Electroweak Symmetry Breaking, New Quarks, and Graphics Processors

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Electroweak Symmetry

- In the 1860's, Maxwell unified the theories of electricity and magnetism – the impact has been profound
- In the 1960's, Weinberg et al. Similarly unified electromagnetism and the weak force – EW symmetry
- At “everyday” energies, EW symmetry is broken – an essential fact of the universe
- **What breaks Electroweak symmetry?**

The Higgs Mechanism

- The Standard Model of Particle Physics:
  - there is a Higgs field governed by a symmetric potential with non-symmetric ground states
  - at low energies, the Higgs symmetry is broken
  - broken Higgs symmetry results in broken EW symmetry through Higgs-EW gauge couplings.
  - broken Higgs symmetry also generates quark and lepton masses through Higgs-fermion couplings
  - The SM has passed test after test, but we still haven't seen a Higgs boson, yet (LHC)

A fundamental Higgs?

- In the Minimal SM, the Higgs is fundamental; its mass, potential, etc. are inputs

- A fundamental Higgs is problematic
  - EW symmetry breaking is “dialed in”
  - Provides no insight into GUT-EW energy hierarchy
  - Provides no insight into flavor symmetry/breaking
  - Experimental results (G_F) lead to a need for $O(10^{-30})$ fine-tuning of the Higgs mass (or SUSY)

Extended Technicolor (ETC)

- We know a way to dynamically generate light bosons from a strong force: *chiral symmetry breaking* in QCD produces pseudo-Goldstone pions
- Technicolor: high energy copy of QCD, produces pseudo-Goldstone Higgs at EW scale through *TC chiral symmetry breaking*
- ETC: unify Technicolor and QCD to generate fermion masses, flavor, and more

Advantages of ETC

Fundamental Higgs	ETC
✗ EW symmetry breaking is "dialed in"	✔ EW symmetry breaking is dynamic and "natural"
✗ Experimental results seem to demand extreme fine-tuning (or SUSY) and an "unnatural" energy hierarchy	✔ No elementary scalars! Fine-tuning is not required and energy hierarchy may be natural, both due to details of renormalization
✗ Provides no insight into flavor generation/symmetry	✔ A potentially fruitful model of flavor is not only possible but convenient

"No other scenario for the physics of the TeV scale solves these problems so neatly. Period."
-Kenneth Lane, 2002

Challenges in Technicolor

- Flavor changing neutral currents
- Precision electroweak measurements
- The top mass

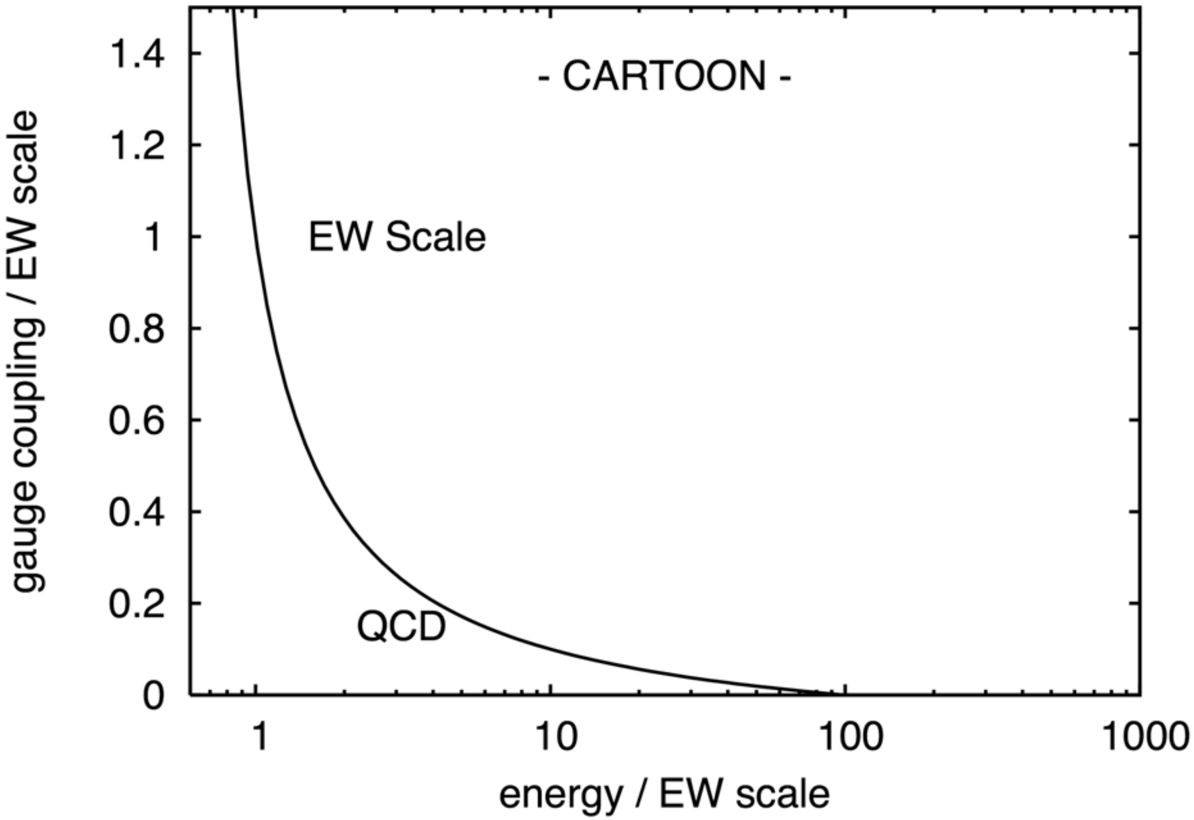
→ Bottom line:

dynamical scale separation is necessary

(but not sufficient)

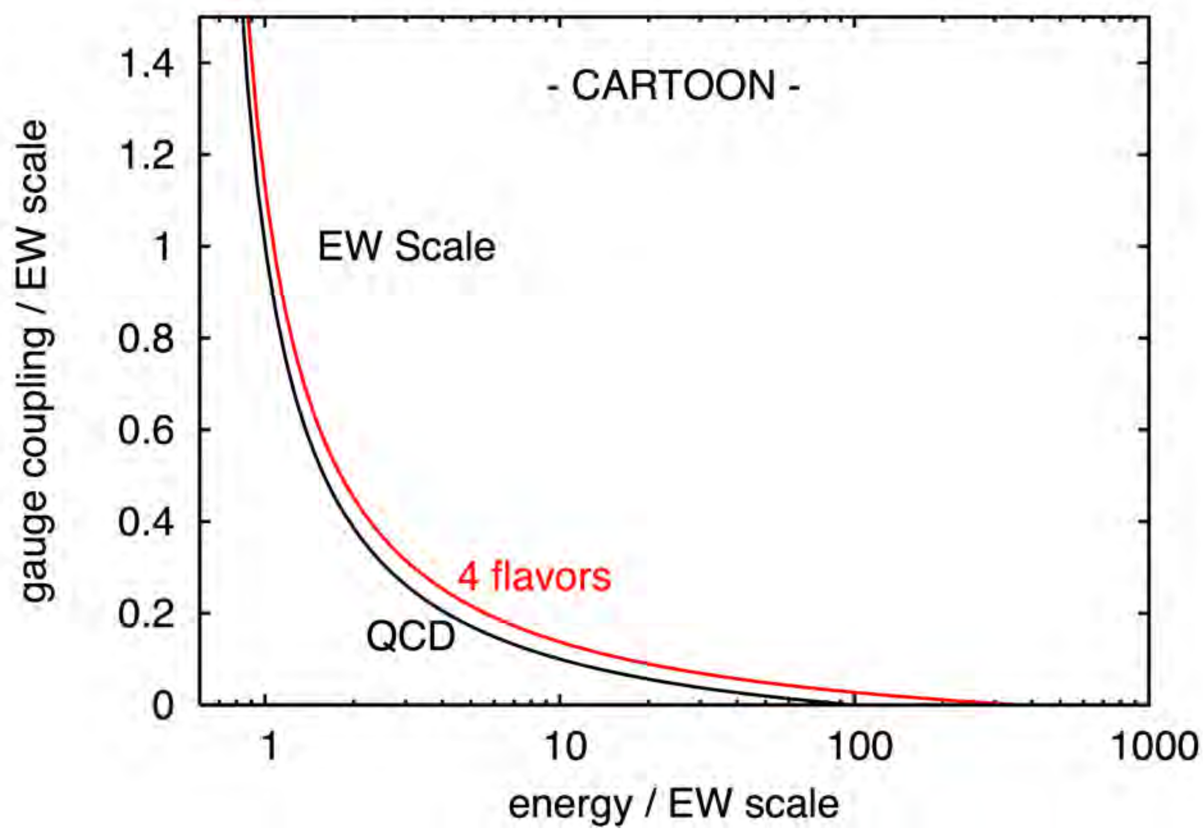
Running couplings

- In QFT, couplings change with energy scale (renormalization)
  - symmetries break as couplings grow
  - symmetry breaking produces (pseudo) Goldstone bosons
  - QCD: 2 light quarks, chiral symmetry



Running couplings

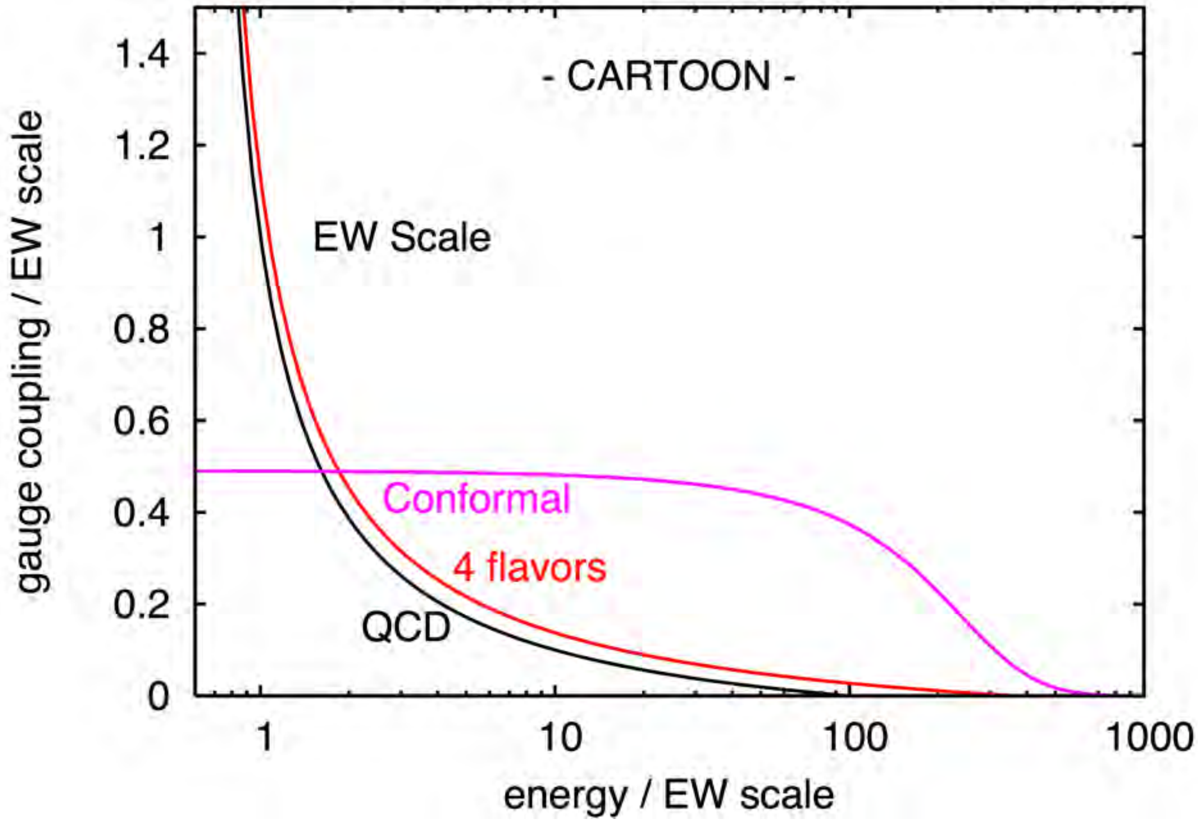
- In QFT, couplings change with energy scale (renormalization)
  - Four light flavors not much different



Running couplings

- In QFT, couplings change with energy scale (renormalization)

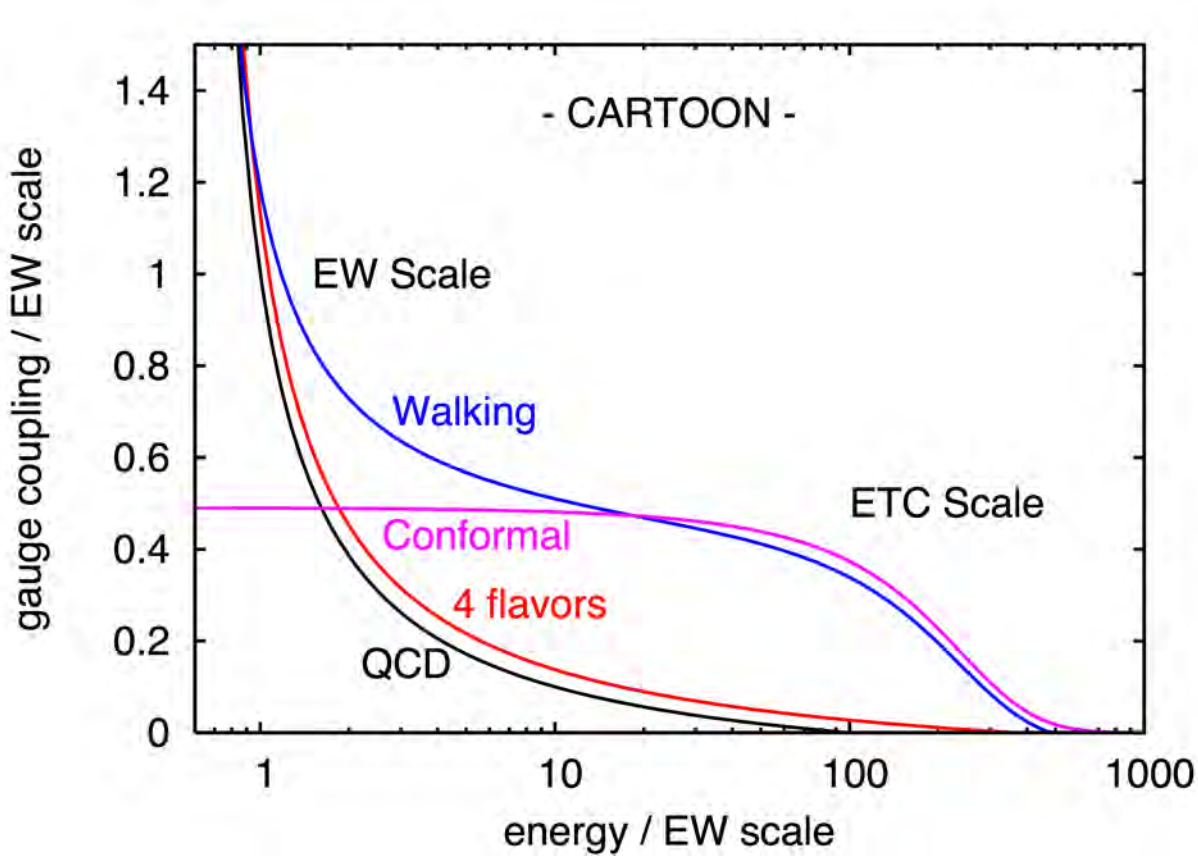
- 16 flavors: conformal running stops at IR fixed point



Running couplings

- In QFT, couplings change with energy scale (renormalization)

- must break ETC symmetry at high scale, EW sym. at usual scale
- → massive ETC gauge bosons
- → ~~FCNC violation~~, ~~PEW violation~~
- top mass?



The hunt for Walking Technicolor

- Start with fundamental representation

  (work has begun on higher rep's)

- Scan N_f from 4 to 16
  - $N_f < 4$ – coupling definitely runs
  - $N_f > 16$ – conformal or not asym. free
- Determine if chiral symmetry is broken at T=0
  - meson generation
  - eigenvalues of Dirac operator

Lattice Quantum Field Theory

- Feynman Path Integral

$$\int dx_1^\mu \; dx_2^\mu \; \ldots \; dx_{20^4}^\mu \; e^{-\bar{\psi}(x)\left(\gamma^\mu D_\mu(x,y)+M_q\right)^{-1}\psi(y)-S^E_{gauge}[U(x)]}$$

- Hybrid Monte Carlo

$$U(x,t_{MD}) \rightarrow U(x,t'_{MD}) \text{ ala Molecular Dynamics}$$

$$\text{with } H = \frac{p^2}{2m_{MD}} + S^E \text{ and random initial } p$$

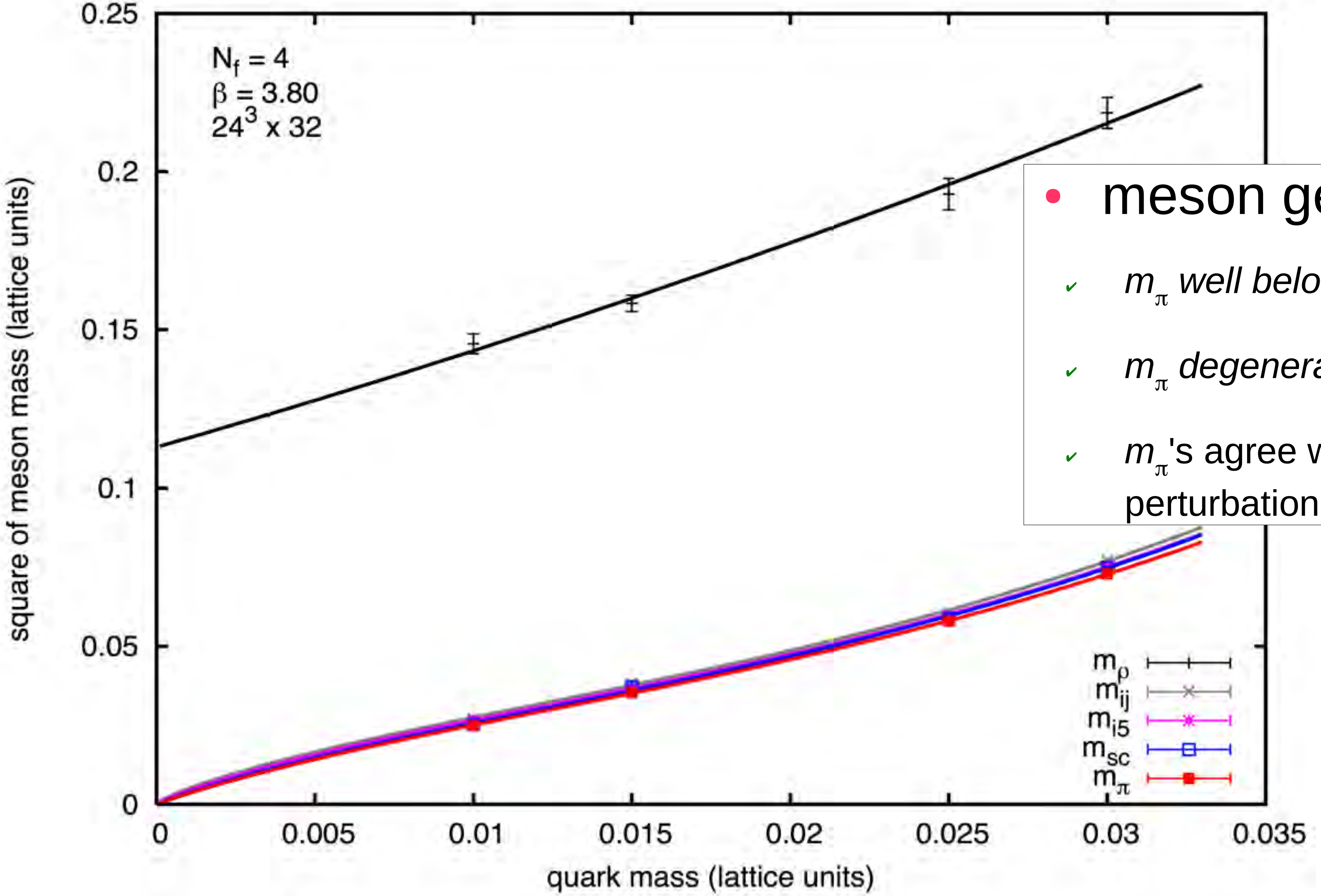
- 80% of computation is sparse matrix-vector multiply in CG for fermion force and action

$$D_\mu(x,y)\;\psi(y)$$

Lattice QFT on a GPU

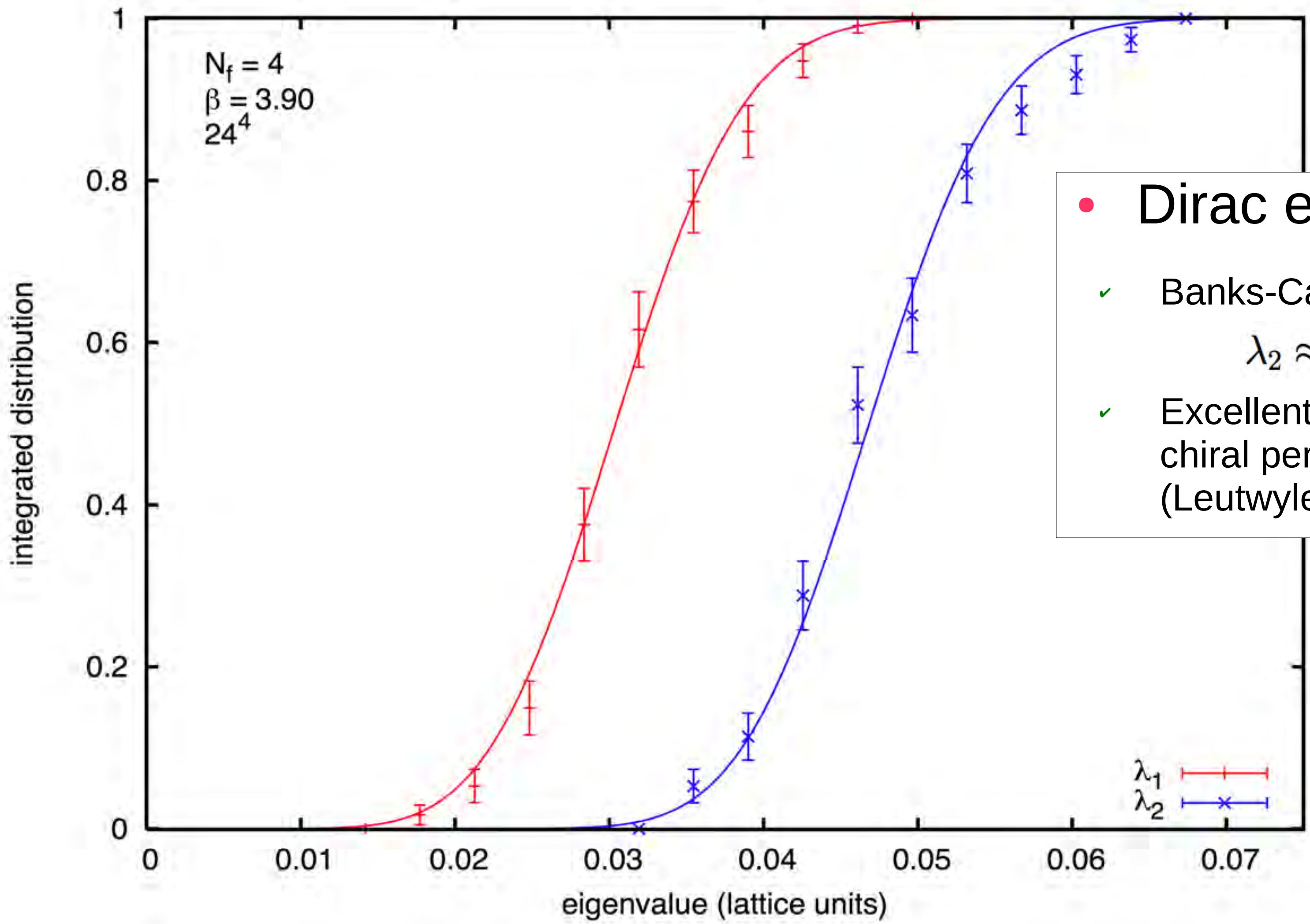
- MC mat-vec is perfect app for GPUs
  - “super” symmetric processing
  - light communication/synchronization
    - – do ~1,000 CG iterations between sync's
  - single GPU jobs good for high capacity
    - – for high capability, use BG/P
    - – multi-GPU code under development
- Result is ~60 GF for 20^4 lattice (GTX 8800), ~20X faster than CPU (AMD Phenom 9950)

Four flavors



- meson generation
  - m_π *well below* m_ρ
  - m_π *degeneracy at low* m_q
  - m_π's agree with chiral perturbation theory

Four flavors

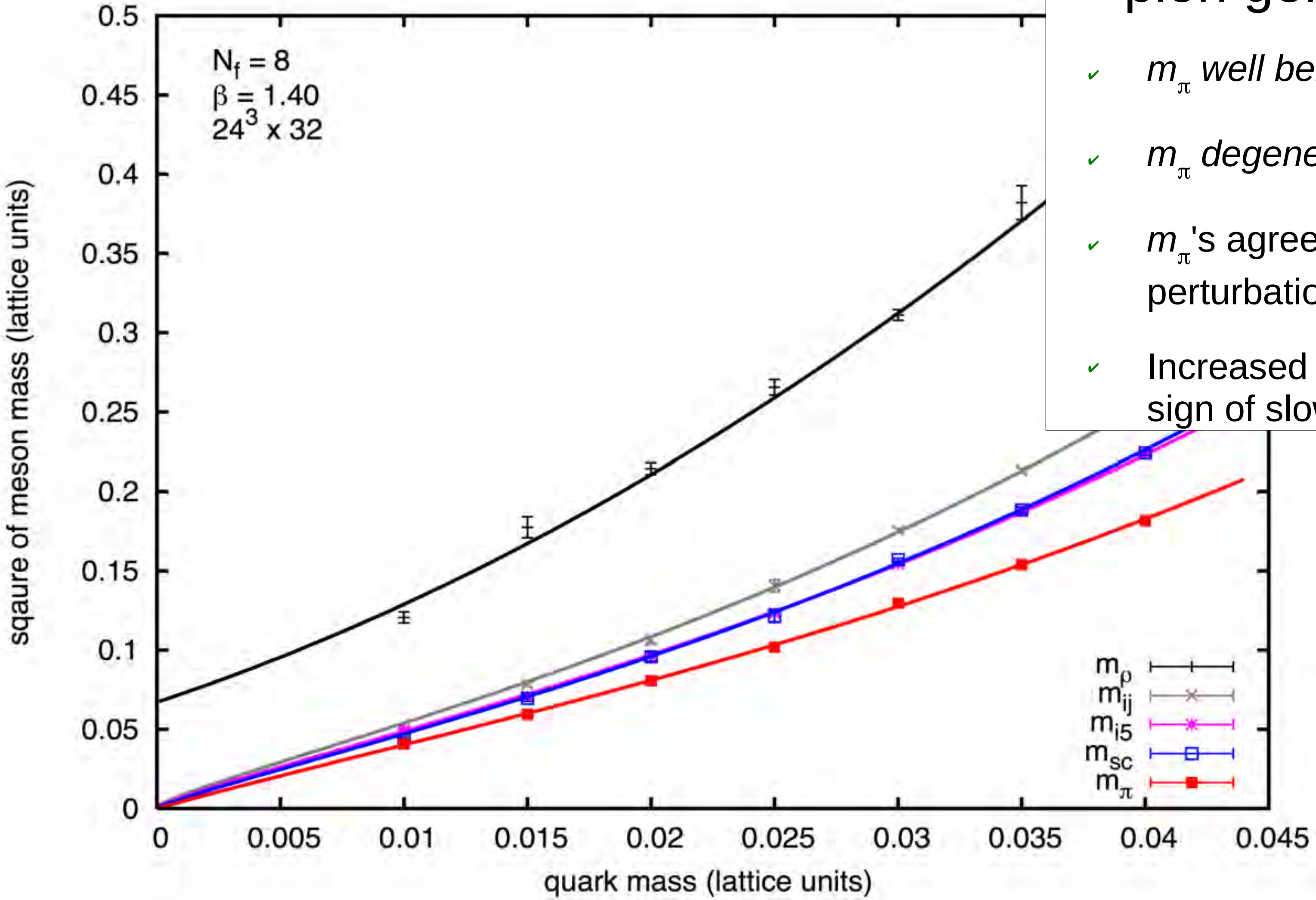


- Dirac eigenvalues
  - Banks-Casher collapse:

    $$\lambda_2 \approx \sqrt{2}\ \lambda_1$$

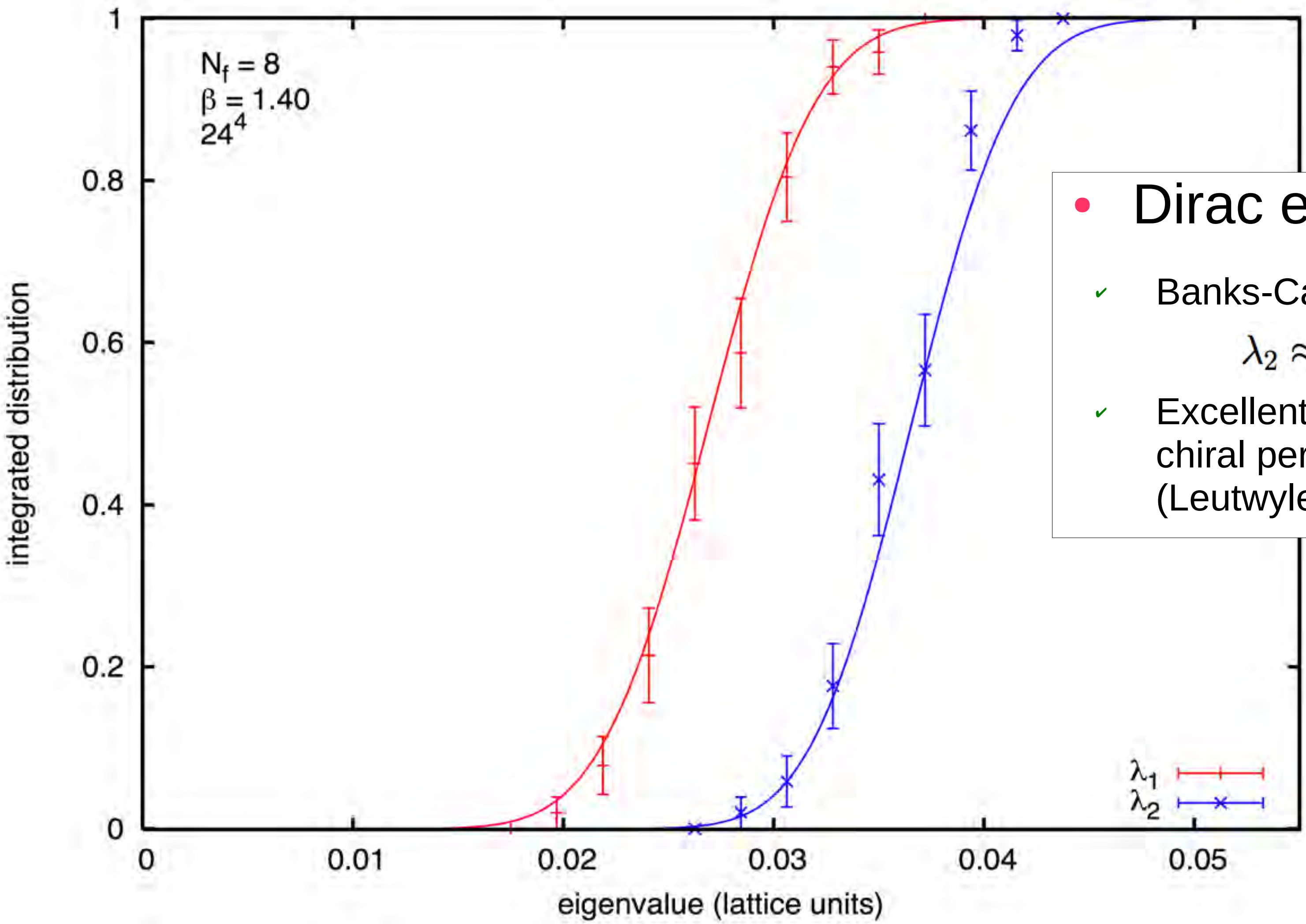
  - Excellent agreement with chiral perturbation theory (Leutwyler, RMT)

Eight flavors



- pion generation
  - *m_π well below m_ρ*
  - *m_π degeneracy at low m_q*
  - m_π's agree with chiral perturbation theory
  - Increased splitting is a sign of slower running

Eight flavors



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Twelve Flavors

?

in progress, results in weeks

Summary

- The mechanism of Electroweak symmetry breaking is a pressing mystery; interpreting LHC results will demand lattice calculations
- Extended Technicolor is an interesting candidate with important advantages over the Minimal Standard Model
- Thorough demo of broken chiral symmetry for 4 and 8 flavors is progress, but we are a long way from demonstrating Technicolor

Thank You!

DOE CSGF

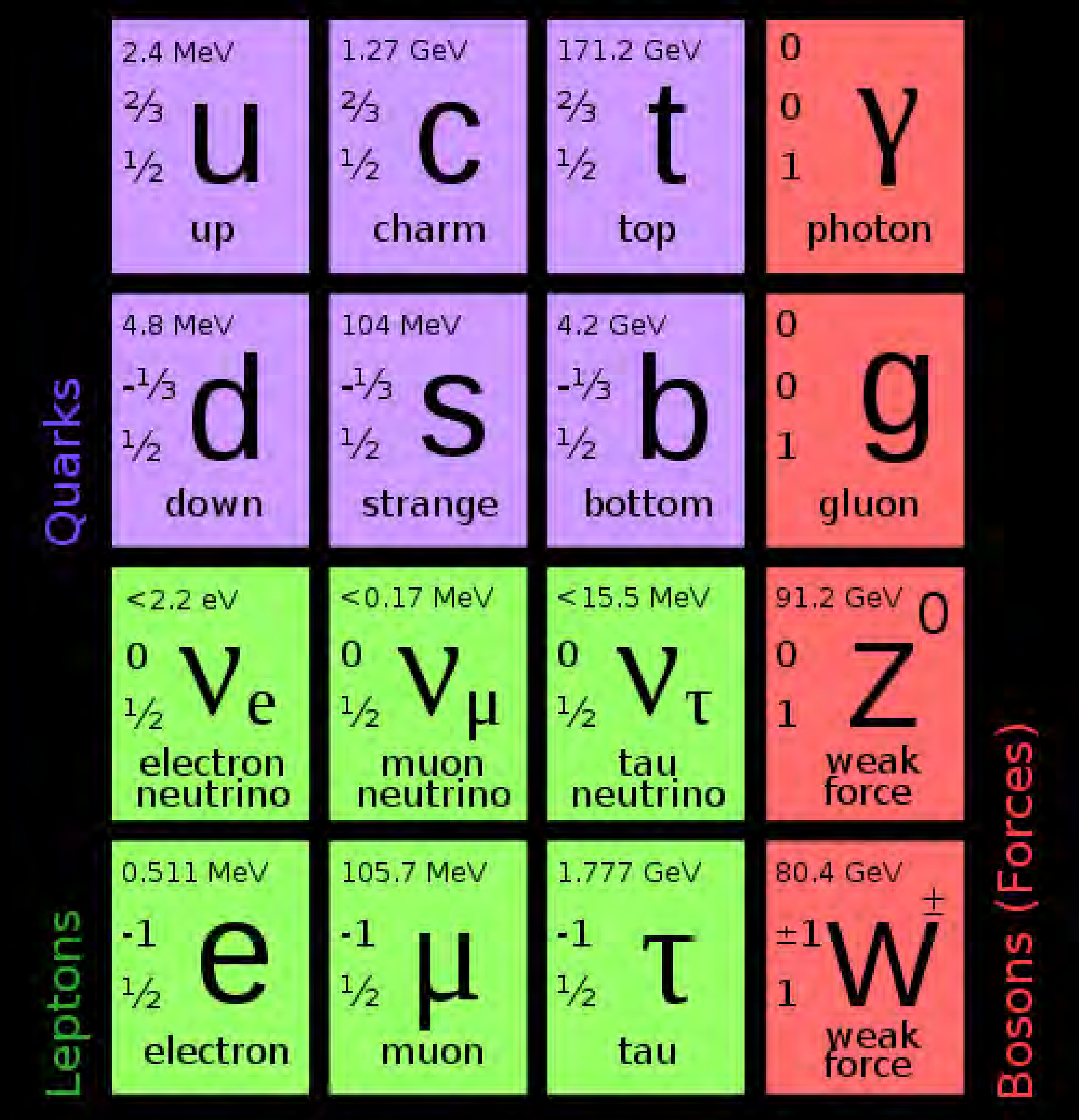
KRELL Institute

Advisor:	Julius Kuti, UCSD
Collaborators:	Zoltan Fodor (U. of Wuppertal) Kieran Holland (U. of Pacific) Daniel Nogradi (UCSD)

Recommended reading

- George Fleming, Strong Interactions for the LHC, 2008.
- Kenneth Lane, Two Lectures on Technicolor, 2002.
- Fodor et al, Probing Technicolor with Staggered Fermions, 2008.
- Egri et al, Lattice Simulation on Graphics Cards, 2006.

particle masses



Scales

• Planck	10^{19} GeV
• GUT	10^{16} GeV
• ETC	10^{4} GeV
• LHC	10^{3} GeV
• TC χSB, Higgs, EW	100 GeV (10^{15} K)
• QCD χSB	0.2 GeV