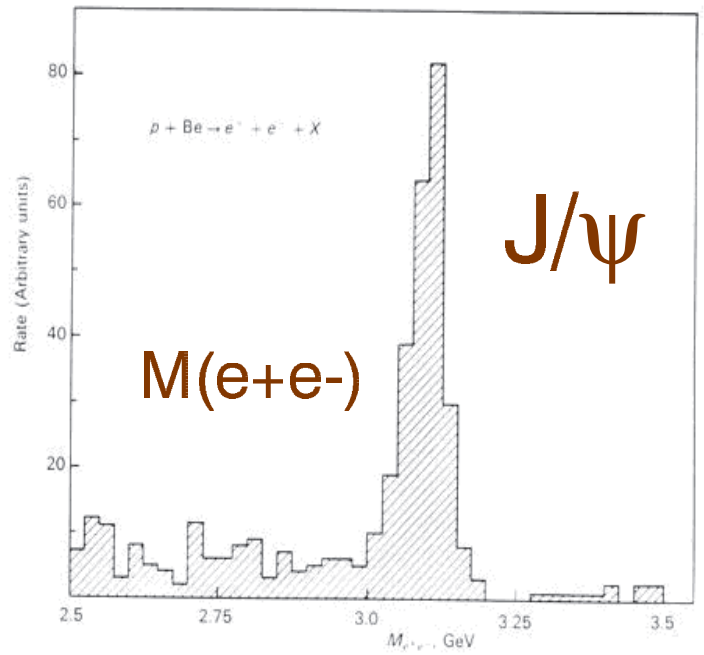
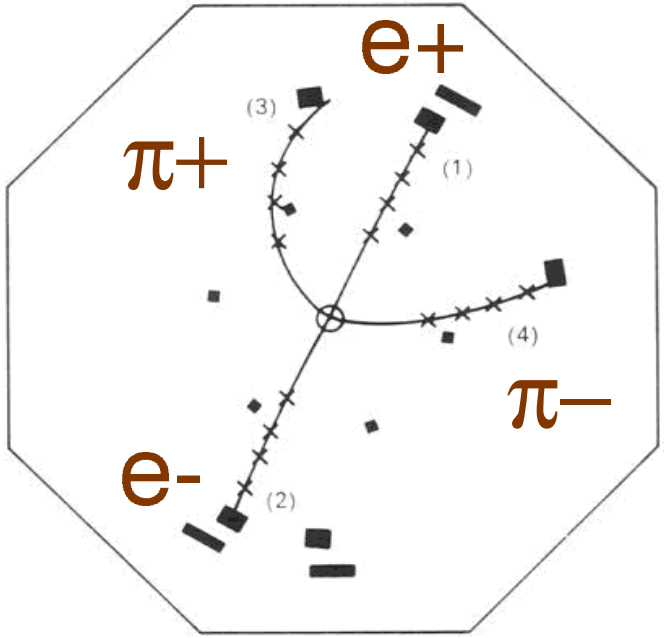
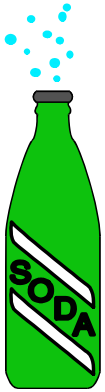
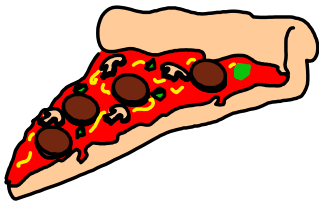
Charm - the Forgotten Quark

Harry W.K. Cheung - Fermilab





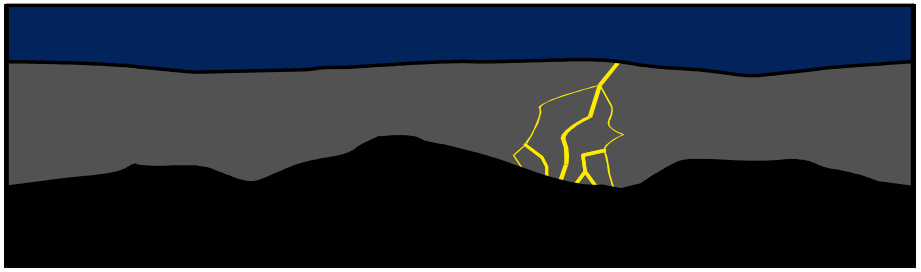




TeVatron University Seminar, June 3rd 1999

CERN Courier Suggested Title:

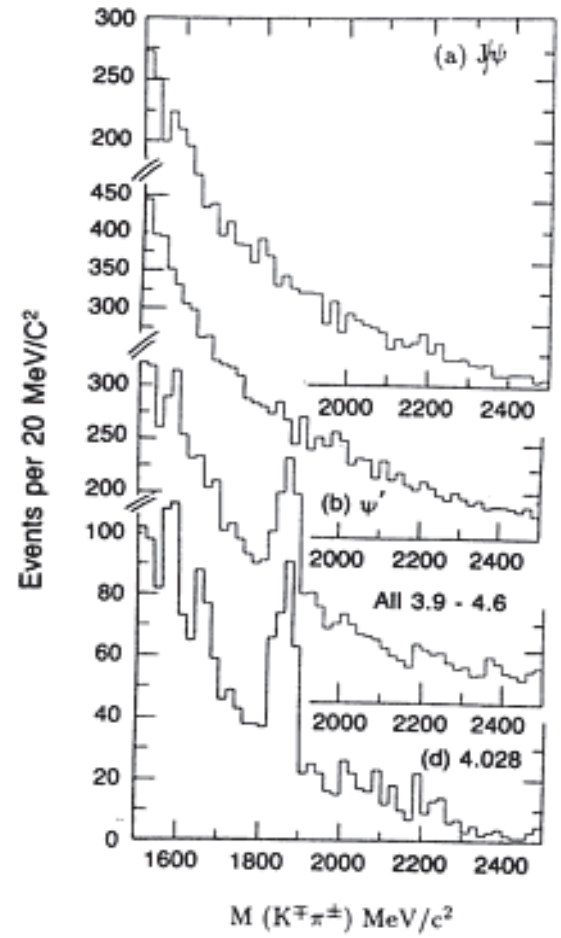
Charm - The Winter of Discontent



Exciting Times in HEP

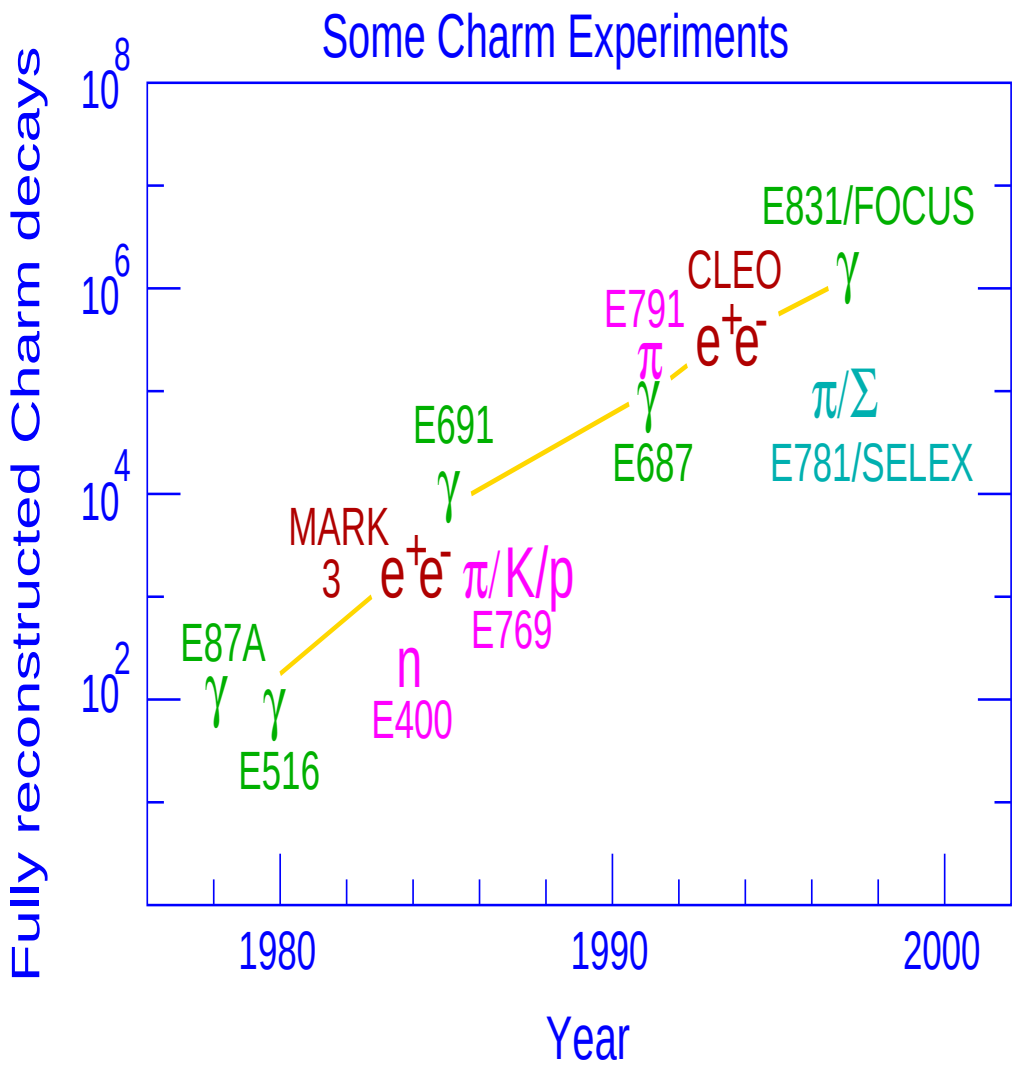
- Discovery of charm
- Discovery of tau
- Emerging Quark Model
- Discovery of open charm
- Still many unknowns

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$?



$D^0 \to K^-\pi^+$

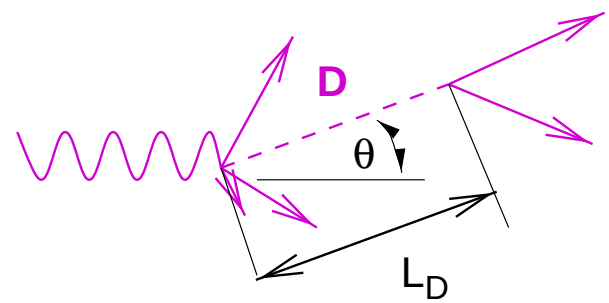
Slow Progress over 25 years



$$\sigma(\gamma N \to e^+e^-) \approx 300$$

$$\sigma(\gamma N \to hadrons) \approx 1$$

$$\sigma(\gamma N \to charm) \approx 0.006$$



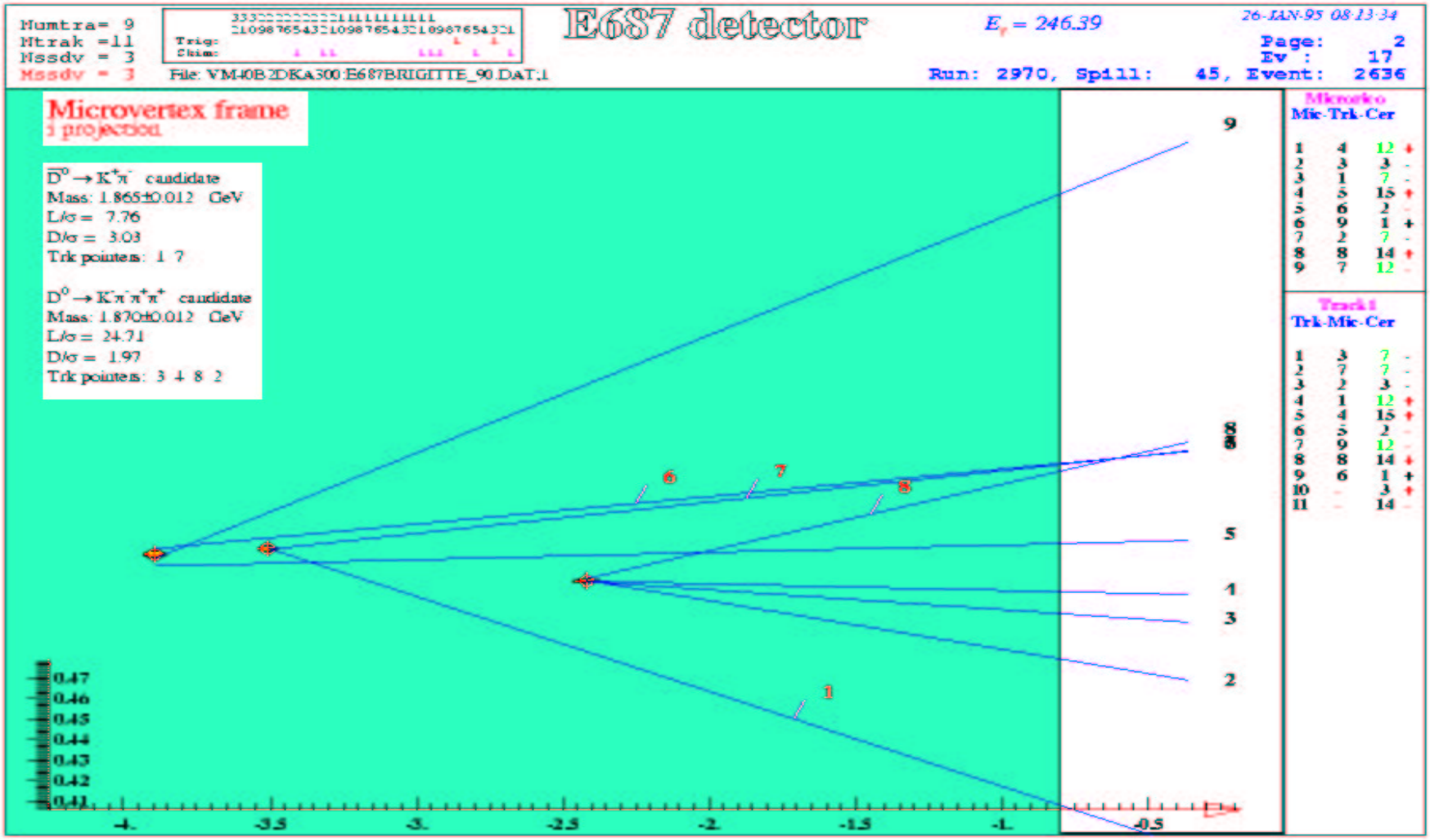
$$\delta L_D << L_D$$

$$\sigma_T << \theta L_D \approx c\tau_D$$

124μm D^0
317μm D^+
60μm Λ_c^+

Event from E687

$\overline{D}^0 \rightarrow K^+\pi^-$, $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$



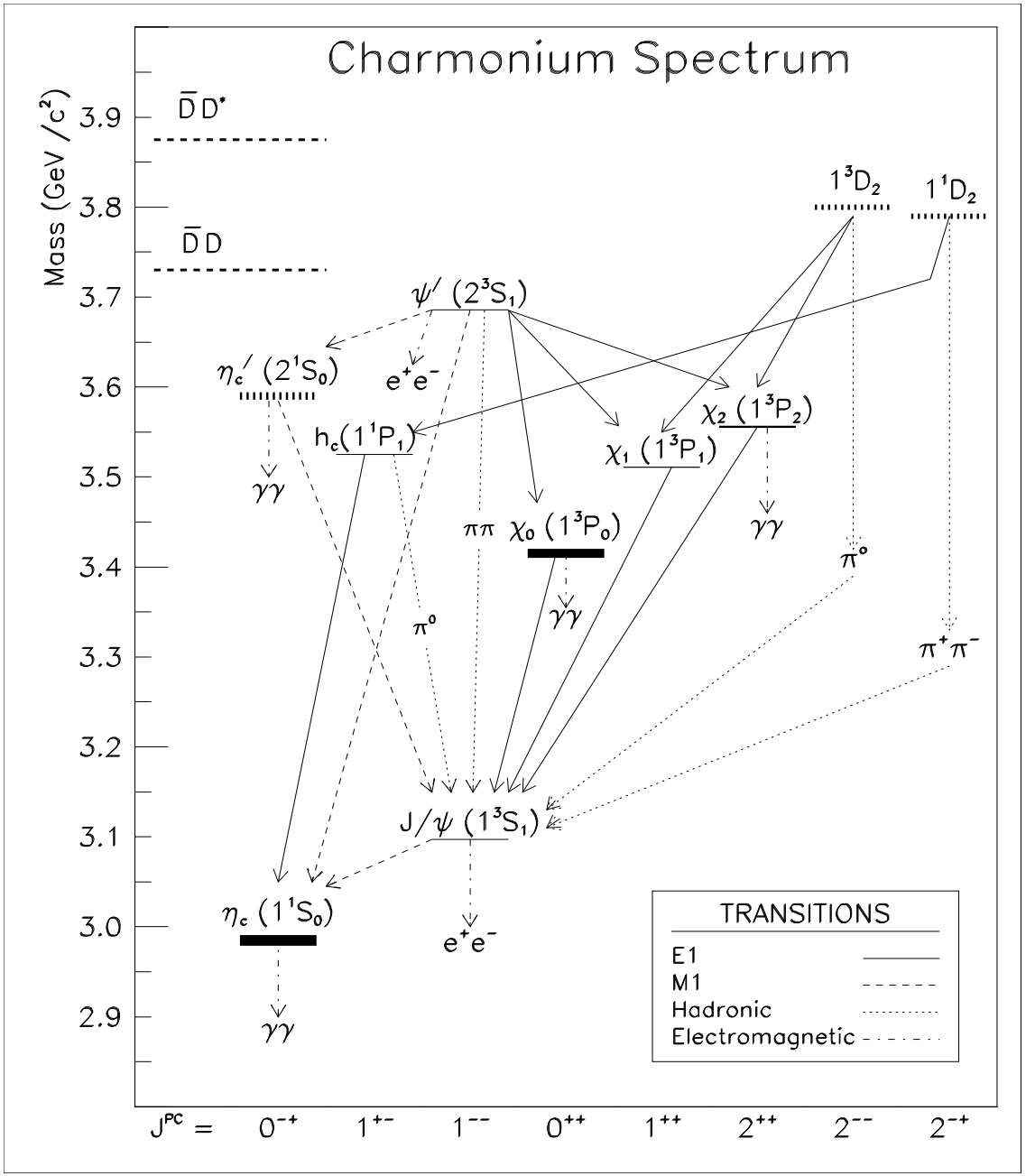
Progress through Silicon Microstrips and Brute Force!

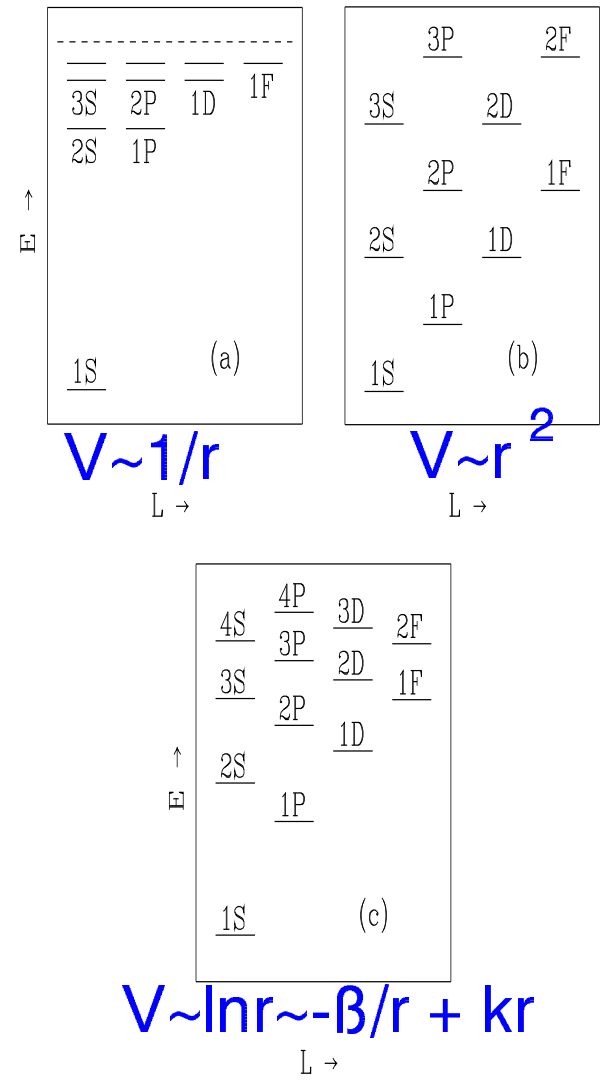
E769 (1987)

E791 (1991)

One Weekend's Data!

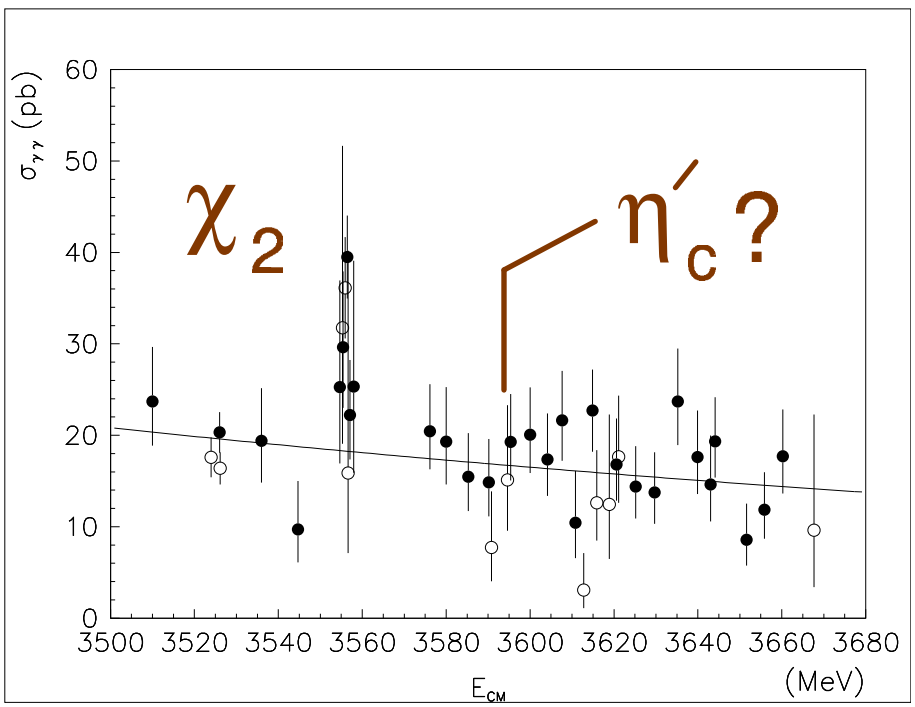
Spectroscopy





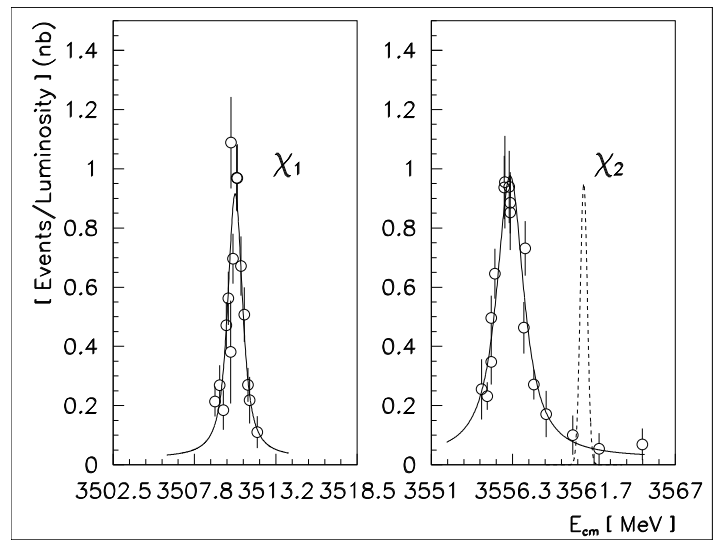
E835 - $\bar{p}$ accumulator and H jet target

- Directly produce all $\bar{c}c$ states
- 0.5 MeV resolution in CMS
- Confirm $h_c(1^1P_1)$ state
- Search for $\eta_c'(2^1S_0)$



E835 + E760 Data

E760 Data



1P-1S mass splittings gives

$$\alpha_{\overline{MS}}(5GeV) = 0.174 \pm 0.012$$

$$\alpha_{\overline{MS}}(M_Z) = 0.105 \pm 0.004$$

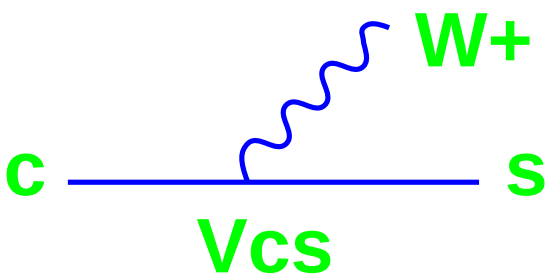
Charm 101

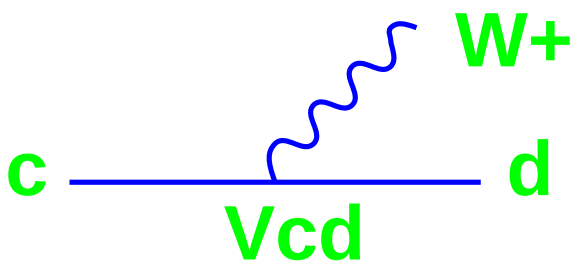
Charm Mesons: D^+ D^0 D_s^+

$c\bar{d}$ $c\bar{u}$ $c\bar{s}$

Charm Baryons: Λ_c^+ Ξ_c^+ Ξ_c^0 Ω_c^0

cud csu csd css





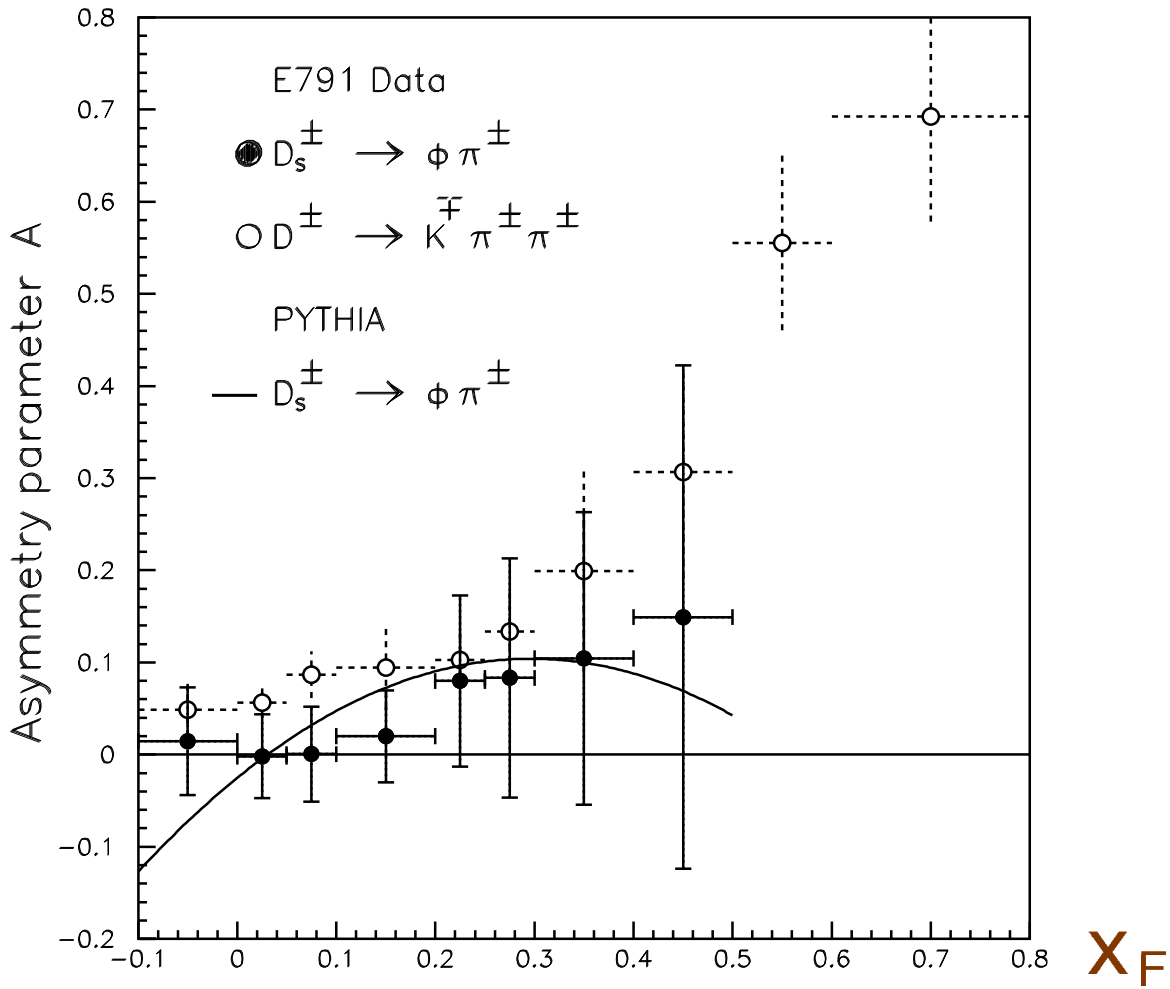
Cabibbo Favored **Cabibbo Suppressed**

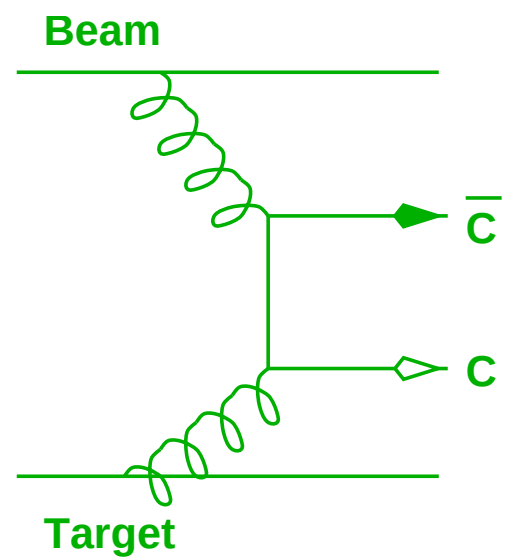
$$\frac{\text{Favored}}{\text{Suppressed}} \sim \left|\frac{V_{cs}}{V_{cd}}\right|^2 \sim 20$$

Production asymmetries with $\pi^-(d\bar{u})$ interactions in E791 ``Leading particle effect''

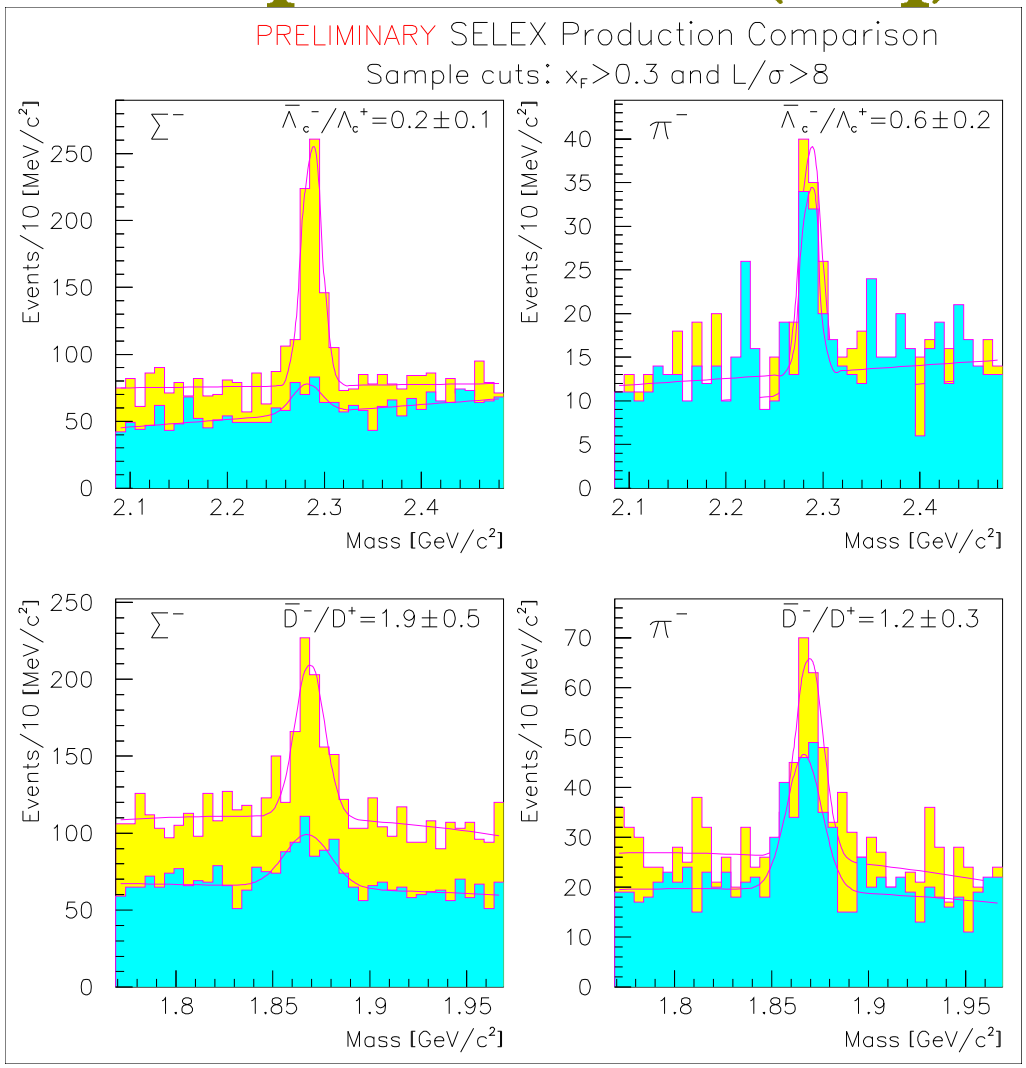
$$Asymmetry = \frac{N_{D^-} - N_{D^+}}{N_{D^-} + N_{D^+}}$$

$$= \frac{N(c\bar{d}) - N(\bar{c}d)}{N(c\bar{d}) + N(\bar{c}d)}$$





SELEX(E781) : Using Σ(sdd) Beam to produce Ξ_c(csq) baryons

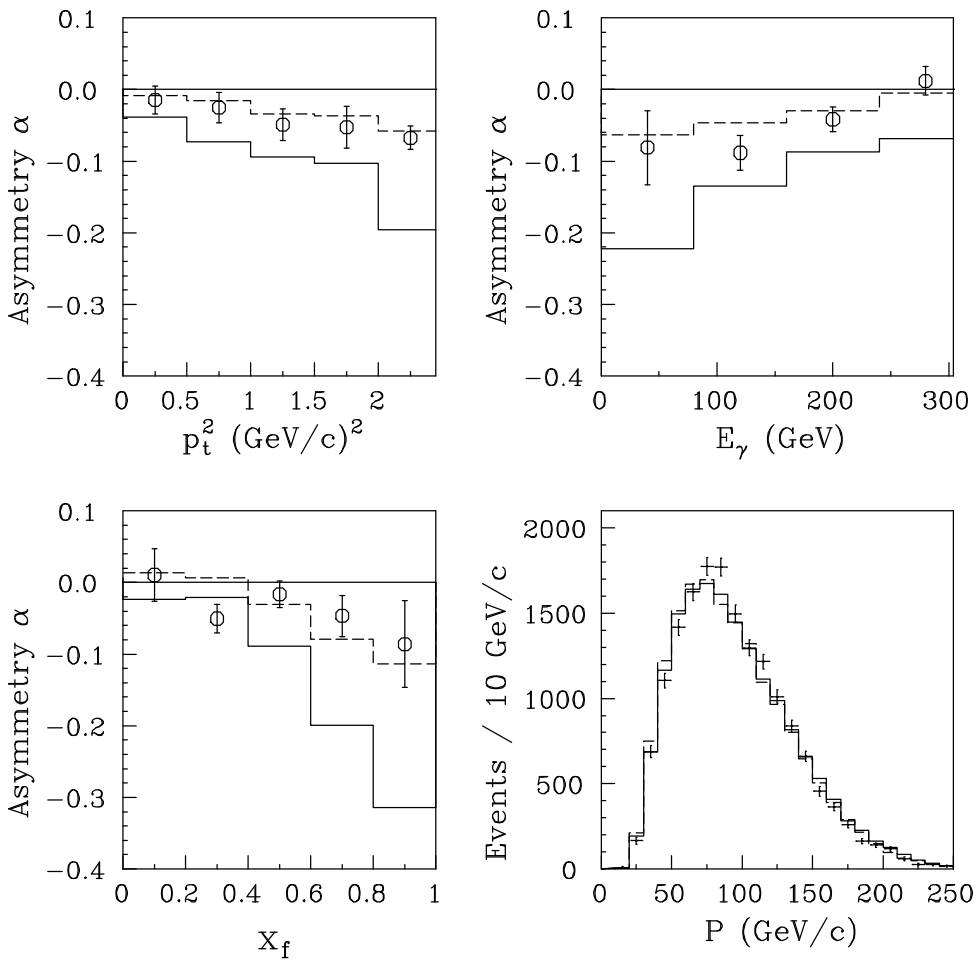


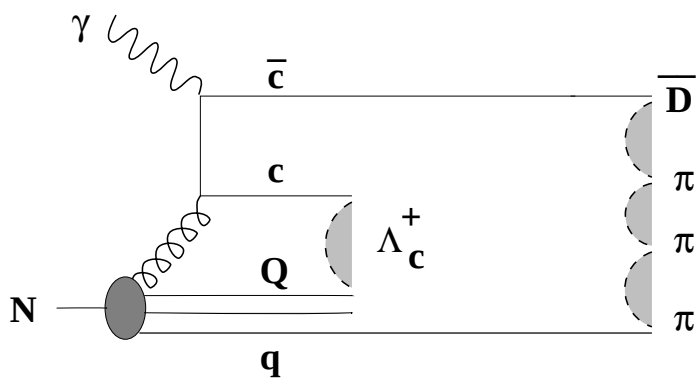
Asymmetry in $D^-(\bar{c}d)$/ $D^+(c\bar{d})$ production is as expected

Is the production asymmetry in Λ_c^+(cud) understood?

E687 - Asymmetries in Photoproduction

$\alpha = N(c) - N(\bar{c}) / N(c) + N(\bar{c})$ for D^+





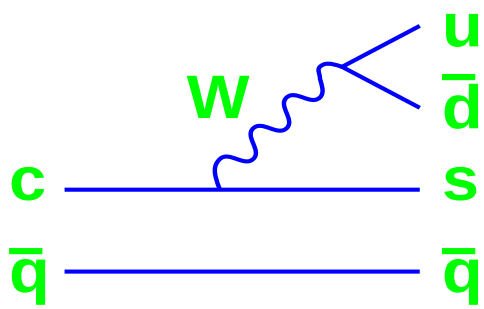
Asymmetries:

	α(%)
$D^+(c\bar{d})$	−3.8±0.9
$D^{*+}(c\bar{d})$	−5.3±1.1
$D^0(c\bar{u})$	−2.0±1.0
$D_s^+(c\bar{s})$	2.5±5.2
$\Lambda_c^+(cud)$	3.5±7.6

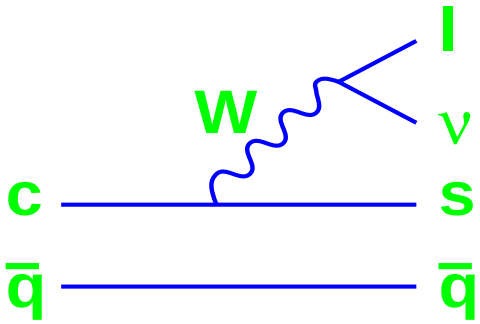
Lifetimes: Example of interaction between Experimental Results and Theory in Decays

Spectator Decays:

$$\tau = \frac{\hbar}{\Gamma_{SL} + \Gamma_{NL} + \Gamma_{PL}}$$



Non-Leptonic



Semi-Leptonic

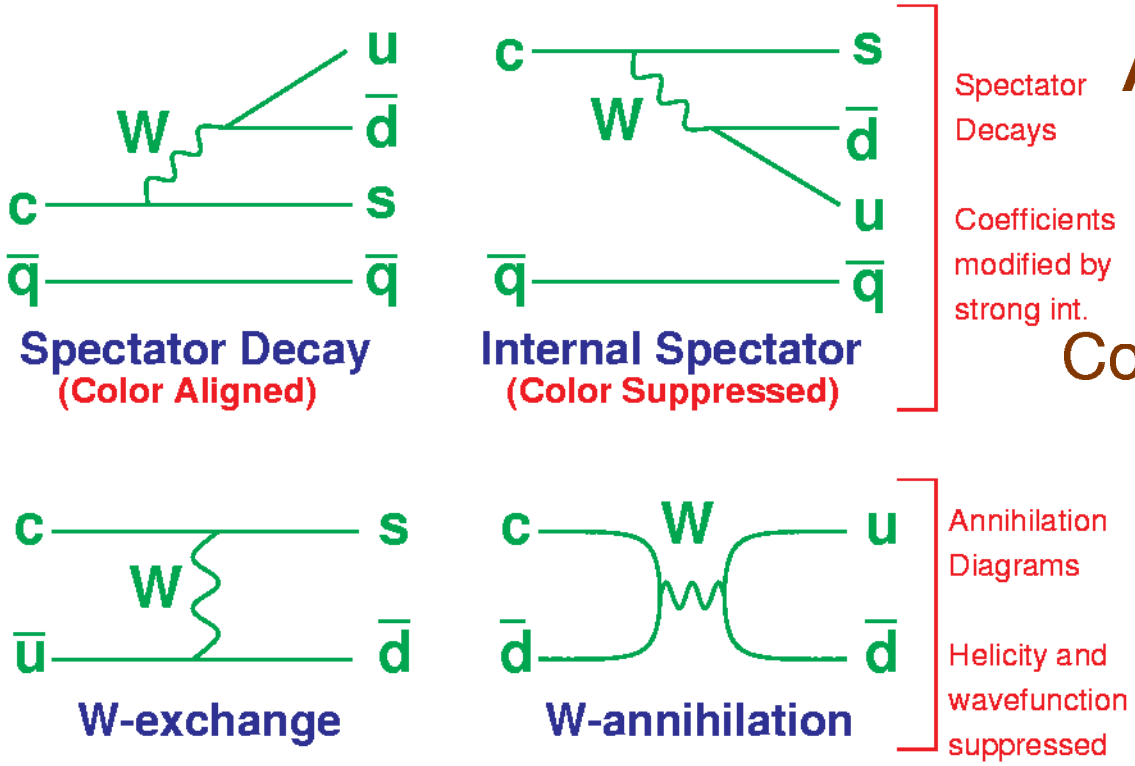
$$\frac{\tau(D^+)}{\tau(D^0)} = 2.55 \pm 0.04$$

$$\Gamma_{SL}(D^+) = (1.071 \pm 0.119) \times 10^{-13} GeV$$

$$\Gamma_{SL}(D^0) = (1.067 \pm 0.041) \times 10^{-13} GeV$$

$$\Gamma_{NL}(D^+) \neq \Gamma_{NL}(D^0)$$

Hadronic Decays



Spectator Decays

Coefficients modified by strong int.

Annihilation Diagrams

Helicity and wavefunction suppressed

Amplitudes:

Colour Aligned

$$\propto \frac{1}{2}(C_+ + C_-)$$

Colour Suppressed

$$\propto \frac{1}{2}(C_+ - C_-)$$

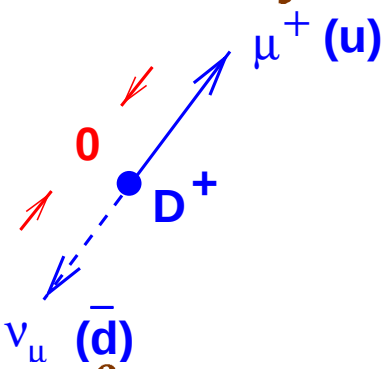
$$C_+ \approx 0.74$$

$$C_- \approx 1.80$$

- **Pauli Interference** $\tau(D^+)/\tau(D^0) < 2.0$
- **W-Annhilation, ?Size?** Supressed by $\approx f_D{}^2 m_s{}^2 / m_c{}^4 \approx 10^{-3}$

W-exchange/annihilation contributions why we believe they are small

- Helicity and wavefunction suppressed

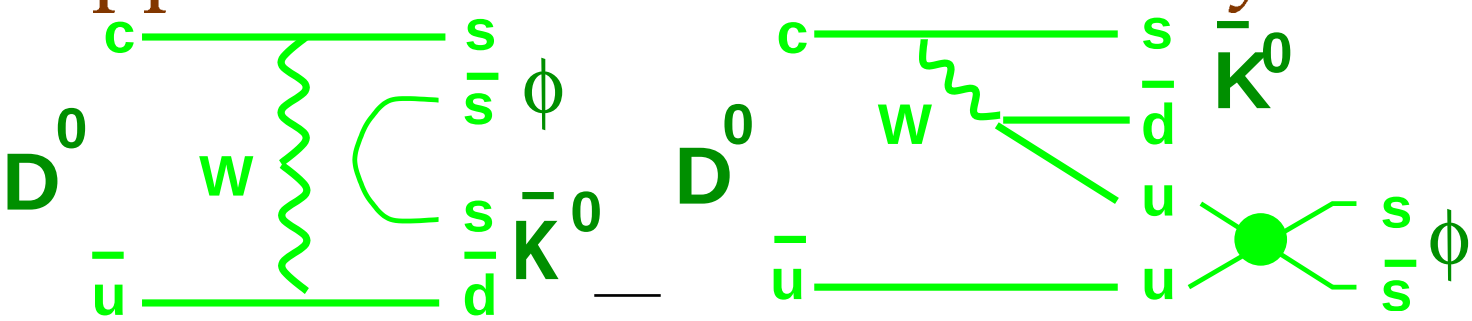


$$\approx f_D^{\,2} m_s^{\,2} / m_c^{\,4} \approx 10^{-3}$$

$$BR(K^+ \to \mu^+ \upsilon) = (63.51 \pm 0.18)\%$$

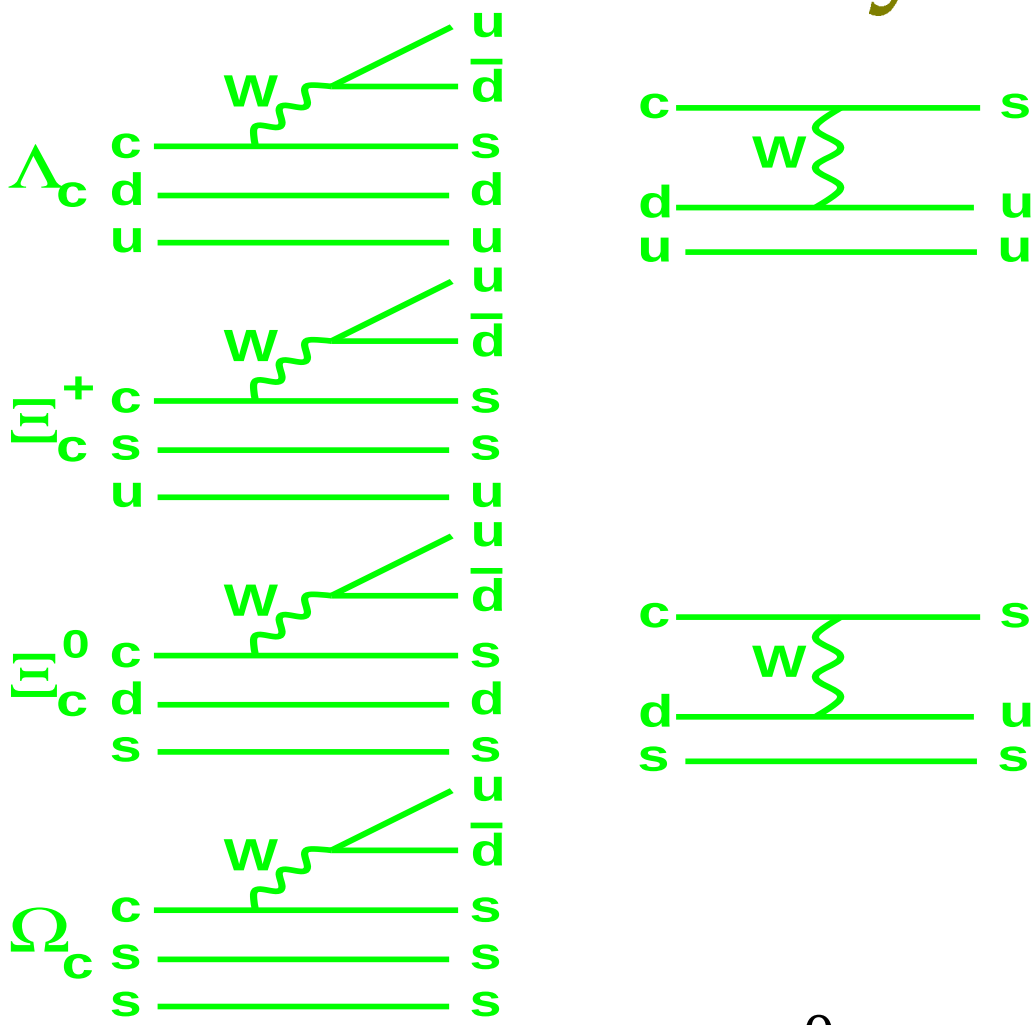
$$BR(K^+ \to e^+ \upsilon) = (1.55 \pm 0.07)\%$$

- D^0 has the expected semileptonic BR
- Appears small in exclusive decays



$$BR(D^0 \to \varphi \overline{K^0}) = 0.0086 \pm 0.0010$$

Other Tests: Baryon Decays



$\Gamma_{DEC} + \Gamma_{EXC} - \Gamma_{INT}^{-}$

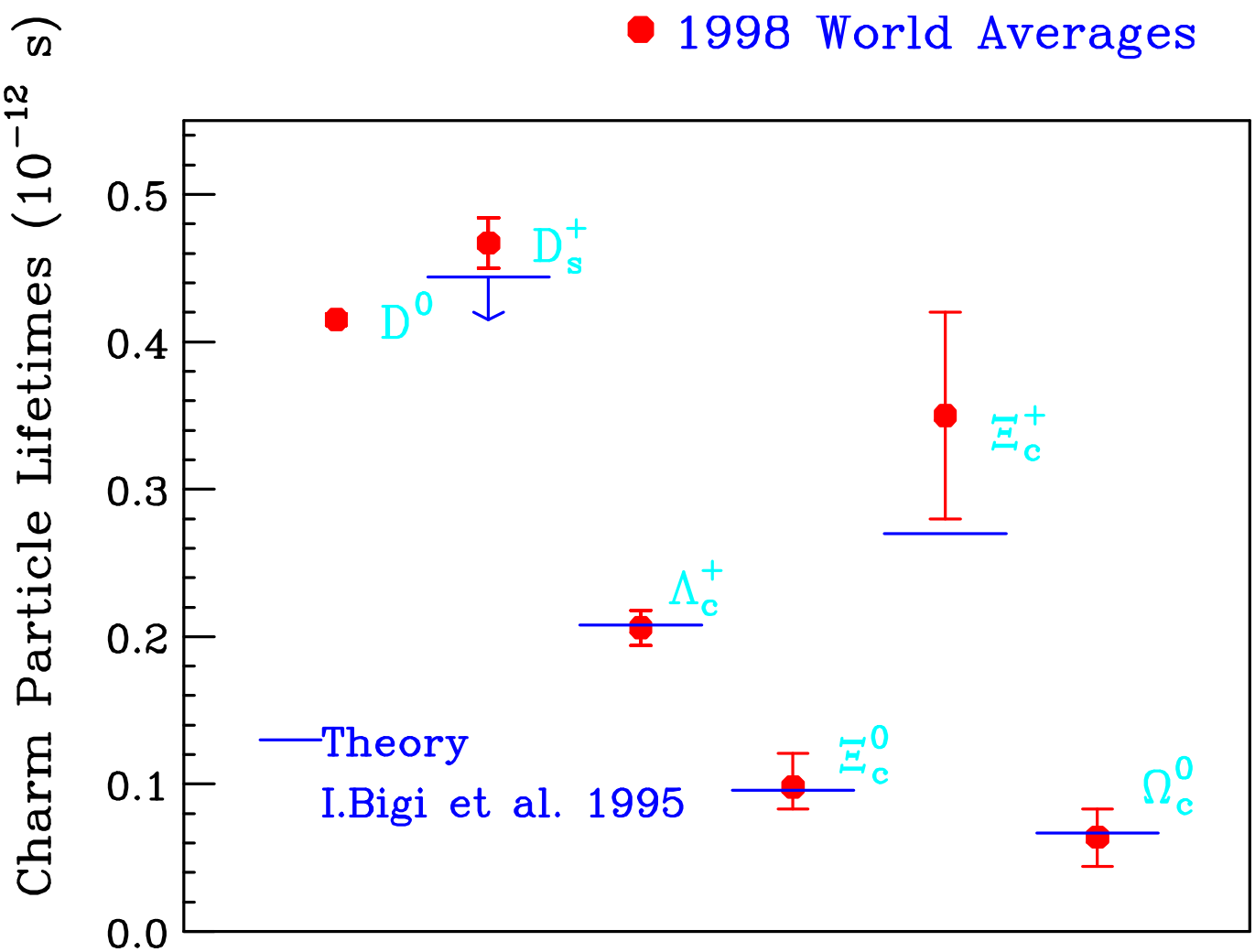
$\Gamma_{DEC} + \Gamma_{INT}^{+} - \Gamma_{INT}^{-}$

$\Gamma_{DEC} + \Gamma_{EXC} + \Gamma_{INT}^{+}$

$\Gamma_{DEC} + (10/3)\, \Gamma_{INT}^{+}$

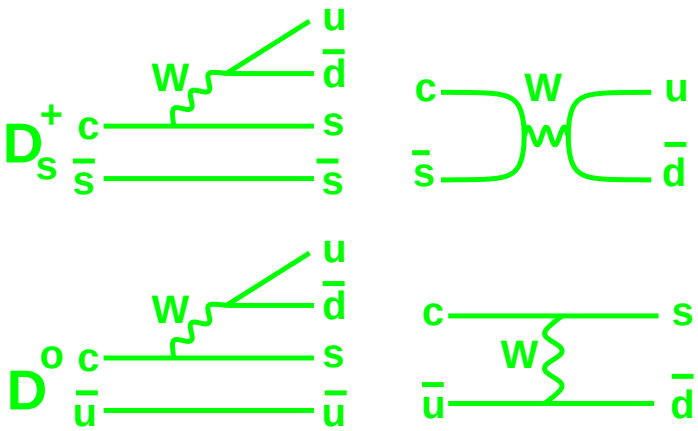
Expect: $\tau(\Omega_C) \approx \tau(\Xi_C{}^0) < \tau(\Lambda_C) < \tau(\Xi_C{}^+)$

Latest Charm lifetime Results



Bigi et al. Uses a systematic method involving an expansion in powers of $1/m_c$ (theory lines are actually wide bands!)

$\tau(D_s^+)$: Spanner in the works?



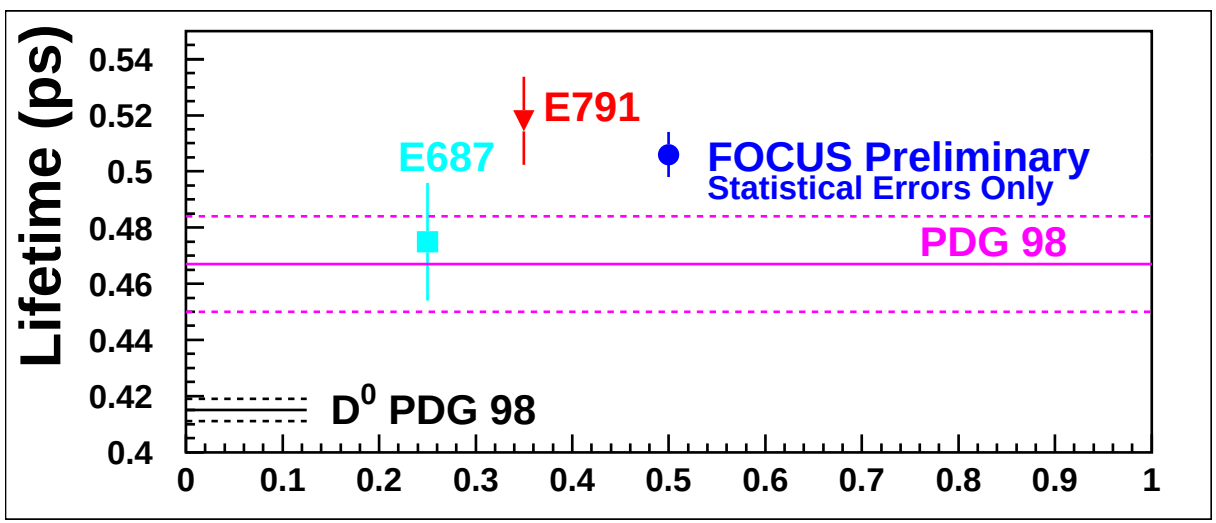
$D_s^+ \to \ell^+\nu_\ell$ $\tau(D_s^+)$ $\Downarrow$ 3%

P.I. in CSD $\tau(D_s^+)$ $\Uparrow$ 4%

"Fermi Motion" $\tau(D_s^+)$ $\Uparrow$ 4%

W-Annhilation must be large?!

Bigi and Uraltsev $\Delta\tau(D_s^+ - D^0) < 7\%$ no WA
Bigi and Uraltsev $\Delta\tau(D_s^+ - D^0) < 20\%$

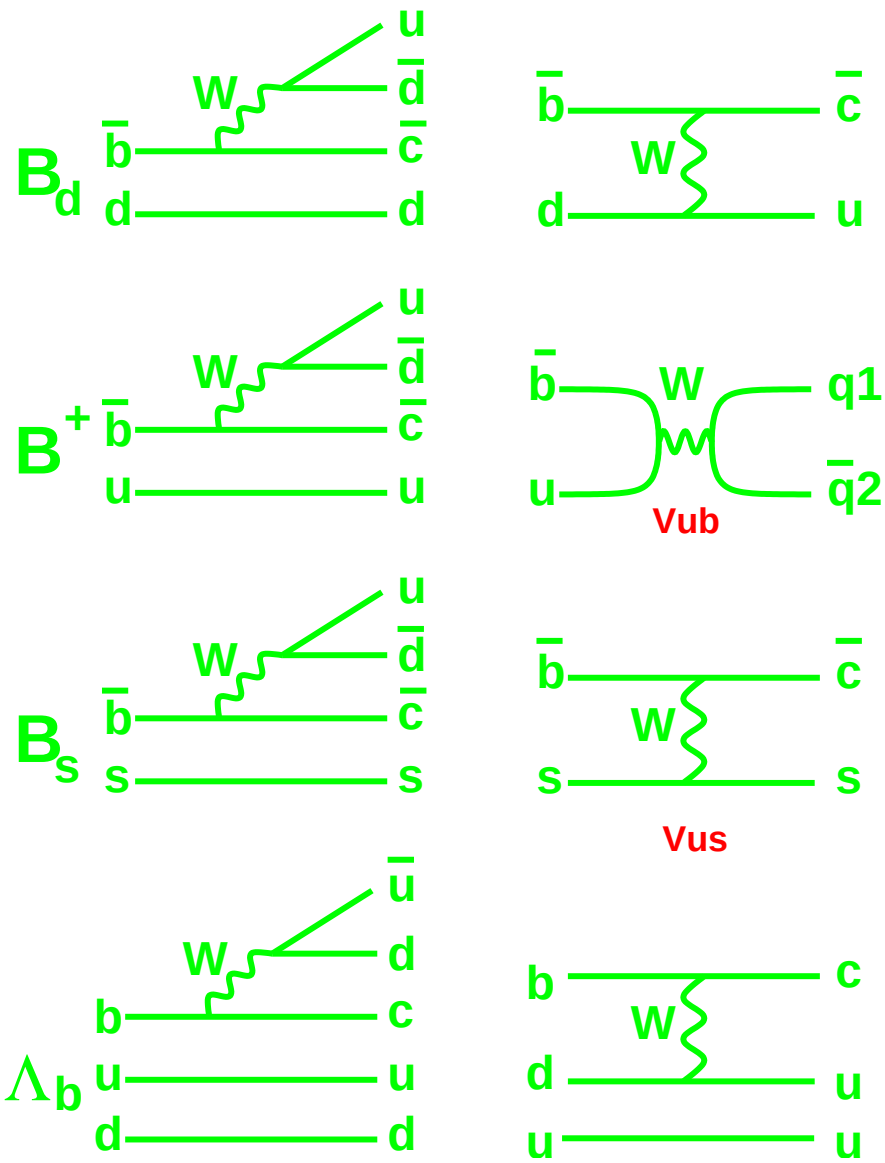


1999 World average:

$\tau(D\ )/\tau(D\ )$= 1.203±0.022

20.3±2.2%

Application: B Lifetimes



$\Delta\Gamma(B^0 - B^+) \leq +10\%$

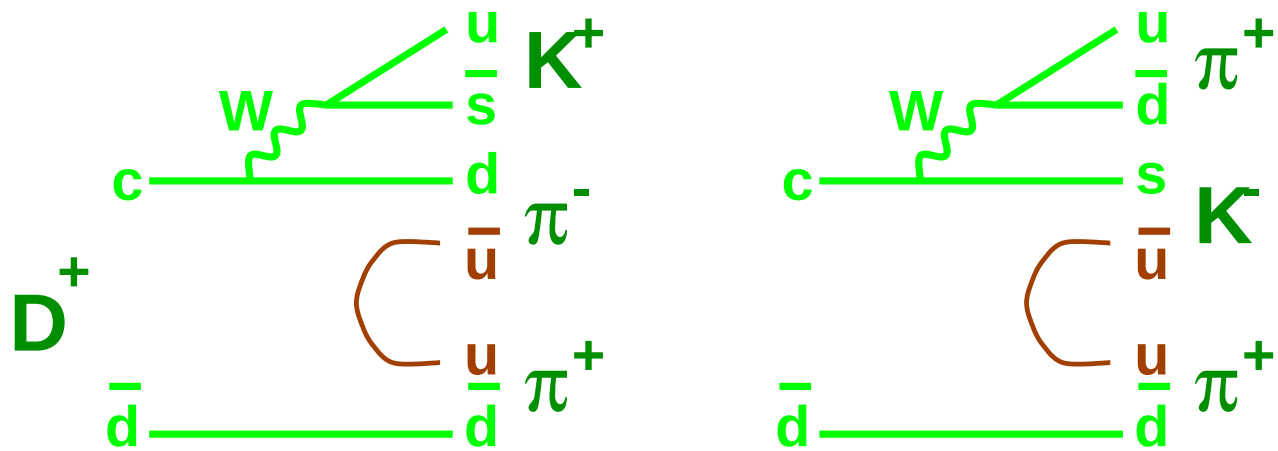
$\Gamma(B_s) \leq \Gamma(B^0)$

$\tau(\Lambda_b)/\tau(B^0) > 0.9$

Current 1999 World average for $\tau(\Lambda_b)/\tau(B^0_d) = 0.80 \pm 0.05$

Not a problem only 2σ and W-exchange may be larger than expected

Looking at the Pauli interference contribution: DCSD $D^+ \to K^+ \pi^- \pi^+$



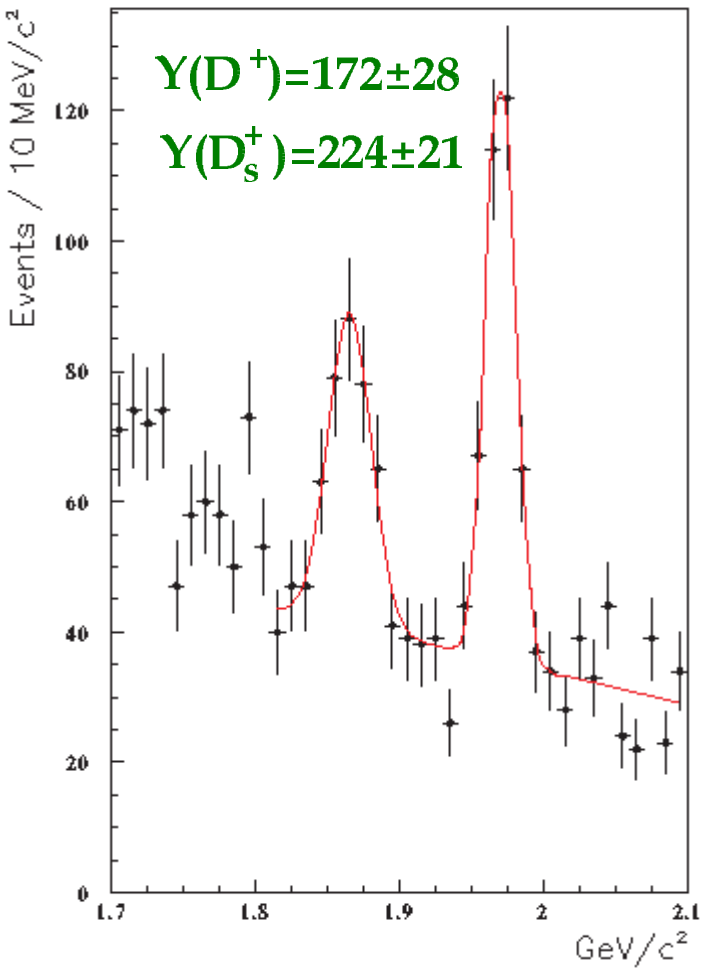
DCSD: no Pauli Interference, so expect without W-exchange:

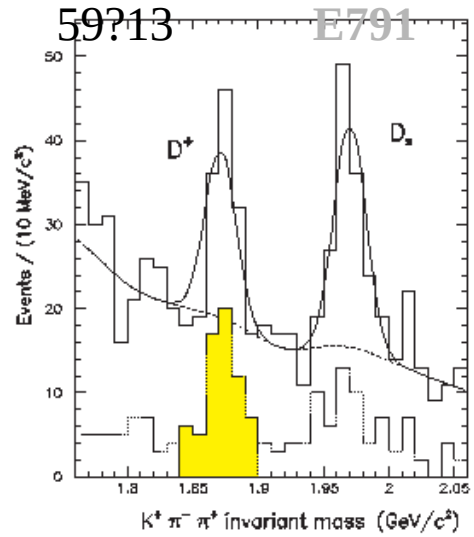
$$BR(K^+\pi^-\pi^+/K^-\pi^+\pi^+) \cong \tau(D^+/D^0) \times \tan^4\theta_C = (2.55 \pm 0.04) \times \tan^4\theta_C$$

$\to$ **$3.05 \times \tan^4\theta_c$ with corrections for semileptonic rate**

Looking at the Pauli interference contribution: DCSD $D^+ \to K^+\pi^-\pi^+$

40% FOCUS Data





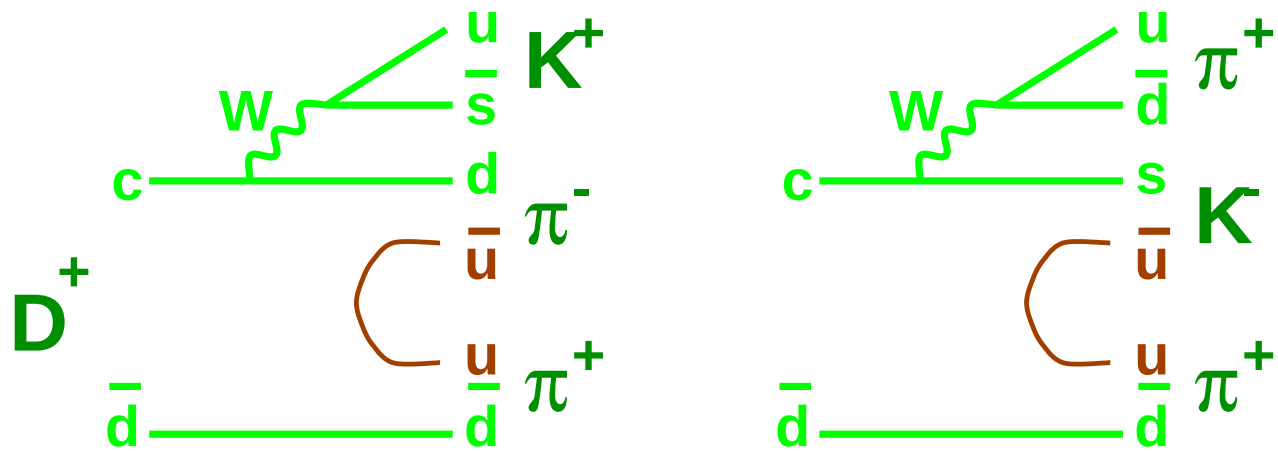
PDG'98 average for BR= (0.75±0.16)%

Preliminary FOCUS value:

$$\Gamma(K^+\pi^+\pi^-)/\Gamma(K^-\pi^+\pi^+) = (0.65 \pm 0.11)\%$$

$$\approx 3 \times \tan^4\theta_C \approx (\tau^+/\tau^-) \times \tan^4\theta_C$$

Looking at the Pauli interference contribution: DCSD $D^+ \to K^+ \pi^- \pi^+$



World average BR= $0.68 \pm 0.09 = 2.5 \times \tan^4 \theta_c$

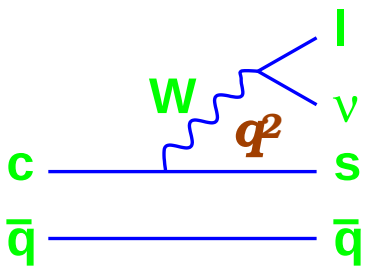
DCSD: no Pauli Interference, so expect without W-exchange:

$BR(K^+\pi^-\pi^+/K^-\pi^+\pi^+) \approx 3.05 \times \tan^4\theta_C$ **with corrections for SL**

with W-exchange included in D^0 decays, World av. BR gives

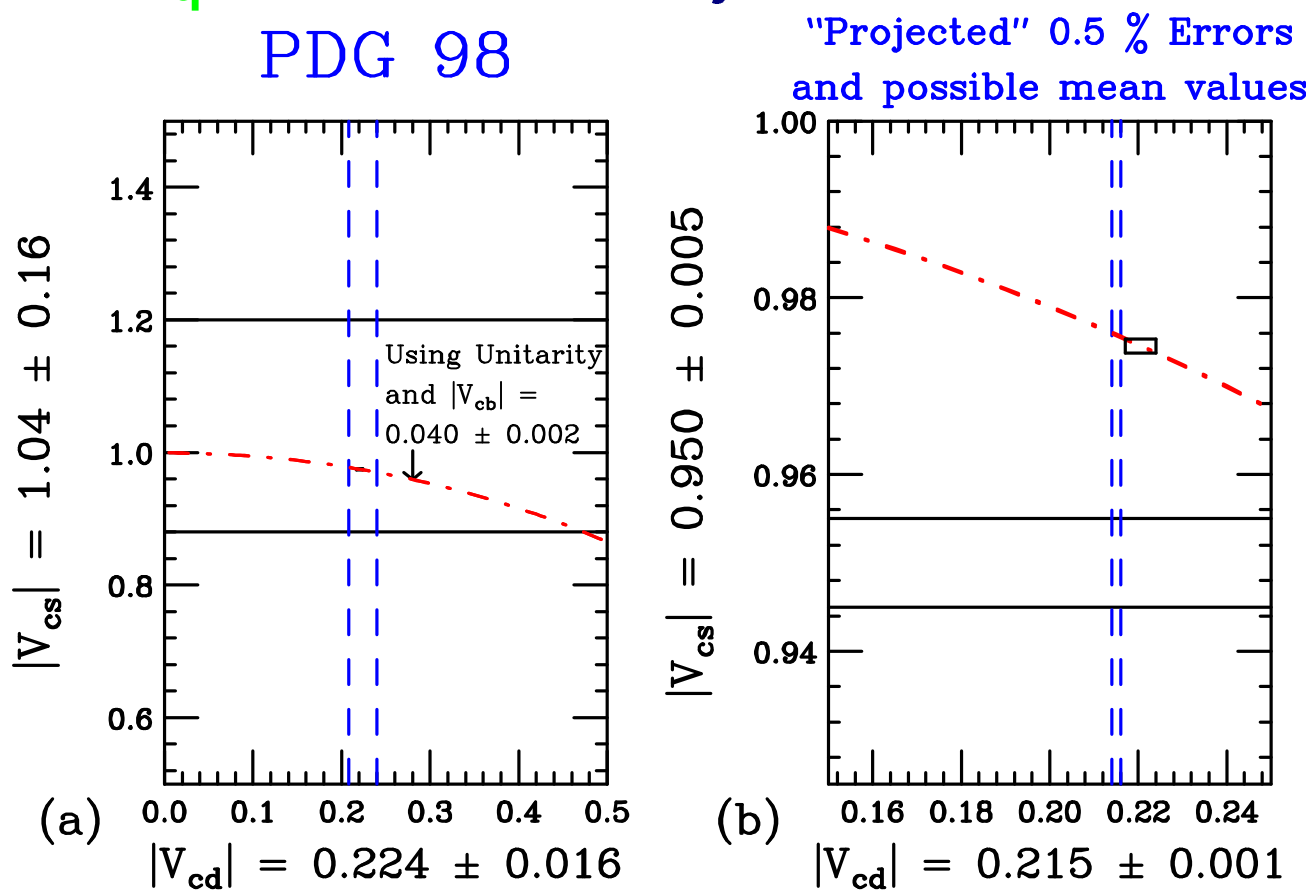
$\Gamma_{WX}/\Gamma_{SPECT} \approx 0.26$ **So W-exchange should be small!**

Measuring SM Parameters $|V_{cs}|$ and $|V_{cd}|$



$$\Gamma(D \to Kl\upsilon) \sim |V_{cs}|^2 \times |f_+^K(q^2)|^2$$

- Study form factors and test against theory
- Measure CKM when f.f. are known to test unitarity of the CKM matrix



Charm as a probe of New Physics

- D^0-$\overline{D}^0$ Mixing Searches
- CP Violation Searches
  Or Observe Standard Model CP Violation!
- Rare and Forbidden Decay Searches

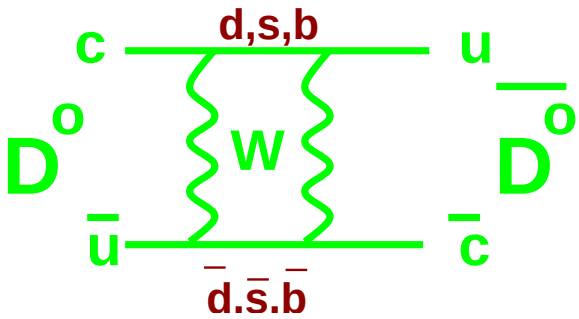
Why look in Charm decays?

- Tiny Standard Model backgrounds
- New physics can give measurable rates
- New Physics could affect up-quark sector differently from down-quarks

D^0-$\overline{D^0}$ Mixing in the SM

$$r_D = \frac{\Gamma(D^0 \to l^- X)}{\Gamma(D^0 \to l^+ X)} \approx \frac{1}{2}\left[\left(\frac{\Delta m_D}{\Gamma}\right)^2 + \left(\frac{\Delta\Gamma_D}{2\Gamma}\right)^2\right]$$

SM Short Distance

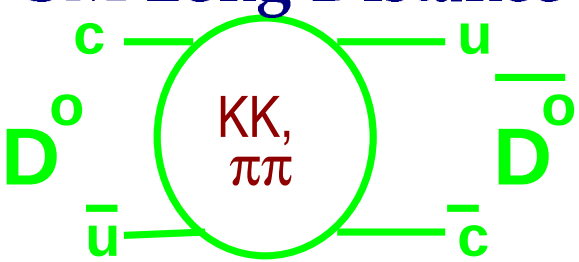


Short Distance contribution:

$$\Delta m_D^{SD} \approx 2.5\times10^{-17} GeV \left(\frac{m_s}{0.3GeV}\right)^4 \left(\frac{f_D}{f_\pi}\right)^2 < 2\times10^{-16} GeV$$

$$\Delta m_D^{SD}/\Gamma < 1\times10^{-4}$$

SM Long Distance



LD Dispersive:

$$\frac{\Delta m_D^{LD}}{\Gamma} \approx 8\times10^{-4}\left(1.46 - \sqrt{b}\right), \quad \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = b\times\tan^4\theta_C$$

$$\Delta m_D^{LD}/\Gamma \approx 2\times10^{-4}$$

LD HQET:

$$\Delta m_D^{LD}/\Gamma \approx (1\text{-}2)\times10^{-5}$$

→ SM Contribution: $\Delta m_D^{SM}/\Gamma < 1\times10^{-4}$

$\Delta m_D^{SM} < 2\times10^{-16}$ GeV

$r_D < 10^{-8}$

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- CP Violation Searches
  Or Observe Standard Model CP Violation!
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- New Physics could affect up-quark sector differently from down-quarks

Future of Charm - Needs a new breakthrough!

- Need orders of magnitude increase in statistics
- Can produce large numbers of $c\bar{c}$ pairs in $p\bar{p}$ at 2 TeV

  E.g. at $2 \times 10^{32} cm^{-2} s^{-1}$ produces about $2 \times 10^{12} c\bar{c}$ pairs!

- Needs an efficient First Level Vertex Trigger

  Could be possible in BTeV with ~10% efficiency however this needs work as the lifetime of charm particles is much smaller than for B mesons

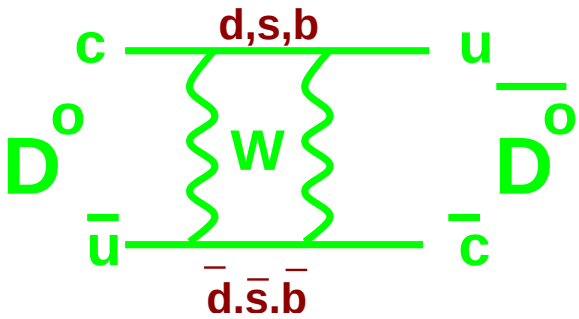
BTeV is an approved R&D project and there will be a proposal to run in the new C0 collision hall in ~ 2005

BTeV proposed mainly to do B physics but can do a lot of charm physics too. Needs optimizing for charm to e.g. see Standard Model CP Violation in charm decays

D^0-$\overline{D^0}$ Mixing in the SM

$$r_D = \frac{\Gamma(D^0 \to l^- X)}{\Gamma(D^0 \to l^+ X)} \approx \frac{1}{2}\left[\left(\frac{\Delta m_D}{\Gamma}\right)^2 + \left(\frac{\Delta\Gamma_D}{2\Gamma}\right)^2\right]$$

SM Short Distance

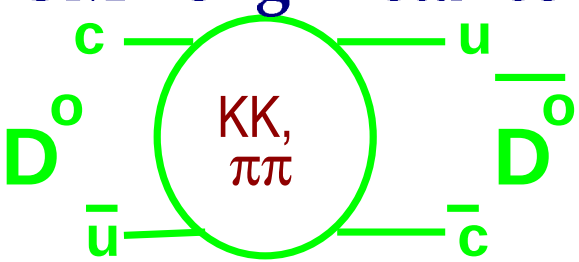


Short Distance contribution:

$$\Delta m_D^{SD} \approx 2.5\times10^{-17} GeV \left(\frac{m_s}{0.3GeV}\right)^4 \left(\frac{f_D}{f_\pi}\right)^2 < 2\times10^{-16} GeV$$

$$\Delta m_D^{SD}/\Gamma < 1\times10^{-4}$$

SM Long Distance



LD Dispersive:

$$\frac{\Delta m_D^{LD}}{\Gamma} \approx 8\times10^{-4}\left(1.46 - \sqrt{b}\right), \quad \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = b\times\tan^4\theta_C$$

$$\Delta m_D^{LD}/\Gamma \approx 2\times10^{-4}$$

LD HQET:

$$\Delta m_D^{LD}/\Gamma \approx (1\text{-}2)\times10^{-5}$$

→ SM Contribution: $\Delta m_D^{SM}/\Gamma < 1\times10^{-4}$

$\Delta m_D^{SM} < 2\times10^{-16}$ GeV

$r_D < 10^{-8}$

Data on D^0-$\overline{D}^0$ Mixing

- Semileptonic Decays (e.g. $D \to Ke\nu$)

  $r_D^{mix} < 5\times10^{-3}$ (E791) Simple to extract r_D^{mix} from BR

  $\Delta m_D/\Gamma < 0.1$ $\Delta m_D < 1.6\times10^{-13}$GeV

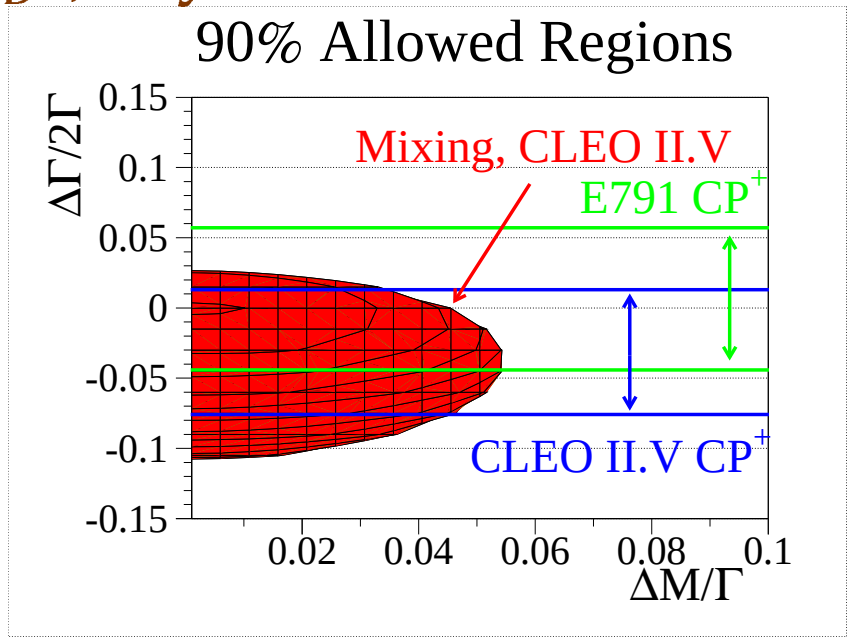
- Hadronic Decays (e.g. $D \to K\pi$, $K3\pi$)

  BR contains DCSD contribution and interference complicates extraction of r_D^{mix};may enhance observable

- Difference in Lifetime in CP eigenstates gives $\Delta\Gamma_D$

  Theory gives Δm_D, need $\Delta\Gamma_D$ to constrain Δm_D from r_D^{mix}

$\Rightarrow$ Lots of "room" for New Physics to show up!



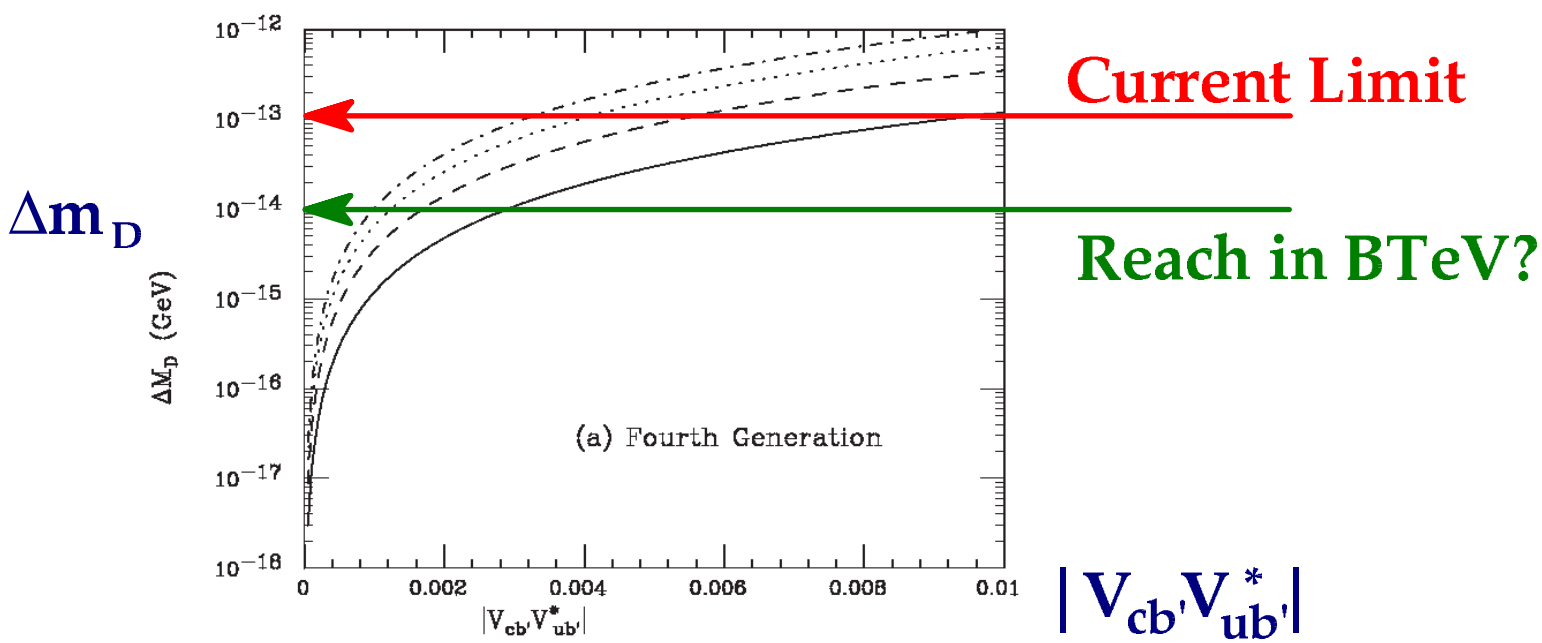
New Physics and D^0-$\overline{D}^0$ Mixing

- Studies and summaries from Burdman, Hewett, Pakvasa
- Beyond SM contributions involve replacing W or d,s,b by new particles

1) Heavy Q=-1/3 Quark

must satisfy current limits: $m_{b'} > 128\ GeV/c^2$

$|V_{ub'}| < 0.08$, $|V_{cb'}| < 0.6$ $\quad |V_{cb'}V^*_{ub'}| < 0.048$

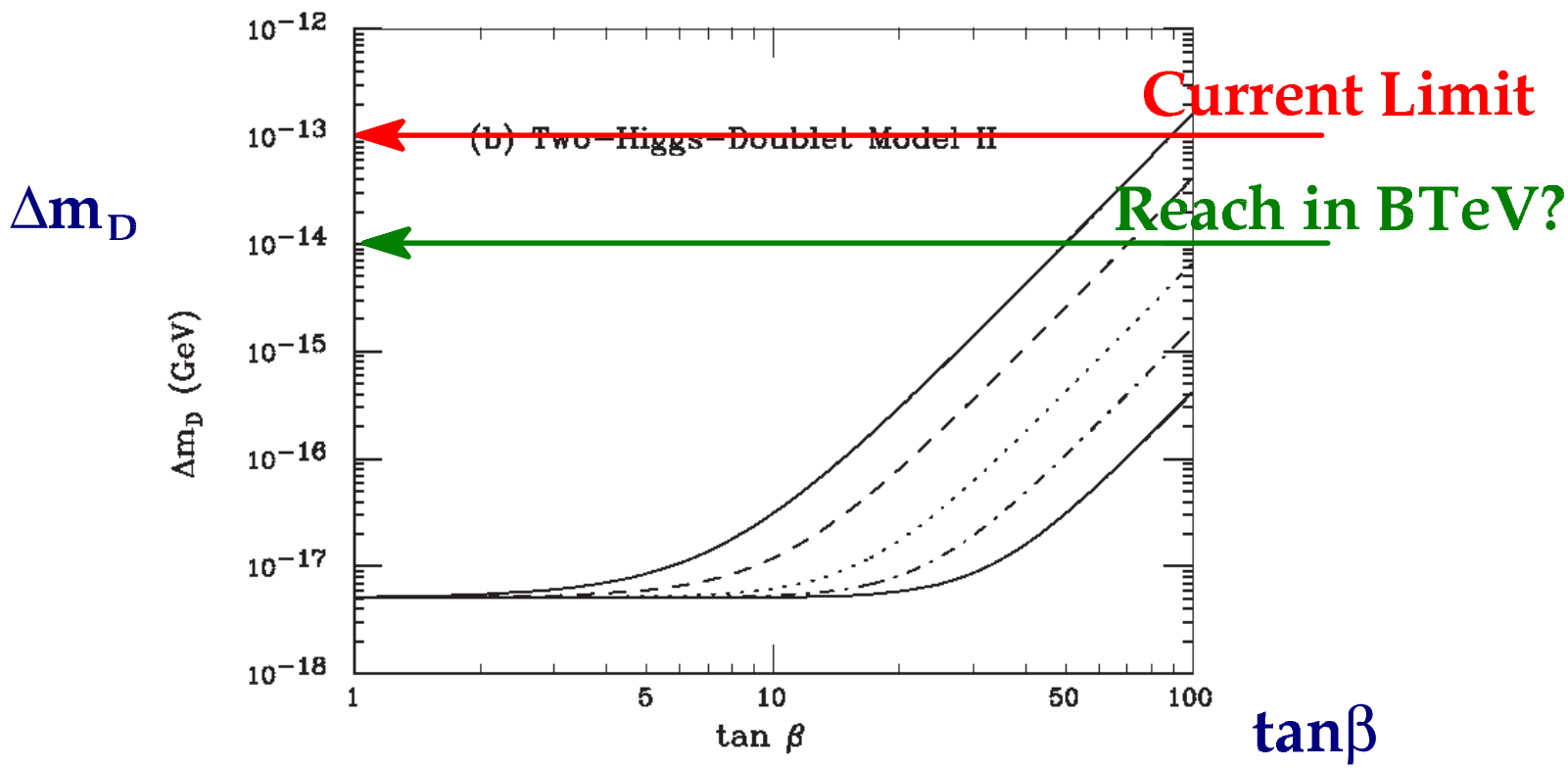


New Physics and D^0-$\overline{D}^0$ Mixing

2) Two Higgs Doublet Models
W replaced by charged Higgs

no sizable Δm_D for Model I (rule out by data on B)

Observable Δm_D for Model II for large $\tan\beta$

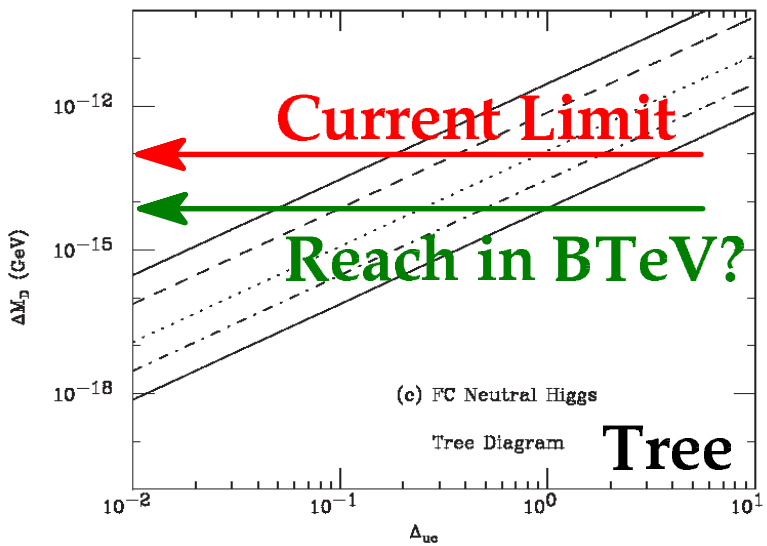


New Physics and D^0-$\overline{D}^0$ Mixing

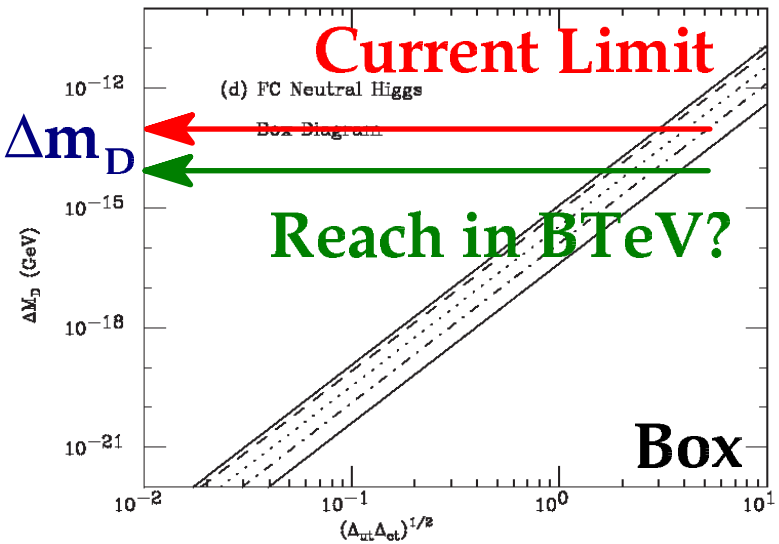
3) Tree Level Flavour Changing Neutral Currents

Must satisfy constraints from B ,K mixing and rare B,K decays

Δm_D



Δm_D



Topcolor assisted technicolor models $\rightarrow \Delta m_D < 8\times10^{-14}$GeV

Composite technicolor schemes $\rightarrow \Delta m_D < 4\times10^{-15}$GeV

New Physics and D^0-$\overline{D}^0$ Mixing

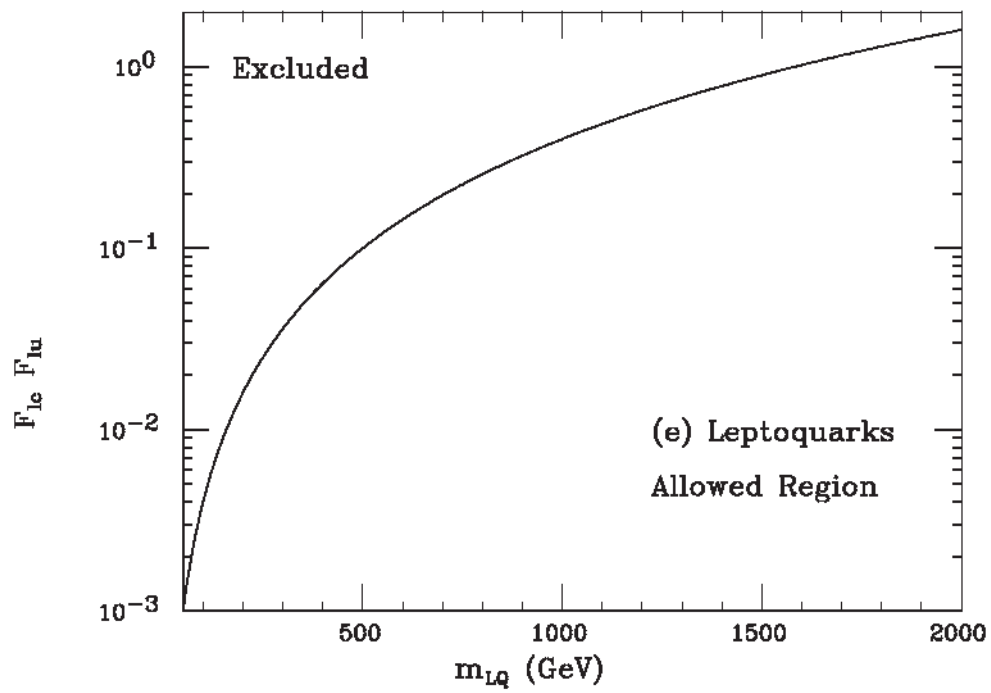
4) Supersymmetry

MSSM squark,gluino box $\rightarrow \Delta m \sim 10^{-18}$ GeV

alternate squark mass $\leftrightarrow$ quark mass
and approaches to handle FCNC can give $\Delta m_D < 10^{-13}$ GeV

5) Leptoquarks

Δm_D used to constrain Leptoquark model parameters



6) Family Symmetry

Volkov,Monich and Struminski $\rightarrow \Delta m_D < 10^{-13}$GeV

CP Violation

Direct CP Violation

$$a_{CP} \equiv \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

$$A(D \to f) = |M_1| + e^{i\Delta\alpha^{strong}} e^{i\Delta\phi^{weak}} |M_2|$$

$$A(\bar{D} \to \bar{f}) = |M_1| + e^{i\Delta\alpha^{strong}} e^{-i\Delta\phi^{weak}} |M_2|$$

$$a_{CP} = \frac{2\rho \sin\Delta\alpha^{strong} \sin\Delta\phi^{weak}}{1 + \rho^2 + 2\rho\cos\Delta\alpha^{strong}\cos\Delta\varphi^{weak}} \quad \rho = |M_1/M_2|$$

- Need CS decays in SM
- Difficult to evaluate strong phase $\Delta\alpha^{strong}$
- in SM $a_{CP} \leq 10^{-3}$, Observation of $a_{CP} \geq 10^{-2}$ signals N.P.
- Possibly observe SM CP violation in charm in e.g. BTeV!

$a_{CP} \approx 2.8 \times 10^{-3}$ for $D^+ \to \overline{K^{*0}} K^+$ $\quad a_{CP} \approx -8.1 \times 10^{-3}$ for $D_S^+ \to K^{*+}\eta'$

$\delta a_{CP} = 1 \times 10^{-3}$ for 10^6 background-free events

Could be possible with (vertex) trigger efficiency > 10%

Indirect CP Violation

Involves D^0- $\overline{D^0}$ Mixing in D^0 decays, SM $a_{CP} \sim 10^{-4}$

New physics gives $a_{CP} \sim \Delta m_D/\Gamma \sim 10^{-2}$- 10^{-1}

Rare and Forbidden Decays

Decays of interest involve $c \to u$ transitions or FCNC

E.g. $c \to u\gamma$, $c \to ul\ l$, $D \to Xl_1^+ l_2^-$, $D \to Xl^+ l^+$

Needs more theoretical work as Long Distance effects are very large compared to SM Short Distance contributions

E.g. $c \to u\gamma$, $D \to \pi l^+ l^-$ new physics dominated by L.D.

$D \to l^+ l^-$ could see new physics but BR unobservable

LFNV and LNV decays forbidden in SM, needs more theoretical work to see if BR due to New Physics is observable

Charm Physics Summary

- Many interesting and intriguing physics topics in charm production and decays
- Study and measure SM parameters using charm spectroscopy and decays
- Interesting potential for New Physics discoveries in Charm in the future

  D^0- $\overline{D^0}$ Mixing , CP Violation and Rare decays

- Charm physics should be a very active field in the future

  FOCUS, SELEX, CLEO, BABAR, BELLE

  CDF?, D0?, BTeV?