PASCOS

THE OHIO STATE UNIVERSITY

The Physics of Charm: Recent Experimental Results

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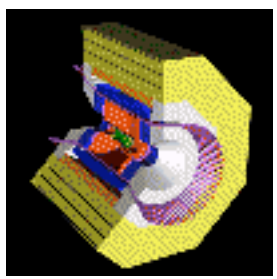
Rensselaer Polytechnic Institute
and the CLEO-c Collaboration

Particles, Strings, and Cosmology Conference 2006

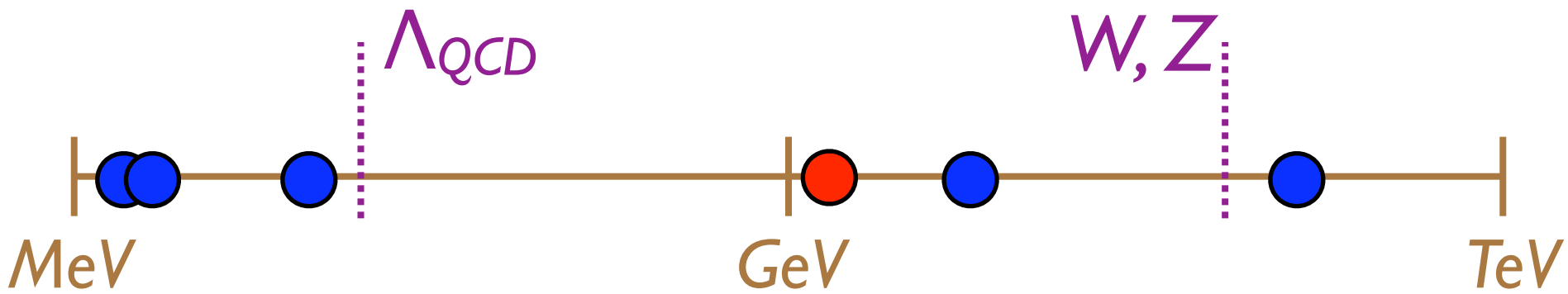
Rensselaer

CLEO-c



What is Special about Charm?

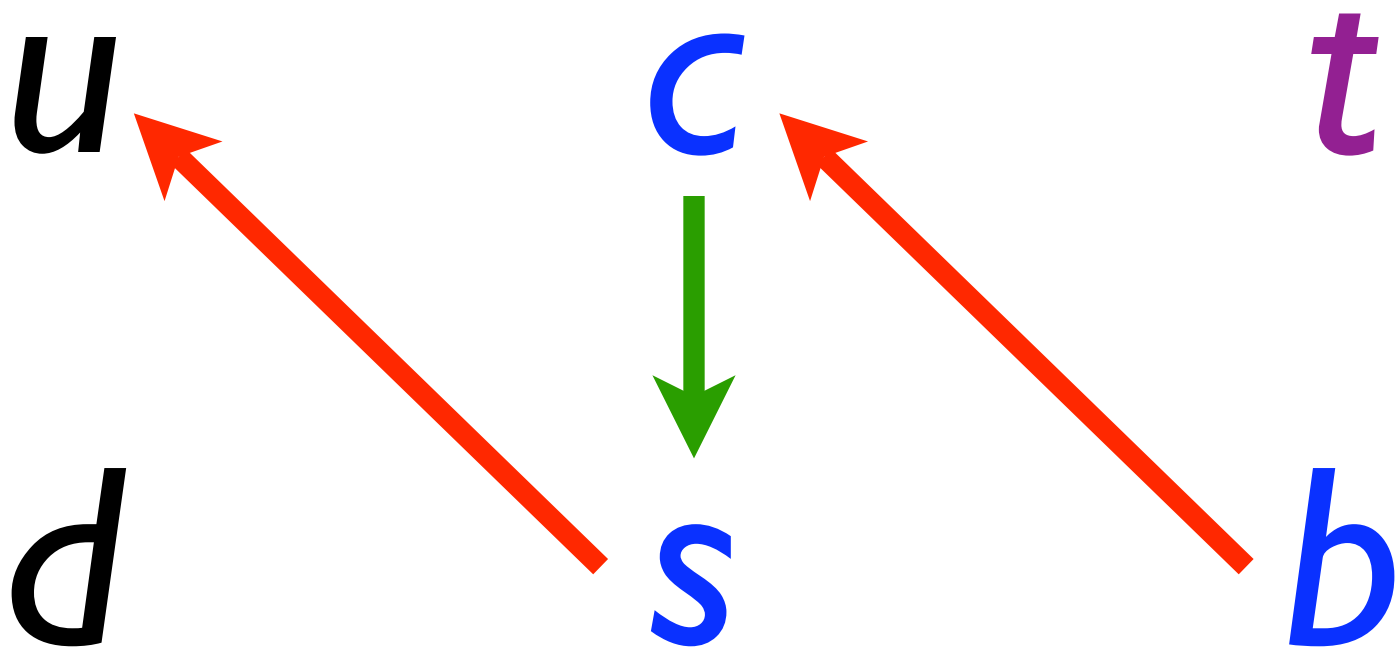
1) *Its mass.* The charm quark is "heavy"...



... but not "too" heavy.

Most decay modes of hadrons with charm are "easy" to observe experimentally.

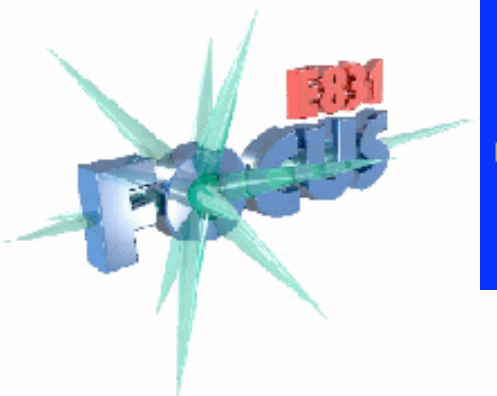
2) *Its decays*. Charm is the only heavy quark that forms hadrons with CKM-allowed decays.



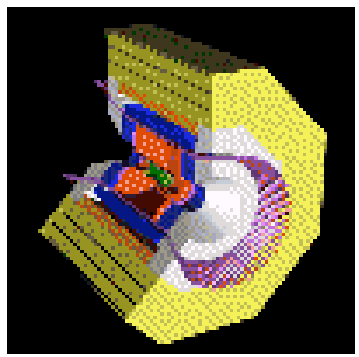
The Experiments

e^+e^- and Photon Beams

BABAR

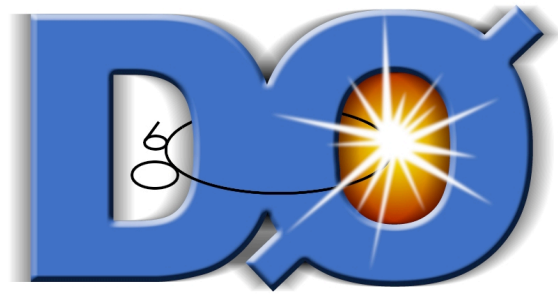


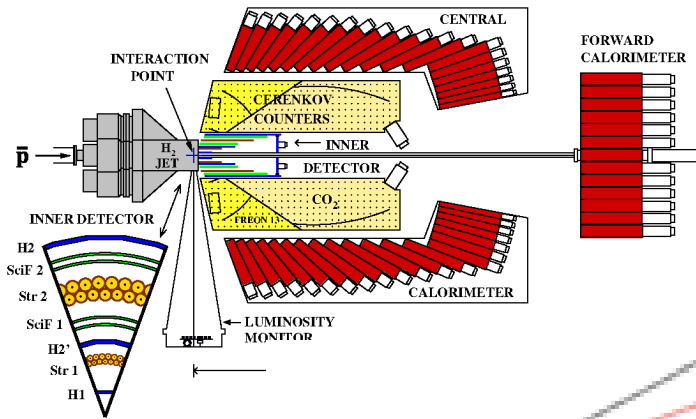
BES



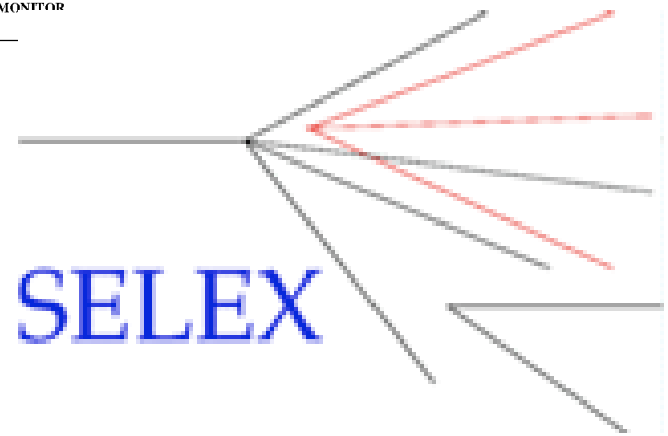
CLEO

Hadroproduction





E835



SELEX

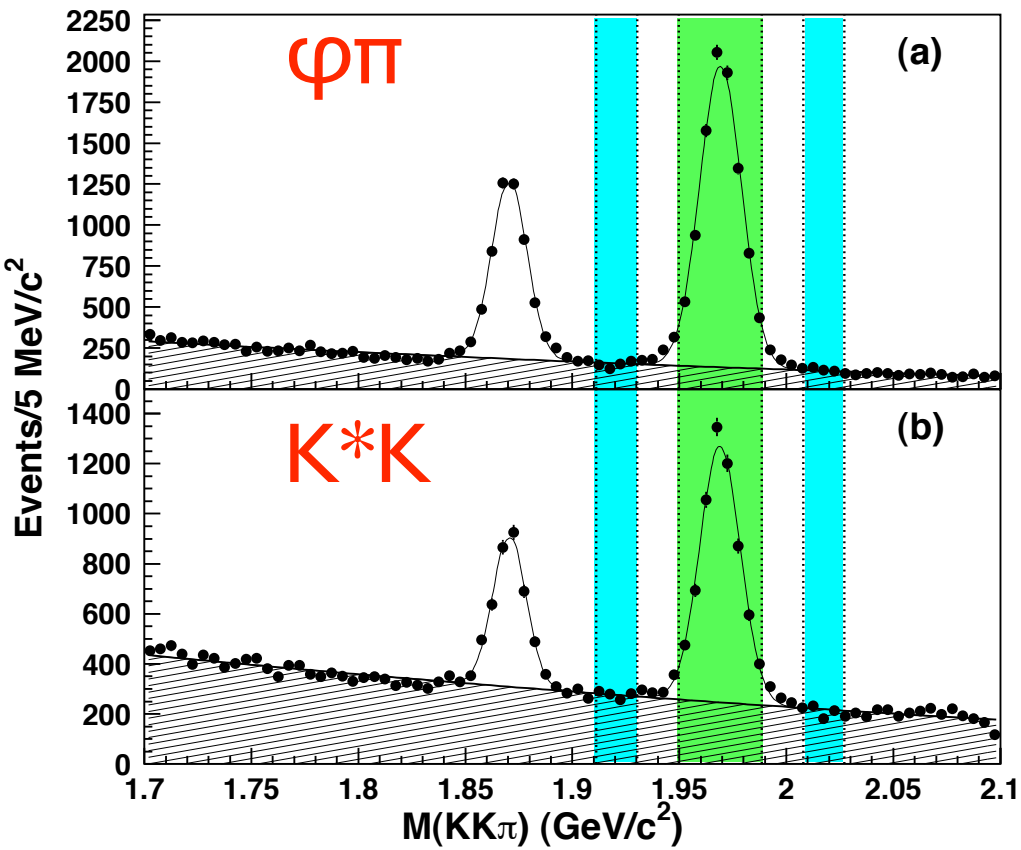
A Survey of Recent Results

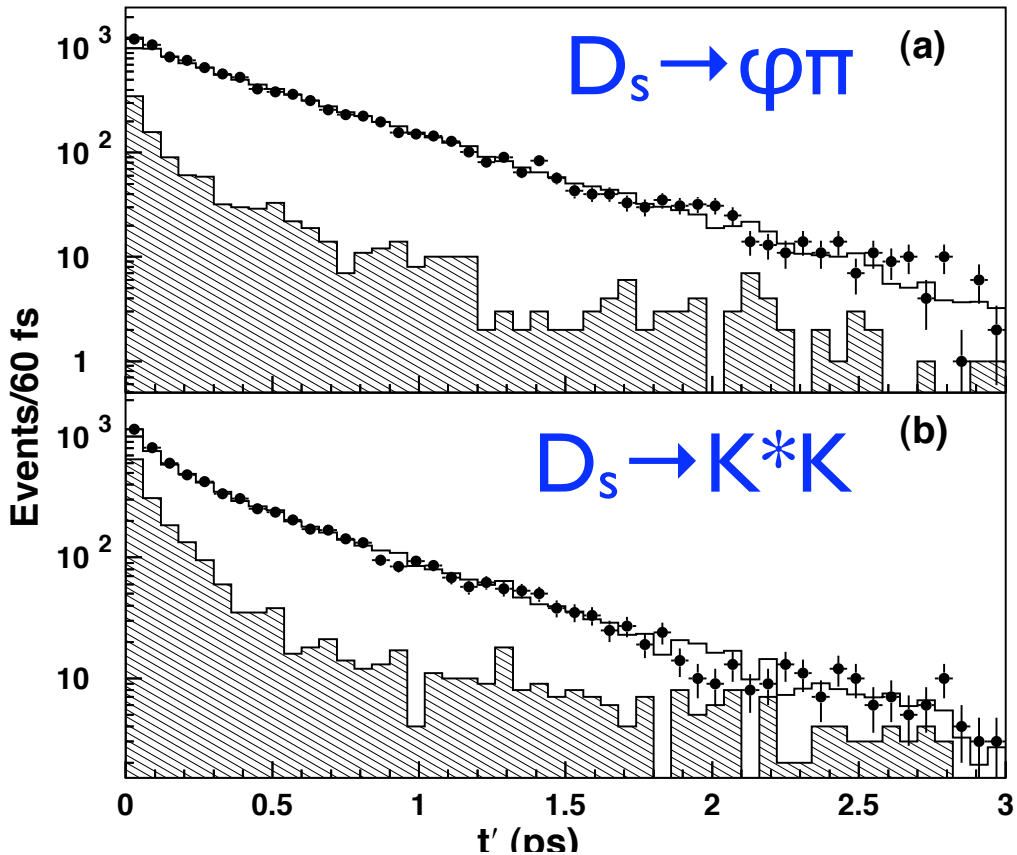
My own selection! My apologies for not covering it all!

- "Precision" Measurements
  Small error bars, stringent limits, and tying up old loose ends
- New States
  A resurgence in charmonium
- Confronting Lattice QCD
  Testing "high precision" lattice calculations
- D^0 Mixing and Tests of CP Violation
  Current status and future prospects

PRL 95(2005)052003

The D_s Lifetime





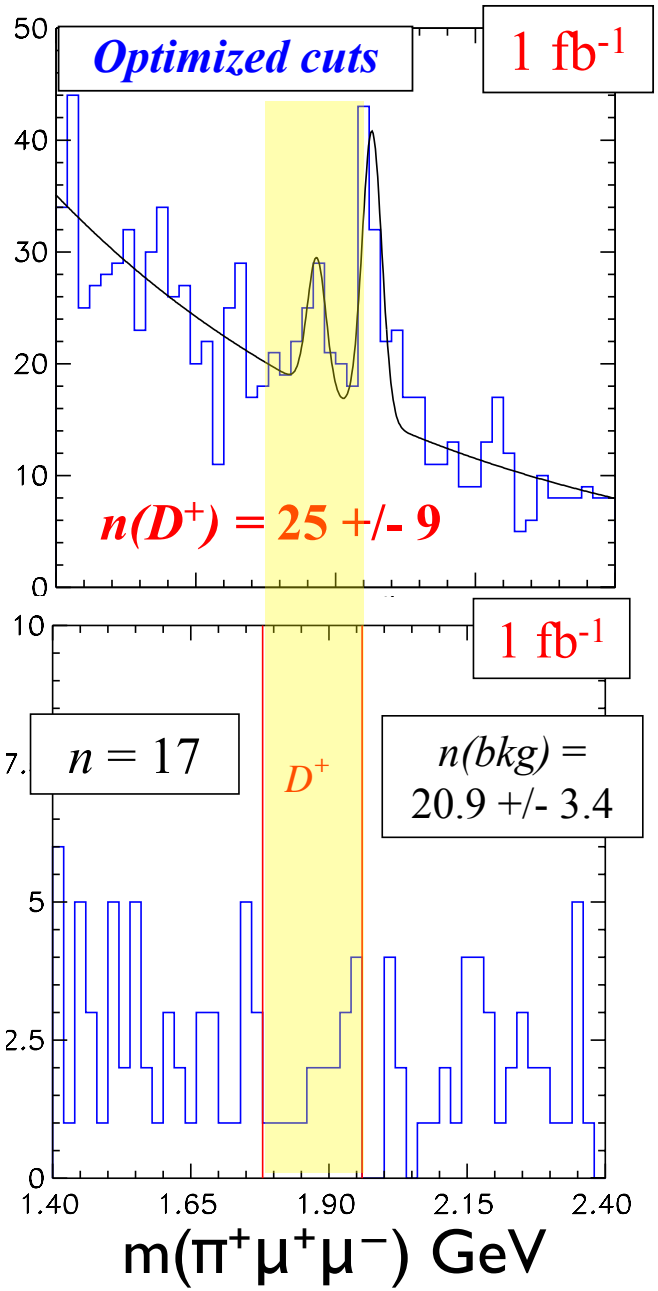
$$\gamma N \rightarrow (K^+K^-\pi^\pm)X$$

D_s signal

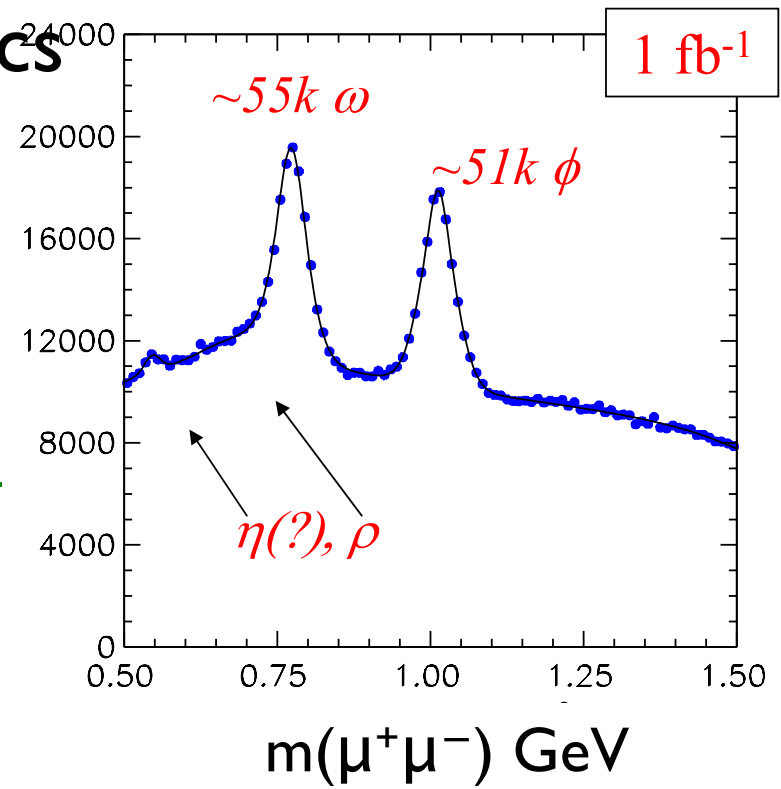
Sidebands

$\tau(D_s)$=507.4±5.5±5.1 fs

Limit: $D^+ \to \pi^+\mu^+\mu^-$



Possible new physics in charm FCNC



Observe:

$D^+ \to \varphi\pi^+$

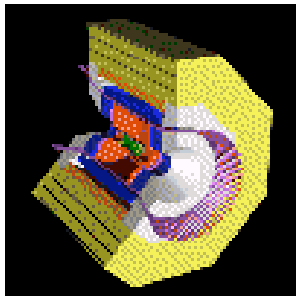
with $\varphi \to \mu^+\mu^-$

Put limits on:

$D^+ \to \pi^+\mu^+\mu^-$ with anti-φ cut

$\Rightarrow BR(D^+ \to \pi^+\mu^+\mu^-) < 4.7\times10^{-6}$

Tevatron experiments make a lot of charm!



ψ(3770) → *hadrons*

CLEO-c: Closing the gap

$$\sigma(e^+e^- \to D\bar{D}) = 6.39 \pm 0.10^{+0.17}_{-0.08}\ nb$$ *PRL 95(2005)121801*

$$\sigma(e^+e^- \to hadrons) = 6.38 \pm 0.08^{+0.41}_{-0.30}\ nb$$ *PRL 96(2006)092002*

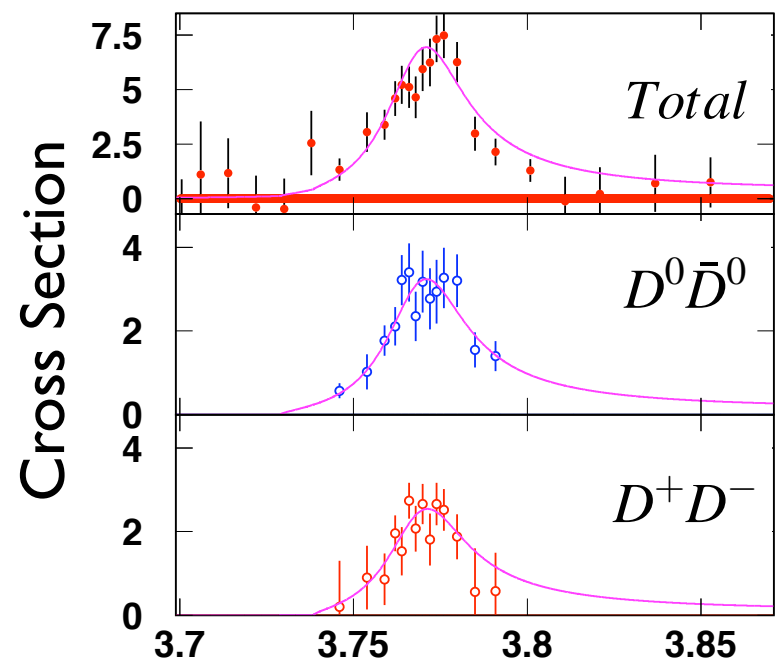
Upper limit on gap is ≈10%. Other observed modes ≈2%.

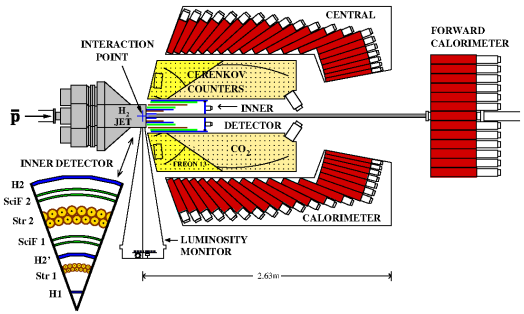
BES III: Resonance scan of ψ(3770)

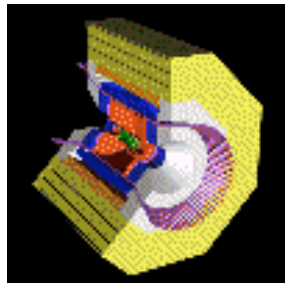
hep-ex/0605105 and hep-ex/0605107

Find room for possible non-*DD* contribution of ≈16±8%.

Consistent with CLEO-c, worth more study.

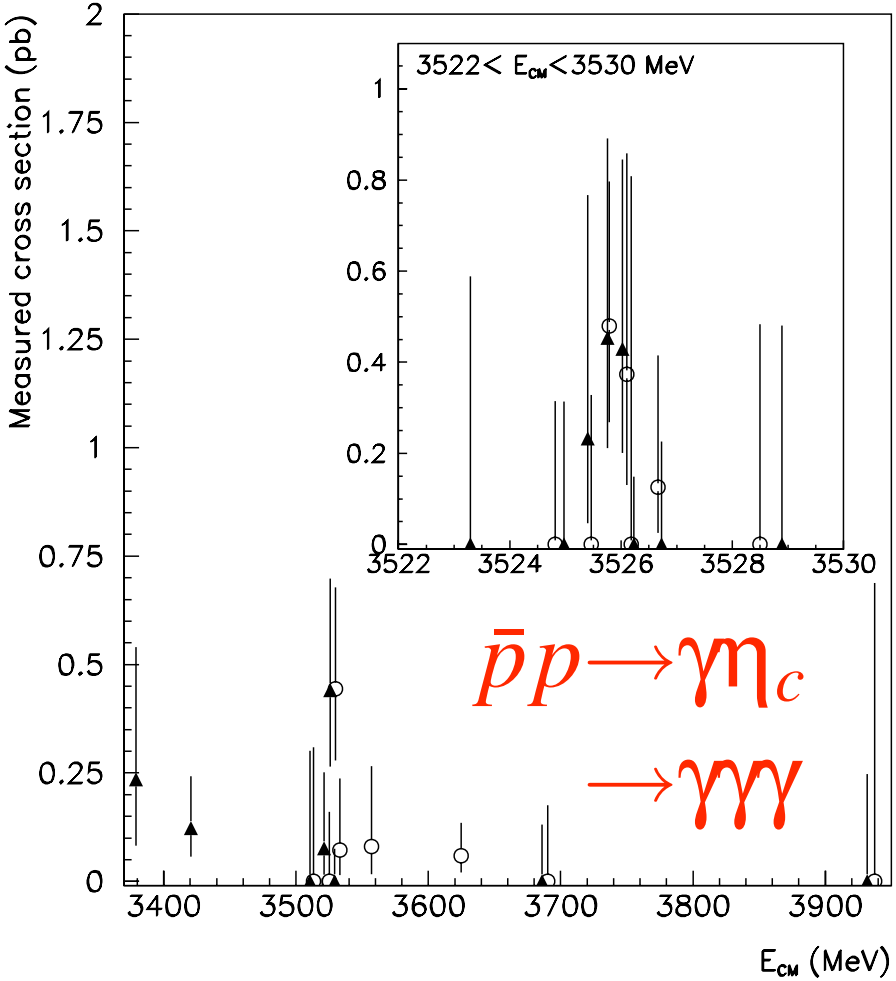




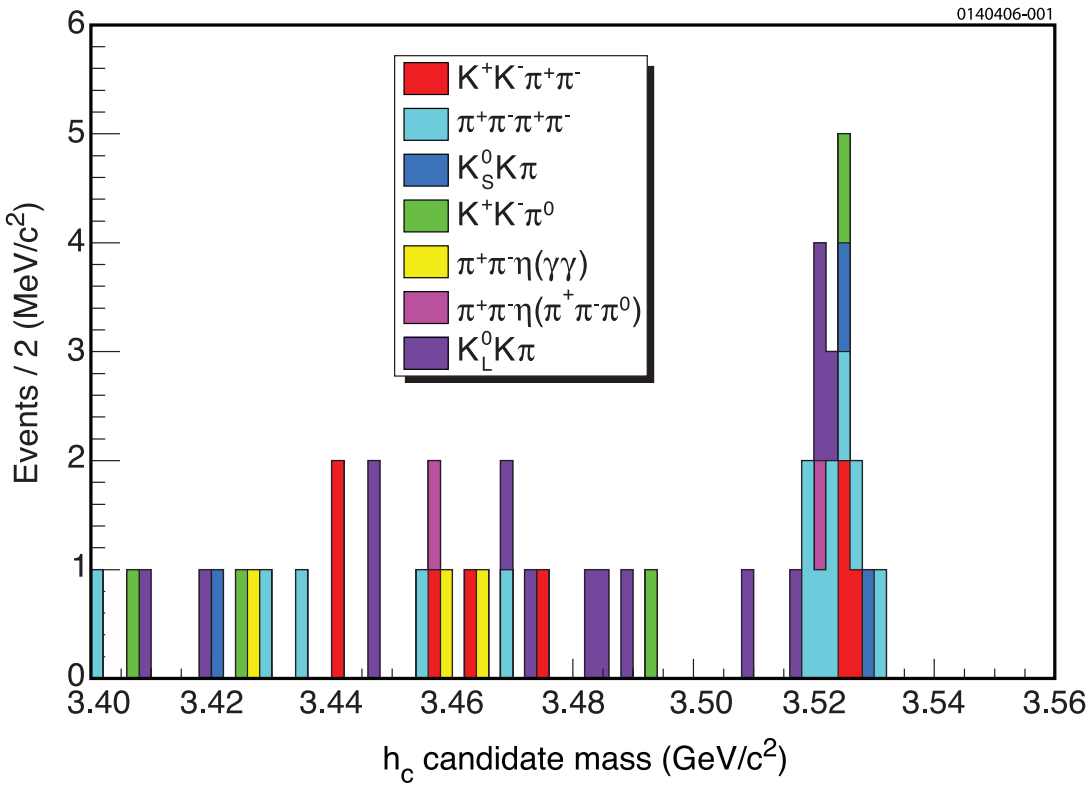


$^1P_1$ Charmonium: The $h_c(3525)$

PRD 72(2005)032001



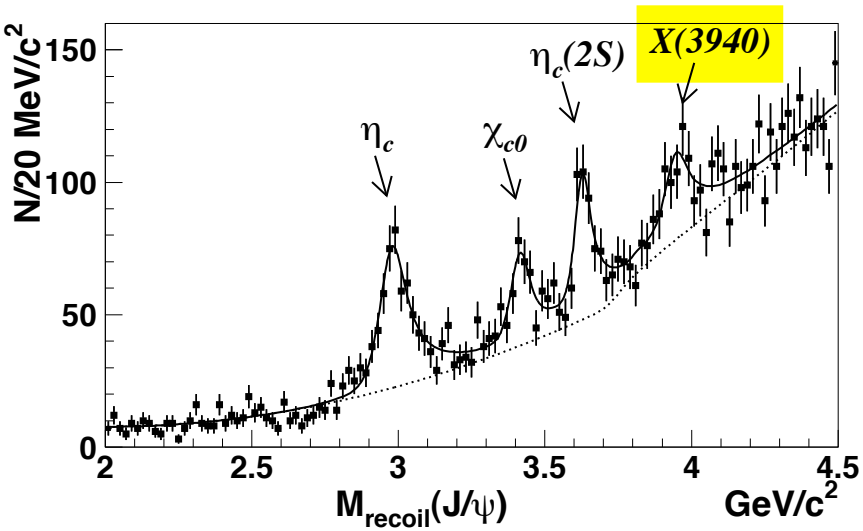
PRD 72(2005)092004



$$e^+e^- \to \psi(2S) \to \pi^0 h_c$$
$$h_c \to \gamma\eta_c$$

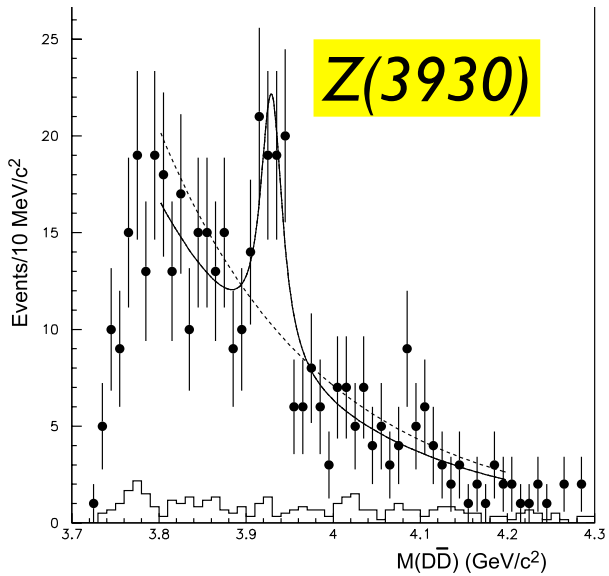
hep-ex/0507019 and PRL 96(2006)082003

Radial χ_{cJ} Excitations?



$e^+e^- \to J/\psi + X(3940)$

Consistent with $J^{PC}=0^{++}$



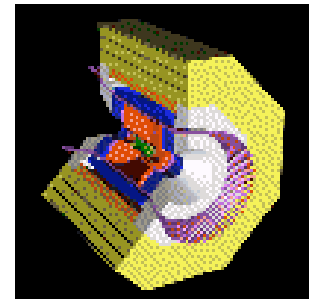
$\gamma\gamma \to Z(3930) \to D\bar{D}$

Consistent with $J^{PC}=2^{++}$

The Y(4260)

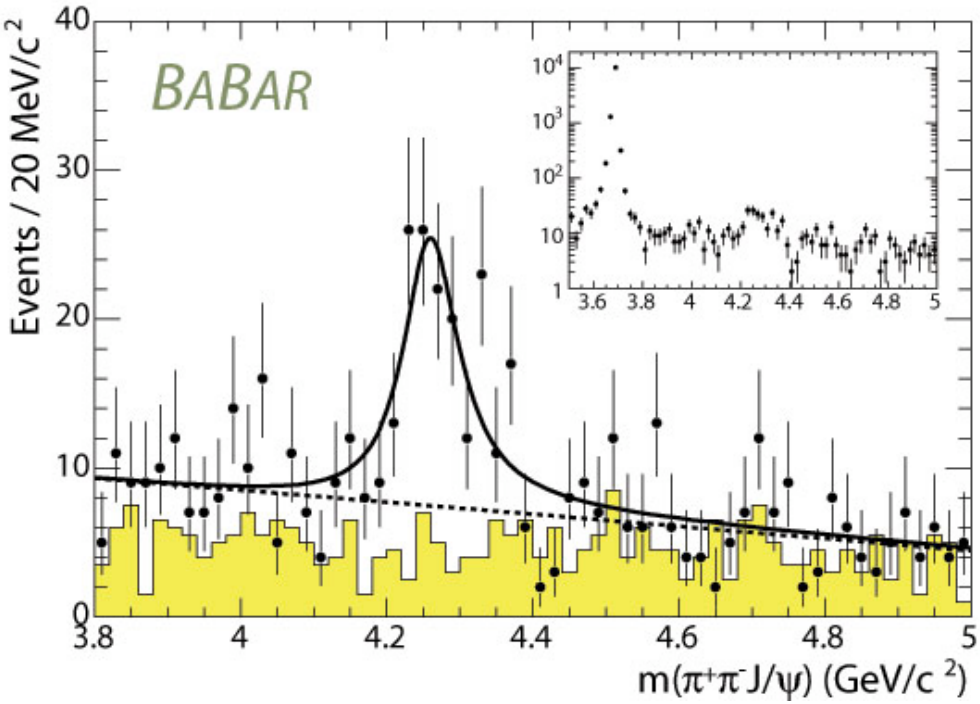
BABAR

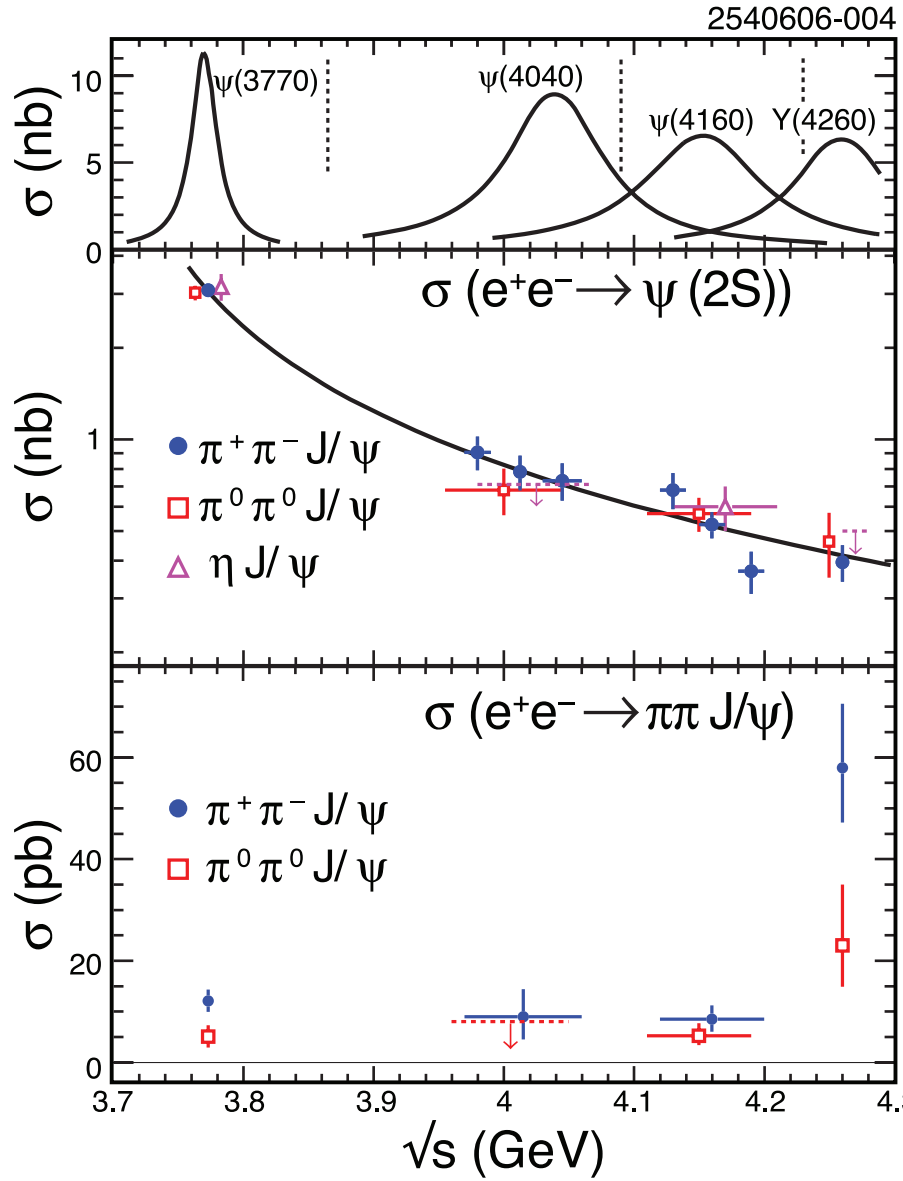
PRL 95(2005)142001



PRL 96(2006) 162003

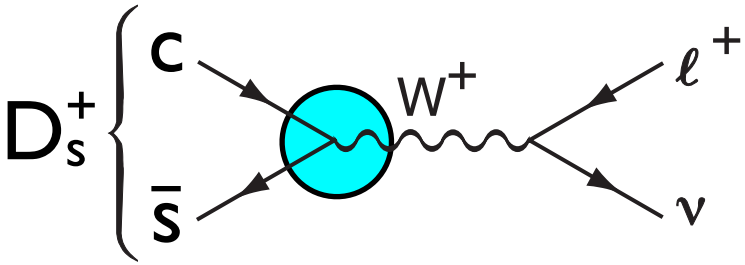
$e^+e^- \to \pi^+\pi^- J/\psi$ *using*
"radiative return"





D_s Decay Constant

Lattice QCD



$f_D \Rightarrow f_B$

Lattice QCD calculates:

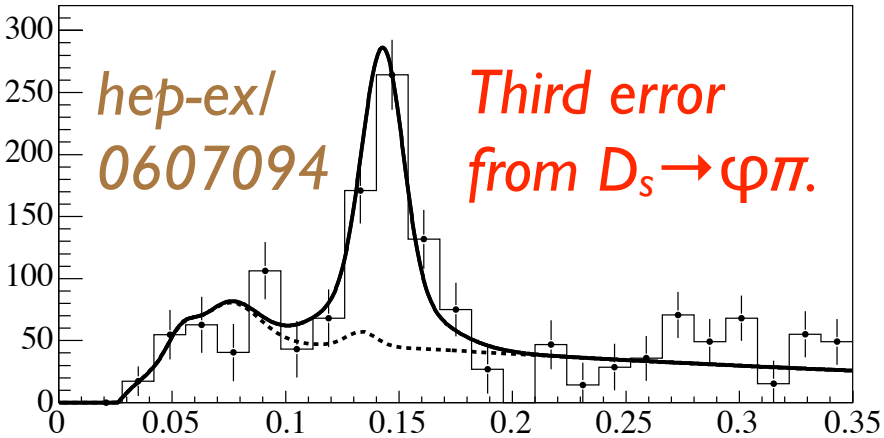
f_{Ds}=249±3±16 MeV

PRL 95(2005)122002

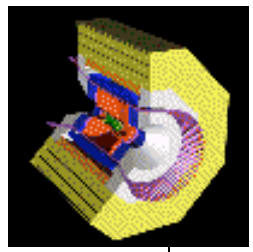
BABAR

BaBar finds:

f_{Ds}=283±17±7±14 MeV

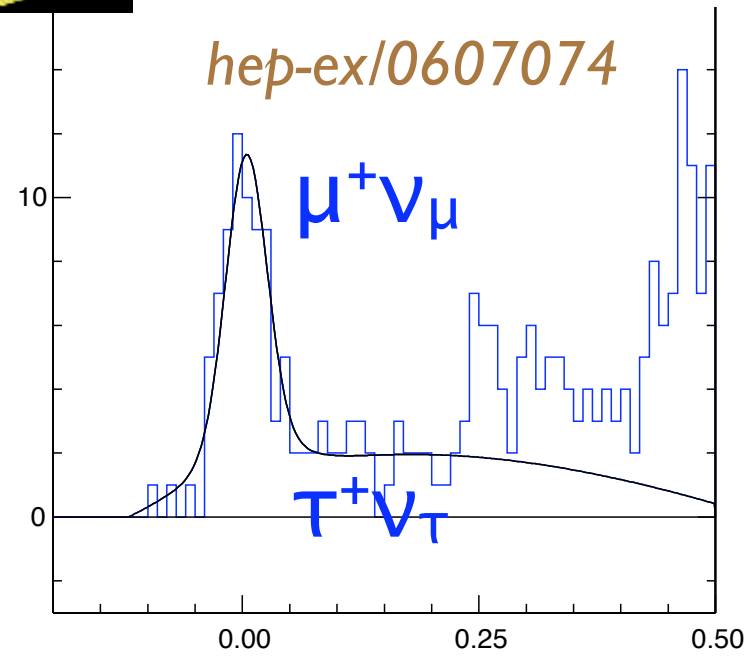


$\Delta M = M_{Ds^*} - M_{Ds}$



CLEO-c finds:

f_{Ds}=282±16±7 MeV

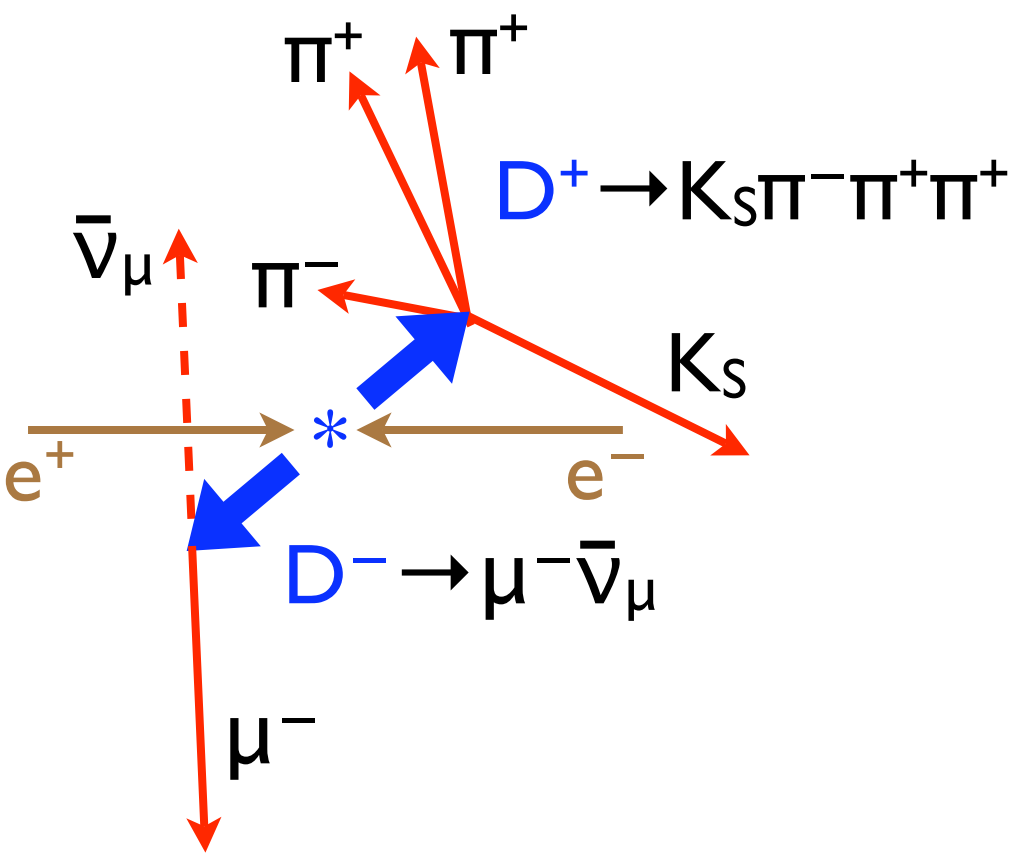


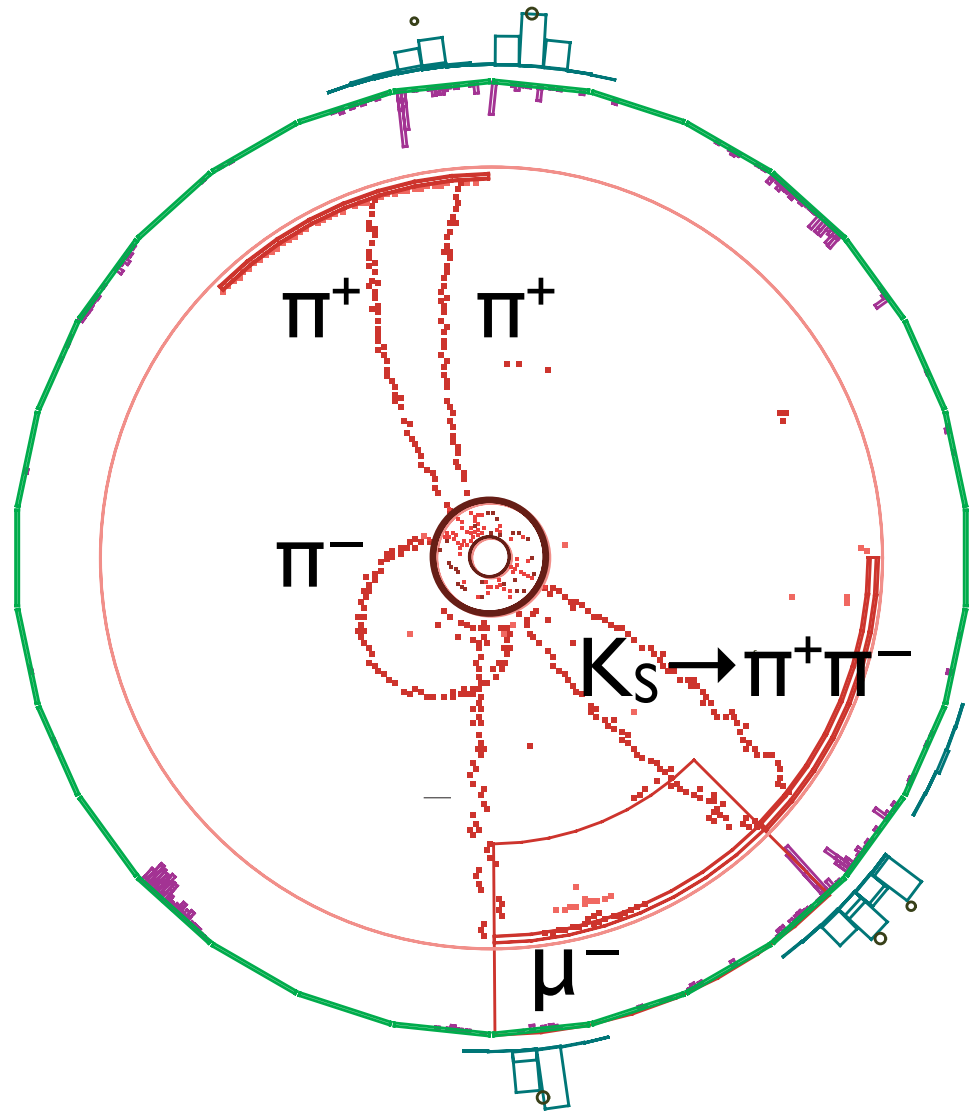
$(\text{Missing Mass})^2$

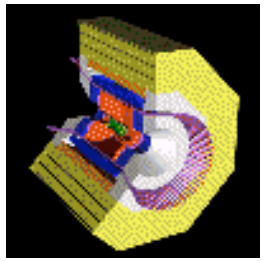
CLEO-c: D Tagging

Example: $D \to \mu\nu$

$e^+e^- \to D^+D^-$

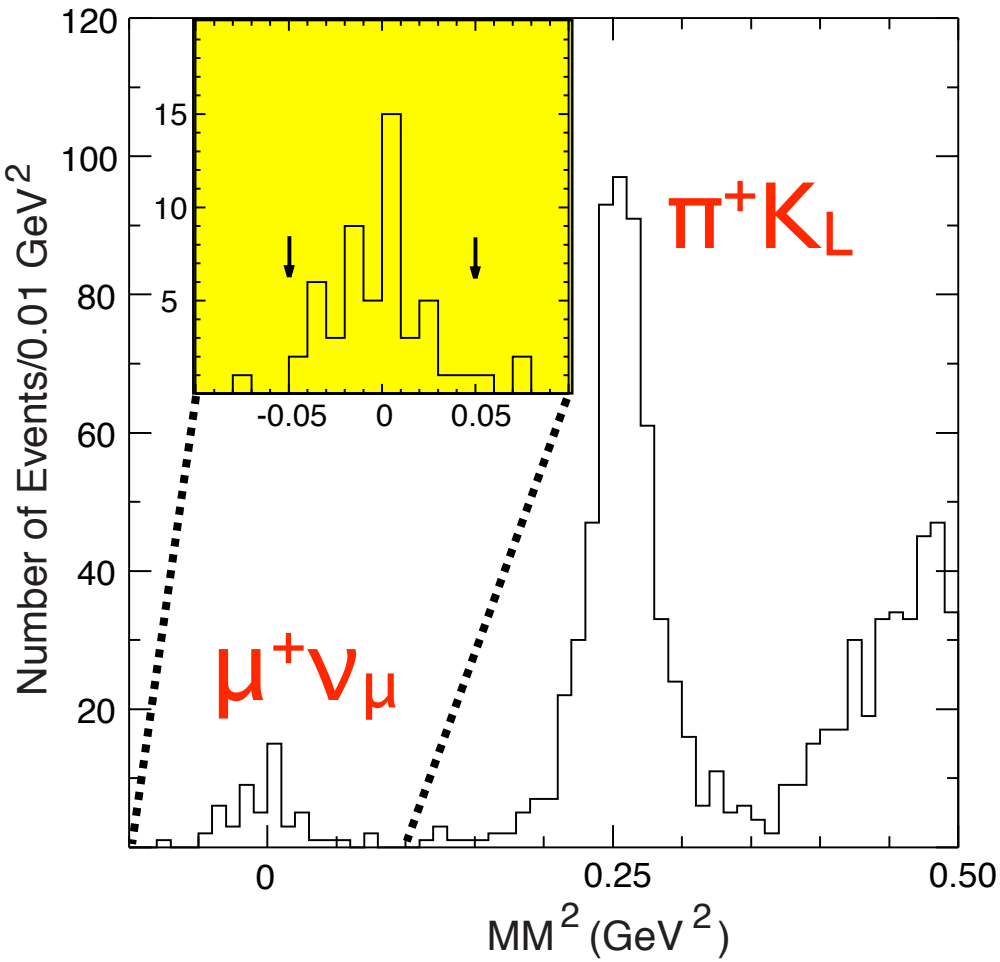






PRL 95(2005)251801

D^+ Decay Constant



Signal in Missing Mass

CLEO-c finds:

$$f_{D^+} = 222.6 \pm 16.7^{+2.8}_{-3.4}\ MeV$$

Lattice QCD calculates:

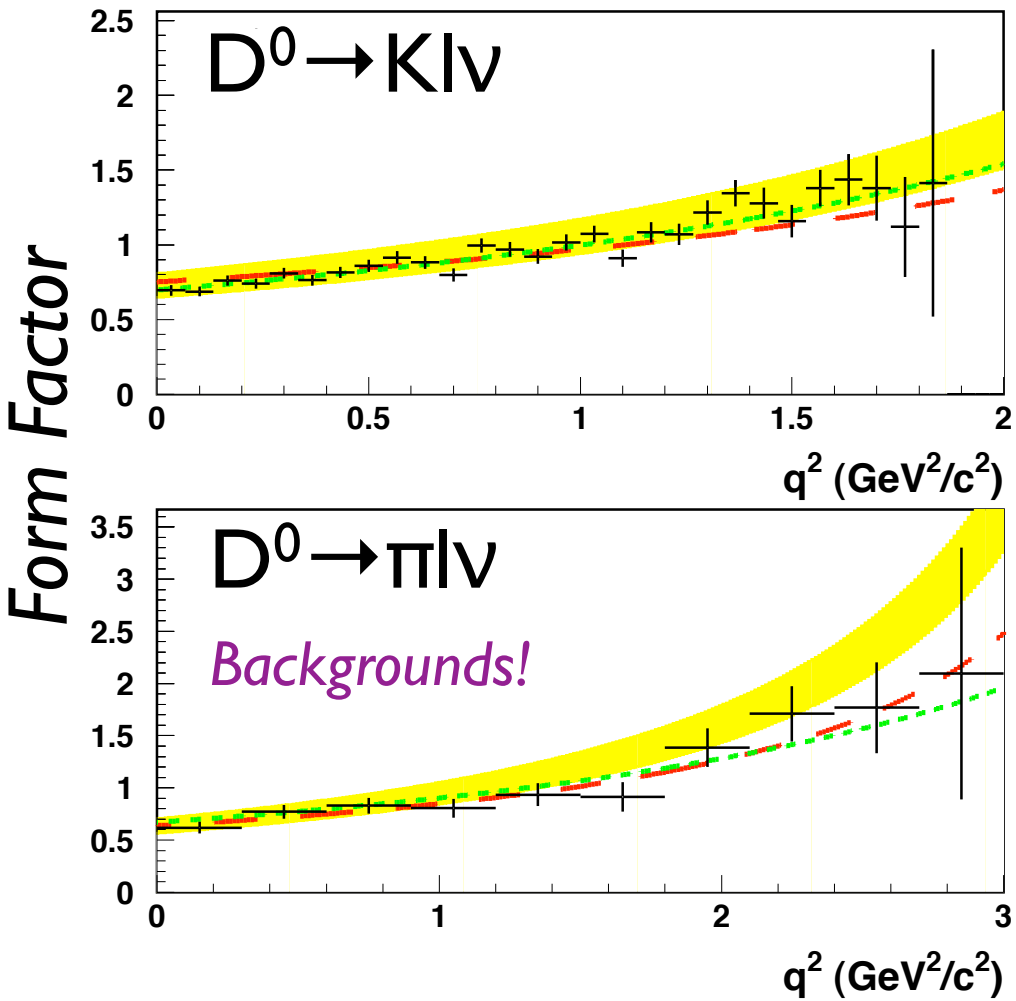
f_D=201±3±17 MeV

PRL 95(2005)122002

- *Important test of actions that use "staggered fermions."*
- *Same for determinations of f_{Ds}.*
- *More results to come!*

Semileptonic Form Factors

Belle: *hep-ex/0604049*



Lattice QCD

Nucl.Phys.Proc.Suppl.129(2004)334

Pole model

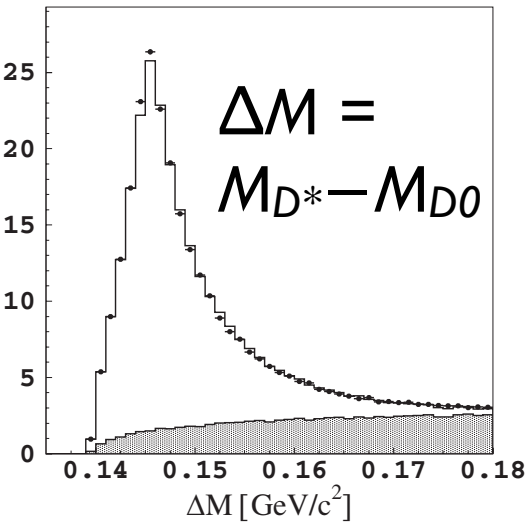
ISGW2 prediction

Low background results from CLEO-c are on the way.

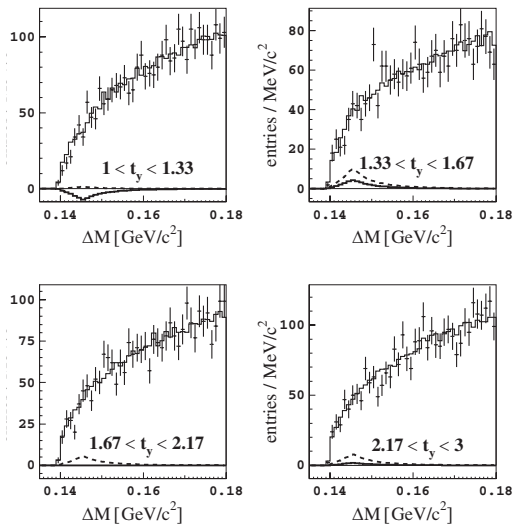
PRD 72(2005)071101

Semileptonic Decay

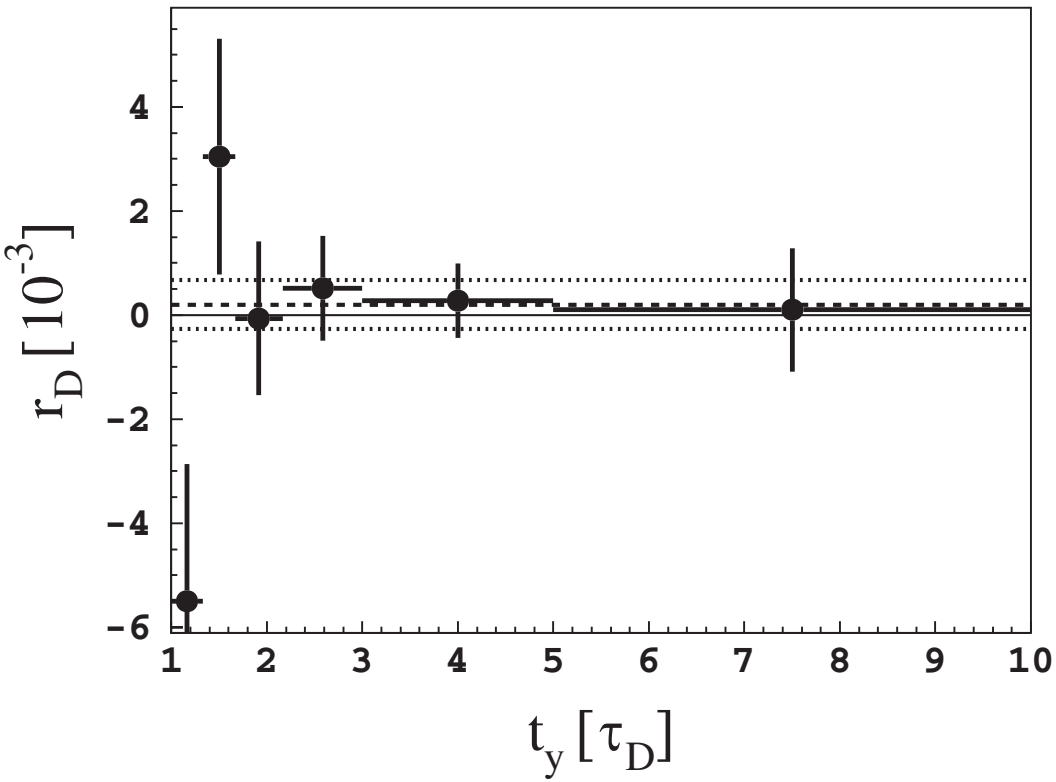
Look for "Wrong Sign" lepton using $D^{*\pm} \to D^0\pi^\pm$ to tag flavor



"Right" Sign



"Wrong" Sign as a function of decay time



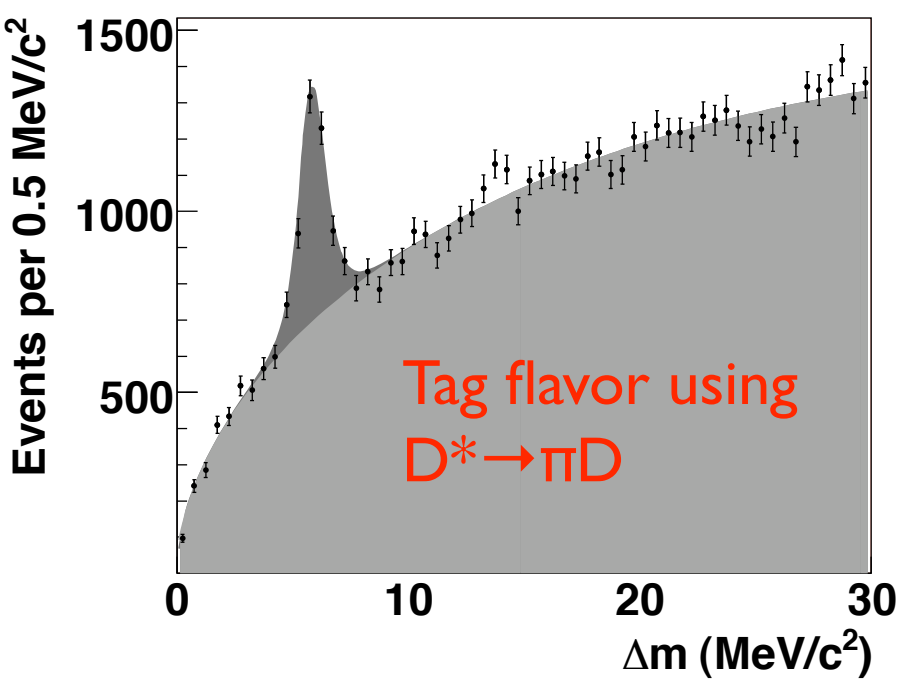
Upper limit on mixing rate $r_D < 1.0\times10^{-3}$

$D^0 \to K\pi$ DCS & Mixing

CDF: Wrong sign $K\pi$

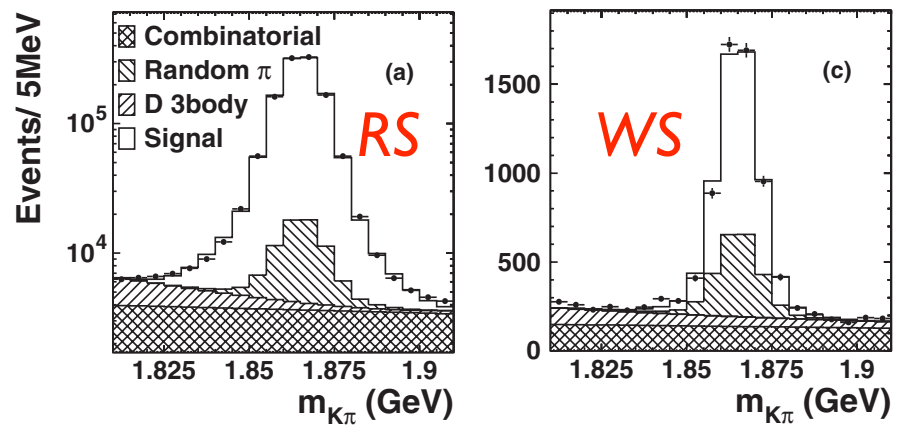
hep-ex/0605027

$R_D = 0.405 \pm 0.021 \pm 0.011\%$

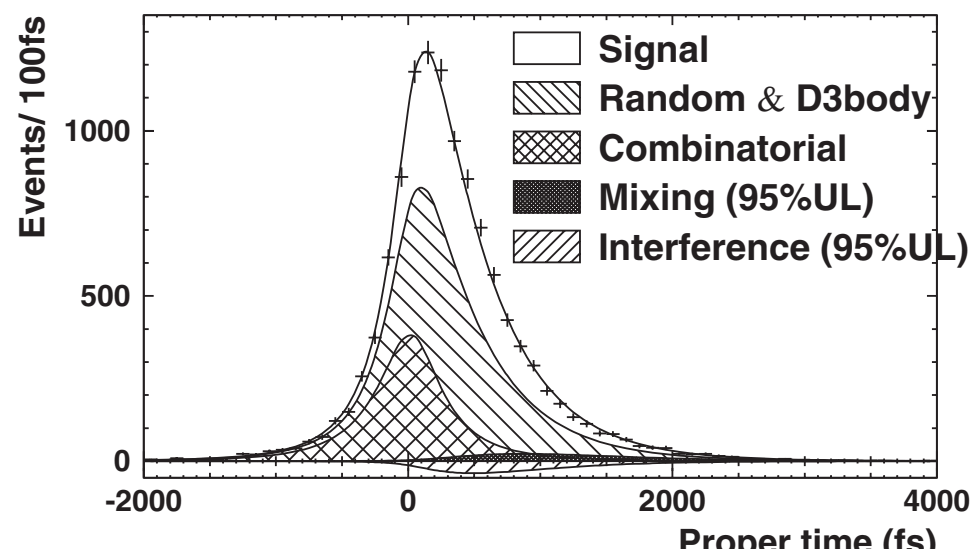


Belle: Time Dependence

PRL 96(2006)151801

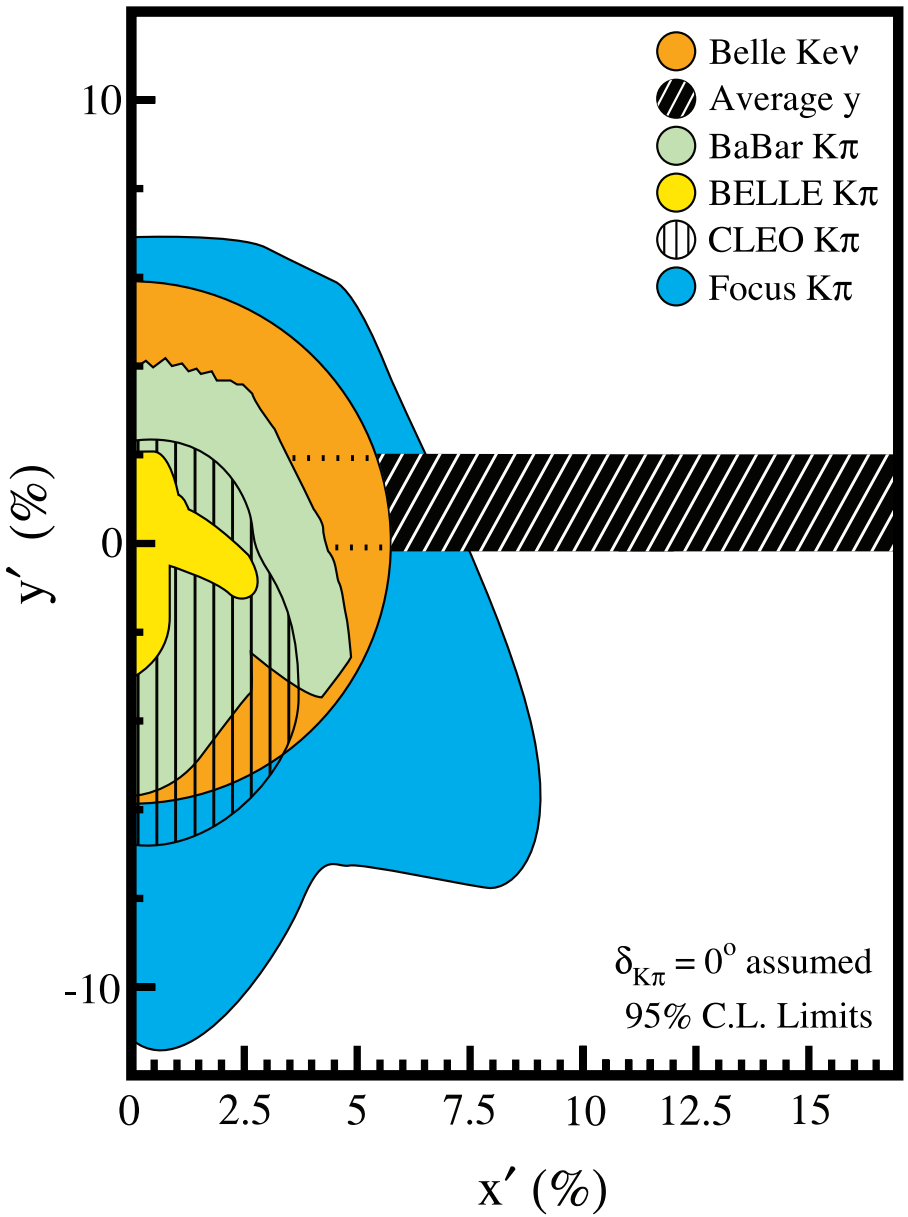


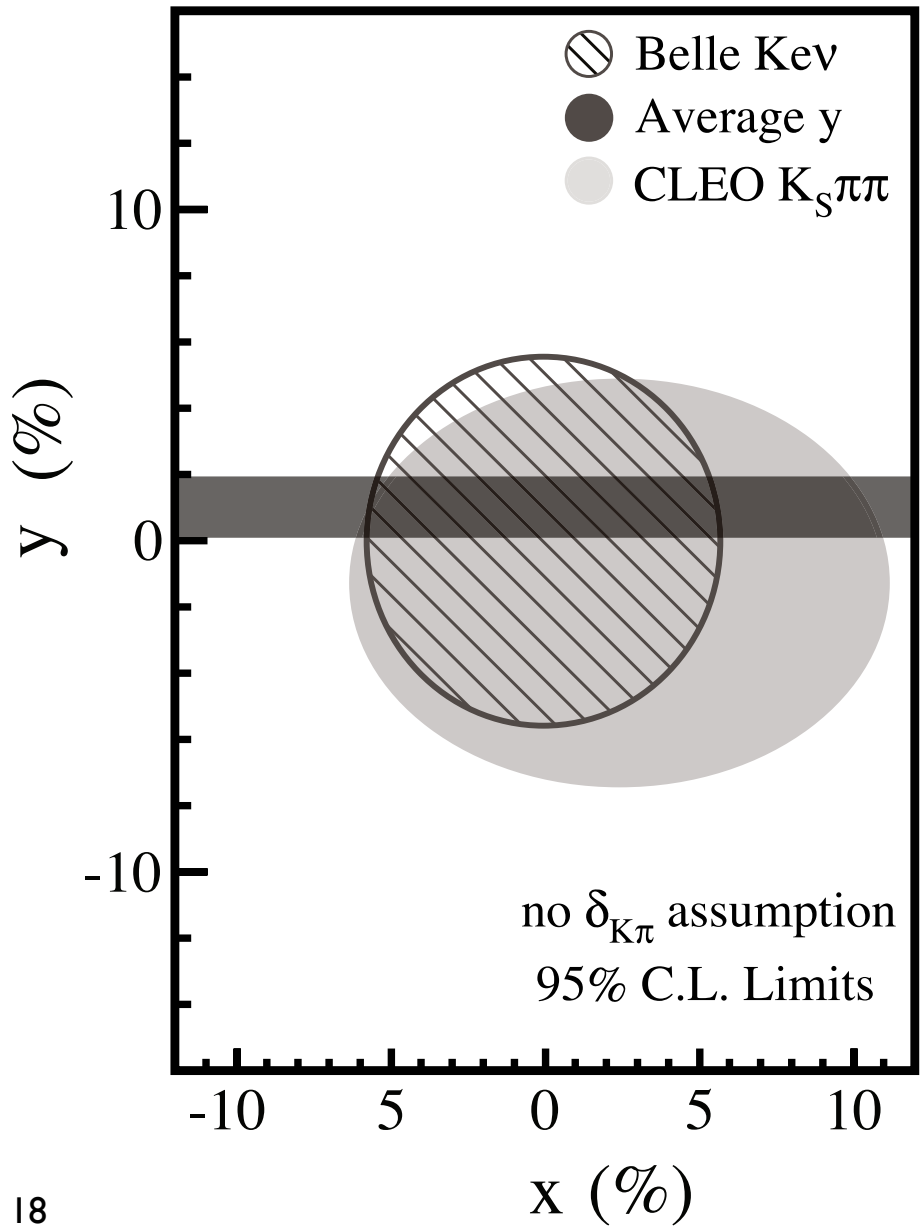
$R_D = 0.377 \pm 0.008 \pm 0.005\%$



Limits on Mixing Parameters

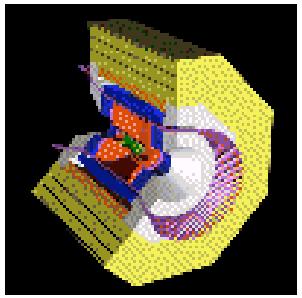
D. Asner, Review in 2006 Particle Data Group compilation



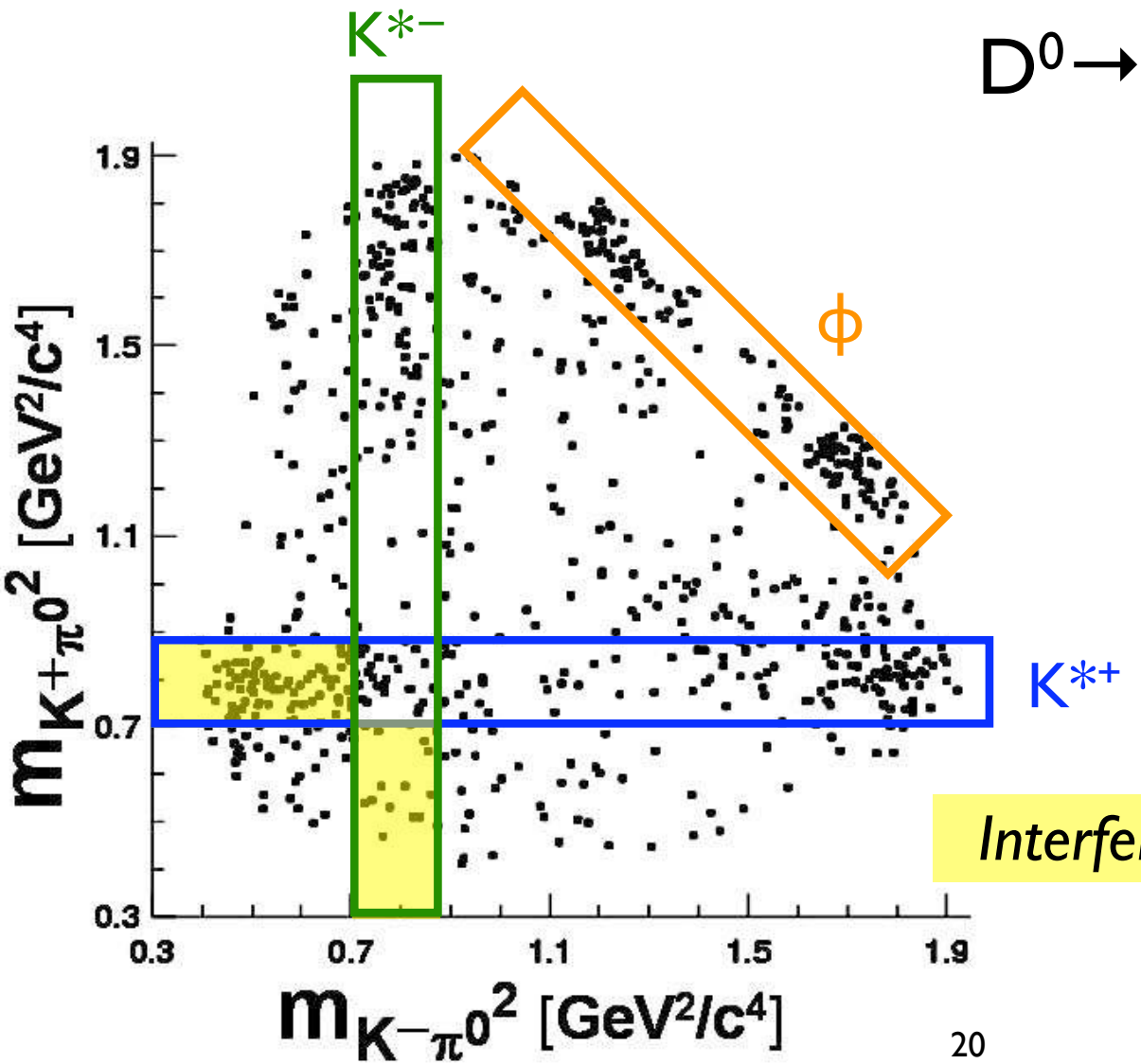


CPV Summary: *S. Stone, FPCP 06*

Experiment	Mode	A_{CP} (%)	Notes
BaBar	$D^+ \to K^+K^-\pi^+$	$1.4 \pm 1.0 \pm 0.8$	Exploits resonant substructure
BaBar	$D^+ \to \varphi\pi^+$	$0.2 \pm 1.5 \pm 1.6$	
BaBar	$D^+ \to K^{*0}K^+$	$0.9 \pm 1.7 \pm 0.7$	
CLEO II.V	$D^0 \to \pi^+\pi^-\pi^0$	$1^{+9}_{-7} \pm 8$	Dalitz plot
CDF	$D^0 \to K^+K^-$	$2.0 \pm 1.2 \pm 0.6$	Direct CP
CDF	$D^0 \to \pi^+\pi^-$	$1.0 \pm 1.3 \pm 0.6$	
FOCUS	$D^0 \to K^+K^-\pi^+\pi^-$	$1.0 \pm 5.7 \pm 3.7$	Triple correlations to get at *T*-violation
FOCUS	$D^+ \to K^0K^+\pi^+\pi^-$	$2.3 \pm 6.2 \pm 2.2$	
FOCUS	$D_s^+ \to K^0K^+\pi^+\pi^-$	$-3.6 \pm 6.7 \pm 2.3$	



$D^0 \to K^*K$: A Tool for $B^\pm \to D^0K^\pm$



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

Destructive interference:

$\delta_D = 332° \pm 8° \pm 11°$

Amplitude ratio:

$|\mathcal{A}(K^{*-}K^+)|/|\mathcal{A}(K^{*+}K^-)| = 0.52 \pm 0.05 \pm 0.04$

Interference!

Phys.Rev.D74(2006)031108

Quantum Correlations

For $e^+e^- \to \bar{D}^0 D^0$ expect $CP(\bar{D}^0 D^0) = -1$

This can be exploited in a number of ways, including extract CP content for multibody charm decays and searching for CP violation.

CLEO-c is studying the ways we can use this in our data, and looking forward to applying these ideas to new data samples.

BES III will be in an excellent position to capitalize!

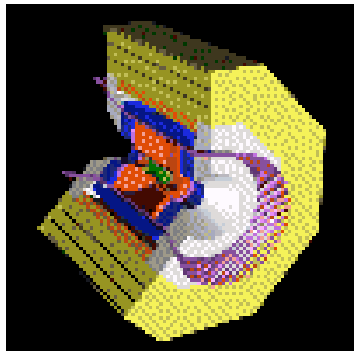
Ref: D. Asner and W. Sun, Phys.Rev.D73(2006)034024

Statistical errors only!

CP+

CP–

No QC Data



Preliminary

See also hep-ex/0603031

	K^+K^-	$\pi^+\pi^-$	$K_S\pi^0\pi^0$	$K_S\pi^0$
K^+K^-	5.2±0.4 -2.2±1.9	4.5±0.3 0.1±0.9	5.7±0.4 1.6±1.3	16.0±0.6 39.6±6.3
$\pi^+\pi^-$		1.1±0.2 0.2±1.4	2.2±0.2 1.6±1.3	5.8±0.4 14.0±3.7
$K_S\pi^0\pi^0$			1.2±0.2 1.0±1.0	7.3±0.4 19.0±4.4
$K_S\pi^0$				9.7±0.5 3.0±1.7

Product CP+

Product CP–

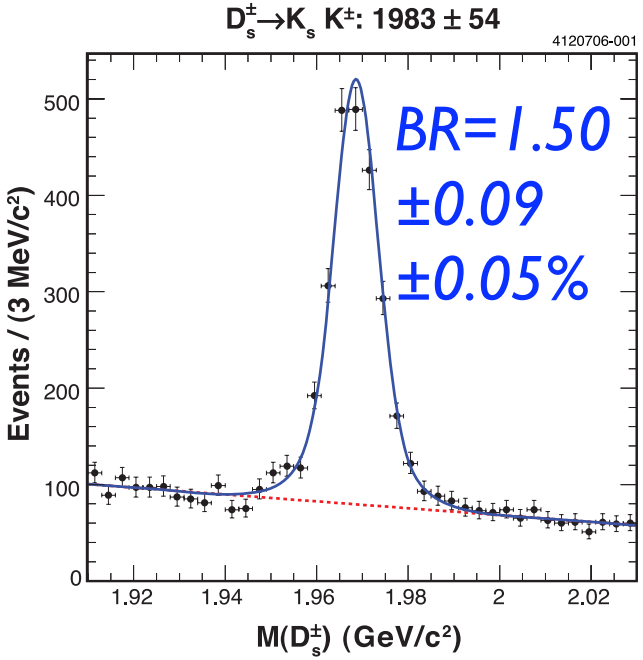
The Future

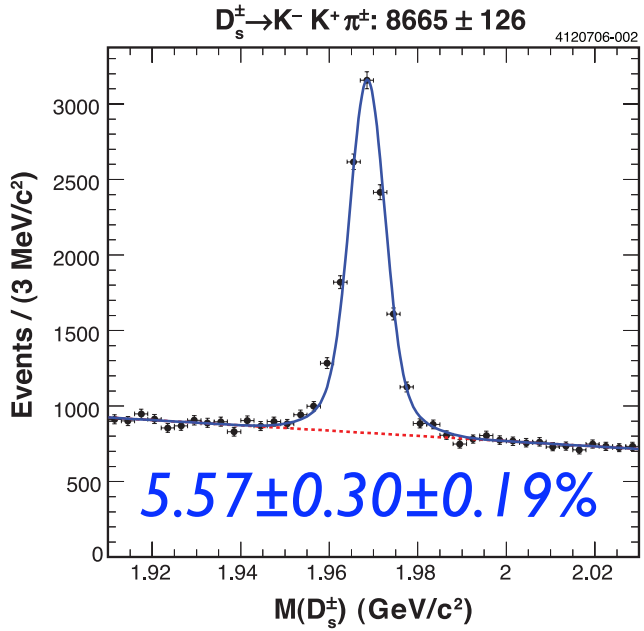
- Expect more from Belle, BaBar, CDF, and D0
  They produce lots of charm!
- CLEO-c will run through March 2008
  Expect ≈3M D-pairs (charged and neutral)
  Also "thousands" of tagged D_s *Sneak Peek!*
- BES III coming on line in the next few years
  Data samples to be ≈25× CLEO-c
- Don't forget about LHCb, PANDA, ...

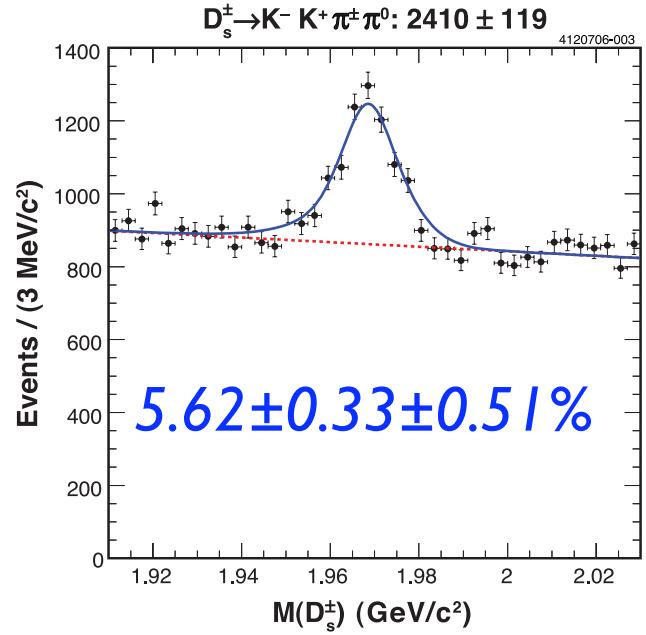
Thank You!!

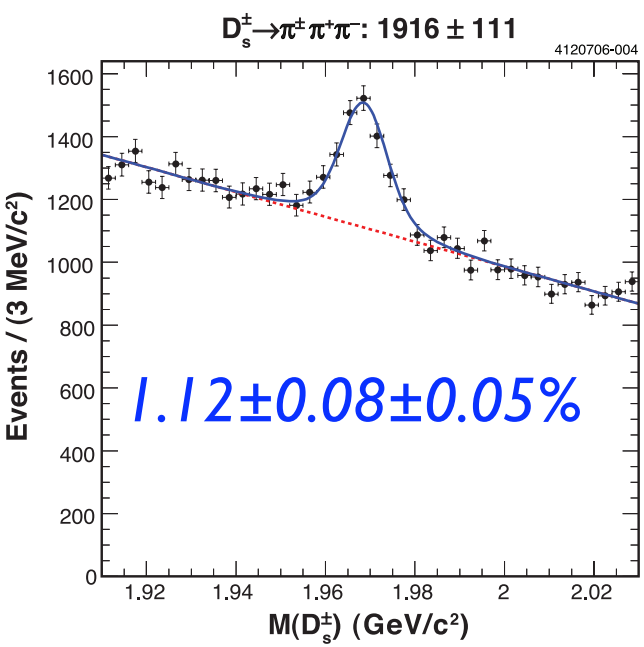
And many thanks to the various experiments for sharing results!

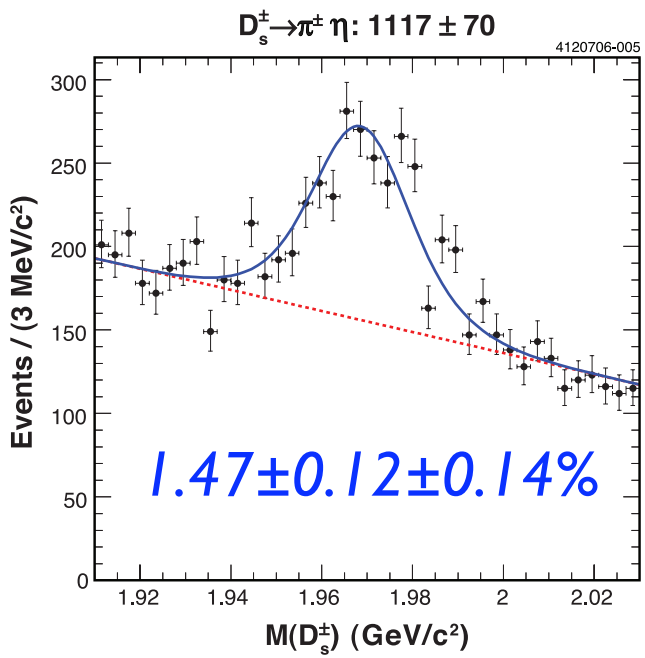
CLEO-c Preliminary: D_s Hadronic Decays

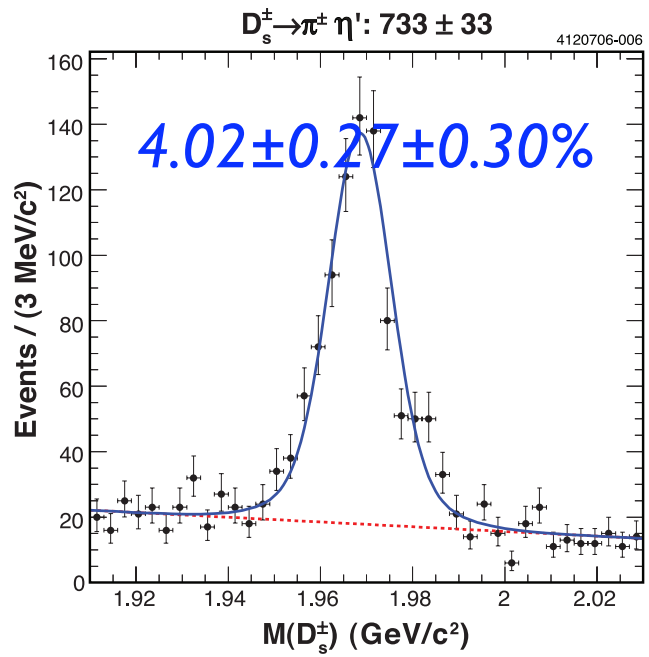












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