# **NEWS FROM LATTICE QCD**

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## **Quantum Chromo** Dynamics

Action (for quarks and gluons)

$$S = \int d^4x \left\{ \frac{1}{2} \operatorname{tr} F_{\mu\nu} F^{\mu\nu} + \sum_f \bar{q}_f [i\gamma D + m_f] q_f \right\}$$

## Candidate theory of the strong interactions

hard scattering (HE) - well described by Perturbation Theory (Asymptotic freedom)

also compute low energy properties of bound states (hadrons)

$$\langle \pi(t)\pi(0)\rangle \propto \int [\mathrm{d}A\mathrm{d}\bar{q}\mathrm{d}q]\mathrm{e}^{-S[A,\bar{q},q]}\pi(t)\pi(0) \sim \mathrm{e}^{-m_{\pi}t}$$

#### LATTICE REGULARIZATION

gauge fields associated with a links  $x \longrightarrow x + a\hat{\mu}$ 

$$A_{\mu}(x) \to U_{\mu}(x) \sim P \exp \int_0^1 dt \, A_{\mu}(x + ta\hat{\mu}) \in SU(3)$$

quark fields q(x) defined at points x on a finite lattice  $\Lambda$ 

$$\int [\mathrm{d}A\mathrm{d}\bar{q}\mathrm{d}q] \to \int \prod_{x \in \Lambda} \mathrm{d}U_{\mu}(x)\mathrm{d}\bar{q}(x)\mathrm{d}q(x)$$

→ a non-perturbative definition of the path integral

The action is **bilinear** in the quark fields

→ "integrate" out exactly:

$$\langle \mathcal{O}[U, \bar{q}, q] \rangle \propto \int [dU] \exp(-S[U]) \mathcal{O}[U, D[U]]$$

$$S[U] = S_{\text{gauge}}[U] - \ln \det(i\gamma D[U] + m)$$

reduces to evaluation of enormous integral (by Monte Carlo)

huge saving in computation if neglect the fermion determinant

→ "Quenched approximation" → uncontrolled systematic errors

"SERIOUS" DYNAMICAL SIMULATIONS ONLY RECENTLY

#### MANY SOURCES OF SYSTEMATIC ERRORS

Source	present simulations	extrapolations
finite lattice spacing	$a \sim 0.2 - 0.07 \text{fm}$	Symanzik
finite volume	$L \sim 1.5 - 2.5 \mathrm{fm}$	Lüscher
large quark mass	$m_{\pi} > \sim 300 \mathrm{MeV}$	Chiral PT

- Big effort in reducing/controlling these effects
- Setting the scales
- When do the theoretically expected behaviors set in?

## **UNIVERSALITY** → freedom in choosing lattice action

Many different gauge and fermion actions  $maintaining\ locality$  in use

## Fermion actions differ on how Chiral Symmetry is treated

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Wilson (O(a) improved): (m_0 = 0), broken, conceptually simple Staggered (Kogut, Susskind): "too much", relatively cheap Overlap (Neuberger, Ginsparg, Wilson) exact, but expensive Domain wall quarks (Kaplan): approximate Perfect action (Hasenfratz, Niedermayer): ""

Twisted mass QCD (Frezzotti, Sint): sort of a compromise
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# Claims of lattice phenomenological successes using using staggered quarks

but problems when  $N_{\rm f}/4 \neq {\rm integer}$ 

"Rooting trick":  $Det(iD + m) \rightarrow Det(iD + m)^{1/4}$  by hand!

from FIRST to SECOND PRINCIPLES!

"Rooted staggered fermions, good, bad or ugly?"

"At least ugly" (Sharpe, LAT06)

see also "The Evil that is rooting" (Creutz '07)

## Wilson quarks not as expensive as previously thought!

# Ops in TFlop Yr req. for an ensemble of 100 gauge fld. configs. \*

$$5.00 \left[\frac{20 \text{MeV}}{m}\right]^3 \left[\frac{0.1 \text{fm}}{a}\right]^7 \left[\frac{L}{3 \text{fm}}\right]^5$$
, Ukawa, LAT01

$$0.05 \left[\frac{20 \text{MeV}}{m}\right]^1 \left[\frac{0.1 \text{fm}}{a}\right]^6 \left[\frac{L}{3 \text{fm}}\right]^5$$
, Giusti, LAT06

\*  $N_{\rm f}=2$ ,  $V=2L\times L^3$ ,  ${\rm O}(a)$ -improved Wilson quarks,  $m=m_{\overline{\rm MS}}(2{\rm GeV})$ .

# Example

 $64 \times 32^3$  lattice

 $L \simeq 2.5 \text{fm}, a \simeq 0.08 \text{fm}$ 

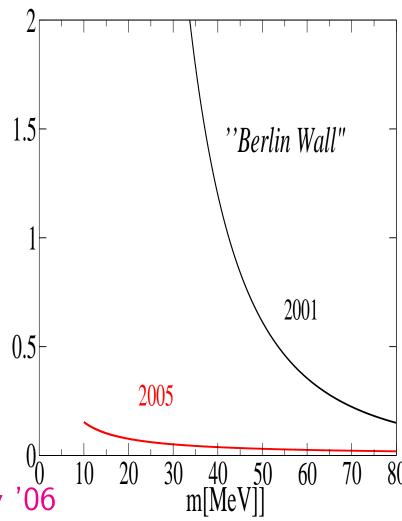
Many groups similar success acceleration due to:

progress in algorithms

Hasenbusch '01, Lüscher '03,  $0_0^{\perp}$  Urbach et al '05, Clark & Kennedy '06

better program efficiency

# Cost [Tflops x year]



## **COMPUTING FACILITIES** (incomplete list)

Peak[TFlops]

Custom computers: Blue GeneL, Jülich 46

KEK 57

PC clusters: Altix, LRZ 26

PACS-CS, Tsukuba 14

"Self-built": QCDOC, BNL 20

APE-next, Rome 8

upcoming International Lattice Data Grid (storing configurations)

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measure Euclidean lattice correlation functions: \langle \mathcal{O}_1 \mathcal{O}_2 \ldots \rangle e.g. \langle \mathcal{O}(0)\mathcal{P}(t)\rangle for large t gives information on \langle 0|\mathcal{O}|P\rangle |P\rangle: the lowest state with quantum numbers of \mathcal{P}
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- → many quantities of interest to hadron structure:
- Spectra (resonances and phase shifts from finite volume effects (Lüscher))
- Hadronic contributions to g-2, running couplings
- Meson distribution amplitudes
- Elastic and transition form factors
- Moments of (generalized) structure functions, .....

For a thorough review see Orginos, LAT06 Also Detmold SF-7, Hart HF-5

#### MESON DISTRIBUTION AMPLITUDES

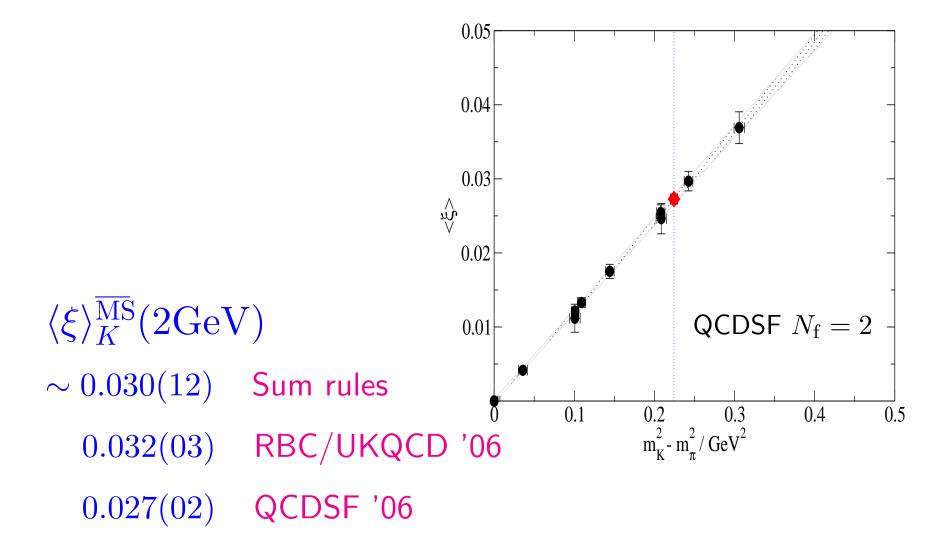
$$\langle 0|\bar{q}(z)\gamma_{\rho}\gamma_{5}P\exp\left[i\int_{-z}^{z}A(x)\cdot\mathrm{d}x\right]s(-z)|K(p)\rangle_{z^{2}=0}$$

$$=f_{K}ip_{\rho}\int_{-1}^{1}\mathrm{d}\xi\,\mathrm{e}^{i\xi p\cdot z}\phi_{K}(\xi,\mu)$$

Moments: 
$$\langle \xi^n \rangle_K(\mu) = \int_{-1}^1 \mathrm{d}\xi \, \xi^n \phi_K(\xi, \mu)$$

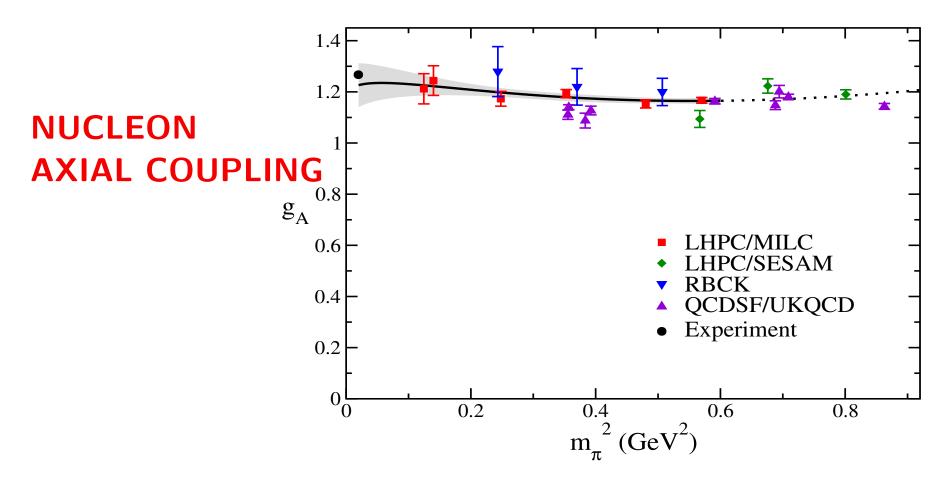
expressed as matrix elements of local operators

$$\langle \xi \rangle_K(\mu) f_K p_\rho p_\nu = \langle 0 | \bar{q}(0) \gamma_\rho \gamma_5 \stackrel{\leftrightarrow}{D}_\nu s(0) | K(p) \rangle$$



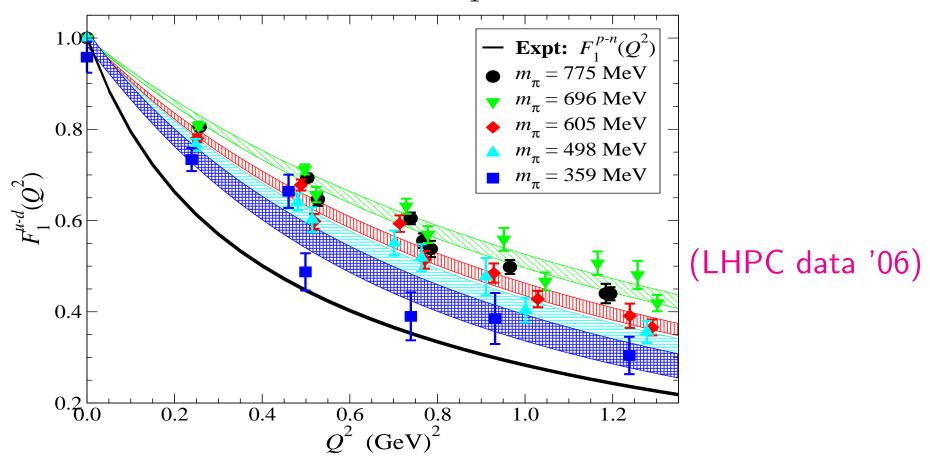
### QCDSF results for 2nd moment:

$$\langle \xi^2 \rangle_K^{\overline{MS}}(2\text{GeV}) = 0.26(2), \ \langle \xi^2 \rangle_{\pi}^{\overline{MS}}(2\text{GeV}) = 0.27(4)$$



- consistent results among groups
- finite volume effects
- ullet weak dependence on  $m_\pi$
- LAT06:  $g_A(m_\pi = 140 \text{MeV}) = 1.23(8)$ ; cf exp. 1.2695(29)
- ullet dynamical 2+1 at smaller  $m_\pi$  under way (RBC/UKQCD/QCDSF)

## **ISOVECTOR** $F_1$ **FORM FACTOR**

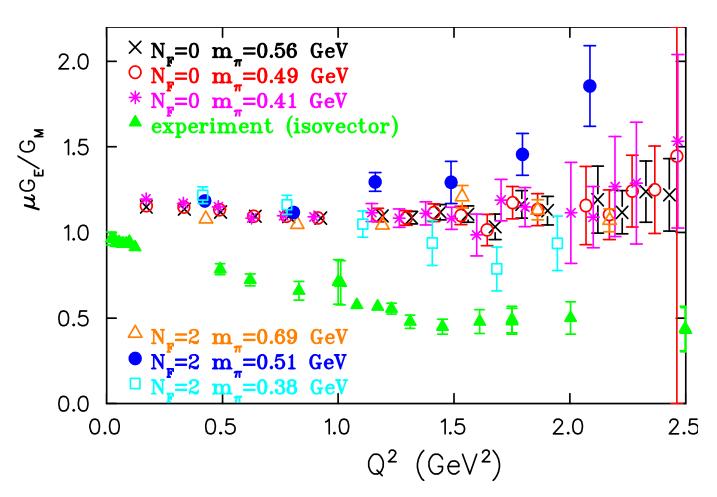


 $m_{\pi}$  still large, but approach experiment as  $m_{\pi}$  decreases

Difficulty: momenta quantized in units  $2\pi/L$  for periodic bc e.g. L=24a with  $a=0.1 {\rm fm}$  gives  $2\pi/L\sim 0.52 {\rm GeV}$  (Bedaque, Sachrajda et al): using twisted pbc  $p_i=(2\pi n+\theta_i)/L$ 

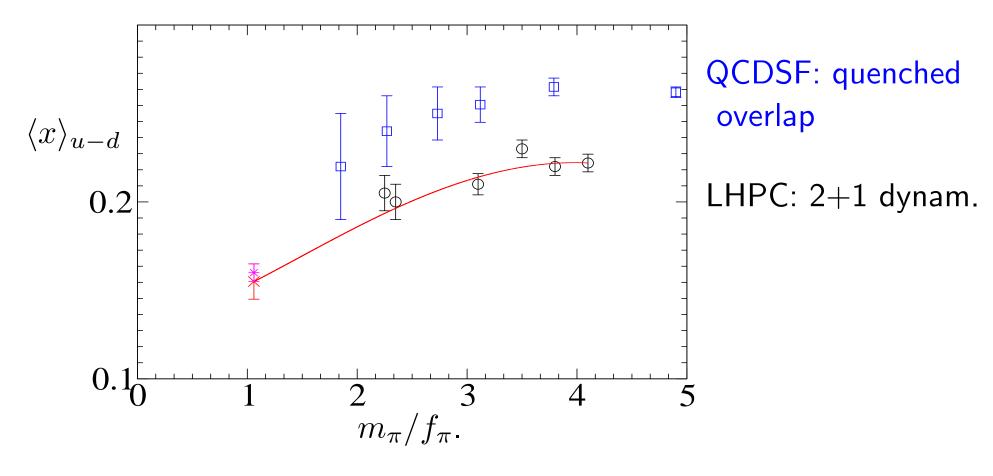
## Ratio of electric and magnetic isovector form factors

Alexandrou et al '06 data



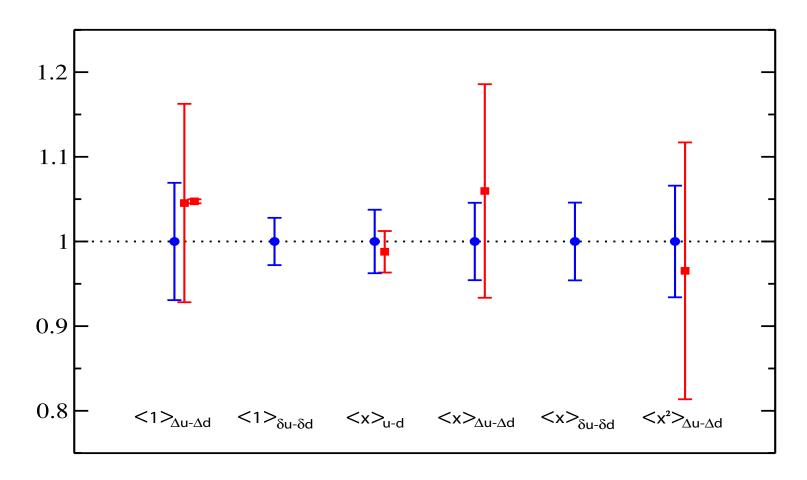
Present disagreement with JLab experimental data Lattice artifacts??

#### MOMENTS OF STRUCTURE FUNCTIONS



large 
$$\chi$$
PT logs:  $\langle x 
angle_{u-d} = C \left[ 1 - r^2 (A \ln r^2 + B) + \ldots 
ight]$   $r = m_\pi/(4\pi f_\pi);$   $A = 6g_A^2 + 2 \sim 11$ 

## Ratios of Moments: Lattice/DIS



## Chiral logs not yet seen in dynamical simulations

But if fit to  $\chi PT$  get good agreement with experiment

#### **SUMMARY**

- ★ much algorithmic progress in the last 5 years
- \* serious dynamical quark simulations of QCD under way
- $\star$  big effort still needed to simulate with  $m_{\pi} \sim 140 {\rm MeV}$
- ★ chiral logs not yet clearly seen
- **\*** lattice  $+ \chi PT$  gives reasonable agreement with experiment
- \* the (effort to) control the various systematic errors is essential for the quality of a lattice experiment

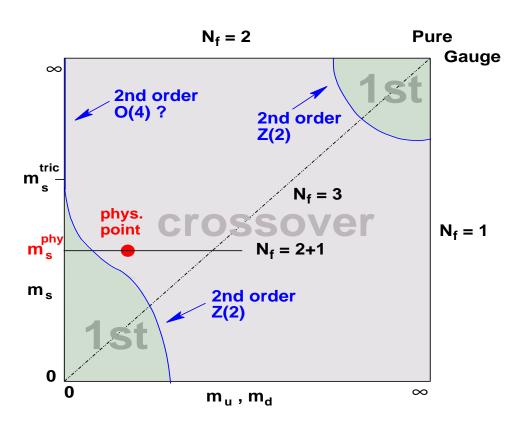
#### Lattice EXPECTATIONS for the NEXT YEARS

(anonymous lattice astrologer '07)

Dynamical quarks (2+1 flavors)

- 2008: reasonable results for  $m_\pi \sim 200 {
  m MeV}$
- 2010: reliable results for  $m_\pi \sim 200 {
  m MeV}$
- 2012: reasonable results for  $m_\pi \sim 140 {
  m MeV}$
- 2014: reliable results for  $m_\pi \sim 140 {\rm MeV}$

## **Finite Temperature**



# $T_c \sim 180(20) \mathrm{MeV}$

## Heller LAT06

