Pushing Lattice to the Edge: Flavor Physics

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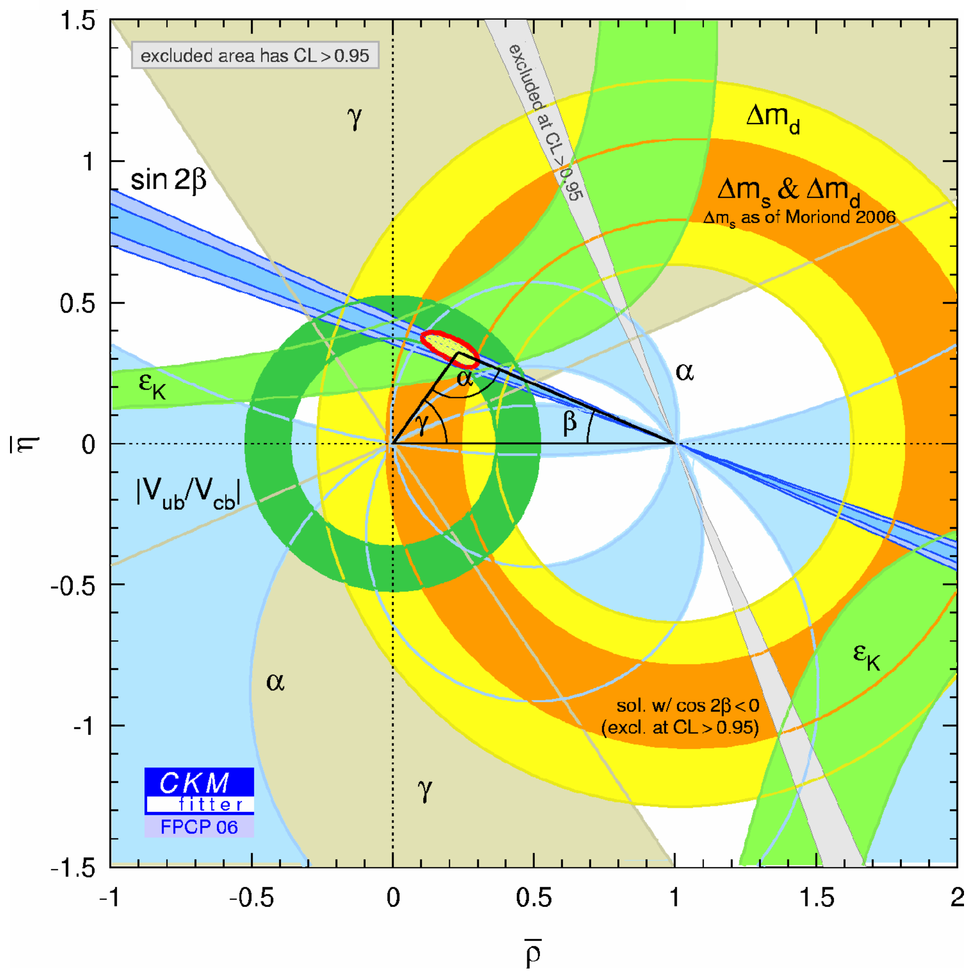
Outline

- (Quick) Introduction
- Leptonic decays
  - $D \rightarrow \mu \upsilon$
  - $B \rightarrow \tau \upsilon$
- Semileptonic Decays
  - $D \rightarrow K l \upsilon$
  - $B \rightarrow X_c l \upsilon$
  - $B \rightarrow X_u l \upsilon$
- Mixing
- Conclusions

CKM and Lattice

- Our knowledge of the unitarity triangle improved dramatically in the next few years!
- Lattice knowledge: necessary ingredient to complete the theoretical picture
- Experiments are becoming more and more accurate, lattice needs to keep the pace!



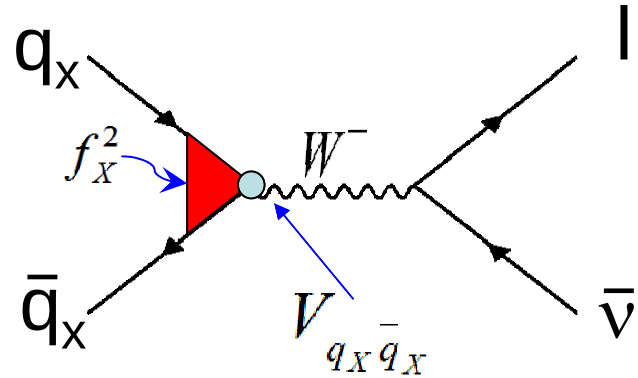
Caveat Emptor

- I will cover mostly b & c related results
- Kaons vs Lattice physics covered by W. Lee on 7/24
- Caveats:
  - This is my personal selection of “hot” topics, more results are available on the market
  - For many of the results I am a(n interested) spectator
  - ICHEP’06 is around the corner: more results to come in <1 Week
  - I took the liberty to emphasize what I know better

Leptonic Decays

Several ways of looking at

$$\frac{B(X \to l\nu)}{\tau_X} = \frac{G_F^2 m_X m_l^2}{8\pi}\left(1 - \frac{m_l^2}{m_X^2}\right)^2 f_X^2 \left|V_{q_X \bar{q}_X}\right|^2$$



- Access to V_{xy}
- Cross-check of f_X prediction

In either case, this is an extremely elegant example of lattice↔experiment interaction

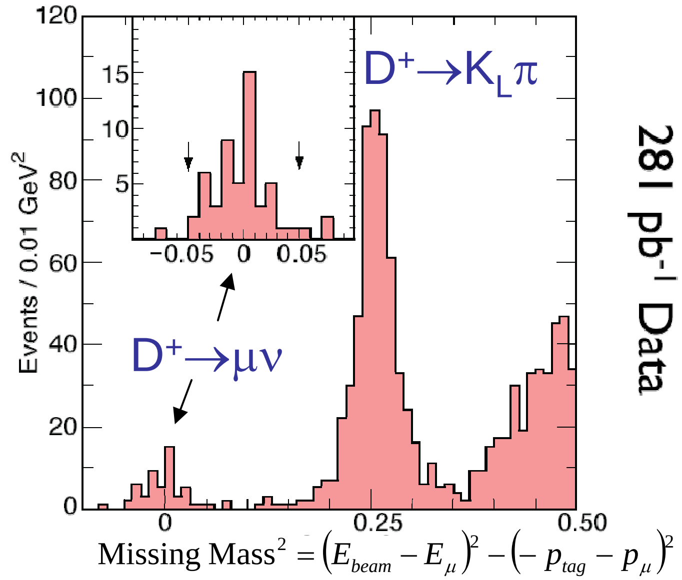
V_{cd}: $D^+ \rightarrow \mu\nu$

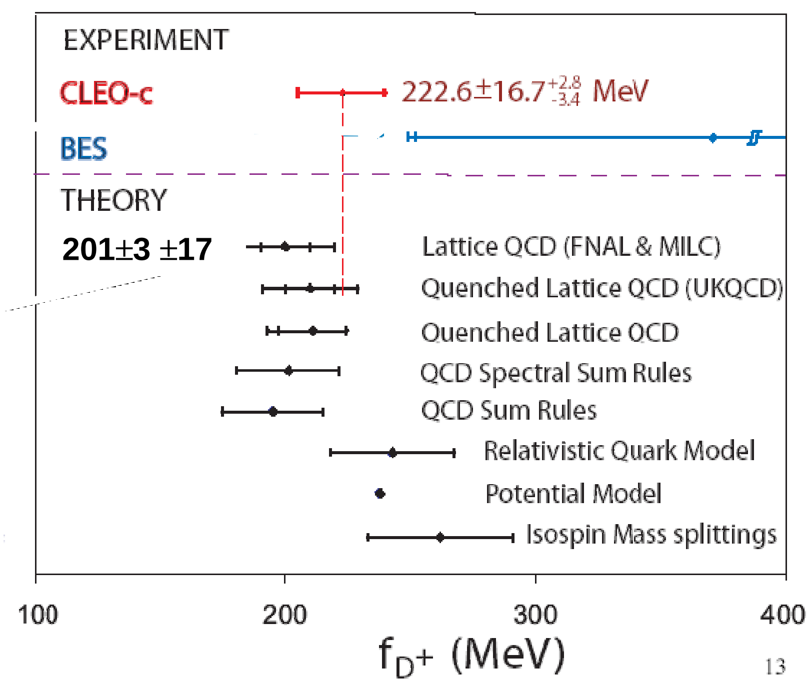
CLEO-c (PRL 95 251801, 2005) measured last year the D^+ mode:

PDG'04 $V_{cd}(=V_{us})$, τ_{D^+}

$$B(D^+ \rightarrow \mu^+ \nu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4}$$

$$f_{D^+} = (222.6 \pm 16.7^{+2.8}_{-0.12})\,MeV$$





- Direct measurement of f_D comparable to LQCD error bars!
- Theoretical predictions at ~10% level
- Recently added: $B(D^+ \rightarrow \tau^+\nu) < 2.1 \times 10^{-3}$ @ 90%CL (PRD73 112005, 2006)
- Expect to measure the Ds decay constant soon… (ICHEP '06?)

V_{cs}: $D^+_s \rightarrow \mu\nu$

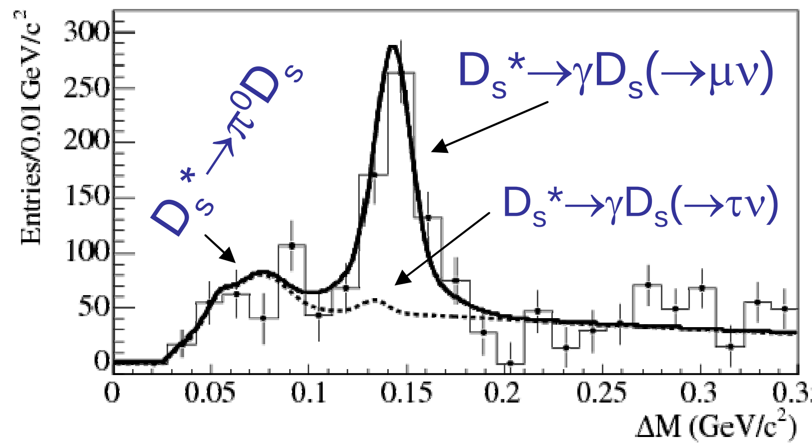
BaBar (see e.g. hep-ex/0605030) nicely provides

PDG'04 $\dfrac{V_{cs}}{B(D_s \rightarrow \phi\pi)}$

$$\frac{\Gamma(D_s \rightarrow \mu\nu)}{\Gamma(D_s \rightarrow \phi\pi)} = 0.143 \pm 0.018 \pm 0.006$$

$$f_{D_s} = (283 \pm 17 \pm 7 \pm 14)\,MeV$$

Stat Sys BR



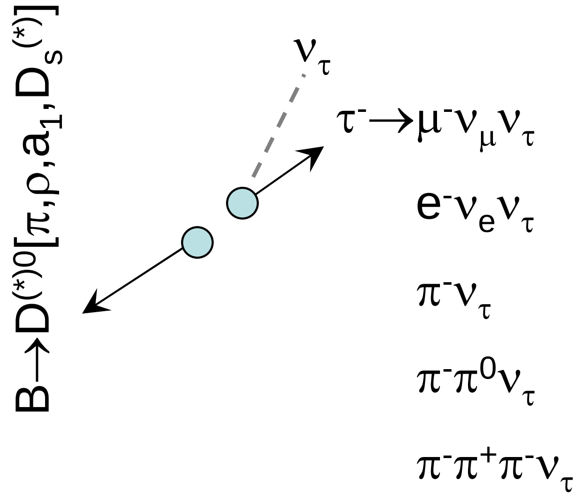
This allows the extraction of f_{Ds}, but also of f_{Ds}/f_{D+}:

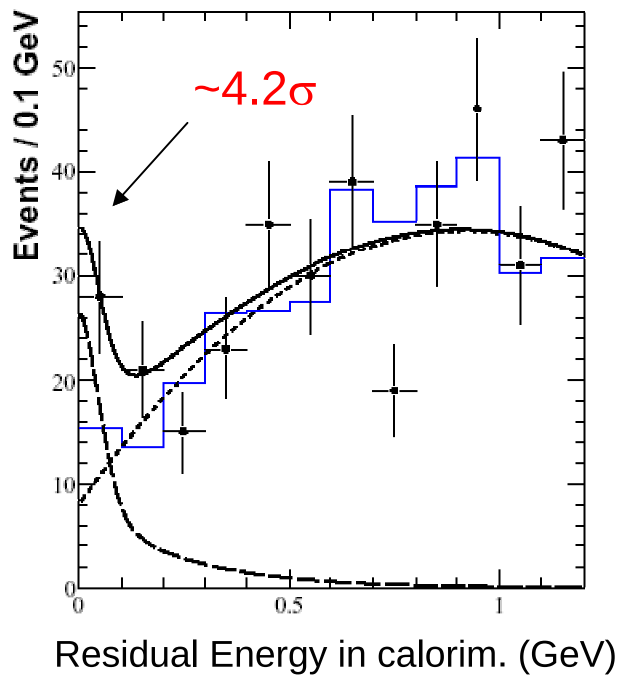
$$\frac{f_{D_s}}{f_{D^+}} = 1.27 \pm 0.14$$

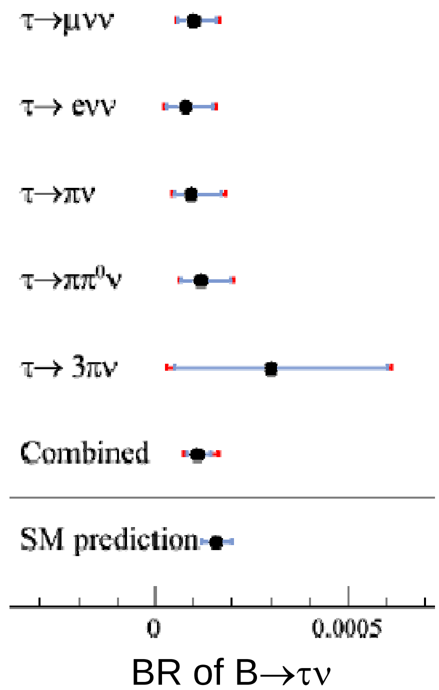
f_{D+}(FNAL/MILC)	201±3±17 MeV
f_{D+} (CLEO-c)	222.6±16.7± MeV
f_{Ds} (BaBar)	279±17±6 ±19 MeV
f_{Ds}/f_{D+}(BaBar/CLEO)	1.27±0.14

V_{ub}: $B^+ \rightarrow \tau\nu$

BELLE (hep-ex/060408) observes:







PDG'04/HFAG

V_{ub}

τ_{B^+}

$$B\left(B^+ \rightarrow \tau^+\nu\right) = \left(1.06^{+0.34}_{-0.28}\ {}^{+0.18}_{-0.16}\right) \times 10^{-4}$$

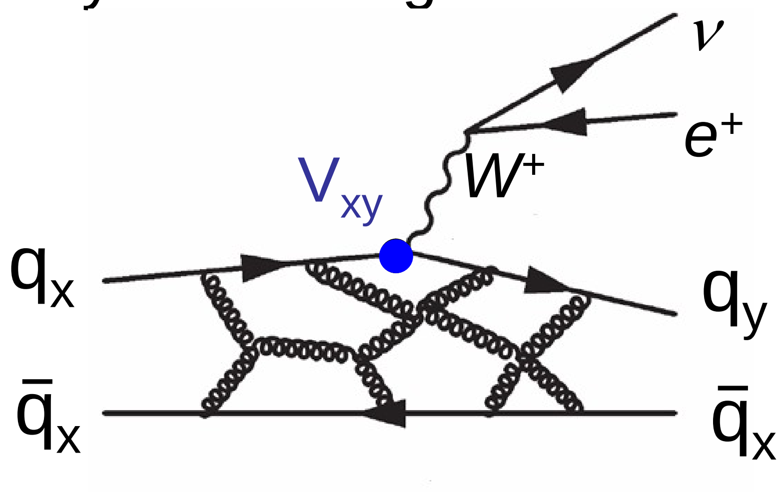
$$f_{B^+} = \left(176^{+28}_{-23}\ {}^{+20}_{-19}\right) MeV$$

First direct measurement of f_B

Compare with f_B=(216±22) MeV (HPQCD)

Semileptonic Decays

Several ways of looking at

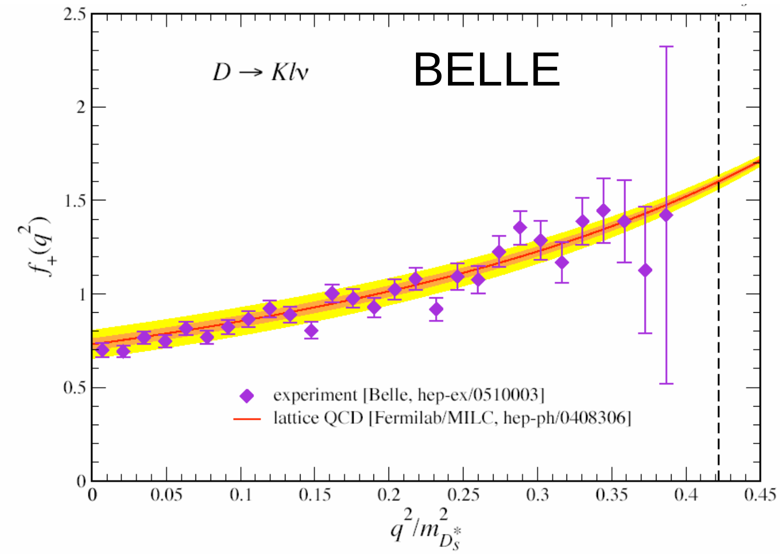


- Access to V_{xy}
- Form factor embeds q^2 dependence $\Rightarrow$ slightly more elaborate example of lattice$\leftrightarrow$experiment interaction
- Studying $\frac{B(D \to l\nu)}{B(D \to \pi l\nu)}$ will yield CKM-independent LQCD checks

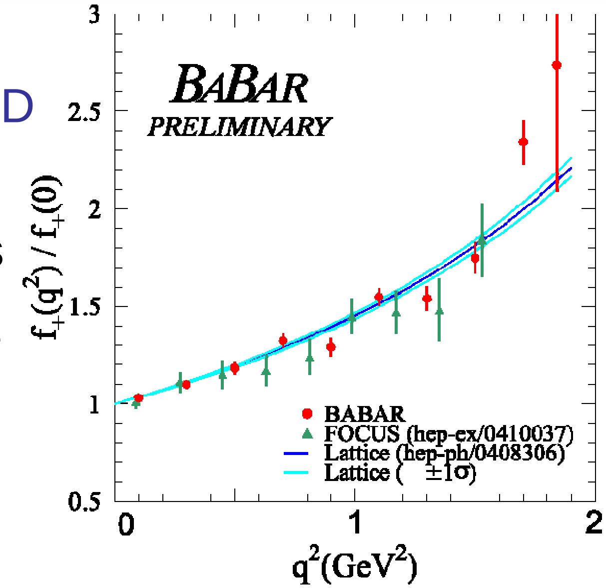
V_{cs}, V_{cd}: $D\to Kl\nu$, $D\to\pi l\nu$

BaBar (ICHEP'06), Belle (hep-ex/0604049), CLEO (PRL, hep-ex/0407035) and FOCUS (PLB607 2005 233) measure the q^2 dependence of f_+ in:

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



- $P^3(q^2)$ strongly peaks near $q^2=0$
  - Extraction of $|V_{cs}|$ requires $f_+(0)$, a tough LQCD bullet!
- $f_+(q^2)/f_+(0)$ measured and compared to predictions
- This is an important playground to understand the extrapolation of $\underset{q^2\to 0}{f_+}\left(q^2\right)$



$D\to Kl\nu$, $D\to \pi l\nu$ Cont.d

Several ways of comparing to predictions:

$$\left|f_+(q^2)\right| = \frac{f_+(0)}{1-\frac{q^2}{m^2_{pole}}}$$

(e.g. Koerner & Schuler Z Phys. C38 1988)

$$\left|f_+(q^2)\right| = \frac{f_+(0)}{\left(1-\frac{q^2}{m^2_{D_s^*}}\right)\left(1-\frac{\alpha_{pole} q^2}{m^2_{D_s^*}}\right)}$$

(Becirevic & Kaidalov, PLB478 2000 417)

$$r_0 = \frac{\left|f_+^{\pi}(0)\right|^2 \left|V_{cd}\right|^2}{\left|f_+^{K}(0)\right|^2 \left|V_{cs}\right|^2}$$

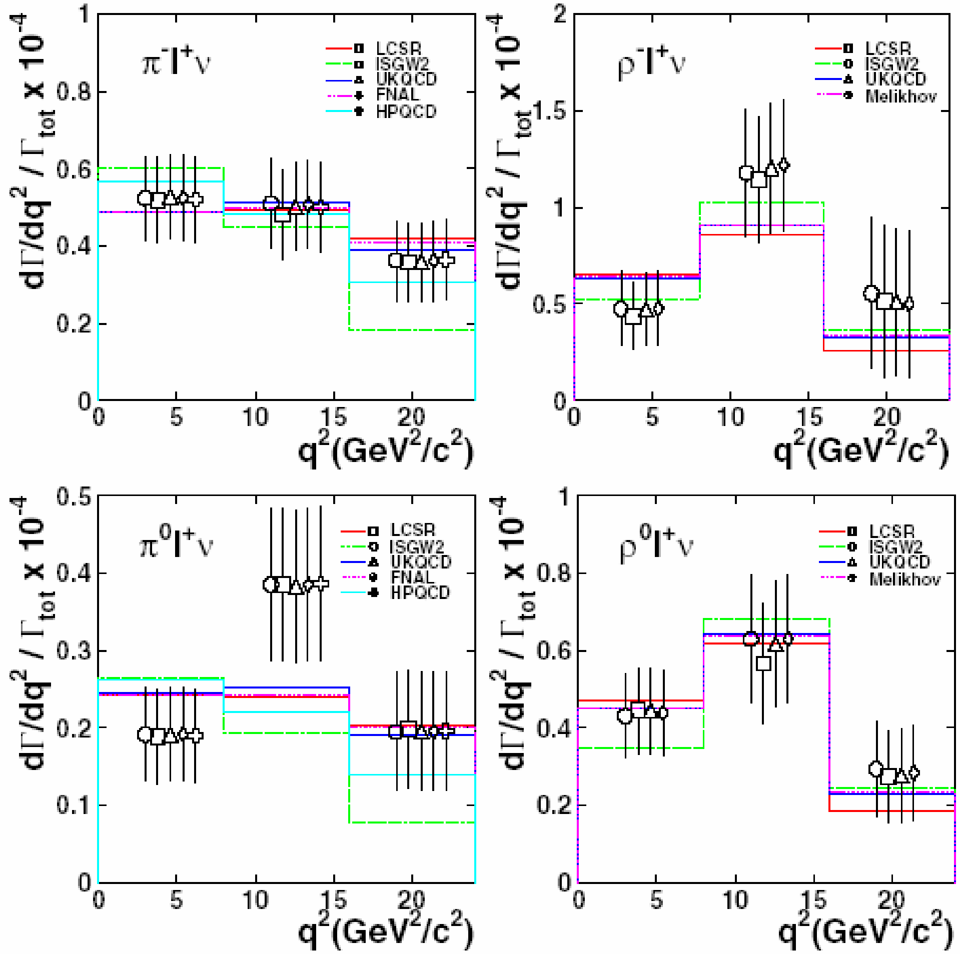
Exp	M_{pole} (Gev/c^2)	α_{pole}	r_0	f(0)
BaBar	K: 1.854±0.016±0.020 -	K: 0.43±0.03±0.04 -	- -	- -
BELLE	K: 1.82±0.04±0.03 π: 1.97±0.08±0.04	K: 0.52±0.08±0.06 π: 0.10 ±0.21±0.10	0.042±0.003±0.003	K: 0.695±0.007±0.022 π: 0.624±0.020±0.030
CLEO	K: $1.89\pm0.05^{+0.04}_{-0.03}$ π: $1.86^{+0.10}_{-0.06}{}^{+0.07}_{-0.03}$	K: $0.36\pm0.10^{+0.03}_{-0.07}$ π: $0.37^{+0.20}_{-0.31}\pm0.15$	$0.038^{+0.006}_{-0.007}{}^{+0.005}_{-0.003}$	- -
FOCUS	K: 1.93±0.05±0.03 π: $1.91^{+0.30}_{-0.15}\pm0.07$	K: 0.28±0.08±0.07	0.037±0.004±0.004	- -
LQCD (hep-ph/0408306)	K: 1.31±0.07 π: 1.41±0.06	K: 0.50±0.04 π: 0.44±0.04	0.04±0.002±0.005	K: 0.73±0.03±0.07 π: 0.64±0.03±0.06

V_{ub}: B→?lν

Analogous form factors can be measured on semileptonic B decays:

- Belle (hep-ex/0604024): ?=ρ,π
- BaBar? (ICHEP'06)?
- Exp→LQCD→CKM
  - Test LQCD
  - Measure V_{xb}

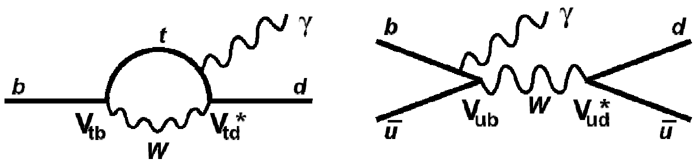
Theory	$\tilde{\Gamma}_{thy}(\mathrm{ps}^{-1})$	Mode	$\lvert V_{ub}\rvert(\times 10^{-3})$
FNAL	1.83 ± 0.50	$\pi^-\ell^+\nu$	$3.59 \pm 0.51 \pm 0.20^{+0.62}_{-0.41}$
		$\pi^0\ell^+\nu$	$3.63 \pm 0.70 \pm 0.20^{+0.63}_{-0.41}$
		$\pi^-\ell^+\nu + \pi^0\ell^+\nu$	$3.60 \pm 0.41 \pm 0.20^{+0.62}_{-0.41}$
HPQCD	1.46 ± 0.35	$\pi^-\ell^+\nu$	$4.02 \pm 0.57 \pm 0.22^{+0.59}_{-0.41}$
		$\pi^0\ell^+\nu$	$4.06 \pm 0.78 \pm 0.22^{+0.60}_{-0.41}$
		$\pi^-\ell^+\nu + \pi^0\ell^+\nu$	$4.03 \pm 0.46 \pm 0.22^{+0.59}_{-0.41}$

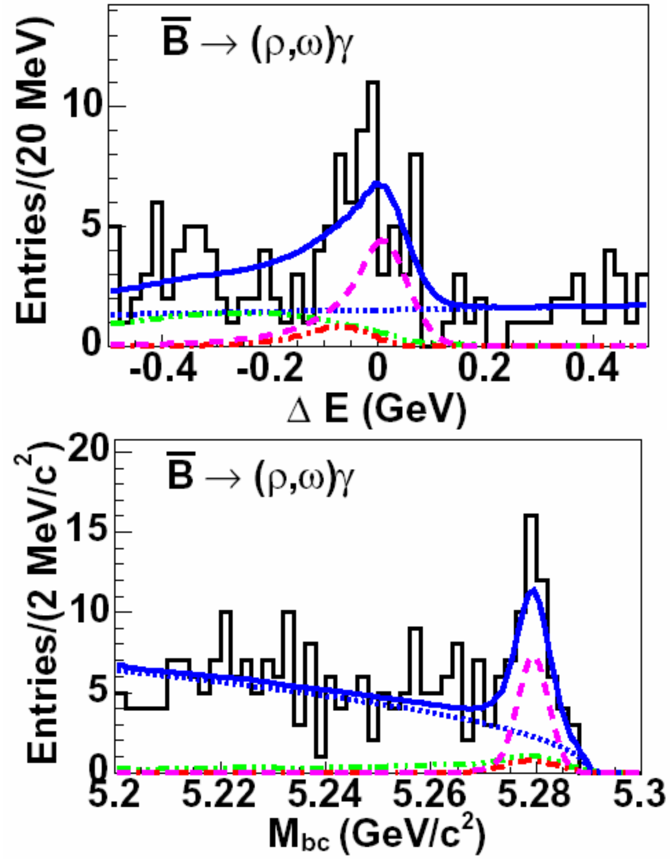


V_{td}/V_{ts}: Belle's $b \to s\gamma$

BELLE (hep-ex/0506079):

- Measure $b \to s\gamma$ and $b \to d\gamma$ in exclusive processes:
  - $B \to (\rho,\omega)\gamma$





- Disentangle loop/annihilation using ρ^0, ρ^+, ω
- Derive:

Mode	$\mathcal{B}$ (10^{-6})
$B^- \to \rho^-\gamma$	$0.55^{+0.42}_{-0.36}{}^{+0.09}_{-0.08}$
$\overline{B}^0 \to \rho^0\gamma$	$1.25^{+0.37}_{-0.33}{}^{+0.07}_{-0.06}$
$\overline{B}^0 \to \omega\gamma$	$0.56^{+0.34}_{-0.27}{}^{+0.05}_{-0.10}$
$\overline{B} \to (\rho,\omega)\gamma$	$1.32^{+0.34}_{-0.31}{}^{+0.10}_{-0.09}$

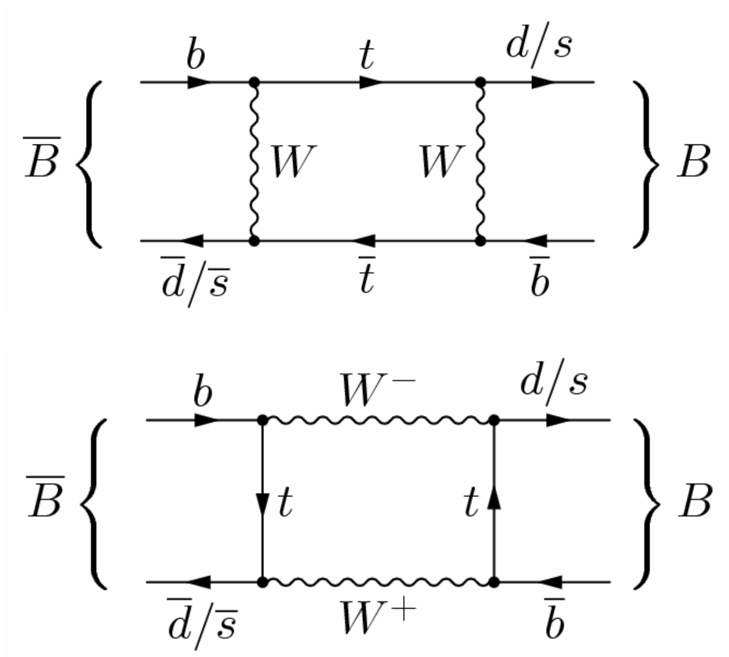
- By normalizing to $B(B \to K^*\gamma)$ obtain:

SU(3) Breaking (~10%)

$$\left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{(1-m^2_{(\rho,\omega)}/m^2_B)^3}{(1-m^2_{K^*}/m^2_B)^3}\zeta^2[1+\Delta R] \;\Rightarrow\; |V_{td}/V_{ts}| = 0.199\,^{+0.026}_{-0.025}(\mathrm{exp.})\,^{+0.018}_{-0.015}(\mathrm{theo.})$$

Ratio of form factors (0.85±0.10)

V_{td}/V_{ts}: B_s Mixing



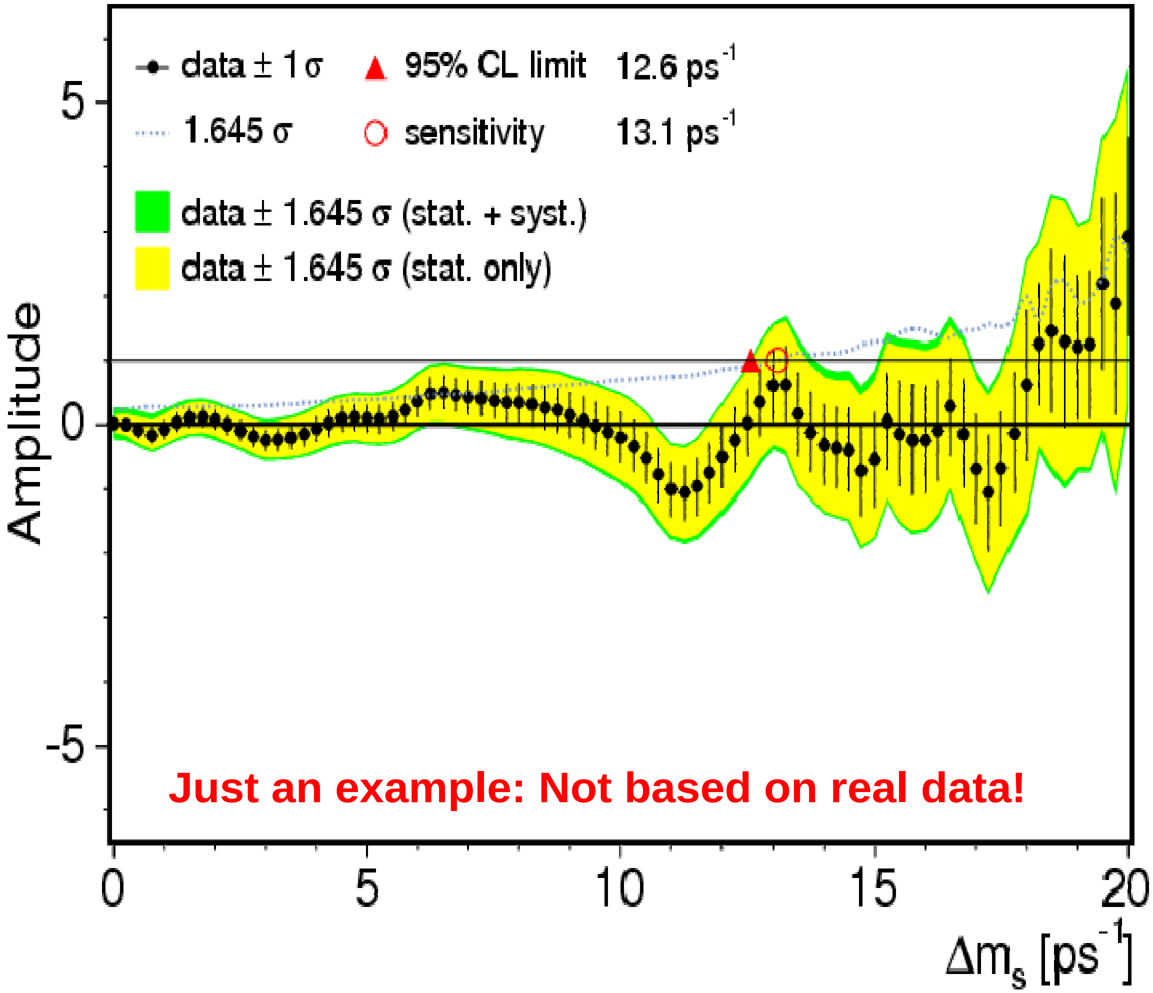
- V_{td}/V_{ts} can also be derived from the $B\overline{B}$ mass difference
- QCD uncertainty is minimized resorting to the relative B_s/ B_d mixing rate (V_{td}/V_{ts})
- Beyond the SM physics could enter in loops!

•Measure mixing rate vs time and fit for oscillation frequency

$$A = \frac{N_{unmix} - N_{mix}}{N_{unmix} + N_{mix}} = \cos(\Delta m\, t)$$

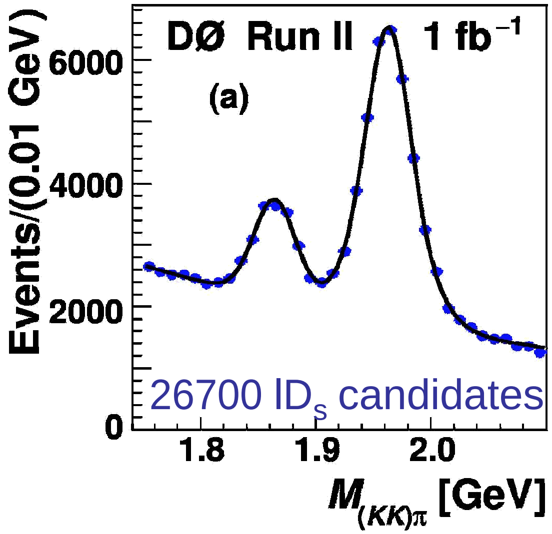
•This is usually done in “fourier transform”: amplitude scan

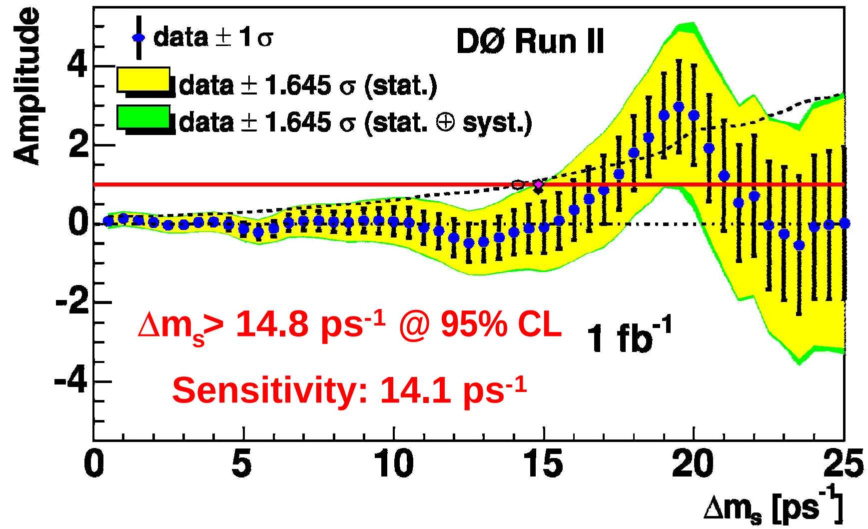
Amplitude Scan

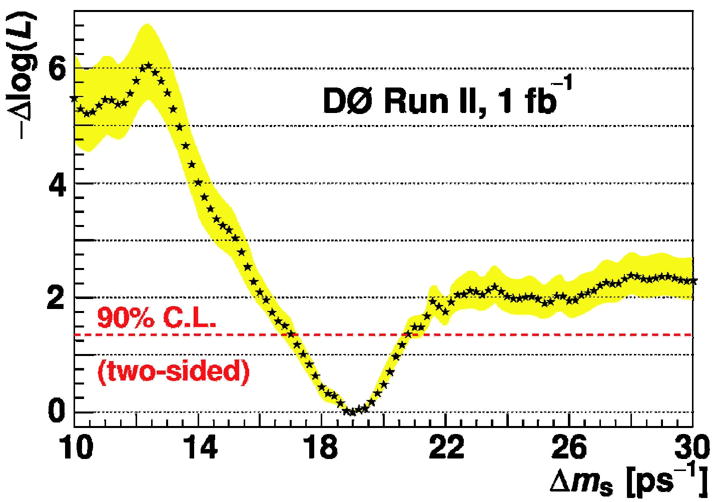


- Mixing amplitude fitted for each (fixed) value of Δm
- On average every Δm value (except the true Δm) will be 0
- "sensitivity" defined for the average experiment [mean 0]
- The actual experiment will have statistical fluctuations
- Actual limit for the actual experiment defined by the systematic band centered at the measured asymmetry

B_s Mixing: D0







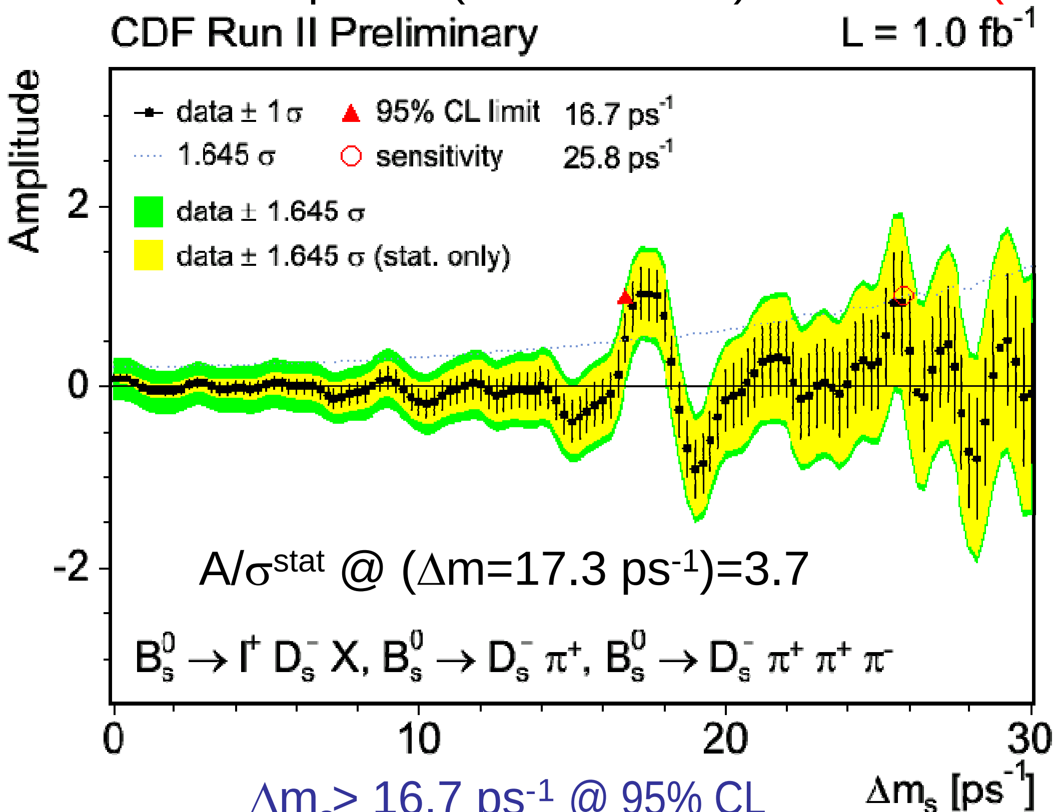
- "signal" above sensitivity threshold
- D0 decides to quote a "two sided bound" from Likelihood profile:

$$\Delta \in [17,19]\text{ps}^{-1} \text{ @ } 90\% \text{ CL}$$

- L dip is nice, should get deeper with more data
- Amplitude is 2.5σ from 0 and 1.6σ from 1

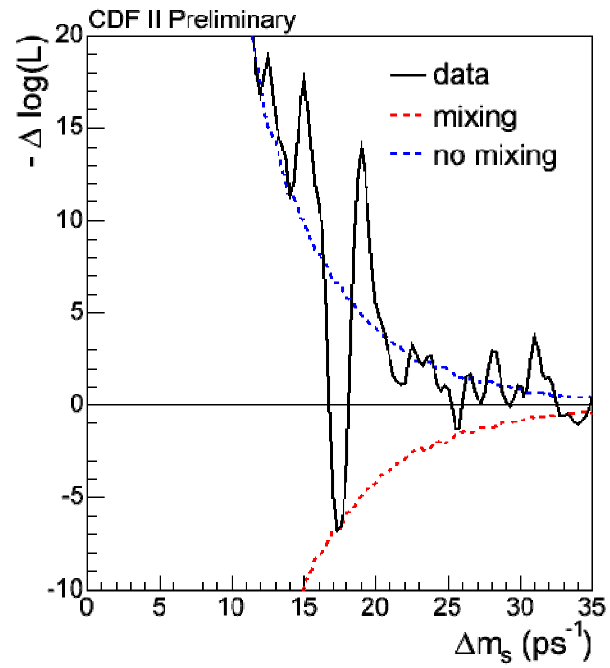
B_s Mixing: CDF

Semileptonic (~50K events)+ hadronic (~3K events) B decays, 1 fb^{-1}



Δm_s> 16.7 ps^{-1} @ 95% CL

Sensitivity: 25.8 ps^{-1}



$$Log\left[L(A=1)/L(A=0)\right] = -6.75$$

Background has ~0.2% probability to mimic this!

$$\Delta m_s = 17.31^{+0.33}_{-0.18} \pm 0.07$$

$$\Delta m_s \in [17.01, 17.48]\, ps^{-1} \quad @ \quad 90\% CL$$

$$\Delta m_s \in [16.96, 17.91]\, ps^{-1} \quad @ \quad 95\% CL$$

V_{td}/V_{ts} from CDF

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

- inputs:
  - → $m(B^0)/m(B_s)$ = 0.98390 (PDG 2006)
  - → $\xi = 1.21^{+0.047}_{-0.035}$ (M. Okamoto, hep-lat/0510113)
  - → $\Delta m_d = 0.505 \pm 0.005$ (PDG 2006)

$$|V_{td}| / |V_{ts}| = 0.208\ ^{+0.001}_{-0.002}\ (\text{exp})\ ^{+0.008}_{-0.006}\ (\text{theo})$$

…CDF can do Lattice computations: $\xi = 1.06^{+0.12}_{-0.05}$

(uncertainty is actually limited by the CKM fit to Vtd/Vts, in particular α and γ)

Conclusions and Outlook

- Flavor physics relies on lattice computations
- In some cases one of the main contributions to syst. on V_{CKM} determination
- New exciting measurements:
  - B_s Mixing
  - $B \rightarrow \tau \nu$
  - $D_{(s)} \rightarrow \mu \nu$
- Expect more news in the next week or so!
- Pressure on the Lattice community for more precise numbers is high!