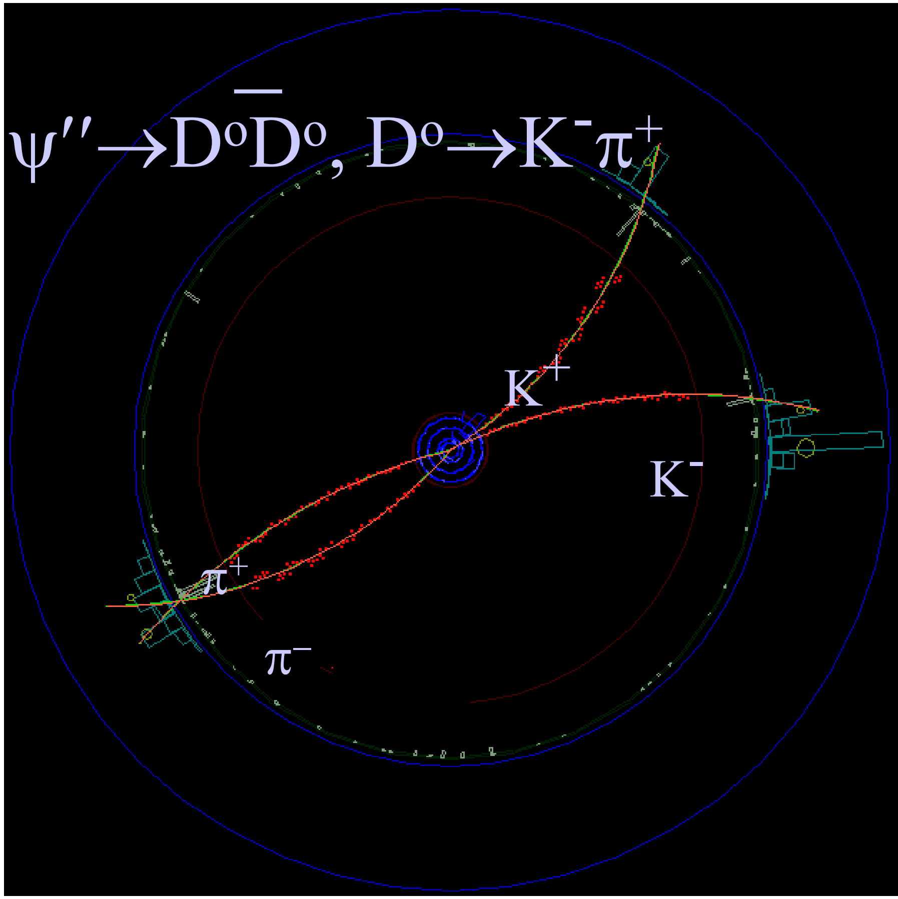
CLEO-c & CESR-c: A New Frontier in Weak and Strong Interactions

The CLEO-c Physics Program Overview



The CLEO-c Collaboration
Carleton, Carnegie Mellon, Cornell, Florida, George Mason, Illinois, Kansas, Northwestern, Minnesota, Pittsburgh, Puerto Rico, Purdue, Rochester, RPI, SMU, Syracuse, Vanderbilt, Wayne State

Ian Shipsey,
co-spokesperson CLEO Collaboration
Purdue University

CLEO-c : the context

This Decade

Flavor Physics: is in "the sin2β era" akin to precision Z. Over constrain CKM matrix with precision measurements. Limiting factor: non-pert. QCD.

The Future

LHC may uncover strongly coupled sectors in the physics that lies beyond the Standard Model
The LC will 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: The Lattice

Complete definition of pert & non. Pert.QCD. Matured over last decade, can calculate to 1-5% B,D,Υ,Ψ…

Charm at threshold can provide the data to calibrate QCD techniques → "CLEO-c/CESR"

CLEO-c Physics Program
What do we need to measure?

•flavor physics: overcome the non pert. QCD roadblock

Precision charm lifetimes ← Exist (not CLEO-c)

do not exist

• precision charm abs. branching ratio measurements (CLEO-c)

Leptonic decays : decay constants

Semileptonic decays: Vcs,Vcd,unitarity form factors

Abs D hadronic Br's normalize B physics

Tests QCD techniques in c sector, apply to b sector

→Improved Vub, Vcb, Vtd & Vts

•strong coupling in Physics beyond the Standard Model

•CLEO-c: precise measurements of quarkonia spectroscopy & decay provide essential data to calibrate theory. ← Important Input for the lattice

•Physics beyond the Standard Model:

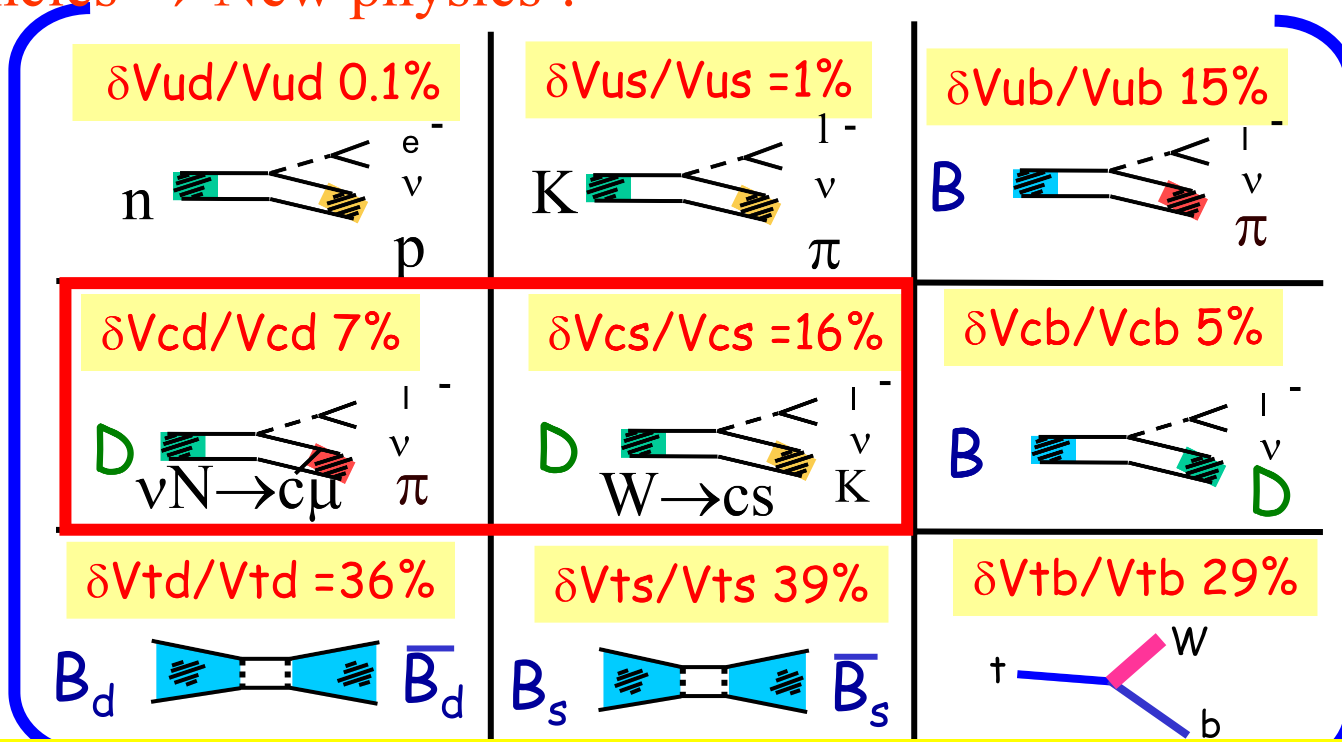
•D-mixing, CPV, rare decays. + measure strong phases

CLEO-c helps build the tools to enable this decade's flavor physics and the next decade's new physics.

Precision Quark Flavor Physics

Goal for the decade: high precision measurements of V_{ub}, V_{cb}, V_{ts}, V_{td}, V_{cs}, V_{cd}, & associated phases. Over-constrain the "Unitarity Triangles" - Inconsistencies → New physics !

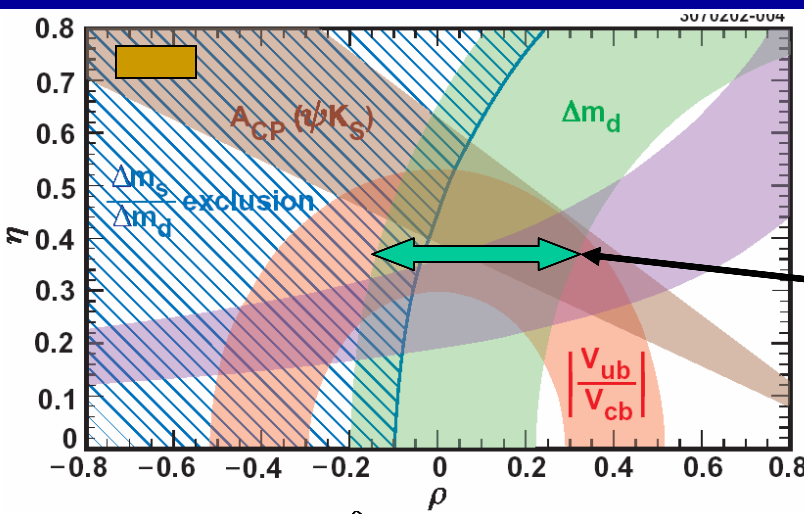
CKM Matrix Current Status:



Many experiments will contribute. Measurement of absolute charm branching ratios at CLEO-c will enable precise 1st column unitarity test & new measurements at Bfactories/Tevatron to be translated into greatly improved CKM precision.

Importance of measuring absolute charm leptonic branching ratios: f_D & $f_{D_s} \rightarrow V_{td}$ & V_{ts}

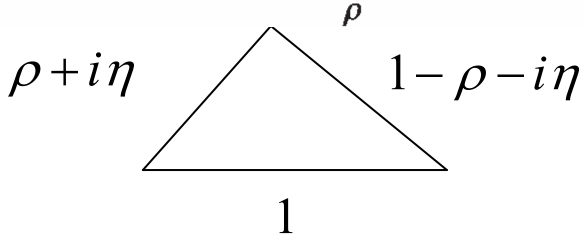
η



$$\Delta M_d = 0.50\,ps^{-1}\left[\frac{\sqrt{B_{B_d}}\,f_{B_d}}{200\,MeV}\right]^2\left[\frac{|V_{td}|}{8.8\times10^{-3}}\right]^2$$

$$\frac{\sigma(\rho)}{\rho} = 0.5\,\frac{\sigma(\Delta M_d)}{\Delta M_d} \oplus \frac{\sigma(f_B\sqrt{B_{B_d}})}{f_B\sqrt{B_{B_d}}}$$

(LP03) 1.2% ~15% (LQCD)



ρ

$$\frac{\Delta M_d}{\Delta M_s} \propto \left[\frac{\sqrt{B_{B_d}}\,f_{B_d}}{\sqrt{B_{B_s}}\,f_{B_s}}\right]^2\left[\frac{|V_{td}|}{|V_{ts}|}\right]^2$$

~5-7%

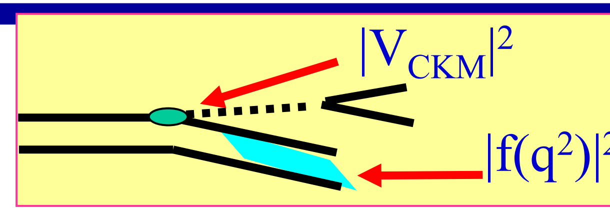
$\frac{\delta f_{D_c}}{f_{D_c}} \sim 14\%$

Lattice predicts f_B/f_D & f_{Bs}/f_{Ds} with small errors
if precision measurements of f_D & f_{Ds} existed (they do not)
We could obtain precision estimates of f_B & f_{Bs}
and hence precision determinations of V_{td} and V_{ts}
Similarly f_D/f_{Ds} checks f_B/f_{Bs}

$\frac{\delta f_{D_c}}{f_{D_c}} \sim 100\%$

Importance of absolute charm semileptonic decay rates.

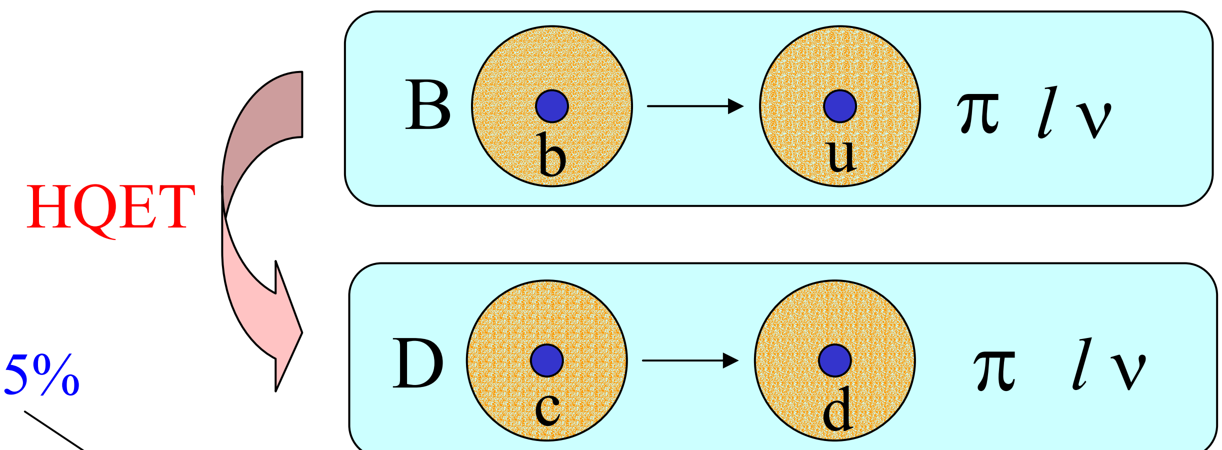
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cs}|^2 p_K^3 |f_+(q^2)|^2$$



I. Absolute magnitude & shape of form factors are a stringent test of theory.

II. Absolute charm semileptonic rate gives direct measurements of V_{cd} and V_{cs}.

III Key input to precise Vub vital CKM cross check of sin2β



$$\frac{\delta B}{B} \sim 25\%$$

1) Measure D→π form factor in D→πlν. Calibrate LQCD uncertainties .

2) Extract V_{ub} at BaBar/Belle using *calibrated* LQCD calc. of B→π form factor.

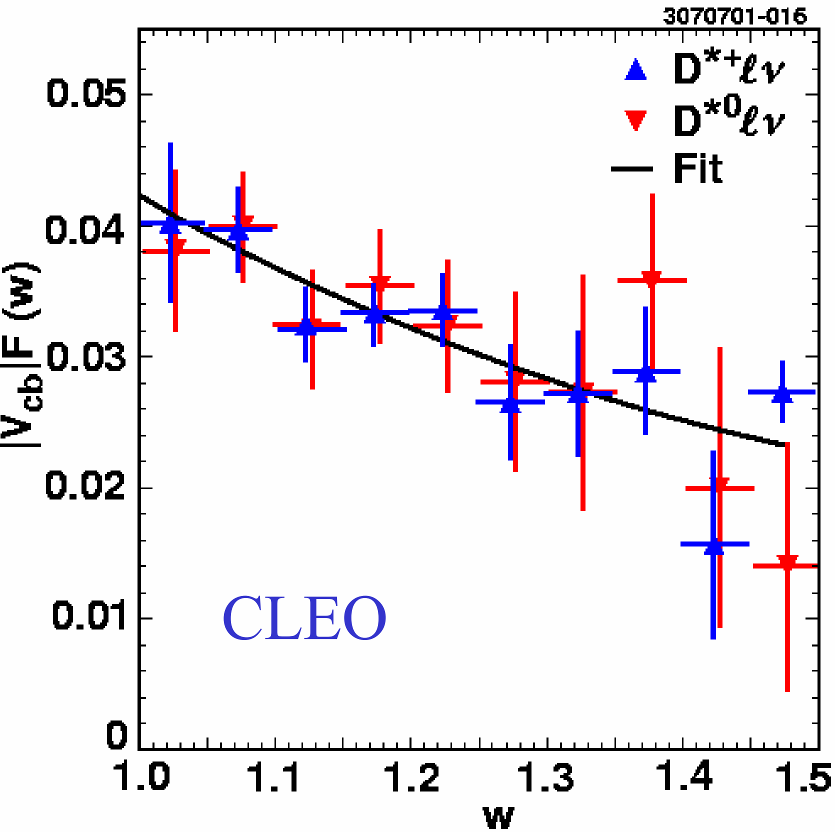
3) But: need absolute Br(D →πlν) and high quality dΓ (D →πlν)/dEπ neither exist

The Importance of Precision Charm Absolute Branching Ratios I

V_{cb} from zero recoil in $B \to D^* l^+ \nu$

CLEO as example

PRL 89 (2002) 081803
PRD 67, 032001 (2003)



$$F(1)|V_{cb}| = (43.1 \pm 1.3 \pm 1.8) \times 10^{-3}$$

$$\boxed{|V_{cb}| = (47.4 \pm 1.4 \pm 2.0 \pm 2.1) \times 10^{-3}}$$

Stat: 3.0% Sys 4.2% theory 4.4%
Dominant Sys: ε_{π}slow, form factors
As B Factory data sets grow, and theory improves

dB(D→Kπ)/dB(D→Kπ)
➔ dV_{cb}/V_{cb}=1.2%

The importance of precision absolute Charm BRs II

HQET spin symmetry test $\frac{\Gamma\left(\bar{B}^{o} \to D^{*+} h^{-}\right)}{\Gamma\left(\bar{B}^{o} \to D^{+} h^{-}\right)} = 1$

Test factorization with $B \to DD_s$

Understanding charm content of B decay (n_c)

Precision $Z \to bb$ and $Z \to cc$ (R_b & R_c)

At LHC/LC $H \to bb$ $H \to cc$

CESR-c

Unmodified CESR

1 day scan of the Ψ′:

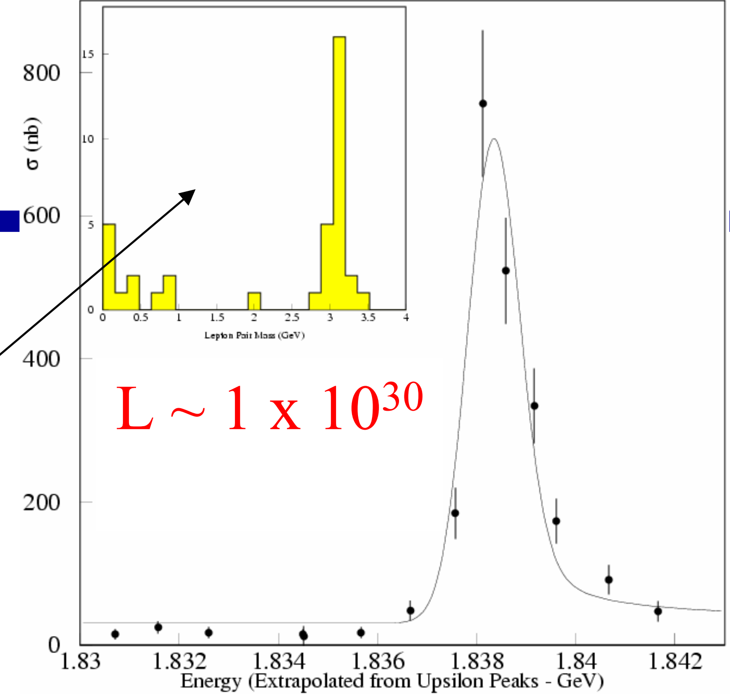
(1/29/02)

CESR

L(@Y(4S)= 1.3 x 10^{33}

$\Psi' \to J/\Psi\pi\pi$

$J/\Psi \to \mu\mu$



- CESR-c
- Being modified for low energy operation:
- wigglers added for transverse cooling

Expected machine performance with full complement of wigglers

$\sqrt{s}$	L (10^{32} cm^{-2} s^{-1})
3.1 GeV	1.5
3.77 GeV	3.0
4.1 GeV	3.6

- ΔE_{beam} ~ 1.2 MeV at J/ψ

CLEO-c Run Plan & Status

2002: Prologue: Upsilons ~4 fb^{-1} at Y(1S),Y(2S),Y(3S) (combined)
Spectroscopy, matrix element, Γ_{ee}, η_B h_b
10-20 times the existing world's data (Nov 2001-Nov 2002)

2003: Installed 1 prototype wiggler spring '03
Took ~5 pb^{-1} at ψ(3770), 3 pb^{-1} ψ(2S)
Installed ½ production wigglers summer'03
9/03-1/04 ψ(3770) ψ(2S,) continuum
54 pb^{-1} 2.5 pb^{-1} 4.4 pb^{-1}
Install ½ production wigglers spring'04

Will show this data

MACHINE CONVERSION

exceeded goal

Fall 2004: ψ(3770) – 3 fb^{-1} (ψ(3770) →DD) 30 million DD
6 million *tagged* D decays assumes $\sigma(\psi(3770) \to D\overline{D} = 10nb)$ BESIII assumes 5nb ➔all following CLEO-c speakers will use 10 nb & 5nb

Fall 2005: $\sqrt{s} \sim 4140$ MeV – 3 fb^{-1} 1.5 million D_sD_s events,
0.3 million *tagged* D_s decays (480 x MARK III, 130 x BESII)

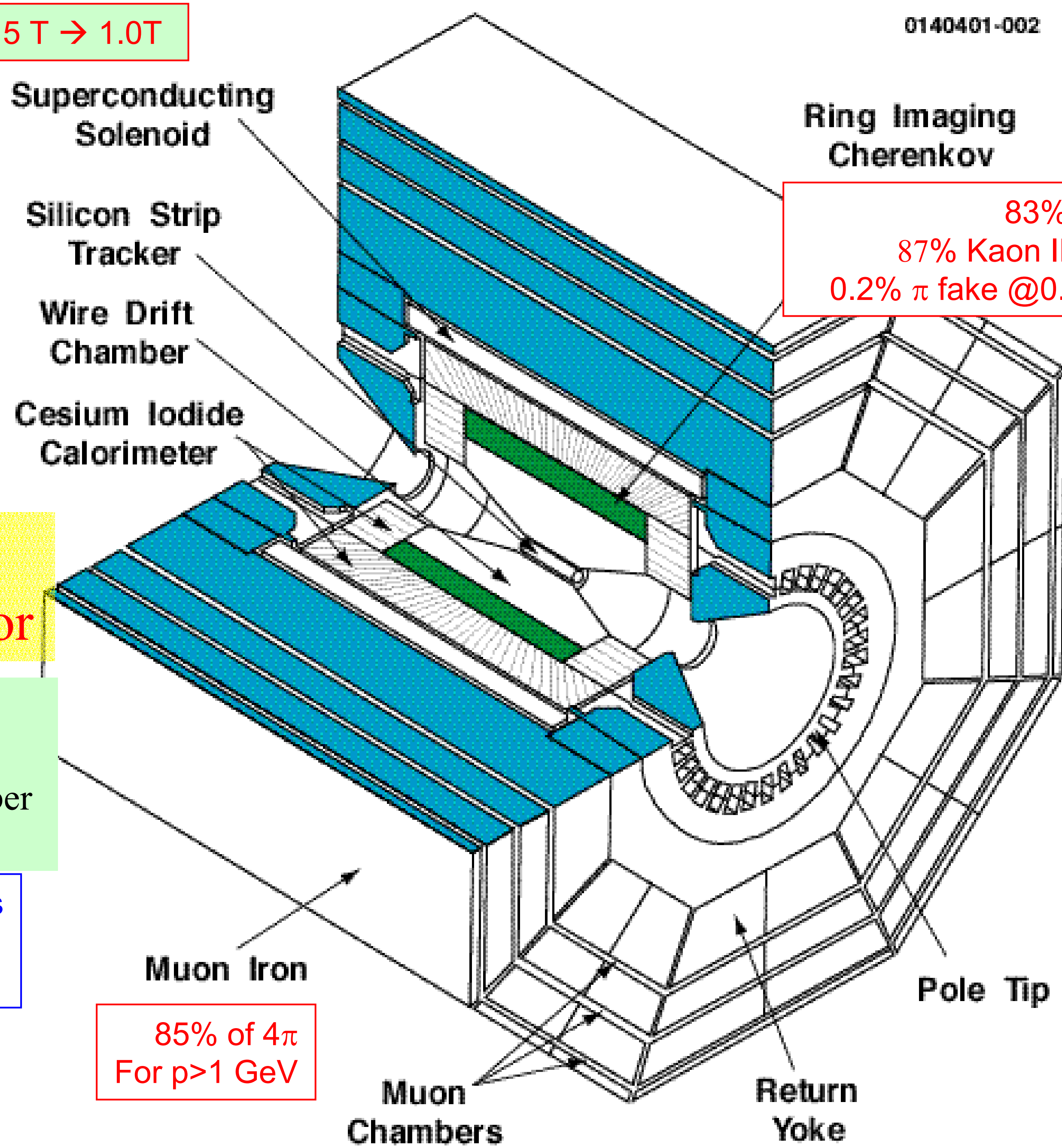
Fall 2006: ψ(3100), 1 fb^{-1} –1 Billion J/ψ decays

C
L
E
O
c

A 3 year program

CLEO III Detector → CLEO-c Detector

1.5 T → 1.0T



93% of 4π
σ_p/p = 0.35% @1GeV
dE/dx: 5.7% π @minI

93% of 4π
σ_E/E = 2% @1GeV
= 4% @100MeV

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

85% of 4π
For p>1 GeV

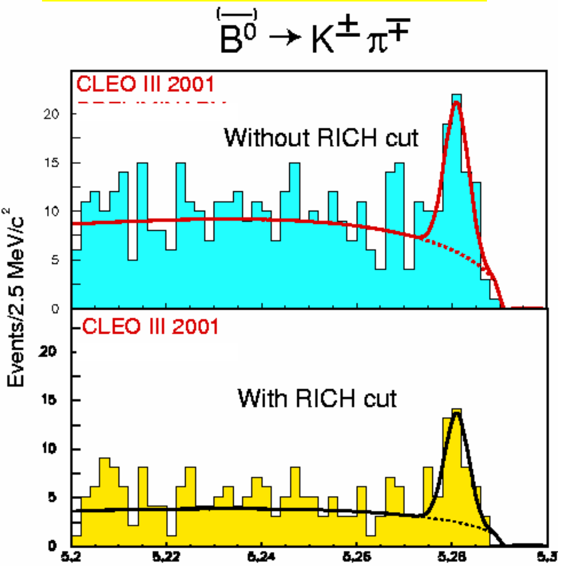
Minor modification:
replaced silicon with
low mass inner drift chamber
summer '03

Trigger: Tracks & Showers
Pipelined
Latency = 2.5μs

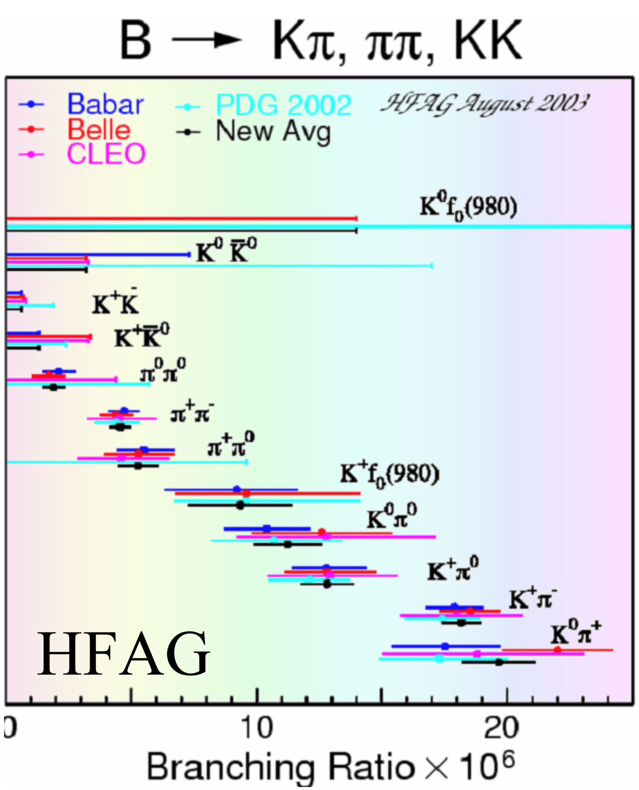
Data Acquisition:
Event size = 25kB
Thruput < 6MB/s

CLEO III Physics: Two Examples

1st result (2001)

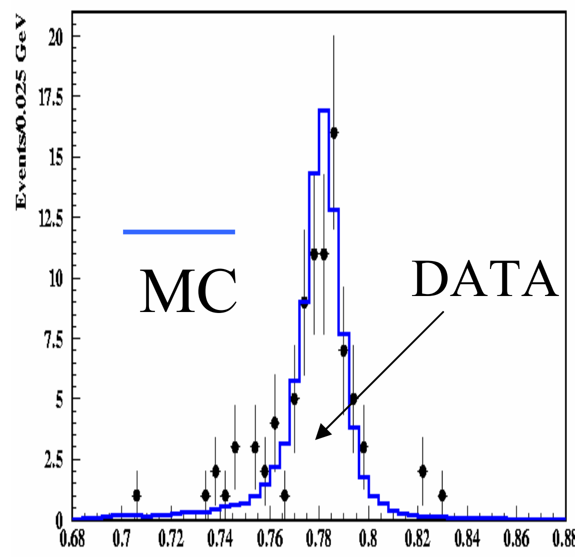


Beam constrained Mass (GeV/c^2)



DISCOVERY (2003):

$\chi_b(1P) \to \omega\Upsilon(1S)$



$M(\pi^+\pi^-\pi^0)$ GeV

1st new hadronic transition observed in Υ system in 20 years

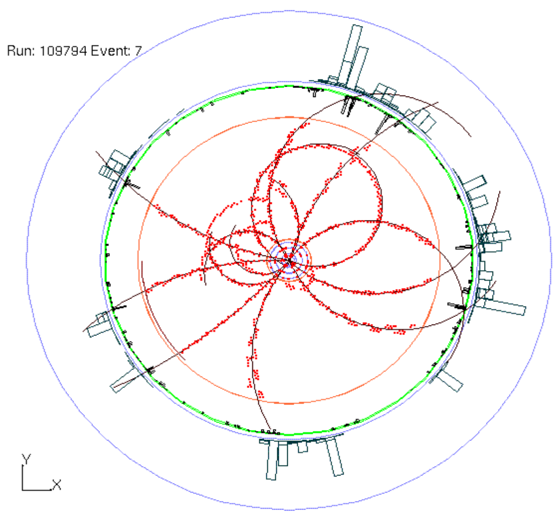
hep-ex/0311043

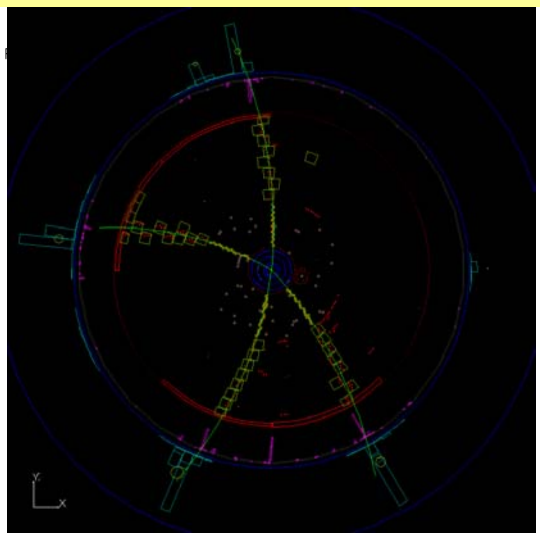
Good agreement: between CLEO BaBar & Belle

CLEO III is well understood detector!

ψ(3770) events: simpler than Y(4S) events

Y(4S) event (2001)   ψ(3770) event (2003)





$D^0 \to K^-\pi^+$ $\overline{D^0} \to K^+e^-\nu$

- 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 cc by 2005, what is the advantage of running at threshold?

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

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

Tagging Technique, Tag Purity @ Threshold CLEO-c simulation

- $\psi(3770) \rightarrow DD$ $\sqrt{s}$ ~4140 $\rightarrow D_sD_s$

Charm mesons have many large branching ratios (~1-15%)

low multiplicity: high reconstruction efficiency

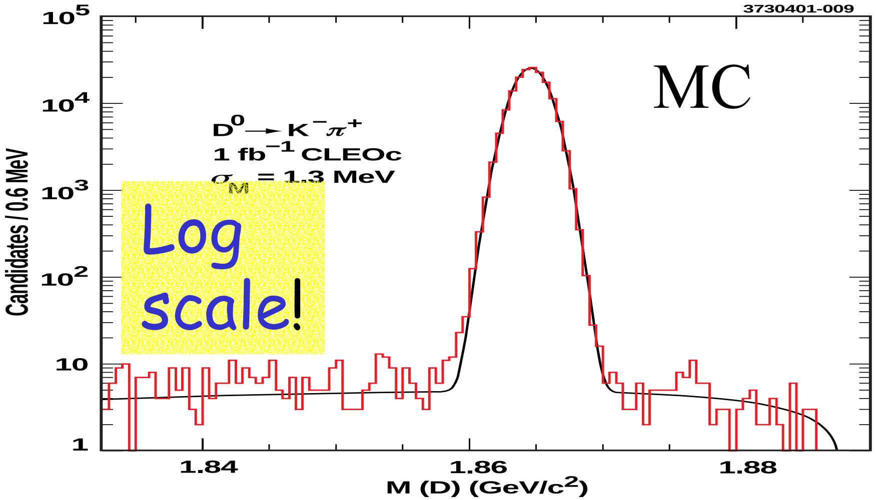
$\rightarrow$ high net tagging efficiency ~20% !

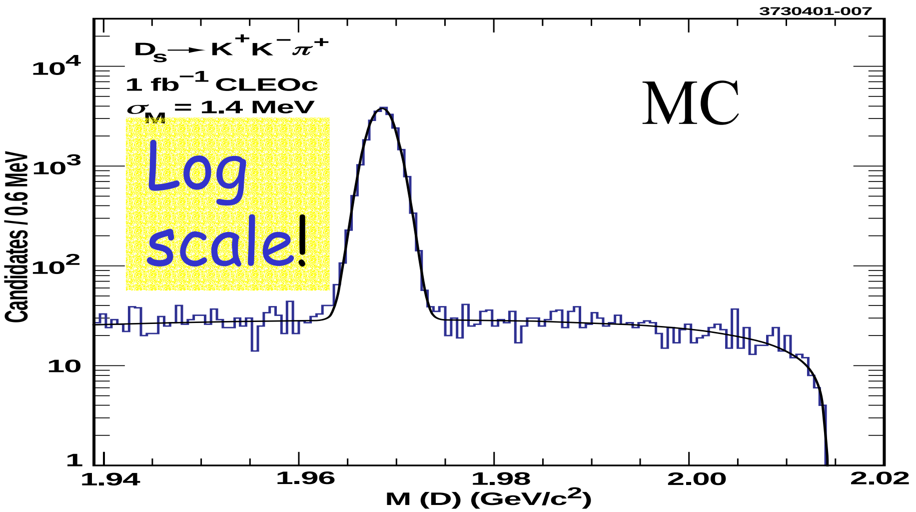
In 1 year At Each $\sqrt{s}$

Anticipate 6M D tags 300K D_s tags:

$D \rightarrow K\pi$ tag. S/B ~5000/1 !

$D_s \rightarrow \phi\pi$ ($\phi \rightarrow KK$) tag. S/B ~100/1



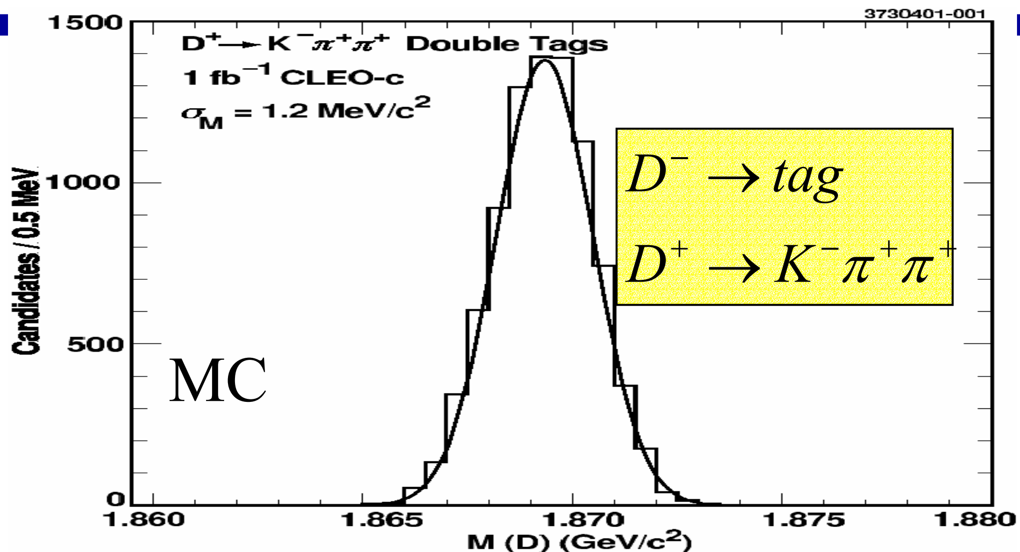


Beam constrained mass

Absolute Branching Ratios

Low background in hadronic tag modes

Measure absolute
Br (D→ X) with double tags
Br = # of X / # of D tags

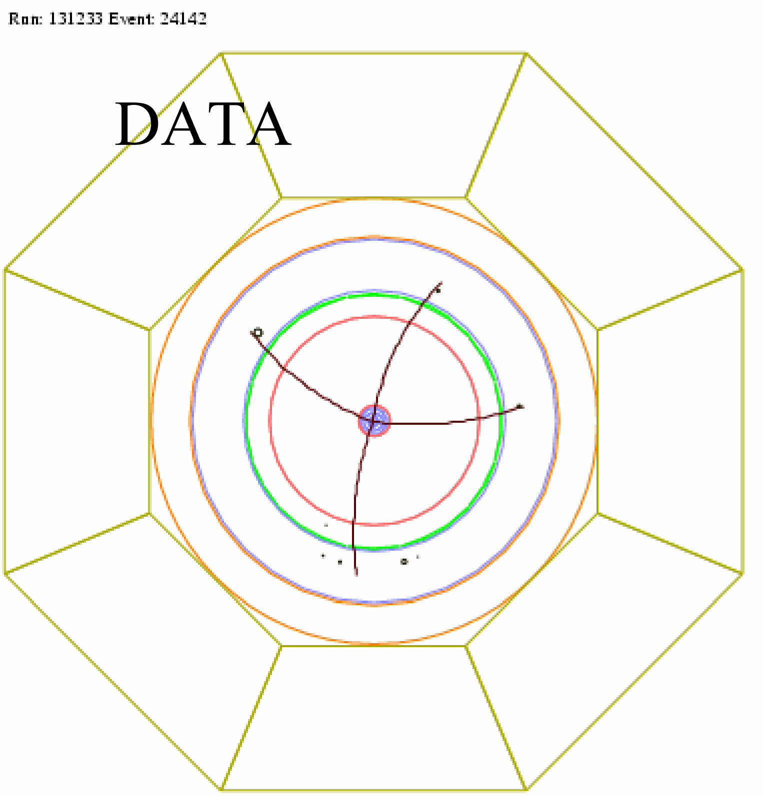


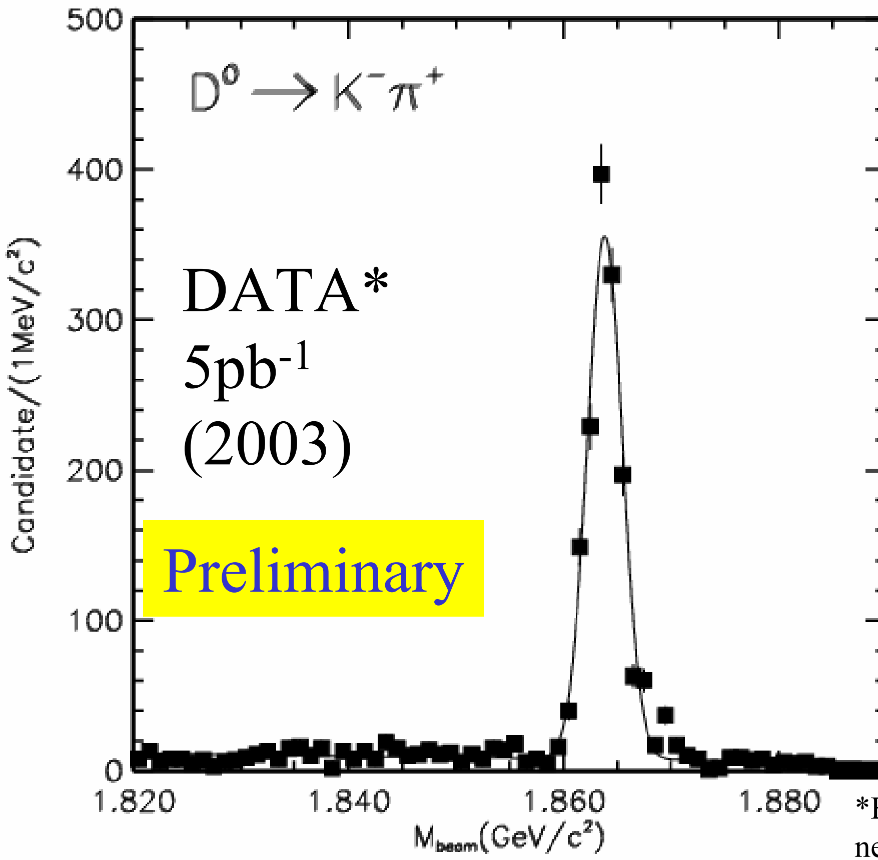
Decay	√s	L fb^{-1}	Double tags	PDG ($\delta B/B$ %)	CLEOc ($\delta B/B$ %)
$D^0 \to K^-\pi^+$	3770	3	53,000	2.4	0.6
$D^+ \to K^-\pi^+\pi^+$	3770	3	60,000	7.2	0.7
$D_s \to \phi\pi$	4140	3	6,000	25	1.9

CLEO-c sets absolute scale for all heavy quark measurements

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

Single tags: CLEO-c DATA





*Before new inner drift chamber installed

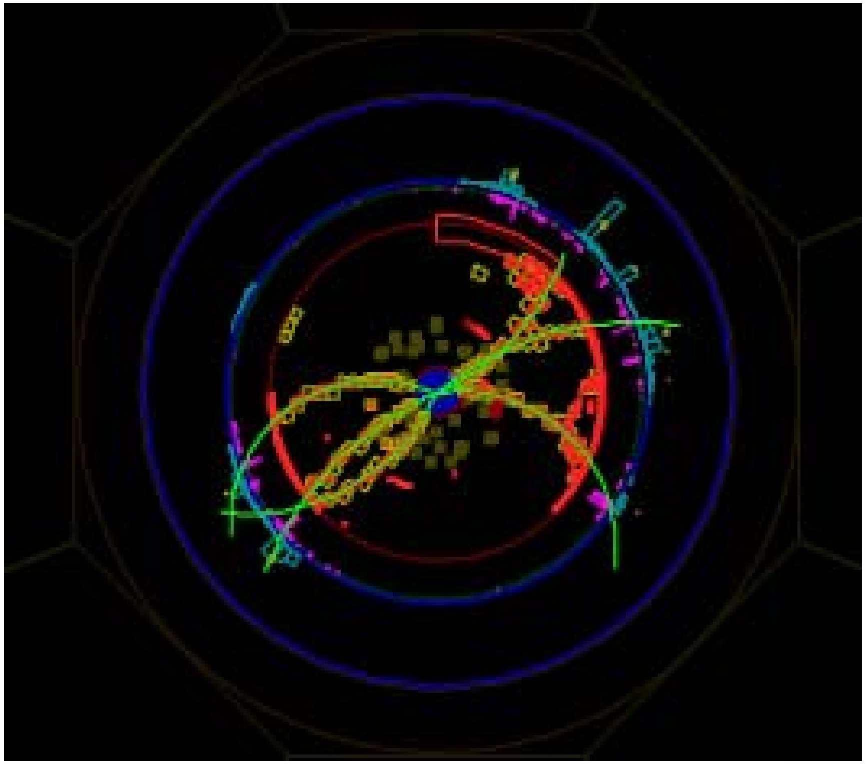
$$D^0 \to K^-\pi^+ \; \overline{D^0} \to K^+\pi^-$$

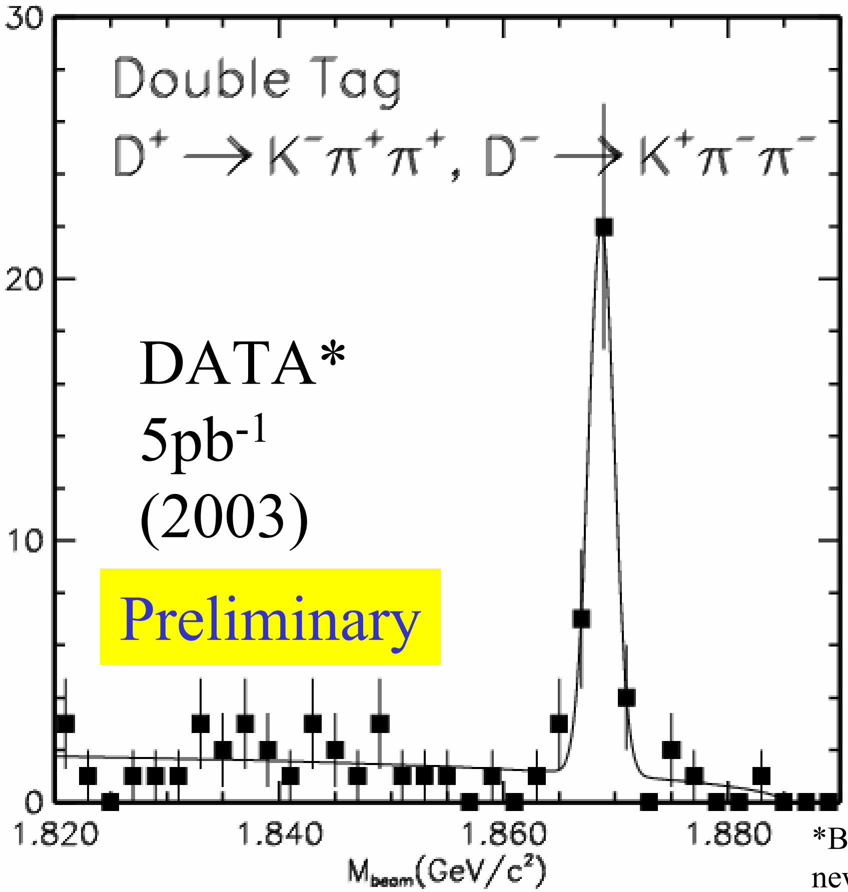
*Before new inner drift Chamber installed

Single tag *are* clean

Double tags: CLEO-c DATA

DATA





DATA*
5pb^{-1}
(2003)

Preliminary

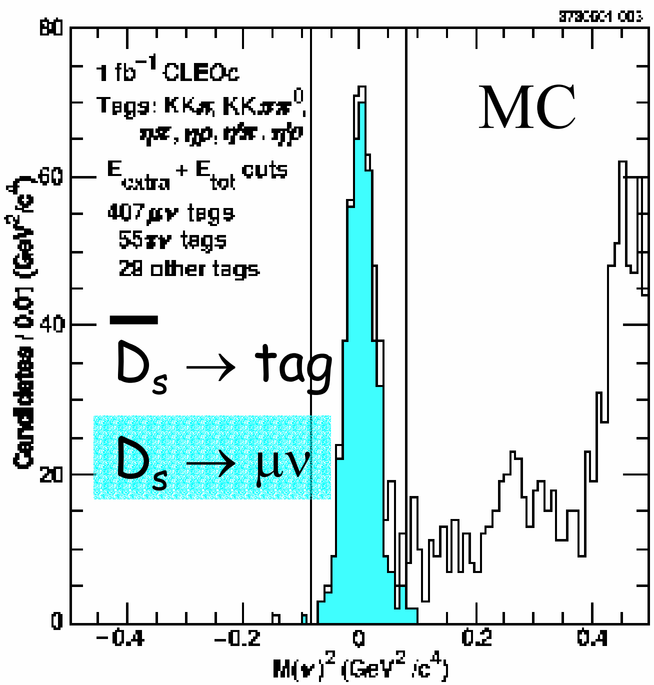
*Before new inner drift chamber installed

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

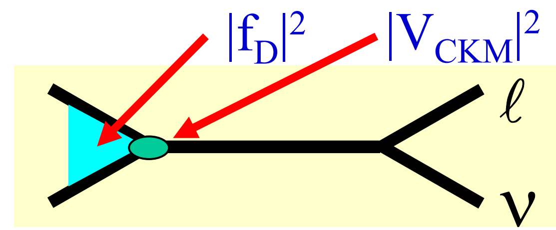
Double tag events *are* clean

➔ giving confidence in our MC simulations & estimates of precision

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



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



•Compute MM²

•Peaks at zero for $D_s^+ \to \mu^+\nu$ decay.

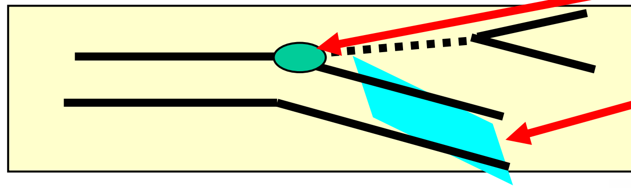
Expect resolution of ~M_{π^0}

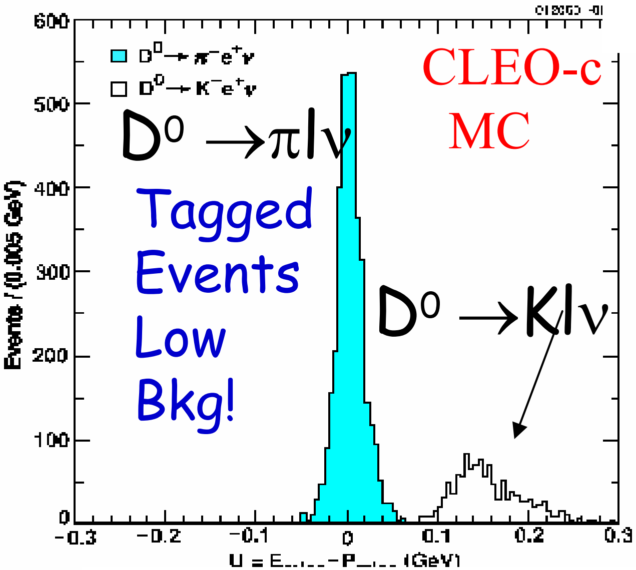
$$M(\nu)^2 = \left[E(D_{tag}) - E(\mu)\right]^2 - \left[P(D_{tag}) - P(\mu)\right]^2$$

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

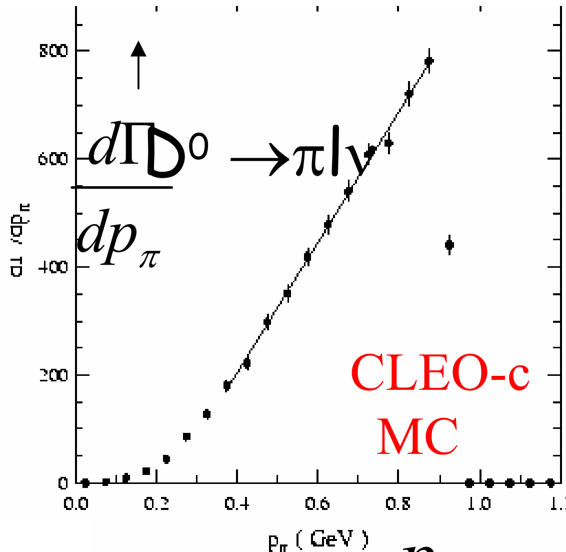
	Reaction	Energy(MeV)	L fb^{-1}	PDG	CLEO-c
f_{D_s}	$D_s^+ \to \mu\nu$	4140	3	17%	1.9%
f_{D_s}	$D_s^+ \to \tau\nu$	4140	3	33%	1.6%
f_{D^+}	$D^+ \to \mu\nu$	3770	3	UL	2.3%

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

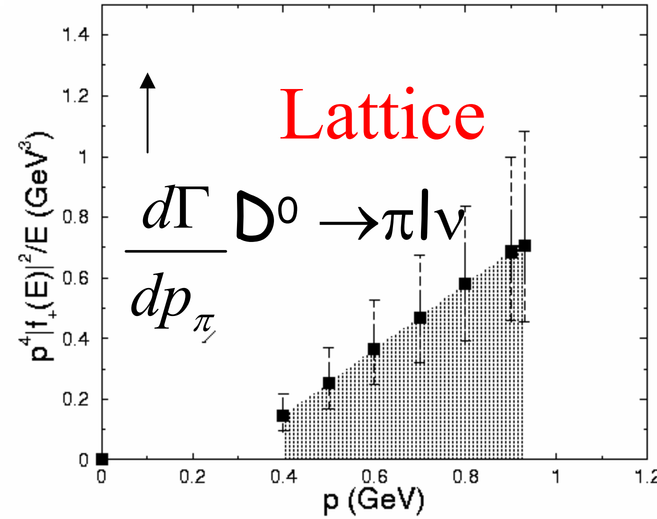




$U = E_{miss} - P_{miss}$



$p_\pi \longrightarrow$



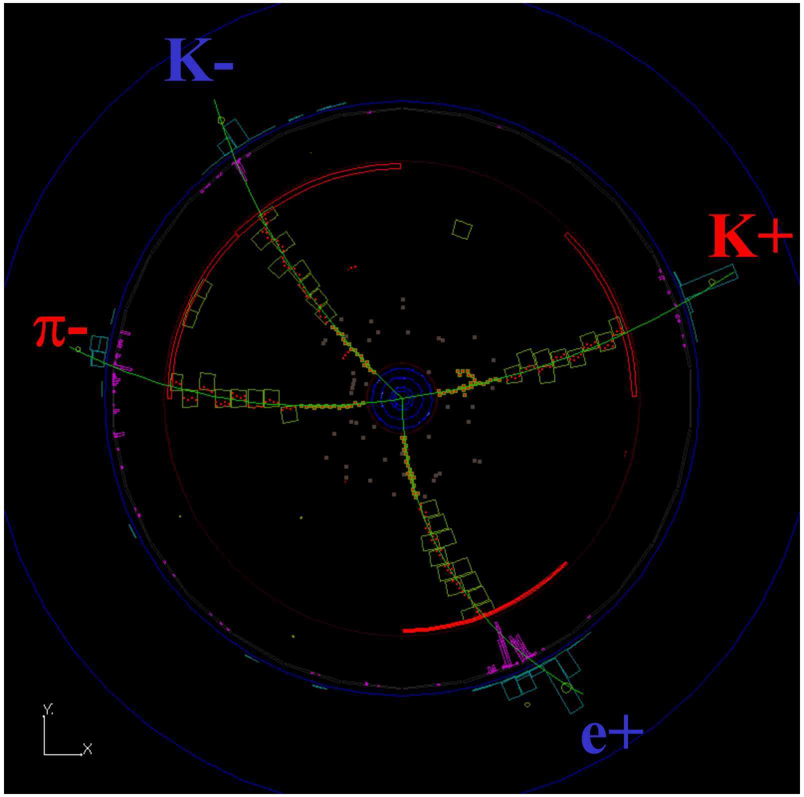
$p_\pi \longrightarrow$

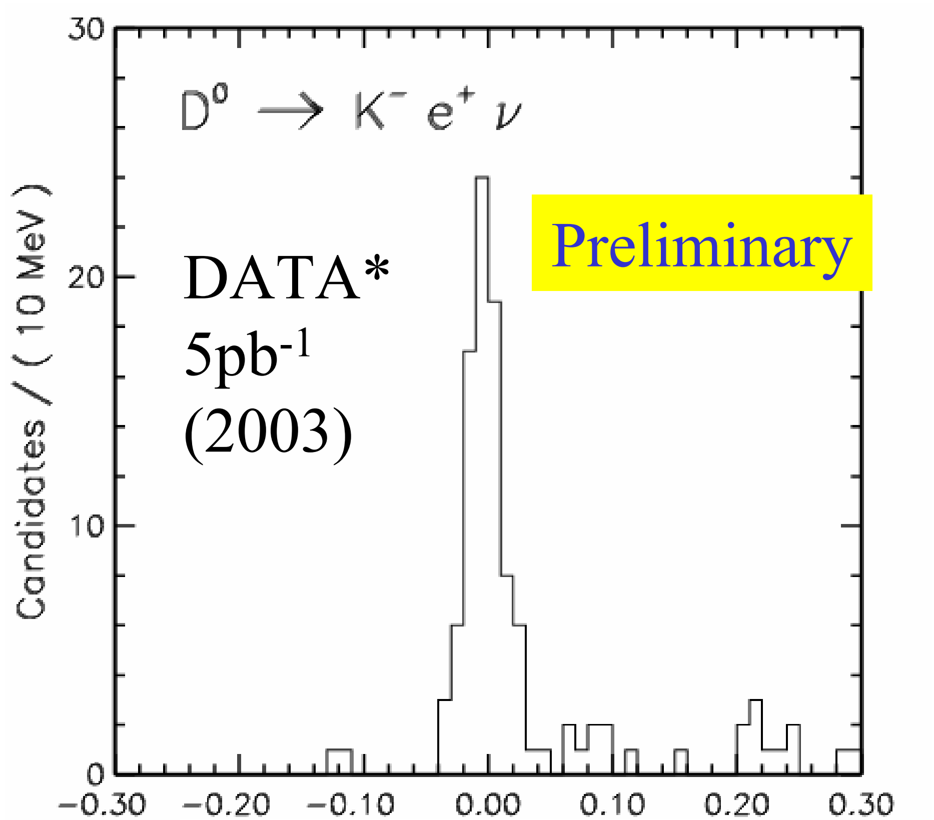
Assume 3 generation unitarity: for the first time measure complete set of charm PS $\to$ PS & PS $\to$ V absolute form factor magnitudes and slopes to a few% with almost no background in one experiment.

Stringent test of theory!

Semileptonic Decays: DATA

$\overline{D^0} \rightarrow$ hadronic tag





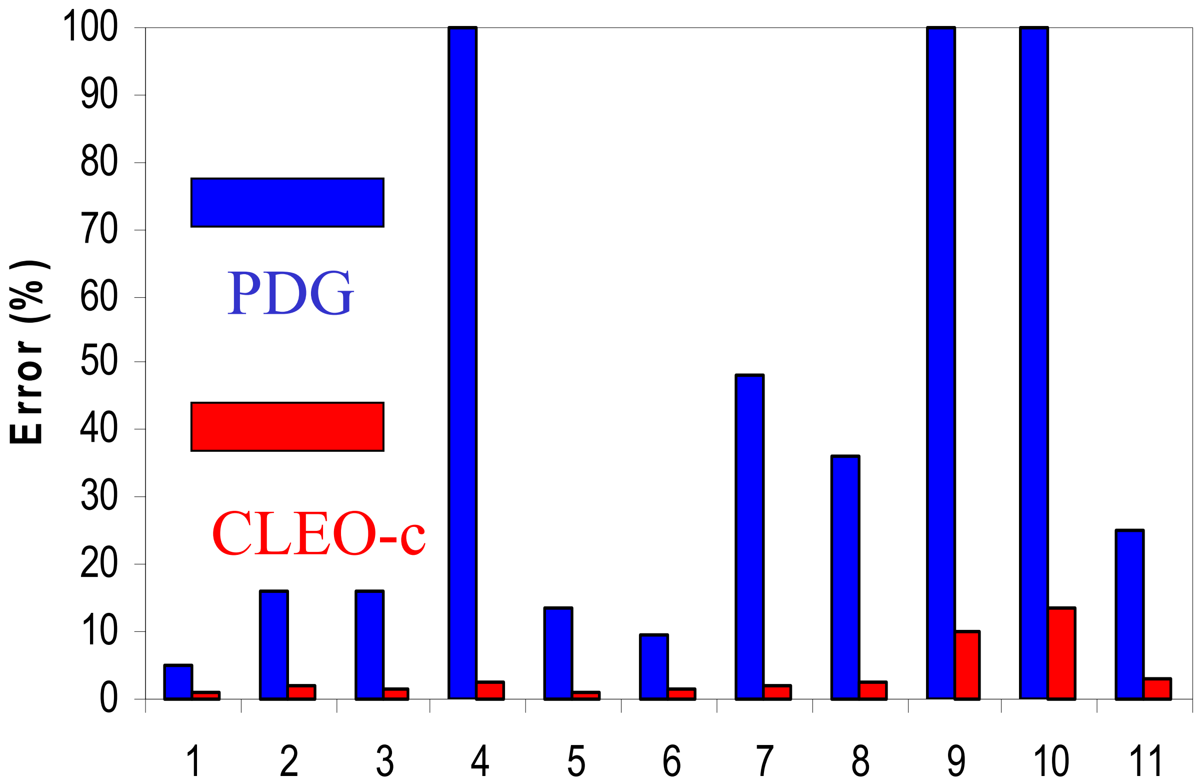
$\overline{D^o} \rightarrow K^+\pi^-$ $D^o \rightarrow K^-e^+\,\nu$

$U = E_{miss} - P_{miss}$

*Before new inner drift chamber installed

CLEO-c Impact semileptonic dB/B

1 : $D^0 \to K^- e^+ \nu$
2 : $D^0 \to K^{*-} e^+ \nu$
3 : $D^0 \to \pi^- e^+ \nu$
4 : $D^0 \to \rho^- e^+ \nu$
5 : $D^+ \to \bar{K}^0 e^+ \nu$
6 : $D^+ \to \bar{K}^{*0} e^+ \nu$
7 : $D^+ \to \pi^0 e^+ \nu$
8 : $D^+ \to \rho^0 e^+ \nu$
9 : $D_s \to K^0 e^+ \nu$
10 : $D_s \to K^{*0} e^+ \nu$
11 : $D_s \to \phi e^+ \nu$



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

Even with 50 pb^{-1} already accumulated CLEO-c will improve on the PDG value of dB/B for *every* D^+ and D^0 exclusive semileptonic and inclusive branching ratio. and will have ~x10 the statistics of the DELCO D➔eX inclusive spectrum (important for B semileptonic decays studies).

Determining Vcs and Vcd

combine semileptonic and leptonic decays eliminating V CKM

$\Gamma(D^+ \to \pi l \nu)$ / $\Gamma(D^+ \to l \nu)$ independent of Vcd
Test rate predictions at ~4%

$\Gamma(D_s \to \phi l \nu)$ / $\Gamma(D_s \to l \nu)$ independent of Vcs
Test rate predictions at ~ 4.5%

Test amplitudes at 2%
Stringent test of theory! If theory passes the test.....

I

$D^0 \to K^- e^+ \upsilon$ δVcs /Vcs = 1.6% (now: 16%)

$D^0 \to \pi^- e^+ \upsilon$ δVcd /Vcd = 1.7% (now: 7%)

II Use CLEO-c validated lattice to calc. B semileptonic form factor, then B factories can use $B \to \rho/\pi/\eta/l\nu$ for precise Vub

Unitarity Constraints

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

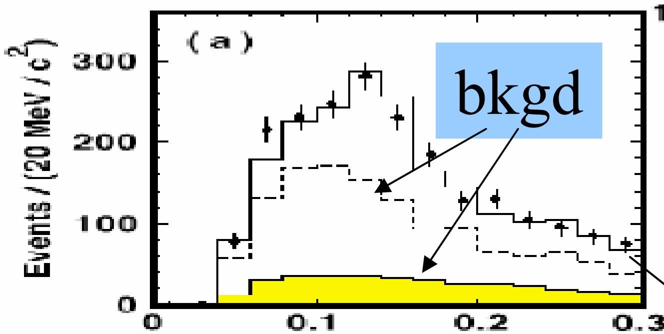
$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- $|Vud|^2 + |Vus|^2 + |Vub|^2 = 1$??
  With current values this test fails at ~2σ (PDG2002)
- $|Vcd|^2 + |Vcs|^2 + |Vcb|^2 = 1$??
  CLEO-c: test to ~3% (if theory $D \to K/\pi l \nu$ good to few %)
  & 1st column: $|Vud|^2 + |Vcd|^2 + |Vtd|^2 = 1$?? with similar precision to 1st row
- 

Compare ratio of long sides to 1.3%
Also major contributions to Vub, Vcb, Vtd, Vts.

Compare B factories & CLEO-c

CLEO: f D_S : $D_S^* \to D_S \gamma$ with $D_S \to \mu\nu$



$\Delta M = M(\mu\nu\gamma) - M(\mu\nu)$ GeV/c

CLEO-c
3 fb^{-1}

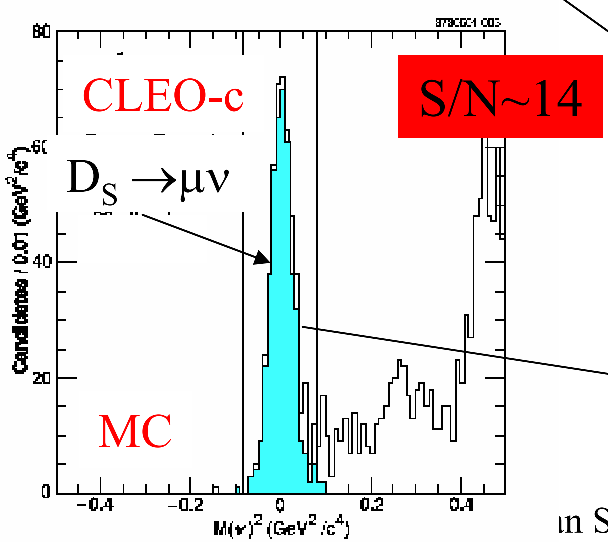
Statistics limited

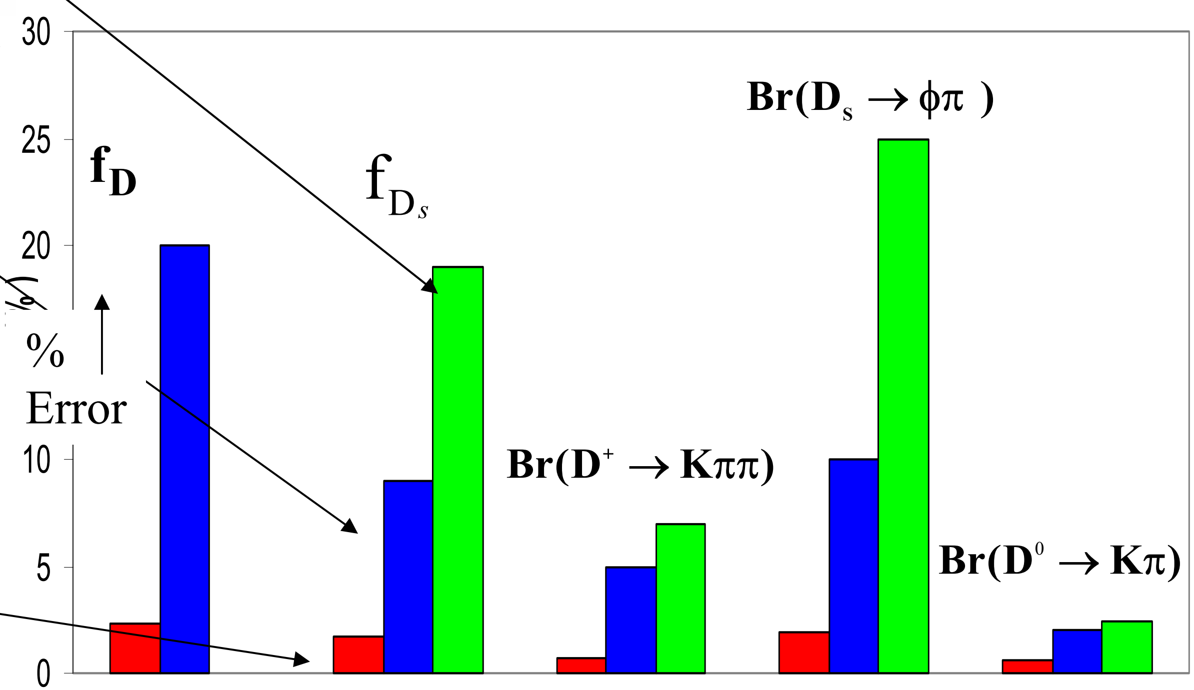
BFactory
400 fb^{-1}

Systematics & Background limited

PDG

B Factory CLEO technique with improvements





CLEO-c Probes of New Physics

D mix & DCPV suppressed in SM – all the more reason to measure them

DD mixing $x = \Delta m/\Gamma$ $y = \Delta\Gamma/2\Gamma$ $\psi(3770) \rightarrow DD(C = -1)$

exploit coherence, no DCSD. $\psi(4140) \rightarrow \gamma DD$ $(C = +1)$

$\sqrt{r_D} = \sqrt{[(x^2+y^2)/2]} < 0.01$ @ 95%CL ($K\pi K\pi$, $Kl\nu, Kl\nu$)

- CP violating asymmetries
  - Sensitivity: $A_{cp} < 0.01$
  - Unique: L=1, C=-1 CP tag one side, opposite side same CP

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

CP Dalitz analyses ex: $D \rightarrow K_s\pi\pi$ may provide greater CPV reach

- CP eigenstate tag X flavor mode

$K^+K^- \leftarrow D_{CP} \leftarrow \psi(3770) \rightarrow D_{CP} \rightarrow K^-\pi^+$

Measures strong phase diff. CF/DCSD

$\Delta\cos\delta \sim 0.05$. Crucial input for B factories

Needed for γ in $B \rightarrow DK$

Gronau, Grossman, Rosner hep-ph/0103110

$$\begin{cases} y' = y\cos\delta - x\sin\delta \\ x' = x\cos\delta + y\sin\delta \end{cases}$$

Rare charm decays. Sensitivity: 10^{-6}

CESR CLEO

Probing QCD

→Verify tools for strongly coupled theories

→ Quantify accuracy for application to flavor physics

- ψ and Υ Spectroscopy
  - Masses, spin fine structure

Confinement,
Relativistic corrections

- Leptonic widths for S-states.
  - EM transition matrix elements
    - Υ resonances complete~ 4 fb^{-1} total

Wave function

Tech: $f_{B,K} \sqrt{B_K}\ f_{D\{s\}}$

Form factors

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

J/Ψ running fall 2006 10^9 J/ Ψ

- Uncover new forms of matter –gauge particles as constituents
  - Glueballs G=|gg⟩ Hybrids H=|gqq⟩

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 ordinary hadron spectrum in 1.5-2.5 GeV mass range.

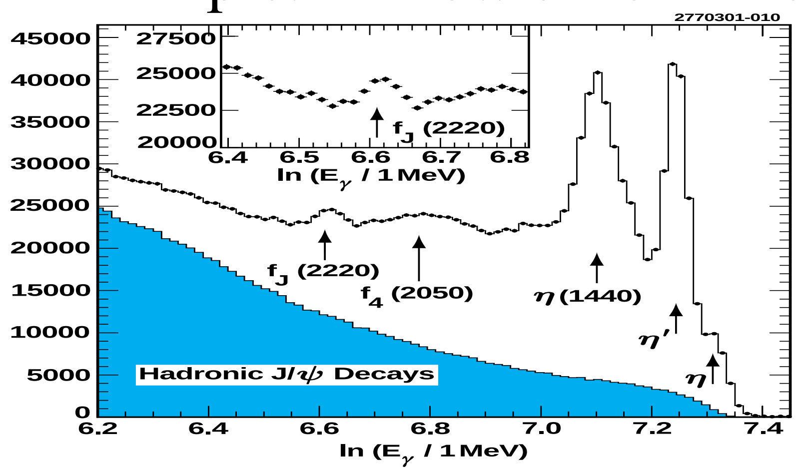
Gluonic Matter

- Gluons carry color charge: *should bind!*

- But, like Jim Morrison, glueballs have been sighted too many times without confirmation.
- CLEO-c 1st high statistics experiment with modern 4π detector covering 1.5-2.5 GeV mass range.
- Radiative ψ decays:ideal glue factory:

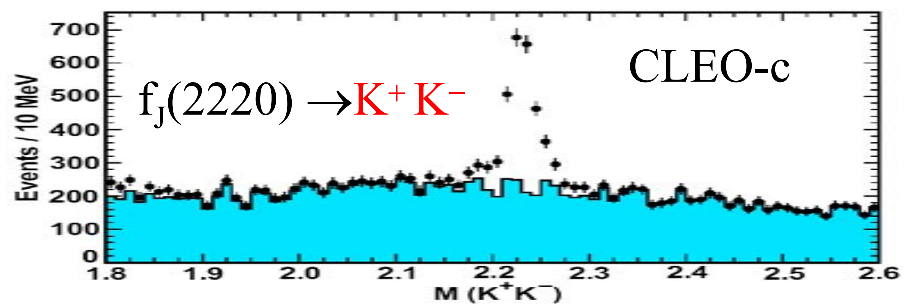
  - (60 M $J/\Psi \to \gamma X$)

Example: Narrow state in inclusive γ



Sensitivity B($J/\Psi \to \gamma X$)~10^{-4}

Exclusive:



Shown B(fJ(2220) $\to K^+ K^-$)= 3.10^{-5}

Sensitivity 5σ B(fJ(2220) $\to K^+ K^-$)= 10^{-6}

corroborating checks:

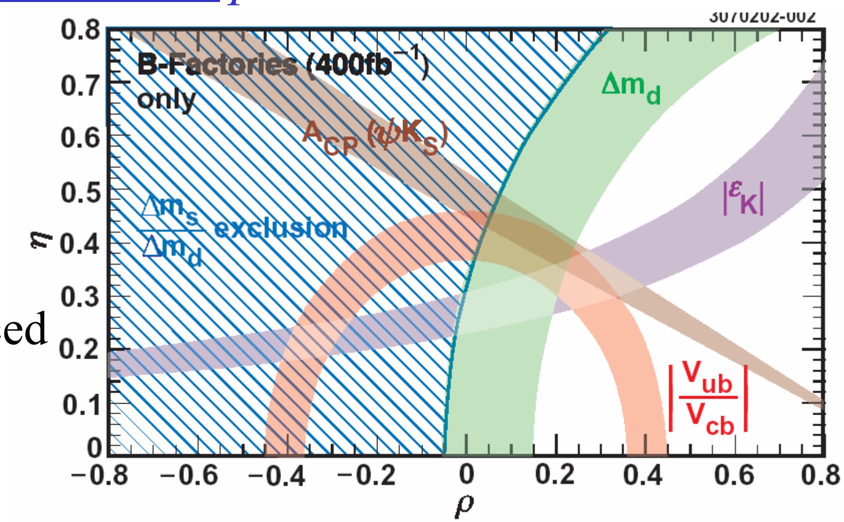
Anti-search in $\gamma\gamma$: /Search in $\Upsilon(1S)$

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



Imagine a world Where we have theoretical mastery of non-perturbative QCD at the 2% level

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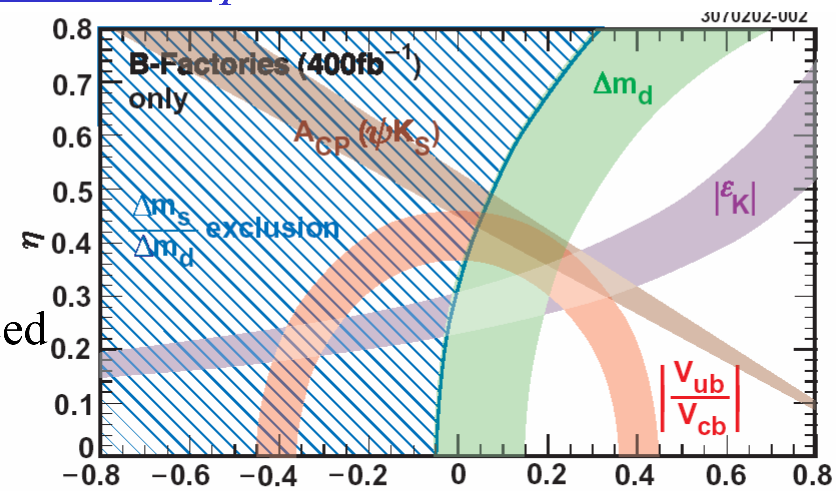
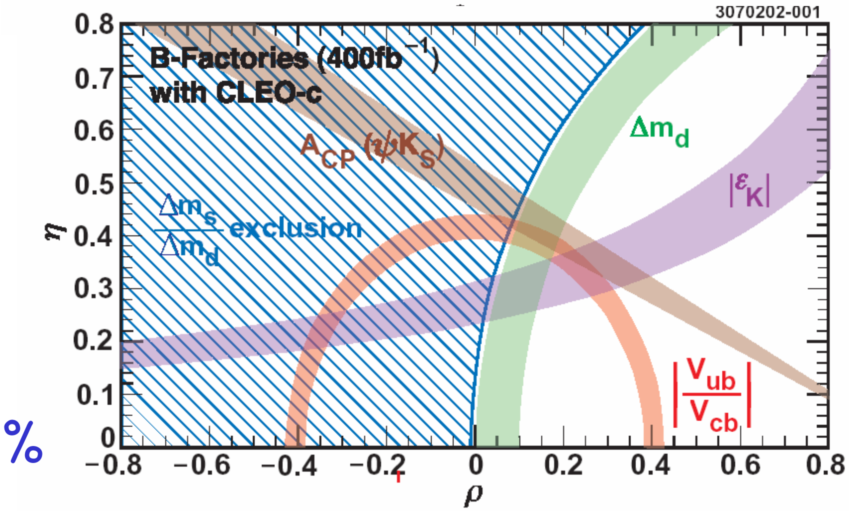


Imagine a world where we have theoretical mastery of non-perturbative QCD at the 2% level

Theory errors = 2%



CLEO-c Physics Impact

- Knowledge of absolute charm branching fractions is now contributing significant errors to measurements involving beauty quarks. CLEO-c can also resolve this problem in a timely fashion
- Improved Knowledge of CKM elements, which is now not very good.

	Vcd	Vcs	Vcb	Vub	Vtd	Vts
PDG	7%	16%	5%	15%	36%	39%
CLEO-c data and LQCD / B Factory/Tevartron Data & CLEO-c Lattice Validation	1.7%	1.6%	3%	5%	5%	5%

PDG

CLEO-c data and **LQCD**

PDG

B Factory/Tevartron Data & CLEO-c Lattice Validation

The potential to observe new forms of matter- glueballs & hybrids, and new physics D mixing/CPV/rare provides a discovery component to the program

The CLEO-c Program: Summary

- Powerful physics case
  - Precision flavor physics – *finally*
  - Nonperturbative QCD – *finally*
  - Probe for New Physics

Direct: Vcs Vcd & tests QCD techniques aids BABAR/Belle/ CDF/D0/BTeV/LHC-b with Vub,Vcb,Vtd,Vts

•This suite of measurements can only be performed with the requisite precision at a facility operating at charm threshold

- Optimal timing
  - LQCD maturing
  - allows Flavor physics to reach
  - its full potential this decade
  - Beyond the SM in next decade

The most comprehensive & in depth study of non-perturbative QCD yet in particle physics

First results from $\psi(3770)$ data in next few months

On behalf of the CLEO Collaboration:

Both BES and CLEO have a great particle physics tradition.
We are delighted to be part of this workshop which is a wonderful opportunity to learn from each other as we both embark on our journey to a new frontier in our understanding of the weak and strong interactions

Thank-you for the warm welcome, the hospitality, and the discussions we will share over the next three days.