CPT and Other Charm Topics

- CPT Violation
- Direct CP violation
- Rare charm decays
- $f(D_s)$
- Semileptonic Decays
- Charm baryons
- Excited D mesons
- BF measurements

•Where are we now?
•What are the limitations?

What is the physics status; what additional studies are needed and what demands are placed on the detector / analysis?

CPT Violation

- Kostelecky *et al.* have described a formalism which is an extension of the Standard Model (the SME) which contains CPT-violation.
  - D. Colladay and V. A. Kostelecky
    - Phys. Rev. D55, 6760 (1997)
    - Phys. Rev. D58, 116002 (1998)
  - V. A. Kostelecky, Phys. Rev. Lett. 80, 1818 (1998).
  - V. A. Kostelecky, Phys. Rev. D64, 076001 (2001).

CPT violation, contd.

- CPT violation can arise from a tiny "preferred 4-vector" term Δa^{μ} or from a "preferred tensor" term such as $c^{\mu\nu}\gamma_{\nu}$, etc. where the terms may depend on the quark species involved.
- Experiments such as BaBar, FOCUS etc. are precessing (with the Earth) relative to, e.g., the vector Δa.
- Kaon results, such as the KTeV result

  $|\Delta M|/M < (4.5 \pm 3.0)\mathrm{x}10^{-19}$

  can be re-cast in this language as

  $\Delta a_X, \Delta a_Y < 9.2\times10^{-22}$ GeV.

CPT Violation, contd.

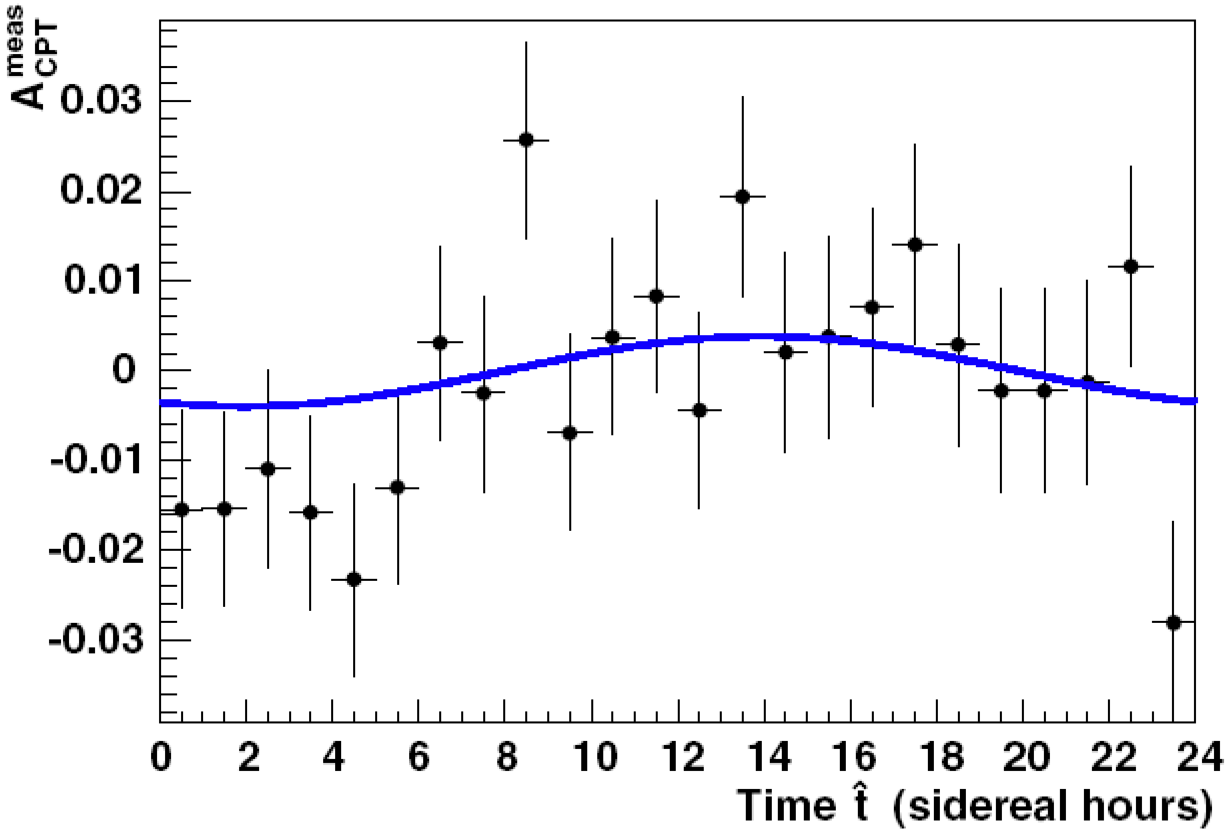
- Kostelecky (2001) describes a useful parameter $\xi = \Delta\Lambda/\Delta\lambda$ where Λ is the usual 2x2 Hamiltonian matrix describing neutral meson oscillations and decay; $\Delta\Lambda = \Lambda_{11} - \Lambda_{22}$ and $\Delta\lambda$ is the difference in eigenvalues.
- BaBar (PRL 100, 131802, 2008) have used this formalism to study time-dependent B meson decays where

  $\Delta a_\mu = r_{q1} a^{q1}{}_\mu - r_{q2} a^{q2}{}_\mu$, where the r_{qi} for the two valence quarks in the B^0 meson are due to quark-binding and normalization effects.
- In the case of B mesons, due to significant oscillation during decays, one finds

$$A_{CPT}(\Delta t) \simeq \frac{-\mathrm{Re}\,\mathsf{z}\,\Delta\Gamma\Delta t + 2\mathrm{Im}\,\mathsf{z}\sin(\Delta m\Delta t)}{\cosh(\Delta\Gamma\Delta t/2) + \cos(\Delta m\Delta t)}.$$

  where $\mathsf{z} \simeq \beta^\mu \Delta a_\mu/(\Delta m - i\Delta\Gamma/2)$. [β^μ is the experiment 4-β and Δm dominates the denominator.]

BaBar, 2008: A_{CPT} vs. Sidereal time



FOCUS ’03 (i)

The case of D mesons has been studied by FOCUS (Phys.Lett. B556, 2003).

$P_f(t)$ is the t-dependent probability for D^0 to decay to final state f; similarly for $\overline{D}^0$. Recall that $\xi = \Delta\Lambda/\Delta\lambda$.

D^0 mixing has small x, y which leads to (4).

$\overline{f}/f$ is the efficiency ratio.

$$P_f(t) \equiv |\langle f|T|D^0(t)\rangle|^2 = \frac{1}{2}|F|^2 \exp(-\frac{\gamma}{2}t) \times [(1+|\xi|^2)\cosh\Delta\gamma t/2 + (1-|\xi|^2)\cos\Delta m t - 2\mathrm{Re}\,\xi\,\sinh\Delta\gamma t/2 - 2\mathrm{Im}\,\xi\,\sin\Delta m t]. \quad (1)$$

$$A_{\mathrm{CPT}}(t) = \frac{\overline{P}_{\overline{f}}(t) - P_f(t)}{\overline{P}_{\overline{f}}(t) + P_f(t)}, \quad (2)$$

which is sensitive to the CPT violating parameter ξ:

$$A_{\mathrm{CPT}}(t) = \frac{2\mathrm{Re}\,\xi\,\sinh\Delta\gamma t/2 + 2\mathrm{Im}\,\xi\,\sin\Delta m t}{(1+|\xi|^2)\cosh\Delta\gamma t/2 + (1-|\xi|^2)\cos\Delta m t}. \quad (3)$$

Experiments show that x, y mixing values are small ($< 5\%$). Equation 3, for small x, y and t, reduces to:

$$A_{\mathrm{CPT}}(t) = (\mathrm{Re}\,\xi\; y - \mathrm{Im}\,\xi\; x)\;\Gamma\; t. \quad (4)$$

$$A_{\mathrm{CPT}}(t') = \frac{\overline{Y}(t') - Y(t')\frac{\overline{f}(t')}{f(t')}}{\overline{Y}(t') + Y(t')\frac{\overline{f}(t')}{f(t')}}, \quad (5)$$

Focus, 2003: A_{CPT} results

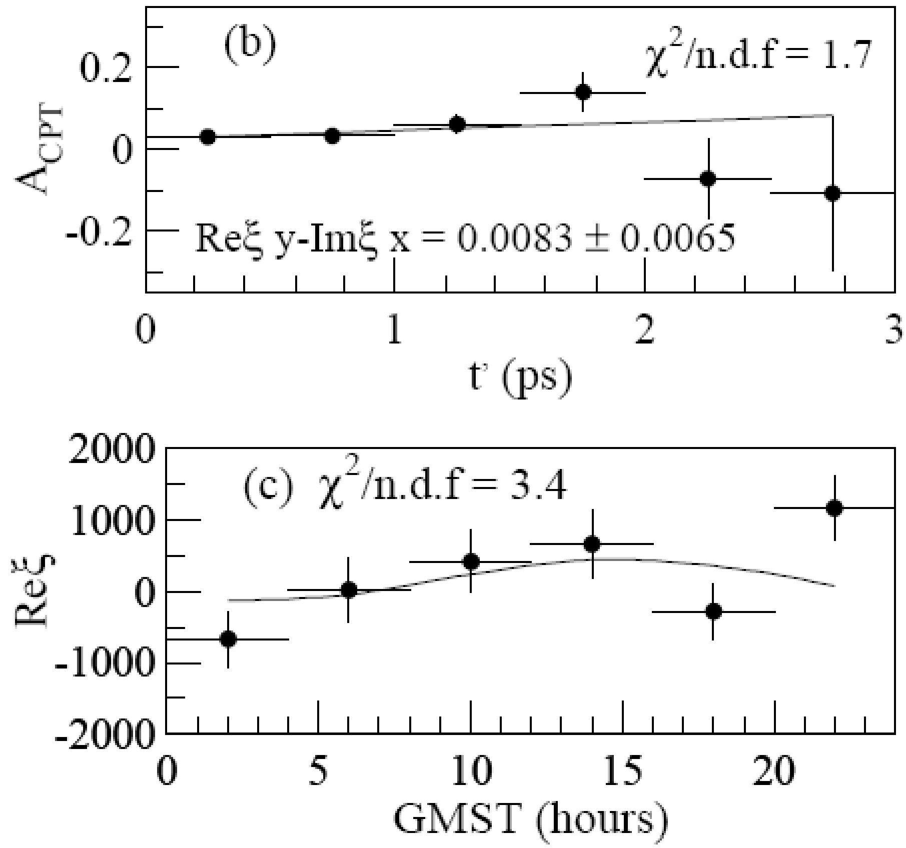


Fig. 2. (a) The ratio of the corrections; (b) A_{CPT} as a function of reduced proper time. The data points represent the A_{CPT} as given in Equation 5 and the solid line represent the fit given in functional form by Equation 4; (c) Re ξ as a function of Greenwich Mean Sidereal Time (GMST).

FOCUS '03 - Results

7 Summary

We have performed the first search for CPT and Lorentz violation in neutral charm meson oscillations. We have measured $\mathrm{Re}\,\xi\, y - \mathrm{Im}\,\xi\, x = 0.0083 \pm 0.0065 \pm 0.0041$ which lead to a 95% confidence level limit of $-0.0068 < \mathrm{Re}\,\xi\, y - \mathrm{Im}\,\xi\, x < 0.0234$. As a specific example, assuming $x = 0$ or $\mathrm{Im}\,\xi = 0$ and $y = 1\%$, one finds $\mathrm{Re}\,\xi = 0.83 \pm 0.65 \pm 0.41$ with a 95% confidence level limit of $-0.68 < \mathrm{Re}\,\xi < 2.34$. Within the Standard Model Extension, we set three independent first limits on the expressions involving coefficients of Lorentz violation of $(-2.8 < N(x,y,\delta)(\Delta a_0 + 0.6\,\Delta a_Z) < 4.8) \times 10^{-16}$ GeV, $(-7.0 < N(x,y,\delta)\Delta a_X < 3.8) \times 10^{-16}$ GeV, and $(-7.0 < N(x,y,\delta)\Delta a_Y < 3.8) \times 10^{-16}$ GeV. As a specific example, assuming $x = 1\%$, $y = 1\%$ and $\delta = 15°$ one finds the 95% limits on the coefficients of Lorentz violation of $(-3.7 < \Delta a_0 + 0.6\,\Delta a_Z < 6.5) \times 10^{-13}$ GeV, $(-9.4 < \Delta a_X < 5.0) \times 10^{-13}$ GeV, and $(-9.3 < \Delta a_Y < 5.1) \times 10^{-13}$ GeV. The measured values are consistent with no CPT or Lorentz invariance violation.

FOCUS '03 - Systematics

Here the quantities C_x etc. are the combinations of Δa found on the previous slide.

Table 1
Contributions to the systematic uncertainty.

Contribution	$\mathrm{Re}\,\xi\, y - \mathrm{Im}\,\xi\, x$	C_X (GeV)
Absorption	± 0.0017	$\pm 0.0 \times 10^{-16}$
Split sample	± 0.0000	$\pm 1.3 \times 10^{-16}$
Fit variant	± 0.0012	$\pm 0.9 \times 10^{-16}$
Cut variant	± 0.0036	$\pm 1.0 \times 10^{-16}$
Total	± 0.0041	$\pm 1.9 \times 10^{-16}$

δ is the strong phase between the DCS and right-sign amplitudes.

Table 2
Contributions to the systematic uncertainty.

Contribution	C_{0Z} (GeV)	C_Y (GeV)
Absorption	$\pm 0.3 \times 10^{-16}$	$\pm 0.1 \times 10^{-16}$
Split sample	$\pm 0.0 \times 10^{-16}$	$\pm 1.6 \times 10^{-16}$
Fit variant	$\pm 0.3 \times 10^{-16}$	$\pm 0.5 \times 10^{-16}$
Cut variant	$\pm 1.5 \times 10^{-16}$	$\pm 1.1 \times 10^{-16}$
Total	$\pm 1.6 \times 10^{-16}$	$\pm 2.0 \times 10^{-16}$

$$N(x, y, \delta) = [xy/3 + 0.06\,(x\ \cos\delta + y\ \sin\delta)]$$

CPT violation: conclusions

- SuperB can test CPT violation and improve established limits using D mixing.

- Other possible sources of CPT violation can also be studied; see for instance B. Altschul, Phys.Rev. D72 (2005) 085003.

Direct CP violation

- Direct CPV studied in many decays, typically SCS, such as
  - $D^+ \rightarrow K^0_S \pi^+$
  - $D^+ \rightarrow K^- K^+ \pi^+$
  - $D^0 \rightarrow K^- K^+, \pi^- \pi^+$
  - $D^+, D_s^+ \rightarrow K^+ K^0_S \pi^+ \pi^-$

- SM gives CP asymmetries from interference of tree-level and penguin diagrams of order 0.1%.
  - M. Golden and B. Grinstein, Phys. Lett. B 222, 501 (1989).
  - F. Buccella, M. Lusignoli, G. Mangano, G. Miele, A. Pugliese and P. Santorelli, Phys. Lett. B 302, 319 (1993).
  - F. Buccella, M. Lusignoli, G. Miele, A. Pugliese and P. Santorelli, Phys. Rev. D 51, 3478 (1995).

- New Physics can lead to order (0.1-1)% asymmetries.
  - A. Le Yaouanc, L. Oliver and J. C. Raynal, Phys. Lett. B292, 353 (1992).
  - S. Bianco, F. L. Fabbri, D. Benson and I. Bigi, Riv. Nuovo Cim. 26N7-8, 1 (2003).
  - Y. Grossman, A. L. Kagan and Y. Nir, Phys. Rev. D 75, 036008 (2007).

Direct CPV: Experimental Results

- Direct CPV studied in many decays, typically SCS, such as
  - $D^+ \to K^0{}_S\,\pi^+$

    BaBar [arXiv:1011.5477] report that $A_{CP} = \frac{\Gamma(D^+ \to K_S^0\pi^+) - \Gamma(D^- \to K_S^0\pi^-)}{\Gamma(D^+ \to K_S^0\pi^+) + \Gamma(D^- \to K_S^0\pi^-)} =$

$(-0.44 \pm 0.13(\mathrm{stat}) \pm 0.10(\mathrm{syst}))\%$, consistent with zero at 2.7 σ and with the standard model prediction of $(-0.332 \pm 0.006)\%$. This is currently the most precise measurement of this parameter.

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

    Here the SM prediction is not affected by K^0-$\overline{K}^0$ effects.

    BaBar, Belle sensitivity should be ~ 0.2-0.3% for integrated measurements and somewhat worse for resonant decays.

    We can probe individual resonances (since some are less and some are more useful for CPV), regions of the Dalitz plot as well as the integrated asymmetry.

  - Also interesting are $D^0 \to K^-K^+, \pi^-\pi^+$ and $D^+, D_s^+ \to K^+K^0{}_S\pi^+\pi^-$ modes.

Direct CPV Modes: Systematic Limitations

$D^+ \to K^0_S\,\pi^+$	**K^0-$\bar{K}^0$ regeneration effects, PID**
$D^+ \to K^- K^+ \pi^+$	Tracking asymmetry
$D^+, D_s^+ \to K^+ K^0_S \pi^+ \pi^-$	Cuts and particle ID

Types of Rare Decays

- Flavor Changing Neutral Currents
  - Forbidden by SM
  - $(c \rightarrow u)$
- GIM suppressed:
  - $D^+ \rightarrow \pi^+ e^+ e^-$
  - $D \rightarrow X\gamma$
- Lepton Flavor Violation & Lepton Number Violation – If seen may indicate Majorana nature of neutrino:
  - $D^+ \rightarrow \pi^- e^+ e^+$,
  - $D^+ \rightarrow \pi^+ e^+ \mu^-$
- Radiative Decays: The long distance contributions are not easily separated from short distance contributions.

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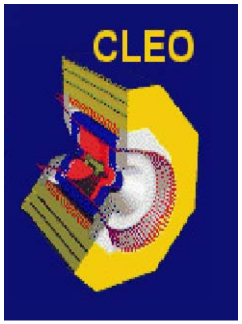
From: “**Flavor Physics in the Quark Sector**”
hep-ph/0907.5386 (2008)
M. Antonelli *et al.*

- It is clear that due to the relatively little experimental progress in this area within the last decade and the large data sets from the flavor factories, that there is a several orders of magnitude in precision to be gained from re-reanalyzing these measurements with meaningful limits to be derived which may have the potential to constrain parameter space for many new physics models.

$D_{(s)}^{+} \rightarrow hee$



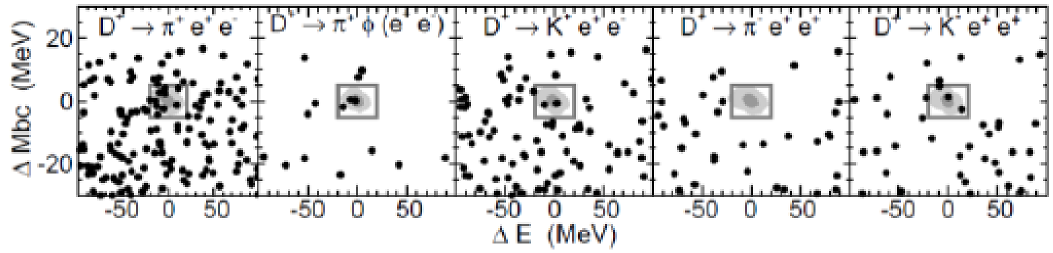


FIG. 1. Scatter plots of ΔM_{bc} vs ΔE. The two contours for each mode enclose regions determined with signal MC simulation to contain 50% and 85% of signal events, respectively. The signal region, defined by $(\Delta E, \Delta M_{bc}) = (\pm 20\,\mathrm{MeV}, \pm 5\,\mathrm{MeV})$, is shown as a box.

D^+
Ecm = 3.774 GeV
L = 818 pb^{-1}
N_{DD} = 2.4 x 10^6

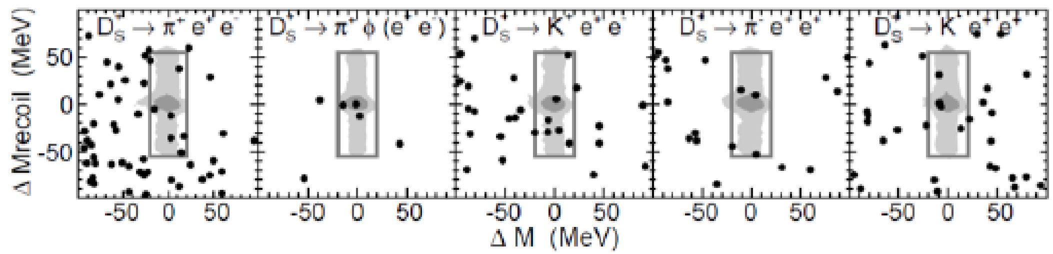


FIG. 2. Scatter plots of ΔM_{recoil} vs ΔM. The two contours for each mode enclose regions determined with signal MC simulation to contain 40% and 85% of signal events, respectively. The signal region, defined by $(\Delta M, \Delta M_{recoil}) = (\pm 20\,\mathrm{MeV}, \pm 55\,\mathrm{MeV})$, is shown as a box.

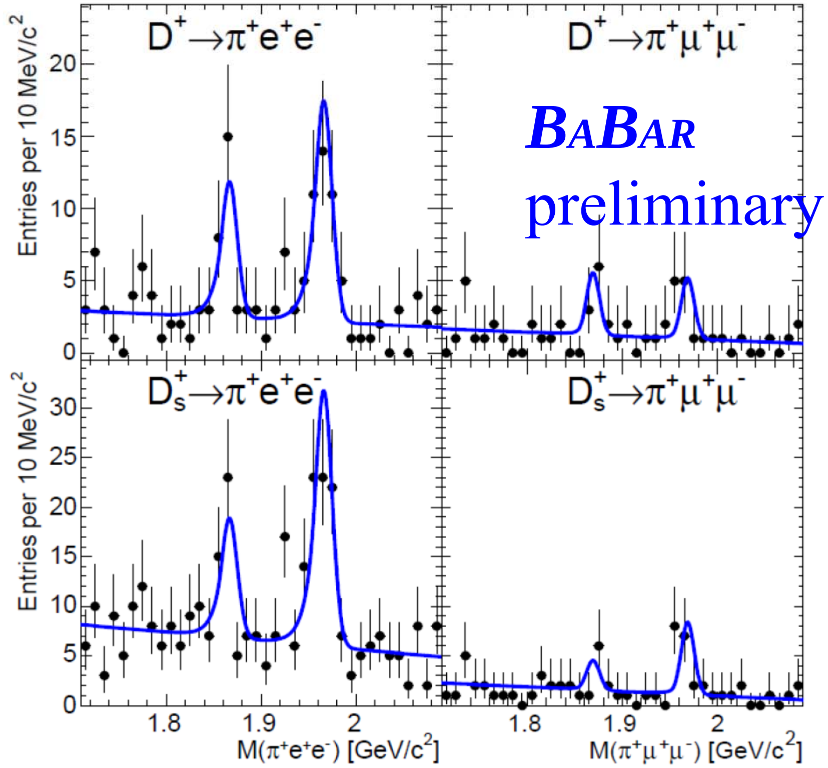
D_s^+
Ecm = 4.170 GeV
L = 602 pb^{-1}
N_{DsDs*} = 0.6 x 10^6

Phys.Rev.D82:092007,2010.

Channel	N	ϵ (%)	N_{exp}	N_{obs}	$\mathcal{C}(N_{obs}\|N_{exp})$	$\mathcal{B}$
$D^+ \to \pi^+ e^+ e^-$	4.76×10^6	33.9	5.7	9	9.3	$< 5.9 \times 10^{-6}$
$D^+ \to \pi^- e^+ e^+$	4.76×10^6	43.5	1.3	0	2.3	$< 1.1 \times 10^{-6}$
$D^+ \to K^+ e^+ e^-$	4.76×10^6	23.1	4.9	2	3.2	$< 3.0 \times 10^{-6}$
$D^+ \to K^- e^+ e^+$	4.76×10^6	35.3	1.2	3	5.8	$< 3.5 \times 10^{-6}$
$D^+ \to \pi^+ \phi(e^+ e^-)$	4.76×10^6	46.2	0.3	4		$(1.7^{+1.4}_{-0.9} \pm 0.1) \times 10^{-6}$
					7.9	$< 3.7 \times 10^{-6}$
$D_s^+ \to \pi^+ e^+ e^-$	1.10×10^6	24.3	6.7	6	5.6	$< 2.2 \times 10^{-5}$
$D_s^+ \to \pi^- e^+ e^+$	1.10×10^6	33.4	2.2	4	6.2	$< 1.8 \times 10^{-5}$
$D_s^+ \to K^+ e^+ e^-$	1.10×10^6	17.3	3.0	7	9.3	$< 5.2 \times 10^{-5}$
$D_s^+ \to K^- e^+ e^+$	1.10×10^6	27.7	4.1	4	5.0	$< 1.7 \times 10^{-5}$
$D_s^+ \to \pi^+ \phi(e^+ e^-)$	1.10×10^6	33.9	0.7	3		$(0.6^{+0.8}_{-0.4} \pm 0.1) \times 10^{-5}$
					6.2	$< 1.8 \times 10^{-5}$

$X_c \rightarrow h l^+ l^-$ – Control Modes

- Before unblinding, checked procedure using ϕ resonance
  - Reverse l^+l^- mass cut:
    $0.995 < m(e^+e^-) < 1.030$ GeV/c^2
    $1.005 < m(\mu^+\mu^-) < 1.030$ GeV/c^2
- Significant signal seen in 3 of 4 modes
- Yield is about as expected
  - 1.5σ low in $D_s^+ \rightarrow \pi\phi$, $\phi \rightarrow e^+e^-$



Decay mode	Yield (events)	Efficiency (%)	Expected yield (events)
$D^+ \to \pi^+\phi_{e^+e^-}$	$21.8 \pm 5.8 \pm 1.5$	5.65	22.2 ± 1.1
$D^+ \to \pi^+\phi_{\mu^+\mu^-}$	$7.5 \pm 3.4 \pm 1.4$	1.11	4.5 ± 0.4
$D_s^+ \to \pi^+\phi_{e^+e^-}$	$62.8 \pm 9.9 \pm 3.0$	6.46	79 ± 3
$D_s^+ \to \pi^+\phi_{\mu^+\mu^-}$	$12.7 \pm 4.3 \pm 2.6$	1.07	13.1 ± 1.2

BABAR preliminary

$X_c \rightarrow hll$
Comparisons to Previous Limits

- Most channels improve upon previous limits
  - Many modes by more than order of magnitude
  - Dimuon modes have the worst limits (lowest efficiency)

Decay mode	BF UL (10^{-6}) 90% CL		
$D^+ \to \pi^+ e^+ e^-$	1.1	5.9	CLEO-c
$D^+ \to \pi^+ \mu^+ \mu^-$	6.5	3.9	D0
$D^+ \to \pi^+ e^+ \mu^-$	2.9	34	E791
$D^+ \to \pi^+ \mu^+ e^-$	3.6	34	E791
$D_s^+ \to \pi^+ e^+ e^-$	13	22	CLEO-c
$D_s^+ \to \pi^+ \mu^+ \mu^-$	43	26	FOCUS
$D_s^+ \to \pi^+ e^+ \mu^-$	12	610	E791
$D_s^+ \to \pi^+ \mu^+ e^-$	20	610	E791
$D^+ \to K^+ e^+ e^-$	1.0	3.0	CLEO-c
$D^+ \to K^+ \mu^+ \mu^-$	4.3	9.2	FOCUS
$D^+ \to K^+ e^+ \mu^-$	1.2	68	E791
$D^+ \to K^+ \mu^+ e^-$	2.8	68	E791
$D_s^+ \to K^+ e^+ e^-$	3.7	52	CLEO-c
$D_s^+ \to K^+ \mu^+ \mu^-$	21	36	FOCUS
$D_s^+ \to K^+ e^+ \mu^-$	14	630	E791
$D_s^+ \to K^+ \mu^+ e^-$	9.7	630	E791
$\Lambda_c^+ \to p e^+ e^-$	5.5	340	E653
$\Lambda_c^+ \to p \mu^+ \mu^-$	44		
$\Lambda_c^+ \to p e^+ \mu^-$	9.9		
$\Lambda_c^+ \to p \mu^+ e^-$	19		

Decay mode	BF UL (10^{-6}) 90% CL		
$D^+ \to \pi^- e^+ e^+$	1.9	1.1	CLEO-c
$D^+ \to \pi^- \mu^+ \mu^+$	2.0	4.8	FOCUS
$D^+ \to \pi^- \mu^+ e^+$	2.0	50	E791
$D_s^+ \to \pi^- e^+ e^+$	4.1	18	CLEO-c
$D_s^+ \to \pi^- \mu^+ \mu^+$	14	29	FOCUS
$D_s^+ \to \pi^- \mu^+ e^+$	8.4	730	E791
$D^+ \to K^- e^+ e^+$	0.9	3.5	CLEO-c
$D^+ \to K^- \mu^+ \mu^+$	10	13	FOCUS
$D^+ \to K^- \mu^+ e^+$	1.9	130	E687
$D_s^+ \to K^- e^+ e^+$	5.2	17	CLEO-c
$D_s^+ \to K^- \mu^+ \mu^+$	13	13	FOCUS
$D_s^+ \to K^- \mu^+ e^+$	6.1	680	E791
$\Lambda_c^+ \to \bar{p} e^+ e^+$	2.7		
$\Lambda_c^+ \to \bar{p} \mu^+ \mu^+$	9.4		
$\Lambda_c^+ \to \bar{p} \mu^+ e^+$	16		

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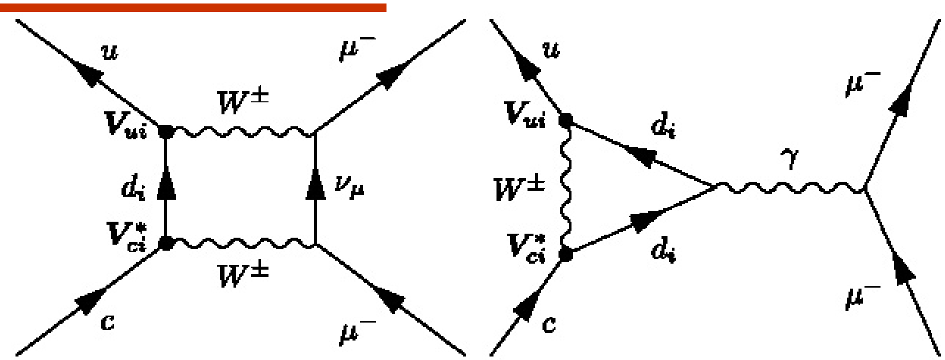
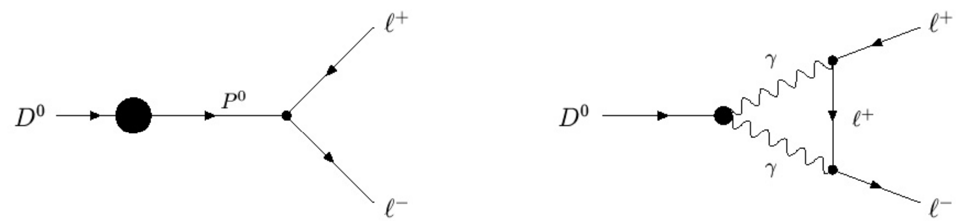
$D^0 \rightarrow \ell^+ \ell^-$

Motivation

FCNC of D mesons
- FCNC of uplike (c) quarks;
- $\Rightarrow$ complementary constraints to B (and K) rare decays;



short distance, B~10^{-18}



long distance, B~few 10^{-13}

G. Burdman et al., PRD66, 014009 (2002)

NP: enhancement of
- B($D^0 \rightarrow \mu^+\mu^-$) and B($D^0 \rightarrow e^+e^-$) by orders of magnitude;
- possibility of LFV $D^0 \rightarrow e^+\mu^-$;

example R SUSY:
- B($D^0 \rightarrow \mu^+\mu^-$) ~ $4\cdot 10^{-6}$
- B($D^0 \rightarrow e^+e^-$) ~ 10^{-10}
- B($D^0 \rightarrow e^+\mu^-$) ~ 10^{-6}

$D^0 \to \ell^+ \ell^-$

Belle, PRD81, 091102 (2010), 660 fb^{-1}

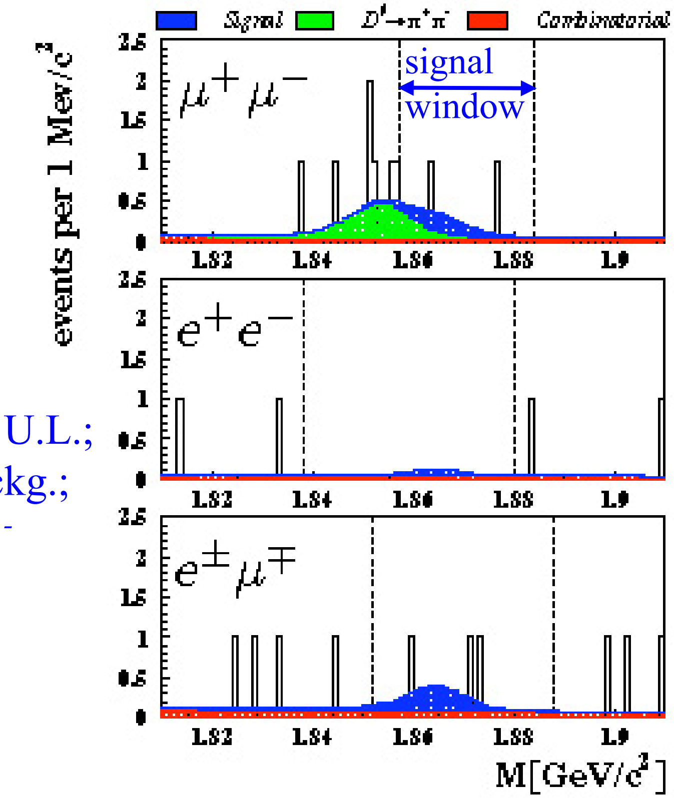
Results

$D^0 \to \ell^+ \ell^-$ yield

channel	$D^0 \to \mu\mu$	$D^0 \to ee$	$D^0 \to e\mu$
N	2	0	3
N_{bg}^{exp}	3.1±0.1	1.7±0.2	2.6±0.2

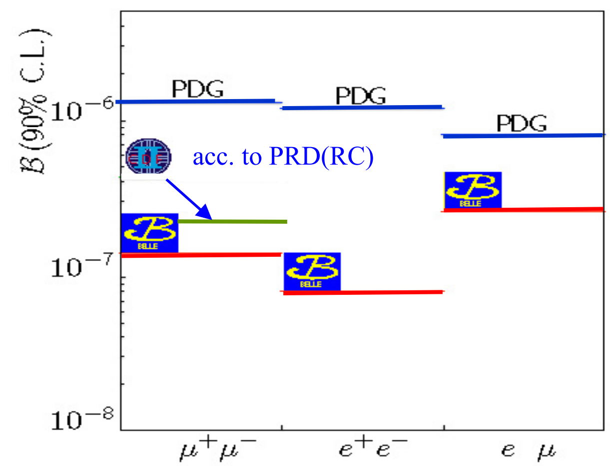
U.L.'s calculated from N and N_{bg}^{exp} including systematic uncertainties (negligible)

signal @ 90% C.L. U.L.; comb. backg.; $D^0 \to \pi^+\pi^-$ backg.; observed;



U.L.'s @ 90% C.L.

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.4 \cdot 10^{-7}$$
$$\mathcal{B}(D^0 \to e^+e^-) < 0.8 \cdot 10^{-7}$$
$$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 2.6 \cdot 10^{-7}$$



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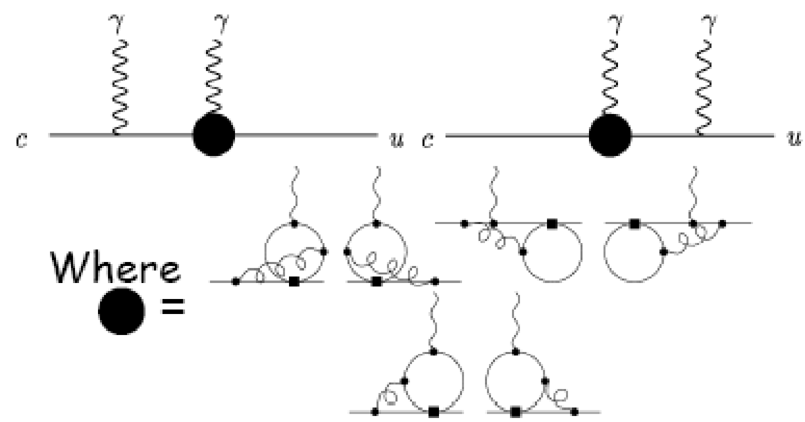
$D^0 \to \gamma\gamma$

- FCNC Decay
  - Forbidden at the tree-level
  - 1-loop GIM suppressed

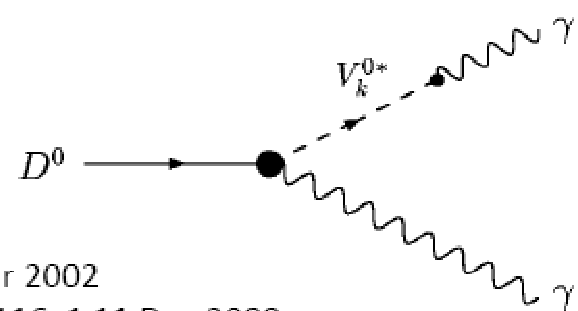
- Dominated by long distance effects [1]
  - Short-range (2-loop dominate):
    $B(D^0 \to \gamma\gamma) \approx 3 \times 10^{-11}$
  - Long-range (VMD contribution dominates):
    $B(D^0 \to \gamma\gamma) \approx 3.5 \times 10^{-8}$

- However, possible 10^2 enhancement from new physics (gluino-exchange of MSSM) [2]
- Within the range of BaBar sensitivity.
- Excellent (but difficult) mode to search for new physics

Short Distance



Long Distance



[1] Burdman et al. hep-ph/0112235v2 1 Mar 2002
[2] S. Prelovsek and D. Wyler, hep-ph/0012116v1 11 Dec 2000

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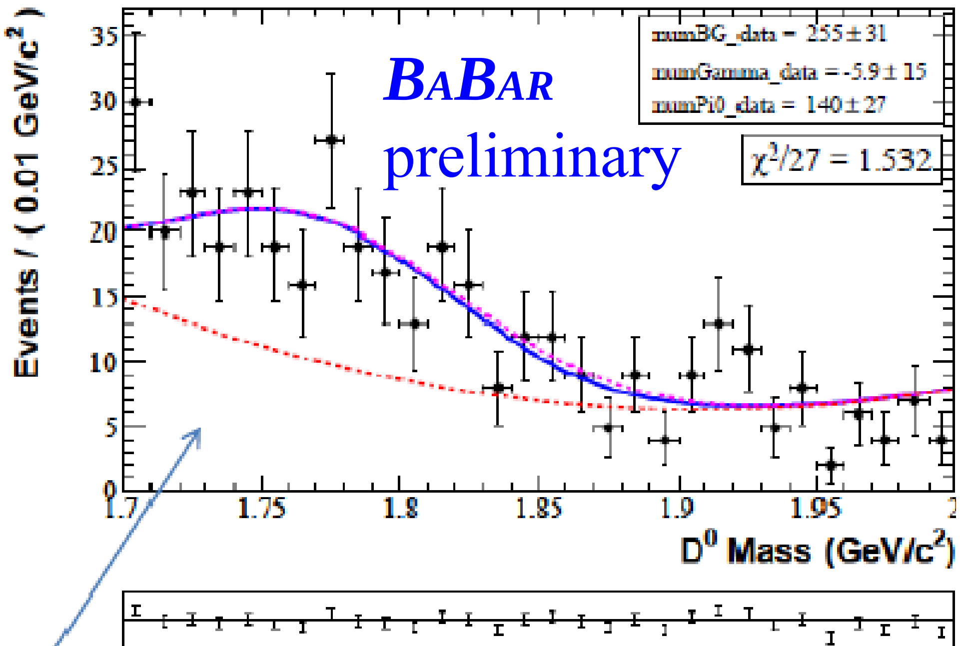
$D^0 \rightarrow \gamma\gamma$



Systematics

Systematic	$\sigma(D^0 \to \gamma\gamma)$ (%)	$\sigma(D^0 \to \pi^0\pi^0)$ (%)
Tracking (K_S^0) and Vertexing	0.96	0.96
Photon Reconstruction	0.60	3.00
π^0 Veto	1.80	-
D^{*+} Fragmentation	0.02	0.03
Signal Shape	*	0.20
Background Shape	*	0.80
Cut selection	*	2.50
$D^0 \to K_s^0\pi^0$ Signal Shape	0.53	0.17
$D^0 \to K_s^0\pi^0$ Background Shape	0.01	0.63
$D^0 \to K_s^0\pi^0$ Cut selection	0.76	0.76
Total Systematic Effect	*	4.23

[*] Near-zero relative errors are ill-defined and is accounted for using toy MC simulation

- $D^0 \rightarrow \gamma\gamma$
  - $B(D^0 \rightarrow \gamma\gamma) < 2.51 \times 10^{-6}$
  - About factor of 10 improvement on previous CLEO measurement

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Status of Rare Charm Decays

- FCNC, LFV, or LNV modes in the charm sector are a relatively inviting way to investigate new physics in the SM.
- Similar arguments hold for rare decays in the K and B sector. However, the charm system is unique in that it couples an up-type quark to new physics.
- Many results had not been updated in over a decade (E791, FOCUS, etc…), but new upper limits from various experiments are improved.
- More recently measurements are starting to confine the allowed parameter space of R-parity violating super-symmetric models.

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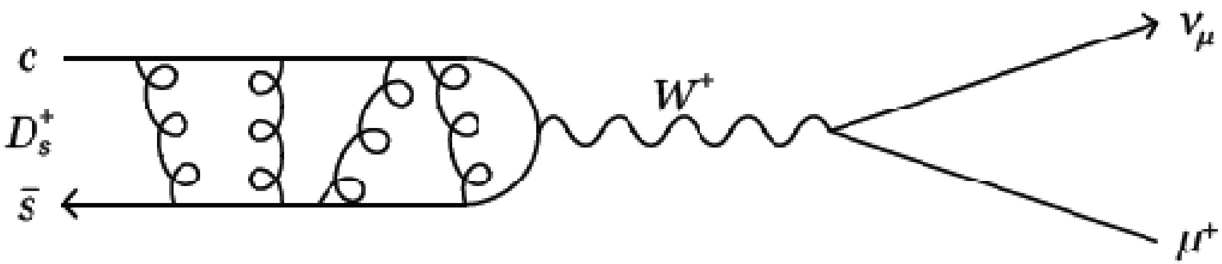
$f(D_s)$

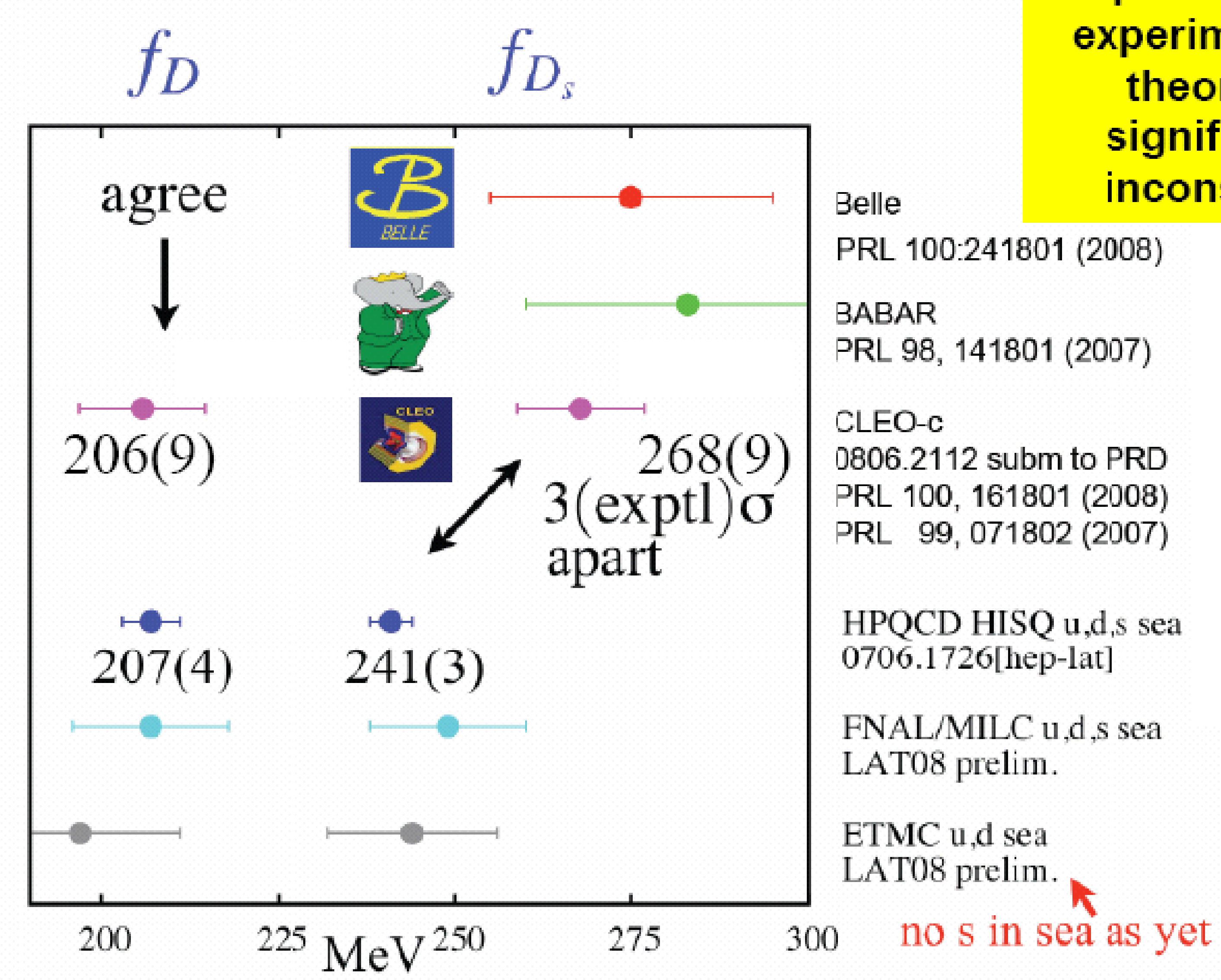
- In the standard model the leptonic decays of the D_s meson provide a clean way to measure the decay constant f_{Ds}:

$$B(D_s \to l\upsilon) = \frac{\Gamma(D_s \to l\upsilon)}{\Gamma(D_s \to all)} = \frac{G_F^2}{8\pi}|V_{cs}|^2 f_{D_s}^2 M_{D_s}^3 \left(\frac{m_l}{M_{D_s}}\right)^2 \left(1 - \frac{m_l^2}{M_{D_s}^2}\right)^2$$



From CKM08

More data required to see if experiment and theory are significantly inconsistent



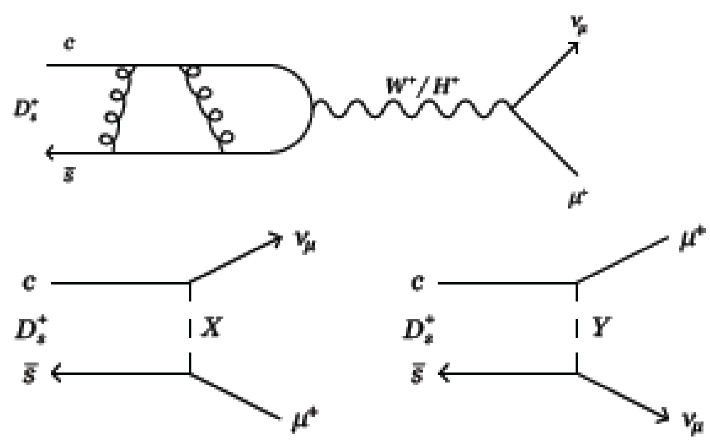
Many Averages, eg:

Previously 3.8 σ disagreement.

Phys.Rev.Lett.100:241802,2008.

& Many Explanations:

- This discrepancy could be the result of new physics:
  - Charged Higgs boson
  - Leptoquarks



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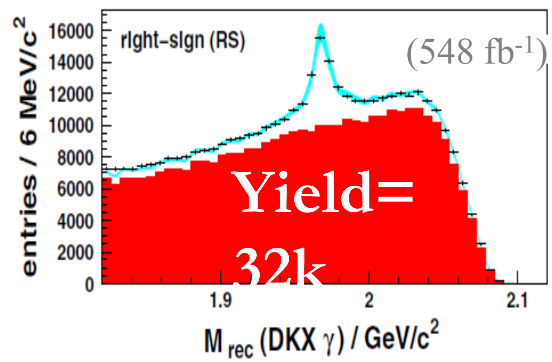
Comparison of BaBar, CLEOc and BELLE

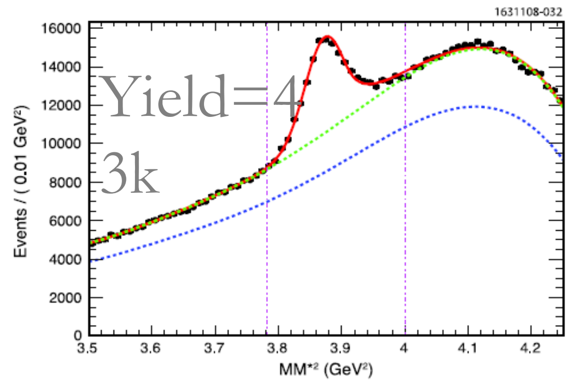
[Phys. Rev. D RC **82**, 091103 (2010)]

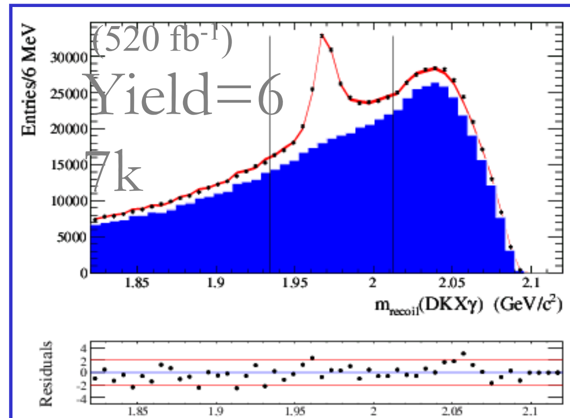
PRL **100**, 241801 (2008)

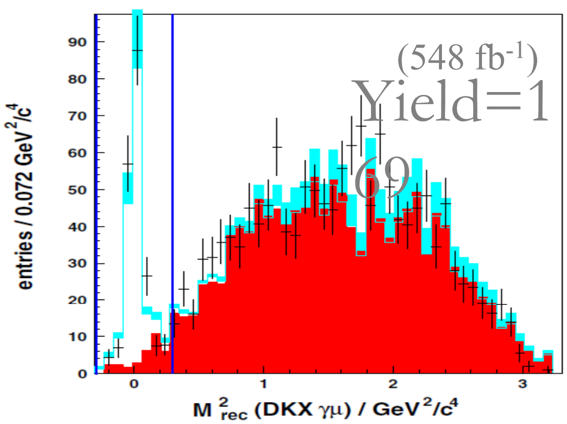
PHYSICAL RE

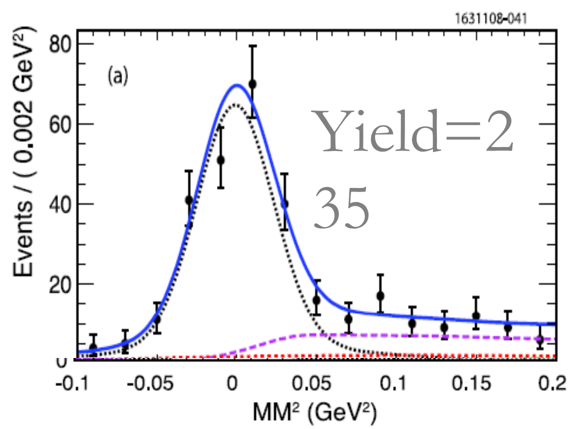


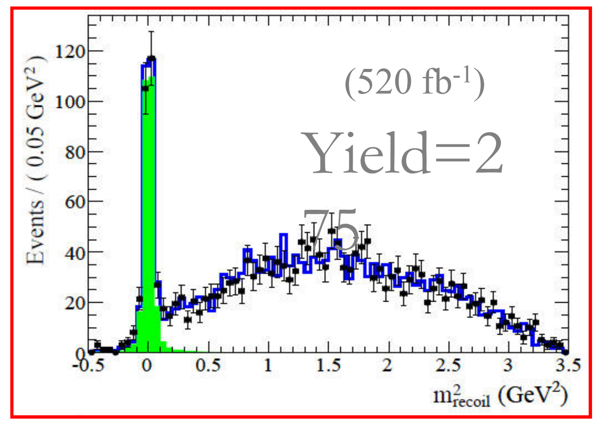
PHYSICAL REVIEW D 79, 052001 (2009)











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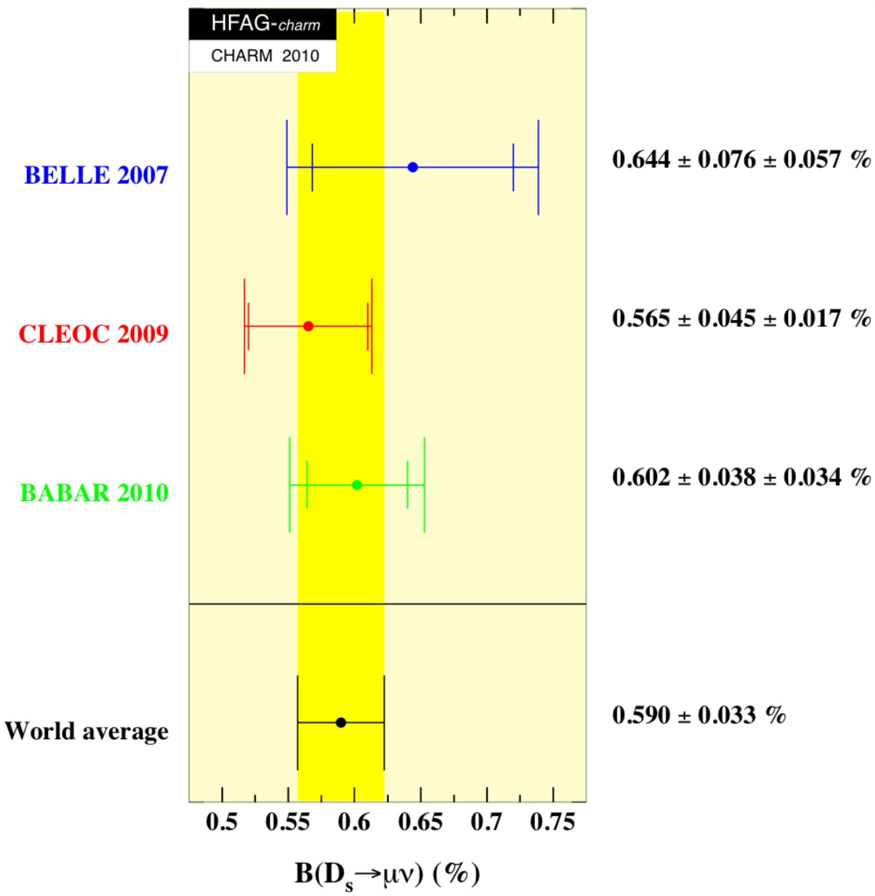
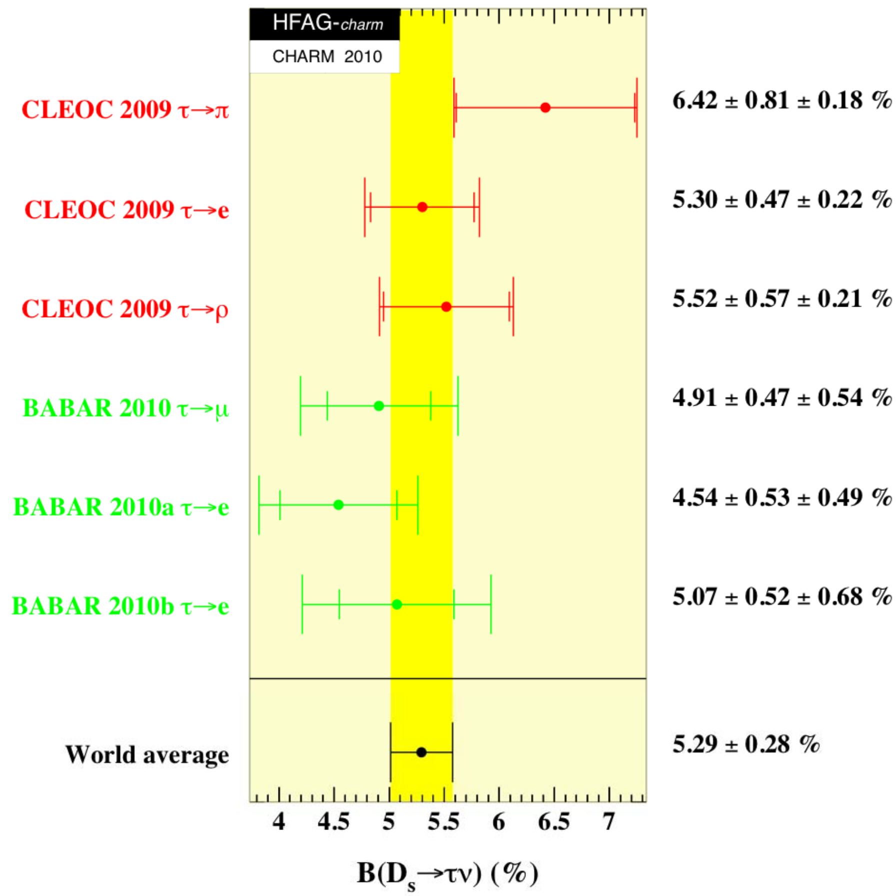
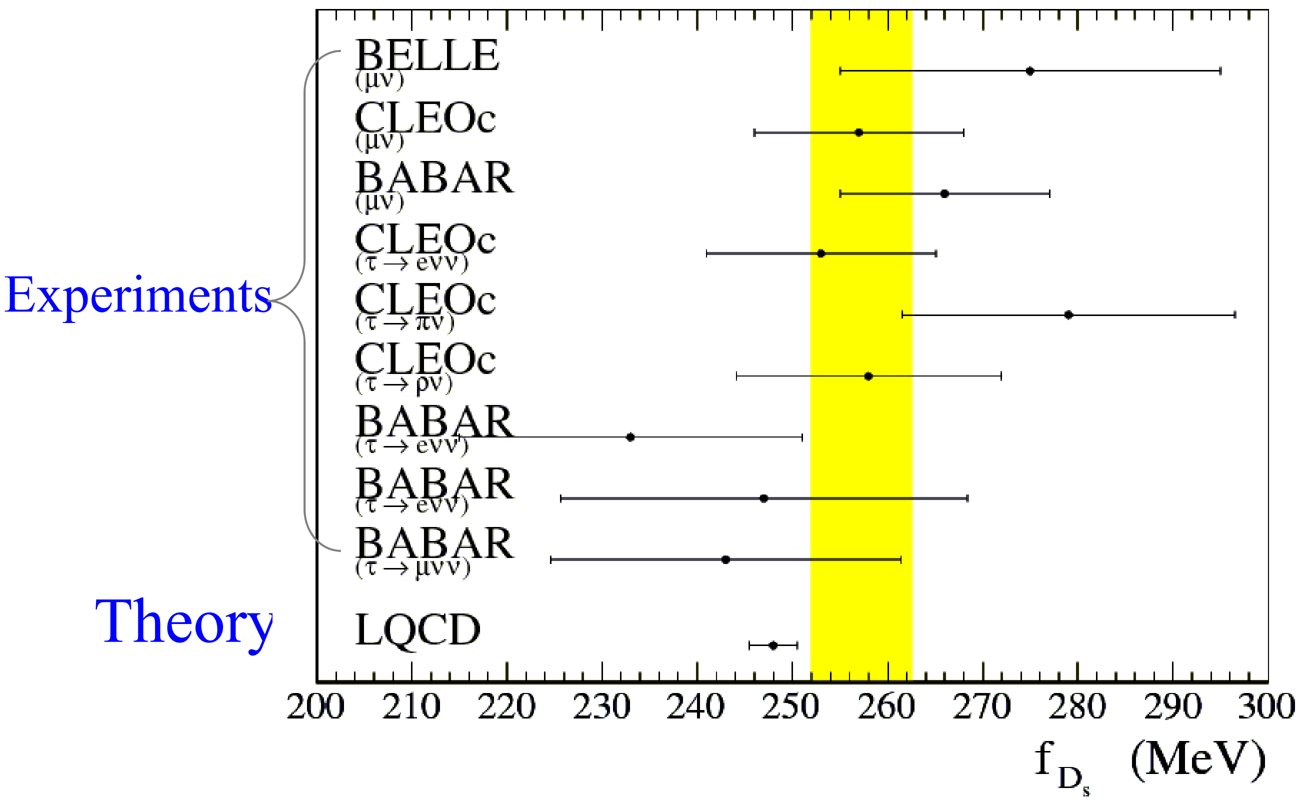
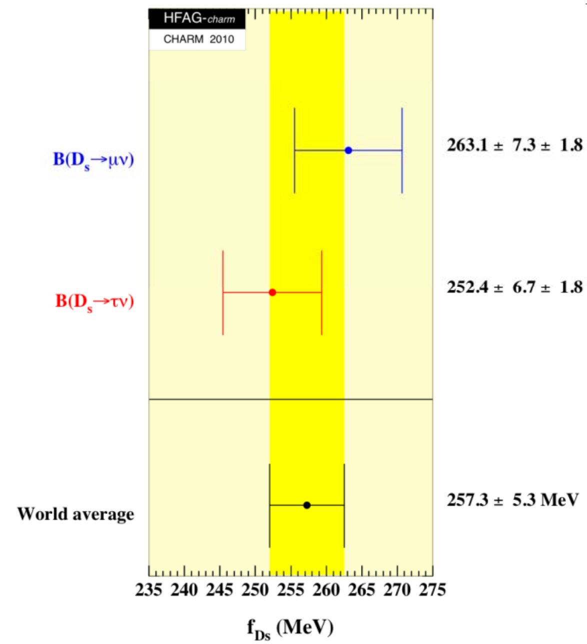
$f(D_s)$: comparison to other experiments





Theory vs. Experiment (new LQCD calculation)





LQCD value changed with their new energy scale calibration.

[PRD 82, 114504 (2010)]

HFAG (2011) = 257.3 +- 5.3
LQCD (2010) = 248.0 +- 2.5

$\Delta = 1.6\ \sigma$

Summary of $f(D_s)$

- *BABAR's* recent absolute measurements use a D_s-tagging technique (similar to the technique *BELLE* used) which reduces the systematic uncertainties. These measurements significantly improved the uncertainty on the world average value of $f(D_s)$.

- The current difference between theory and experiment for $f(D_s)$ is only about 1.6σ after the shift upwards in the new LQCD calculations.
  - A real difference would indicate contributions from Non-SM particles contributing in the decays.

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Charm Semileptonic Decays

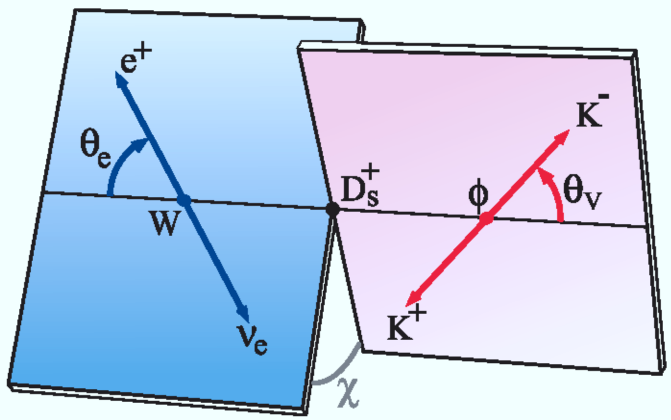


Figure 1: Decay angles θ_V, θ_ℓ and χ. Note that the angle χ between the decay planes is defined in the D-meson reference frame, whereas the angles θ_V and θ_ℓ are defined in the V meson and W reference frames, respectively.

Charm Semileptonic Decays

Kinematics require that $A_3(0) = A_0(0)$. The differential partial width is

$$\begin{aligned}\frac{d\Gamma(D \to V\ell\bar{\nu}_\ell)}{dq^2\, d\cos\theta_\ell} &= \frac{G_F^2\,|V_{cq}|^2}{128\pi^3 M_D^2}\, p^*\, q^2 \times \\ &\left[\frac{(1-\cos\theta_\ell)^2}{2}|H_-|^2 \;+\; \frac{(1+\cos\theta_\ell)^2}{2}|H_+|^2 \;+\; \sin^2\theta_\ell |H_0|^2\right], \qquad (15)\end{aligned}$$

where $H_\pm$ and H_0 are helicity amplitudes given by

$$H_\pm = \frac{1}{M_D + m_h}\left[(M_B + m_h)^2 A_1(q^2) \;\mp\; 2M_D\, p^* V(q^2)\right] \qquad (16)$$

$$\begin{aligned}H_0 &= \frac{1}{|q|}\frac{M_B^2}{2m_h(M_D+m_h)} \times \\ &\left[\left(1 - \frac{m_h^2 - q^2}{M_D^2}\right)(M_D^2 + m_h^2)A_1(q^2) \;-\; 4p^{*2}A_2(q^2)\right]. \qquad (17)\end{aligned}$$

The left-handed nature of the quark current manifests itself as $|H_-| > |H_+|$. The differential decay rate for $D \to V\ell\nu$ followed by the vector meson decaying into two pseudoscalars is

$$\begin{aligned}\frac{d\Gamma(D \to V\ell\nu, V \to P_1P_2)}{dq^2 d\cos\theta_V d\cos\theta_\ell d\chi} &= \frac{3G_F^2}{2048\pi^4}|V_{cq}|^2\frac{p^*(q^2)q^2}{M_D^2}\mathcal{B}(V \to P_1P_2) \;\times \\ &\{(1+\cos\theta_\ell)^2\sin^2\theta_V |H_+(q^2)|^2 \\ &+ (1-\cos\theta_\ell)^2\sin^2\theta_V |H_-(q^2)|^2 \\ &+ 4\sin^2\theta_\ell\cos^2\theta_V |H_0(q^2)|^2 \\ &+ 4\sin\theta_\ell(1+\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi H_+(q^2)H_0(q^2) \\ &- 4\sin\theta_\ell(1-\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi H_-(q^2)H_0(q^2) \\ &- 2\sin^2\theta_\ell\sin^2\theta_V\cos 2\chi H_+(q^2)H_-(q^2)\}, \qquad (18)\end{aligned}$$

where the angles θ_ℓ, θ_V, and χ are defined in Fig. 1.

Assuming that the simple pole form of Eq. (5) describes the q^2-dependence of the form factors, the distribution of Eq. (18) will depend only on the parameters

$$r_V \equiv V(0)/A_1(0), \qquad r_2 \equiv A_2(0)/A_1(0). \qquad (19)$$

Charm Semileptonic Decays

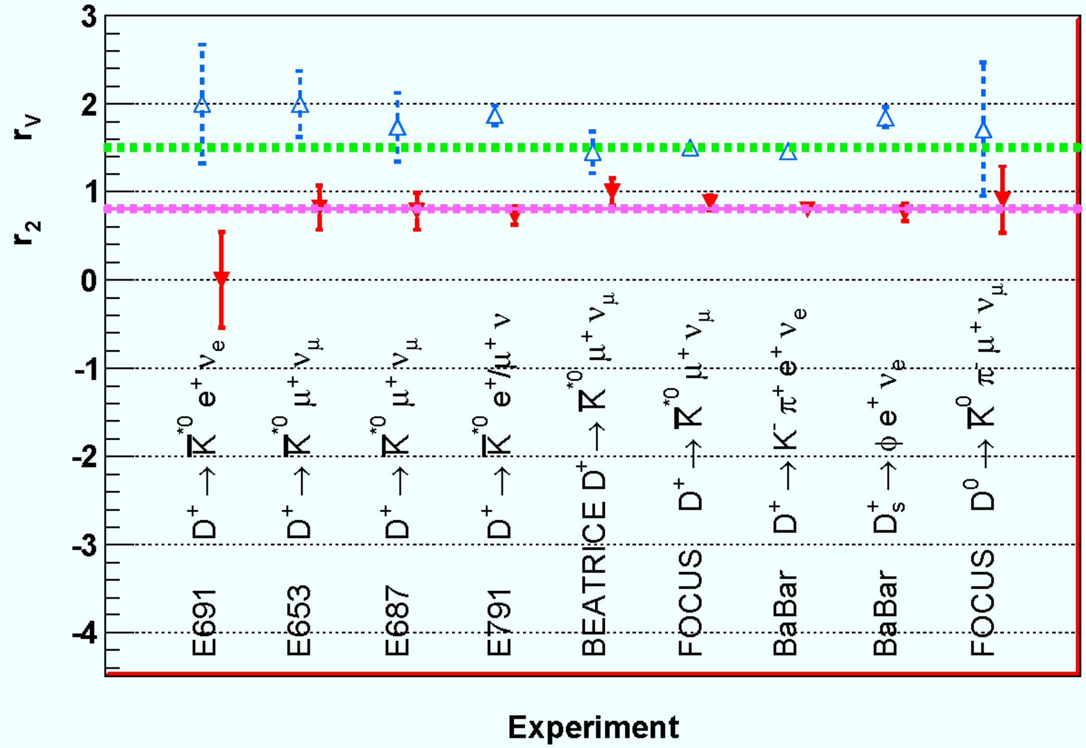


Figure 2: A comparison of r_2 and r_V values from various experiments. The first seven measurements are for $D^+ \to K^-\pi^+l^+\nu_l$ decays. Also shown as a line with 1-σ limits is the average of these. The last two points are D_s^+ decays and Cabibbo-suppressed D decays.

Charm Semileptonic Decays

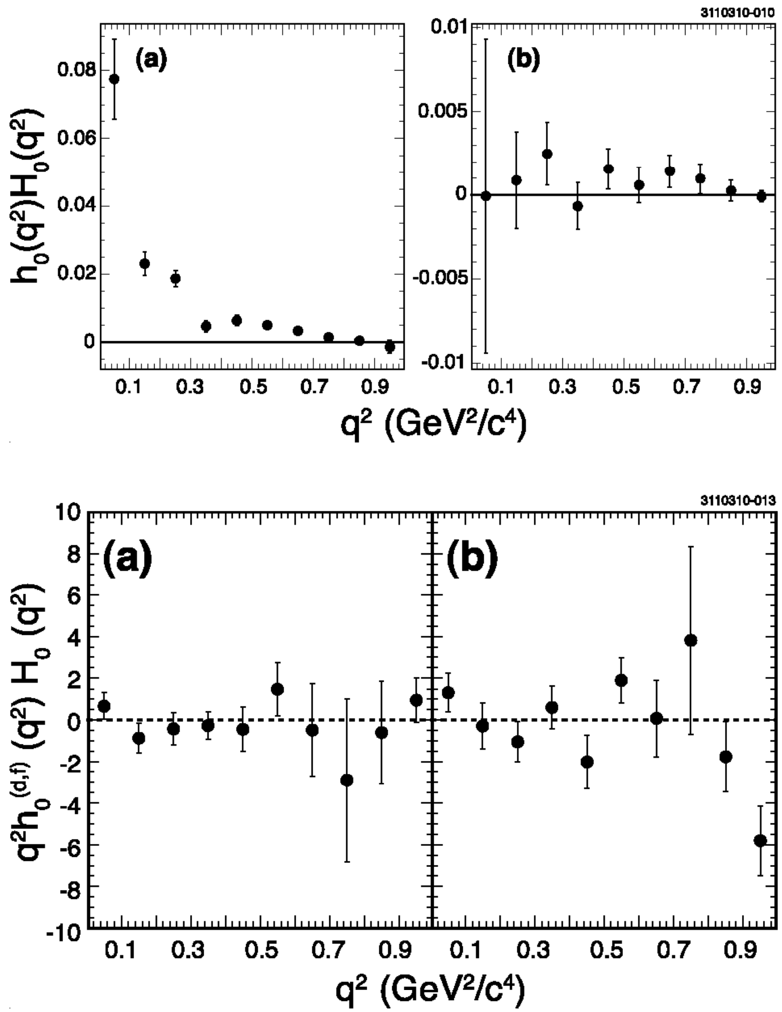


Figure 3: Model-independent form factors $h_0(q^2)$ measured by CLEO-c[21].

Charm Semileptonic Decays

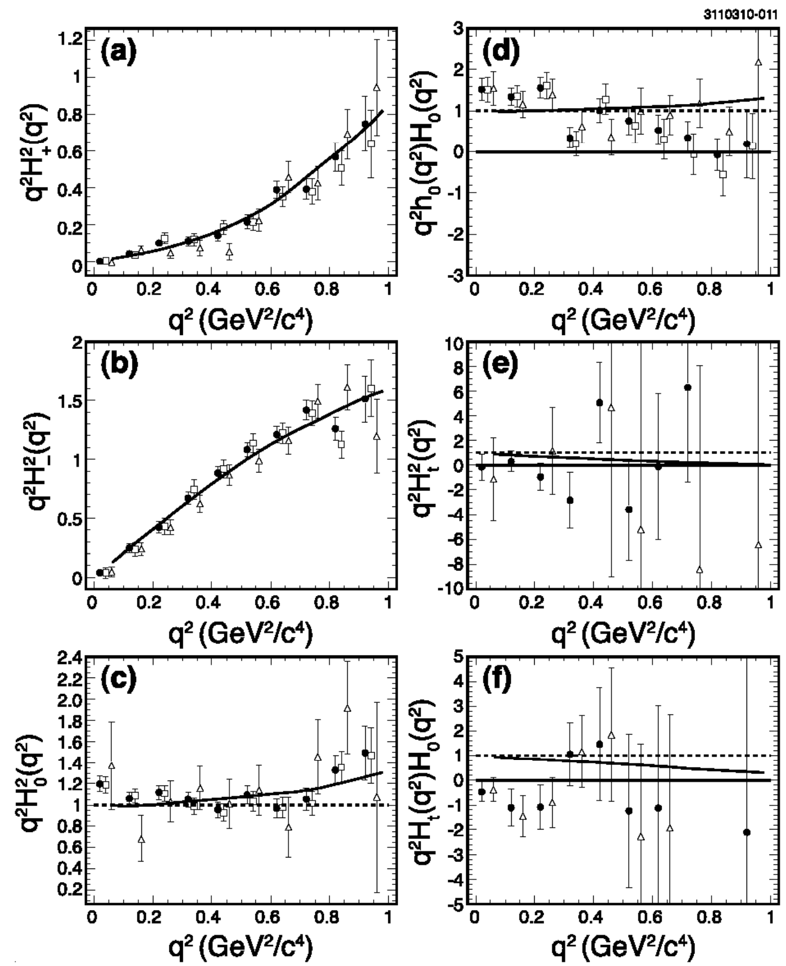


Figure 4: Model-independent form factors $H(q^2)$ measured by CLEO-c[21].

Acknowledgements

- Thanks to Brian Meadows, Brett Altschul, Jon Coleman, Nicola Neri,

  HFAG people, *et al.*

Charm Physics at SuperB: Summary

- There are many contributions to make in
  - CPT Violation
  - CP violation
  - D mixing
  - Rare charm decays
  - $f(D_s)$
  - Semileptonic Decays
  - Charm baryons
  - Excited D mesons
  - BF measurements
- In many cases New Physics can be explored
- There is an exciting road ahead!

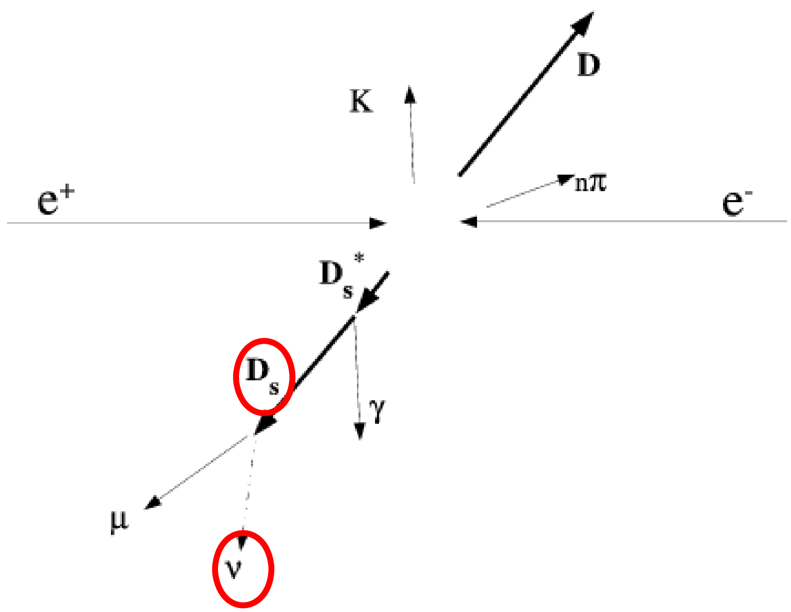
Extra Slides

[Phys. Rev. D RC **82**, 091103 (2010)]

$f(D_s)$ Analysis Strategy

Event reconstruction :

$$e^+e^- \rightarrow c\,\bar{c} \rightarrow D\,K\,X\,D_s^{*-} \rightarrow D\,K\,X\,\gamma\,\ell^-\,\bar{\nu}$$
$$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \lfloor D_s^-\,\gamma$$



- A normalization sample is created by D_s Tagging using the recoil mass:

$m_{Ds}^2 = [p_{e+} + p_{e-} - (p_D + p_K + p_X + p_\gamma)]^2$

- $D_s^- \rightarrow \mu^-\nu$, $e^-\nu$ events can be can be detected by calculating the mass of the neutrino:

$m_\nu^2 = [p_{e+} + p_{e-} - (p_D + p_K + p_X + p_\gamma + p_\ell)]^2$

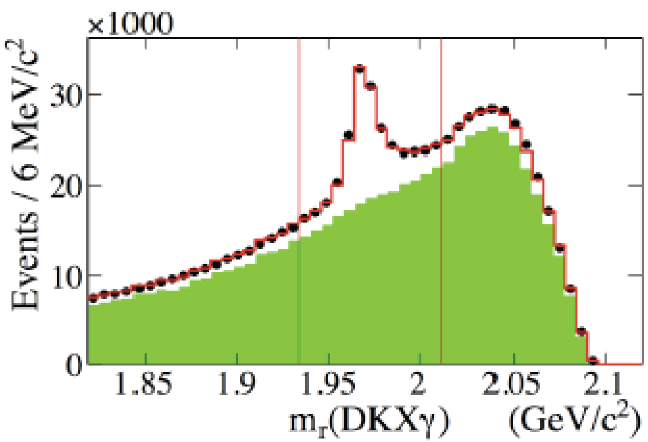
- $D_s^- \rightarrow \tau^-\nu$ events are counted using the distribution of extra energy in the EMC which should peak towards 0.

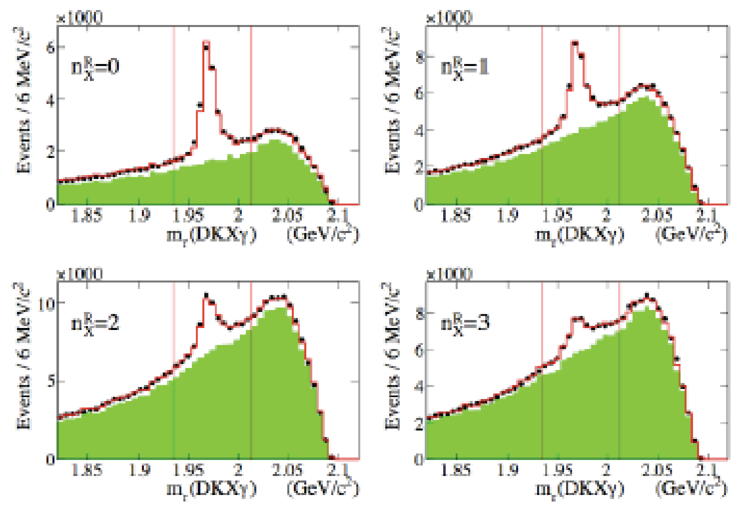
X = reconstructed pions

[Phys. Rev. D RC **82**, 091103 (2010)]

$f(D_s)$ The Denominator

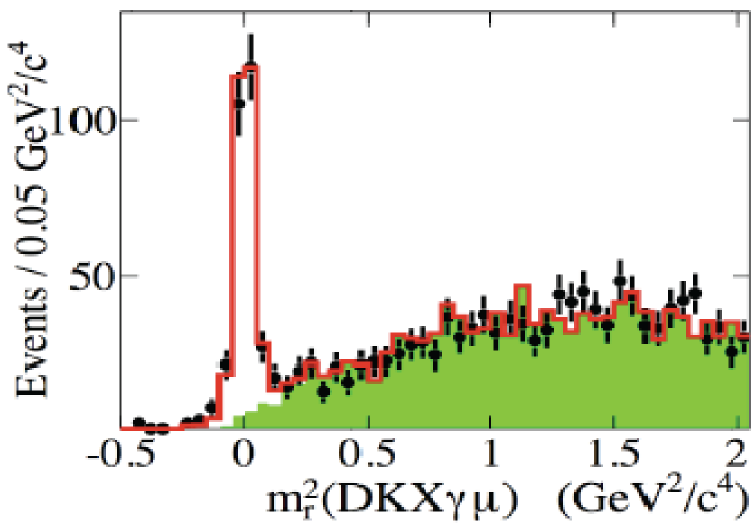
- The yield of Ds mesons is determined using a 2-D fit to:
  - Mass recoiling against the DKX γ system
  - n_X^R, the reconstructed number of pions in the fragmentation system.
- We obtain $n(D_s) = 67{,}200 \pm 1500$.





$D_s \rightarrow \mu\upsilon$ reconstruction

- **A muon** candidate is identified, using standard particle identification techniques.
- The mass of the D_s candidate is constrained to the mass provided by the Particle Data Group.
- We require E_{Extra}<1GeV.
- A kinematic fit to the whole event is performed.
- A binned maximum likelihood fit to the mass squared recoiling against the DKX γ μ system, m_m^2, is performed.



We obtain events 274 ± 17, which yields $B(D_s \rightarrow \mu\ \nu) = (6.02 \pm 0.37 \pm 0.33) \times 10^{-3}$

[Phys. Rev. D RC **82**, 091103 (2010)]

[Phys. Rev. D RC **82**, 091103 (2010)]

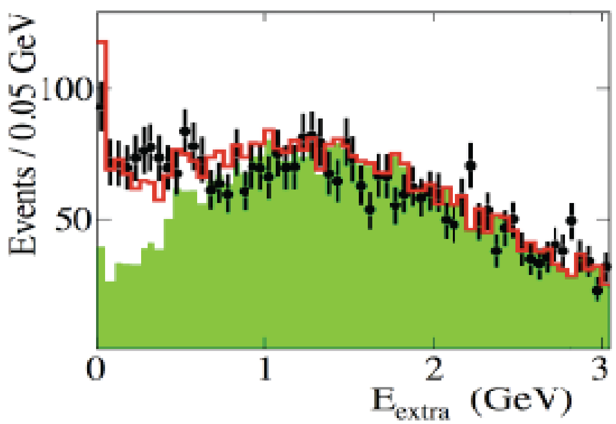
$D_s \to \tau\ \nu$ reconstruction

$\tau \to \pi\nu$ impossible due to backgrounds

- We measure the final states
  - $\tau \to e \nu\ \nu$
  - $\tau \to \mu\ \nu\ \nu$ first measurement since LEP
- Particle identification procedure remains the same as for $D_s \to e\nu$ and $D_s \to \mu\ \nu$ as appropriate.
- For $D_s \to \tau\ \nu$; $\tau \to \mu\ \nu\ \nu$ we require $m_m^2 > 0.3\ \mathrm{GeV}^2 c^{-4}$ to remove backgrounds from $D_s \to \mu\ \nu$ events.
- For $D_s \to \tau\ \nu$ decays we perform a binned maximum likelihood fit to E_{Extra}.

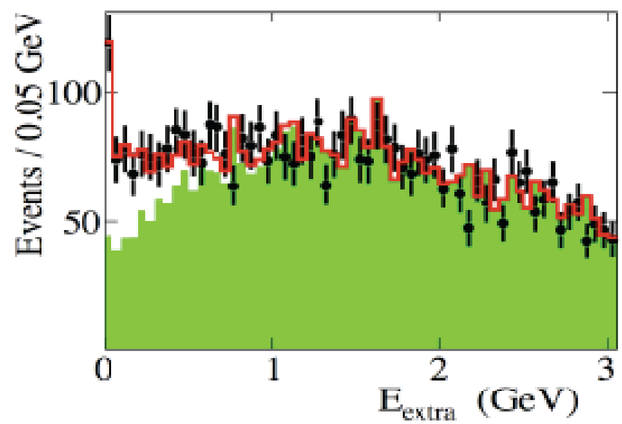
[Phys. Rev. D RC **82**, 091103 (2010)]

$D_s \rightarrow \tau\ \nu$ reconstruction



Left: $\tau \rightarrow e\, \nu\ \nu$

Right: $\tau \rightarrow \mu\ \nu\ \nu$



Mode	Yield	Branching fraction
$D_s \rightarrow \tau\ \nu$; $\tau \rightarrow e\, \nu\ \nu$	408 ± 42	$(4.91 \pm 0.50 \pm 0.66) \times 10^{-2}$
$D_s \rightarrow \tau\ \nu$; $\tau \rightarrow \mu\ \nu\ \nu$	340 ± 32	$(5.07 \pm 0.48 \pm 0.54) \times 10^{-2}$
Combined		$(5.00 \pm 0.35 \pm 0.49) \times 10^{-2}$

[Phys. Rev. D RC **82**, 091103 (2010)]

- Due to the nature of the reconstruction, most of the systematic uncertainties cancel out exactly
- Remaining dominant systematic uncertainties arise from signal and background models

□ Values for f_{D_s} are obtained using the formula:

$$f_{D_s^+} = \frac{1}{G_F m_\ell \left(1 - \frac{m_\ell^2}{M_{D_s^+}^2}\right) |V_{cs}|} \sqrt{\frac{8\pi B(D_s^+ \to \ell\nu)}{M_{D_s^+} \tau_{D_s^+}}}$$

Decay mode	B(Ds→l ν)	f_{Ds}
$D_s \to \mu\ \nu$	$(6.02 \pm 0.37 \pm 0.33) \times 10^{-3}$	$(265.7 \pm 8.4 \pm 7.9)$ MeV
$D_s \to \tau\ \nu$; $\tau \to e\ \nu\ \nu$	$(4.91 \pm 0.50 \pm 0.66) \times 10^{-2}$	$(247 \pm 13 \pm 17)$ MeV
$D_s \to \tau\ \nu$; $\tau \to \mu\ \nu\ \nu$	$(5.07 \pm 0.48 \pm 0.54) \times 10^{-2}$	$(243 \pm 12 \pm 14)$ MeV
Combined		$(258.6 \pm 6.4 \pm 7.5)$ MeV

Relative Measurement of $D_s^- \rightarrow \tau^- \bar{\nu}$ using $D_s^- \rightarrow K_s K^-$

[arXiv: 1003.3063]

- Reconstruct recoil mass against $DKX\gamma$ to tag D_s events
- Require an additional electron tagging $\tau^- \rightarrow e^- \nu \nu$
- Peaking backgrounds remaining are estimated.
- Similarly, create separate sample which is tagged as $D_s^- \rightarrow K_s K^-$
- Signal yields: 448±36 for $D_s \rightarrow \tau\nu$ and 333 ± 28 for $K_s K$.