Charm Results from CLEO-c

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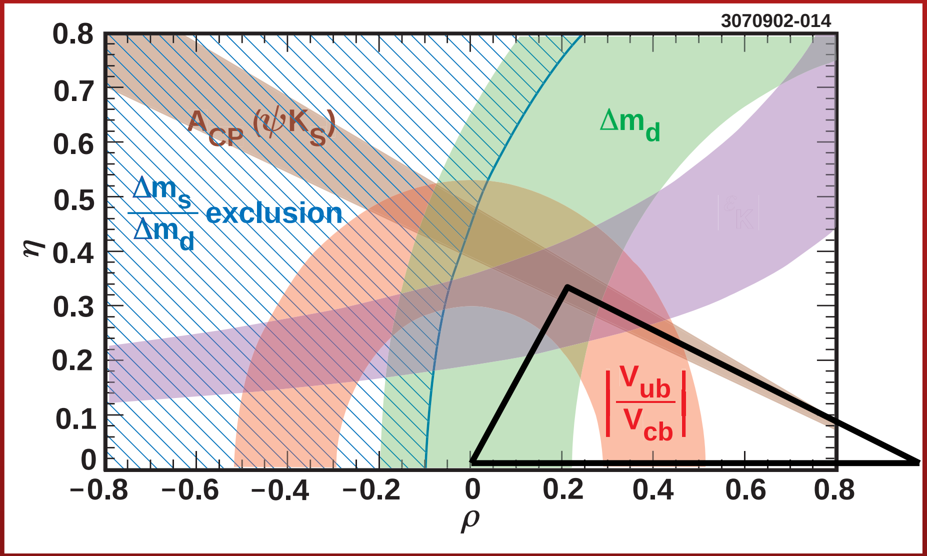
Context for CLEO-c



CPV & Flavor physics:

- Overconstrain V_{CKM}
- Inconsistency → new physics
- Interpretation limited by strong interaction effects

- Sin 2β is clean
- $|V_{ub}|$ is not
- B mixing is not

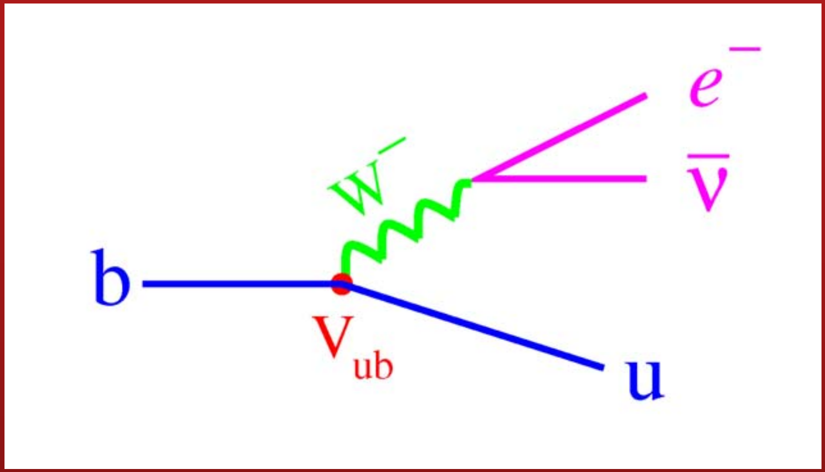
Hadronic uncertainties confound the extraction of weak physics

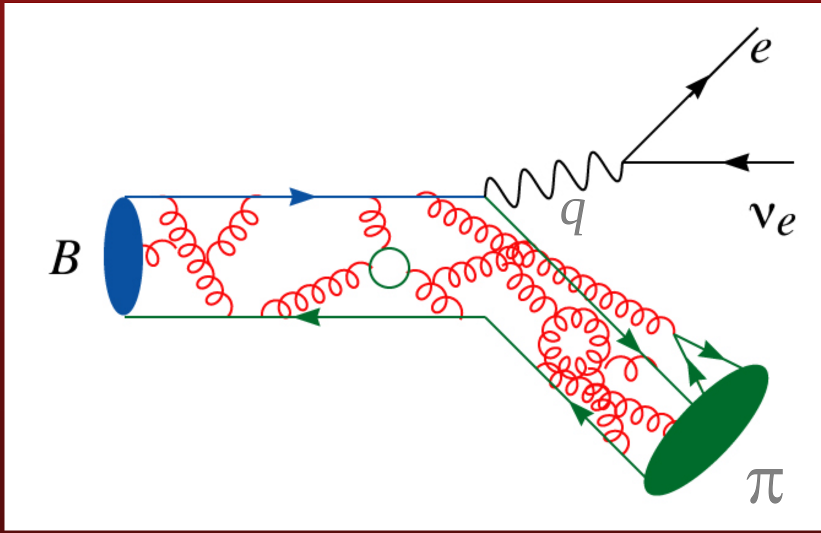
- Non-perturbative QCD
- Perturbative QCD (on better ground)

Driving Idea behind CLEO-c weak decay program

- Measurements in Charm decays can validate QCD corrections needed to extract Weak physics from observables

$|V_{ub}|$ from semileptonic B decay





If quarks were like muons:

$$\Gamma(b \to u e \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{ub}|^2$$

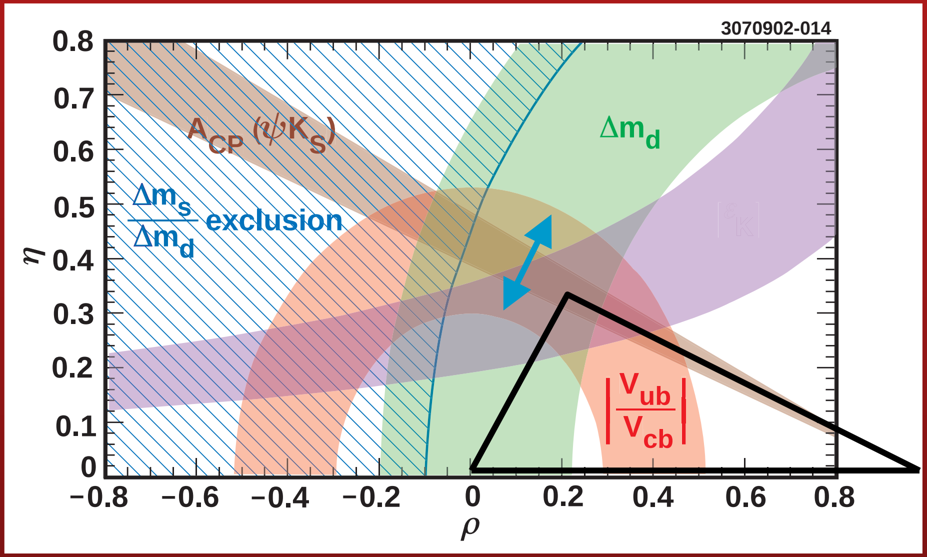
- Rate goes like $|V_{ub}|^2$

But quarks always in hadrons

- QCD form factor $f_+(q^2)$ needed to extract weak decay physics

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

UT Constraint from $|V_{ub}|$



$|V_{ub}|$ from $B \to \pi \ell \nu$:

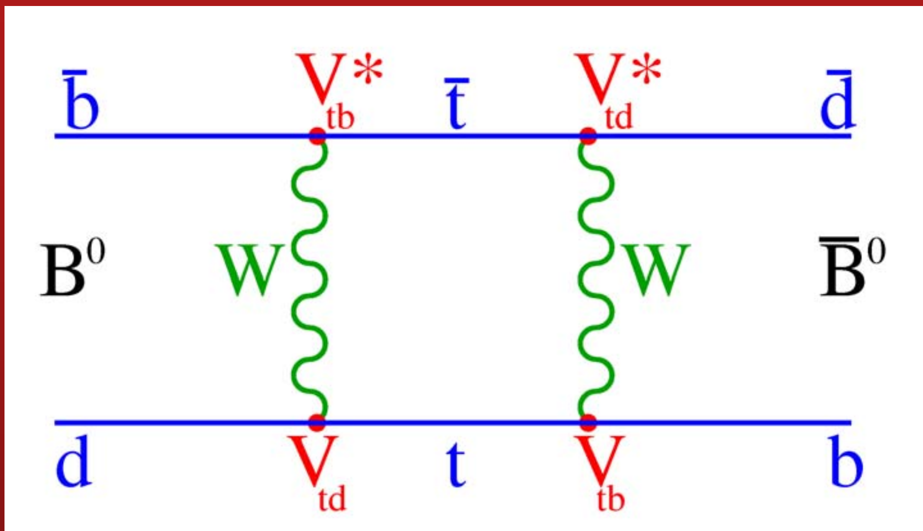
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 p_\pi^3 |f_+(q^2)|^2$$

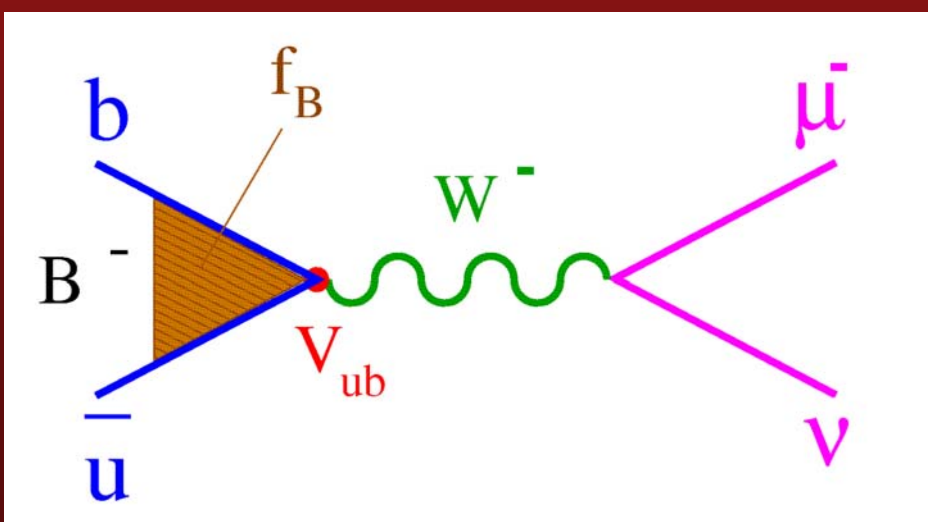
Form factor $f(q^2)$:

- Hard to calculate
- Limits $|V_{ub}|$ precision
- Computed in Lattice QCD

- Heavy quark symmetry relates $D \to \pi \ell \nu$ to $B \to \pi \ell \nu$
- A precise measurement of $D \to \pi \ell \nu$ can calibrate LQCD and allow a precise extraction of $|V_{ub}|$ from $B \to \pi \ell \nu$
- Absolute rate and shape is a stringent test of theory

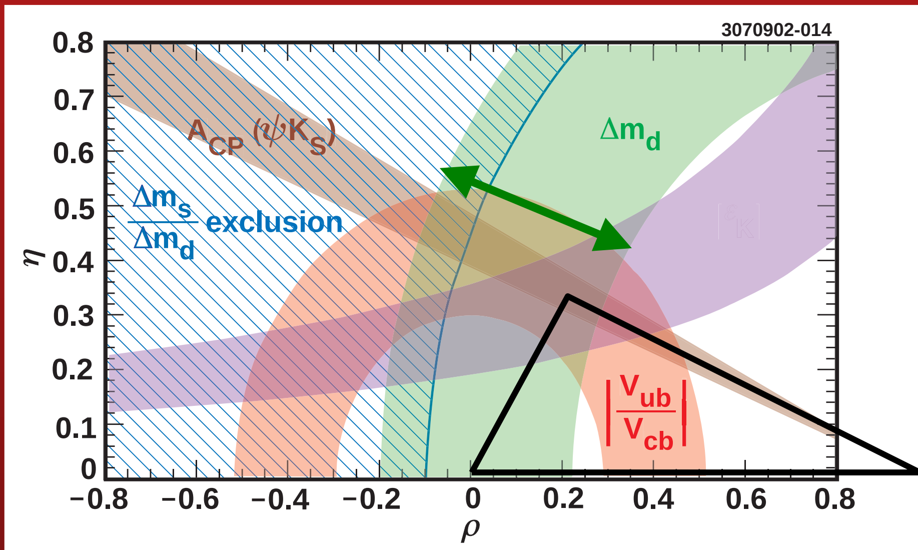
$|V_{td}|$ from B^0-$\overline{B^0}$ mixing





- Mixing rate depends on $|V_{td}|^2$
- QCD correction here is partly decay constant f_B
  - probability of wave function overlap $\psi(r=0)$
- Same for meson decay
- Hard to calculate in low energy QCD
  - Lattice QCD to ~15%
- Can measure annihilation decay (in principle)

UT Constraint from B mixing



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

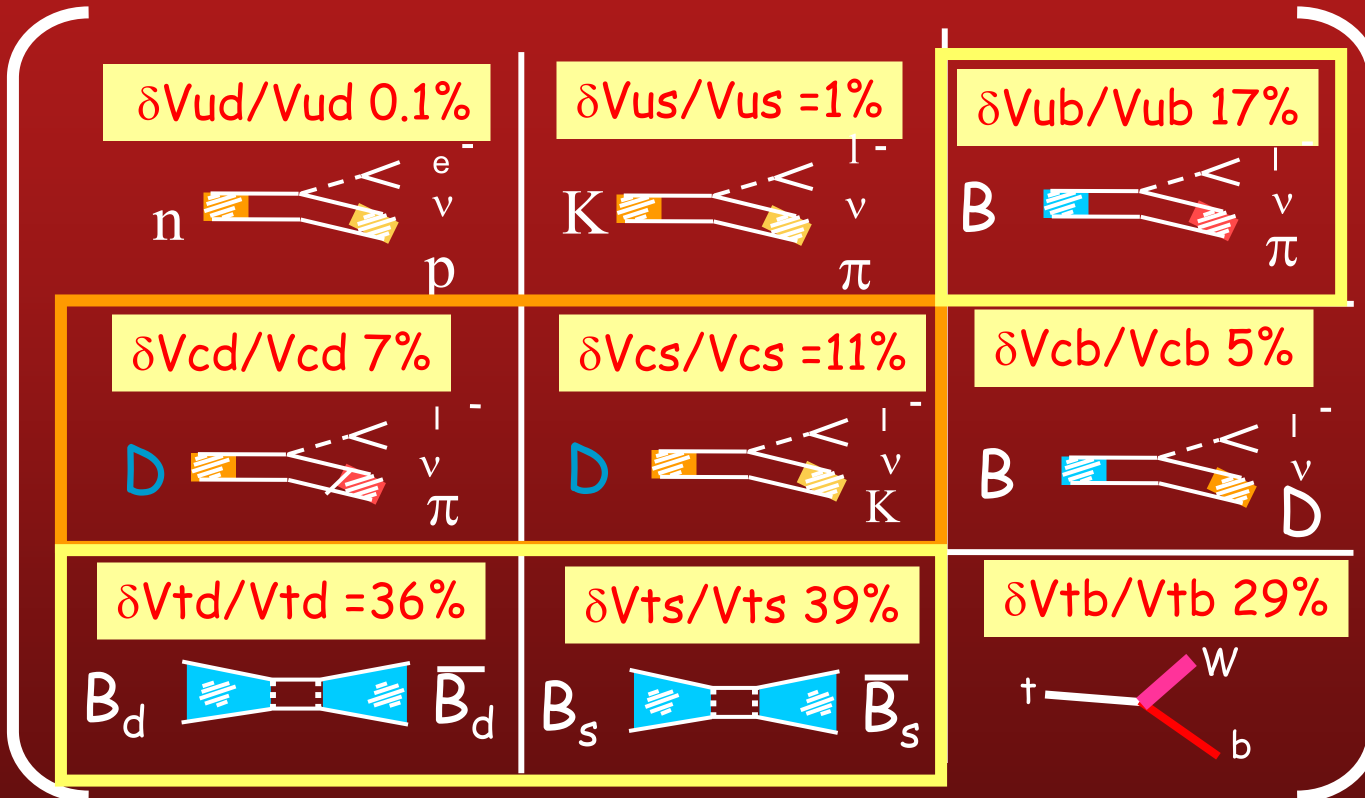
$$\frac{\sigma(|V_{td}|)}{|V_{td}|} = 0.5\frac{\sigma(\Delta M_d)}{\Delta M_d} \oplus \frac{\sigma(f_B\sqrt{B_{B_d}})}{f_B\sqrt{B_{B_d}}}$$

1.2% ~15% (LQCD)

- Lattice QCD predicts decay constants f_D & f_B
- If precise measurements of f_D and f_{Ds} exist, then our confidence in the non-perturbative QCD calculations needed to make constraints on the UT is increased.
- CLEO-c can help here by measuring $f_{D(s)}$ from $D_{(s)} \to \mu\nu$
  - direct measurement of $B_{(s)} \to \mu\nu$ is much harder!

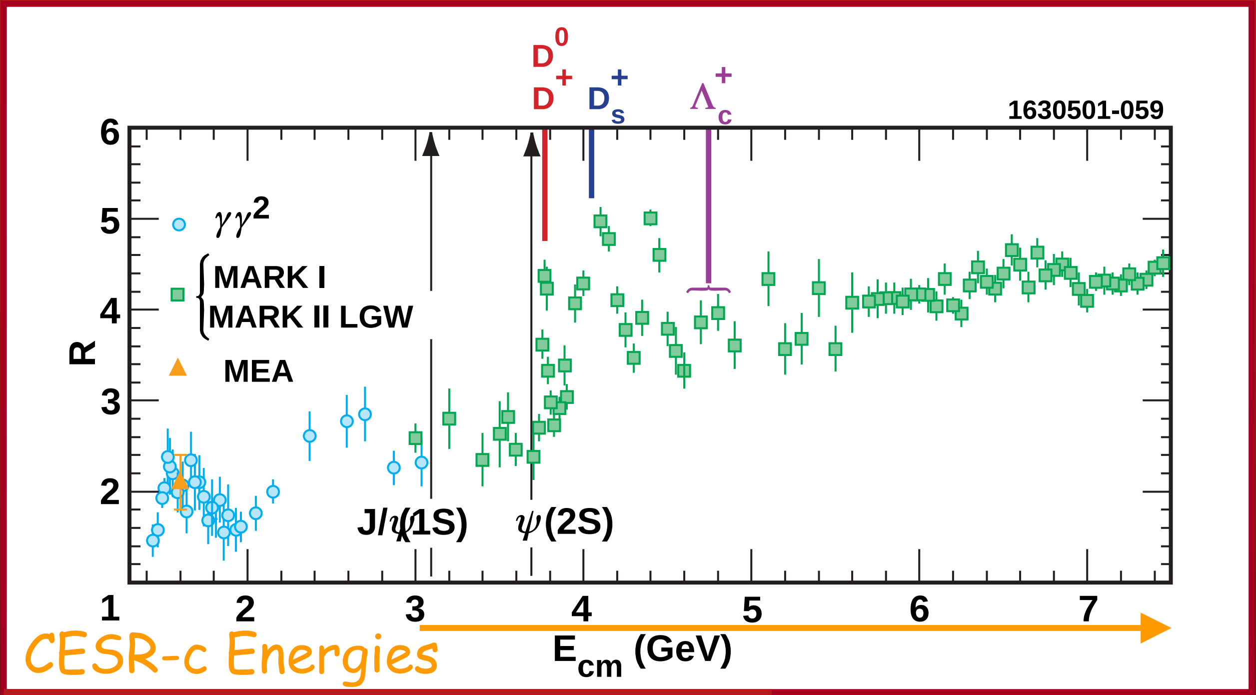
Status of CKM Matrix

Current V_{CKM}
From direct
Measurements
-no unitarity
imposed

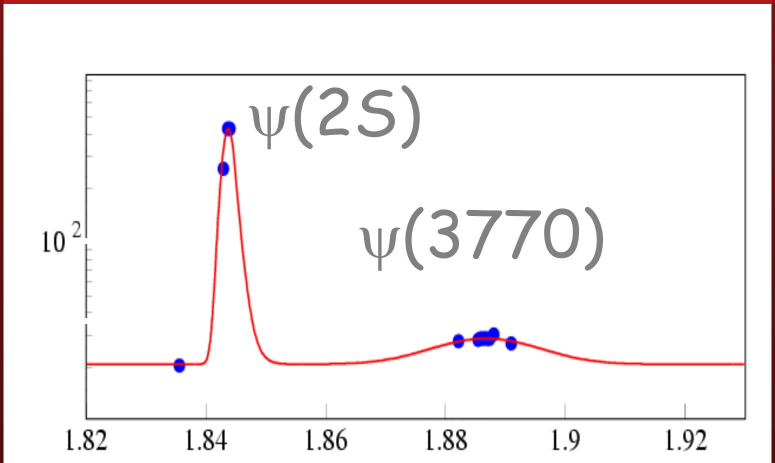


CLEO-c will redefine 2nd generation elements
And enable improvements in 3rd generation

Charm Threshold Region



- D^+D^-, $D^0\overline{D}^0$ at $\psi(3770)$
- $D_s^+D_s^-$ at $\sqrt{s}$=4.14 GeV
- Will also run on ψ' – many QCD topics, charmonium spectroscopy



$D\overline{D}$ cross section at $\psi(3770)$ ~6 nb

$D_sD_s^*$ cross section at 4170 ~1 nb

CLEO-c Run Plan

Region I: $\psi(3770)$ – 1000 pb^{-1} ($\psi(3770) \rightarrow D\overline{D}$)

10 million $D\overline{D}$ events, 2 million *tagged* D decays
(100 times MARK III)

Region II: $\sqrt{s}$=4170 MeV – 500 pb^{-1}

0.5 million $D_s\overline{D}_s^*$ events, 0.1 million *tagged* D_s decays
(150 times MARK III, 40 times BES)

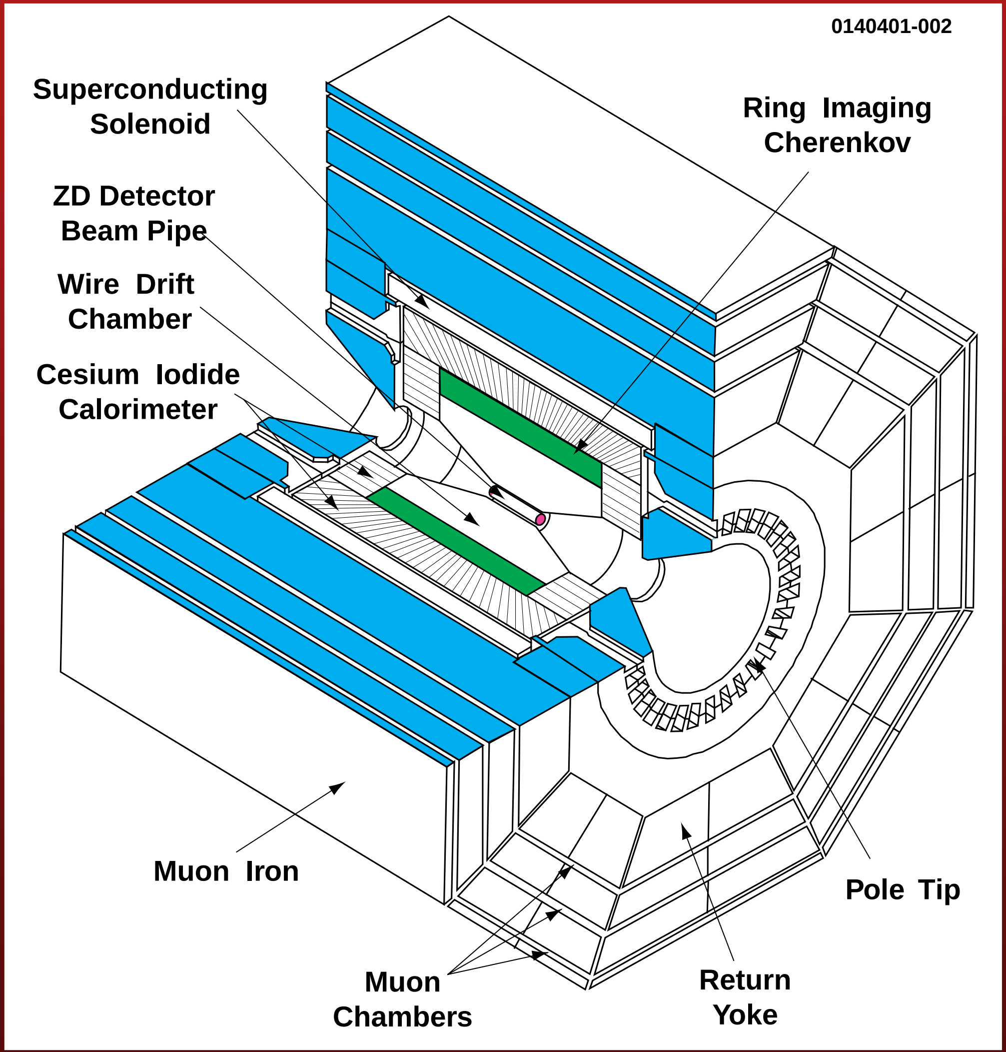
Region III: $\psi'(3686)$

30 million ψ' decays
(10 times current CLEO-c sample ~ BES)

So far:
Oct'03—Mar'04 60 pb^{-1} $\psi(3770)$, 3 Million ψ'
Sep'04—Apr'05 220 pb^{-1} $\psi(3770)$
Sep'05—Jan'06 60 pb^{-1} D_s scan; 60 pb^{-1} at 4170

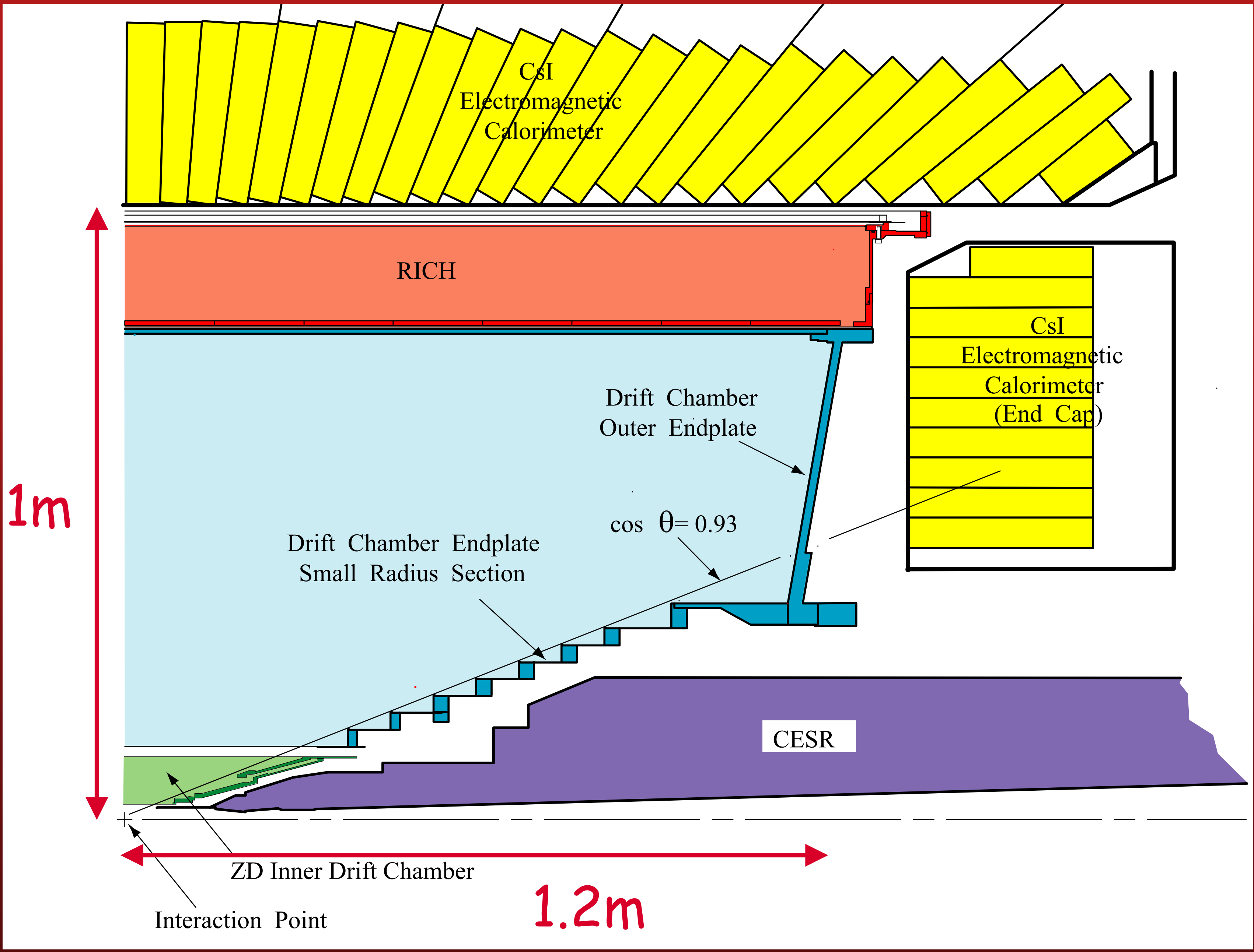
Expecting:
Mar'06—Mar'08
5 more runs
$\approx$250 pb^{-1} each

CLEO-c Detector

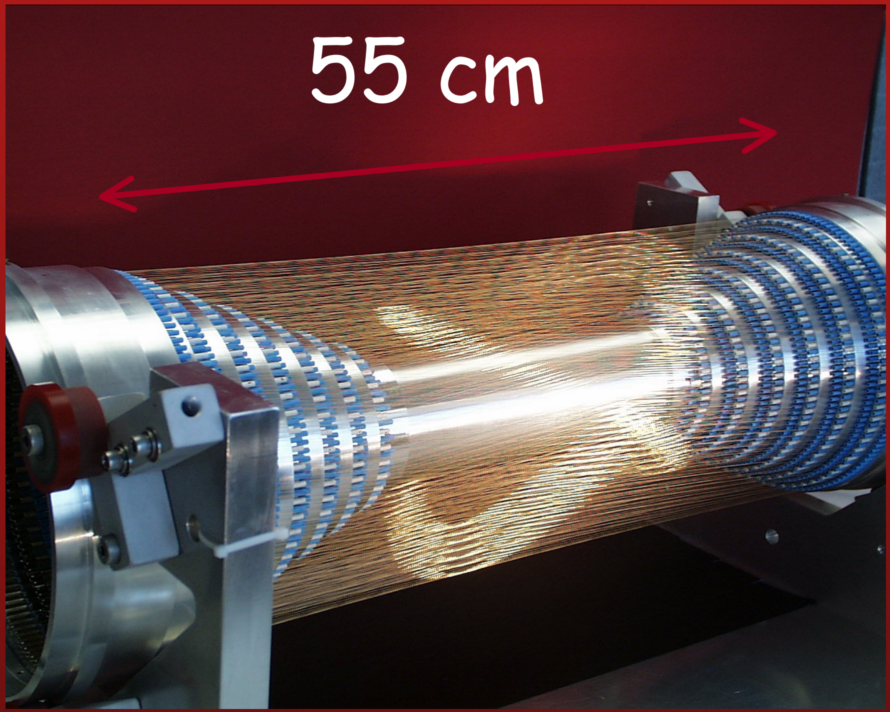


State of Art Detector:

- Drift Chamber Tracking
  - $\sigma_p/p = 0.6\%$ @ 1 GeV/c
- Super Cond. Solenoid
- RICH Particle ID
- CsI EM Calorimetry
  - $\sigma_E/E = 2.2\%$ @ 1 GeV
  - $\sigma_E/E = 5\%$ @ 100 MeV
- 93% of solid angle
- Only small changes from CLEO III
  - B field 1.5 → 1 T
  - Silicon → drift chamber


CsI
Electromagnetic
Calorimeter
RICH
CsI
Electromagnetic
Calorimeter
(End Cap)
Drift Chamber
Outer Endplate
cos θ= 0.93
Drift Chamber Endplate
Small Radius Section
1m
CESR
ZD Inner Drift Chamber
Interaction Point
1.2m

New Inner Detector



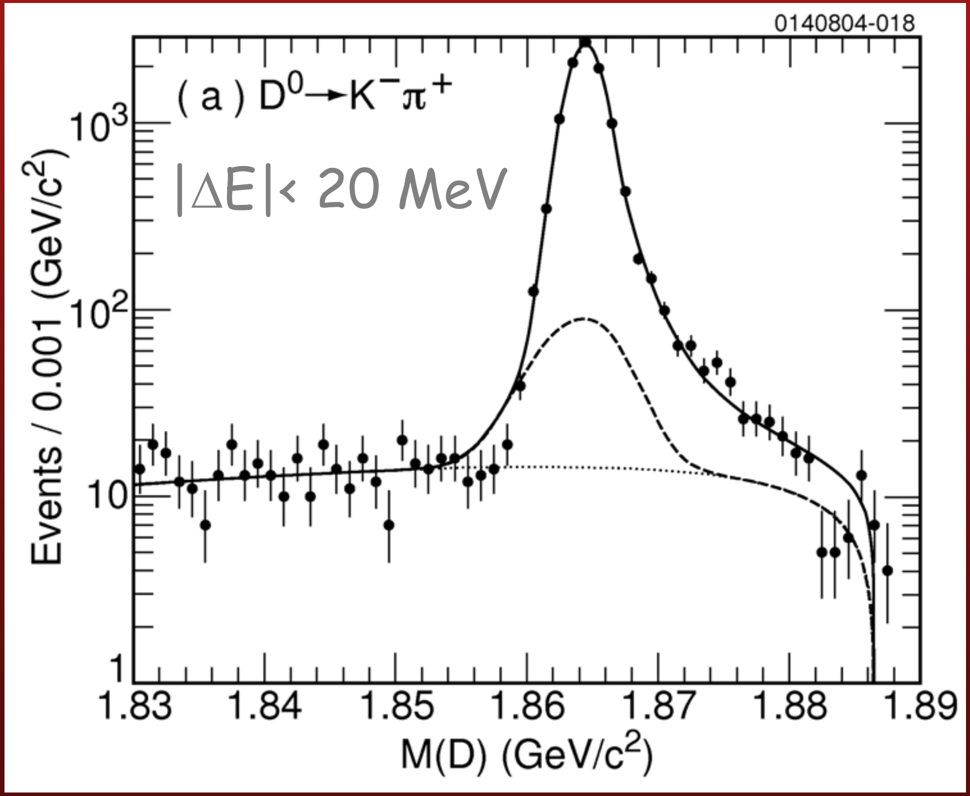
- Replaced Silicon Vertex Detector in May 2003
- 6 stereo layers:
  - r=5.3 cm – 10.5 cm
  - 12-15° stereo angle
  - $|\cos\theta| < 0.93$
- 300, 10 mm cells
- 100 μm hit resolution
- 1% X_0 inner Al tube .8mm
- Helium-Propane (60:40)
- 20 μm Au-W sense wires
- 110 μm Au-Al field wires
- Outer Al-Mylar skin

- Continuous tracking volume
- Low mass (σ_p is MS limited)
- Nothing to vertex at charm threshold!

Hadronic D Decays

$\psi(3770) \rightarrow D\,\bar{D}$

- At threshold no additional particles are produced
- Fully reconstruct one D in the event, e.g. $D^0 \rightarrow K^- \pi^+$



Energy and Momentum Conservation:

$$E_D = E_K + E_\pi$$

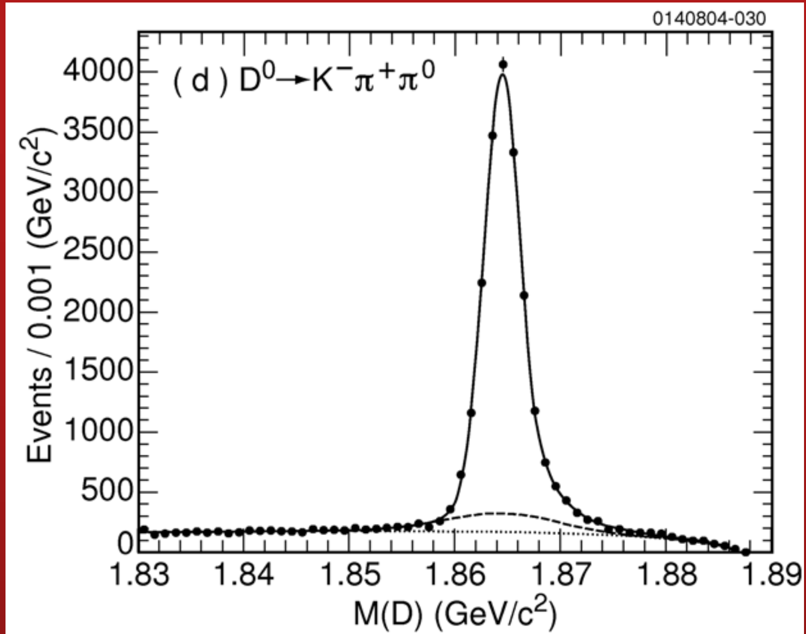
$$\vec{p}_D = \vec{p}_K + \vec{p}_\pi$$

resolution:

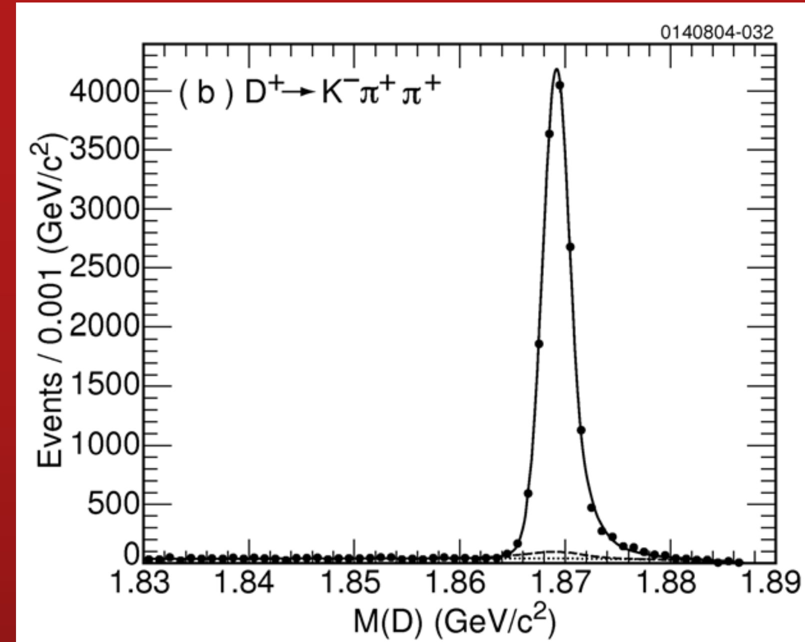
$$\Delta E = E_{\text{beam}} - E_D$$ 7-10 MeV

$$M(D) = \sqrt{E_{\text{beam}}^2 - |p_D|^2}$$ 1.3 MeV

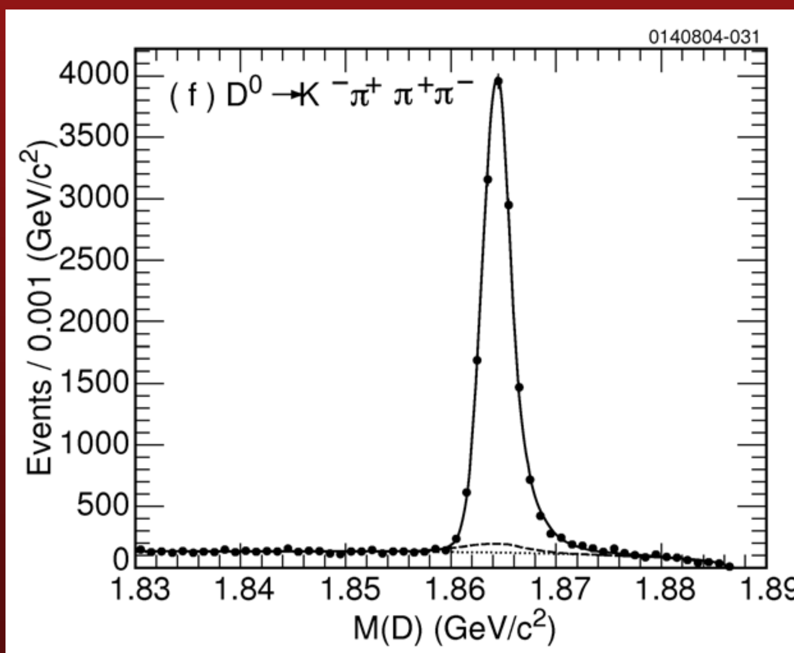
$D^0 \rightarrow K^- \pi^+ \pi^0$



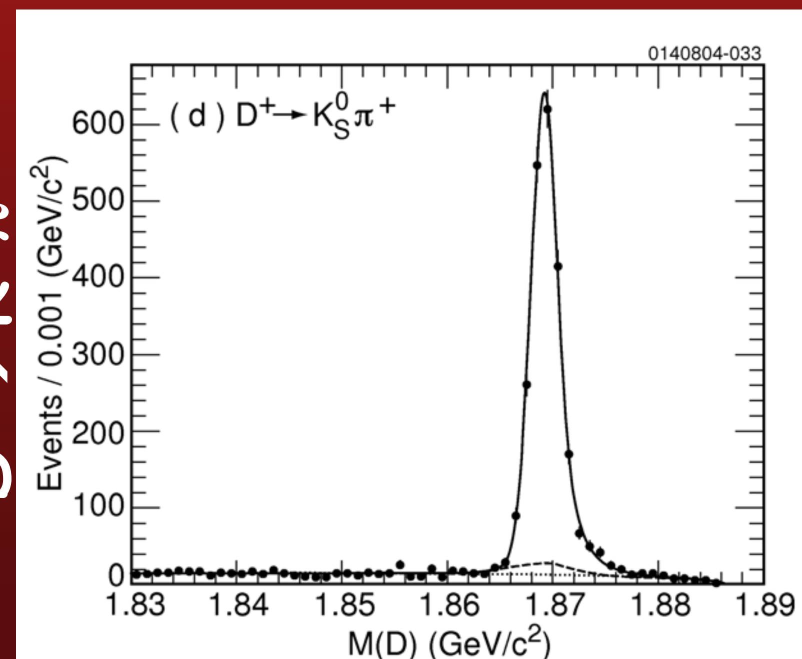
$D^+ \rightarrow K^- \pi^+ \pi^+$



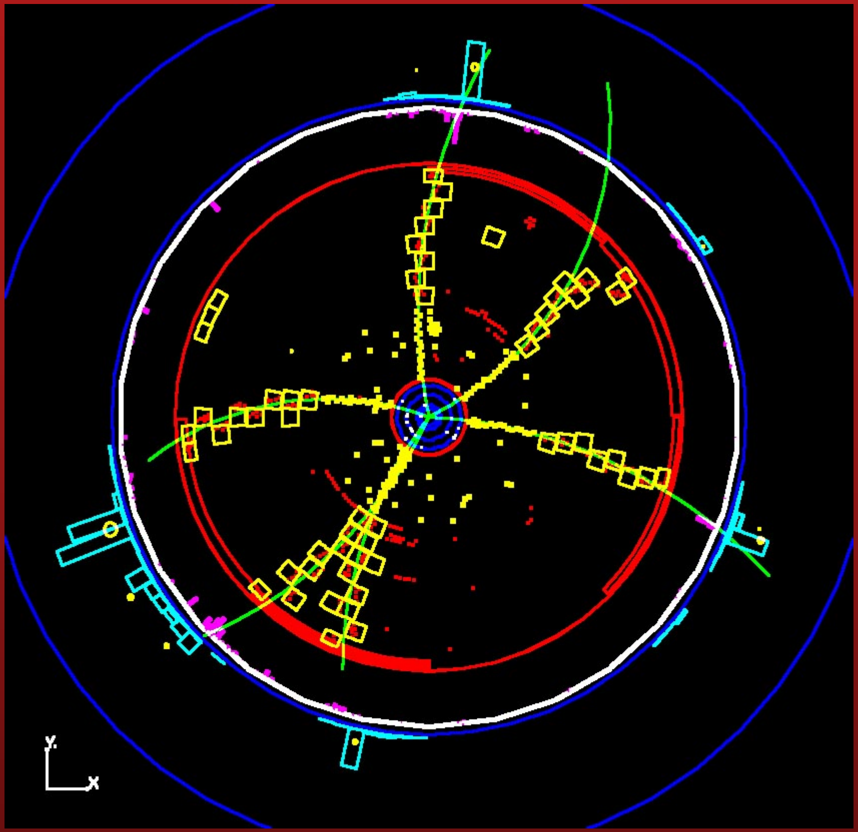
$D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$

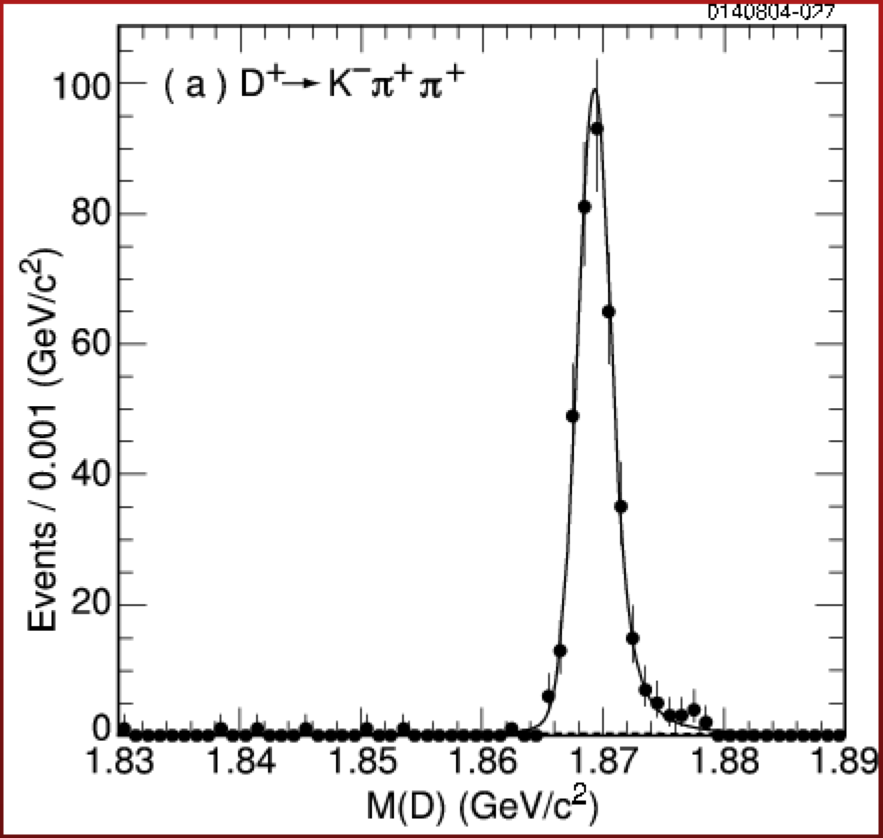


$D^+ \rightarrow \overline{K}^0 \pi^+$



Double Tag Events

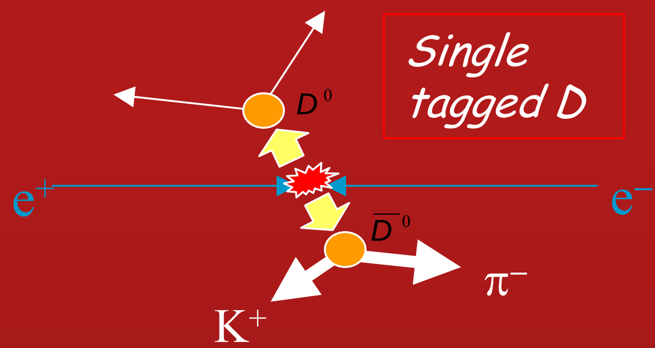




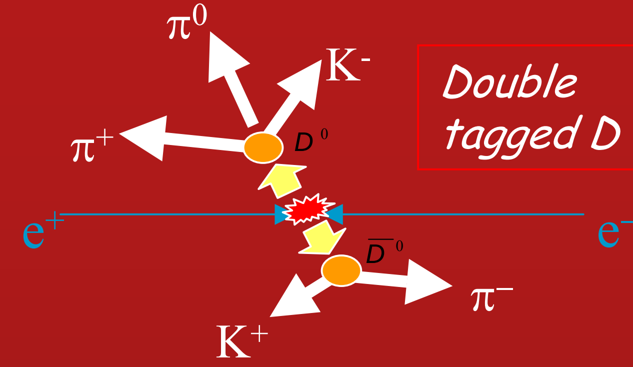
$D^+ \to K^-\pi^+\pi^+$ & $D^- \to K^+\pi^-\pi^-$

- Tagging effectively makes a single D beam
- Can tag ≈22% of D's produced!

$$\mathcal{B}(D \to X) = \frac{N(D \to X)}{\text{Efficiency} \times N_{\text{tags}}}$$



Single tagged D



Double tagged D

$$N_i = N_{D\bar{D}} B_i \varepsilon_i$$

$$N_{ij} = N_{D\bar{D}} B_i B_j \varepsilon_{ij}$$

$$B_i = \frac{N_{ij}}{N_j} \frac{\varepsilon_j}{\varepsilon_{ij}}$$

$$N_{D\bar{D}} = \frac{N_i N_j}{N_{ij}} \frac{\varepsilon_{ij}}{\varepsilon_i \varepsilon_j}$$

$$\varepsilon_{ij} \approx \varepsilon_i \varepsilon_j$$

ε_i=16—65%

D Decay Mode	Fitted $\mathcal{B}$ (%)	PDG $\mathcal{B}$ (%)	$\Delta_{\rm FSR}$
$K^-\pi^+$	$3.91 \pm 0.08 \pm 0.09$	3.80 ± 0.09	-2.0%
$K^-\pi^+\pi^0$	$14.9 \pm 0.3 \pm 0.5$	13.0 ± 0.8	-0.8%
$K^-\pi^+\pi^+\pi^-$	$8.3 \pm 0.2 \pm 0.3$	7.46 ± 0.31	-1.7%
$K^-\pi^+\pi^+$	$9.5 \pm 0.2 \pm 0.3$	9.2 ± 0.6	-2.2%
$K^-\pi^+\pi^+\pi^0$	$6.0 \pm 0.2 \pm 0.2$	6.5 ± 1.1	-0.6%
$K^0_S\pi^+$	$1.55 \pm 0.05 \pm 0.06$	1.41 ± 0.10	-1.8%
$K^0_S\pi^+\pi^0$	$7.2 \pm 0.2 \pm 0.4$	4.9 ± 1.5	-0.8%
$K^0_S\pi^+\pi^+\pi^-$	$3.2 \pm 0.1 \pm 0.2$	3.6 ± 0.5	-1.4%
$K^+K^-\pi^+$	$0.97 \pm 0.04 \pm 0.04$	0.89 ± 0.08	-0.9%
$D\bar{D}$ Yield	Fitted Value		$\Delta_{\rm FSR}$
$N_{D^0\bar{D}^0}$	$(2.01 \pm 0.04 \pm 0.02) \times 10^5$		-0.2%
$N_{D^+D^-}$	$(1.56 \pm 0.04 \pm 0.01) \times 10^5$		-0.2%

9 modes, simultaneous χ^2 fit including correlations on N, ε to extract 9 B_i & N(DD)

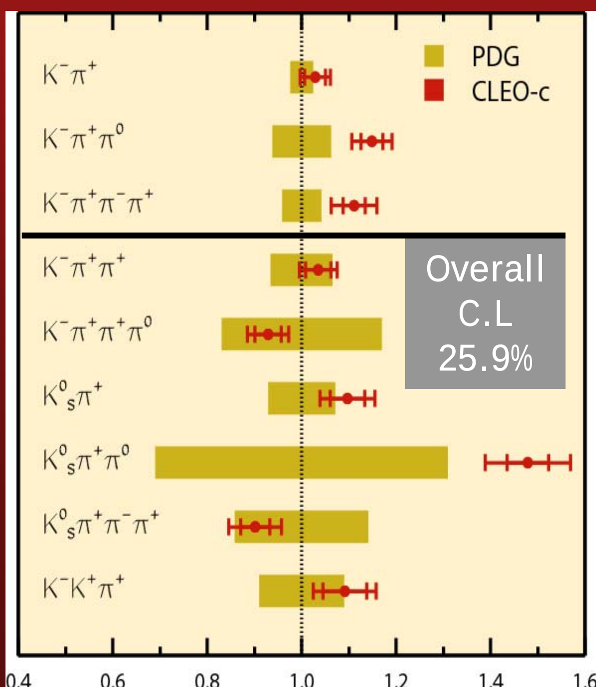
With 55.8 pb^{-1},
$\sigma(D^0\bar{D}^0)$ = (3.60 ± 0.07 ± 0.07) nb
$\sigma(D^+D^-)$ = (2.79 ± 0.07 ± 0.10) nb
$\sigma(D\bar{D})$ = (6.39 ± 0.10 ± 0.17) nb

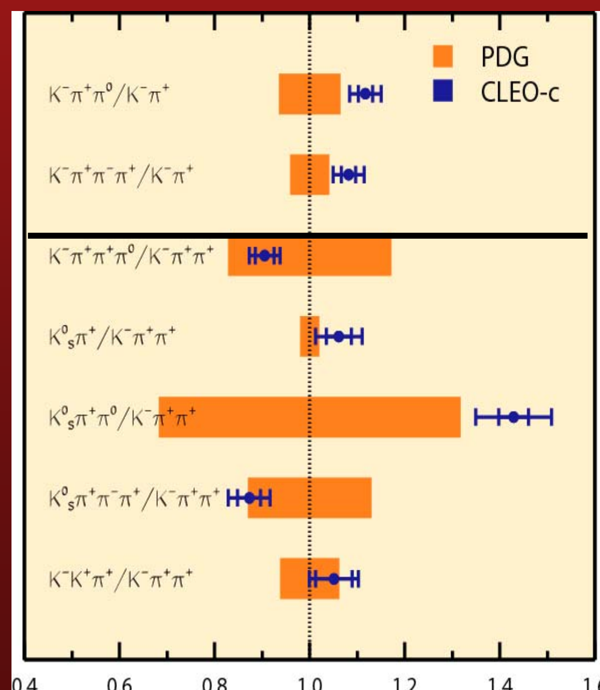
σ(DD) =(5.0 ± 0.5)nb (Mark III)

PRL 95 121801 (2005)

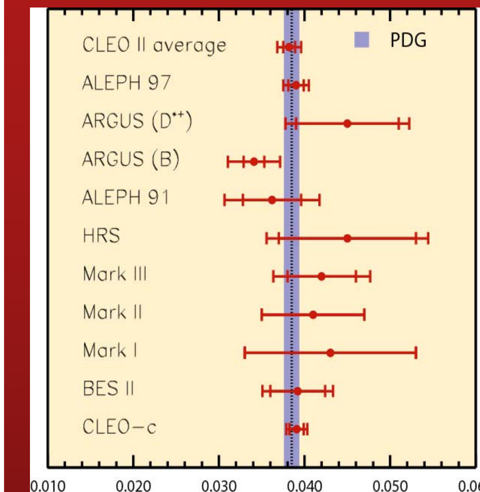
Comparison with PDG 2004

- Measurements and errors normalized to Particle Data Group World Average
- No FSR corrections in PDG measurements
- Our measurements are correlated (statistics and efficiency systematics)

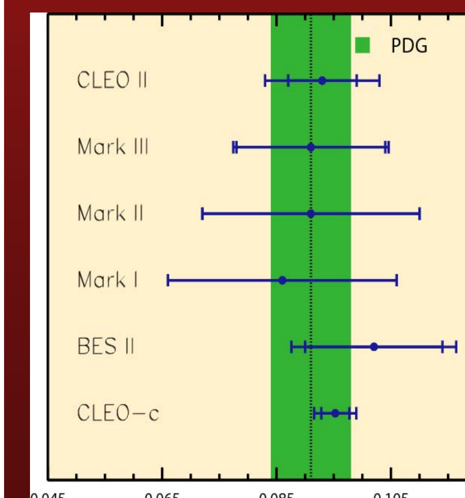




Other *direct* meas.

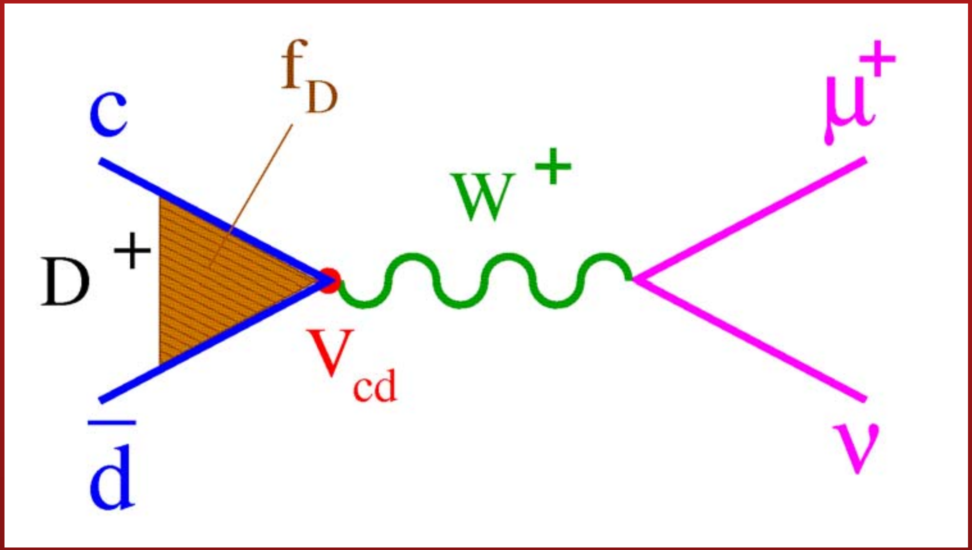


$\mathcal{B}(D^0 \to K^-\pi^+)$



$\mathcal{B}(D^+ \to K^- \pi^+\pi^+)$

Leptonic D Decay



- Measure rate to extract f_D
- Useful to calibrate V_{td} from B^0 mixing
- CLEO goal is 4%
- Pre-2004, only a few events seen

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

$$\mathcal{B}(D \to \mu\nu) = \Gamma \tau_D \approx 5 \times 10^{-4}$$

decay constant

measures overlap of quark wave functions

Analysis Strategy

$e^+ e^- \rightarrow \psi(3770) \rightarrow D^+ D^-$

Signal Side

$\mu^- \nu_\mu$

Tagged Side

fully reconstructed D

- $K^- \pi^+ \pi^+$
- $K^- \pi^+ \pi^+ \pi^0$
- $K_s \pi^+ \pi^0$
- $K_s \pi^+$
- $K_s \pi^+ \pi^- \pi^+$
- $K^- K^+ \pi^+$

$N_{tag} = 158{,}354 \pm 496 \pm 950$

Require event to have only tag & μ candidate:

Veto events with

- extra tracks
- any unmatched shower E>250 MeV
- $\mathcal{B}(D^+ \rightarrow \pi^+ \pi^0) = 0.13\%$

(Missing Mass)^2

$$\vec{p}_D = \vec{p}_\mu + \vec{p}_\nu = -\vec{p}_{D_{tag}}$$
$$E_D = E_\mu + E_\nu = E_{beam}$$

$$MM^2 \equiv E_\nu^2 - p_\nu^2$$
$$MM^2 = (E_{beam} - E_\mu)^2 - (-\vec{p}_{D_{tag}} - \vec{p}_\mu)^2$$

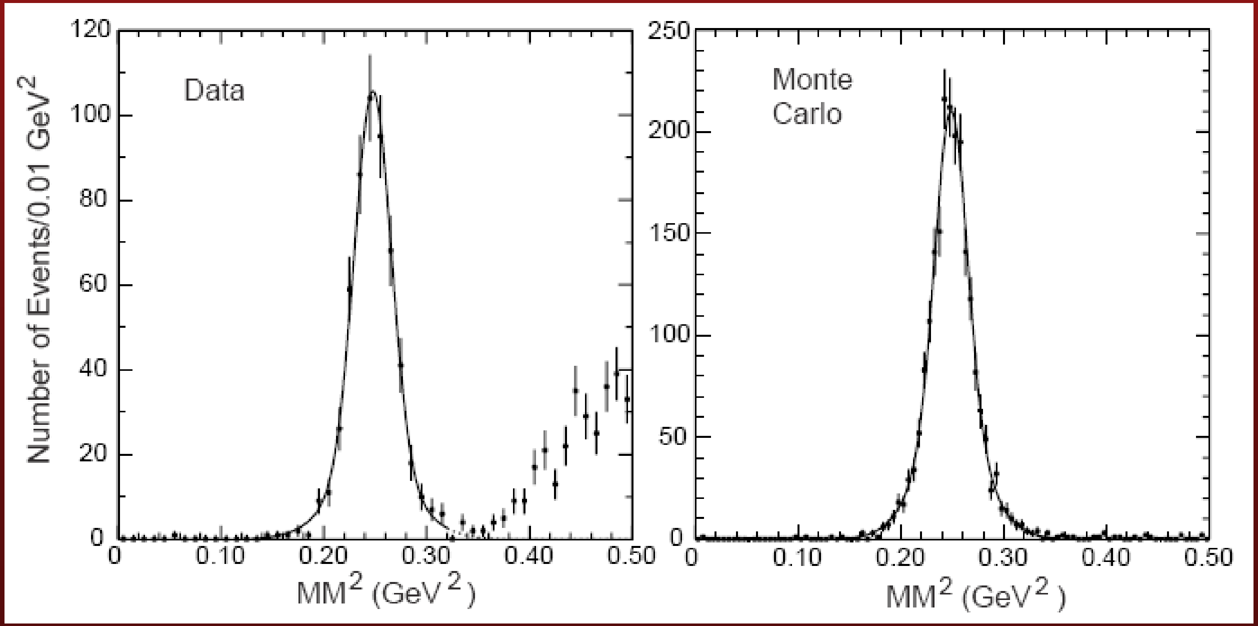
Signal will peak at $M_\nu^2=0$

Calibration with $D^- \rightarrow K_s \pi^-$

$\sigma = 0.0223 \pm 0.0009$ GeV^2

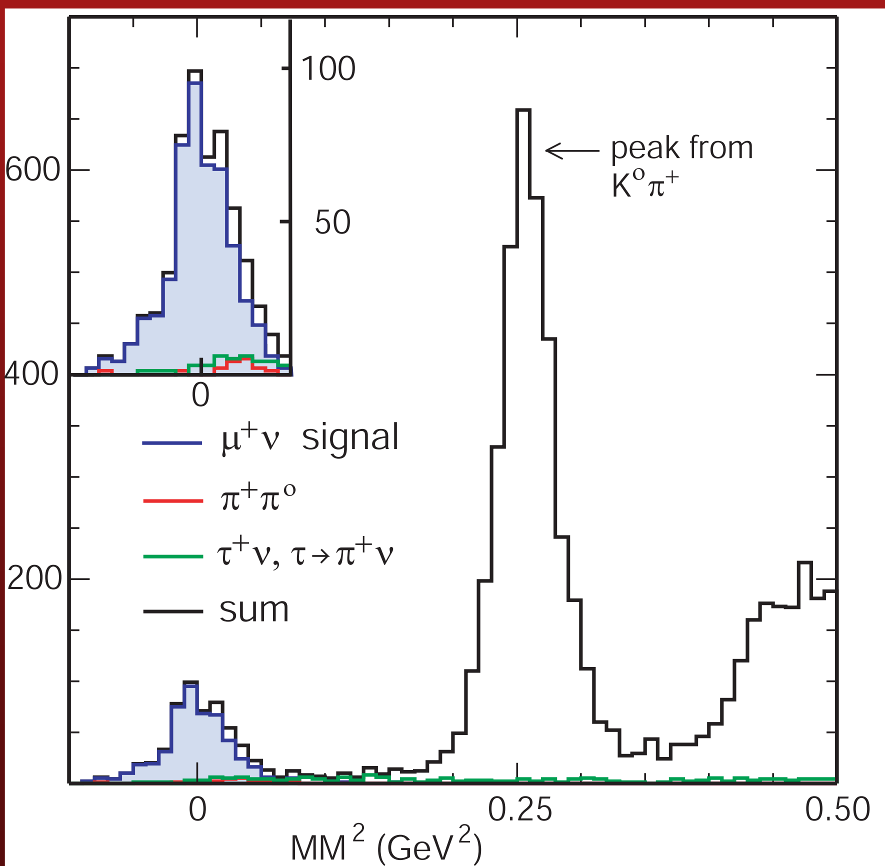
Use tagged $D^- \rightarrow K_s \pi^-$ sample to check data and MC consistency

Here we ignore the K_S to compute MM^2

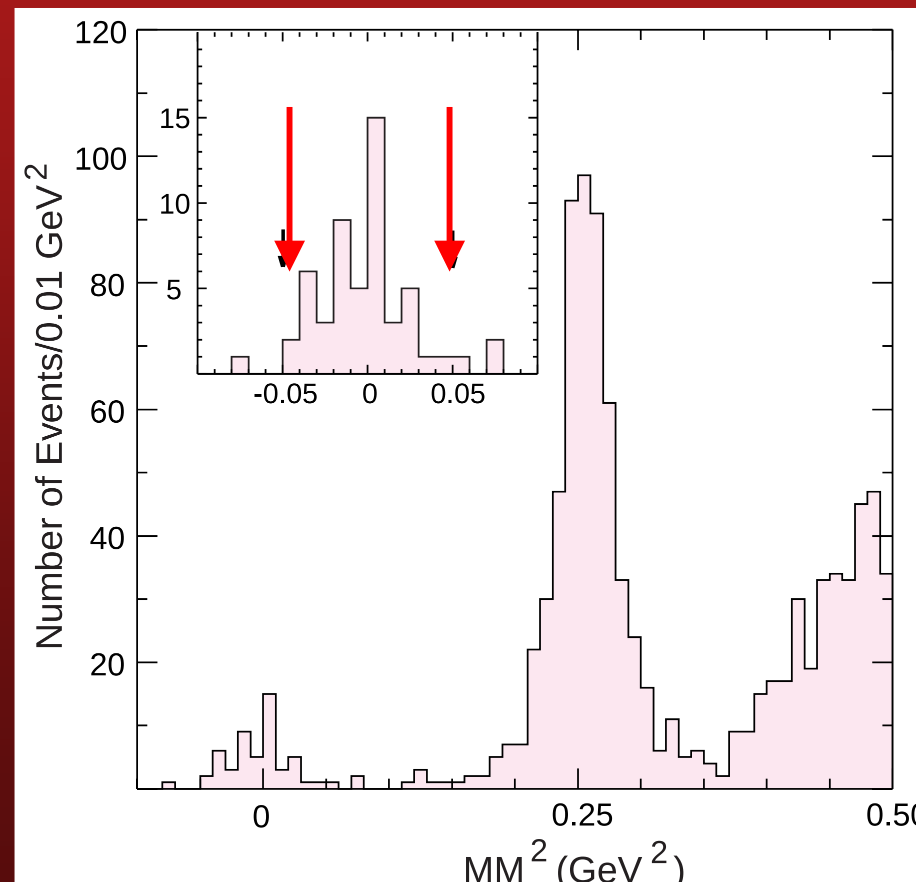


MM^2 Distribution

Monte Carlo Simulation of 1700 pb^{-1}, 6 x data



Data: 50 events in the signal region in 281 pb^{-1}



Measuring f_{D+}

Backgrounds		
Mode	$\mathcal{B}$(%)	# Events
$\pi^+\pi^0$	0.13±0.02	1.40±0.18±0.22
$K^0\pi^+$	2.77±0.18	0.33±0.19±0.02
$\tau^+\nu$ ($\tau\rightarrow\pi^+\nu$)	2.65*$\mathcal{B}(D^+\rightarrow\mu^+\nu)$	1.08±0.15±0.16
Other D^+, D^o		<0.4, <0.4 @ 90% c.l.
Continuum		<1.2 @ 90% c.l.
Total Background		$2.81\pm0.30^{+0.84}_{-0.27}$

$$\mathcal{B}\left(\mathcal{D}^+ \rightarrow \mu^+\nu\right) = \frac{\mathcal{N}_{sig}}{\varepsilon * \mathcal{N}_{tag}}$$

$\mathcal{B} = (4.40\pm0.66\ ^{+0.09}_{-0.12})\times10^{-4}$

$f_D = (222.6\pm16.7\ ^{+2.8}_{-3.4})$ MeV

Efficiency from data: 67.7%

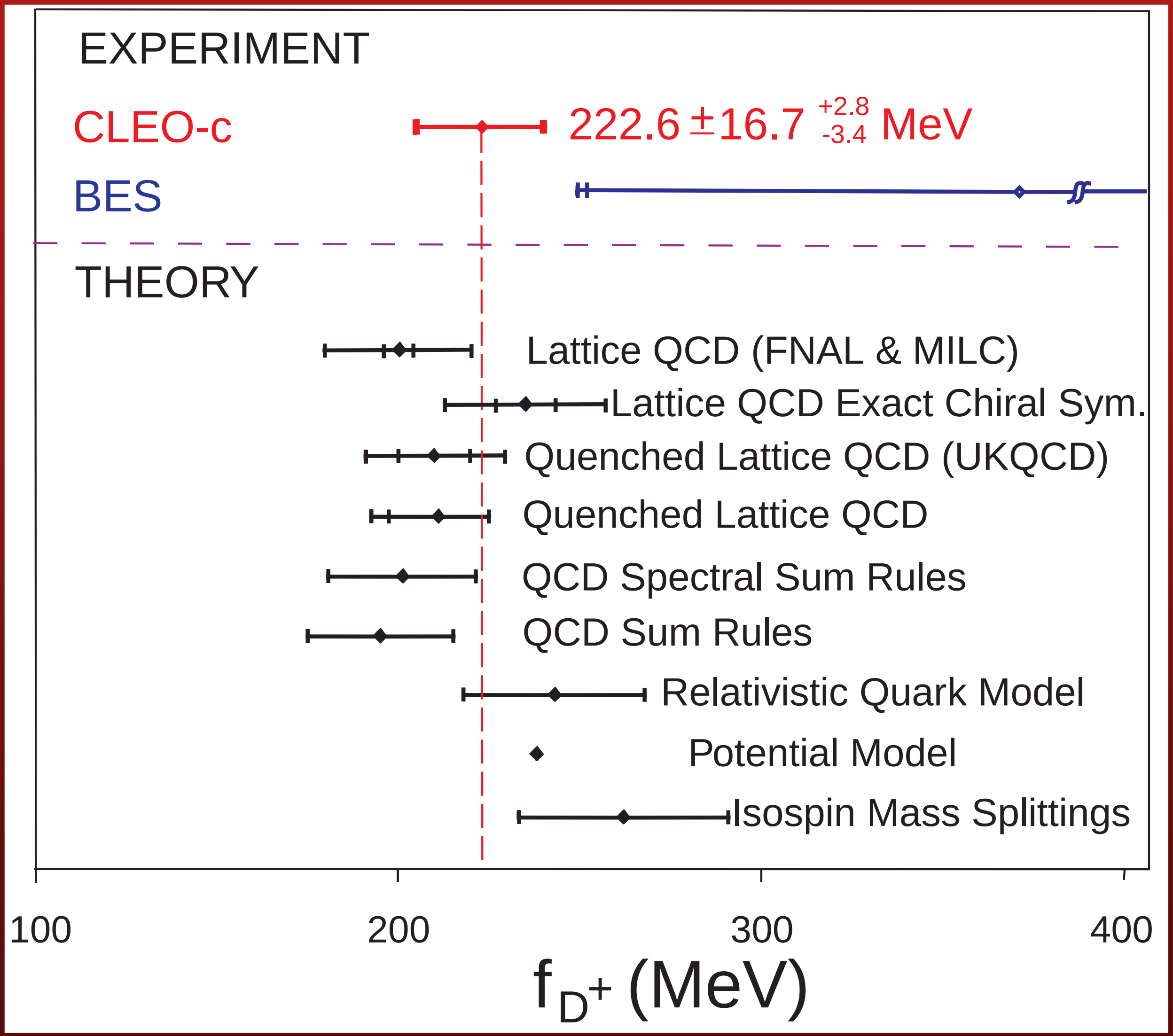
Fractional systematic errors on B:

a) μ detection ε (2%)

b) background (1.7%)

c) tagged sample size (0.6%)

Measurements vs. Predictions

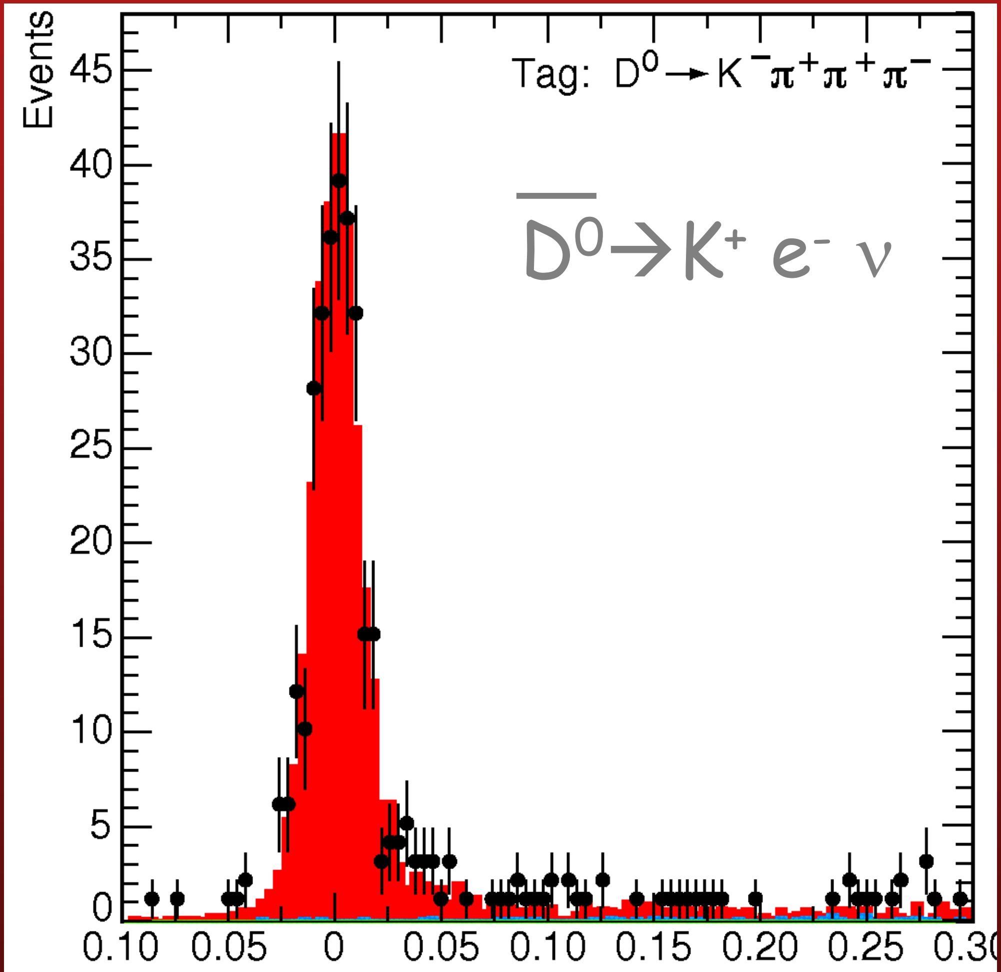


CLEO-c 281 pb^{-1}
PRL 95, 251801 (2005)

Unquenched Lattice QCD
201±3±17 MeV
PRL 95, 122002 (2005)

Both Lattice QCD and experiment will improve

Semileptonic D Decays



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

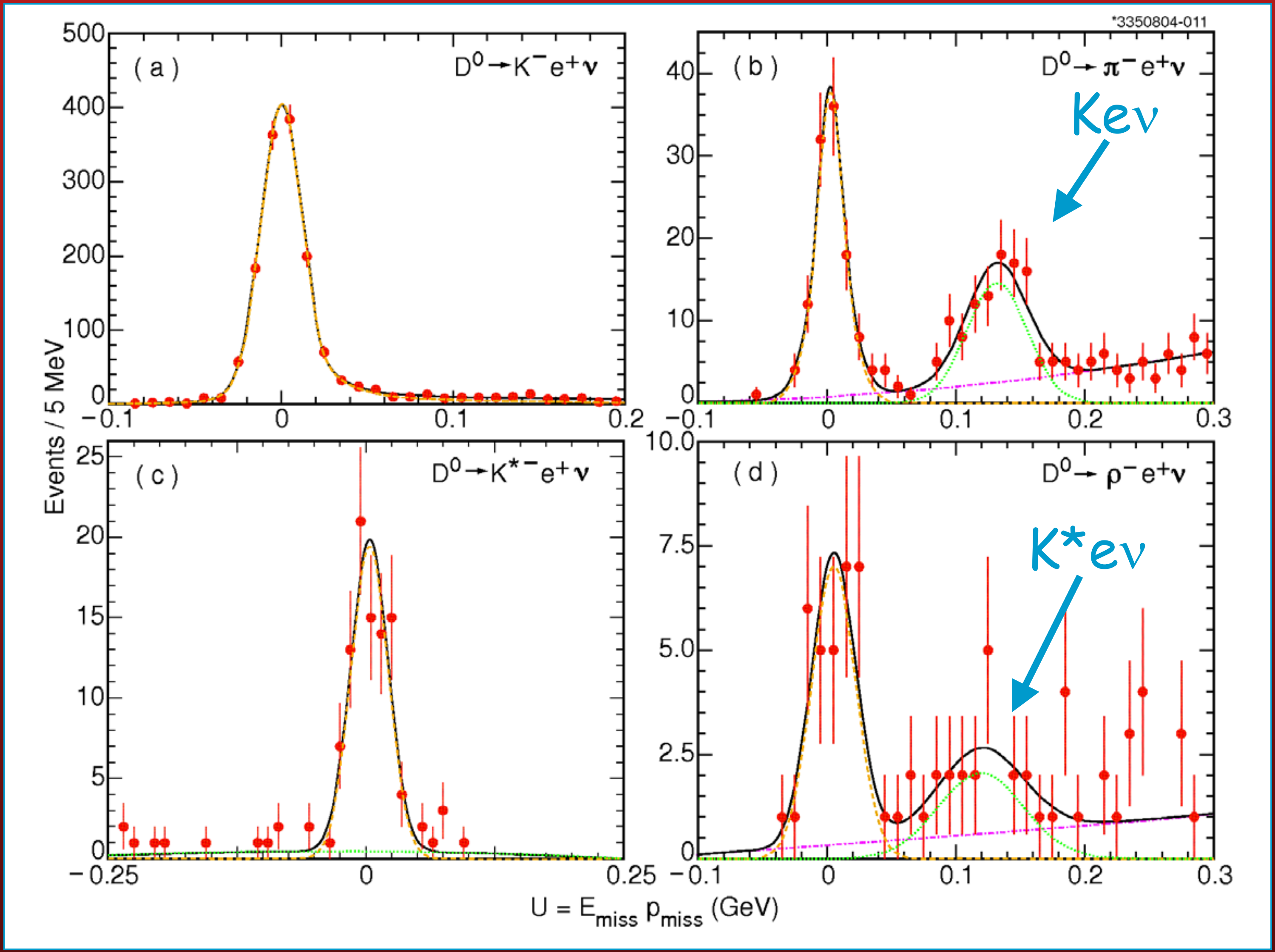
- Again use tagged D^0's
  - N_{tag}=60,000 (57 pb^{-1})
- Look for electron
  - p>200 MeV/c
- And hadron (K, π, K^*, ρ)
- Kinematics:

$$E_{miss} = E_{beam} - E_K - E_e$$

$$\vec{p}_{miss} = -\vec{p}_{D\,tag} - \vec{p}_K - \vec{p}_e$$

$$U \equiv E_{miss} - \left|\vec{p}_{miss}\right|$$

Results from 57 pb^{-1}



Very clean
$\pi^- e^+ \nu$
109±11 evts

First time
$\rho^- e^+ \nu$
seen
30±6 evts

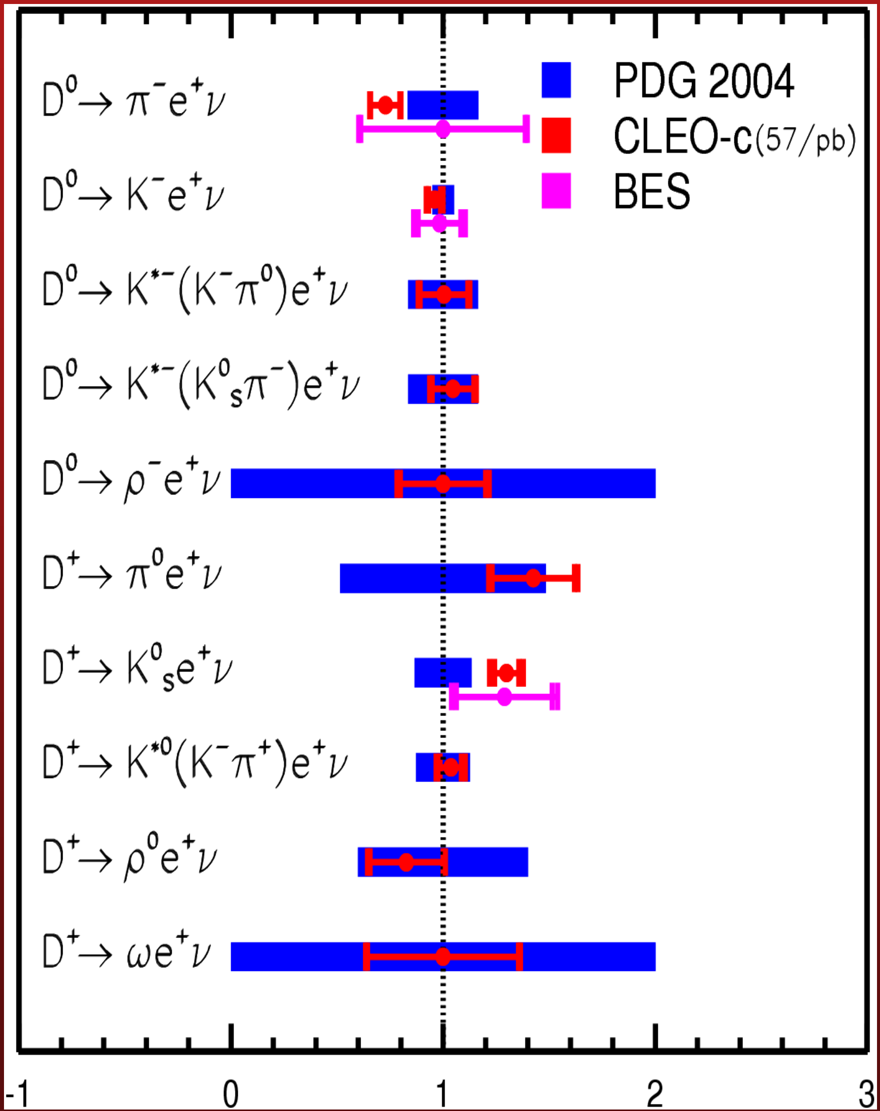
Cabibbo Favored: V_{cs} Cabibbo Suppressed: V_{cd}

Semileptonic Results

PRL 95 181801 (2005) D^+

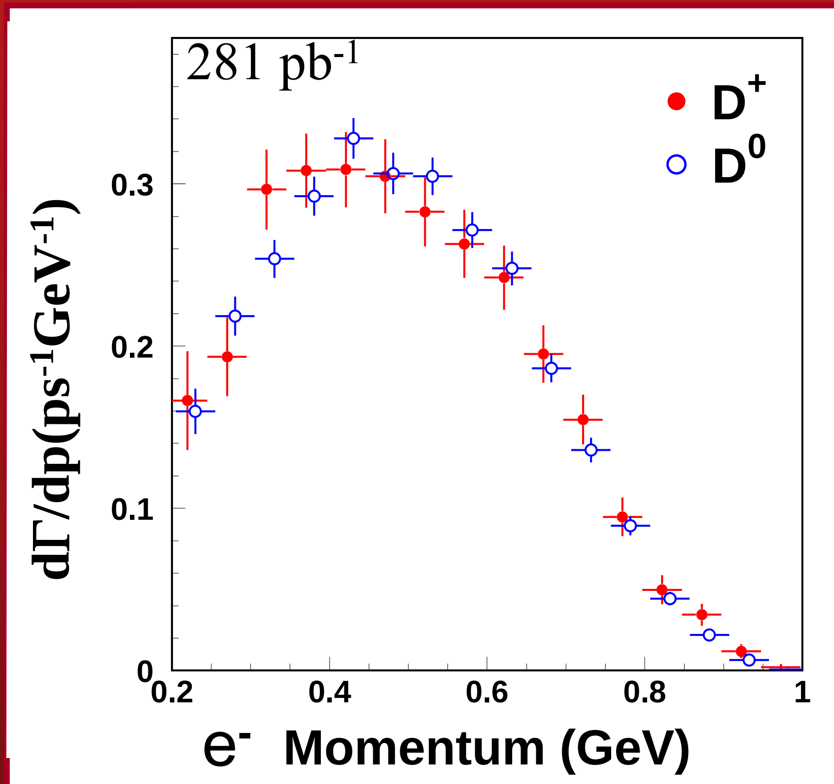
PRL 95 181802 (2005) D^0

- Even with first data set ($57\ pb^{-1}$) making most competitive results
- With additional data will study q^2 dependence to extract form factors
  - terrific resolution 0.01–0.025 GeV^2
  - FF analysis in progress:
    - $K e \nu$
    - $\pi e \nu$
    - $K \pi e \nu$



Inclusive semileptonic D Decays

preliminary



Lab momentum spectrum

(no FSR correction)

Important for B decays:

- charm feeddown
- test of quark-hardon duality

- Tagged sample: only "golden modes" $D^0 \to K^-\pi^+$(47.4k) and $D^+ \to K^-\pi^+\pi^+$(73.7k)
- Measure electrons inclusively
- Correct for fakes and efficiency using data
- Subtract small backgrounds
- Extrapolate below p_e cut (~8%)

  $\mathcal{B}(D^+ \to Xe^+\nu)$=(16.13 ± 0.20 ± 0.30)%

  $\mathcal{B}(D^0 \to Xe^+\nu)$=(6.46 ± 0.17 ± 0.12)%

Sum of exclusive modes nearly saturates inclusive BF:

$\mathcal{B}(D^+ \to Xe^+\nu)$=(15.1 ± 0.5 ± 0.5)%

$\mathcal{B}(D^0 \to Xe^+\nu)$=(6.1 ± 0.2 ± 0.2)%

Isospin test:

$$\frac{\Gamma(D^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.984 \pm 0.028 \pm 0.015$$

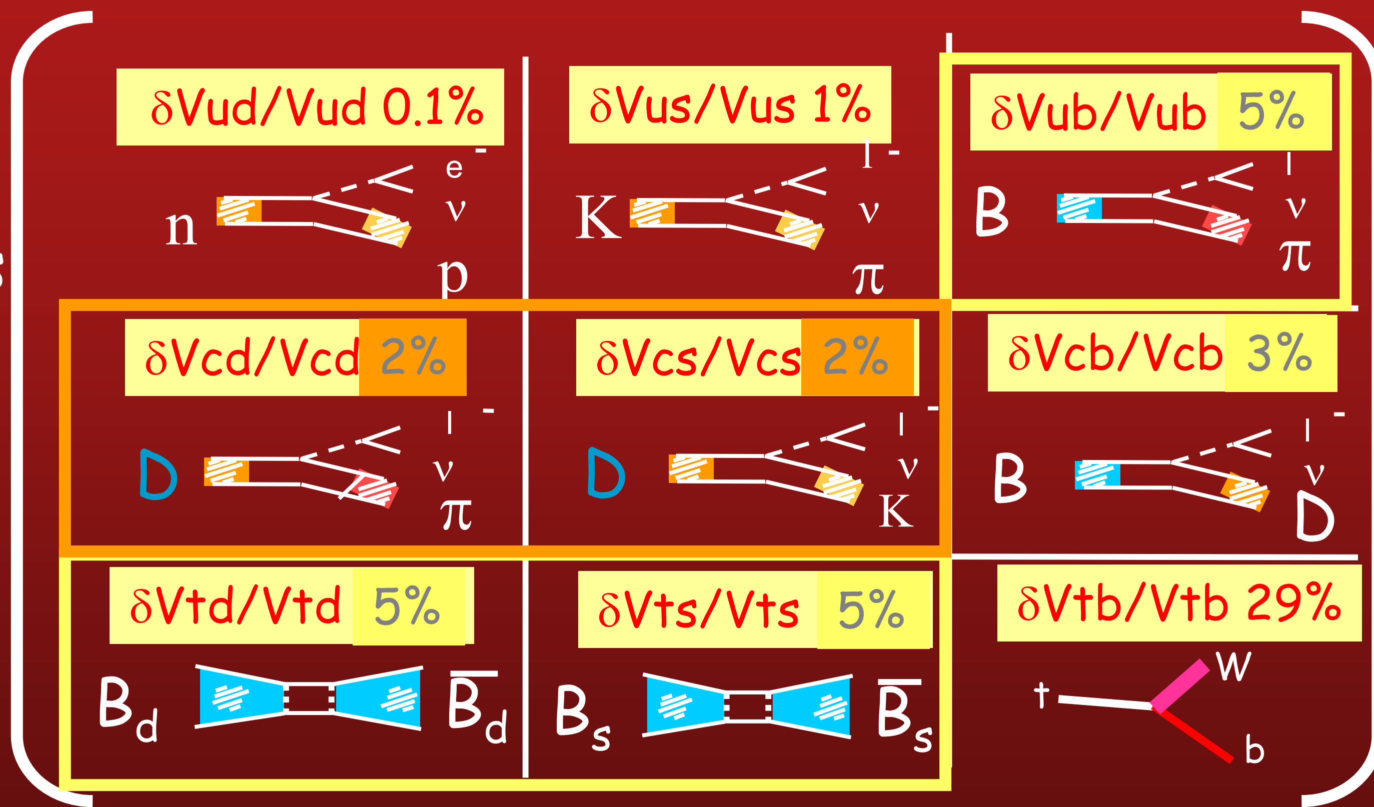
Conclusion/Summary

- Results from first charm threshold running
  - semileptonic & hadronic branching fractions (60 pb^{-1})
  - leptonic decay and f_D to 7.5% (280 pb^{-1})
- Outlook
  - from 281 pb^{-1} 3770 MeV (data in hand)
    - semileptonic branching fractions and form factors $K e \nu$, $\pi e \nu$, $K^* e \nu$, $\rho e \nu$
    - improved hadronic branching fractions
  - from 60 pb^{-1} D_s scan data (3960-4260 MeV) and 60 pb^{-1} at 4170 MeV (data in hand)
    - open charm cross sections: DD, D*D, D*D*, D_sD_s, $D_sD_s^*$, $D_s^*D_s^*$
    - leptonic $D_s \rightarrow \mu \nu$
    - D_s hadronic and semileptonic branching fractions
  - next two years 1250 pb^{-1} additional data
    - 3770: improved BFs, f_D to ~4%, $\pi e \nu$ FF for V_{ub}
    - 4170: D_s branching fractions, f_{Ds}

Potential Impact on V_{CKM}

Current V_{CKM}
From direct
Measurements
-no unitarity
imposed

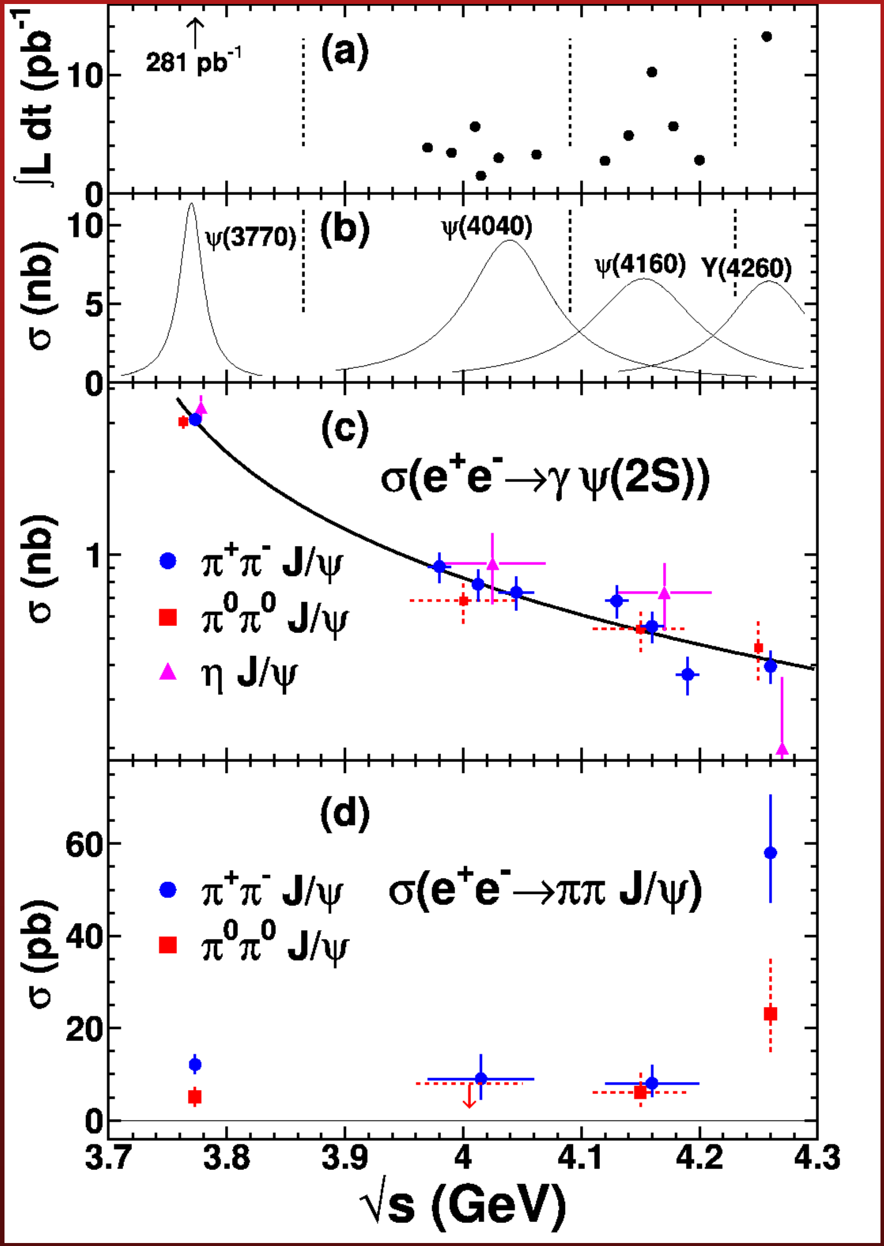
Future V_{CKM}



CLEO-c will redefine 2nd generation elements
And enable improvements in 3rd generation

Investigation of Y(4260)

- Recent scan data from $\sqrt{s}$=3770 – 4260 MeV
- BaBar reported a 1^{--} state Y(4260) → $\pi^+\pi^- J/\psi$ in ISR $e^+e^- \to \gamma$ Y(4260)
  PRL 95 142001 (2005)
- Also in $B \to K \pi^+\pi^- J/\psi$
- Should be directly produced in $e^+e^- \to$ Y(4260)
- What does CLEO see?
- search for 16 modes
  - $\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$
  - $\eta J/\psi$, $\pi^0 J/\psi$, $\eta' J/\psi$, $\eta\eta J/\psi$
  - $\pi^+\pi^-\psi(2S)$, $\eta\psi(2S)$
  - $\gamma\chi_{c1,2}$, $\omega\chi_{c0}$, $\pi^+\pi^-\phi$
  - $\pi^+\pi^-\pi^0 J/\psi$, $\pi^+\pi^-\pi^0\chi_{c1,2}$



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New information on Y(4260)

- Confirmed observation of $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ (11σ)
- Observed $\pi^0\pi^0 J/\psi$ (5.1σ)
- Evidence for $K^+K^- J/\psi$ (3.7σ)
- Limits on other modes

Implications for Y(4260)

Interpretation (cite theories)

- $\pi^0\pi^0 J/\psi$ and $K^+K^- J/\psi$ seen
  $\rightarrow$ not a $\psi\rho^0$ molecule
  $\rightarrow$ baryonium disfavored
- $\psi(4040)$, $\psi(4160)$
- hybrids still alive?
- $D_{(s)}^{(*)} D_{(s)}^{(*)}$ search underway

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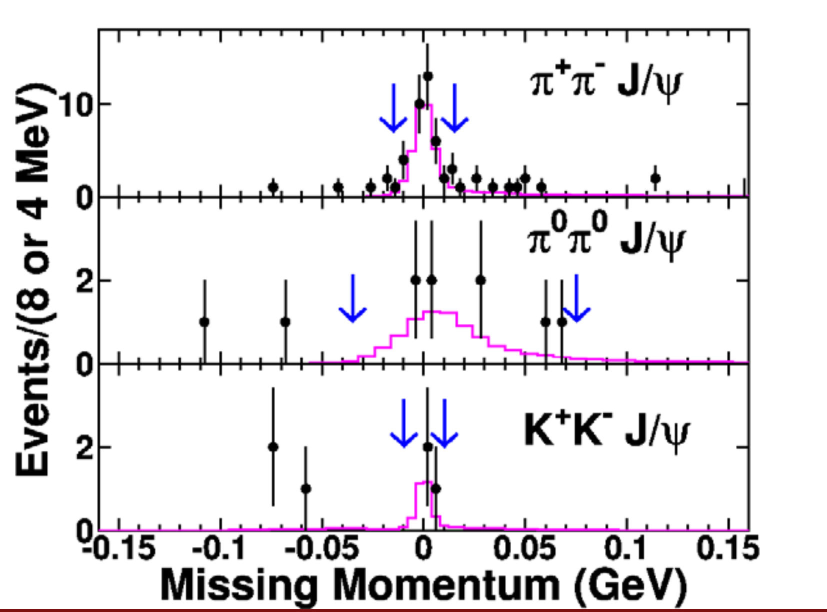

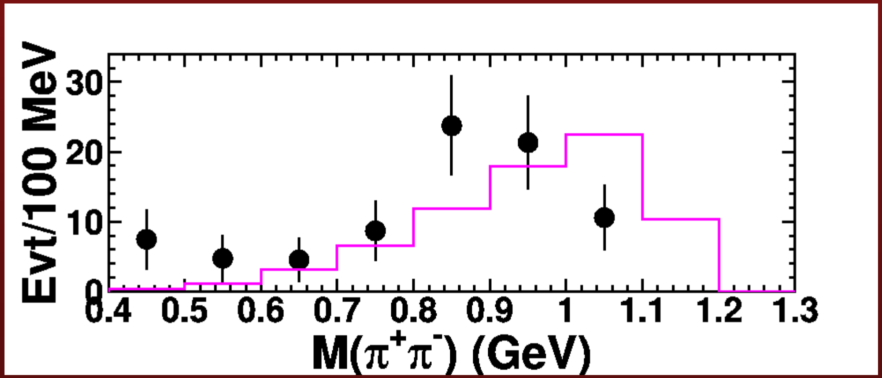

$M(\pi\pi)$ similar to $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$