Charm physics in lattice QCD

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Charm physics in lattice QCD

- 格点QCD
- 粲物理相关的格点QCD计算
  - 衰变常数
  - 形状因子(半轻树图过程)
  - 粲夸克质量
  - D-Dbar混合
- 小结

格点量子色动力学(Lattice QCD)

- 高能实验和微扰计算告诉我们，**QCD**是描写夸克、胶子之间强相互作用的正确理论
- 但怎么将强子与**QCD**的基本自由度夸克、胶子联系起来？
- 低能标下**QCD**不能微扰求解，需要非微扰的办法
- 格点**QCD**用数值模拟的办法，能非微扰地研究低能**QCD**性质
- 固定参数 α_s 和夸克(流)质量后，即可给出其他物理量

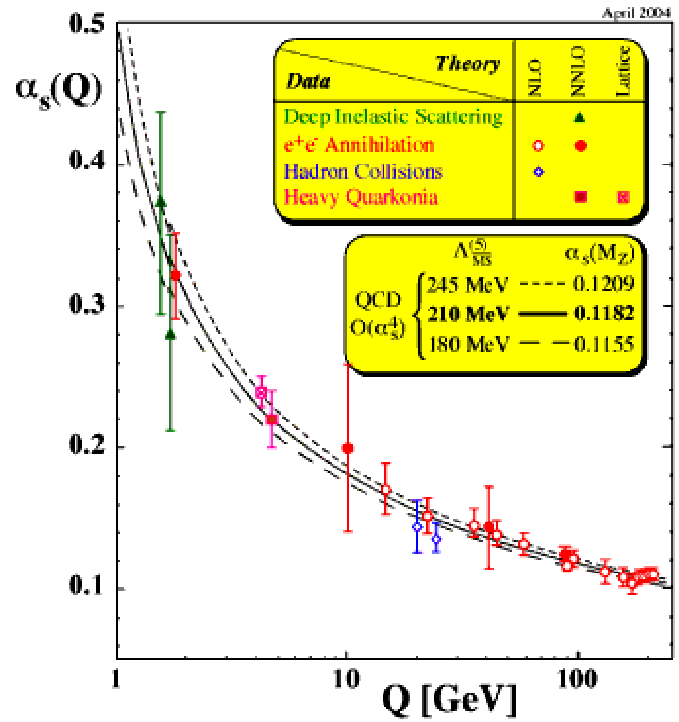


FIG. 1: QCD running coupling constant

格点QCD

- **1973年Kenneth G. Wilson提出**
- **1979年M. Creutz首个计算机上的数值计算**
- **1980年开始制造并行计算机专用于LQCD计算**

Edison, NERSC

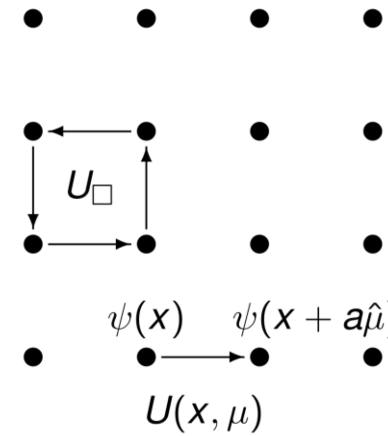
2.57 Pflops 2014

QCD on chips(QCDOC)

2X10 Tflops 2005

IBM (BG/L)

格点QCD



- LQCD is based on the path integral formalism in Euclidean space.
- $\langle O \rangle = \dfrac{\int DA_\mu D\bar{\psi} D\psi O[A,\bar{\psi},\psi] e^{-\int \mathcal{L}_{QCD}\, d^4x}}{\int DA_\mu D\bar{\psi} D\psi e^{-\int \mathcal{L}_{QCD}\, d^4x}}$,

where $\mathcal{L}_{QCD} = \bar{\psi} M[A] \psi + \mathcal{L}_G$, $\quad M = \gamma \cdot D + m_q$

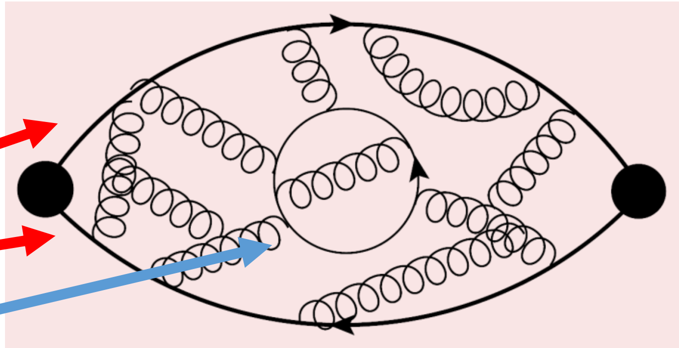
- On the 4D lattice, the A fields are put on the links

$$U(x,\mu) = e^{igaA_\mu}.$$

- 完成费米子场的积分:

$$\langle O \rangle = \frac{\int DU_\mu O[U, M^{-1}[U]] \mathrm{Det}[M[U]] e^{-S_G}}{\int DU_\mu \mathrm{Det}[M[U]] e^{-S_G}}$$

Lattice QCD



- $\langle O\rangle = \frac{\int DU_\mu O[U, M^{-1}[U]]\mathrm{Det}[M[U]]e^{-S_G}}{\int DU_\mu \mathrm{Det}[M[U]]e^{-S_G}}$
- 价夸克传播子 $M^{-1}[U]$
- 海夸克效应 $\mathrm{Det}[M[U]]$
- 用重点抽样产生组态：**gluon fields** U (最耗费机时的部分)
- 计算价夸克传播子和强子关联函数 (很耗费机时, 大量硬盘空间)
- 数据分析和拟合：强子质量及矩阵元
- 确定格距 a 和夸克质量 m_q， 给出其他物理结果

按几率分布产生组态

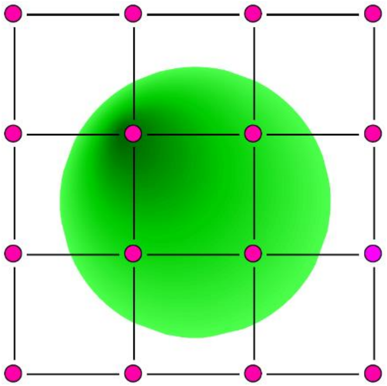
$P[U] \propto \mathrm{Det}[M[U]]e^{-S_G}$

对规范场的路径积分变为对组态的统计平均

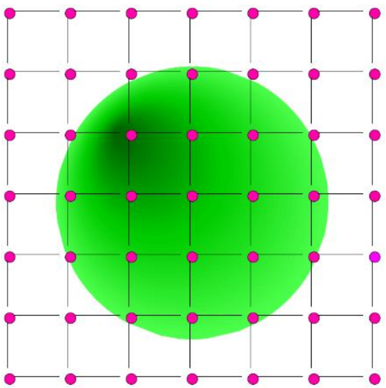
$\langle O\rangle = \frac{1}{N}\sum_{i=1}^{N} O_i$

统计误差：N有限

格点QCD：误差



- 除了统计误差，还有系统误差
  - 非零格距a引入离散误差，连续极限$a \to 0$
  - 多数情况下$m_\pi > 135$ MeV，手征外推
  - 有限体积，格子边长L需大于π介子康普顿波长$1/m_\pi$
- 在多个不同的a、L、m_π下作计算，量化和控制系统误差
- 其他误差来源：重整化常数, ……
- 目前最小的$a \approx 0.05$ fm (a越小，同样体积需要格子数越多)
- 海夸克味道数$N_f = 2+1+1, 2+1, 2, 0$(淬火近似)
- 已开始有$m_\pi = 135$ MeV的组态产生



味物理与LQCD

- LQCD can calculate form factors and meson decay constants appearing in weak decays of hadrons
- Combined with experiments, they can give us CKM matrix elements
- Test the SM (is CKM unitary?)
- Or use V_{ab} from elsewhere to compare QCD/SM results with experiments

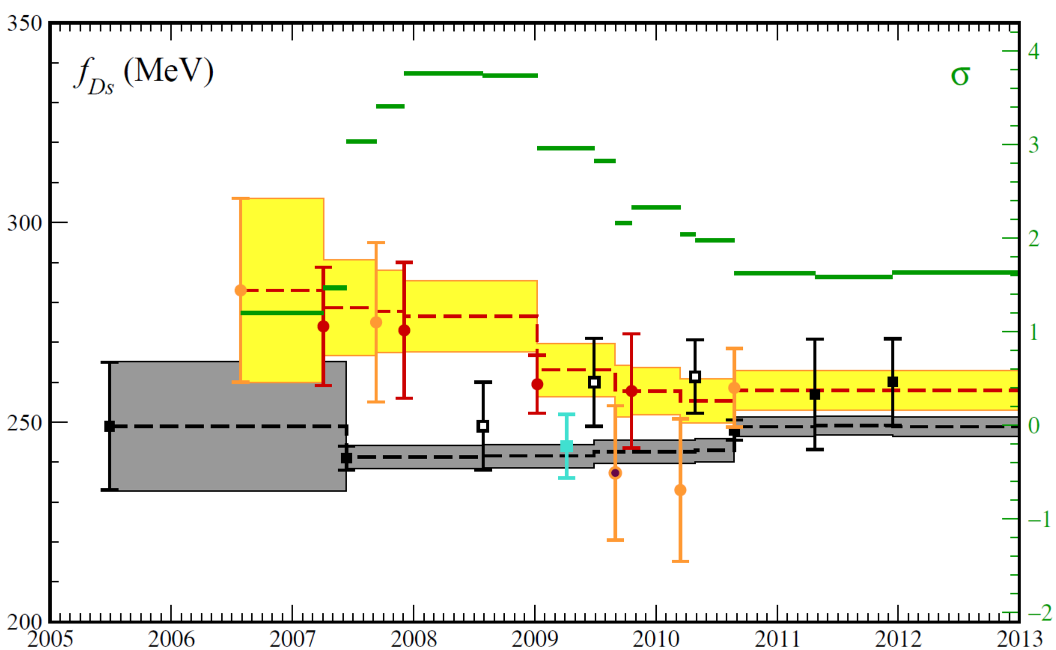
$$\begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \pi \to \ell\nu & K \to \ell\nu & B \to \pi\ell\nu \\ & K \to \pi\ell\nu & \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ D \to \ell\nu & D_s \to \ell\nu & B \to D\ell\nu \\ D \to \pi\ell\nu & D \to K\ell\nu & B \to D^*\ell\nu \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\ B_d \leftrightarrow \overline{B}_d & B_s \leftrightarrow \overline{B}_s & \end{pmatrix}$$

Can be calculated by LQCD

例如: $$\Gamma(P \to \ell\nu) = \frac{G_F^2 |V_{q_1 q_2}|^2}{8\pi} f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2$$

衰变常数，例如f_{D_s}

- 衰变常数与纯轻衰变的实验测量结合起来可确定$|V_{cd}|$和$|V_{cs}|$



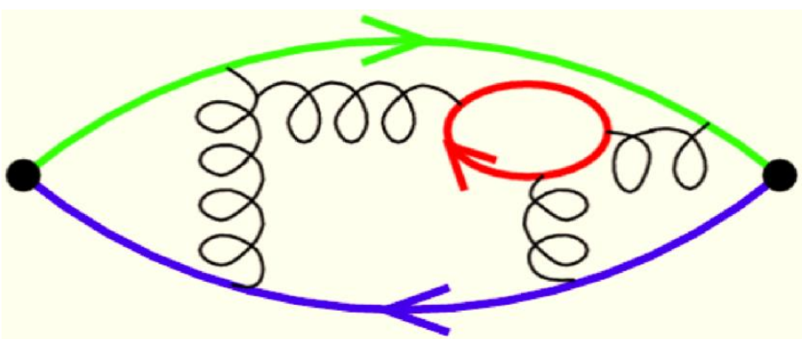
- **2013年之前的情况**
- **灰颜色：2+1味格点平均(FNAL/MILC, HPQCD, PACS-CS)**
- **黄颜色：实验平均 (BaBar, Belle, CLEO-c)**
- **青色点：ETMC 2味格点计算, 未计入平均**

Kronfeld, 1203.1204

赝标介子衰变常数

- $\langle 0|\overline{q}\gamma_\mu\gamma_5 c|P(p)\rangle = f_P p_\mu, \quad q = d, s$
- **Let $O = \overline{q}\gamma_0\gamma_5 c$, its matrix element can be obtained from**

$$C(t) = \langle 0|O(t)O^\dagger(0)|0\rangle \xrightarrow{t\to\infty} |\langle 0|O|P\rangle|^2 e^{-m_P t}$$



Heavier hadrons with same quantum numbers as O are suppressed at large t.

f_{D_s}

χQCD Collaboration:
Y.-B. Yang et al., PRD92, 2015
ZL et al., PRD90, 2014 (Z_m, Z_A...)

- $\langle 0|\bar{s}\gamma_\mu\gamma_5 c|D_s\rangle = f_{D_s} p_\mu$
- The local current $\bar{s}\gamma_\mu\gamma_5 c$ on the lattice needs a (re)normalization Z_A
- Using the PCAC relation, one can also get f_{D_s} by

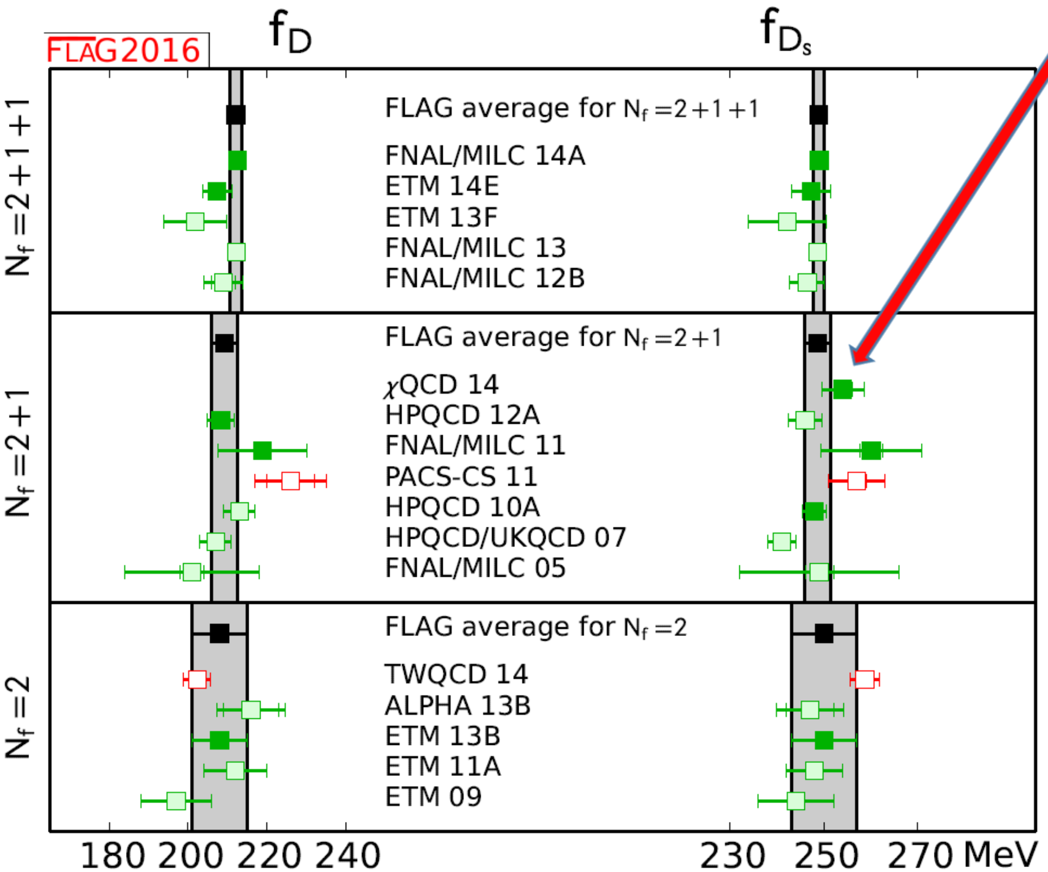
$$(m_s + m_c)\langle 0|\bar{s}\gamma_5 c|D_s\rangle = f_{D_s} M_{D_s}^2$$

No renormalization is needed due to $Z_P Z_m = 1$ (for chiral fermions on the lattice)

- f_{D_s} are obtained from both methods in our work (2+1味).
- We find $f_{D_s} = 254(2)(4)$ MeV

f_D和f_{D_s}

ZL et al., PRD90, 2014
Y.-B. Yang et al., PRD92, 2015



FLAG2016, arXiv:1607.00299

- $N_f = 2+1$:
  $f_{D_s} = 249.8(2.3)$ MeV
- $N_f = 2+1+1$:
  $f_{D_s} = 248.83(1.27)$ MeV
- PDG2016 (CPC40,100001):
  $f_{D_s^+}^{exp} = 257.8(4.1)$ MeV
- 格点结果与实验在2σ之内一致
- 预期2020年实验精度将与理论精度持平（BESIII和BelleII）

f_{D_s}和f_D

N_f	Collaboration	f_D [MeV]	f_{D_s} [MeV]	m_π^{min} [MeV]	a [fm]	# a
2+1	RBC/UKQCD [2]	$208.7(2.8)\left(^{+2.1}_{-1.8}\right)$	$246.4(1.3)\left(^{+1.3}_{-1.9}\right)$	**139**	0.07-0.11	3
	JLQCD [3][1]	212.8(1.7)(3.6)	244.0(0.8)(4.1)	230	0.044-0.08	3
	χQCD [4]		254(2)(4)	300	0.08-0.11	2
	HPQCD [5]	208.3(1.0)(3.3)	246.0(0.7)(3.5)	245	0.08-0.12	2
	HPQCD [6]		248.0(2.5)	260	0.045-0.15	5
	FNAL/MILC [7]	218.9(11.3)	260.1(10.8)	230	0.09-0.15	3
2+1+1	FNAL/MILC [8]	$212.6(0.4)\left(^{+1.0}_{-1.2}\right)$	$249.0(0.3)\left(^{+1.1}_{-1.5}\right)$	**130**	0.06-0.15	4
	ETM [9]	207.4(3.8)	247.2(4.1)	210	0.06-0.09	3

[1702.05360]

- **2015年后的两个计算：RBC/UKQCD (1701.02644)，JLQCD**
- **JLQCD (lattice2016, 1702.02303)：系统误差尚只考虑了格距标定。**

f_{D^*}和$f_{D_s^*}$

- 矢量介子衰变常数的定义：

$$\langle 0|\bar{q}(0)\gamma^{\mu}q'(0)|V(p,\lambda)\rangle = f_V m_V e_{\lambda}^{\mu}$$

- 矢量介子的纯轻衰变宽度，如D_s^*(尚无实验测量)

$$\Gamma_{(D_s^*\to\ell\nu)} = \frac{G_F^2}{12\pi}|V_{cs}|^2 f_{D_s^*}^2 M_{D_s^*}^3 \left(1-\frac{m_\ell^2}{M_{D_s^*}^2}\right)^2\left(1+\frac{m_\ell^2}{2M_{D_s^*}^2}\right)$$

- 用因子化方法研究$B\to D^{(*)}M$等过程时也需要用到f_{D^*}等衰变常数

f_{D^*}和$f_{D_s^*}$

- 我们正在做的一个计算(overlap on domain wall)

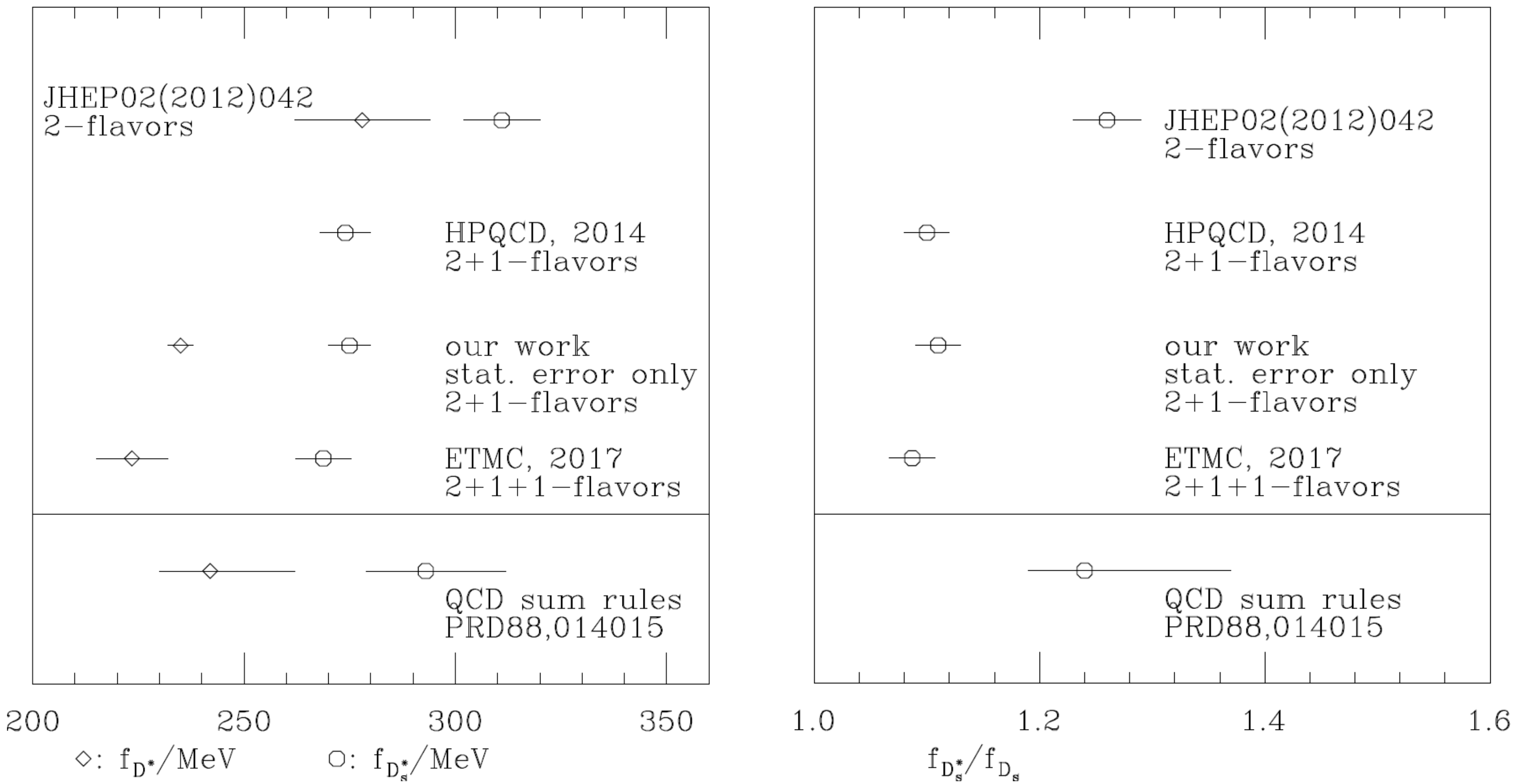
$1/a$(GeV)	label	am_{sea}	volume
1.730(4)	48I	0.00078/0.0362	$48^3 \times 96$

- 轻夸克质量接近物理点：$m_\pi = 139.2(4)$ MeV
- 2+1味组态(RBC/UKQCD合作组产生)
- 初步结果(尚无系统误差)

	D	D^*	D_s	D_s^*
f_M/MeV	213(1)	235(3)	248(2)	275(5)

$f_{D^*}/f_D = 1.10(3)$　　　　$f_{D_s^*}/f_{D_s} = 1.11(2)$

f_{D^*}和$f_{D_s^*}$



- **HPQCD, PRL112, 212002 (2014)** **2个格距, 2+1味**
- **ETMC, PRD96, 034524 (2017)** **3个格距, 2+1+1味**
- **Becirevic et al., JHEP02 (2012) 042** **4个格距, 2味**
- **Large sea quark effects?**

粲介子半轻衰变（树图过程）

- $D \to \pi l \nu$， $D \to K l \nu$可用于确定 $|V_{cd}|$和$|V_{cs}|$

$$\frac{d\Gamma(D \to K\ell\nu)}{dq^2} = (\text{known})\,|\mathbf{p}_K|^3\,|V_{cs}|^2\,\left|f_+^{D\to K}(q^2)\right|^2$$

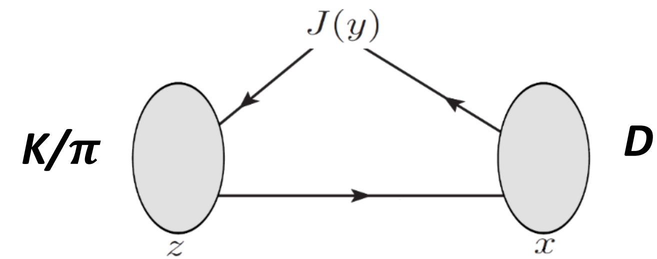
- 需要形状因子f_+

$$\langle K|V^\mu|D\rangle = f_+(q^2)\left(p_D^\mu + p_K^\mu - \frac{m_D^2 - m_K^2}{q^2}q^\mu\right) + f_0(q^2)\frac{m_D^2 - m_K^2}{q^2}q^\mu$$

(对于$l = e, \mu$, 形状因子f_0的贡献可忽略)

- 其他道：$D_s \to \phi l \nu$，$D_s \to \eta^{(\prime)} l \nu$

形状因子的格点计算



- 计算三点函数, 例如:

$$C_3(\vec{p},\vec{p}',T,t) = \sum_{\vec{x}}\sum_{\vec{y}} \langle 0|O_D(\vec{x},T)J(\vec{y},t)O_P^\dagger(\vec{z},0)|0\rangle e^{-i\vec{p}\cdot\vec{x}} e^{i\vec{q}\cdot\vec{y}}$$

$$\xrightarrow[(T-t)\to\infty]{t\to\infty,\ T\to\infty} \langle 0|O_D|D\rangle\langle D|J|P\rangle\langle P|O_P^\dagger|0\rangle e^{-m_P t} e^{-m_D(T-t)}$$

- $q^2 = (p-p')^2$, 格点计算中3-动量取分立值(周期性BC)
- 对于$D\to K/\pi$, $q^2=0$附近有数值结果, 可内插, 对q^2依赖的参数化形式不敏感
- 或者用twisted BC直接在$q^2=0$点计算

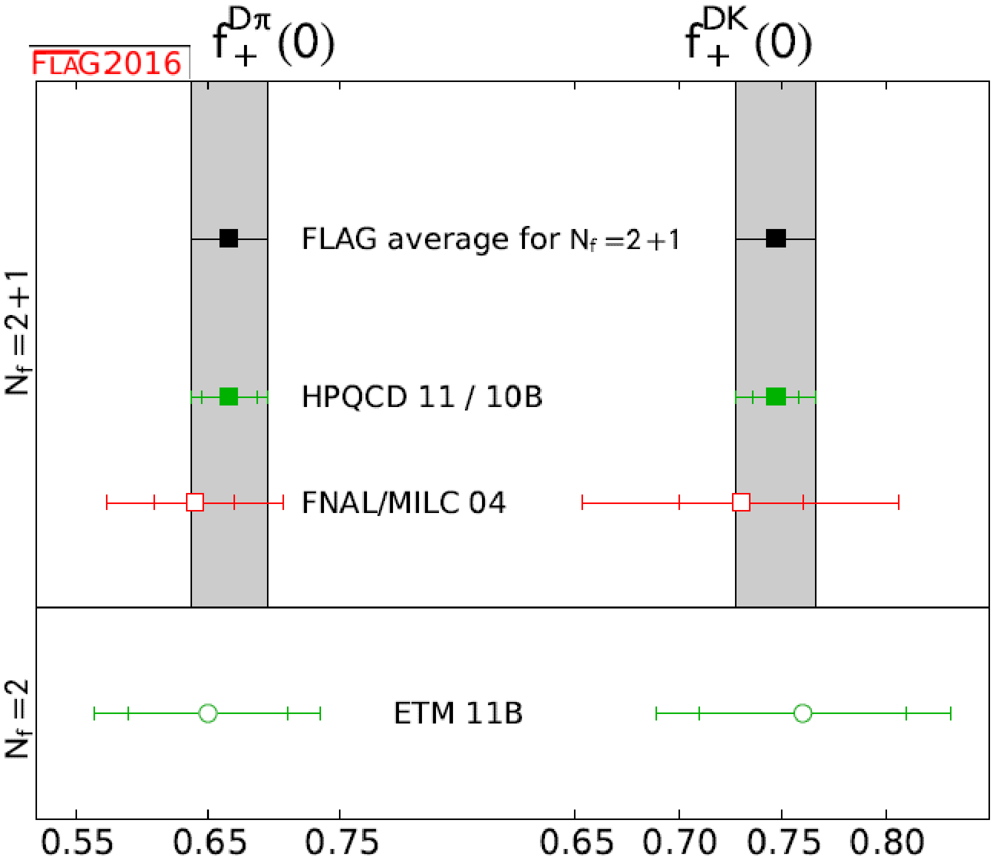
形状因子的格点计算

- 直接算f_+需要V^μ的重整化常数，引入额外误差
- HPQCD计算$f_+(0) = f_0(0)$
- 利用PCVC：$\partial_\mu V^\mu = (m_c - m_s)S$, 可得

$$\langle K|S|D\rangle = f_0^{D\to K}(q^2)\frac{M_D^2 - M_K^2}{m_c - m_s}$$

- 手征格点费米子有$Z_S Z_m = 1$, 无需计算重整化常数
- 但不能考察f_+随q^2的变化行为

$f_+(q^2 = 0)$



- **FNAL/MILC/HPQCD 04: 一个格距，m_π大于500 MeV**
- $f_+^{D\pi}(0) = 0.666(29)$ **[HPQCD, PRD84,114505, 1109.1501]**
- $f_+^{DK}(0) = 0.747(19)$ **[HPQCD, PRD82,114506, 1008.4562]**

ETMC, LAT2010

FLAG2016, arXiv:1607.00299

$|V_{cd}|$和$|V_{cs}|$

- **PDG2016(CPC40,100001)**:

$$f_D|V_{cd}| = 45.91(1.05)\ \text{MeV}$$

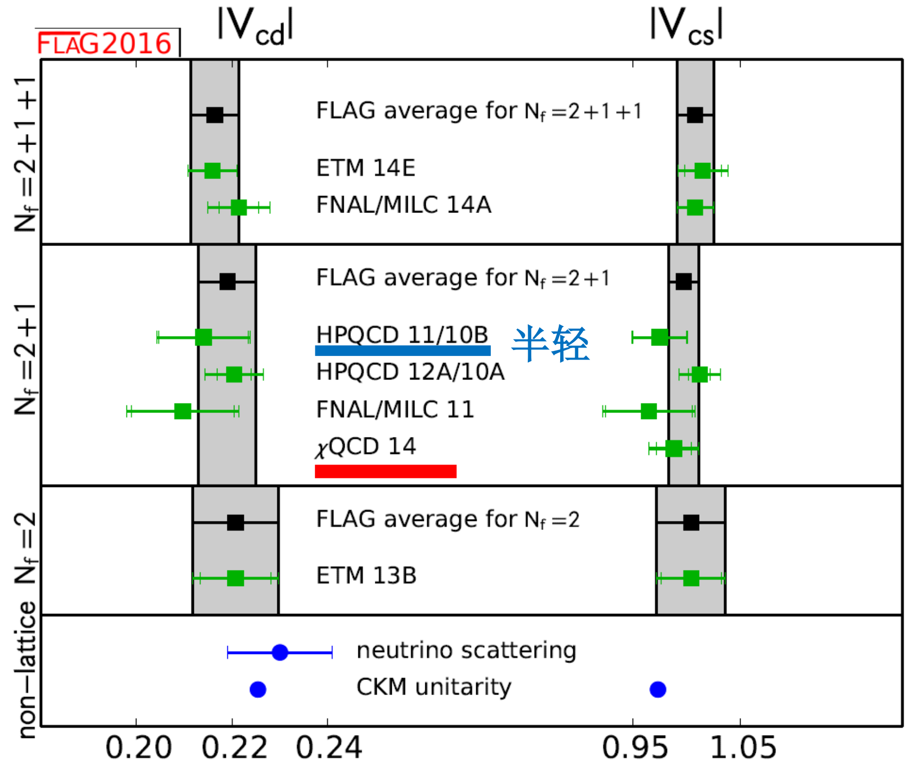
$$f_{D_s}|V_{cs}| = 250.9(4.0)\ \text{MeV}$$

- **HFAG2014**:

$$f_+^{D\pi}(0)|V_{cd}| = 0.1425(19)$$

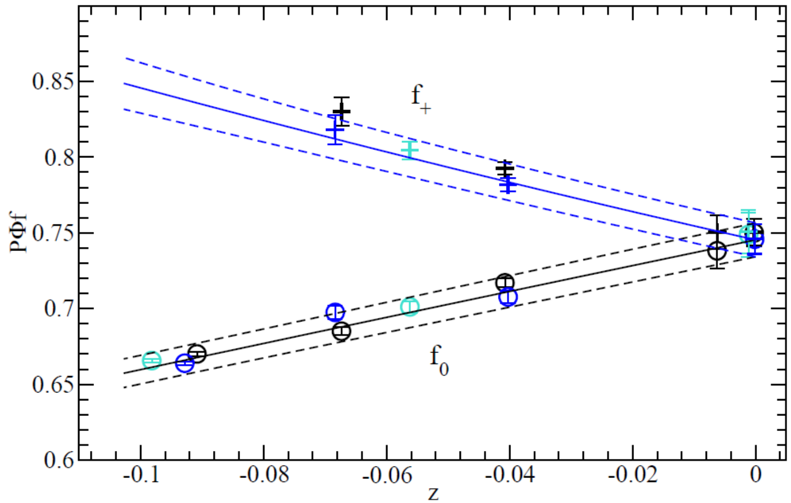
$$f_+^{DK}(0)|V_{cs}| = 0.728(5)$$

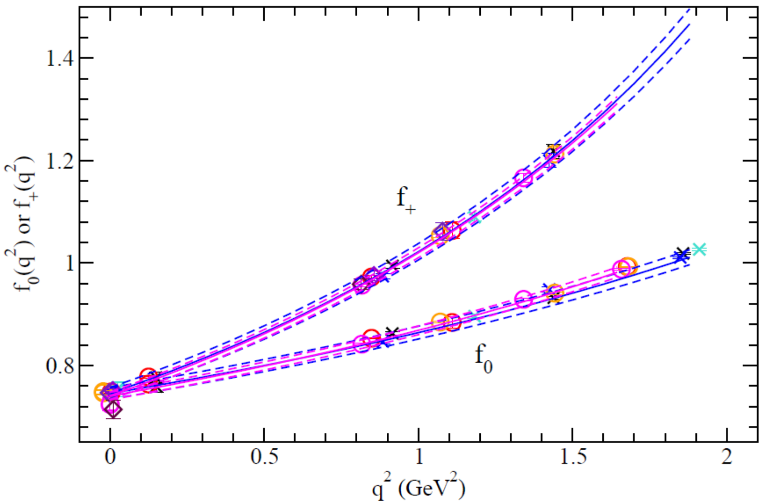
- **LQCD误差比实验误差大(半轻)**
- **和CKM幺正性结果~2σ一致**



Form factor shapes

- **Form factor shape对参数化形式有依赖，现在一般用z-expansion**
- **HPQCD, LAT2011(1111.0225), Charm2012(1208.6242), 1305.1462**
- $\boldsymbol{f_+^{DK}(0) = 0.745(11)}$



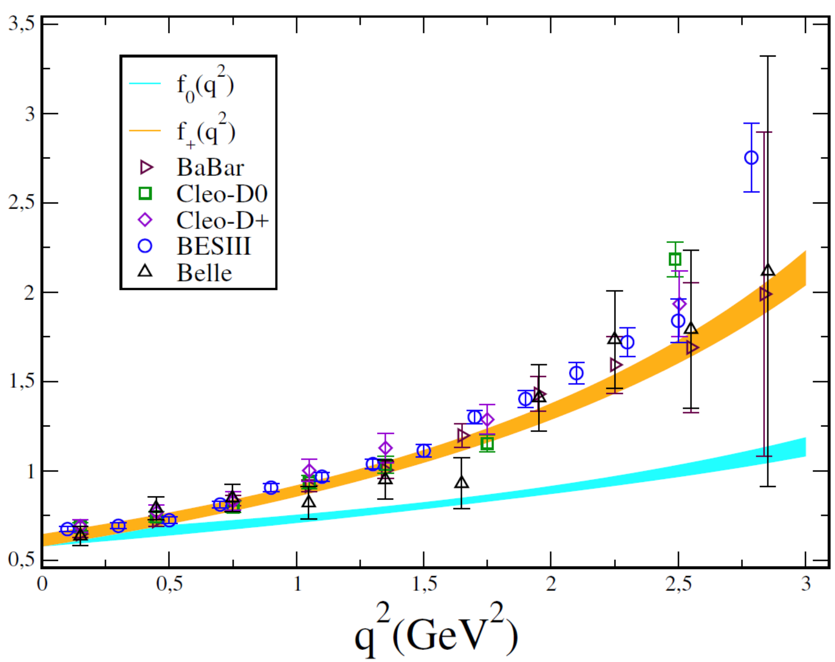


$\boldsymbol{D \to Kl\nu}$, **HPQCD 1305.1462**

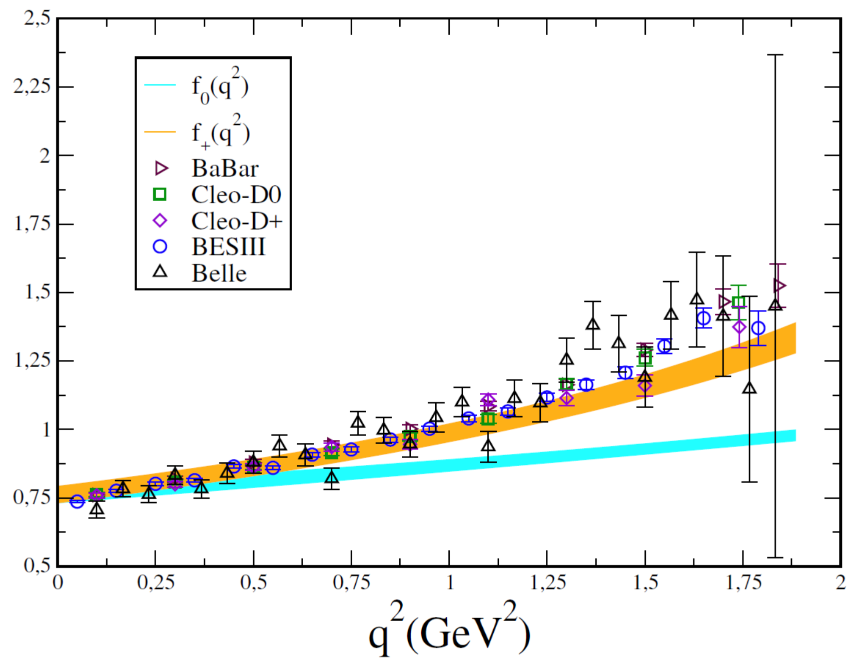
$f_+^{D\pi(K)}$和$f_0^{D\pi(K)}$：2015年后的计算

- JLQCD, Lattice2016, 1701.00942,初步结果
  - 3个格距，2+1味，Mobius domain wall fermions
  - $f_+^{D\pi}(0) = 0.644(49)(27), f_+^{DK}(0) = 0.701(46)(33)$
- ETMC, 1706.03017
  - 3个格距，2+1+1味，Twisted mass fermions

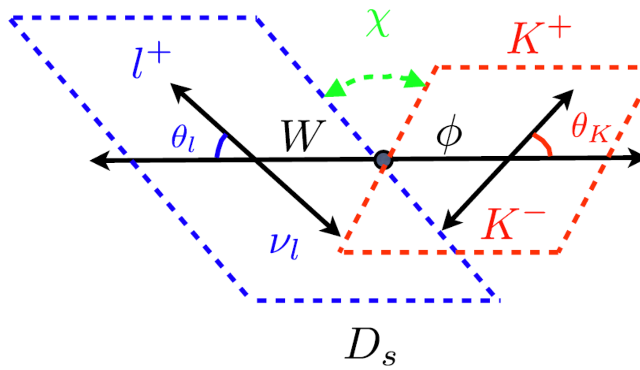
$D \to \pi$



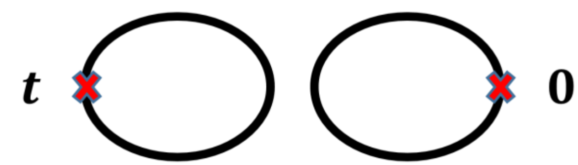
$D \to K$



其他衰变道



- D_s的半轻衰变主要是到ϕ、$\eta^{(\prime)}$
- 格点计算牵涉到(费米子线)非连通图, 更困难
- $D_s \to \phi l \nu$ [HPQCD, PRD90, 1311.6669]
  - 除了在q^2-bin中比较截面, 还有更多观测量, $\phi \to K\bar{K}$
  - 计算忽略非连通图贡献(OZI压低)
  - 数据中ϕ不衰变; ϕ宽度较窄, 预期阈效应小
  - 形状因子V, A_2, A_1, A_0；z-expansion
  - 2+1味；两个格距；HISQ价夸克作用量
  - 和*BABAR*, CLEO $D \to K^*$的结果做了比较
  (假设spectator quark的影响很小)



其他衰变道

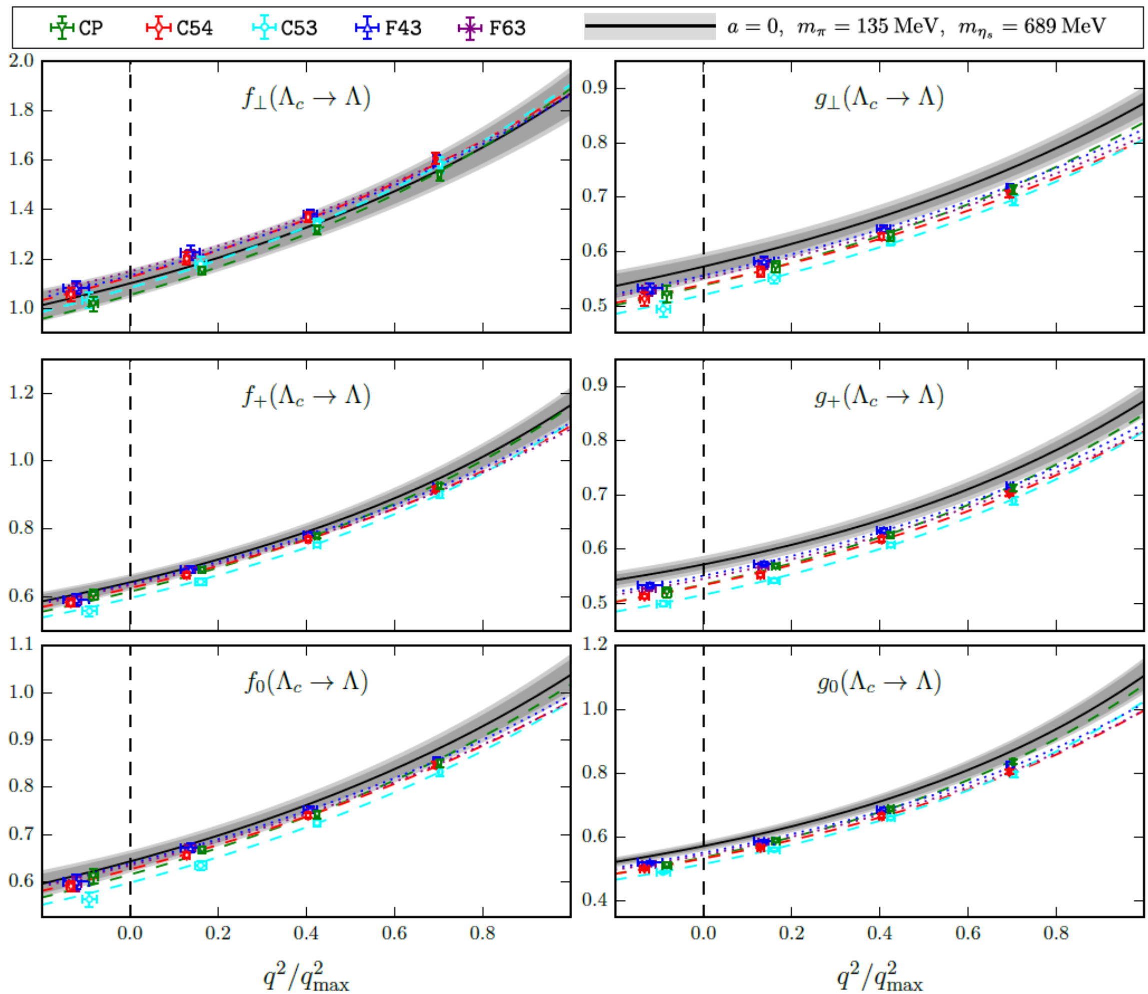
- $D_s \to \eta^{(\prime)} l\nu$ [G. S. Bali, S. Collins, S. Durr, I. Kanamori, PRD91,014503 (2015) 1406.5449]
  - 2+1味；一个格距：~0.075 fm
  - 两个轻夸克质量点：m_π = 370和470 MeV
  - 计算了非连通图
  - 用标量算符计算f_0；
  - 单极点ansatz参数化q^2依赖
- $\Lambda_c \to \Lambda l\nu$: [S. Meinel, PRL (2017) 1611.09696]
  - 2+1味；两个格距；m_π = 139 -- 352 MeV(4个取值)；
  - (轴)矢量流：6个形状因子
  - z-expansion

$\Lambda_c \to \Lambda l\nu$

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0380(19)_{\rm LQCD}(11)_{\tau_{\Lambda_c}}, & \ell = e, \\ 0.0369(19)_{\rm LQCD}(11)_{\tau_{\Lambda_c}}, & \ell = \mu \end{cases}$$

S. Meinel, PRL(2017) 1611.09696

- 得到的$|V_{cs}|$和从$D_s \to l\nu$得到的一致



$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0363(38)(20), & \ell = e, \\ 0.0349(46)(27), & \ell = \mu. \end{cases}$$

BESIII, PRL(2015) 1510.02610
BESIII, PLB(2017) 1611.04382

小结

- 粲物理相关的格点QCD计算有助于精确检验标准模型
  - 衰变常数
  - 形状因子
  - 粲夸克质量
  - D-Dbar混合
- 结果正变得越来越精确(误差百分之几)
- 相关强子矩阵元的格点计算需要大量计算资源

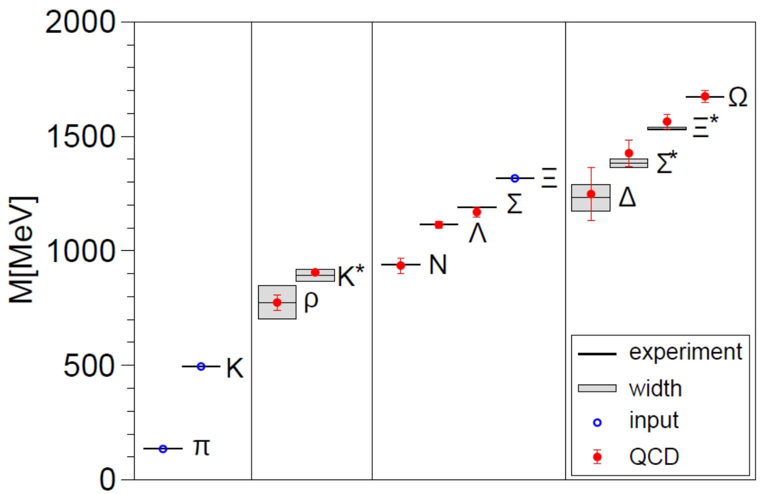
  ($\sim\boldsymbol{O}(10-100)$百万 cpu-hours/project, 不含组态产生)

请大家多多支持CLQCD！

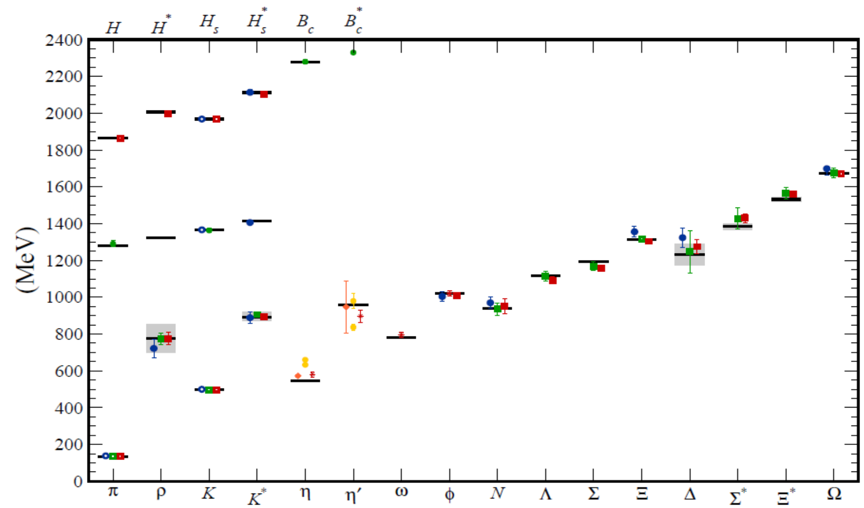
谢谢！

格点QCD

- 强子谱：实验输入(如$m_\pi, m_K, \ldots$)定出 a 和 m_q，输出其他强子质量
- 不同格点作用量给出一致结果；预言了B_c和B_c^*的质量(HPQCD)



Science 2008, BMW

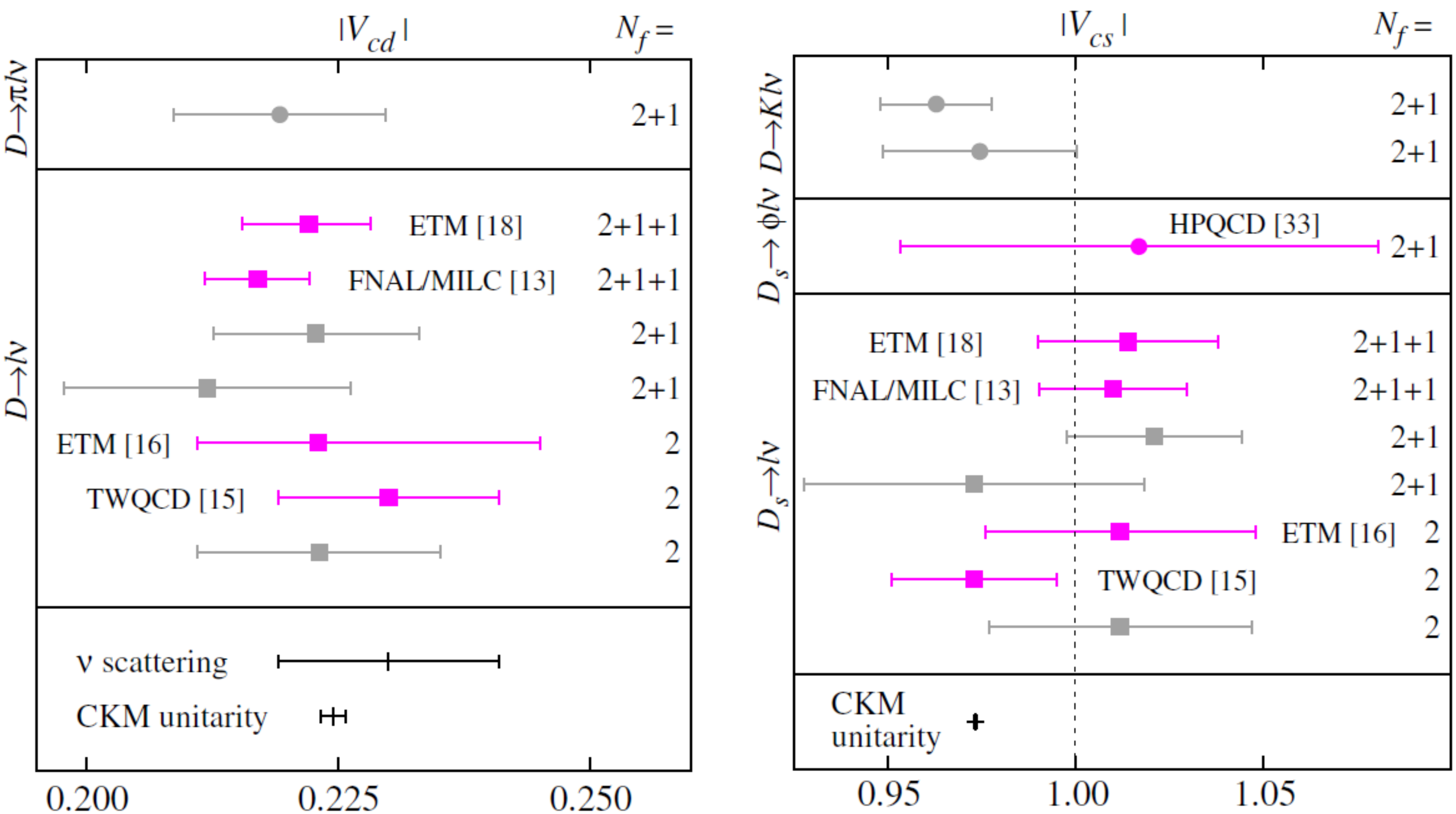


MILC,PACS-CS,BMW,RBC-UKQCD……,arXiv:1203.1204

- 胶球， J/psi辐射衰变
- D介子低能散射的研究：XYZ相关
- 强子结构：PDF，质子自旋
- 有限温度有限密度QCD
- ……

$|V_{cd}|$和$|V_{cs}|$

[Bouchard, Lattice2014]



$\Lambda_c \to \Lambda l\nu$

- **6个形状因子**
- **b is to be replaced by c at below**

$$\langle\Lambda(p',s')|\bar{s}\gamma^\mu b|\Lambda_b(p,s)\rangle = \bar{u}_\Lambda(p',s')\bigg[f_0(q^2)(m_{\Lambda_b}-m_\Lambda)\frac{q^\mu}{q^2} + f_+(q^2)\frac{m_{\Lambda_b}+m_\Lambda}{s_+}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_\Lambda^2)\frac{q^\mu}{q^2}\right)$$
$$+ f_\perp(q^2)\left(\gamma^\mu - \frac{2m_\Lambda}{s_+}p^\mu - \frac{2m_{\Lambda_b}}{s_+}p'^\mu\right)\bigg]u_{\Lambda_b}(p,s),$$

$$\langle\Lambda(p',s')|\bar{s}\gamma^\mu\gamma_5 b|\Lambda_b(p,s)\rangle = -\bar{u}_\Lambda(p',s')\gamma_5\bigg[g_0(q^2)(m_{\Lambda_b}+m_\Lambda)\frac{q^\mu}{q^2} + g_+(q^2)\frac{m_{\Lambda_b}-m_\Lambda}{s_-}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_\Lambda^2)\frac{q^\mu}{q^2}\right)$$
$$+ g_\perp(q^2)\left(\gamma^\mu + \frac{2m_\Lambda}{s_-}p^\mu - \frac{2m_{\Lambda_b}}{s_-}p'^\mu\right)\bigg]u_{\Lambda_b}(p,s),$$

FLAG：味物理格点计算平均

- 始于2007：http://itpwiki.unibe.ch/flag
- FLAG-2, Eur. J. Phys. C74 (2014) 2890
- FLAG-3, arXiv:1607.00299
- Continuum extrapolation(# a's, <0.1 fm?)
- Chiral extrapolation of light quark masses ($m_{\pi,min}$<200 MeV, 400 MeV?)
- Finite volume($m_{\pi,\mathrm{min}}L > 4$, or 3?)
- Renormalization(non-perturbative? 1-loop?)
- Heavy quark treatment (O(a) improved?)
- Publication status (published, preprint, conference)

Color-coding of systematic errors:

★ has been estimated in a satisfactory manner.

○ reasonable, could be improved.

■ no estimation, or unsatisfactory.

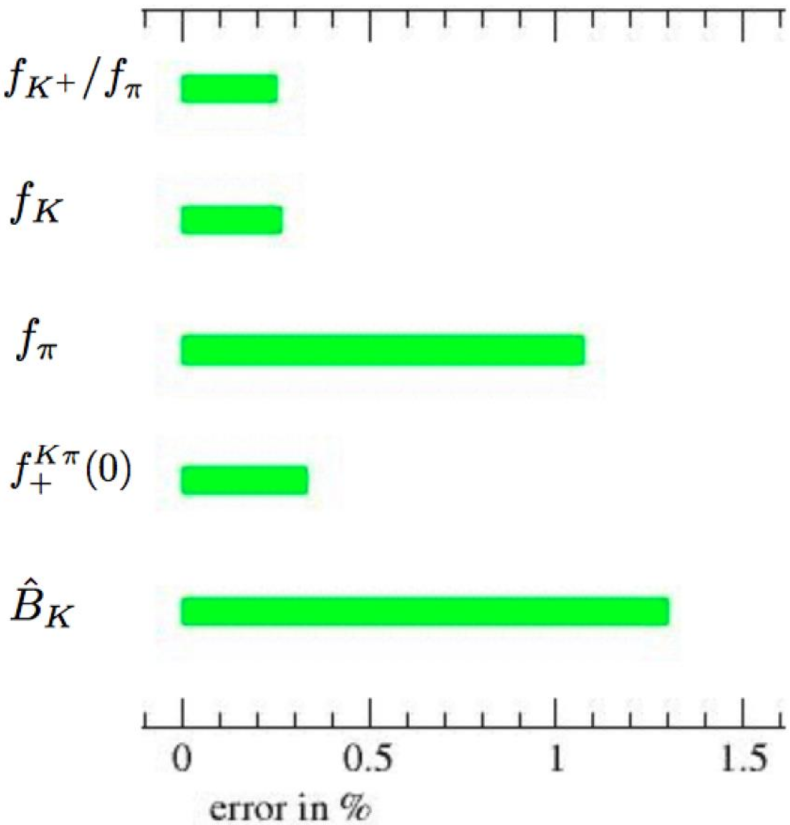
■ Included in the average.

□ Not included, but pass quality criteria.

■ Other results.

轻介子衰变常数与形状因子

- Flavor Lattice Averaging Group (FLAG) arXiv:1607.00299
- 截止到2015年11月30日



粲夸克质量

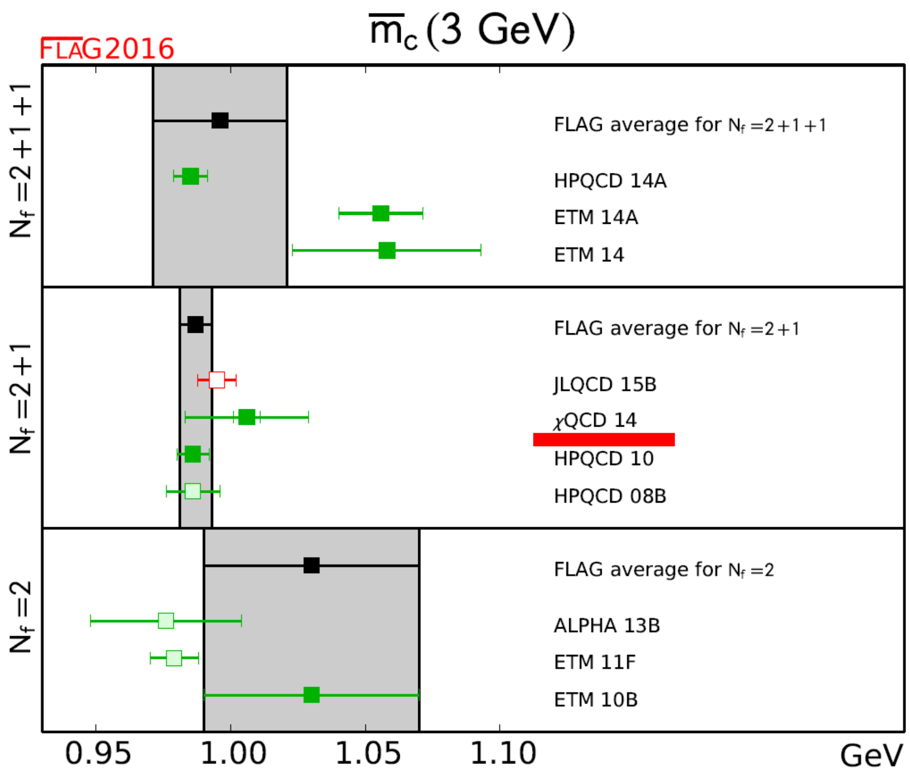
- 夸克质量是标准模型的基本参数之一
- LQCD计算含粲夸克的强子质量, 如D, D_s, ……
- 输入强子质量的实验值定出m_c
- 需要质量重整化常数Z_m
- LQCD计算moments of pseudoscalar-pseudoscalar correlators, 微扰可算, 解出m_c
- 可不用计算Z_m ($Z_m Z_P = 1$)

Inputs: $M_{D_s} = 1.9685$ GeV
$M_{D_s^*} - M_{D_s} = 0.1438$ GeV
$M_{J/\psi} = 3.0969$ GeV

Outputs: $r_0 = 0.465(4)(9)$ fm
$m_s^{\overline{\text{MS}}}(2\text{ GeV}) = 0.101(3)(6)$ GeV
$m_c^{\overline{\text{MS}}}(2\text{ GeV}) = 1.118(6)(24)$ GeV

χQCD Collaboration:
Y.-B. Yang et al., PRD92, 2015
ZL et al., PRD90, 2014 (Z_m, Z_A...)

粲夸克质量格点计算平均值



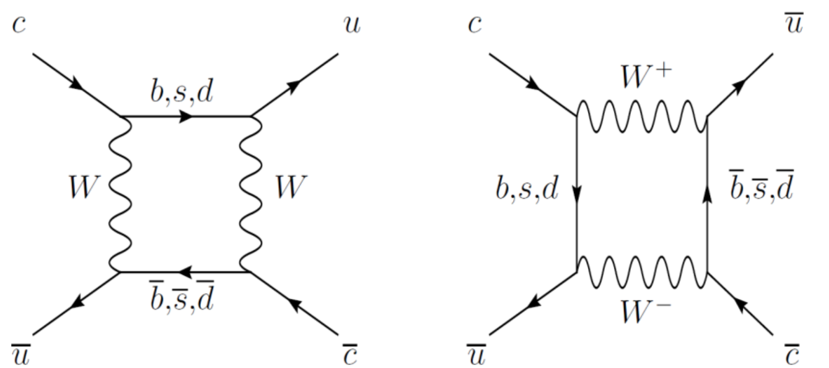
- $N_f = 2+1+1$:
  $\bar{m}_c(3\ \mathrm{GeV}) = 0.996(25)$ GeV
- $N_f = 2+1$:
  $\bar{m}_c(3\ \mathrm{GeV}) = 0.987(6)$ GeV
- $N_f = 2$:
  $\bar{m}_c(3\ \mathrm{GeV}) = 1.03(4)$ GeV

FLAG2016, arXiv:1607.00299

Flavor Lattice Averaging Group (FLAG)

D-meson mixing

- **D-mixing 被doubly Cabibbo压低（ $|V_{ub}V_{cb}^*|^2$ ）, long distance contribution dominates**



- **但标准模型里long distance contribution中的CP破坏可忽略，所以可以考虑新物理中local有效算符带来的CP破坏**
- **最一般的$\Delta C = 2$有效哈密顿量(dimenson-6)：**

$$H_{\text{eff}}^{\Delta C=2} = \frac{1}{4}\sum_{i=1}^{5} C_i(\mu)Q_i(\mu)$$

D-meson mixing

- In the SUSY basis, they are:

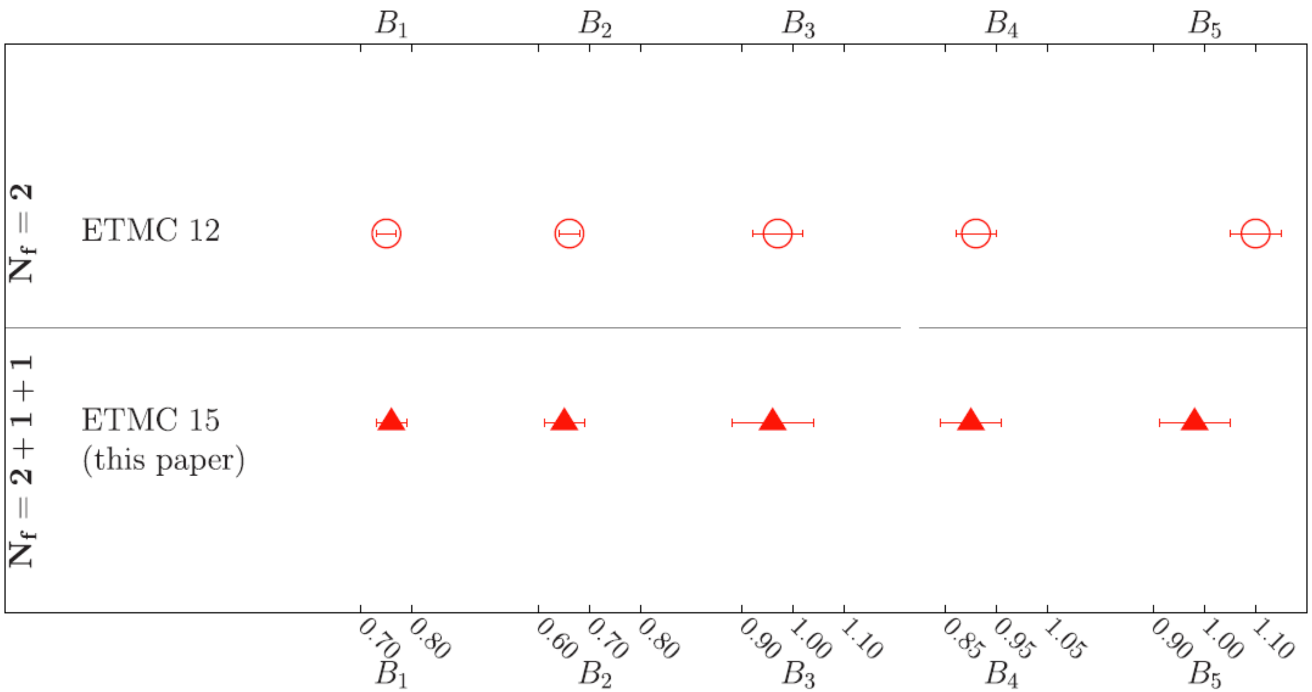
$$Q_1 = [\bar{c}^a\gamma_\mu(1-\gamma_5)\ell^a][\bar{c}^b\gamma_\mu(1-\gamma_5)\ell^b],$$
$$Q_2 = [\bar{c}^a(1-\gamma_5)\ell^a][\bar{c}^b(1-\gamma_5)\ell^b],$$
$$Q_3 = [\bar{c}^a(1-\gamma_5)\ell^b][\bar{c}^b(1-\gamma_5)\ell^a],$$
$$Q_4 = [\bar{c}^a(1-\gamma_5)\ell^a][\bar{c}^b(1+\gamma_5)\ell^b],$$
$$Q_5 = [\bar{c}^a(1-\gamma_5)\ell^b][\bar{c}^b(1+\gamma_5)\ell^a],$$

标准模型里，只有Q_1有贡献

- 5个算符矩阵元的格点QCD计算有两家(unquenched)
- ETMC, 2味(2014)和2+1+1味(2015)
- FNAL/MILC (2+1味, 4a's, preliminary, LAT2014,2015)
- LQCD结果比实验精度高; 估计到2020年两者精度持平

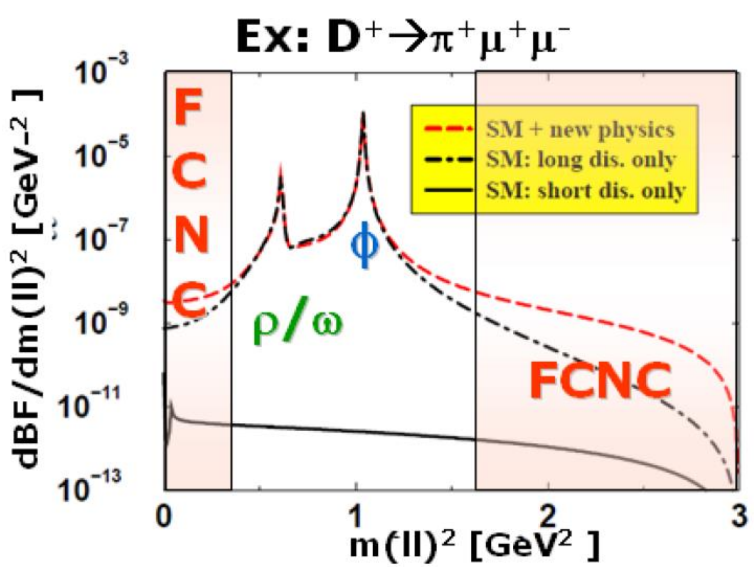
D-meson mixing

- **ETMC (2味, 精度3-5%, bag parameters, 4a's; PRD90(2014), 1403.7302)**
- **ETMC (2+1+1味, 4-8%, 3a's; PRD92(2015), 1505.06639)**



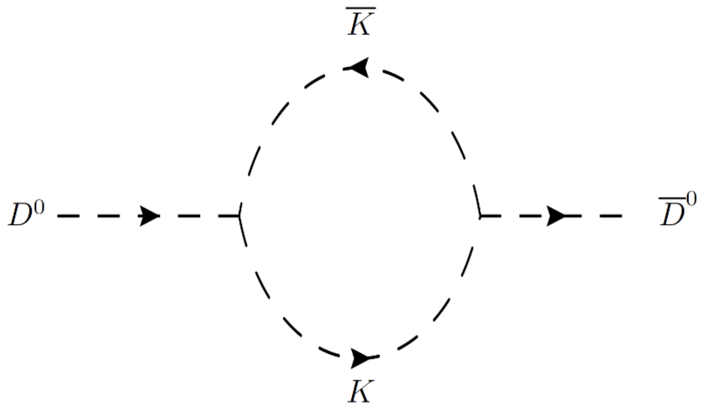
D介子稀有衰变（FCNC：$c \to ull$）

- The total rate of $D \to Xl^+l^-$ is dominated by long-distance resonant contributions at dilepton mass $m_{ll} = m_\rho, m_\omega, m_\phi$
- New physics could only modify the distribution below ρ or above ϕ
- There is a broad kinematical region above ϕ resonance in $D \to \pi l^+l^-$
- $D \to \pi l^+l^-$ and $D^0 \to \rho^0 l^+l^-$ are the best exclusive decays in experimental searches
- 尚无有关D介子稀有衰变的格点QCD计算



Long distance contribution to D-mixing

- The long distance contributions are nonperturbative
- Coming from transitions to final states that are accessible to both D^0 and $\bar{D}^0$
- Down and strange quarks circulating in the box diagrams



LQCD和超级计算机

- **2011年11月Top500排名第8。153,408个核， 峰值1.28Pflops**

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Project	Machine	CPU Cores	CPU Core Hours Used
Quantum Chromodynamics with four flavors of dynamical quarks PI: Doug Toussaint, University of Arizona	Hopper	18,432	128,947
QCD Thermodynamics at High Temperature PI: Alexei Bazavov, Brookhaven National Lab	Hopper	18,432	115,779
Large Scale 3D Geophsycial Inversion & Imaging PI: Gregory A. Newman, Lawrence Berkeley National Laboratory	Hopper	16,896	27,386.(