Status of Pentaquark Searches

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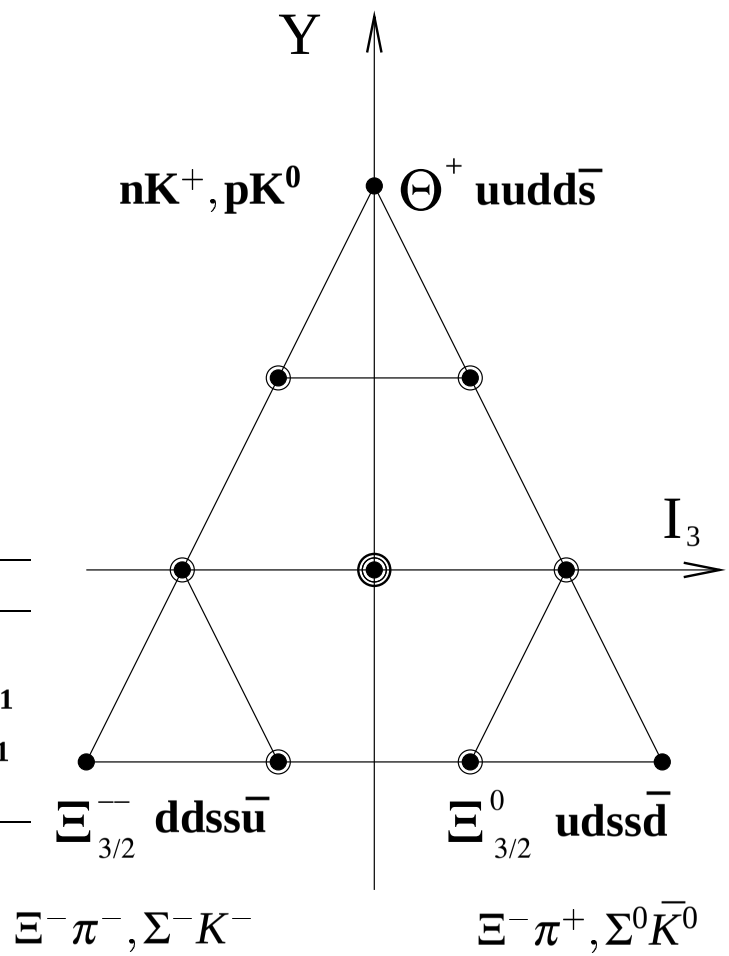
Motivation

- 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 $\sim 1540\ MeV/c^2$, 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	$\Xi(2030)$

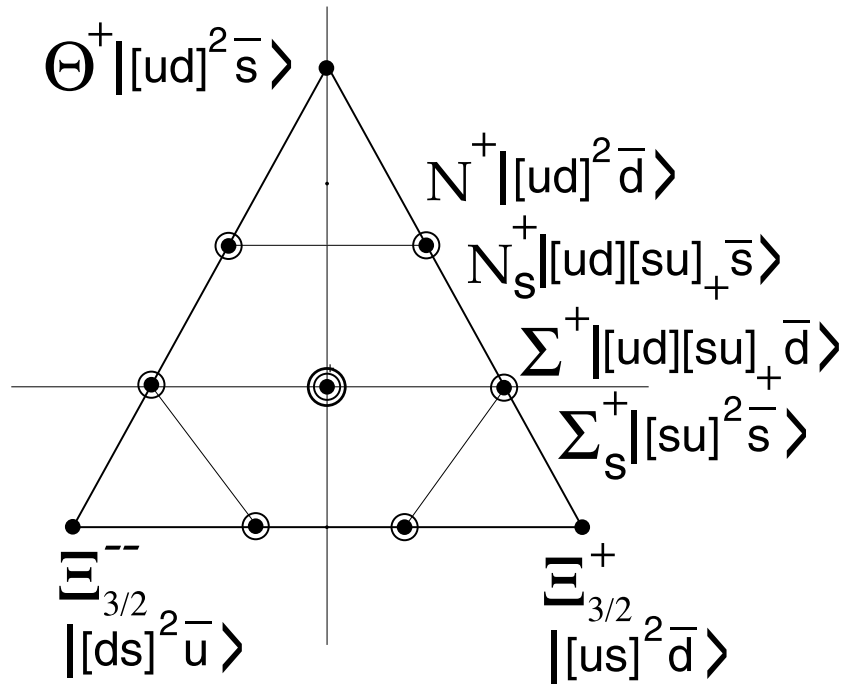
- $\mathbf{8_f} \oplus \mathbf{\bar{10}_f}$ of exotic baryons



Motivation

- In Correlated Quark approach:
  $[\mathrm{ud}]^2\bar{\mathrm{s}}$: $\underbrace{\bar{3}_f \otimes \bar{3}_f}_{\bar{6}_f} \otimes \bar{3}_f = 8_f \oplus \overline{10}_f$ (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 $\Xi^{--}_{3/2}, \Xi^{0}_{3/2}$, $M \sim 1860\ \mathrm{MeV}/c^2$, decaying to $\Xi^-\pi^-, \Xi^-\pi^+$
- H1 Experiment reported anti-charmed analogue ($uudd\bar{c}$) of the Θ^+ state decaying to $D^{*+}\bar{p}$. $M(\Theta^0_c) = (3,099 \pm 3 \pm 5)\ \mathrm{MeV}/c^2$

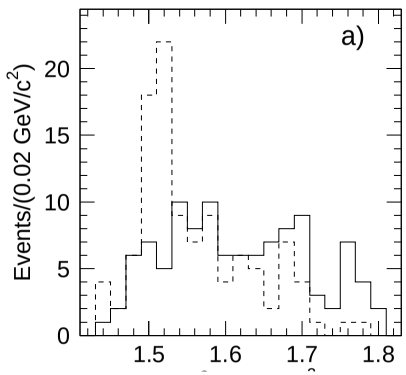


(from hep-ph/0307341 (JW))

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.

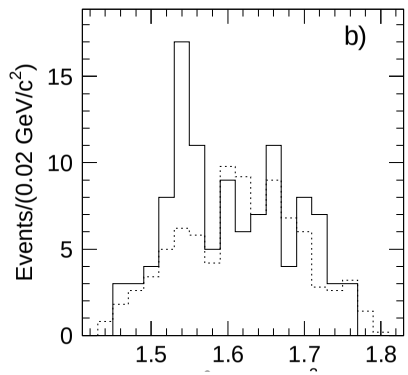
Θ^+ discovery

- LEPS experiment at SPring-8 (Japan): tagged γ produced by Compton scattering of laser beam $\mathbf{1.5GeV < E_\gamma < 2.4GeV}$
- γs hit $\mathbf{LH_2}$ $^{12}\mathbf{C}$ targets
- $\gamma n \to K^- \boxed{K^+ n}$
- $\gamma p \to K^+ K^- p$ (veto on proton in SSD)
- remove ϕ $1 < M(K^+K^-) < 1.04\ GeV/c^2$



$\mathbf{MM_{\gamma,K^+}[GeV/c^2]}$

dashes $\gamma p \to K^+\Lambda(1520)$
solid - proton veto



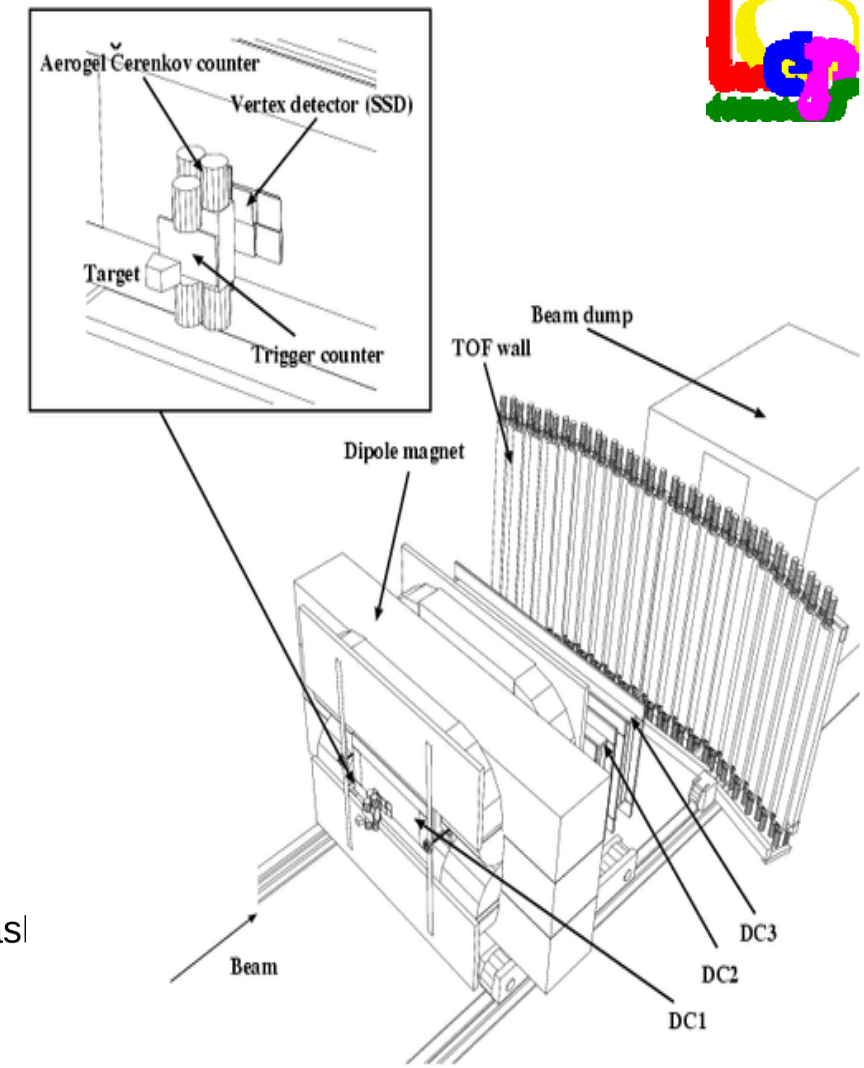
$\mathbf{MM_{\gamma,K^-}[GeV/c^2]}$

proton veto(solid),$\mathbf{LH_2}$ (das

$S = 19.0 \pm 2.8$

$B = 17.0 \pm 2.8$

$S/\sqrt{B} = 4.6\sigma$

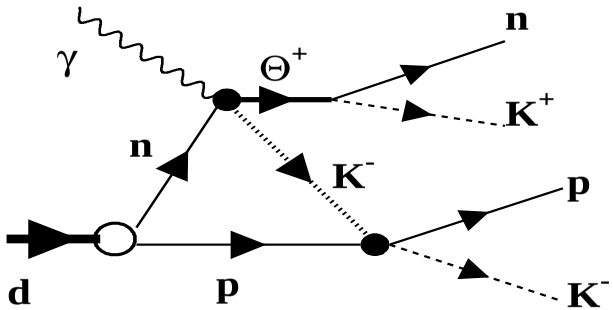


$M = (1.54 \pm 0.01(stat.) \pm 0.005(syst.))\ GeV/c^2, \Gamma < 25\ MeV/c^2$ @ 90%CL PRL,91:012002,2003

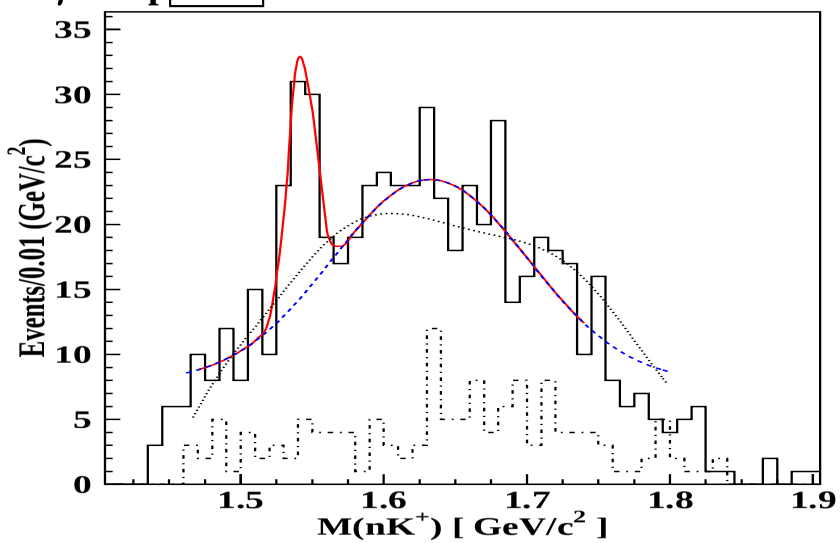
Θ^+ sightings

CLAS experiment at JLAB

- tagged γ beam $1.5\ \mathrm{GeV} < E_\gamma < 2.9\ \mathrm{GeV}$



- $\gamma d \to p\,\boxed{nK^+}\,K^-$

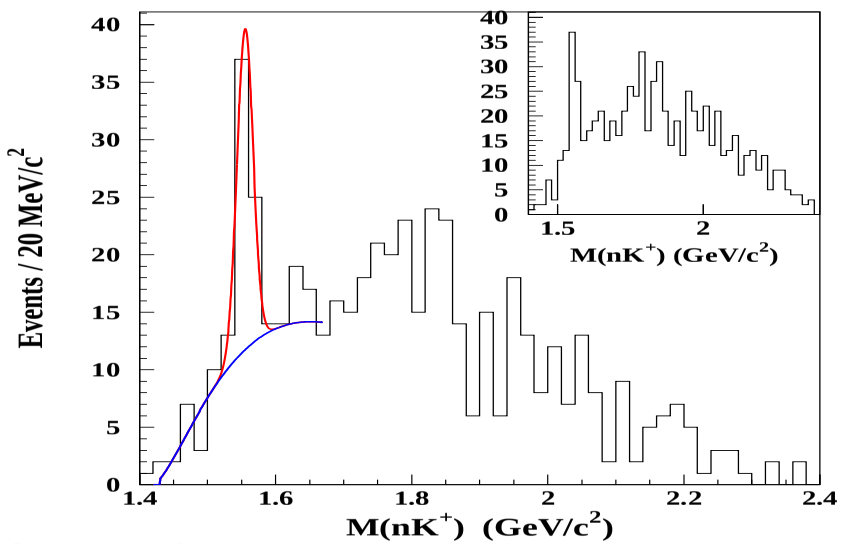


$S = 43$
$B = 54$
$S/\sqrt{B} = 5.8\sigma$

$\boxed{M = 1.542 \pm 0.005\ \mathrm{GeV}/c^2}$

$\Theta^{++} \to pK^+$ not seen
PRL,91:252001,2003

- $3\ \mathrm{GeV} < E_\gamma < 5.5\ \mathrm{GeV}$
- $\gamma p \to \pi^+\,\boxed{nK^+}\,K^-$
- $\cos\theta^*_{\pi^+} > 0.8$ (cms angle w.r.t γ direction)
- $\cos\theta^*_{K^+} < 0.6$



$S = 41 \pm 10$
$B = 35$
$S/\sqrt{B} = 7.8\sigma$ most significant result on Θ^+

$\boxed{M = (1.555 \pm 0.001 \pm 0.010)\ \mathrm{GeV}/c^2}$

PRL,92:032001,2004

Θ^+ sightings

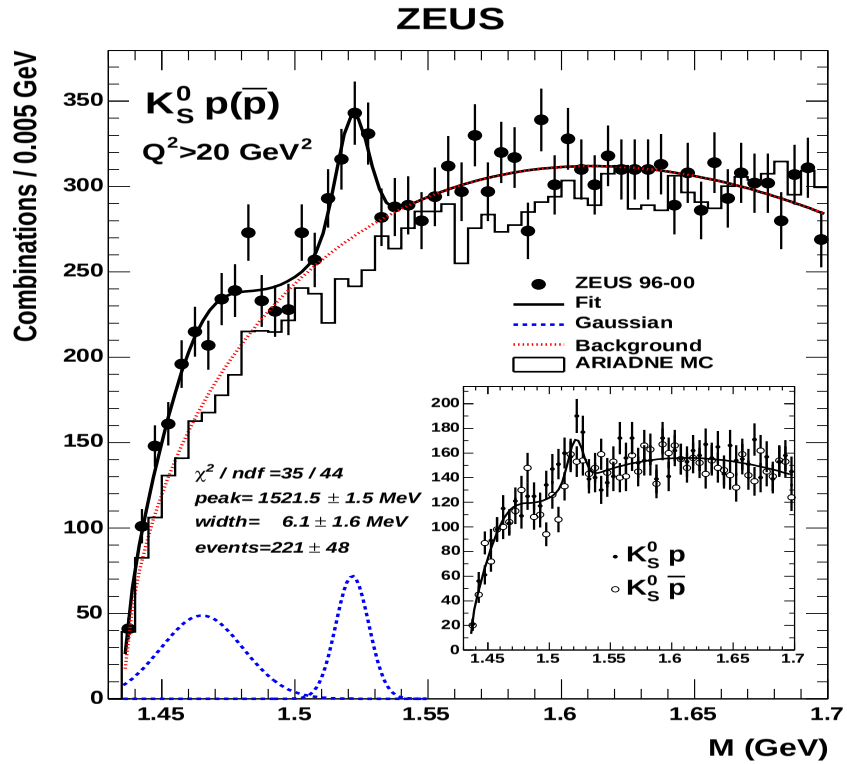
- ZEUS Experiment, HERA (hep-ex/0404007)
- ep collisions, DIS, $Q^2 > 20\ GeV^2$
- $\gamma^* p \to \boxed{pK^0_S} X$
- cuts
  - all tracks $|\eta| < 1.75$
  - $|\eta(K^0_S)| < 1.5$
  - anti Λ cut $M(p\pi) < 1.112\ GeV/c^2$
  - $p_T(K^0_S) > 0.3\ GeV/c$
  - dE/dx based proton PID, $p_p < 1.5\ GeV/c$

$S = 221 \pm 48$
$S/\sqrt{S+B} = 4.6\sigma$

$\boxed{M = (1,521.5 \pm 1.5^{+2.8}_{-1.8})\ MeV/c^2}$

$\boxed{\Gamma = (8 \pm 4)\ MeV/c^2}$

The only collider experiment seeing Θ^+

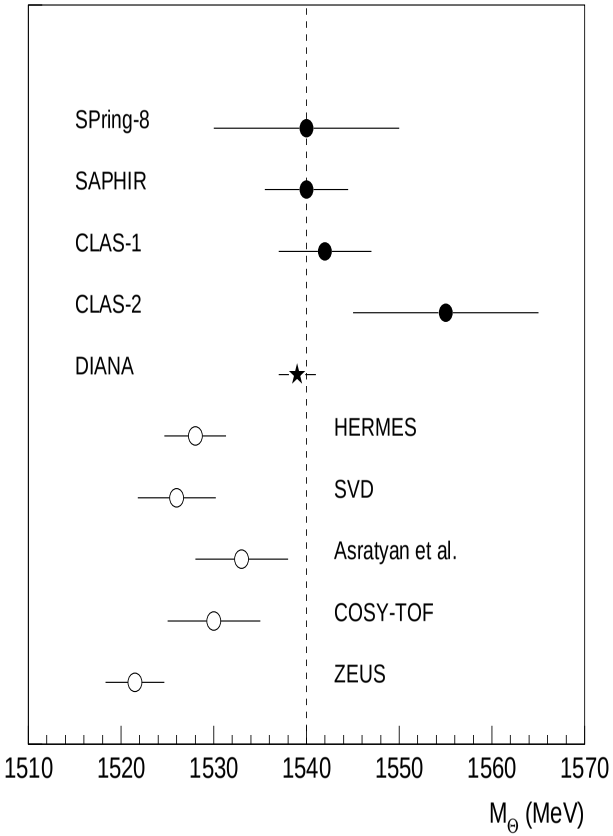


- HERMES experiment, HERA 27.6 GeV positron beam (PR,D71,2005)
  - $ed \to \boxed{pK^0_S} X$ $\boxed{M = (1.528 \pm 0.0026 \pm 0.0021)\ GeV/c^2}$ $\boxed{\Gamma = (17 \pm 9 \pm 3)\ MeV/c^2}$
  - relative yield (assuming $B(\Theta^+ \to pK^0_S) = 0.25$):

$$\sigma(ed \to \Theta^+)/\sigma(ed \to \Lambda(1520)) = 1.6 - 3.5 \quad !!!$$

Θ^+ status summary

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	small	$\gamma d \to K^- p \boxed{K^+ n}$
CLAS-2	1555 ± 10	small	$\gamma p \to K^- \pi^+ \boxed{K^+ n}$
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	$1521.5 \pm 1.5^{+2.8}_{-1.7}$	8 ± 4	$\gamma^* p \to \boxed{K^0_S p} + X$



- $\Theta^+ \not\to pK^+$ (not seen) suggesting Θ^+ is indeed isosinglet.
- Narrow widths are consistent with detector resolutions (highly unusual in strong decays)
- Mass measurements are not consistent between $K^0_S p$ and $K^+ n$ final states
- Statistics is poor. Signal significance is overestimated by many sightings.

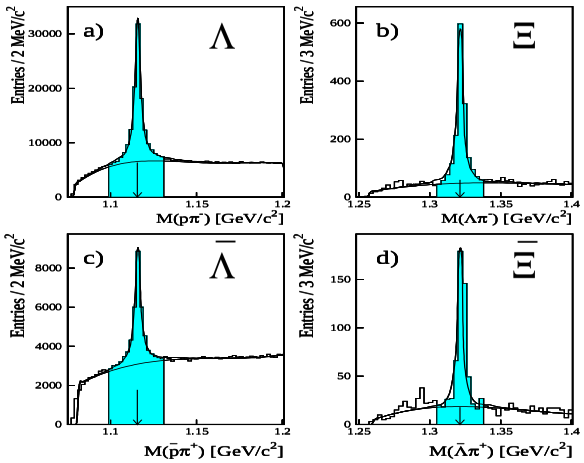
Need more data to establish Θ^+ unambiguously

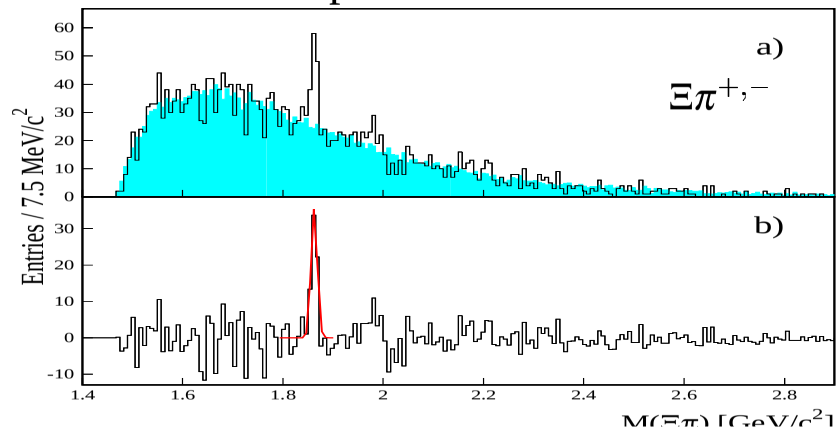
Exotic Cascade signal

- NA49 @ CERN SPS **pp** @ $\sqrt{s} = 17.2$GeV $\quad \Xi^{--,0}_{3/2} \to \Xi^{-}\pi^{-,+}$

$$\hookrightarrow \Lambda\pi^{-}$$

$$\hookrightarrow p\pi^{-}$$





$\Xi(1530)$ suppressed by $\theta(\Xi,\pi) > 4.8°$ and $\mathbf{p}_{\pi+} > \mathbf{3\ GeV/c}$ cuts

$$\begin{aligned} N(\Xi^{-}) &= 1,640 \\ N(\bar{\Xi}^{+}) &= 551 \\ N(\Xi(1530)^{0}) &\sim 150 \\ N(\Xi(1860)) &= 67.5 \end{aligned}$$

$$\frac{\sigma(pp \to \Xi(1860)) \cdot Br(\Xi(1860) \to \Xi\pi^{\pm}) \cdot a(\Xi(1860))}{\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))} \sim 0.30(0.15, 0.15)$$

$$\frac{\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))}{\sigma(pp \to \Xi) \cdot a(\Xi)} \sim 0.101$$

- Mass = $(1,862 \pm 2)\ \mathrm{MeV/c^2}$, Gaussian width of the peak, $(7.2 \pm 1.2)\ \mathrm{MeV/c^2}$, is consistent with detector resolution (mass 100 MeV heavier than predicted by Jaffe & Wilczek)

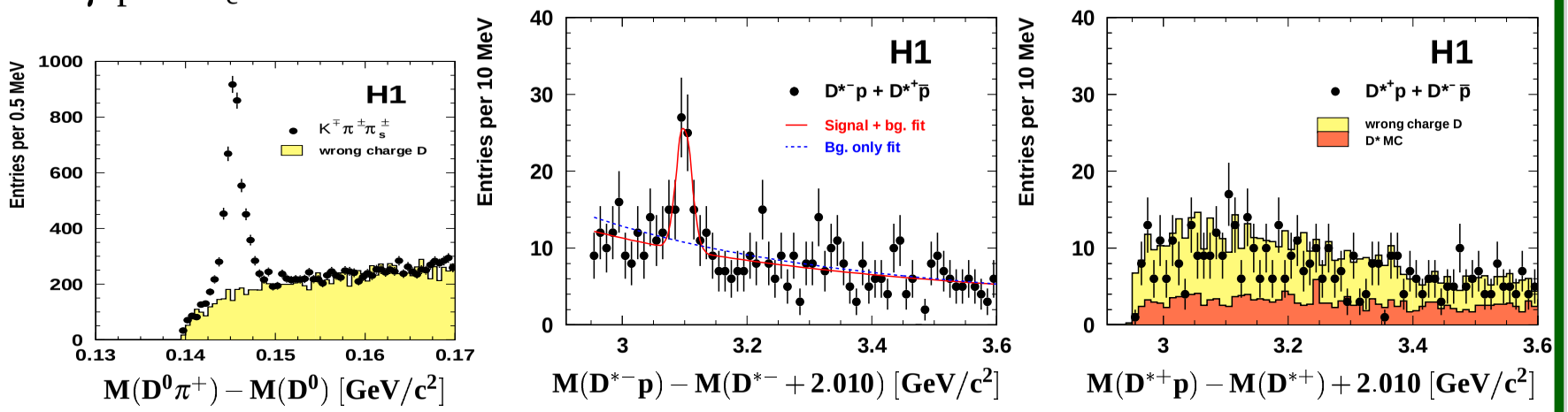
- Needs independent confirmation

Θ_c signal

H1 Experiment @ HERA $ep \to \Theta_c^0 X \ \sqrt{s} = 300, 320$ GeV

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

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



$S = 50.6 \pm 11.2$, significance 6.2σ

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

Gaussian width of the peak, $(12 \pm 3(\text{stat.}))$ 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 evidence in Photoproduction $\gamma p \to \Theta_c X$
- Needs independent confirmation

PQ searches at CDF

Search strategy at CDF

CDF advantages

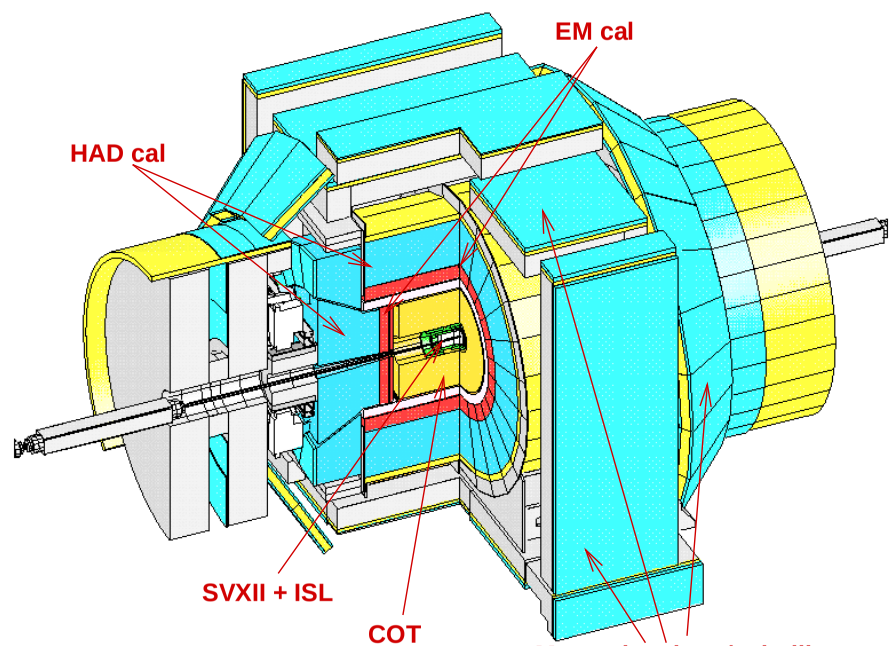
- high statistics samples
- excellent tracking:
  - good 3D vertexing reduces background
  - excellent mass resolution
  - ability to track long lived hyperons (Ξ^-, Ω^-) in SVX
- good PID capabilities based on ToF and dE/dx to identify protons, kaons.
- It may be difficult to connect results, especially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

Run II CDF Detector

- **CDF is general purpose detector at Tevatron $p\bar{p} = 1.96$ TeV**
- **tracking**
  - L00 + 5 layers of SVX + 2/1 outer layers of ISL ($1.5 < R < 30$cm, $|Z| < 45$cm). $r\phi$, rz, stereo strips. 720,000 channels. Si tracking up to $|\eta| < 2$.
  - Central Outer Tracker (COT), ($40 < R < 138$cm), 30,240 sense wires, 96 layer drift wire chamber. $\sigma(1/p_T) \sim 0.1\%/(\mathrm{GeV}/c)$, $\sigma(\mathrm{hit}) \sim 150\mu\mathrm{m}$. dE/dx PID.
- **ToF system, (120 ps @ 138 cm)**
- **improved DAQ and trigger systems**
  - Level 1 all digital, 132 ns pipeline
  - 20000/300/70 Hz
  - COT Tracks @ Level 1
  - Si Tracks @ Level 2
  - Full analysis @ Level 3
  - First hadronic B-trigger



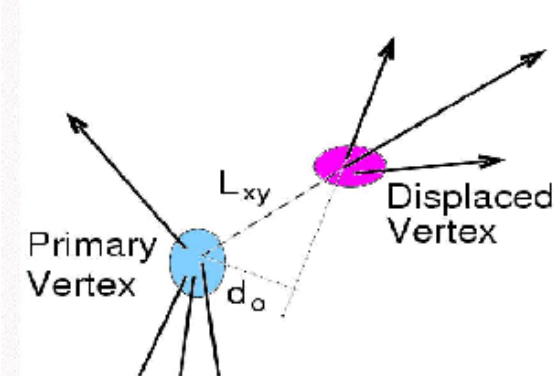
Hadronic Trigger

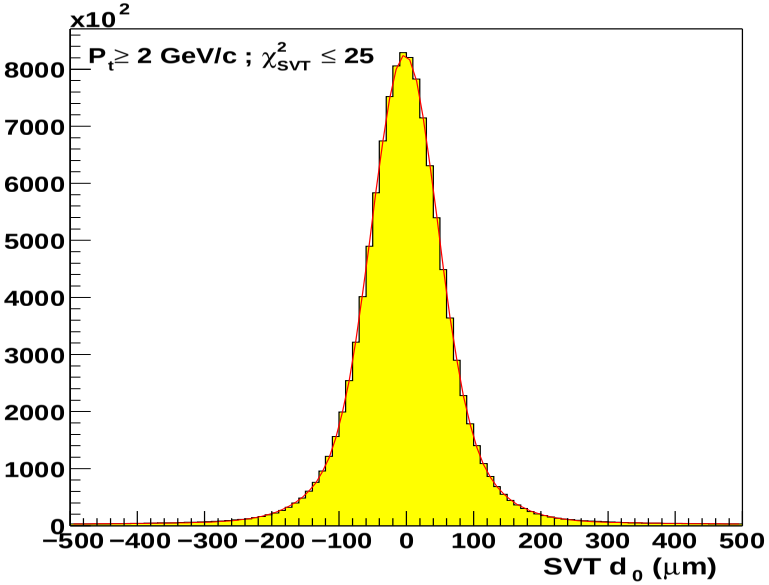
CDF as Charm Factory

- 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
    - ✓ $\Sigma p_T > 5.5\ \mathrm{GeV/c}$
    - ✓ $2^\circ < \Delta\phi < 90^\circ$
  - Level 2
    - ✓ XFT track seeds SVT boards, that perform fast $(r-\phi)$ track fit
    - ✓ repeat Level 1 cuts
    - ✓ require tracks impact parameter to be $0.012 < |d_0| < 0.1\ \mathrm{cm}$

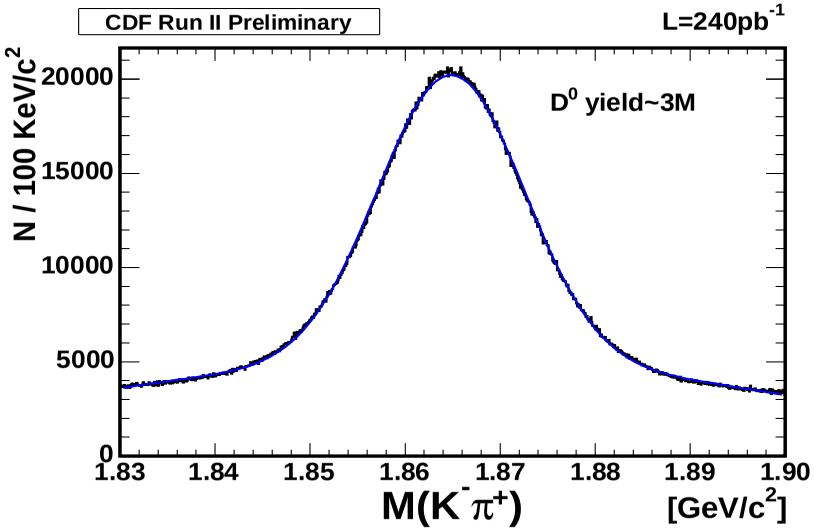
  ℓ+track uses different cuts.

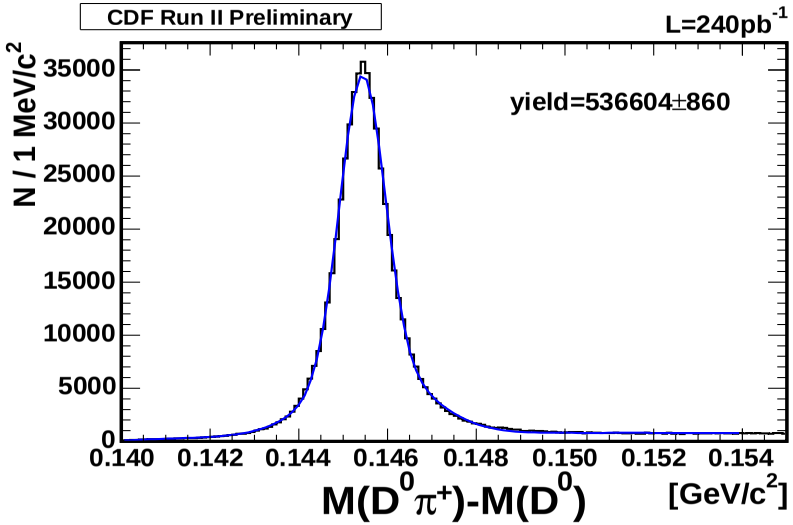
$\sigma(d_0)_{SVT} = 48\ \mu m$ (including $\sigma(beam) = 33\ \mu m$)





Charm Signals in Hadronic Dataset





3M D^0 and 0.5M D^{*+}
(This is 180x increase compared to H1 statistics)

Datasets

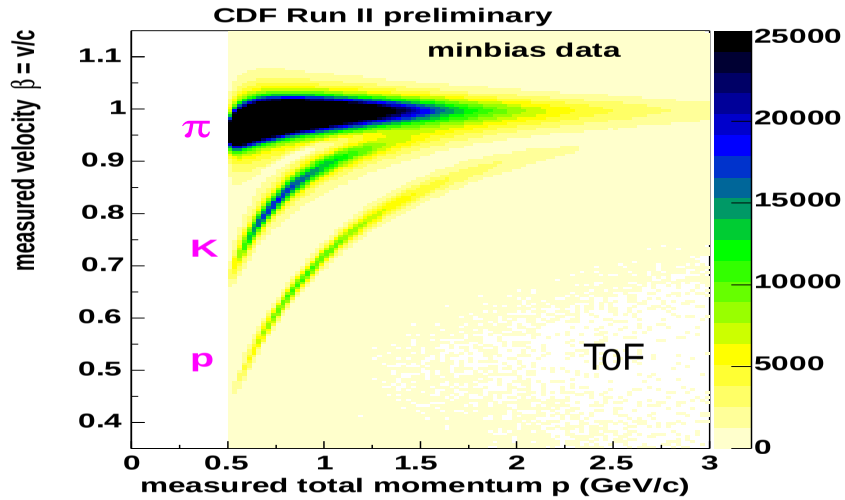
- hadronic trigger data
  - events with at least 2 displaced tracks
  - hard scattering events
  - sample enriched with decay products of charmed and bottom hadrons
- Jet20 trigger
  - each event has at least one jet with $\mathbf{E_T > 20\ GeV}$, generic QCD
  - prescaled trigger – lower statistics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

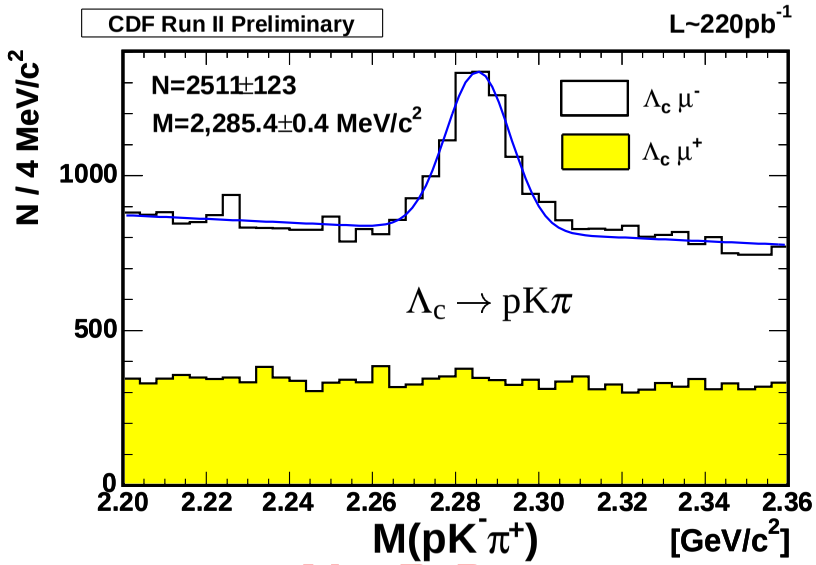
Particle identification

- 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:

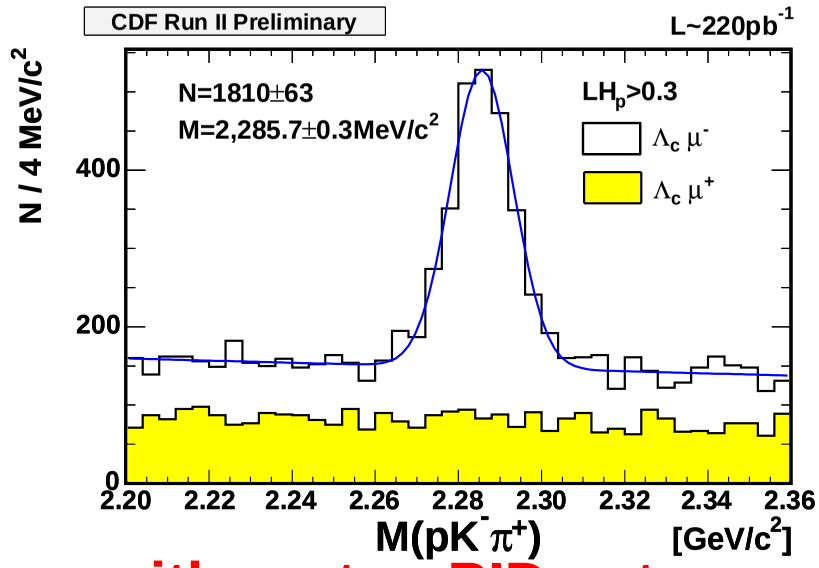
$$\mathrm{LH_i} = \frac{\mathrm{lh(i)}}{\mathrm{lh(p)} + \mathrm{lh(K)} + \mathrm{lh(e)} + \mathrm{lh}(\mu) + \mathrm{lh}(\pi)}$$

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





No PID cut

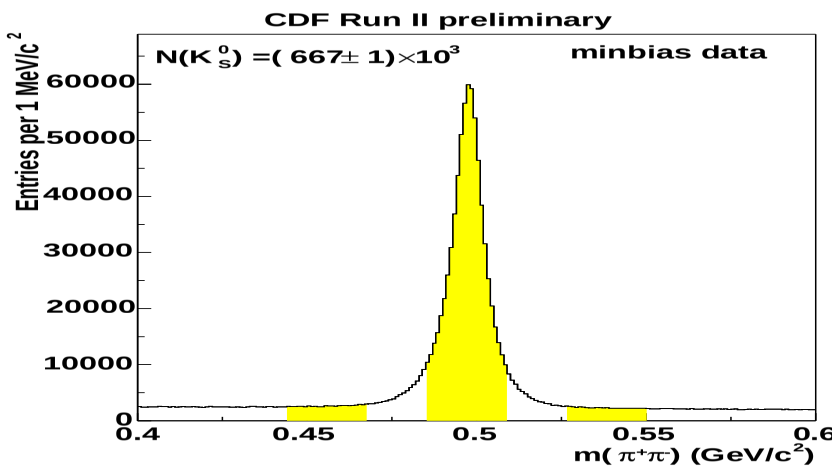


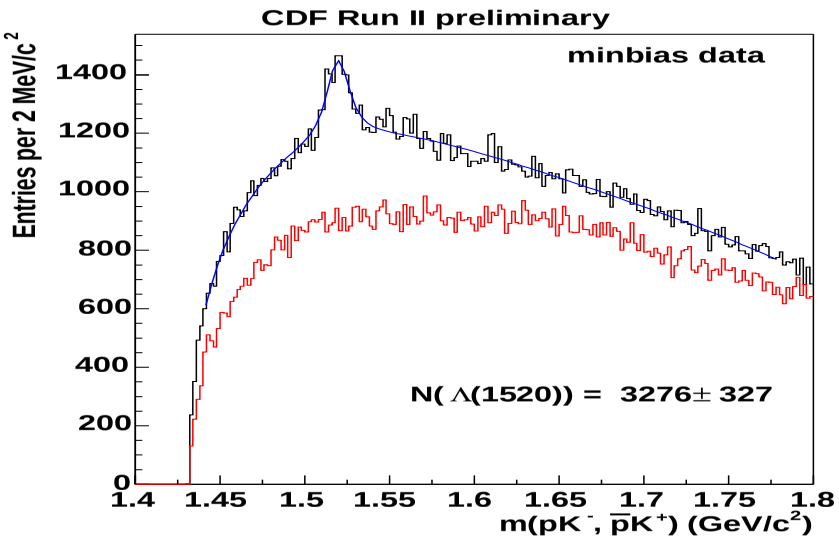
with proton PID cut

Search for Θ^+

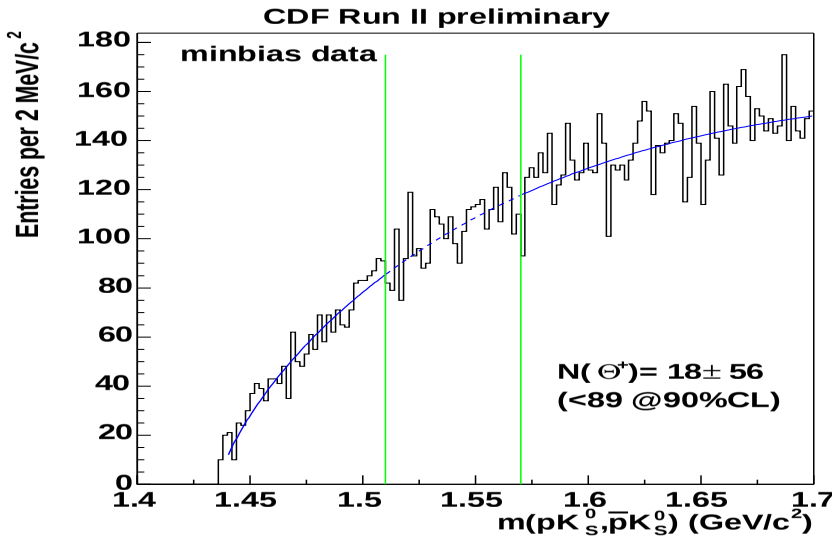
$$\Theta^+ \to K^0_S p$$
$$\hookrightarrow \pi^+\pi^-$$

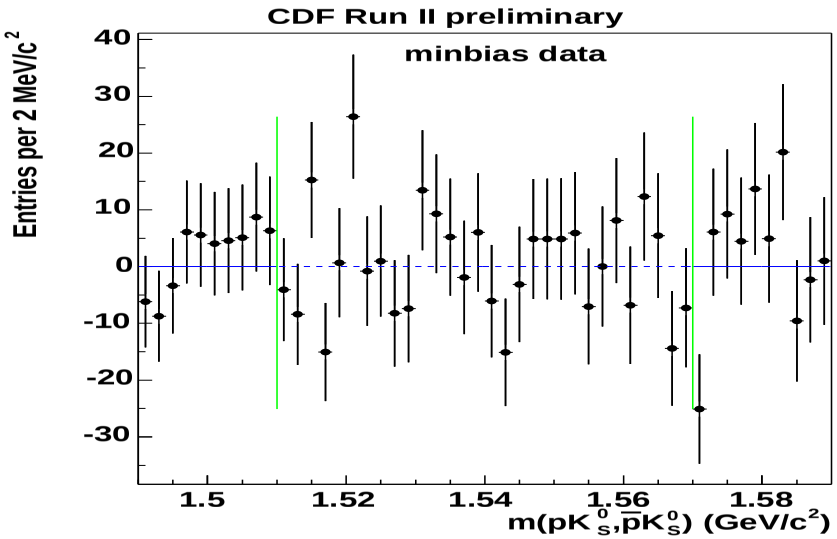
- use TOF to identify protons $0.5 < p_T < 2.1\ \mathrm{GeV/c}$
- Data samples used:
  - MINBIAS 12×10^6 events, ZEROBIAS 8×10^6 events
  - JET20 16×10^6 events





The Signal





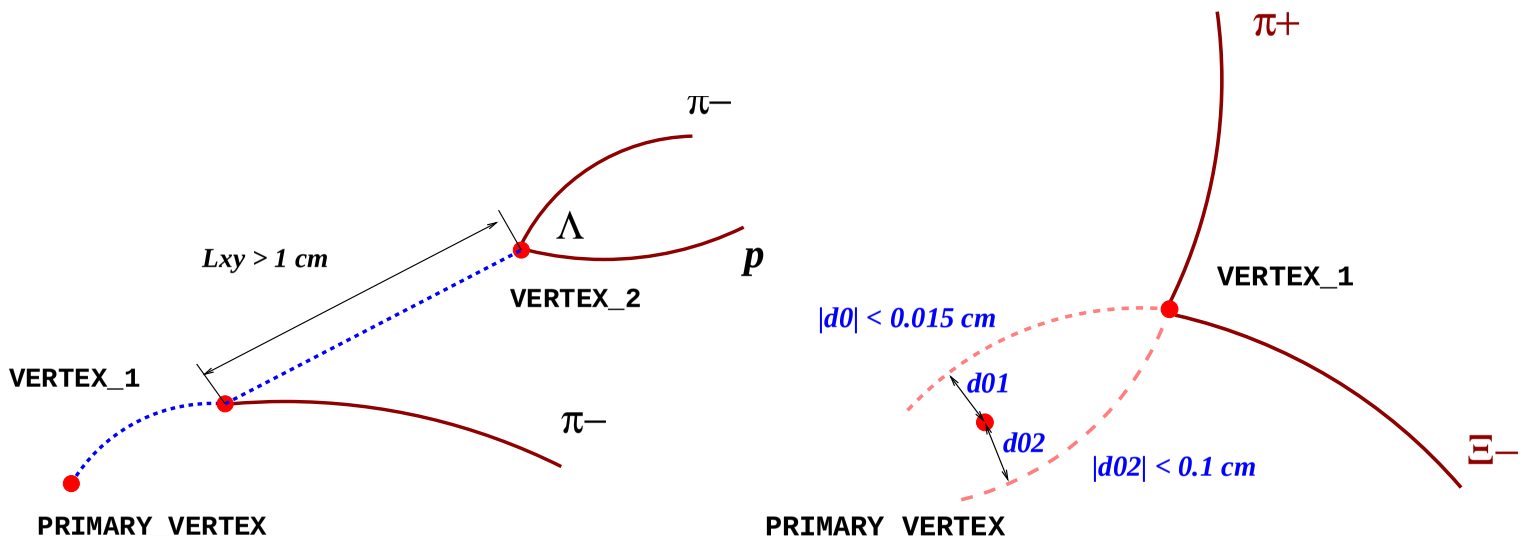
Resonance	Minbias data
$\phi \to K^+K^-$	$19,721 \pm 273$
$\Lambda \to pK^-$	$3,276 \pm 327$
$K^{*+} \to K^0_S\pi^+$	$15,695 \pm 775$
$\Theta^+ \to pK^0_S$	18 ± 56
90% CL limit on Θ^+	< 89

work on relative yield $\Theta^+/\Lambda(152)$ is in progress. The relative yield (assuming $B(\Theta^+ \to pK^0_S) = 0.25$) is in the the ballpark of 5%.

Exotic Cascade

$$\Xi^{0,--}_{3/2} \to \Xi^- + \pi^{+,-}$$

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

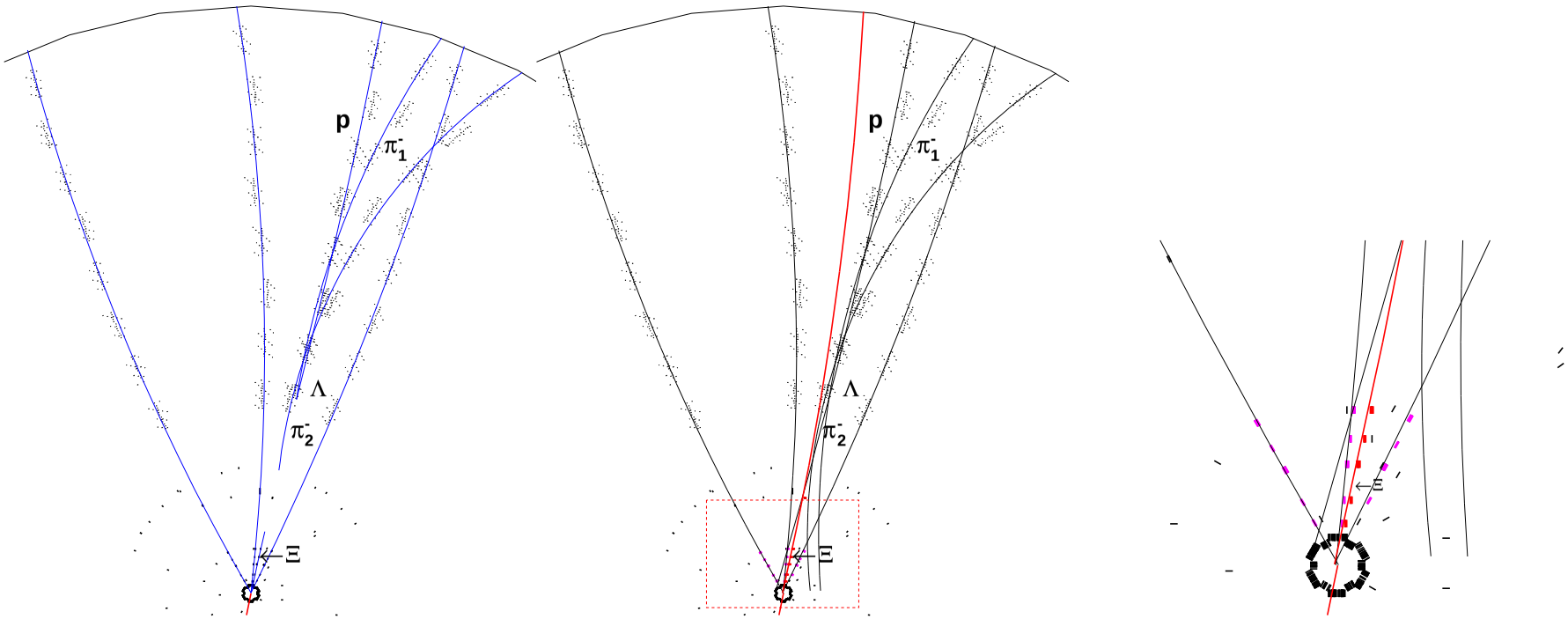


- find Ξ track in SVX.
- attach pion track to Ξ, fit the vertex, apply impact parameter cuts

Cascade tracking in SVX at CDF

Hyperon Are Tracked in Silicon

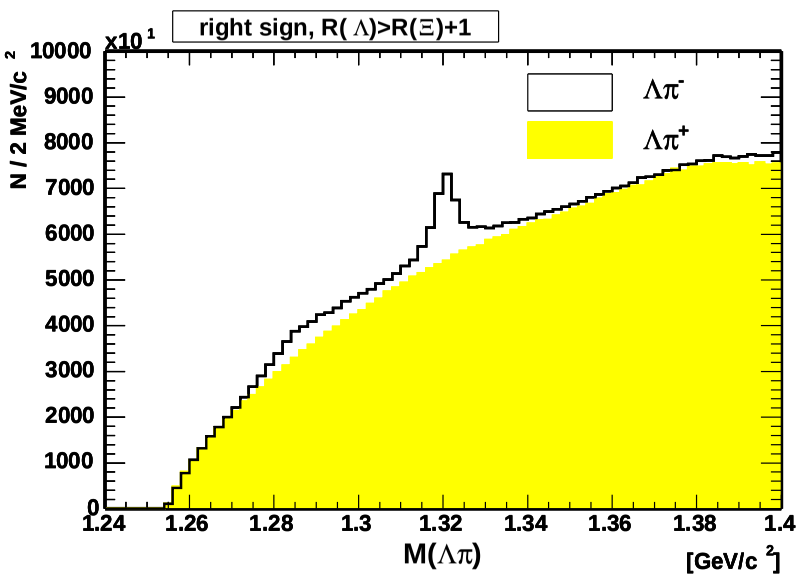
- $\Xi^- \to \Lambda^0 \pi^-$ is long lived $c\tau = 4.91cm$. It leaves hits in SVX detector. Momentum and vertex of $\Lambda\pi^-$ are used to seed specialized tracking algorithm that finds Ξ tracks in silicon.

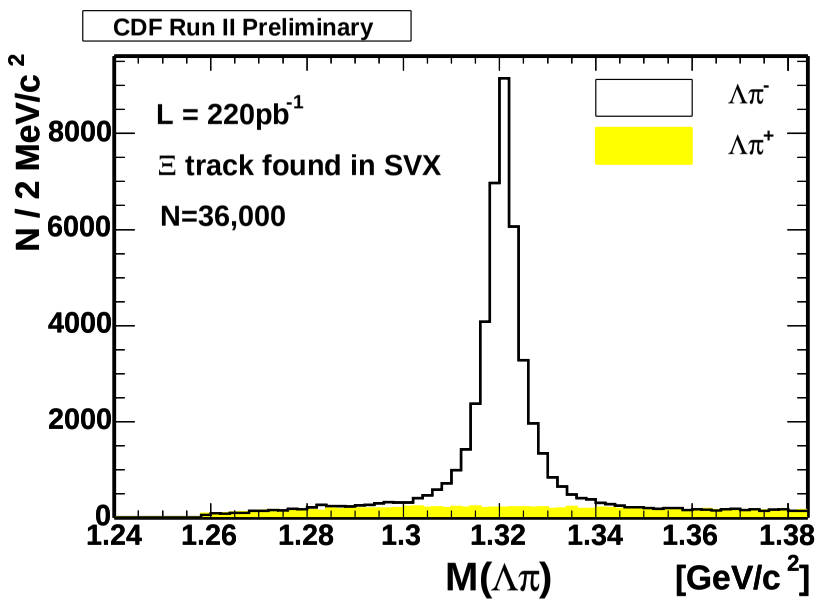


MC : $\Xi_b \to \Xi_c^+ \pi^- \quad \Xi_c^+ \to \Xi^- \pi^+ \pi^+ \quad \Xi^- \to \Lambda \pi_2^- \quad \Lambda \to p \pi_1^-$

Tracked Hyperon signals

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



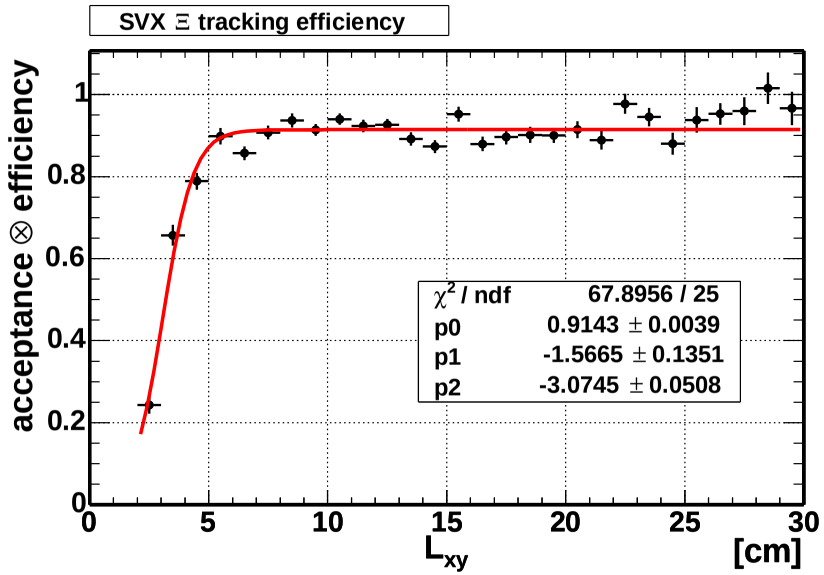


Hadron trigger data

- 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

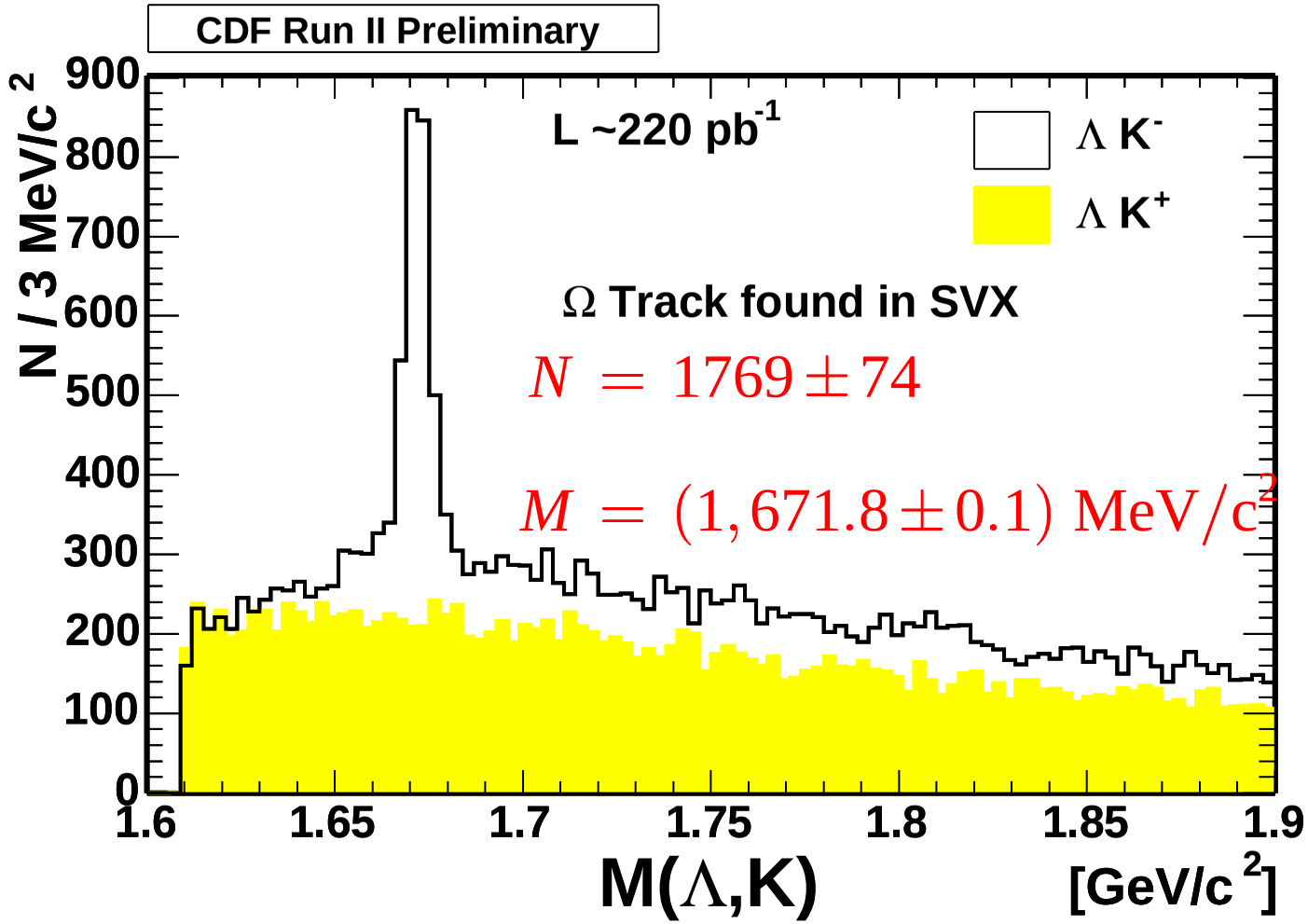
relative Ξ SVX tracking efficiency vs L_{xy}



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

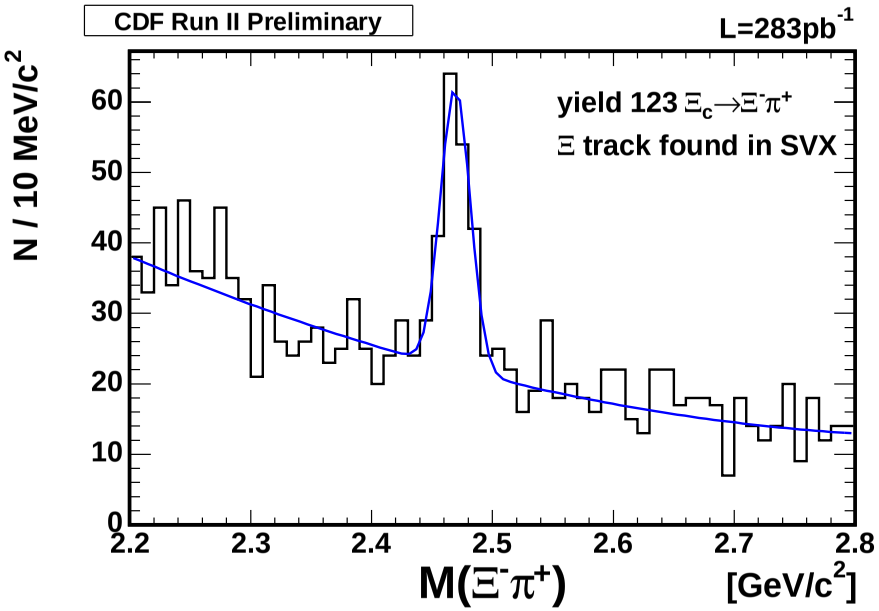
Omega

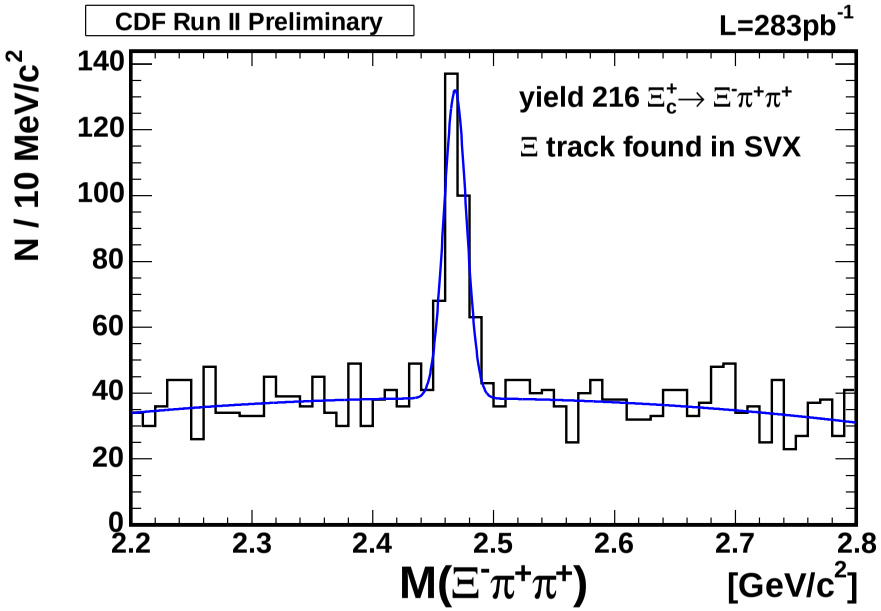
Ω reconstructed in SVX detector



Charmed-strange signals @ CDF

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





Signals from Ξ_c^0 and Ξ_c^+

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:

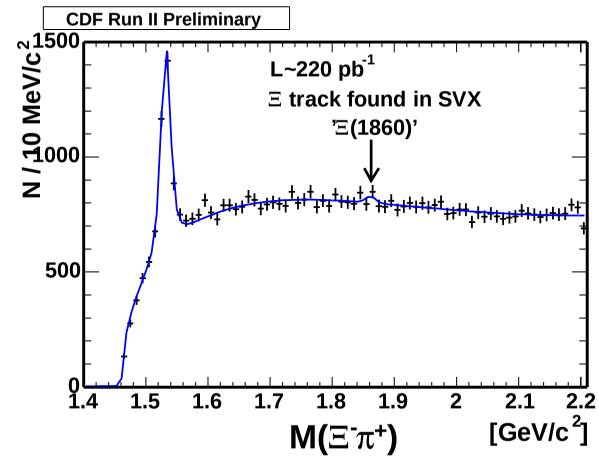
$$N(\Xi(1530)) = 2,182 \pm 92$$
$$M = (1,5320 \pm 0.4)\ \mathrm{MeV/c^2}$$

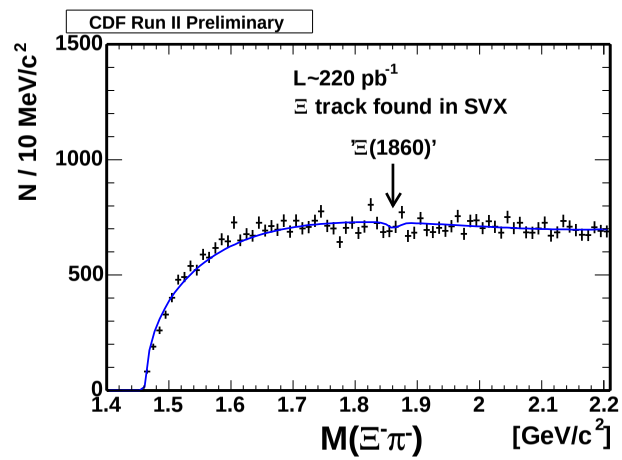
$$\frac{\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))}{\sigma(pp \to \Xi) \cdot a(\Xi)} \sim 0.091$$

Channel	# of events	95 % CL	relative yield
$\Xi^-\pi^+$	57±51	144	0.05
$\Xi^-\pi^-$	-54±47	63	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 $\Xi^{\pm}$

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

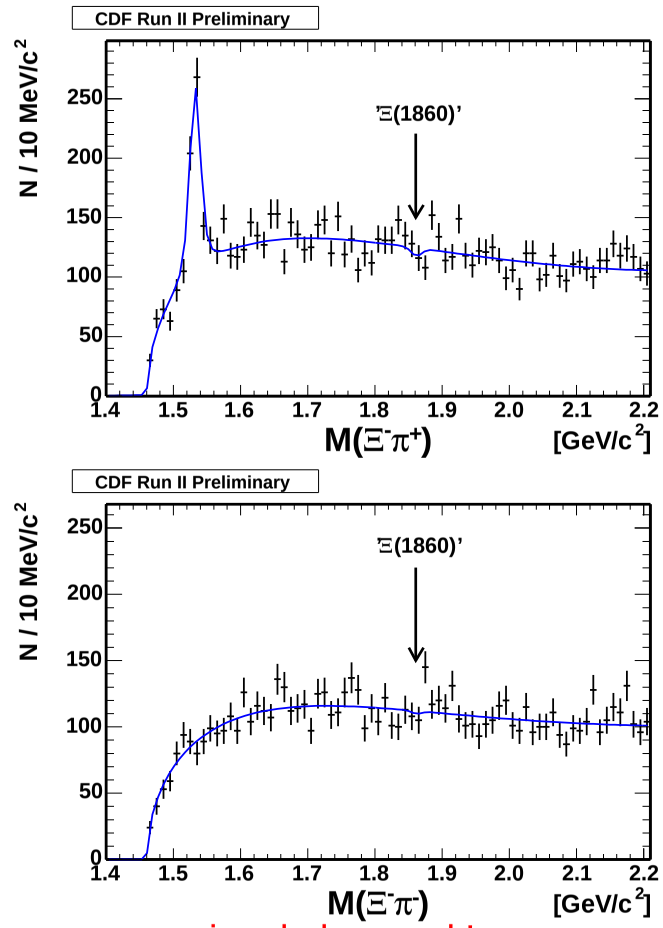
$$\frac{\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))}{\sigma(pp \to \Xi) \cdot a(\Xi)} \sim 0.12$$

(similar to TTT sample and similar to NA49)

Channel	# of events	95 % CL	relative yield
$\Xi^-\pi^+$	-14±19	30	0.054
$\Xi^-\pi^-$	-4±18	33	0.060

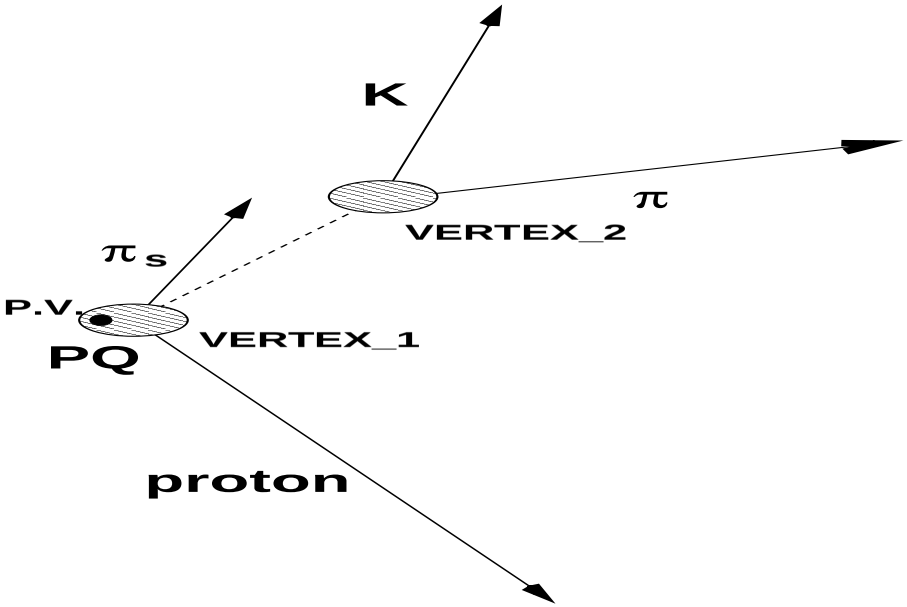
(Relative yields of $\Xi(1860)/\Xi(1530)$ assuming equal detector efficiency)

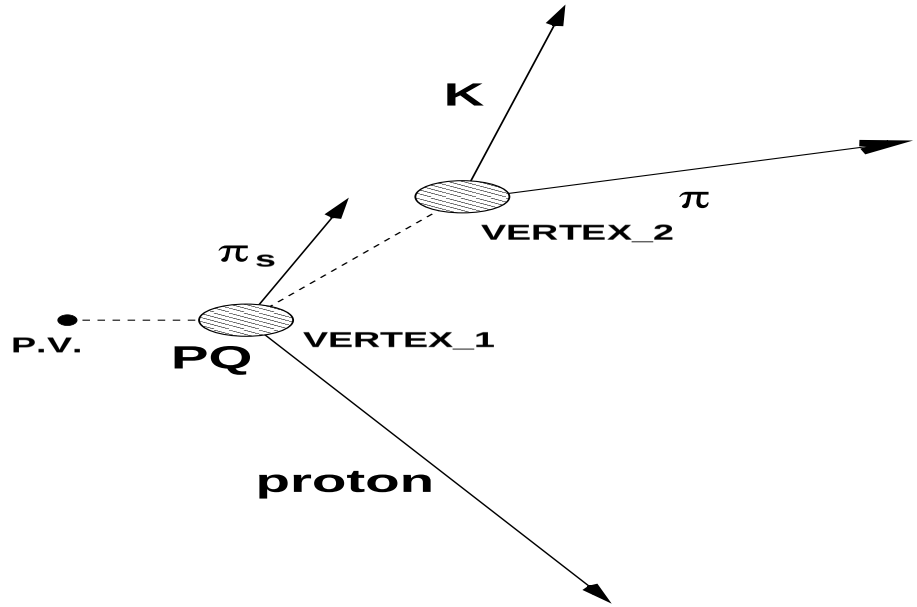
Jet20 sample



no signal observed !

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.

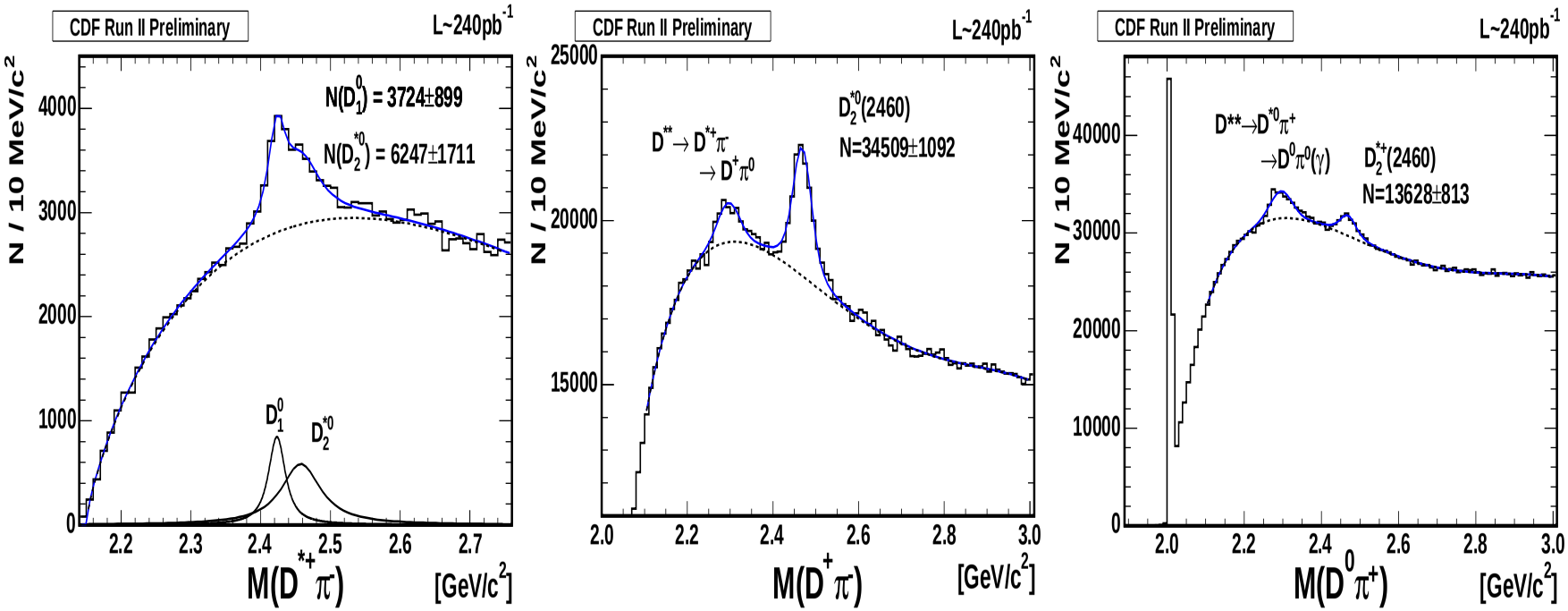
- prompt
- $|L_{xy}(PQ)| < 0.04$ cm
- $\left|L_{xy}(PQ)/\sigma_{L_{xy}}(PQ)\right| < 3$

- from B-decays or secondary production
- $L_{xy}(PQ) > 0.04$ 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

Reference Signals

Reference channels

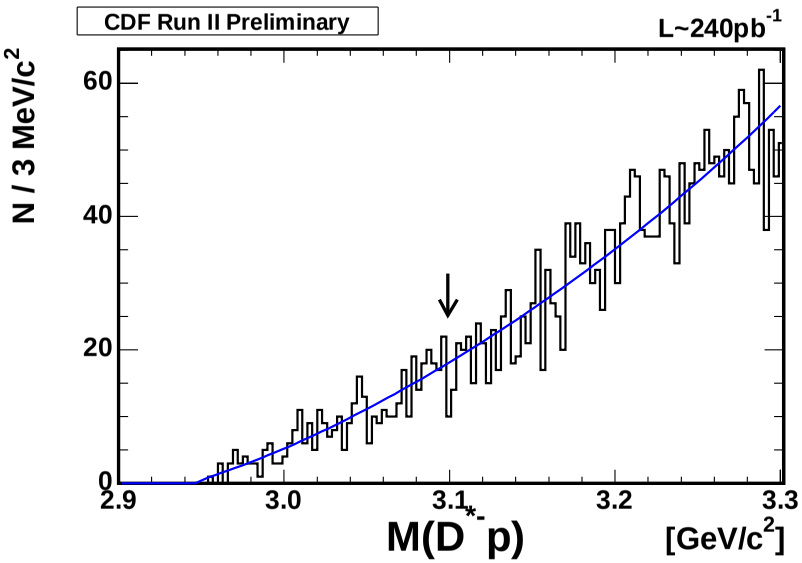


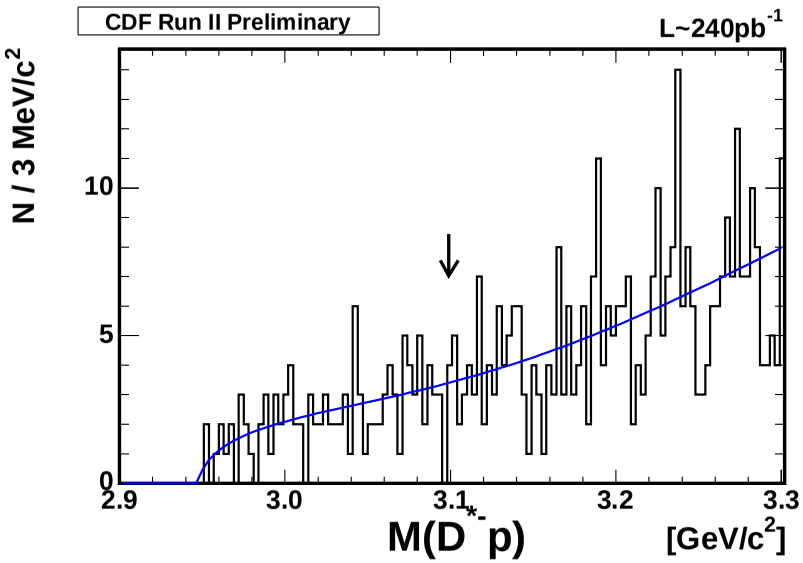
$$D^{**} \to D^{*+}\pi^- \hookrightarrow D^0\pi^+ \hookrightarrow K^-\pi^+$$

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

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

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



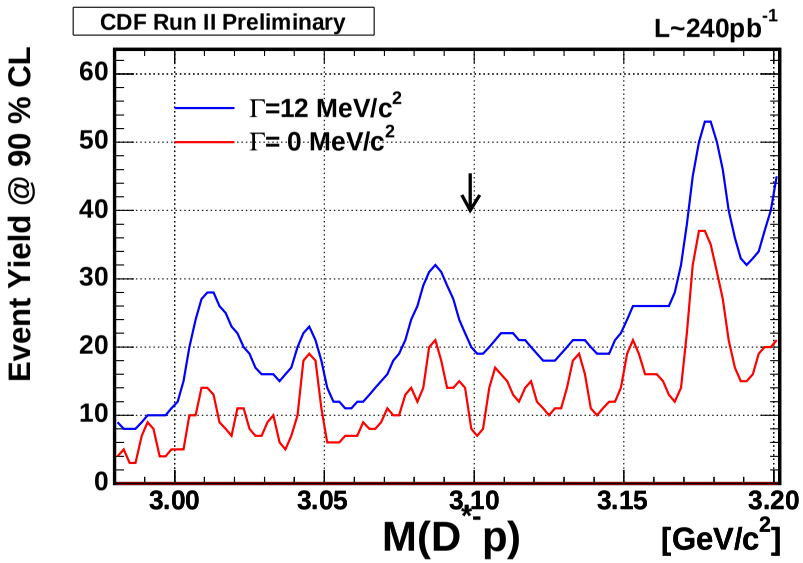


- prompt production
- $\Gamma = 0$ MeV/c^2: 21@90%CL
- $\Gamma = 12$ MeV/c^2: 32@90%CL

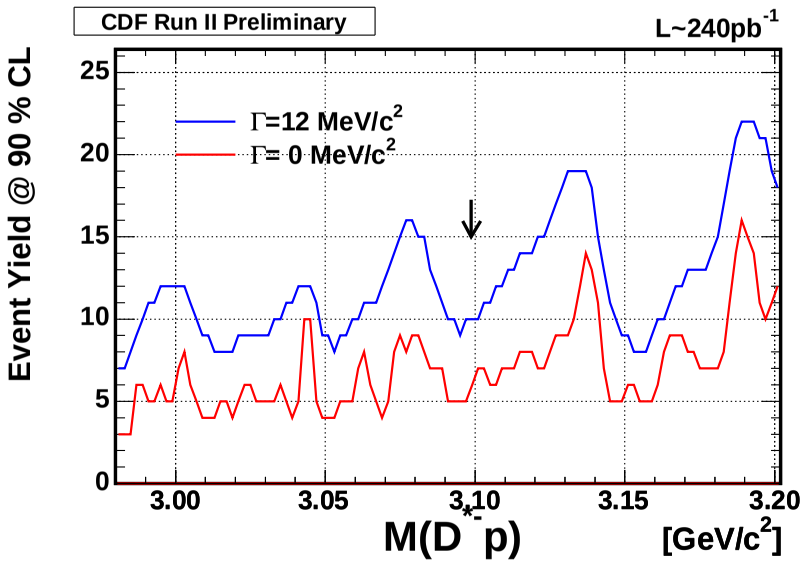
- secondary production
- $\Gamma = 0$ MeV/c^2: 8@90%CL
- $\Gamma = 12$ MeV/c^2: 15@90%CL

Event yield vs mass

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

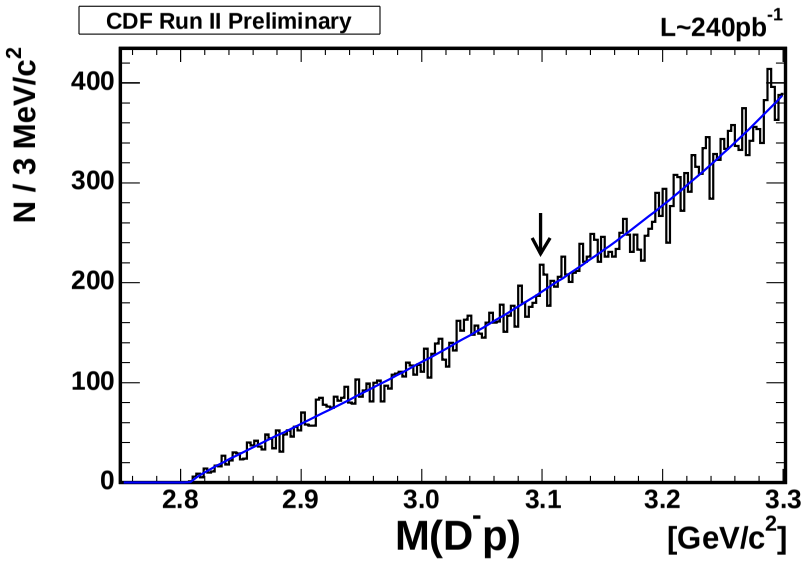


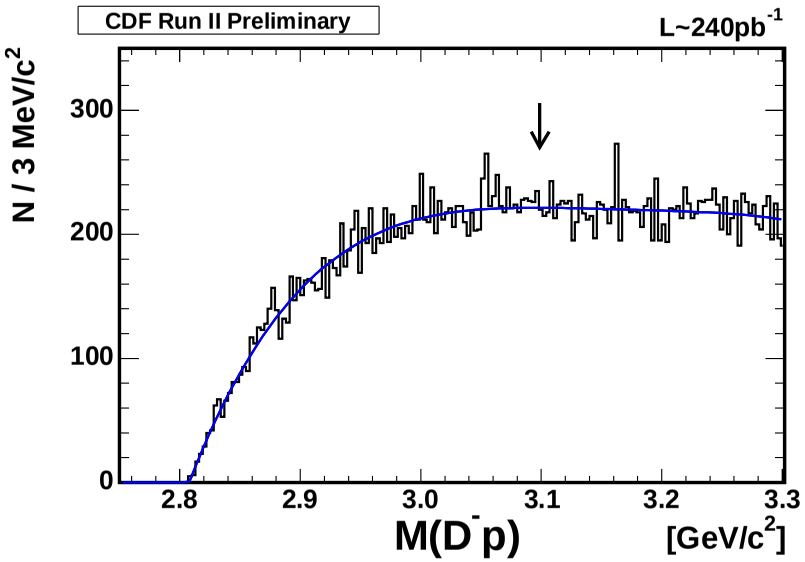
- prompt production



- secondary prouction

D^-p spectrum w/ proton PID



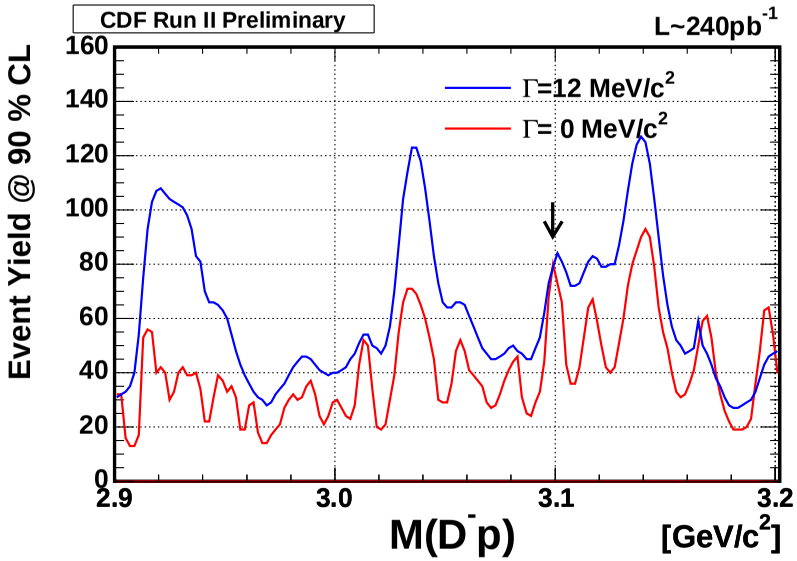


- prompt production
- $\Gamma = 0$ MeV/c^2: 80 @90%CL
- $\Gamma = 12$ MeV/c^2: 84 @90%CL

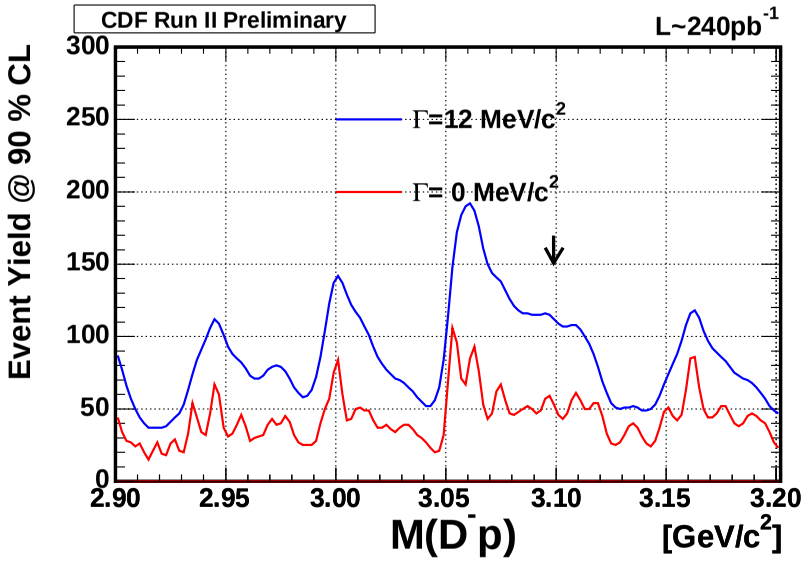
- secondary production
- $\Gamma = 0$ MeV/c^2: 61 @90%CL
- $\Gamma = 12$ MeV/c^2:
- 118 @90%CL

UL vs mass

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

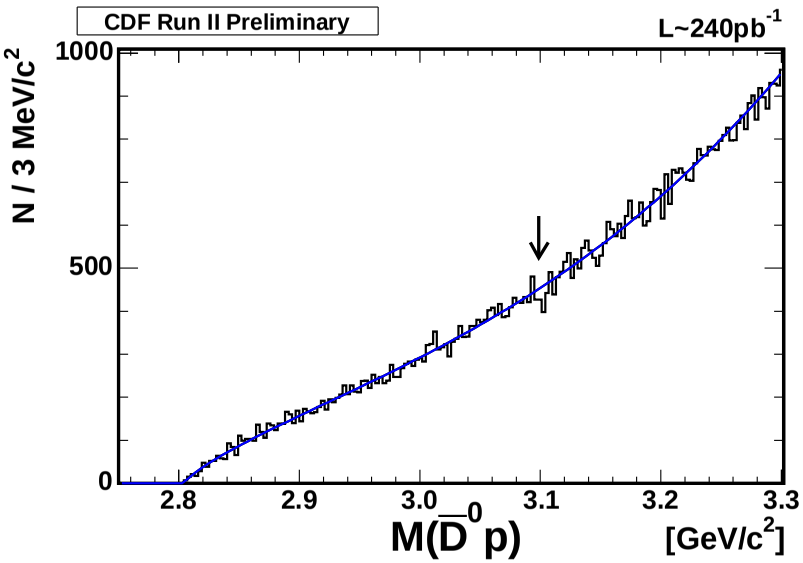


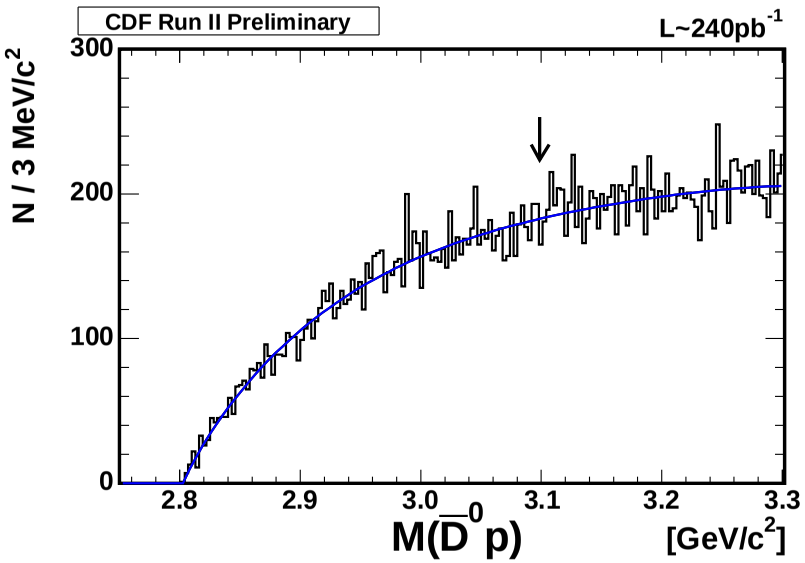
- prompt production



- secondary production

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

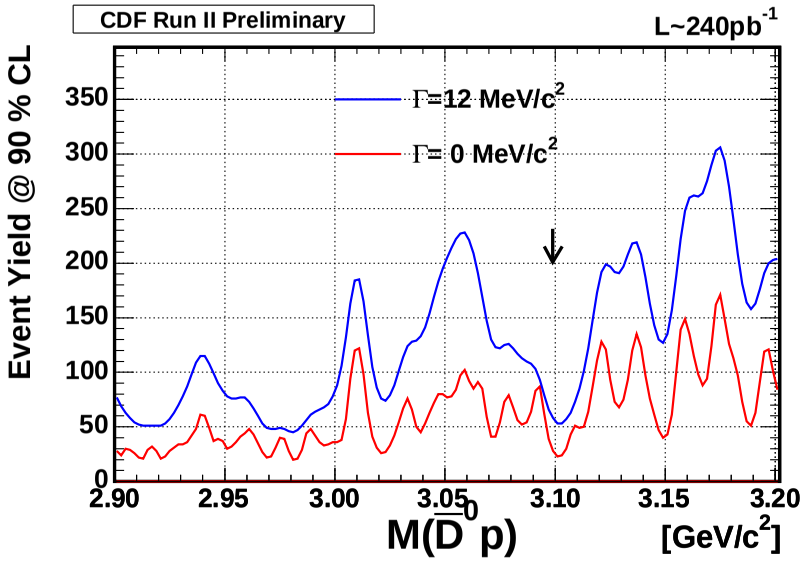




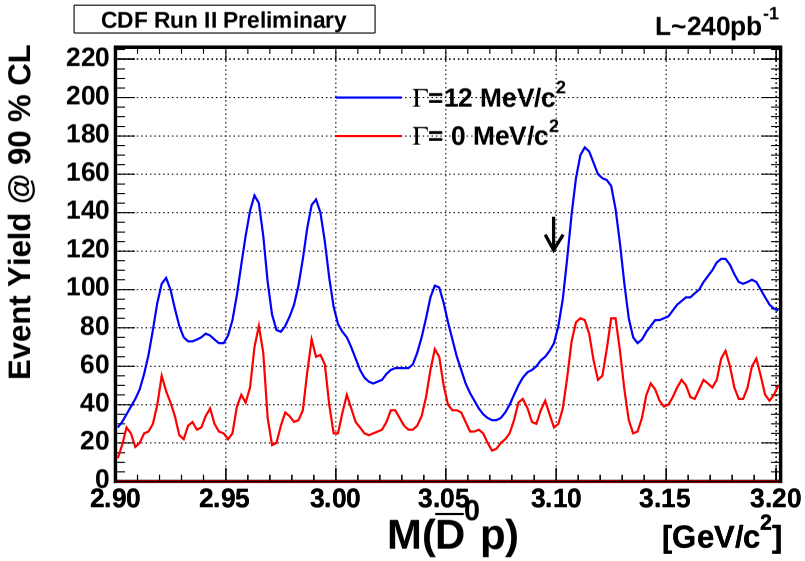
- prompt production
- $\Gamma = 0$ MeV/c^2: 87 @90%CL
- $\Gamma = 12$ MeV/c^2: 122 @90%CL

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

UL vs mass

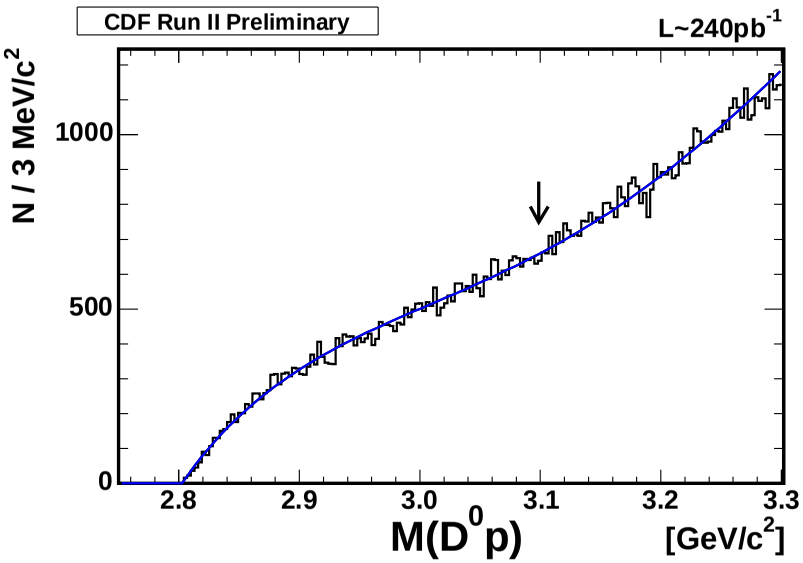


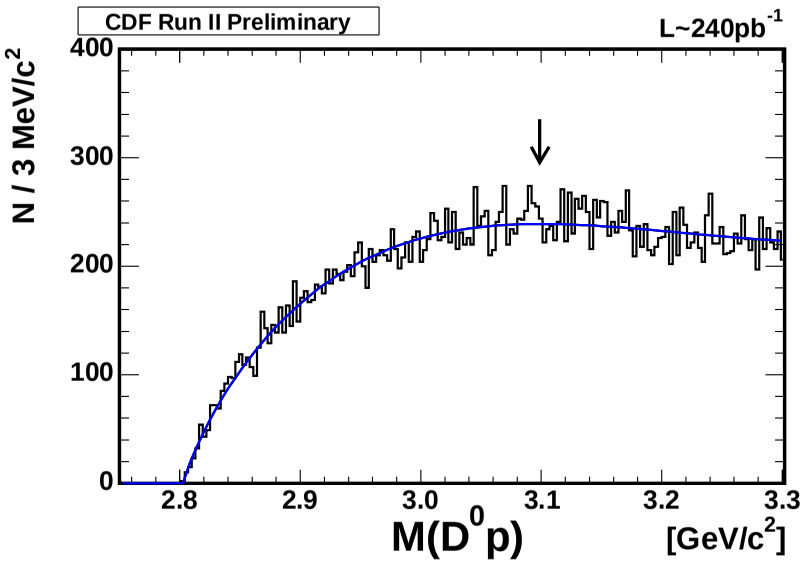
- prompt production



- secondary production

D^0p spectrum w/ proton PID

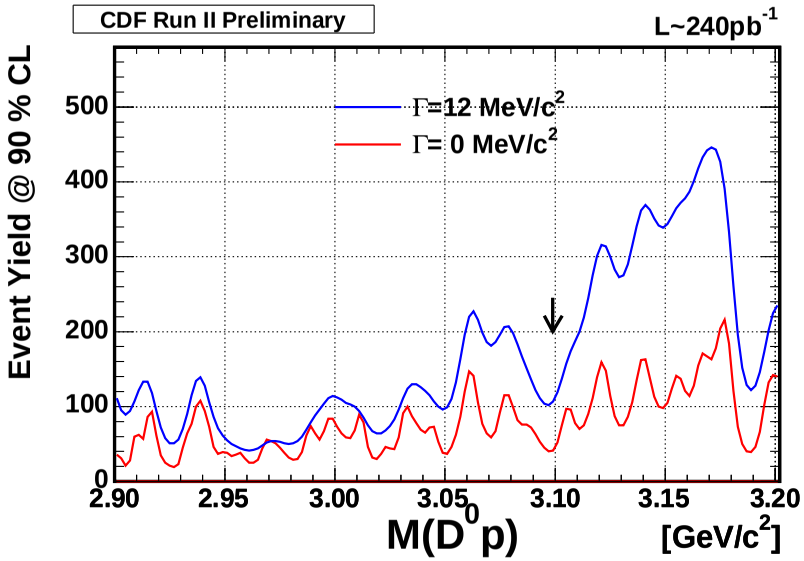




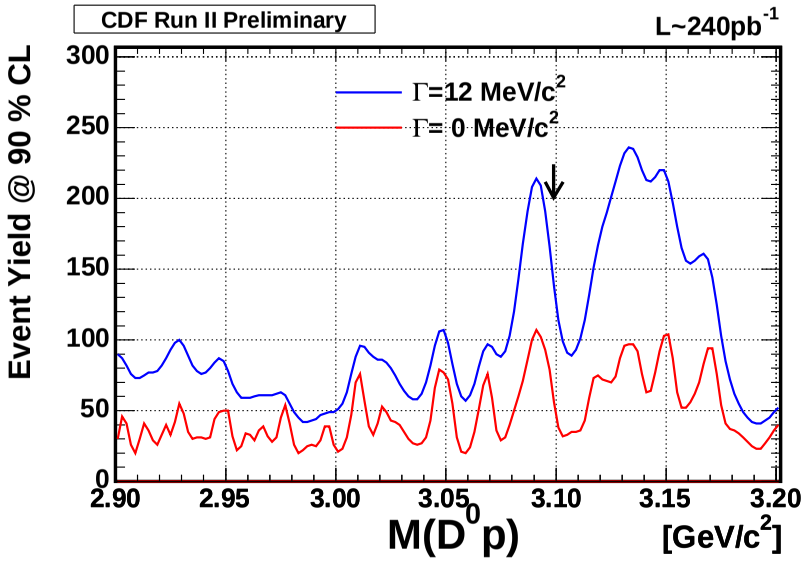
- prompt production
- $\Gamma = 0$ MeV/c^2: 97 @90%CL
- $\Gamma = 12$ MeV/c^2: 245 @90%CL

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

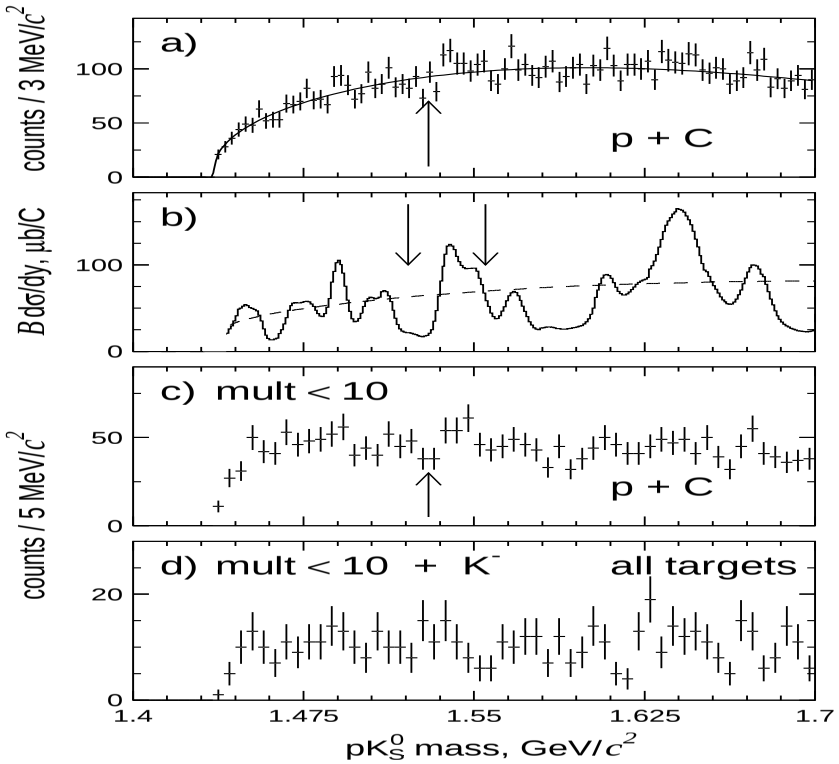
Reference channel		Search channel	
$D_2^{*0} \to D^+\pi^-$	6247 ± 1711	$\Theta_c^0 \to D^{*-}p$	< 21 @ 90% CL
$D_2^{*0} \to D^+\pi^-$	34509 ± 1092	$\Theta_c^0 \to D^-p$	< 89 @ 90% CL
$D_2^{*+} \to D^0\pi^+$	13628 ± 813	$\Theta_c^+ \to \bar{D}^0p$	< 87 @ 90% CL
		$\Theta_c^+ \to D^0p$	< 97 @ 90% CL

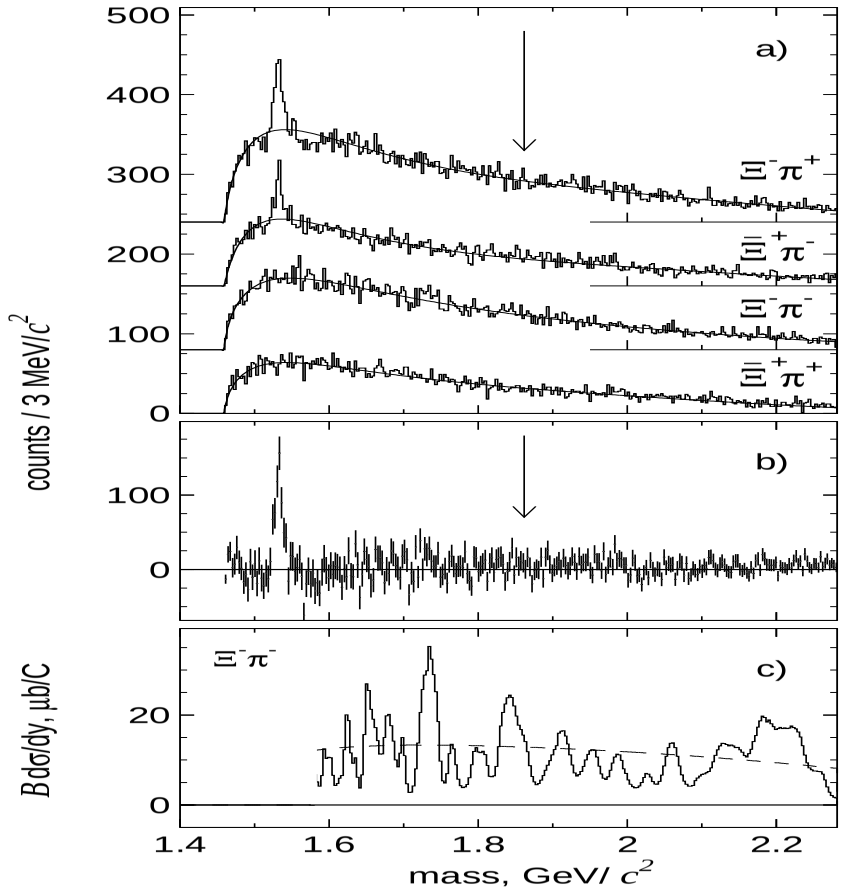
- conversion of event yields into $\sigma \times B$ limits is on the way.

Other Experiments

HERA-B

- Hera-B @ Hera, 920 GeV proton beam incident on tagret (C,Ti,W), $\sqrt{s} = 41.6$ GeV
- 2×10^8 minbias events





$$B(\Theta^+ \to pK^0_S) \times \frac{d\sigma}{dy}|_{y\approx 0} < 3.7\ \mu b/N \quad @\ 95\%CL$$

$$B \times \Theta^+/\Lambda(1520) < 1.7\%$$

$$B(\Xi^{--} \to \Xi\pi^-) \times \frac{d\sigma}{dy}|_{y\approx 0} < 2.5\ \mu b/N \quad @\ 95\%CL$$

$$B \times \Xi^{--}/\Xi(1530) < 4\%$$

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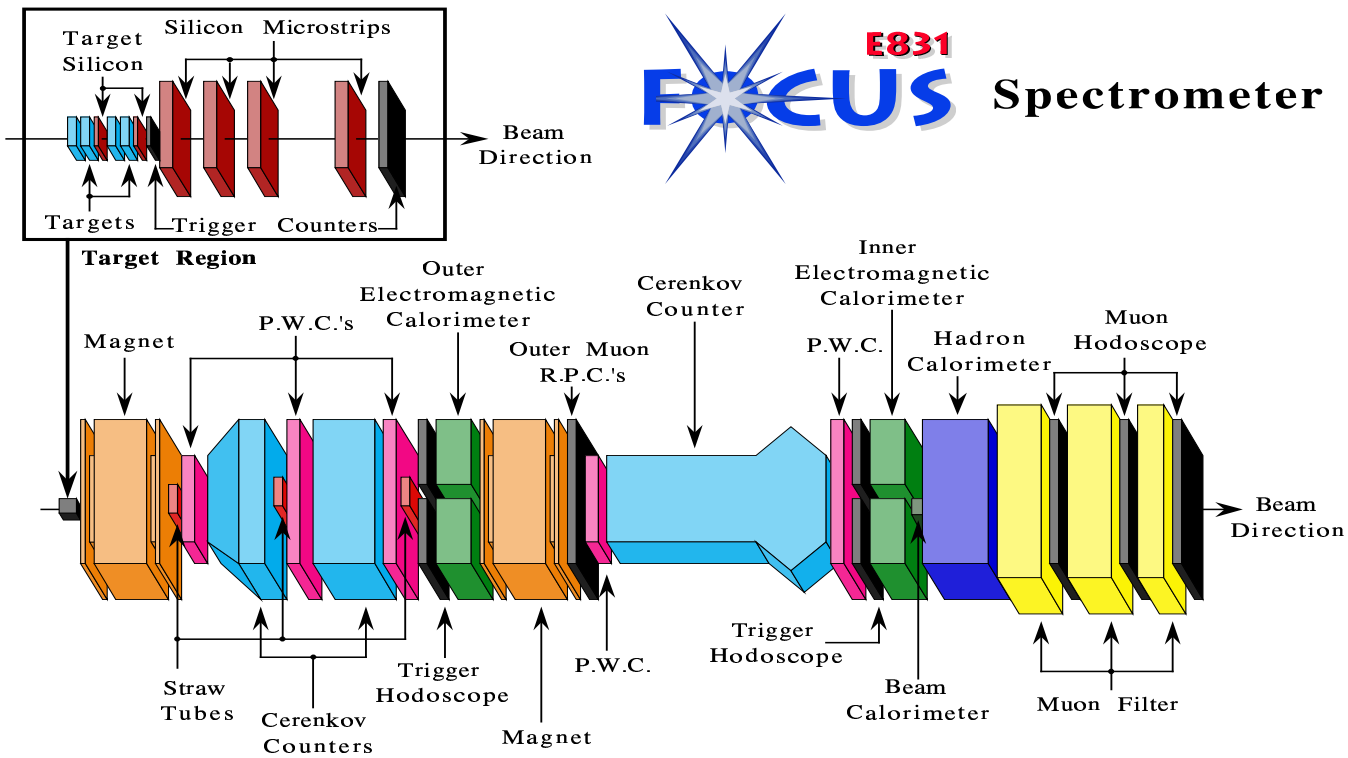
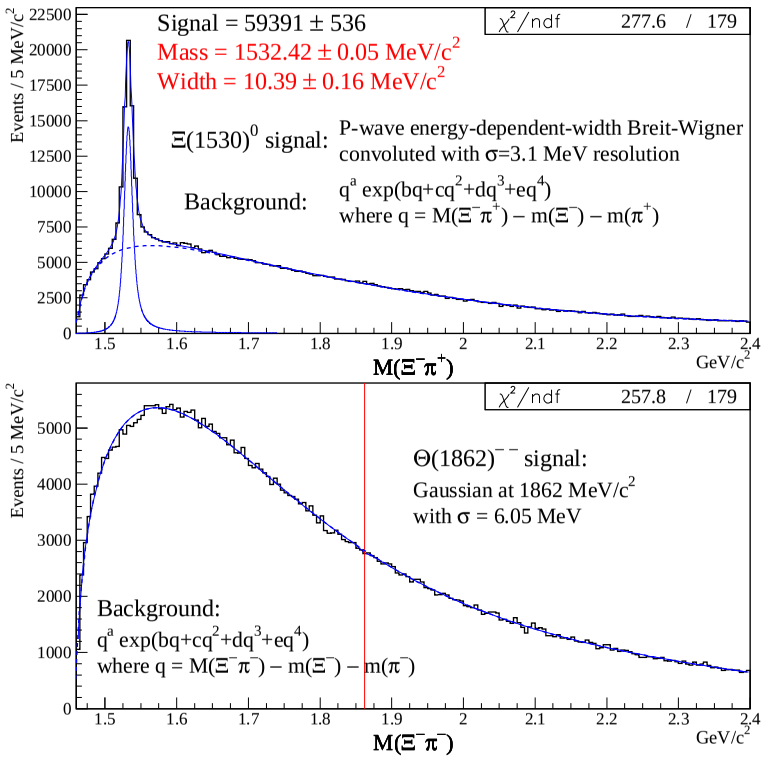
FOCUS

- Photon beam from brehmsstrahlung of 300 GeV electron and positron beams hitting BeO targets
- 2×10^9 events on tape
- 63×10^6 K^0_S candidates 8×10^6 Λ candidates
- $800,000$ Ξ^- candidates



FOCUS

- $\Xi^{0,--} \to \Xi^{+,-}$

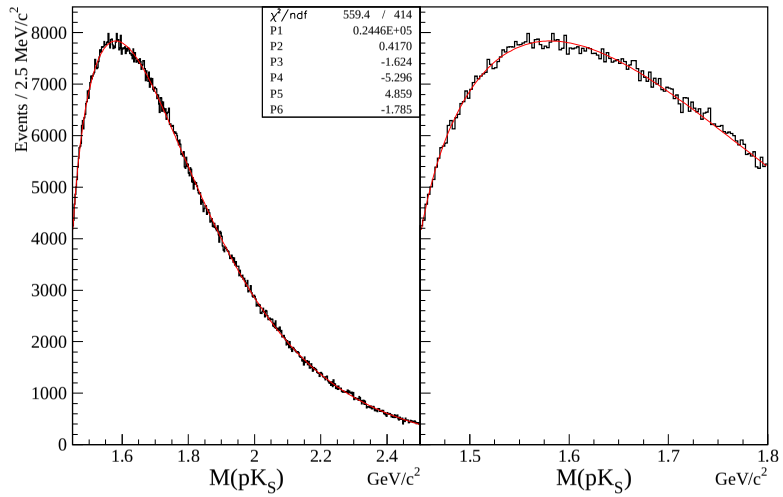


$$N(\Xi(1530)) = 59391 \pm 536$$

$$\frac{\sigma(\Xi^{--}) \cdot Br(\Xi^{--} \to \Xi\pi^-)}{\sigma(\Xi(1530))} < 0.25\%(0.37\%) \ @ \ 95\%CL$$

- Assuming equal detection efficiencies and $\Gamma = \mathbf{0(15)\ MeV/c^2}$

- $\Theta^+ \to \mathbf{pK^0_S}$



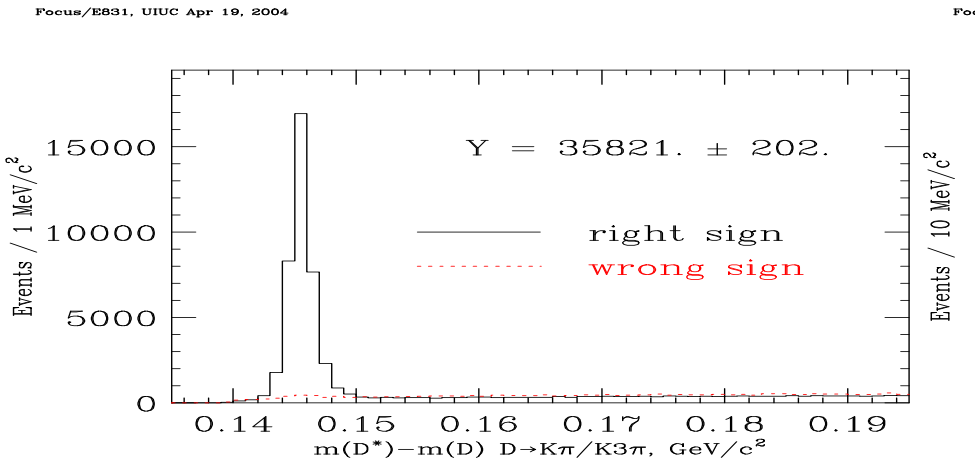
- $\mathbf{1.51 < M < 1.56\ GeV/c^2}$

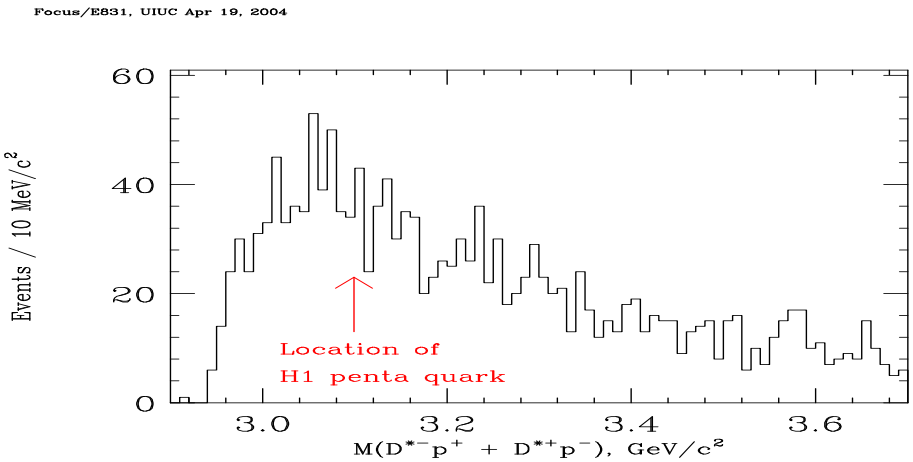
$$\sigma(\Theta^+)/\sigma(\Sigma(1385)^{+-}) < 0.7\%\ (2.1\%)$$
$$\sigma(\Theta^+)/\sigma(K^*(892)^-) < 0.07\%\ (0.17\%)$$

- Assuming $\Gamma = \mathbf{0(15)\ MeV/c^2}$
  $\mathbf{B(\Theta^+) \to pK^0_S = 0.25}$

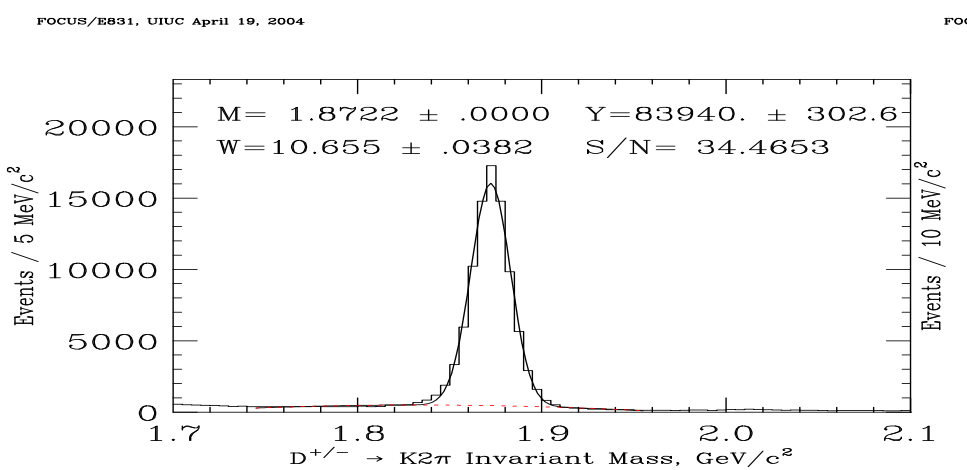
FOCUS

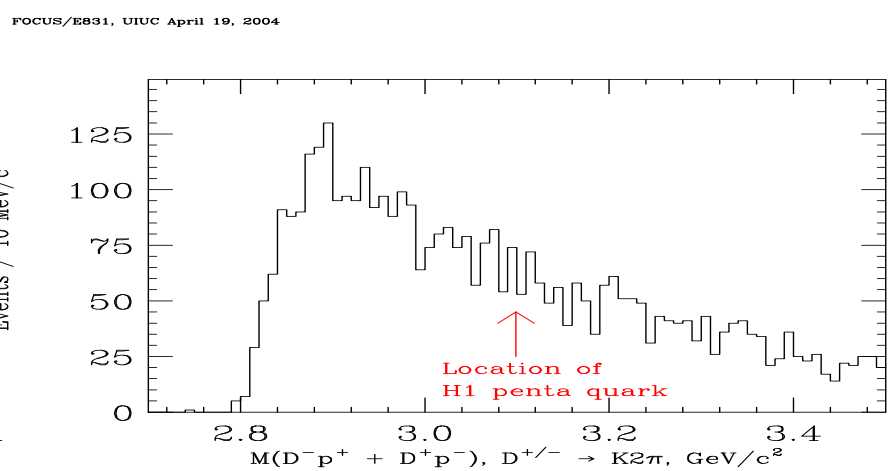
- $\Theta_c \to D^{*-}p$, $D^* \to D\pi$, $D^0 \to K\pi, K3\pi$





- $\Theta_c \to D^-p$, $D^+ \to K^-\pi^+\pi^+$

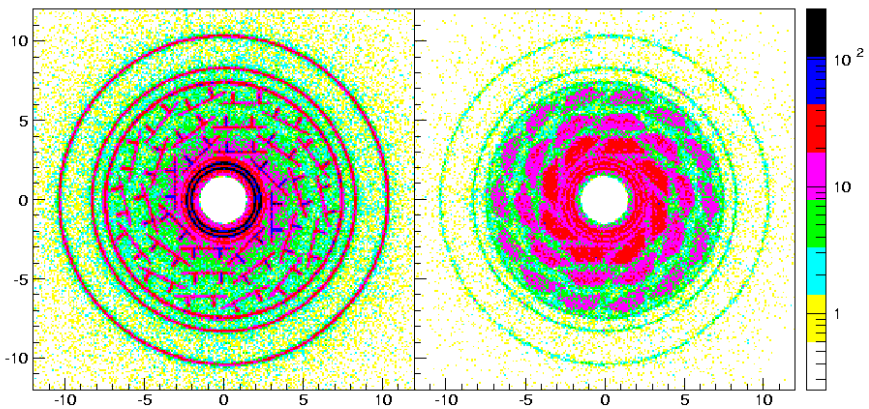




Belle

e^+e^- at KEK, $\sqrt{s} = 10.5$ GeV

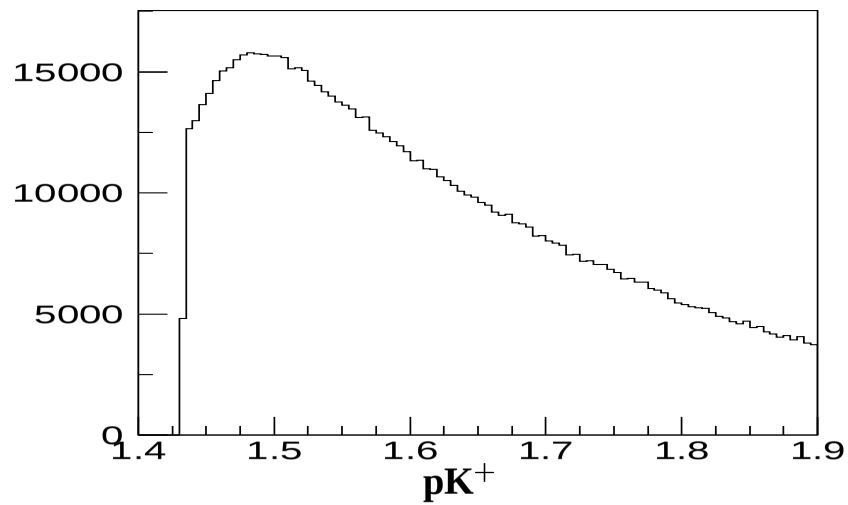
- Θ^+ production in the detector material $KN \to \Theta^+ X$
- PID based on dE/dx, TOF and Cherenkov angle
- require pK to form secondary vertices

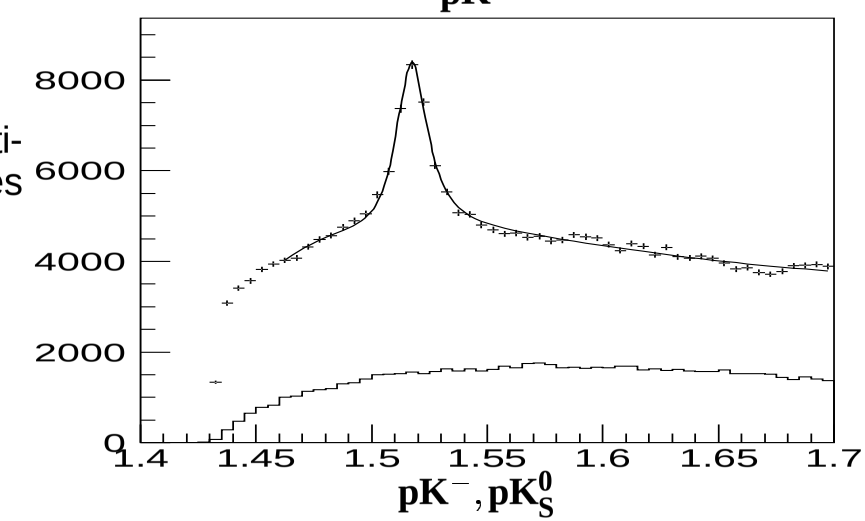


- tomography of the Belle tracker by strange particles. $x-y$ distribution of secondary pK^- vertices produced in: $KN \to \Lambda(1520)X$
- $N(\Lambda(1520)) = 15519 \pm 412$
  $N(\Theta^+) = 29 \pm 65$

$$\sigma(\Theta^+)/\sigma(\Lambda(1520)) < 2\% \ @ \ 90\% \ CL$$

two orders of magnitude lower than HERMES

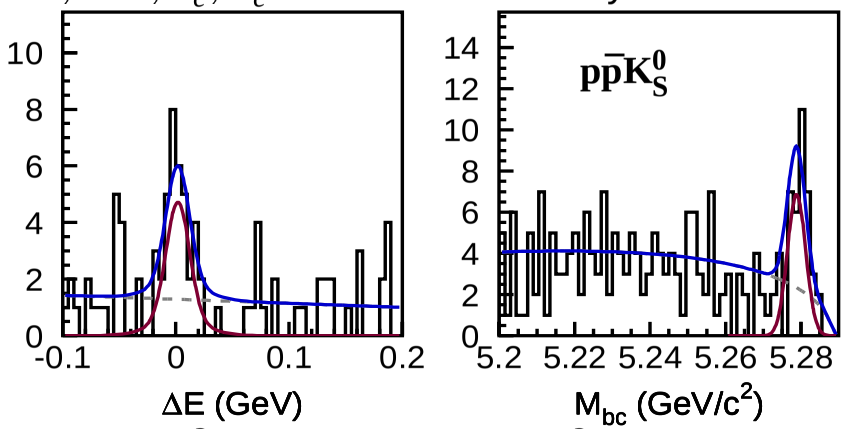




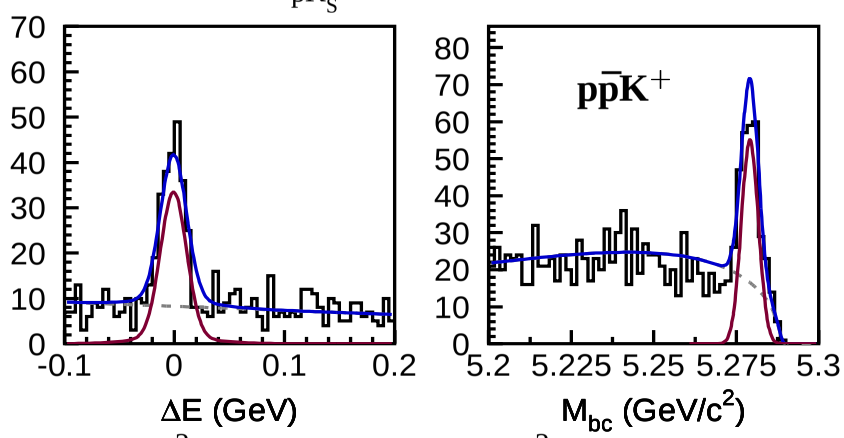
Belle

e^+e^- at KEK, $\sqrt{s} = 10.5$ GeV

- $\Theta^+, \Theta^{++}, \Theta_c^0, \Theta_c^+$ in exclusive B decays



$1.53\ \mathrm{GeV/c^2} < M_{pK_S^0} < 1.55\ \mathrm{GeV/c^2}$ got 0 events



$1.6\ \mathrm{GeV/c^2} < M_{pK_S^0} < 1.8\ \mathrm{GeV/c^2}$ got 0 events

- Results:

$$\frac{B(B^0 \to \Theta^+ \bar{p}) \times B(\Theta^+ \to pK_S^0)}{B(B^0 \to p\bar{p}K_S^0)} < 22\% \ \ 90\%\, CL$$

$$\frac{B(B^0 \to \Theta^{*++} \bar{p}) \times B(\Theta^{*++} \to pK^+)}{B(B^0 \to p\bar{p}K^+)} < 2\% \ \ 90\%\, CL$$

$$\frac{B(B^0 \to \Theta_c^0 \bar{p}\pi^+) \times B(\Theta_c^0 \to D^- p)}{B(B^0 \to D^- p\bar{p}\pi^+)} < 1.2\% \ \ 90\%\, CL$$

$$\frac{B(B^0 \to \Theta_c^0 \bar{p}\pi^+) \times B(\Theta_c^0 \to D^{*-} p)}{B(B^0 \to D^{*-} p\bar{p}\pi^+)} < 11\% \ \ 90\%\, CL$$

$$\frac{B(B^0 \to \Theta_c^+ \bar{p}) \times B(\Theta_c^+ \to \bar{D}^0 p)}{B(B^0 \to \bar{D}^0 p\bar{p})} < 5.9\% \ \ 90\%\, CL$$

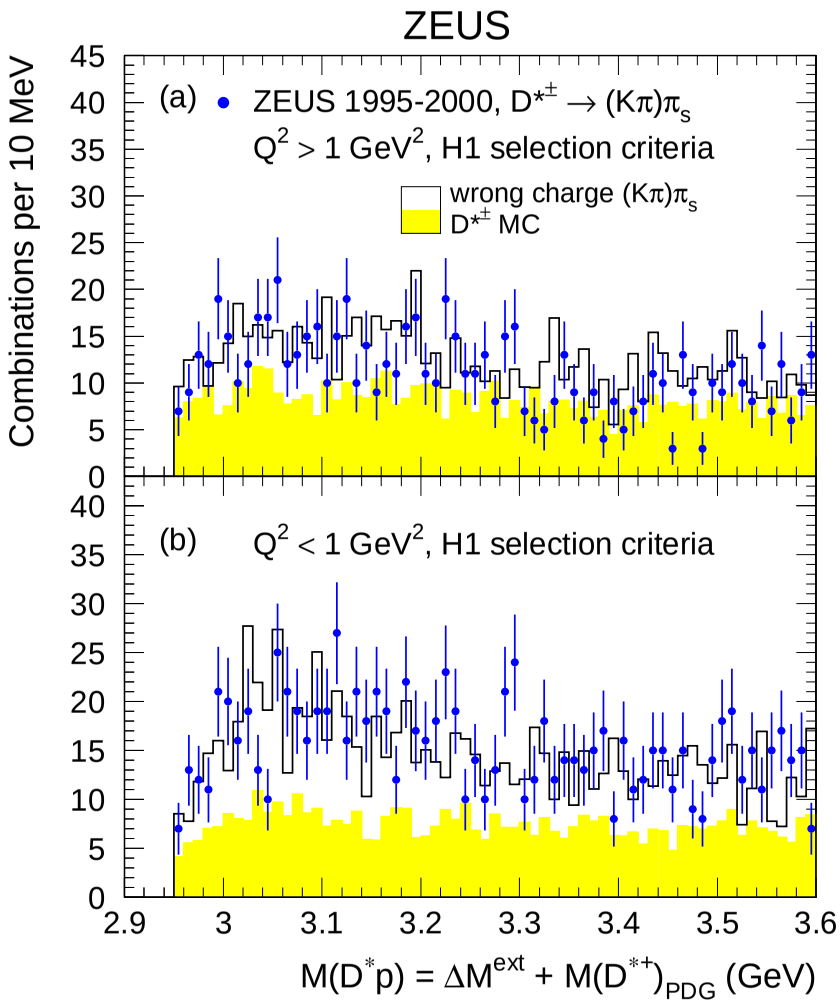
ZEUS

- $ep \to \Theta_c^0 X \ \mathscr{L} = 126 pb^{-1}$
- 60,000 D^*s
- $Q^2 > 1\ \mathrm{GeV}^2$

$$\frac{\sigma(\gamma^* p \to \Theta_c) \cdot B(\Theta_c \to D^{*-} p)}{\sigma(\gamma^* p \to D^{*-})} < 0.35\% \ @\ 95\%\mathrm{CL}$$

- Rules out H1 result

Eur.Phys J. C38



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

- $\Xi^{0,--}$:
  - is ruled out by larger statistics experiments
  - consistency argument. NA49 signal contradicts their own non-observation of Θ^+ in both nK^+ and pK^0_s modes. Given 43 events in Ξ^{--} they should have up to 80,000 $\Theta^+ \to \mathrm{nK}^+$ which they haven't (based on charge and s-quark penalty popping arguments (Fischer & Wenig hep-ex/0401014)
- Θ_c:
  - is ruled out by ZEUS running in the same conditions and w/ higher statistics sample
  - is rules out by 2 orders of magnitude higher statistics based CDF upper limit

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

- Θ^+:
  - All observations (13 experiments) are made in low statistics, low energy fixed target (with exception of ZEUS) experiments with poor momentum resolution
  - majority of experiments estimate signal significance as $S/\sqrt{B}$ neglecting uncertainty on B. Significance is overestimated.
  - The positions of various peaks are not fully consistent
  - Kinematical reflections from conventional processes are not always excluded.
  - All non-observing experiments (16):
    - have large/huge statistics
    - have good to excellent PID
    - excellent momentum resolution
  - Observations/non observations are at the 13/16 level
- Ξ^{--} 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.

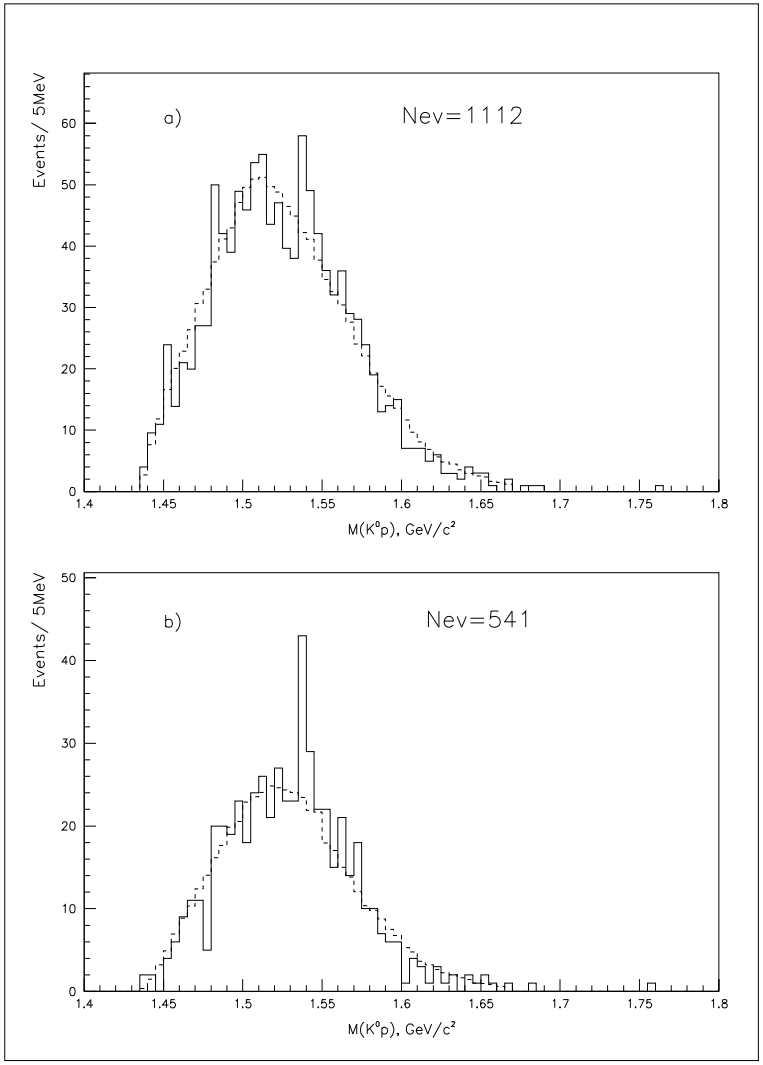
Backup Slides

Θ^+ sightings

$$\Theta^+ \to K^0 p$$

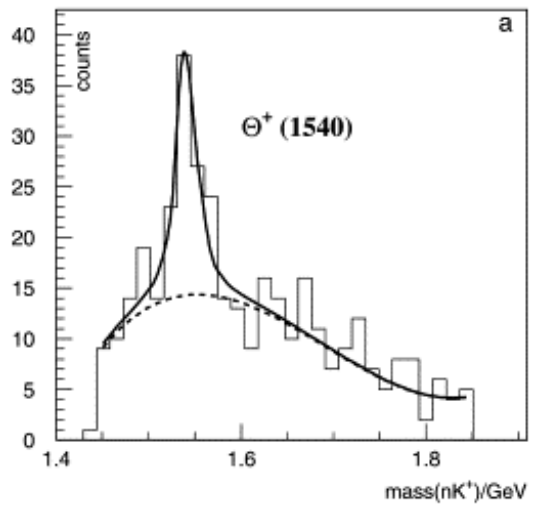
- DIANA : Stopped Kaons in bubble chamber (ITEP, Russia)
- $K^+ Xe \to \boxed{K^0_S p} Xe'$
- cuts:
  - $p(K^+) < 530\ MeV/c$
  - $\theta_p < 100^\circ, \theta_{K^0} < 100^\circ$ (angles w.r.t. Kaon direction in lab frame)
  - $\cos\phi < 0$ (proton and K^0 are back to back in the plane transverse to beam direction
- $S = 29$
- $B = 44$
- $S/\sqrt{B} = 4.4\sigma$
- $\boxed{M = (1539 \pm 2)\ MeV/c^2, \Gamma < 9.1\ MeV/c^2}$

Phys.Atom.Nucl.66:1715-1718,2003



Θ^+ sightings

- SAPHIR Experiment (PL B572,2003)
- tagged γ beam $0.8\ \mathrm{GeV} < E_\gamma < 2.6\ \mathrm{GeV}$
- $\gamma p \to \boxed{nK^+} K^0_S$
- remove events consistent with
  - $\gamma p \to p\pi^+\pi^-$, $\gamma p \to p\,K^+K^-$,
  - $\gamma p \to pe^+e^-$, $\gamma p \to p\pi^+\pi^-\pi^0$,
  - $\gamma p \to p\pi^-K^+$, $\gamma p \to p\pi^-K^+\pi^0$,
- $\cos\theta^*_{K^0_S} > 0.5$

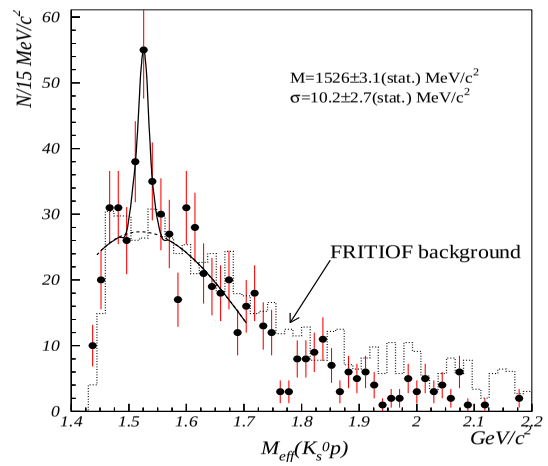


$S = 55$
$B = 56$
$S/\sqrt{S+B} = 5.2\sigma$

$M = (1.540 \pm 0.004 \pm 0.002)\ \mathrm{GeV}/c^2$

$\Gamma < 25\ \mathrm{MeV}/c^2$ @ 90% CL

- SVD experiment, 70 GeV/c proton beam incident on C,Si,Pb targets (hep-ex/0401024)
- $pN \to \boxed{pK^0_S} X$
- $N_{ch} < 6$
- $\cos\alpha > 0$ where α angle between pK^0_S system direction in the cm frame of proton and target and proton beam direction
- $p_{K^0_S} < p_p$ (anti Σ^* cut)



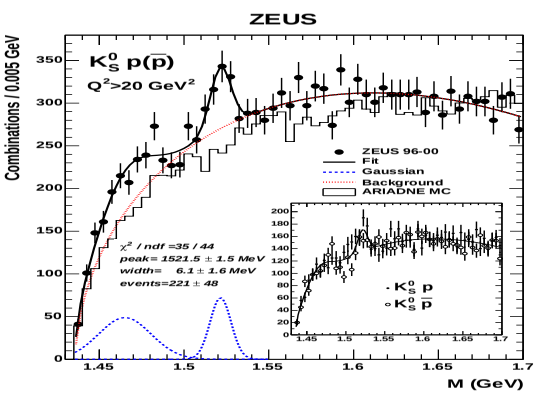
$S = 50$
$B = 78$
$S/\sqrt{B} = 5.6\sigma$

$M = (1.526 \pm 0.003 \pm 0.003)\ \mathrm{GeV}/c^2$

$\Gamma < 24\ \mathrm{MeV}/c^2$ @ 90% CL

Θ^+ sightings

- ZEUS Experiment, HERA (hep-ex/0404007)
- ep collisions, DIS, $Q^2 > 1\ GeV^2$
- $\gamma^* p \to \boxed{pK^0_S} X$
- cuts
  - all tracks $|\eta| < 1.75$
  - $|\eta(K^0_S)| < 1.5$
  - anti Λ cut $M(p\pi) < 1.112\ GeV/c^2$
  - $p_T(K^0_S) > 0.3\ GeV/c$
  - dE/dx based proton PID, $p_p < 1.5\ GeV/c$

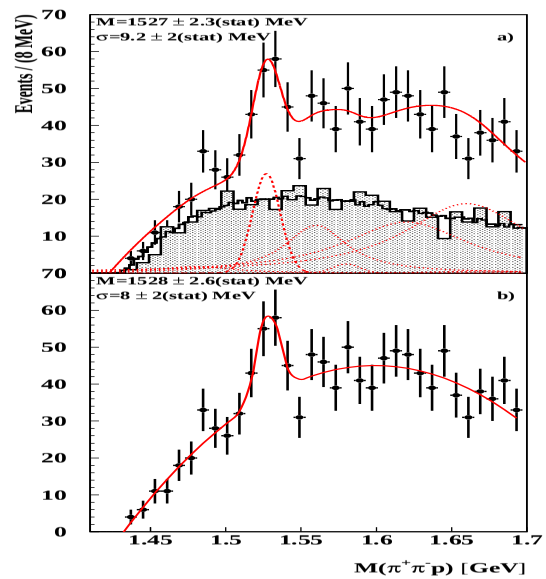


$S = 221 \pm 48$
$S/\sqrt{S+B} = 4.6\sigma$

$M = (1{,}521.5 \pm 1.5^{+2.8}_{-1.8})\ MeV/c^2$

$\Gamma = (8 \pm 4)\ MeV/c^2$

- HERMES experiment, HERA 27.6 GeV positron beam PR,D71,2005
- $ed \to \boxed{pK^0_S} X$



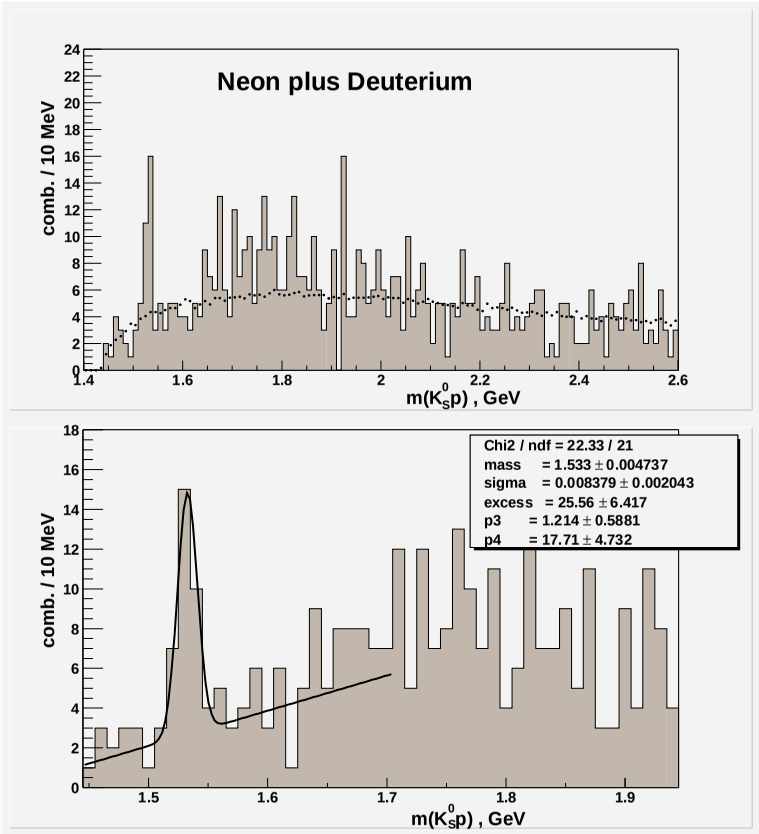
$S = 52$
$B = 155$
$S/\sqrt{B} = 4.2\sigma$

$M = (1.528 \pm 0.0026 \pm 0.0021)\ GeV/c^2$

$\Gamma = (17 \pm 9 \pm 3)\ MeV/c^2$

$$\frac{\sigma(ed \to \Theta^+)}{\sigma(ed \to \Lambda(1520))} = 1.6 - 3.5$$

Θ^+ sightings



- neutrino experiments on BEBC at CERN and 15-foot chamber at Fermilab
- database of data from WA21(hydrogen), WA25(deuterium), WA59(neon-hydrogen), E180(neon-hydrogen), E632(neon-hydrogen)
- $\nu \mathbf{A} \rightarrow \boxed{\mathbf{p K^0_S}} \mathbf{X}$
- $\mathbf{300 < p_p < 900\ MeV/c}$

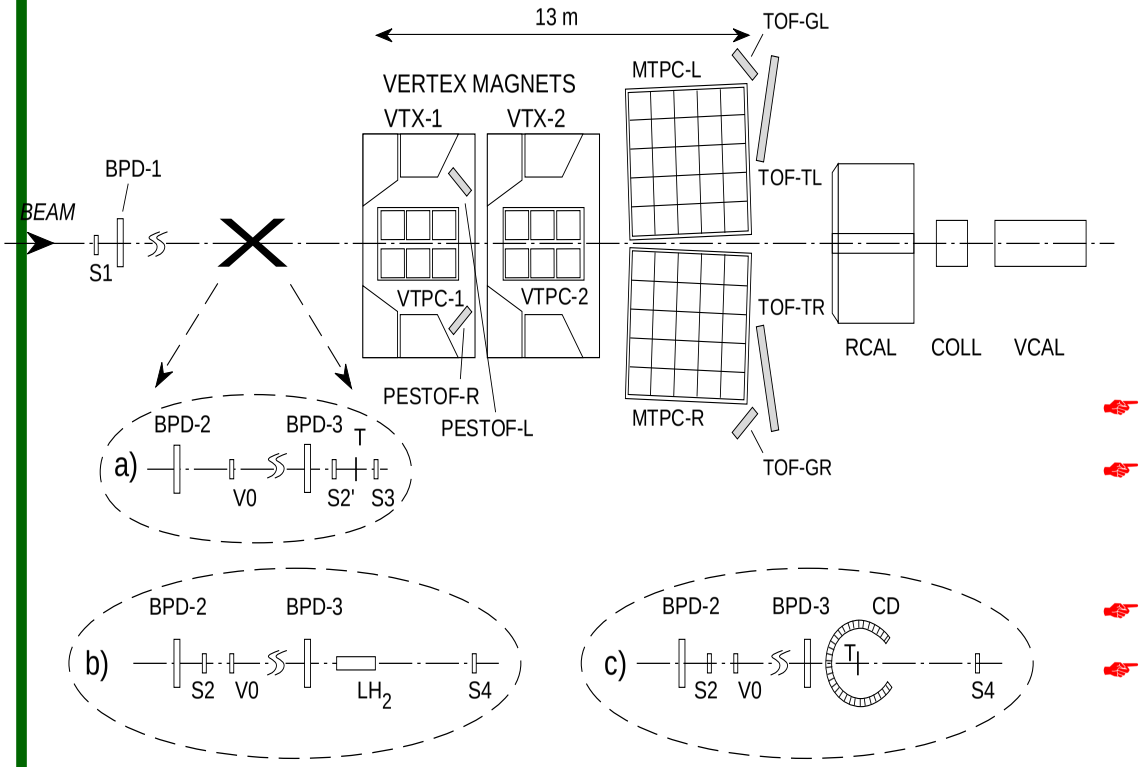
$\boxed{\mathbf{M = (1.533 \pm 0.005)\ GeV/c^2}}$

$\boxed{\Gamma < \mathbf{20\ MeV/c^2}\ @\ 90\%\ CL}$

Phys.Atom.Nucl,67,2004,

Exotic Cascade

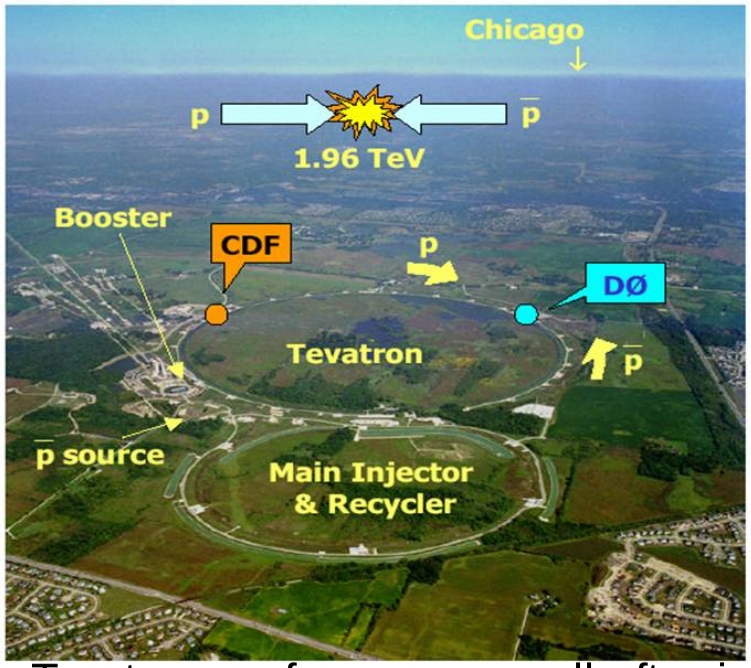
NA49 Experiment at CERN SPS



- $\mathbf{pp}$ @ $\sqrt{\mathbf{s}} = \mathbf{17.2}$GeV
- Search for $\mathbf{pp} \to \Xi^{0,--}_{3/2}\mathbf{X}$ with $\Xi^{0,--}_{3/2} \to \Xi\pi^{+,-}$ $\mathbf{udss\bar{d}}$
- $\theta(\Xi\pi) > 4.5°$
- $\mathbf{p}_{\pi^+} > \mathbf{3\ GeV/c}$

Tevatron at Fermilab

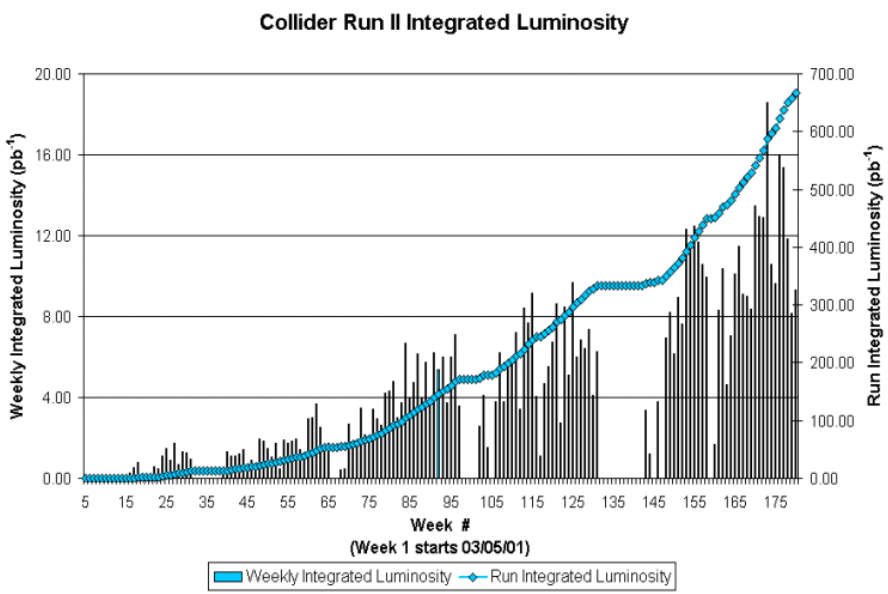
World's largest collider

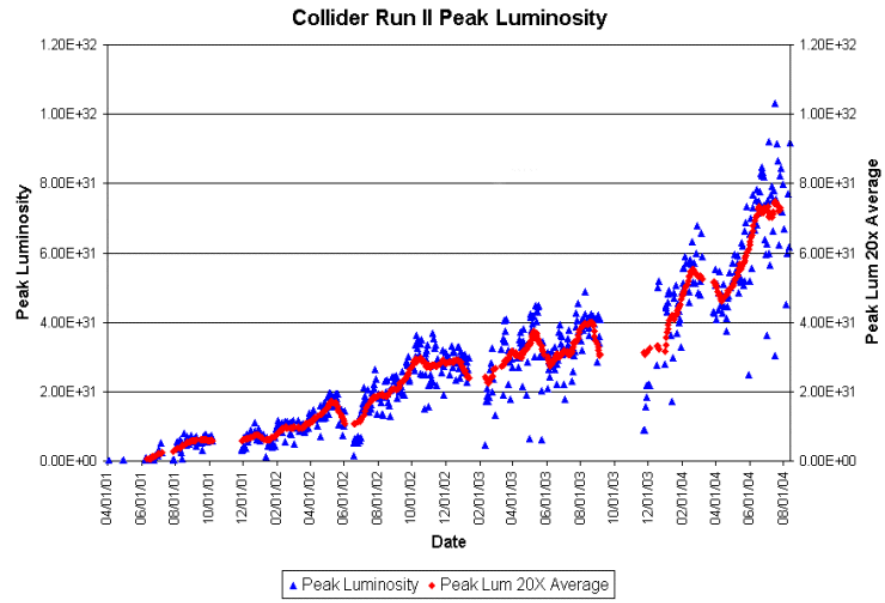


- Tevatron performs very well after initially slow start
- $\int \mathscr{L} dt \sim 700 pb^{-1}$ ($\sim 550 pb^{-1}$ on tape)
- CDF & D0 efficiency $\sim 80\%$
- expect $2\ fb^{-1}$ for Run IIa
- $4-8\ fb^{-1}$ by 2009

- 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
  - $\mathscr{L}_{inst} = 10.5 \times 10^{31} cm^{-2} s^{-1}$(record) (goal $8.1 \times 10^{31} cm^{-2} s^{-1}$)
  - high beam-beam crossing (inter-bunch spacing 396 ns), low pileup

Collider Luminosity

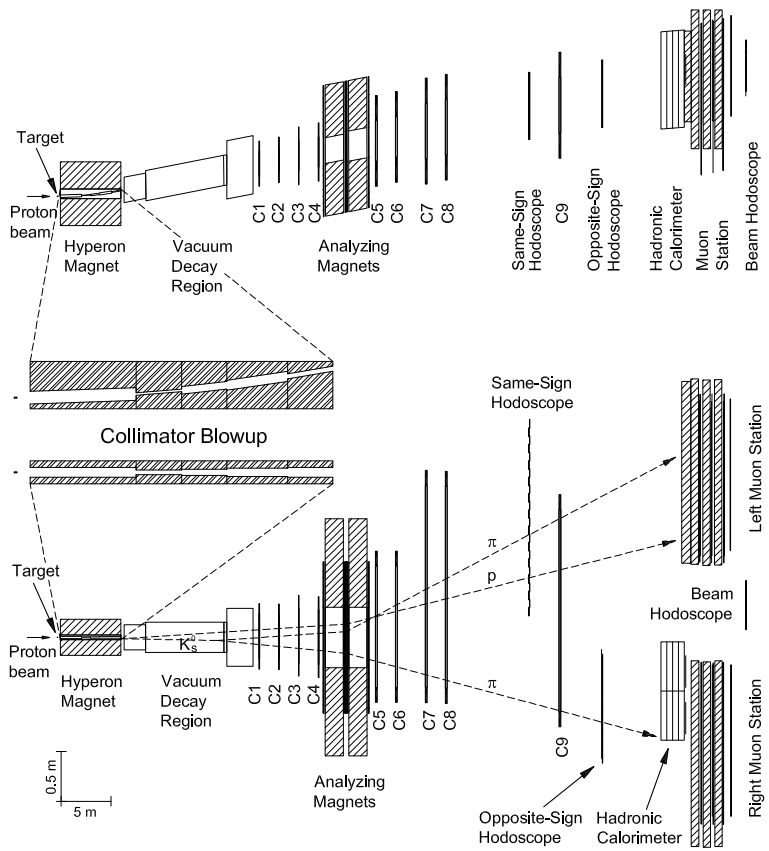




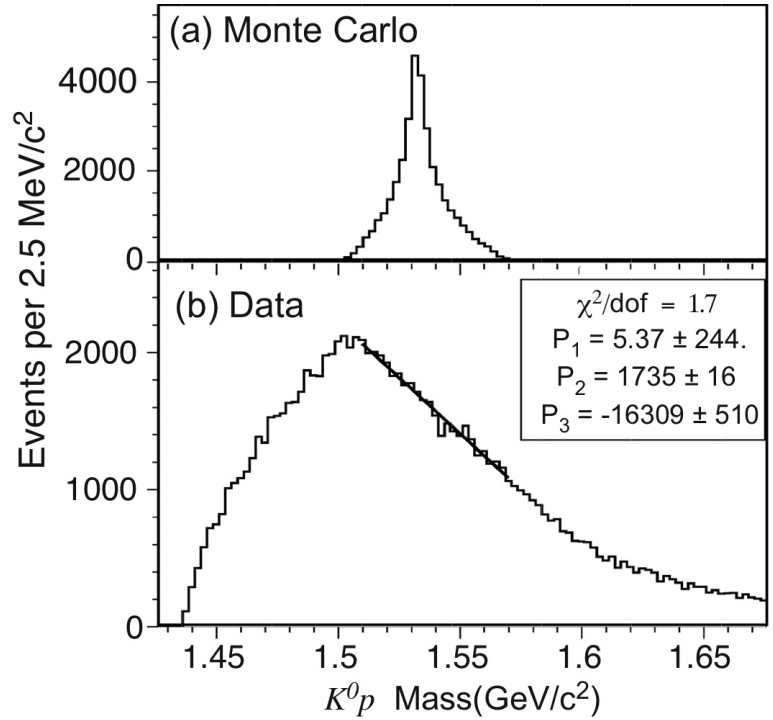
Analyses presented based on $240 - 280\mathrm{pb}^{-1}$ of integrated luminosity

HyperCP

- 120 GeV/c - 200 GeV/c beam of mixture of $\mathbf{p}, \pi, \mathbf{K}$



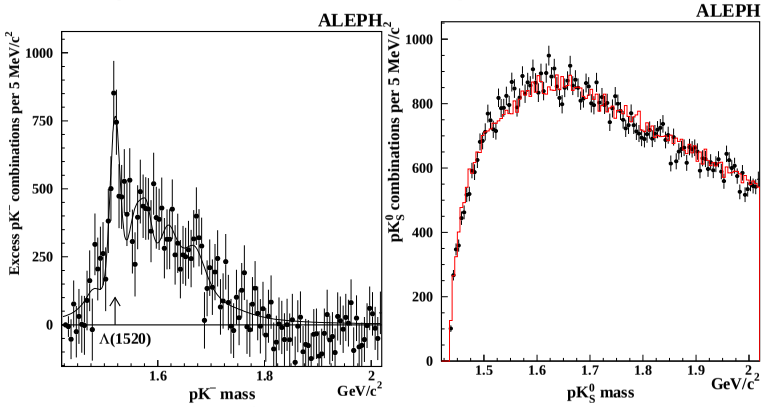
- $\Theta^+ \to \mathbf{pK_S^0}$



- of 106,000 $\mathbf{pK_S^0}$ candidates find < 317 Θ^+ candidates => < 0.3% $\mathbf{pK_S^0}$ candidates come form Θ^+
PR, D70,2004

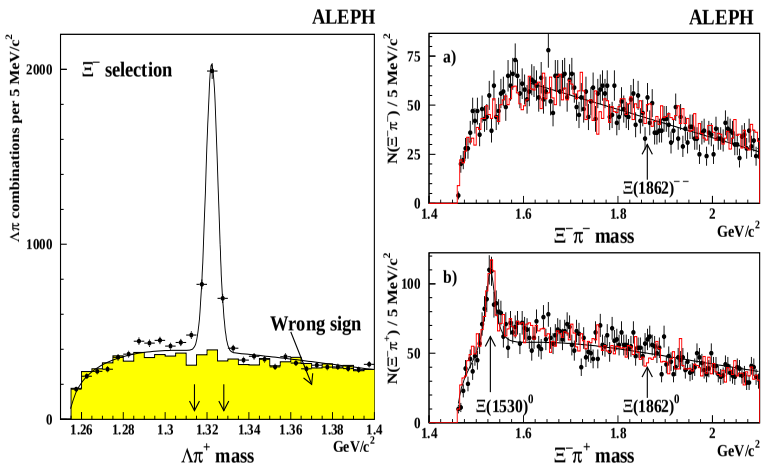
ALEPH

- Θ^+ production in Z decays



$$N_\Theta \cdot B(\Theta \to pK^0_S)/N_{\Lambda(1520)} < 0.027$$

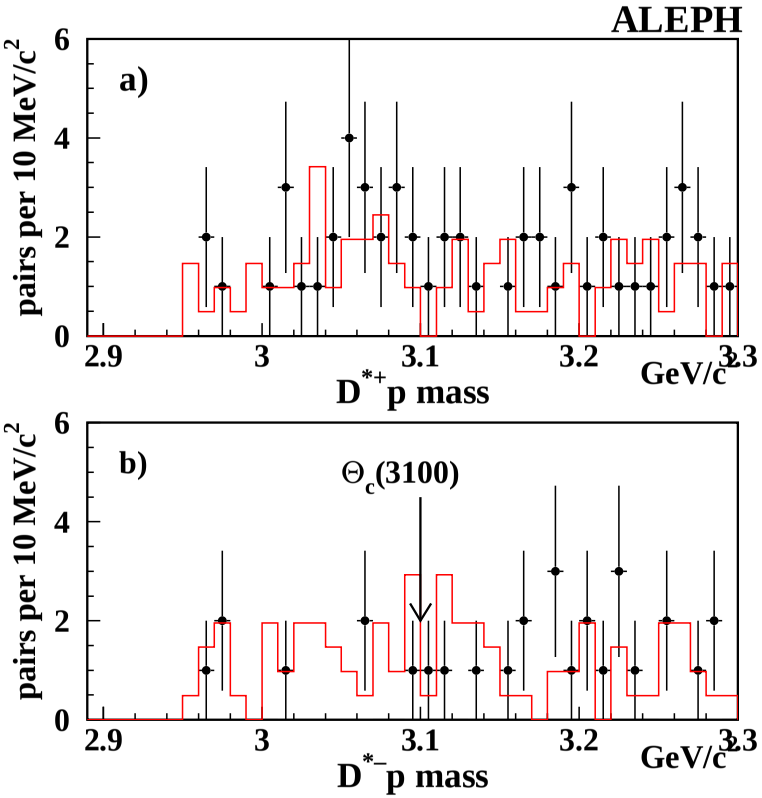
- Ξ^{--} production in Z decays



$$N_{\Xi^{--}} \cdot B(\Xi^{--} \to \Xi\pi^-)/N_{\Xi(1530)} < 0.082$$

$$N^0_\Xi \cdot B(\Xi^0 \to \Xi\pi^+)/N_{\Xi(1530)} < 0.16$$

- Θ^0_c production in Z decays



$$N_{\Theta^0_c} \cdot B(\Theta^0_c \to D^{*-}p)/N_{D^{*-}} < 0.0031$$

$$N_{\Theta^0_c} \cdot B(\Theta^0_c \to D^-p)/N_{D^-} < 0.018$$

limits are at 95% CL
P.L., B 599 (2004)