Charm physics results from SELEX

by Sasha Kushnirenko

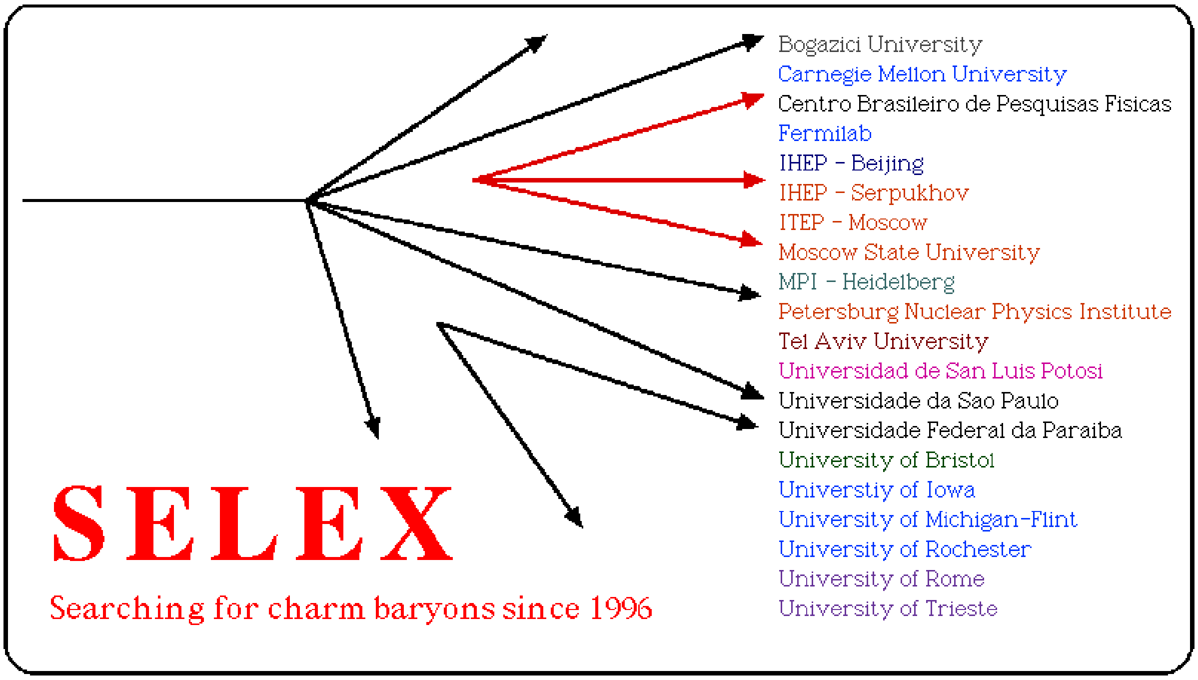
October 12, 2000

HEP Seminar

Brookhaven National Laboratory

Talk outline

- SELEX experiment
- Data taking and Processing
- Physics results:
  - Charm States Observed
  - Charm hadroproduction in in p, Σ^- and π^- beams (asymmetry, x_F, p_t)
  - Cabibbo supressed decay mode $\Xi_c^+ \to pK^-\pi^+$
  - D^0, Λ_c^+, D_s^+ Lifetimes
    - Physics motivation
    - Measurement procedure
    - Efficiency calculations
    - Systematic errors
    - Results
- Conclusions



Segmented Large x_F Baryon Spectrometer

Selex(E781) is a **NEW** multi-stage spectrometer with high acceptance for forward interactions and decays. It took data in 1996-97 with 600 GeV Σ^-, π^- and 540 GeV p beams.

The **GOAL** of SELEX is to obtain large sample of charm baryon decays using a variety of incident beam particles and targets.

SELEX Charm Program

- Compare Production by Σ^-, π^- and p beams:
  - x_F and p_t dependency (F.Garcia)
  - Charm - Anticharm production asymmetry (F.Garcia)
  - Production of excited states
  - Charm pair production
  - Search for polarization effects
  - ...

- Decay Physics:
  - Precision measurement of charm lifetimes (A.Kushnirenko)
  - Search for new decay modes (Soon Jun)
  - Study of Cabibbo-suppressed modes (Soon Jun)
  - Charm baryon semi-leptonic decay
  - ...

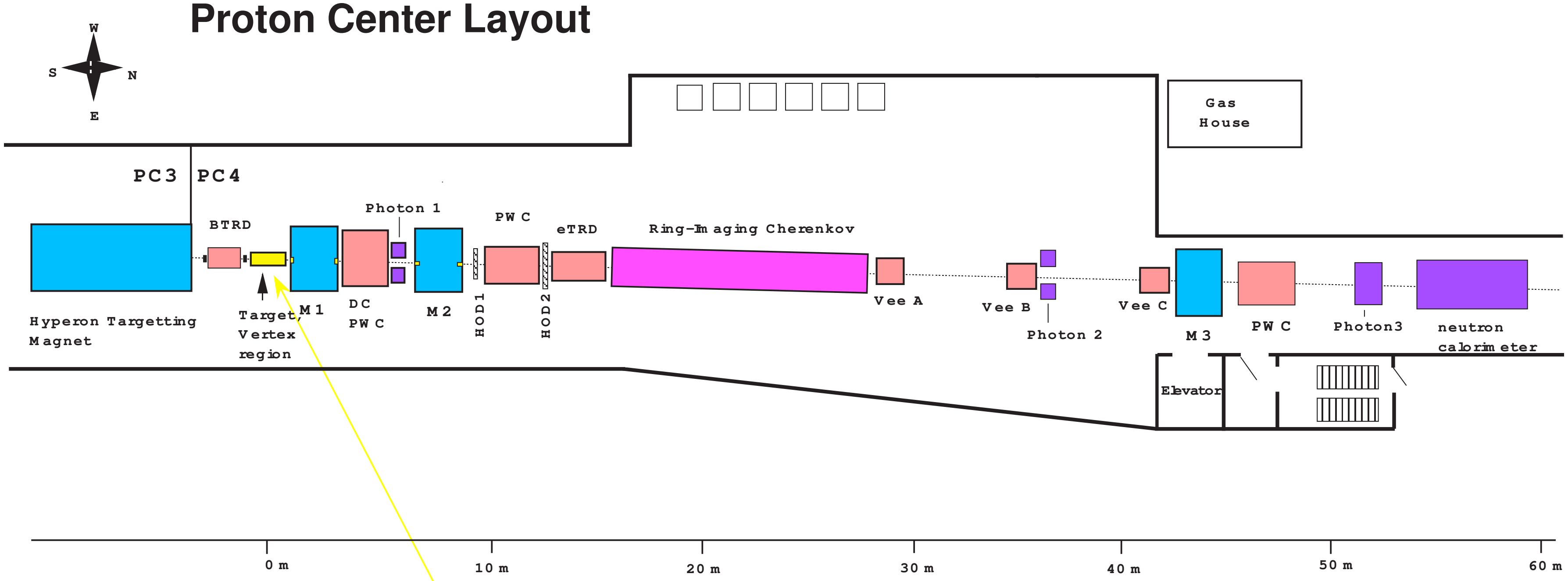
- Spectroscopy:
  - Measure excited state characteristics (Mark Mattson)
  - Search for new excited states
  - ...

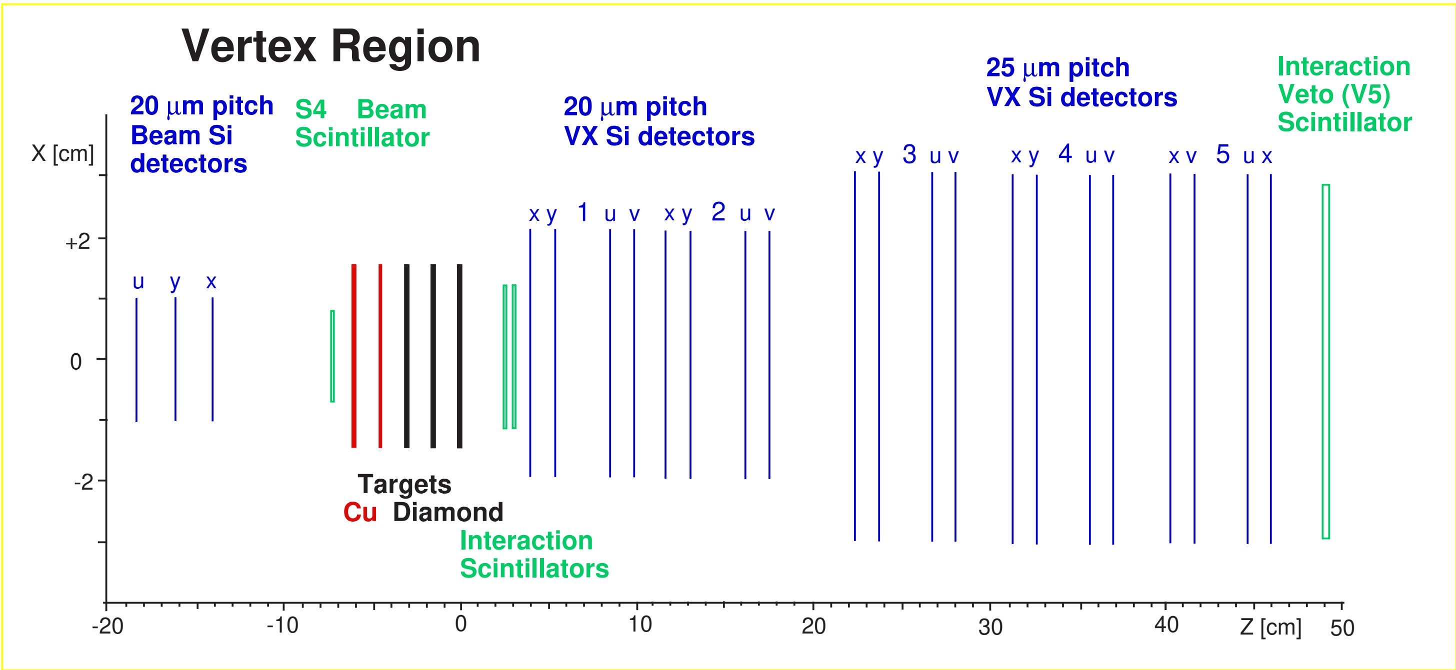
SELEX Apparatus

3 segment forward spectrometer ($x_F > 0.1$)

- 74000 strip silicon system, $4\mu m$ transverse position resolution at 600 GeV
- Beam tagging ($\Sigma^-/\pi^-, p/\pi^+$) with Beam TRD
- 3000 phototube RICH - K/π separation up to 165 GeV (J.Engelfried, L.Stutte, A. Kozhevnikov, . . .)
- Secondary e^- with Electron TRD for semileptonic decays
- Precise downstream tracking
  - 18 large silicon planes ($\sigma \sim 8\mu m$)
  - 26 PWC planes ($\sigma \sim 0.6 - 1mm$)
  - 3×24 Vector Drift chambers ($\sigma \sim 100\mu m$)
- 3 lead glass photon detectors

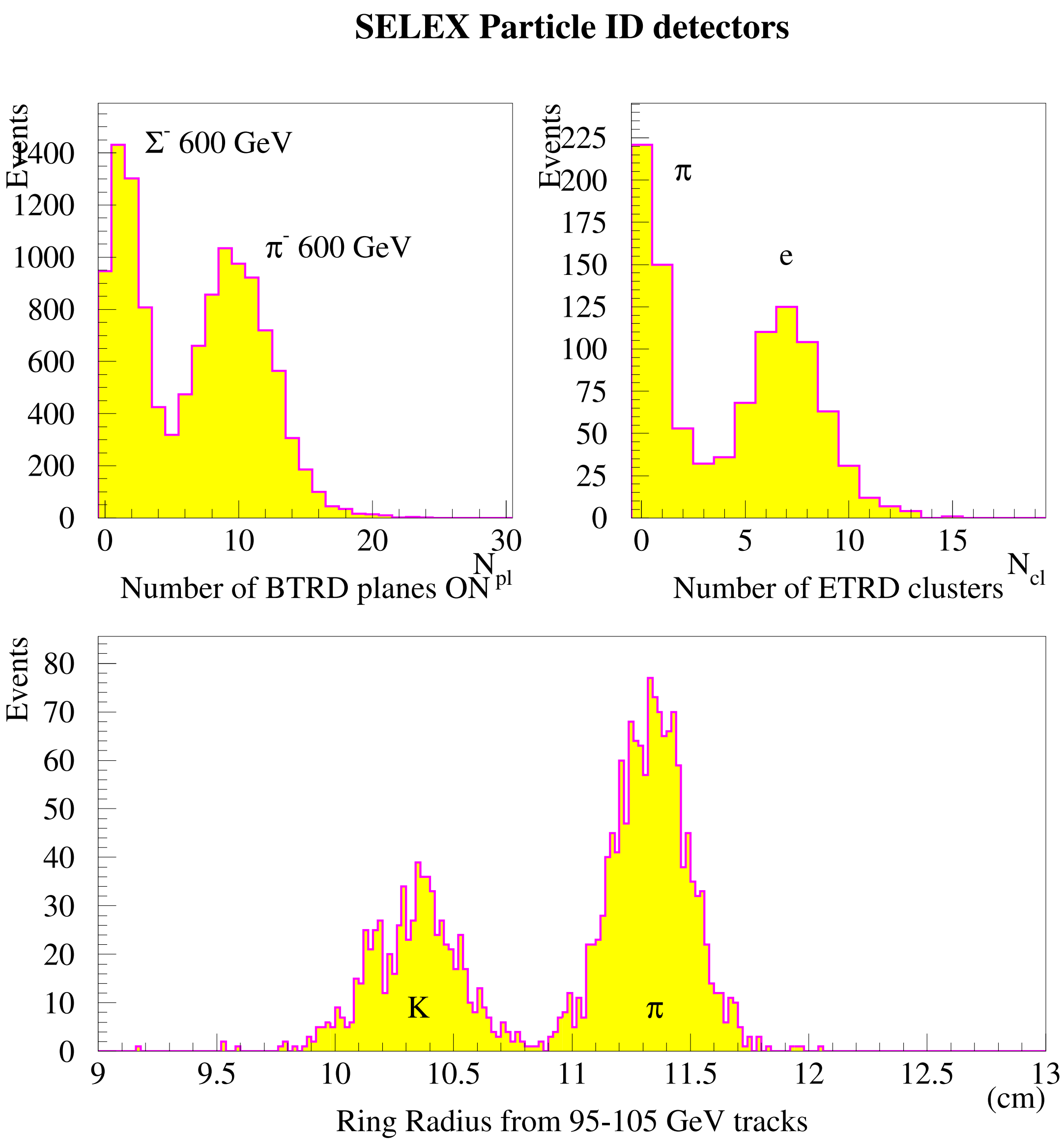
Selex (E781)
Proton Center Layout





AK @ BNL 10/12/2000

SELEX Particle Identification



Charm mass reflections are greatly suppressed

Online Filter

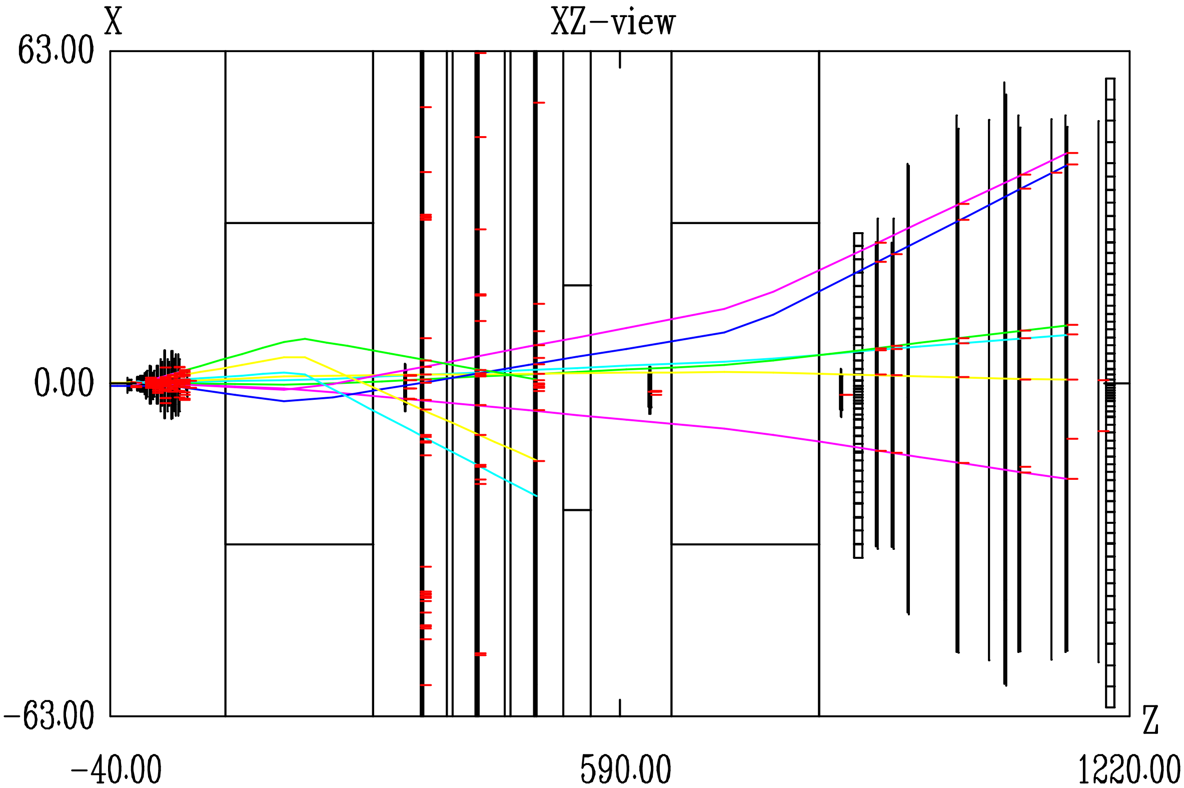
Filter is **Online Program** which select events that have evidence for a secondary vertex.

- Algorithm: (M.Mattson, A.Kushnirenko)
  - Start from downstream tracking to find high-momentum $(p > 20GeV)$ tracks in PWC chambers
  - Extrapolate tracks back to vertex silicon within the roads predicted by downstream tracking
  - Reject events if tracks form just a primary vertex

To run ... or not to run?

- Charm efficiency about 50%,
  Background rejection about 8

- 4 times more charm per tape.
  8 times faster to process.


X
XZ−view
63.00
0.00
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Z
−40.00
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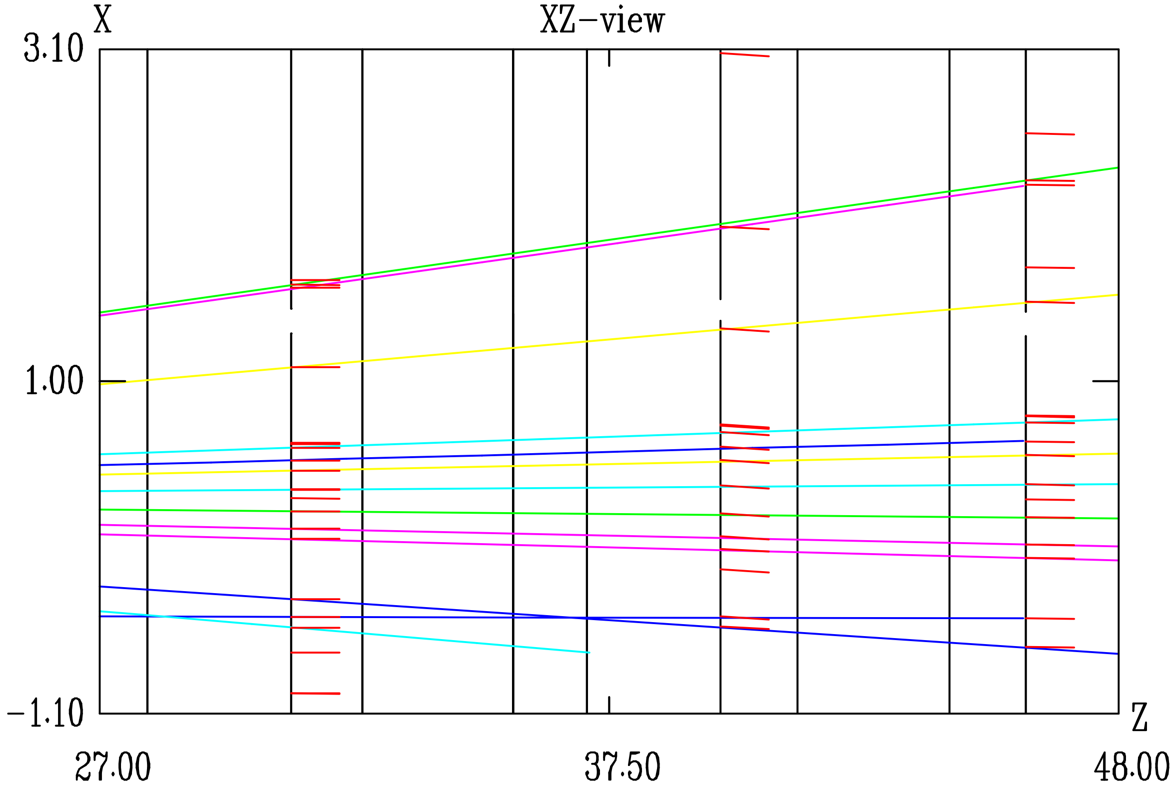
1220.00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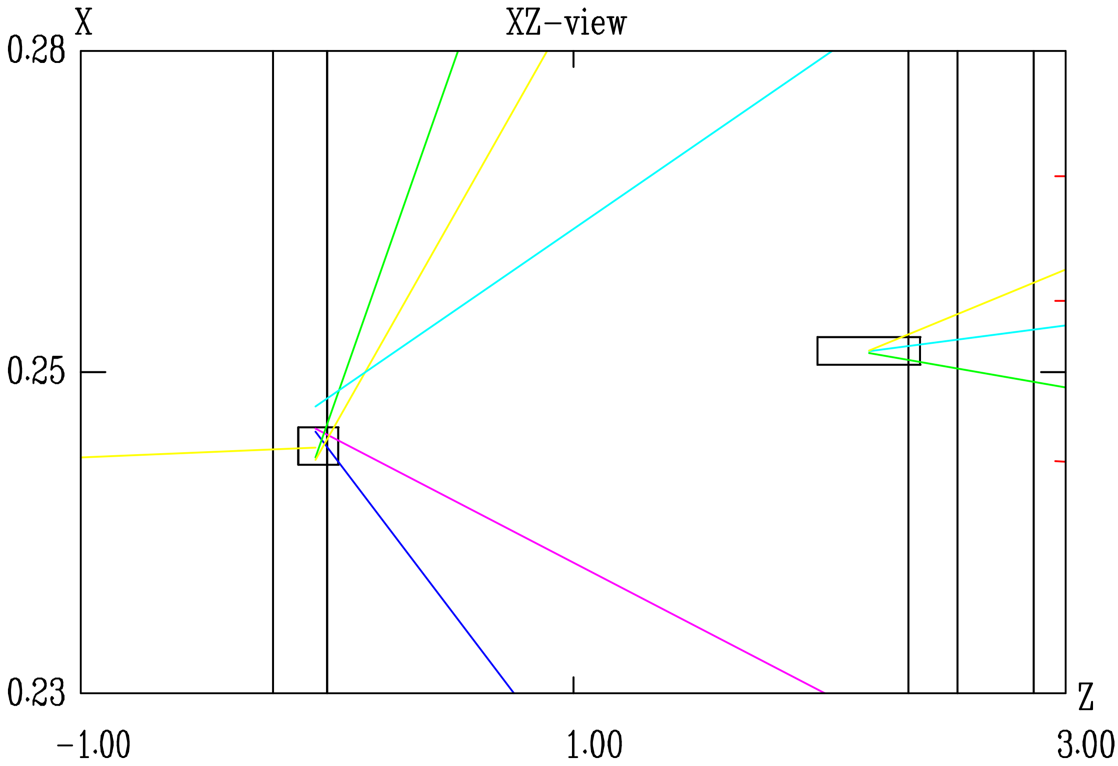
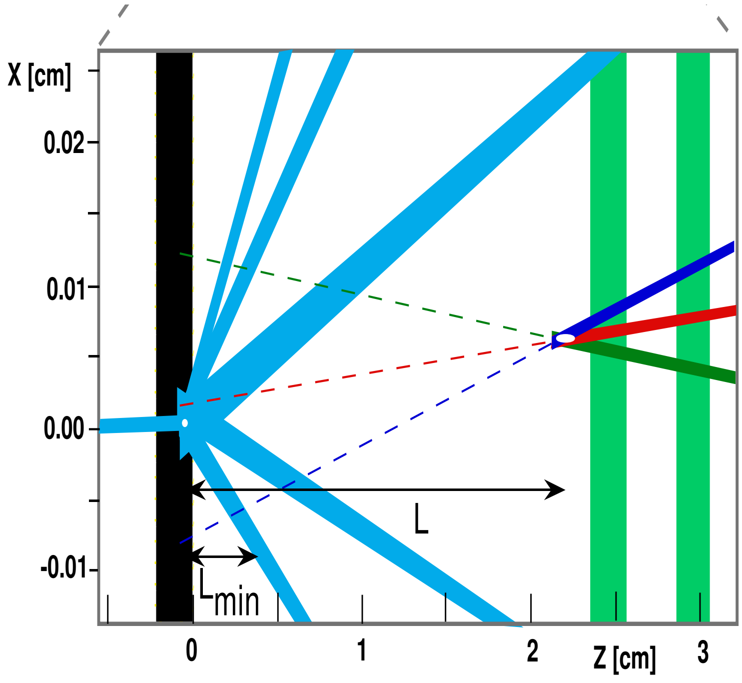
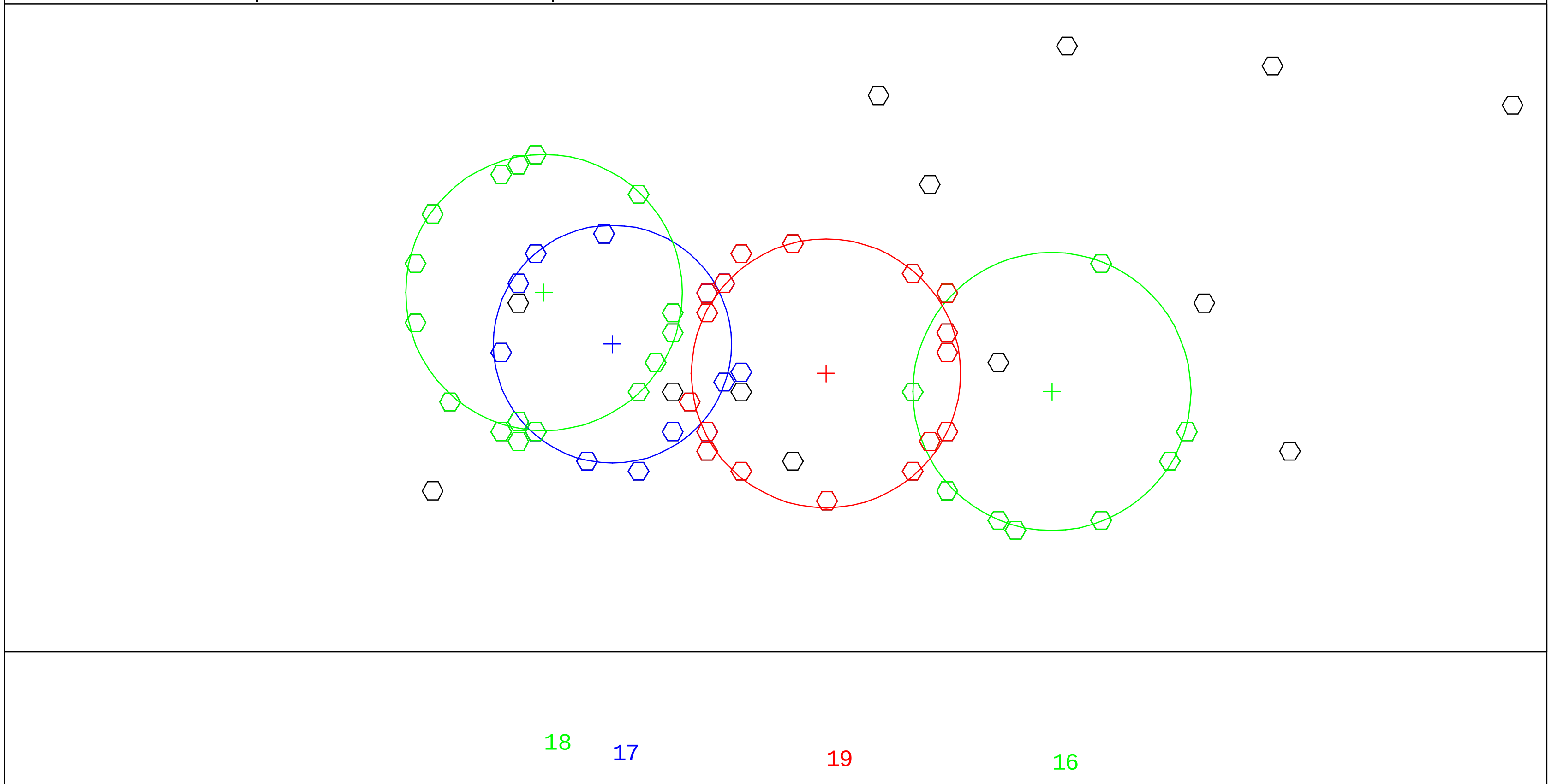
XZ−view
3.10
1.00
−1.10
Z
27.00
37.50
48.00





P[GeV/c]		
Λ_c^+	381	$M = 2287(5)$ MeV/c^2
K^-	153	$L = 2.245(56)$ cm
p	154	$L_{min} = 0.445$ cm [8σ]
π^+	74	$\tau = [L - L_{min}]M/Pc$
		$= 359(11)$ fsec
		$\sim 1.8\ \tau[\Lambda_c^+]$

Date: 98/10/08 22.59.43
Run: 10439 Spill: 41 Event_in_Spill: 17156 Event: 100034284 Tubes: 63



Tracks :	16	17	18	19
Momenta:	-095	+154	+074	-153

Masses: Sigma Proton Kaon Pion Muon Electron Backgrnd

Faster, faster, faster ...

When we turned on apparatus we observed twice as many hits as Monte-Carlo predicted.

- We decreased beam intensity, so that DAQ could read out events.

- Filter algorithm was efficient enough to processing high-multiplicity events, but too slow ($time \sim \#hits^{3-4}$). At the beginning of the run we throw away 50% of the data.

  Filter improvements

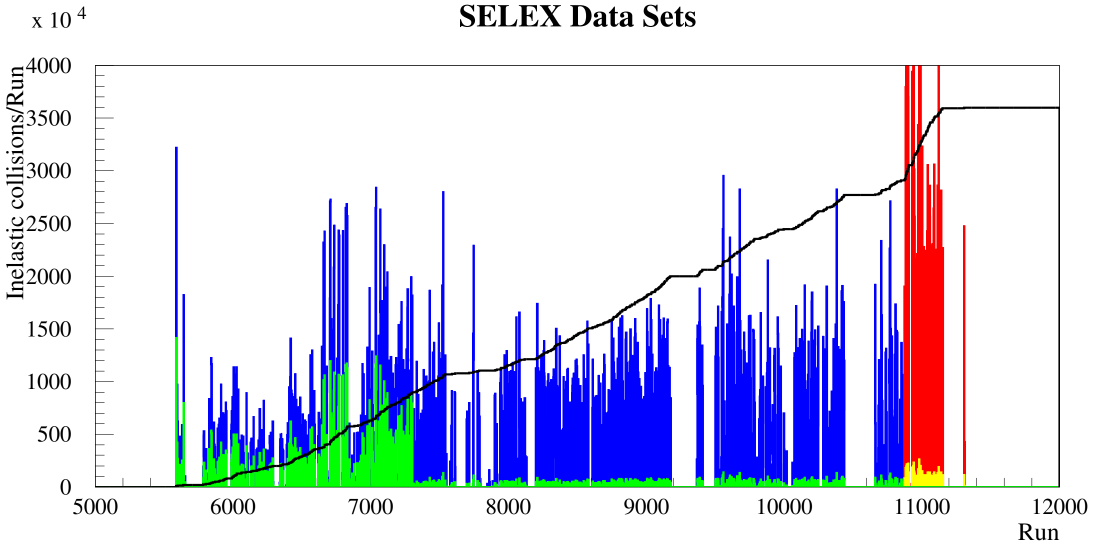
  – Better programming x2
  – Physics driven search ($p_{T_{charm}} < p_{T_{magnets}}$) x3-4
  – Extra computing x1.5

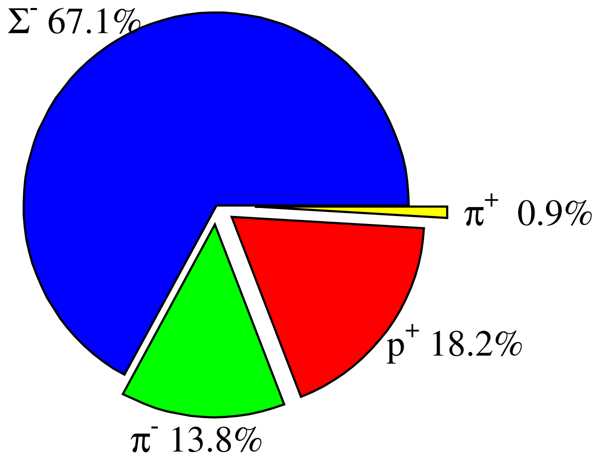
- Along the run we made improvements in

  – Filter speed and efficiency
  – Trigger and DAQ
  – Detector performance

  which led to ~ 3 times higher charm yields per billion interactions at the end of the run.

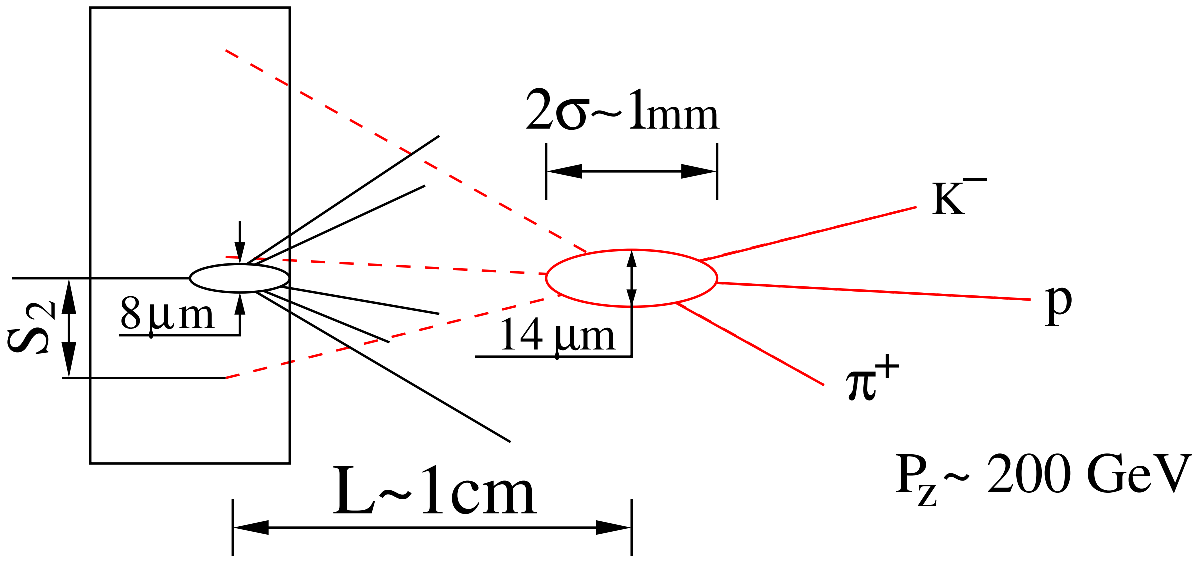
SELEX Data Sets





Total 15.2 Billion interactions

Sample definition

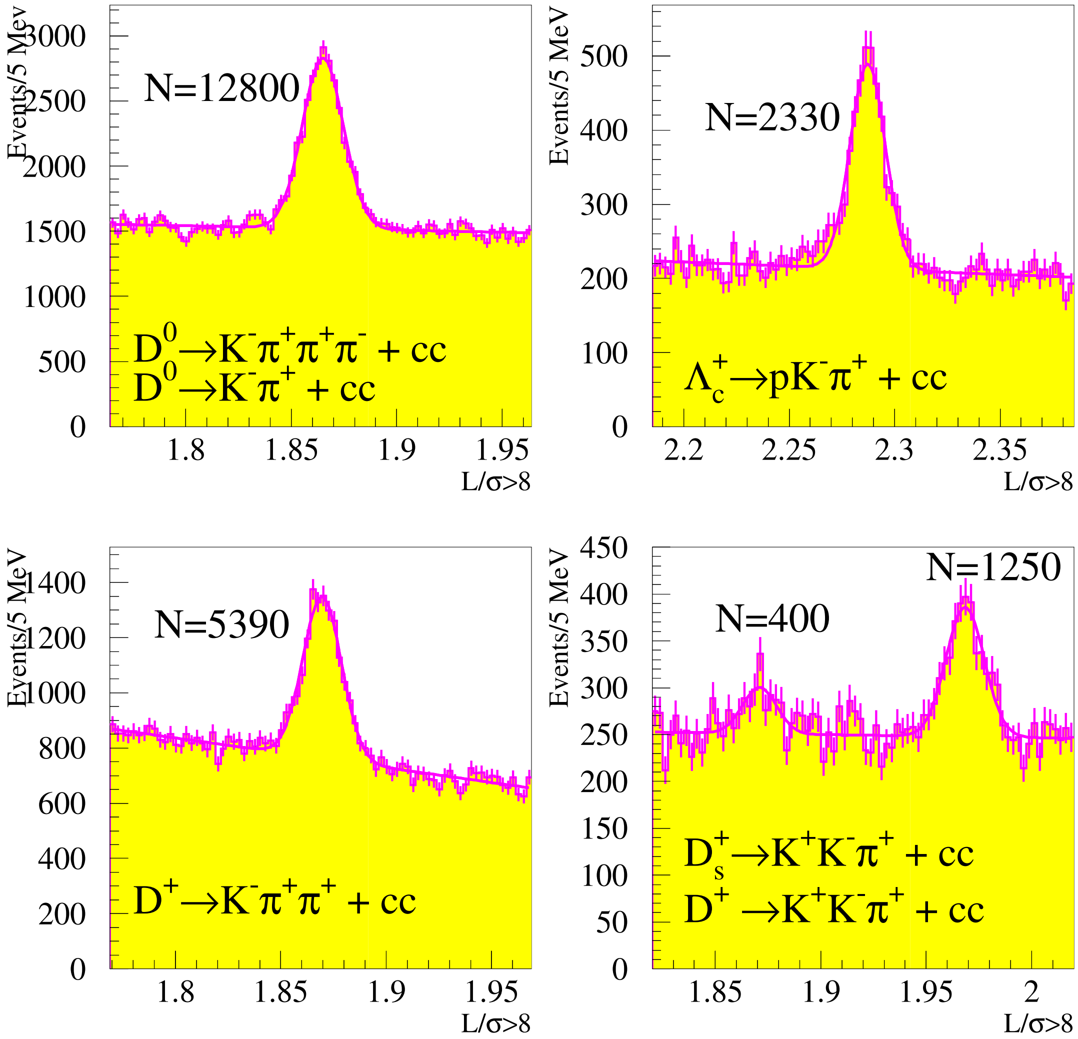


Charm sample definition

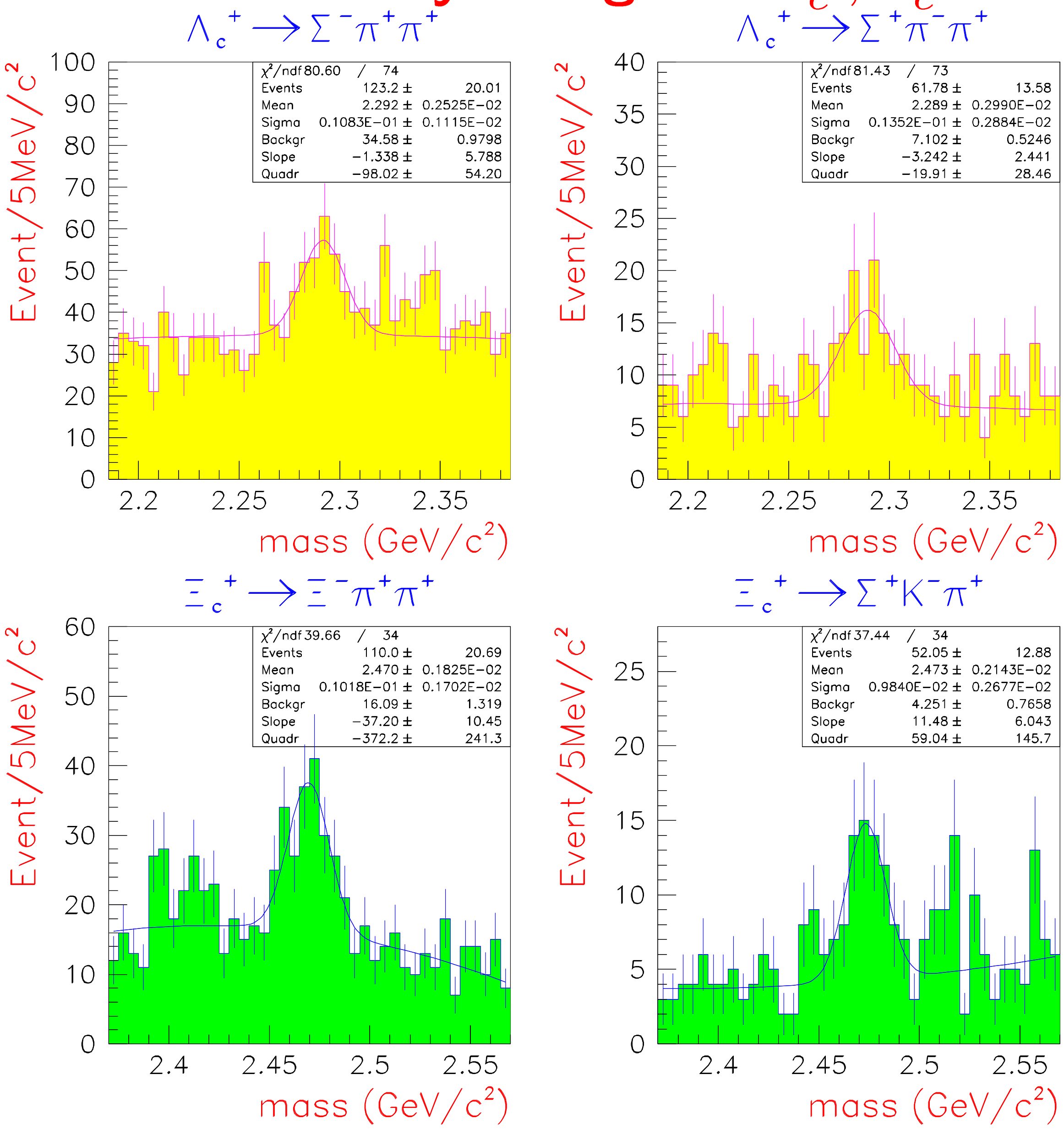
- $L/\sigma_L > 8$ vertex separation
- $s_2 > 20\mu m$ - second largest misdisstance
- $P_{vtx} < 12$ - charm track points back to primary vertex
- $Z_{sec} < 2.5cm$ - no escape into silicon
- $t > 500\mu m$ - distance to the closest target
- K, p should be identified by RICH
- $p_\pi > 8$ GeV - slow $\pi^\pm$ rejection

Charm Signals

SELEX Charm signals



Charm Baryon Signals Λ_c^+, Ξ_c^+



- $L/\sigma_L > 14$ for $\Lambda_c^+ \to \Sigma^+\pi^-\pi^+$
- Kinematical cuts for Ξ_c^+
- Pass2 dedicated to Charm Baryons

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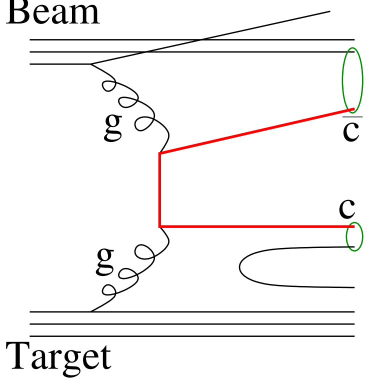
Charm hadroproduction



Theoretical challenges

- $c\bar{c}$ production (pQCD)
- hadronization (Non-pQCD)

Experimentally we study

- charm - anticharm production assymetries
- $x_F \simeq p_c/p_{beam}$ and p_t distribution

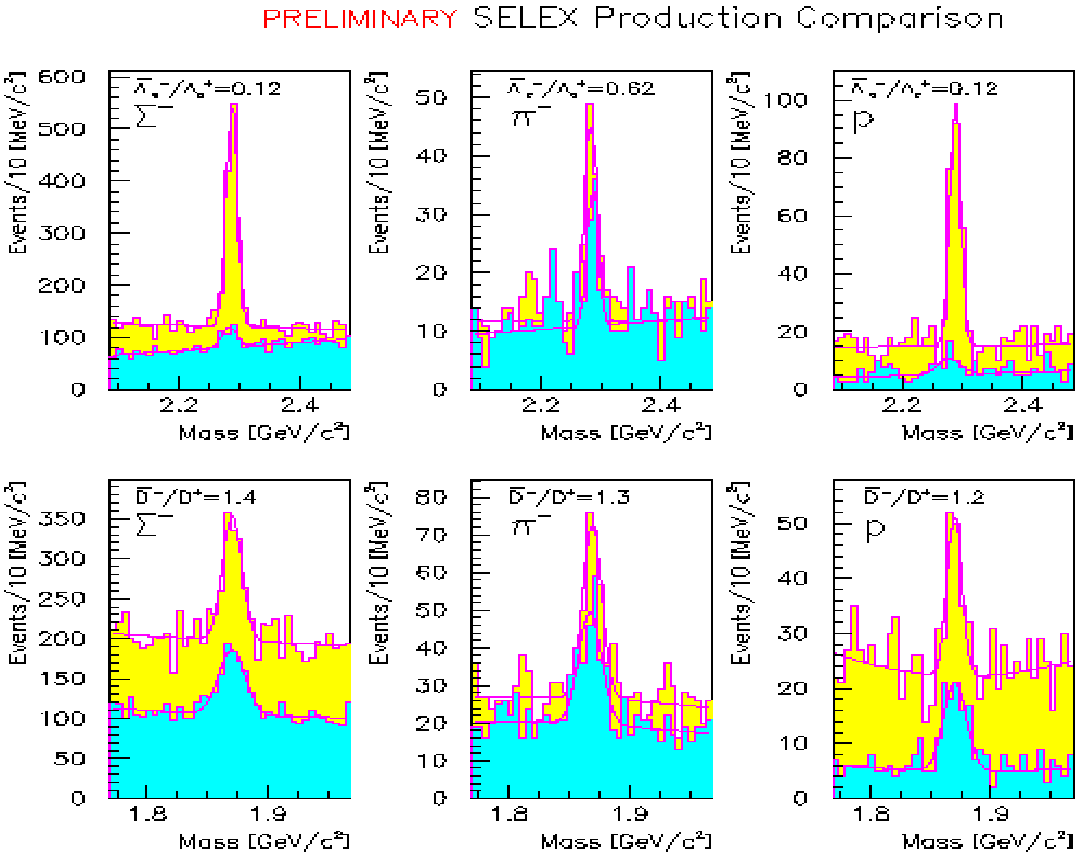
Leading Particle effect

$$\begin{array}{rcl} \pi^-(\overline{u}d) & \to & D^-(d\overline{c}) \;\; \Lambda_c^+(udc) \;\; \overline{\Lambda}_c^-(\overline{u}\overline{d}\overline{c}) \\ \Sigma^-(dds) & \to & D^-(d\overline{c}) \;\; \Lambda_c^+(udc) \\ p(uud) & \to & D^-(d\overline{c}) \;\; \Lambda_c^+(udc) \end{array}$$

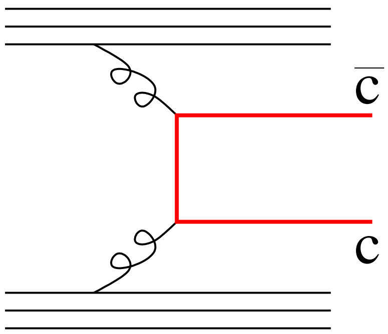
$D^+(c\overline{d})$ is not leading in any beam

Heavy quark hadronization: b-tagging efficiency, dilution factor, training neural networks, . . .

Charm assymetry



- In LO QCD $c\bar{c}$ produced symmetrically
- In NLO QCD assymetry $< 1\%$
- Fragmentation models are developed:
  String fragmentation (T.Sjostrand) PYTHIA;
  Mangano-Nason-Ridolfi code;
  Intrinsic Charm (S.J.Crodsky, R.Vogt)



Λ_c^+ / $\overline{\Lambda_c^-}$ assymetry

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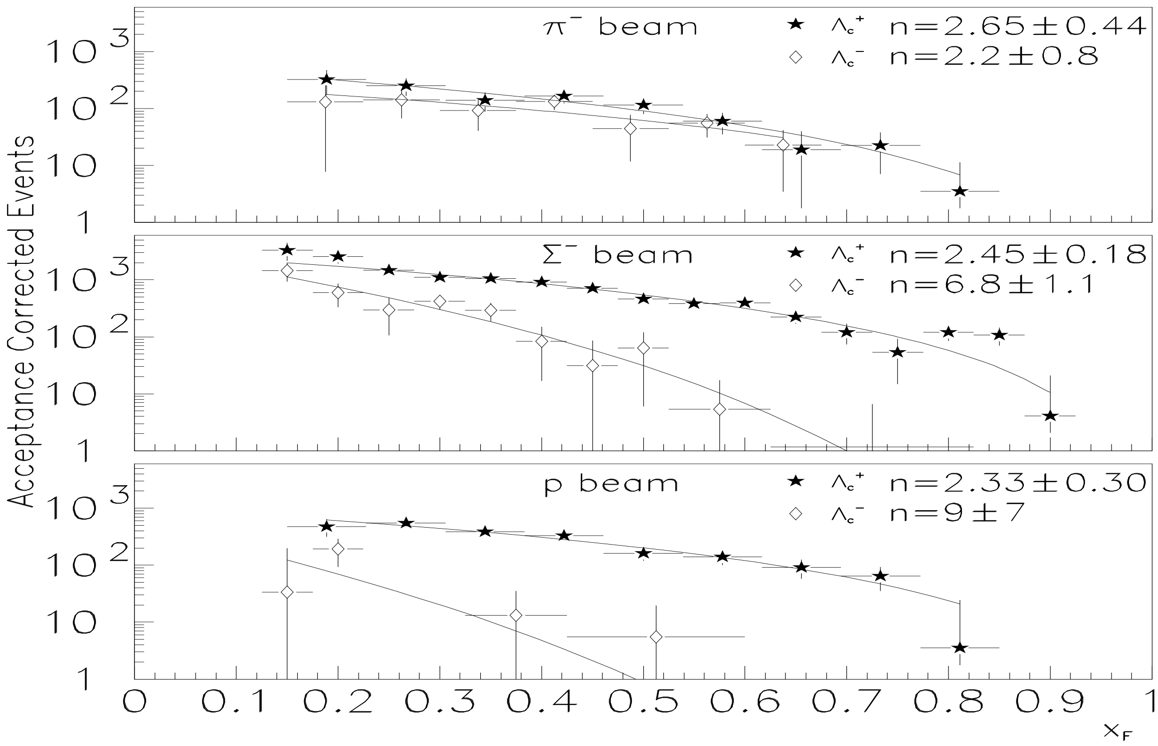

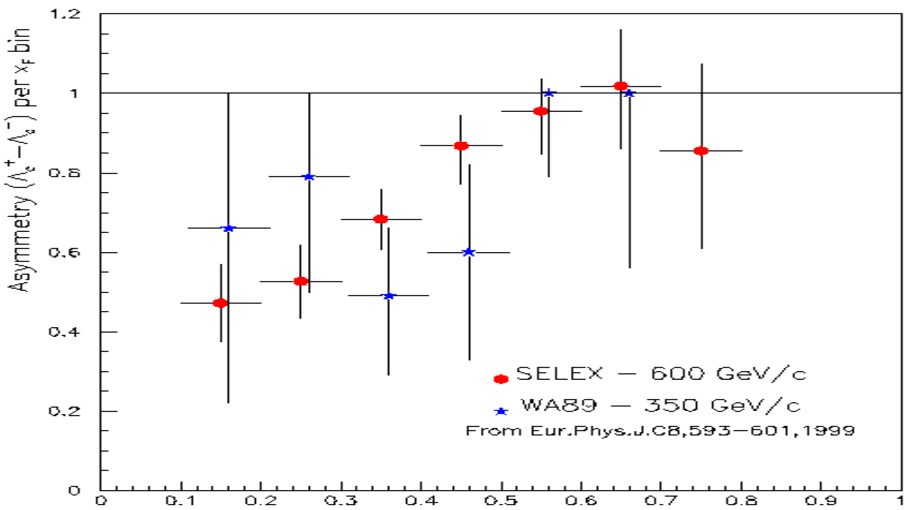

- Good agreement with leading particle phenomena: Λ_c^+ is produced more copiously than $\overline{\Lambda_c^-}$ in Σ and p beams.
- SELEX agrees with WA89 (Σ^--beam)
- Comparison with E791 (π^--beam) and FOCUS (γ-beam)

Λ_c^+ p_t^2 distribution

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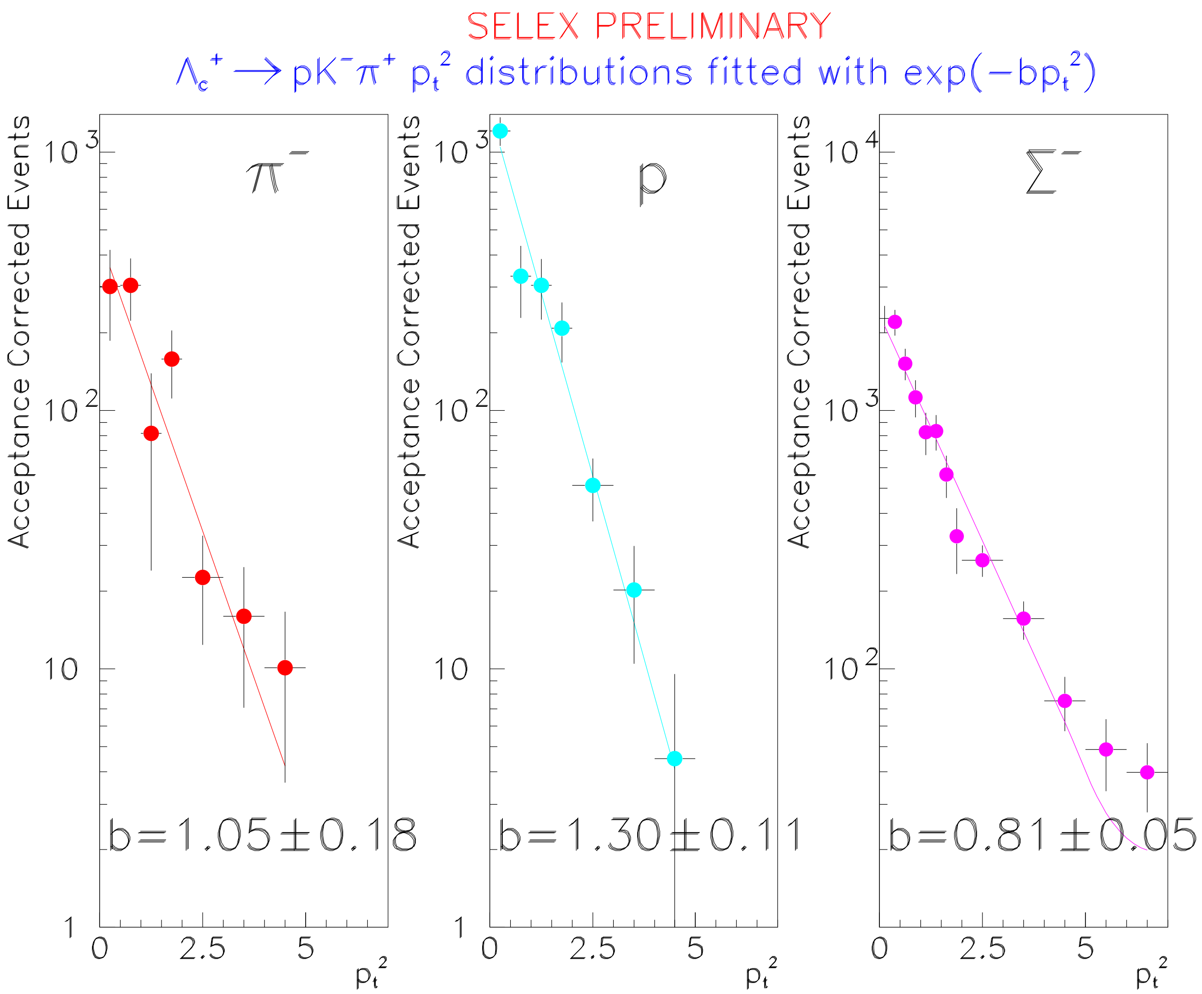

D^+/D^- assymetry

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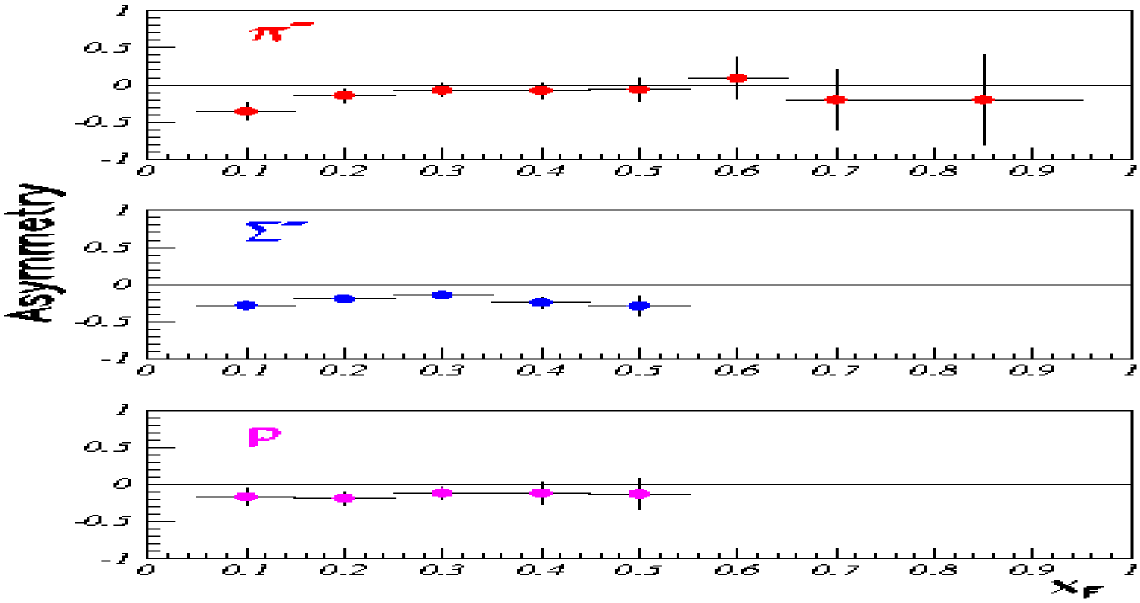

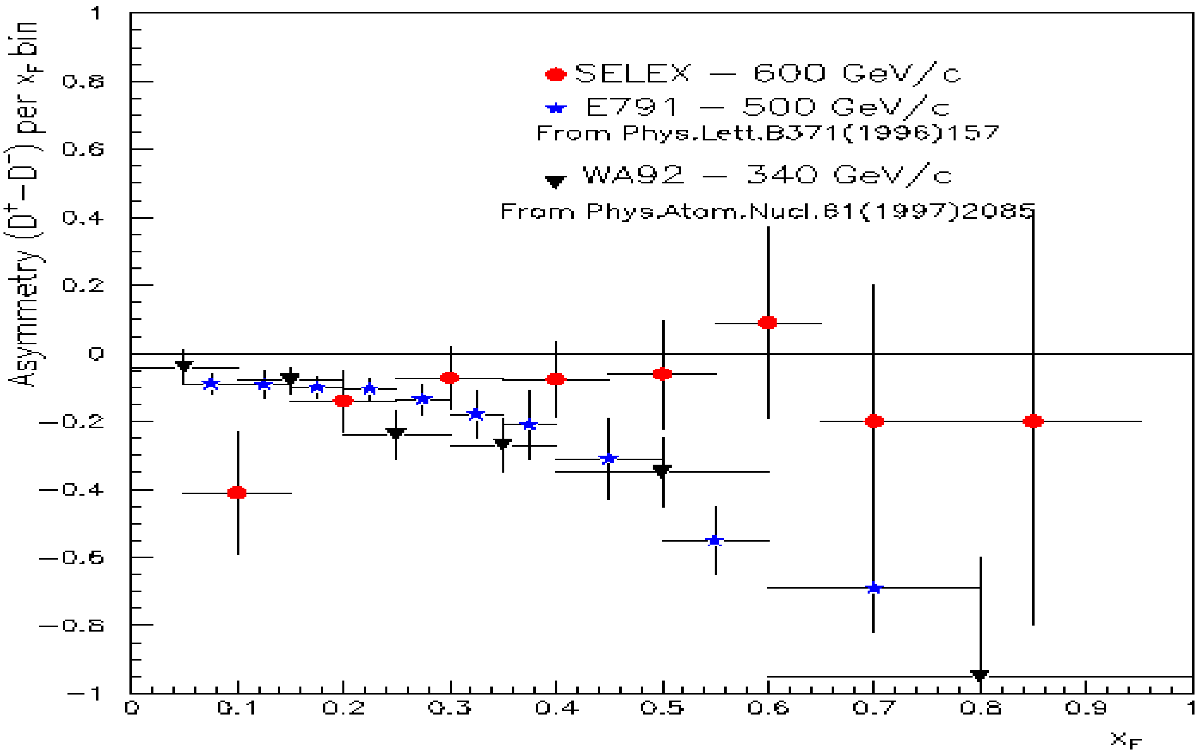

Assymetry is small

We do not see large assymetry as E791 and WA92

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Charm hadroproduction summary

- SELEX has big opportunities in charm hadroproduction, because of a variety of beam particles and charm states.

- $\Lambda_c^+/\overline{\Lambda_c^-}$ production (x_F, assymetry) seems to be consistent with leading particle effect

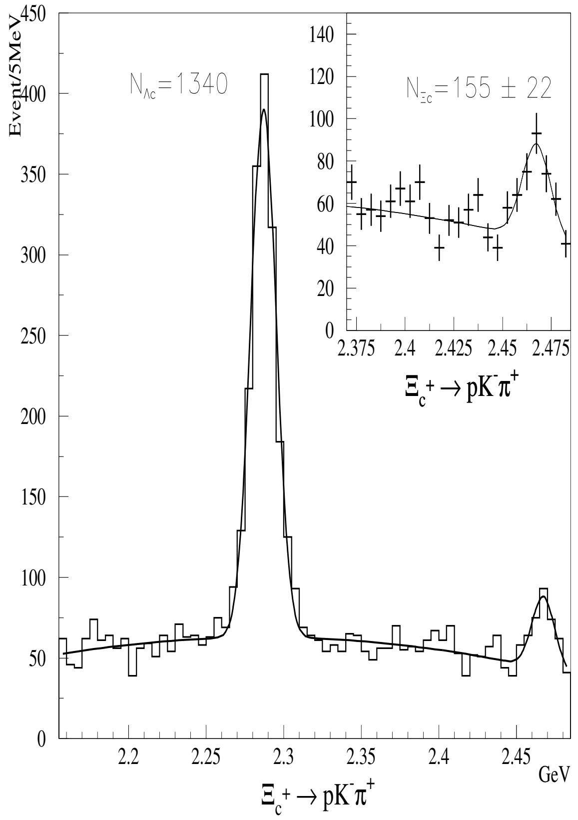
- For charm mesons D^+/D^- leading particle effect is not large. Also we do not see large assymetry for large x_F

- Input from models required to describe p_t and x_F distribution.

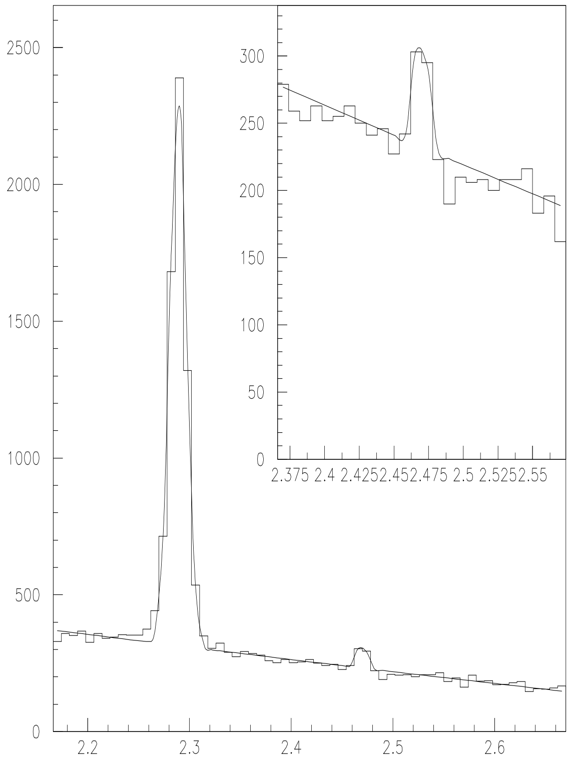
Soon Jun

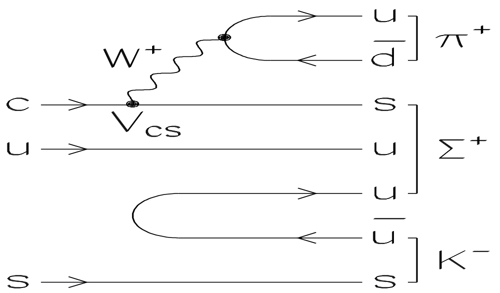
Observation of $\Xi_c^+ \to pK^-\pi^+$ CS decay

SELEX *Phys.Rev.Lett.84 (2000)*

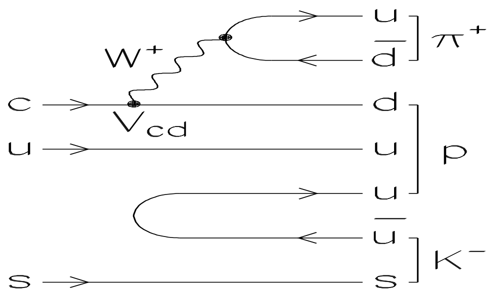


FOCUS *Preliminary*





(a)



(b)

- SELEX: $\frac{B(\Xi_c^+ \to pK^-\pi^+)}{B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)} = 0.20 \pm 0.04 \pm 0.02 \sim 4 \times \tan\vartheta_c^2$
.
- Relative production of Ξ_c^+ compared to Λ_c^+ is higher in hadron beam, than in photon beam.

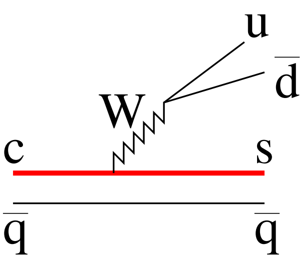
Charm Lifetimes:
Early days of spectator model

In charm hadrons light quarks acts as spectators:

$$B_{SL} = \frac{\Gamma(C \to e^+\nu_e X)}{\Gamma(C \to all)} \sim \frac{1_{e\nu}}{1_{e\nu} + 1_{\mu\nu} + 3_{u\bar{d}}} = 20\%$$

$$B_{SL}(D^+ \to e^+ X) = 17.2 \pm 1.2\%$$

$$B_{SL}(\tau^- \to e^- \overline{\nu}_e \nu_\tau) = 17.81 \pm 0.07\%$$



but...

$$B_{SL}(D^0 \to e^+ X) = 6.75 \pm 0.29\%$$

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.547 \pm 0.043$$

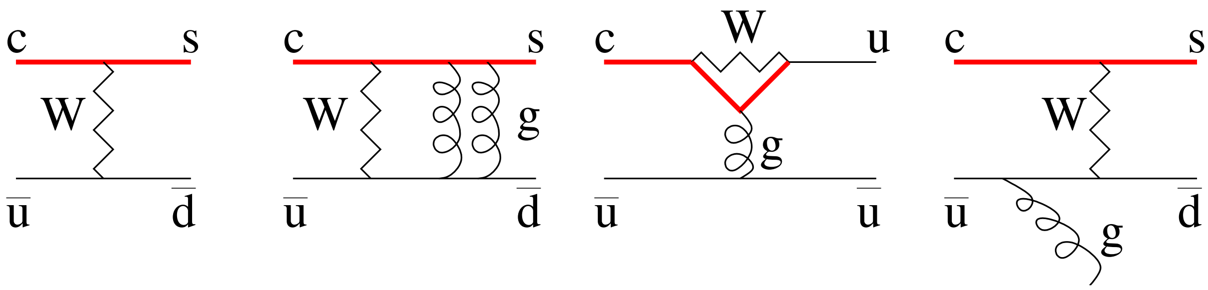
Increasing $\Gamma_{NL}(D^0)$ as in K_s/K^+

Still there is a good news that

$$\Gamma_{SL}(D^+) = B_{SL}/\tau(D^+) = (1.63 \pm 0.18) \times 10^{11}\, s^{-1}$$
$$\Gamma_{SL}(D^0) = B_{SL}/\tau(D^0) = (1.62 \pm 0.07) \times 10^{11}\, s^{-1}$$

Difference is in Nonleptonic decay rates. How one can make D^0 decay 3 times faster in NL mode? How about QCD mechanism that generates $\Delta I = 1/2$ rule. (Lev Okun)

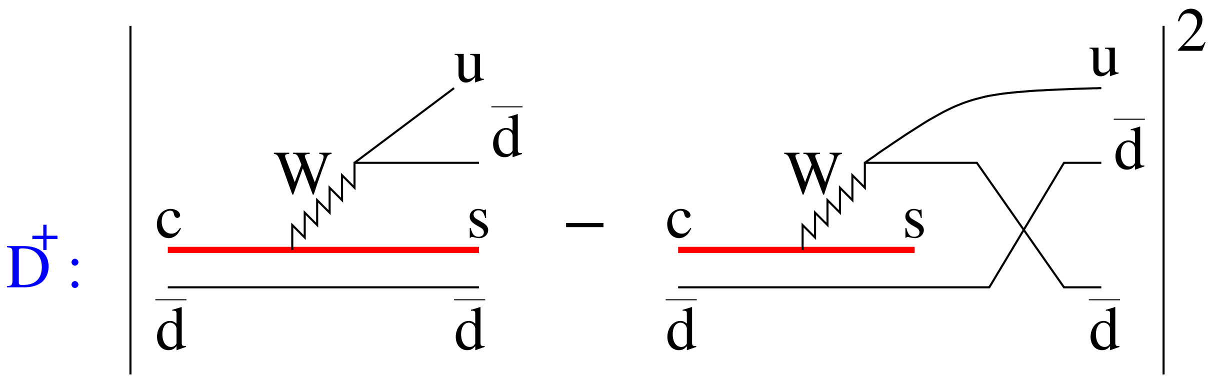
$$\frac{\Gamma(K_s \to \pi\pi \quad \Delta I = 1/2, 3/2)}{\Gamma(K^+ \to \pi^+\pi^0 \;\; \Delta I = 3/2)} = 650.$$



"wavefunction overlap" penalty $(f_D/m_c)^2 \sim 10^{-2}$
helicity suppression $(m_s/m_c)^2 \sim 10^{-1}$

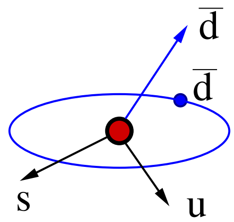
It gives extra $\sim 30 - 50\%$ to $\Gamma_{NL}(D^0)$,
we need 300%.

Decreasing $\Gamma_{NL}(D^+)$: Pauli Interference



Two $\bar{d}$ quarks interfere in the final state.

- **Coherence** QCD corr is important (accelerate $\bar{d}$)



decreases as $\frac{1}{m_Q^N}$

- **Interference** can be
  Destructive D^+, Λ_c^+
  Constructive Ξ_c^0, Ω_c^0
  Ξ_c^+ has both constructive and destructive

Theory: Heavy Quark Expansion

HQE calculates inclusive $H_Q \to qq\ldots$ decay rates
HQET calculates exclusive $H_Q \to H_{Q'}X$ decay rates
(Isgur, Wise, Bigi, Uraltsev, Voloshin, Shifman, Guberina...)

$$\Gamma_{SL,NL}(H_c \to f) = \Gamma_{spec}(1 + A_2/m_c{}^2 + A_3/m_c{}^3 + \ldots)$$

$A_2/m_c{}^2$ include: $\Gamma_{spec} = \frac{G_F^2 \cdot m_c^5}{192\pi^3}$

- $\frac{\vec{p}^2}{2 \cdot m_c{}^2}$ - time dilation of c quark
  ≥ 0.20 is the same for D mesons $(SU_3)_f$
  $\sim 10\%$ smaller term for baryons
- $\frac{\mu_G{}^2}{2 \cdot m_c{}^2}$ - chromomagnetic moment
  $\simeq 0.20$ for D mesons
  $= 0$ for $\Lambda_c{}^+, \Xi_c{}^+, \Xi_c{}^0$ as (qq) has spin 0
  $\simeq 0.12$ for $\Omega_c{}^0$ as (ss) has spin 1

Both terms enter in M_c and can be derived from masses of heavy hadrons with about 30% uncertainty.

$$M_{H_Q} = m_Q + \overline{\Lambda} + \frac{\vec{p}^2}{2m_Q{}^2} + \frac{\mu_G{}^2}{2m_Q{}^2} + \mathcal{O}(1/m_Q{}^2)$$

Theory: Heavy Quark Expansion

$$\Gamma_{SL,NL}(H_c \to f) = \Gamma_{spec}(1 + A_2/{m_c}^2 + A_3/{m_c}^3 + ...)$$

$A_3/{m_c}^3$ include:

- WA/WS annihilation terms
  mesons - greatly suppressed
  baryons - ~ 10 larger (no helicity suppression)

- PI terms
  mesons - affect only Γ_{NL}
  baryons - affect both Γ_{NL} and Γ_{SL}

Application for beauty

- $A_2/m_b^2 (\propto \Delta M_B) \sim 10$ times smaller

- WA/PI terms about ~ 30 times smaller
  $\Longrightarrow B$ lifetimes are much closer

- but.. strong interactions at different scale

HQE predictions

- Γ_{SL} for all mesons are the same:

$$\begin{aligned} \Gamma_{SL}(D^+) &= (1.63 \pm 0.18) \times 10^{11}\, s^{-1} \\ \Gamma_{SL}(D^0) &= (1.62 \pm 0.07) \times 10^{11}\, s^{-1} \\ \Gamma_{SL}(D_s^+) &= (1.6 \pm 1.1) \times 10^{11}\, s^{-1} \end{aligned}$$

- $\tau(D^+)/\tau(D^0)$ is due to PI in D^+ (A_3/m_c^3)

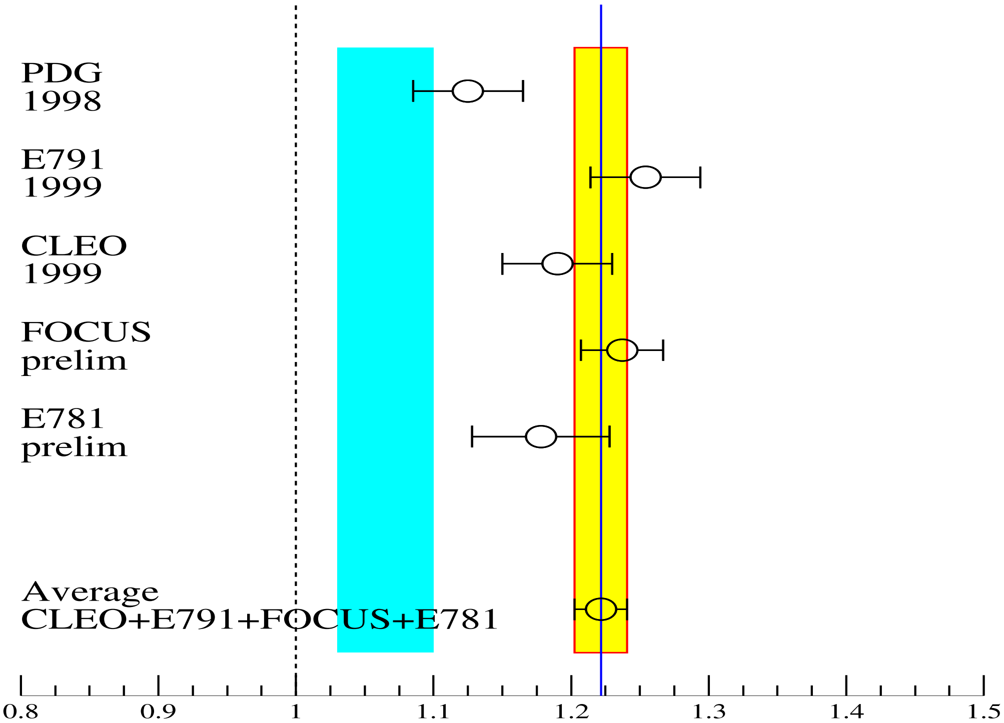
$$\begin{aligned} \frac{\tau(D^+)}{\tau(D^0)} &\simeq 1 + (\frac{f_D}{200MeV})^2 \sim 2 \qquad \textit{huge!} \\ \frac{\tau(D^+)}{\tau(D^0)} &= 2.547 \pm 0.043 \end{aligned}$$

D_s^+/D^0 Lifetime Puzzle

- $\tau(D_s{}^+)/\tau(D^0)$ is $\leq 1 + 10\%$

$$\frac{\tau(D_s{}^+)}{\tau(D^0)} \simeq 1 - 0.03\ (D_s \to \tau\nu)$$
$$+0.04\ (\text{PI in CS } c \to s\bar{s}u)$$
$$+0.03\ (\text{diff in } \vec{p}^2/m_c{}^2)$$
$$+0.01\ (\text{diff in } \mu_G{}^2/m_c{}^2)$$
$$\pm???\ (\text{WA})$$
$$\pm???\ (\text{quark} - \text{hadron duality})$$

$$\frac{\tau(D_s{}^+)}{\tau(D^0)} = 1.25 \pm 0.04 \quad (6 \times \sigma\ E791\ 1999)$$



HQE predictions

- Baryons

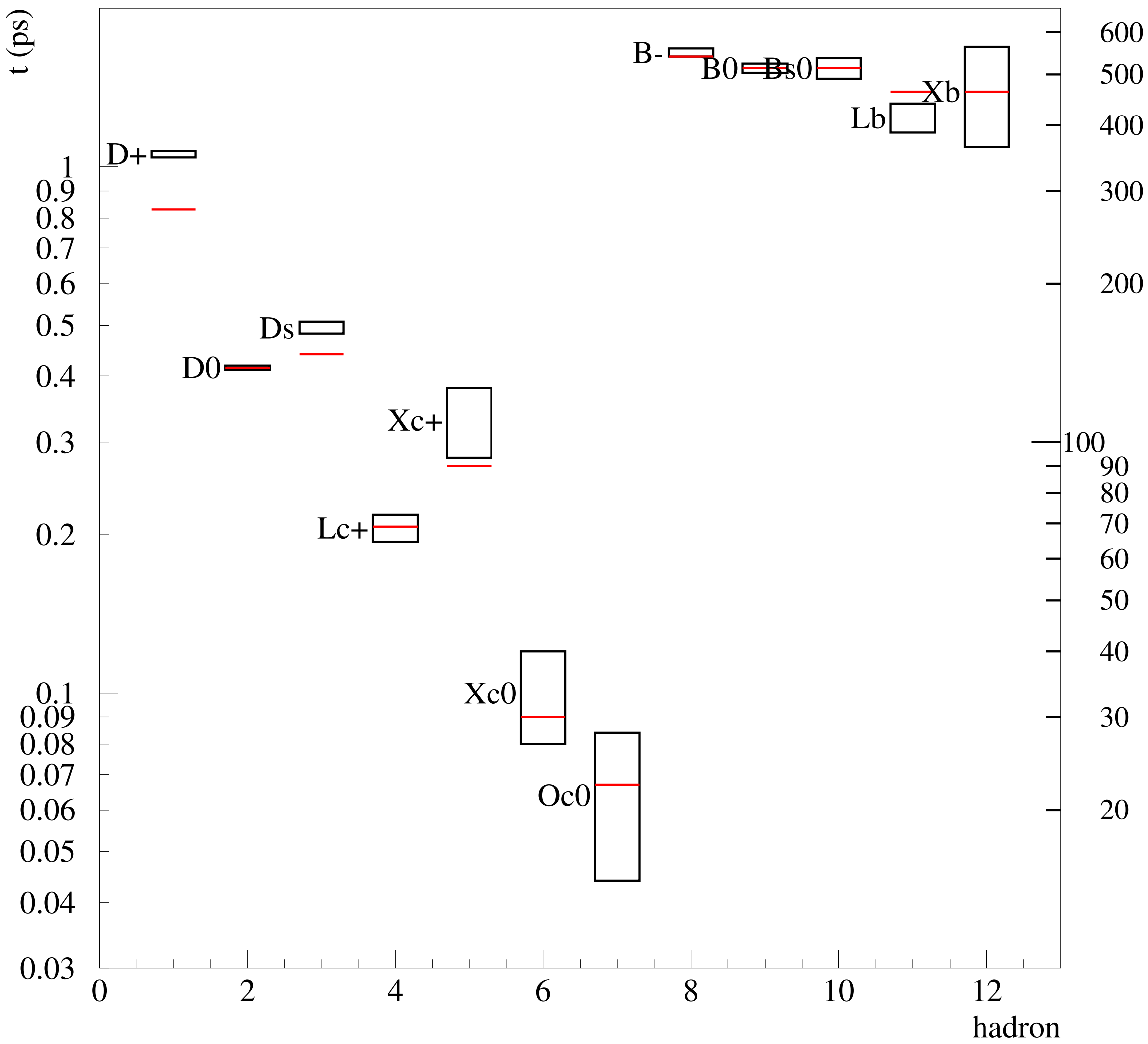
$$
\begin{aligned}
\Gamma(\Lambda_c^+ \; cud) &= \Gamma_0(1 + \frac{\vec{p}^2}{2 \cdot {m_c}^2} + WX - PI_{uu}) \\
\Gamma(\Xi_c^+ \; csu) &= \Gamma_0(1 + \frac{\vec{p}^2}{2 \cdot {m_c}^2} + PI_{ss} - PI_{uu}) \\
\Gamma(\Xi_c^0 \; csd) &= \Gamma_0(1 + \frac{\vec{p}^2}{2 \cdot {m_c}^2} + WX + PI_{ss}) \\
\Gamma(\Omega_c^0 \; css) &= \Gamma_0(1 + \frac{\vec{p}^2}{2 \cdot {m_c}^2} + \frac{\mu_G^2}{2 \cdot {m_c}^2} + 3 \cdot PI_{ss})
\end{aligned}
$$

$$
\begin{array}{cc}
\Gamma(\Lambda_c^+) < \Gamma(\Xi_c^0), & \Gamma(\Lambda_c^+) \; ? \; \Gamma(\Xi_c^+), \\
\Gamma(\Xi_c^+) < \Gamma(\Xi_c^0), & \Gamma(\Xi_c^0) \; ? \; \Gamma(\Omega_c^0).
\end{array}
$$

- Semileptonic decay rates

$$
\begin{gathered}
\Gamma_{SL}(D) : \Gamma_{SL}(\Lambda_c^+) : \Gamma_{SL}(\Omega_c) : \Gamma_{SL}(\Xi_c^{0+}) \\
\simeq 1 : 1.5 : 1.2 : 2
\end{gathered}
$$

Charm and beauty lifetimes



experimental points - PDG99

theoretical lines - G.Bellini, I.I.Bigi, P.J.Dornan Phys.Rep.289(1997)1

Lifetime: technique and errors

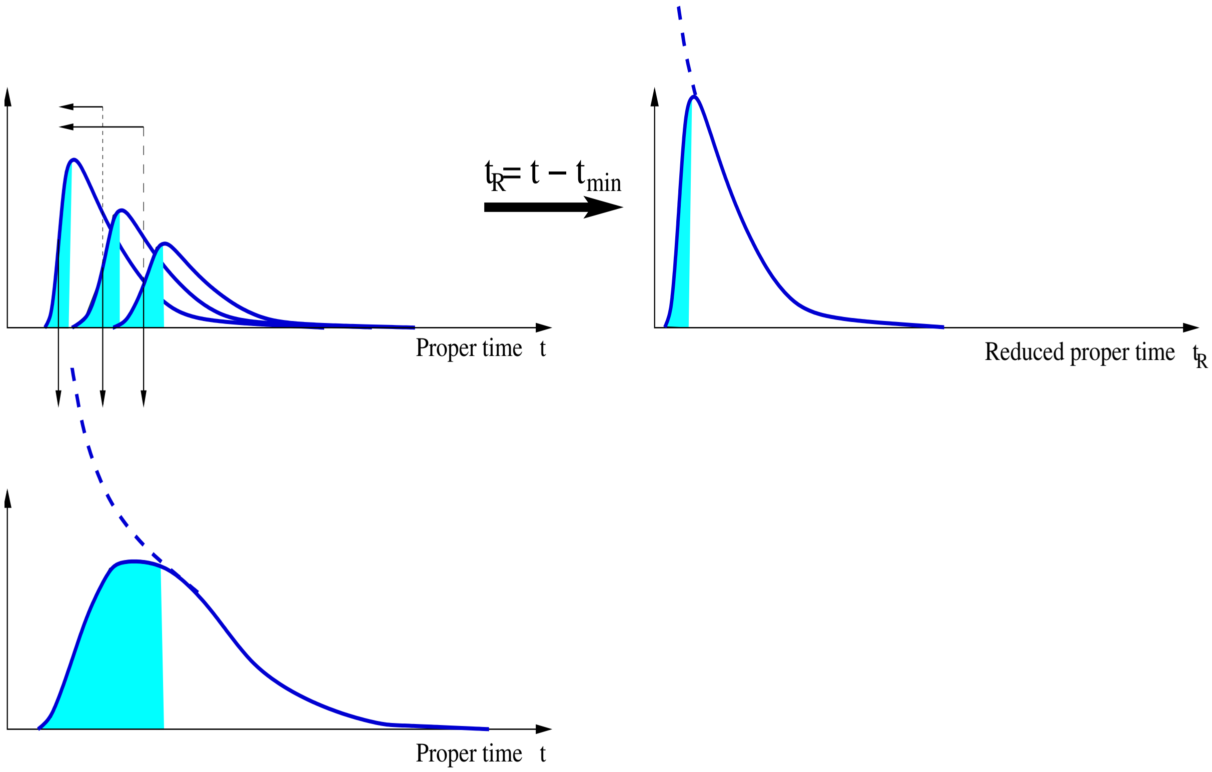
1. Measure $ct = L/p_z * M_c$
2. Book reduced proper time $t_r = t - t_{min}$
3. Find background contribution
4. Correct for efficiency $\epsilon(t)$
5. Fit

This analysis features

- Do D^0 to establish technique
- Resolution effects are small $\sigma_{ct} \simeq 5\mu m \ll c\tau$
- Background subtraction effects - small
- Efficiency calculations are quite important
- Cross checks with Monte-Carlo, K_s, D^+ samples

Why reduced proper time?

t_{min} is calculated on event by event basis.
simplistic case: $ct_{min} = 8 \cdot \sigma/\gamma$



- Correction function is closer to 1

- "Uncertain" region is smaller

Efficiency $\epsilon(t)$ calculation

Conventional technique

$$\epsilon(t) = \frac{n(t)}{n_0(t)} = \frac{\int n_0(\vec{p}) \cdot \epsilon(\vec{p}, t)\, d\vec{p}}{\int n_0(\vec{p})\, d\vec{p}} \tag{1}$$

We wanted to use events from the sample to find $\epsilon(t)$ to reduce systematics from production and correlations uncertainties.

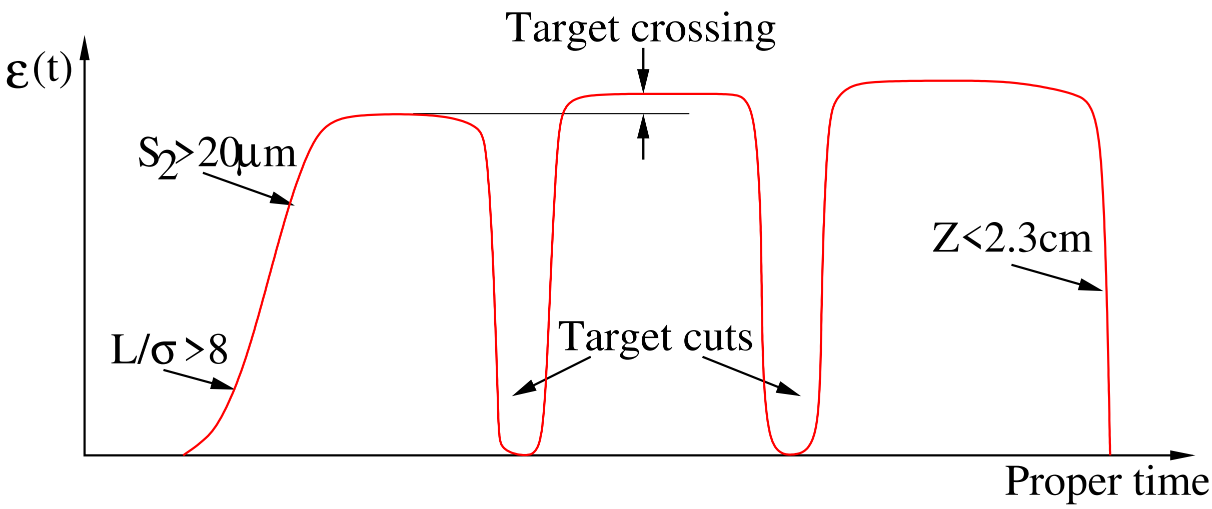
Each event was used to generate 1000 similar events with the same $\vec{p}$, but different proper time t, for those efficiency $\epsilon(\vec{p}, t)$ was simulated. Overall efficiency $\epsilon(t)$ then:

$$\epsilon(t) = \frac{\int n(\vec{p}) \cdot w(\vec{p}) \cdot \epsilon(\vec{p}, t)\, d\vec{p}}{\int n(\vec{p}) \cdot w(\vec{p})\, d\vec{p}} \tag{2}$$

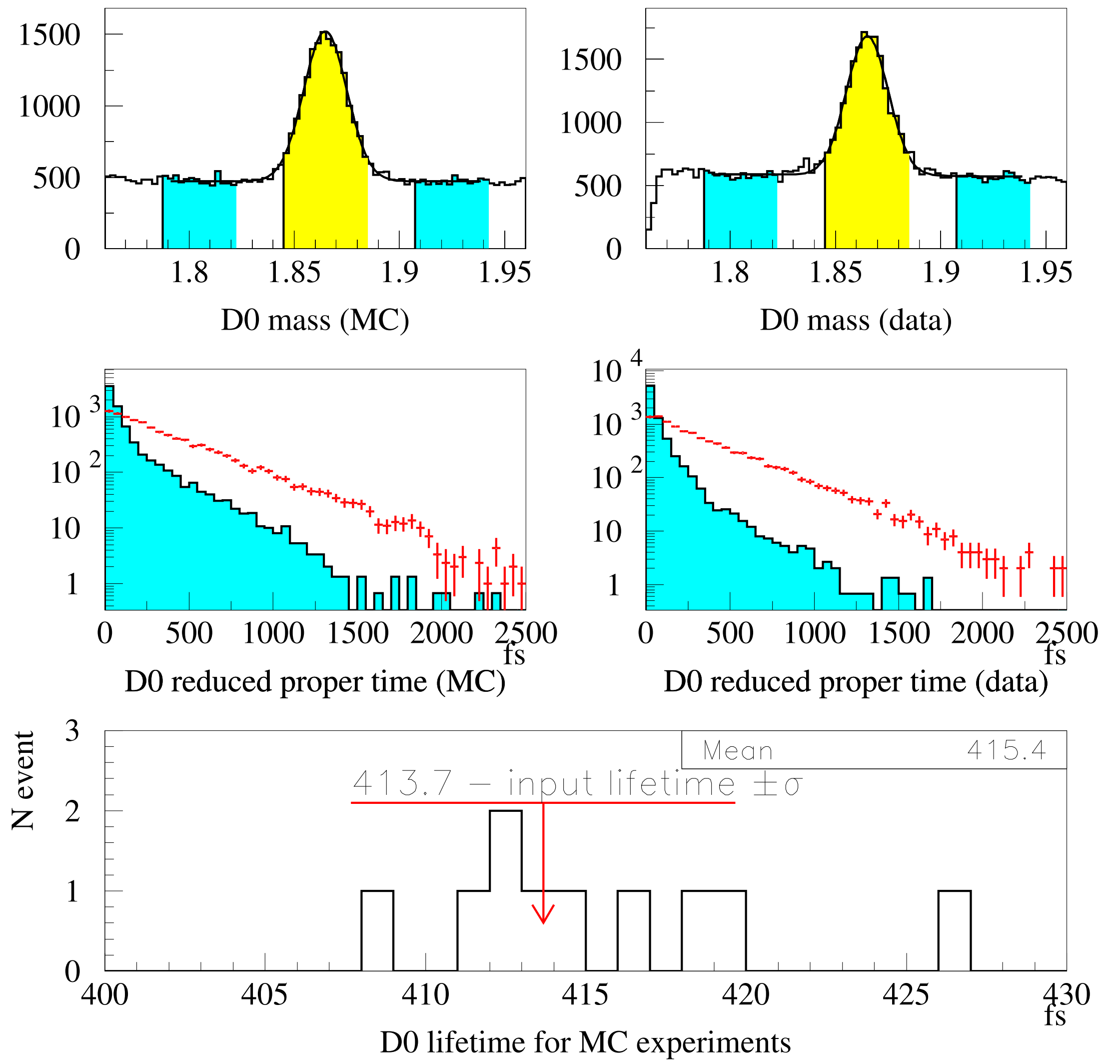
$$w^{-1}(\vec{p}) = \int \frac{1}{\tau} e^{-t/\tau} \cdot \epsilon(\vec{p}, t)\, d\vec{p} \tag{3}$$

Downstream efficiency $\epsilon(\vec{p})$ cancells out.

Single event efficiency $\epsilon(\vec{p}, t)$

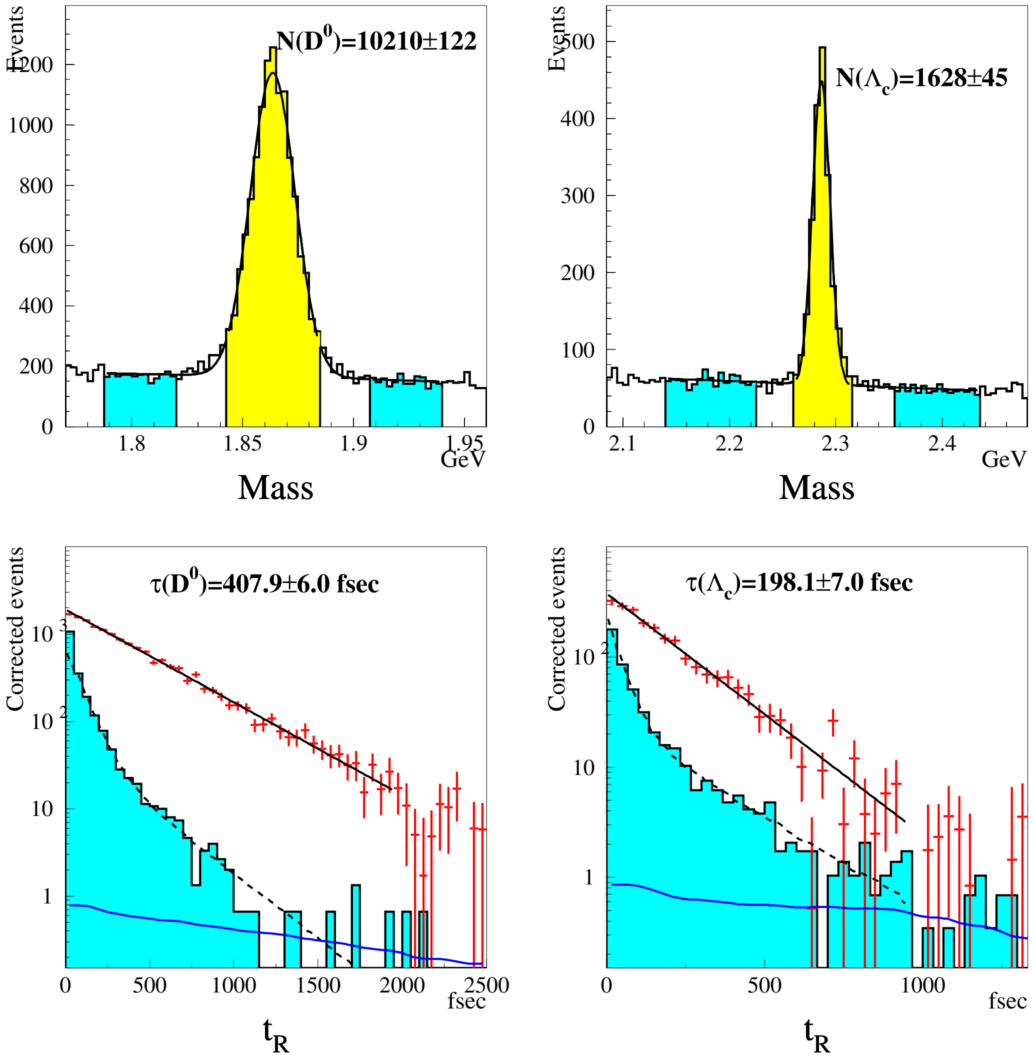


Is math done right in $\epsilon(t)$ calculations?



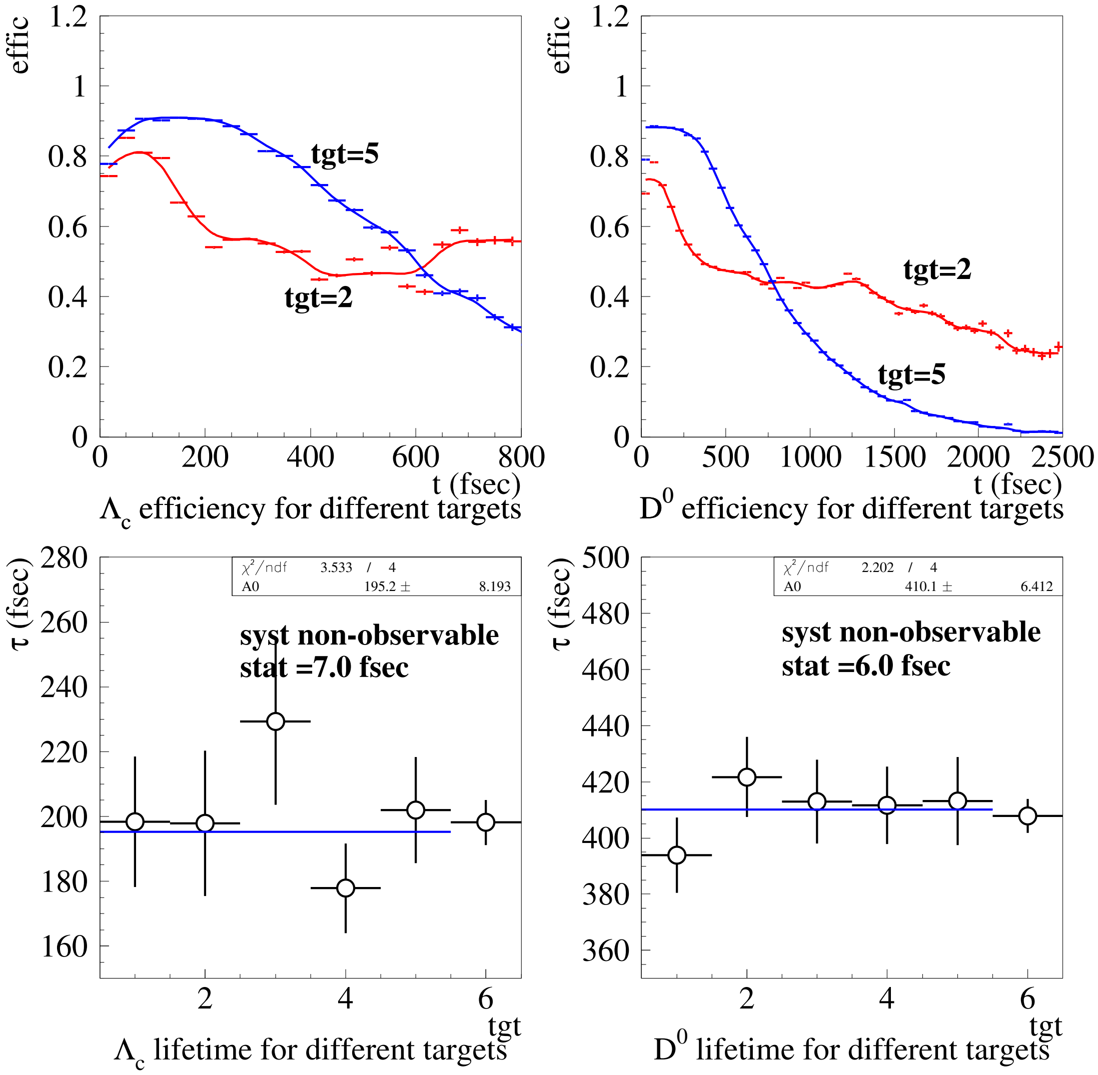
Can you find lifetime τ given properties of the sample $n(\vec{p})$ and $\epsilon(\vec{p}, t)$ for each event? Yes

Λ_c^+ and D^0 Lifetimes

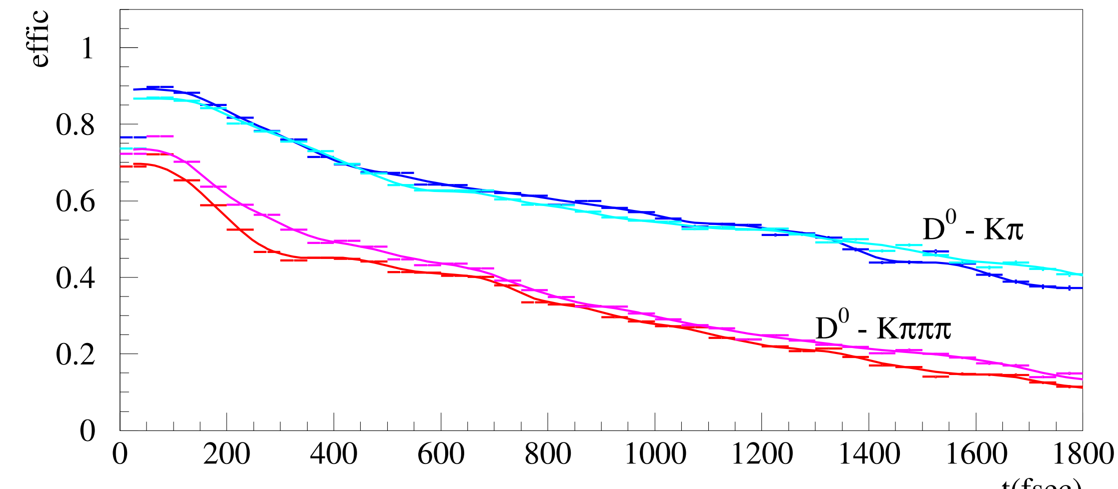


- Binned log-likelihood fit of Signal+Background
- S $= \epsilon(t) \times N_s \cdot e^{-t_r/\tau}$
- B $= N_1 \cdot e^{-t_r/\tau_1} + N_2 \cdot e^{-t_r/\tau_2}$
- Integration over bin taken into account.

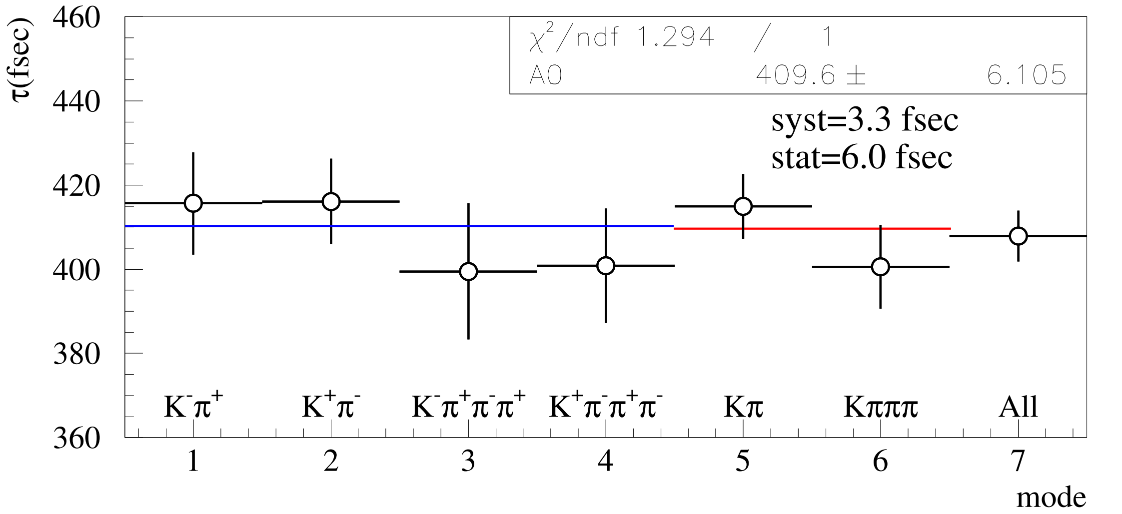
Systematics due to different targets



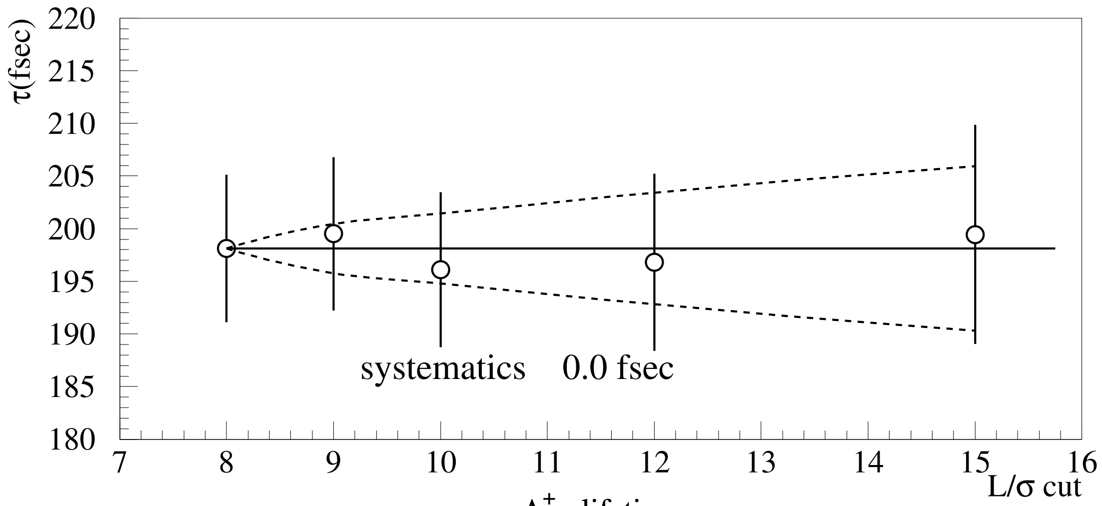
Systematics due to different decay mode



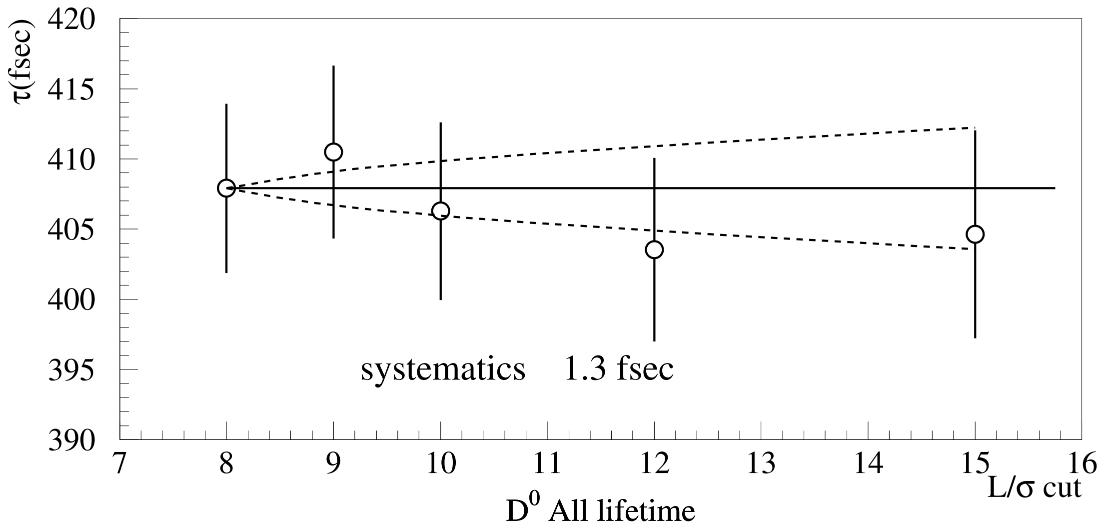
Efficiency for different decay modes



Systematics due to L/σ cut



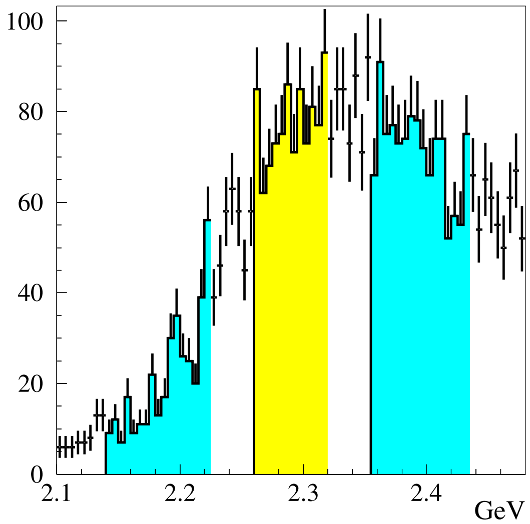
Λ^+_c lifetime



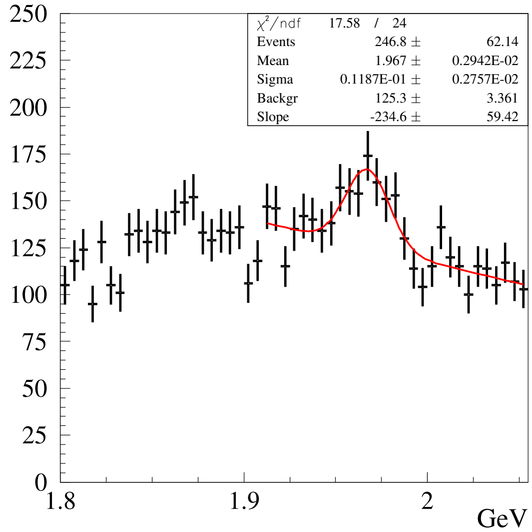
D^0 All lifetime

Charm mass reflections

Λ_c^+ has contribution from $D_s^+ \to K^- K^+ \pi^+$,
where K^+ is misidentified with p.



Ds reflection on Lc

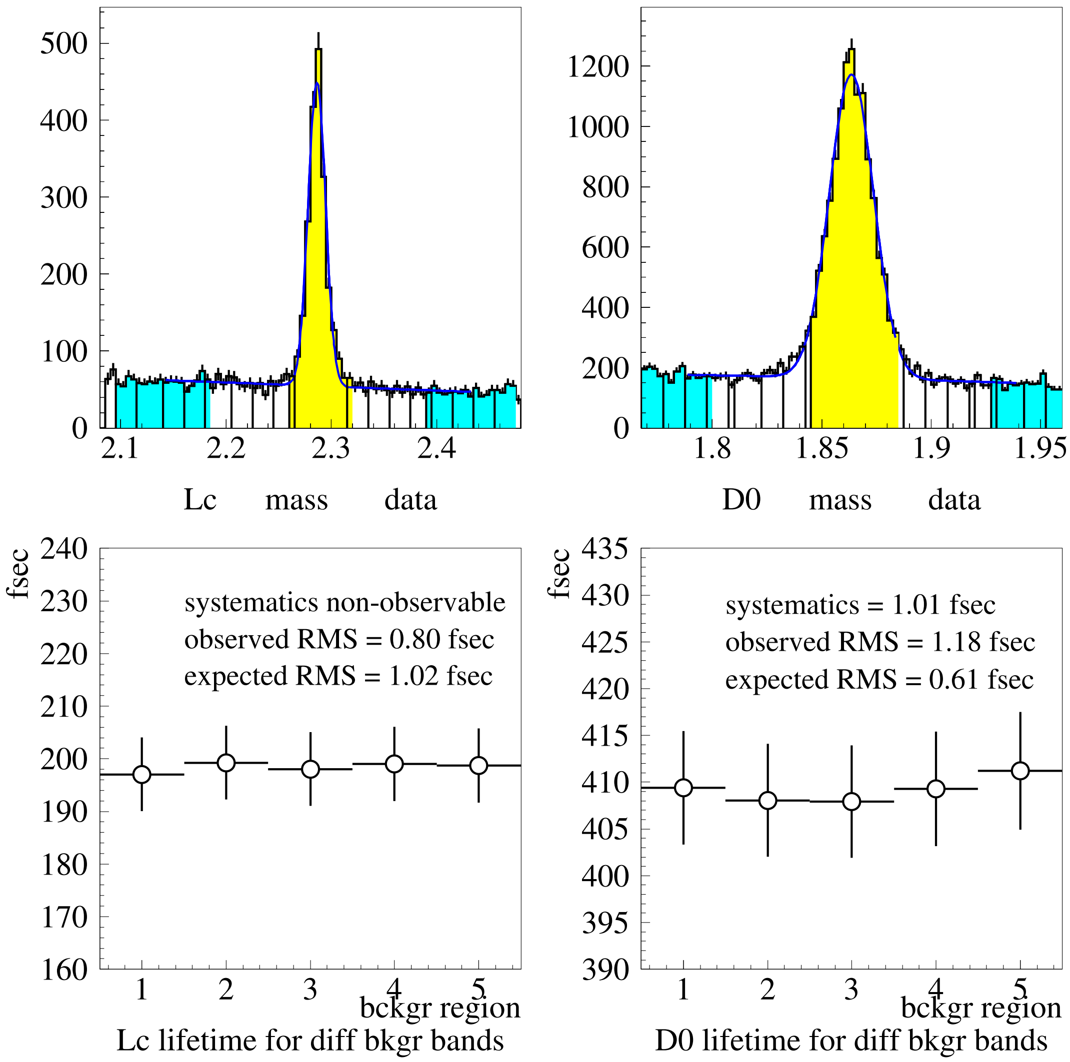


Ds from All Lc sample

To suppress reflections p/K^+ separation was applied.
Less than 2.5% of signal was lost.

Decay	With p/K^+ separation		
	unsubtr fraction	observed signal	$\Delta\tau$ (fsec)
$D_s^+ \to K^- K^+ \pi^+$	1.2 %	112	0.2
$D^+ \to K^- K^+ \pi^+$	4.0 %	35	0.7
$D^+ \to K^- \pi^+ \pi^+$	1.0 %	75	0.4
Total			1.3

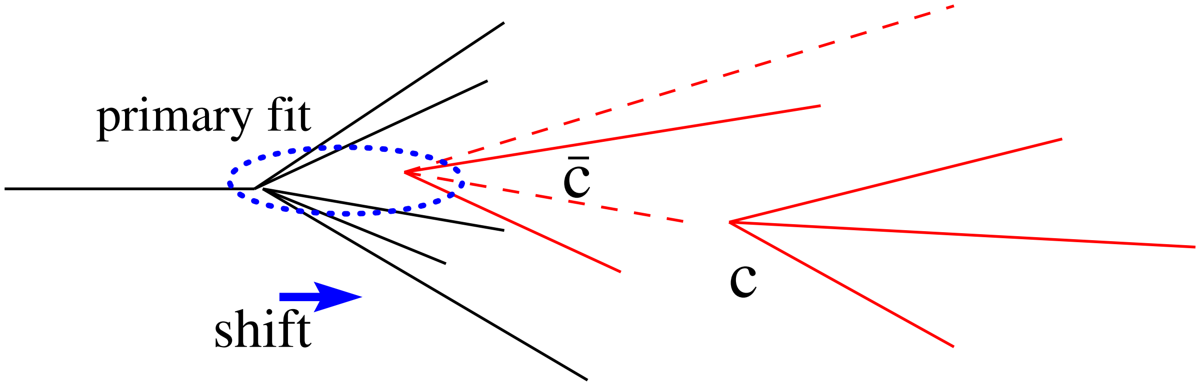
Systematics due to sideband subtraction



Expected RMS of lifetime variations due to different choices of sidebands was estimated repeating this study on 10 MC samples which have only statistical fluctuations.

Small systematics observed.

Systematics due to primary vertex reconstruction



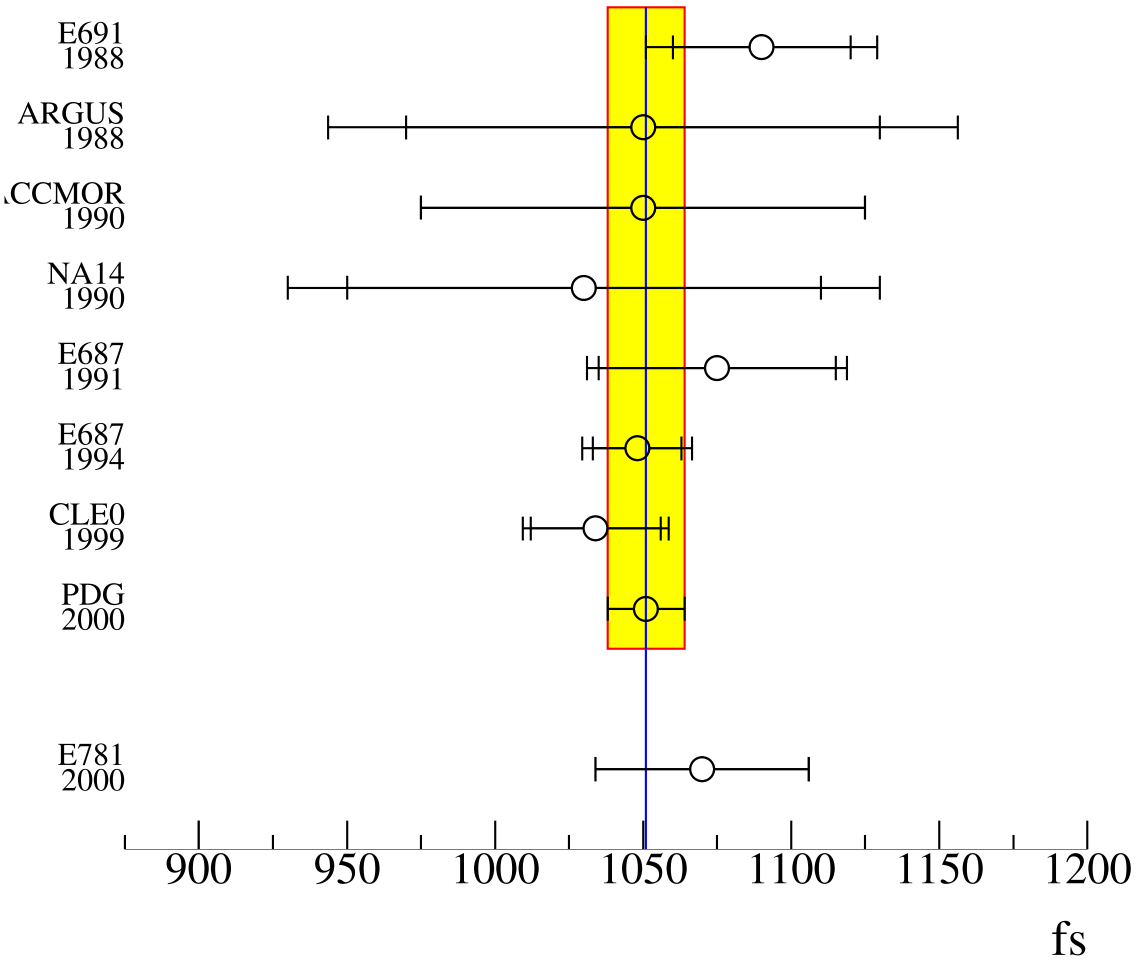
Due to another charm in the event primary vertex is pulled forward by $\sim 100-200\mu m$. Predicted by GE781 and observed in data.

Effect is smaller than individual event $\sigma_L \simeq 500\mu m$.

Systematic estimate < 1 fsec.

Supporting evidence

- K_s studies
- Charm yields for different targets
  $N = N_{observed}/\epsilon$
- D^+ lifetime measurement



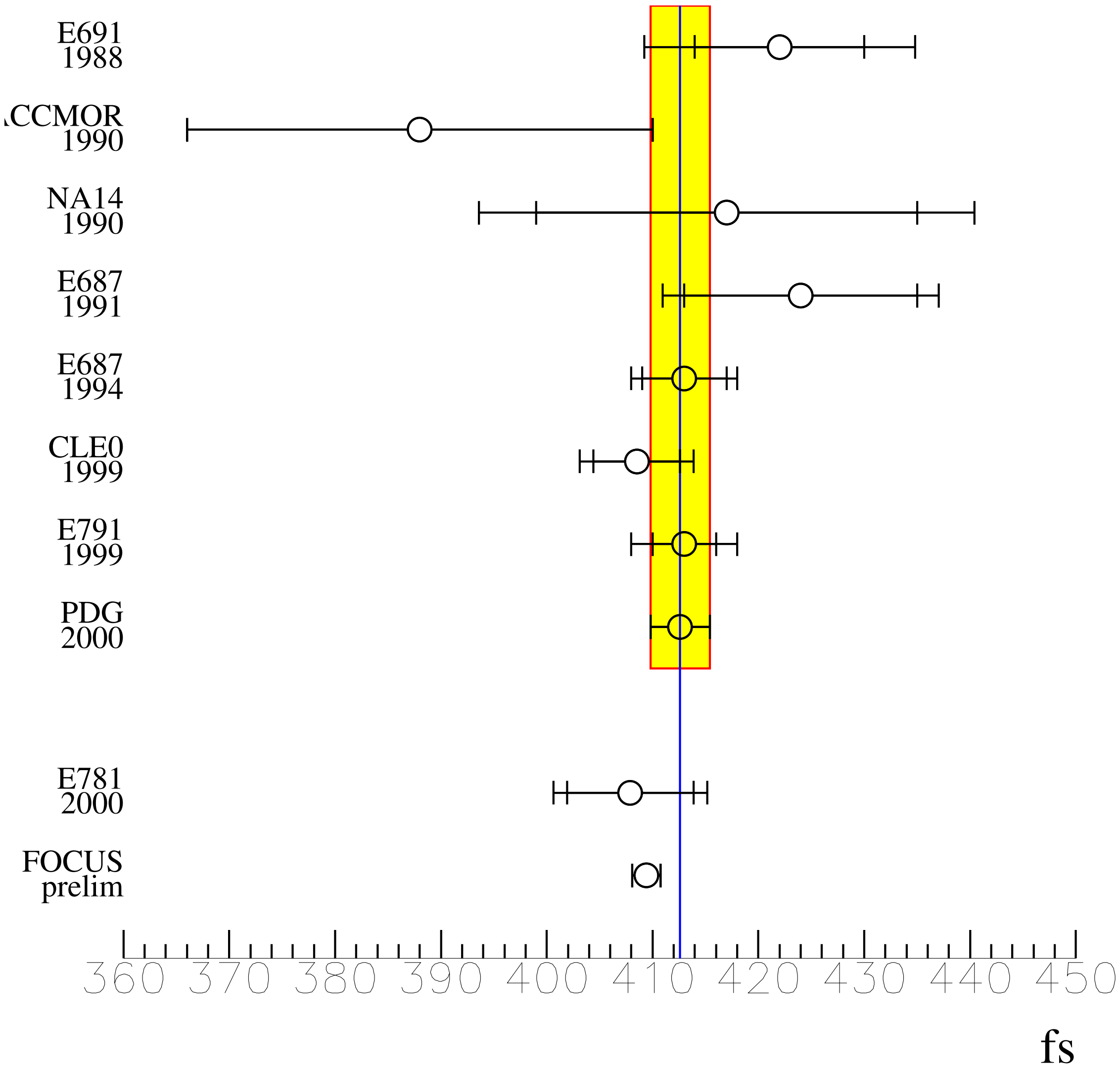
Miscellaneous systematics

- Wrong smearing simulation: < 0.2 fsec
- Charm induced backgrounds - not observable
- Separate fit of background < 0.3 fsec
- Smoothing of efficiency: $D0\ \Delta ct < 0.3$ fsec
- Systematcis due to finding $t_{min} < 1.5$ fsec
- Initial value of t in weight calculations $\simeq 0.3$ fsec
- Different fitting technique < 0.1 fsec

Systematics summary

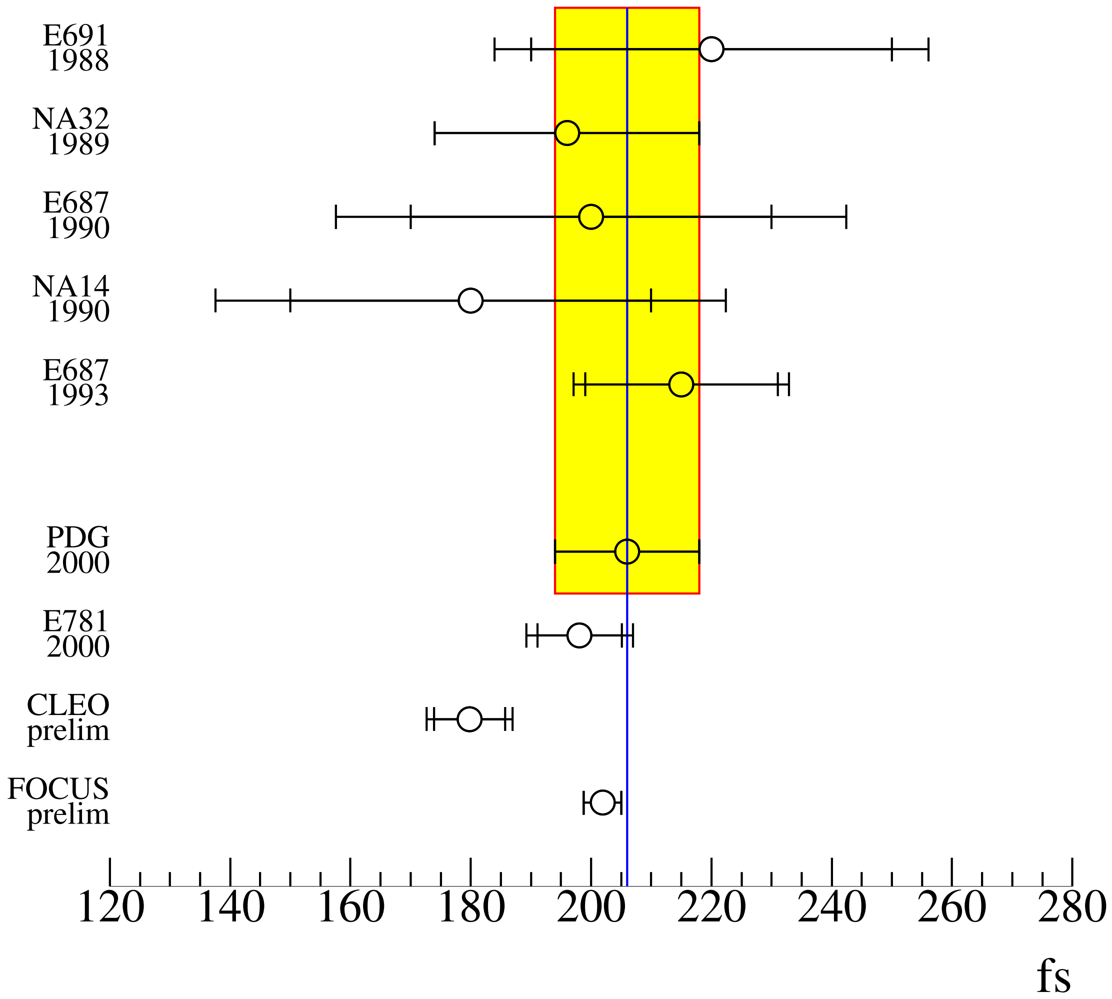
Systematics	Λ_c^+	D^0
Mass reflections	1.3	-
Primary vertex shift	1.0	1.0
Background subtraction	-	1.0
Miscelaneous	1.5	1.5
Efficiency	5.1	3.8
targets	-	-
2 prong vs 4-prong		3.3
high-mult effects	3.2	-
charm-momentum	-	-
L/σ_L	-	1.3
sim of large L events	1.2	0.9
sim of target losses	3.0	1.2
min π energy	2.3	-
Total	5.6	4.3

D^0 Lifetime measurement



$$\tau(D^0) = 407.9 \pm 6.0 \pm 4.4 \text{ fs from 10210 events}$$

Λ_c Lifetime measurement



$\tau(\Lambda_c) = 198.1 \pm 7.0 \pm 5.5$ fs from 1630 events

Summary

- $\frac{\tau(D_s^+)}{\tau(D^0)}$ difference

- More precise charm baryon lifetime measurement are needed. Both experimentally and theoretically

- $\frac{\tau(\Lambda_b)}{\tau(B^0)}$ puzzle. Can charm help?

SELEX prospects

- Final results for Λ_c^+ and D^0 hep-ex/0010014

- Analysis for D_s^+ and Ξ_c^+

- We want to reanalize all data to get larger samples for Ξ_c^0 and Ω_c^0