Flavor Physics and Lattice QCD

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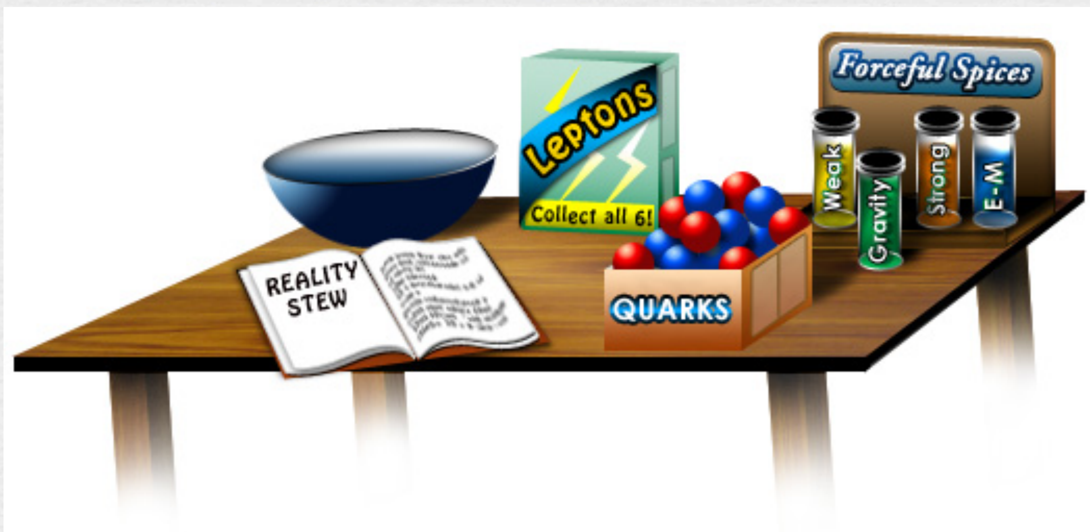
Weak Interactions and Neutrinos - WIN'09
Relais San Clemente, 14-19 September 2009



What are we after?

Sensitivity to New Physics $\Lambda_{\rm NP} \gg E_{\rm exp}$

QUESTIONS:

❶ Standard Model Flavor Puzzle

Why is there a hierarchy of small parameters?

❷ New Physics Flavor Puzzle

If the new physics is at about 1 TeV, why FCNC are so small?

❸ What about the baryon asymmetry?

Not enough CP for baryogenesis ; flavor matters in leptogenesis

Strong CP-problem : $\widetilde{\theta} \lesssim 10^{-10}$ Vs $\delta_{\rm CKM} \sim 1$

SM Flavor Physics Issues

Interaction occurring between flavor generations

✗ Yukawa interactions i.e. no self-interactions

(unlike gauge and Higgs sectors)

✗ Flavor physics parameters :

fermion masses and mixing parameters (angles and phases)

Extract them by comparing theory expressions to experimental data

Non-perturbative QCD ?

Lattice QCD

We can:

✔ calculate hadronic properties from first principles - non-perturbative QCD

✔ reach an arbitrary accuracy (in principle)

Not now but maybe...

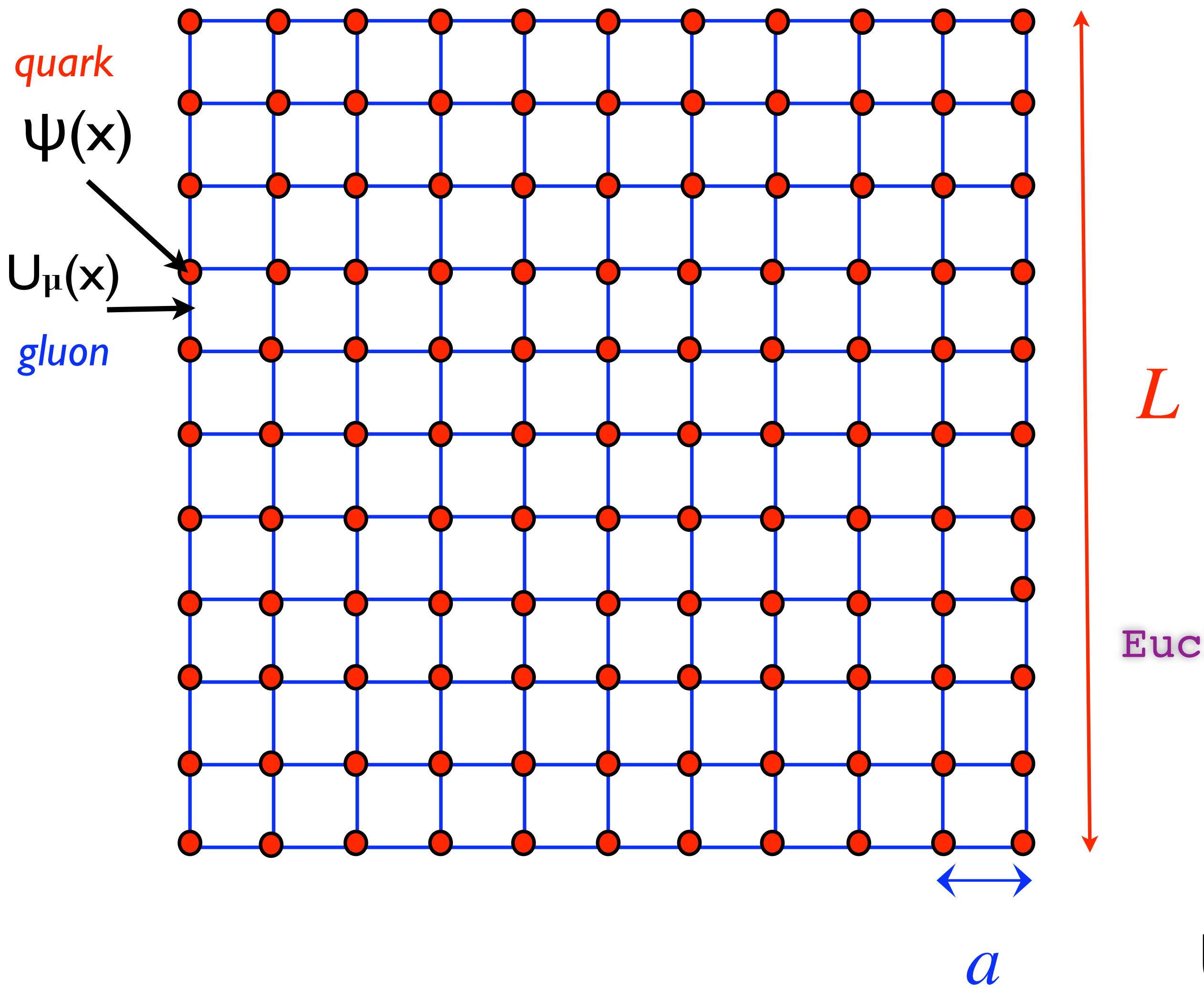
? compute the strong phase (accurately)

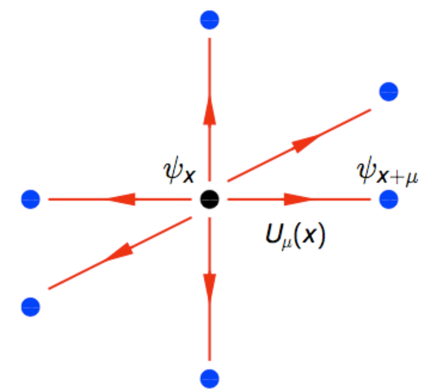
? control the systematics to arbitrary accuracy

✔ hadronic matrix elements: hadron leptonic, semileptonic, radiative, some rare decays [hadron →vacuum, hadron→hadron]

✘ non-leptonic decays [hadron → (n≥2) hadrons]

Lattice QCD



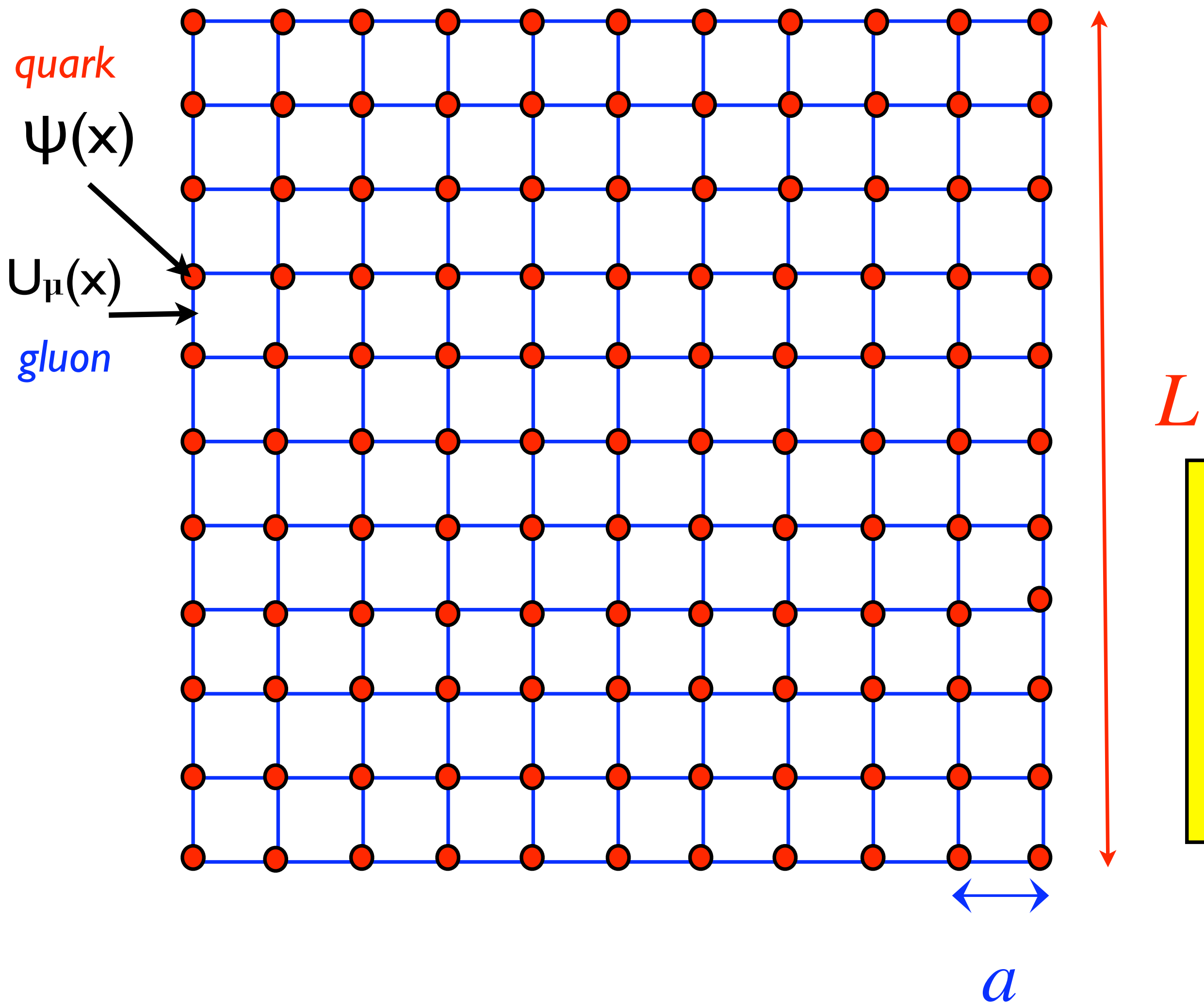


IR cutoff

Euclidean space-time

UV cutoff

Lattice QCD



IR cutoff

Clean (the only?) way to define QFT

$\mathcal{L}_{\rm YM} \rightarrow \mathcal{L}_{LYM}$

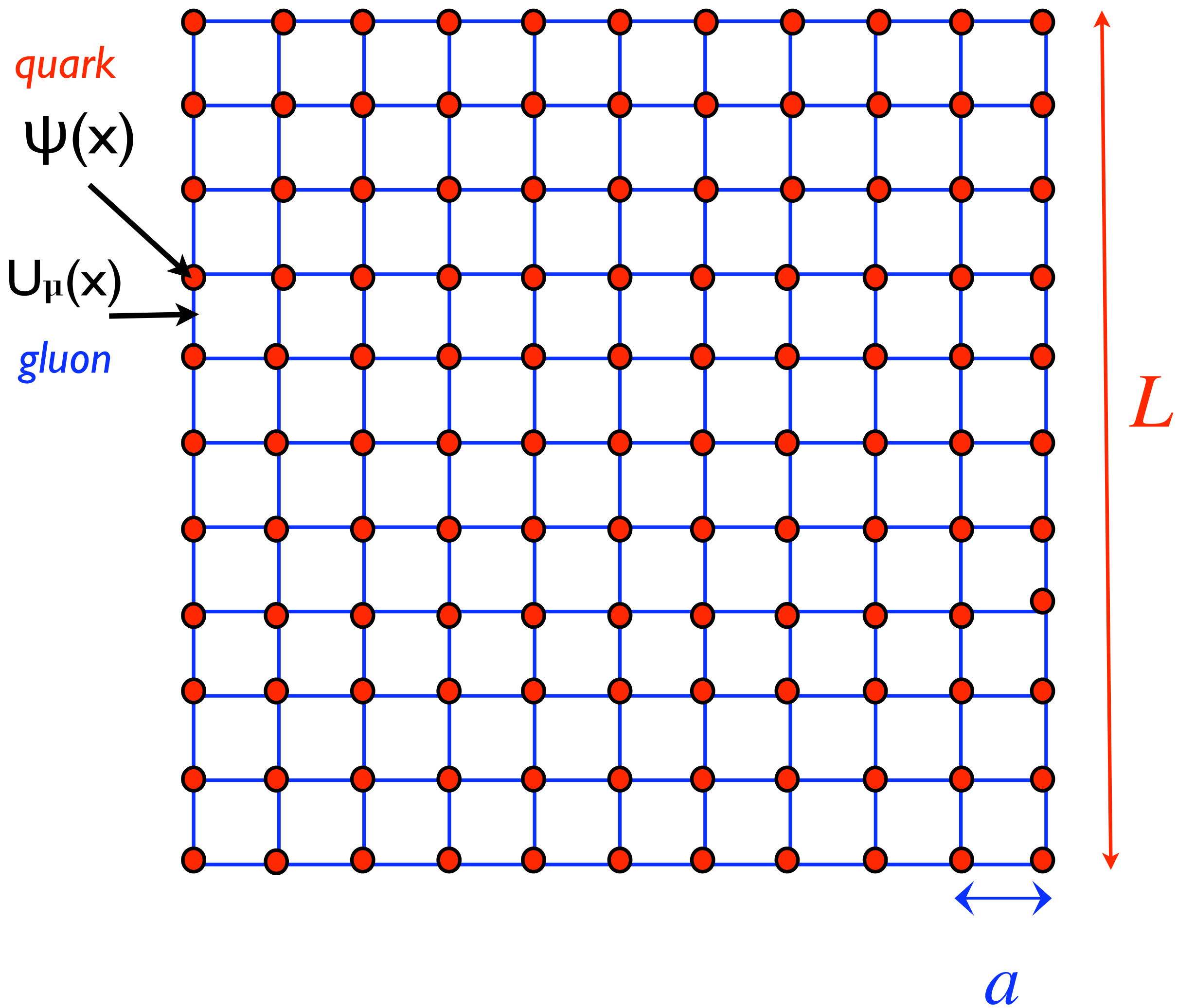
$\mathcal{L}_{\rm Dirac} \rightarrow \mathcal{L}_{\rm naive}$

SIC : doublers $2^4 = 16$

when $a \rightarrow 0$

UV cutoff

Lattice QCD



Get rid of the doublers :

* add a D'Alambert term to decouple doublers [WILSON] (breaks chiral symmetry)
- Overlap to restore a peculiar form of chiral symmetry [expensive]
- Domain Wall in 5th dim. to separate chiralities in 4D [need large 5th Dim, residual mass very small]
- twisted (maximally)

$\bar{\psi}(x)[D_\mu \gamma_\mu + i\mu\gamma_5\tau_3]\psi(x)$

to get closer to chiral limit

* distribute spinor components over a lattice cell : 16 → 4 [staggered quarks, U(1)]

QCD on the lattice

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \prod_{x,\mu} dU_\mu(x) \mathcal{O}(U) \det M(U) e^{-S_g(U)}$$

Unquenched - extra problems

Manipulating large determinants is computationally expensive. A "bosonisation" trick is commonly used: the pseudofermion field.

For two flavours of fermions with a γ_5-hermian lattice representation of the Dirac matrix, we have

$$\det M^2 = \det M^\dagger M = \frac{1}{\det\,[M^\dagger M]^{-1}}$$

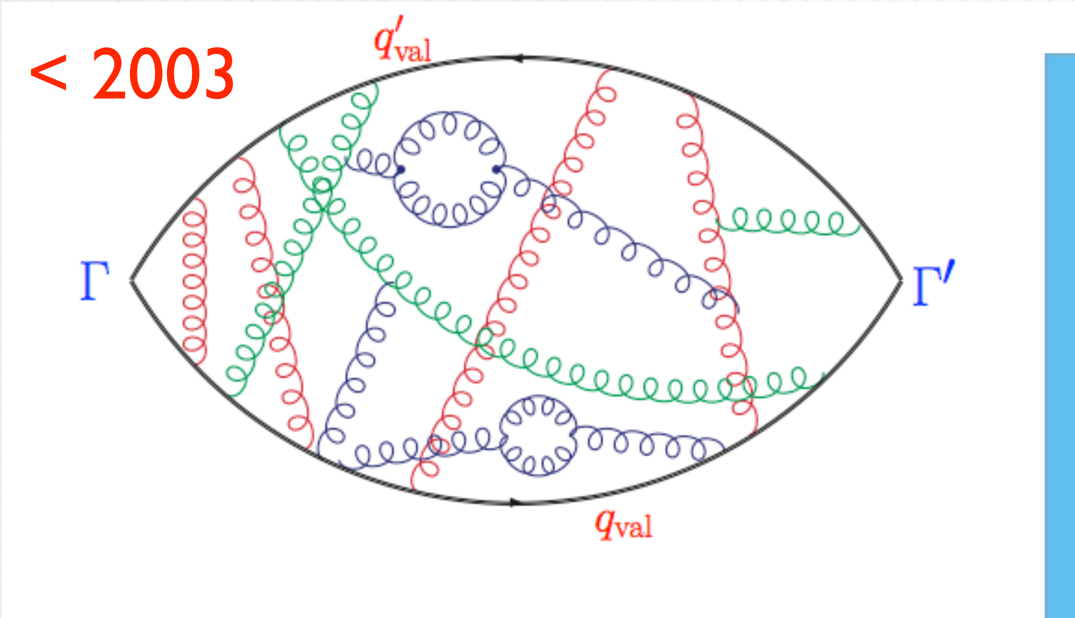
and this is represented as a gaussian integral;

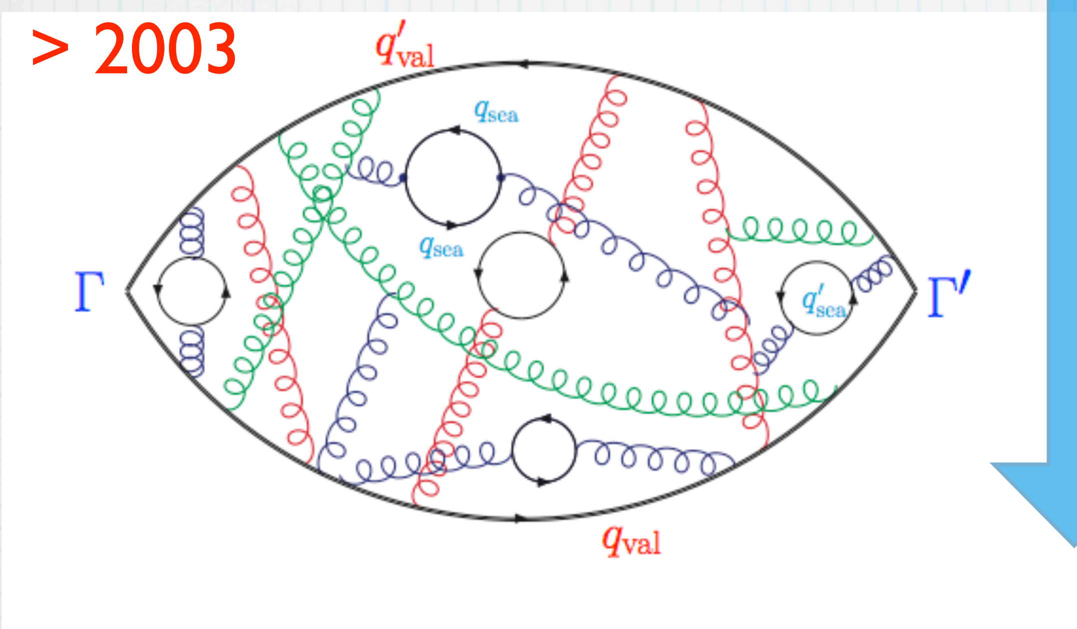
$$\frac{1}{\det\,[M^\dagger M]^{-1}} = \int \mathcal{D}\phi \mathcal{D}\phi^* \quad e^{-\phi^*[M^\dagger M]^{-1}\phi}$$

The pseudofermions inherit the spin structure and colour charge.

If the staggered pions were degenerate, taking the 4th root would be fine

Otherwise -- non-localities shadow of doubt in spite of correct phenomenology so far...





$m_q^{\rm sea} \to \infty$

Quenched QCD

Partially Quenched QCD

$m_q^{\rm val} \neq m_q^{\rm sea}$

UNQuenched QCD

$m_q^{\rm val} = m_q^{\rm sea}$

Non-Unitary

$\mathcal{L}^{\rm val}_{\rm LQCD} \neq \mathcal{L}^{\rm sea}_{\rm LQCD}$

Unitary

$\mathcal{L}^{\rm val}_{\rm LQCD} = \mathcal{L}^{\rm sea}_{\rm LQCD}$

Lattice QCD

Main worries:

✔ reduce statistical errors

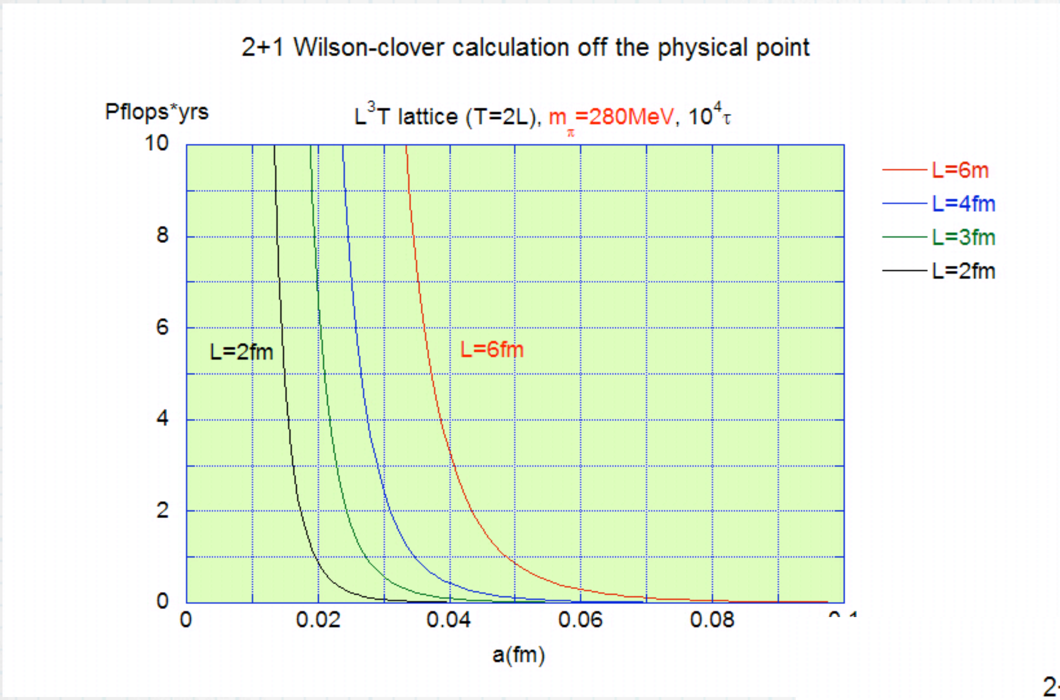
✔? control chiral extrapolation while keeping the finite volume effects under control

✔? control the discretization effects

- matching and renormalization

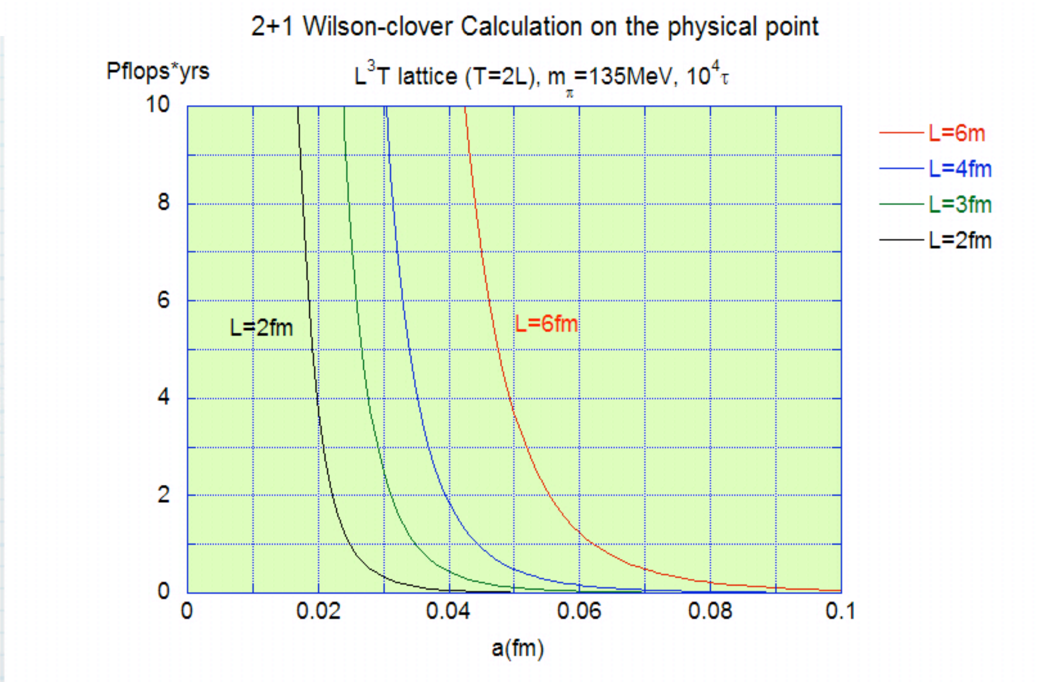
✔? inclusion of 2,3,4 sea quark flavors

✘ unstable resonances (signal extraction...)



Need Better Machines!

Teraflop era
PetaQCD [on CELL...]



Need Better Algorithms!

Improve HMC

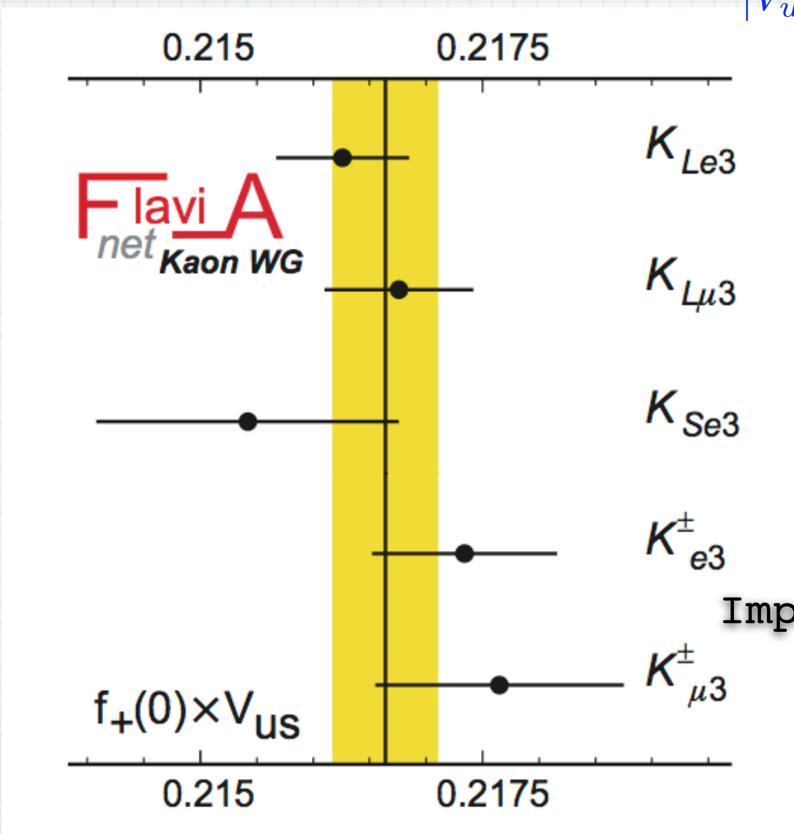
Kaon physics: semileptonics

Tree level decay

$$K \to \pi \ell \nu$$

$$\left(|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2}\right) \overset{?}{\neq} 1$$

$|V_{ud}| = 0.97425(22)$ from Hardy & Towner 08



$$|V_{ud}|^2 + |V_{us}^{Kl3}|^2 = 0.9995(7)$$

Impressive check of the CKM unitarity

⇔ universality of G_μ

Kaon physics: semileptonics

$K \rightarrow \pi \ell \nu$

hadronic uncertainty!

$\langle \pi | \bar{s} \gamma_\mu u | K \rangle \rightarrow f_{0,+}(q^2)$

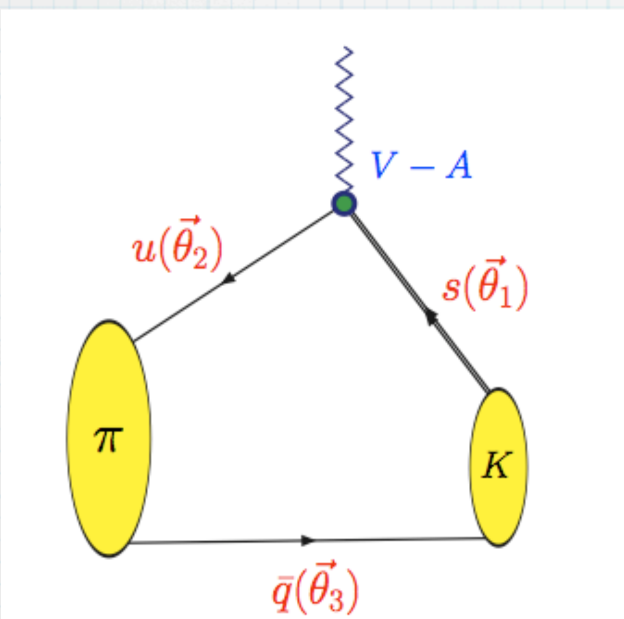
$f_0(0) = f_+(0)$

$$f_+(0) = 1 + f_2 + f_4 + \mathcal{O}(p^8)$$

CVC

-0.023
Ademollo-Gatto

$\propto (m_s - m_u)^2$
lattice QCD



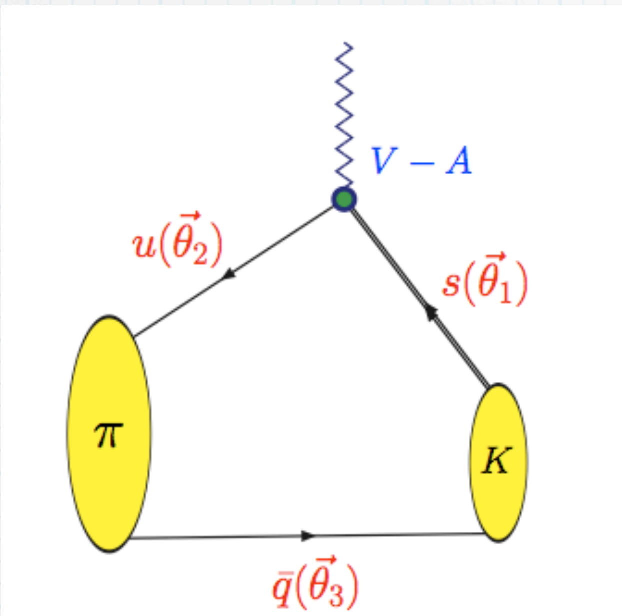
$$\frac{\langle \pi | \bar{s} \gamma_0 u | K \rangle \langle K | \bar{u} \gamma_0 s | \pi \rangle}{\langle K | \bar{s} \gamma_0 s | K \rangle \langle \pi | \bar{u} \gamma_0 u | \pi \rangle} = \frac{(m_K + m_\pi)^2}{4 m_K m_\pi} \left(f_0(q^2_{\mathrm{max}}) \right)^2$$

Nf=2+1 by RBC/UKQCD 0710.5136

- use twisted boundary condition to go to q^2=0
- extrapolation to physical pion and kaon by using ChPT
- $m_\pi \geq$ 330 MeV, $Lm_\pi \geq 4$
  a=0.11 fm

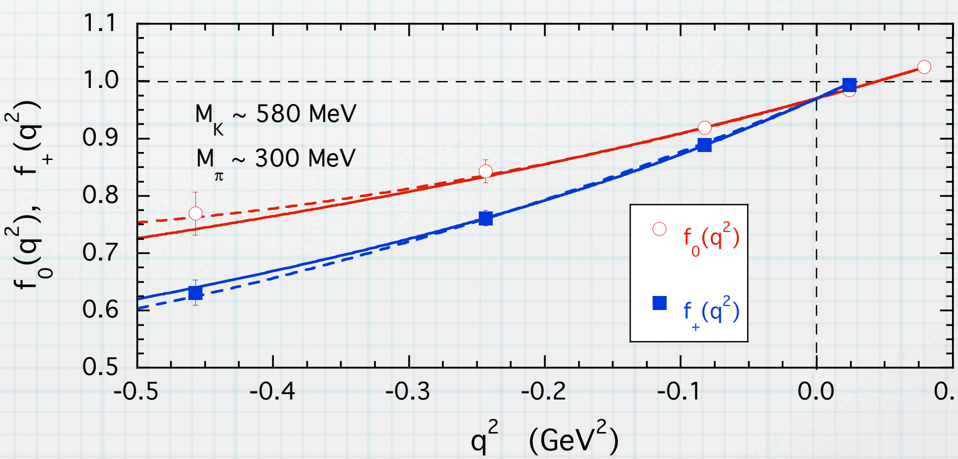
Kaon physics: semileptonics

$K \to \pi \ell \nu$



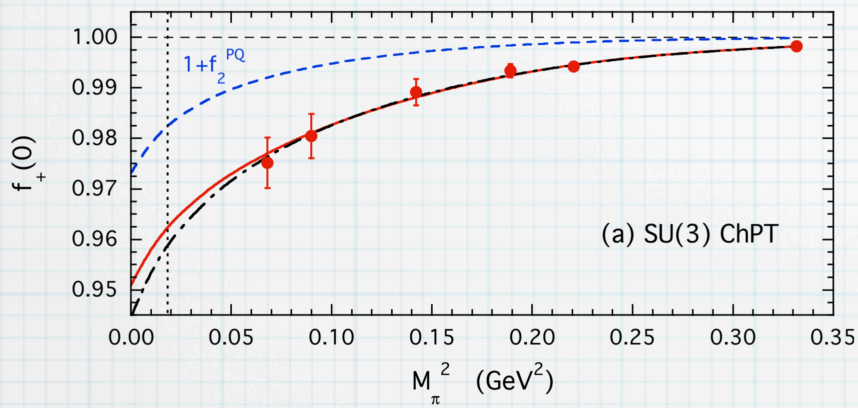
Nf=2 by ETMC 0906.4728

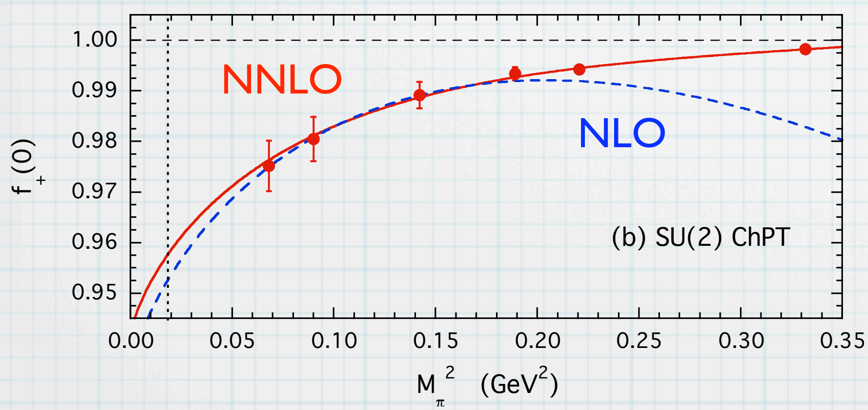
- use twisted boundary conditions to smoothly reach q^2=0
- extrapolation to physical pion and kaon by using ChPT
- $m_\pi \geq 260$ MeV, $Lm_\pi \geq 3.7$
- 2 lattice spacings



Kaon physics: semileptonics

$K \to \pi \ell \nu$





Nf=2 by ETMC 0906.4728

- use twisted boundary condition to go to q^2=0
- extrapolation to physical pion and kaon by using ChPT
- $m_\pi \geq 260$ MeV, $Lm_\pi \geq 3.7$
- 2 lattice spacings

$$f_+(0) = 0.9644(33)(37)$$

RBC/UKQCD Nf=2+1

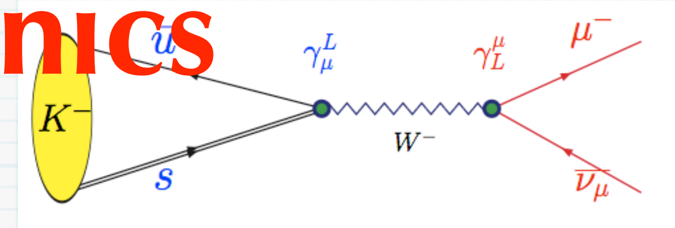
$$f_+(0) = 0.9560(57)(62)$$

ETMC Nf=2

$$f_+(0) = 0.962(3)(4)$$

V.Lubicz @ Lattice'09

Kaon physics: leptonics

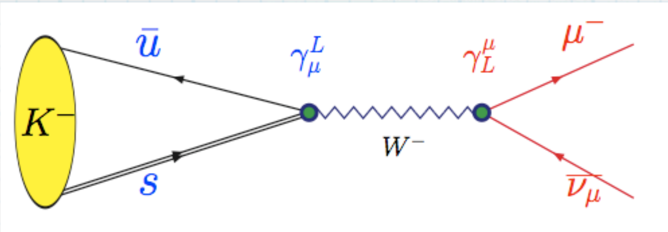


	N_f	a [fm]	m_{PS} [MeV]	N^{n}LO		$m_{PS}L$
ETMC	2 twisted m.	0.08, 0.07, 0.05 $\rightarrow$ 0	250–600	2	compl. SU(2)	≥ 3.0
JLQCD	2 overlap	0.12	290–750	2	"ξ" SU(2)	≥ 2.8
	2+1 overlap	0.10	320–800	2	"ξ" SU(2),SU(3)	≥ 2.8
PACS-CS	2+1 iWilson	0.09	160–410 reweight $\rightarrow m_\pi$	1	compl. SU(2)	≥ 2.3
MILC	2+1 staggered	0.09,0.06 $\rightarrow$ 0	180–380	1	rSχPT SU(3)	≥ 4.0
				2	compl. SU(3)	
			180–540	3,4	analytic	
Aubin et al.	2+1 stagg/DWF	0.12,0.09 $\rightarrow$ 0	240–500	1	SU(3) MAχPT	≥ 4.0
				≥ 3	analytic	
RBC/UKQCD	2+1 DWF	0.11, 0.09 $\rightarrow$ 0	290–420	1,2	compl. SU(2)	≥ 4

Kaon physics: leptonics

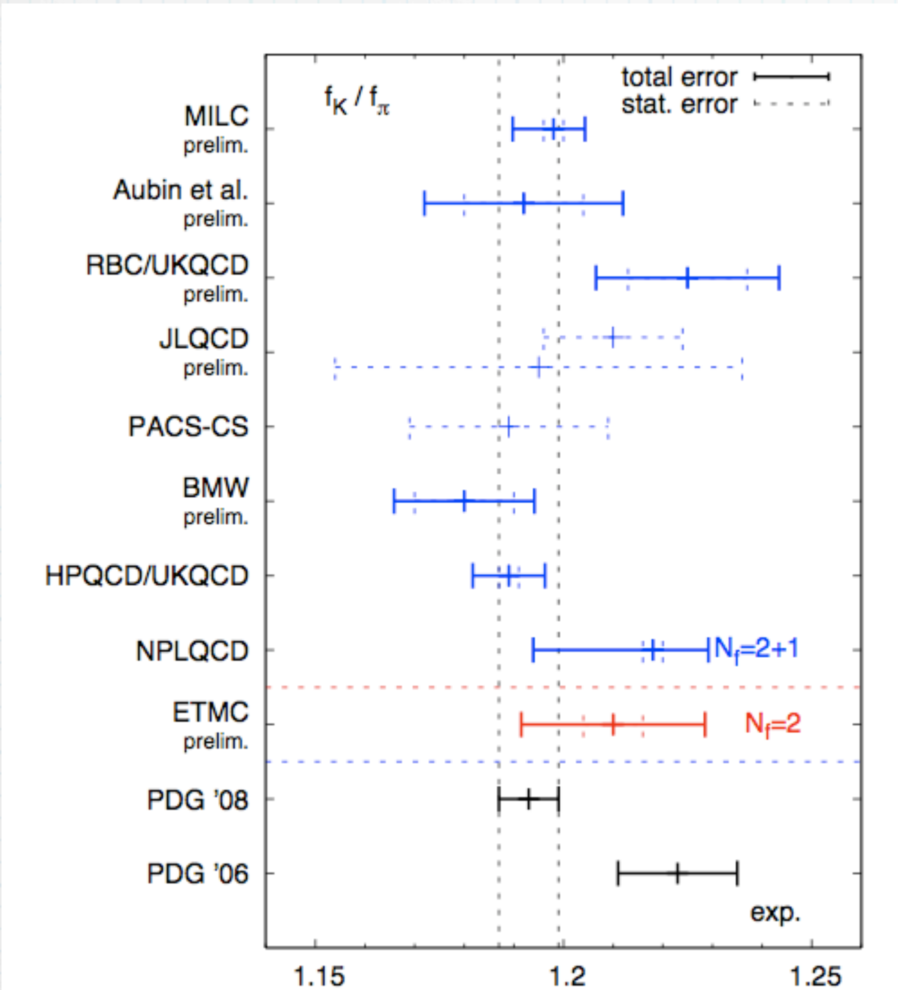
	f_π	f_K	f SU(2)	f_0 SU(3)
ETMC	input	158.1(0.8)(2.0)(1.1)	121.57(70)	
JLQCD (2)	$119.6(3.0)(1.0)(^{+6.4}_{-0.0})$		$111.7(3.5)(1.0)(^{+6.0}_{-0.0})$	
JLQCD (2+1)	121.2(5.6)	149.6(6.0)	112.5(9.2)	73(19)
JLQCD (2+1)	input	157.2(6.4)	121(14)	79(20)
RBC/UKQCD	122.2(3.4)(7.3)	149.7(3.8)(2.0)	113.0(3.8)(6.8)	93.5(7.3) ['08]
PACS-CS	134.0(4.3)	159.4(3.1)	126.4(4.7)	118.5(9.0)
MILC	128.0(.3)(2.9)	153.8(0.3)(3.9)	122.8(.3)(.5)	111.0(2.0)(4.1)
Aubin et al.	131.1(1.3)(2.2)	156.3(1.3)(2.0)		
PDG '08	130.4(.04)(.2)	155.5(.2)(.8)(.2)	blue marks **prelim. results**	

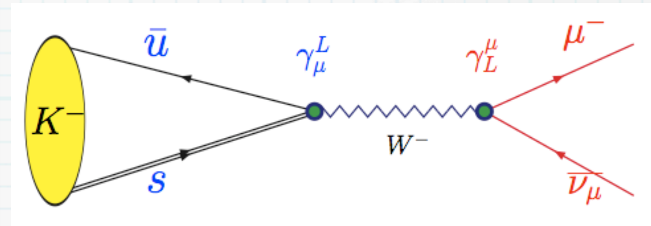
NEW RESULTS : summary by Scholz @ Lattice'09



Convergence of ChPT with Nf=3 is still unclear :
need checks with lower/unphysical strange quark

Kaon physics: leptonics





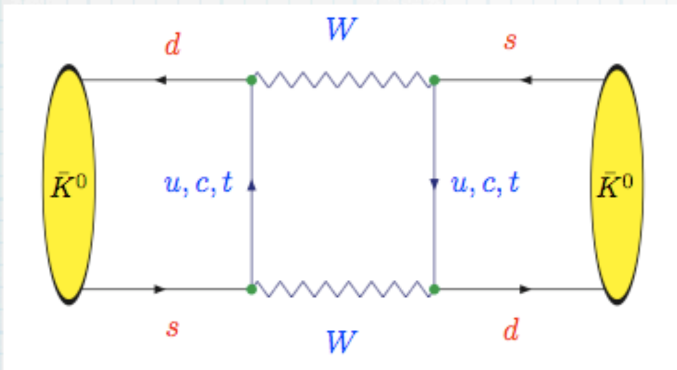
New Average @ Lattice'09

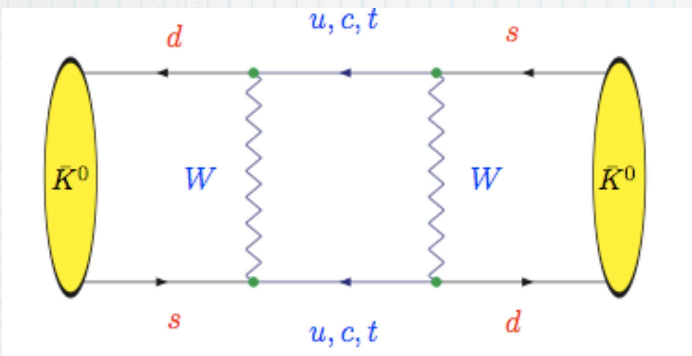
$$f_K/f_\pi = 1.196(1)(10)$$

UT + $|V_{ud}|$ + experiment

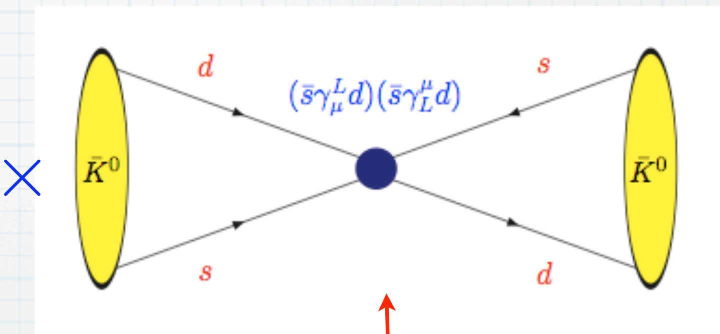
$$f_K/f_\pi = 1.193(6)$$

Kaon physics: B_K





$$= C_{\mathrm{SM}}^{\mathrm{RGI}} \times$$



$$\langle \bar{K}^0 | (\bar{s}\gamma_\mu^L d)(\bar{s}\gamma_L^\mu d) | K^0 \rangle = \frac{8}{3} m_K^2 f_K^2 B_K$$

RGI from NLO QCD pert.th
(NDR-MS,RI/MOM,SF)

LATTICE QCD
B_K

In 10 years the central value for B_K changed from 0.90 to 0.72 and the error from about 20% to about 5%

Kaon physics: B_K

3 NEW RESULTS :

(1) Aubin et al, 0905.3947
\`mixed' action Stagg/DWF with Nf=2+1; a=0.12, 0.09 fm; NP-Renorm

$$\hat{B}_K = 0.724(8)(28)$$

(2) ETMC, to appear
OS/tmQCD with Nf=2; a=0.10, 0.09, 0.07 fm; NP-Renormalization

$$\hat{B}_K = 0.730(30)(30)$$

(3) RBC/UKQCD, updating on 0710.5136
DWF with Nf=2+1; a=0.11, 0.08 fm; NP-Renormalization

$$\hat{B}_K = 0.738(8)(25)$$

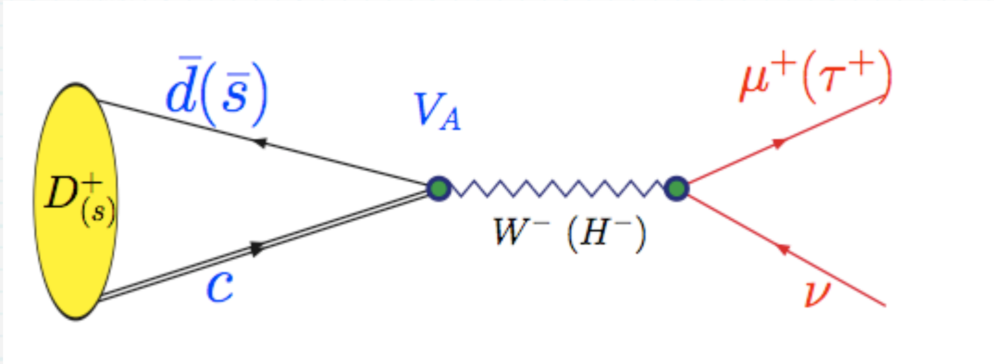
$$\text{avg}: \ \hat{B}_K = 0.731(7)(35)$$

Note that this error is no more dominant :

$$\varepsilon_K^{\text{exp}} \propto A^2 \bar{\eta} \hat{B}_K$$

It is comparable to that of $A = V_{cb}/\lambda^2$

Charm physics: f_D , f_{Ds}



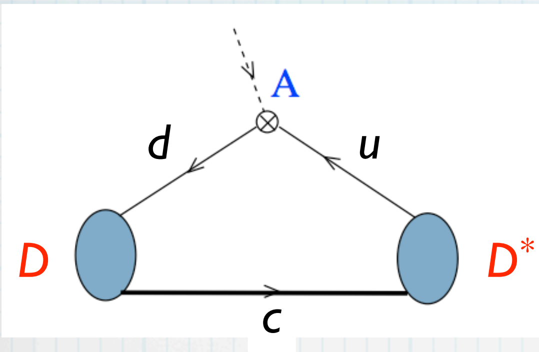
$$\langle 0|\bar{q}\gamma_\mu\gamma_5 c|D_q(p)\rangle = ip_\mu f_{D_q}$$

$$\Gamma(D_q \to \ell\nu) = \frac{G_F^2}{8\pi} f_{D_q}^2 |V_{cq}|^2 m_\ell^2 m_{D_q} \left(1 - \frac{m_\ell^2}{m_{D_q}^2}\right)^2 R_q^2$$

$$R_q = 1 + \frac{m_{D_q}^2}{M_H^2} \frac{m_c - m_q \tan^2\beta}{m_c + m_q}$$

|Vcs| and |Vcd| only known from the CKM unitarity :
CLEO-c from leptonic decays extracted
$|V_{cs}| = (1.08\pm0.05)\ |V_{cs}|^{UTA}$ and $|V_{cd}| = (1.00\pm0.05)\ |V_{cd}|^{UTA}$

Charm physics: f_D , f_{Ds}

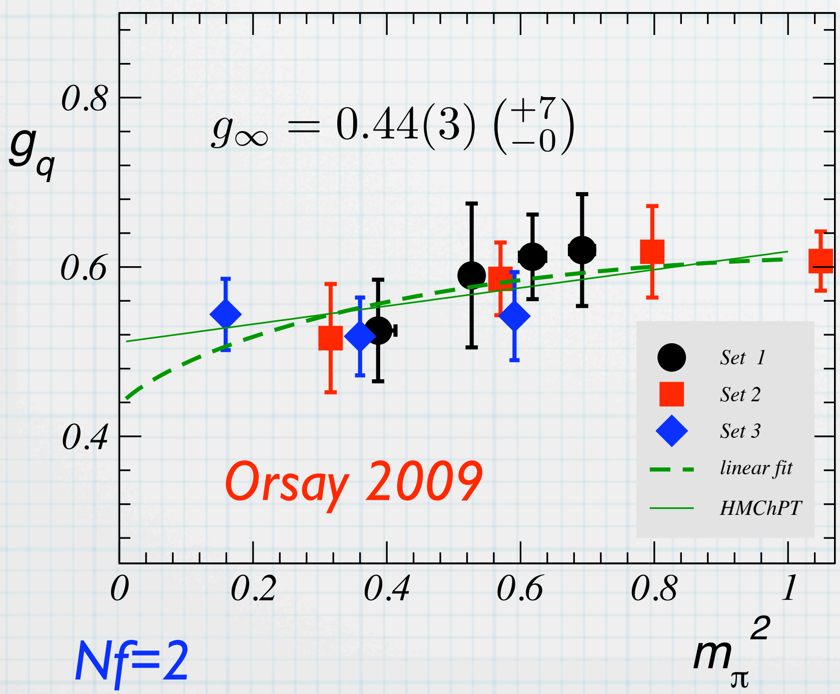


$$\Phi_{D_q} = f_{D_q}\sqrt{m_{D_q}}$$

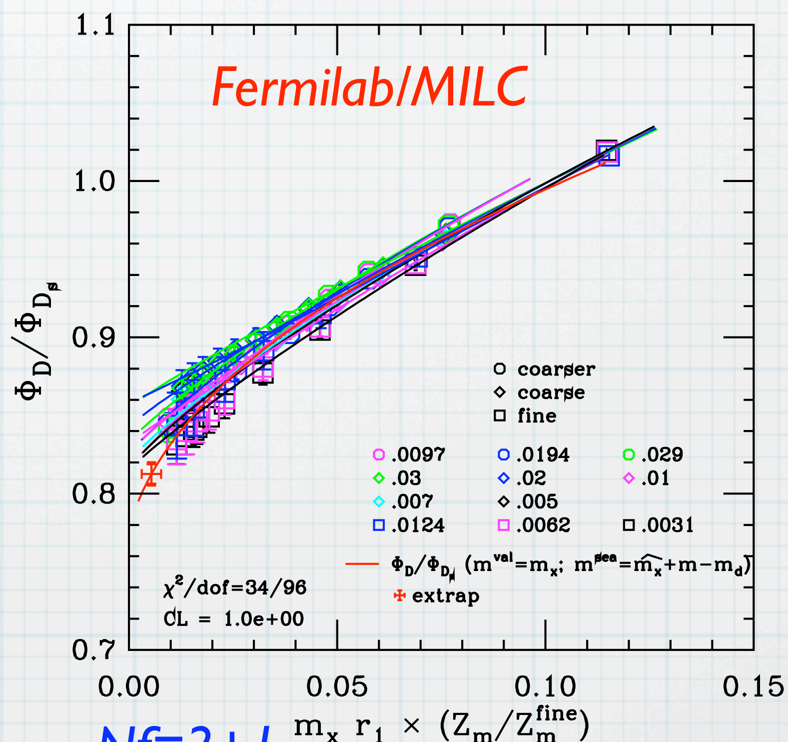
Use of HMChPT for the charm (g=?, static value < charmed)

StagHMChPT... for Fermilab/MILC and HPQCD/MILC

$g_c = 0.68(7)$



Nf=2



Nf=2+1

2009 - Epilogue (?)

Experimental average (CLEO-c!)

$$f_{D_s} = (277 \pm 9)\ \text{MeV}\ [2007] \rightarrow (271 \pm 8)\ \text{MeV}\ [2008] \rightarrow (263 \pm 9)\ \text{MeV}\ [2009]$$

CLEO-c in PRD79:052001,2009

WHY? $D \rightarrow \mu\nu_\mu$ stable, $D \rightarrow \tau\nu_\tau$ changed a lot!

$$f_{D_s}^{(\tau)} = (285 \pm 15)\ \text{MeV}\ [2007] \rightarrow (272 \pm 13)\ \text{MeV}\ [2008] \rightarrow (260 \pm 8)\ \text{MeV}\ [2009]$$

Lattice QCD - f_{D_s}

Staggered
$N_\mathrm{f} = 2+1$
Fermilab/MILC
249 ± 11 MeV [0904.1895]
241 ± 3 MeV [0706.1726]
HPQCD/MILC

tmLQCD
$N_\mathrm{f} = 2$
ETMC
244 ± 8 MeV [0904.0954]

Wilson-impr.
$N_\mathrm{f} = 2$
DB,B.Haas 2009
242 ± 19 MeV

$f_{D_s}^{\text{quench}} = 252 \pm 9$ MeV [PLB560, 59(2003)]
Alpha

NO MORE PUZZLE (?)

B-physics

Vcb:

- ✔ HFAG (winter 2009) : $|V_{cb}|^{\rm incl.} = 41.5(5)(7) \times 10^{-3}$
- ✔ Fermilab/MILC (2008) : $|V_{cb}|^{\rm excl.} = 38.6(1.2) \times 10^{-3}$
- ✔ any improvement on inclusive side?
- ✔ on exclusive end, revise the strategy which relies on HQET (relations among slope and curvature...) There is a full QCD method which can be used to compute both form factors without recourse to HQET

Vub::

- ? tension still present $|V_{ub}|^{\rm excl.} = 3.42(37) \times 10^{-3}$
- ? inclusive depend on the ``scheme"/strategy and cv $> 4 \times 10^{-3}$

B-physics:Step Scaling Method

Method proposed and tested in Quenched Approximation to obtain accurate values for D, B decay constants and form factors in QCD (no recourse to HQET)

Rome-2 : N.Tantalo et al 2002, 2007, 2008

- Compute an $F(m_b, m_q, L)$
- Compute an $F(m_b, m_q, 2L)$ and define

$$\sigma(m_b, m_q, L) = \frac{F(m_b, m_q, 2L)}{F(m_b, m_q, L)}$$

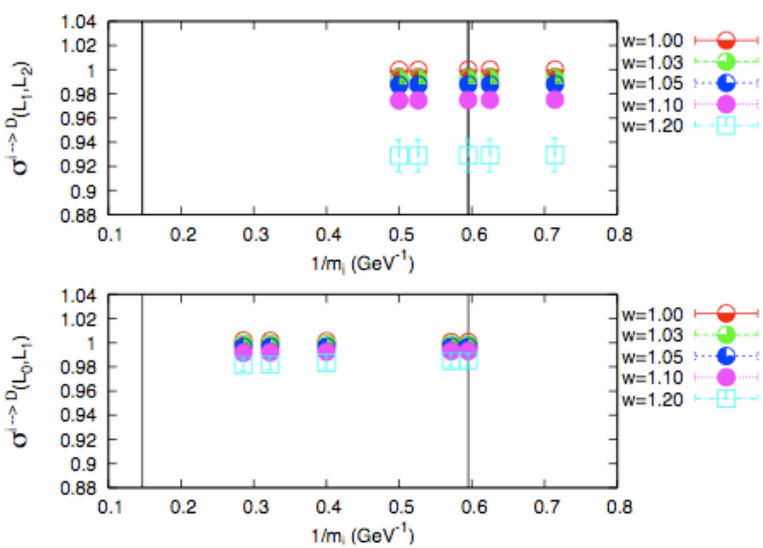
- Compute an $F(m_b, m_q, 4L)$ and check how fast $\sigma(m_b, m_q, 2nL)$ converges to 1
- Indeed for

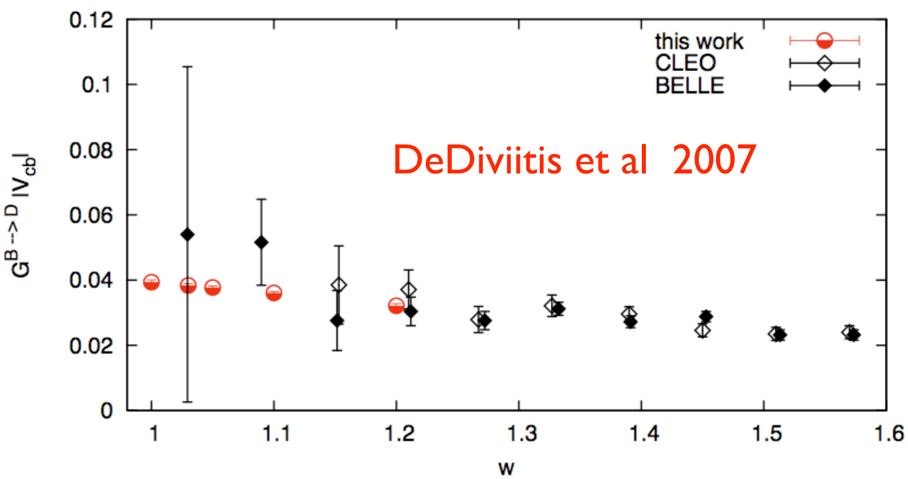
$$F(m_b, m_q, L) = F_0(m_q, L)\left[1 + \frac{F_1(m_q, L)}{m_b}\right] \Longrightarrow$$

$$\sigma(m_b, m_q, L) = \frac{F_0(m_q, 2L)}{F_0(m_q, L)}\left[1 + \frac{F_1(m_q, 2L) - F_1(m_q, L)}{m_b}\right]$$

B-physics:Step Scaling Method

$$\sigma^{i\to D}(w; L_0, L_1) = \frac{G^{i\to D}(w; L_1)}{G^{i\to D}(w; L_0)}$$





Unquenching is hard but feasible! Underway!
These results will be available and one then should use standard QCD expression for the decay spectra (no HQET).

Extending this strategy to $B \to \pi \ell \nu$ (?)

B-physics

$f_{B_{(s)}}$ and $f_{+,0}^{B/D}(q^2)$ simulations made with $N_{\rm f} = 2+1$ but only by using Staggered light quark = MILC configurations

f_B	f_{B_s}	f_D
Fermilab/MILC 0904.1895	Fermilab/MILC 0904.1895	Fermilab/MILC 0904.1895
195 ± 11 MeV	243 ± 11 MeV	207 ± 11 MeV
HPQCD/MILC 0507.015	HPQCD/MILC 0507.015	HPQCD/MILC 0706.1726
$216 \pm 22 \pm 7$ MeV	$1.20(3)(1) \times f_B$	208 ± 4 MeV

Chiral extrapolations guided by HMChPT

Range of validity compromised by the nearness of orbital excitations

$$\Delta_{S_s} \equiv m_{D^*_{0s}} - m_{D_s} = m_{D_{1s}} - m_{D^*_s} = 350 \text{ MeV}$$

$$\Delta_{S_{s,q}} < \Lambda_\chi, m_\eta, m_K$$

Work only with very light pions (cf.hep-ph/0612224)

ETMC 0904.0954

197 ± 9 MeV

DB & B.Haas to appear

205 ± 18 MeV

B-physics

$f_{B_{(s)}}$ and $f_{+,0}^{B/D}(q^2)$ simulations made with $N_{\rm f} = 2+1$ but only by using Staggered light quark = MILC configurations

f_B

Fermilab/MILC 0904.1895
195 ± 11 MeV

HPQCD/MILC 0507.015
$216 \pm 22 \pm 7$ MeV

f_{B_s}

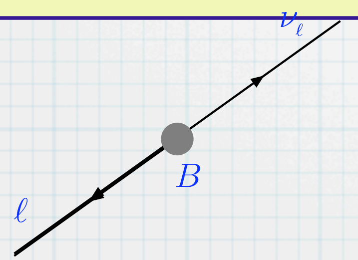
Fermilab/MILC 0904.1895
243 ± 11 MeV

HPQCD/MILC 0507.015
$1.20(3)(1) \times f_B$

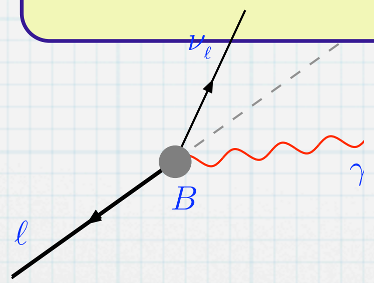
f_D

Fermilab/MILC 0904.1895
207 ± 11 MeV

HPQCD/MILC 0706.1726
208 ± 4 MeV



True leptonic event
$E_\ell = \frac{m_B}{2}$



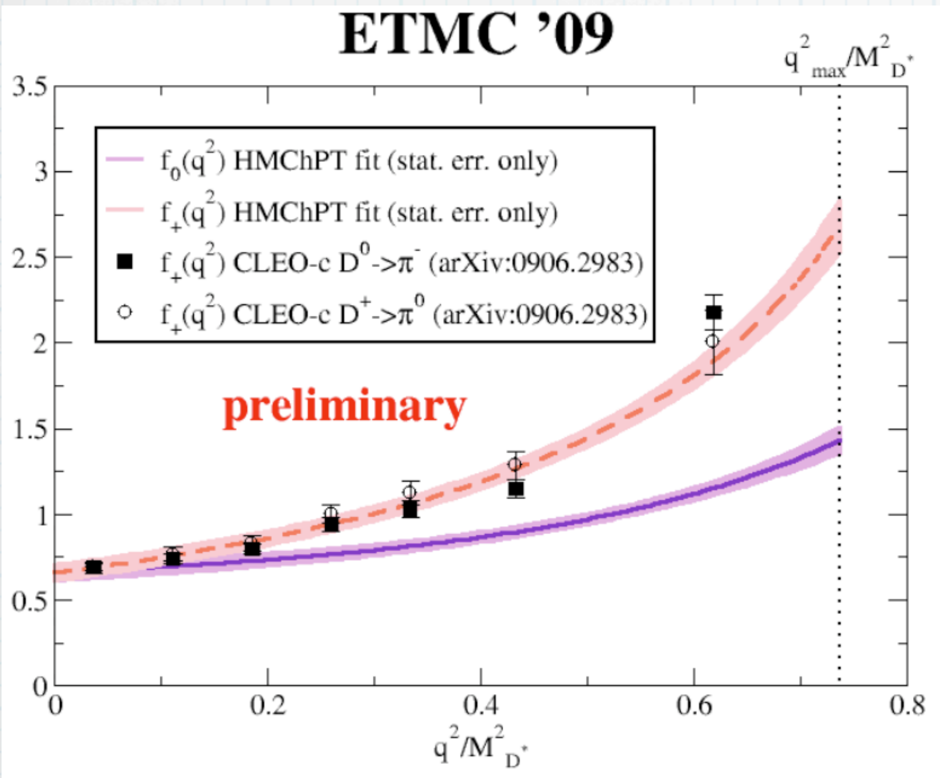
Fake leptonic event
$E_\ell \approx \frac{m_B}{2}$

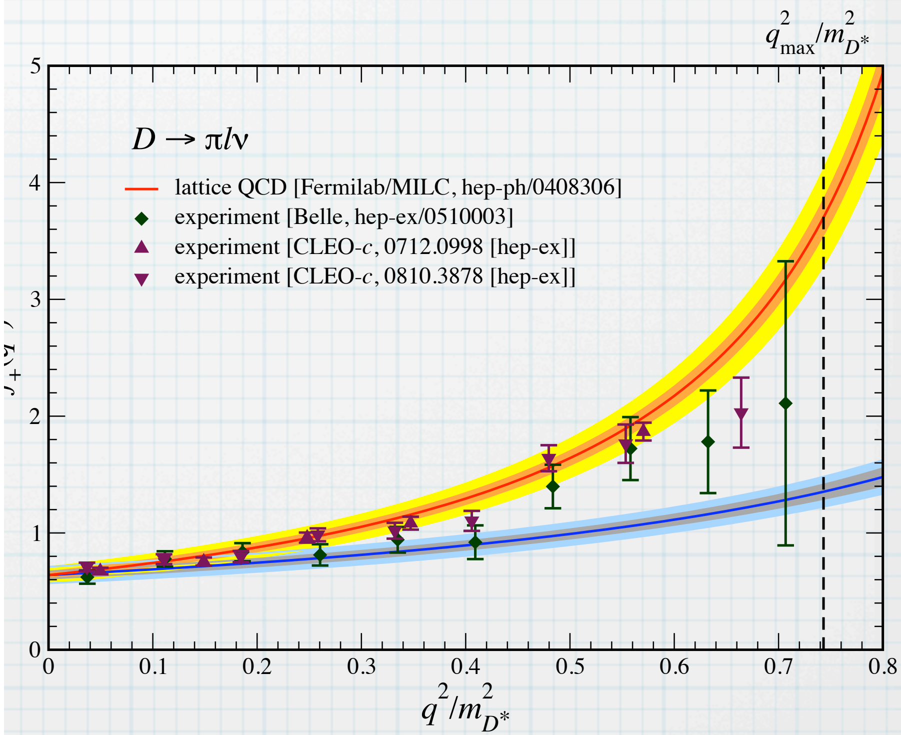
ETMC 0904.0954
197 ± 9 MeV

DB & B.Haas to appear
205 ± 18 MeV

Be VERY afraid of soft photon radiation : SD may be huge and compromise the study of $B \to \mu\nu_\mu$ c.f. 0907.1845 !!!

Heavy-to-light decay form factors





New physics flavor problem

New physics effects through higher dim. operators

e.g.

$$\frac{C_{sd}}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\mu^L d)(\bar{s}\gamma_L^\mu d) + \frac{C_{cu}}{\Lambda_{\rm NP}^2}(\bar{c}\gamma_\mu^L u)(\bar{c}\gamma_L^\mu u)$$
$$+\frac{C_{bd}}{\Lambda_{\rm NP}^2}(\bar{b}\gamma_\mu^L d)(\bar{b}\gamma_L^\mu d) + \frac{C_{bs}}{\Lambda_{\rm NP}^2}(\bar{b}\gamma_\mu^L s)(\bar{b}\gamma_L^\mu s)$$

if NP had a generic flavor structure then all $C_{xy} \sim 1$

Meson mixing:

$$\frac{\Delta M_B}{M_B} \approx C_{bd}\left(\frac{f_B}{\Lambda_{\rm NP}}\right)^2$$

New physics flavor problem

if NP had a generic flavor structure then all $C_{xy} \sim 1$

As a result

$$\Lambda_{\rm NP} \gtrsim \begin{cases} 1 \times 10^4 \ \text{TeV} & \varepsilon_K \\ 9 \times 10^2 \ \text{TeV} & \Delta M_D \\ 4 \times 10^2 \ \text{TeV} & \Delta M_B \\ 7 \times 10^1 \ \text{TeV} & \Delta M_{B_s} \end{cases}$$

New physics flavor problem

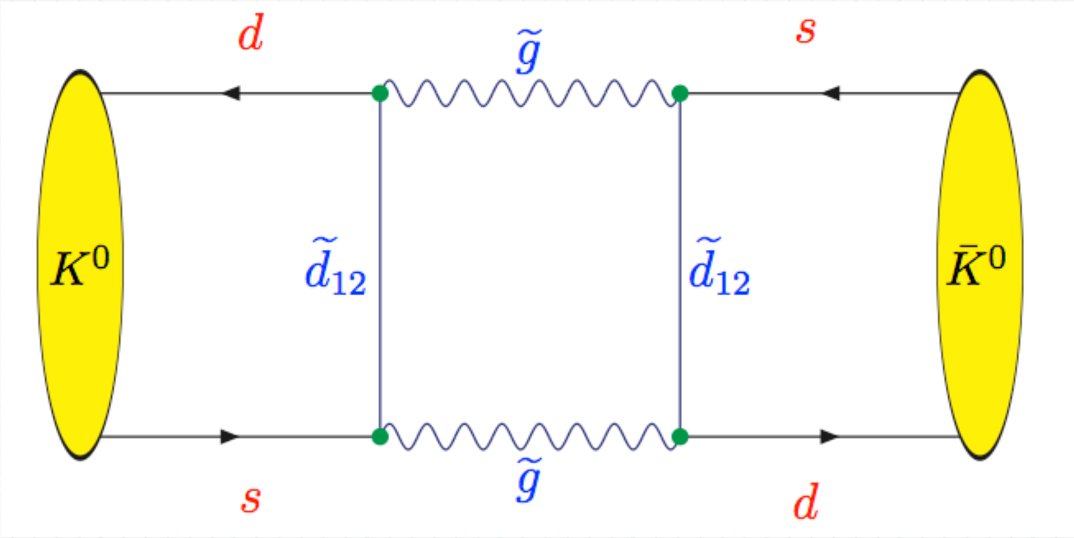
For $\Lambda_{\rm NP} = 1\ {\rm TeV}$

$$\begin{aligned}
{\rm Im}[C_{sd}] &\lesssim 6 \times 10^{-9} \\
{\rm Im}[C_{cu}] &\lesssim 1 \times 10^{-6} \\
{\rm Im}[C_{bd}] &\lesssim 2 \times 10^{-6} \\
{\rm Im}[C_{bs}] &\lesssim 2 \times 10^{-4}
\end{aligned}$$

The flavor structure of NP is not generic! Why?

SUSY flavor problem

For



$$\frac{\Delta M_K}{M_K} = 7.0 \times 10^{-15}$$

$$= \eta_K g(m_{\tilde{g}}^2/m_{\tilde{d}}^2) \frac{\alpha_s^2}{108} \frac{B_K f_K}{m_{\tilde{d}}^2} \frac{(\Delta m_{\tilde{d}}^2)^2}{m_{\tilde{d}}^4} \left(K_{21}^d K_{11}^d\right)^2$$

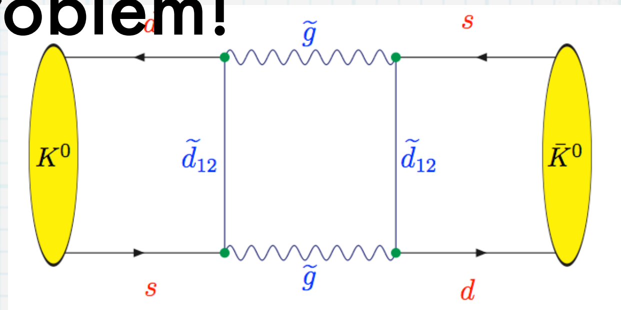
$$\Longrightarrow \frac{\text{TeV}}{m_{\tilde{q}}} \times \frac{\Delta m_{\tilde{q}}^2}{m_{\tilde{q}}^2} \times \sin\theta_d \leq 0.01$$

SUSY flavor problem

Beyond MFV - extra operators LR, RL, RR

- matrix elements LQCD + 2loop ADM
- many more parameters

you do not dodge the flavor problem!



$$\frac{\Delta M_K}{M_K} = 7.0 \times 10^{-15}$$

$$= \eta_K g(m^2_{\tilde{g}}/m^2_{\tilde{d}}) \frac{\alpha_s^2}{108} \frac{B_K f_K}{m^2_{\tilde{d}}} \frac{(\Delta m^2_{\tilde{d}})^2}{m^4_{\tilde{d}}} \left(K^d_{21} K^d_{11}\right)^2$$

$$\Longrightarrow \quad \frac{\mathrm{TeV}}{m_{\tilde{q}}} \times \frac{\Delta m^2_{\tilde{q}}}{m^2_{\tilde{q}}} \times \sin\theta_d \leq 0.01$$

SUSY flavor problem

$$\frac{\Delta M_K}{M_K} = 7.0 \times 10^{-15} \Longrightarrow \frac{\text{TeV}}{m_{\tilde{q}}} \times \frac{\Delta m^2_{\tilde{q}}}{m^2_{\tilde{q}}} \times \sin\theta_d \leq 0.01$$

$$\frac{\Delta M_D}{M_D} \lesssim 2.0 \times 10^{-14} \Longrightarrow \frac{\text{TeV}}{m_{\tilde{q}}} \times \frac{\Delta m^2_{\tilde{q}}}{m^2_{\tilde{q}}} \times \sin\theta_u \leq 0.10$$

Heavy $m_{\tilde{q}} \gg 1\ \text{TeV}$ [split SUSY]

Degeneracy $(\Delta m_{\tilde{q}})^2 \ll m^2_{\tilde{q}}$ [gauge mediation]

Alignment $\sin\theta_d \ll 1$ [horizontal symm]