CLEO Collaboration: Status Report & Physics in the Completion Period

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Why I am here

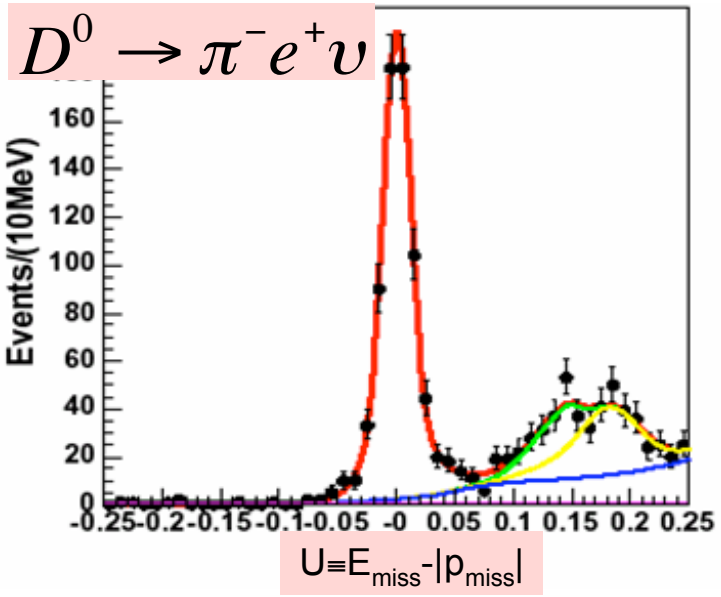
- CLEO-c begins its final data run Dec 7
- Data taking ends on March 31, 2008
- CLEO-c collaborators will need support
  - To complete analyses, Ph.D. theses, publish papers
  - For graduate students and post-docs
- Today I am here to report on the status of the broad CLEO-c physics program and to share with you our excitement for the future of CLEO

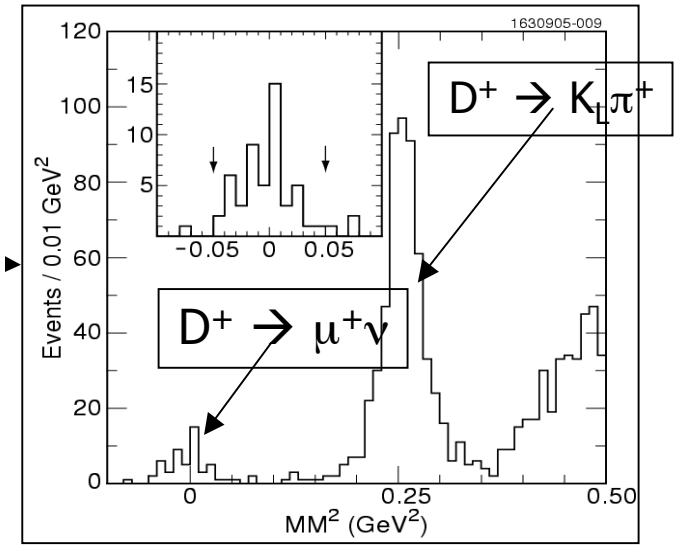
CLEO-c data sample is unique

- High precision, low-energy probe of charm quark physics
- Charm production at threshold is ideal for many important measurements
  - Some cannot be done elsewhere
  - OR cannot be done nearly as precisely

Advantages of Threshold Production

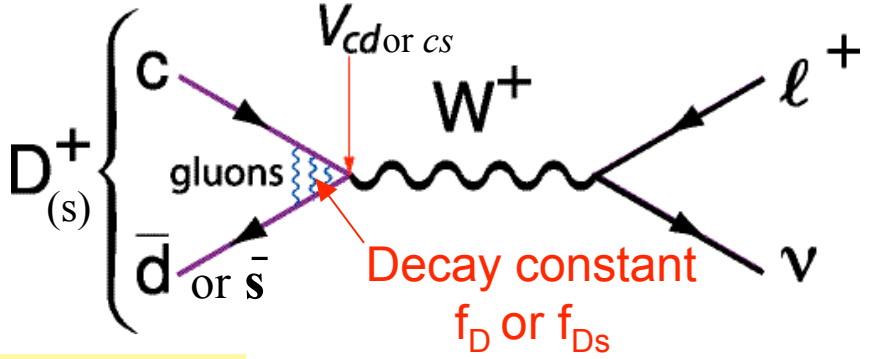
- $e^+e^- \rightarrow$ DD or $D_s^+D_s^{*-}$ ($E_D=E_{beam}$)
  - no additional particles produced
- Important for final states with one missing particle
  - neutrino in (semi)leptonic decays
  - K_L in $K_L\pi$ or $K_L\pi\pi$
- CLEO-c detector covers 93% of 4π
  - First detector at 4 GeV with RICH for particle ID and CsI for EM Calorimetry
- Enables 'reconstruction' of
  - (Missing mass)^2
  - U= E_{miss} - $|p_{miss}|$





$$MM^2 = \left(E_{CM} - E_{D_{tag}} - E_\mu\right)^2 - \left(-\vec{p}_{D_{tag}} - \vec{p}_\mu\right)^2$$

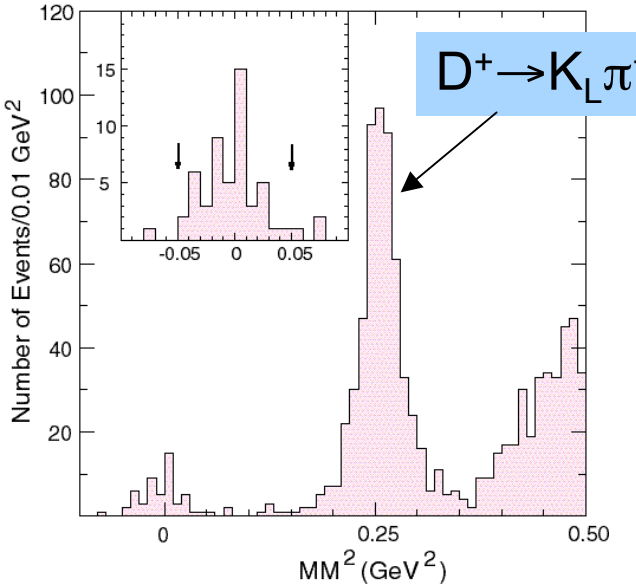
Leptonic Decays at CLEO-c

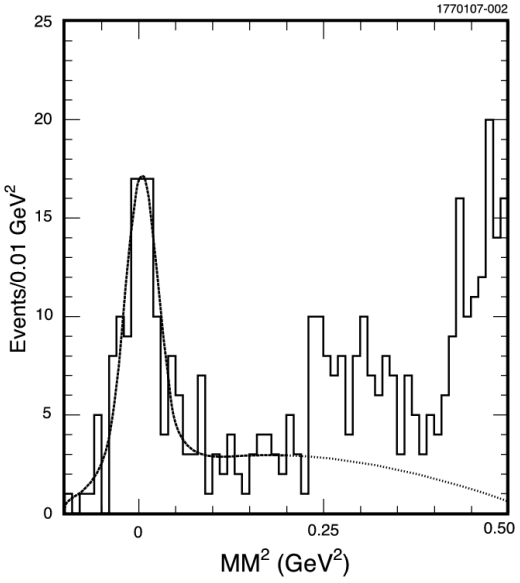


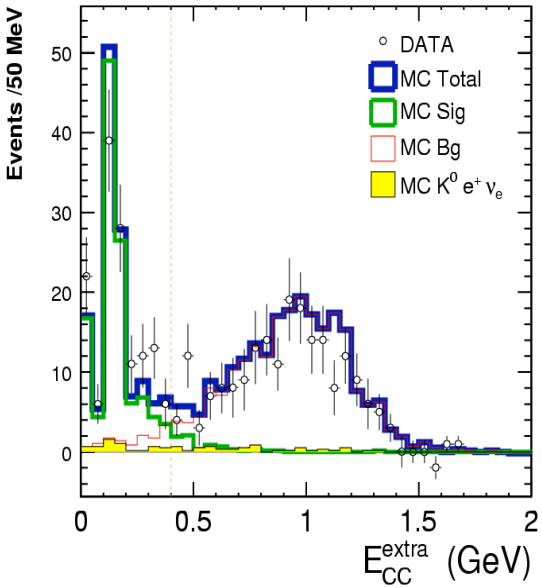
First and only measurement
$D^+ \to \mu^+\nu$

Most Precise
$D_s^+ \to \mu^+\nu$

Most Precise
$D_s^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu$



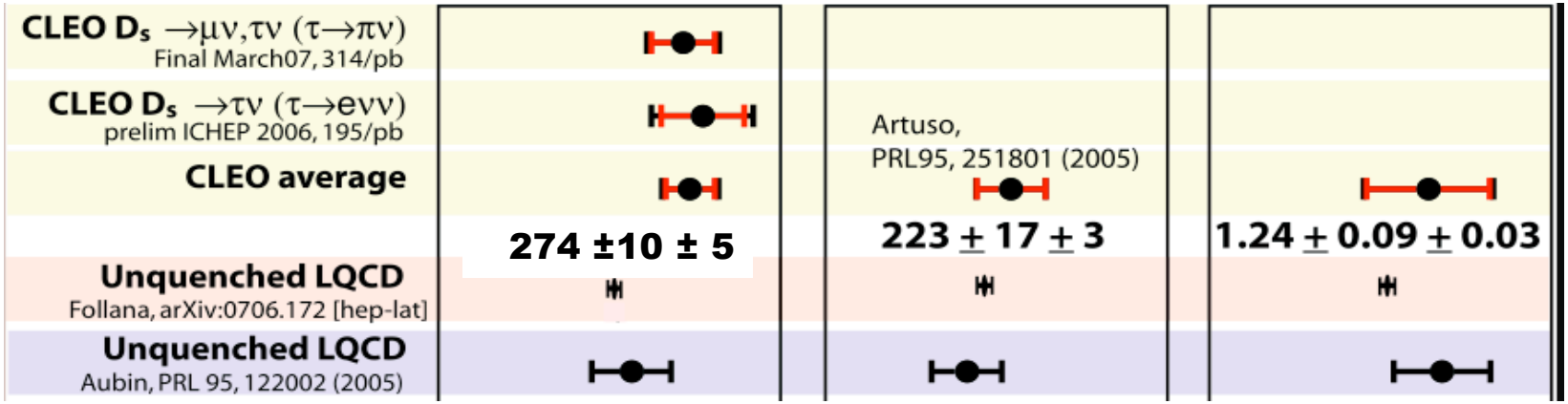




$f_{D^+} = (222.6 \pm 16.7^{+2.3}_{-3.4})$ MeV

$f_{Ds} = (274 \pm 10 \pm 5)$ MeV

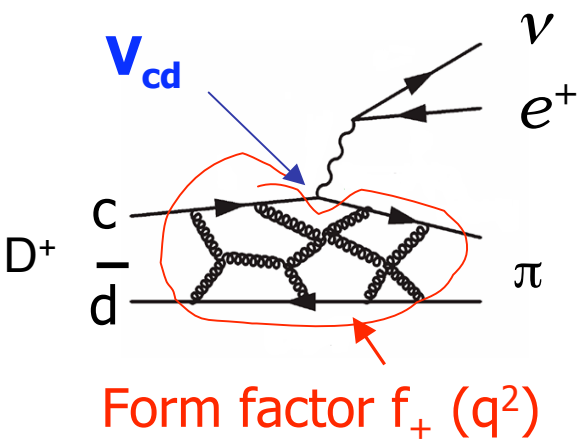
CLEO-c Leptonic Results Confront LQCD

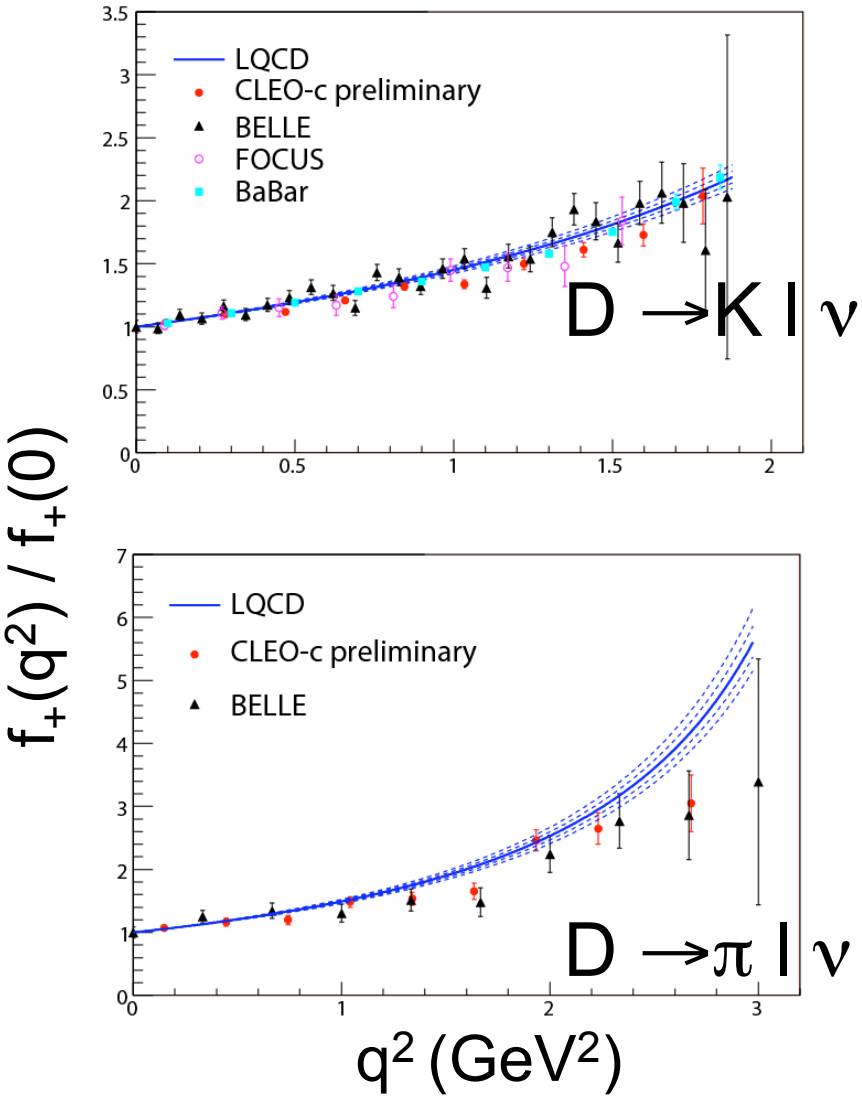


- Recent LQCD - Follana et al.
  - f_{Ds} = 241±3 MeV
- Experimental average (CLEO-c + Belle)
  - f_{Ds} = 274±10 MeV

3.2 sigma discrepancy between data and LQCD!
Expect factor of two more CLEO-c data

Semileptonic Decays and form factors





Generally good agreement between experiments

LQCD $\pi e \nu$ points a bit high

Theory prediction more precise than experiment

Quantum Correlations at CLEO-c

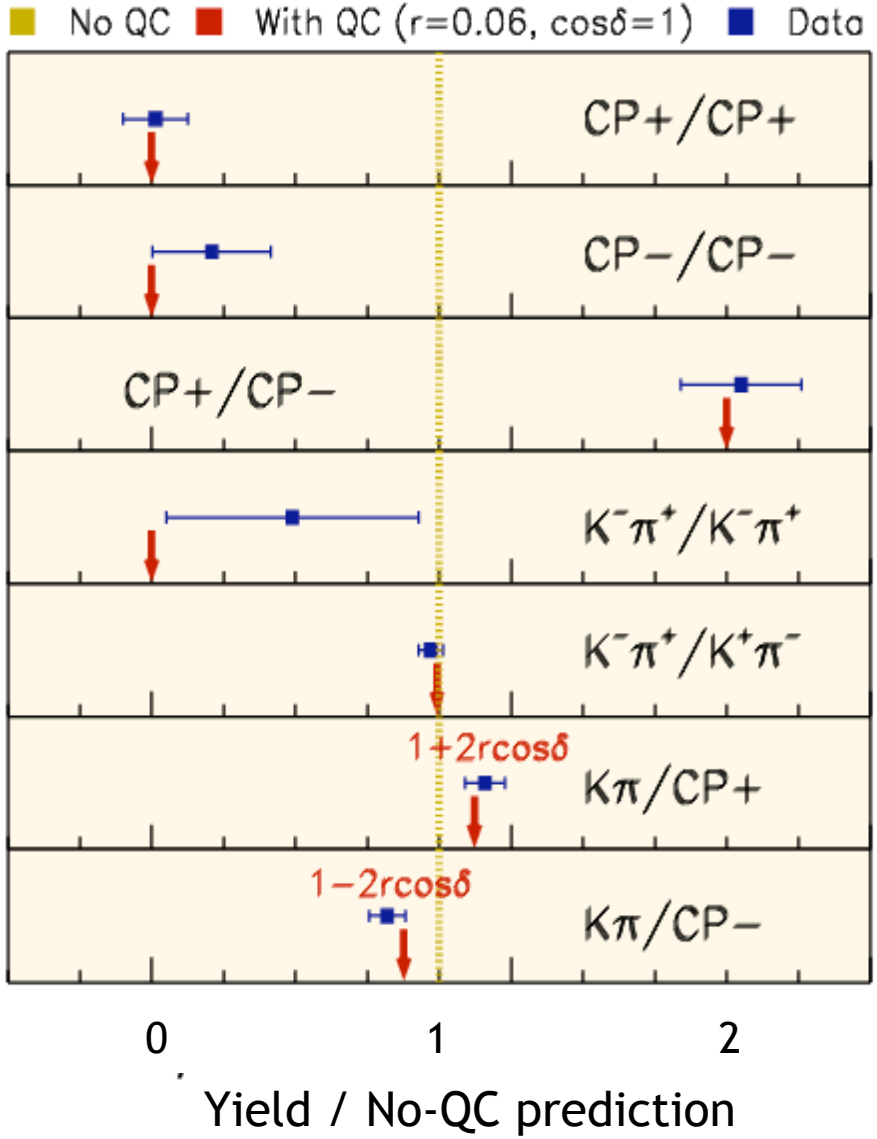
Enable strong phase measurements

- sys. err. $10^o \rightarrow 3^o$ on phase of V_{ub}
- 50% smaller err. on D mixing amplitude

Initial State C = –1

$e^+e^- \rightarrow \gamma^* \xrightarrow{\psi(3770)} D^0\bar{D}^0$

Forbidden by CP conservation	$CP+$	$CP+$
	$CP-$	$CP-$
Maximal enhancement	$CP+$	$CP-$
Forbidden if no mixing	$K^-\pi^+$	$K^-\pi^+$
Interference of CF with DCS	$K^-\pi^+$	$CP\pm$
	$CP\pm$	$K^-\pi^+$
Unaffected	X	$K^+l^-\nu$



Impact of CLEO Physics

- Broad impact on heavy flavor physics and QCD

- Focused and crisp challenges to theoretical techniques for QCD calculations - particularly techniques for non-perturbative QCD
  - Important if New Physics observed at LHC has strongly coupled sector

- Leptonic Decays
  - Measure decay constants f_D, f_{Ds} - stringent test of LQCD
  - Validated LQCD provides f_B, f_{Bs} - important for V_{ts}, V_{td}

- Semileptonic Decays + validated LQCD
  - Provide V_{cs}, V_{cd}, test CKM unitarity
  - Decay rates, q^2 dependence - stringent tests of LQCD
  - Improved V_{ub} - only with validated LQCD q^2 dependence calculation

Flavor Physics and the LHC

- Measurements of CKM angles and other CP violating and rare processes, should show effects of any new particles found directly by ATLAS/CMS

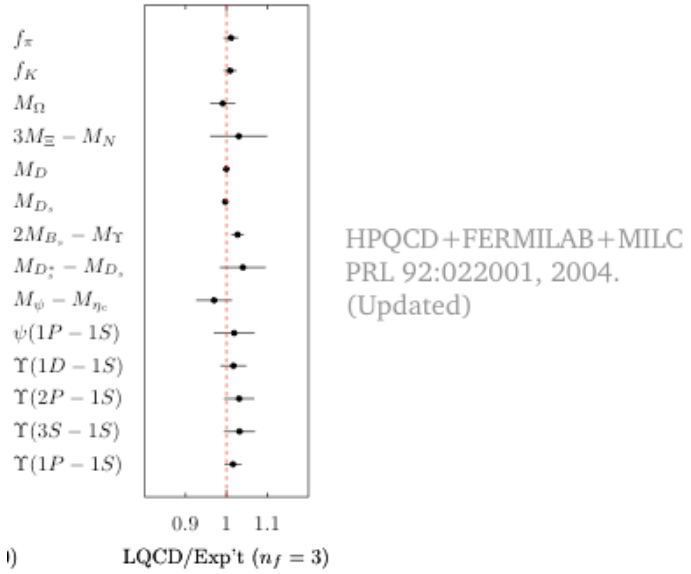
- Precision Electroweak results imply New Physics ~ 1 TeV
- Precision Flavor results imply New Physics ~ 10-100 TeV

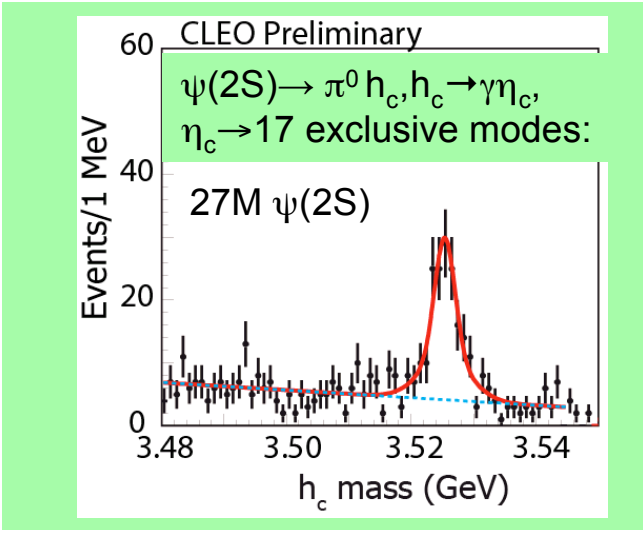
- CERN is studying the relationship between New Physics observed at the LHC and flavor physics through a pair of Workshop series
  - CERN Workshop Series "Flavor in the Era of the LHC"
    - http://mlm.home.cern.ch/mlm/FlavLHC.html
  - Follow-up workshop series "Interplay of Collider and Flavour Physics"
    - https://twiki.cern.ch/twiki/bin/view/Main/ColliderAndFlavour

- Validating QCD calculations is important for use in a wide variety of measurements that will elucidate the nature of this New Physics
  - Proven techniques especially important if New Physics observed at LHC has strongly coupled sector

Charmonia and Bottomonia

- LQCD - single formalism relaets D/B to ψ/Υ
  - Independent calibration in D/B
    - Form factors, decay constants, etc…
- >30 gold-plated quantities where few % LQCD calculations possible
  - Masses, Mass differences
  - Decay widths, Ratios of decay widths
  - Decay dynamics
- Υ(nS) data "oldest"
  - Most stringent lattice test
    - CLEO Γ_{ee} (Υ(2S))/ Γ_{ee}(Υ(1S)=0.457 ±0.006 (1.2%) - c.w. Lattice 0.48 ±0.05
  - Search for h_b, η_b
- ψ(2S) data 89% recorded in 2006
  - Additional stringent LQCD tests
  - Precision h_c mass
    - Hyperfine splitting uncertainty $\Delta M(1P)=1.0\pm0.6\pm0.4$ MeV dominated by h_c
  - Γ_{ee} (J/ψ, ψ(2S), ψ(3770))
    - CLEO Γ_{ee} (ψ(2S))/ Γ_{ee}(J/ψ) = 0.45 ± 0.02 (5%)





The CLEO Collaboration

- ~110 Scientists (60 FTE), 22 Institutions
  - Bristol, Buffalo, Carleton, Chicago, Carnegie Mellon, Cornell, Florida, George Mason, Illinois, Indiana, Kansas, Luther, NWU, Minnesota, Oxford, Pittsburgh, Puerto Rico, Purdue, Rochester, RPI, Syracuse, Wayne State
    - Supported by NSERC (1), PPARC (2), DOE (10), NSF (9)

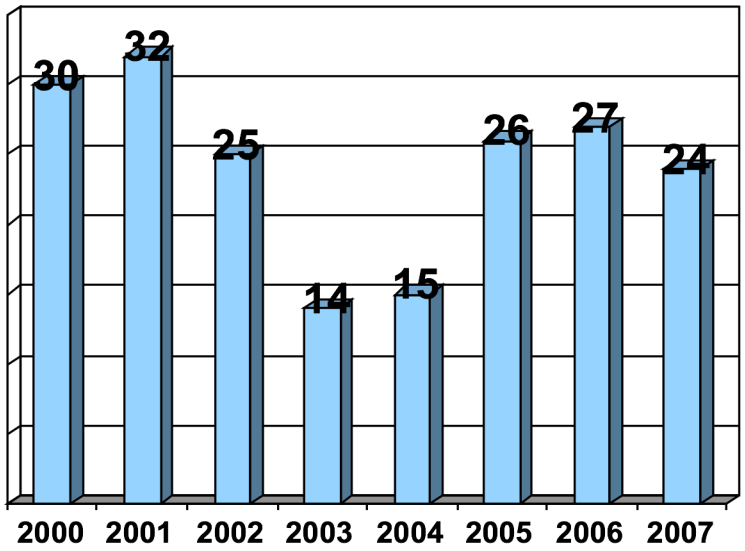
Manpower Projections

Nov 2005: 81 FTE's
Nov 2006: 72
Nov 2007: 60 (109 Authors 33 grad students, 21 post-docs)
--- Mar 31 2008 --- data taking ends
Nov 2008: 44

Enough manpower for data taking until March 31, 2008
Enough manpower to continue physics analyses until 2011

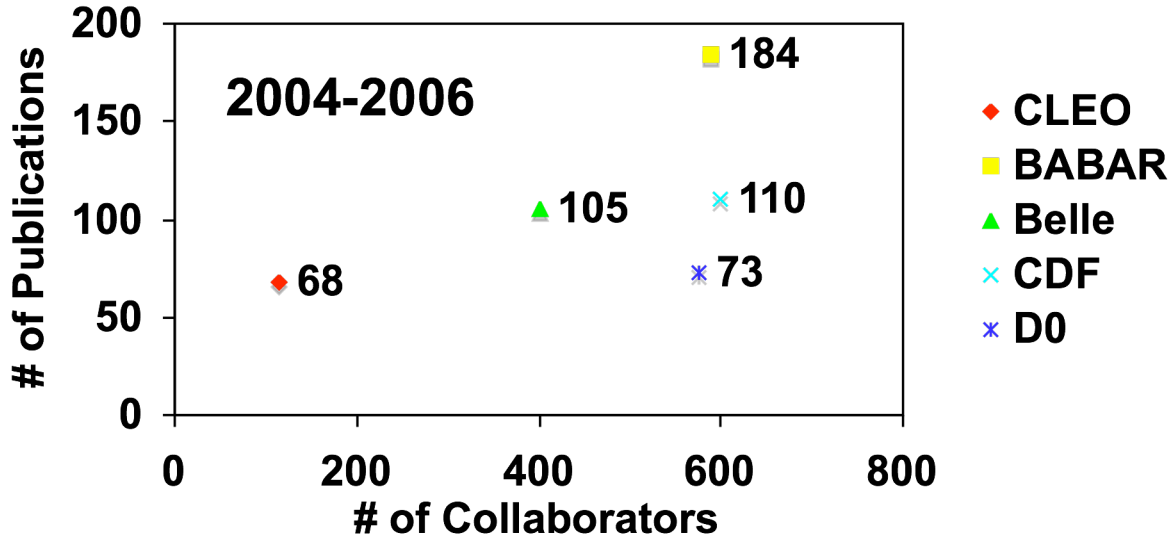
30+ Ph.D. theses over next 3 years

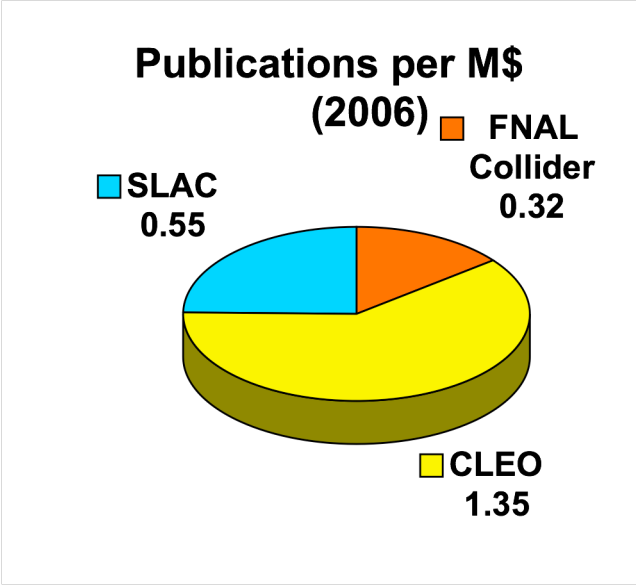
CLEO Publication Record



Recent CLEO PRL+PRD publications by year

CLEO published 450th paper in 2007





CLEO Completion

- The Collaboration plans to analyze the unique CLEO-c data sample for 3 years (the completion period) after the end of data taking March 31, 2008
- Current CLEO results based on a fraction of the data
- Anticipate 70-90 publications and ~30 theses during the CLEO completion period on the full data sample
- Cornell has submitted a grant proposal to the NSF requesting support to maintain the computing infrastructure necessary for this analysis effort
- CLEO groups need base support for physics

CLEO Physics

CLEO completion proposal features

	Precision	Full Data Precision
$B(D \to K\pi)$	2.0%	Syst. limited
$B(D \to K\pi\pi)$	2.2%	Syst. limited
$B(D_s \to KK\pi)$	5.3%	4%
$B(D^+ \to \mu\nu)$	15%	9%
$B(D_s^+ \to \mu\nu)$	11%	7%
$B(D_s^+ \to \tau\nu)$	10%	7%
f_D/f_{Ds}	8.4%	5.1%
V_{cd}, V_{cs} (Excl LQCD err.)	3.7%, 1.3%	~2%, ~1%
D(anti-D)$\to K\pi$ phase diff.	$\cos\delta$ $\pm0.19\pm0.08$	±0.08 $\pm0.??$
D(anti-D)$\to K_S\pi\pi$ phase diff.	No public result	V_{ub} phase γ 3^o sys. err.

Closing Remarks

- CLEO-c has an important physics program and has done great work (with high yield per dollar)
- The collaboration is strong and will remain strong enough to continue into the completion era.
- Physics to be done in the completion era is important & will significantly improve many results.
  - Anticipate ~30 Ph.D. theses and 70-90 publications in 2008-11 (c.w. 100 pubs since 2003)
  - Mature software & experienced collaboration make this physics output possible with the expected decline in FTE's.
- Excited about strong finish to CLEO physics program

Backup Slides

CLEO data samples and publications

Large data samples
+ excellent detector

= New observations
Precision measurements
Systematic surveys

CLEO Data Sets	Luminosity (pb^{-1})	Events ($x10^6$)	Comment
$\psi(3770)$	800	5.2	D^0,D^+
E_{cm} = 4170	315 (630)	2.8 (5.7)	$D_s^+D_s^{*-}$
$\psi(2S)$	54	27M	14M (BES)
Below $\psi(2S)$	21		
Scan ~4GeV	60		
$\Upsilon(1S)$	1100	22M	
$\Upsilon(2S)$	1200	9M	
$\Upsilon(3S)$	1200	6M	11M (Belle)

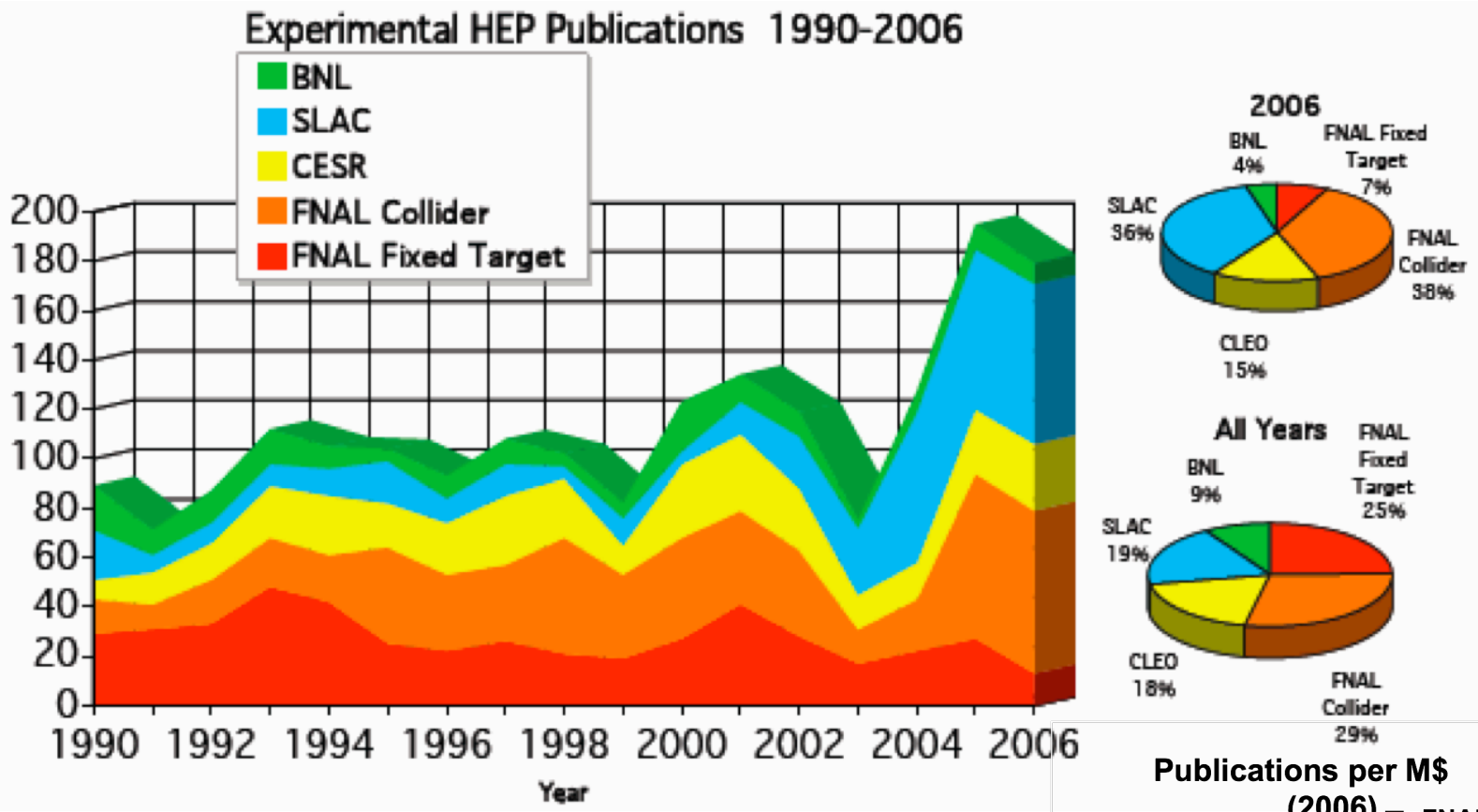
~20 PRL/PRD published
56 or 281 pb^{-1}
25-30 more to come

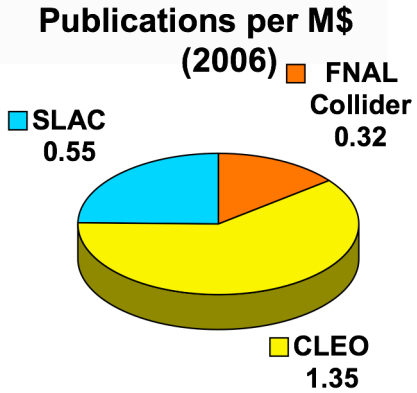
4 PRL/PRD published
195 or 325 pb^{-1}
15-20 more to come

~25 PRL/PRD published,
80% on 3M $\psi(2S)$
25-30 more to come

~20 PRL/PRD published
5-10 more to come

U.S Experimental Particle Physics





Information compiled by Fermilab

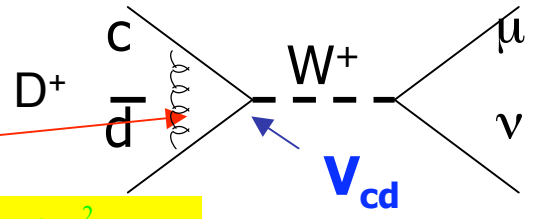
Impact of CLEO Physics

- Intellectual Merit of CLEO Physics program stems from its broad impact on heavy flavor physics and QCD
- Results from CLEO provide
  - Focused and crisp challenges to theoretical techniques for QCD calculations - particularly techniques for non-perturbative QCD
    - Leptonic and semileptonic provide unique tests on theoretical calculations
      - Such as unquenched lattice gauge calcuations
    - Important if New Physics observed at LHC as strongly coupled sector
  - Reliable calculations maximize worldwide investment in heavy flavour physics - CLEO-c, BESIII, BaBar, Belle, CDF, D0, LHCb
    - Determination f_B, f_{Bs} , V_{ub}, V_{cb}, V_{td}, V_{ts} , γ depend on charm + theory
    - Overconstraining quark mixing matrix probes New Physics and CPV
  - Charm Sector Measurements - D, D_s, and charmonium
    - f_D, f_{Ds}, V_{cd}, V_{cs}
    - Leptonic, Semileptonic, Hadronic Decays
    - Strong Phases, Dalitz Plots
    - Rare $D_{(s)}$ processes: Oscillations, CP violation, Rare Decay
    - New observations, masses, widths, rates, dynamics in charmonium

Leptonic Decays, Decay Constants, LQCD tests

Similar for D_s, B, B_s, …

Decay constant f_D

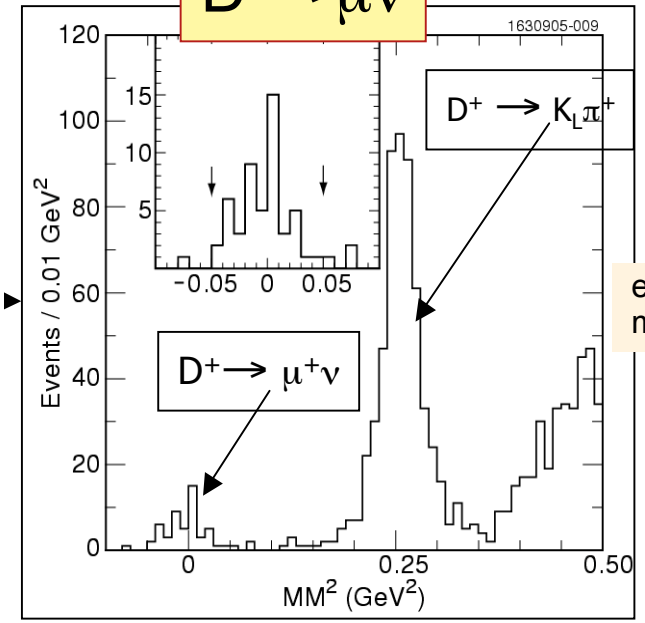


Challenge: understand QCD portion in a "simple" weak process

$$\Gamma(D^+ \to \ell^+\nu) = \frac{1}{8\pi} G_F^2 f_D^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{cd}|^2$$

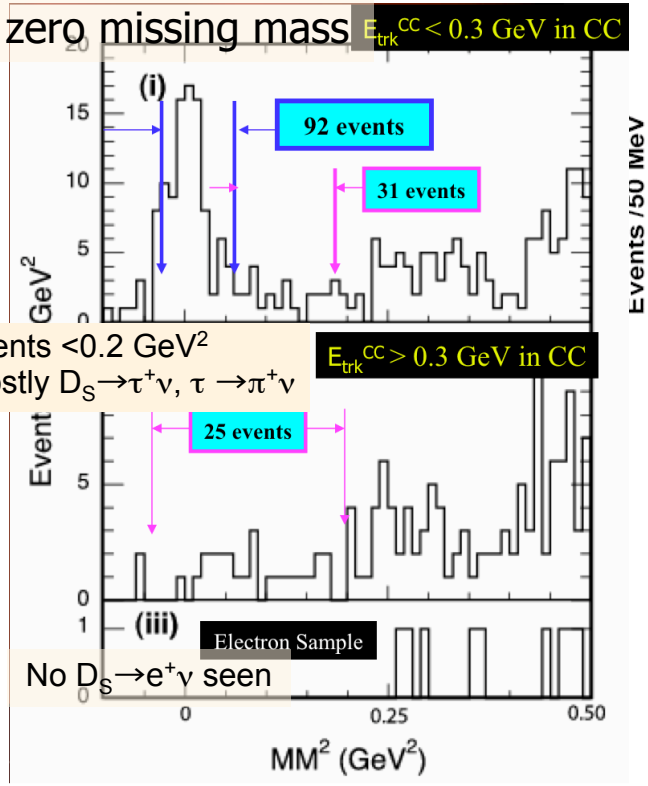
"Decay constant" f_D, encapsulates the overlap of the c and d wavefunctions, probability of annihilation ∝overlap

$D^+ \to \mu\nu$



$$MM^2 = \left(E_{CM} - E_{D_{tag}} - E_\mu\right)^2 - \left(-\vec{p}_{D_{tag}} - \vec{p}_\mu\right)^2$$

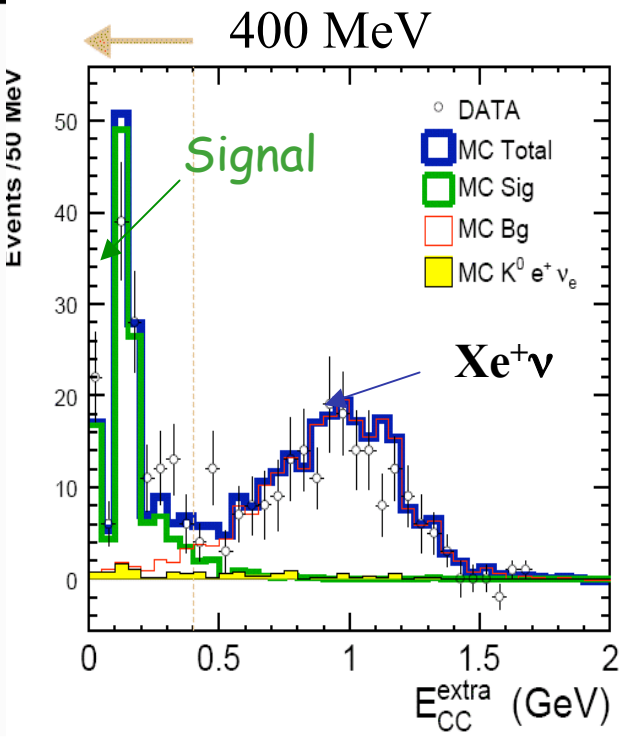
Clear $D_S^+ \to \mu^+\nu$ at zero missing mass



events <0.2 GeV²
mostly $D_S \to \tau^+\nu$, $\tau \to \pi^+\nu$

No $D_S \to e^+\nu$ seen

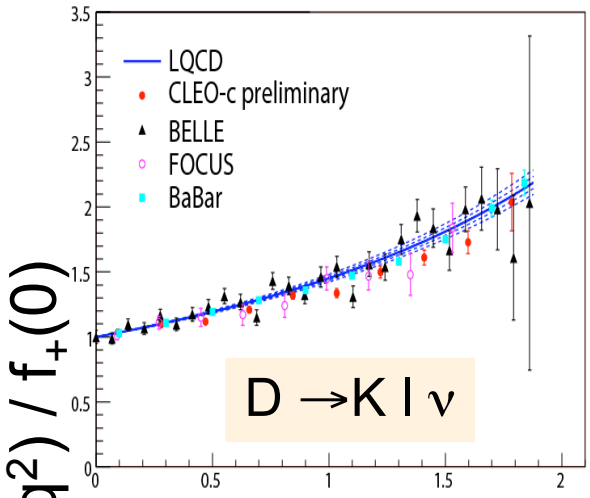
$D_s \to \tau\nu$, $\tau \to e\nu$

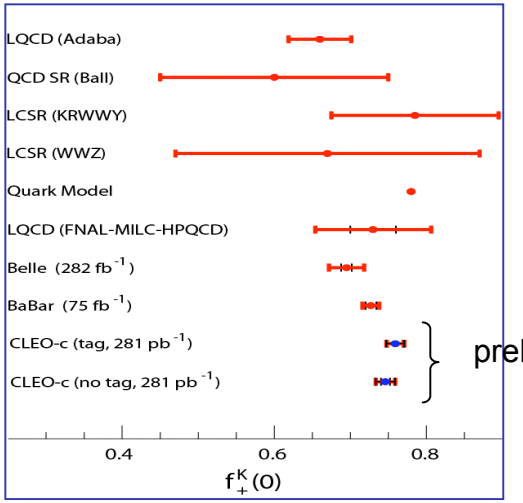


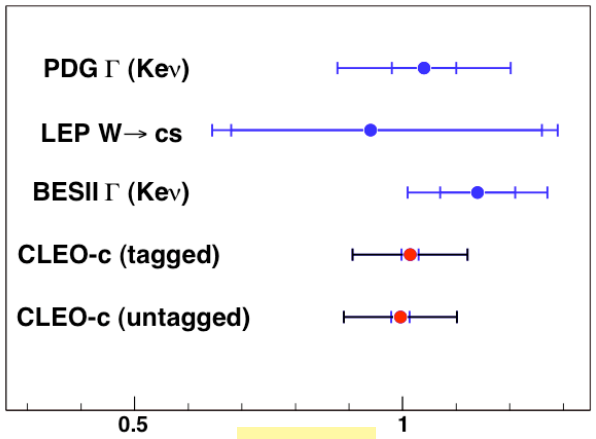
CLEO-c Semileptonic Results Confront LQCD

Recall BR is $\propto |V_{cq}|^2 \times |f_+^{\pi,K}(0)|^2$, use Becher-Hill parameterization & FNAL/MILC/HPQCD for $f_+(0)$

Uncertainty: Expt ~ 2%, LQCD ~ 10%





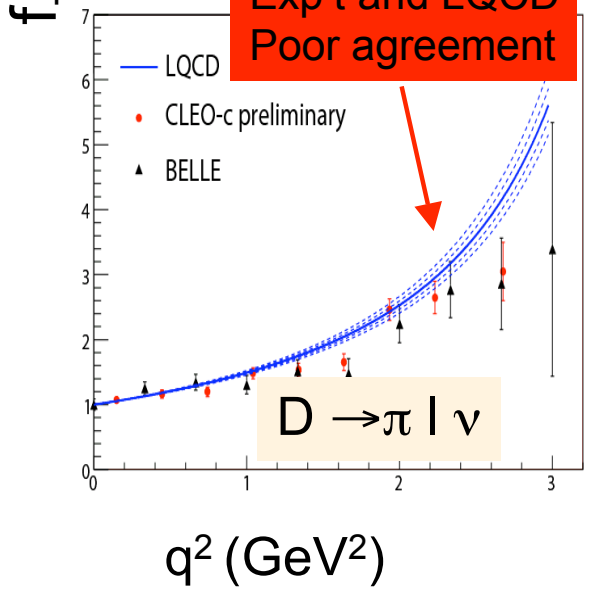


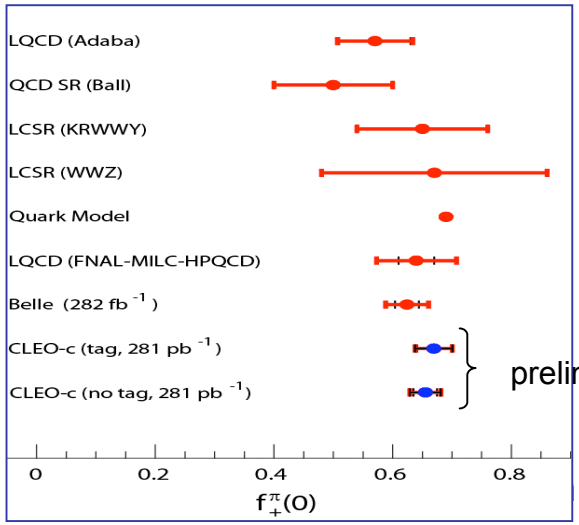
V_{cs}

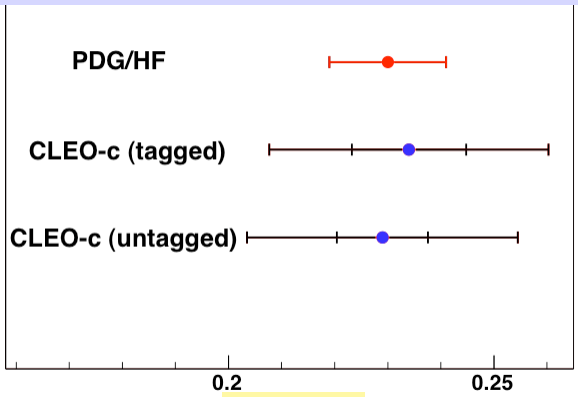
Exp't and LQCD Poor agreement

Uncertainty: Expt ~ 4%, LQCD ~ 10%

LQCD Dominant uncertainty

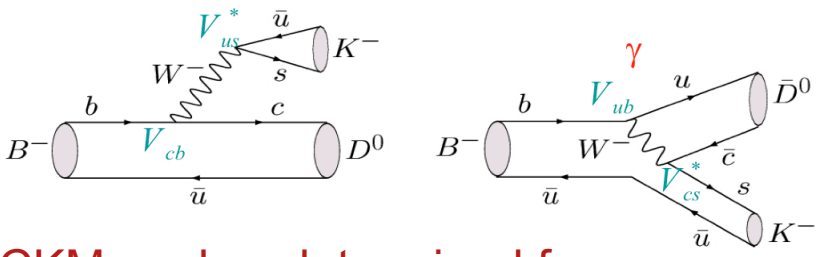






V_{cd}

CLEO-c and CKM Angle γ



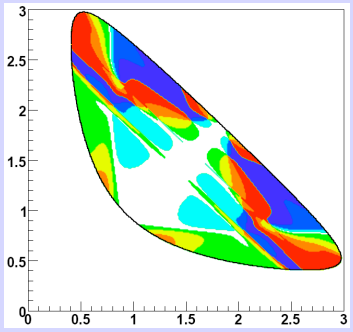
CKM angle γ determined from asymmetry in $B^- \to DK^-$, $D \to K_S\pi^+\pi^-$ decays

Amplitude ratio and D → multibody phase difference required

- Can be included in B-factory fit at expense of large statistical errors
  OR D model can be assumed but then dominates systematic uncertainty

CLEO exploits quantum correlations to directly measure phase difference

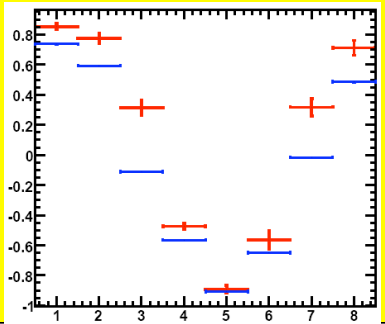
- Count events in bins on $D \to K_S\pi^+\pi^-$ Dalitz plot (CP tagged & flavor tagged)
  - CLEO-c CP tagged sample unique
- Enhance statistics (factor of 3) by using $D \to K_L\pi^+\pi^-$ and $D \to K_L\pi^0$ (CP+ tag)
  - $D \to K_L\pi^+\pi^-$ not identical to $D \to K_S\pi^+\pi^-$ Dalitz plot but difference is understood
- Full data sample will reduce systematic uncertainty on γ from 10° → 3°
  - Anticipate stat. err. from B-factories ~6°



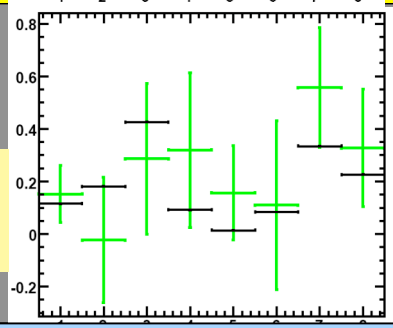
Phase diff calculated from model

$K_L\pi\pi$

$K_S\pi\pi$



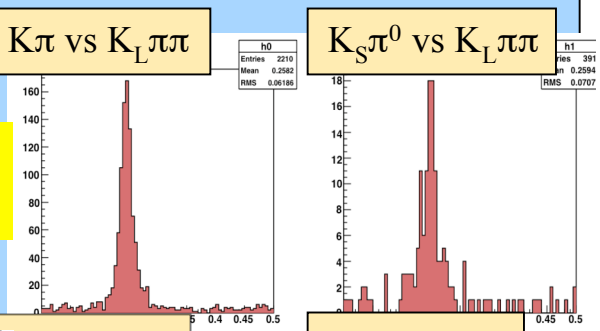
Symmetric binning in phase

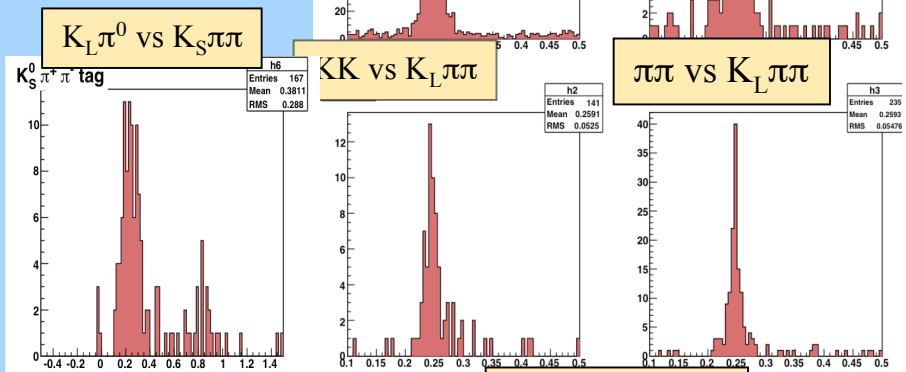


Difference in $D \to K_S/K_L\pi^+\pi^-$ Phase diff Model and Data

$K_S\pi\pi$ Bkgd free

$K_L\pi\pi$ Bkgd~5%





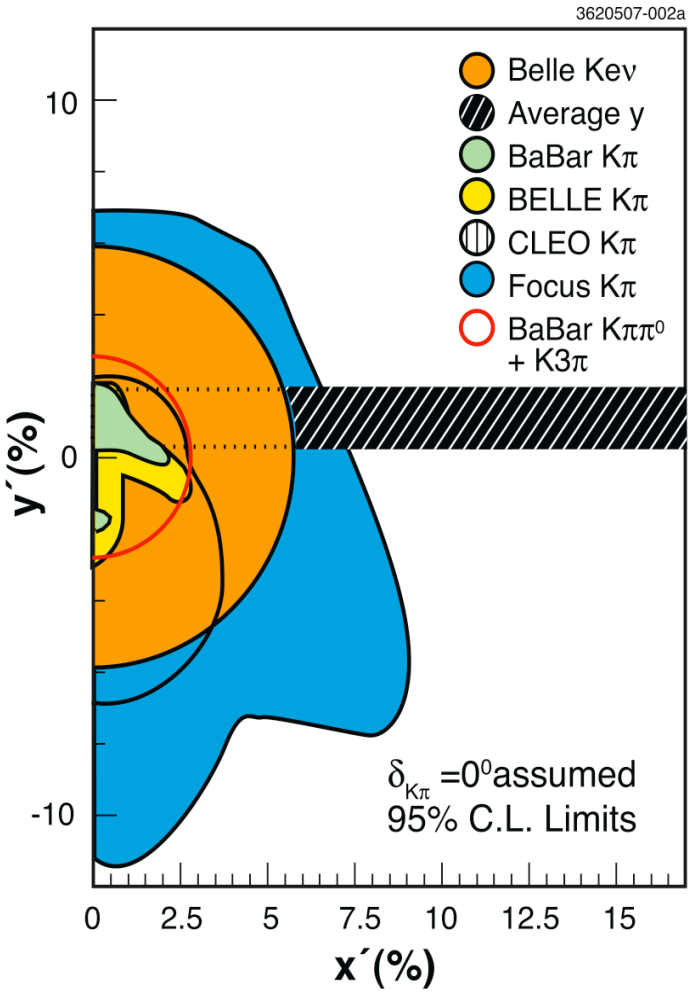
MM^2 $(GeV)^2$

Strong Phases & Charm Mixing

- Following method D. Asner & W. Sun Phys. Rev. D **73**, 034024 (2006)
- Charm mixing results from B-factories
  - $y \sim \Delta\Gamma$ from $\Gamma(D^0 \to K^+K^-, \pi^+\pi^-)$
  - $y' = y\cos\delta - x\sin\delta$ from $D^0 \to K^+\pi^-$
- Quantum correlations - Sensitive to $\cos\delta$
  - asymmetry in CP vs $K\pi$
  - Difference in e^+ and $K^-\pi^+$ tagged Dalitz plots ($K_S\pi^+\pi^-$)
- CLEO (preliminary) result improves World Average on y by factor of 1.5

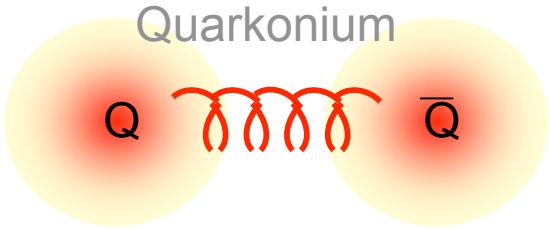
$$\cos\delta = 1.03 \pm 0.19 \pm 0.08$$

- Anticipate final stat. err. ± 0.08

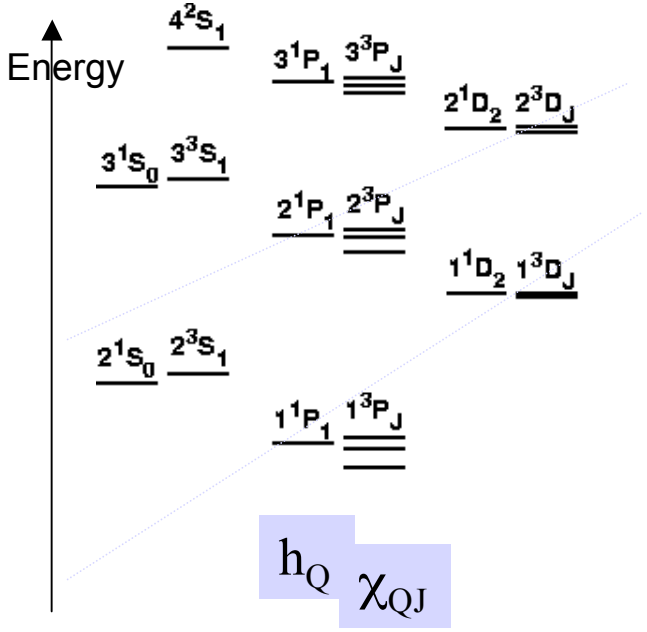


Quarkonium Studies

• Charmonium and bottomonium samples from running "on resonance"
  – Run on ψ(2S), Y(4260), ϒ(1S), ϒ(2S), ϒ(3S)



• CLEO-c measures masses, widths, dynamics providing stringent tests of LQCD
  • Discovery of ϒ(1D) and mass measurement
  • Leptonic (e,μ,τ) width of ϒ(1S), ϒ(2S), ϒ(3S)
    – Γ_{ee} is most stringent test of LQCD
  • Ongoing searches for h_b and η_b



  • Discovery of h_c and mass measurement
  • Γ_{ee} of J/ψ, ψ(2S), ψ(3770)
  • Extend ψ(2S) results from 11%→full sample

• LQCD - single formalism relates D/B to ψ/ϒ
  • Independent calibration of techniques in D/B
    – form factors, decay constants, etc…

CLEO Publications

2000: 30	2003: 14	2006: 27
2001: 32	2004: 15	2007: 22
2002: 25	2005: 26	

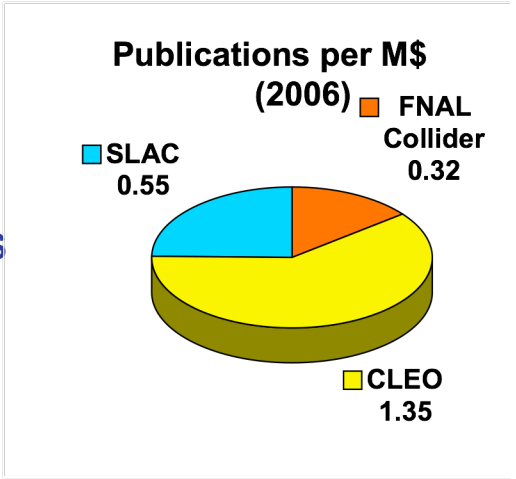
CLEO published 450th paper in 2007

2007 on track to be another good year

- published in PRL/PRD(22), accepted for publication (2)
- submitted to journal (1), collaboration approved (10)

Comparison 2004-2006 average (by journal date)

– CDF	37	(30+44+36)	~600 Authors
– D0	24	(19+20+34)	~575 Authors
– BaBaR:	61	(57+62+65)	575-600 Authors
– Belle:	35	(30+43+32)	~400 Collaborators
– CLEO-c	23	(15+26+27)	~115 Authors



- CLEO-c compares favorably with much larger efforts