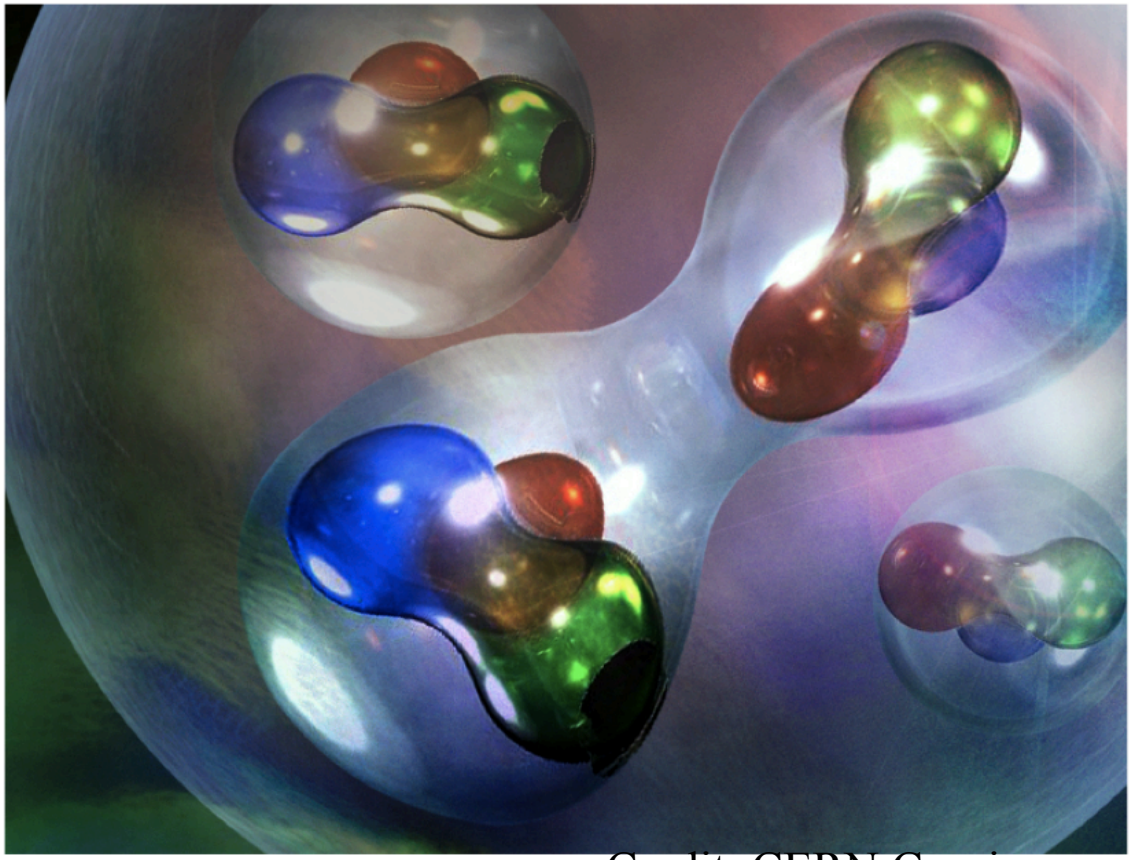
Fun with QCD



Credit: CERN Courier

Jiunn-Wei Chen, National Taiwan U.

An Ultimate Question in Science

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Life = Physical Laws ?

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Or more specifically,

Life = known Physical Laws?

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No new particles.

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No new particles.

No new interactions.

An Ultimate Question in Science

Life = Physical Laws ?

Or more specifically,

Life = known Physical Laws?

No new particles.

No new interactions.

No practical applications.

The answer has profound implications in science, philosophy and even theology.

"Life = known Physical Laws?"

--- a computational problem!

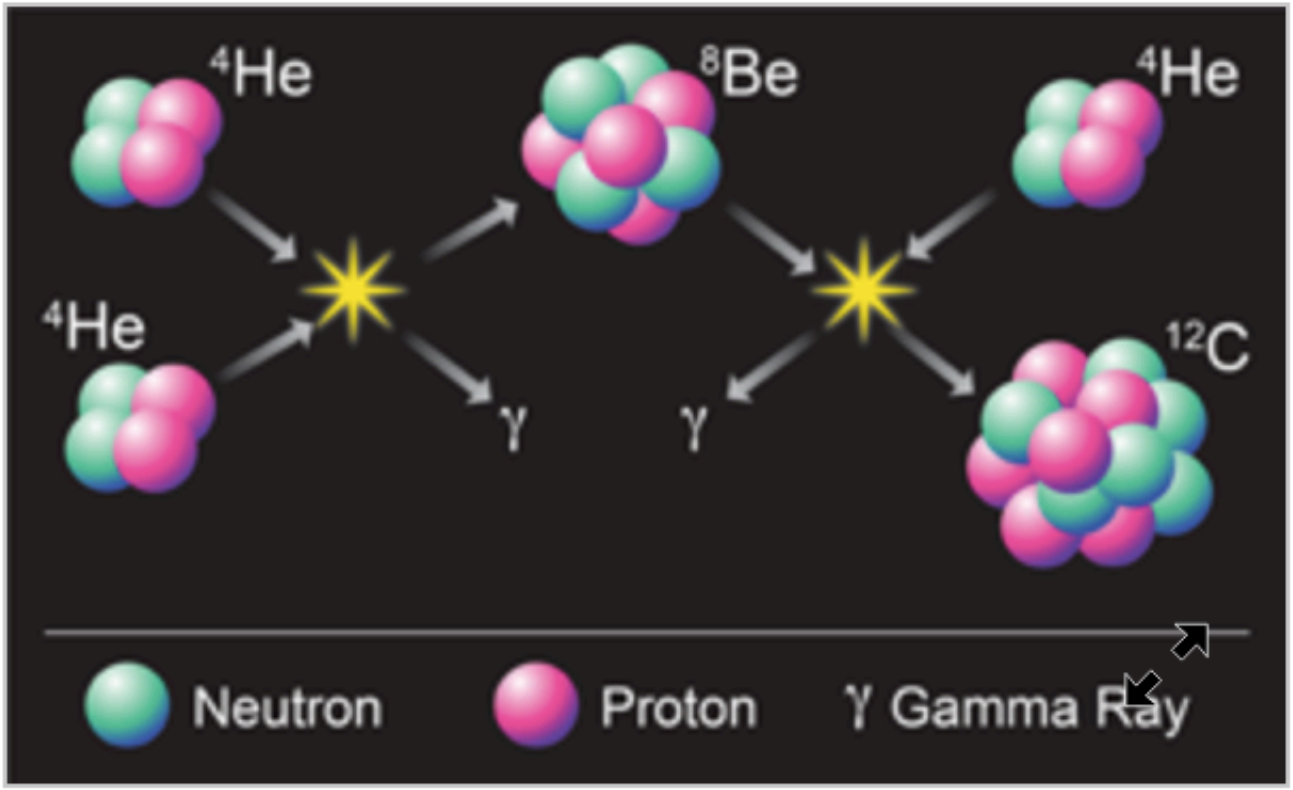
Emergence of complexity from simple rules

- Condensed matter
- Nuclear physics, large number of nucleons in a nucleus

Complexity: superfluidity from nucleon pairing; complicated spectra, e.g. the Hoyle state

Hoyle State

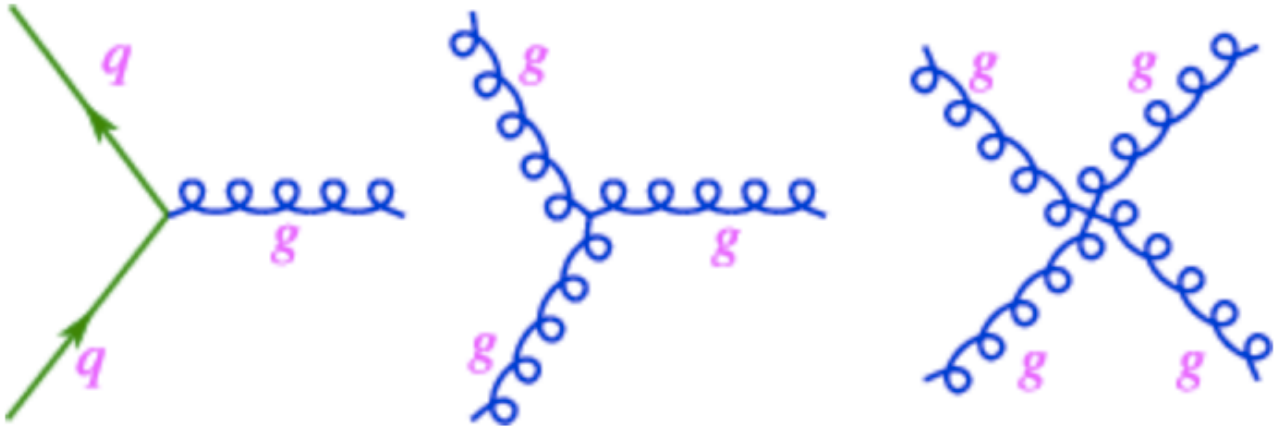
An excited state of C12 predicted by Hoyle with energy close to 3 alpha threshold so C12 (and life) can be formed



Credit: Carin Cain

While the theory, QCD, is very simple!

- QCD (Quantum Chromodynamics)



Computations in QCD is challenging

- Interaction is strong at long distance (>1fm). Non-perturbative
- Systematic methods:

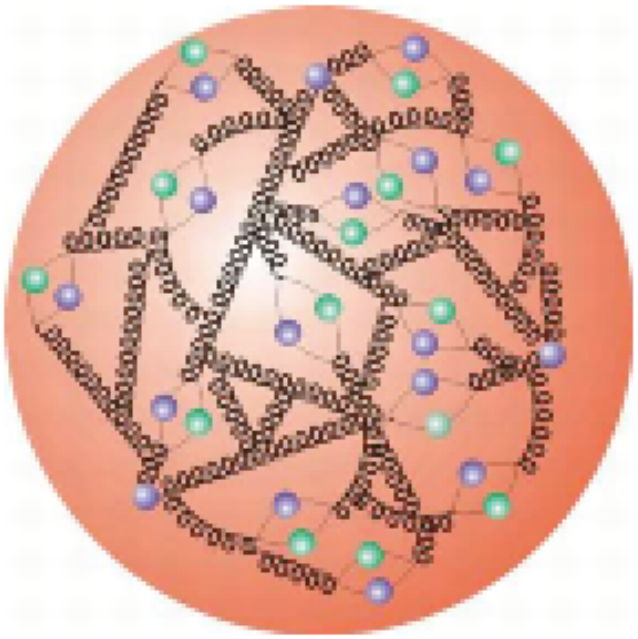
  Lattice QCD

  Effective Field Theory (EFT) (Wilson '71)

  …

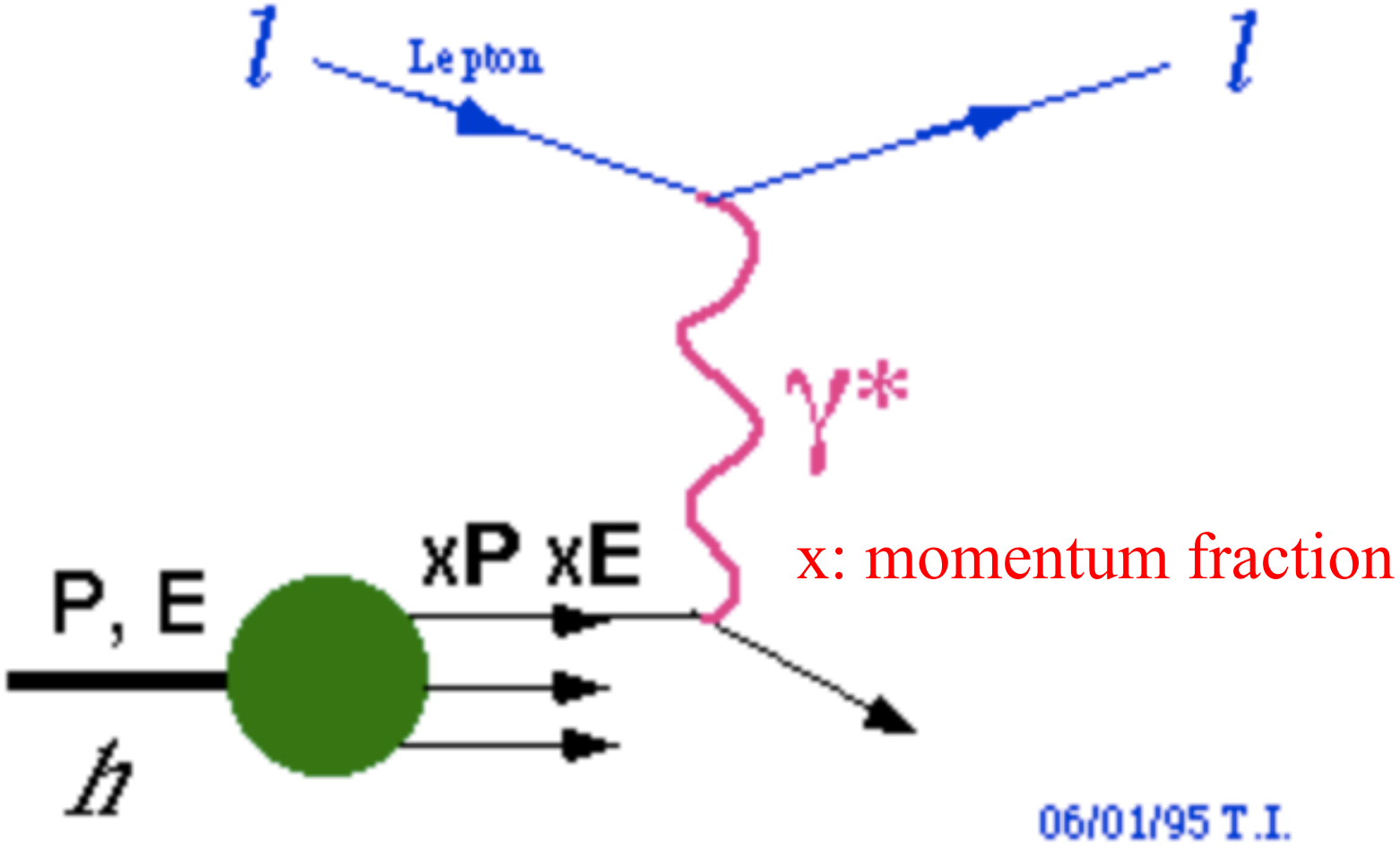
- Even the structure of proton is complicated already…

Feynman's Parton Model



The momentum distributions of partons (quarks, antiquarks and gluons) become one dimensional distributions in the infinite momentum frame.

Measuring Parton Distributions Using DIS experiments



x: momentum fraction

Credit: *T.Ichihara*

Current Status of Proton PDFs

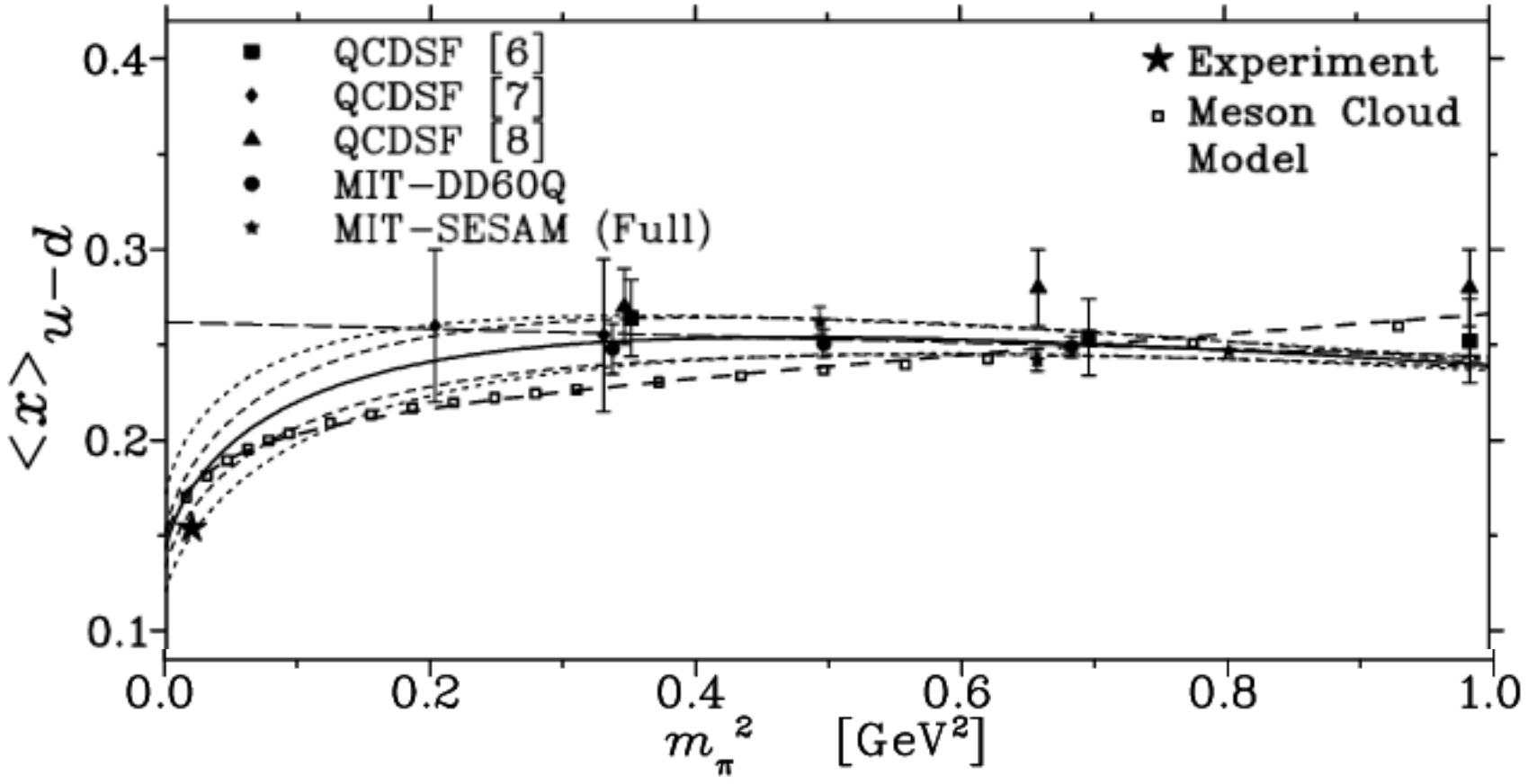
How do momentum and spin distribute among partons?

- Exp: 1d mom. dist. largely mapped out (up to parameterizations of the functional forms); largest sys. uncertainty in Higgs production.

  improve 1d(spin)+3d: BNL, JLab, J-PARC, COMPASS, GSI, EIC, LHeC, ...

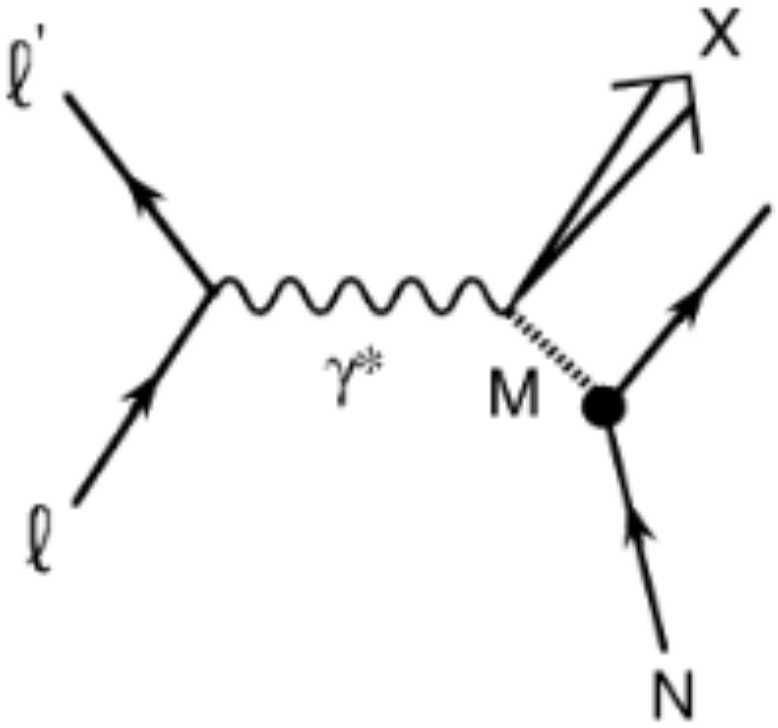
- Theory: Only first few moments could be computed directly from QCD until recent years

Negele's colloquium @ Maryland



Detmold, Melnitchouk, Negele, Renner, Thomas
Phys. Rev. Lett. 87 (2001) 172001

Meson Cloud Model



$$\langle x^n \rangle_{u-d} = a_n + b_n m_\pi^2 + a_n c_{\mathrm{LNA}} m_\pi^2 \ln\left(\frac{m_\pi^2}{m_\pi^2 + \mu^2}\right)$$

A Eureka Moment

--- I can do it by
Chiral Perturbation theory!

Chiral Perturbation Theory: an Effective Field Theory of QCD

- QCD with three light flavors: “a theoretical paradise” (Leutwyler)
- Exhibits spontaneous and explicit chiral symmetry breaking
- Can be analyzed systematically in quark mass and momentum double expansions (Weinberg (1979) Gasser, Leutwyler (1984,1985))
- A model independent approach

The floodgate was open

JWC, Ji, Phys. Lett. B523 (2001) 107

Phys.Rev.Lett. 87 (2001) 152002

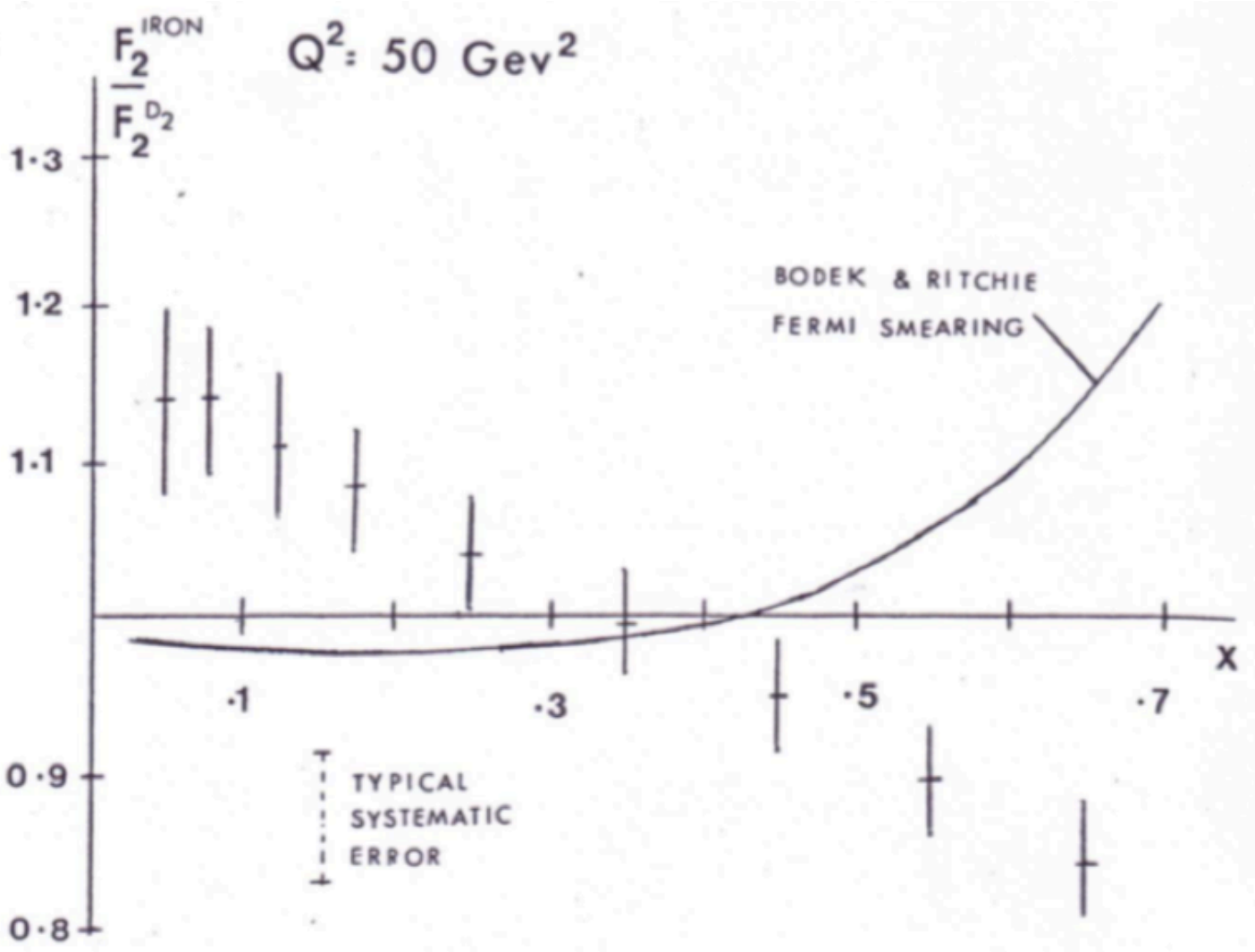
Phys.Rev.Lett. 88 (2002) 052003

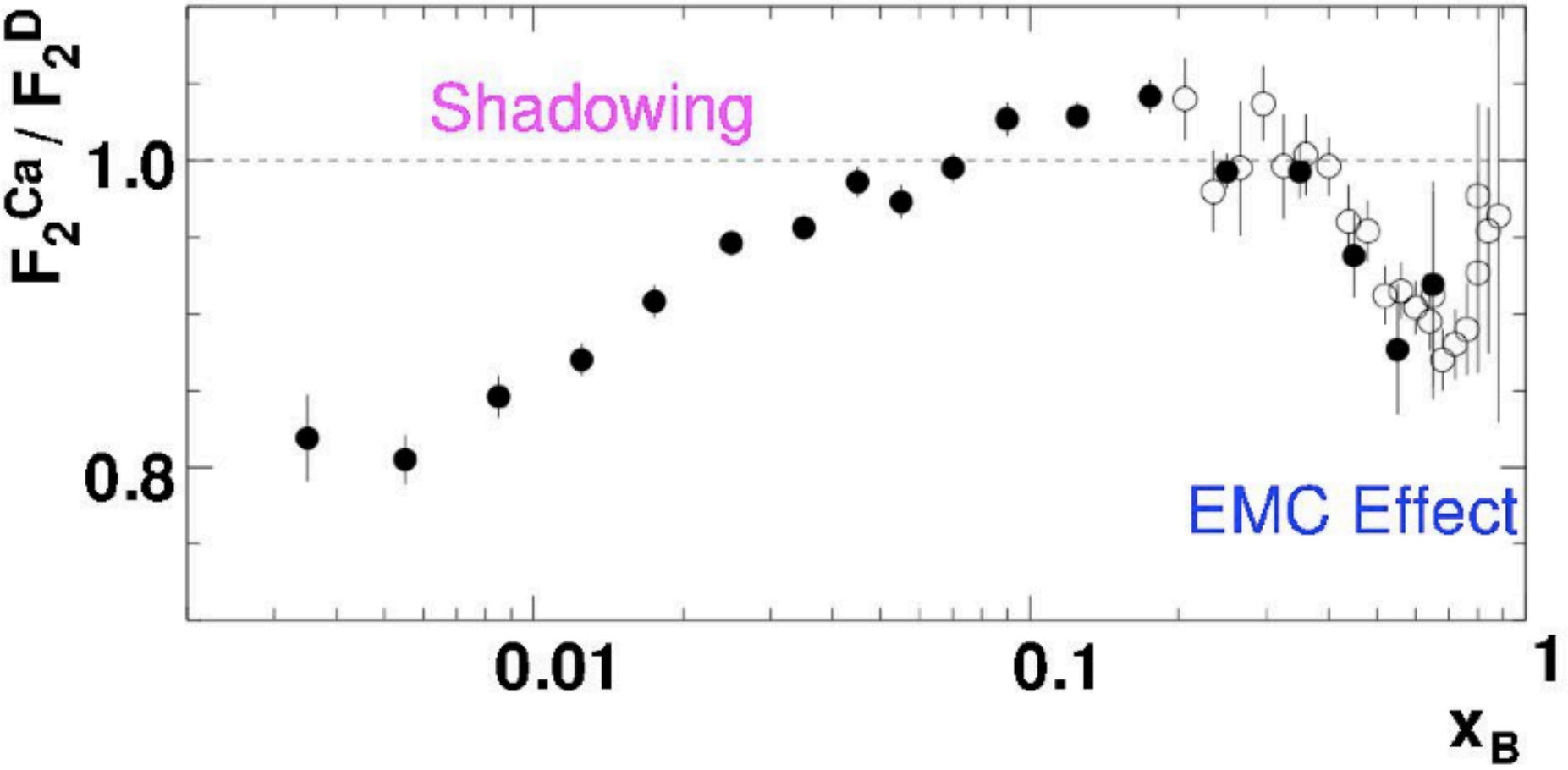
JWC, Stewart, Phys.Rev.Lett. 92 (2004) 202001

Got a call from MIT…

2004 “Effective Summer” at Berkeley Lab: do it for nuclear systems

EMC effect (‘83): nuclear modification of the nucleon parton distributions



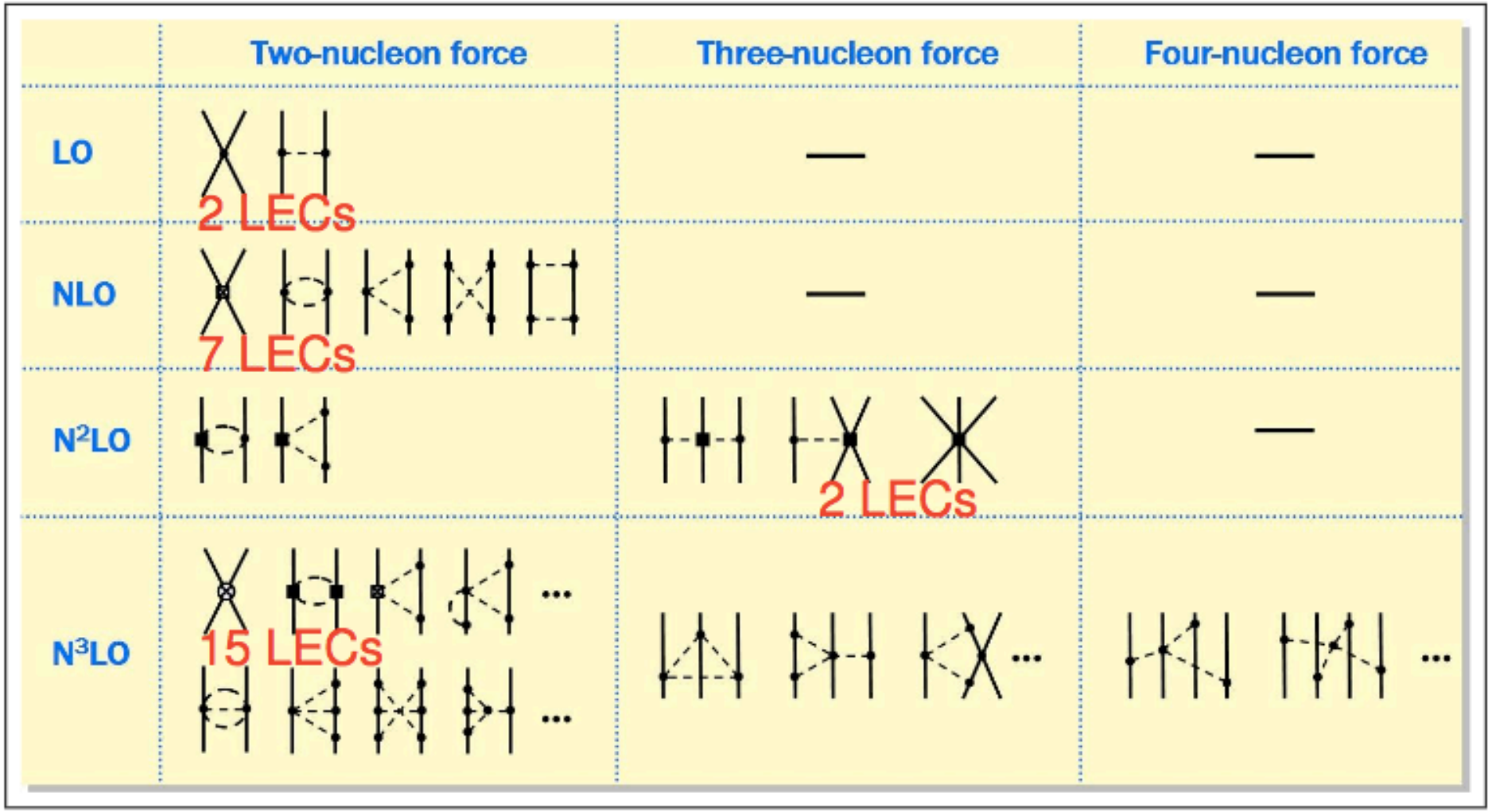

F_2^{Ca} / F_2^D
1.0
0.8
Shadowing
EMC Effect
0.01
0.1
1
x_B

Jerry Miller:

EMC =

Everyone's Model is Cool

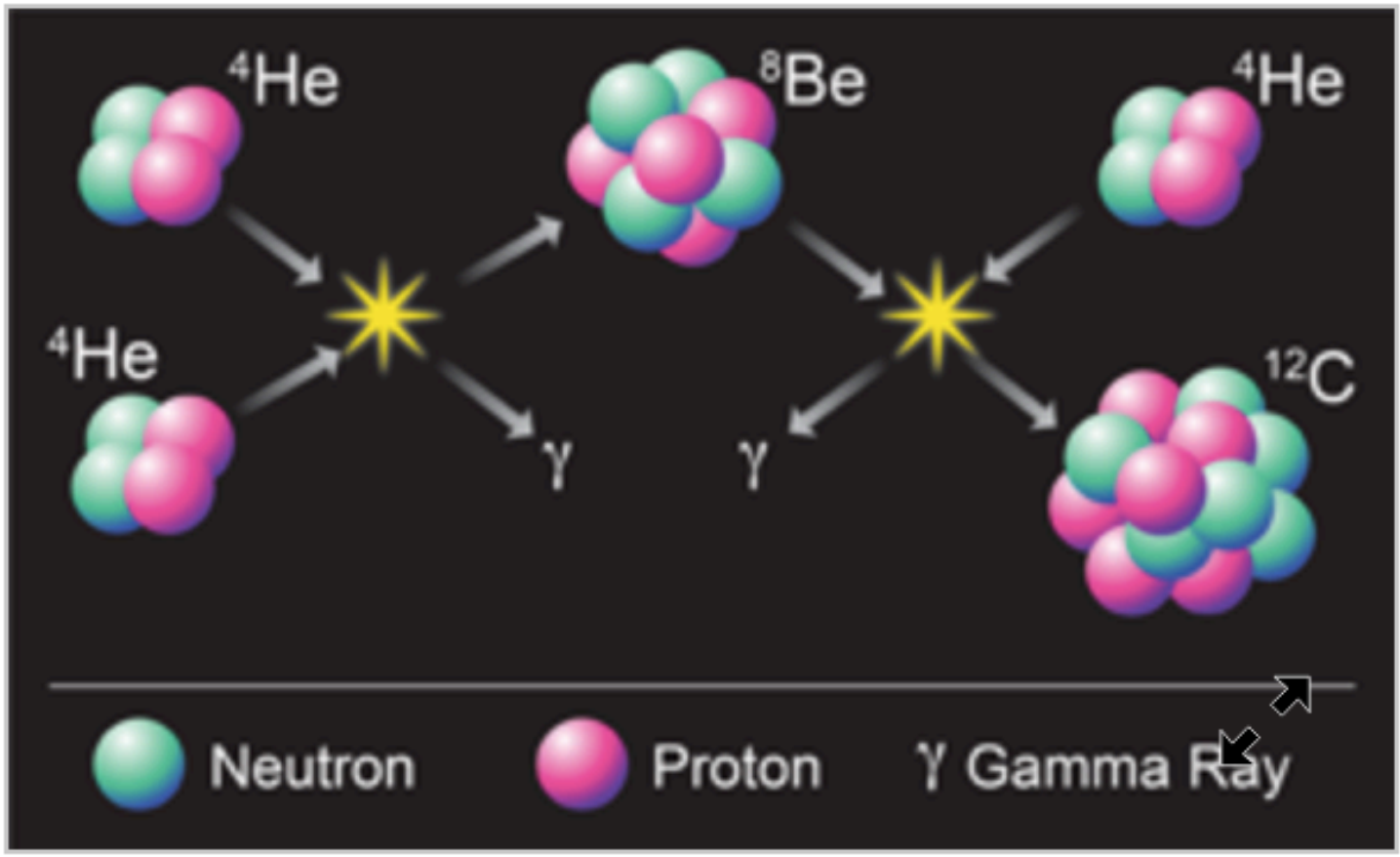
Using ChPT again to nuclear systems



Credit: U-G Meissner

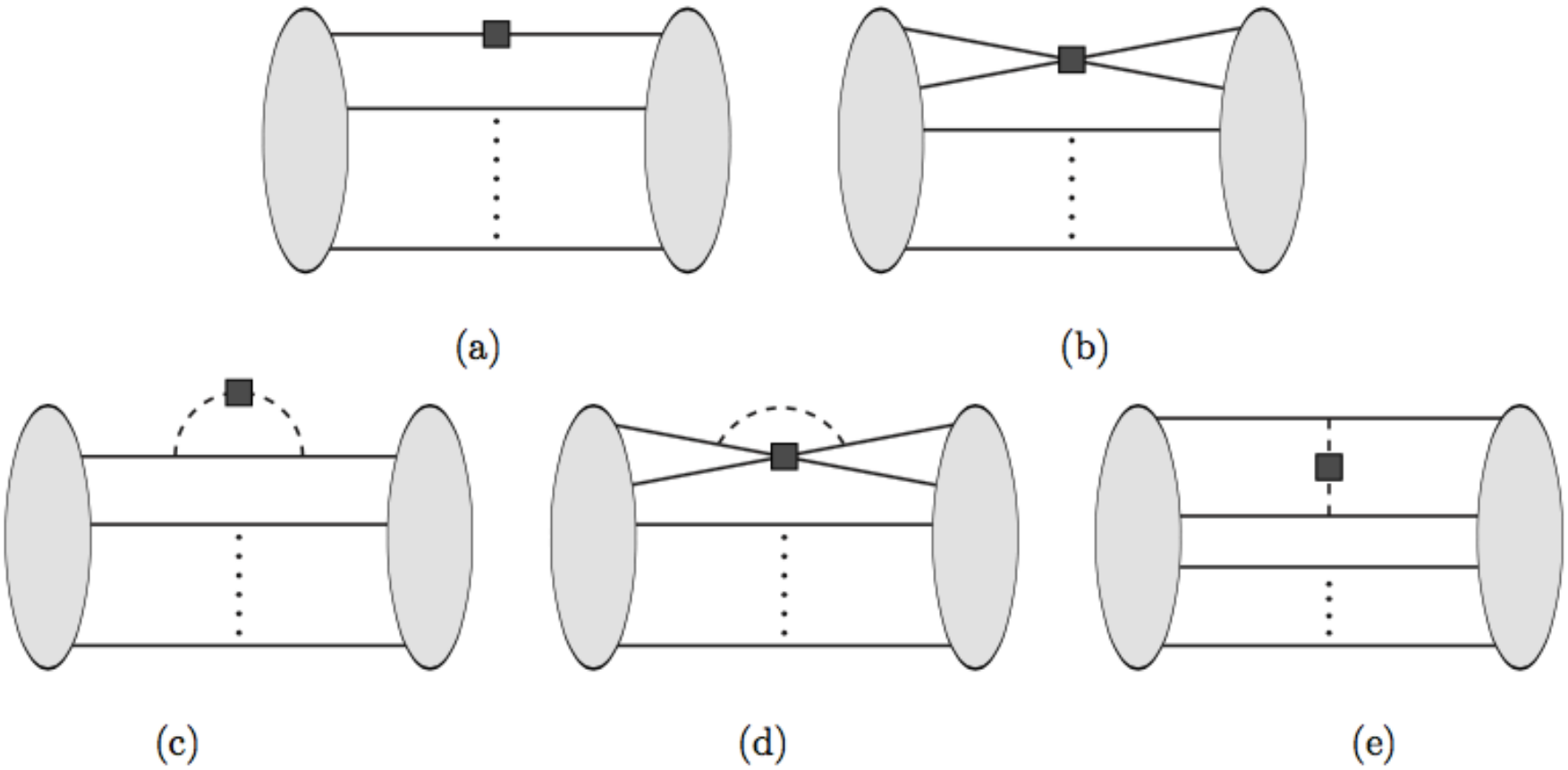
Hoyle State Obtained

Epelbaum, Krebs, Lee, Meißner, Phys. Rev. Lett. 106, 192501 (2011)



Credit: Carin Cain

Using large Nc counting



Factorization
Implies prediction power!

$$q_A(x)/A = q_N(x) + g_2(A,\Lambda)\tilde{q}_2(x,\Lambda)$$

1-body op. 2-body op. determined by deuteron

EFT predicts: $R_A(x) - 1 = f(A)\phi(x)$

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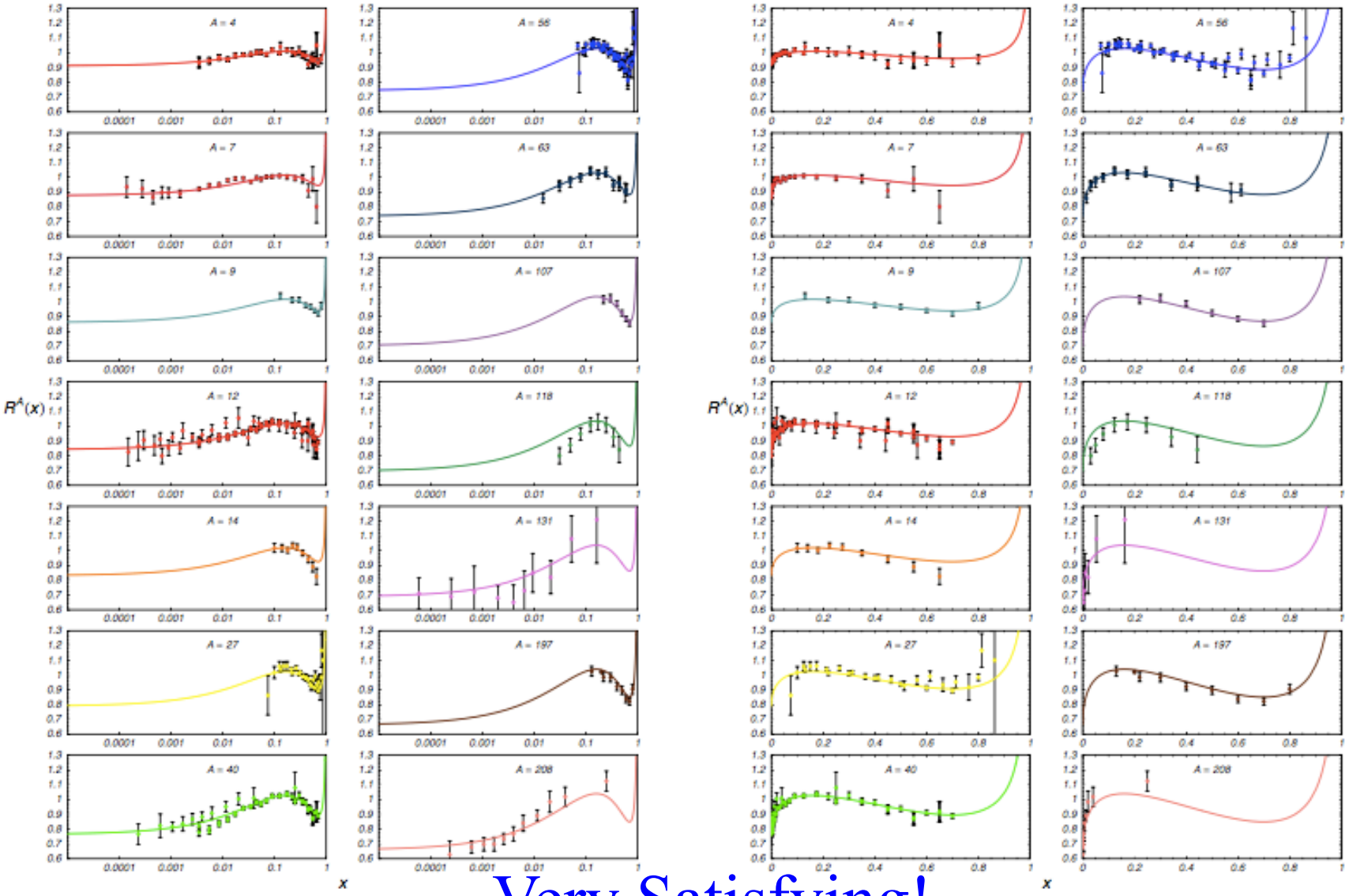


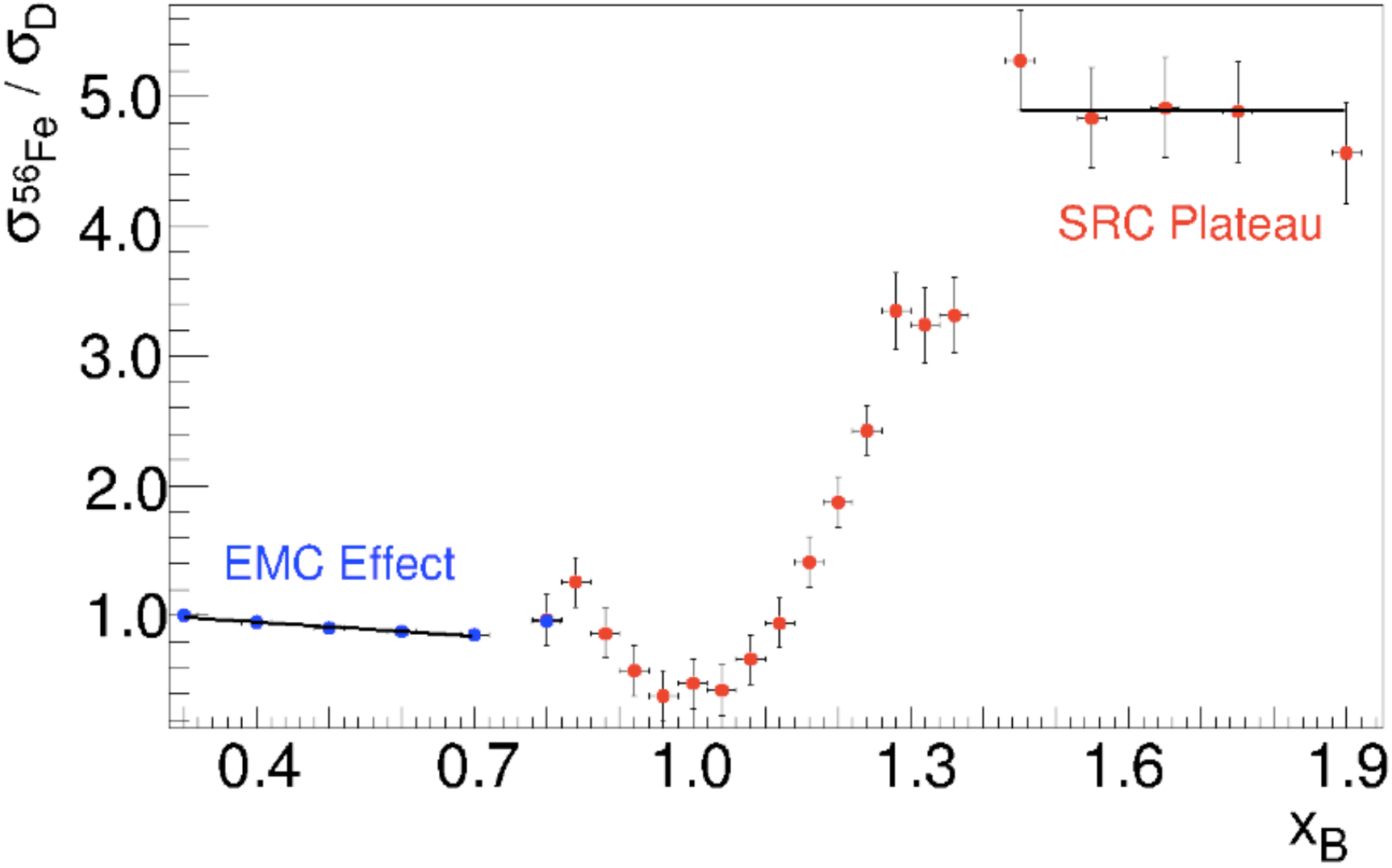
Very Satisfying!

- Finished in one week and gave a talk while at LBL
- Had a hard time with PRL… JWC, Detmold, Phys. Lett. B625 (2005) 165

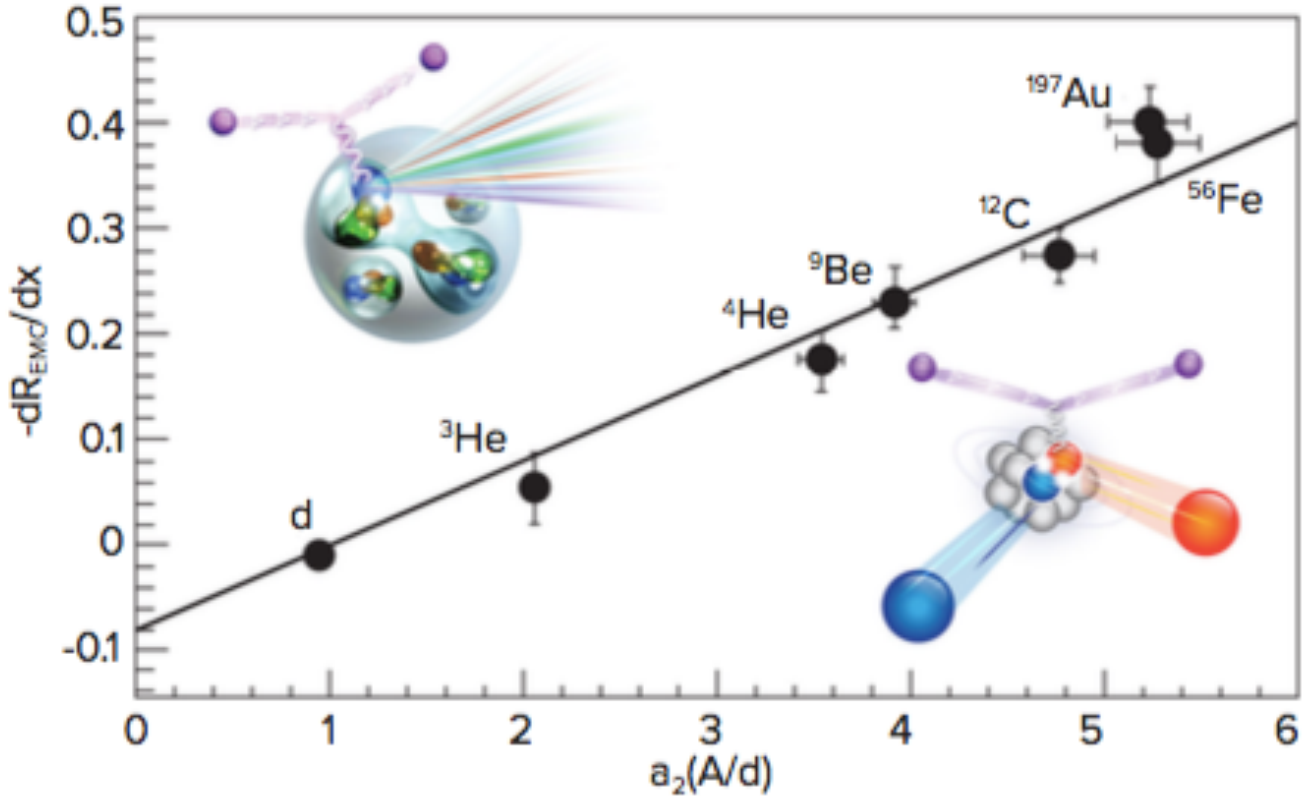
- Nobody cared..., until 2014

A New Twist

--- x > 1 results learned in Adelaide, 2014

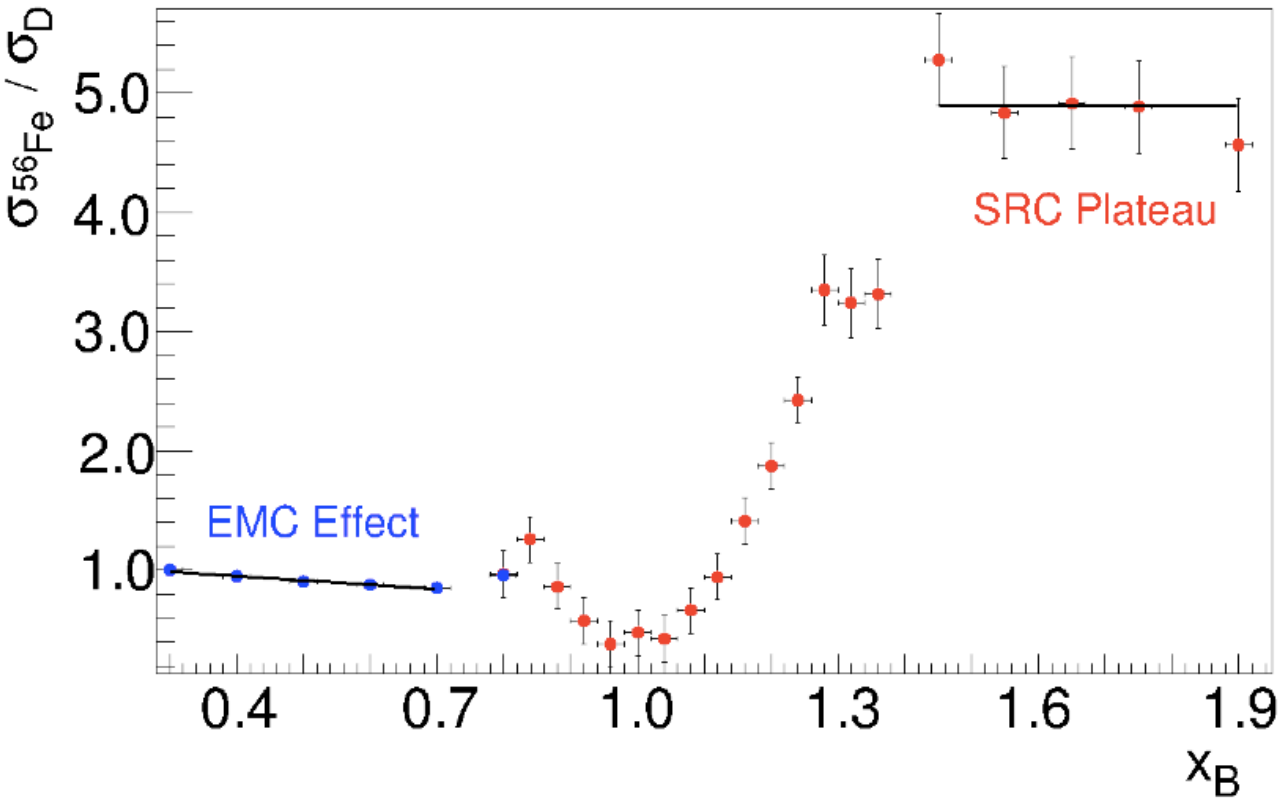


An Astonishing Empirical Result!



Weinstein et al., Phys. Rev. Lett.106, 052301 (2011)
A highlight in 2015 US NSAC Long Range Plan

Another Eureka Moment!

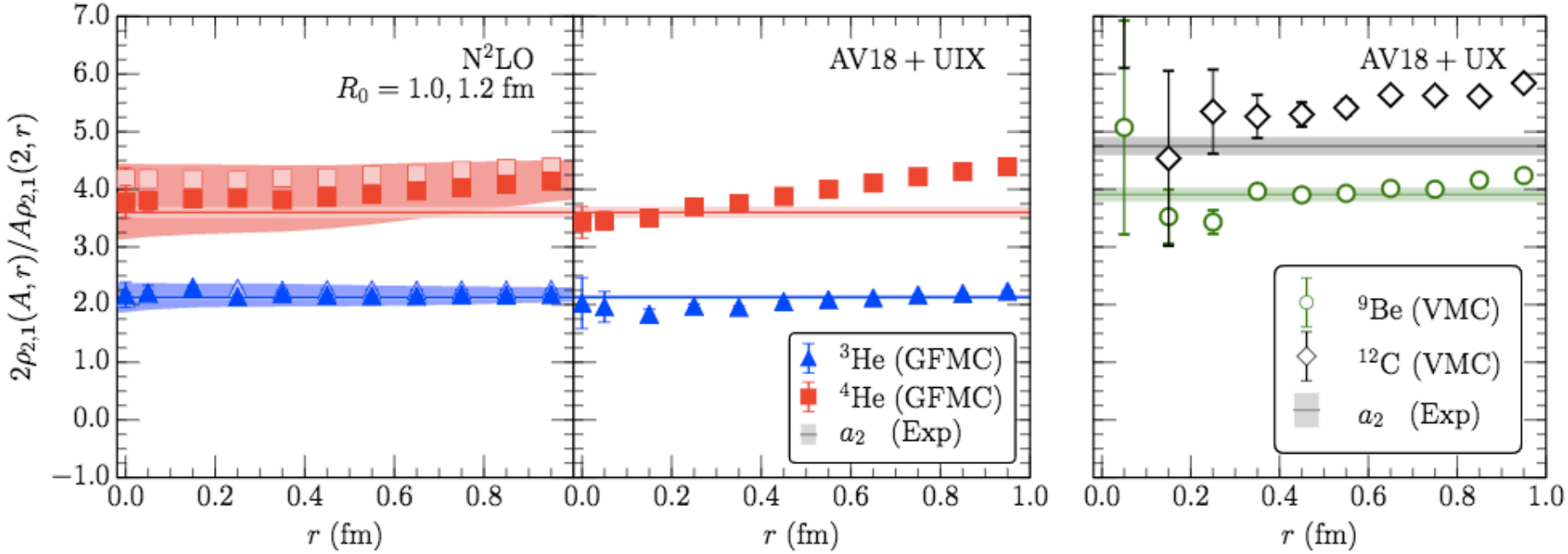


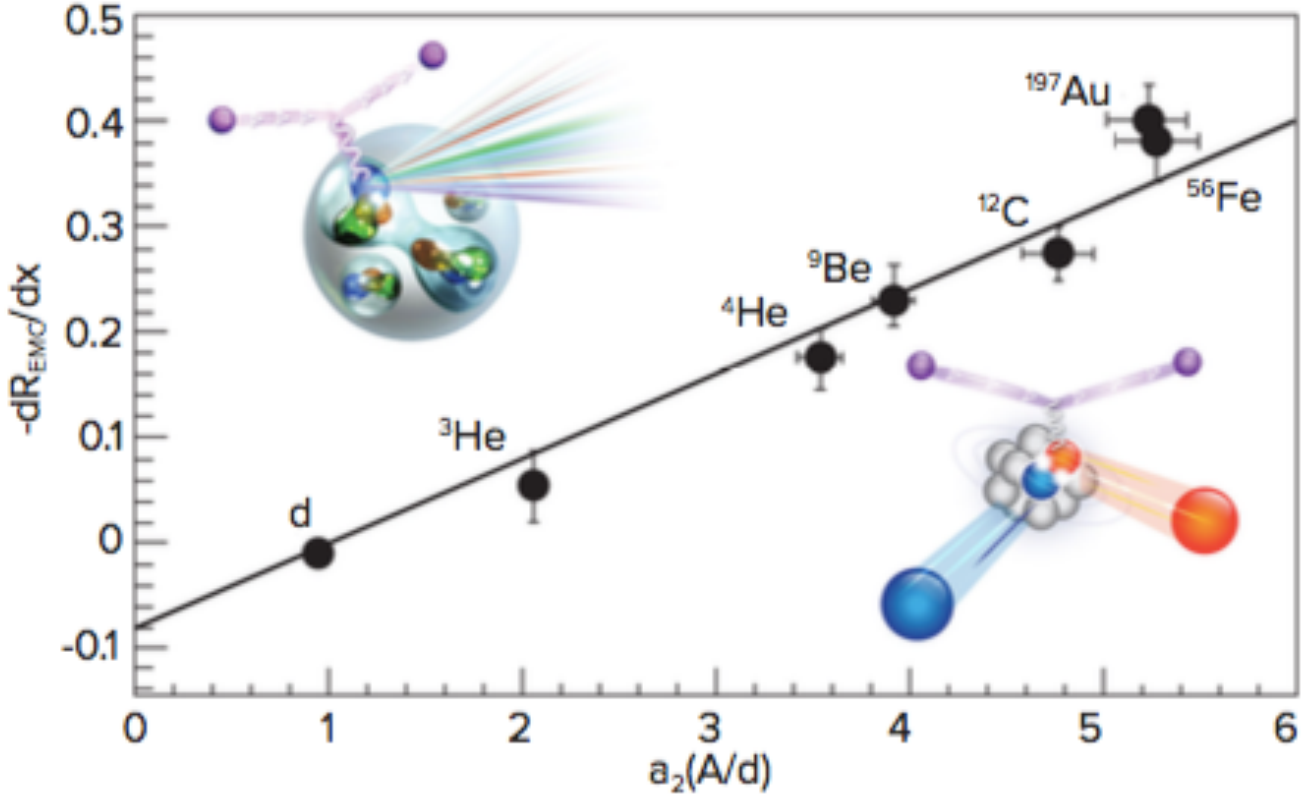
$$q_A(x)/A = q_N(x) + g_2(A,\Lambda)\tilde{q}_2(x,\Lambda) \qquad q_N(x>1) = 0$$

Indept of scheme & scale!

$$a_2(A, x>1) = \frac{2q_A(x)}{Aq_d(x)} = \frac{g_2(A,\Lambda)\tilde{q}_2(x,\Lambda)}{g_2(2,\Lambda)\tilde{q}_2(x,\Lambda)} = \frac{g_2(A,\Lambda)}{g_2(2,\Lambda)}$$

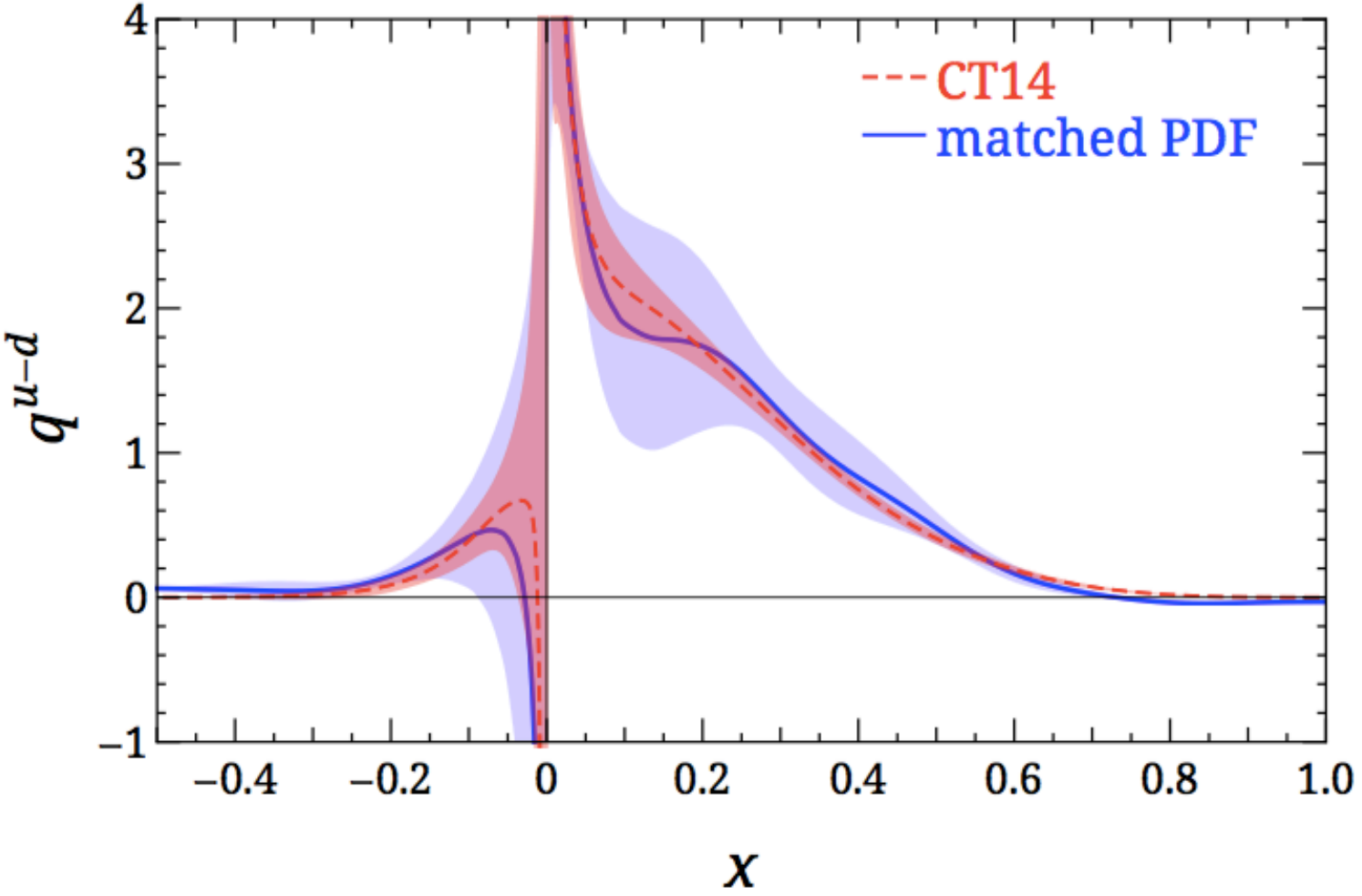
a_2: scheme and scale independent



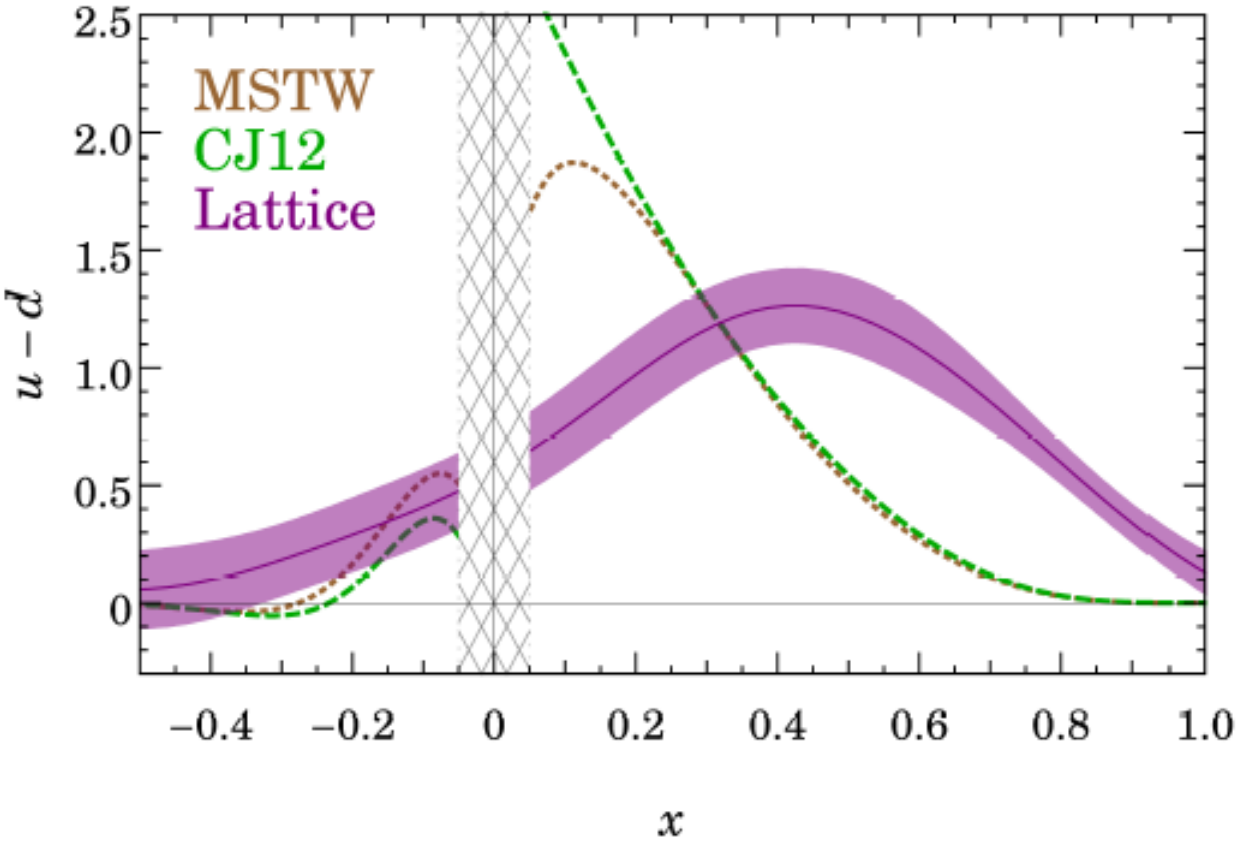


- EMC-SRC linear relation reproduced
- Some a_2 reproduced ab initioly
- Remaining problem: EMC slope from LQCD (only need deuteron)

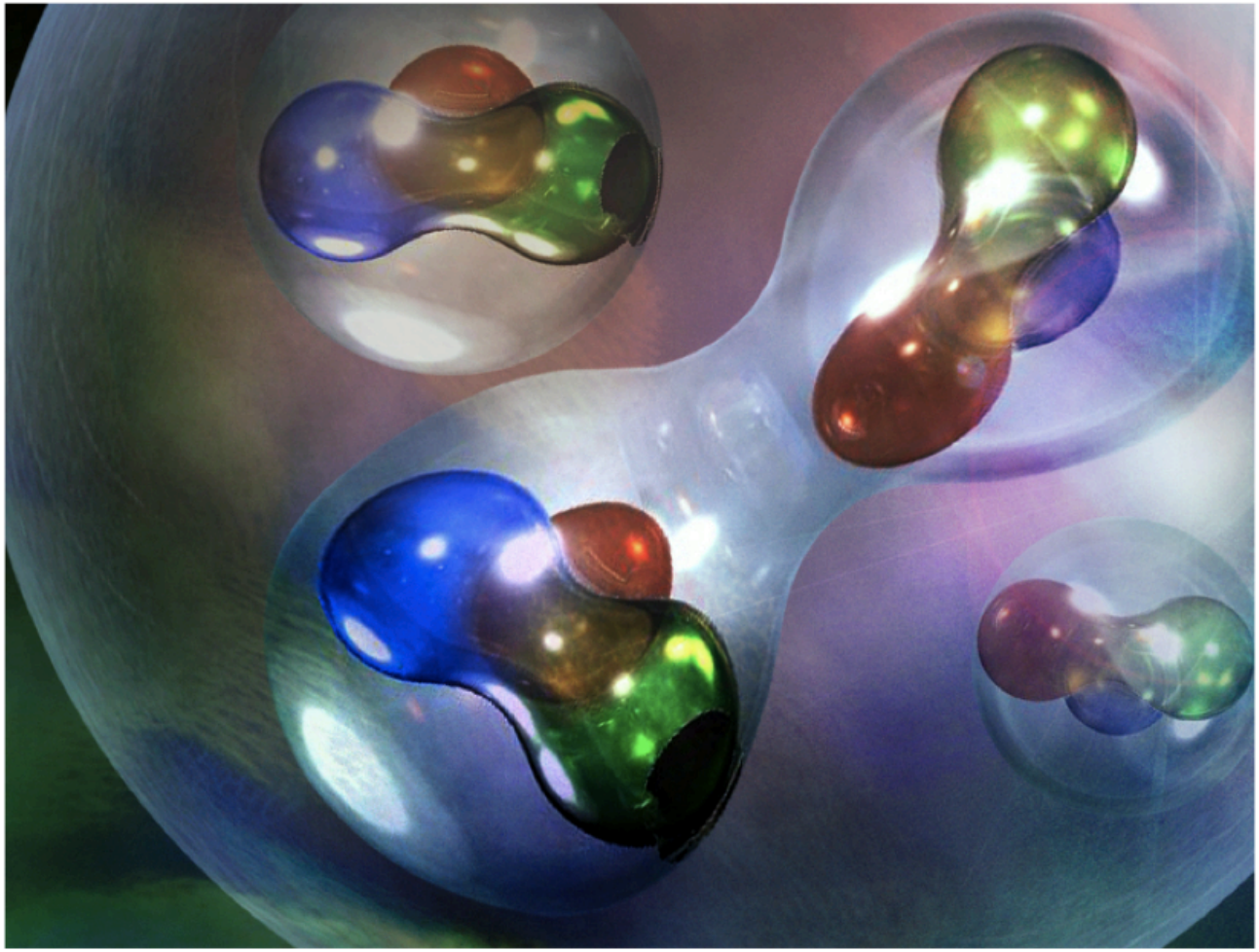
PDF from Lattice w/ Physical Pion Mass (JWC et al. 1803.04393)



Good progress from 2014



Summary and Outlook



Credit: CERN Courier

Outlook

- EMC-SRC relation: a simple and elegant empirical result explained by a simple, elegant, and predictive theory

- Applications: ν-A scattering for long baseline exp., MiniBooNe, NuTeV
- LQCD might get the EMC-SRC slope in 5 years to complete the picture
- 3D imagining of nuclear PDFs

Backup