The

CLEO-c

Research Program

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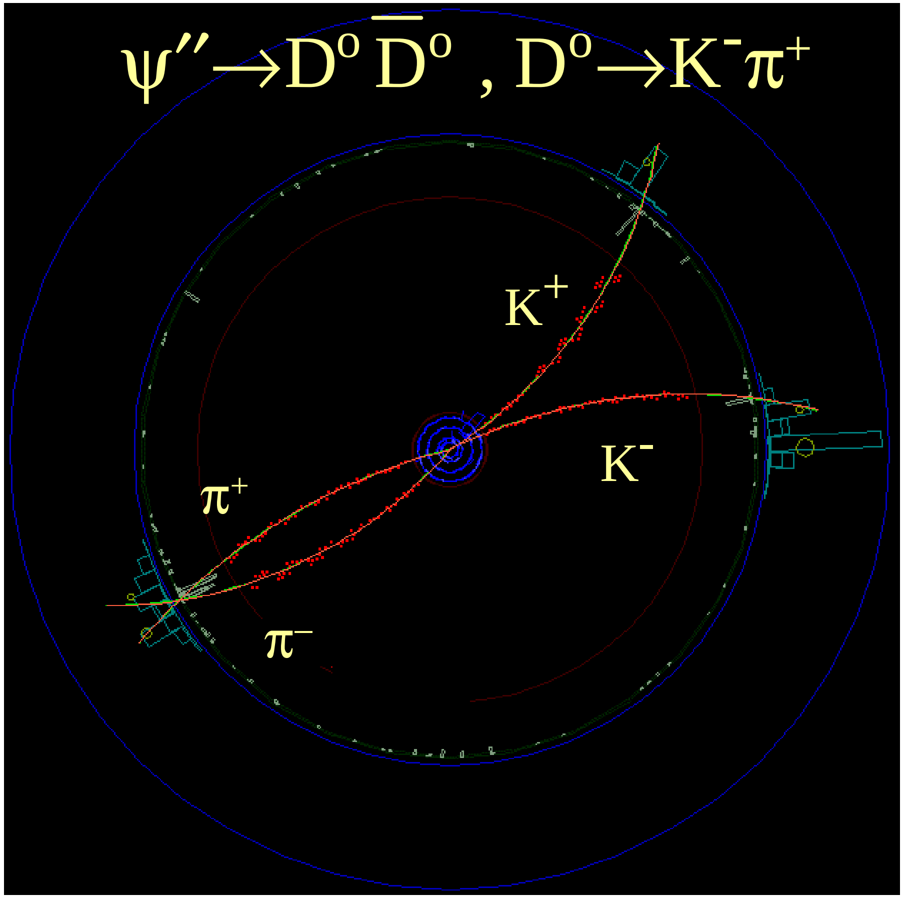


HADRON '03 – X. International Conference on Hadron Spectroscopy

CLEO-c – The Context

The Past — CLEO made major contributions to B/c/t physics. But, with the spectacular success of the B factories, CLEO is no longer taking data at the ¡(4S) resonance. Last run was June 25^{th}, 2001.

The Present — Flavour Physics is in the “B Factory era” akin to precision Z. Over-constrain CKM matrix with precision measurements. Limiting factor is non-pertubative QCD.

The Future — LHC may uncover strongly coupled sectors in the physics that lie beyond the Standard Model. The LC may then study them.

Strongly-coupled field theories are an outstanding challenge to theoretical physics. Critical need for reliable theoretical techniques & detailed data to calibrate them.

Example: Complete definition of pertubative & non-pertubative QCD.

Lattice QCD Matured over last decade and can calculate to 1-5% B, D, ¡, y …

Charm at threshold can provide the data to calibrate QCD techniques
→ Convert CESR/CLEO to a charm/QCD factory

CESR-c/CLEO-c

CLEO-c Physics Program

Charm measurements

CLEO-c: Precise charm absolute branching ratio measurements

Leptonic decays:	decay constants f_D and f_{Ds}
Semileptonic decays:	form factors, V_{cs}, V_{cd}, test unitarity
Hadronic decays:	normalize B physics

QCD studies

CLEO-c: Precise measurements of quarkonia spectroscopy

Searches for glue-rich exotic states:
Glueballs and hybrids

Probes for Physics beyond the Standard Model

CLEO-c: D-mixing, CP Violation, rare D decays

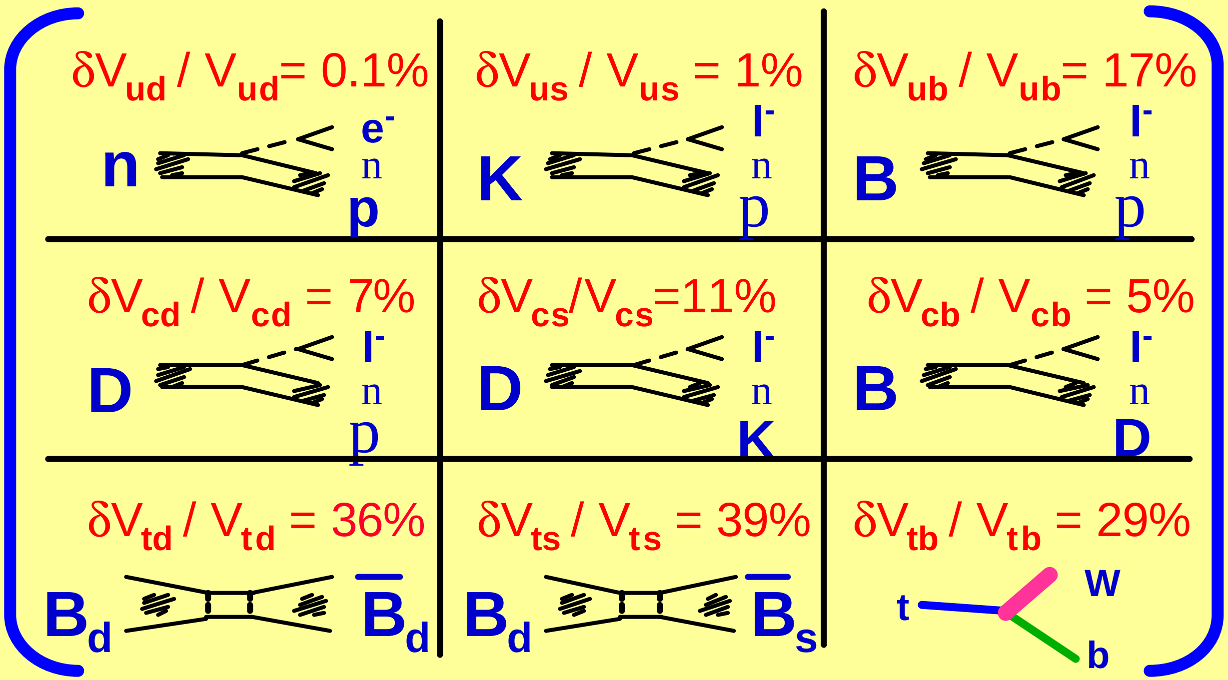
Precision Flavour Physics

Goal for the decade:

High precision measurements of all CKM matrix elements & associated phases – over-constrain the "Unitary Triangles"

Inconsistencies → New Physics !

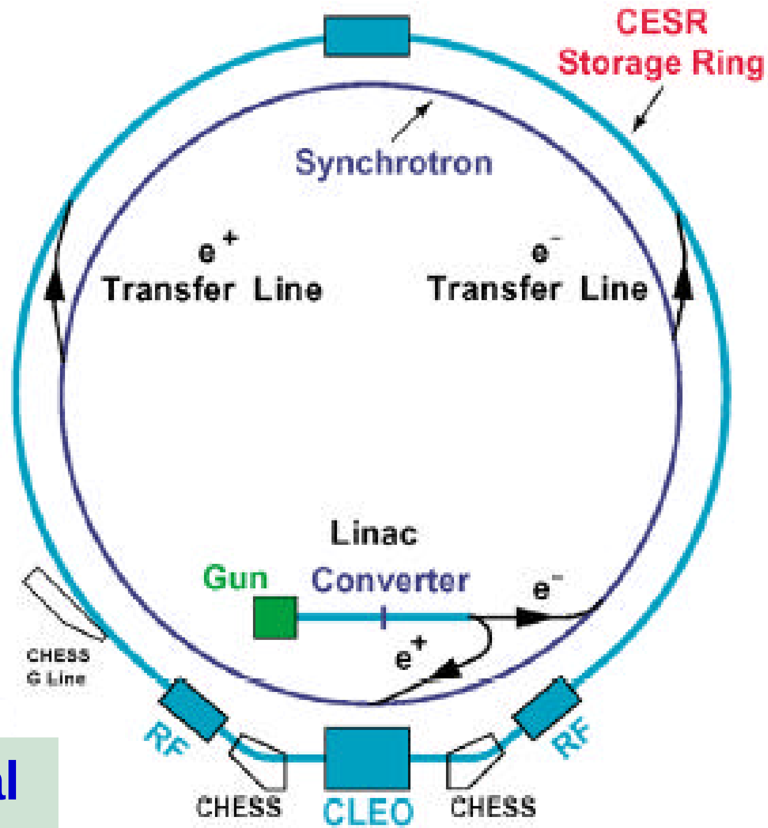
CKM Matrix Current Status:

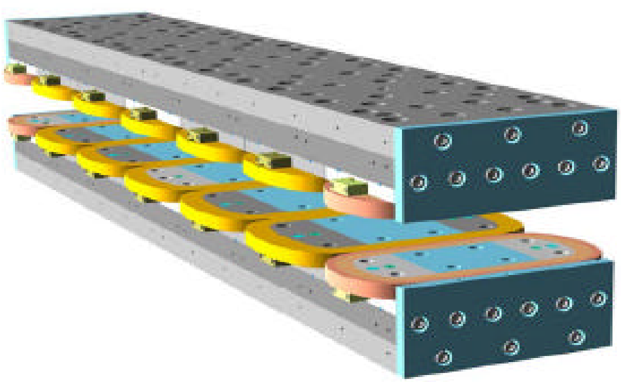


Many experiments will contribute:

CLEO-c will enable precise 1st column unitarity test & new measurements at B-Factories/Tevatron to be translated into greatly improved CKM precision

The Cornell Electron Storage Ring





14 additional wigglers to improve transverse cooling

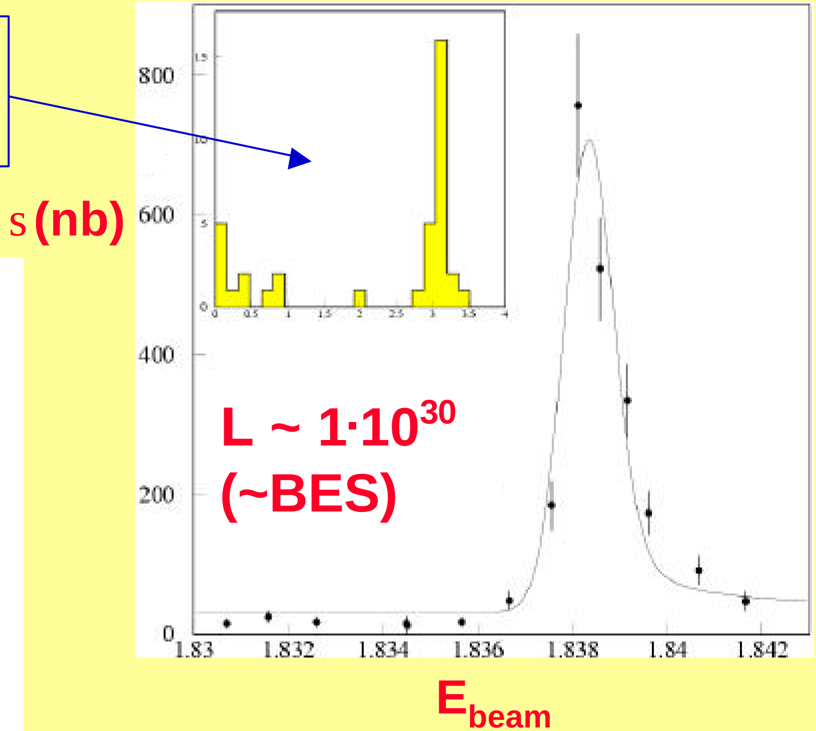
E = 1.5 - 3 GeV

CESR-c

CESR: L(¡(4S)) = $1.3 \cdot 10^{33}$ cm^{-2} s^{-1}

One day scan of y':

y¢® **J/**y pp
J/y ® mm



CESR-c:

Ös	L(10^{32} cm^{-2} s^{-1})
3.1 GeV	2.0
3.77 GeV	3.0
4.1 GeV	3.6

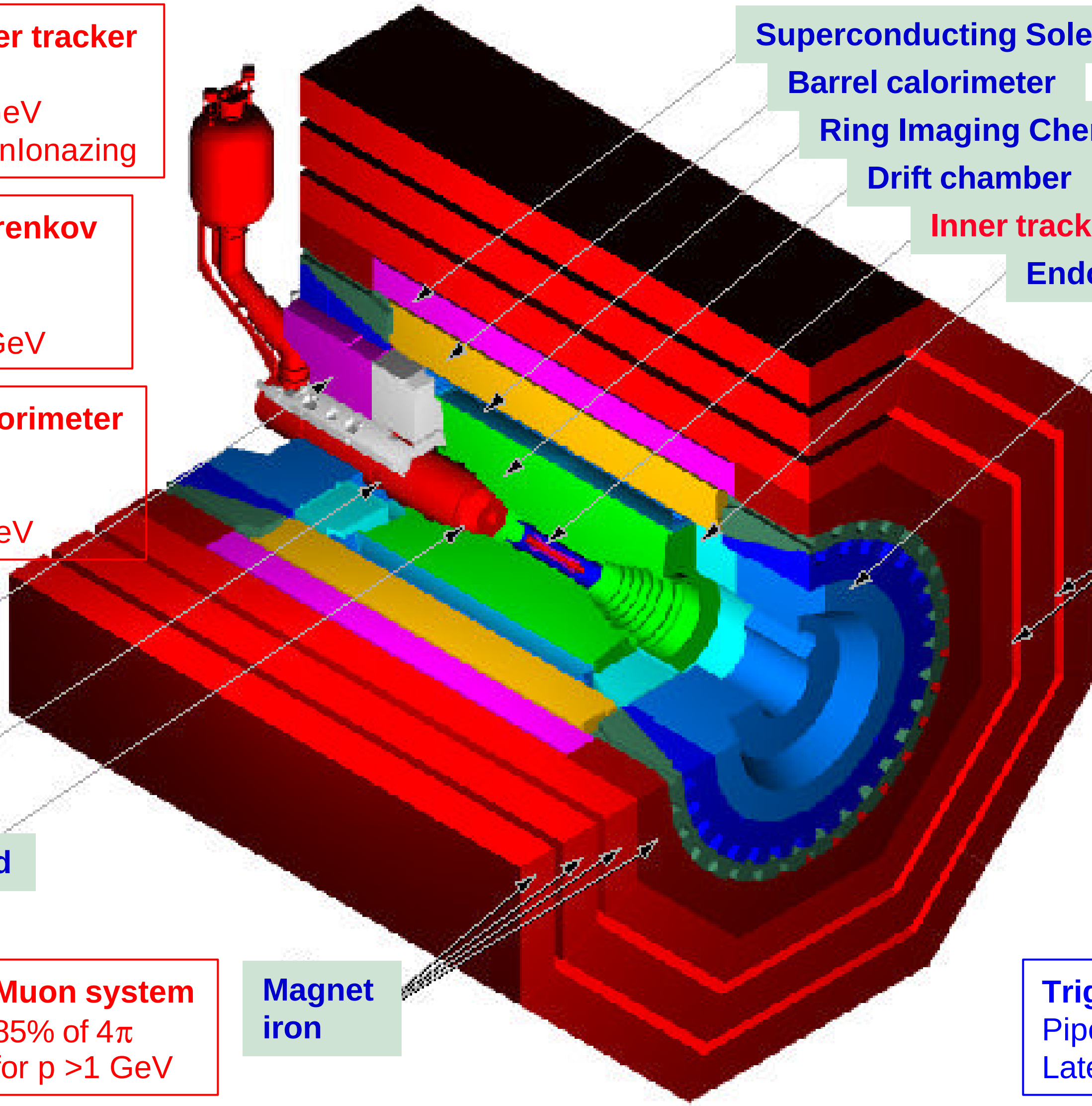
Expected machine performance: D E_{beam} ~ 1.2 MeV at J/y

The CLEO-c Experiment

Drift chamber/ Inner tracker
93% of 4π
s_p/p = 0.35% @ 1 GeV
dE/dx: 5.7% p @ minIonazing

Ring Imaging Cherenkov
83% of 4π
87% Kaon ID with
0.2% π fake @ 0.9GeV

Cesium Iodide Calorimeter
93% of 4π
s_E/E = 2% @ 1GeV
= 4% @ 100MeV



Muon system
85% of 4π
for p >1 GeV

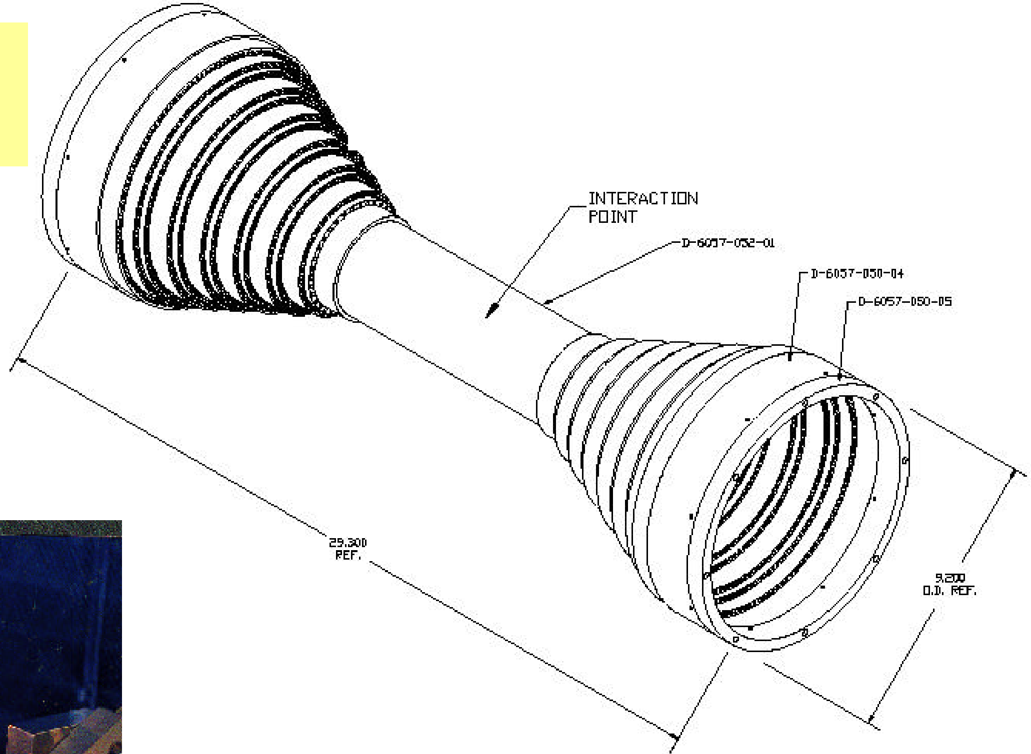
Data Acquisition
Event size = 25kB
Thruput < 6MB/s

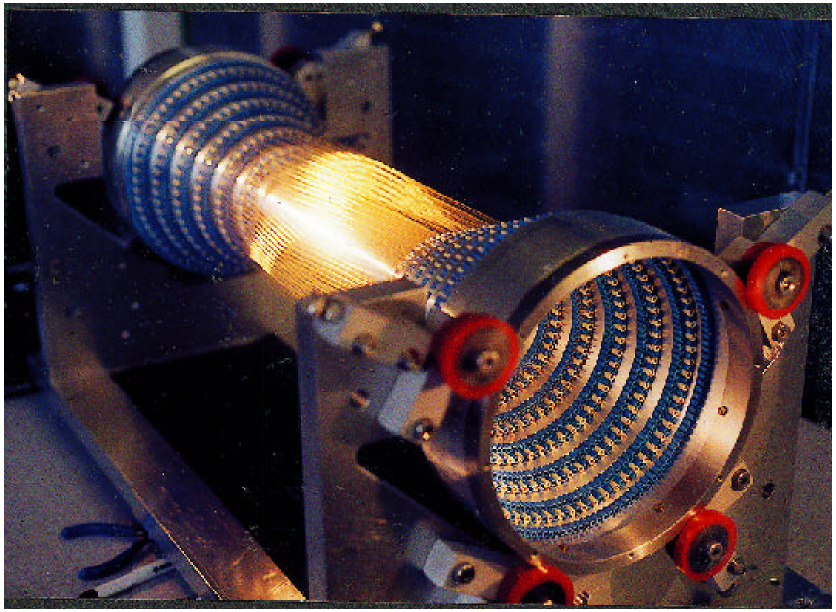
Trigger - Tracks & Showers
Pipelined
Latency = 2.5ms

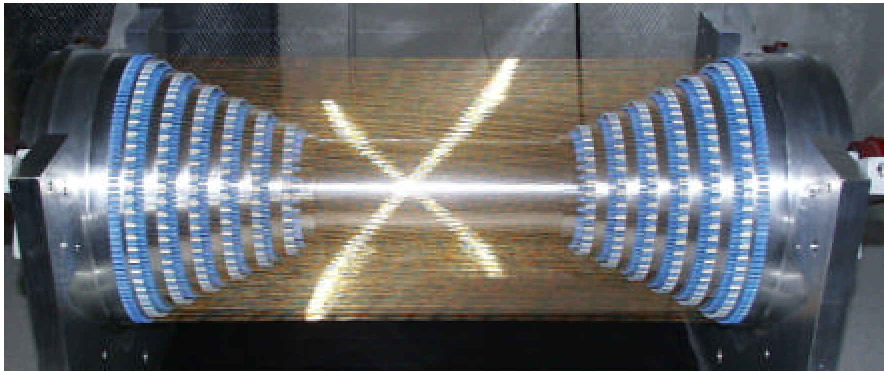
NEW - Inner Drift Chamber

Replace Silicon Vertex Detector with Inner Drift Chamber

6 layers
2cm < R < 12cm
All stereo
300 channels







Run Plan

2002 – 2003 Epilogue & Prologue

Upsilons ~1-2 fb^{-1} each at $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and $\Upsilon(5S)$

Spectroscopy, matrix elements, Γ_{ee}, η_b, η_c

Last run of CLEO III @ $\Upsilon(5S)$ on March 3rd 2003

Year 1

$\psi(3770)$ ~3 fb^{-1} ($\psi(3770) \rightarrow D\bar{D}$)

30 million $D\bar{D}$ events, 6 million *tagged* D decays

310 times of MARK III data

Year 2

$\sqrt{s}$ ~ 4140 MeV ~3 fb^{-1}

1.5 million $D_s\bar{D}_s$ events, 0.3 million *tagged* D_s decays

480 times of MARK III data, 130 times of BES data

Year 3

$\psi(3100)$ ~1 fb^{-1}

1 billion J/ψ decays

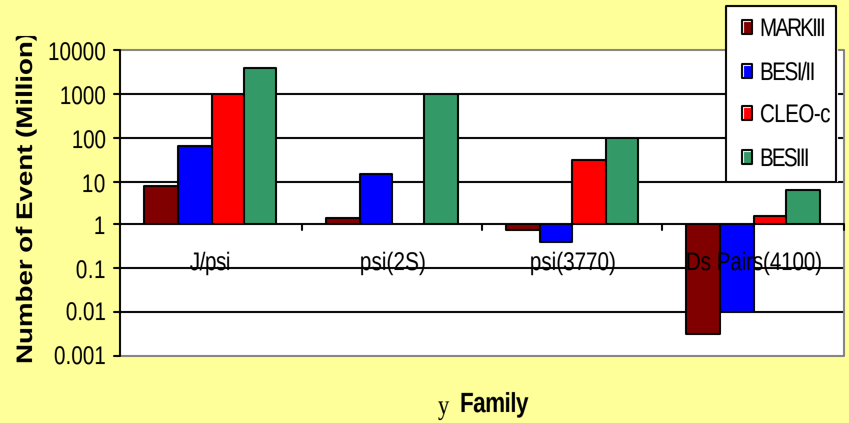
170 times of MARK III data, 20 times of BES II data

CLEO-c

Open Charm Production

The y (3770) is by far the best place to determine absolute charm branching ratios.

Experiments at y (3770)	L
Mark III	9.6 pb^{-1}
BES II	8 pb^{-1}
CLEO III	5 pb^{-1}
CLEO-c	3 fb^{-1}
BES III (approved)	30 fb^{-1}



CLEO-c
Physics Run

MARKIII

BESII

BESIII
Construction

BESIII
Engineer & Physics Run

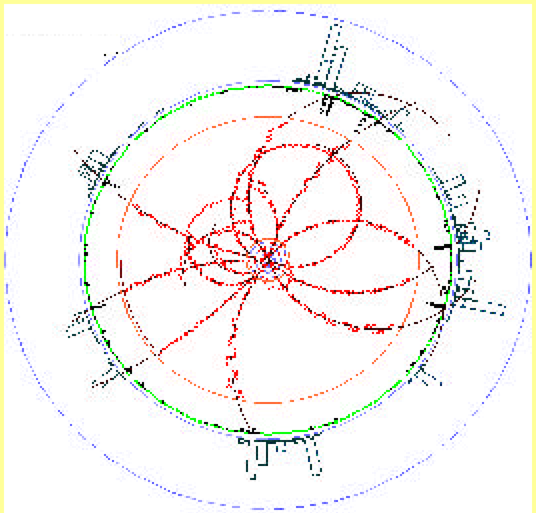
1984 1988 2000 2005 2010

Year

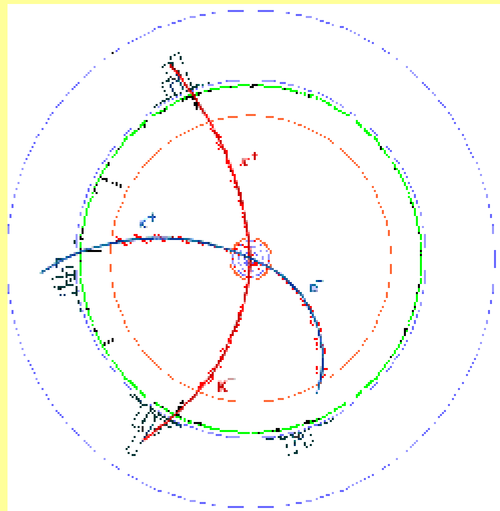
CLEO-c Signature

y(3770) events are simpler than ¡(4S) events!

¡(4S) event



y(3770) event



D^0 ® K^-p^+ D^0 ® K^+e^- n

The demands of doing physics in the 3 - 5 GeV range are easily met by the existing detector

BUT

B factories: 400 fb^{-1}

→ ~500M $c\bar{c}$ by 2005

What is the advantage of running at threshold?

- **Charm events produced at threshold are extremely clean**
- **Large cross section, low multiplicity**
- **Pure initial state: no fragmentation**
- **Signal/Background is optimum at threshold**

- **Double tag events are pristine**
  These events are the key to make absolute BR measurements
- **Neutrino reconstruction is clean**
- **Quantum coherence aids D mixing & CP violation studies**

Tagging Technique – Tag Purity

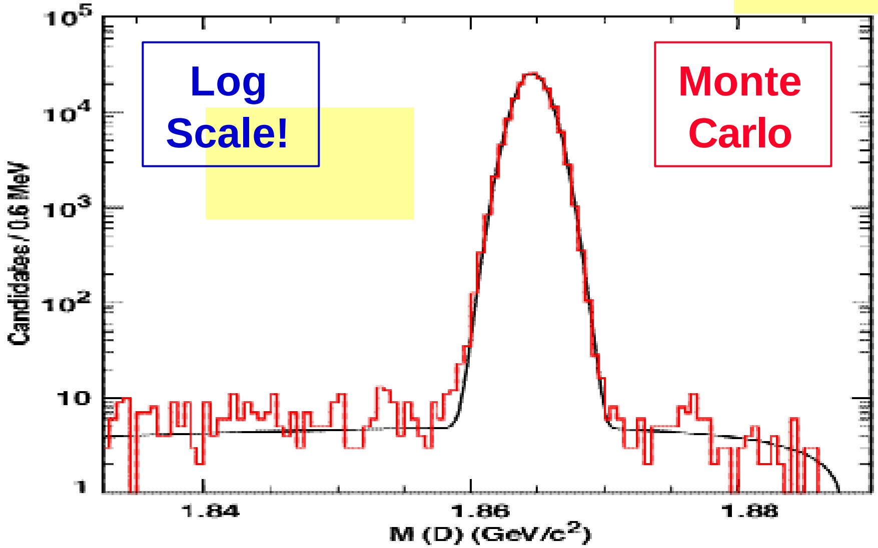
$\psi(3770) \to D\bar{D}$ $\sqrt{s} \sim 4140 \to D_s \bar{D}_s$

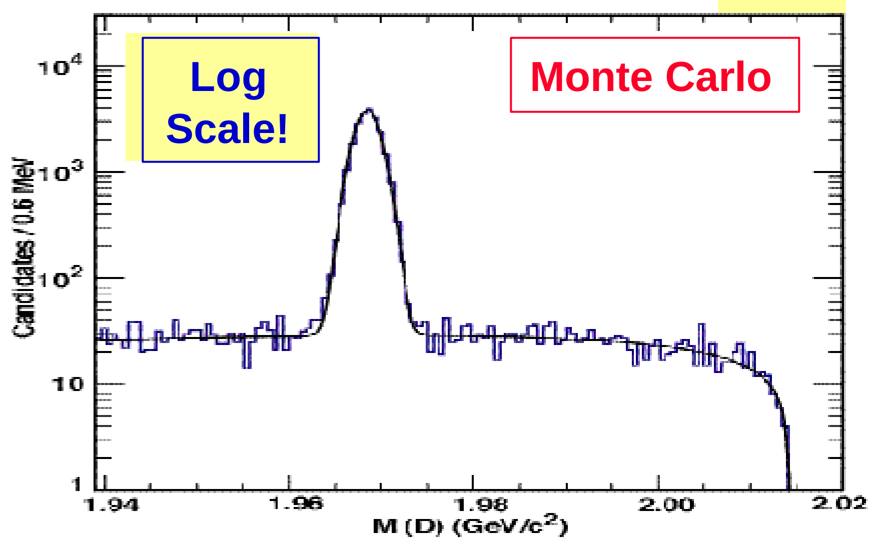
- **Charm mesons have many large branching ratios (~1 - 15%)**
- **High reconstruction efficiency**

→ High net tagging efficiency ~20%

Anticipate 6M D tags and 0.3M D_s tags

$D \to K\pi$ tag: S/B ~ 5000/1 $D_s \to \phi\pi$ ($\phi \to KK$) tag: S/B ~ 100/1





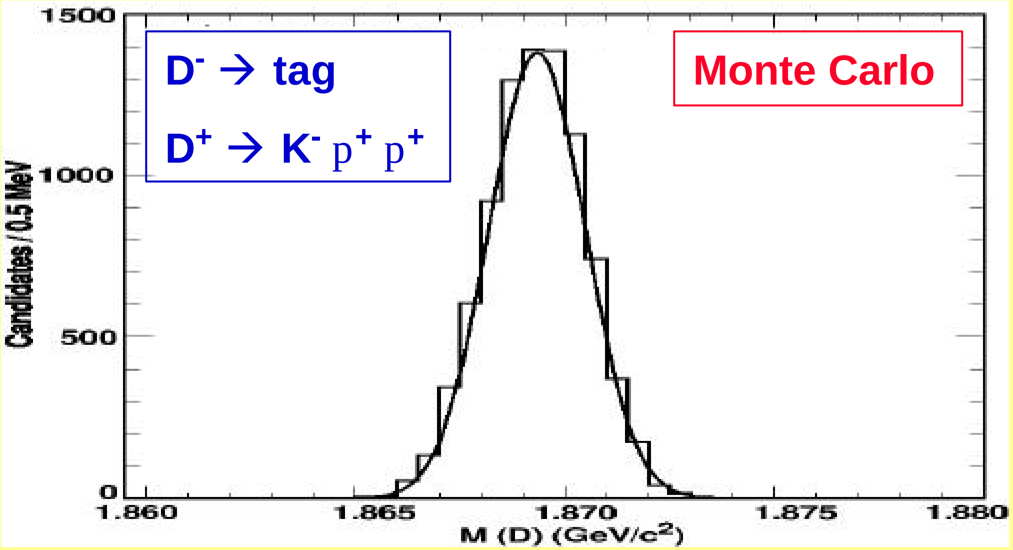
Absolute Charm Branching Ratios

Double tag technique:

Almost zero background in hadronic tag modes

Measure absolute B(D → X) with double tags

$$B = \frac{\#\text{ of }X}{\#\text{ of }D\text{ tags}}$$

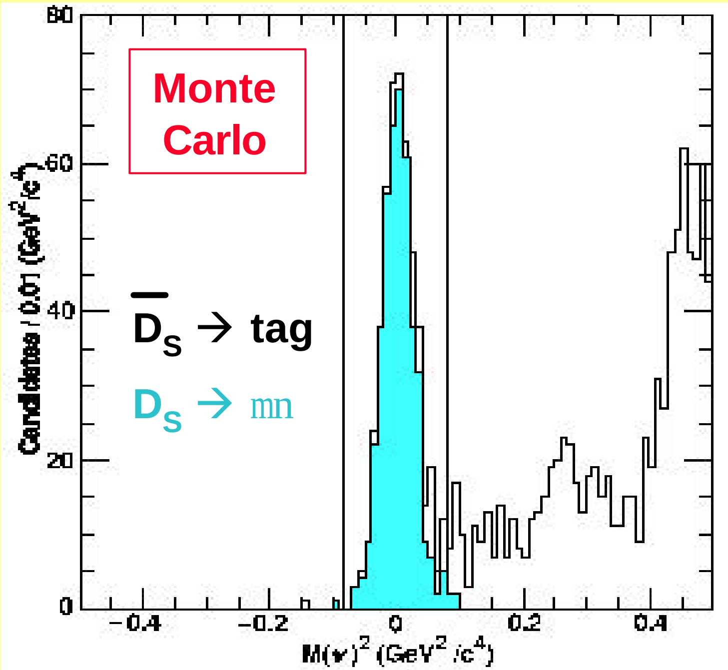


Decay	Ös	L (fb^{-1})	Double tags	dB / B (%) PDG	dB / B (%) CLEO-c
$D^0 \to K^- p^+$	3770	3	53,000	2.4	0.6
$D^+ \to K^- p^+ p^+$	3770	3	60,000	7.2	0.7
$D_s \to f\ p$	4140	3	6,000	25	1.9

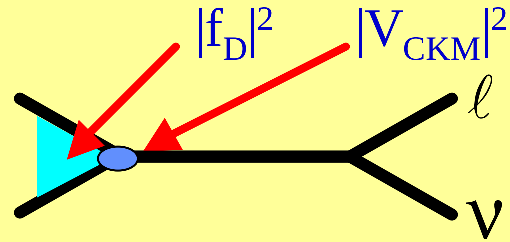
CLEO-c: potential to set absolute scale for all heavy quark measurements

50 pb^{-1} → ~1,000 events → x2 improvement (stat) on $D^+ \to K^- p^+ p^+$ PDG dB/B

f_{Ds} from Absolute $B(D_s \to \mu^+\nu)$



- Measure absolute $B(D_s \to \mu\nu)$
- Fully reconstruct one D (tag)
- Require one additional charged track and no additional photons

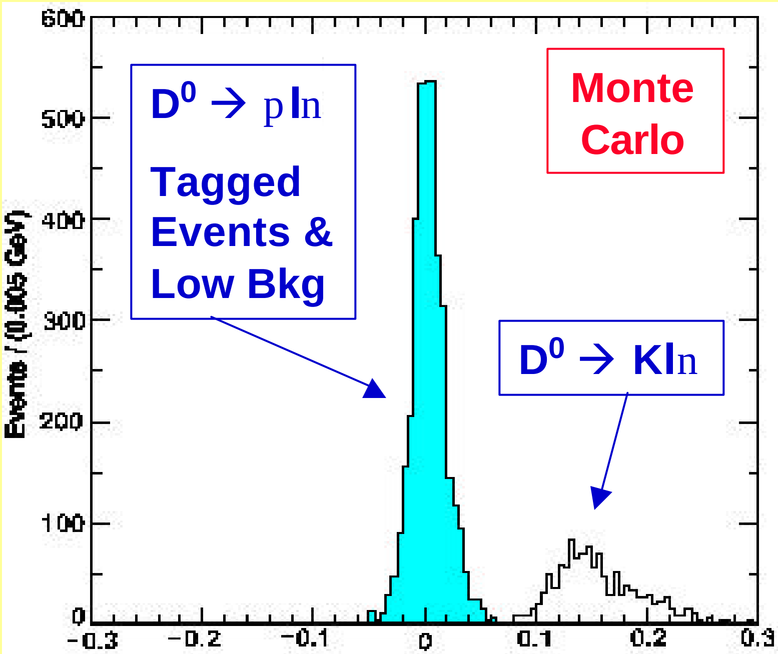


- Compute MM^2
- Peaks at zero for $D_s^+ \to \mu^+\nu$ decay
- Expect resolution of ~$O(M_{\pi^0})$

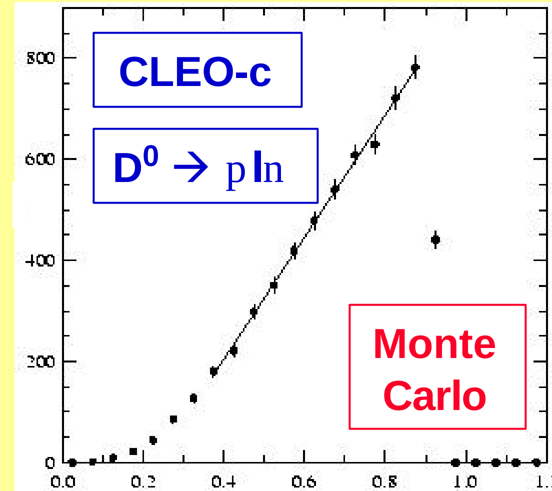
Vcs (Vcd) known from unitarity to 0.1% (1.1%)

Decay Constant	Reaction	Energy (MeV)	L (fb^{-1})	$\delta f / f$ (%) PDG	$\delta f / f$ (%) CLEO-c
f_{Ds}	$D_s^+ \to \mu\nu$	4140	3	17	1.9
f_{Ds}	$D_s^+ \to \tau\nu$	4140	3	33	1.6
f_{D+}	$D^+ \to \mu\nu$	3770	3	UL	2.3

Semileptonic Decays $|V_{CKM}|^2 \ |f(q^2)|^2$

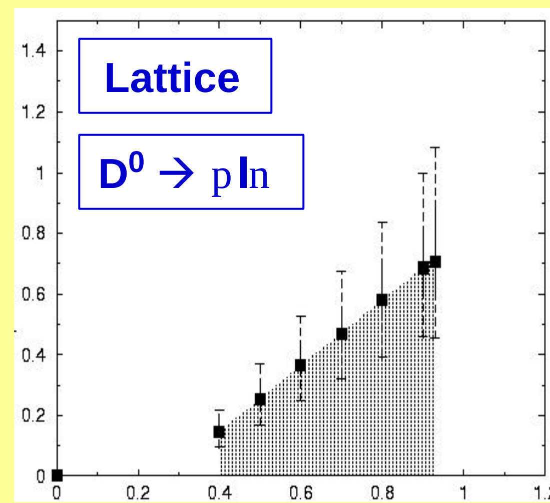


E_{miss} - P_{miss}



dG/dp$_p$

p$_p$



dG/dp$_p$

p$_p$

First time measurement of complete set of charm PS → PS & PS → V absolute form factor magnitudes and slopes to a few % with almost no background in one experiment

Stringent test of theory!

CLEO-c Impact on Semileptonic dB/B

1: $D^0 \rightarrow K^- e^+$ n

2: $D^0 \rightarrow K^{*-} e^+$ n

3: $D^0 \rightarrow$ $p^- e^+$ n

4: $D^0 \rightarrow$ $r^- e^+$ n

5: $D^+ \rightarrow \overline{K}^0 e^+$ n

6: $D^+ \rightarrow \overline{K}^{*0} e^+$ n

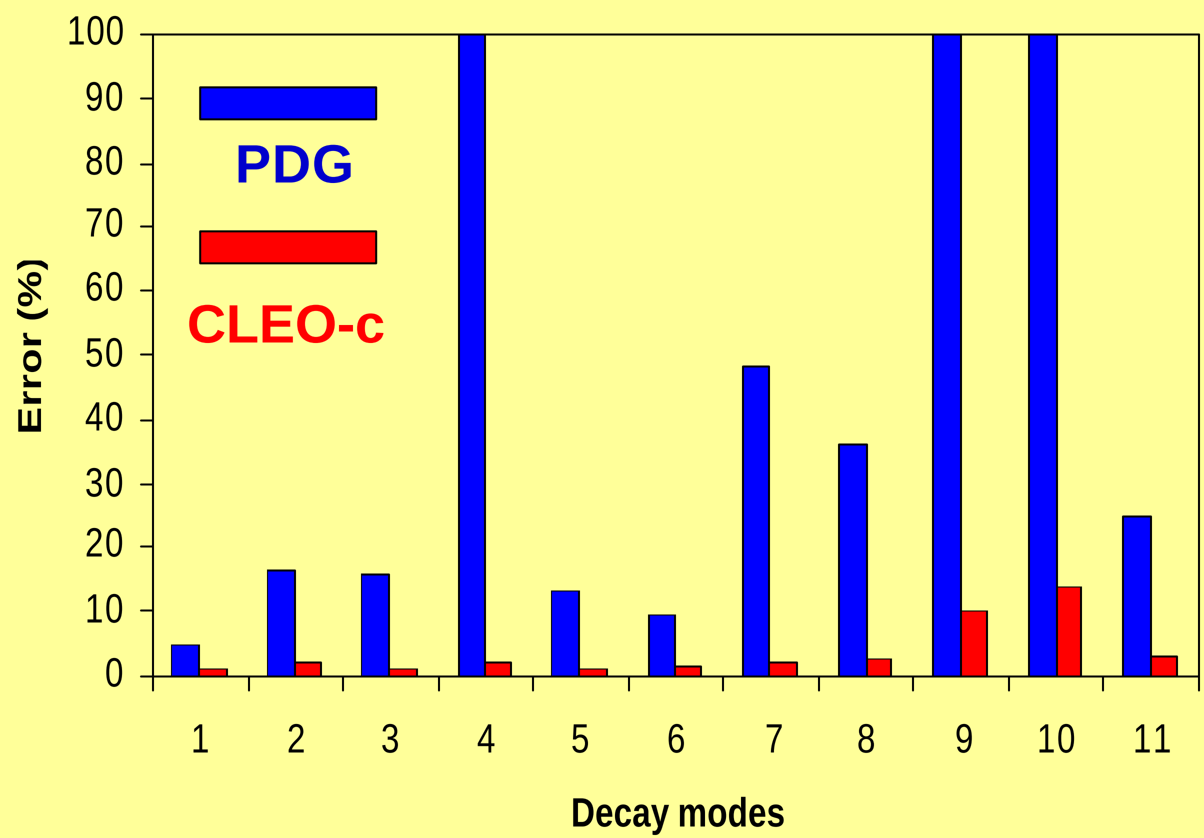
7: $D^+ \rightarrow$ $p^0 e^+$ n

8: $D^+ \rightarrow$ $r^0 e^+$ n

9: $D_s \rightarrow K^0 e^+$ n

10: $D_s \rightarrow K^{*0} e^+$ n

11: $D_s \rightarrow$ f e^+ n



CLEO-c will make significant improvements in the precision with which each absolute charm semileptonic branching ratio is known!

Determining V_{cs} and V_{cd}

Combine semileptonic and leptonic decays – eliminating V_{CKM}

G(D$^+$ → p l n) / G(D$^+$ → l n) independent of V_{cd}

Test rate predictions at ~4% level

G(D$_s$ → f l n) / G(D$_s$ → l n) independent of V_{cs}

Test rate predictions at ~4.5% level

Test amplitudes at 2% level

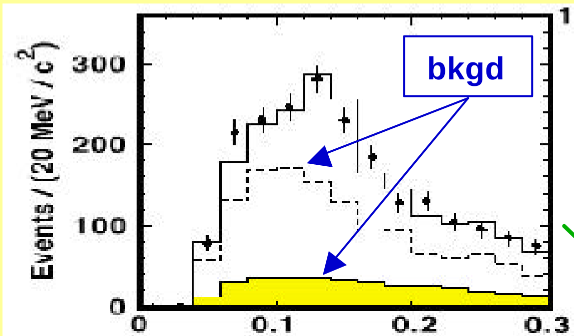
Stringent test of theory - If theory passes test …

D^0 → K$^-$ e$^+$ n	dV_{cs}/V_{cs} = 1.6%	(now: 11%)
D^0 → p$^-$ e$^+$ n	dV_{cd}/V_{cd} = 1.7%	(now: 7%)

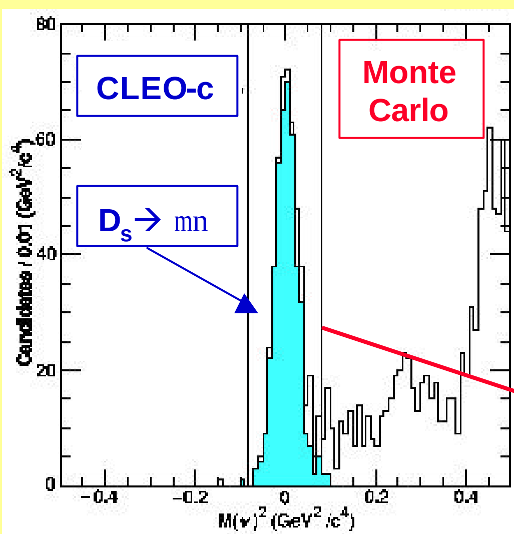
Use CLEO-c validated lattice to calculate B semileptonic form factor
→ Then B factories can use B → r/p/h/ln for precise V_{ub} determinat.

Comparison: B Factories & CLEO-c

CLEO: f_{Ds}: $D_s^* \rightarrow D_s$ g with $D_s \rightarrow$ mn



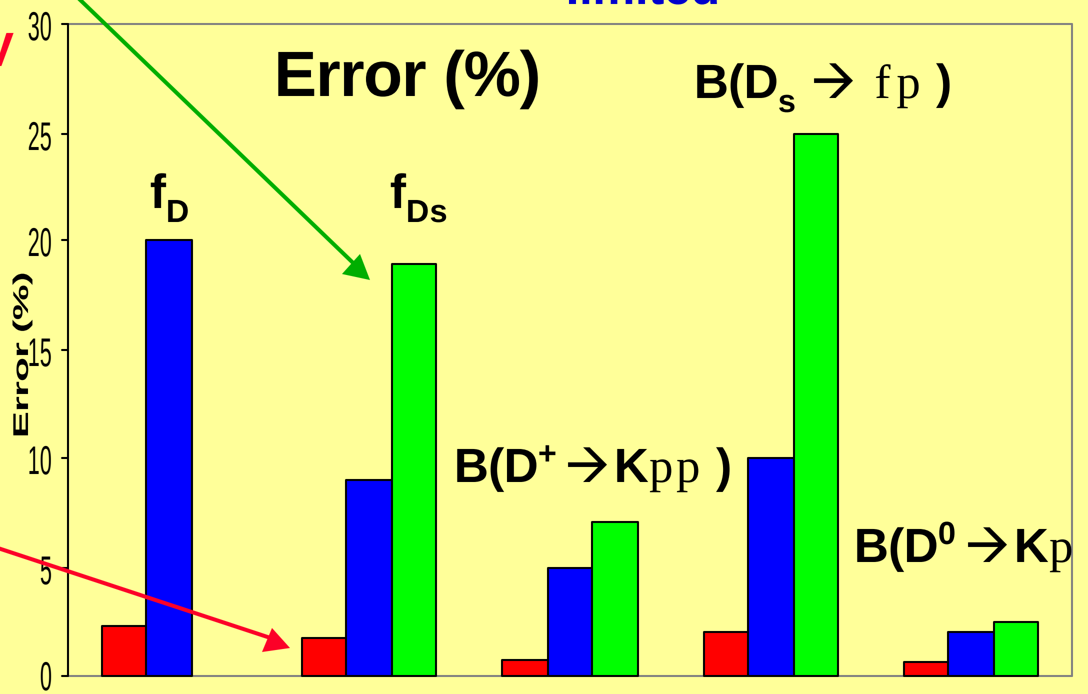
DM = M(mng) – M(mn) / GeV



CLEO-c 3 fb^{-1} | **B Factory 400 fb^{-1}** | **PDG**

Statistics limited

Systematics & Background limited



CLEO-c Probes of New Physics

- **DD mixing**

  Exploit coherence: $\psi(3770) \to DD$ (C = -1)
  for mixing no DCSD $\sqrt{s} \sim 4140 \to \gamma DD$ (C = +1)

  D mixing & Double CP Violation suppressed in SM – all the more reason to measure it

- **CP violating asymmetries**

  Sensitivity: $A_{CP} < 0.01$

  Unique: L = 1, C = -1 CP tag on one side, same CP on opposite side

  $CP = \pm 1 \leftarrow \psi(3770) \to CP = \pm 1$ = CPV

- **Rare charm decays**

  Sensitivity: 10^{-6}

CLEO-c Probes of QCD

Verify tools for strongly coupled theories
Quantify accuracy for application to flavour physics

- y and ¡ spectroscopy

  Masses, spin fine structure

- Leptonic widths of S-states

  EM transition matrix elements

Confinement,
Relativistic corrections

Wave function
Tech: $f_{B,K}$ Ö$\overline{B}_K$ f_{Ds}

Form factors

Rich calibration and testing ground for theoretical techniques → apply to flavour physics

¡ resonances done in fall 2001 - fall 2002 ~4 fb^{-1}
$D\overline{D}$ / $D_s\overline{D}_s$ running in 2003 – 2004 anticipate each ~3 fb^{-1}
J/y running in 2005 anticipate 1 billion J/y

- Uncover new forms of matter – gauge particles as constituents

  Glueballs G = | gg ñ
  Hybrids H = | $gq\overline{q}$ ñ

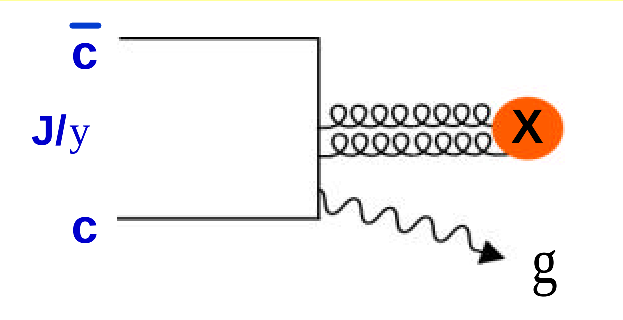
Study fundamental states of the theory

The current lack of strong evidence for these states is a fundamental issue in QCD → Requires detailed understanding of the ordinary hadron spectrum in the 1.5 – 2.5 GeV mass range

Gluonic Matter

- Gluons carry color charge → They should bind !
- Glueball sightings: MARK III, BES, Crystal Barrel
- But glueballs have been sighted too many times without confirmation

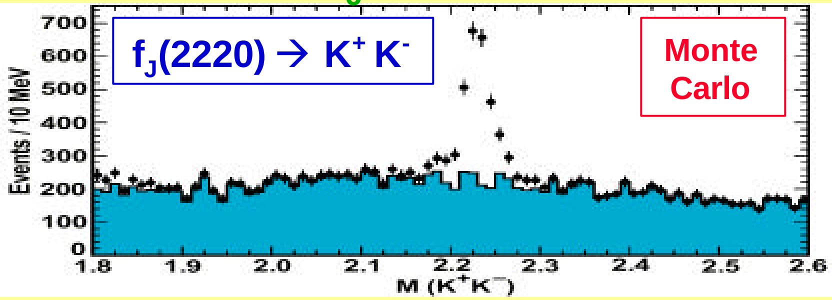
CLEO-c 1st high statistics experiment with modern 4p detector covering the 1.5 - 2.5 GeV mass range

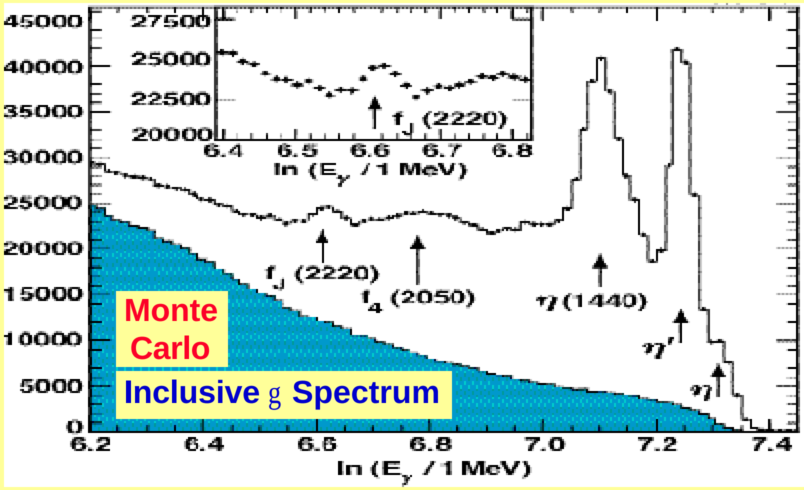


Radiative J/y decays are ideal glue factory

anticipate 60 million J/y radiative decays

Example: $f_J(2220)$ exclusive





BES `96: 44 events CLEO-c: 18k events

Corroborating checks: Anti-search in gg

Search in ¡(1S)

BESII no longer sees evidence for $f_J(2220)$

Scalar-Glueball Mixing

WA 102:

(D. Barberis et al., Phys. Lett. B 479 59 (2000))

Most comprehensive data set on pp, hh and $K\bar{K}$ decay ratios for f_0 scalar triplet

→Input for glueball - scalar mixing models

(F. Close et al., Eur. Phys. J. C 21 531 (2001))

$$\frac{f_0(1370) \to pp}{f_0(1370) \to K\bar{K}} = 2.17 \pm 0.90$$

$$\frac{f_0(1370) \to hh}{f_0(1370) \to K\bar{K}} = 0.35 \pm 0.21$$

$$\frac{f_0(1500) \to pp}{f_0(1500) \to hh} = 5.5 \pm 0.84$$

$$\frac{f_0(1500) \to K\bar{K}}{f_0(1500) \to pp} = 0.32 \pm 0.07$$

$$\frac{f_0(1500) \to hh'}{f_0(1500) \to hh} = 0.52 \pm 0.16$$

$$\frac{f_0(1710) \to pp}{f_0(1710) \to K\bar{K}} = 0.20 \pm 0.03$$

$$\frac{f_0(1710) \to hh}{f_0(1710) \to K\bar{K}} = 0.48 \pm 0.14$$

$$\frac{f_0(1710) \to hh'}{f_0(1710) \to hh} < 0.05(90\% cl)$$

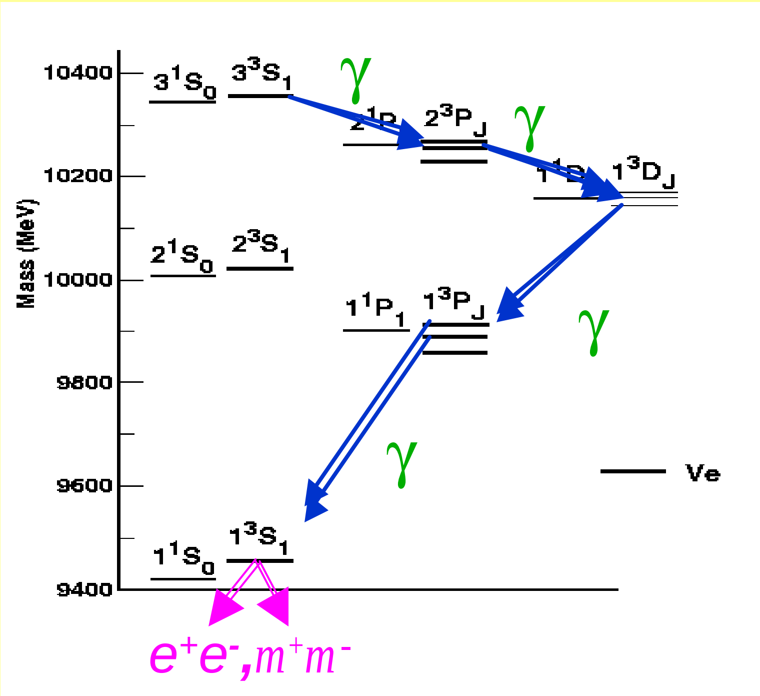
CLEO-c:

Mode	CLEO-c
J/y → g f_0(1500): f_0(1500) → $p^+p^-p^+p^-$	123,000
J/y → g f_0(1710): f_0(1710) → $p^+p^-p^+p^-$	123,000
J/y → g f_0(1710): f_0(1710) → pp	93,000
J/y → g f_0(1710): f_0(1710) → KK	250,000

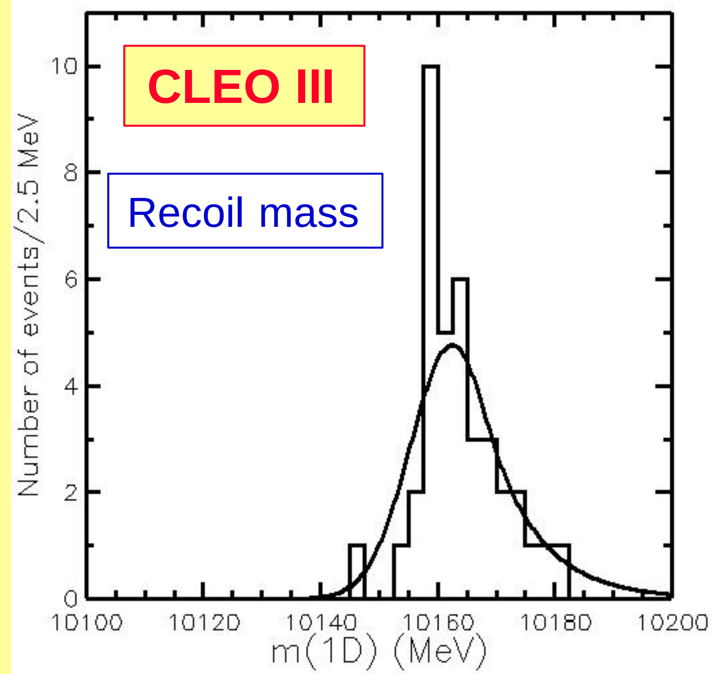
¡ Spectroscopy: Observation of ¡(1^3D_2)

Preliminary results at ICHEP02

Update: More data and better background suppression



M(¡(1^3D_2))= 10161.1 ± 0.6 ± 1.6 MeV



B(¡(3S) → gg ¡(1D) → gg gg ¡(1S) → gg gg l^+l^-)
= (2.6 ± 0.5 ± 0.5) 10^{-5}

Theory = 3.8 10^{-5}

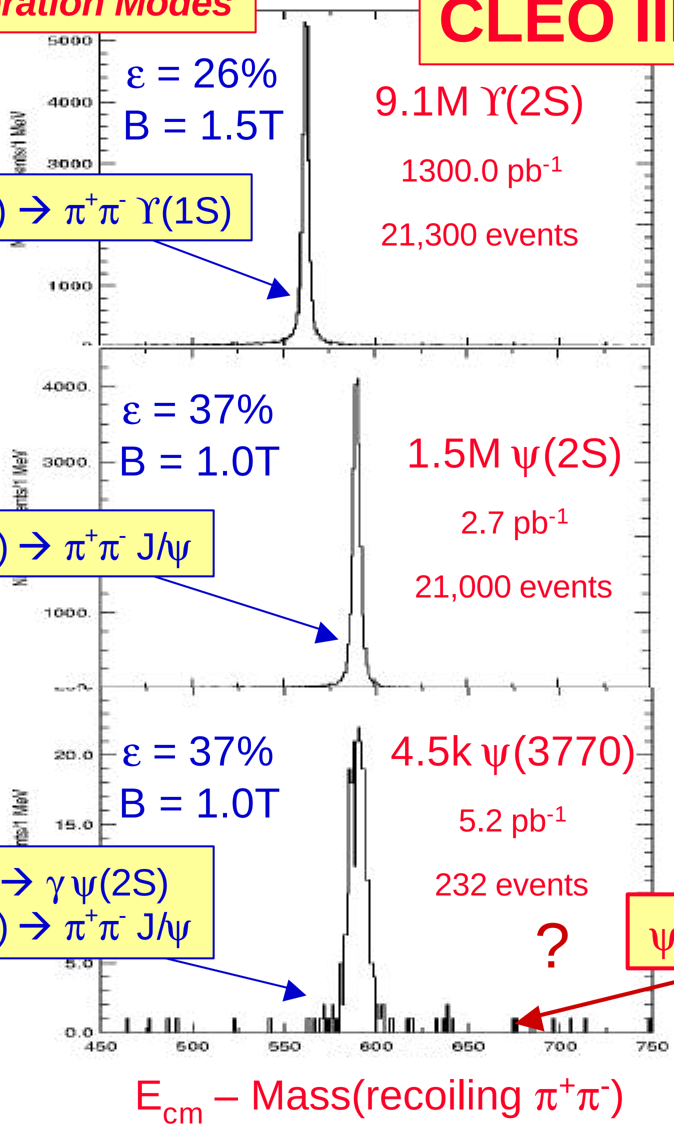
(Godfrey & Rosner PRD 64 097501 (2001))

B(¡(3S) → gg ¡(1D))
x B(¡(1D) → h ¡(1S)) < 2.3 10^{-4}

$$\frac{B(¡(1D_2) \to h\ ¡(1S))}{B(¡(1D_2) \to gg\ ¡(1S))} < 0.25 \text{ (90\% C.L.)}$$

CLEO III Running at y (3770)

Calibration Modes



y (3770) → p^+p^- J/y

- Data sample: 5.2 ± 0.2 pb^{-1}
- (4.5 ± 0.4) 10^4 y (3770) decays
- Efficiency: 37.1%
- < 4.75 events at 90% C.L.

Upper limit branching ratio:

B (y (3770) → p^+p^- J/y)
< 0.26% at 90% C.L.

BES II: B = (0.59 ± 0.26 ± 0.16)%
(hep-ex/0307028)

$p^+p^-l^+l^-$ events

After cuts on M(l^+l^-) to make it close to M(J/y) or M(¡ (2S))

CLEO-c Additional Topics

- ψ' spectroscopy
  - 10^8 decays
  - η_c', h_c …
- $\tau^+\tau^-$ at threshold
  - 0.25 fb^{-1}
  - measure m_τ to $\pm$ 0.1 MeV
  - heavy lepton, exotics searches
- $\Lambda_c\bar{\Lambda}_c$ at threshold
  - 1 fb^{-1}
  - calibrate absolute $B(\Lambda_c \rightarrow pK\pi)$
- R measurements
  - $R = \sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-)$
  - spot checks

Likely to be added to run plan (ψ' spectroscopy)

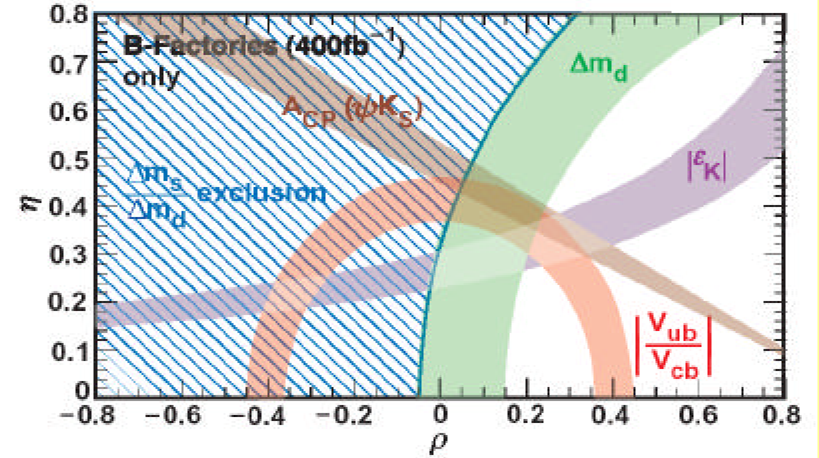
If time permits ($\tau^+\tau^-$, $\Lambda_c\bar{\Lambda}_c$, R measurements)

CLEO-c Physics Impact

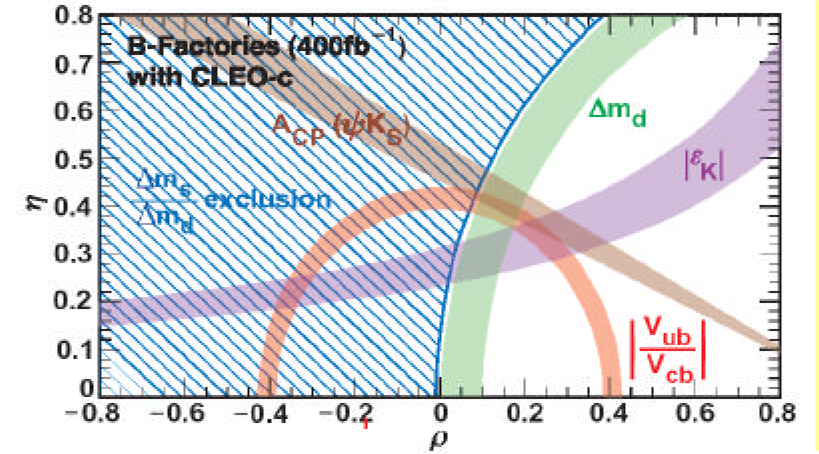
Crucial Validation of Lattice QCD:

Lattice QCD will be able to calculate with accuracies of 1 - 2%. The CLEO-c decay constant and semileptonic data will provide a “golden” & timely test . QCD & charmonium data provide additional benchmarks.

B Factories only ~2005 → Assumes theory errors reduced by x2



B Factories + CLEO-c → Theory errors = 2%



CLEO-c Physics Impact

- Knowledge of absolute charm branching fractions is now contributing significant errors to measurements involving b's. CLEO-c can also resolve this problem in a timely fashion.

- Improved knowledge of CKM elements, which is now not very good

	V_{cd}	V_{cs}	V_{cb}	V_{ub}	V_{td}	V_{ts}
PDG	7%	11%	5%	17%	36%	39%
CLEO-c Data and LQCD / B Factory/Tevatron Data & CLEO-c Lattice Validation	1.7%	1.6%	3%	5%	5%	5%

PDG → first row. CLEO-c Data and LQCD → V_{cd}, V_{cs} of second row. B Factory/Tevatron Data & CLEO-c Lattice Validation → V_{cb}, V_{ub}, V_{td}, V_{ts} of second row.

- The potential to observe new forms of matter – glueballs & hybrids – and new physics – D mixing / CP Violation / rare decays – provides a discovery component to the CLEO-c research program.

- Complementary to Hall D / HESR / BEPCII-BESIII – Not in Competition! All experiments are in the late decade & at various stages in the approval process.

The CLEO-c Collaboration

The

CLEO-c

Collaboration

University at Albany, SUNY
Carleton University
Carnegie Mellon University
Cornell University
University of Florida
University of Illinois
University of Kansas
University of Minnesota
Northwestern University
University of Oklahoma
University of Pittsburgh
Purdue University
Rensselaer Polytechnic Institute
University of Rochester
Southern Methodist University
University of California at Santa Barbara
Syracuse University
University of Texas - Pan American
Vanderbilt University
Wayne State University