An Experimenter's View of: Lattice Heavy Quark Flavor Physics

Outline:

Goals of quark flavor physics:
Quark Mixing & CP Violation
Physics Beyond the Standard Model

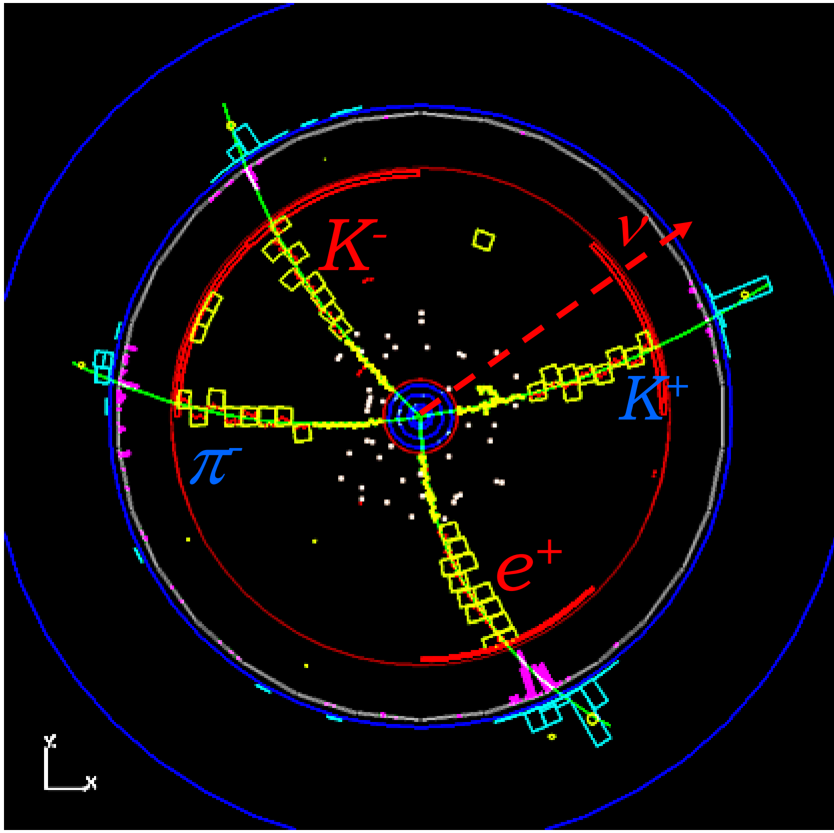
Status of key quark flavor measurements where the lattice role is significant

How charm tests lattice QCD techniques

1st charm results from CLEO-c

Issues & Outlook

Conclusion



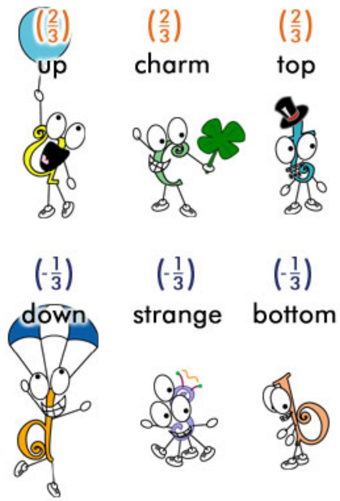
See also talks by Matt Wingate & Vittorio Lubicz

Ian Shipsey,
Purdue University

Big Questions in Flavor Physics

Dynamics of flavor?

Why generations?
Why a hierarchy of masses
& mixings?



Origin of Baryogenesis?

Sakharov's criteria: Baryon number violation
CP violation Non-equilibrium

3 examples: Universe, kaons, beauty but Standard Model CP violation too small, need additional sources of CP violation

Connection between flavor physics & electroweak symmetry breaking?

Extensions of the Standard Model (ex: SUSY) contain flavor & CP violating couplings that should show up at some level in flavor physics, but *precision* measurements and *precision* theory are required to detect the new physics

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.

Premier Example: The Lattice

Complete definition of pert & non. Pert.QCD. A goal is to calculate to few% in B,D,Υ,Ψ

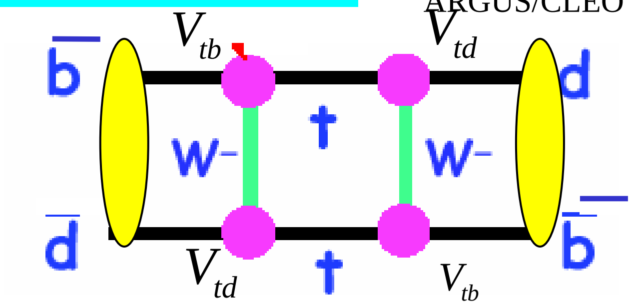
Charm at threshold can provide the data to test & calibrate QCD techniques such as Lattice

Status of B_d & B_s mixing

(See Daria Zieminska talk tomorrow for details of Bd/Bs mixing)

$B_d \to \overline{B_d}$ mixing

ALEPH,CDF,DELPHI, L3,OPAL.BABAR/BELLE, ARGUS/CLEO



$$\Delta m_d = \frac{G_F^2 \; m_{B_d} f_{B_d}^2 B_{B_d} \eta_B}{6\pi^2} |V_{td}|^2 |V_{tb}|^2 f(m_t^2, m_W^2)$$

$\Delta M_d = 0.502 \pm 0.007$ ps^{-1}

$$\frac{\delta \Delta M_d}{\Delta M_d} = 1.4\%$$

$f_B^2 B_B = (223 \pm 33 \pm 12)^2$ MeV^2 } Typical Lattice value

$|V_{td}| \cdot |V_{tb}| = (9.2 \pm 1.4 \pm 0.5)\ 10^{-3}$

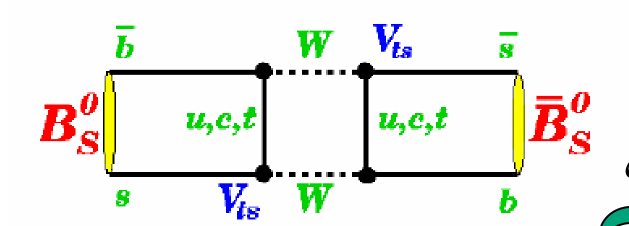
(15-20% error)

$f_{Bd}\sqrt{B_d}$ was known to 3%

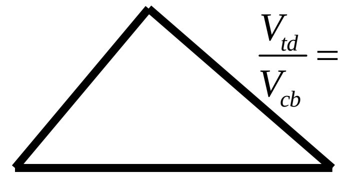
$|V_{td}||V_{tb}|$ would be known to ~5%

$B_s \to \overline{B_s}$ mixing

ALEPH,CDF, DELPHI,OPAL.SLD



ξ^2 (lattice)



$$\frac{V_{td}}{V_{cb}} = \frac{V_{td}}{V_{ts}}$$

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

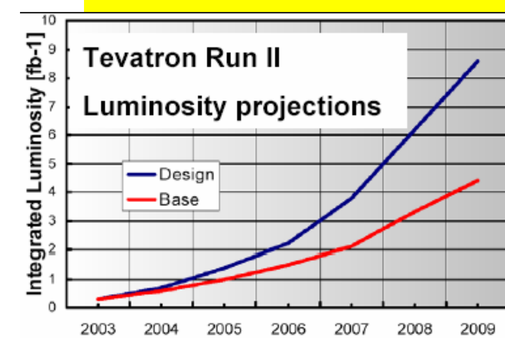
$\delta\xi/\xi \sim 6-8\%$??

Dominant error

World Average

Δms<14.5/ps

Prospects:

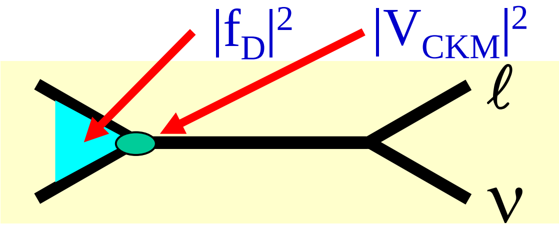


2σ for Δm=15/ps with 0.5 fb^{-1} Near term D0/CDF

5σ for Δm=18/ps with 1.7 fb^{-1}

5σ for Δm=24/ps with 3.2 fb^{-1} } Long term CDF

precision absolute charm leptonic decay rates are a test of LQCD decay constant calculations



$$B(D^+ \to \mu\nu)/\tau_{D^+} = (const.) f_{D^+}^2 |V_{cd}|^2$$
$$B(D_s^+ \to \mu\nu)/\tau_{D^+} = (const.) f_{D_s^+}^2 |V_{cs}|^2$$

Lattice predicts: f_B/f_{Bs} & f_D/f_{Ds} with small errors if precision measurements of f_D & f_{Ds} existed (they do not)

Some Possibilities:

$$\frac{\delta f_{D_s}}{f_{D_s}} \sim 14\%$$ PDG

$$\frac{\delta f_{D+}}{f_{D+}} \sim 55\%$$ PDG

f_D/f_{Ds} (expt.) *tests* f_D/f_{Ds} (lattice) & gives confidence to f_B/f_{Bs} (lattice)

Lattice errors on f_B/f_D & f_{Bs}/f_{Ds} also smaller than on individual f's

Use f_B/f_D (lattice) & f_D (expt.) + B_d mixing → precision V_{td}

Use f_{Bs}/f_{Ds} (lattice) & f_{Ds} (expt.) + B_s mixing → precision V_{ts}

f_D (expt.) *tests* f_D (lattice) & f_{Ds} (expt.) *tests* f_{Ds} (lattice)

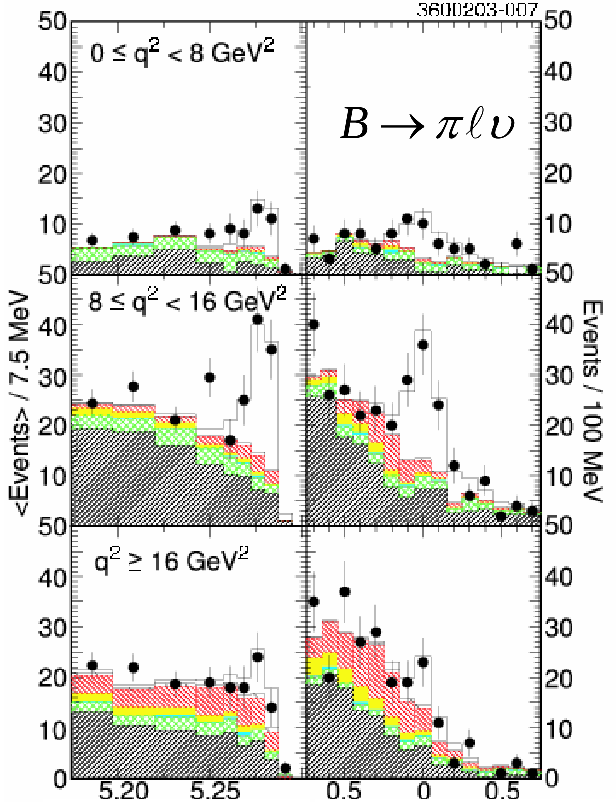
(precision test)

Status of Vub (exclusive method)

BABAR/Belle/CLEO

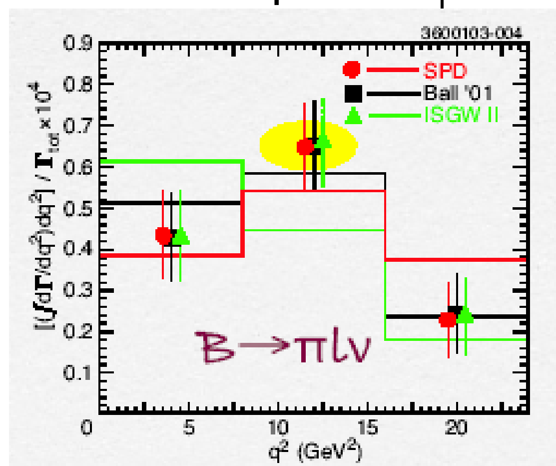
Exclusive $|V_{ub}|$ from $\pi^- l^+\nu$, $\pi^0 l^+\nu$, $\eta l^+\nu$, $\rho^- l^+\nu$, $\rho^0 l^+\nu$, $\omega l^+\nu$ CLEO 10 M $\Upsilon(4S)$

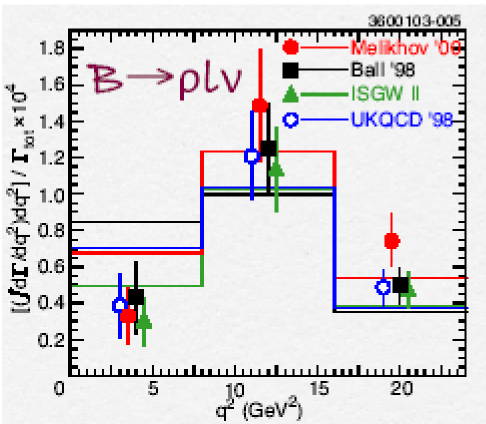
Detector hermeticity $\Rightarrow$ „ν reconstruction“ q^2 and E_l >1.0 GeV (π), >1.5 GeV (ρ)



$M_{ml\nu}$ (GeV) ΔE (GeV)

$=(E_{ml\nu} - E_{beam})$





Measure $d\Gamma/dq^2$

Reduce FF shape dependence

Test FF calcs models/LCSR/lattice

$B\rightarrow\pi l\nu$ (best)

$B\rightarrow\rho l\nu$ (difficult expt. & lattice)

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

Average of BABAR CLEO π /ρ l+ν (Gibbons, Beauty 03)

$$|V_{ub}|_{excl} = (3.27 \pm 0.13 \pm 0.19^{+0.51}_{-0.45}) \times 10^{-3}$$

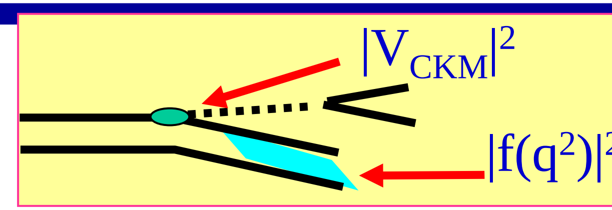
Stat sys FF

Theory systematic dominates

Traditional ν recon. sys limited. Fully recon. Btags from BABAR/BELLE will improve δM x50! → reduced expt. systematic δVub_{exp} ~ 4% (6%) all q^2 (high) @500 fb^{-1}

absolute charm semileptonic decay rates as a test of LQCD form factors

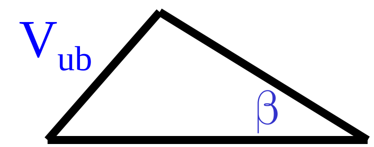
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cs}|^2 p_K^3 |f_+(q^2)|^2$$

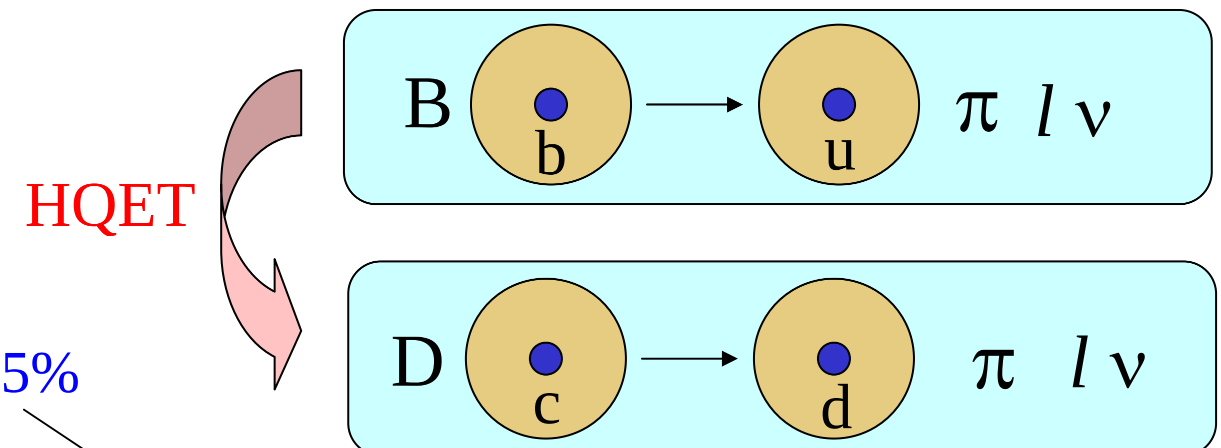


I. Absolute magnitude & shape of form factors are a stringent test of theory.

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. *Tests* LQCD D→π form factor calculation.

2) BaBar/Belle can extract V_{ub} using *tested* LQCD calc. of B→π form factor.

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

Status of Vcb (exclusive)

Zero recoil in $B \to D^* l^+ \nu$ & $B \to D l^+ \nu$

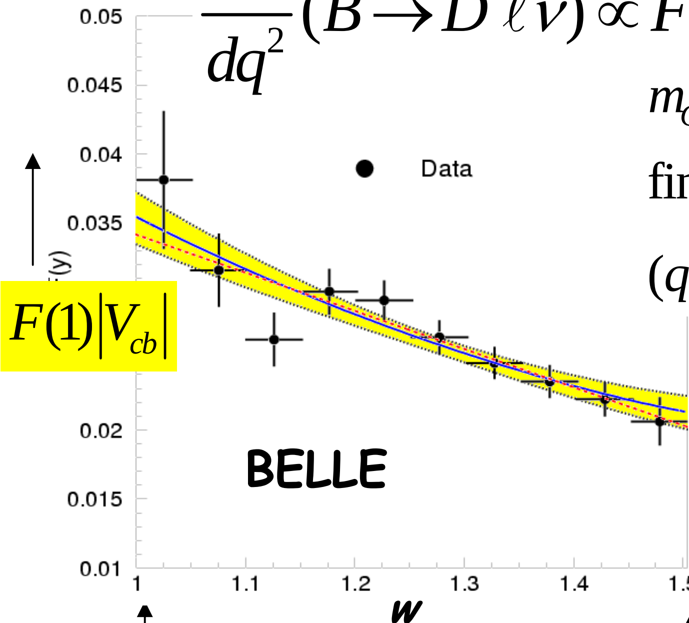
$$\frac{d\Gamma}{dq^2}(B \to D^* \ell \nu) \propto F(q^2)^2 |V_{cb}|^2$$

$$m_Q \to \infty, F(q^2_{max}) = 1$$

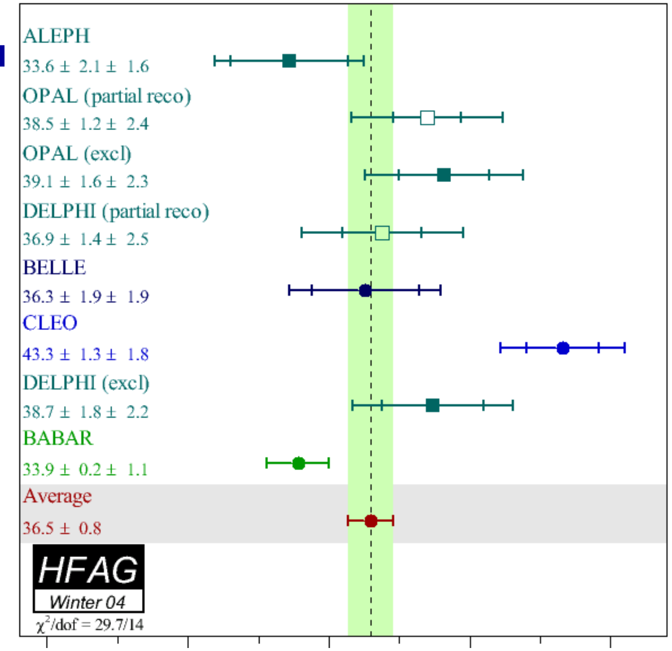
$$\text{finite } m_Q F(1) = 0.91 \pm 0.04$$

$$(q^2_{max} : w = 1)$$

Lattice & sum rule



$q^2 = q^2_{max}$ $\qquad$ $q^2 = 0$



$$F(1)|V_{cb}| = (36.5 \pm 0.3_{stat} \pm 0.8_{sys}) \times 10^{-3}$$

$$|V_{cb}| = (40.1 \pm 0.9_{exp} \pm 1.8_{theo}) \times 10^{-3}$$

As B Factory data sets grow, & Lattice calculation of form factor improve a limiting systematic for Vcb via $B \to D^*/Dl^+\nu$

precision absolute charm branching ratios can improve the situation

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

CLEO-c Physics Program

- 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: form factors Vcs,Vcd,unitarity

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 test theory. ← Important Input for the lattice

- Physics beyond the Standard Model:
- D-mixing, CPV, rare decays. + measure strong phases

} Not covered in this talk

This program helps build & test the QCD tools to enable this decade's flavor physics and the next decade's new physics.

CLEO-c Run Plan & Status

2002: Prologue: Y(1S),Y(2S),Y(3S) (combined)
Spectroscopy, matrix element, Γ_{ee}, η_B h_b
10-20 times the existing world's data

2003: 2004 CESR upgraded to CESR-c (12 wigglers)
6 last summer – 6 this summer (for damping at low energy)

	$\psi(3770)$	$\psi(2S,)$	continuum
9/03-4/04			
$L = 4.6 \times 10^{31}$ (as expected)	55 pb^{-1}	3 pb^{-1}	20 pb^{-1}

MACHINE CONVERSION & PILOT RUN

2.5 times world's existing data

Fall 2004: $\psi(3770)$ – 3 fb^{-1} ($\psi(3770) \to DD$) ~20 million DD
~5 million *tagged* D decays (60 X data in hand)

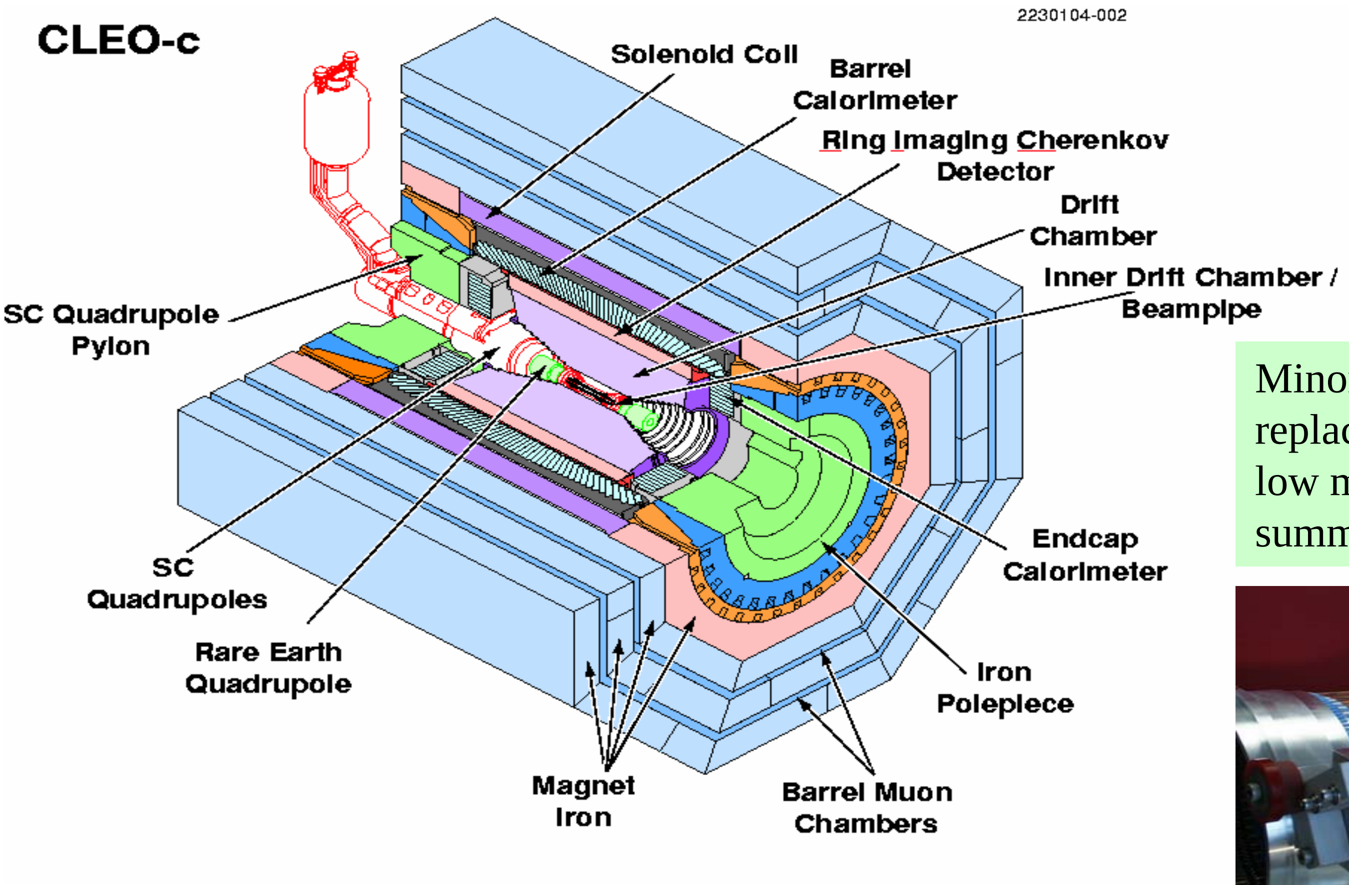
Fall 2005: $\sqrt{s} \sim 4140$ MeV – 3 fb^{-1} 1.5 million D_sD_s events,
0.3 million *tagged* D_s decays (480 x MARK III, 130 x BESII)

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

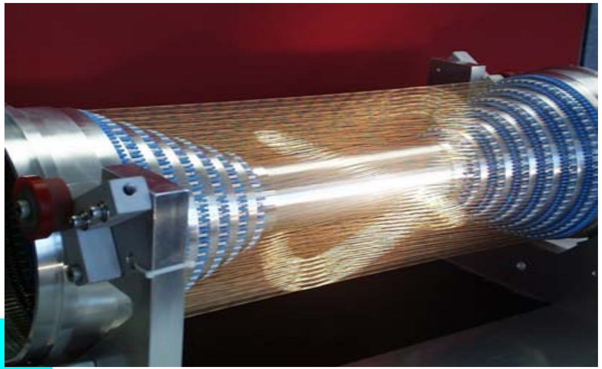
A 3 year program

CLEO c

CLEO III Detector → CLEO-c Detector



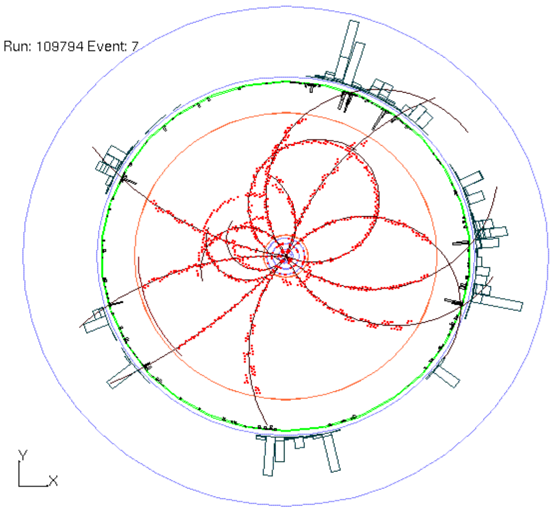
Minor modification:
replaced silicon with 6 layer low mass inner drift chamber summer ‘03

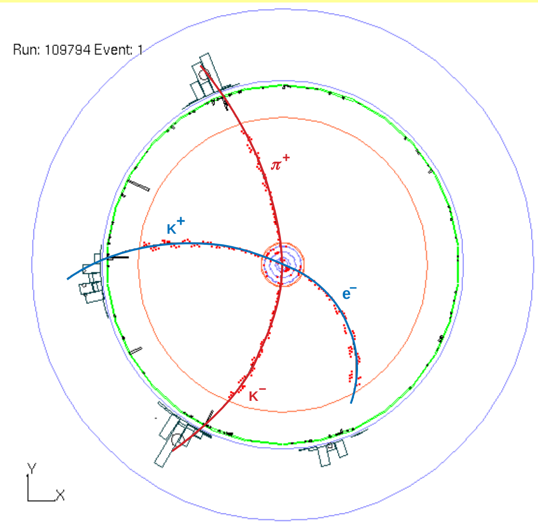


CLEO III is already a well understood detector that has produced numerous physics results at 10 GeV

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

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





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

- 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 what is the advantage of running at threshold?

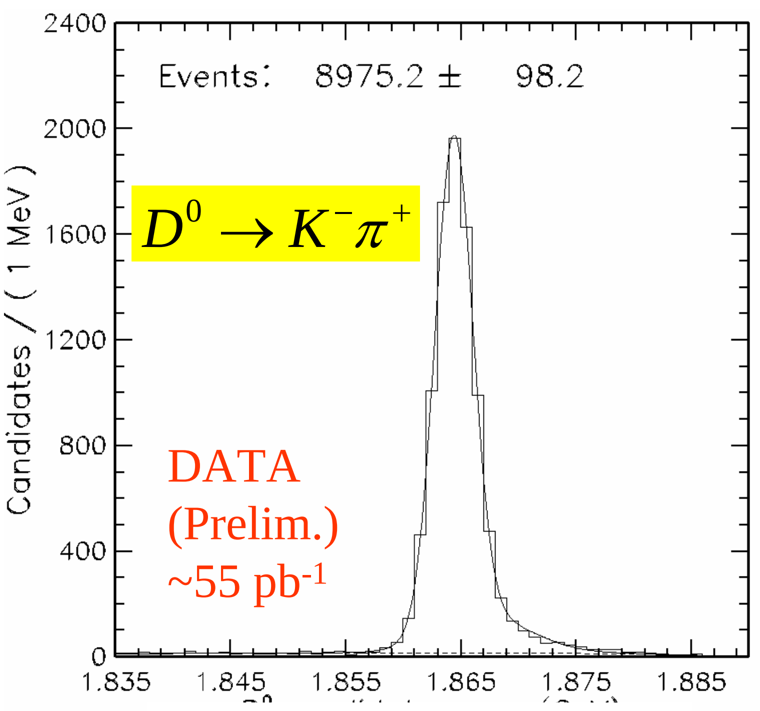
- Charm events produced at threshold are extremely clean
- Large σ, low multiplicity
- Pure initial state: no fragmentation
- Signal/Background is optimum at threshold

- 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

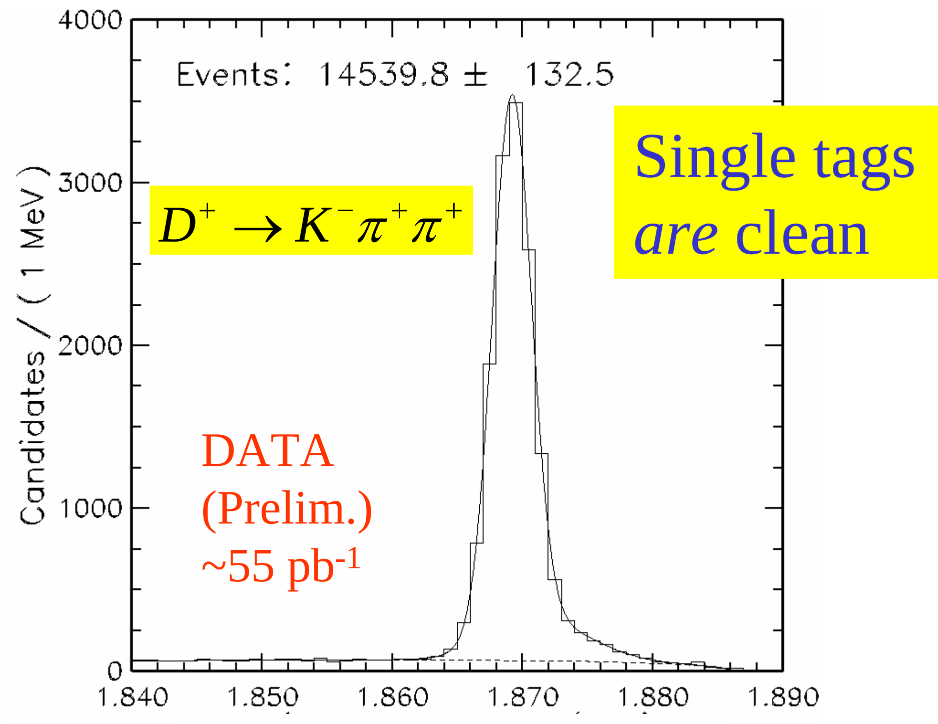
Single tags: 1st CLEO-c DATA

- $\psi(3770) \to D\bar{D}$
- An initial D state can be tagged by reconstructing the "other-side" $\bar{D}$
  - Charm mesons have many large branching ratios ~1-15%
  - low multiplicity: high reconstruction efficiency favorable S/N

➔ High net tagging efficiency: ~26% of all D's produced are reconstructed (achieved)

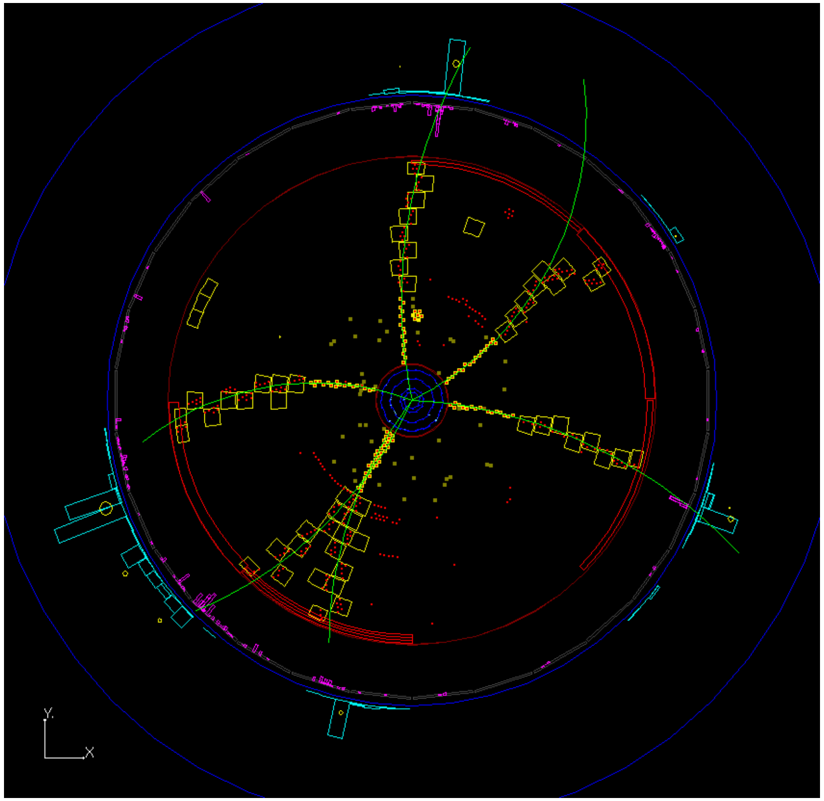


D^0 candidate Mass (GeV)



D^0 candidate Mass (GeV)

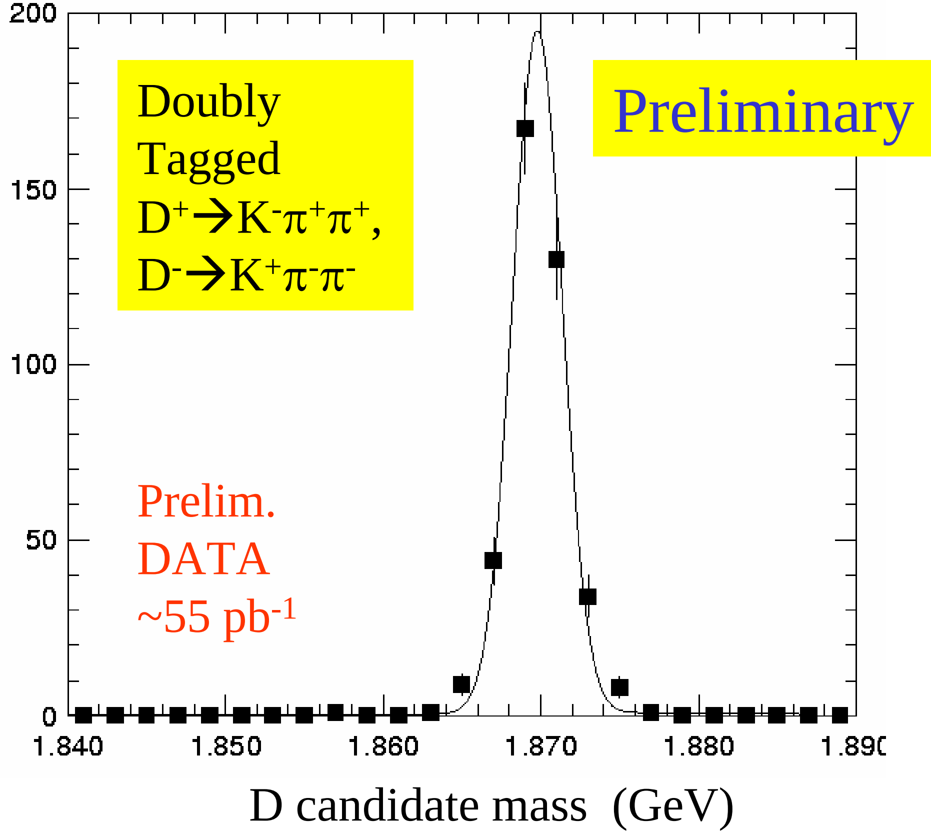
Double tags: 1st CLEO-c DATA



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

Tagging effectively creates a single D beam

From single and double tags we measure indpendent of D Br's

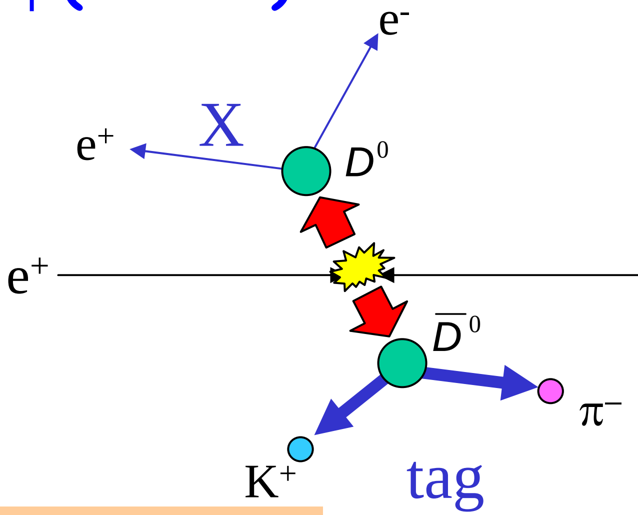


Double tagged events *are* pristine

$\sigma(DD) = 6.48 \pm 0.44 \pm 0.39$nb

Absolute Charm Branching Ratios at Threshold

$\psi(3770) \to DD$



Tagging effectively creates a single D beam

$$Br(D \to X) = \frac{\#\text{X Observed}}{\text{efficiency for X} \bullet \#\text{D's}}$$

Where # of D's = # of tagged events

Meson Factory Figure of merit:

$$\frac{\#\text{B tags @B Factory}}{\#\text{D tags @Charm Factory}} = \frac{\sigma(BB)\ \varepsilon\text{tag} \int Ldt = 500fb^{-1}}{\sigma(DD)\ \varepsilon\text{tag} \int Ldt = 3fb^{-1}} \sim 1$$

Extrapolate to full data set.

Extrapolations use:
σ(DD)εtag= 10 nb (0.19)=1.9 nb
We measure:
σ(DD)εtag~ 6.5 nb (0.26)=1.7 nb
close enough not to revise predictions

Decay	$\sqrt{s}$	L (fb^{-1})	Double tags	δB / B (%) PDG	δB / B (%) CLEO-c
$D^0 \to K^- \pi^+$	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

f_D from Absolute Br($D^+ \to \mu^+\nu$)

Hadronic tag ← $D^- D^+ \to \mu^+\nu$ — 1 track consistent with a μ

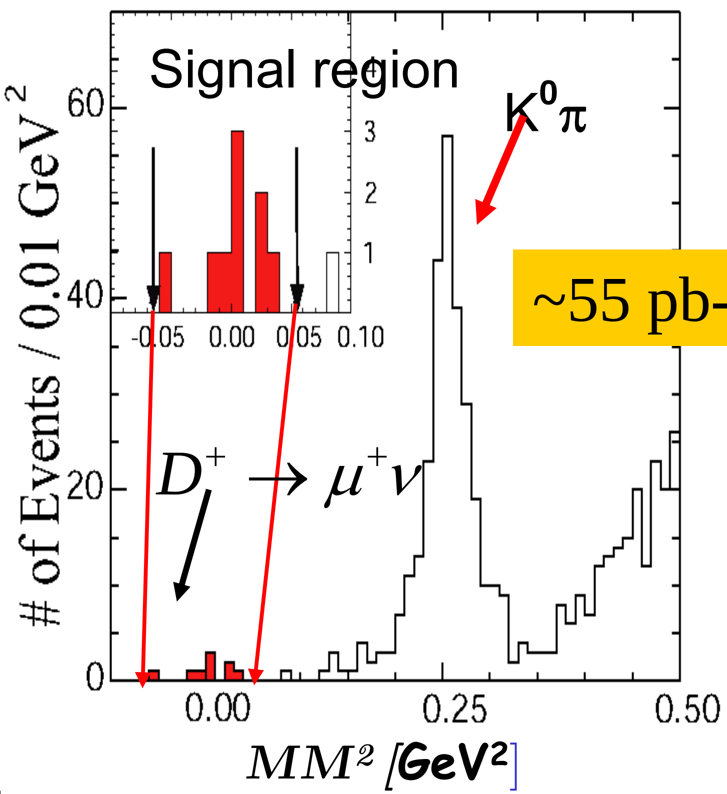
[m.i.p. Ecalorimeter<400 MeV
p too low to reach μ detector]

No additional track or shower.

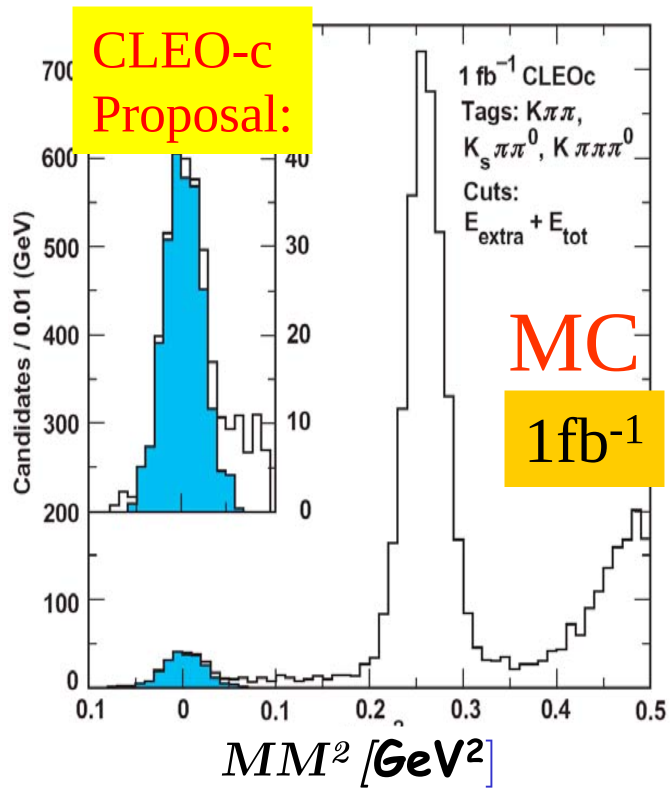
Compute MM² peaks at zero if only a neutrino is missing

$$MM^2 = (E_{beam} - E_\mu)^2 - (-\overrightarrow{P_{Dtag^+}} - \overrightarrow{P_\mu})^2$$

DATA **Preliminary**



CLEO-c Proposal:



f_D from Absolute $Br(D^+ \to \mu^+\nu)$

9 events within 2σ
($-0.056<MM^2<0.056$ GeV^2)
0.67 ± 0.24 estimated
background events.

SIGNIFICANT SIGNAL

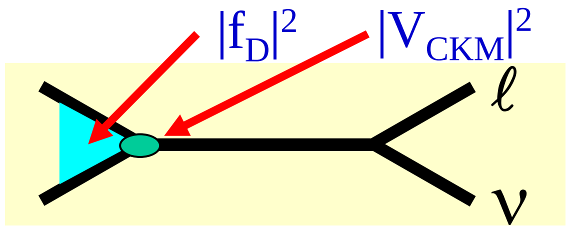
Reconstruction efficiency ~70%

$\mathcal{B}$ = Signal / (Tags x Efficiency)

$$\boldsymbol{B} = (4.57 \pm 1.66 \pm 0.41) \times 10^{-4}$$

$$f_D = (230 \pm 42 \pm 10)\,\boldsymbol{MeV}$$

Statistically Limited
Soon 60 x the dataset!



$$B(D^+ \to \mu\nu)/\tau_{D^+} = (const.)\, f_{D^+}^2 \left|V_{cd}\right|^2$$

V_{cd} (1.1%) from 3 generation unitarity
τ_{D+} well-measured (0.3%)

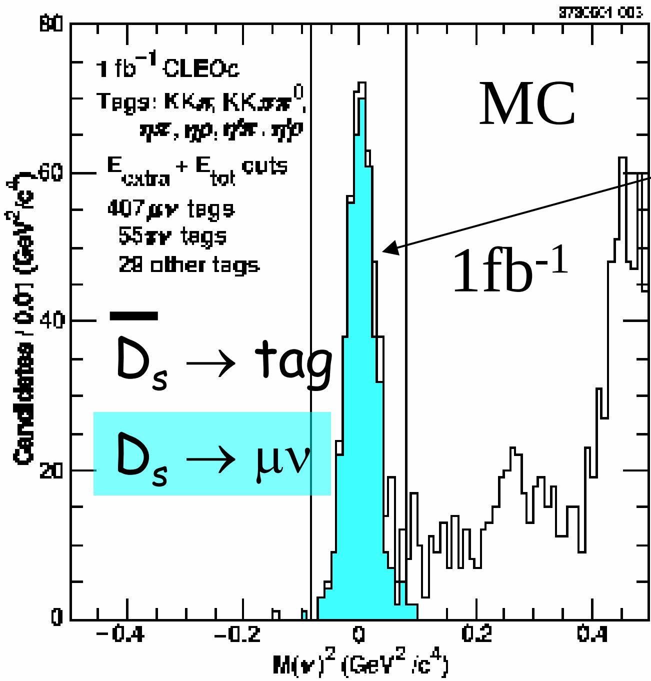
Winter 2004 Conferences:
BESII 3 events

$$B = (0.12\,^{+0.092}_{-0,063}\,^{+0.01}_{-0.009})\%$$

$$f_D = (365\,^{+121}_{-113}\,^{+32}_{-28})\ \text{MeV}$$

hep-ex/0406027

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



Works for D_s too!

$\sqrt{s}$ ~4140 → D_sD_s

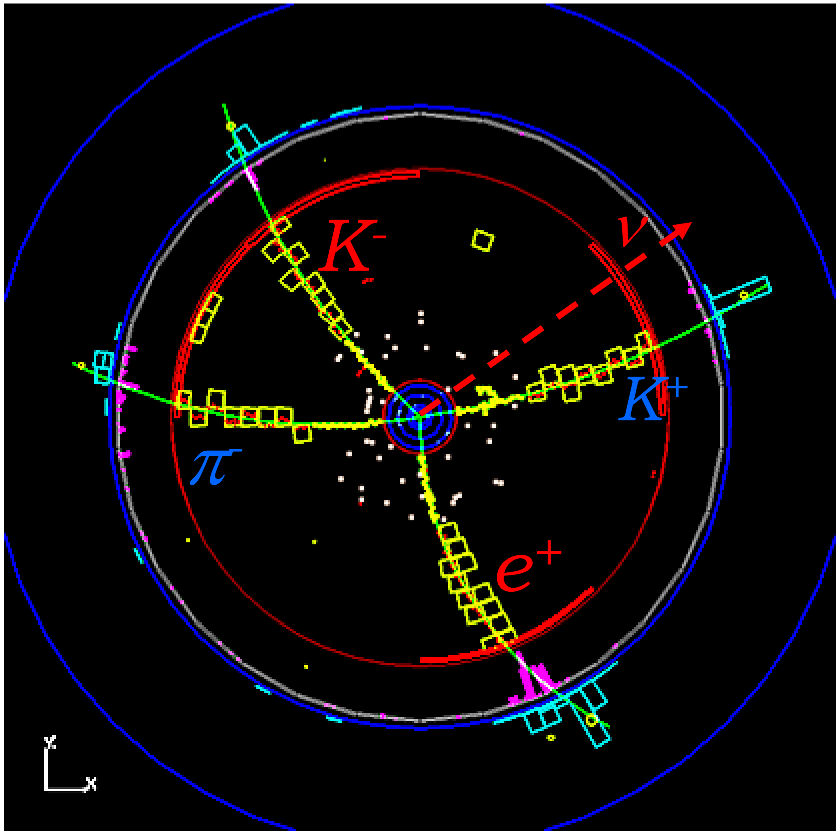
Vcs known from unitarity to 0.1%

τDs known to 2%

Projection to full data set:

	Reaction	Energy(MeV)	L fb^{-1}	PDG	CLEO-c	Year of Data taking:
f_{Ds}	$D_s^+ \to \mu\nu$	4140	3	17%	1.9%	2005
f_{Ds}	$D_s^+ \to \tau\nu$	4140	3	33%	1.6%	2005
f_{D+}	$D^+ \to \mu\nu$	3770	3	55%	2.3%	2004

Semileptonic Decays: 1st CLEO-c DATA

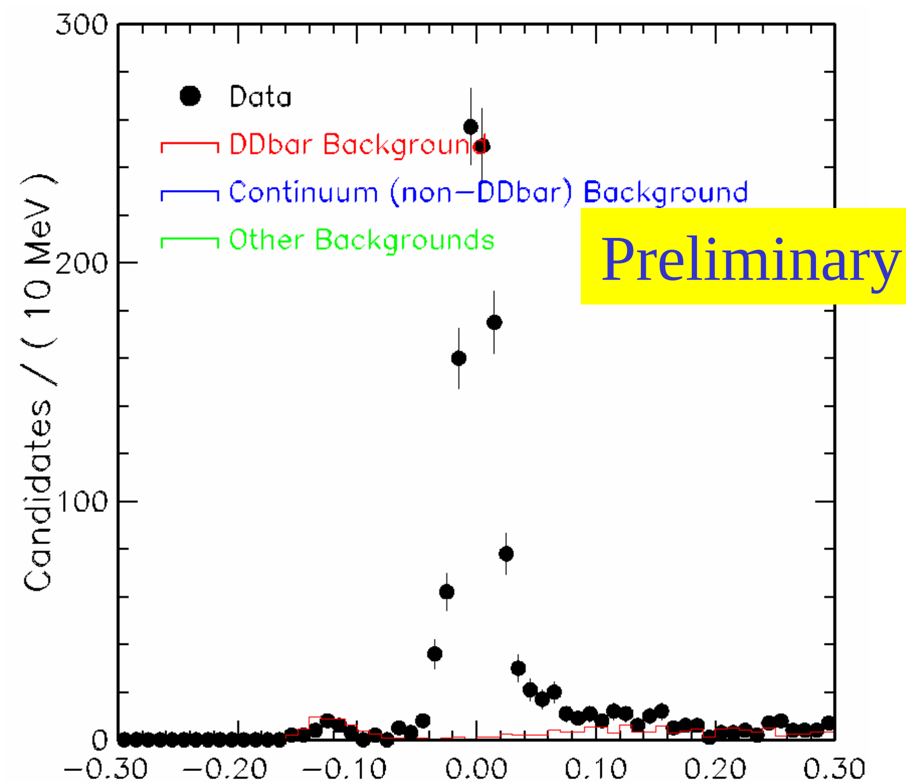


$\psi(3770)\rightarrow D^0\ \overline{D}^0$

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

$D^0\rightarrow$ hadronic tag,

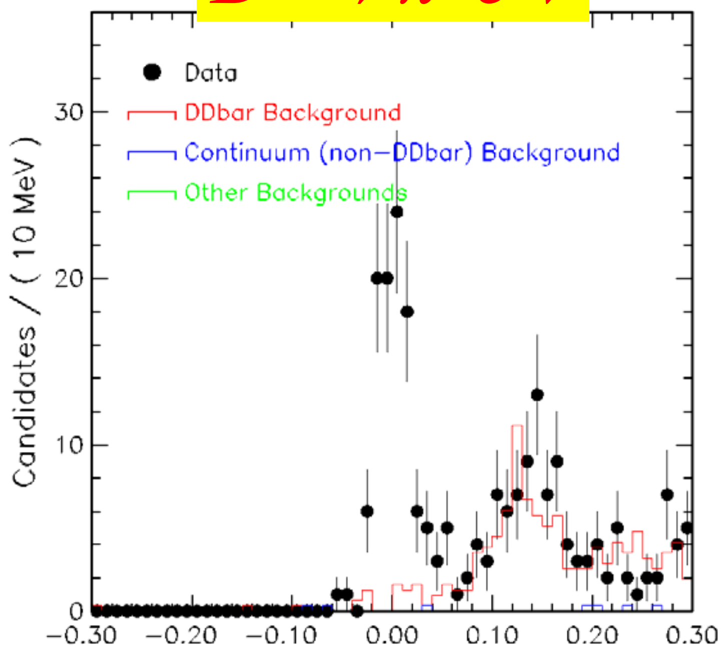
$D^0\rightarrow K^- e^+\nu$



$U = E_{miss} - P_{miss}$ (GeV)

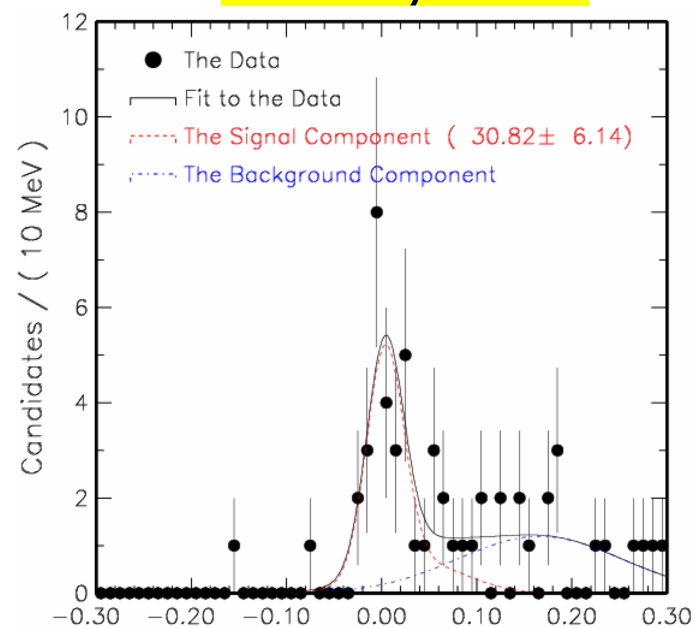
More semileptonic modes

$D^0 \to \pi^- e^+ \nu$



$U = E_{miss} - P_{miss}$ (GeV)

$D^0 \to \rho^- e^+ \nu$



$U = E_{miss} - P_{miss}$ (GeV)

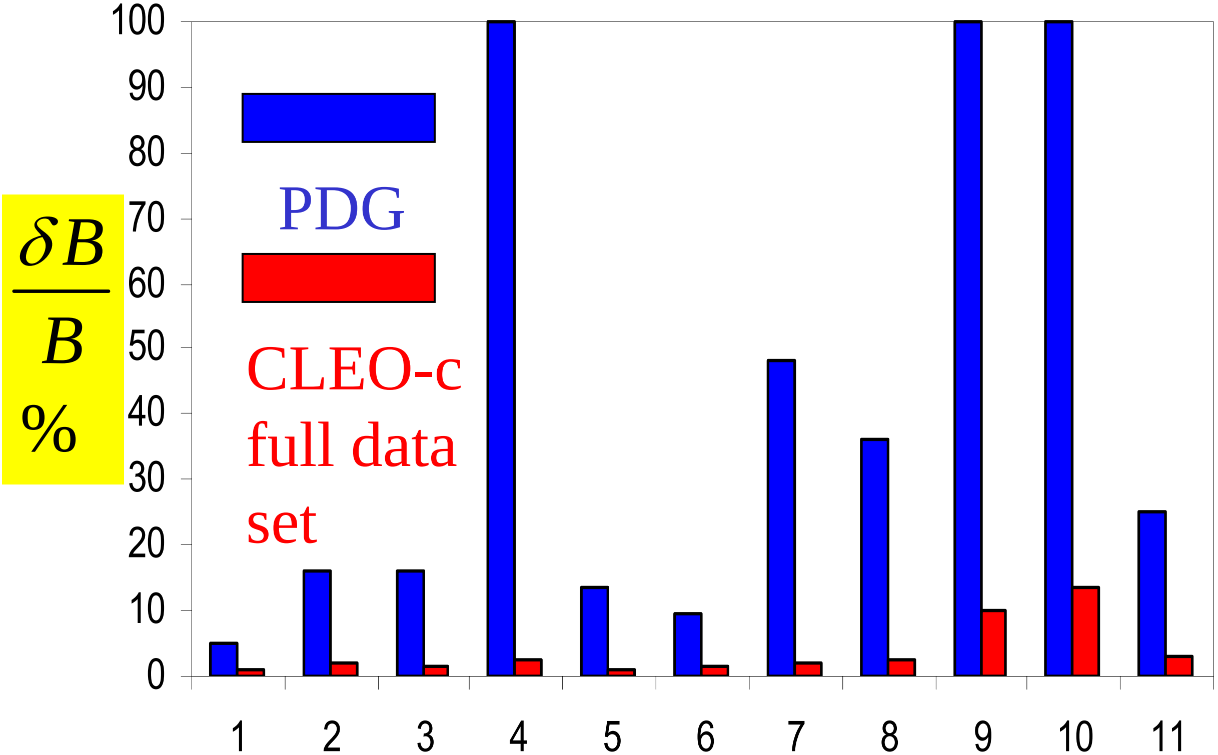
All Plots Preliminary

Recall this is 55 pb^{-1} plan for x60 data starting fall 2004

First observation of $D^0 \to \rho^- e^+ \nu$ **~30 events**

CLEO-c Impact semileptonic dB/B

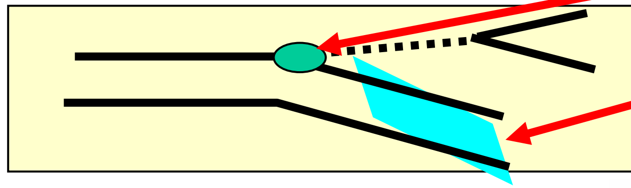
1 : $D^0 \to K^- e^+ \nu$
2 : $D^0 \to K^{*-} e^+ \nu$
3 : $D^0 \to \pi^- e^+ \nu$
4 : $D^0 \to \rho^- e^+ \nu$
5 : $D^+ \to \bar{K}^0 e^+ \nu$
6 : $D^+ \to \bar{K}^{*0} e^+ \nu$
7 : $D^+ \to \pi^0 e^+ \nu$
8 : $D^+ \to \rho^0 e^+ \nu$
9 : $D_s \to K^0 e^+ \nu$
10 : $D_s \to K^{*0} e^+ \nu$
11 : $D_s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

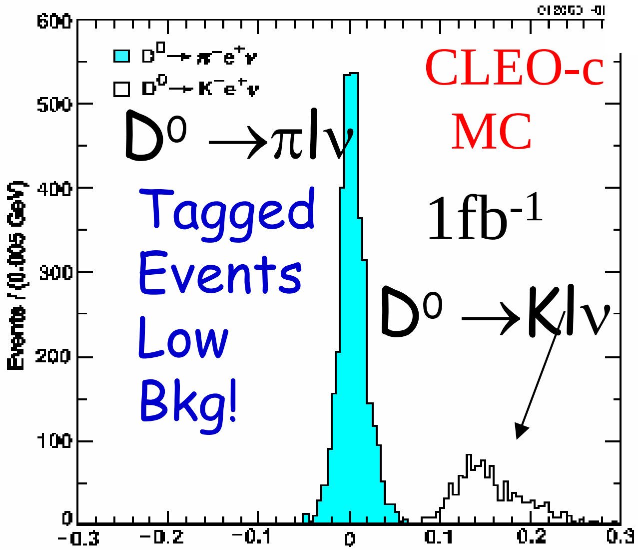


Full CLEO-c data set will make *significant* improvements in the precision with which each absolute charm semileptonic branching ratio is known

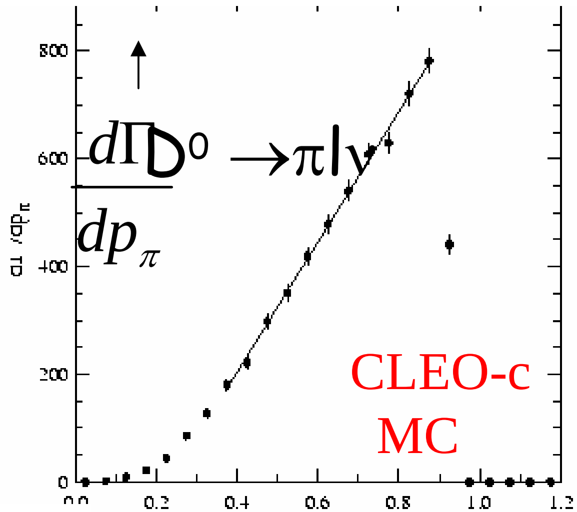
With 55 pb^{-1} already accumulated CLEO-c will equal or improve on the PDG value of dB/B for *every* D^+ and D^0 exclusive semileptonic and inclusive branching ratio. and ~x10 the statistics of the DELCO D➔eX inclusive spectrum (important also for B inclusive semileptonic decay studies).

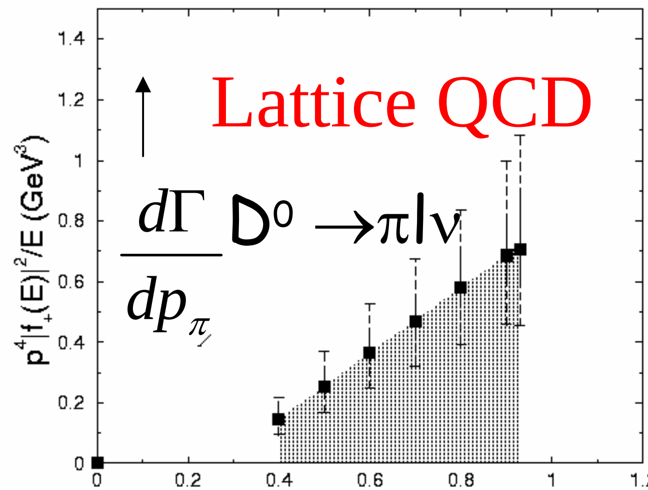
Semileptonic Decays $|V_{CKM}|^2 \, |f(q^2)|^2$





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





p_π (GeV/c)

Extrapolation to 1/3 of the full data set shown.

For the *first* time measure complete set of charm PS → PS & PS → V *absolute* form factor magnitudes and slopes to a few% with almost no background in one experiment.

Common disconnect: LQCD *most* precise where data is *least* but full q^2 range calculable ➔Would like LQCD FF magnitudes & slopes with few % precision. Stringent test of theory!

Determination of Vcs and Vcd

internal consistency? 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%

$\Gamma(D_s \to \eta l \nu) / \Gamma(D_s \to l \nu)$ independent of Vcs
Test rate predictions at ~ 4%

(With full data set)

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

I

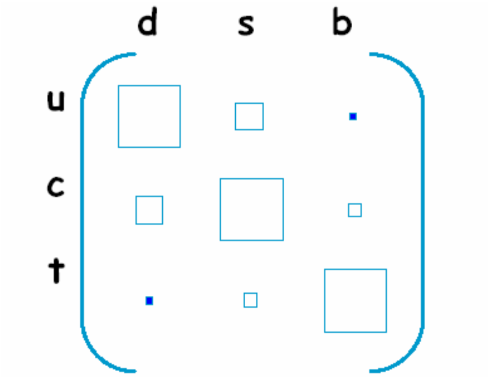
$D^0 \to K^- e^+ \upsilon$ δVcs /Vcs = 1.6% (now: 16%)
$D^0 \to \pi^- e^+ \upsilon$ δVcd /Vcd = 1.7% (now: 7%)

II

tested lattice to calc. B semileptonic form factor,
B factories use $B \to \pi/\eta/l\nu$ for precise Vub
shape is an additional cross check

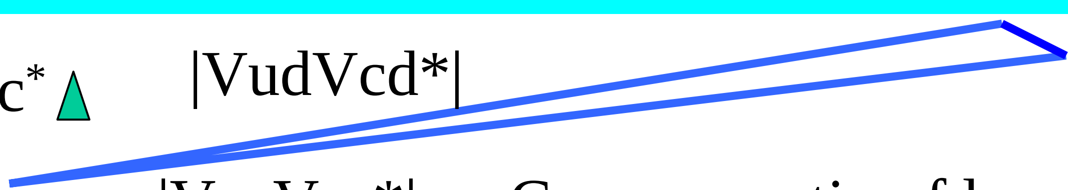
Unitarity Constraints

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



$uc^{*}=0$

- 1st row: $|Vud|^2 + |Vus|^2 + |Vub|^2 = 1$??
  fails at ~2σ (PDG2002), now consistent KTeV (2004)
- 2nd row: $|Vcd|^2 + |Vcs|^2 + |Vcb|^2 = 1$??
  CLEO-c: test to ~3% (if theory $D \rightarrow K/\pi l\nu$ good to few %)
  & 1st column: $|Vud|^2 + |Vcd|^2 + |Vtd|^2 = 1$?? with similar precision to 1st row
- uc^{*} △



Compare ratio of long sides to 1.3%

Probing QCD with Onia

→Verify tools for strongly coupled theories
→ Quantify accuracy for application to flavor physics

- ψ and Y Spectroscopy
  - Masses, spin fine structure
- Leptonic widths for S-states.
  - EM transition matrix elements

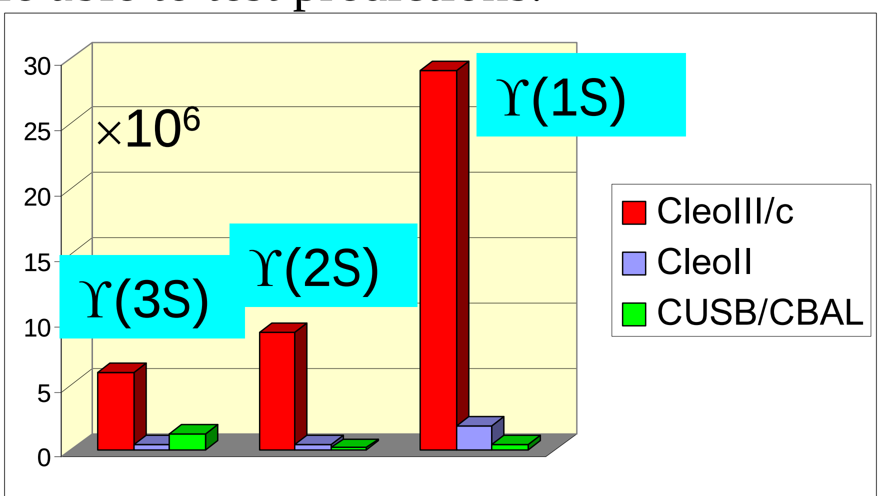
Confinement, Relativistic corrections

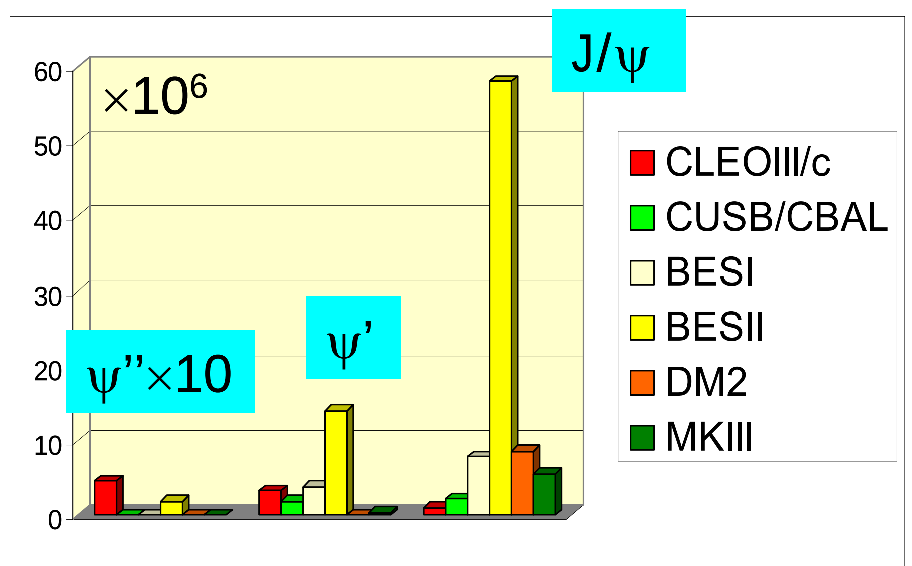
Wave function
Tech: $f_{B,K} \sqrt{B_K}\ f_{D\{s)}$

Form factors

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

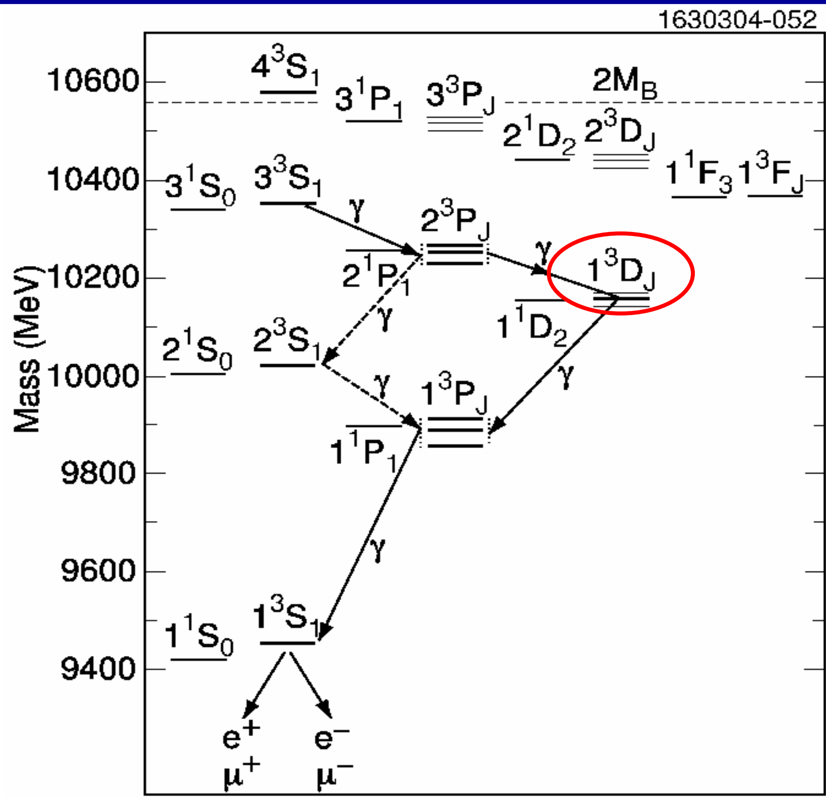
LQCD hopes to predict to several %. Recent order of magnitude increase in dataset size able to test predictions:



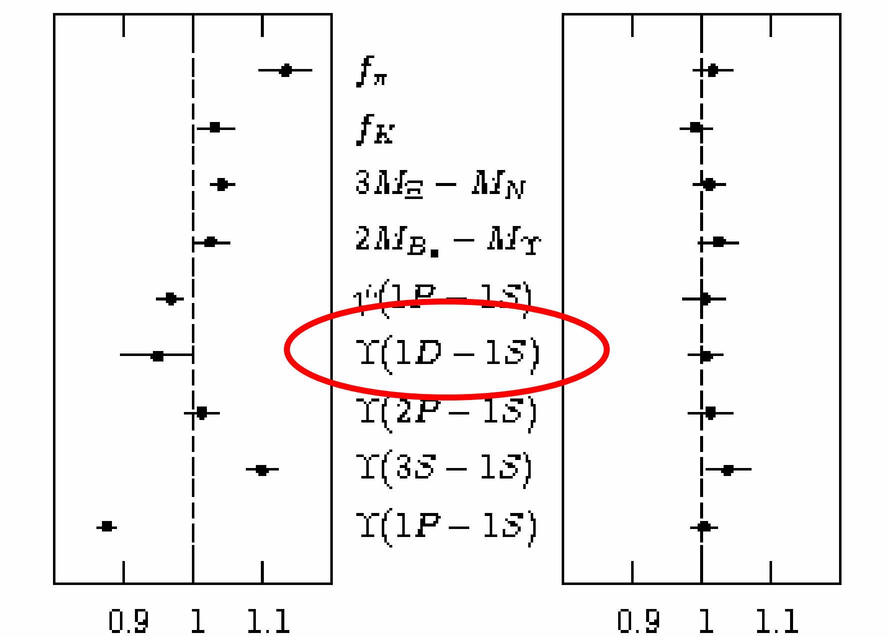


Observation of $\Upsilon(1D)$ & Impact

[CLEO]



Ratio = LQCD/Expt



Quenched **Unquenched (n_f=3)**

[CTH Davies et al., PRL **92**:022001 (2004)]

Four γ cascade; exclusive $\Upsilon(1S)$ channel

Background thru 2^3S_1

First reported ICHEP'02 with 80% of data … now final

Submitted to PRD [hep-ex/0404021]

M = 10161.1±0.6±1.6 MeV

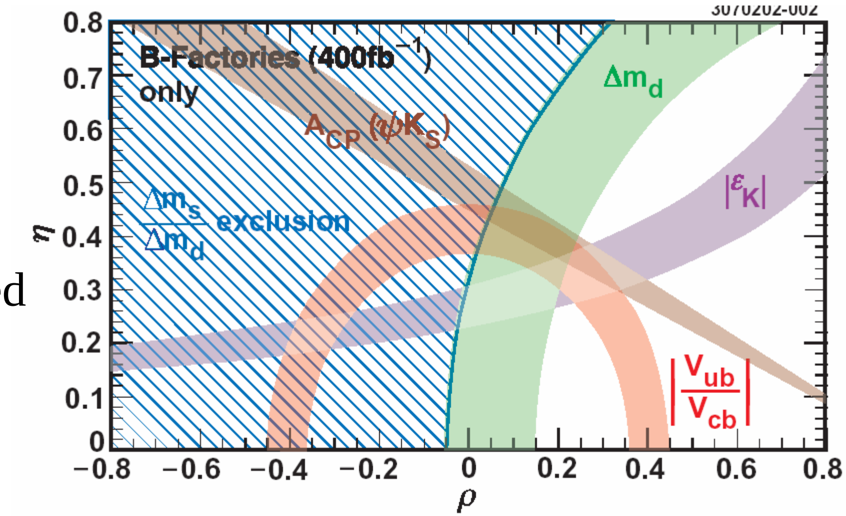
Tests LQCD at high L

Lattice Impact on Flavor Physics

- *Crucial Validation of Lattice QCD:* Lattice QCD hopes 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
400 fb^{-1}

Assumes Theory Errors reduced by x2



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

Theory errors = 2%

Lattice Impact on Flavor Physics

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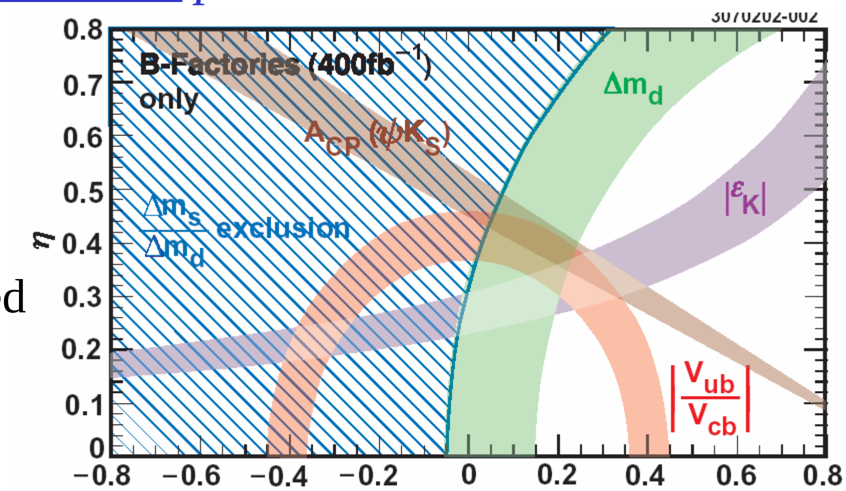
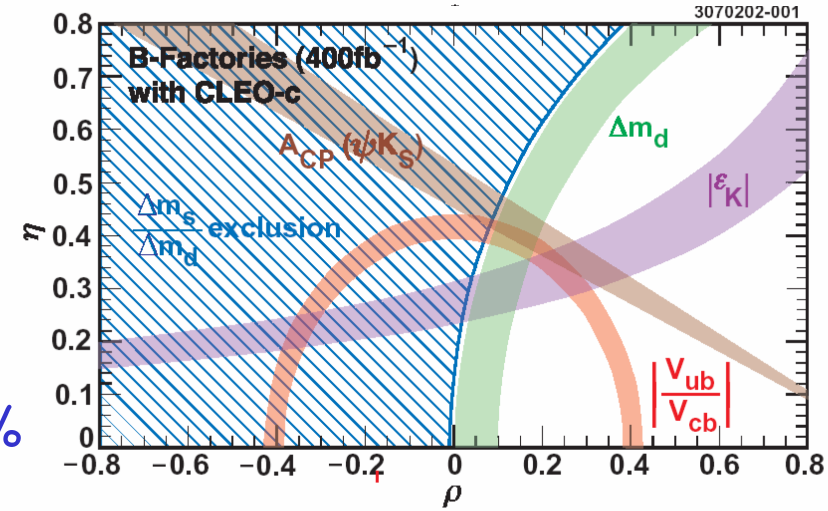


Imagine a world where we have theoretical mastery of non-perturbative QCD at the 2% level

Theory errors = 2%



Lattice Impact on Flavor Physics

Or in tabular form:

Current Precision →

Vcd	Vcs	Vcb	Vub	Vtd	Vts
7%	16%	4%	15%	36%	39%
1.7%	1.6%	3%	5%	5%	5%

← Current Precision

CLEO-c data and **LQCD**

B Factory & Tevatron Data & LQCD

Issues

How can we be sure that if LQCD works for D's it also works in B's?
Or equivalently is CLEO-c data enough?

Two independent methods: NRQCD, Fermilab for D decays

Leptonic decays are simple

SL decays
Many modes +
Shape cross check

$$\frac{d\Gamma(B \to \pi l \upsilon)}{dp_\pi}$$ BABAR/Belle

$$\frac{d\Gamma(D \to \pi l \upsilon)}{dp_\pi}$$ CLEO-c

Both methods also for Γee & EM transitions in Υ ψ sectors

Main sys. errors limiting accuracy: m(light) and related chiral extrapolations, peturbation theory, finite lattice spacing are similar for charm and beauty quarks,

CLEO-c + onia + light quark physics can establish whether or not systematic errors are under control

Lattice technique is all encompassing but LQCD practitioners are conservative about what it can calculate.(not a criticism). Much of the excitement at the moment in B physics revolves around sin2β(ψK_s) vs sin2β(ϕK_s)

Need to move beyond gold-plated quantities in the next few years:
Resonances, e.g. $\rho \to \pi \pi$, ϕ, K^* States near threshold $\psi(2S)$, $D_s(0^+)$,
hadronic weak decays

Systematic Errors

It will take accurate and precise experimental measurements from experiments combined with accurate and precise theoretical calculations to search for new physics in the CKM matrix. Therefore, it is essential to chase down each and every source of systematic error.

With experimentalists and phenomenologists in mind:

1) Include a comprehensive table of systematic errors with *every* calculation (it is already included in many/most? cases). This makes it more straightforward to compare results from different groups. It is understood that different groups use different methods and will have somewhat different lists.

2) A statement of whether an error is Gaussian or non-Gaussian. Errors are often estimates of higher order terms in a truncated expansion, so the quoted error bar is non-Gaussian. For the statistical error a distribution could be provided.

3) The correlation between individual systematic errors (if such correlation exists).

4) Provide an overall systematic error by suitably combining individual errors, this is redundant and should not replace the individual error breakdown, but certainly convenient.

Outlook for the next ~~5 years~~ (2 years)?

expect to see a growing number of lattice results for gold plated quantities within the next few years ⇒ ultimate goal: ~ few % errors in < 5 years

Famous Lattice Theorist (2003)

Prediction is better than *postdiction*

Every experimentalist (anytime)

need high precision experimental results in order to test lattice QCD ⇒ CLEO-c for D decays

Famous Lattice Theorist (2003)

CLEO-c may have a few % preliminary determination of f_D as early as the summer conferences in 2005

An unquenched lattice calculation for f_D with systematic error budget & analysis correlations?/PDFs? *before* the CLEO-c result is published will clearly demonstrate the *current* precision of the lattice approach to experimentalists & non-lattice theorists & add confidence to the ultimate goal of few % errors

+ f_{Ds} *before* the CLEO-c preliminary result is announced (which could be as early at the summer conferences in 2006)

+ form factors in D → K/pi lv (2005) and D_s semileptonic decays (2006)

Summary

- This is a special time for flavor physics and the lattice
- Lattice goal to calculate to few % precision in D,B,Υ,ψ
- CLEO-c (later BESIII) about to provide few % tests of lattice calculations in the D system & in onia, quantifying the accuracy for application of LQCD to the B system BABAR/Belle/CDF/D0 (later BTeV/LHC-b/ATLAS/CMS SuperBFac) + LQCD can reach few % precision Vub,Vcb,Vtd,Vts

precision LQCD confronts experiment
precision experiment confronts LQCD
allows Flavor physics to reach its full potential this decade
Paves the way for understanding beyond the SM physics in the next decade

Additional Slides

Additional topics

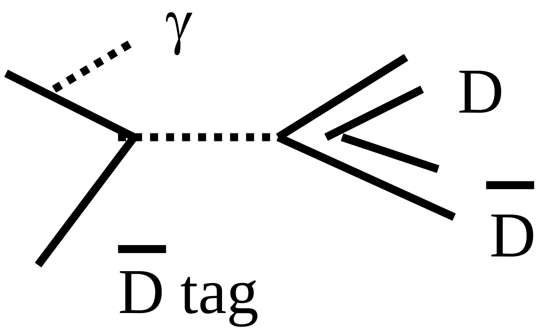
- Ψ' spectroscopy (10^8 decays) $\eta'_c h_c$....
- $\tau^+\tau^-$ at threshold (0.25 fb^{-1})
  - measure m_τ to ± 0.1 MeV
  - heavy lepton, exotics searches
- $\Lambda_c\Lambda_c$ at threshold (1 fb^{-1})
  - calibrate absolute $BR(\Lambda_c \to pK\pi)$
- $R=\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$
  - spot checks

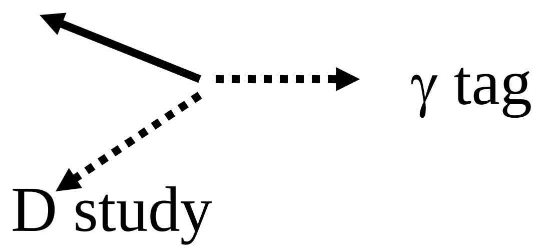
Likely to be added to run plan

If time permits

ISR Charm Events at B Factories

Initial State Radiation photon reduces √s





Measurement	#events	
	BaBar/Belle	CLEOc
	500 fb^{-1}	3fb^{-1}
$D_s^+ \to \mu\nu$	330	1,221
$D^+ \to \mu\nu$	50	672
$D^+ \to K^- \pi^+\pi^+$	6,750	60,000
$D_s^+ \to \phi\pi$	221	6,000

ISR projections made by BaBar show ISR technique is not statistically competitive with CLEO-c. Systematic errors are also much larger.

Probing QCD with Onia

→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. — Wave function Tech: $f_{B,K} \sqrt{B_K}\ f_{D\{s\}}$
  - EM transition matrix elements — Form factors
    - Υ resonances complete~ 4 fb^{-1} currently being analyzed)

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

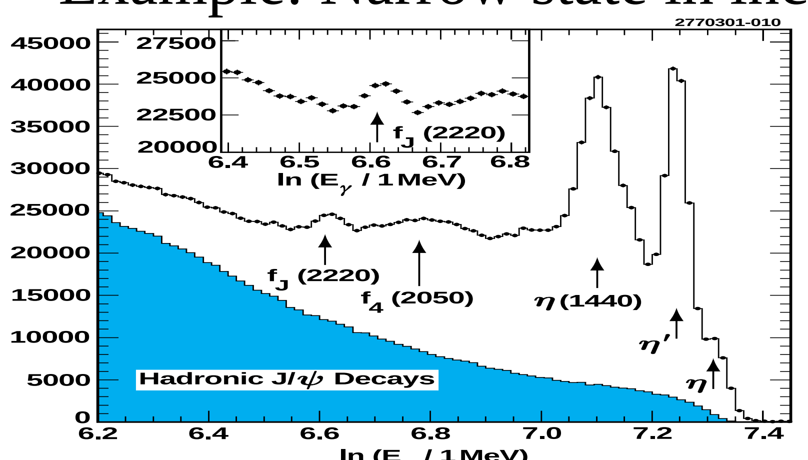
The current lack of strong evidence for these states is a fundamental issue in **QCD** ➔ Requires detailed understanding of ordinary hadron spectrum in 1.5-2.5 GeV mass range.

Gluonic Matter

- Gluons carry color charge: *should bind!*

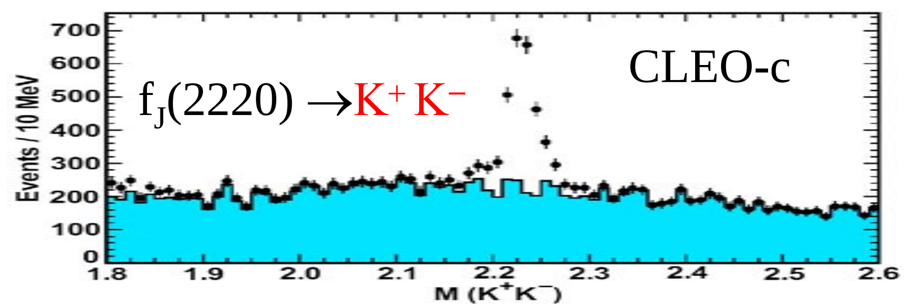
- But, like Jim Morrison, glueballs have been sighted too many times without confirmation.
- CLEO-c 1st high statistics experiment with modern 4π detector covering 1.5-2.5 GeV mass range.
- Radiative ψ decays:ideal glue factory:
  - (60 M $J/\Psi \rightarrow \gamma X$)

Example: Narrow state in inclusive γ



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

Exclusive:



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

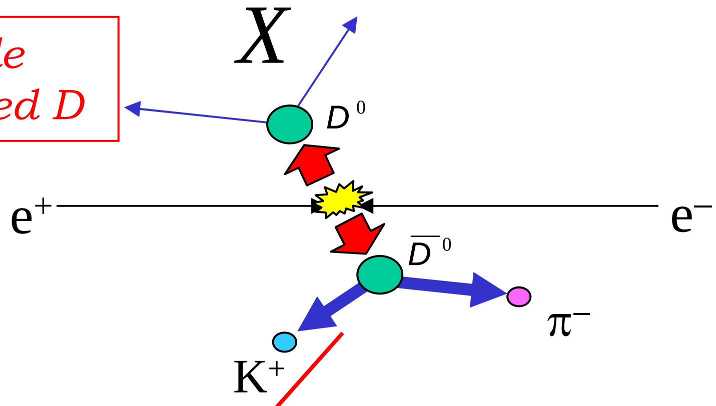
Sensitivity 5σ B(fJ(2220) $\rightarrow K^+ K^-$)= 10^{-6}

corroborating checks:

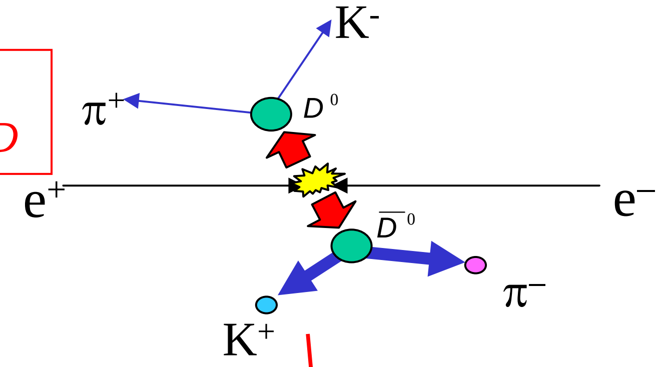
Anti-search in $\gamma\gamma$: /Search in Υ(1S)

Using double tags to measure $\sigma(D\bar{D})$

Single tagged D



Double tagged D



$$S = 2N_{D\bar{D}} B\varepsilon_1$$

$$\varepsilon_2 = \varepsilon_1^2$$

$$D = N_{D\bar{D}} B^2 \varepsilon_2$$

$$N_{D\bar{D}} = S^2 / 4D$$

$\sigma(D\bar{D})$ required to estimate physics reach of CLEO-c

$$\sigma_{D\bar{D}} = \frac{S^2}{4DL}$$

So far use only 2 modes:

$D^0 \to K^-\pi^+ \; \overline{D^0} \to K^+\pi^- \; 102 \pm 11$

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

338 ± 19

(independent on *B* and ε in the approximation $\varepsilon_2 = \varepsilon_1^2$)

Summary for $\sigma(D\bar{D})$

- Our result which is independent of charm branching ratios is in agreement with BESII (April 2004). The BES experiment used a single tag method which is dependent on charm branching ratios from the PDG .

	$\sigma(D^+D^-)$(nb) (stat.err)(sys.err)	$\sigma(D^0D^0)$(nb) (stat.err)(sys.err)	σ(DD) (nb) (stat.err)(sys.err)	$\sigma(D^+D^-)/\sigma(D^0D^0)$
CLEO (55pb^{-1})	2.58±0.15 ±0.16	3.93±0.42±0.23	6.48±0.44±0.39*	0.656
BES II (17.7pb^{-1})	2.52±0.07 ±0.23	3.26±0.09±0.26	5.78±0.11 ±0.38	0.773
MARK III(9.pb^{-1})	2.1±0.3	2.9 ± 0.4	5.0 ± 0.5	0.724

- Unlike MARKIII, CLEO measurement uses only one D^+ and one D^0 decay mode.
- There are many other decay modes CLEO can use and we expect a much more precise result later this summer.

All CLEO-c numbers are preliminary

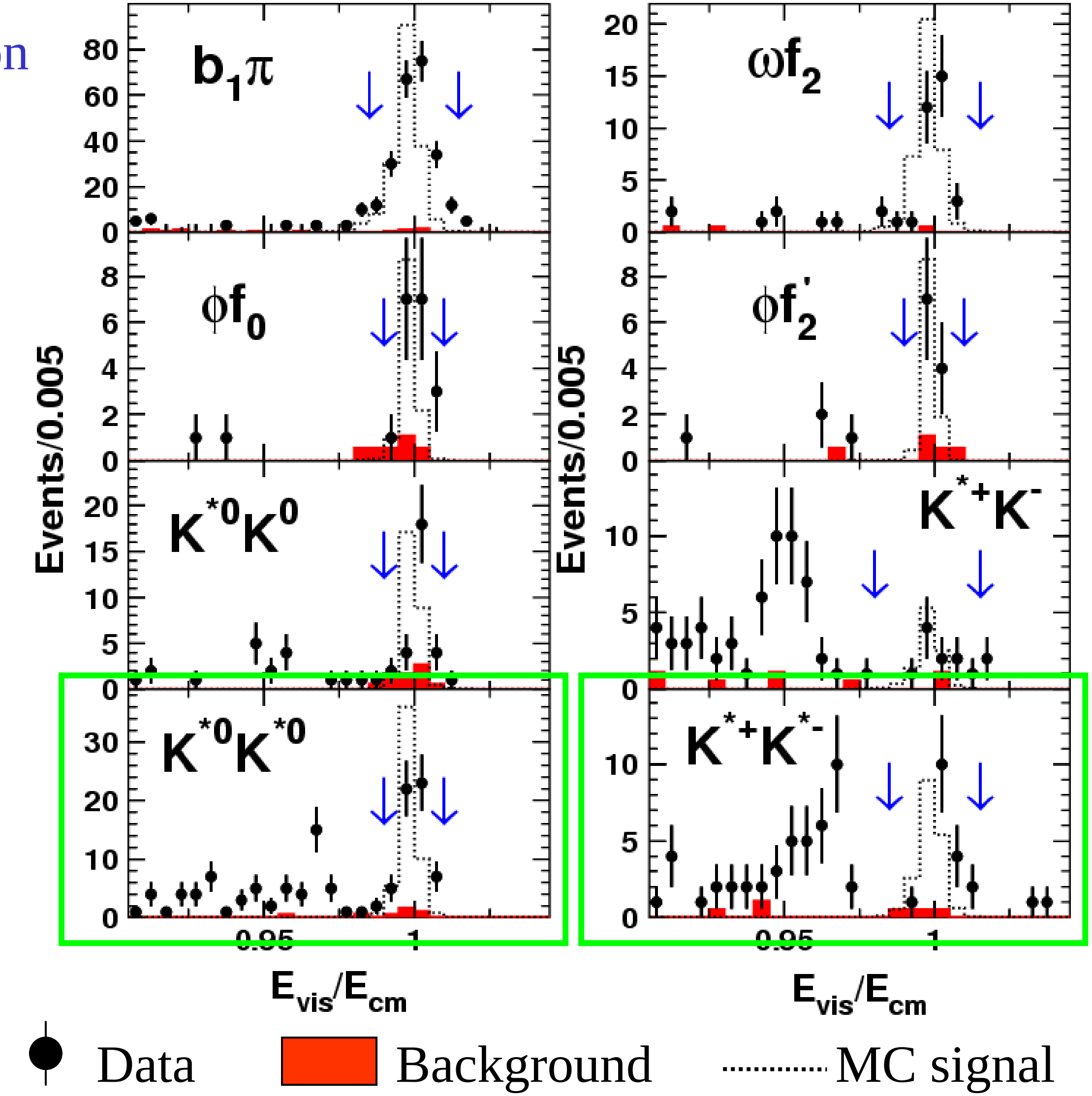
*A correct of -0.03 has been applied to allow for the absence of DCSD $D^0 \rightarrow K^+\pi^-$ at the $\psi(3770)$

CLEO-c Hadronic Two-body ψ(2S) Decays

- Violations of naïve annihilation prediction:

$$\frac{BR(\psi(2S)\to H)}{BR(J/\psi \to H)} \approx \frac{BR(\psi(2S)\to e^+e^-)}{BR(J/\psi \to e^+e^-)}$$

- Works for some modes, not others. Fails miserably in ρπ mode
- 3M ψ(2S) decays collected
- First results from data:
  - ψ(2S) →
    - $b_1(1235)\pi$
    - $\omega f_2(1270)$
    - $\omega\pi^+\pi^-$ —
    - $\phi f_0(980)$
    - $\phi f_2'(1525)$
    - $K^*(892)K$
    - K^*K^*



Tagging Efficiency is high

D^0 Decay Mode	$\mathcal{B}$ (%) (PDG-02)
$D^0 \to K^-\pi^+$	(3.80 ± 0.09)
$D^0 \to K^-\pi^+\pi^0$	(13.1 ± 0.9)
$D^0 \to K^-\pi^+\pi^+\pi^-$	(7.46 ± 0.31)
$D^0 \to \overline{K^0}\pi^0$	(2.28 ± 0.22)
$D^0 \to \overline{K^0}\pi^+\pi^-$	(5.92 ± 0.35)
$D^0 \to \overline{K^0}\pi^+\pi^-\pi^0$	(10.8 ± 1.3)
$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$	(4.0 ± 0.4)
$D^0 \to \overline{K^0}K^+K^-$	(1.0 ± 0.1)
$D^0 \to \pi^+\pi^-\pi^0$	(1.1 ± 0.4)
$D^0 \to K^+K^-$	(0.41 ± 0.01)
$D^0 \to \pi^+\pi^-$	(0.14 ± 0.01)
$D^0 \to K^-\pi^+\pi^0\pi^0$	

D^+ Decay Mode	$\mathcal{B}$ (%) (PDG-02)
$D^+ \to \overline{K^0}\pi^+$	(2.77 ± 0.18)
$D^+ \to K^-\pi^+\pi^+$	(9.1 ± 0.6)
$D^+ \to \overline{K^0}\pi^+\pi^0$	(9.7 ± 3.0)
$D^+ \to K^-\pi^+\pi^+\pi^0$	(6.4 ± 1.1)
$D^+ \to \overline{K^0}\pi^+\pi^+\pi^-$	(7.0 ± 0.9)
$D^+ \to K^+K^-\pi^+$	(0.9 ± 0.1)

Number of D^+ tags ~30K in 55/pb

Number of D^0 tags ~62K in 55/pb

Preliminary

$$\text{tag efficiency} \sim \frac{\#\text{ tags reconstructed}}{\#DD\text{ pairs}}$$

$$\text{tag efficiency} \sim \frac{62+30=92K}{L\sigma(DD)} = \frac{92K}{6.51\text{nb} \bullet 55\text{pb}^{-1}} \sim 26\%$$

(higher than the 19% assumed in projections)

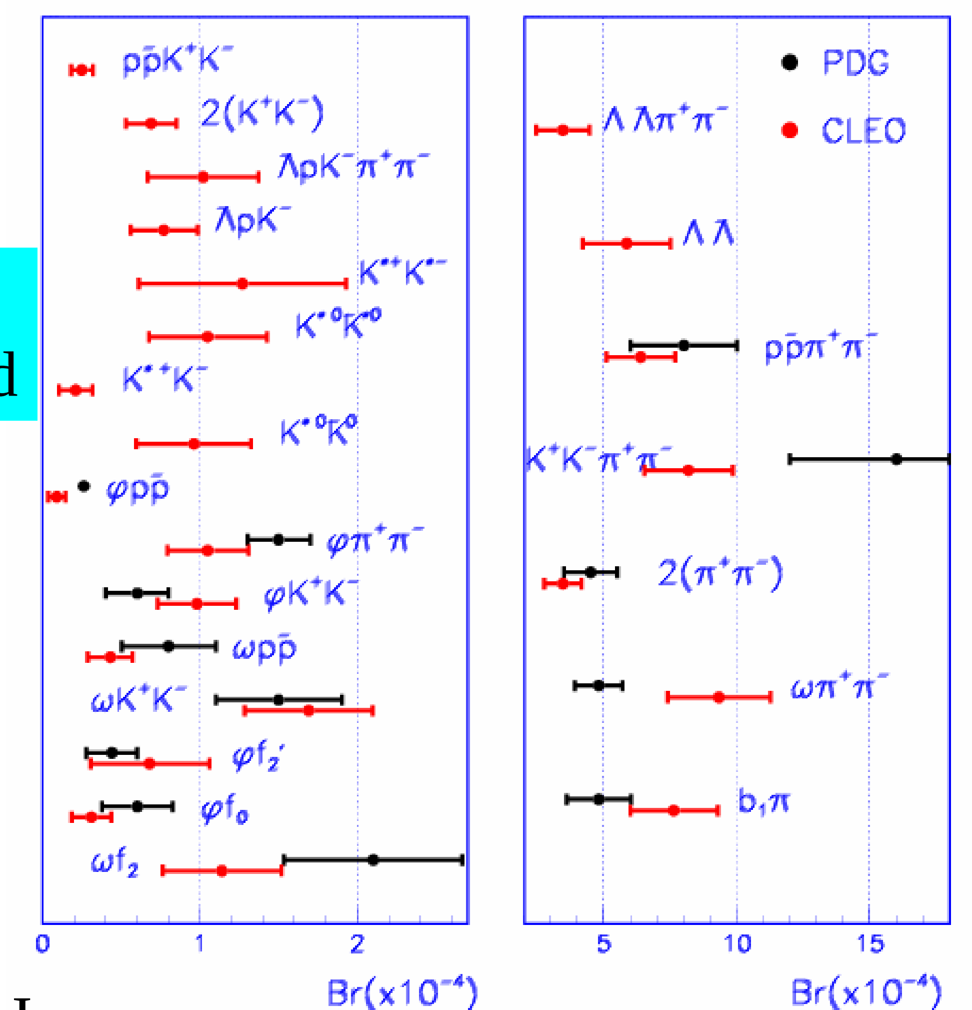
Hadronic 2,3,4 body ψ(2S) Decays

With 3M ψ(2S) collected
23 decay modes measured

Agreement with PDG
for modes previously observed

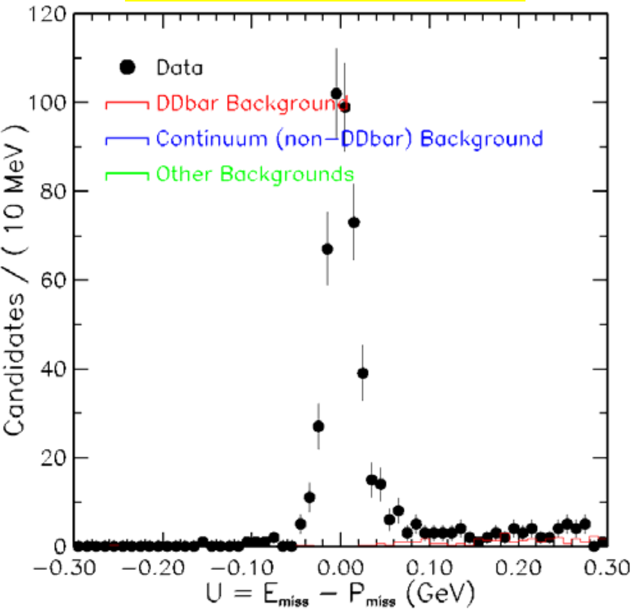
10 first measurements

Reported at APS
May, 2004 More modes
next week at HQL in San Juan

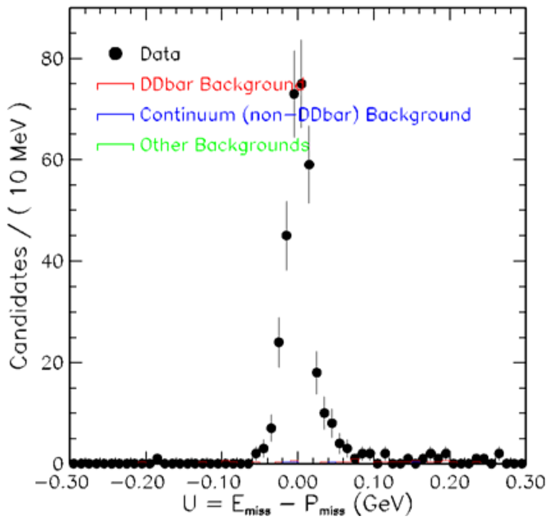


D^+ semileptonic modes

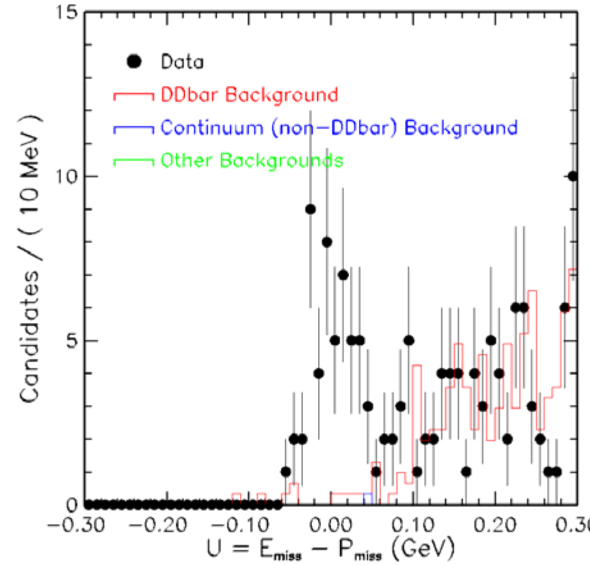
$D^+ \to \overline{K^0} e^+ \nu$



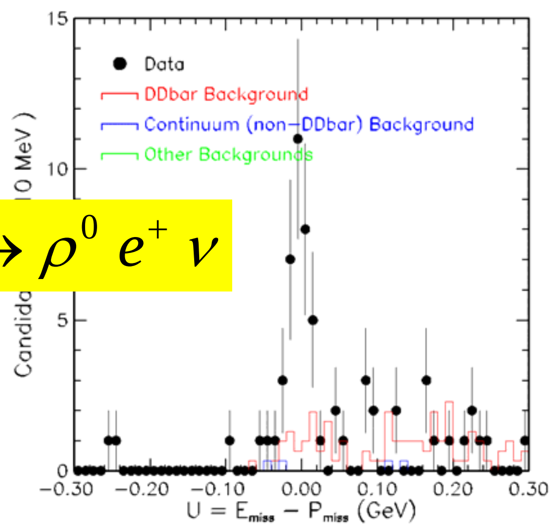
$D^+ \to K^{*0} e^+ \nu, \quad K^{*0} \to K^- \pi^+$



$D^+ \to \pi^0 e^+ \nu$



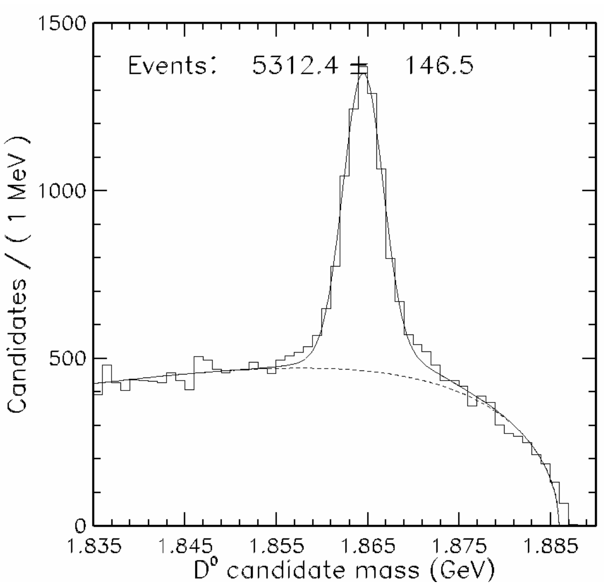
$D^+ \to \rho^0 e^+ \nu$



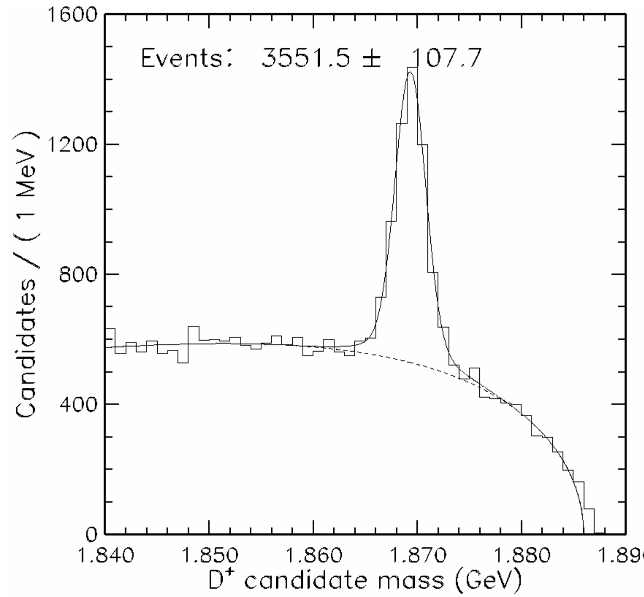
All Plots Preliminary

More D^0 and D^+ tags

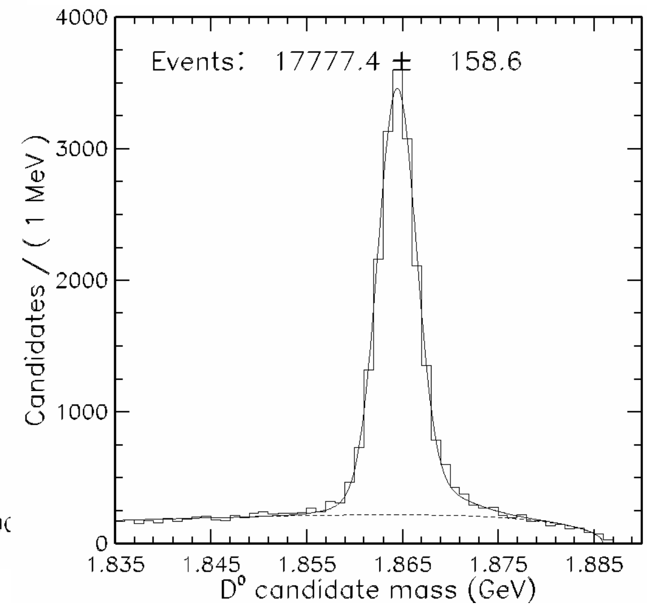
All Plots Preliminary



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



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



Number of D^0 tags ~62K in 55/pb

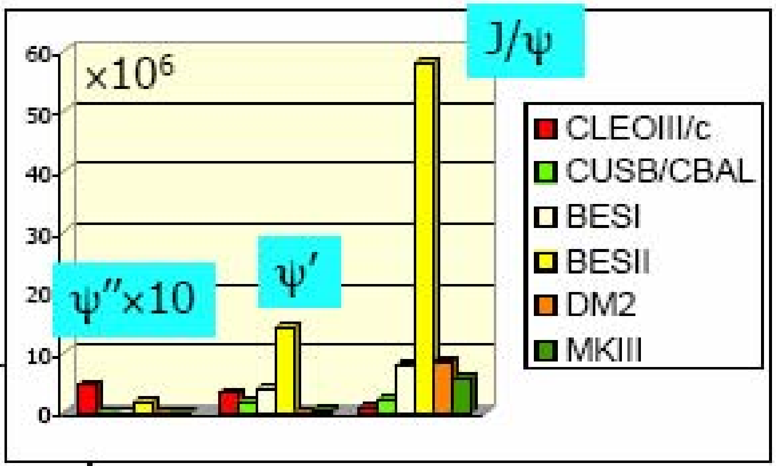
Number of D^+ tags ~30K in 55/pb

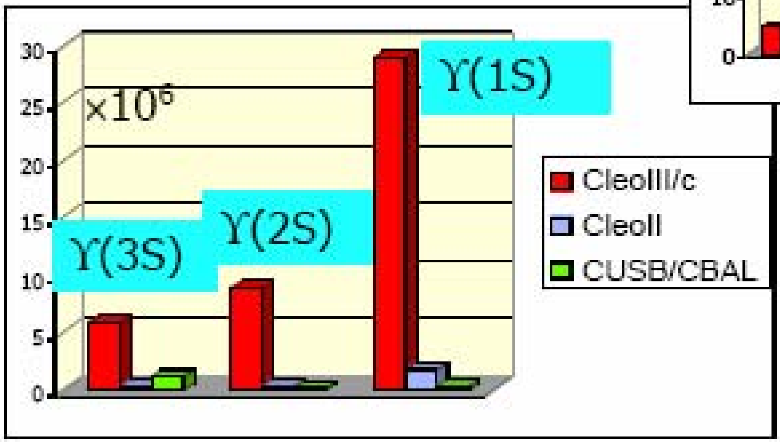
$$\text{tag efficiency} \sim \frac{\#\text{ tags reconstructed}}{\#\text{DD pairs}}$$

$$\text{tag efficiency} \sim \frac{62+30=92\text{K}}{\text{L}\sigma(\text{DD})} = \frac{92K}{6.51\text{nb} \bullet 55\text{pb}^{-1}} \sim 26\%$$

Experimental Progress in Onia

Large new datasets from e^+e^- machines on the 1^{--} vector states …





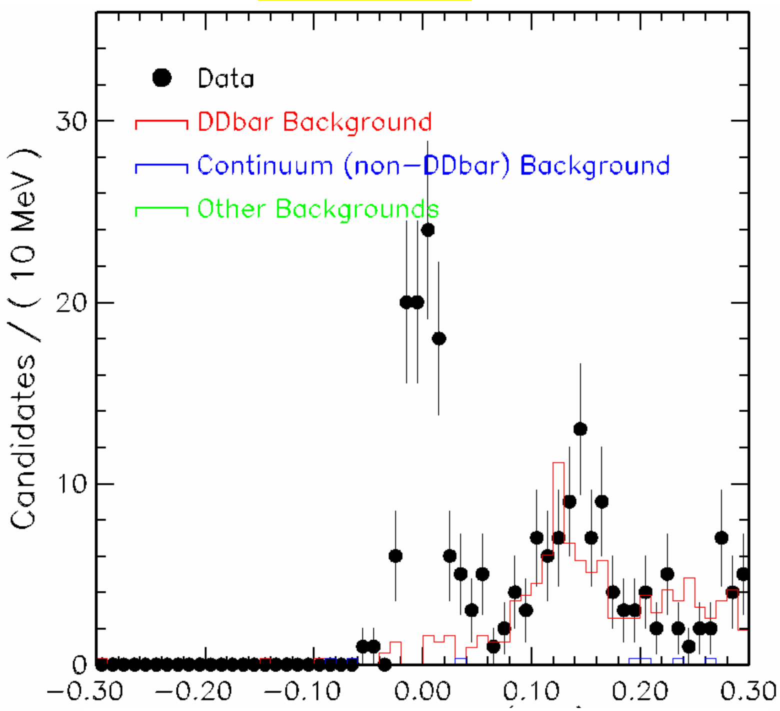
… and many new contributions from B-factories and hadron colliders as well

See Daria Zieminska talk tomorrow for discussion X(3872), new cs states etc/

$D^0 \to \pi^- e^+ \nu$

1st CLEO-c DATA

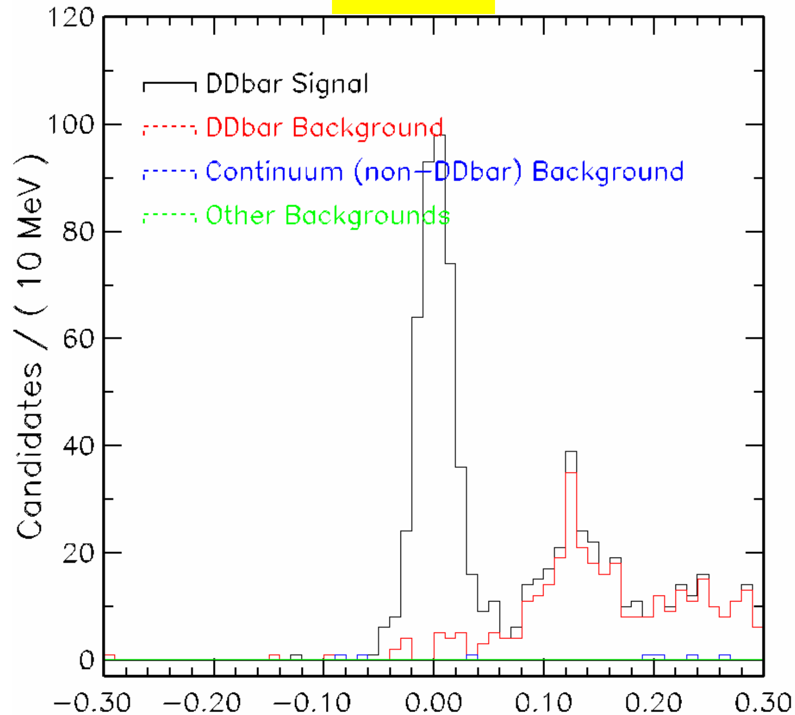
Data



$U = E_{miss} - P_{miss}$ (GeV)

Excess of ~100 events

MC

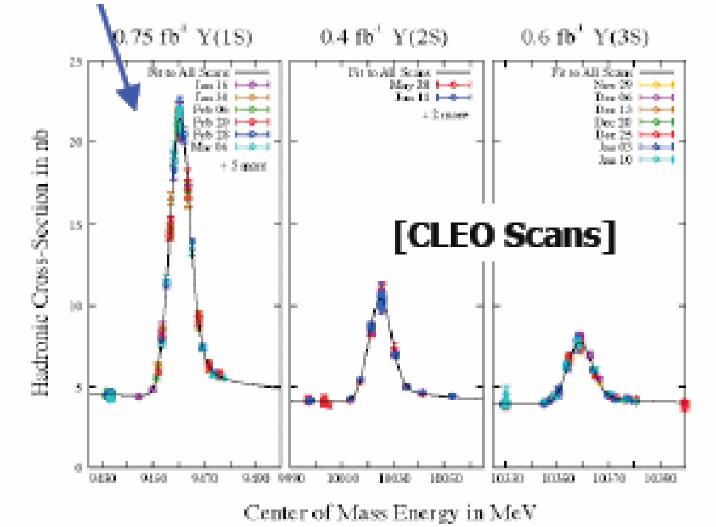


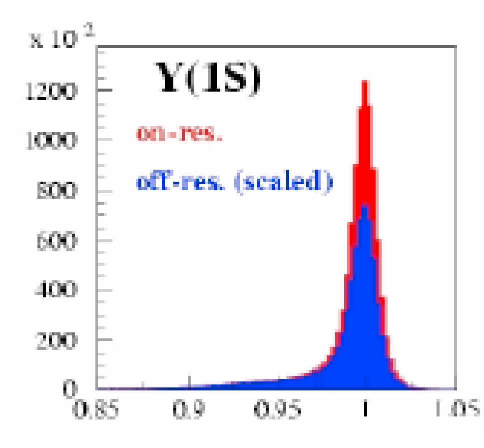
$U = E_{miss} - P_{miss}$ (GeV)

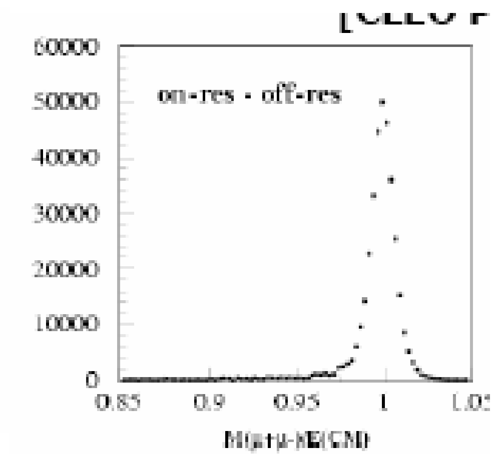
Data well simulated by GEANT MC giving confidence to estimates of precision in the CLEO-c proposal

Towards a precision Γee in the Υ system

Now: Υ(nS) δΓee 4-12%. Precision measurement of B(Υ(nS)➔μμ) needed to get Γ_{tot} from narrow resonances for Γ_{ee}







Most precise measurements to date. Few % precision reached

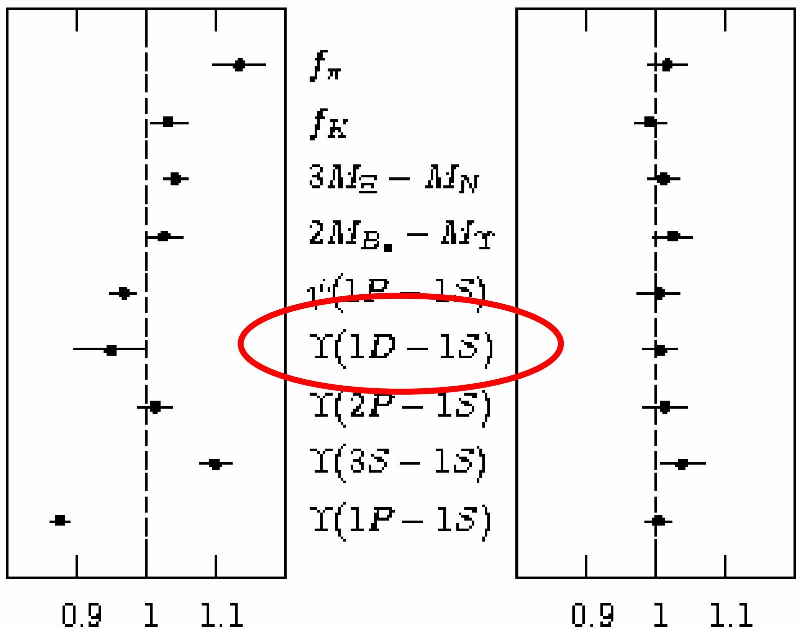
Υ(2S,3S) higher than PDG

	$B_{\mu\mu}$ (%)		Γ_{tot} (keV)	
	CLEO *preliminary*	PDG	CLEO *preliminary*	PDG
Υ(1S)	2.46 ± 0.02 ±0.05	2.48 ± 0.06	53.4 ± 1.5	52.5 ± 1.8
Υ(2S)	**2.00** ± 0.03 ±0.05	**1.31** ± 0.21	**29.5** ± 1.4	**44** ± 7
Υ(3S)	2.34 ± 0.07 ±0.05	1.81 ± 0.17	20.7 ± 2.1	26.3 ± 3.5

➔Expect 2-3% precision for Γee (results soon)

Υ(1D) Impact on LQCD

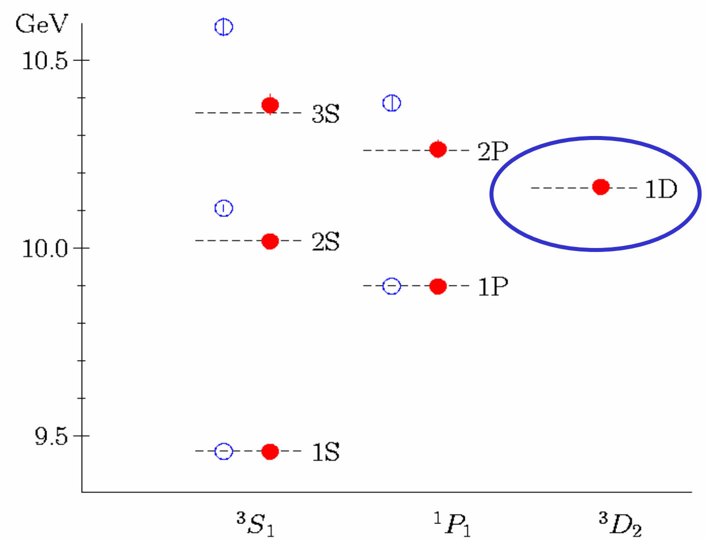
Ratio = LQCD/Expt



Quenched **Unquenched (n_f=3)**

[CTH Davies et al., PRL **92**:022001 (2004)]

Υ Spectrum



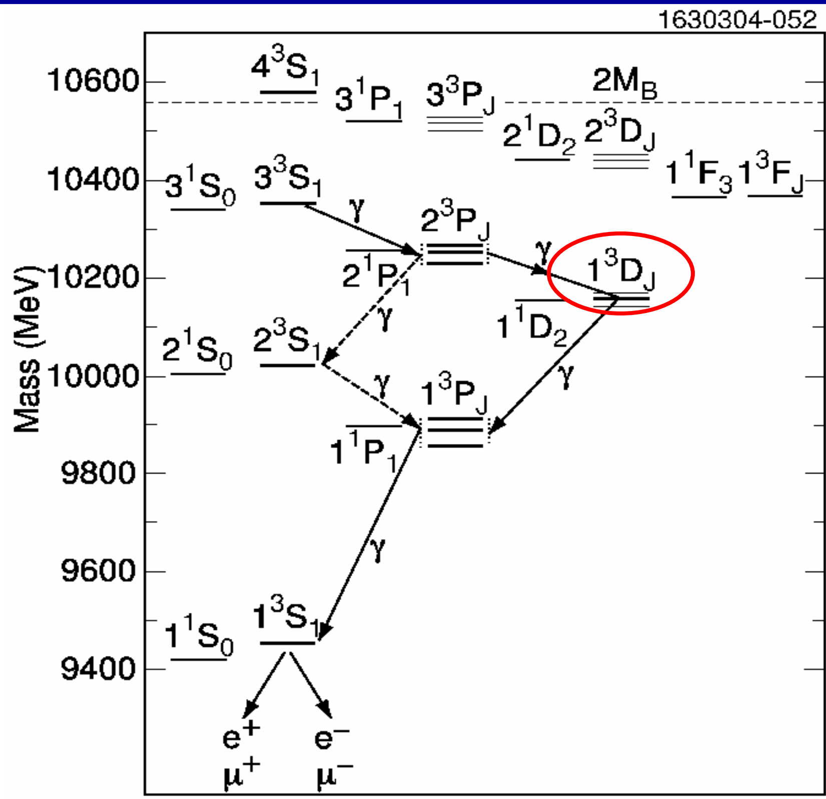
○ Quenched

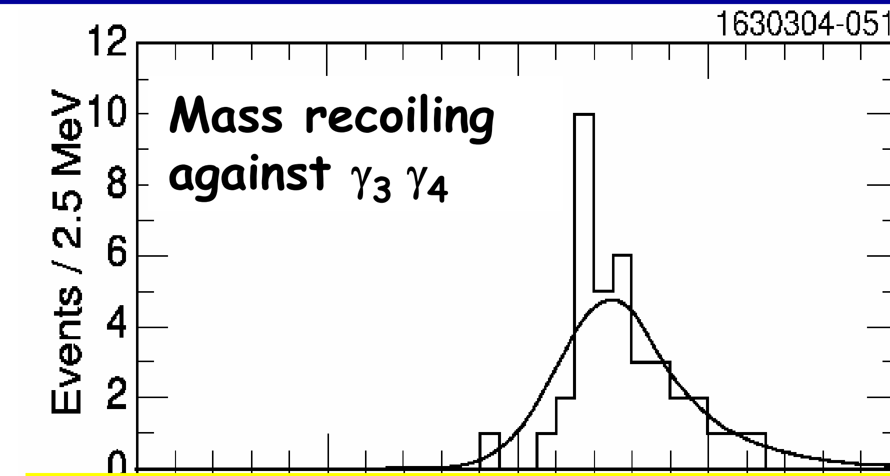
● $m_u = m_d = m_s/5$

[Coutesy: J.P. Lepage]

Observation of $\Upsilon(1D)$ & Impact

[CLEO]





>10 std dev significance

M = 10161.1±0.6±1.6 MeV

Consistent with 1 $^3D_2$

Tests LQCD at high L

Four γ cascade; exclusive $\Upsilon(1S)$ channel

Background thru 2^3S_1

First reported ICHEP'02 with 80% of data … now final

Submitted to PRD [hep-ex/0404021]

Status of Vub (inclusive method)

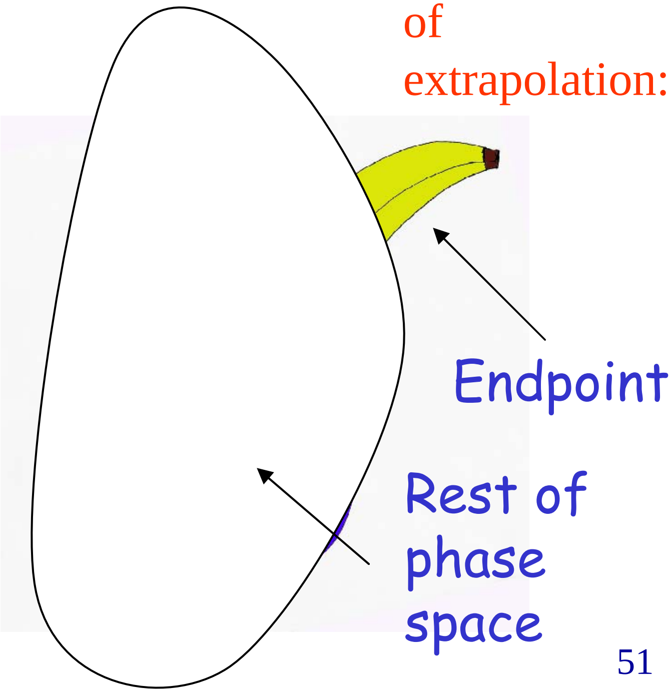
- **Inclusive method: Severe background: b→clν~ x100 b→ulν lead to measurements in small regions of phase space large extrapolation to obtain Vub**

Inclusive methods:
To distinguish b→u from b→c theoretically:

	better		better	
q^2-m_{had} spectrum	>	m_{had} spectrum	>	E_{lepton} spectrum

But experimental difficulty in opposite order

The dangers of extrapolation:



Status of Vub (inclusive method)

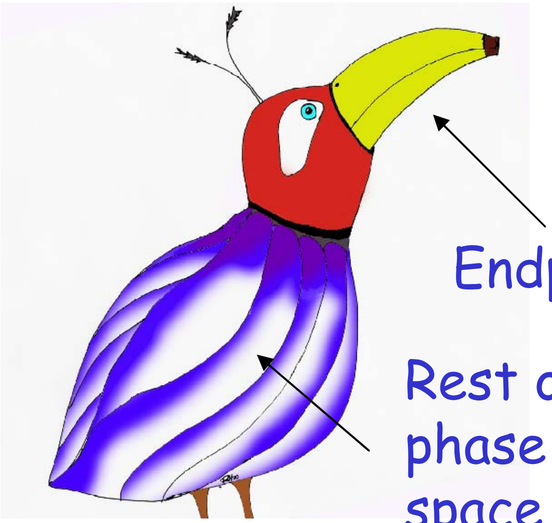
- **Inclusive method: Severe background: $b \to cl\nu$~ x100 $b \to ul\nu$ lead to measurements in small regions of phase space large extrapolation to obtain Vub**

Inclusive methods:
To distinguish $b \to u$ from $b \to c$ theoretically:

better **better**

q^{2}-m_{had} spectrum > m_{had} spectrum > E_{lepton} spectrum
But experimental difficulty in opposite order

The dangers of extrapolation:



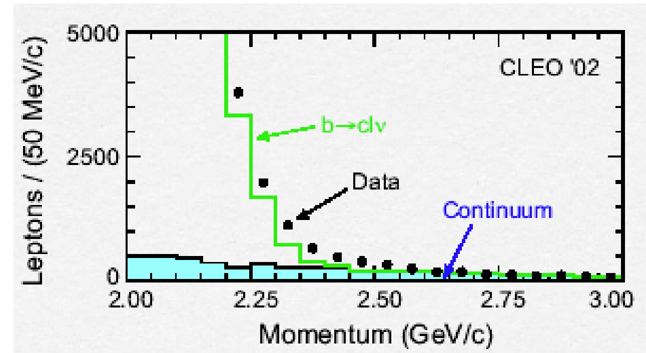
Endpoint

Rest of phase space

Status of Vub (inclusive method)

- **Inclusive method: Severe background: b→clν~ x100 b→ulν lead to measurements in small regions of phase space large extrapolation to obtain Vub**

CLEO 10 MΥ(4S),



Inclusive methods:
To distinguish b→u from b→c theoretically:

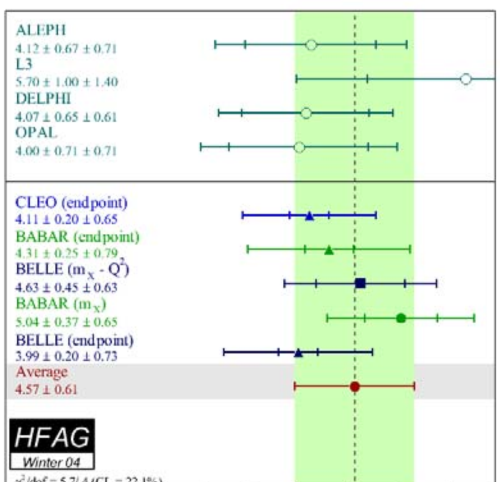
better **better**

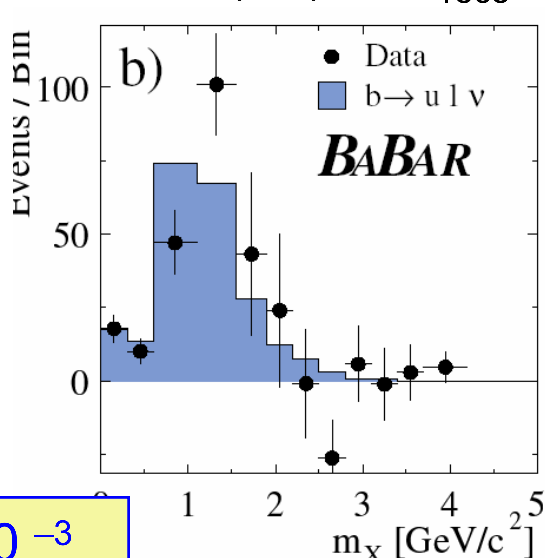
q^2-m_{had} spectrum > m_{had} spectrum > E_{lepton} spectrum

But experimental difficulty in opposite order

All 3 methods now attempted E_{lepton} & m_{had} method shown

BABAR 89 MΥ(4S), 32 k events Υ(4S) → $B_{reco}B_{sig}$, E_l >1 GeV





Use b→ sγ spectrum important input for extrapolation

Error on extrapolation dominant theory error

(No Lattice Involvement)

$|V_{ub}|_{incl}$ = (4.57 ± 0.61) 10^{-3}

1.5 T → 1.0T

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

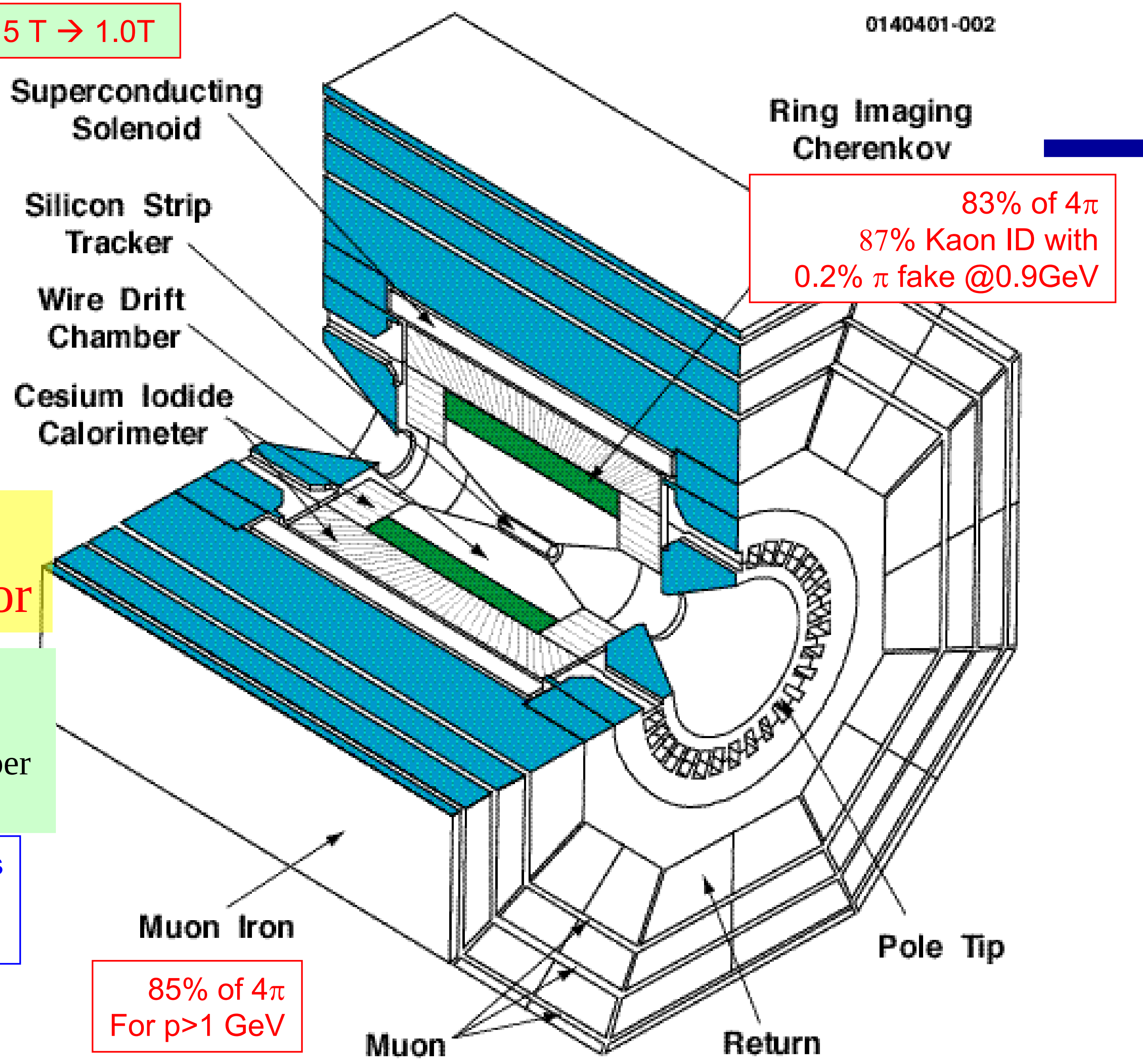
93% of 4π
σ_E/E = 2% @1GeV
= 4% @100MeV

CLEO III Detector → CLEO-c Detector

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



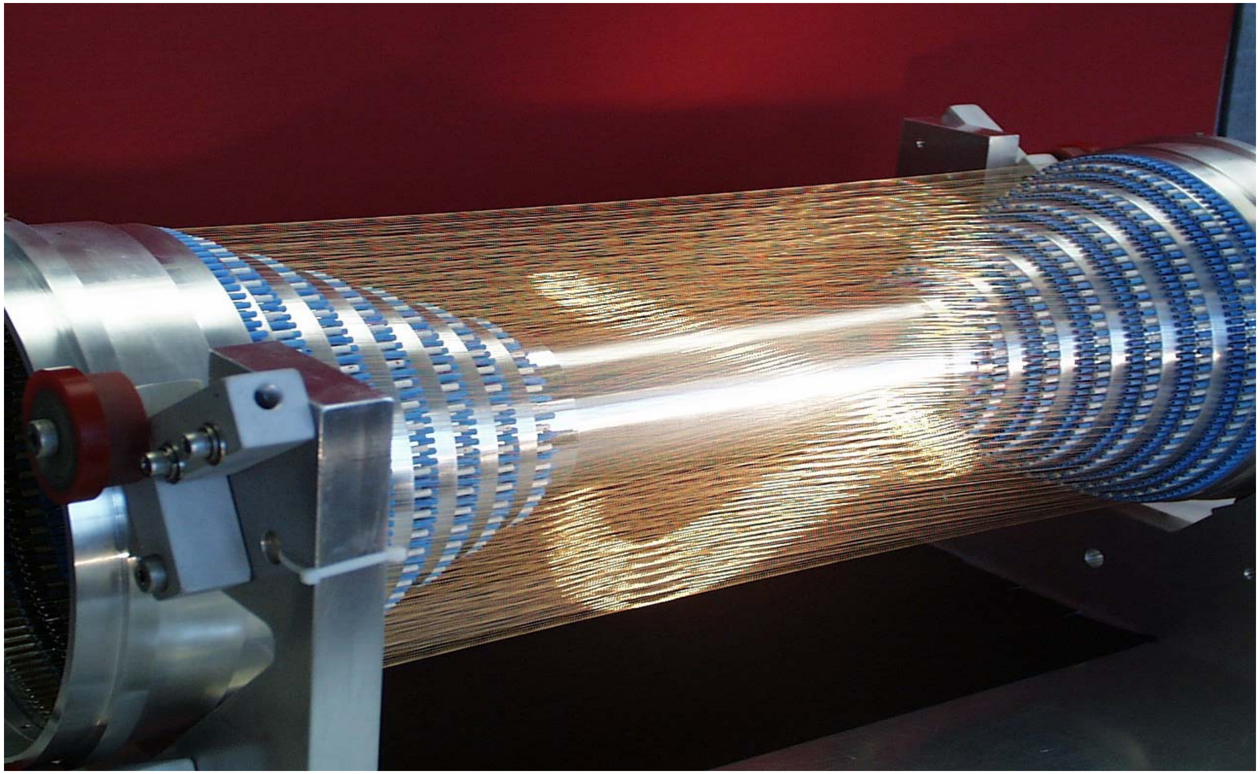
83% of 4π
87% Kaon ID with
0.2% π fake @0.9GeV

85% of 4π
For p>1 GeV

CLEO III: numerous physics results & well understood

"ZD" Inner Drift Chamber

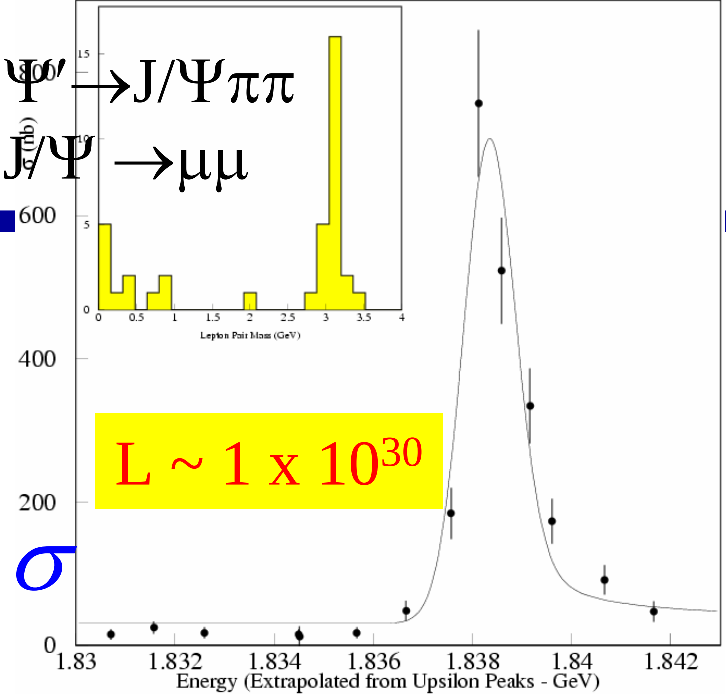
- Extends from 4.1cm to 11.8cm along the radial direction.
- 6 stereo layers - 12-15^{o}
- 300, 10 mm cells
- 60:40 Helium-Propane
- 1% X_0, 0.8mm Al inner tube
- Outer Al-mylar skin



CESR-c

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

Unmodified CESR
1 day scan of the Ψ′:
(1/29/02) →



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

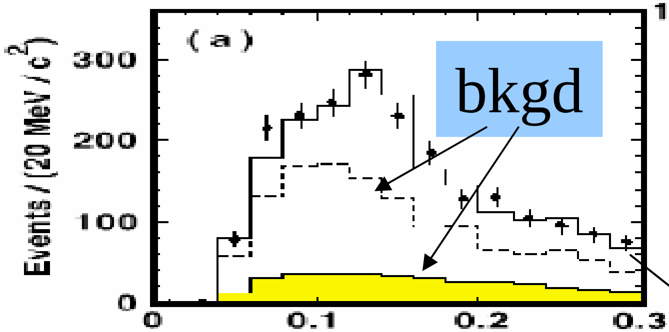
Expected machine performance with full complement of wigglers

√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

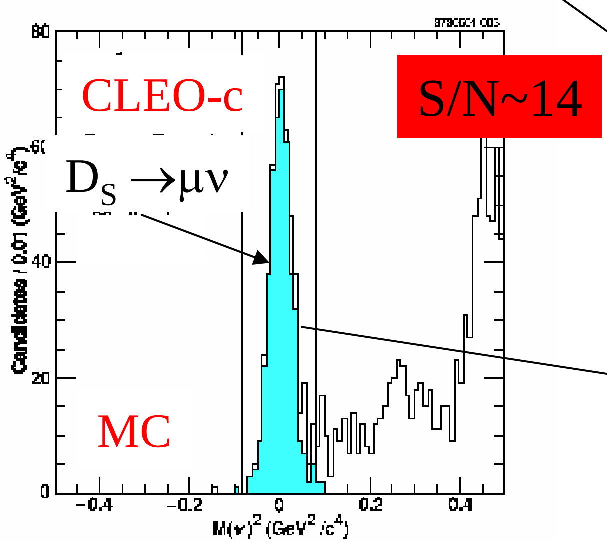
Compare B factories & CLEO-c

CLEOII: 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

B Factory CLEO technique with improvements



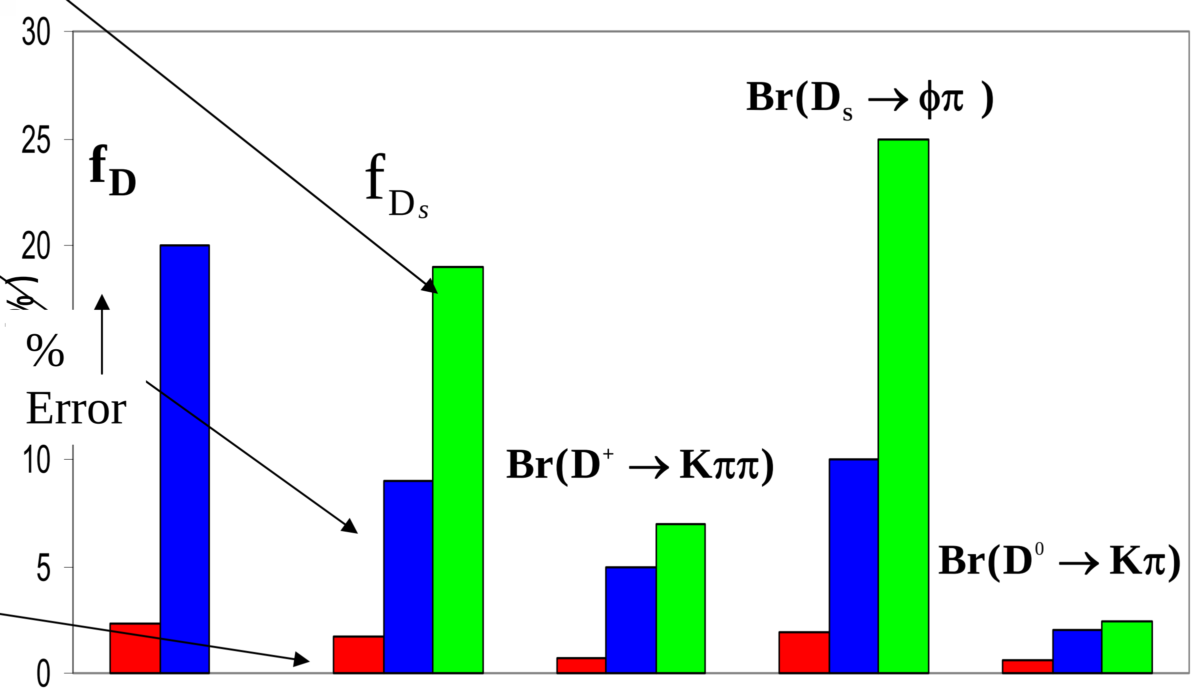
CLEO-c
3 fb^{-1}

BFactory
400 fb^{-1}

Statistics limited

Systematics & Background limited

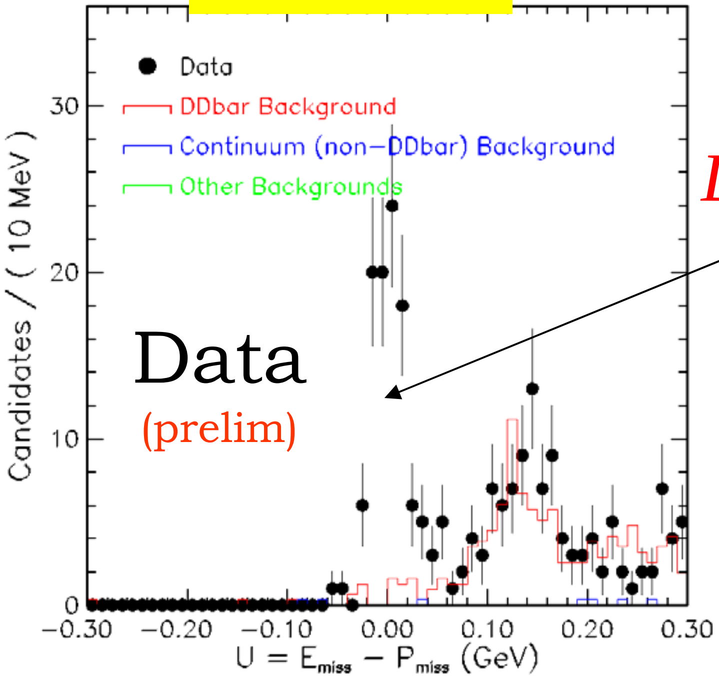
PDG



The power of running at threshold

$D^0 \to \pi^- e^+ \nu$ The power of threshold running

CLEO-c

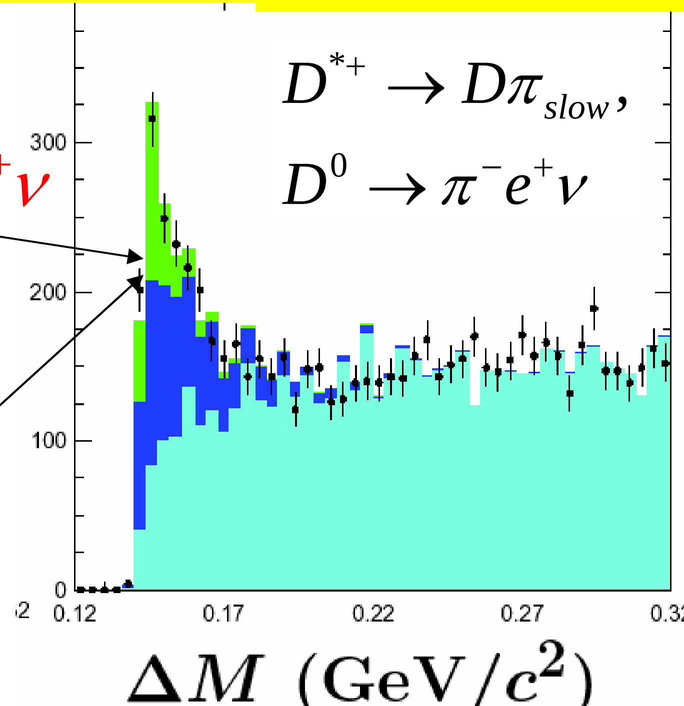


$D^0 \to \pi^- e^+ \nu$

S/N ~25/1

S/N 1/4

CLEO-III $e^+e^- \to c\bar{c}$ at 10 GeV



$$\Delta M \equiv M(\pi_{slow} D) - M(D)$$

Data
Signal $D^0 \to \pi^- e^+ \nu$
Peaking Background
Flat Background

The power of threshold running is amply demonstrated by comparison to the $D^0 \to \pi^- e^+ \nu$ signal in the world's most precise measurement of

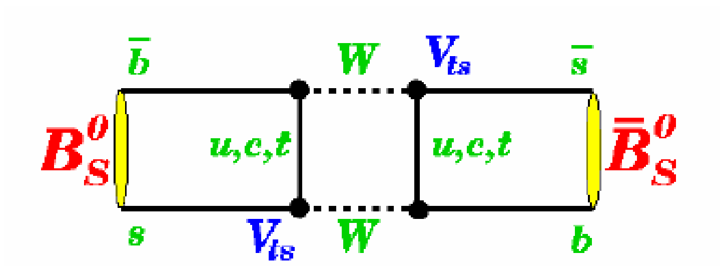
$$\frac{\mathcal{B}(D^0 \to \pi e \nu)}{\mathcal{B}(D^0 \to K e \nu)} = 0.097 \pm 0.010 \pm 0.010$$

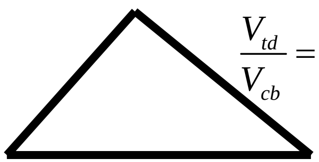
(CLEO III to be submitted to PRL 2004)

Status of B_s mixing

$B_s \rightarrow \overline{B}_s$ mixing

ALEPH,CDF,
DELPHI,OPAL.SLD





$$\frac{V_{td}}{V_{cb}} = \frac{V_{td}}{V_{ts}}$$

ξ^2 (lattice)

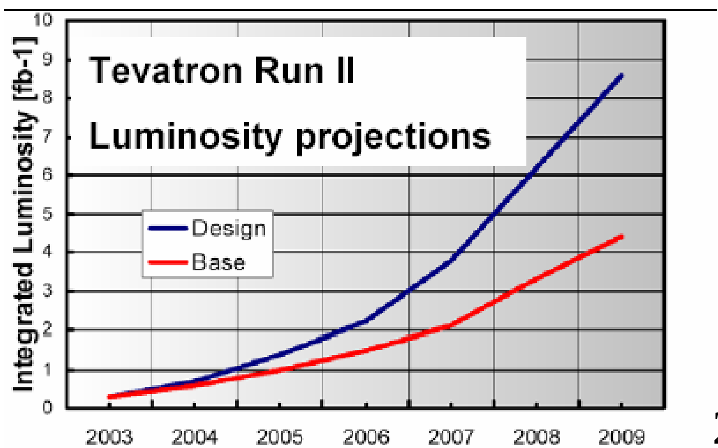
World Average

Δms<14.5/ps

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

$$\delta\xi / \xi \sim 6\text{–}8\%??$$

dominant error



High resolution on proper decay time required

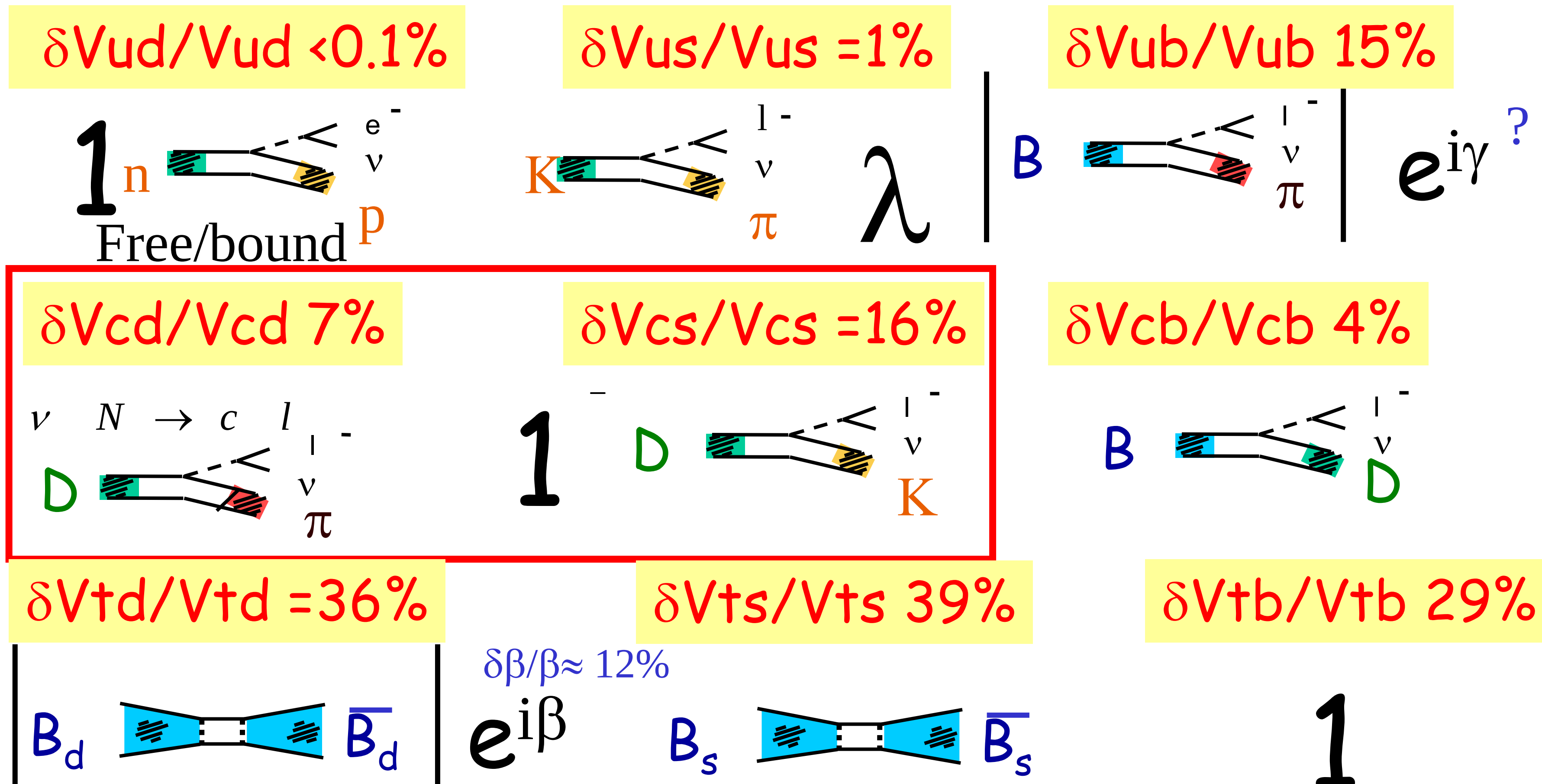
Prospects:

2σ for Δm=15/ps with 0.5 fb^{-1}
5σ for Δm=18/ps with 1.7 fb^{-1}
5σ for Δm=24/ps with 3.2 fb^{-1}

Near term D0/CDF
Long term CDF

See Daria Zieminska talk tomorrow for discussion B_s mixing

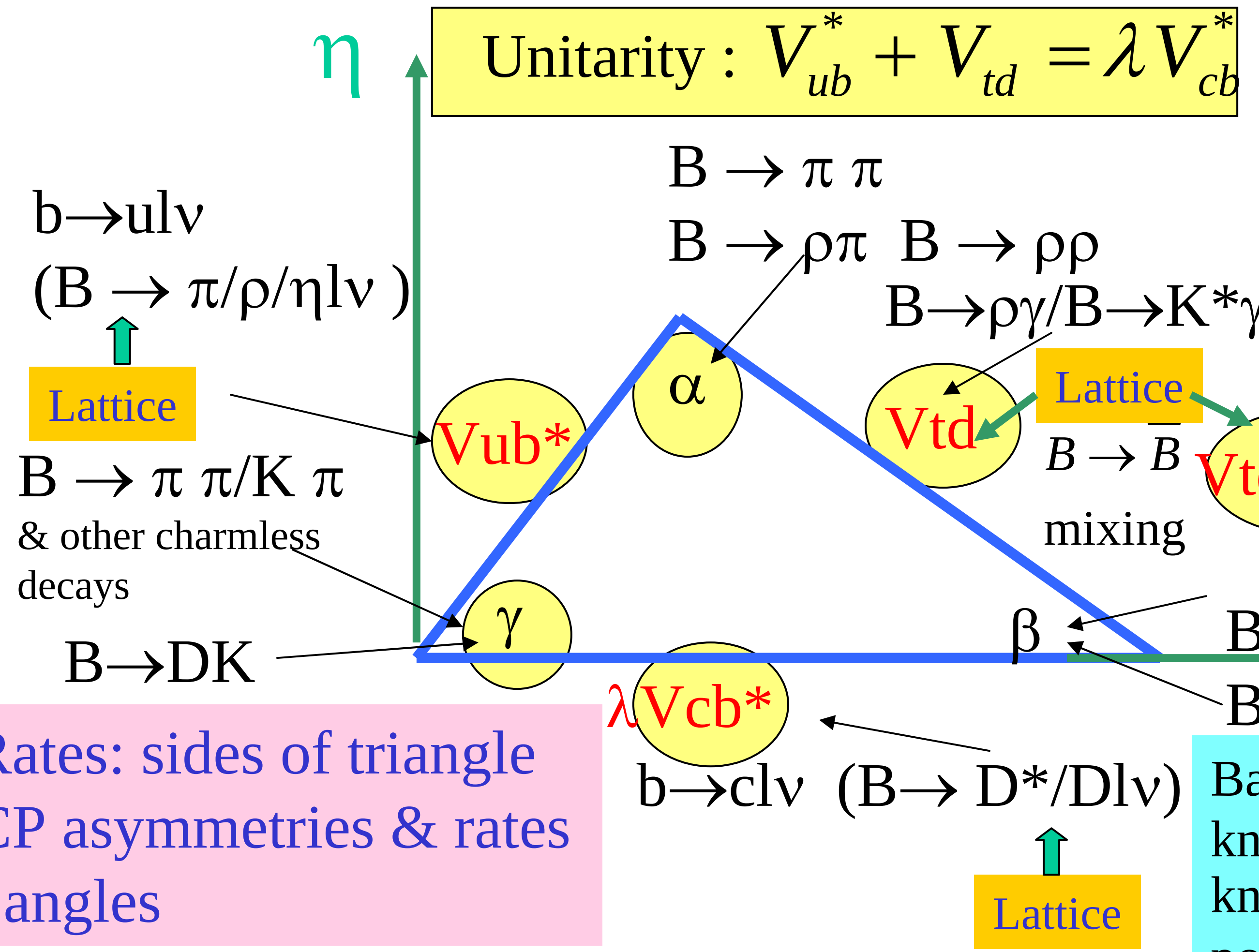
CKM Matrix Status



Vud, Vus and Vcb are the best determined due to flavor symmetries: I, SU(3), HQS. Charm (Vcd & Vcs) and rest of the sector determined by beauty decays (Vub, Vtd, Vts) are poorly determined. Theoretical errors on hadronic matrix elements dominate.

B Decays & the Unitarity Triangle

Goals for the decade: precision measurements of Vub, Vcb, Vts, Vtd, Vcs, Vcd, α, β, γ. Test SM description of CP violation and search for new physics.



SM: side & angles measured in many processes are self consistent otherwise: new physics

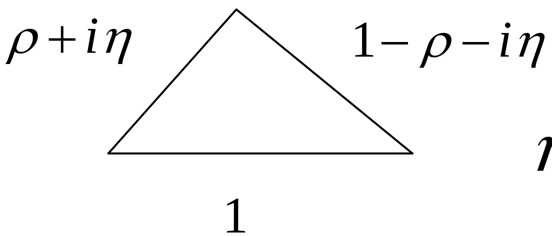
= hadronic uncertainty a significant factor

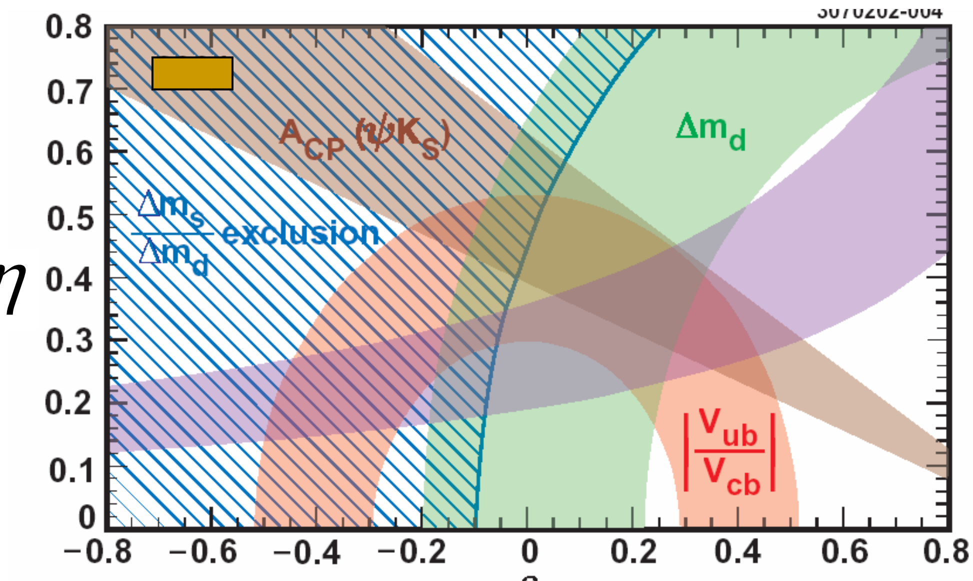
Rates: sides of triangle
CP asymmetries & rates : angles

Base λVcb relatively well known, other sides poorly known β ~12% angles α poorly known γ unknown

Unitarity Triangle Status

2004



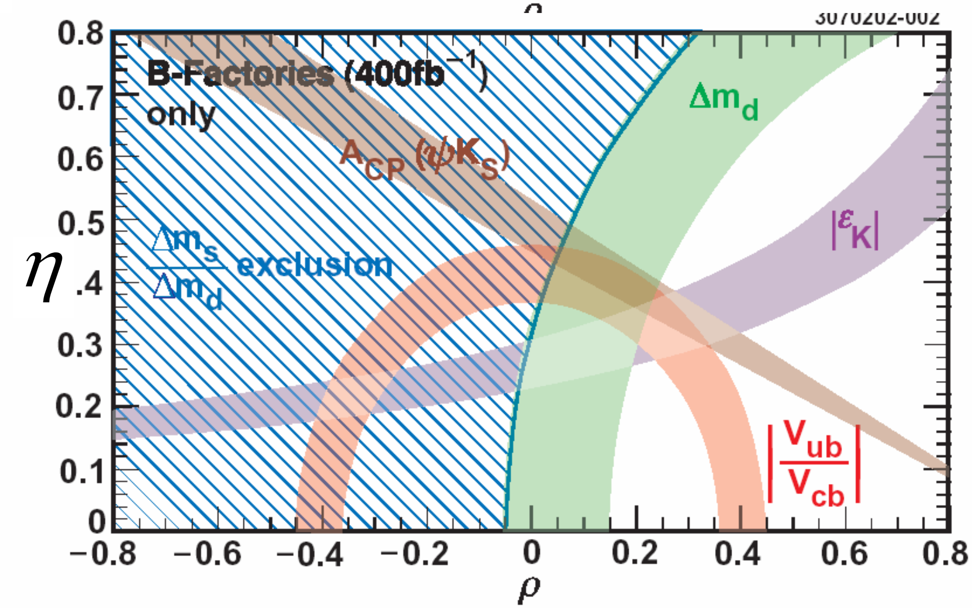


Theoretical errors dominate width of bands

Assume improvements in theory: theory errors reduced by x2

+

B Factories with 400 fb^{-1}



Theoretical errors still dominate width of bands