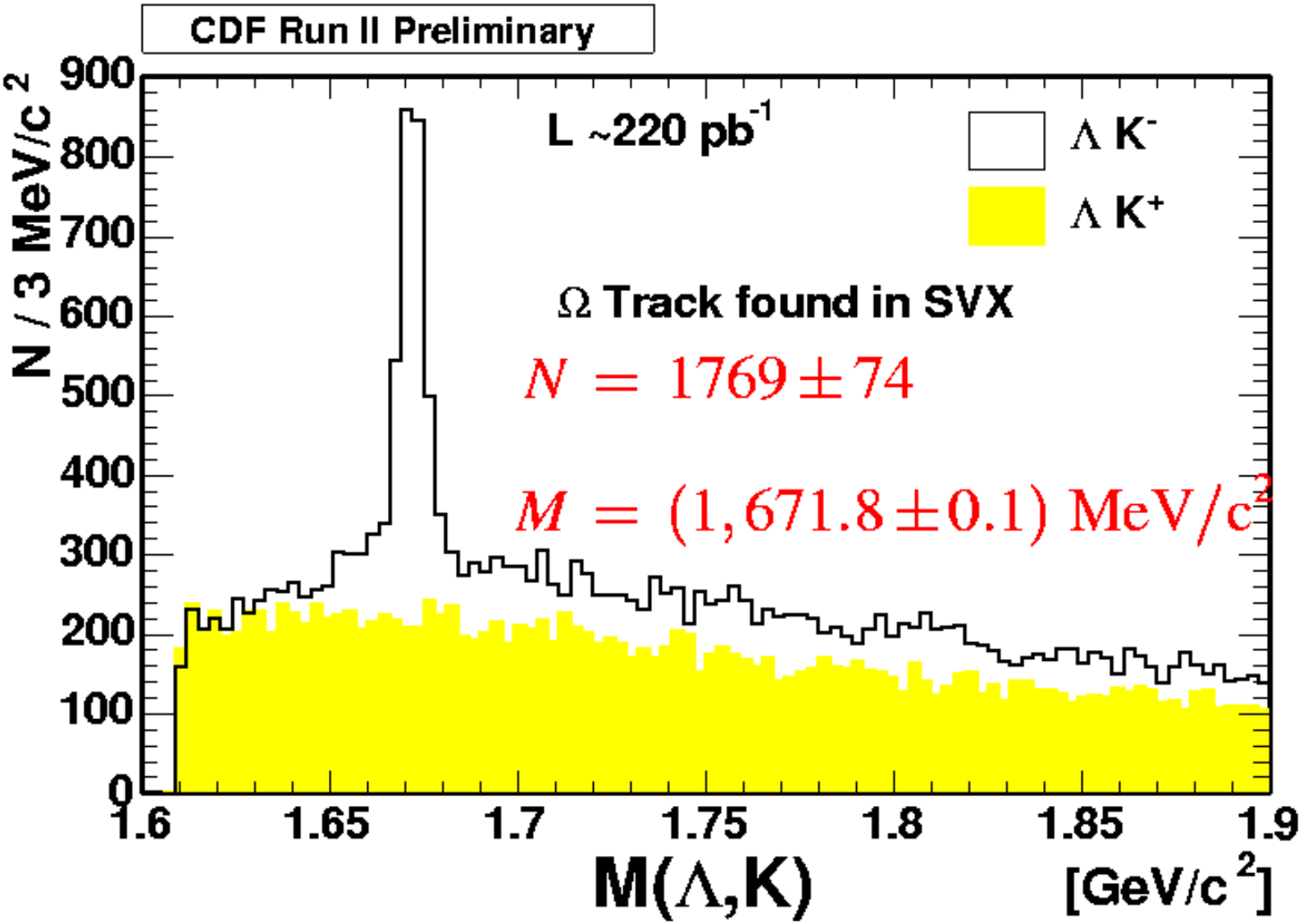
$\Xi^- \to \Lambda\pi^-$ leaves tracks with hits in our Si detector ($c\tau$=4.91 cm)

Dedicated hyperon tracking substantially reduces backgrounds

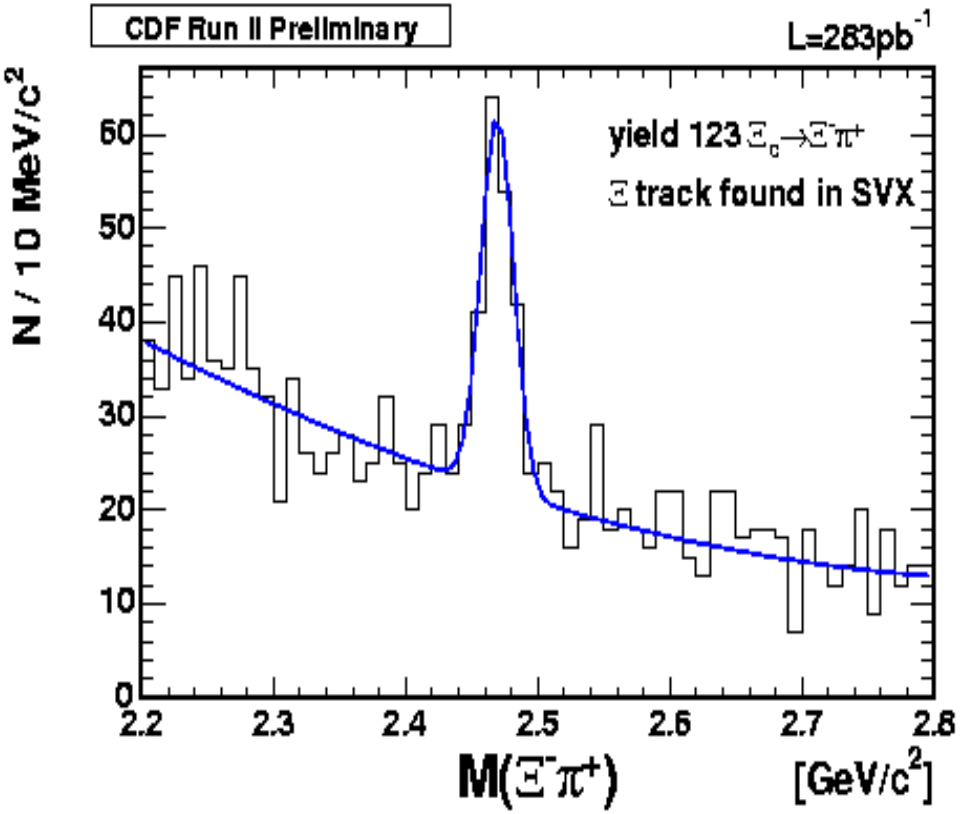


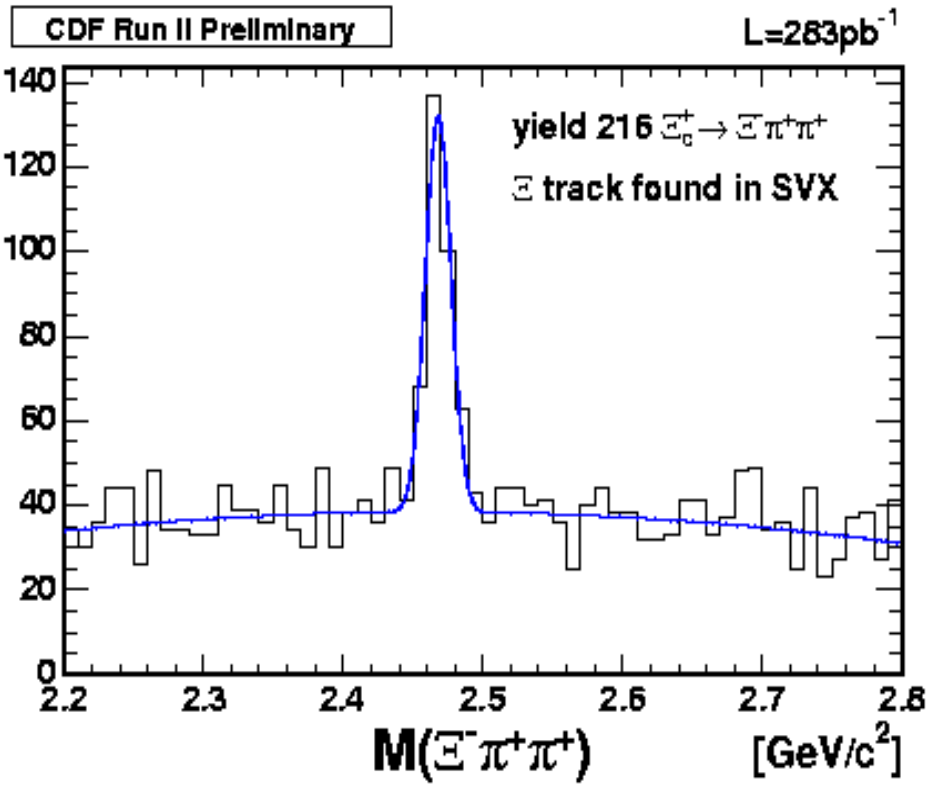


Ω^- Reconstructed in SVX



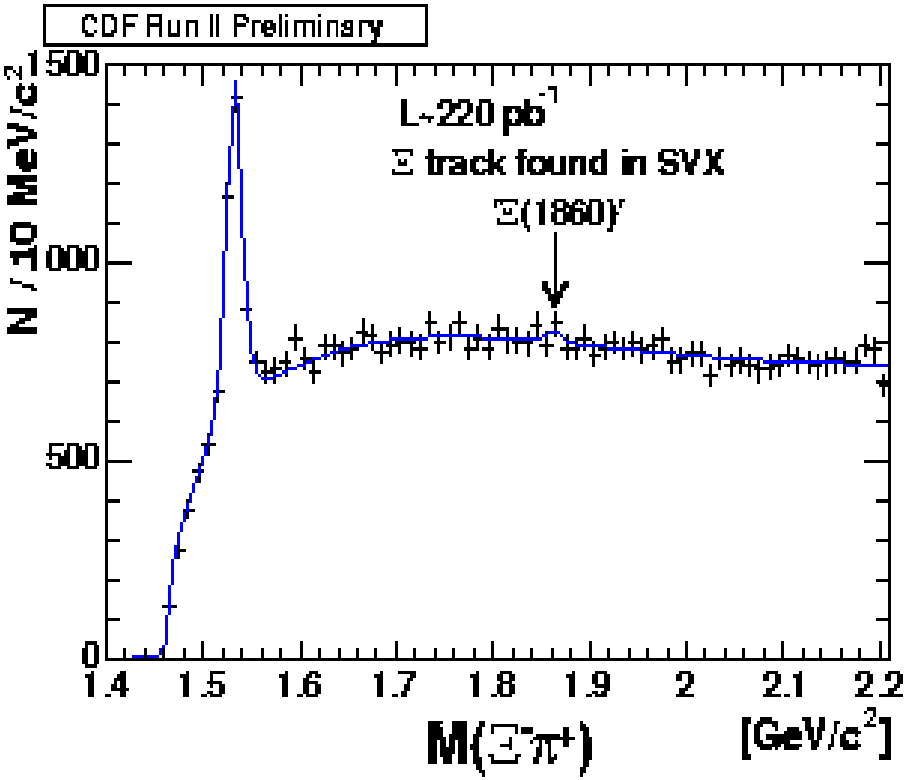
Charmed Cascades

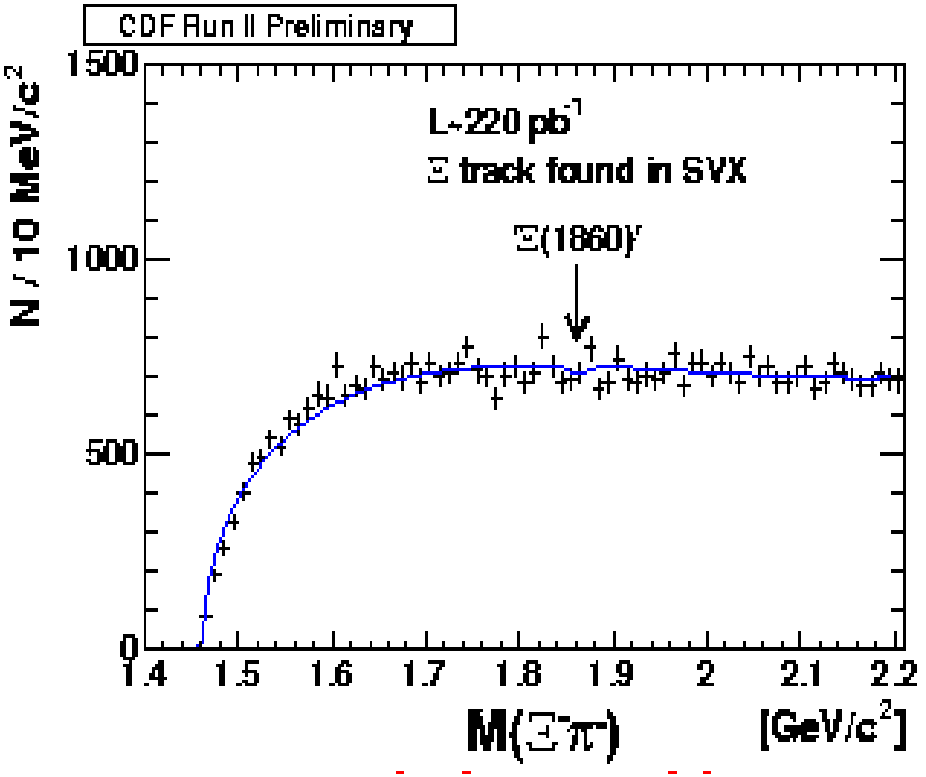




Signals from Ξ_c^0 and Ξ_c^+ : First Observation in $p\bar{p}$ collisions

$\Xi^-\pi^+$ Mass (Hadronic Trigger)



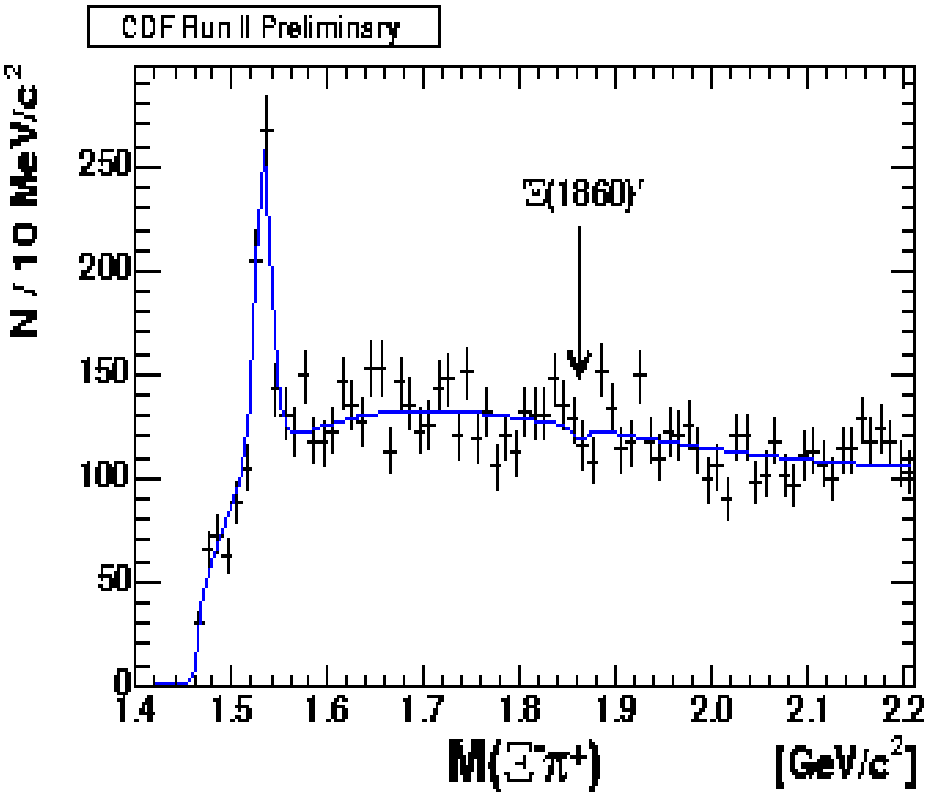


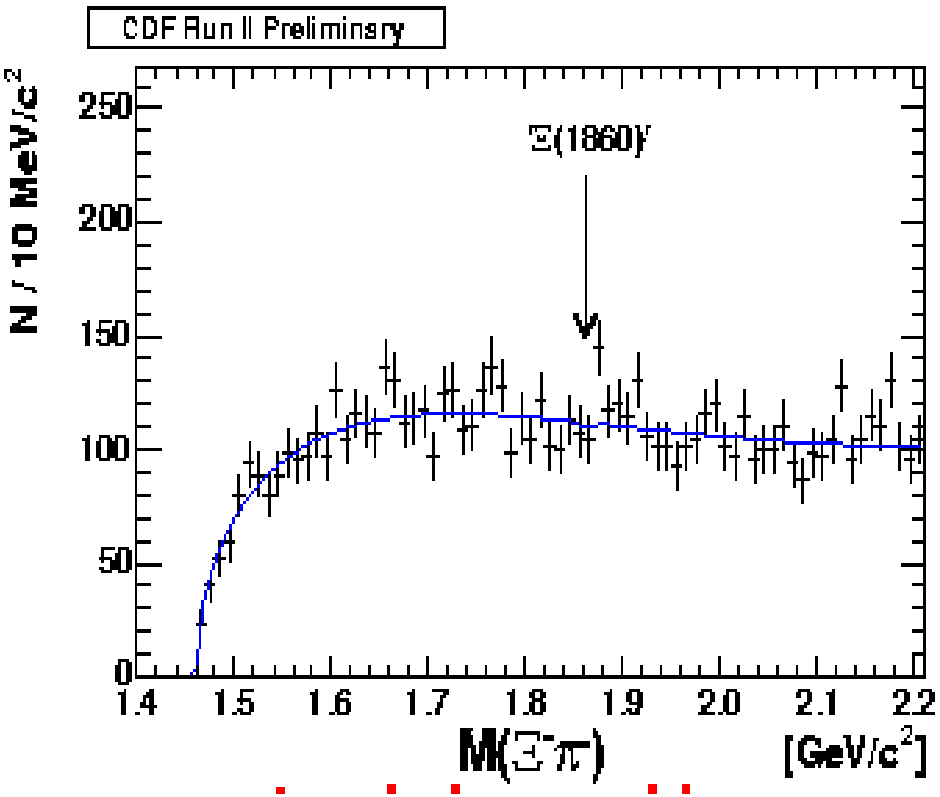
No PQ signals found

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)

$\Xi^-\pi^\pm$ Invariant Mass (Jet20)





No PQ signals found

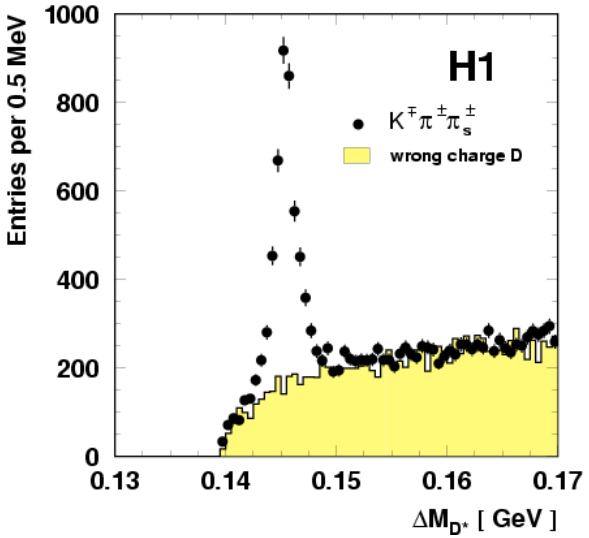
Channel	# of events	90 % CL	relative yield
$\Xi^-\pi^+$	-14±19	25	0.08
$\Xi^-\pi^-$	-4±18	28	0.09

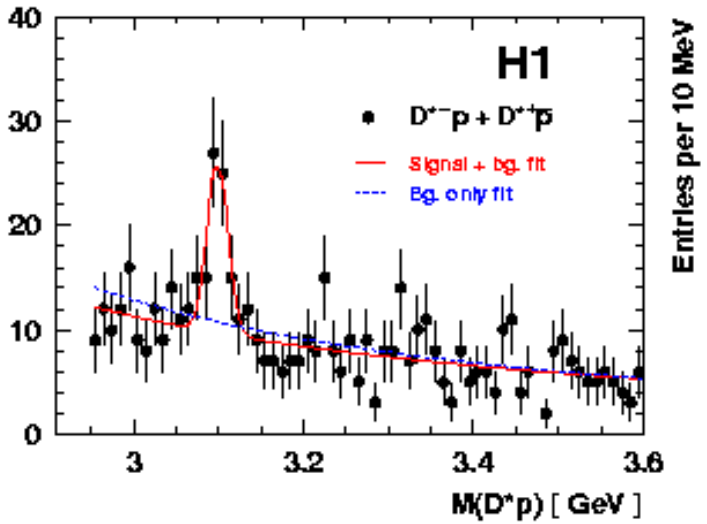
(Relative yields of $\Xi(1860)/\Xi(1530)$ assuming equal detector efficiency)

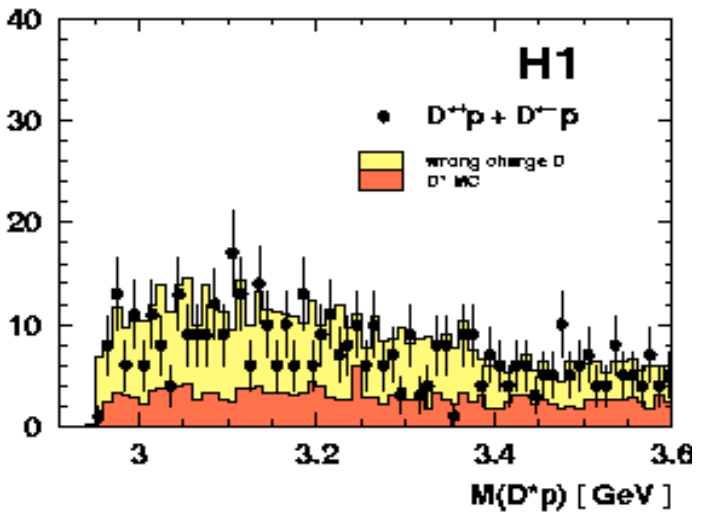
Θ_c^0 Evidence from H1

$\Theta_c^0 \to D^{*-}\pi^{-,+}$ with $D^{*-} \to D^0\pi^-$ and $D^0 \to K^+\pi^-$

$\gamma^* p \to \Theta_c^0 X$:







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

Mass = 3099 ± 3(stat) ± 5(syst) MeV/c^2

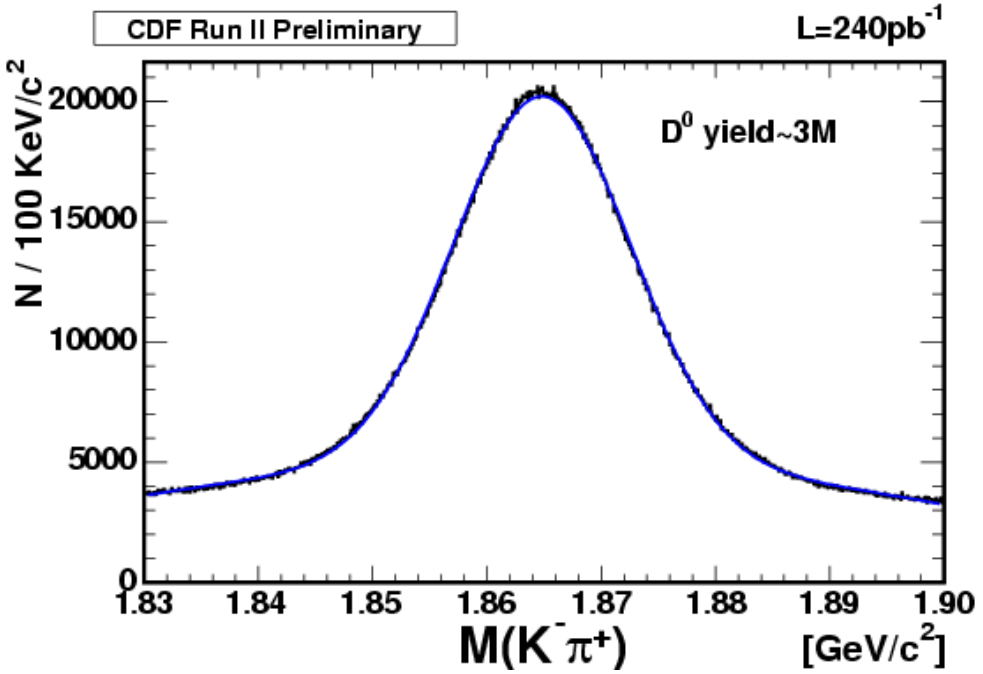
Width = 12 ± 3 (stat) MeV/c^2,
consistent with detector resolution

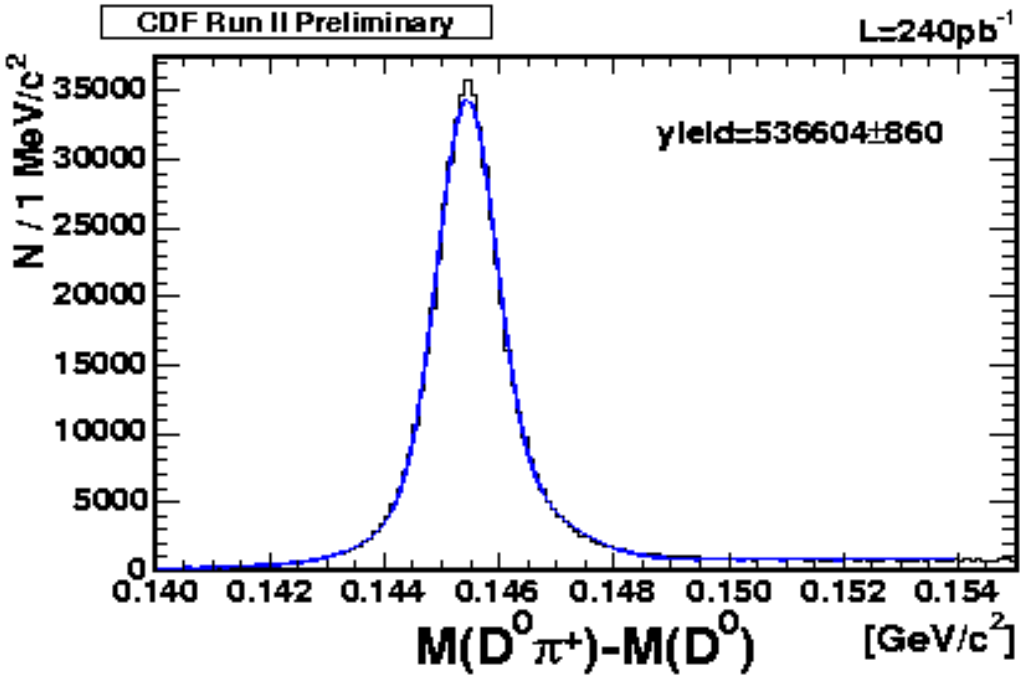
Also seen in $\gamma p \to \Theta_c^0 X$

Also not seen at Zeus

Charm Signals in Hadronic Trigger

CDF Hadronic Trigger affords us huge charm samples, both prompt and from B-decays



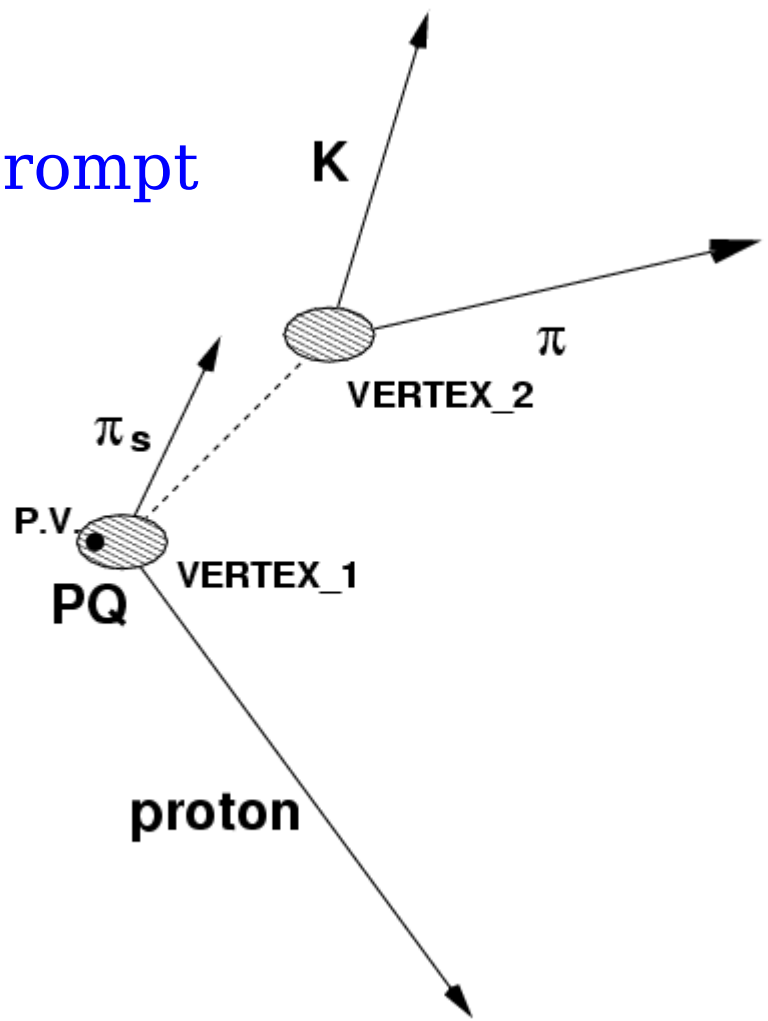


~3 million $D^0 \to K\pi$

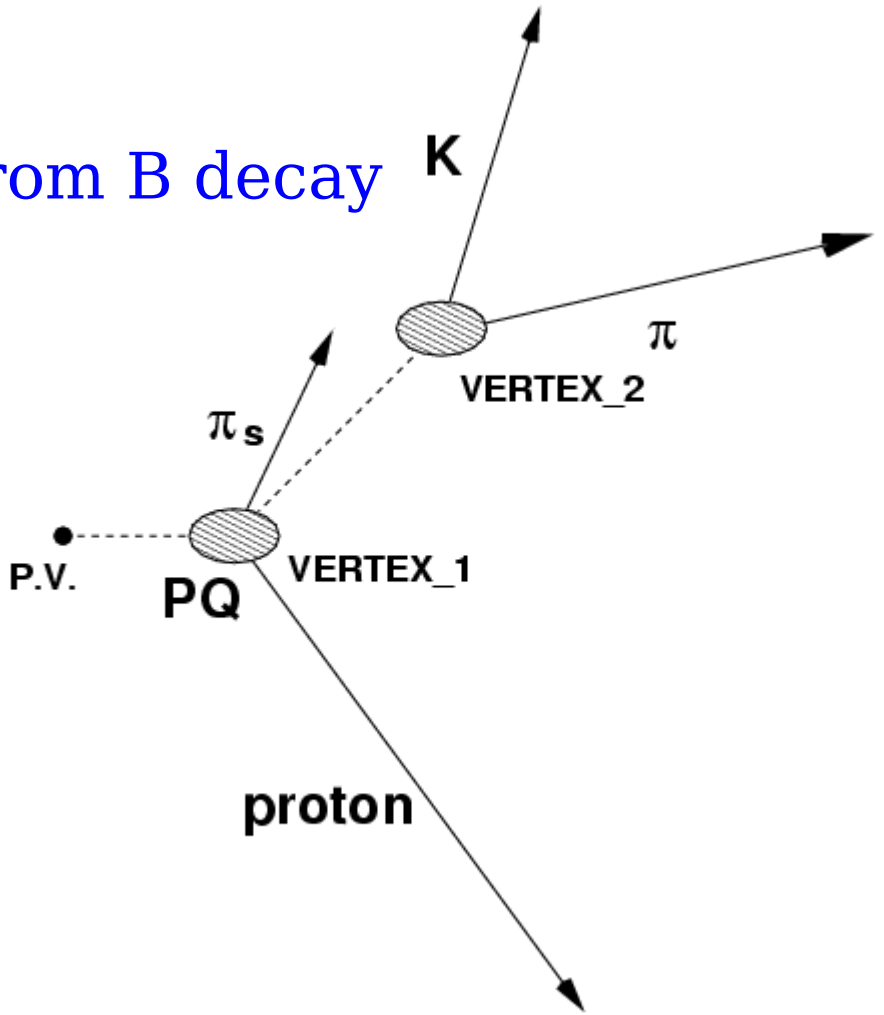
~0.54 million $D^{*+} \to D^0\pi$
(170× H1 yield)

$\Theta_c^{0,+}$: Decay Topologies

Prompt



From B decay



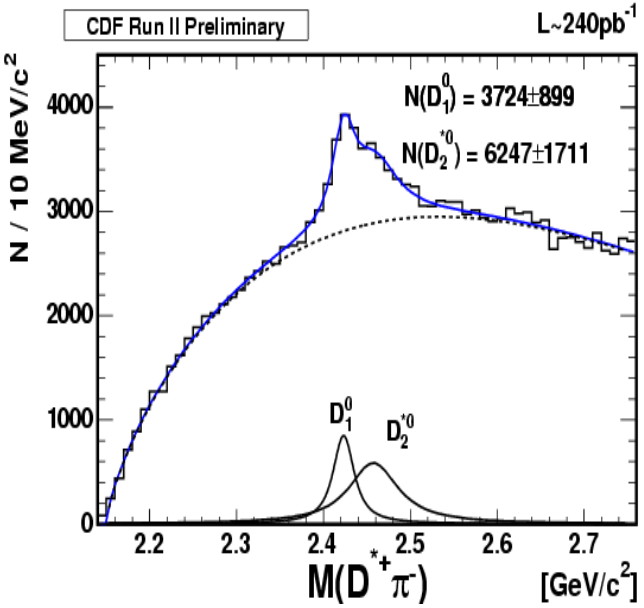
$|L_{xy}(PQ)| < 0.04\text{cm}$

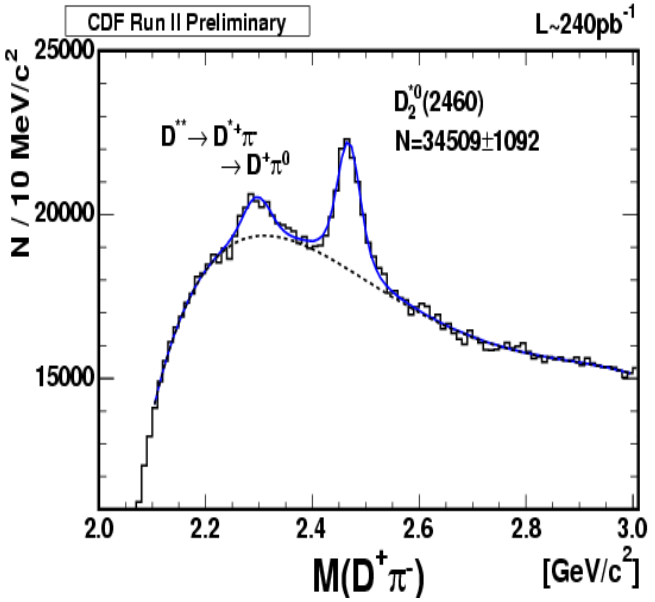
$|L_{xy}(PQ)/\sigma_{Lxy}(PQ)| < 3$

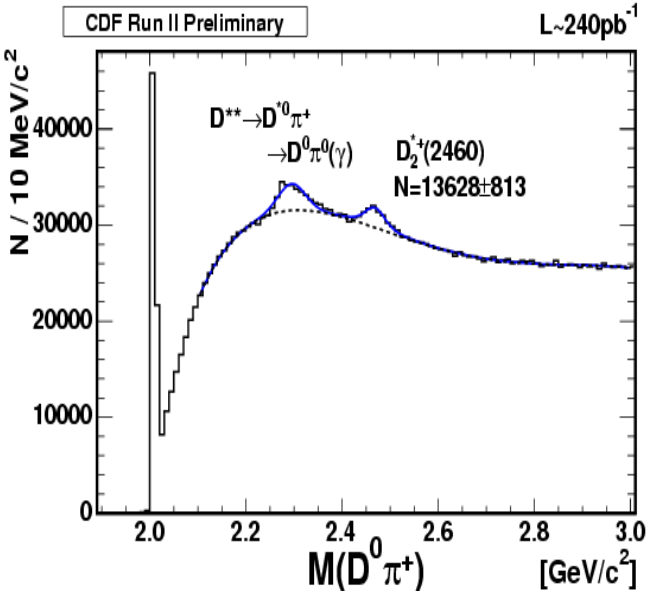
$|L_{xy}(PQ)| > 0.04\text{cm}$

$|L_{xy}(PQ)/\sigma_{Lxy}(PQ)| > 3$

$\Theta_c^{0,+}$: Reference Signals





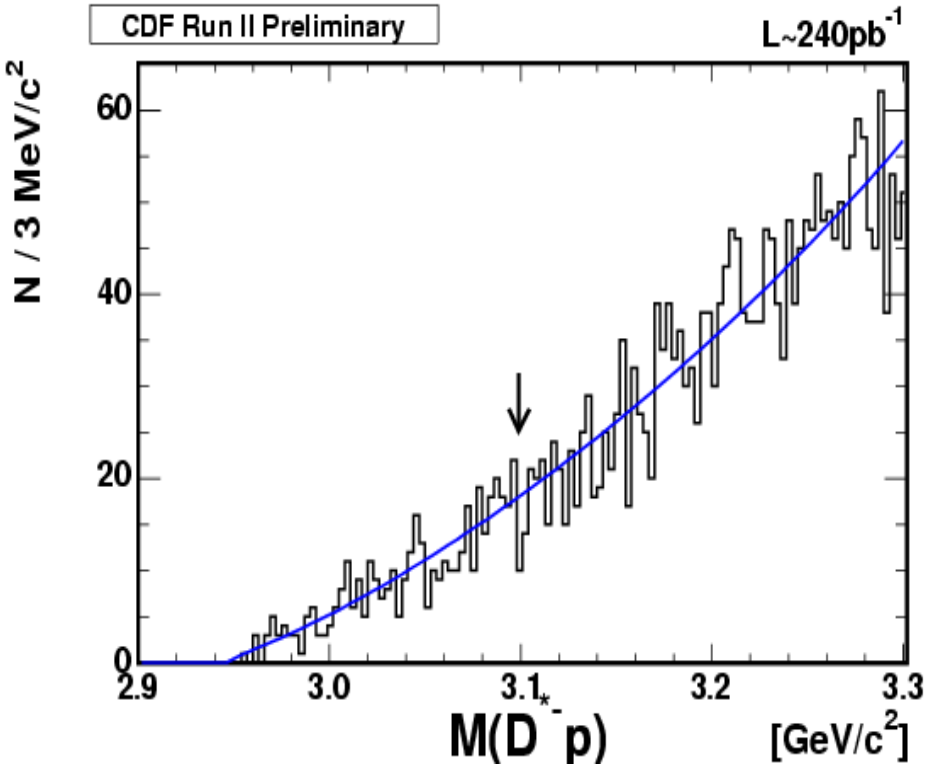


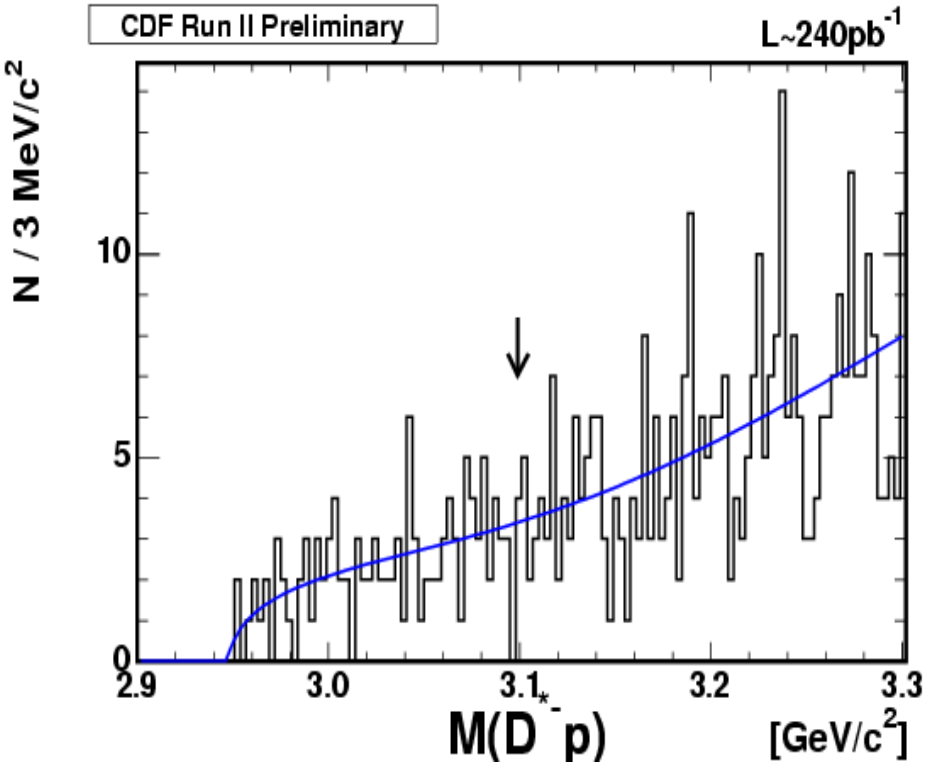
$$D^{**} \to D^{*+}\pi^- \hookrightarrow D^0\pi^+ \hookrightarrow K^-\pi^+$$

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

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

Θ_c^0: $D^{*-}p$ Invariant Mass



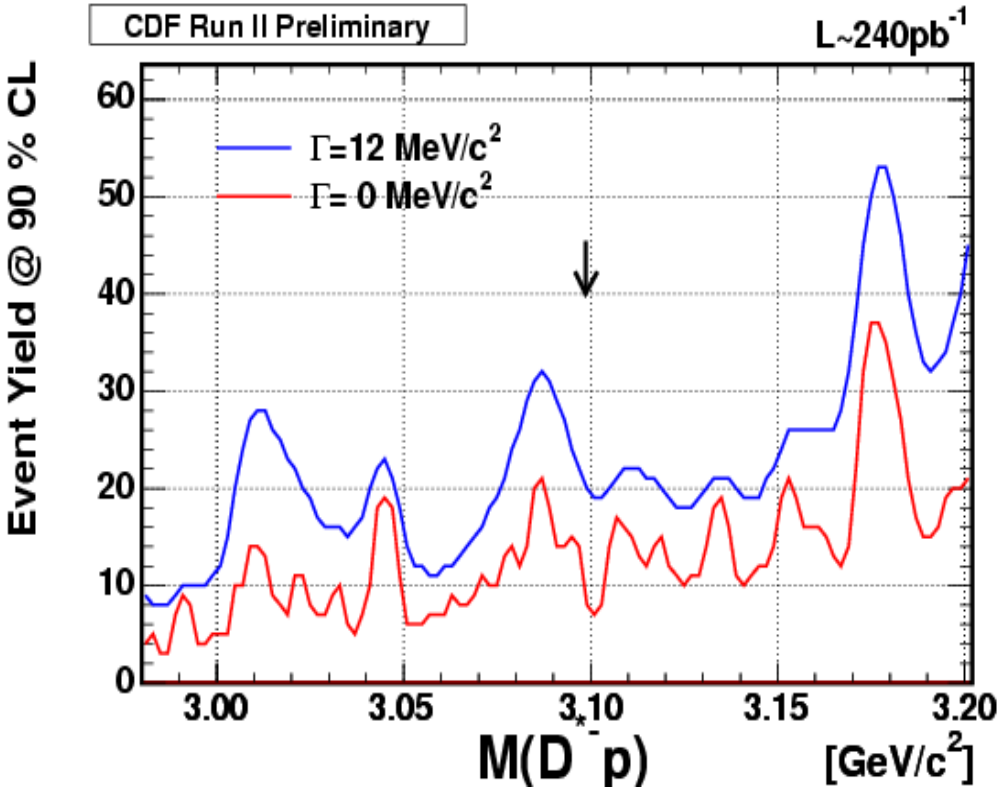


Prompt selection

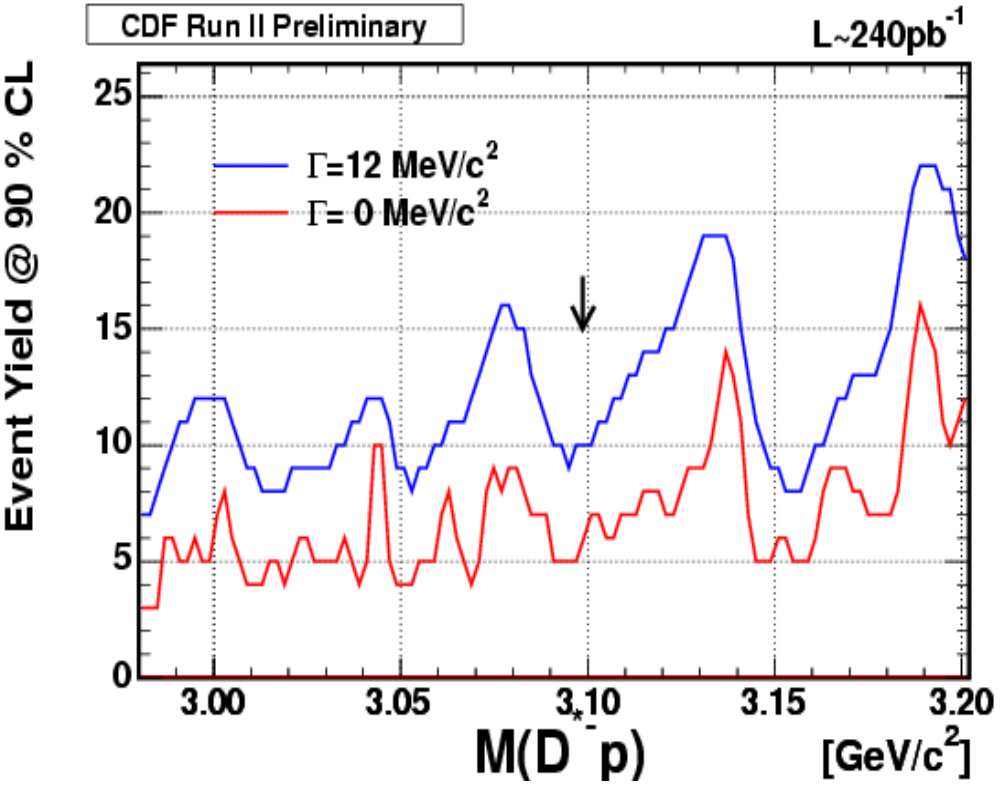
Decay from B selection

No signals observed

$\Theta_c^0 \rightarrow D^{*-}p$ Upper Limits

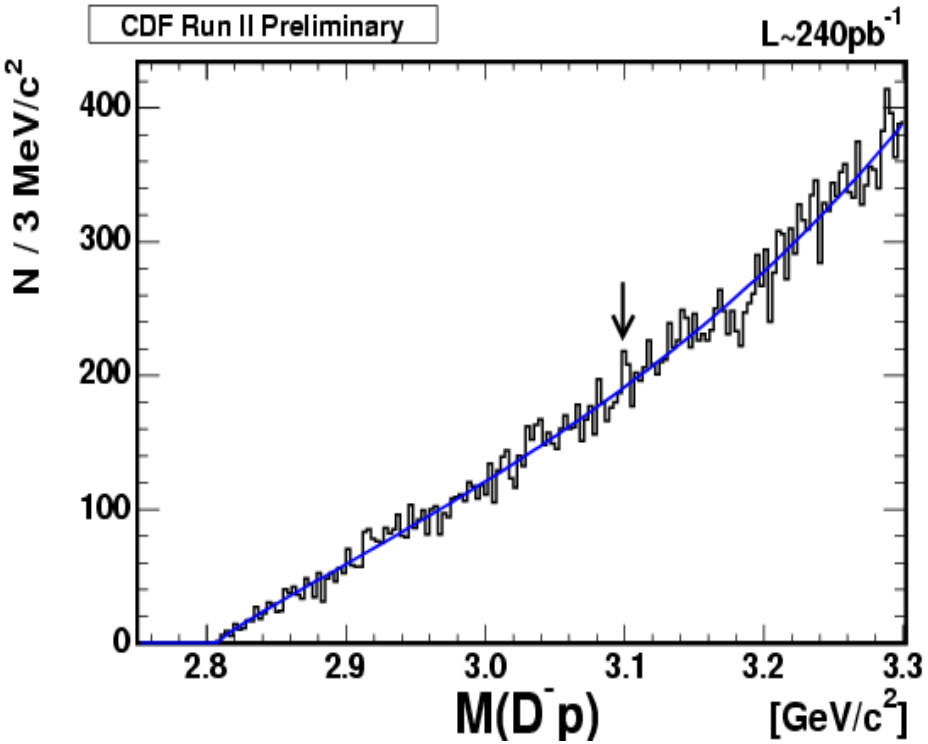


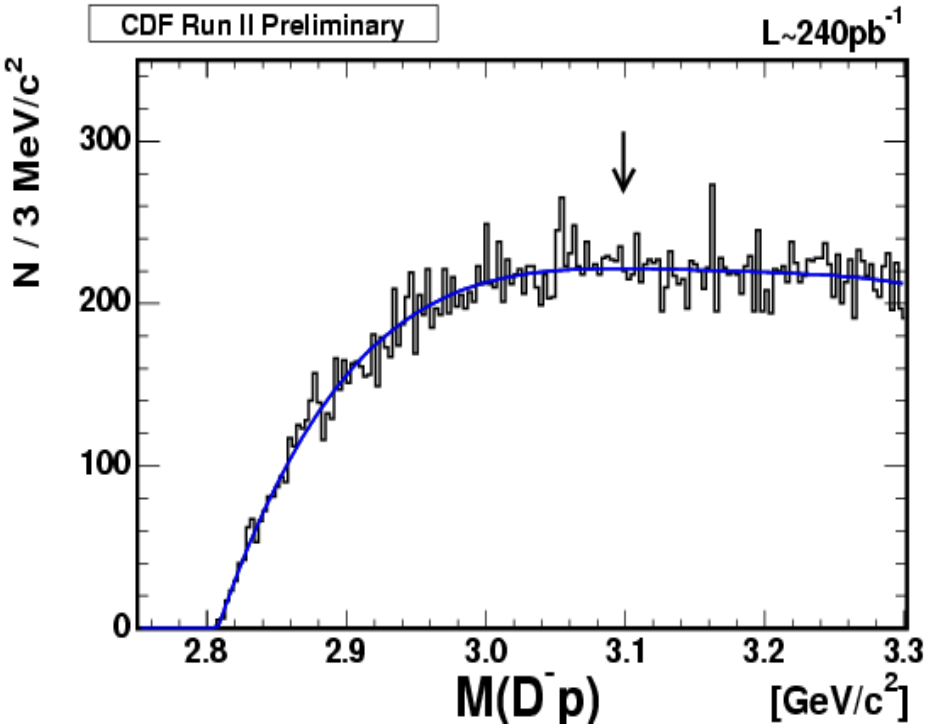
Prompt selection



Decay from B selection

Θ_c^0: D^-p Invariant Mass



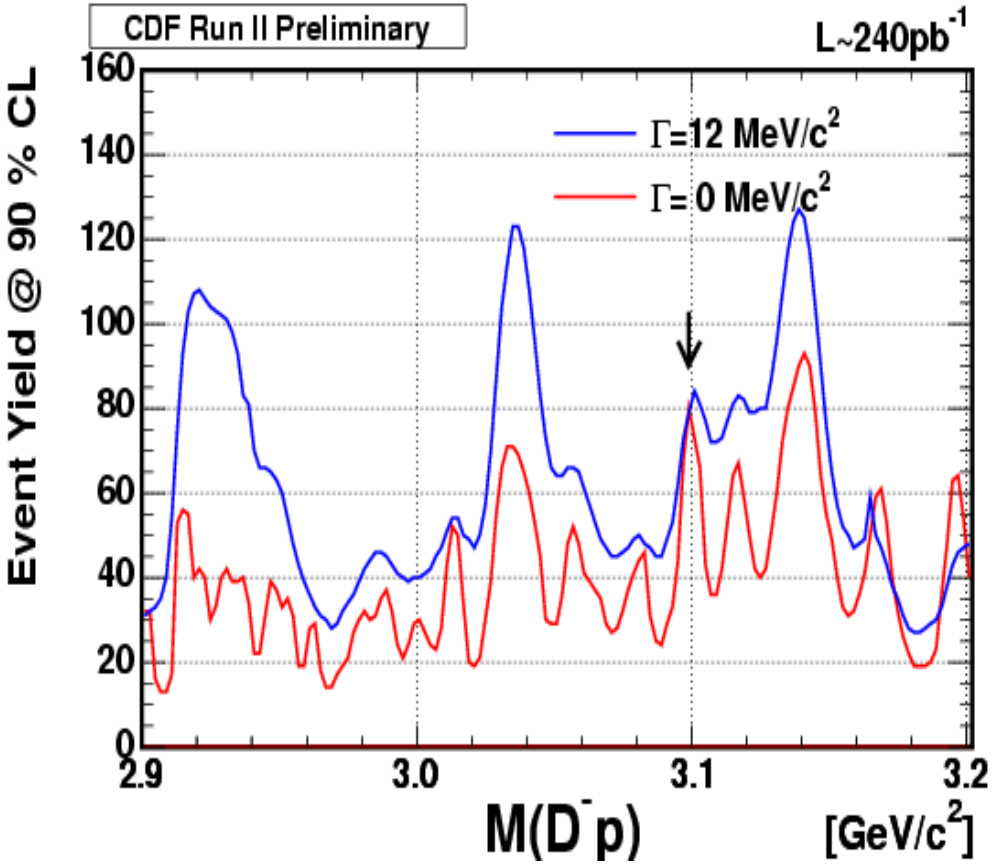


Prompt selection

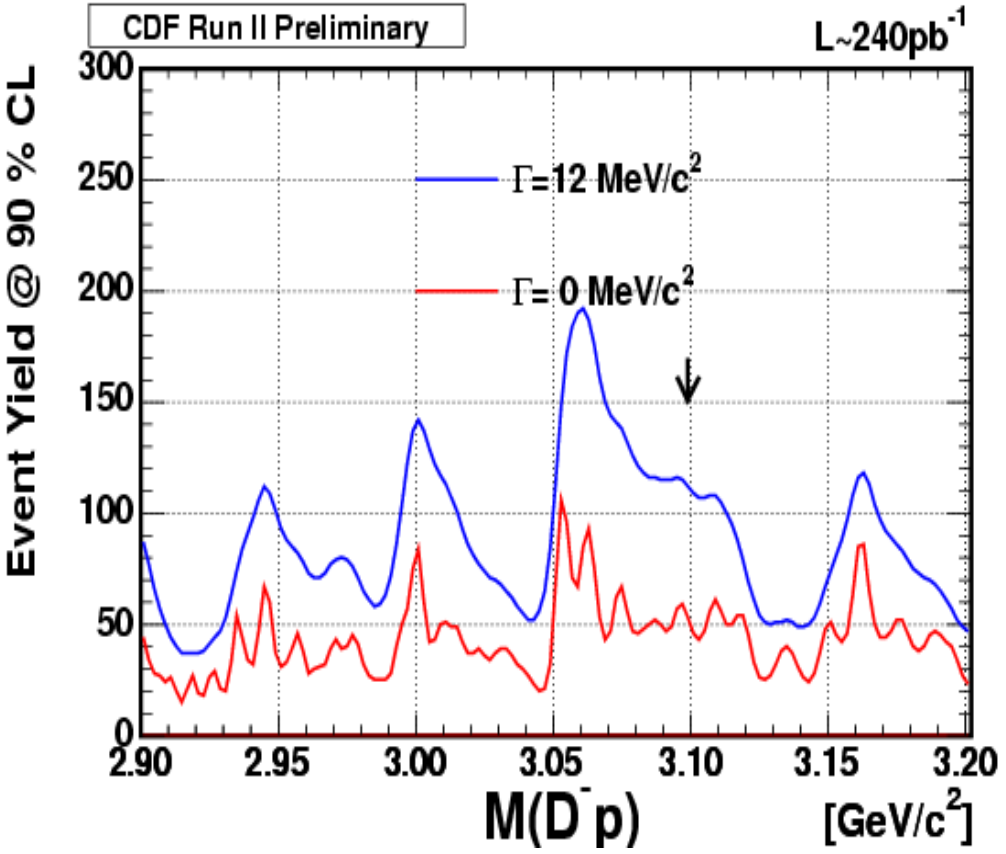
Decay from B selection

No signals observed

$\Theta_c^0 \rightarrow D^- p$ Upper Limits

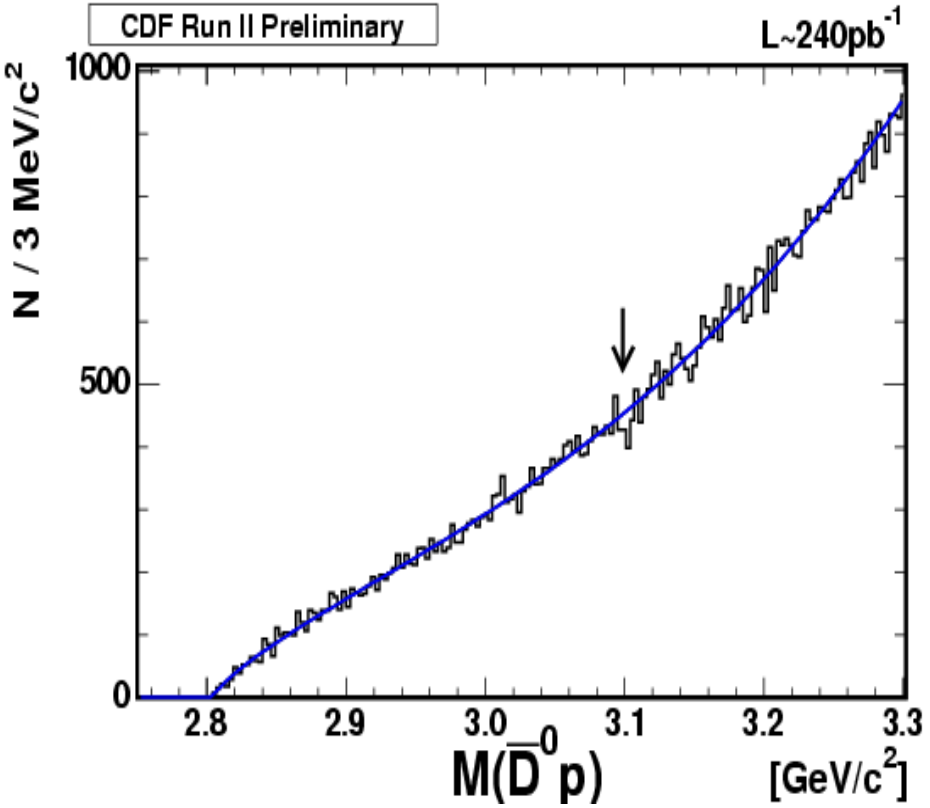


Prompt selection

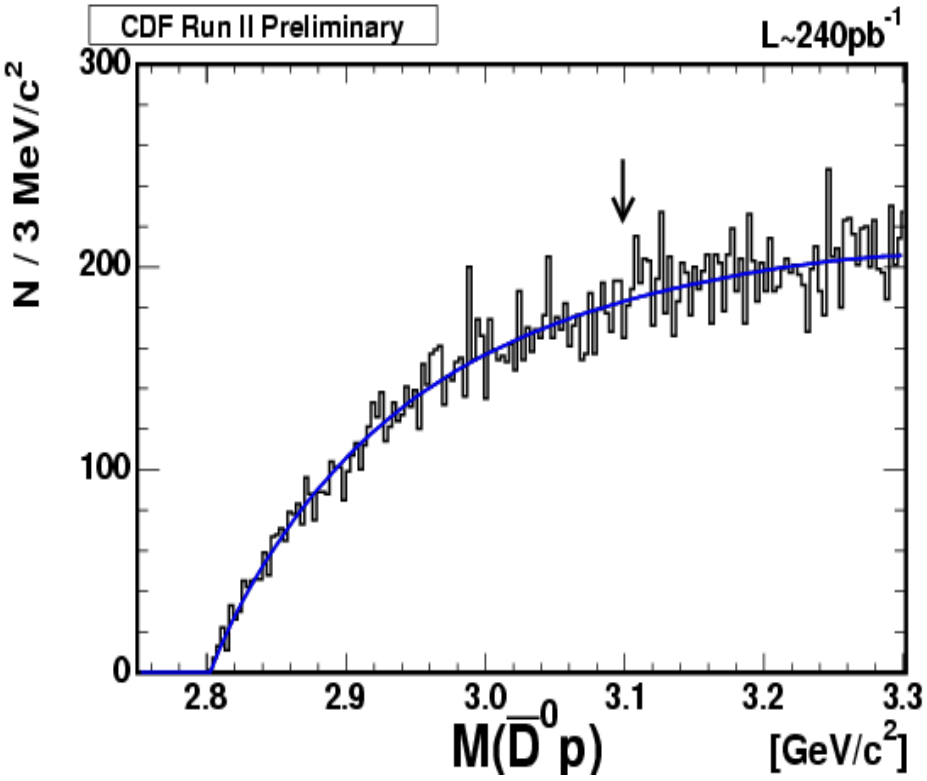


Decay from B selection

Θ_c^+: D^0p Invariant Mass



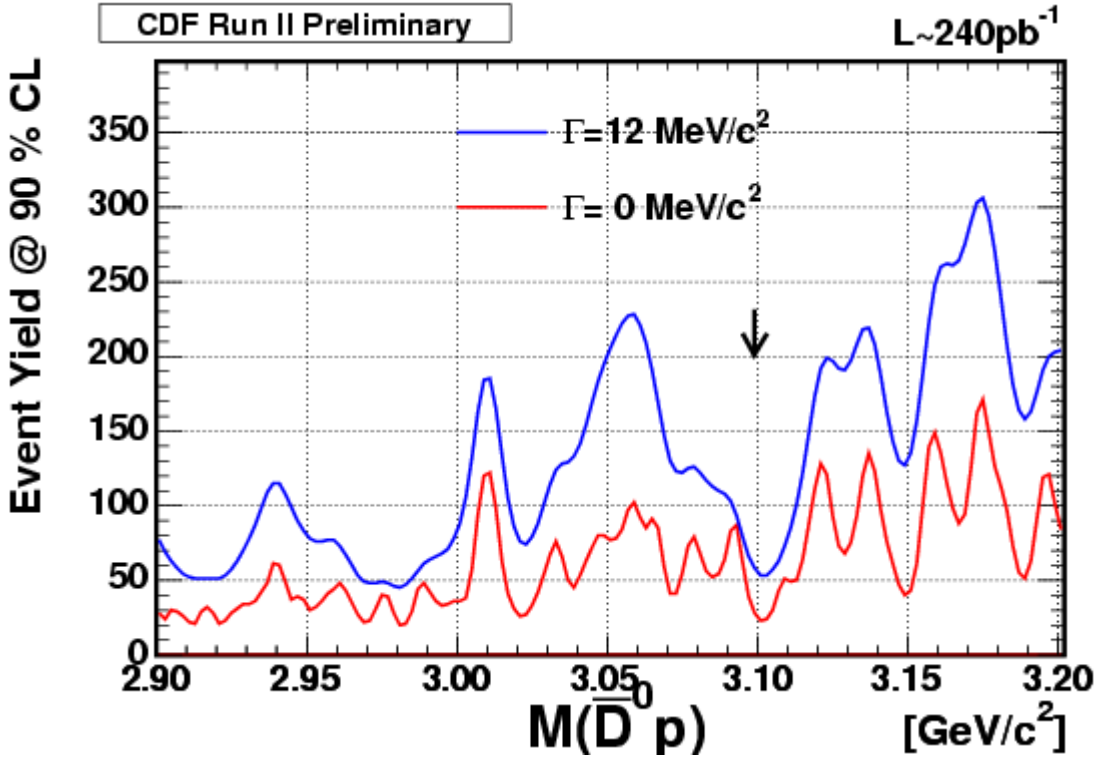
Prompt selection



From B selection

No signals observed

$\Theta_c^0 \to D^0 p$ Upper Limits



Prompt selection

Θ_c^0 Search Summary

Search window 3.099 ± 18 MeV/c^2

Take worst limit from UL versus mass inside search window

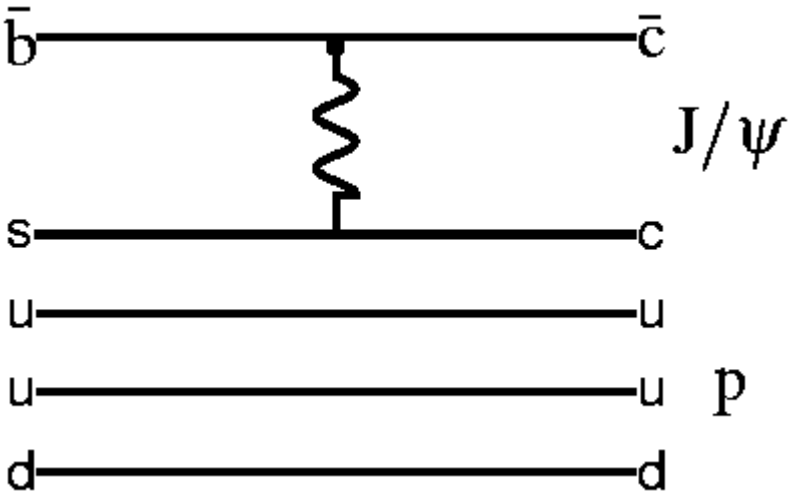
Reference channel		Search channel	
$D_2^{*0} \to D^{*+}\pi^-$	6247 ± 1711	$\Theta_c^0 \to D^{*-}p$	< 21 @ 90% CL
$D_2^{*0} \to D^{+}\pi^-$	34509 ± 1092	$\Theta_c^0 \to D^{-}p$	< 89 @ 90% CL
$D_2^{*+} \to D^{0}\pi^+$	13628 ± 813	$\Theta_c^+ \to \bar{D}^0 p$	< 87 @ 90% CL
		$\Theta_c^+ \to D^0 p$	< 97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

Search for Stable PQ

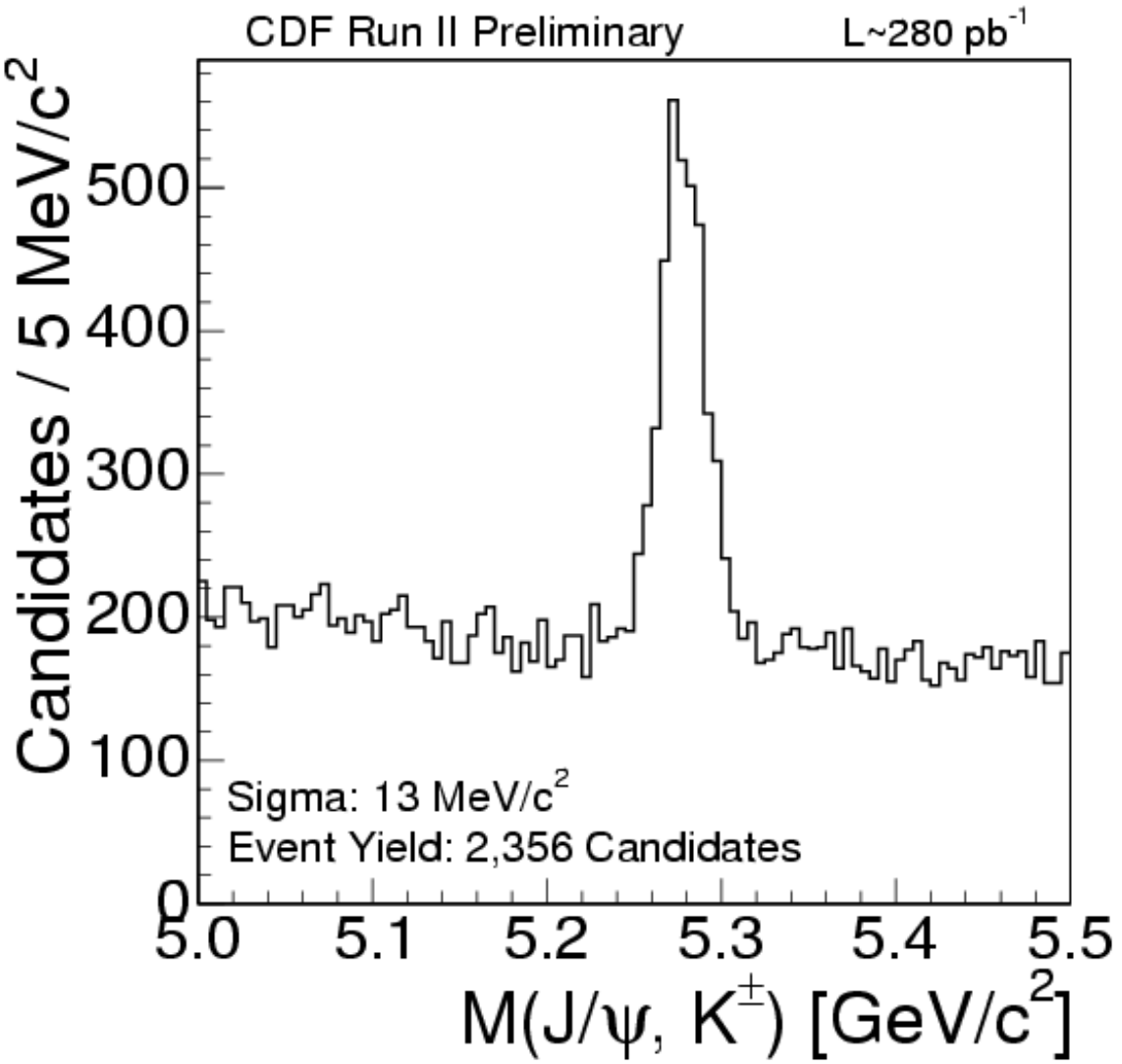
Consider R_s^+ ($uuds\bar{b}$) (notation from W.Stewart, *et. Al*, hep-ph/0402076) that is stable against strong decay:

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

Possible weak decay:



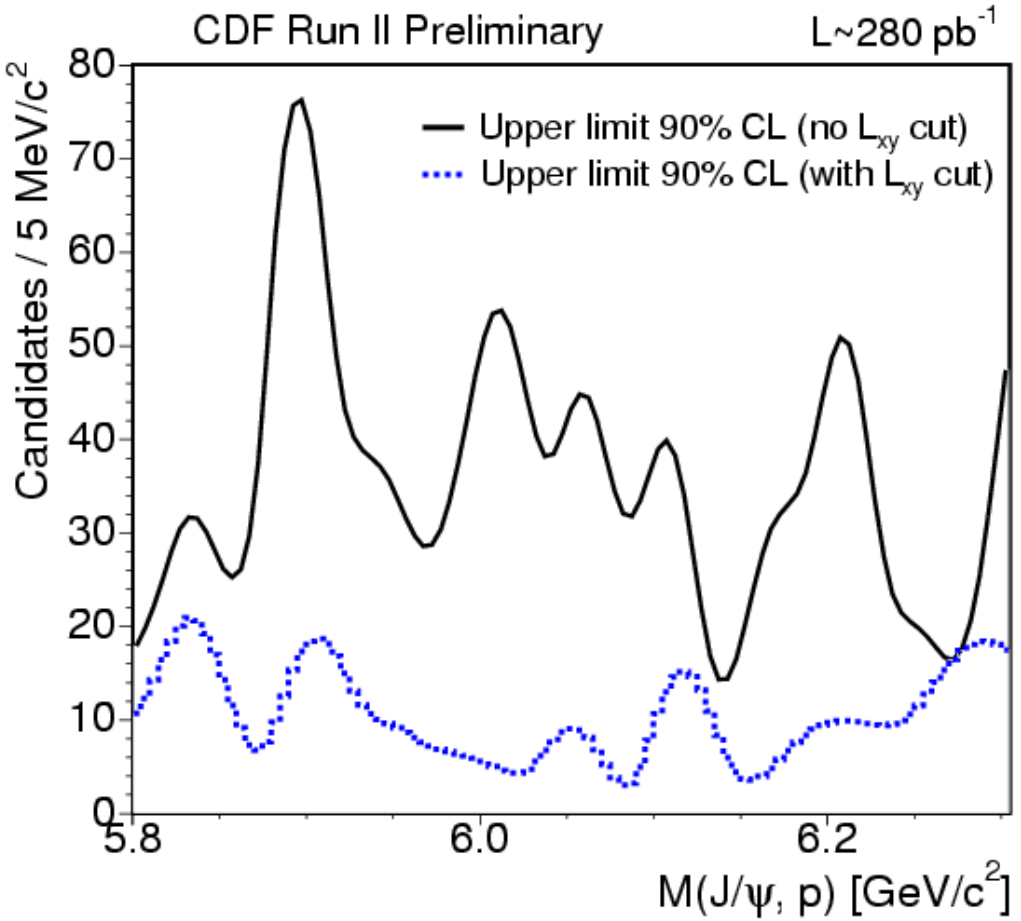
R_s^+: Reference Mode

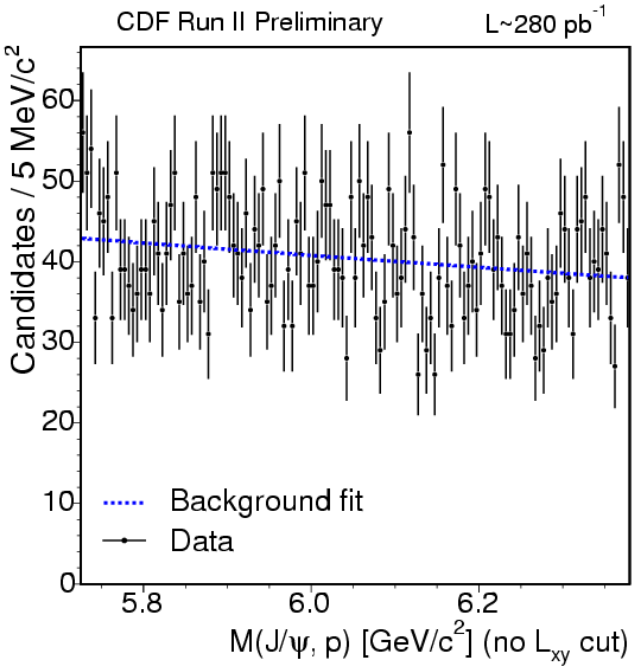


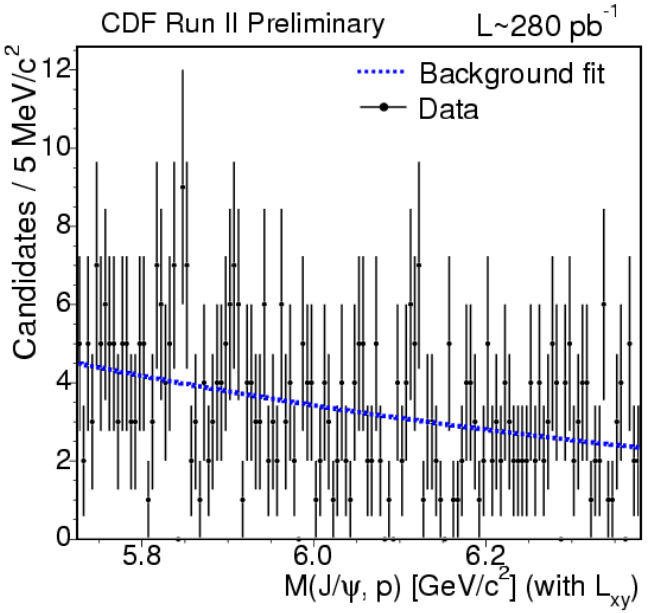
R_s^+: Invariant Mass and ULs

Two lifetimes (decay length cuts) considered:

- no Lxy cut
- |Lxy| > 100 μm







Summary and Conclusions

- CDF has searched for pentaquark states observed in other experiments. No evidence for these signals was found.
- CDF has also searched for PQ signatures that have yet to be observed, including those decaying to D^0p, D^+p, and $J/\psi p$. No signals were found.
- If pentaquarks exist, then their production in fragmentation must be highly supressed relative to normal baryon production. Exotic production mechanisms?
- We are now working on other search modes and publishing cross-section $\times$ BR limits on the modes reported in this talk.