Hadron Spectroscopy at Tevatron

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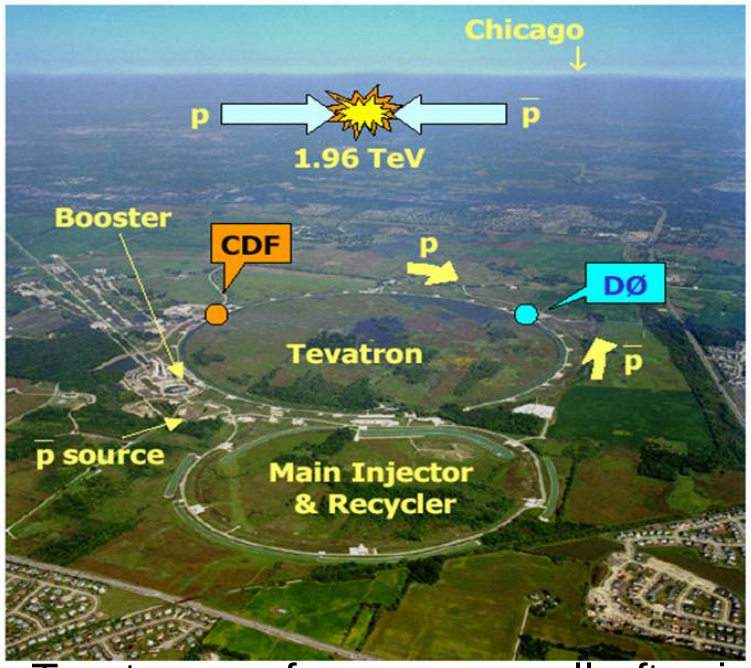
The Future of QCD at the Tevatron

Tevatron at Fermilab

World's largest collider



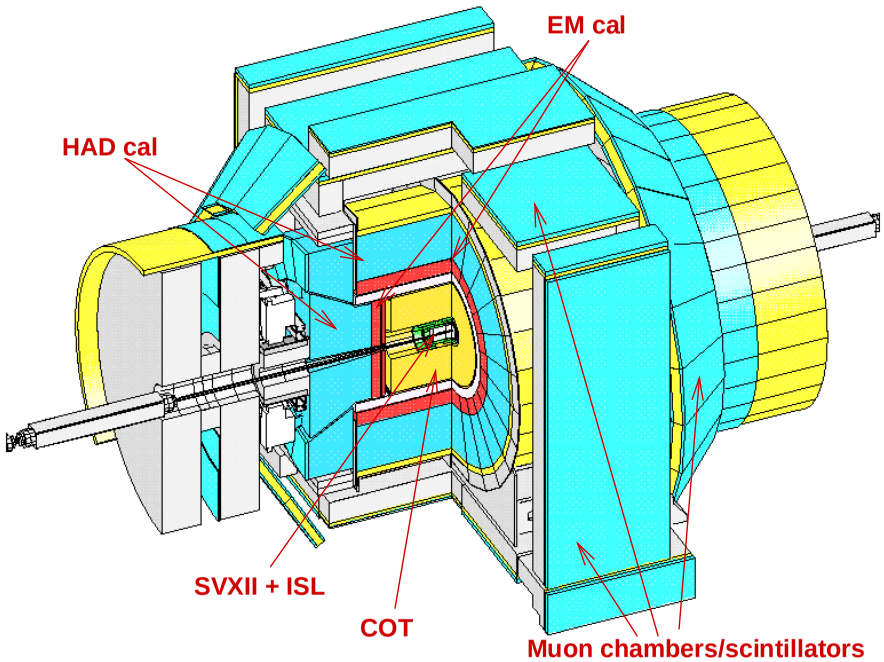
- Tevatron performs very well after initially slow start
- $\int \mathscr{L} dt \sim 300 pb^{-1}$ ($\sim 250 pb^{-1}$ on tape)
- CDF & D0 efficiency $\sim 80\%$
- expect2 fb^{-1} for Run IIa
- $4-8$ fb^{-1} by 2009

- 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
  - $\mathscr{L}_{inst} = 7.2 \times 10^{31} cm^{-2} s^{-1}$(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 ($1.5 < R < 30\text{cm}$, $|Z| < 45\text{cm}$). $r\phi$, 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. $\sigma(1/p_T) \sim 0.1\%/(\text{GeV}/c)$, $\sigma(\text{hit}) \sim 150\mu\text{m}$. dE/dx PID.
- **new plug calorimeter**
- **extended muon coverage, $|\eta| < 1.5$**
- **ToF system, (100 ps @ 150 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
    - **Silicon vertex trigger (SVT)**
    - **PID with ToF and dE/dx**
    - **Excellent mass resolution**

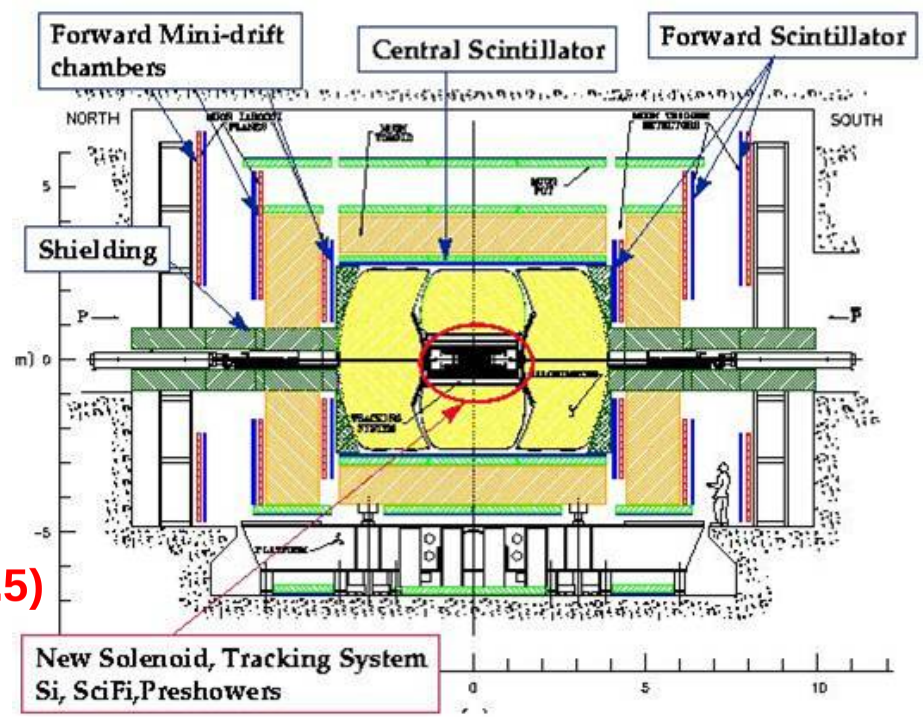


Run II D0 Detector

Upgraded D0 Detector

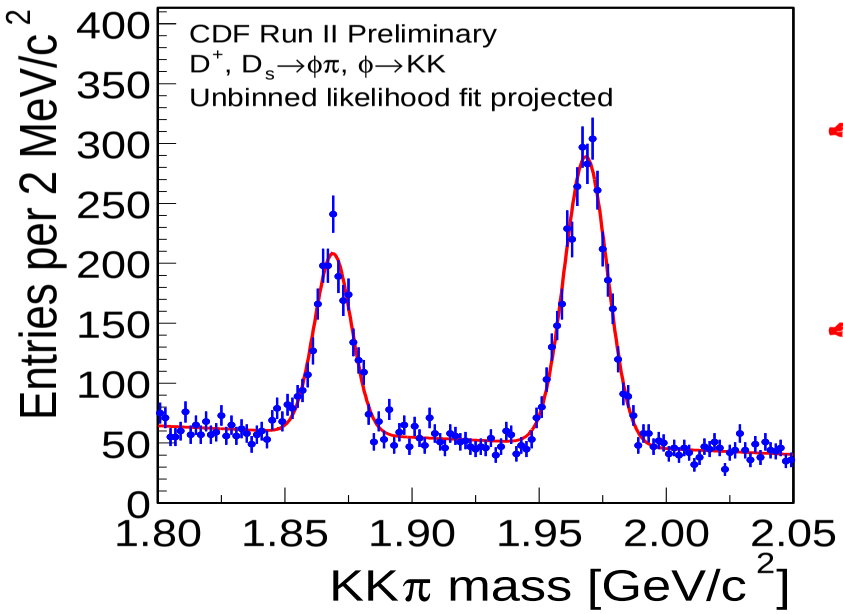
- solenoid
- tracking
  - silicon tracker
  - fiber tracker
- improved muon system
- improved calorimeter system
- fast DAQ
- enhanced trigger system

- Excellent electron and muon ID
- Superior tracking η coverage (up to 2.5)



Why spectroscopy?

"Measurement of the Mass Difference $M(D_s^+) - M(D^+)$ at CDF II"
Phys. Rev. D 68, 072004 (2003), a result on spectroscopy of charmed mesons became the first Run II paper



- mass measurements allow to check predictions of QCD inspired quark models.
- studies of mesons containing heavy quarks test predictions of HQET. e.g.

$$m(D_s^+) - m(D^+) = m(B_s^+) - m(B^+)$$

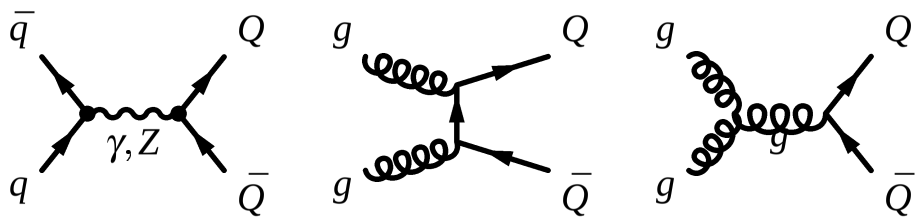
- a bump in an invariant mass spectrum of fully reconstructed decay products usually provides the most unambiguous evidence for a state.
- mass measurements of known states allow to
  - calibrate absolute tracking momentum scale
    - dE/dx and MCS corrections due to detector material
    - B field corrections
  - understand alignment corrections

$$m(D_s^+) - m(D^+) = 99.41 \pm 0.38(\text{stat.}) \pm 0.21(\text{syst.})\ \text{MeV}/c^2$$

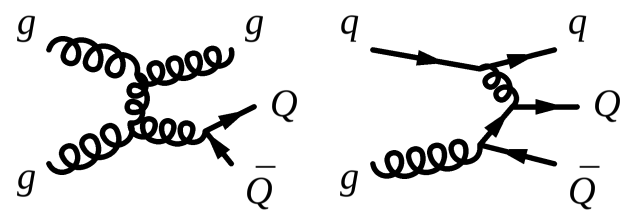
better than PDG's $(99.2 \pm 0.5)\ \text{MeV}/c^2$

Heavy Flavor Production at Tevatron

LO Heavy quark production



NLO Heavy quark production



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

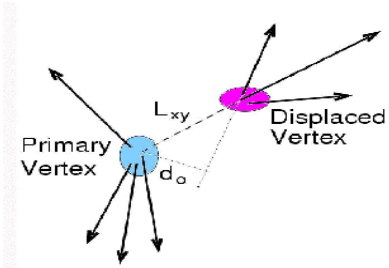
Q fragments into final states $\mathrm{B_u, B_d, B_s, Baryon_b}$ with the following fractions:

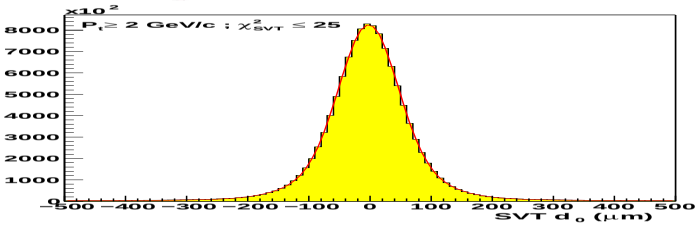
$$\mathrm{B_u : B_d : B_s : Baryon_b} = 0.388 : 0.388 : 0.106 : 0.118$$

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

Heavy Flavor Triggers

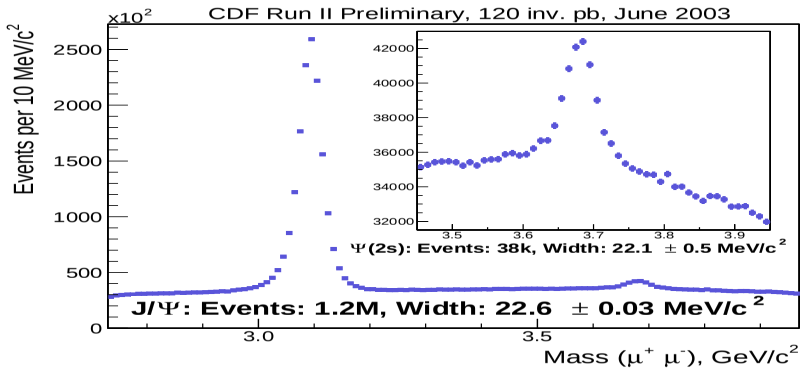
- unique displaced track trigger at CDF
  - Level 1
    - ✓ XFT tracking in COT ($r-\phi$)
    - ✓ opposite charged track pair with $p_T > 2\ \mathrm{GeV/c}$ each
    - ✓ $\Sigma p_T > 5.5\ \mathrm{GeV/c}$
    - ✓ $\Delta\phi < 135°$
  - Level 2
    - ✓ XFT track seeds SVT boards, that perform fast ($r-\phi$) track fit
    - ✓ require tracks impact parameter to be $0.012 < |d_0| < 0.1\ \mathrm{cm}$



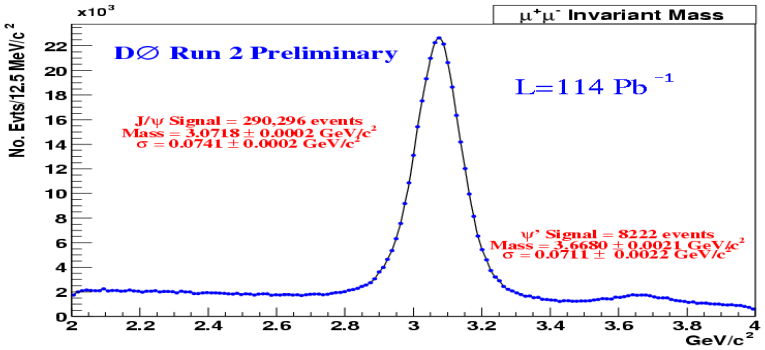


$$\sigma(d_0)_{SVT} = 47\ \mu m$$

- traditional di-muon triggers:
  - CDF
    - two central muons ($|\eta| < 1$)
    - $p_T(\mu) > 1.5\ \mathrm{GeV/c}$



  - D0
    - two muons ($|\eta| < 2$)
    - $p_T(\mu) > 2-4\ \mathrm{GeV/c}$ (η dependent)



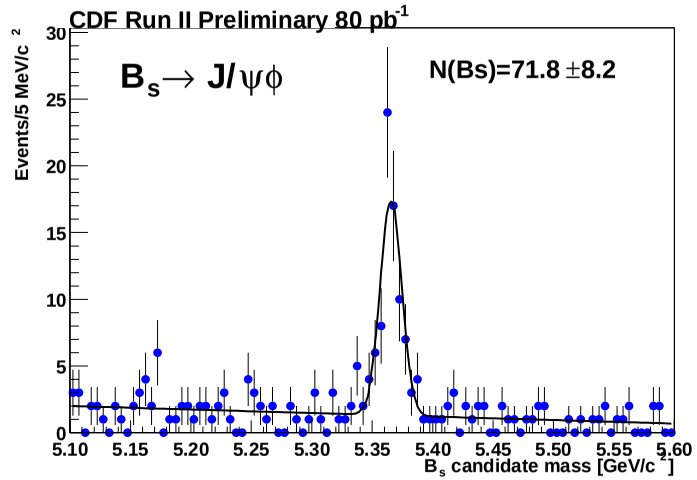
B-Hadron masses

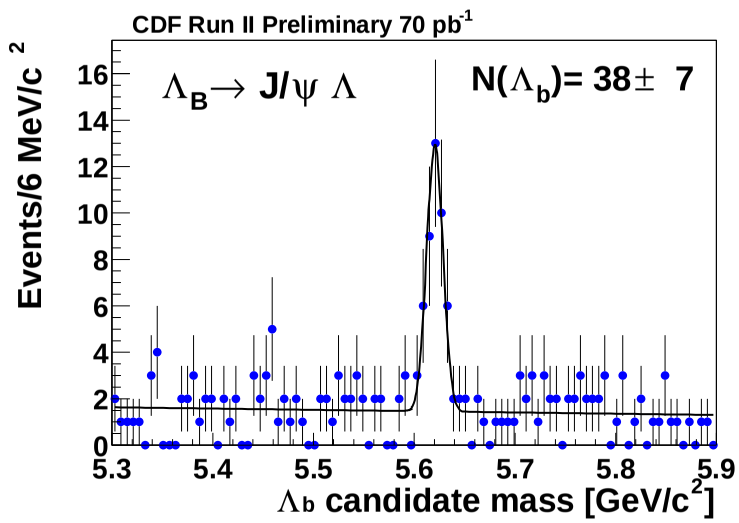
- measure masses in fully reconstructed $B \to J/\psi X$ modes
- use high statistics $J/\psi \to \mu\mu$ and $\psi(2S) \to J/\psi\pi\pi$ to calibrate tracking momentum scale
- systematic uncertainties in tracking momentum scale are due to:
  - magnetic field
  - material description
- results with 80 pb^{-1} of data:

$$m_{B^0} = (5280.30 \pm 0.92 \pm 0.96)\ \mathrm{MeV/c^2}$$
$$m_{B^+} = (5279.32 \pm 0.68 \pm 0.94)\ \mathrm{MeV/c^2}$$

- consistent with PDG average
- B_s and Λ_b are world's best

$$m_{B_s} = (5365.50 \pm 1.29 \pm 0.94)\ \mathrm{MeV/c^2}$$
$$m_{\Lambda_b} = (5620.4 \pm 1.6 \pm 1.2)\ \mathrm{MeV/c^2}$$

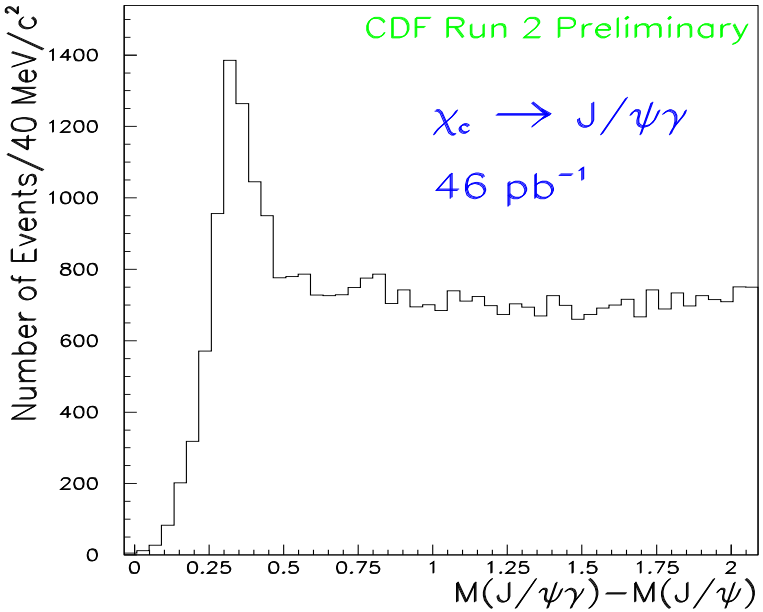




Observation of χ_c states

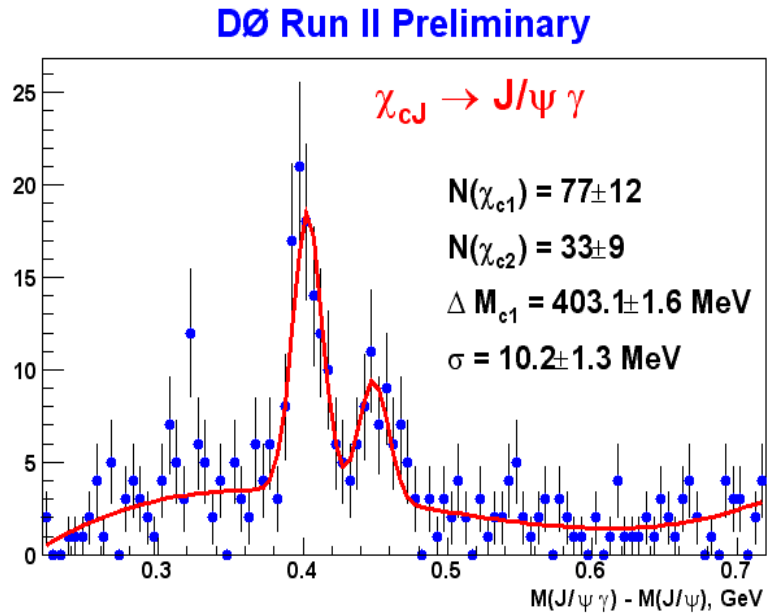
$$\chi_{c_{1,2}} \to J/\psi\gamma$$

- **CDF**



- **di-muon trigger,** 46pb^{-1}
- $|M(\mu\mu) - M(J/\psi)| < 80\ \text{MeV/c}^2$
- **calorimeter photons,** $p_T(\gamma) > 1\ \text{GeV/c}$
- $p_T(\mu) > 2\ \text{GeV/c}$

- **D0**



- **di-muon trigger,** 114pb^{-1}
- $|M(\mu\mu) - M(J/\psi)| < 200\ \text{MeV/c}^2$
- **use** γ **converted in detector material**
- $p_T(\gamma) > 1\ \text{GeV/c}$

X(3870) at CDF

- new narrow state observed by Belle in exclusive $B^+ \to J/\psi\pi^+\pi^-K^+$
- $^3D_2$ charmonium state? or $D^0\bar{D}^{*0}$ molecule?

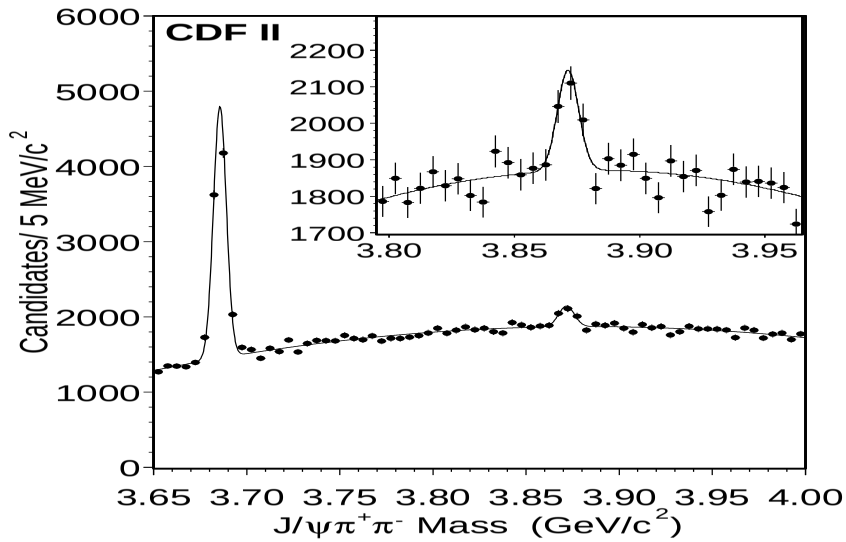
- using 220 pb^{-1} ($\sim$ 2M $J/\psi \to \mu\mu$ decays) CDF produced first confirmation of Belle result in the inclusive $p\bar{p} \to J/\psi\pi^+\pi^-X$ production
- cuts optimized on $\psi(2S)$ signal
- pions required to be in a cone $\sqrt{\Delta\phi^2+\Delta\eta^2} < 0.7$ around $J/\psi\pi\pi$ system momentum direction
- $p_T(J/\psi) > 4\,\mathrm{GeV/c}$

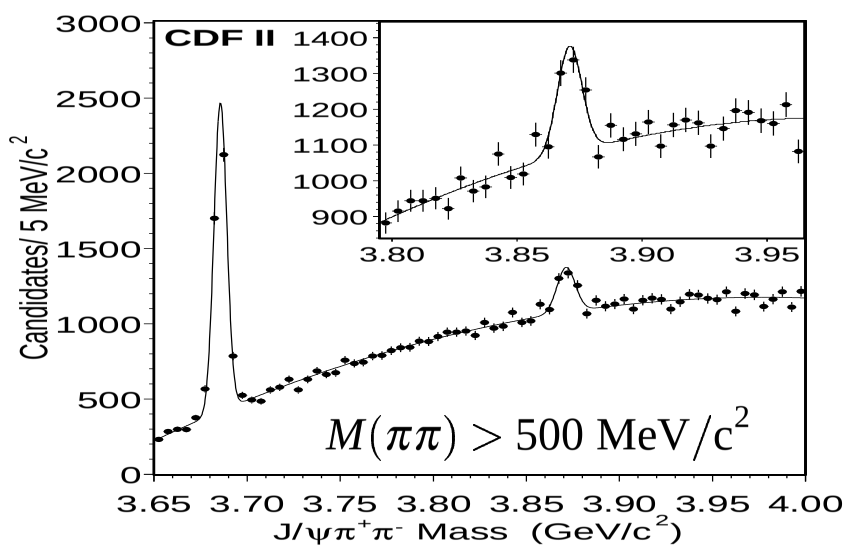
☛ 730 ± 90 around 3870 $\mathrm{MeV/c^2}$

CDF: $m_{X(3870)}$ = $(3871.3 \pm 0.7 \pm 0.4)\ \mathrm{MeV/c^2}$

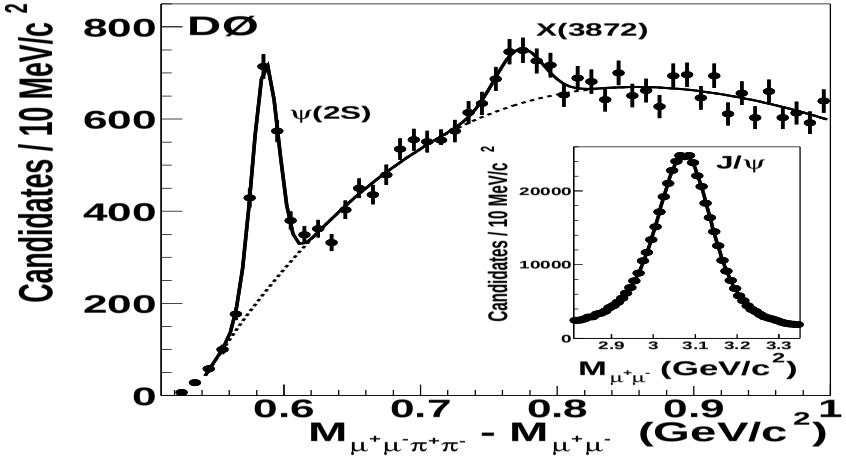
Belle: $m_{X(3870)}$ = $(3872.0 \pm 0.6 \pm 0.5)\ \mathrm{MeV/c^2}$

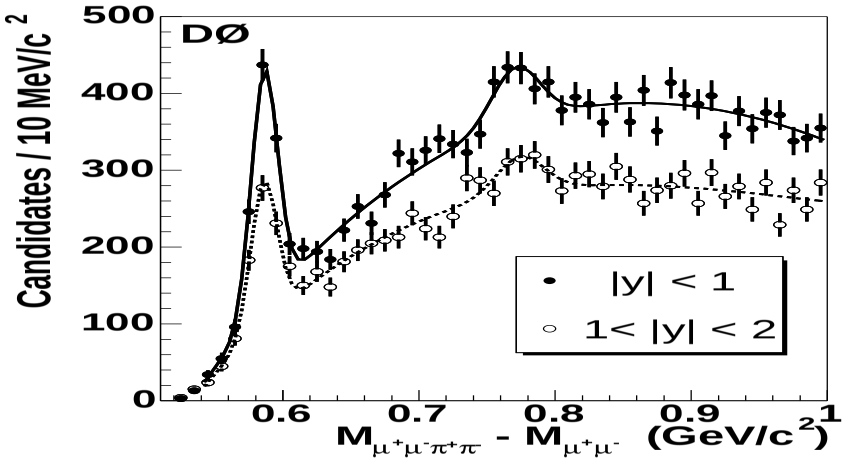
- Statistically sound sample of X(3870) warrants further studies:
  - lifetime
  - angular analysis
  - $M(\pi\pi)$ analysis





X(3870) at D0





- **230 pb^{-1} di-muon trigger**
- $3.80 < M(\mu\mu) < 3.35\ \mathrm{GeV/c^2}$
- $p_T(J/\psi) > 5\ \mathrm{GeV/c}$
- $p_T(\pi) > 0.7\ \mathrm{GeV/c}$
- $\sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.4$ **around** $J/\psi\pi\pi$ **system momentum direction**
- $m(\pi\pi) > 0.52\ \mathrm{GeV/c^2}$

D0: $\Delta M(X(3870))$ = $(774.9 \pm 3.1 \pm 3.0)\ \mathrm{MeV/c^2}$

- **properties similar to** $\psi(2S)$

☛ **X is** $60\ \mathrm{MeV/c^2}$ **heavier than potential quark model predictions for** $^3D_2\ c\bar{c}$ **state**

☛ **observation of** $X \to \chi_{c_1}\gamma$ **would indicate** $c\bar{c}$ **state (Belle does not report seeing this decay)**

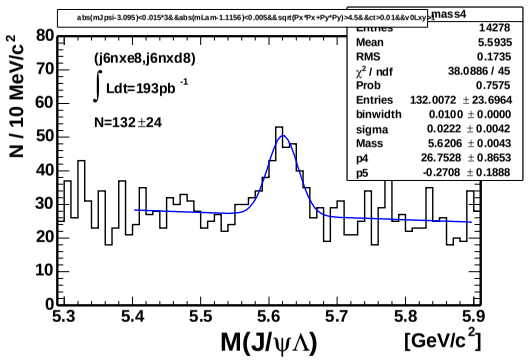
☛ **data favors large** $M(\pi\pi)$**, for** $^3D_2$ **the decay** $X \to J/\psi\rho$ **is forbidden**

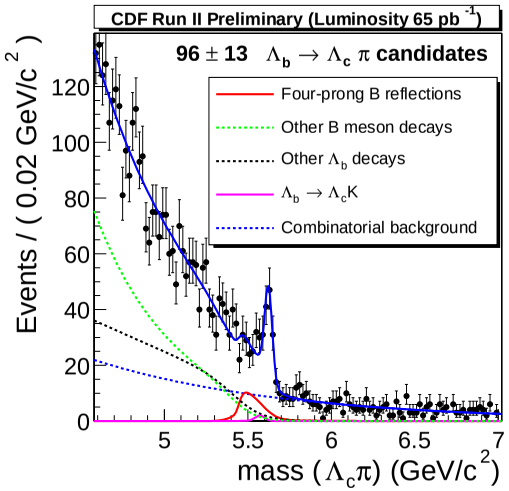
☛ **observation of** $X^+ \to J/\psi\pi^+\pi^0$ **at about the same mass would rule out** $c\bar{c}$ **state**

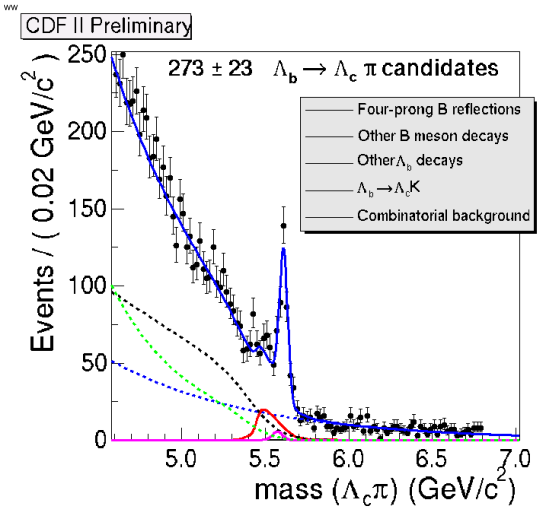
☛ **work in progress**

Baryons

- Over the last decade there has been substantial progress in precise measurements of the masses, lifetimes and branching ratios of baryons containing one charmed quark. Baryons containing two charmed quarks were observed recently
- For the bottom baryons so far only the lowest lying state Λ_b has been observed.
- CDF has accumulated the world largest sample of Λ_b baryons:







Total sample ~ 500 events!

- Other baryons? Baryon studies suffer from low yields, low branching ratios and backgrounds from meson decays due to particle mis-identification.

Ground states B=1, C=0

Weakly decaying ground state b-baryons

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

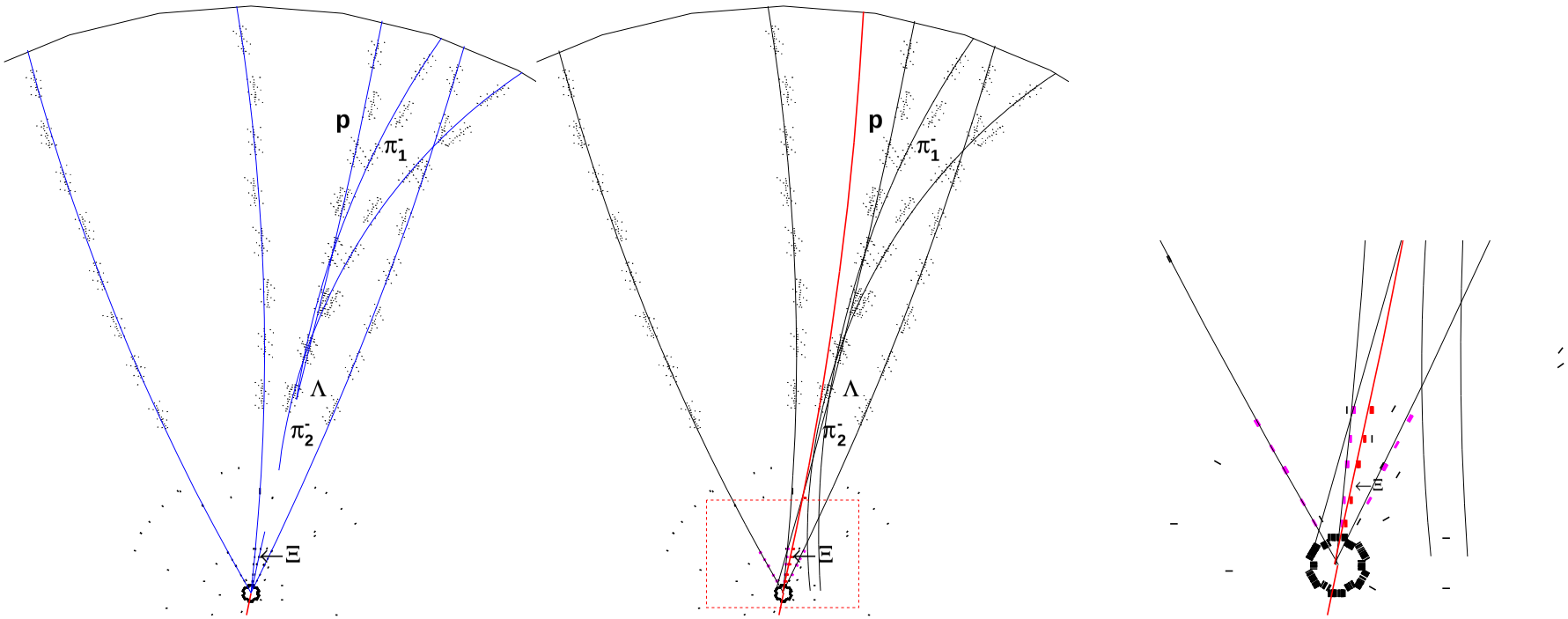
Theoretical mass assignments are taken from seminal work by A. De Rújula, H. Georgi and S. L. Glashow, Phys. Rev. D12(1975) 147. Quoted Λ_b mass is CDF measurement.

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

Cascade tracking in SVX at CDF

Hyperon Are Tracked in Silicon

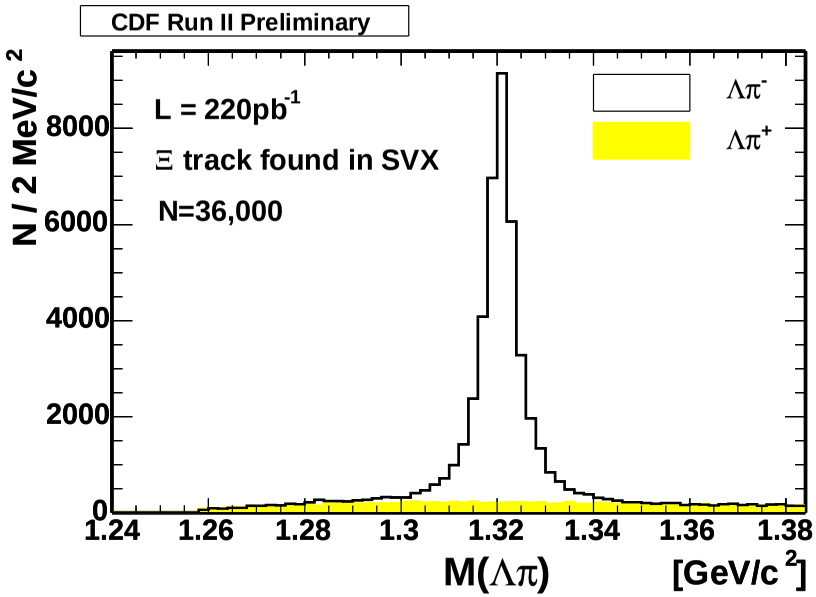
- $\Xi^- \to \Lambda^0 \pi^-$ is a long lived particle $c\tau = 4.91cm$. It leaves hits in SVX detector. CDF developed dedicated tracking Ξ in Silicon.

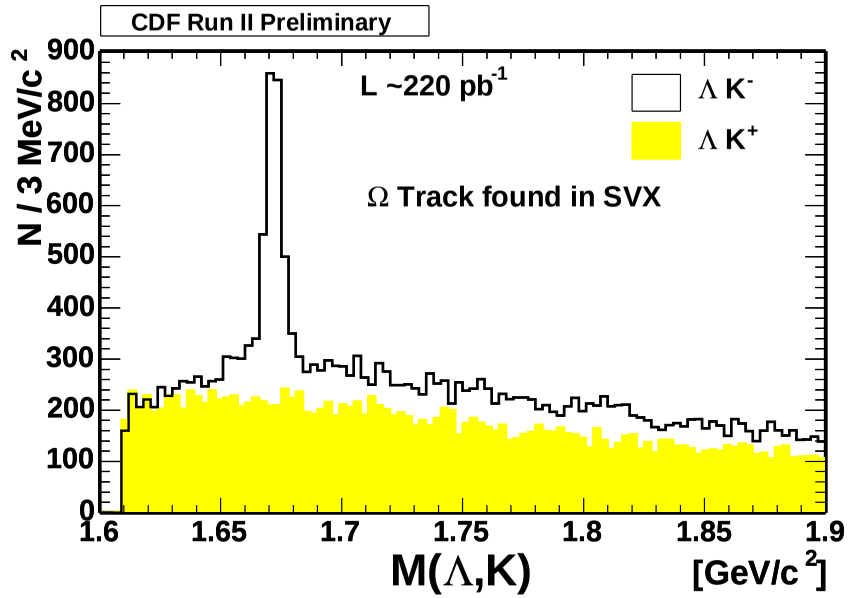


MC : $\Xi_b \to \Xi_c^+ \pi^- \quad \Xi_c^+ \to \Xi^- \pi^+ \pi^+ \quad \Xi^- \to \Lambda \pi_2^- \quad \Lambda \to p \pi_1^-$

Tracked Hyperon signals

- CDF has developed tracking of long lived hyperons (Ξ and Ω) in the SVX detector.
- silicon tracking of hyperons improves momentum and impact parameter resolution as well as results in excellent background suppression





Two Track trigger data

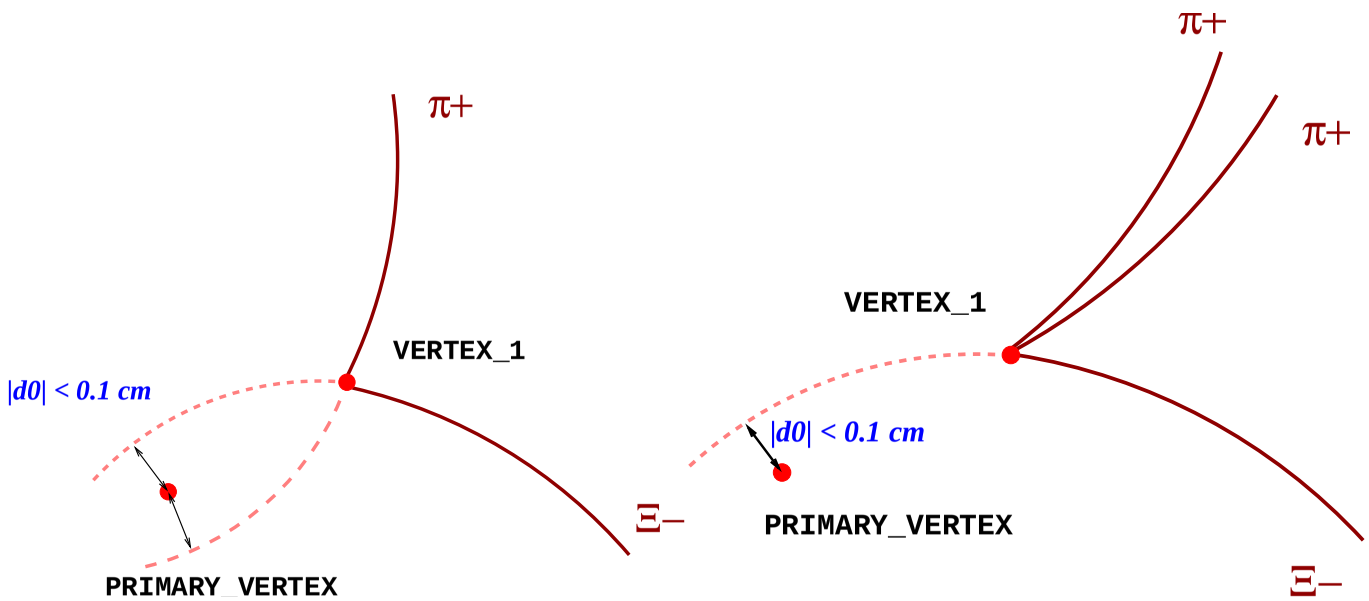
- hyperon tracks reconstructed in SVX are used to probe production of Ξ_b and Ω_b in decays accessible to CDF triggers (work in progress)

Charmed-Strange baryons

$$\Xi_c^0 \to \Xi^- + \pi^+ \quad , \Xi_c^+ \to \Xi^- + \pi^+\pi^+ \ ,$$

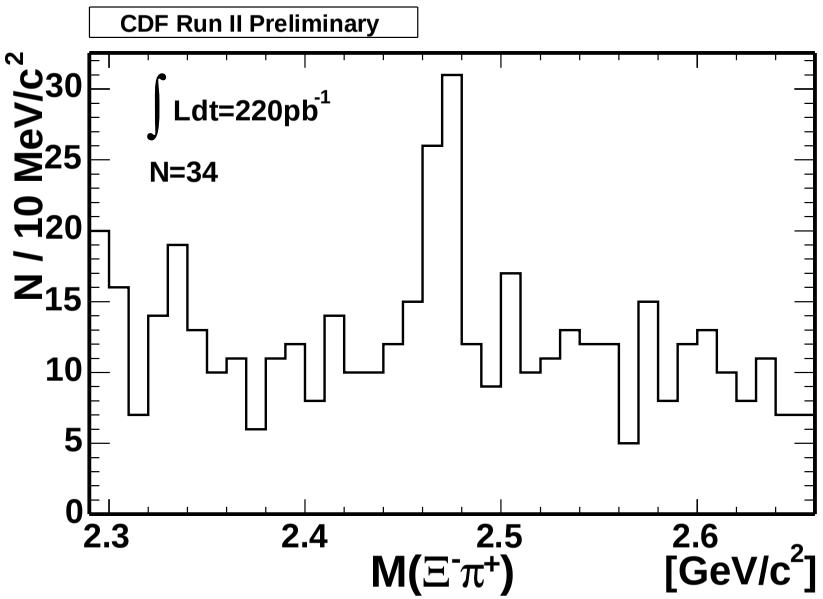
$$\hookrightarrow \Lambda\pi^- \qquad\qquad \hookrightarrow \Lambda\pi^-$$

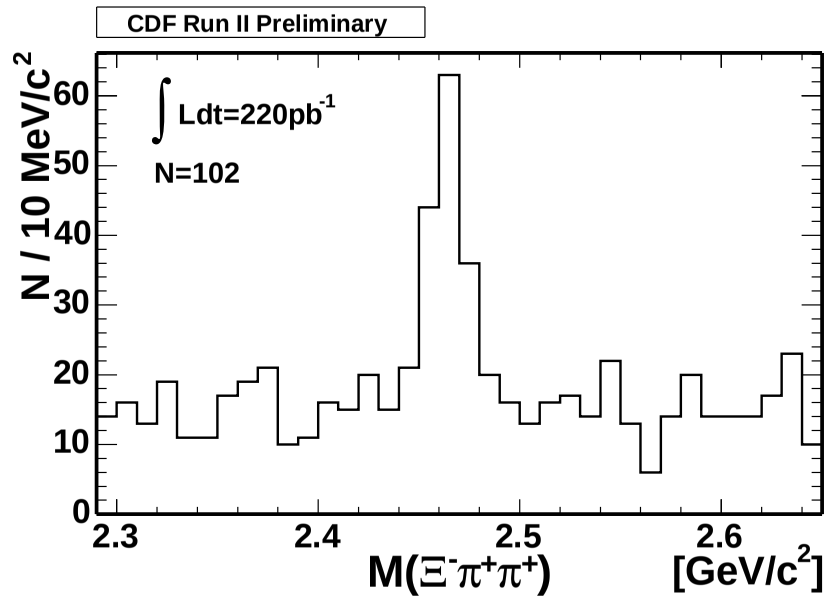
$$ct = 29\mu m \qquad\qquad ct = 132\mu m$$



Charmed-Strange Baryons

$L_{xy} > 0.05$ and $L_{xy}/\sigma > 3$

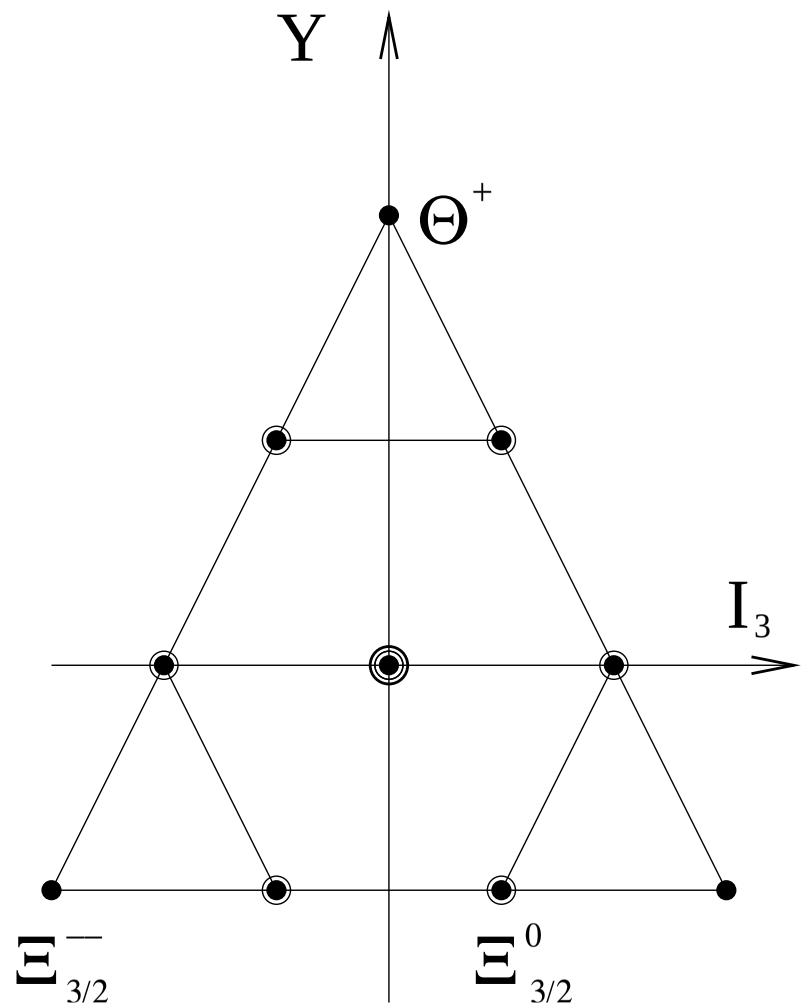




First observation of charmed-strange isodoublet $\left\{\Xi_c^0, \Xi_c^+\right\}$ in $p\bar{p}$ collider

Motivation

- Recent flurry of reports of experimental evidences for a narrow exotic baryon state decaying to nK^+, pK^0_S at the mass of $\sim 1540\ MeV/c^2$, interpreted as 5-quark, ($uudd\bar{s}$), Θ^+ state predicted in chiral soliton model of baryons by Diakonov, Petrov, Polyakov (cf. hep-ph/9703373) revitalized interest in baryon spectroscopy.
- ✗ Not seen by Hera-B, Phenix, BES
- Followed by observation of Ξ^{--}, Ξ^0, $M \sim 1860\ MeV/c^2$, decaying to $\Xi^-\pi^-, \Xi^-\pi^+$, by NA49 Experiment. Members of $S = -2$ ($qqss\bar{q}, q = u, d$) quadruplet of the SU(3) $\overline{10}$ of pentaquarks. (cf. Phys.Rev.Lett.92:042003,2004)
- ✗ Not seen by Hera-B, WA86
- Recently H1 Experiment reported anti-charmed analogue ($uudd\bar{c}$) of the Θ^+ state decaying to $D^{*+}\bar{p}$. $M(\Theta^0_c) = (3,099 \pm 3 \pm 5)\ MeV/c^2$ (cf. hep-ex/0403017)
- All reported resonances are narrow with witdhs compatible with the apparatus resolutions.



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.

CDF $\Xi^-\pi^\pm$ spectra

$$\Xi(1860)^{--,0} \to \Xi^- + \pi^{-,+}$$
$$\hookrightarrow \Lambda\pi^-$$

fit function:

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

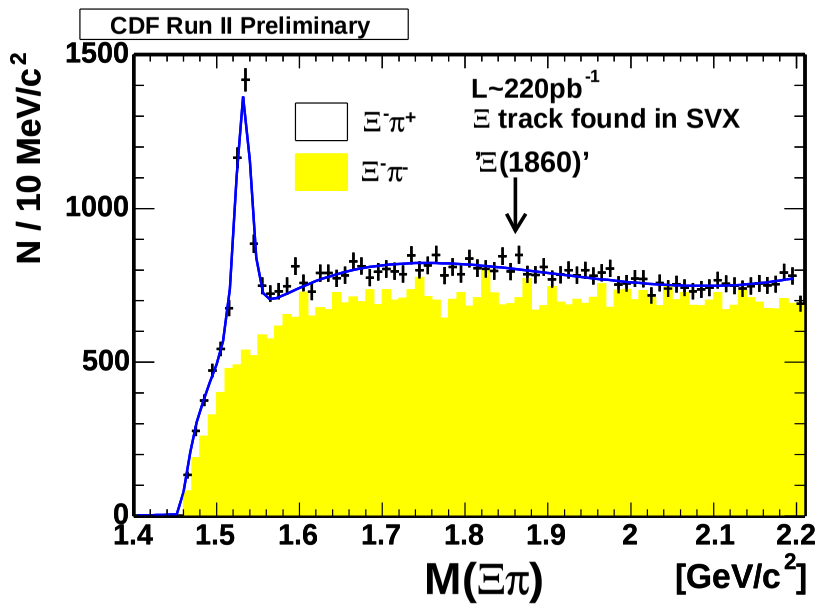
Γ is fixed to PDG value of 9.1 MeV/c^2

$$N(\Xi(1530)) = 2,182 \pm 92$$
$$M = 1,5320 \pm 0.5\ \mathrm{MeV/c^2}$$

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

(similar to NA49)

- displaced trigger sample, SVX tracked Ξ^-
- require prompt Ξ^-, $|d_0(\Xi)| < 0.015$ cm



Channel	# of events	UL 90 % CL	UL 95 % CL
$\Xi^-\pi^+$	57±51	126	144
$\Xi^-\pi^-$	-54±47	51	63

displaced trigger sample is biased towards $c\bar{c}, b\bar{b}$
check on unbiased soft $E_T > 20$ GeV jet data

CDF $\Xi\pi^{\pm}$ spectra

- $E_T > 20$ GeV jet trigger data, SVX tracked $\Xi^{\pm}$
- require prompt Ξ, $|d_0(\Xi)| < 0.015$ cm

$$N(\Xi(1530)) = 387 \pm 34$$

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

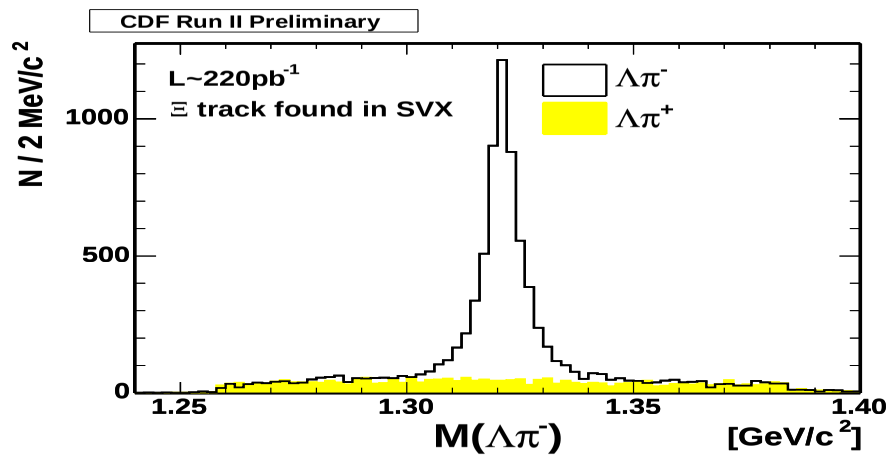
$$\sigma = 5.8\ \mathrm{MeV/c^2 (fixed)}$$

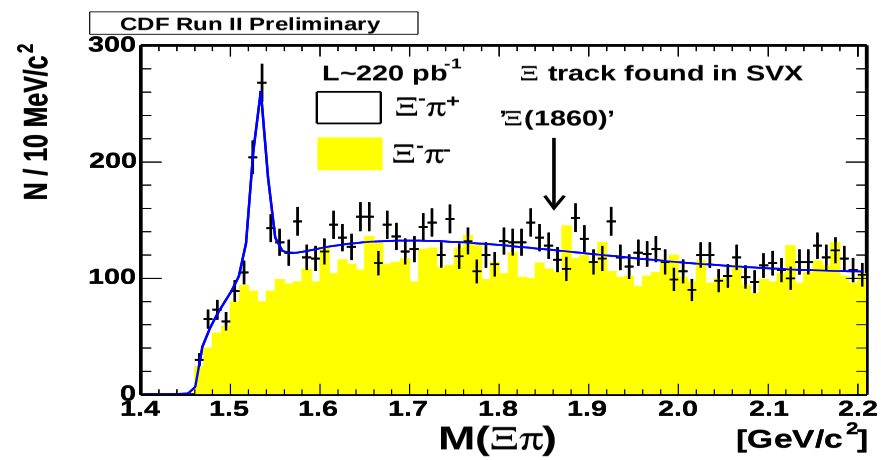
$$\frac{\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))}{\sigma(pp \to \Xi) \cdot a(\Xi)} \sim 0.08$$

(similar to TTT sample and similar to NA49)

Channel	# of events	UL 90 % CL	UL 95 % C
$\Xi^-\pi^+$	-14±19	25	30
$\Xi^-\pi^-$	-4±18	28	33

- $N(\Xi) = 4,870 \pm 122$. Statistics is twice compared to NA49





Summary numbers

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

TTT data

yield	UL 90 % CL	UL 95 % CL
r^0_{CDF}	0.06	0.07
r^{--}_{CDF}	0.03	0.04

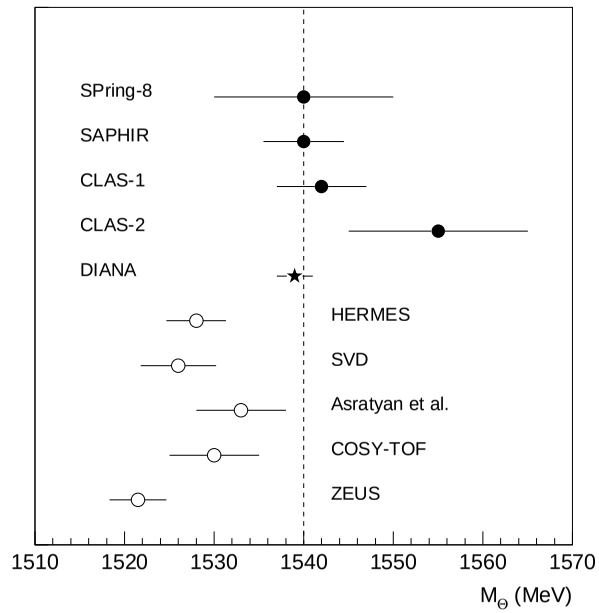
JET20 data

yield	UL 90 % CL	UL 95 % CL
r^0_{CDF}	0.06	0.08
r^{--}_{CDF}	0.07	0.09

Θ^+ Mass Status

$$\Theta^+ \to K^0_S p \qquad \Theta^+ \to K^+ n$$

$$\hookrightarrow \pi^+\pi^-$$

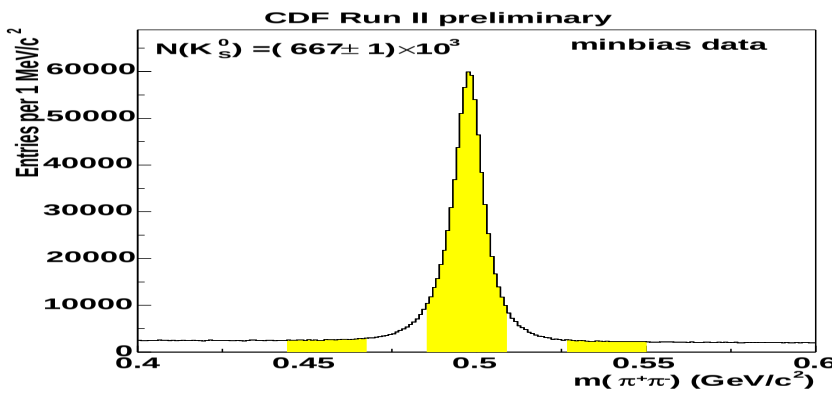


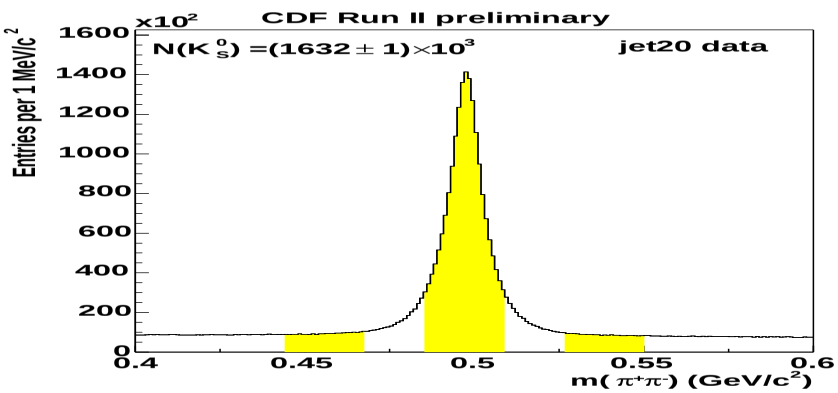
Experimental data on narrow baryon decaying to pK^0_S (open circles) and to K^+n (solid circles) , DIANA collaboration observes both modes

CDF Θ^+ search

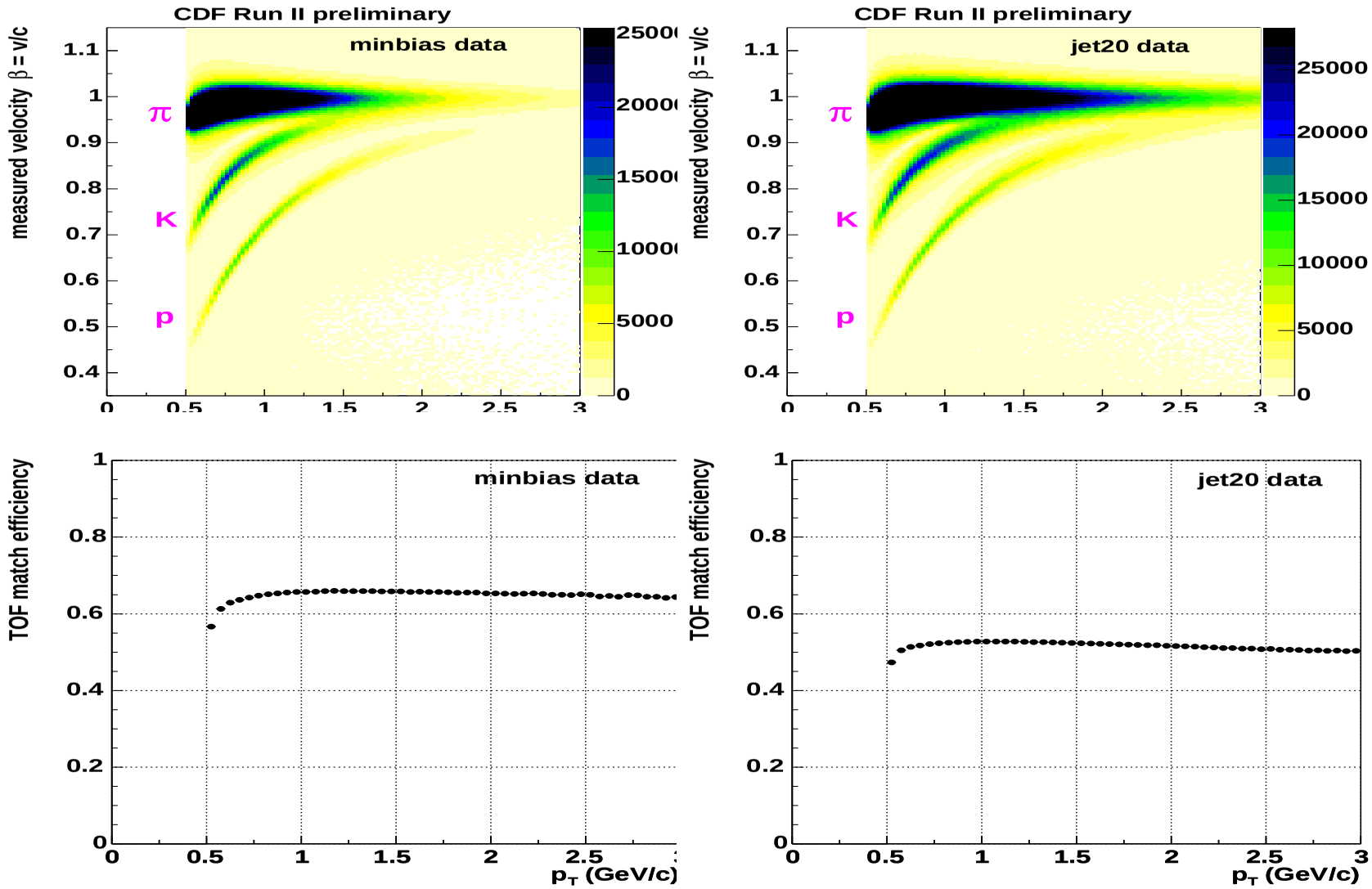
$$\Theta^+ \to K^0_S p$$
$$\hookrightarrow \pi^+\pi^-$$

- 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 (Jet with $E_T > 20$ GeV)
- Feb 2002 – August 2003 data, $\mathscr{L} \approx 180\mathrm{pb}^{-1}$

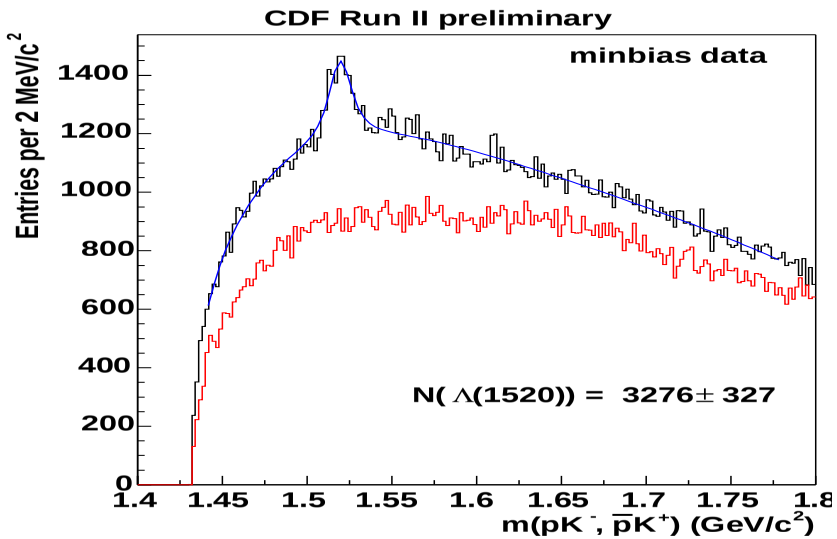


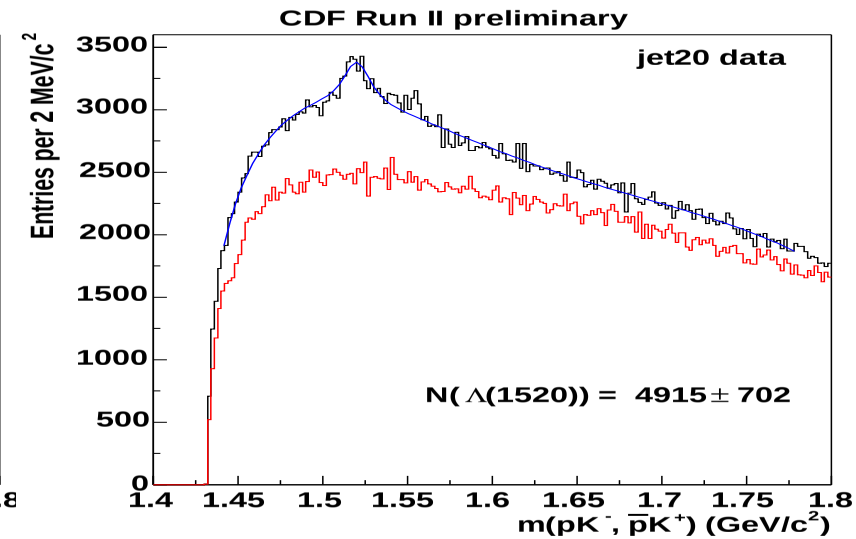


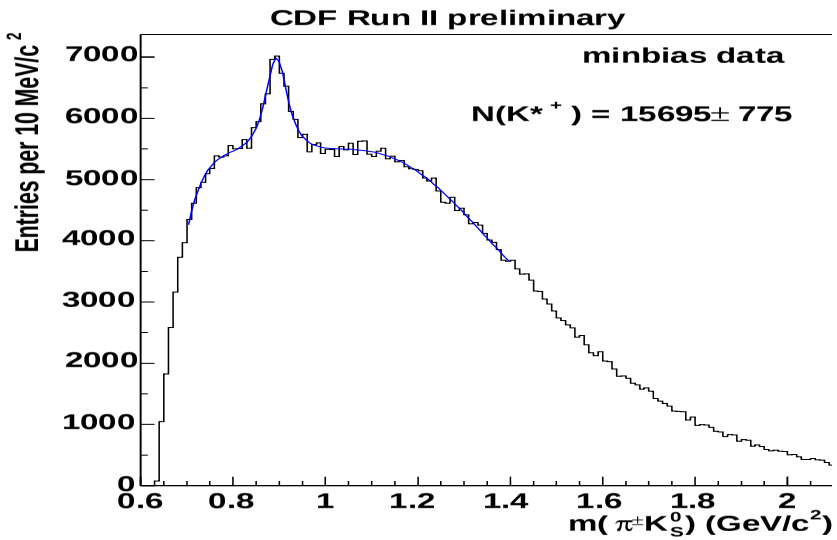
ToF performance

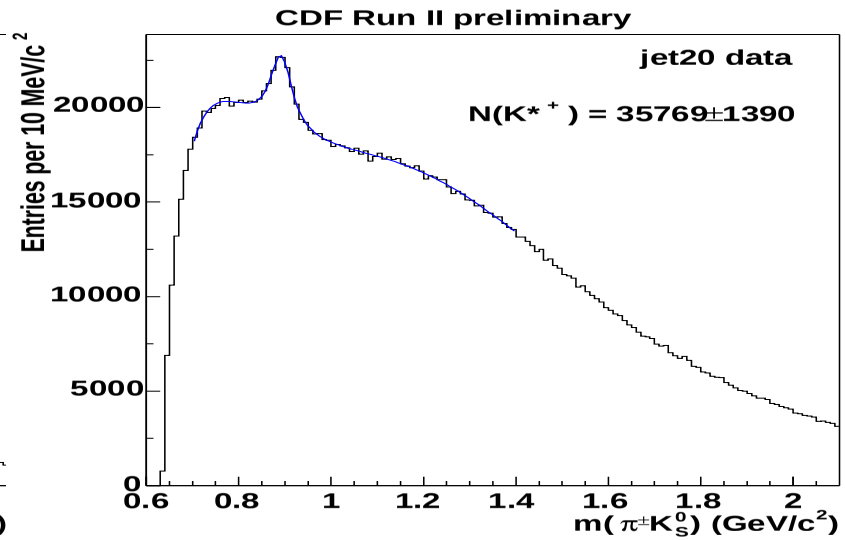


Known Resonances

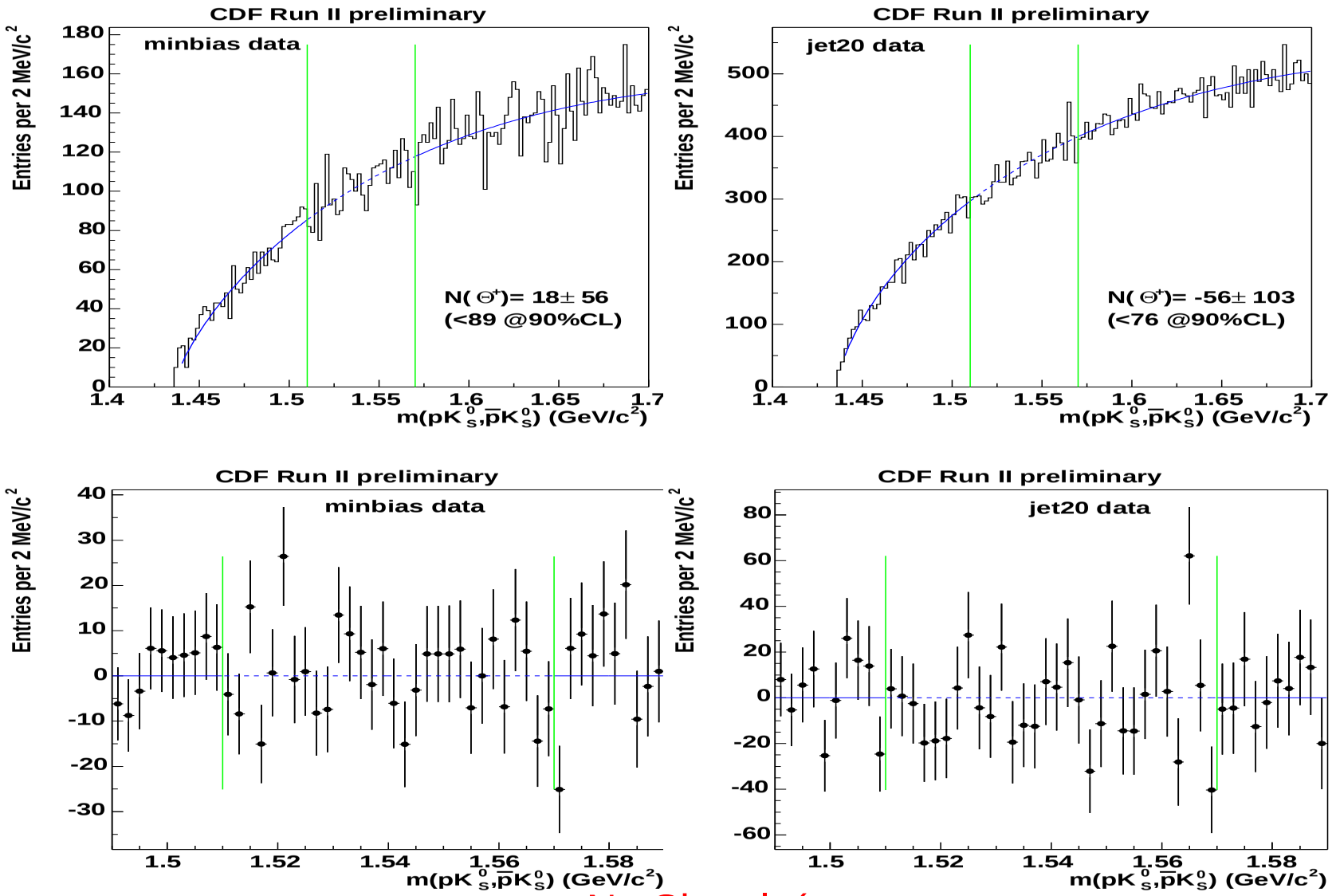








The Signal



No Signal :(

Yields

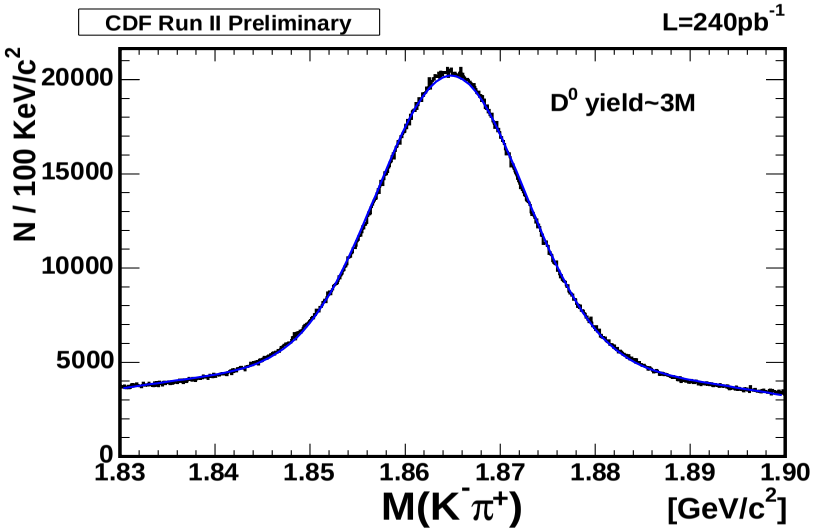
Resonance	Minbias data	Jet20 data
$\phi \to K^+K^-$	$19,721 \pm 273$	$26,658 \pm 385$
$\Lambda \to pK^-$	$3,276 \pm 327$	$4,915 \pm 702$
$K^{*+} \to K^0_S\pi^+$	$15,695 \pm 775$	$37,769 \pm 1,390$
$\Theta^+ \to pK^0_S$	18 ± 56	-56 ± 103
90% CL limit on Θ^+	<89	< 76

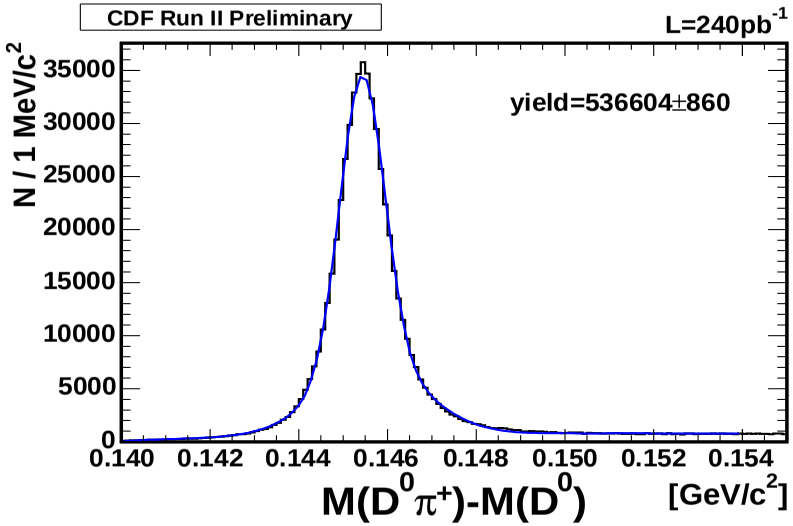
- presented at APS'04

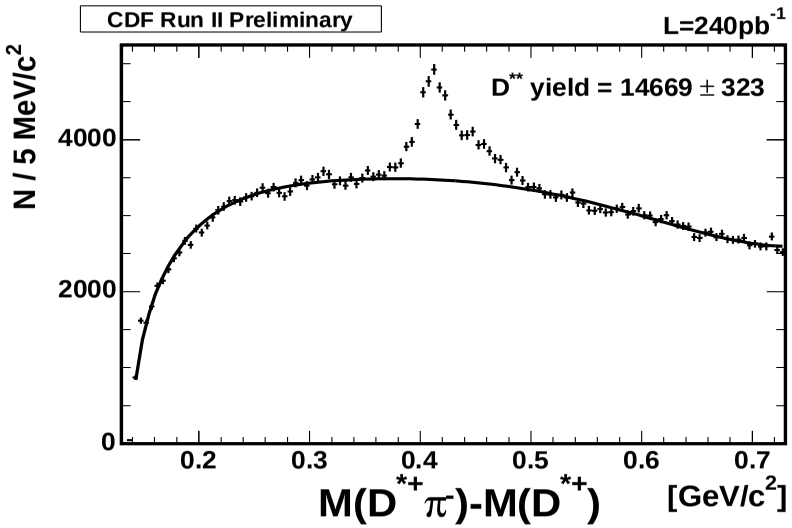
Θ_c

- $$\Theta_c \to D^{*+}\bar{p}_{dec}(p_{dec}) \qquad D^{**} \to D^{*+}\pi_{dec}$$
  $$\hookrightarrow D^0\pi^+_{slow} \qquad \hookrightarrow D^0\pi^+_{slow}$$
  $$\hookrightarrow \boxed{K^-}\boxed{\pi^+_{D^0}} \qquad \hookrightarrow \boxed{K^-}\boxed{\pi^+_{D^0}}$$
- Use both TOF and dE/dx to identify proton in appropriate momentum ranges
- displaced trigger data, $\mathscr{L} \approx 240\text{pb}^{-1}$
- D^{**} as reference channel
- $D^0 \to K^-\pi^+$ pass SVT-track trigger track match. Trigger cuts confirmed on off-line tracks.

$D^0/D^*/D^{**}$ Signals

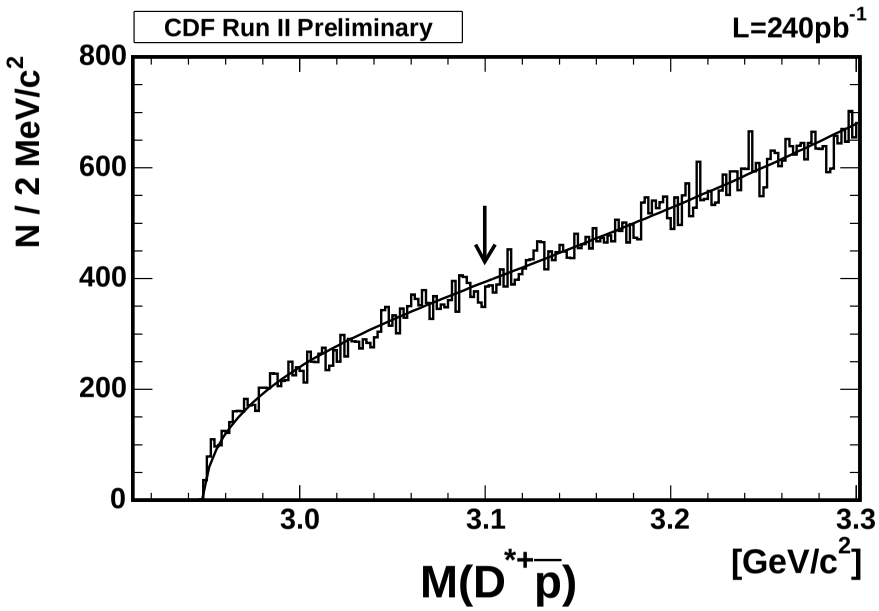






Θ_c^0 Signal no PID

$$M(D^{*+}\overline{p}) = M(D^{*+}\overline{p}) - M(D^{*+}) + 2.010\ \mathrm{GeV}/c^2$$



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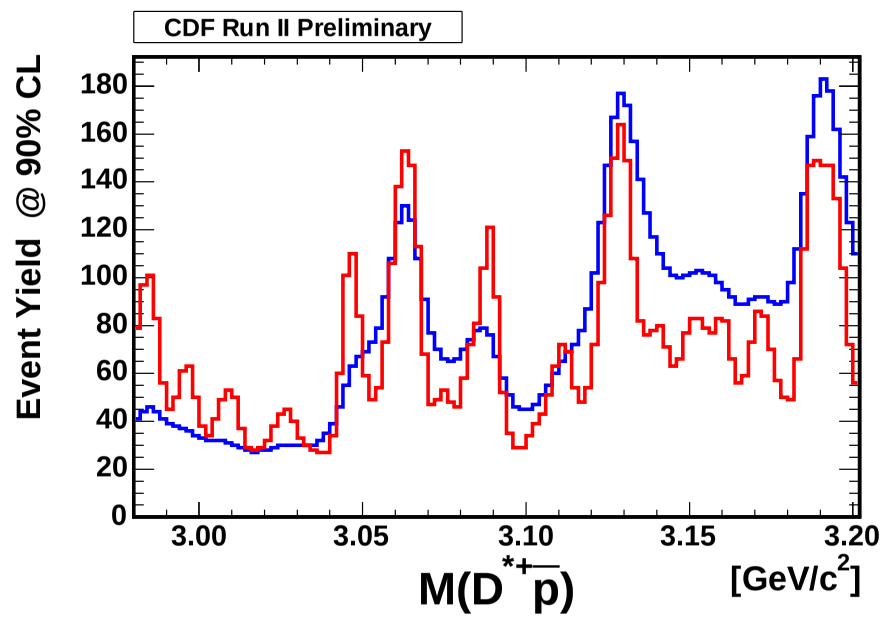
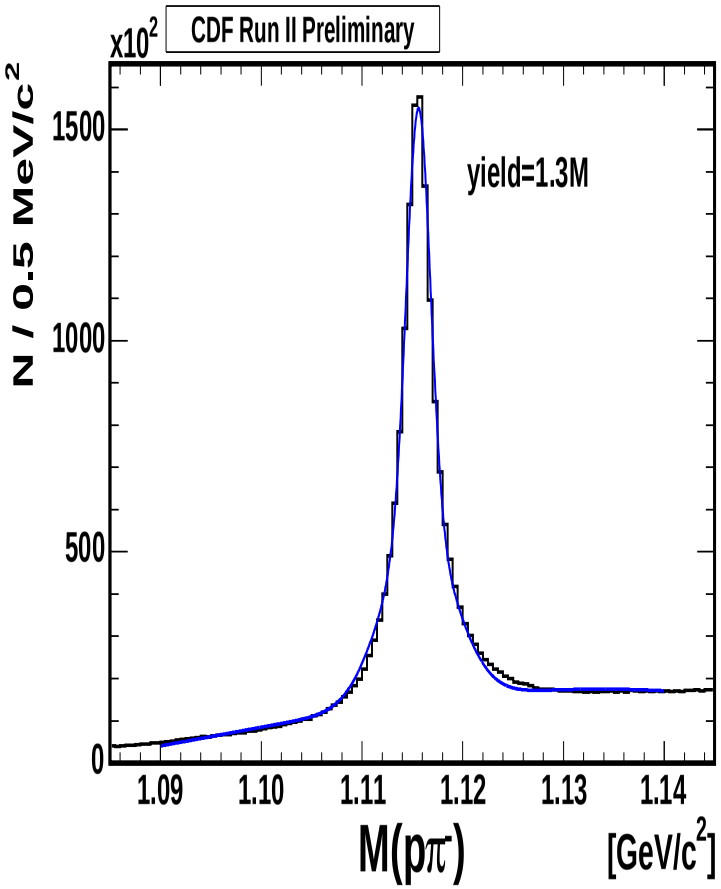
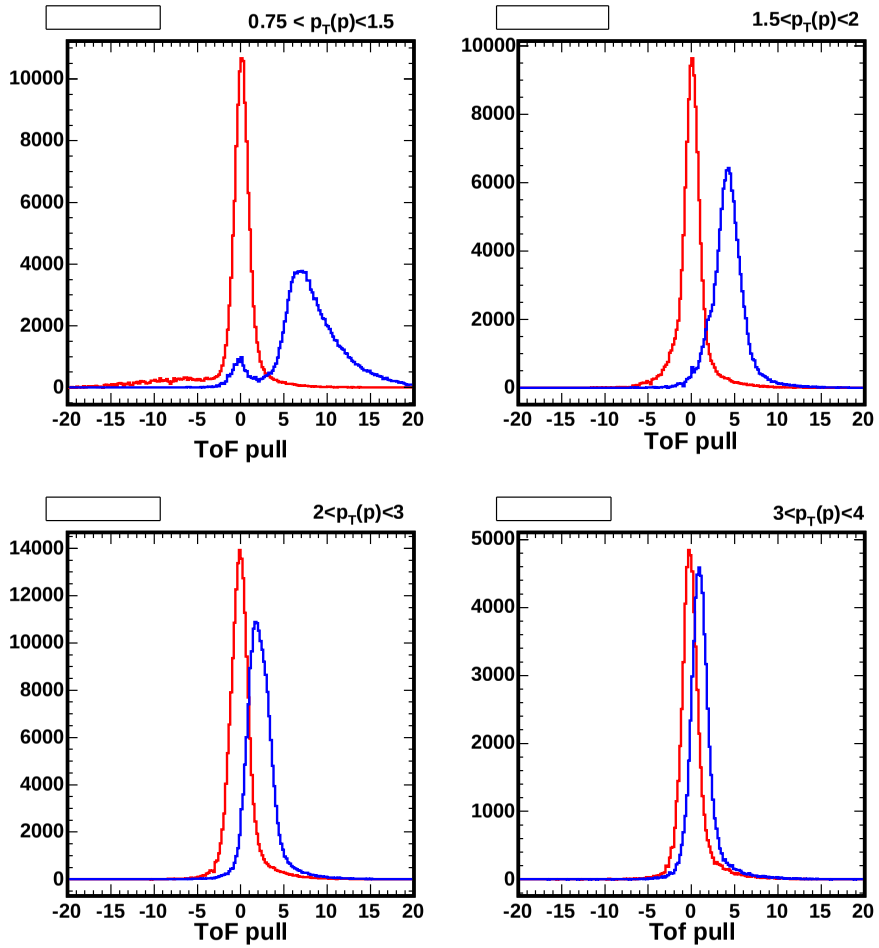


- $\Gamma = 0\ \mathrm{MeV}/c^2$: 29 (90% CL) and 37 (95% CL)
- $\Gamma = 12\ \mathrm{MeV}/c^2$: 44 (90% CL) and 57 (95% CL)

Upper limits on the number of events vs mass , red – $\Gamma = 0\ \mathrm{MeV}/c^2$, blue – $\Gamma = 12\ \mathrm{MeV}/c^2$

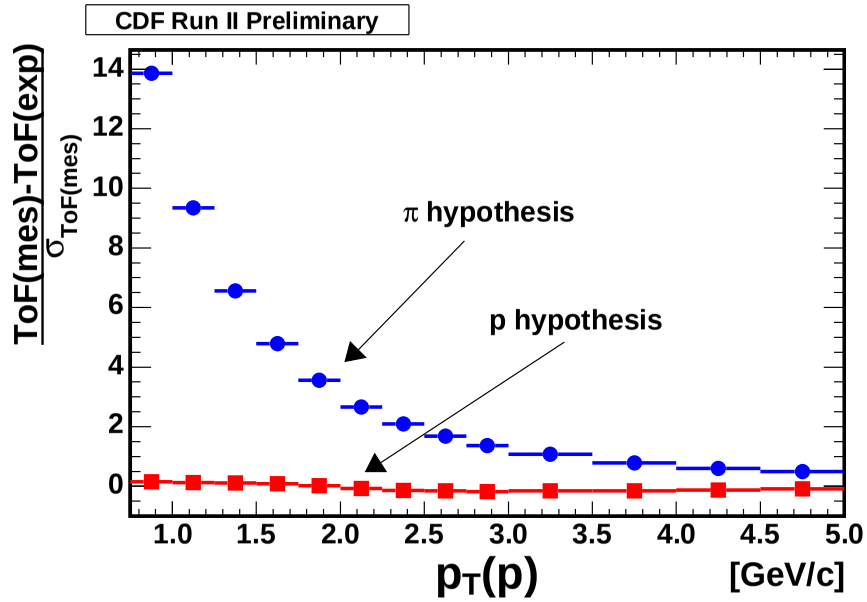
ToF



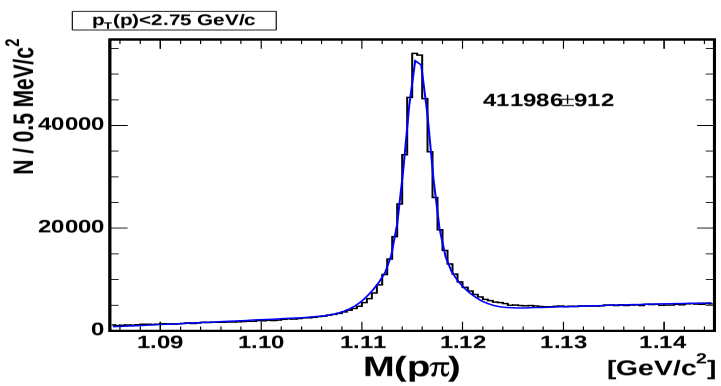


ToF pulls $((\mathrm{ToF(mes)} - \mathrm{ToF(exp)})/\sigma_{\mathrm{ToF}})$ for protons from Λ for proton (red) and pion(blue) hypotheses in diff proton pt

ToF Separation

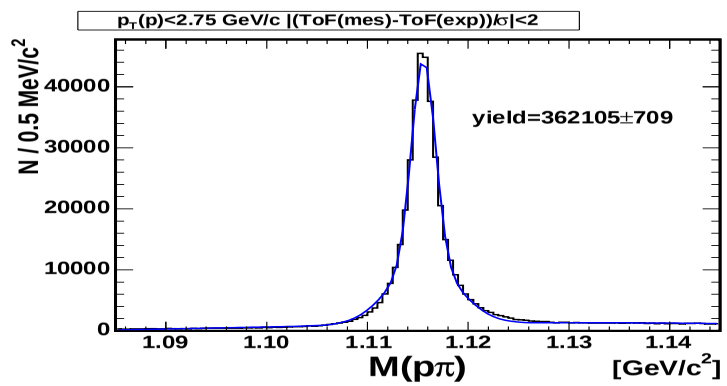


- $p_T(p) < 2.75\ \mathrm{GeV/c},\ |(\mathrm{ToF(mes)} - \mathrm{ToF(exp)})/\sigma_{\mathrm{ToF}}| < 2$



without cut

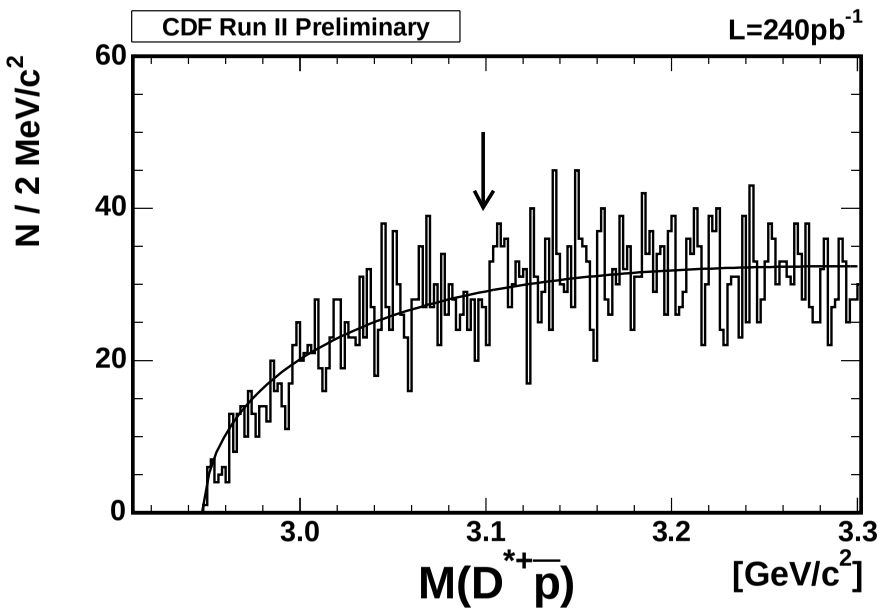
,



with cut

with ToF

- $|(\mathrm{ToF(mes)} - \mathrm{ToF(exp)})/\sigma_{\mathrm{ToF}}| < 2$, $p_T(p) < 2.75$ GeV/c



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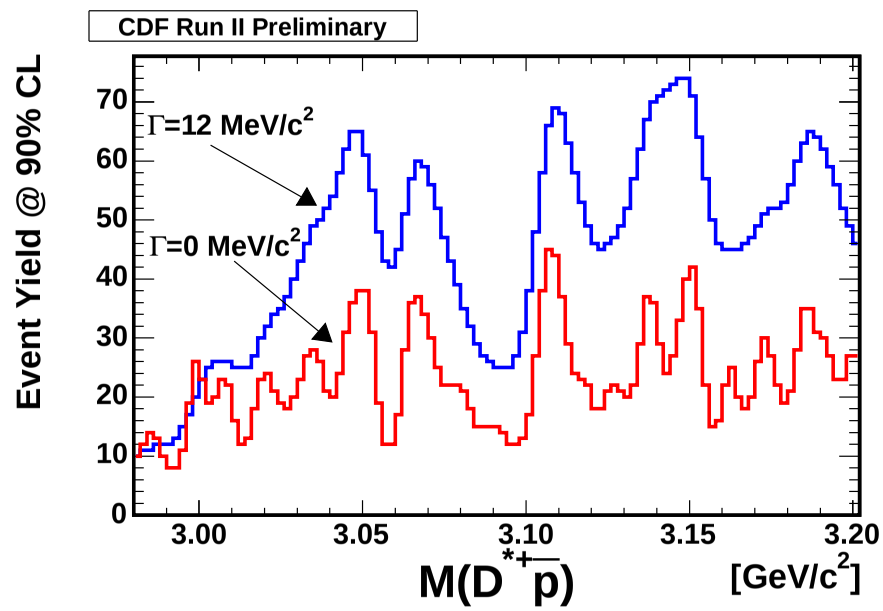
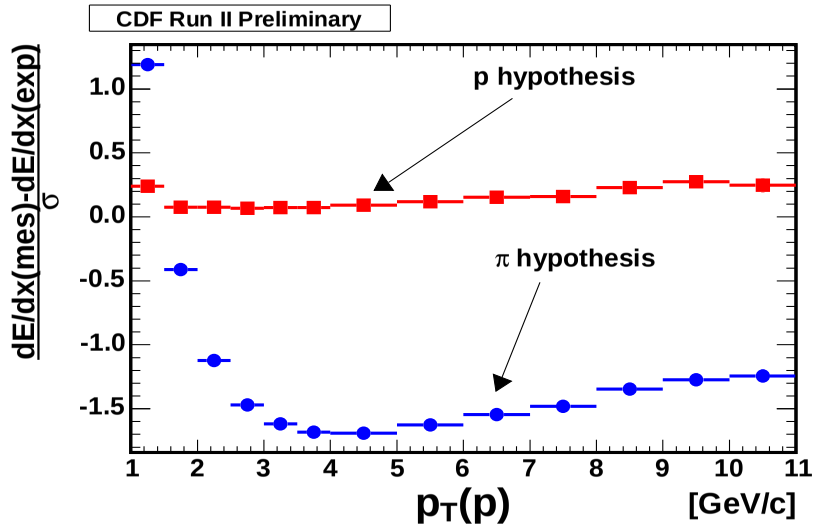


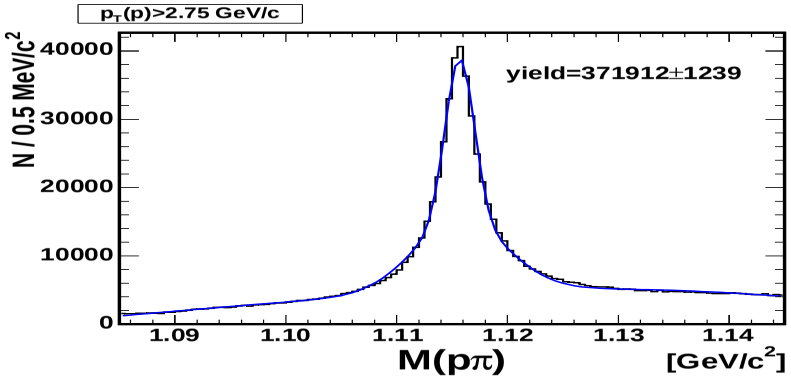
- $\Gamma = 0$ MeV/c^2 : 12 (90% CL) and 15 (95% CL)
- $\Gamma = 12$ MeV/c^2 : 25 (90% CL) and 32 (95% CL)

Upper limits on the number of events vs mass

dE/dx Separation



- $\left|(dE/dx(mes) - dE/dx(exp))/\sigma_{dE/dx}\right| < 1.3$, $p_T(p) > 2.75$ GeV/c



without cut

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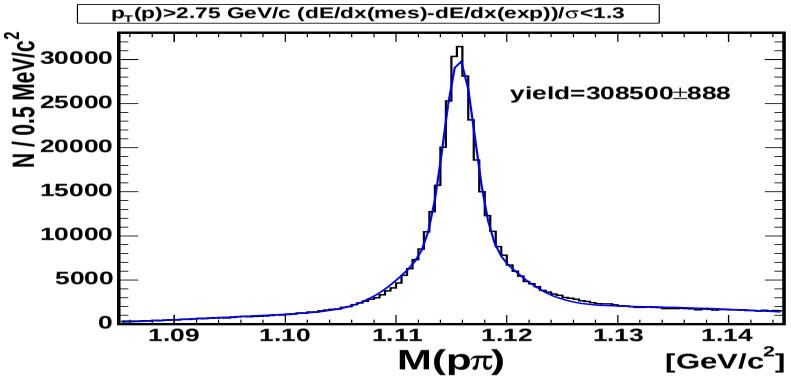
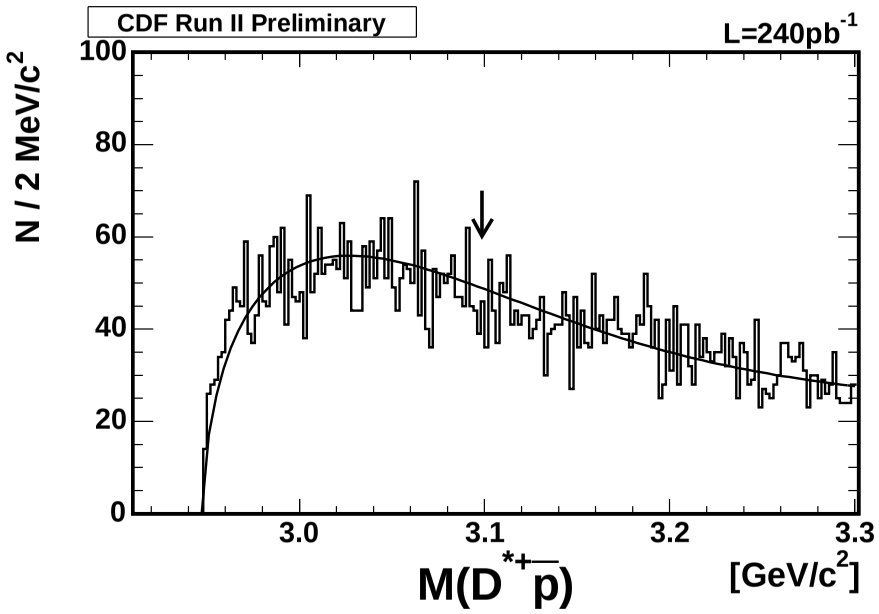
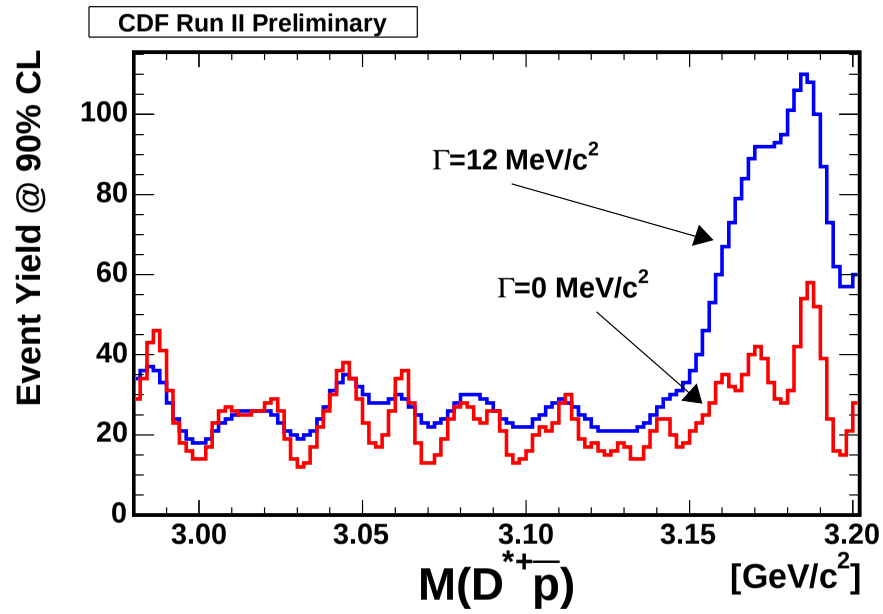


with cut

with dE/dx

$$\left|(dE/dx(mes) - dE/dx(exp))/\sigma_{dE/dx}\right| < 1.3\,,\ p_T(p) > 2.75\ GeV/c$$





- $\Gamma = 0\ MeV/c^2$: 19 (90% CL) and 24 (95% CL)
- $\Gamma = 12\ MeV/c^2$: 30 (90% CL) and 38 (95% CL)

Upper limits on the number of events vs mass

Conclusion/Outlook

- CDF and D0 detectors work well delivering world best data on heavy hadron spectroscopy
- CDF and D0 confirmed Belle's new particle $X(3870)$ ongoing effort of studying its properties
- Expect improved mass measurements of existing states and discoveries of new states (new results) in coming year as the data samples grow:
  - Heavy baryons $\Sigma_b \to \Lambda_b \pi$
  - Heavy-strange baryons Ξ_b Ω_b
  - $c\bar{c}$ and $b\bar{b}$ states
  - Improved measurements of excited states, B^{**}
- CDF performed search for exotic baryon states $\Xi(1860), \Theta^+, \Theta_c$ No signals found, limits on relative yields with respect to known states established.
- CDF has vigorous program of studying exotic charmed and bottom baryons exploiting its displaced track, and J/ψ triggers
- Hadron Spectroscopy at Tevatron is thriving!