From QCD to Nuclear Physics

The Seventh International Symposium on Chiral Symmetry in Hadrons and Nuclei

Beihang University, Beijing China, 27-30 October 2013

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The College of William & Mary

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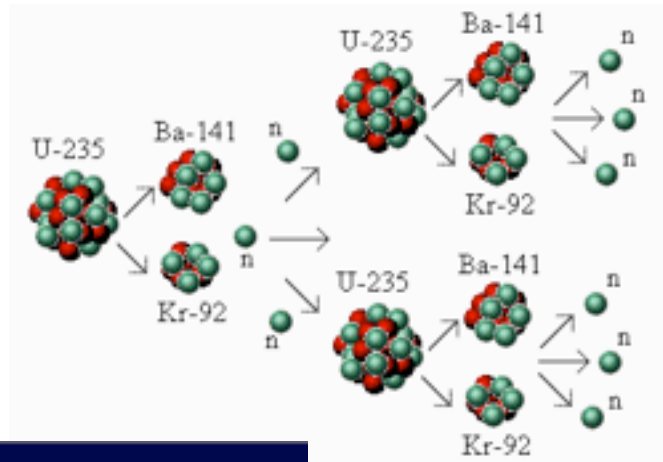
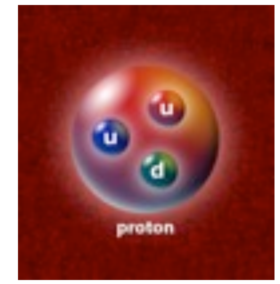
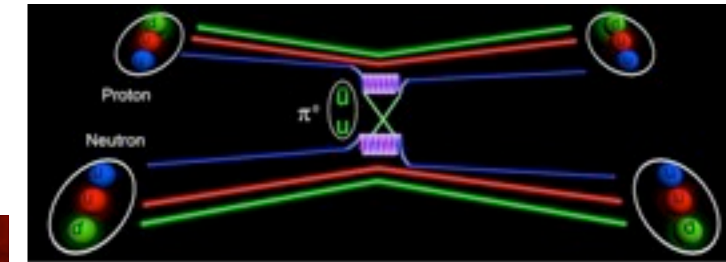
Outline: Nuclei and Lattice QCD

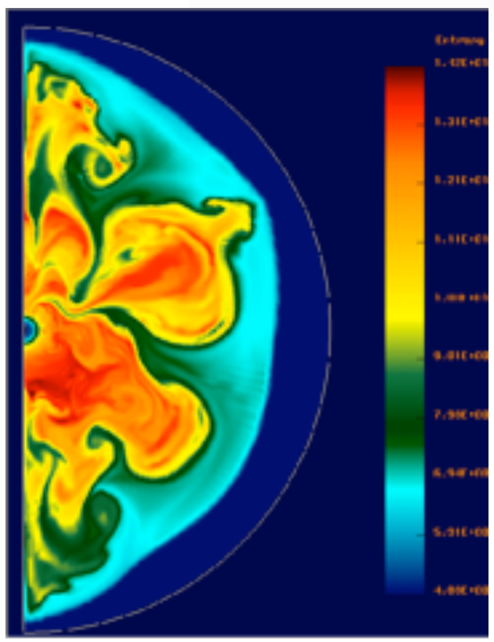
- Introduction
- Challenges and Progress
- Status Report
- Quarks, Nuclei and the Early Universe
- Conclusions

Introduction

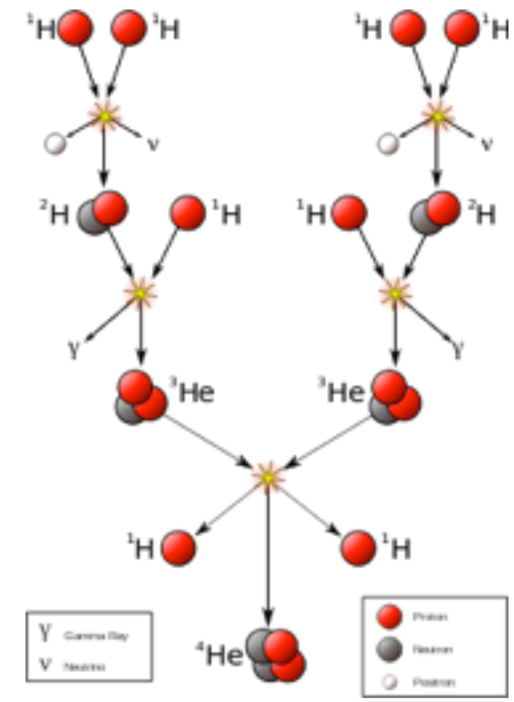


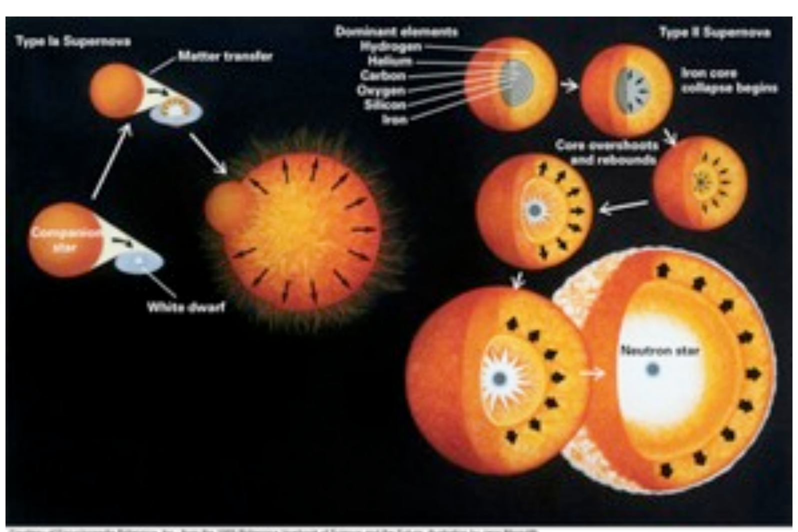


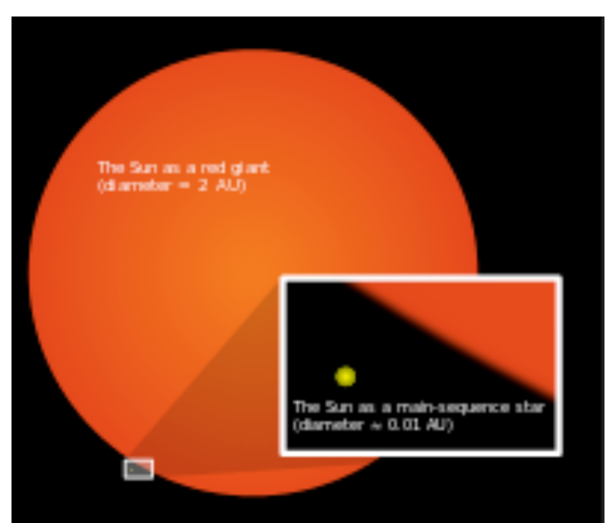


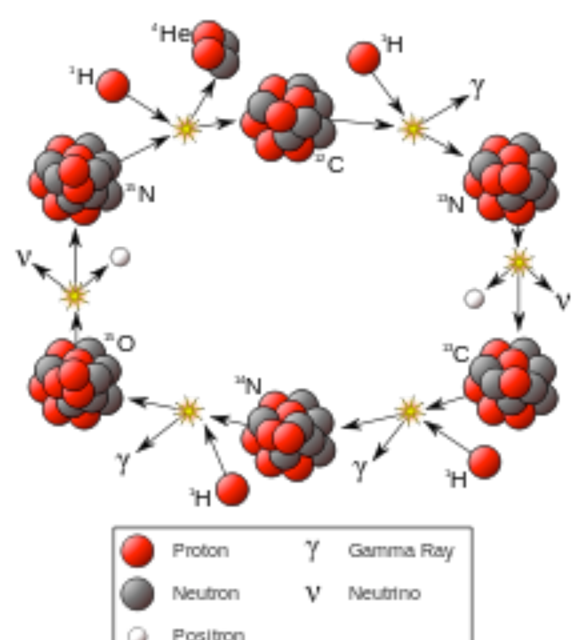


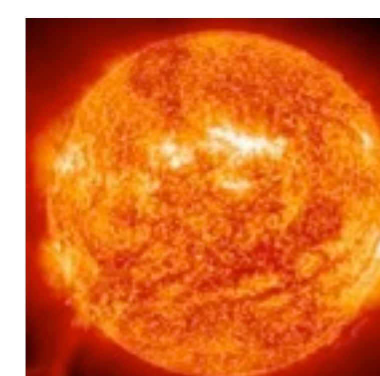
Quantum ChromoDynamics
is *The* fundamental
theory of nuclear physics











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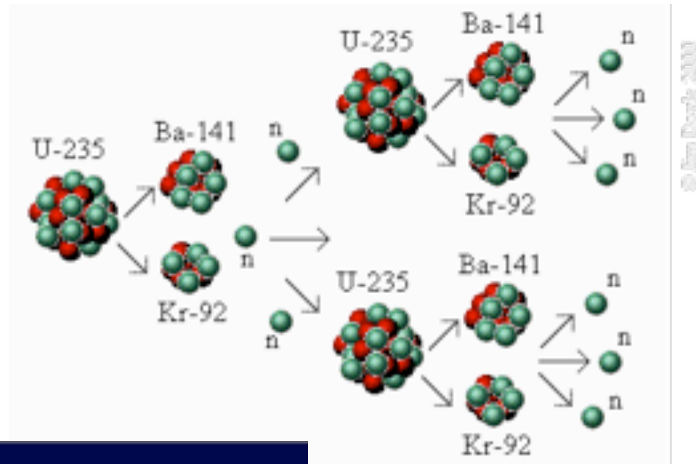
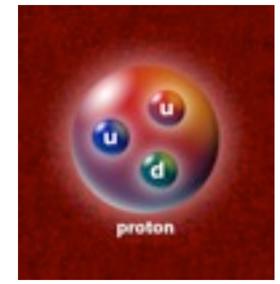
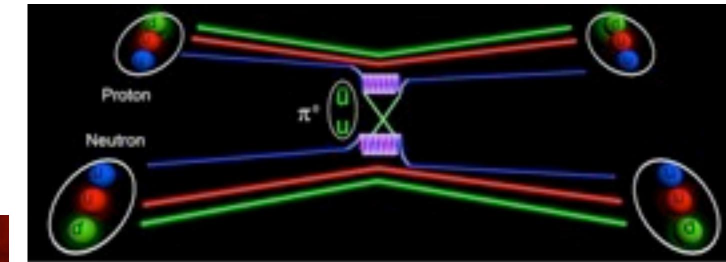
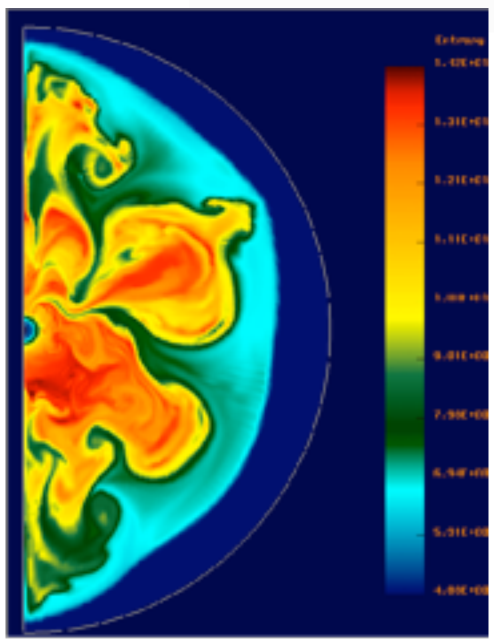
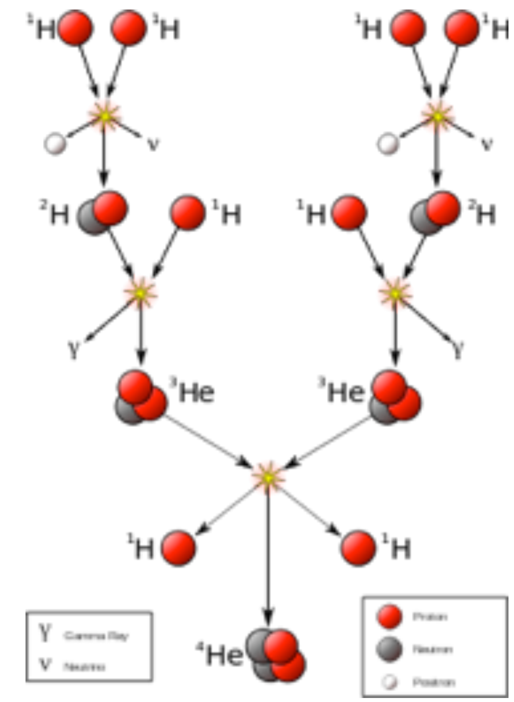


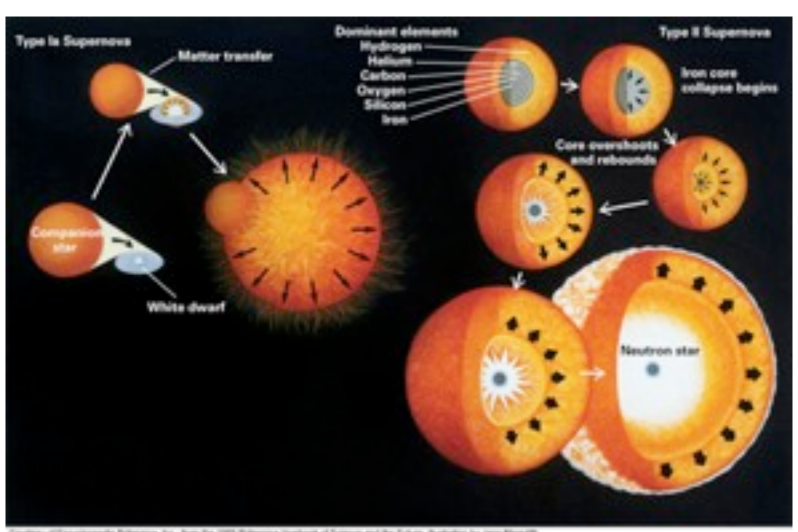


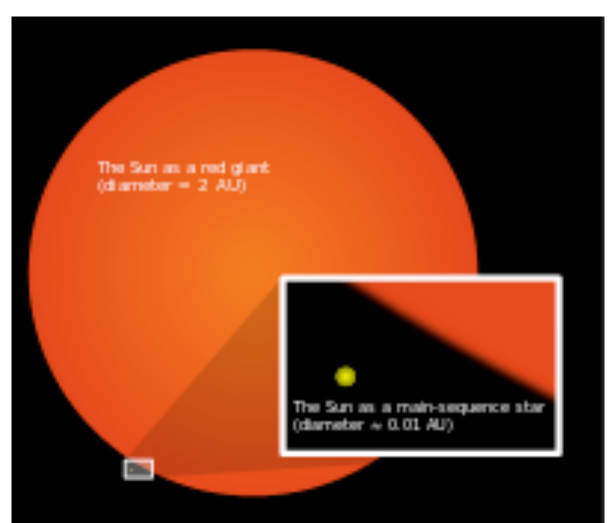


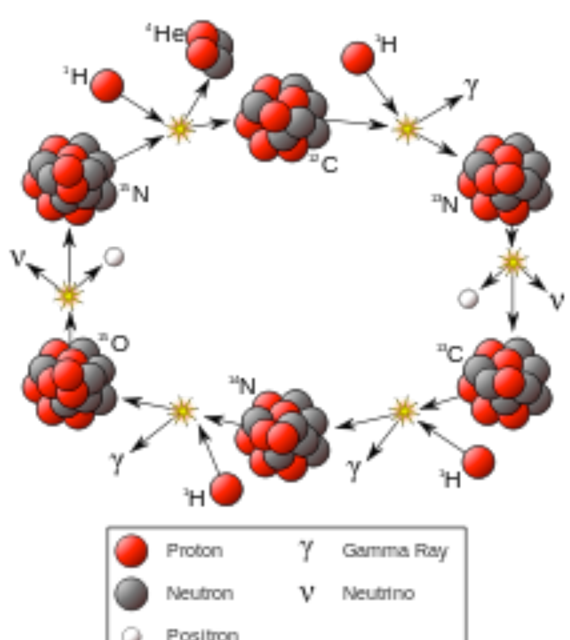


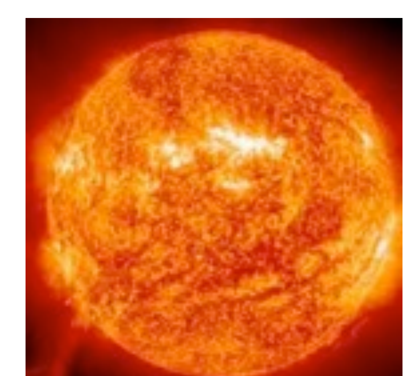


How much of this can we *quantitatively* connect to QCD?

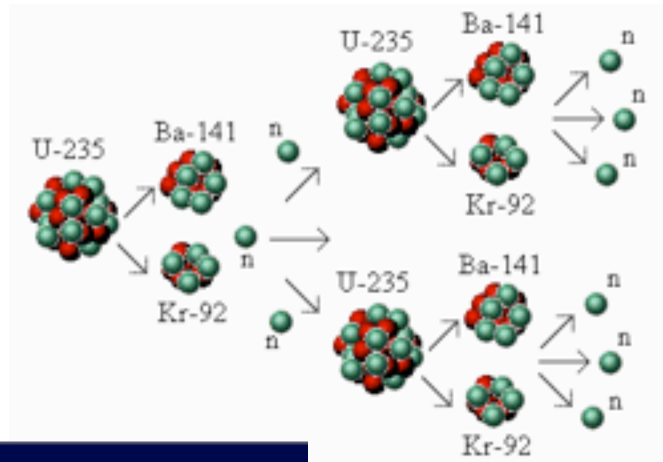


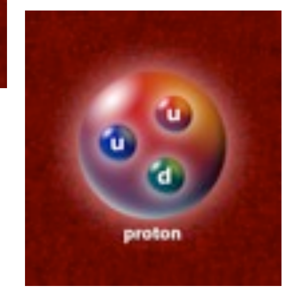


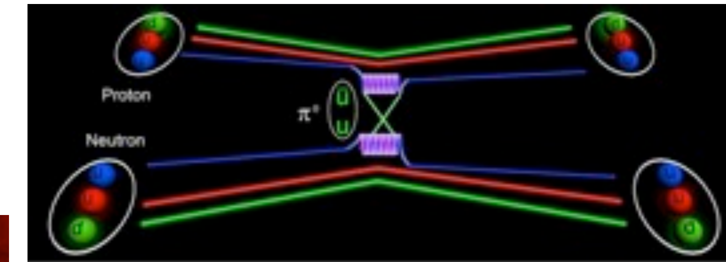


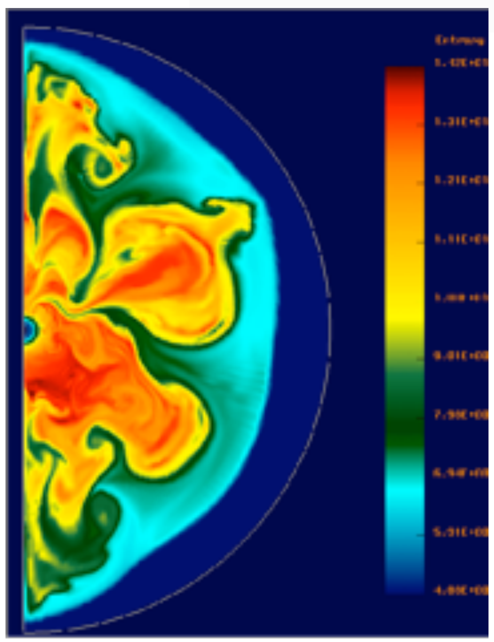


Introduction

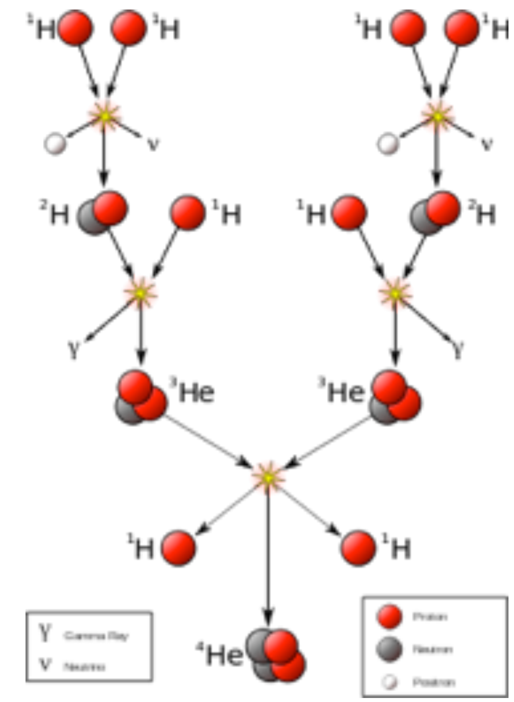


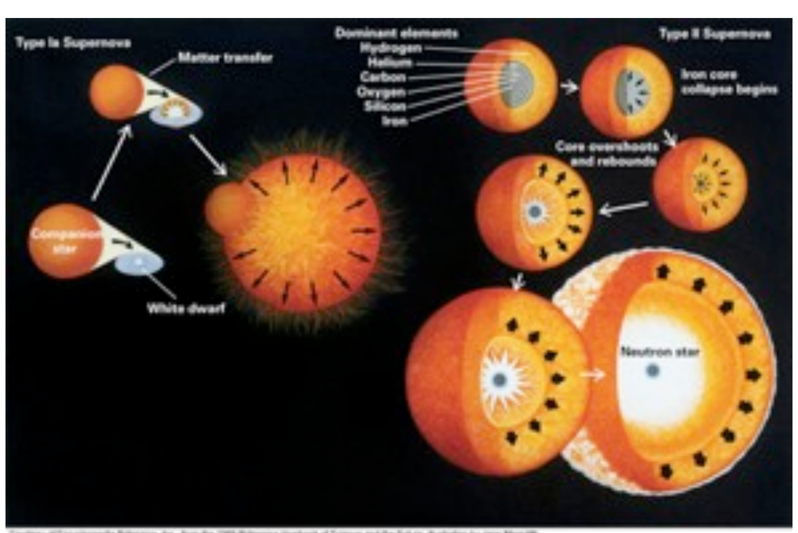


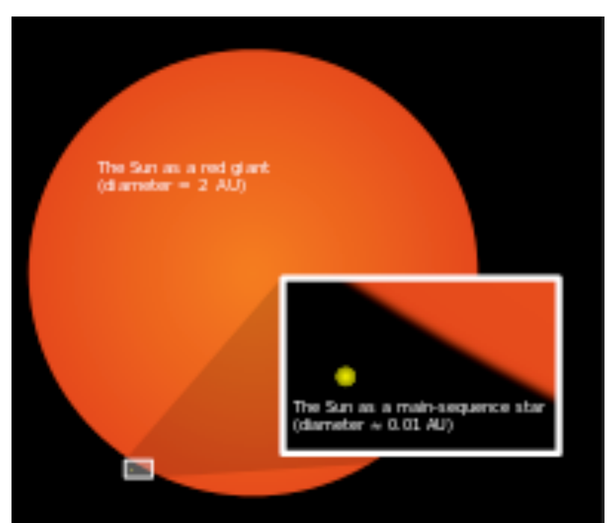


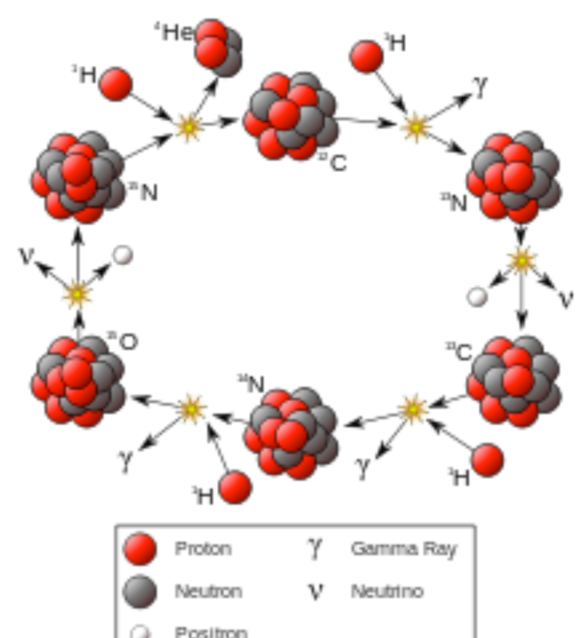


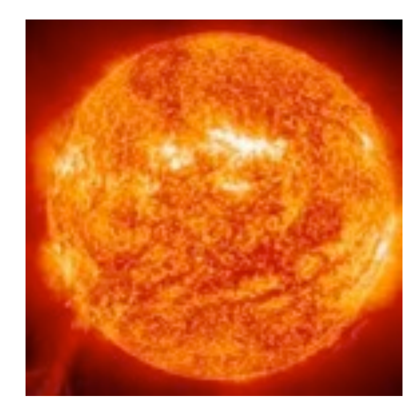
QCD is the most perfect physical theory... until one wants to compute properties of matter











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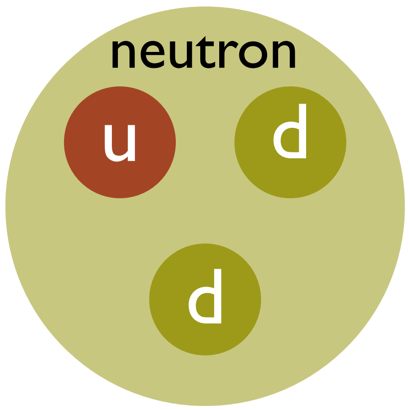
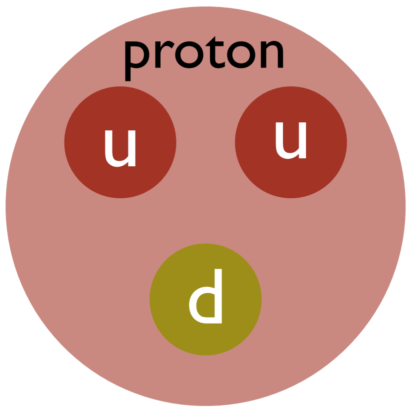
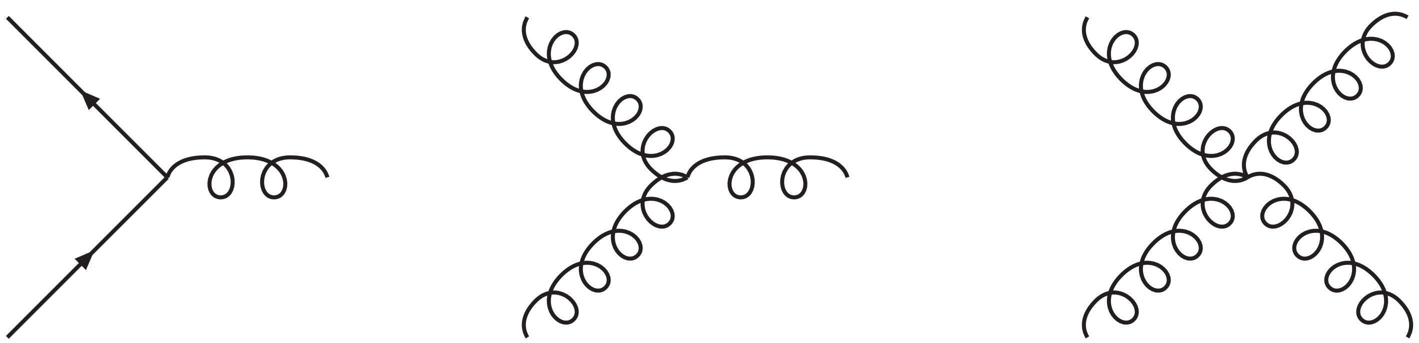


QCD describes the interaction between quarks and gluons



Neutrons and Protons are composed of confined quarks and gluons



g g g^2

quark-gluon interactions

3- and 4-gluon interactions

like electromagnetism

responsible for non-perturbative nature

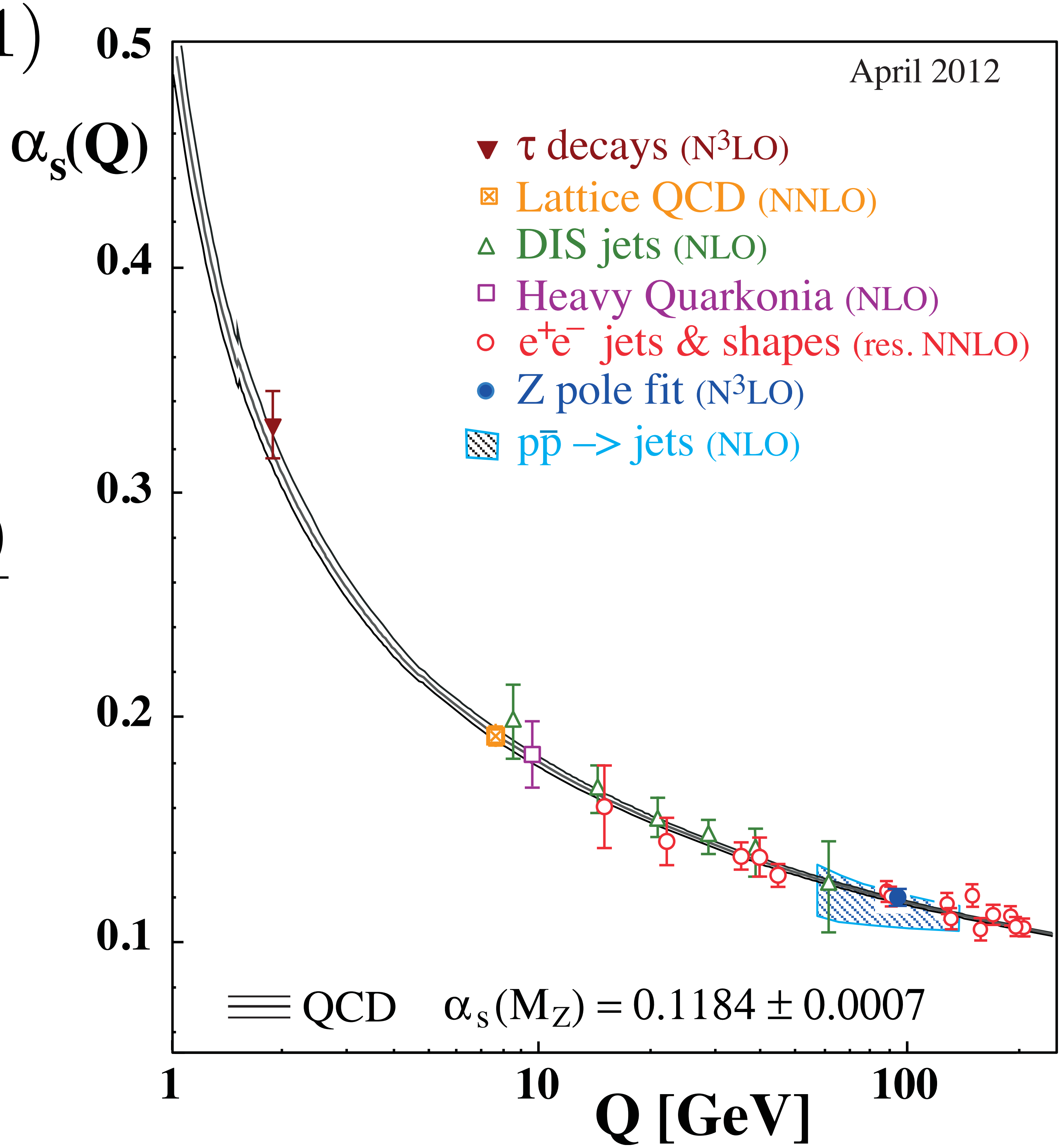
Introduction

low energy → high energy

$g \sim \mathcal{O}(1)$

Strong Coupling

$$\alpha_s(Q) = \frac{g^2(Q)}{4\pi}$$



$g \to 0$

Asymptotic Freedom

2004 Nobel Prize

David Gross

David Politzer

Frank Wilczek

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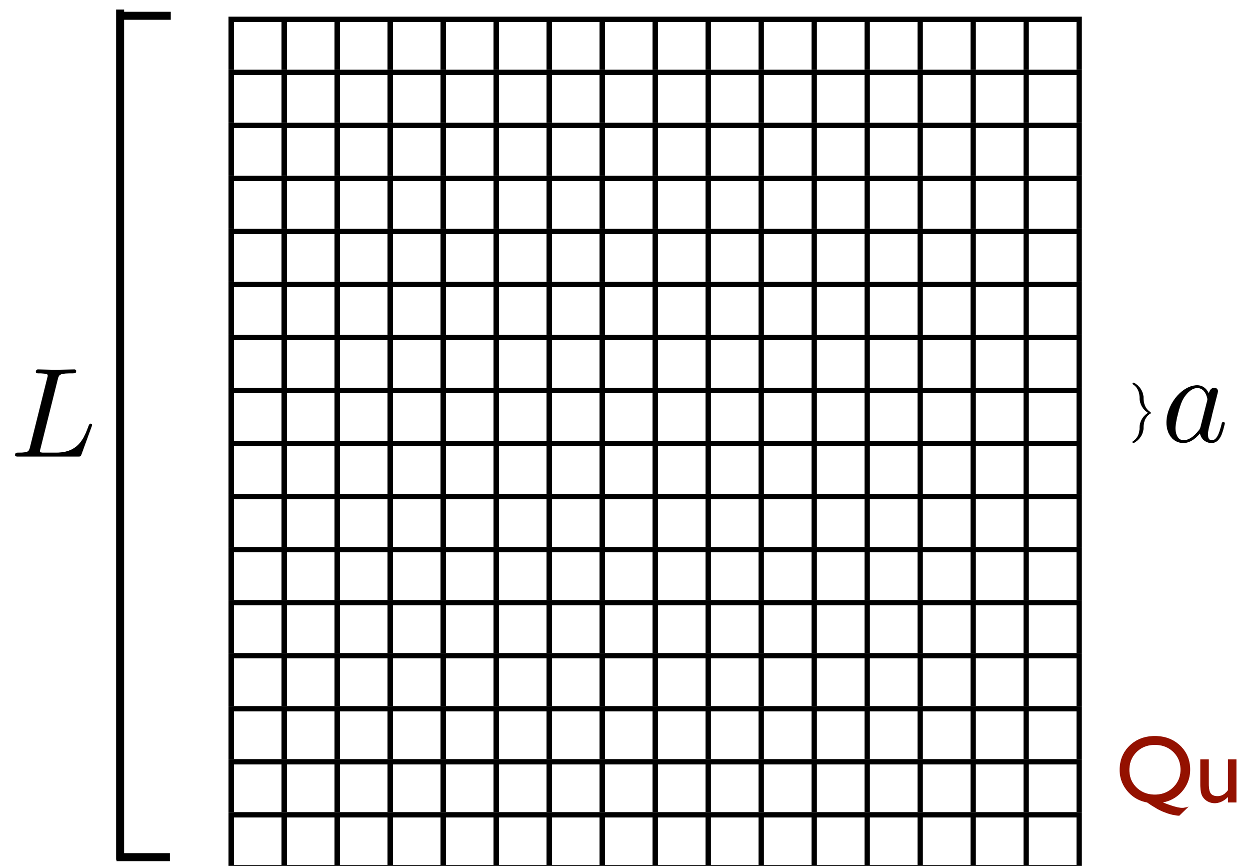

universe

$\sim L^4$

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Quantum Mechanics:

uncertainty principle

small distance

=

large energy

take discretization scale to zero $a \to 0$

we know the *exact* theory to put

on the computer

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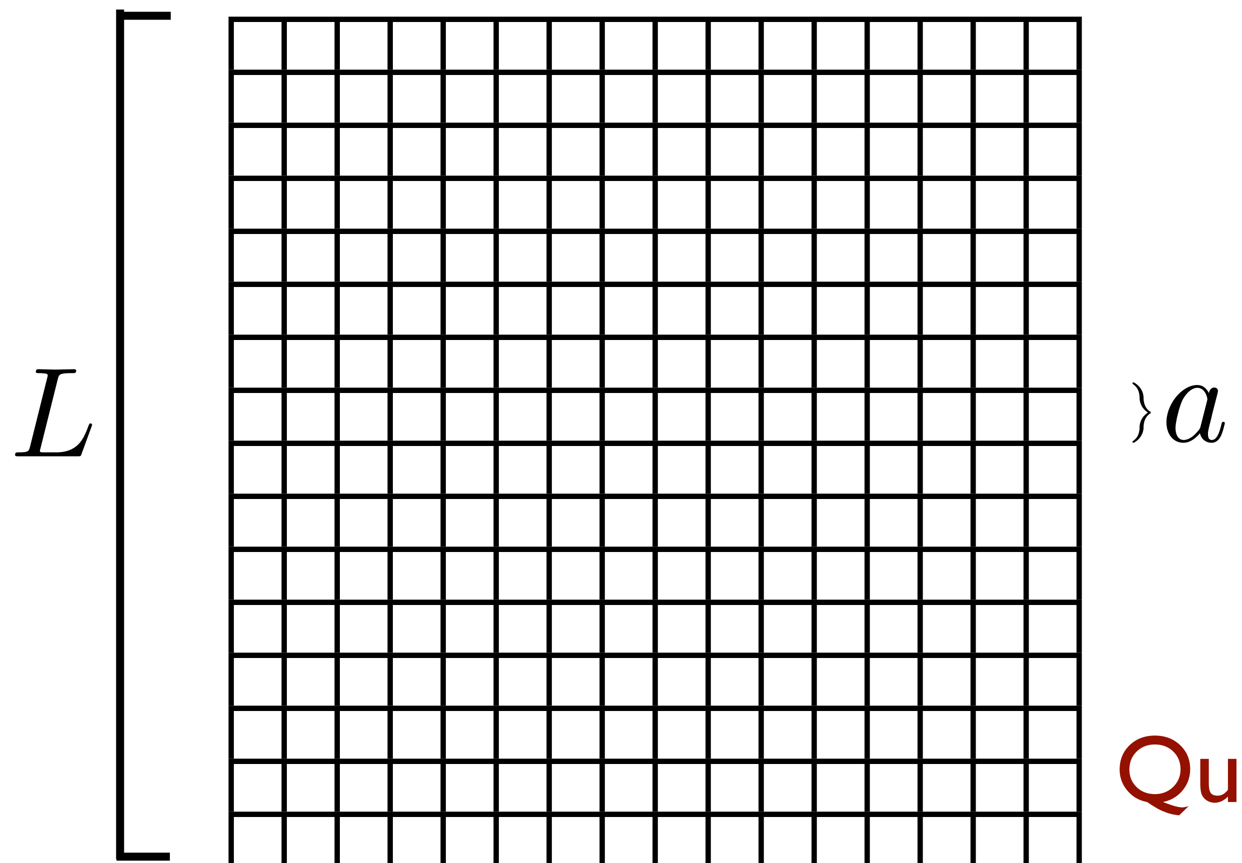
Strong Coupling



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but $t_{comp} \sim \dfrac{1}{a^6}$

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Strong Coupling

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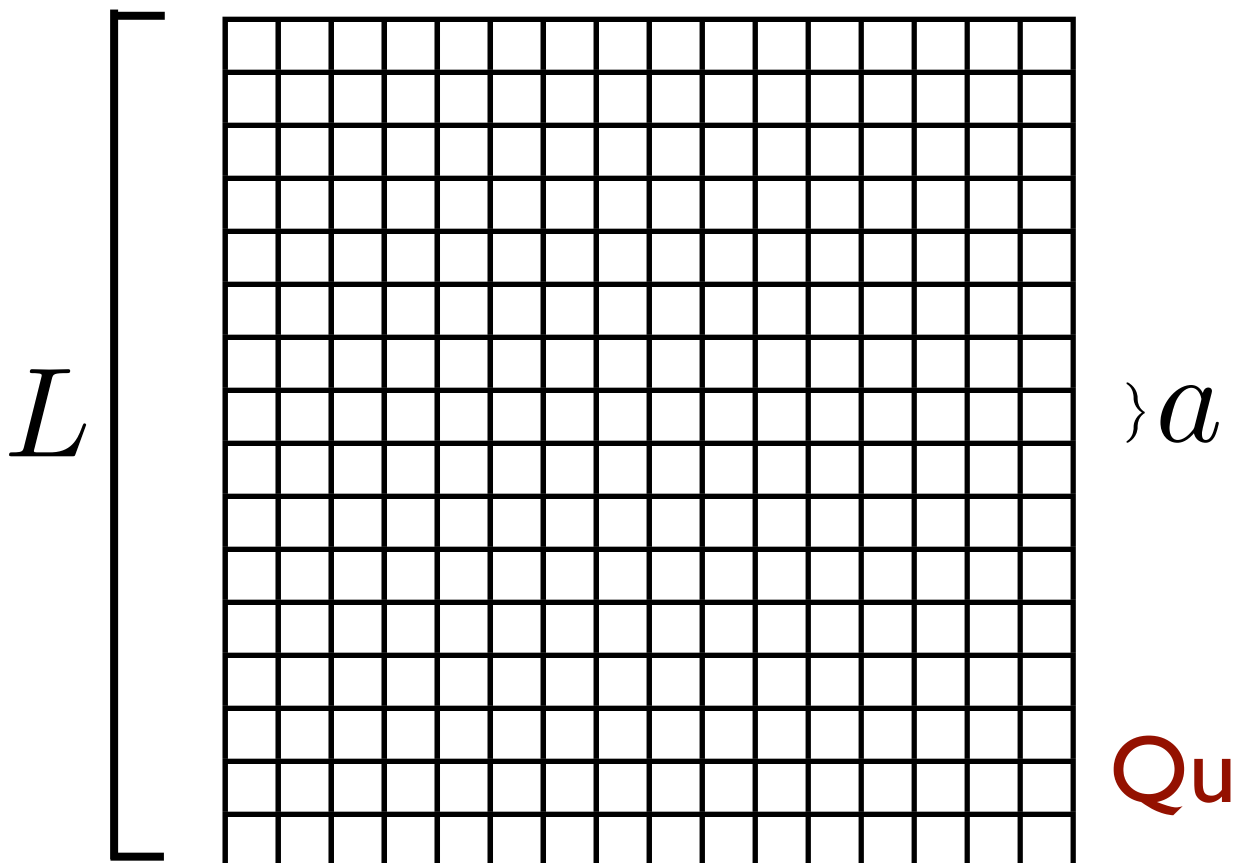
Asymptotic Freedom



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We need BIG computers

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Strong Coupling

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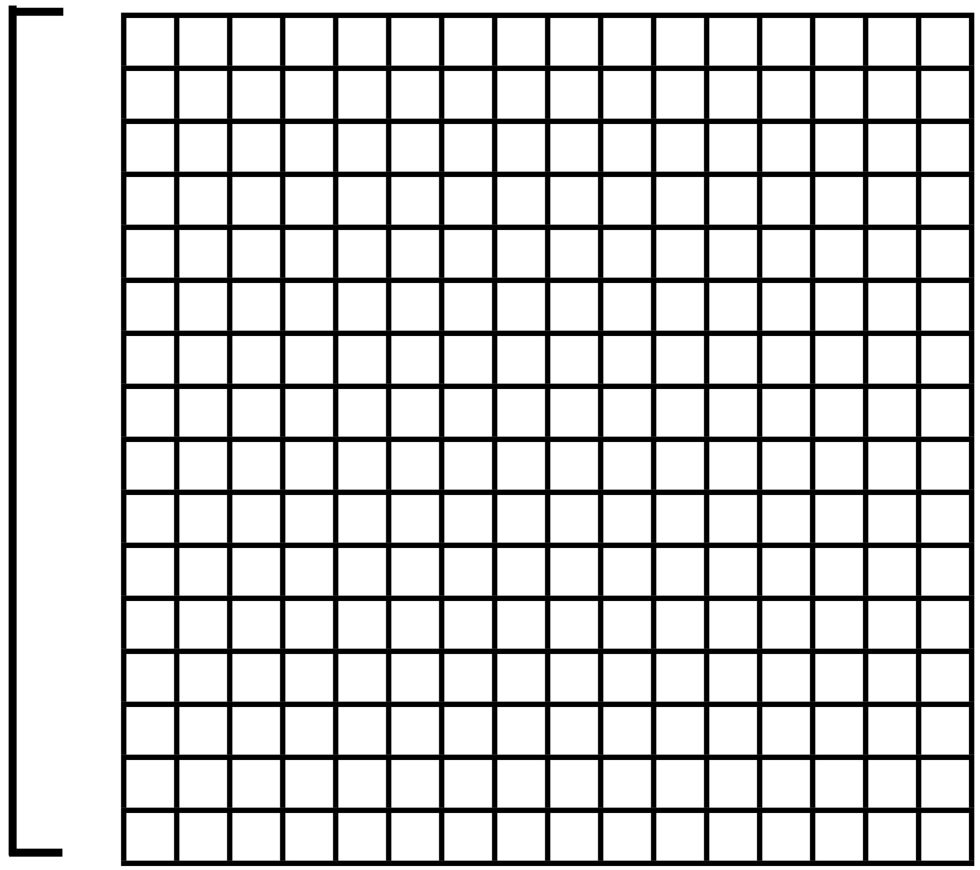
Asymptotic Freedom

L



a

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Quantum Mechanics:

uncertainty principle

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=

large energy

state of the art today: $L = 64 - 128$

lattice QCD calculations will really flourish in the exa-scale era

Challenges and Progress

- Signal-to-noise degrades exponentially in time

$$\frac{Sig}{Noise} \propto \sqrt{N} e^{-A(m_N - 3/2 m_\pi)t}$$

- numerical cost of performing quark-level Wick contractions can be prohibitively expensive

- Interpolating field overlap with eigenstates of interest

- large separation of scales between interesting (binding) energies and total mass (A nucleons) requires very high statistics calculations

- Finite Volume formalism for multi-hadron interactions only exists for two and three bodies:

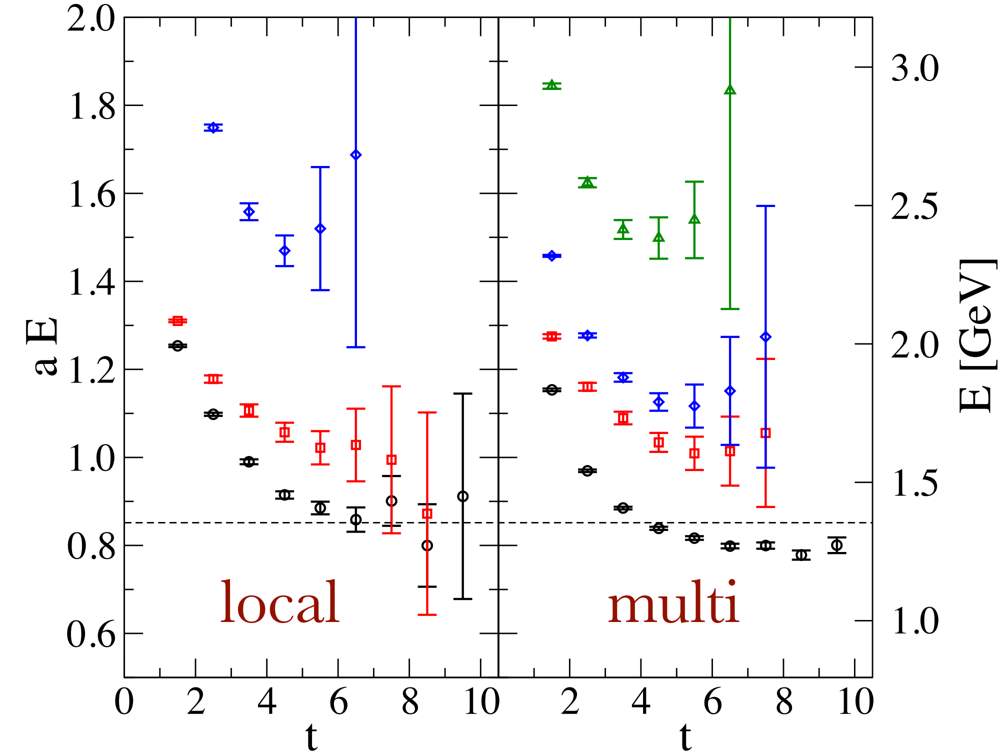
Challenges and Progress

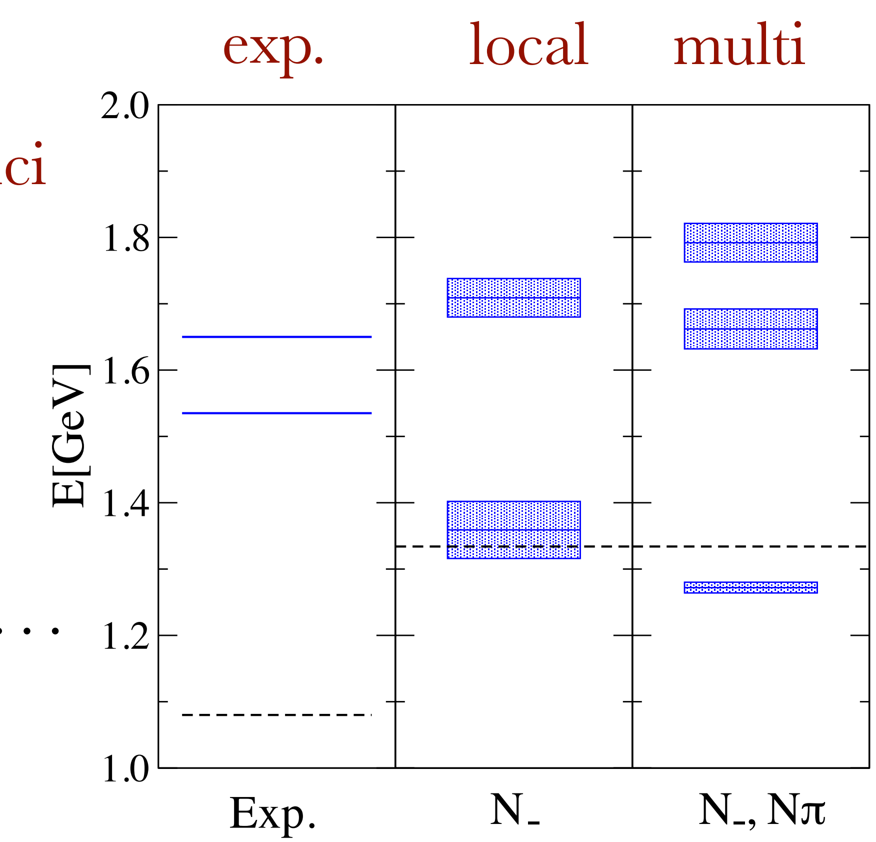
Coupled Channels and Inelastic States

- Calculations of NN interactions with near physical pion masses and large volumes (8-10 fm) requires an understanding of coupled channels and use of multiple operators

$$NN \to NN\pi$$

- without including operators which couple to all relevant states - the spectrum is not determined correctly





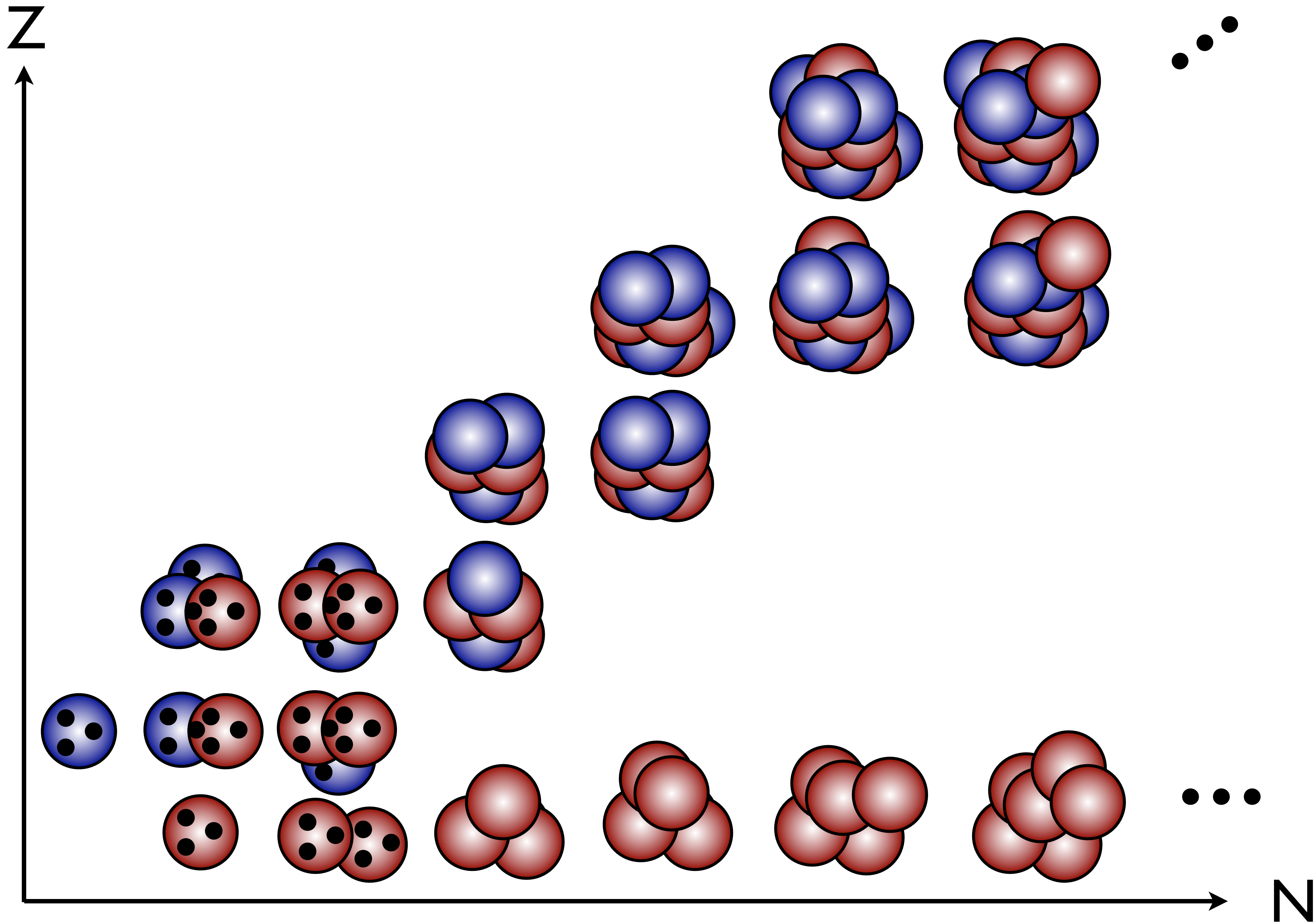
C.Lang and V.Verduci
PRD 87 (2013)

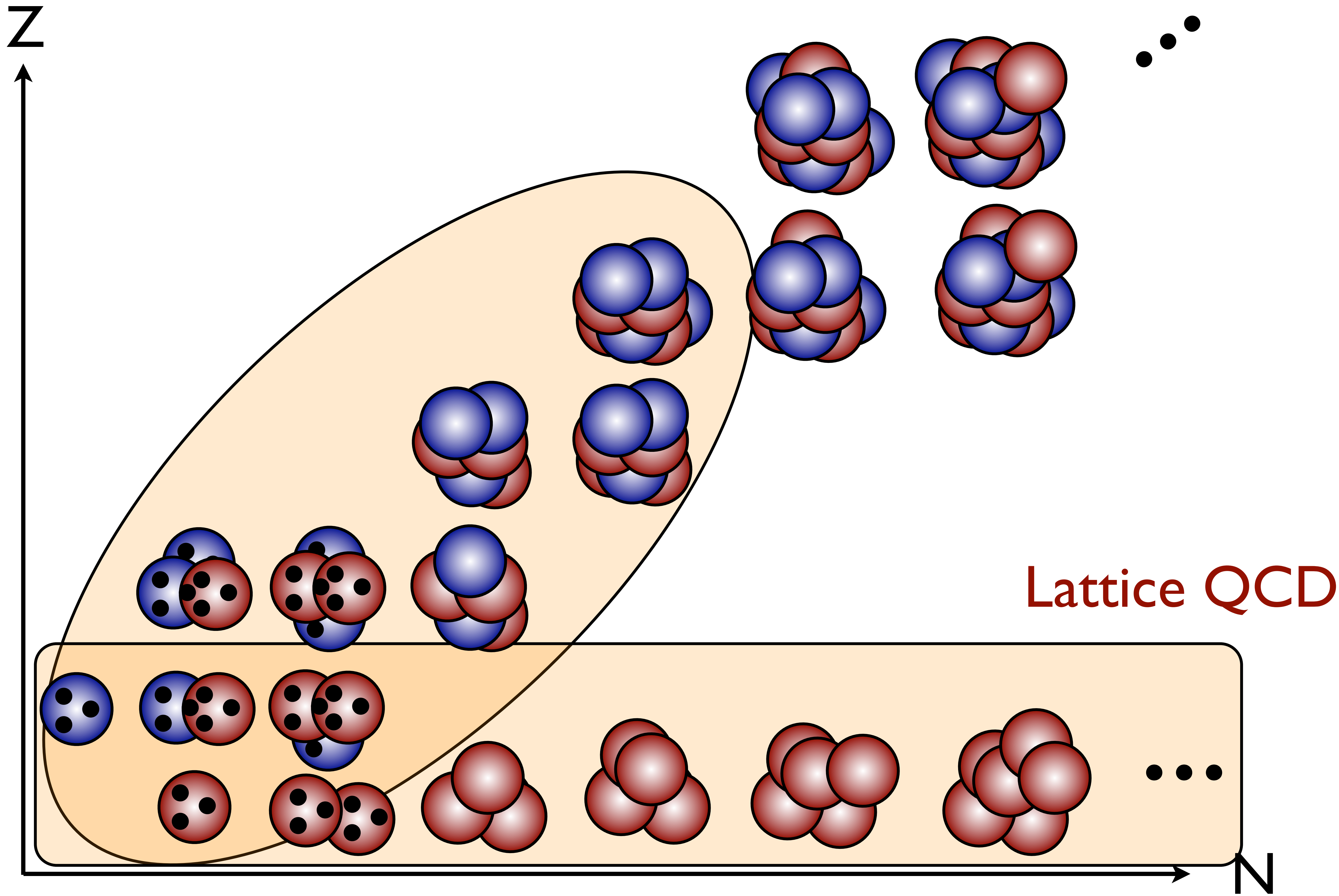
local

$$\left[(u^T C\gamma_5 d)\frac{1-\gamma_4}{2}u\right]^\dagger |0\rangle = Z_{N^-}|N^-\rangle + Z_{N\pi}|N\pi\rangle + \ldots$$

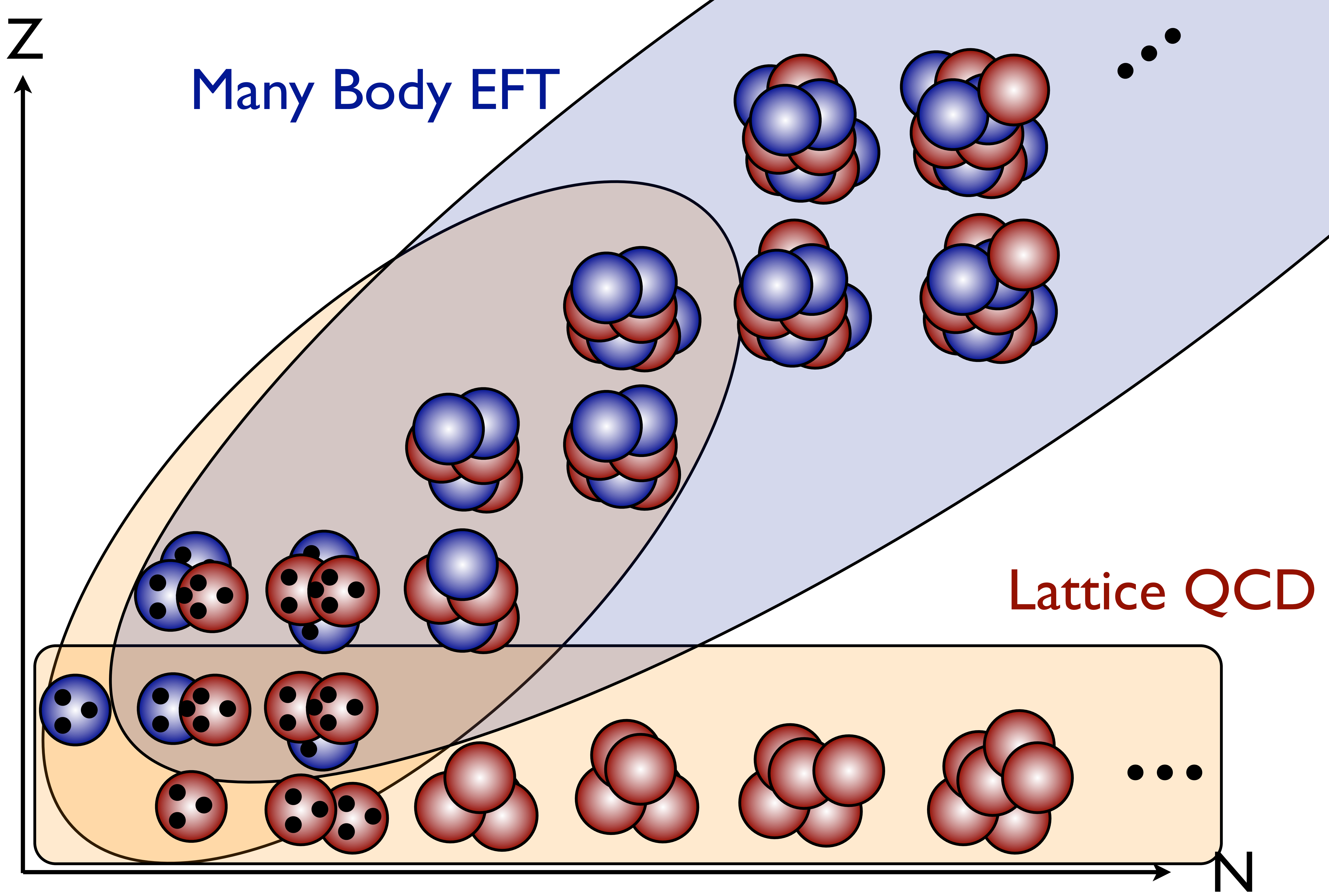
$$\left[(u^T C\gamma_5 d)\frac{1+\gamma_4}{2}u\right]^\dagger [\bar{q}\tau\gamma_5 q]^\dagger|0\rangle = Z'_{N^-}|N^-\rangle + Z'_{N\pi}|N\pi\rangle + \ldots$$

multi-hadron


Z
N



Determine 2, 3, 4 body forces directly from QCD

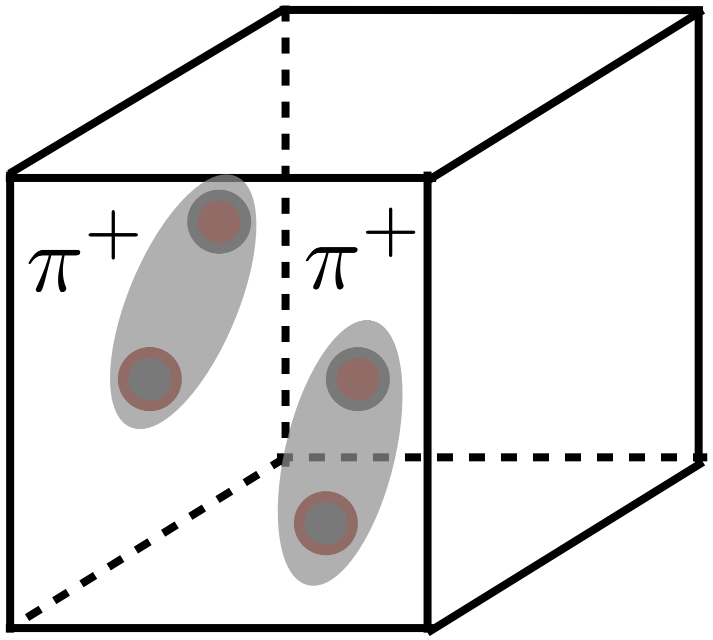


Determine 2, 3, 4 body forces directly from QCD
match onto many body effective field theory

lattice QCD calculations performed in finite volume

infinite volume scattering phase shifts

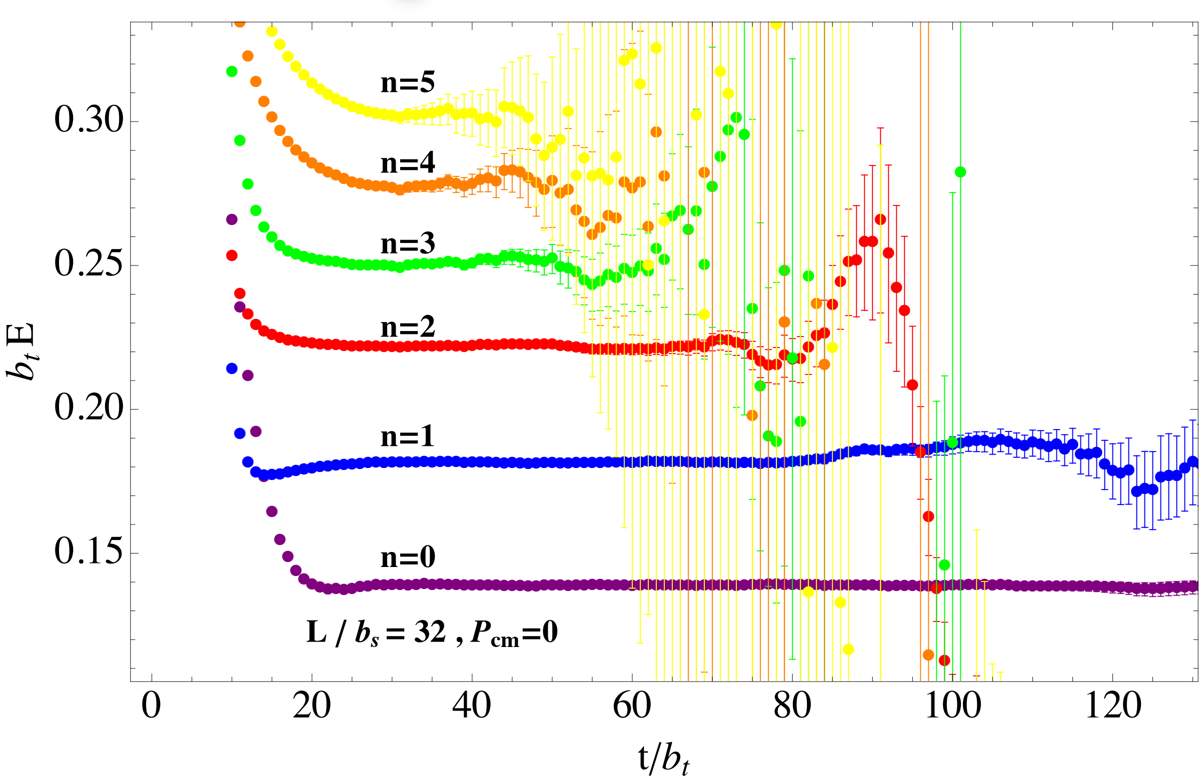
(Lüscher Method)



$$E = 2\sqrt{m^2 + p^2}$$ (two particles)

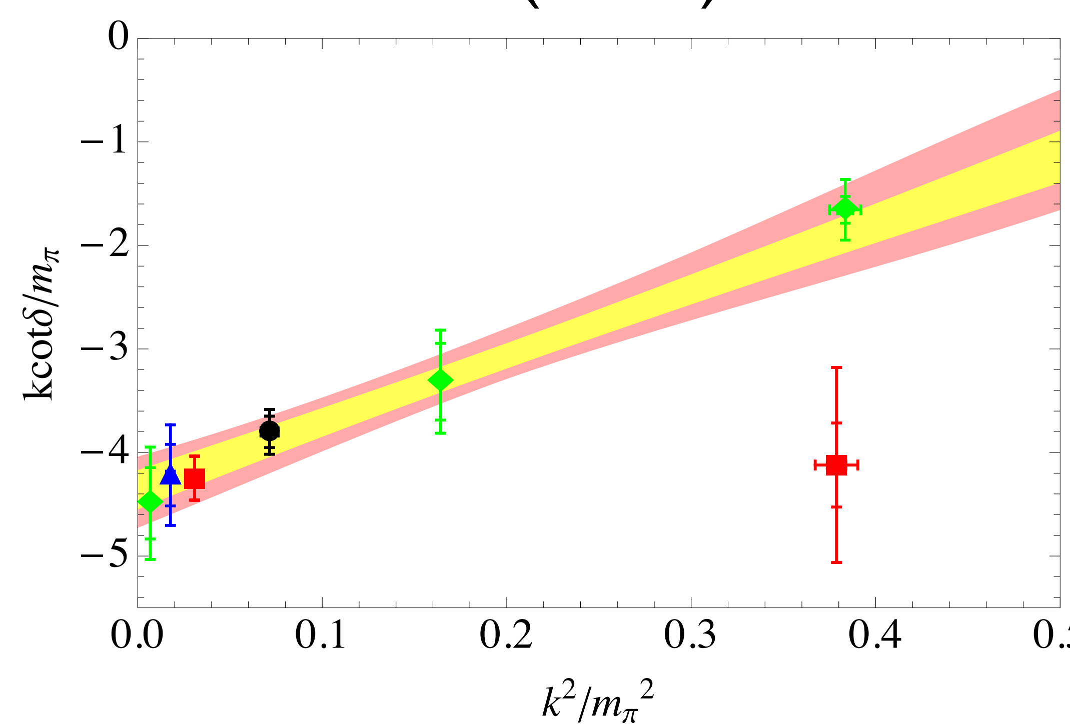
$$p \cot \delta(p) = \frac{1}{\pi L} \sum_{|\vec{n}|<\Lambda} \frac{1}{|\vec{n}|^2 - \frac{p^2 L^2}{4\pi^2}} - 4\pi\Lambda$$

(includes bound states)



A. Walker-Loud w/NPLQCD

PRD 85 (2012) 034505



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infinite volume scattering phase shifts
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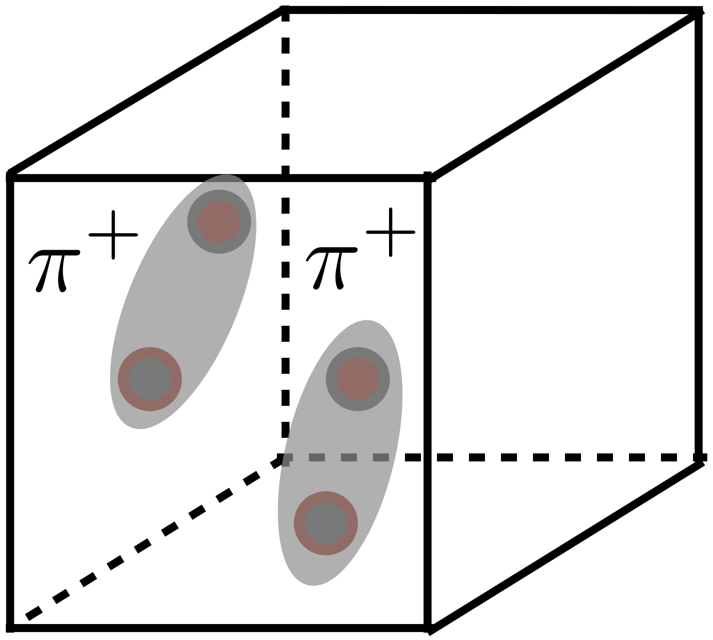

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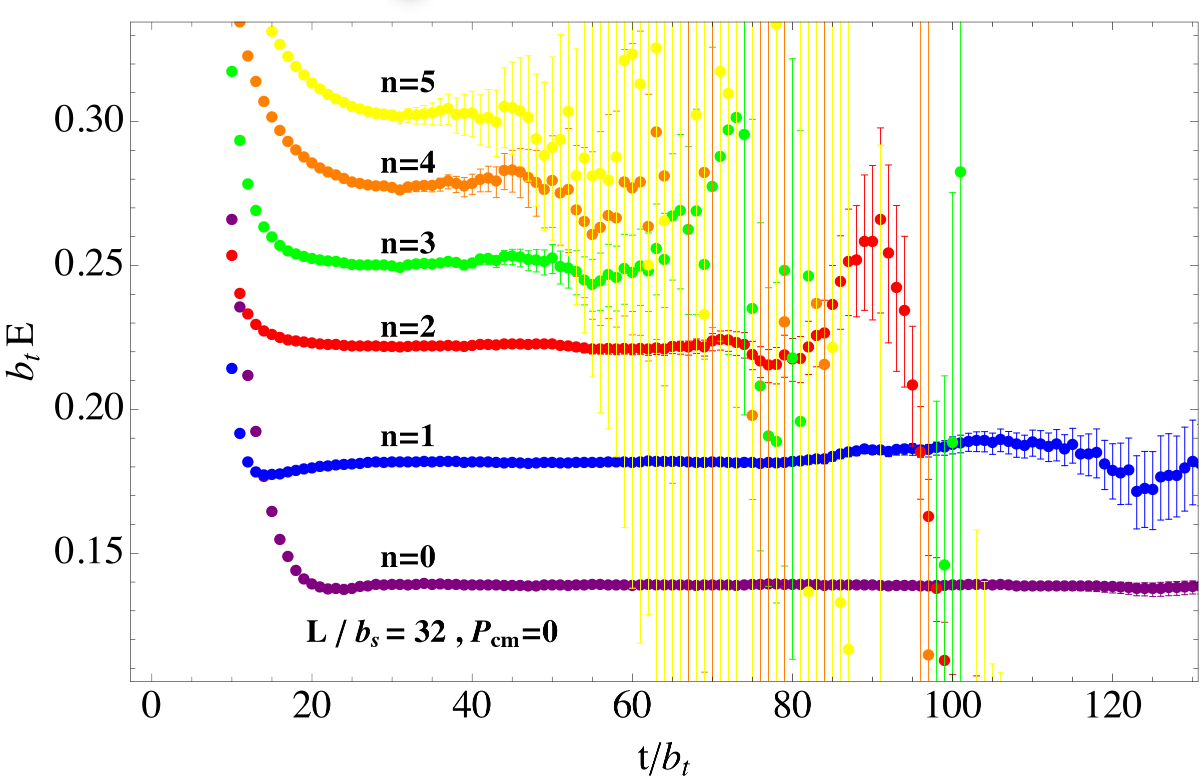

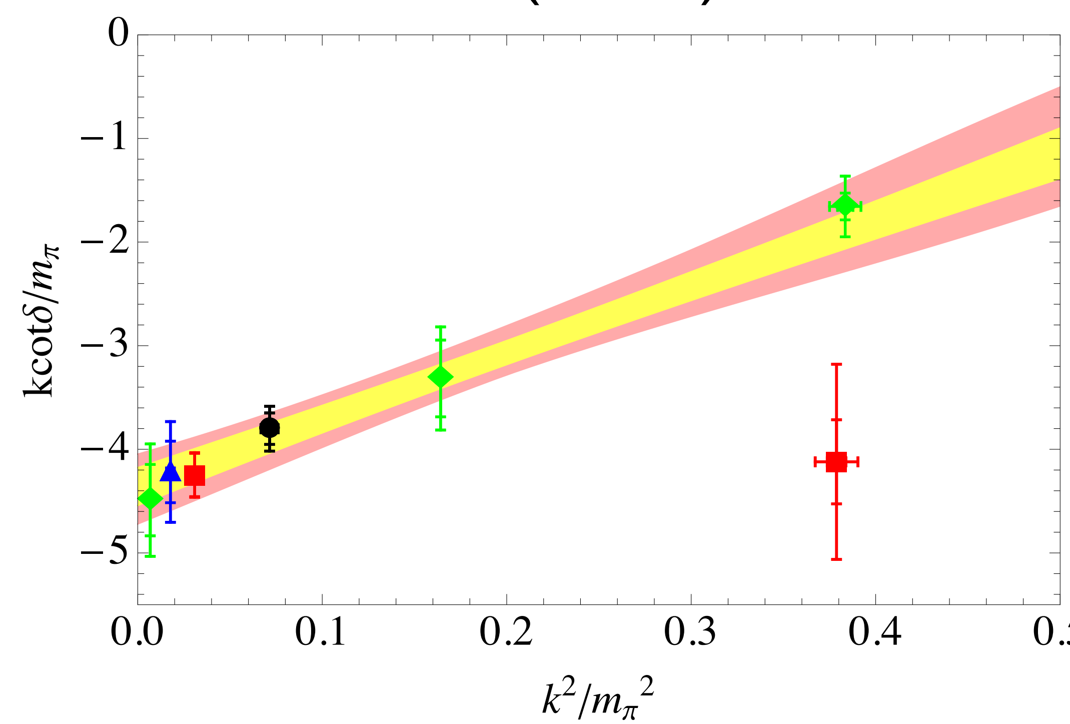

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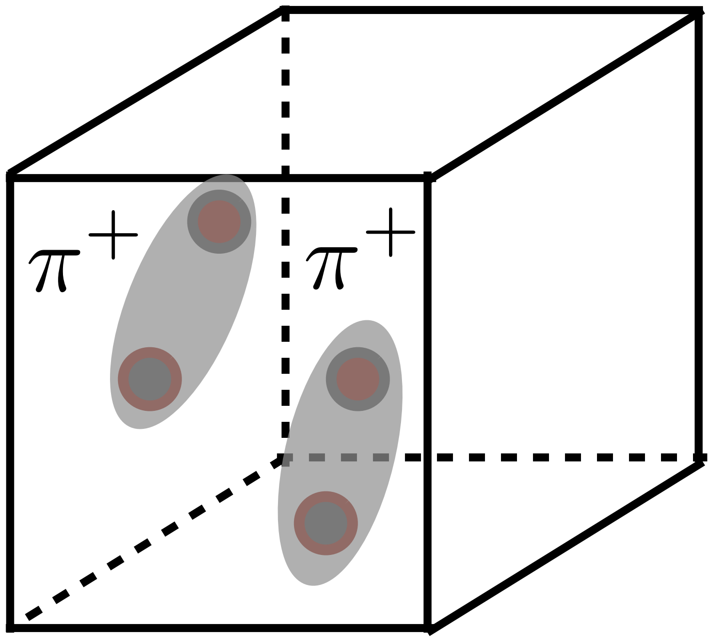

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A. Walker-Loud w/NPLQCD

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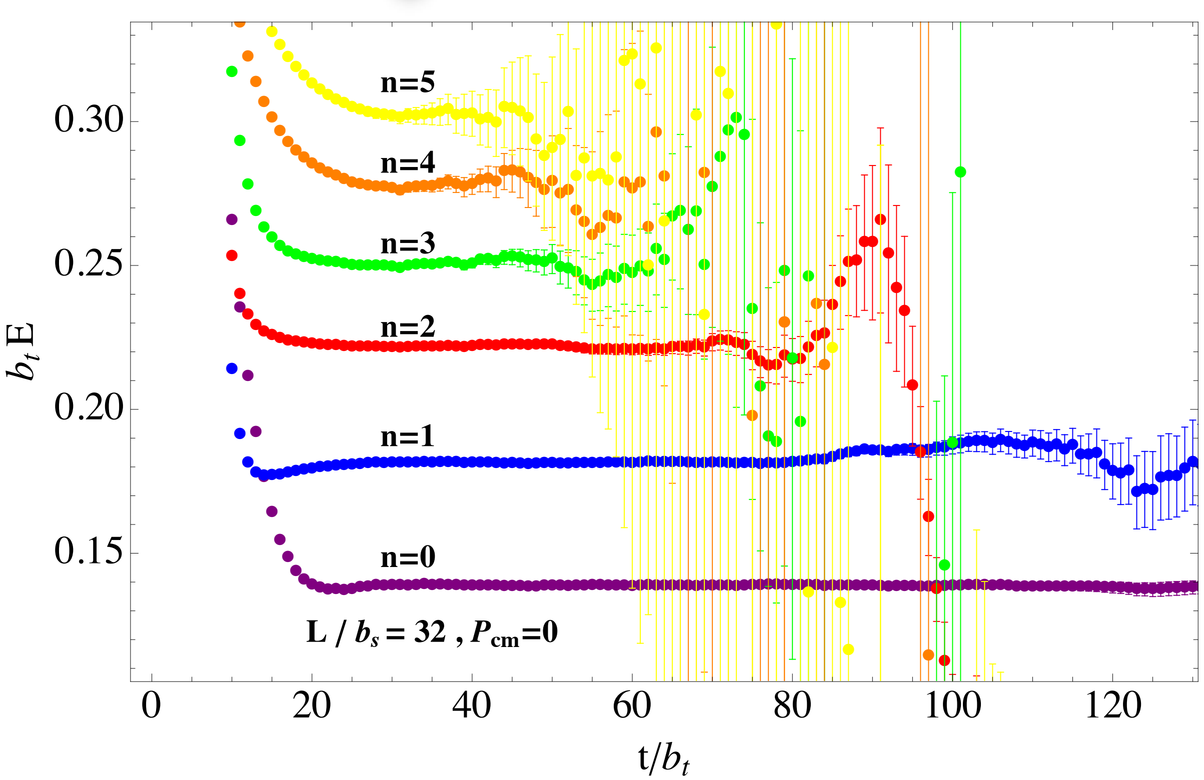
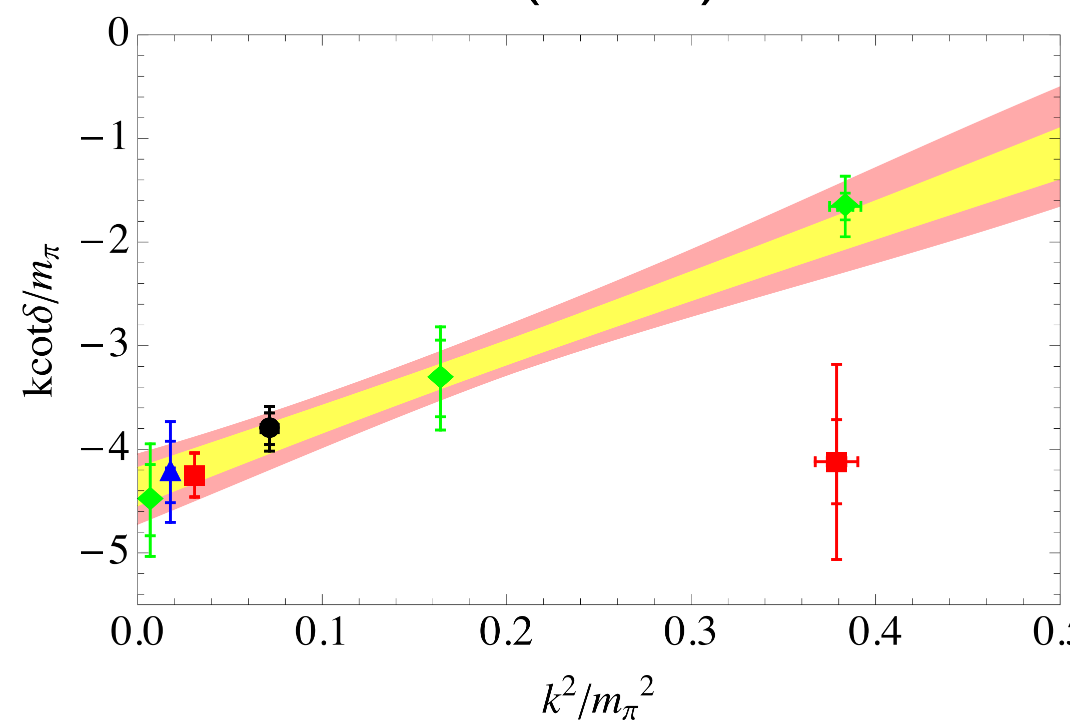


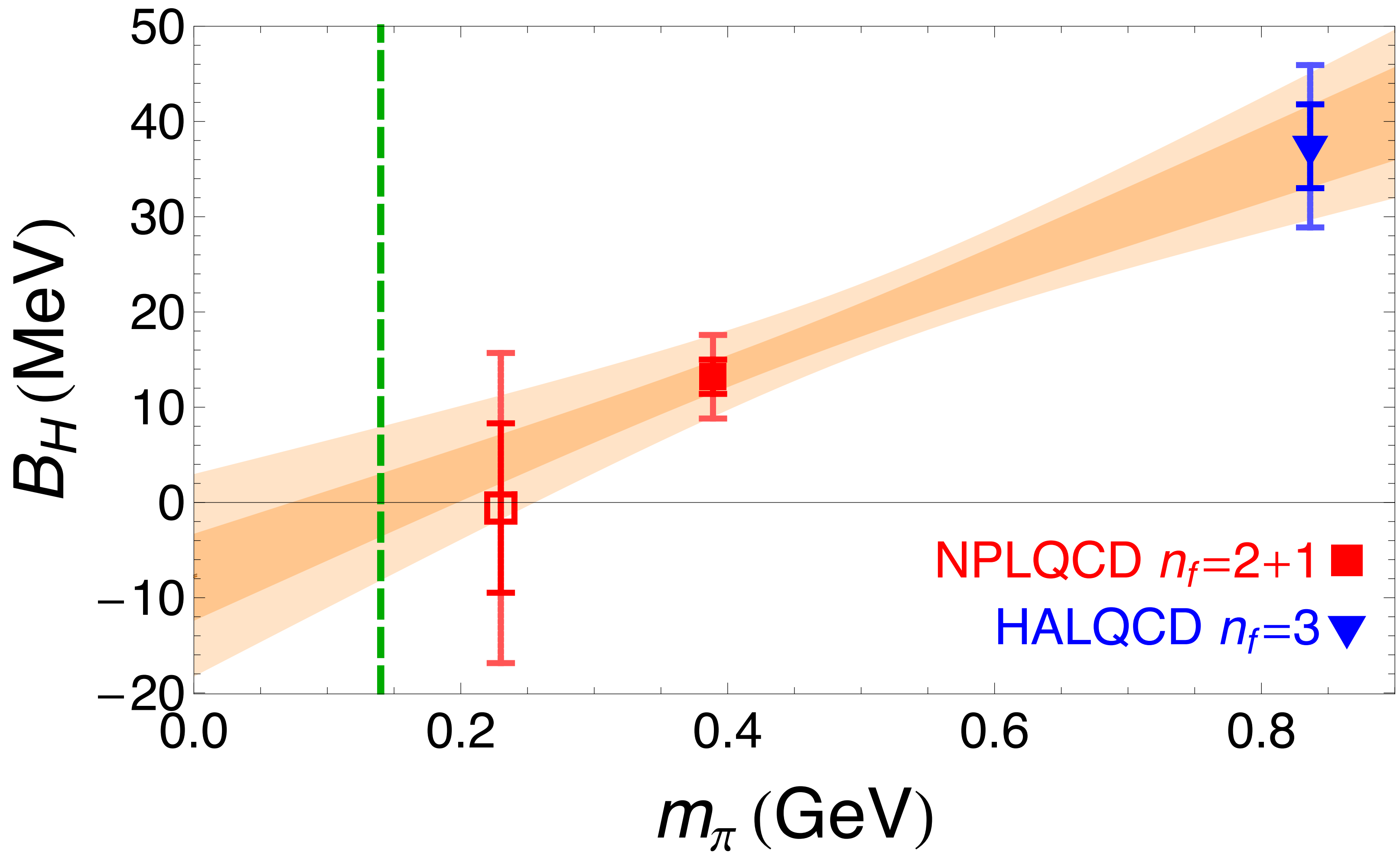


H-Dibaryon $|H\rangle \sim |\Lambda\Lambda\rangle \sim |uds\ uds\rangle$

Physical Review Letters – 22 April 2011.
Volume 106, Issue 16

Evidence for a Bound H Dibaryon from Lattice QCD
S. R. Beane, E. Chang, W. Detmold, B. Joo, H. W. Lin, T. C. Luu, K. Orginos, A. Parreño, M. J. Savage, A. Torok, and A. Walker-Loud (NPLQCD Collaboration)
Published 20 April 2011 (4 pages), 162001.

Bound H Dibaryon in Flavor SU(3) Limit of Lattice QCD
Takashi Inoue, Noriyoshi Ishii, Sinya Aoki, Takumi Doi, Tetsuo Hatsuda, Yoichi Ikeda, Keiko Murano, Hidekatsu Nemura, and Kenji Sasaki (HAL QCD Collaboration)
Published 20 April 2011 (4 pages), 162002.



Status Report

NN Interactions

$^1S_0$

di-neutron

$a \simeq -24$ fm

$$\left(\lim_{p \to 0} p \cot \delta(p) = -\frac{1}{a} \right)$$

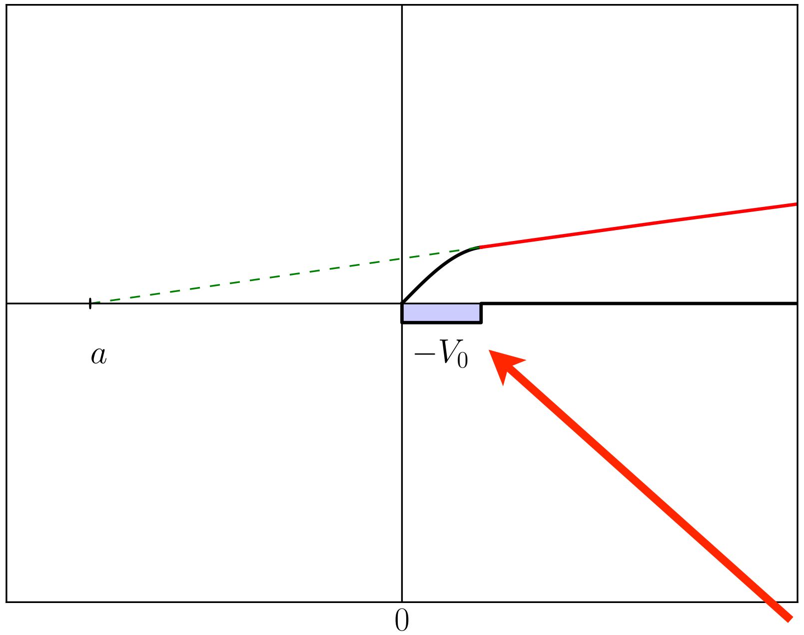
$^3S_1$

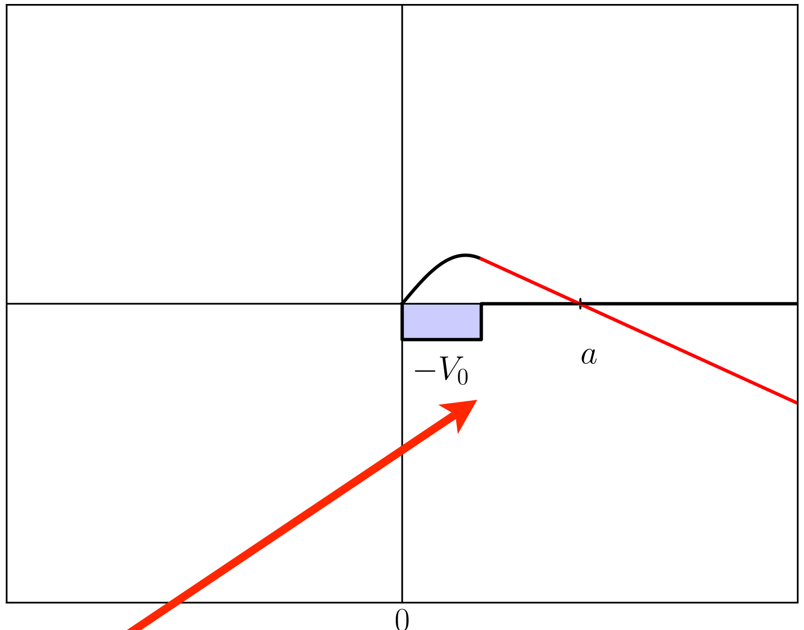
deuteron

$B_d = 2.2245(2)$ MeV

$a \simeq 5.5$ fm

threshold scattering is finely tuned



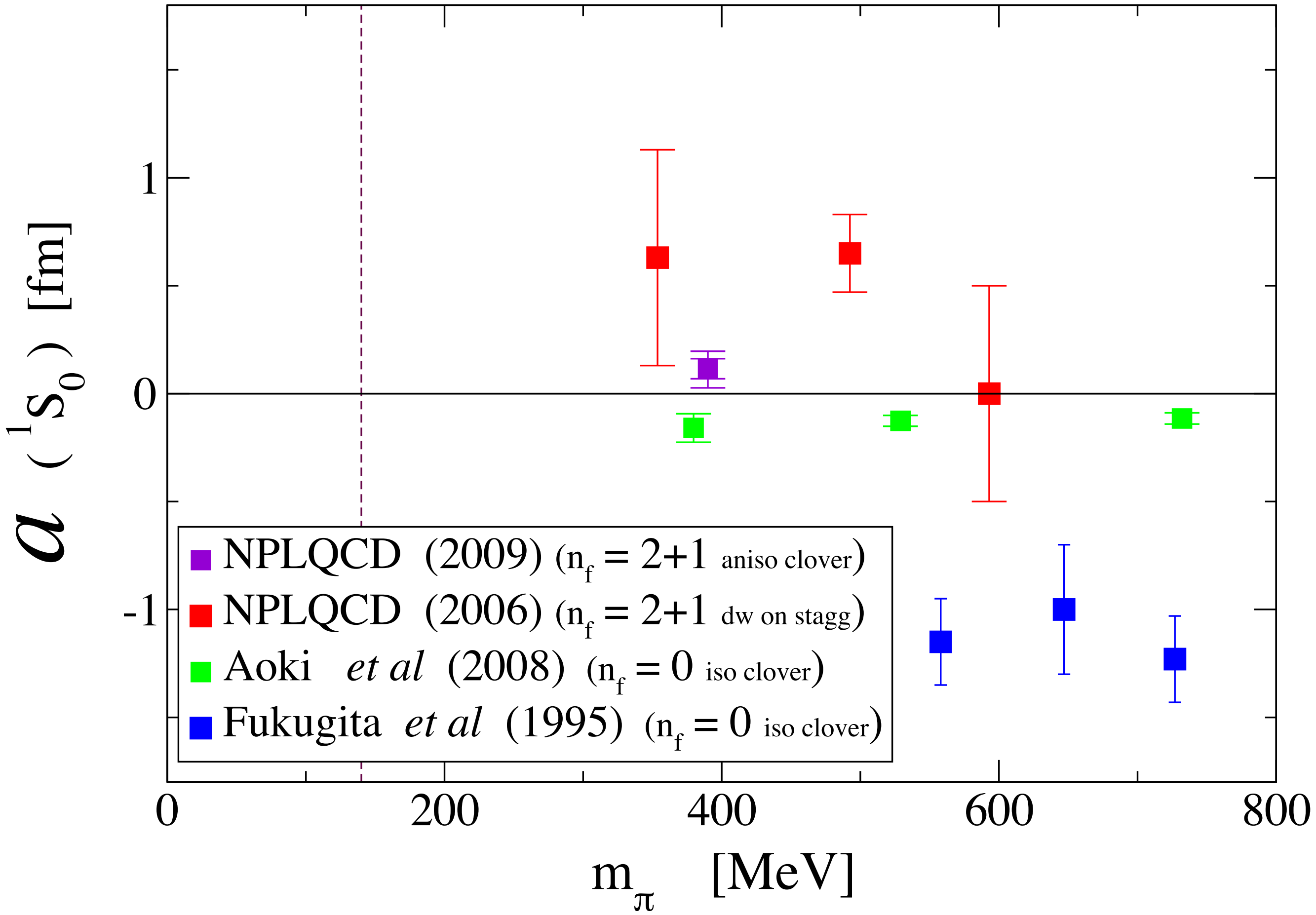


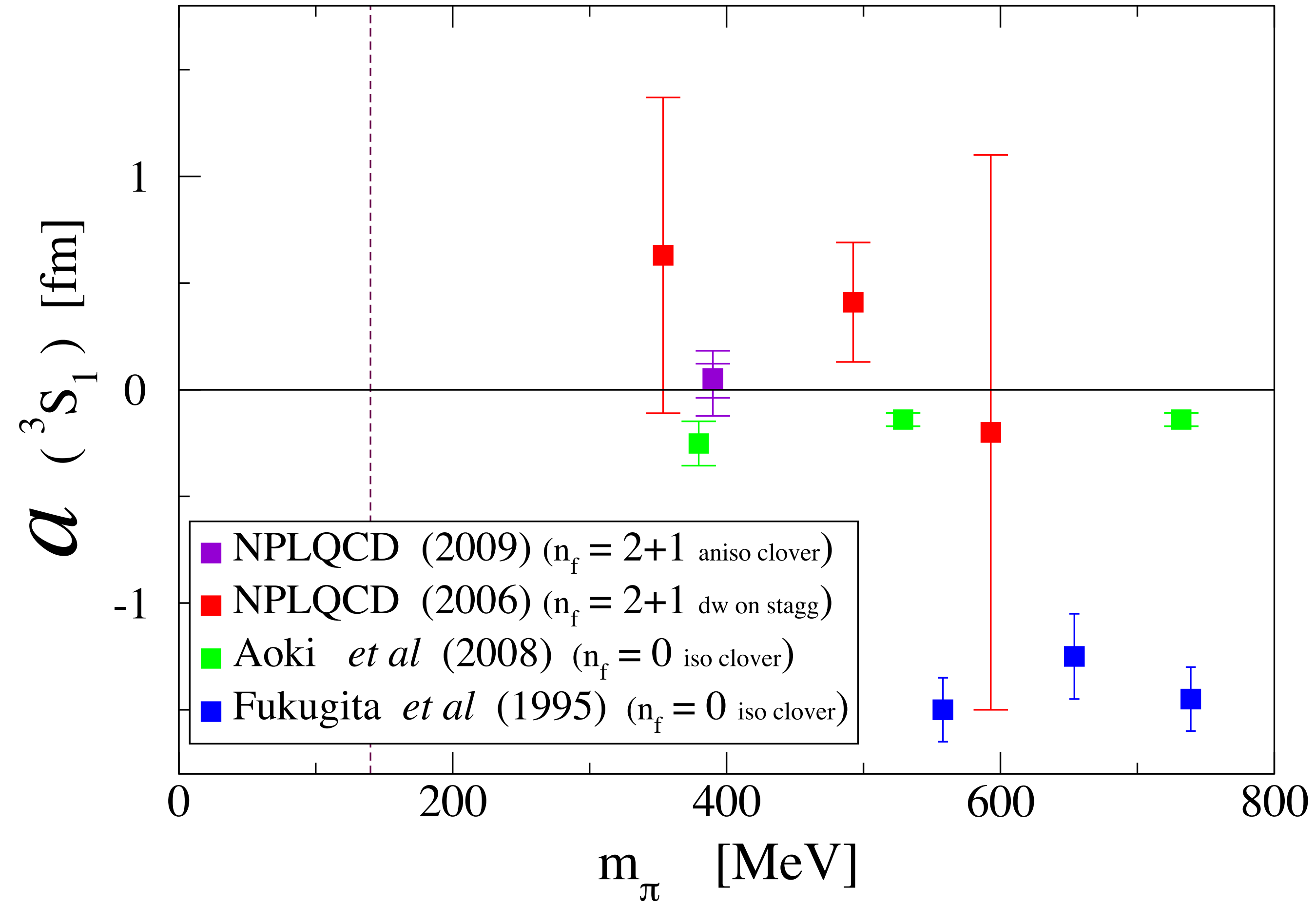
$$R_{NN} \sim \frac{1}{m_\pi} \sim 1.4 \text{ fm}$$

Status Report

NN Interactions

early calculations indicate the large scattering lengths relax for larger pion masses





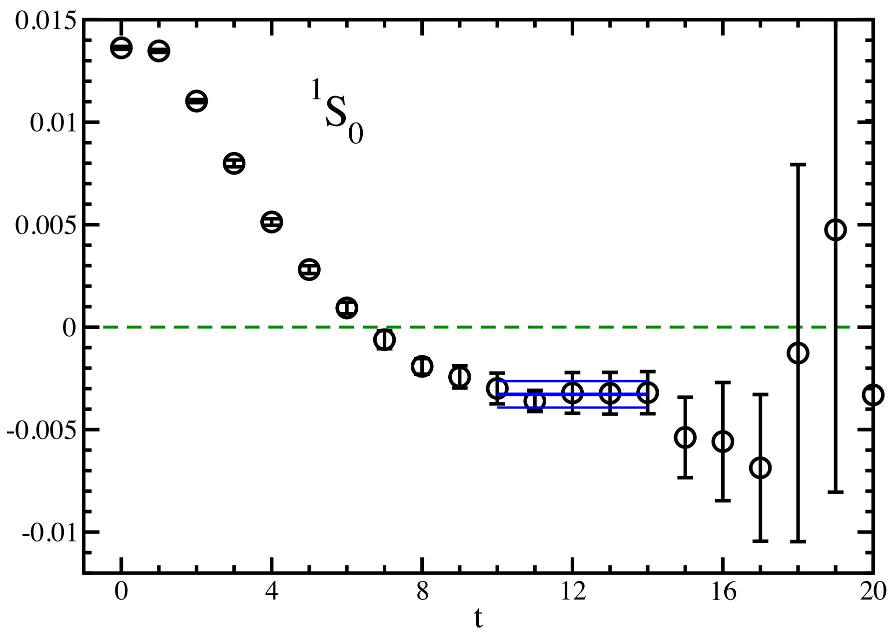
NPLQCD PRD 81 (2010)

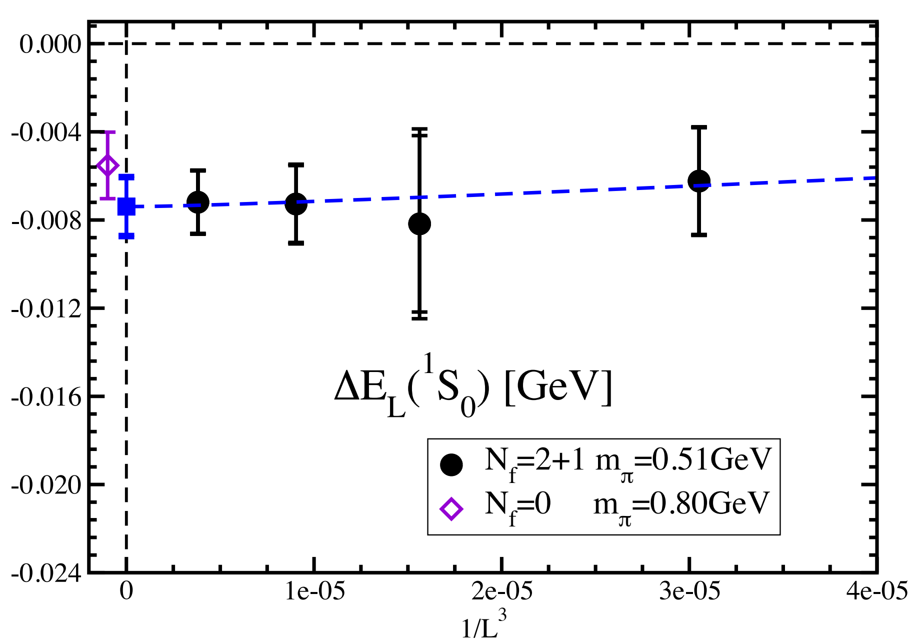
Status Report

NN Interactions $^{1}S_0$

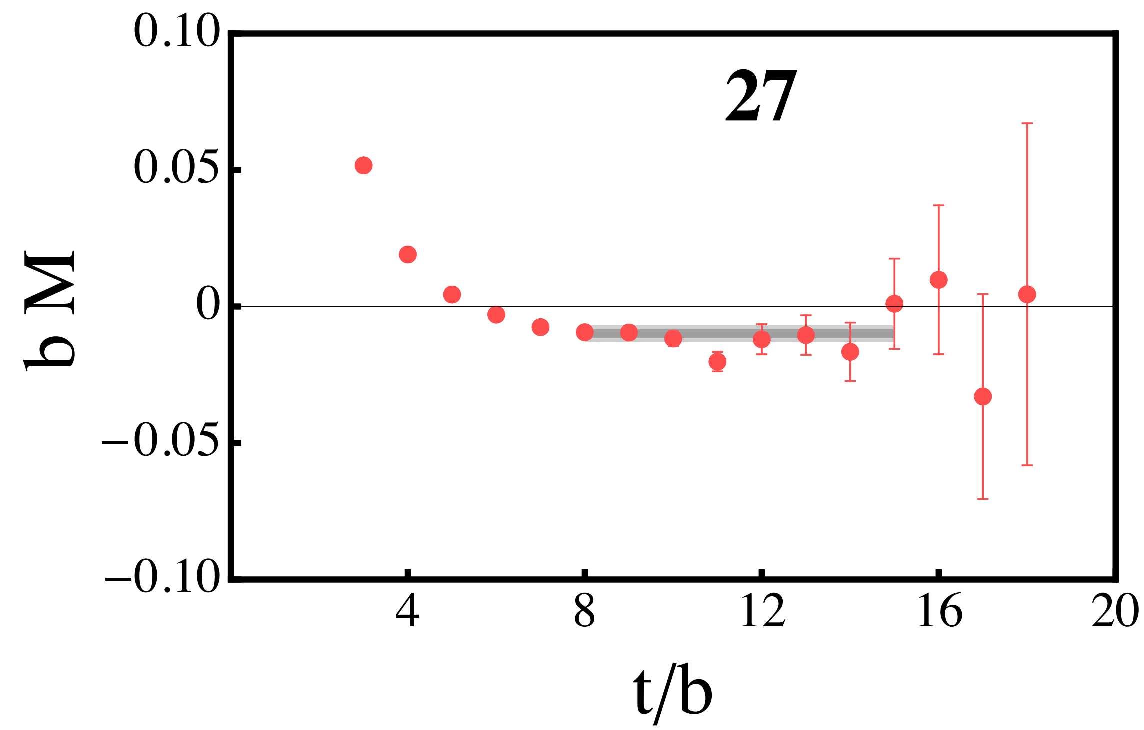
more recent calculations, with higher statistics, have indicated the di-neutron even becomes bound

Yamazaki et al., PRD 86 (2012)





NPLQCD PRD 87 (2013)

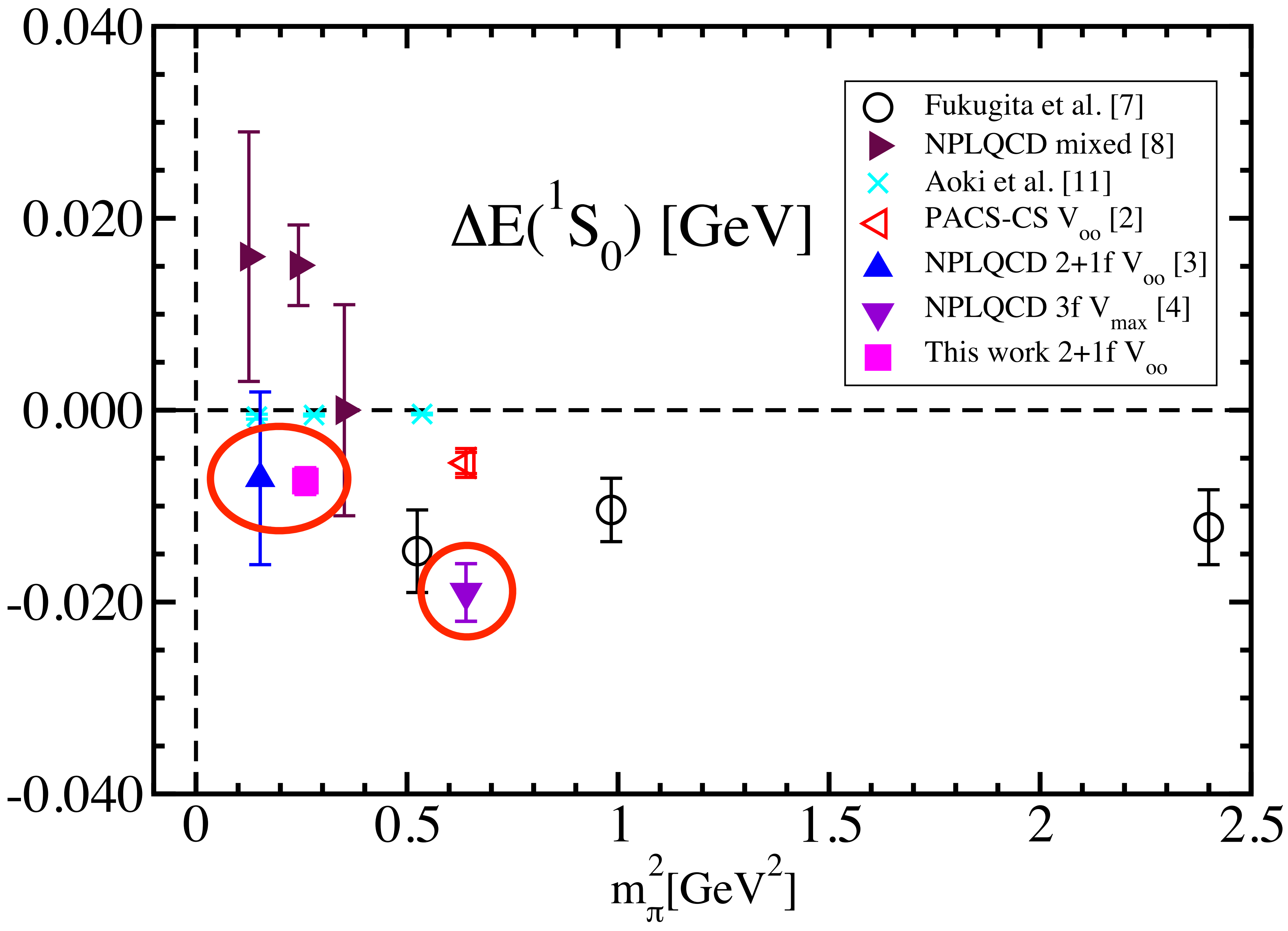


both calculations clearly find a bound di-neutron

Status Report

NN Interactions $^1S_0$

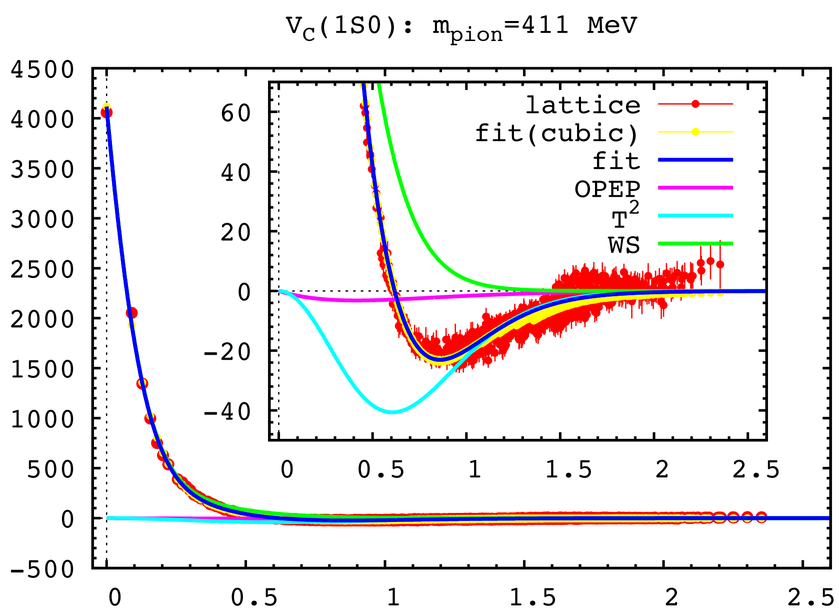
more recent calculations, with higher statistics, have indicated the di-neutron even becomes bound

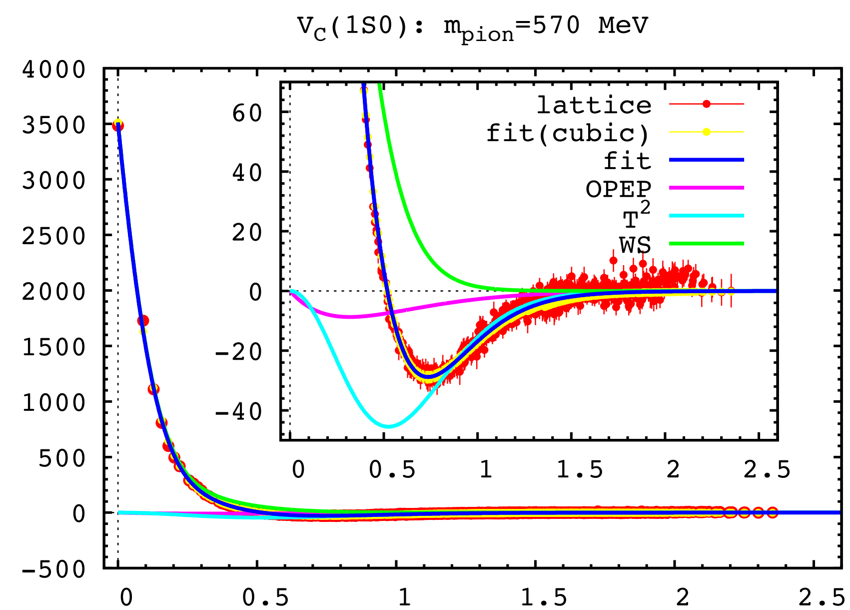


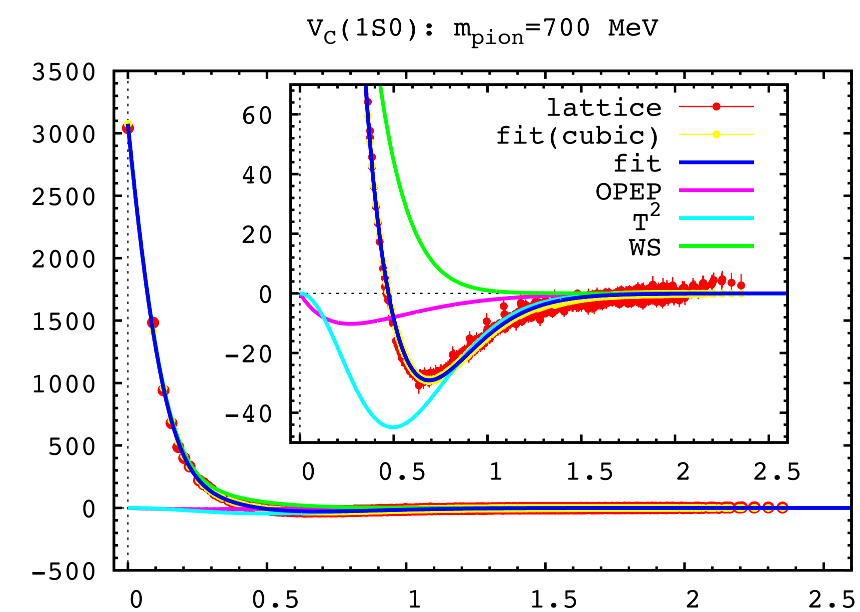
Status Report

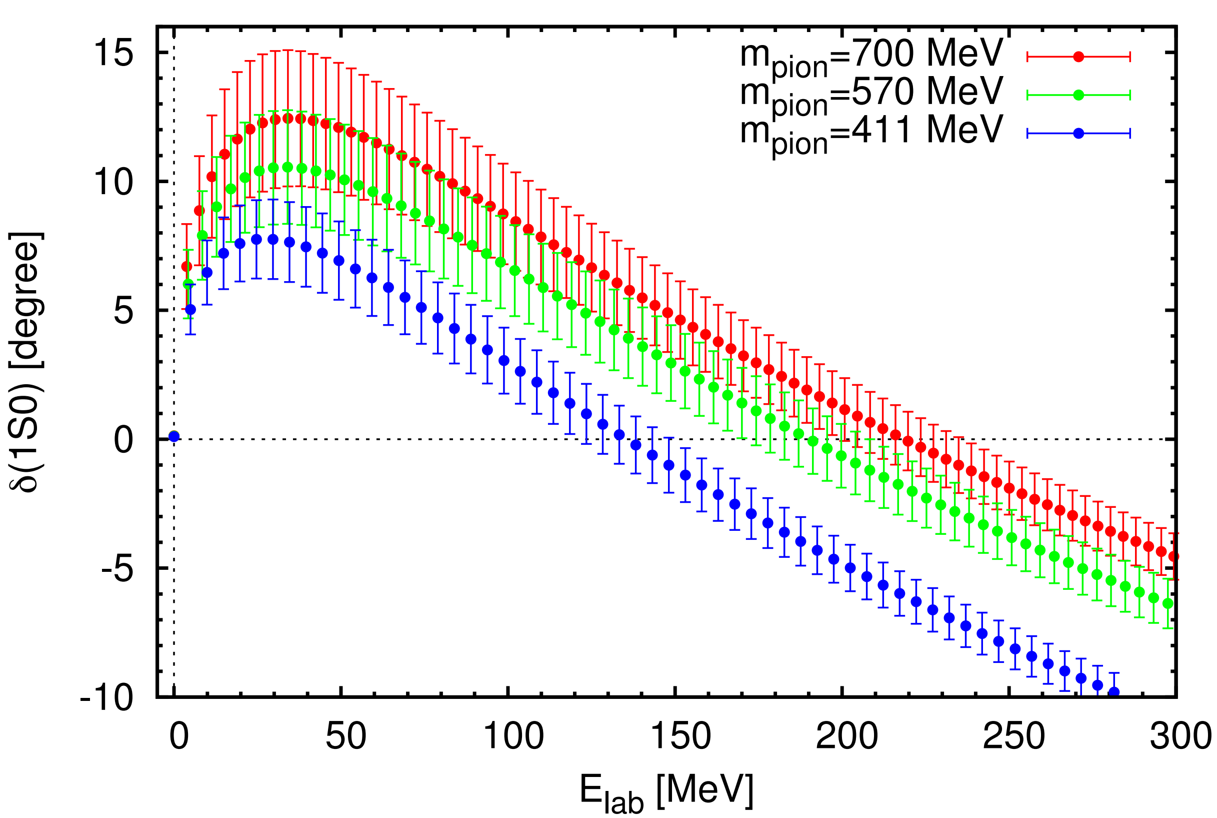
NN Interactions $^1S_0$

contrast with results from the HALQCD method

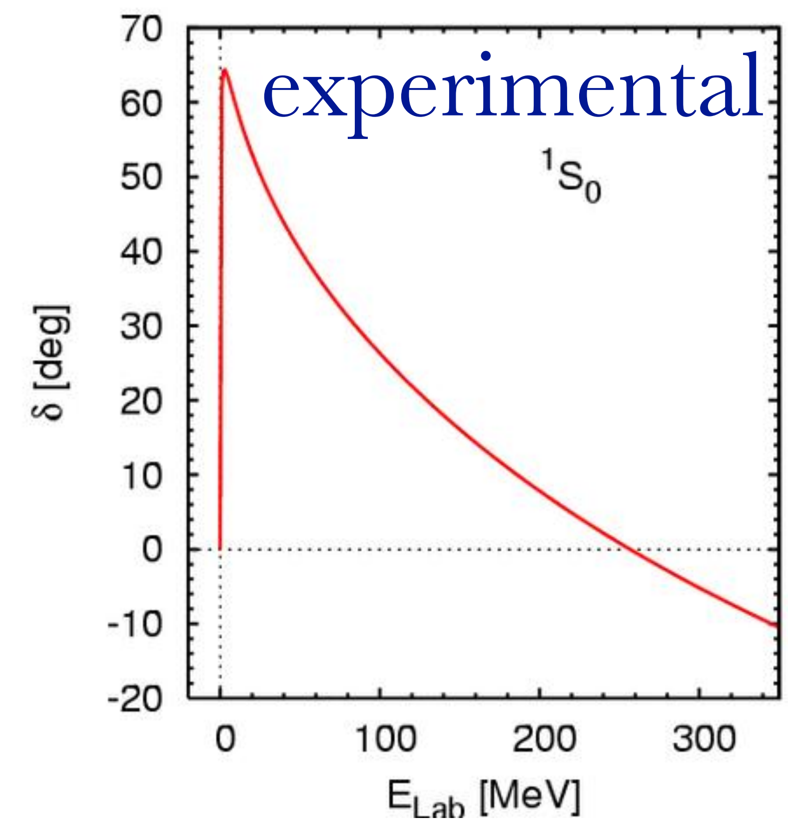








(Thanks to HALQCD)

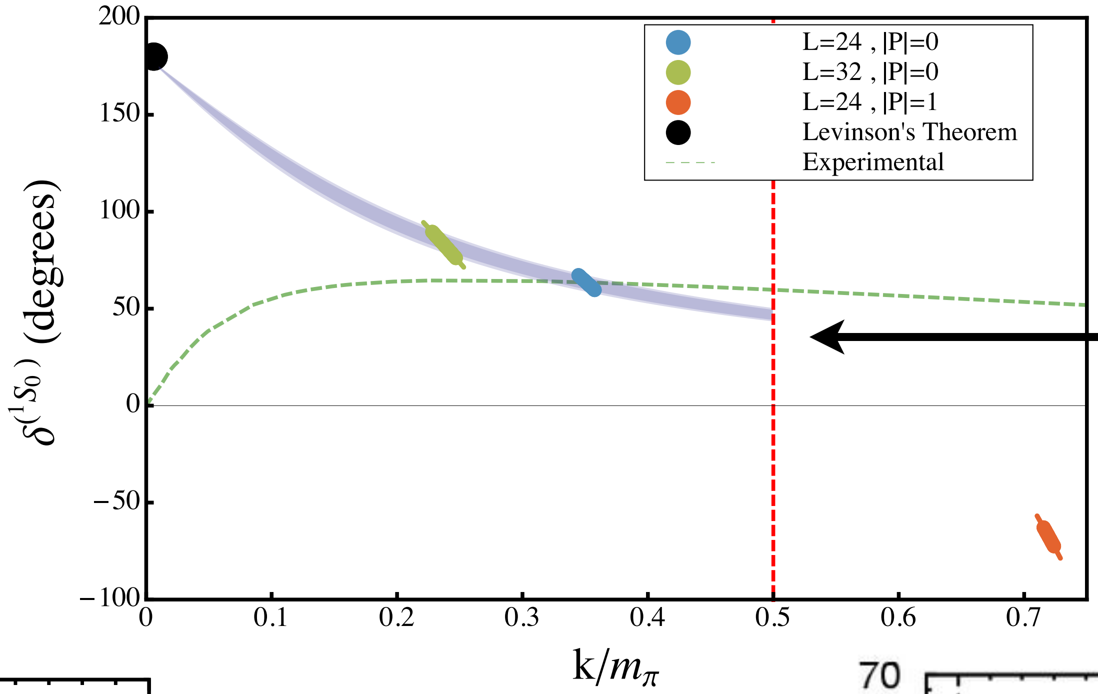


Status Report

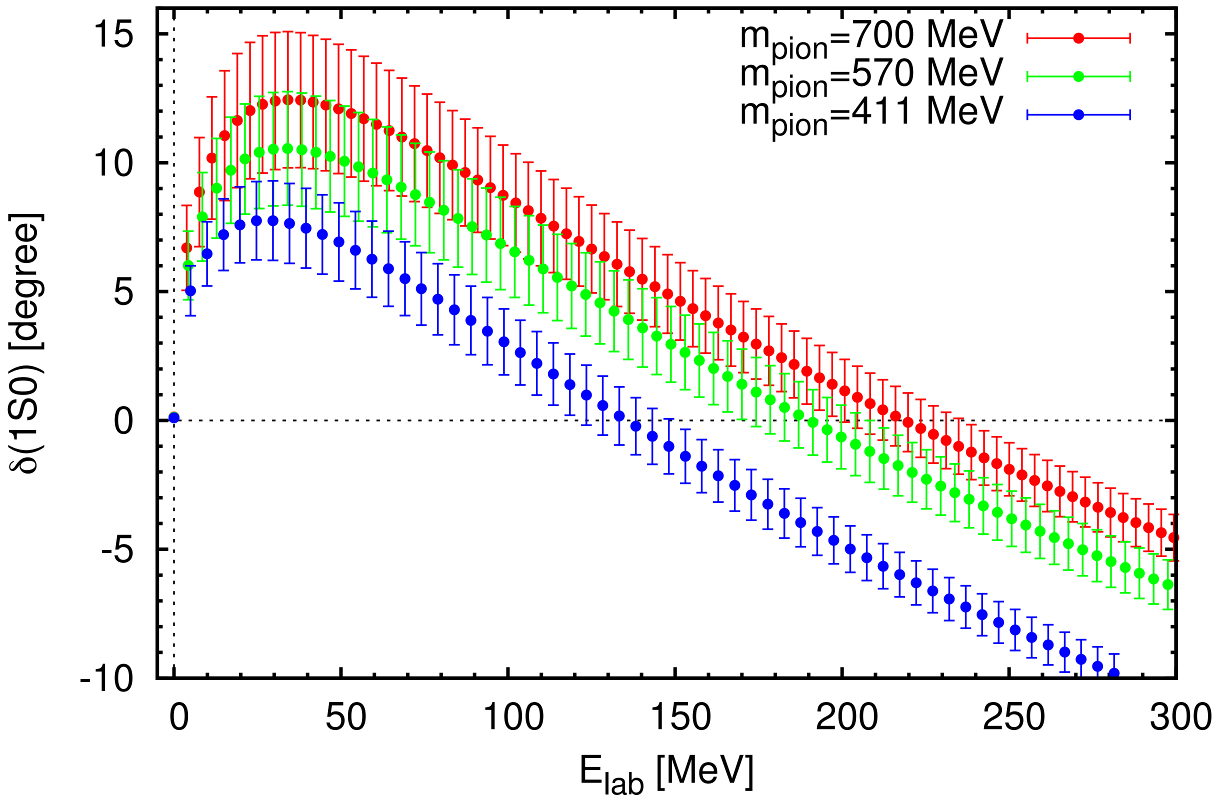
NN Interactions $^1S_0$

contrast with results from the HALQCD method

NPLQCD PRC88 (2013) 024003
arXiv:1301.5790

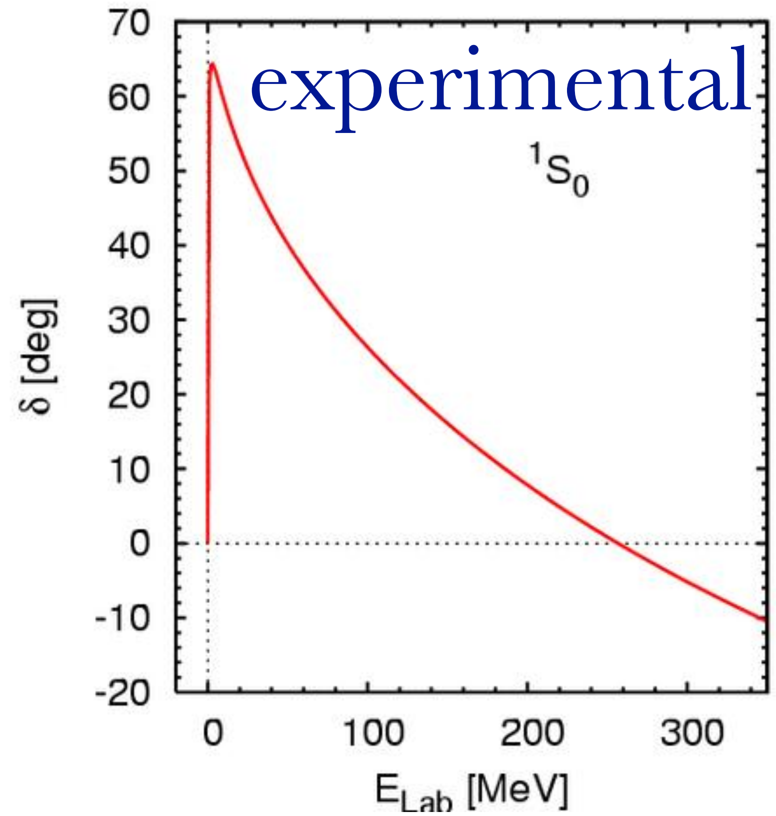


t-channel cut



(Thanks to HALQCD)

experimental



Status Report

NN Interactions $^1S_0$

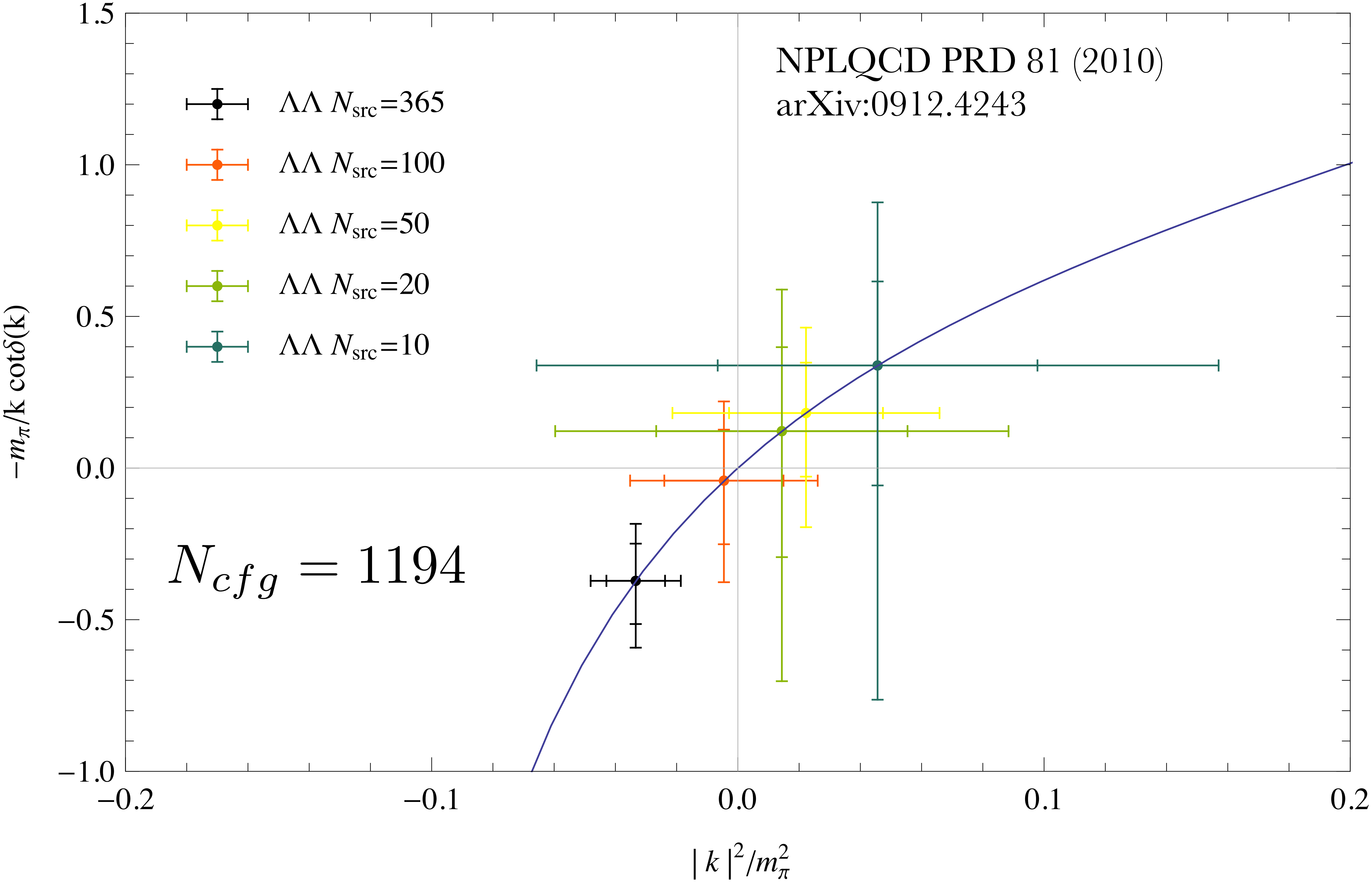
Heavy pion mass: $(m_\pi \gtrsim 390 \text{ MeV})$

- NPLQCD finds a bound state
- Yamazaki et.al. find a bound state
- HALQCD does NOT find a bound state

- my speculation: HALQCD does not have enough statistics to resolve the long-range potential, which contributes significantly to the low-energy phase shift
- HALQCD method includes more systematics that are difficult to quantify - see review talk at Lattice 2013: AWL - "Nuclear Physics Review"

Status Report

NN Interactions $^1S_0$



Status Report

While nuclear "potentials" from lattice QCD may warm the heart, the technique introduces further systematics which are difficult to quantify, and most likely not under control at the moment.

It is now up to HALQCD to demonstrate their technique is in agreement with the standard "Lüscher" method.

Before this demonstration, be cautious drawing conclusions.

Status Report

NPLQCD, PRD 87 (2013)

Light Nuclei

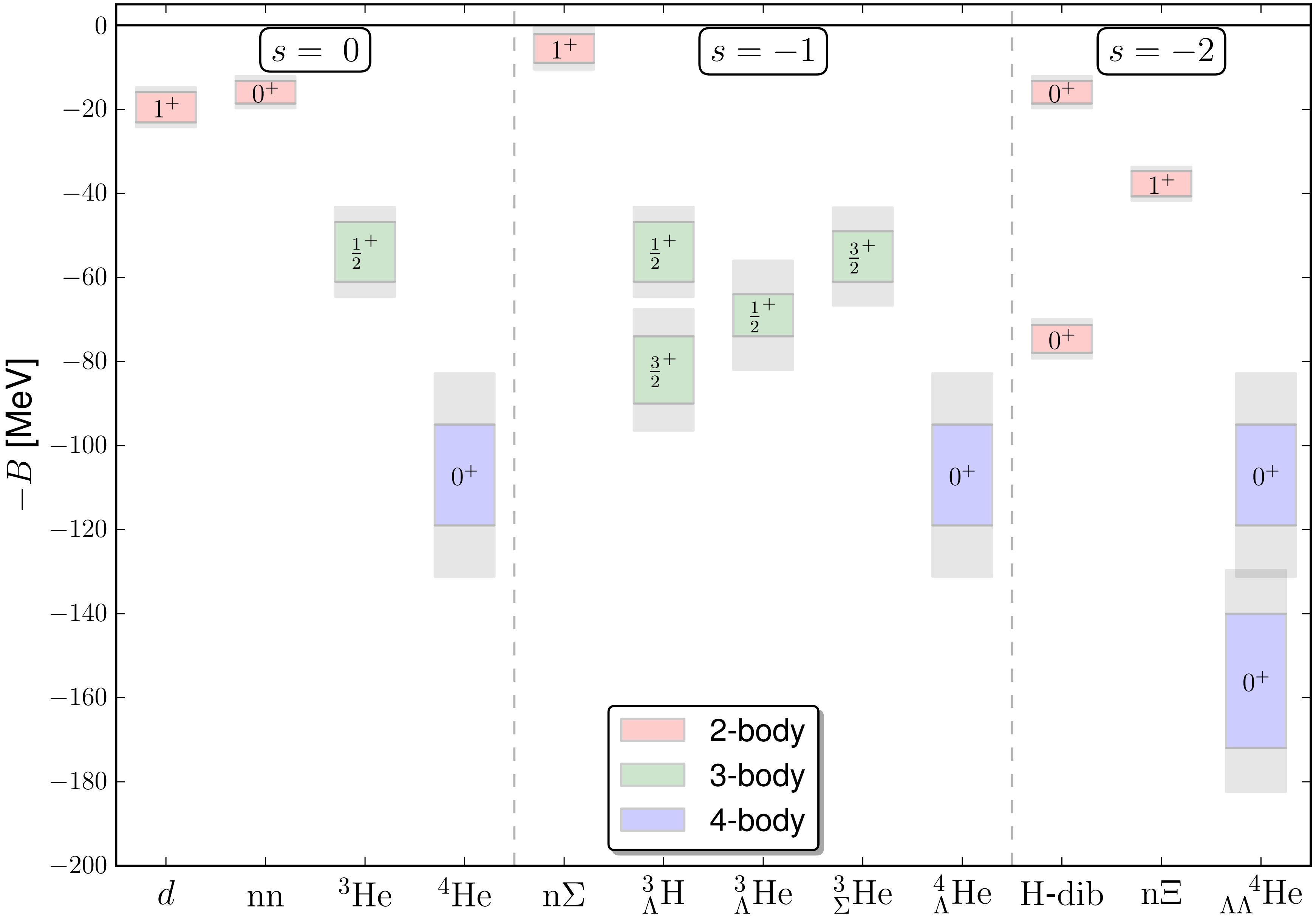
$N_f = 3$

clover-Wilson

$a \sim 0.145$ fm

$m_{\pi,K} = 807$ MeV

$$V = \begin{cases} 24^3 \times 48 \\ 32^3 \times 48 \\ 48^3 \times 64 \end{cases}$$

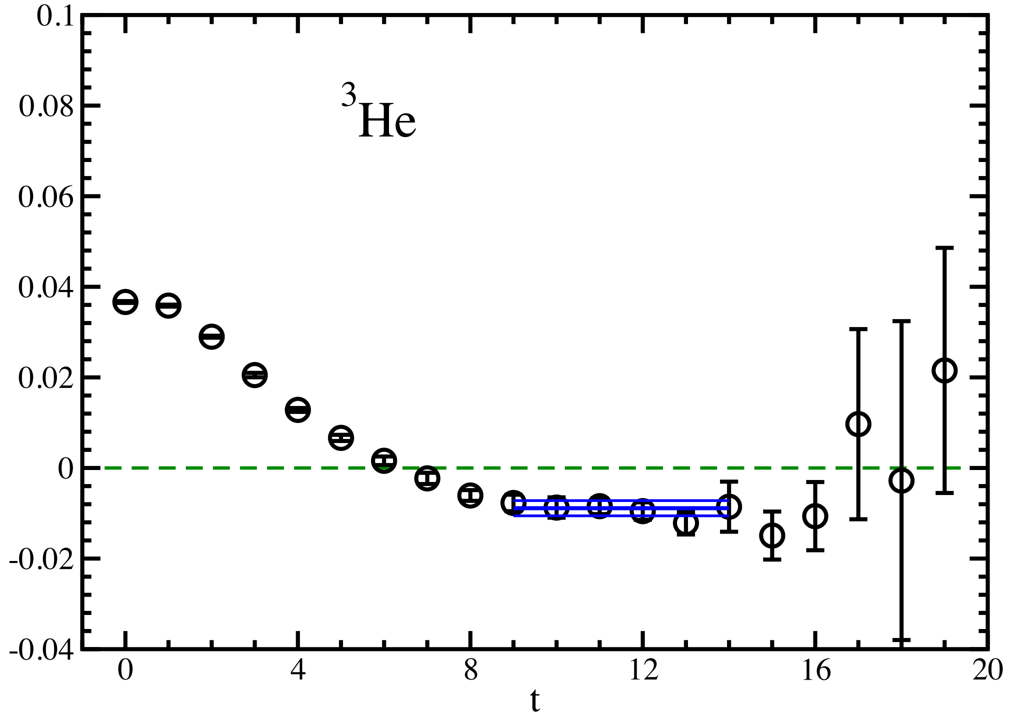


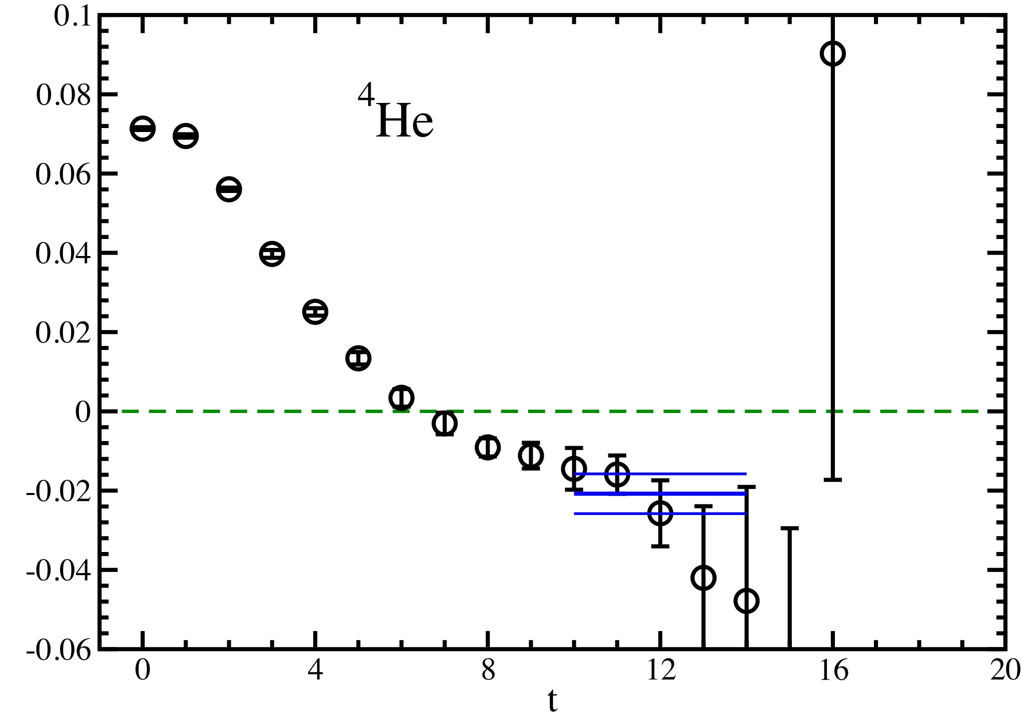
New contraction codes were developed and tested with heavy pion masses (numerically cheap).

Status Report

Yamazaki et al., PRD 86 (2012)

Light Nuclei

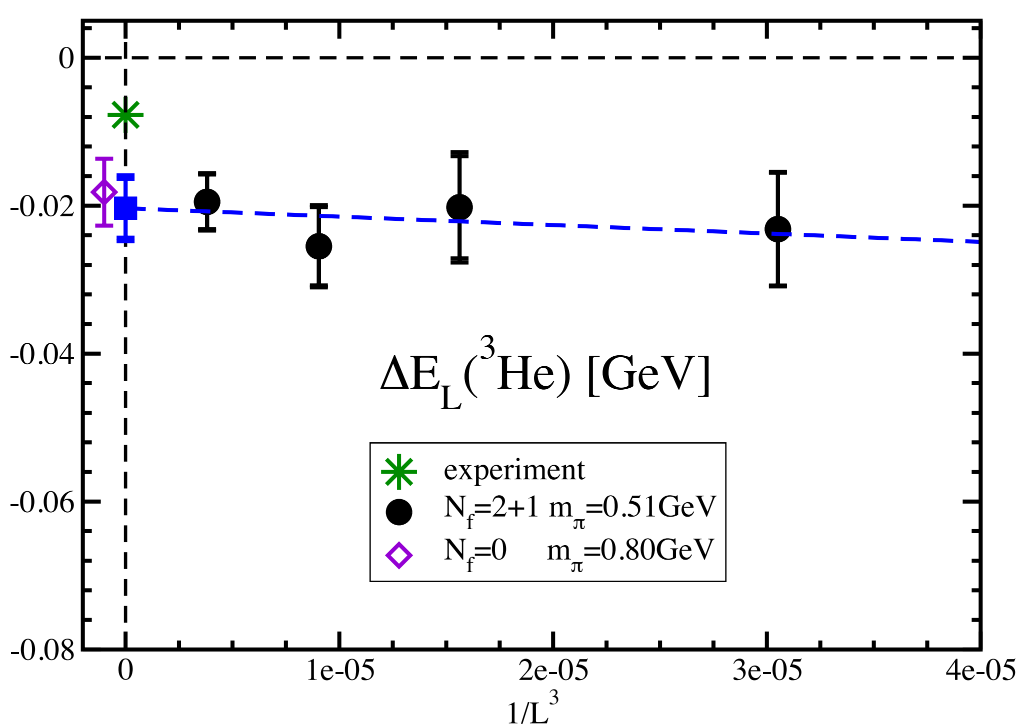


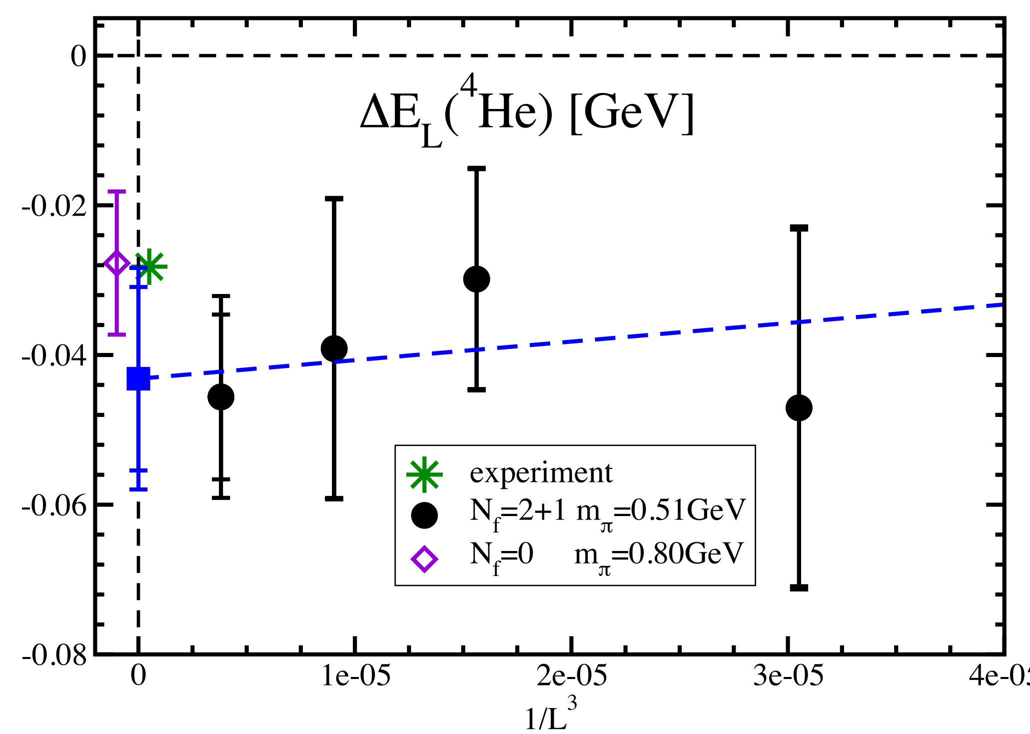


$m_\pi \simeq 510$ MeV

$N_f = 2 + 1$

PACS-CS parameters





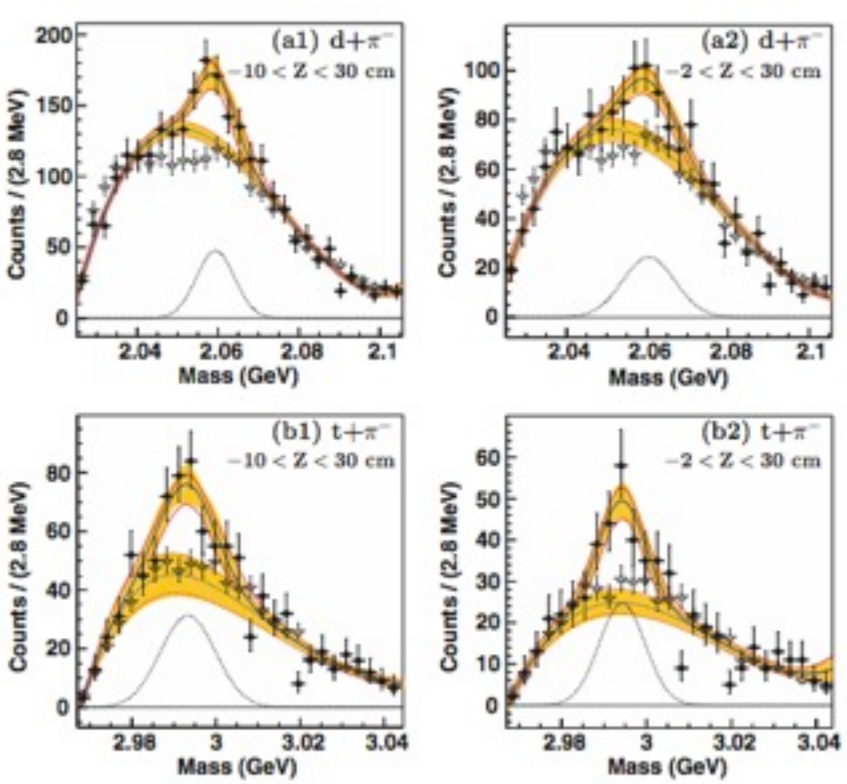
Status Report

Significant experimental effort to study hyper-nuclei:

JLAB, JPARC, FAIR, ...

Hyper-nuclear interactions and Hyperon-Hyperon interactions provide an opportunity for lattice QCD to make significant contributions as the experimental understanding is much more limited due to the weak decays (also 3-nucleon forces)

See recent HypHI Collaboration results: evidence for ${}^{3}_{\Lambda}n$
PRC 88 041001(R)



Isospin violation and Big Bang Nucleosynthesis

(subset of what Ulf Meißner discussed Sunday)

Isospin Breaking: $M_n - M_p$

- Nature: $M_n - M_p = 1.29333217(42)\ \mathrm{MeV}$

CODATA
PDG (2012)

- Standard Model has two sources of isospin breaking

$$\hat{Q} = \frac{1}{6}\mathbb{1} + \frac{1}{2}\tau_3 \qquad m_q = \hat{m}\mathbb{1} - \delta\tau_3$$

- Given only electro-static forces, one would predict

$$M_p > M_n$$

- The contribution from $m_d - m_u$ is comparable in size but opposite in sign

Isospin Breaking: $M_n - M_p$

- $M_n - M_p$ plays an extremely significant role in the evolution of the universe as we know it

Initial conditions for Big Bang Nucleosynthesis (BBN)

$$\frac{X_n}{X_p} = e^{-\frac{M_n - M_p}{T}}$$

- The neutron lifetime is highly sensitive to the value of this mass splitting

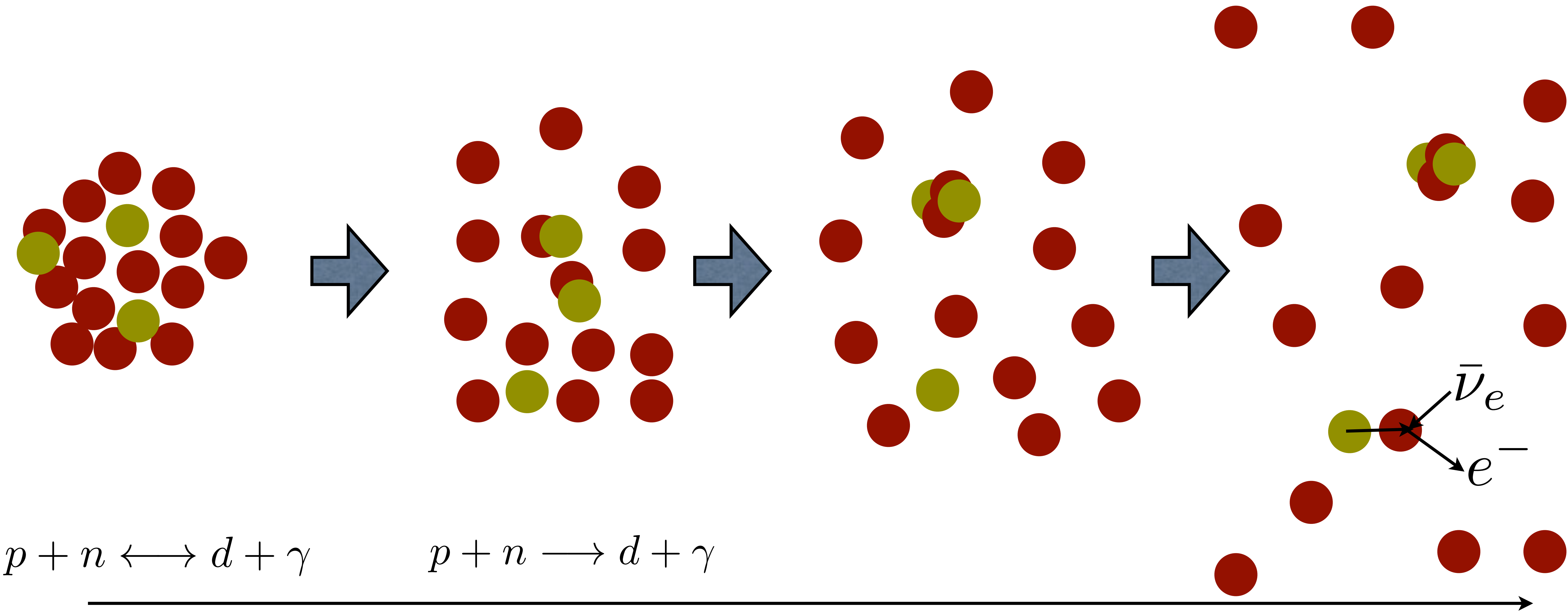
$$\frac{1}{\tau_n} = \frac{(G_F \cos\theta_C)^2}{2\pi^3} m_e^5 (1 + 3g_A^2)\, f\left(\frac{M_n - M_p}{m_e}\right)$$

Point Nucleons $f(a) \simeq \frac{1}{15}\left(2a^4 - 9a^2 - 8\right)\sqrt{a^2 - 1} + a \ln\left(a + \sqrt{a^2 - 1}\right)$

Griffiths "Introduction to Elementary Particles"

10% change in $M_n - M_p$ corresponds to ~100% change neutron lifetime

Isospin Breaking: $M_n - M_p$ Big Bang Nucleosynthesis



$p + n \longleftrightarrow d + \gamma$ $p + n \longrightarrow d + \gamma$

$t \sim 1$ sec	$t \sim 3$ min	$t \sim 3^+$ min	$t \sim 15$min
$T \sim 1$ MeV	$T \sim 0.1$ MeV	$T \sim 0.1^-$ MeV	$T \sim 0.01$ MeV

$$\frac{X_n}{X_p} = e^{-\frac{M_n - M_p}{T}}$$

Initial conditions

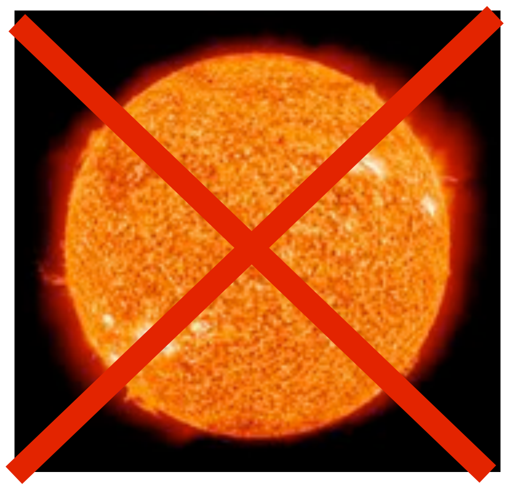
B_d

deuterium binding energy

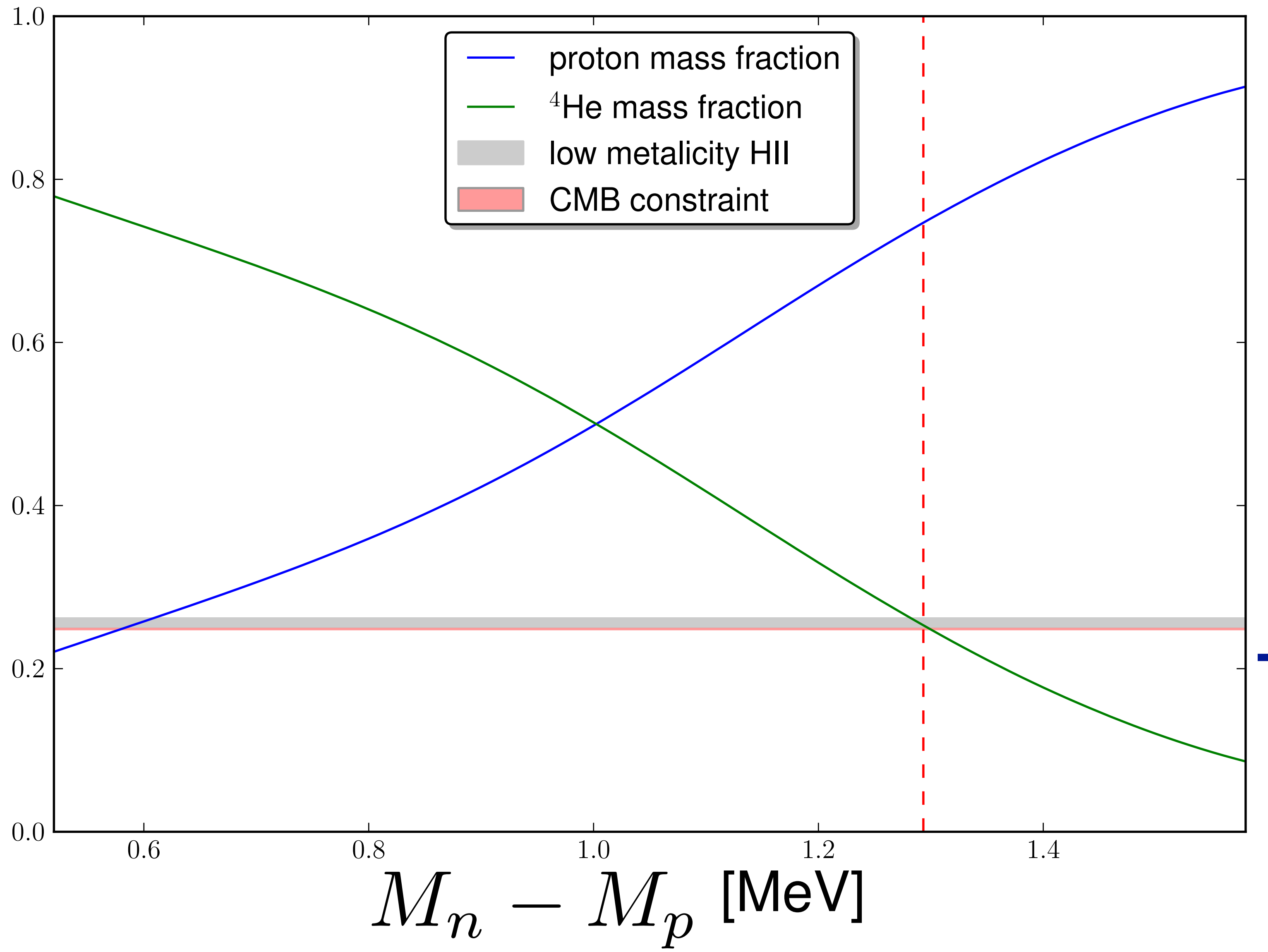
τ_n

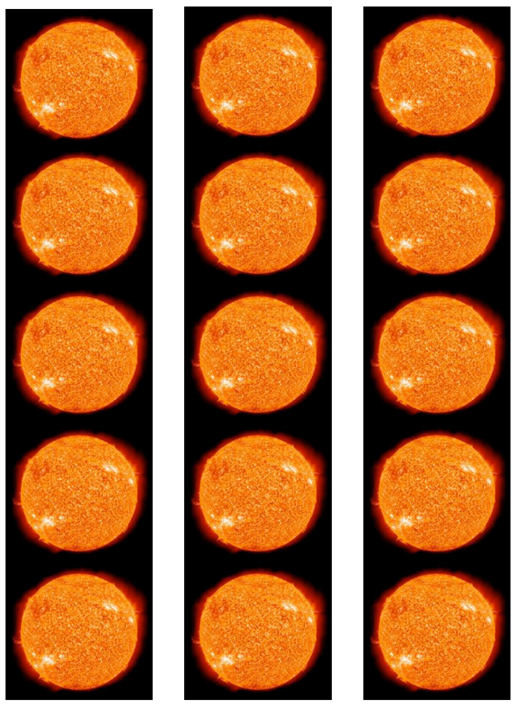
neutron lifetime

Isospin Breaking: M_n - M_p



No Sun!





Too many suns?

Isospin Breaking: M_n - M_p What do we know?

- We would like to understand the Neutron-Proton mass splitting from first principles

- $M_n - M_p = \delta M^\gamma + \delta M^{m_d - m_u}$ Separation only valid at LO in isospin breaking

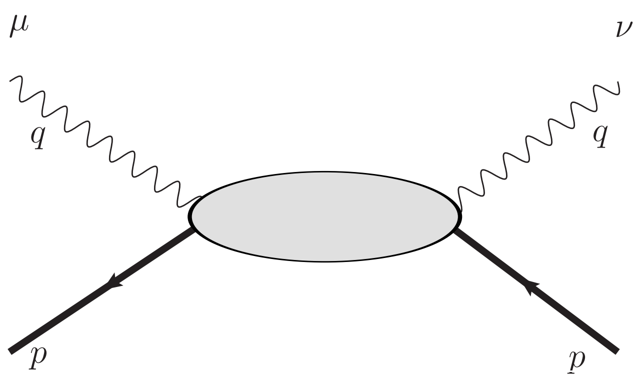
- $\delta M^{m_d - m_u}$ Well understood from lattice QCD

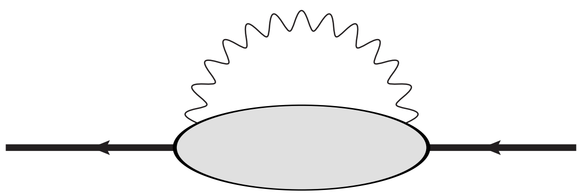
  δM^γ Disparate scales relevant for QCD and QED make this a very challenging problem to solve with LQCD: large systematic uncertainties

- Alternative means to determine δM^γ
  Cottingham Formulation

Isospin Breaking: M_n - M_p What do we know?

Cottingham Formulation





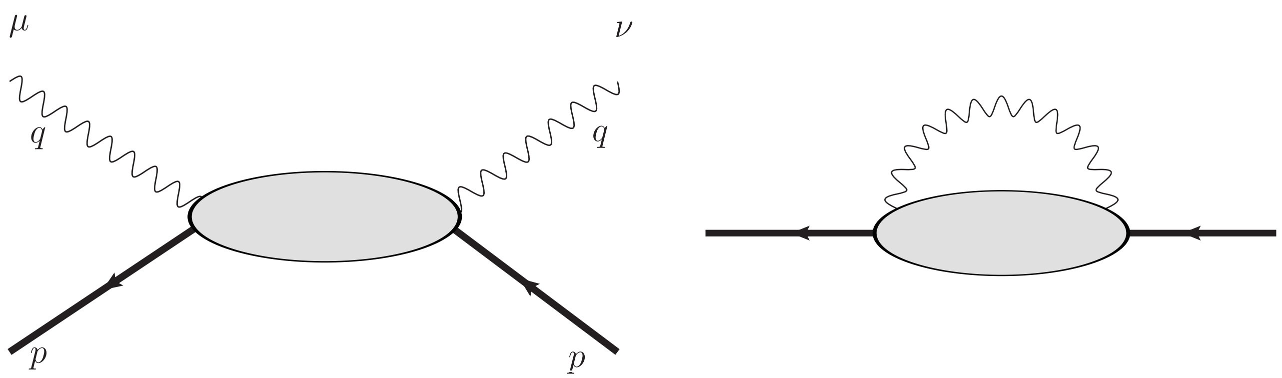
Cini, Ferrari, Gato PRL 2 (1959)
Cottingham Annals Phys 25 (1963)
Gasser, Leutwyler Nucl. Phys. B94 (1975)
Collins Nucl. Phys. B149 (1979)
Gasser, Leutwyler Phys. Rept 87 (1982)
AWL, C.Carlson, G.Miller PRL 108 (2012)
AWL, C.Carlson, G.Miller PoS LATT (2012)

$$\delta M^\gamma = \frac{i}{2M}\frac{e^2/4\pi}{(2\pi)^3}\int_R d^4q \frac{T^\mu_\mu(p,q)}{q^2+i\epsilon}$$

$$T_{\mu\nu} = \frac{i}{2}\sum_\sigma \int d^4\xi\ e^{iq\cdot\xi}\langle p\sigma| T\left\{J_\mu(\xi)J_\nu(0)\right\}|p\sigma\rangle$$

Isospin Breaking: $M_n - M_p$ What do we know?

Cottingham Formulation



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After some manipulations, renormalization and a subtracted dispersion integral

AWL, C.Carlson, G.Miller PRL 108 (2012)

$$\delta M^{\gamma}_{p-n}[\text{MeV}] = 0.83(03) - \frac{3\beta_M^{p-n}}{8\pi}\int_0^{\Lambda_0^2} dQ^2 Q^2 f(Q^2) \qquad \lim_{Q^2\to\infty} f(Q^2) \propto \frac{1}{Q^4}$$

$$\beta_M^{p-n} = -1.0 \pm 1.0 \times 10^{-4}\ \text{fm}^3$$

Magnetic polarizability

H.W. Griesshammer, J.A. McGovern, D.R. Phillips, G. Feldman: Prog.Nucl.Part.Phys. (2012)

Isospin Breaking: M_n - M_p What do we know?

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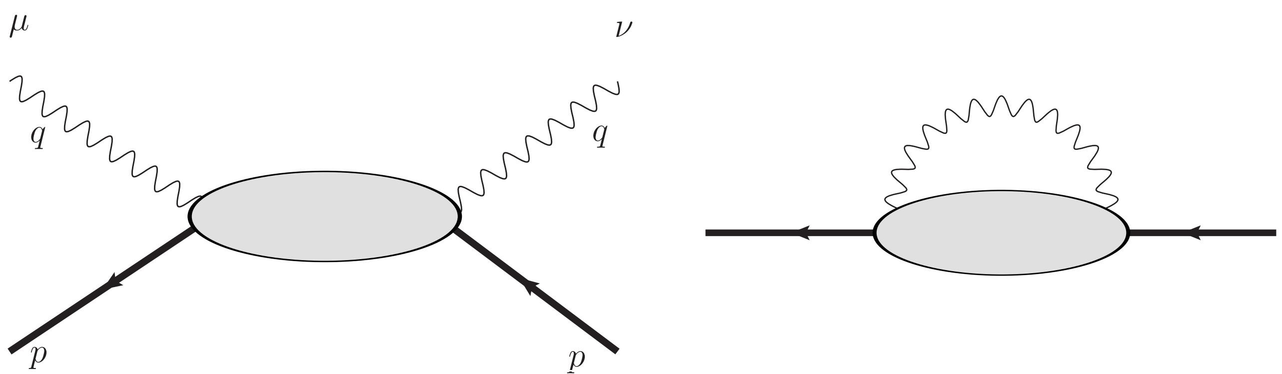

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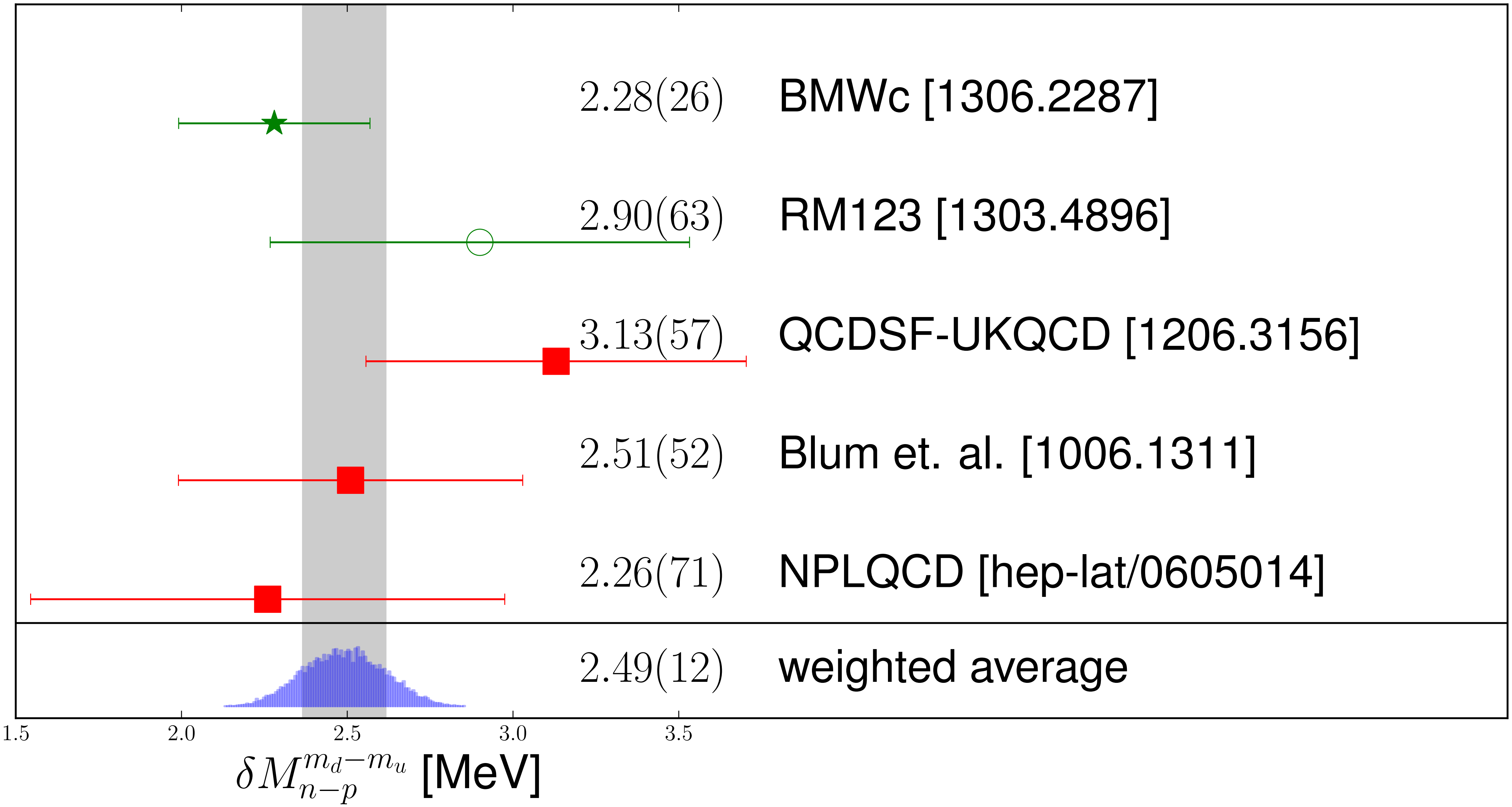
Magnetic polarizability

H.W. Griesshammer, J.A. McGovern, D.R. Phillips, G. Feldman: Prog.Nucl.Part.Phys. (2012)

$$f(Q^2) = \left(\frac{1}{1 + Q^2/m_0^2} \right)^2 \quad \Rightarrow \quad \delta M^{\gamma}_{p-n}[\text{MeV}] = 1.40(.03)(.47)$$

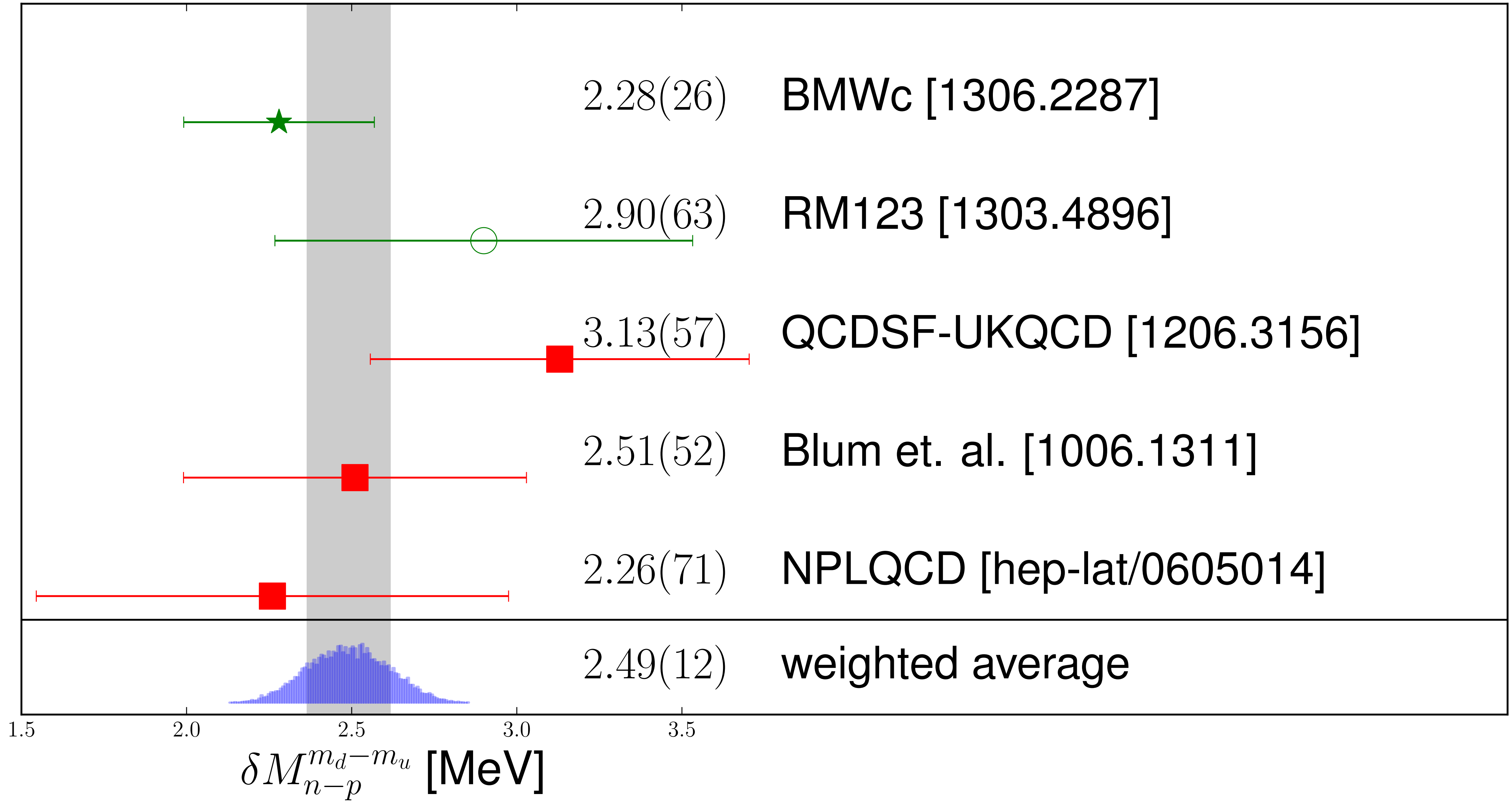
Isospin Breaking: M_n - M_p What do we know?

- $\delta M_{n-p}^{m_d - m_u} = 2.49(12)$ MeV



Isospin Breaking: M_n - M_p What do we know?

- $\delta M_{n-p}^{m_d - m_u} = 2.49(12)\ \mathrm{MeV}$



$$\delta M_{p-n}^{\gamma} = M_p - M_n - \delta M_{p-n}^{m_d-m_u} = 1.20(12)\ \mathrm{MeV}$$

[AWL, C.Carlson, G.Miller PRL 108 (2012) $1.40(03)(47)\ \mathrm{MeV}$]

Strong Isospin Breaking: m_d - m_u PRELIMINARY

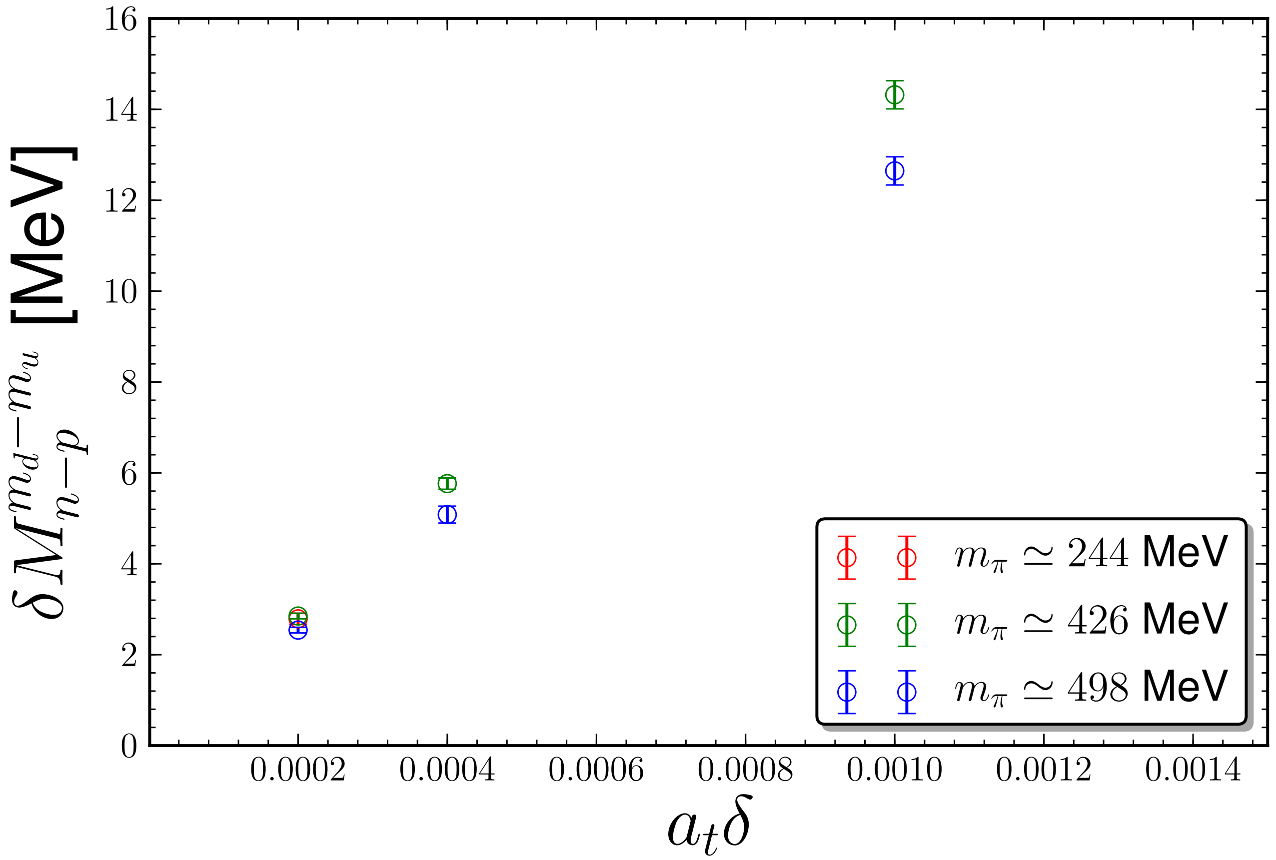
lattice QCD calculation performed using the Spectrum Collaboration anisotropic clover-Wilson gauge ensembles (developed @JLAB)

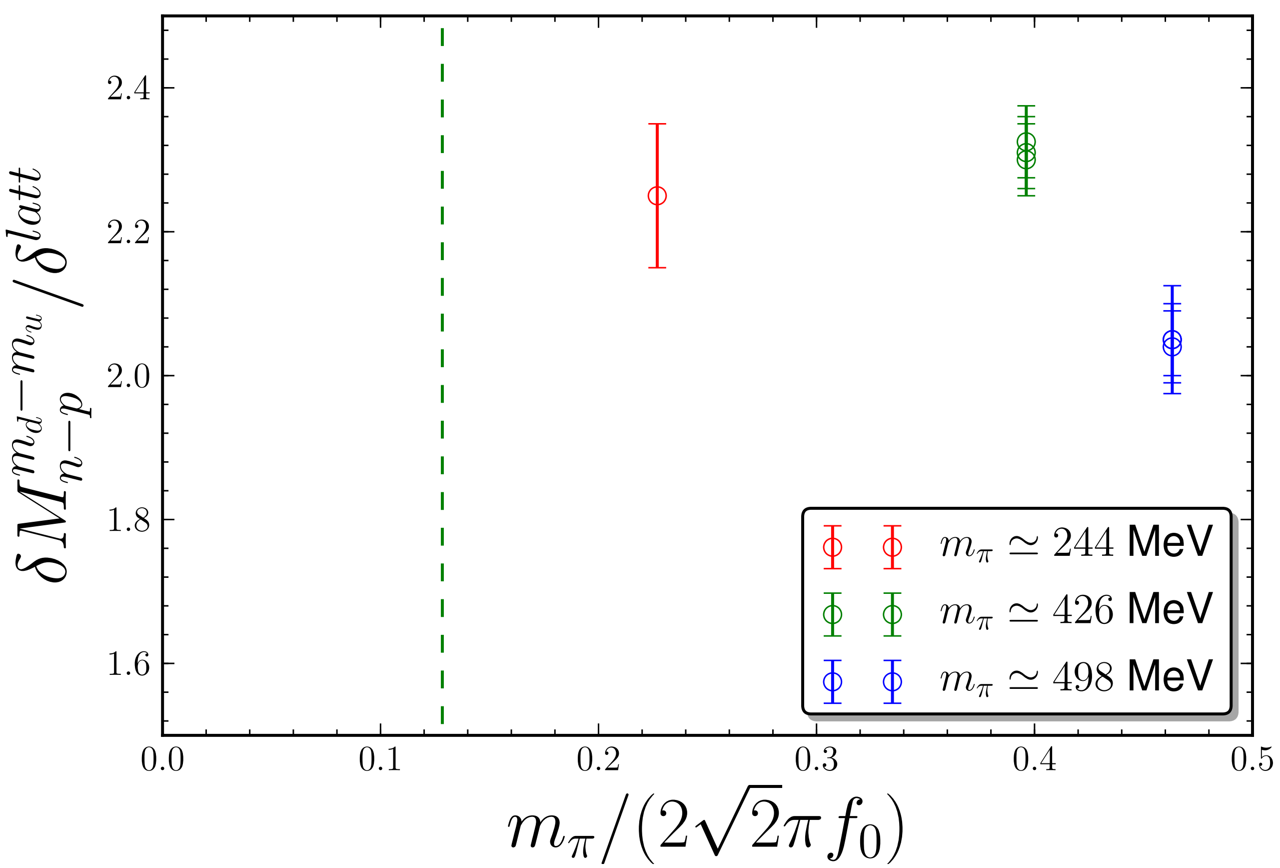
ensemble				m_π	m_K	$a_t\delta$ $[N_{cfg} \times N_{src}]$			
L	T	$a_t m_l$	$a_t m_s$	[MeV]	[MeV]	0.0002	0.0004	0.0010	0.0020
16	128	-0.0830	-0.0743	500	647	207×16	207×16	207×16	207×16
16	128	-0.0840	-0.0743	426	608	166×25	166×25	166×25	166×50
20	128	-0.0840	-0.0743	426	608	120×25	–	–	–
24	128	-0.0840	-0.0743	426	608	97×25	–	193×25	–
32	256	-0.0840	-0.0743	426	608	291×10	291×10	291×10	–
24	128	-0.0860	-0.0743	244	520	118×26	–	–	–
32	256	-0.0860	-0.0743	244	520	842×11	–	–	–

M_Ω scale setting

C.Aubin, W.Detmold,
Emanuele Mereghetti,
K.Orginos, S.Syritsyn,
B.Tiburzi,
AWL

Strong Isospin Breaking: $m_d - m_u$ PRELIMINARY

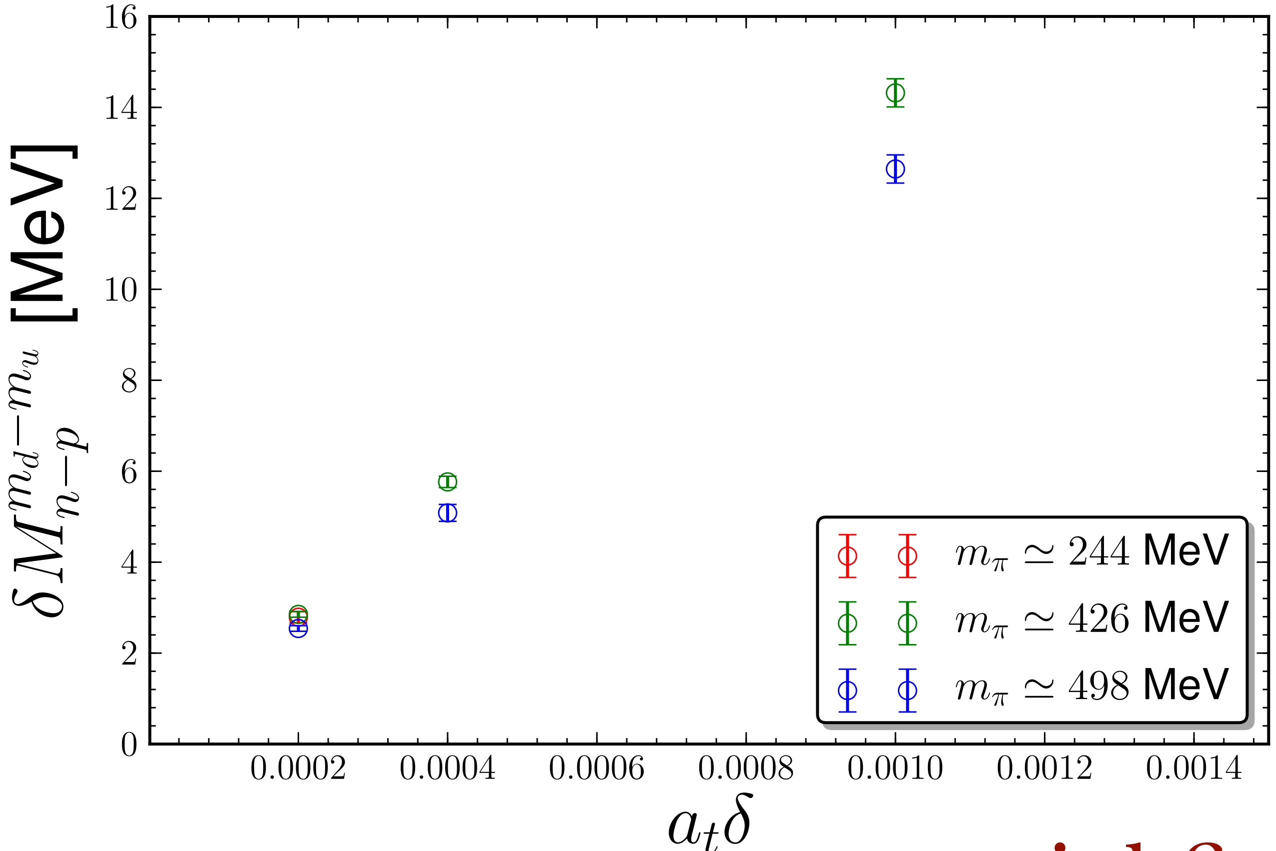


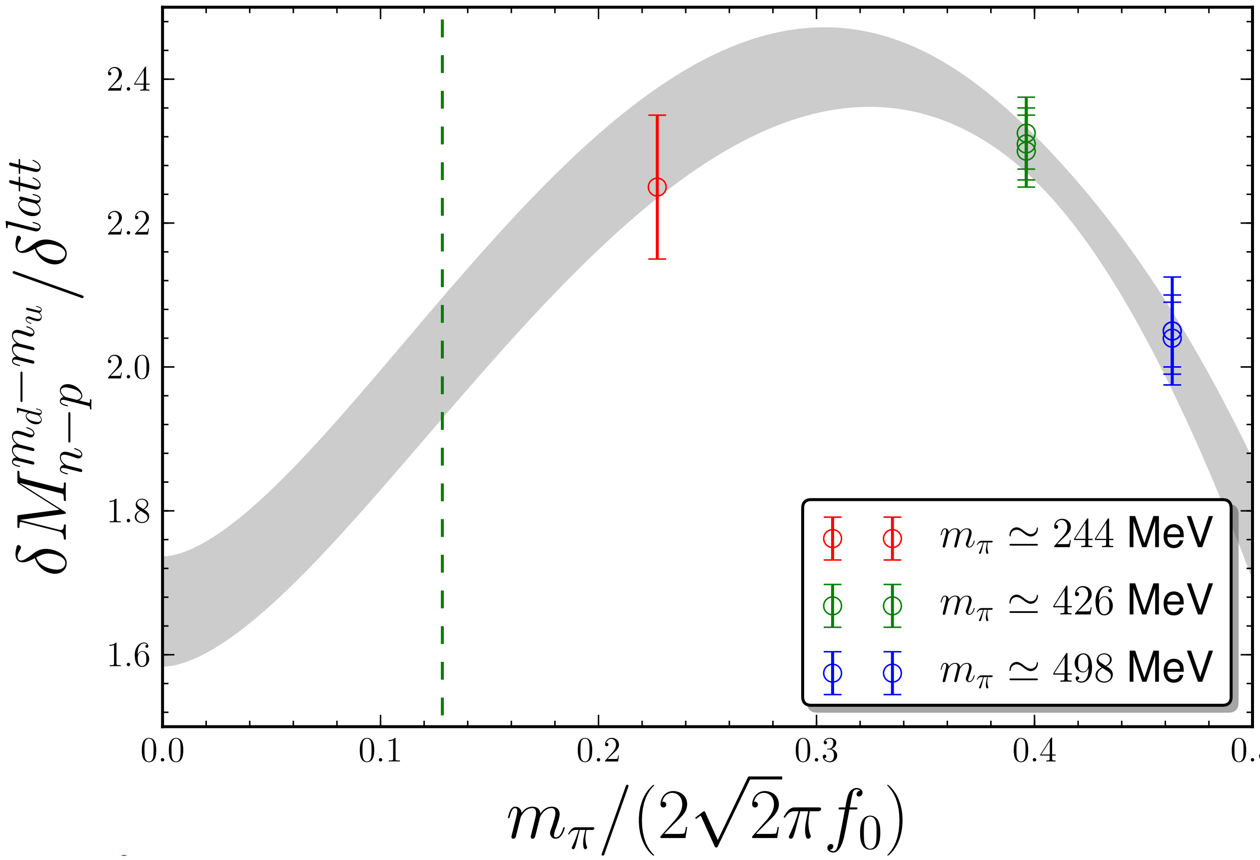


slope depends slightly on pion mass

no evidence for deviations from linear δ dependence

Strong Isospin Breaking: m_d - m_u PRELIMINARY





trial fit functions

polynomial in m_π^2

$$\delta M_{n-p}^{m_d-m_u} = \delta \left\{ \alpha + \beta \frac{m_\pi^2}{(4\pi f_\pi)^2} \right\}$$

$$\chi^2/dof = 13/5 = 2.6$$

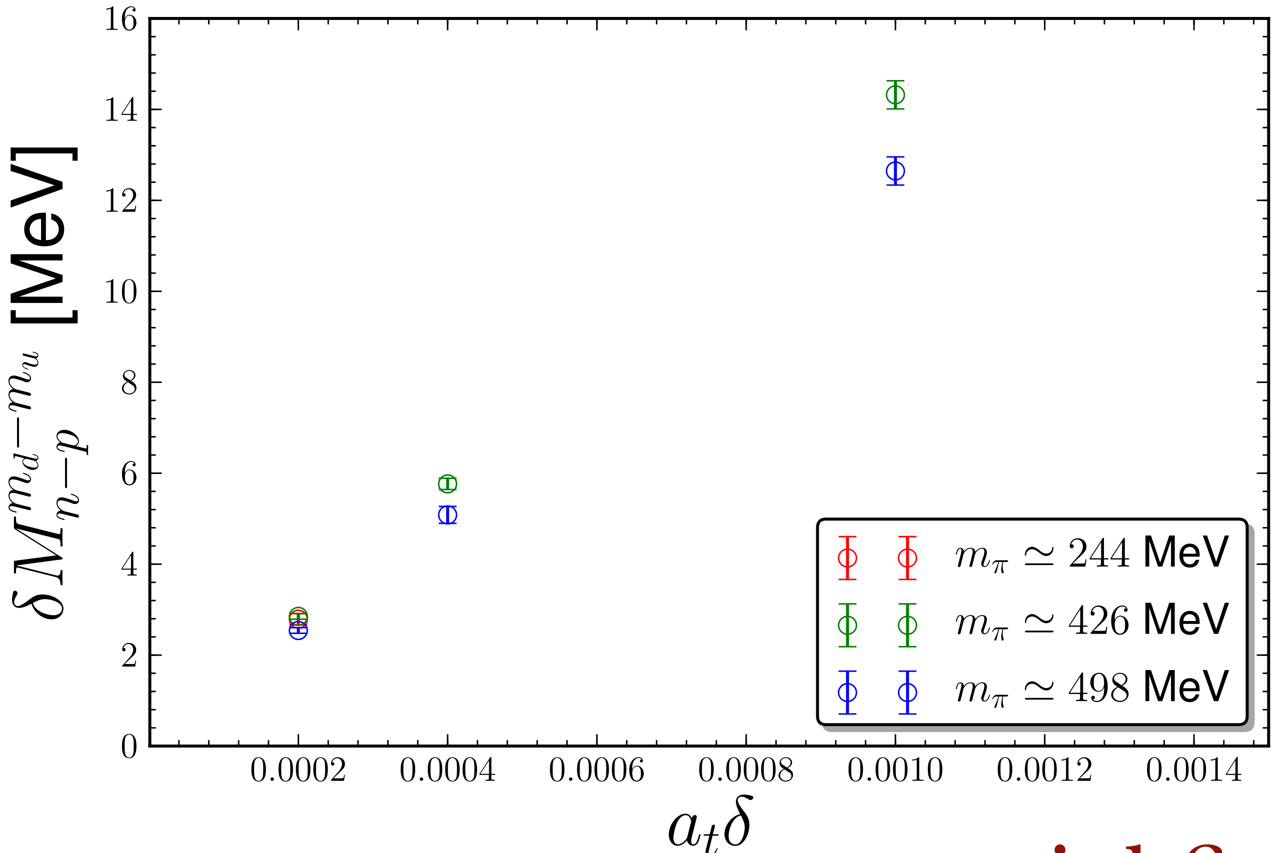
NNLO χPT

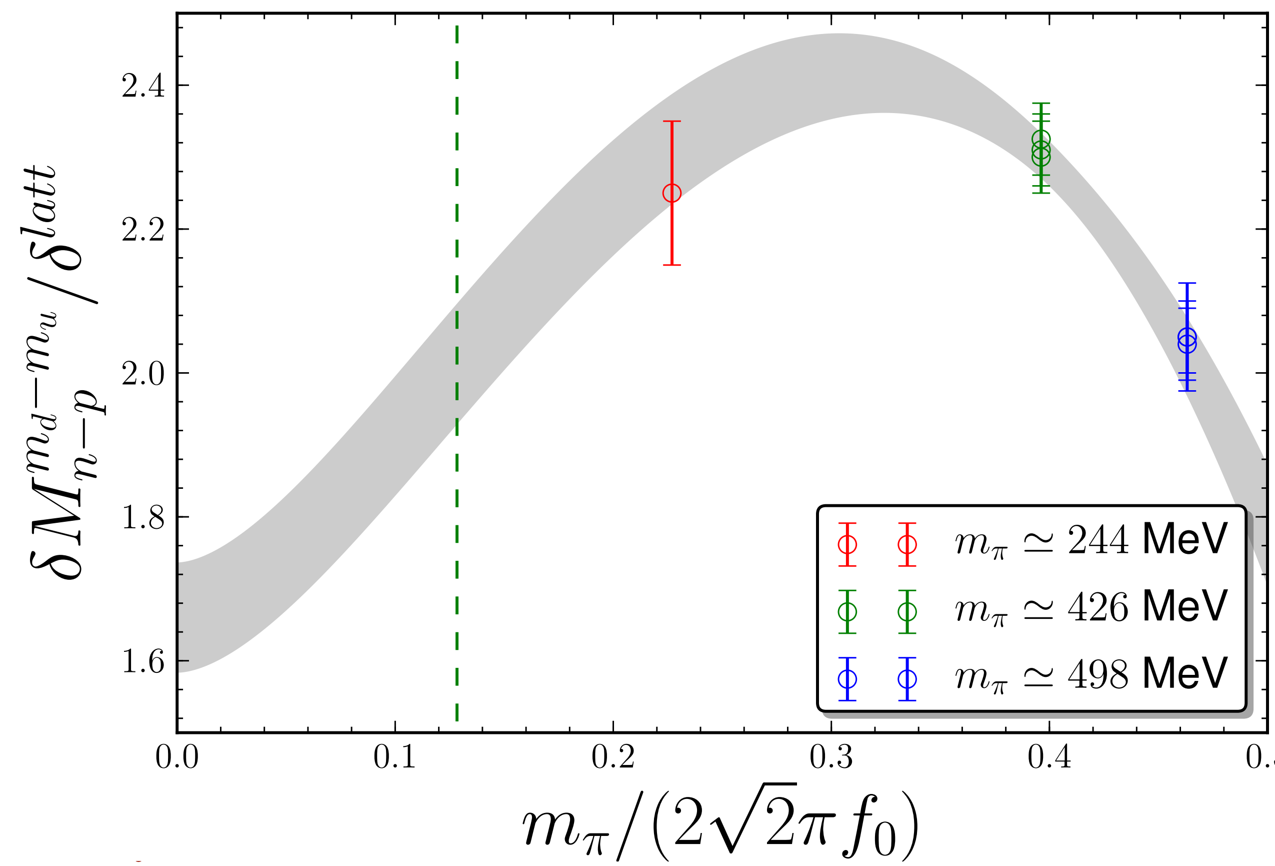
$$\delta M_{n-p}^{m_d-m_u} = \delta \left\{ \alpha \left[1 - \frac{m_\pi^2}{(4\pi f_\pi)^2}(6g_A^2+1)\ln\left(\frac{m_\pi^2}{\mu^2}\right) \right] + \beta(\mu)\frac{2m_\pi^2}{(4\pi f_\pi)^2} \right\}$$

$(g_A = 1.27, f_\pi = 130 \text{ MeV})$

$$\chi^2/dof = 1.66/5 = 0.33$$

Strong Isospin Breaking: m_d - m_u PRELIMINARY





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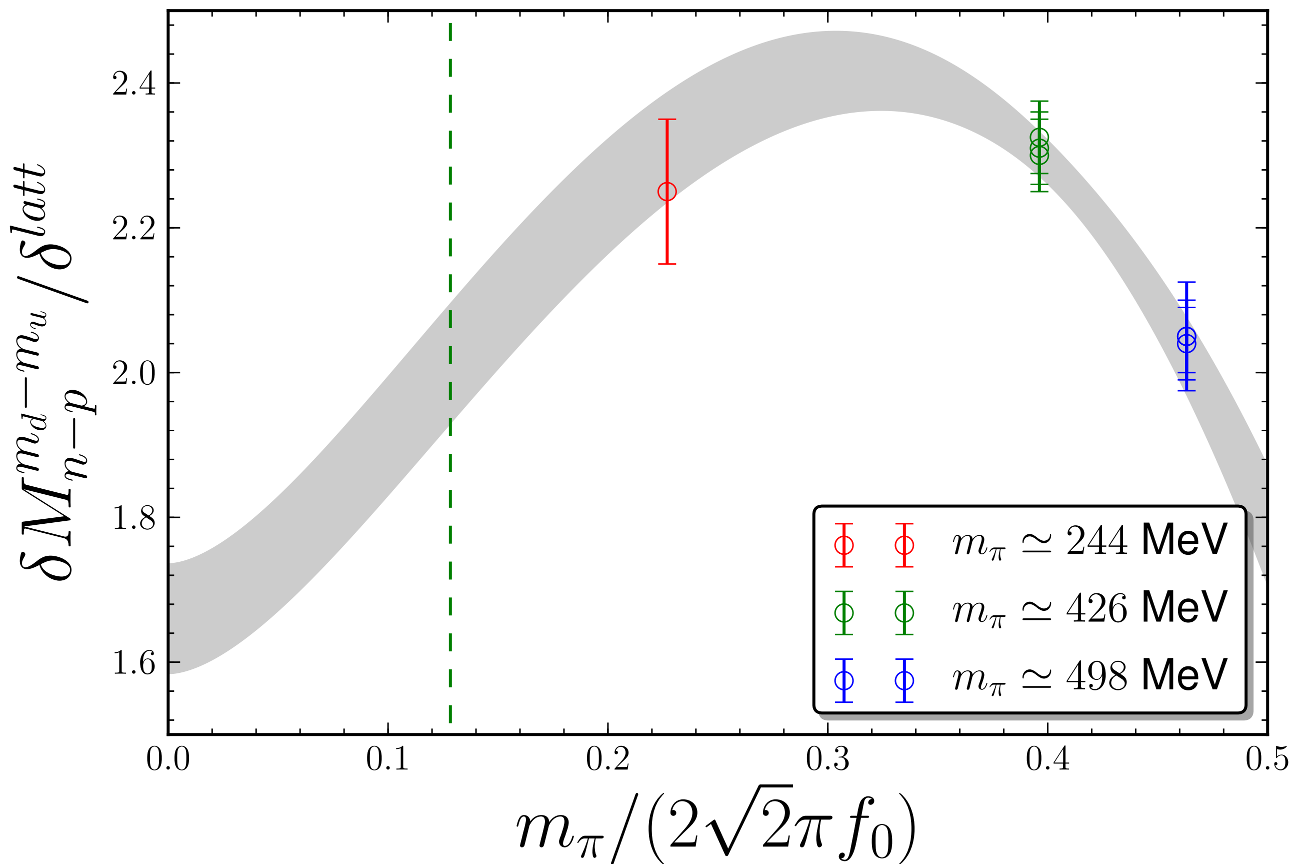
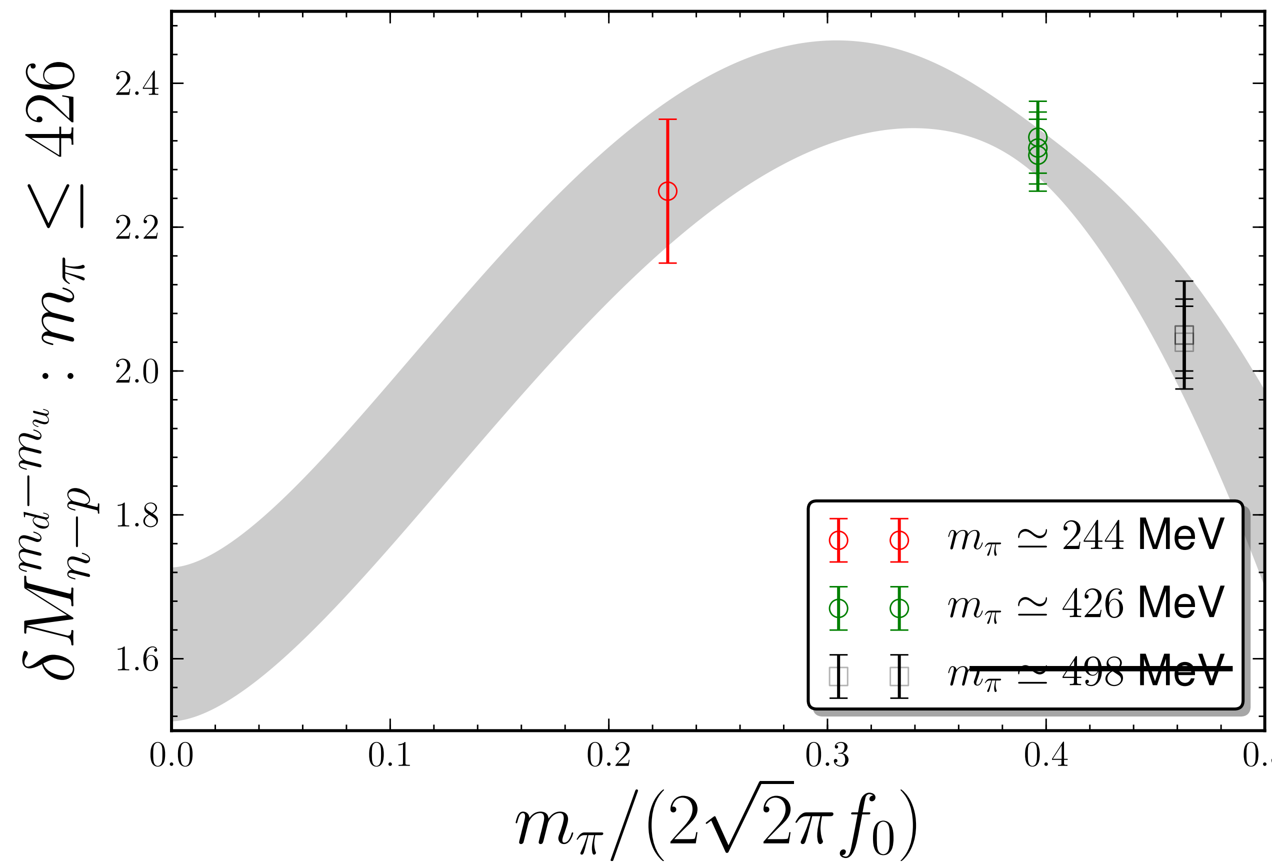
$(f_\pi = 130 \text{ MeV})$

$$\chi^2/dof = 1.34/4 = 0.33$$

→ $g_A = 1.50(.29)$

Strong Isospin Breaking: m_d - m_u PRELIMINARY





NNLO χPT

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$(g_A = 1.27, f_\pi = 130 \text{ MeV})$

$$\chi^2/dof = 1.66/5 = 0.33$$

exclude heavy mass point

this is striking evidence of a chiral logarithm

C.Aubin, W.Detmold,
Emanuele Mereghetti,
K.Orginos, S.Syritsyn,
B.Tiburzi,
AWL

Big Bang Nucleosynthesis and $M_n - M_p$

$$M_n - M_p = \delta M^{\gamma}_{n-p} + \delta M^{m_d - m_u}_{n-p}$$
$$= -178(04)(64)\ \text{MeV} \times \alpha_{f.s.} + 1.01(5)(9) \times (m_d - m_u)$$

(lattice average)

my value *hopefully* more precise

Big Bang Nucleosynthesis and $M_n - M_p$

$$M_n - M_p = \delta M^{\gamma}_{n-p} + \delta M^{m_d - m_u}_{n-p}$$
$$= -178(04)(64)\ \mathrm{MeV} \times \alpha_{f.s.} + 1.01(5)(9) \times (m_d - m_u)$$

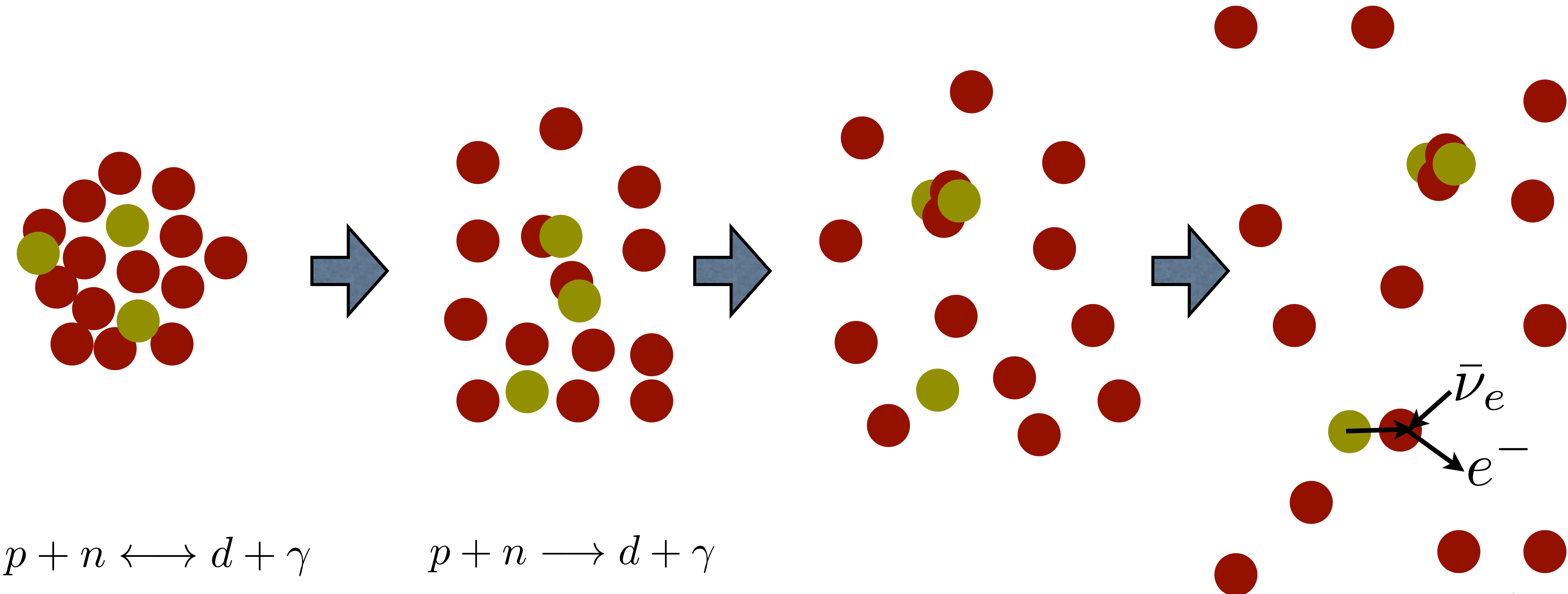
(lattice average)

my value *hopefully* more precise

Big Bang Nucleosynthesis highly constrains variation of $M_n - M_p$ and hence variation of fundamental constants

for now - freeze electromagnetic coupling and just look at effects of quark mass splitting

Big Bang Nucleosynthesis and $M_n - M_p$



$p + n \longleftrightarrow d + \gamma$

$p + n \longrightarrow d + \gamma$

$t \sim 1$ sec
$T \sim 1$ MeV

$t \sim 3$ min
$T \sim 0.1$ MeV

$t \sim 3^+$ min
$T \sim 0.1^-$ MeV

$t \sim 15$min
$T \sim 0.01$ MeV

$$\frac{X_n}{X_p} = e^{-\frac{M_n - M_p}{T}}$$

Initial conditions

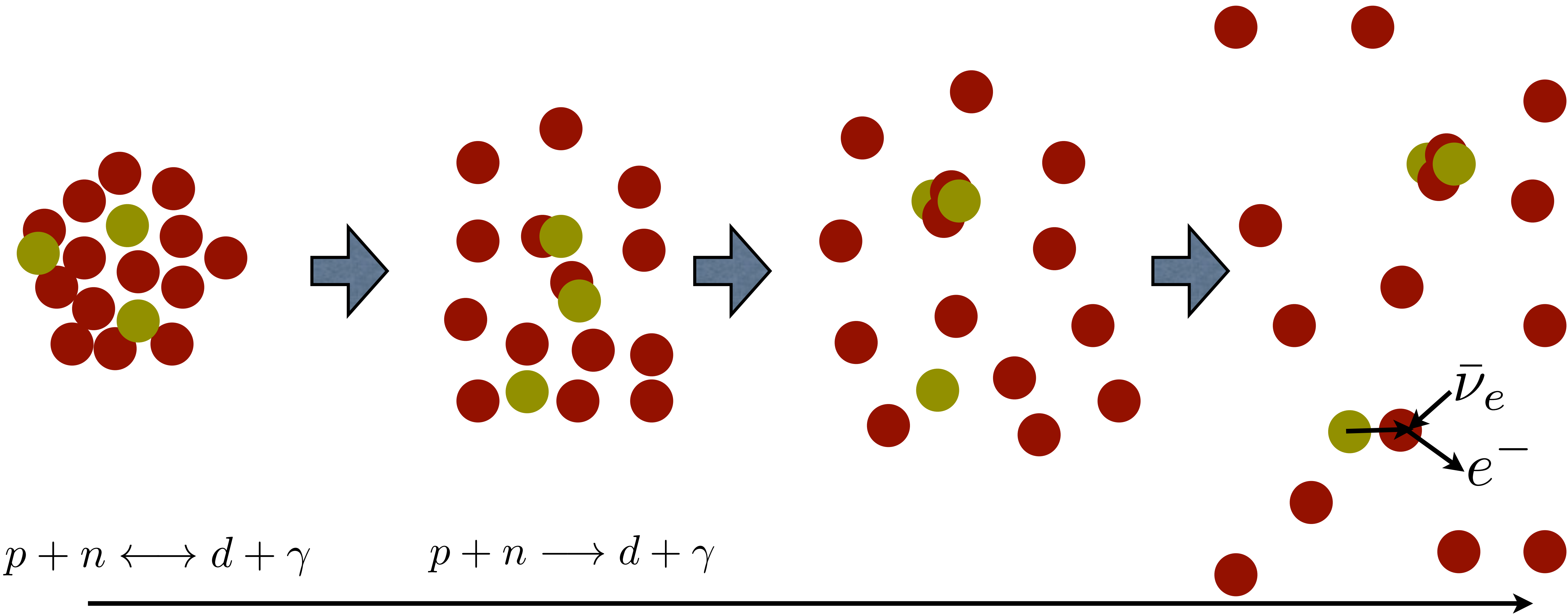
B_d

deuterium
binding energy

τ_n

neutron
lifetime

Big Bang Nucleosynthesis and $M_n - M_p$



$t \sim 1$ sec	$t \sim 3$ min	$t \sim 3^+$ min	$t \sim 15$min
$T \sim 1$ MeV	$T \sim 0.1$ MeV	$T \sim 0.1^-$ MeV	$T \sim 0.01$ MeV

$$\frac{X_n}{X_p} = e^{-\frac{M_n - M_p}{T}}$$

Initial conditions

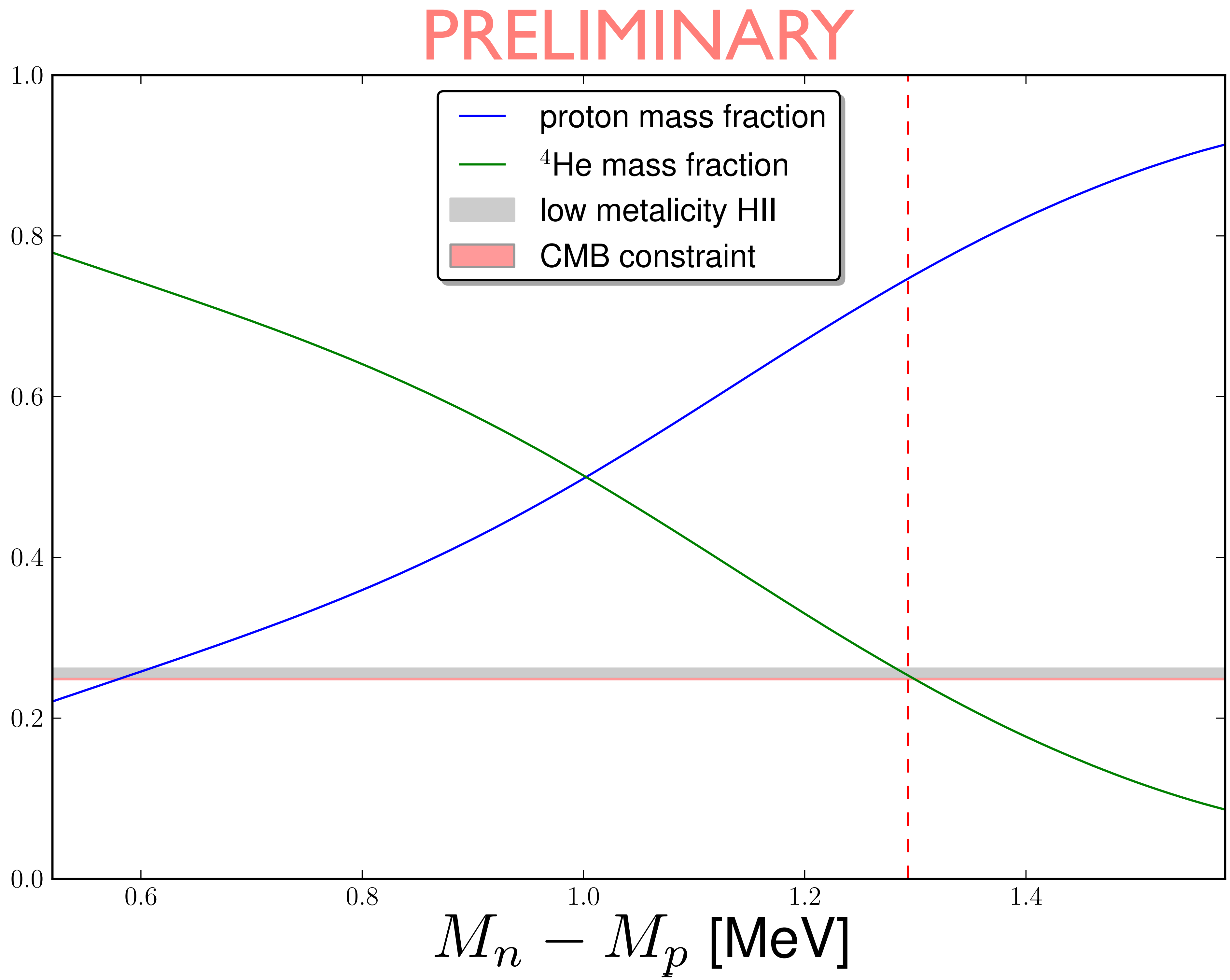
focus on leading isospin breaking

τ_n

neutron lifetime

Big Bang Nucleosynthesis and $M_n - M_p$

P. Banerjee, T. Luu, S. Syritsyn AWL



Big Bang Nucleosynthesis and $M_n - M_p$

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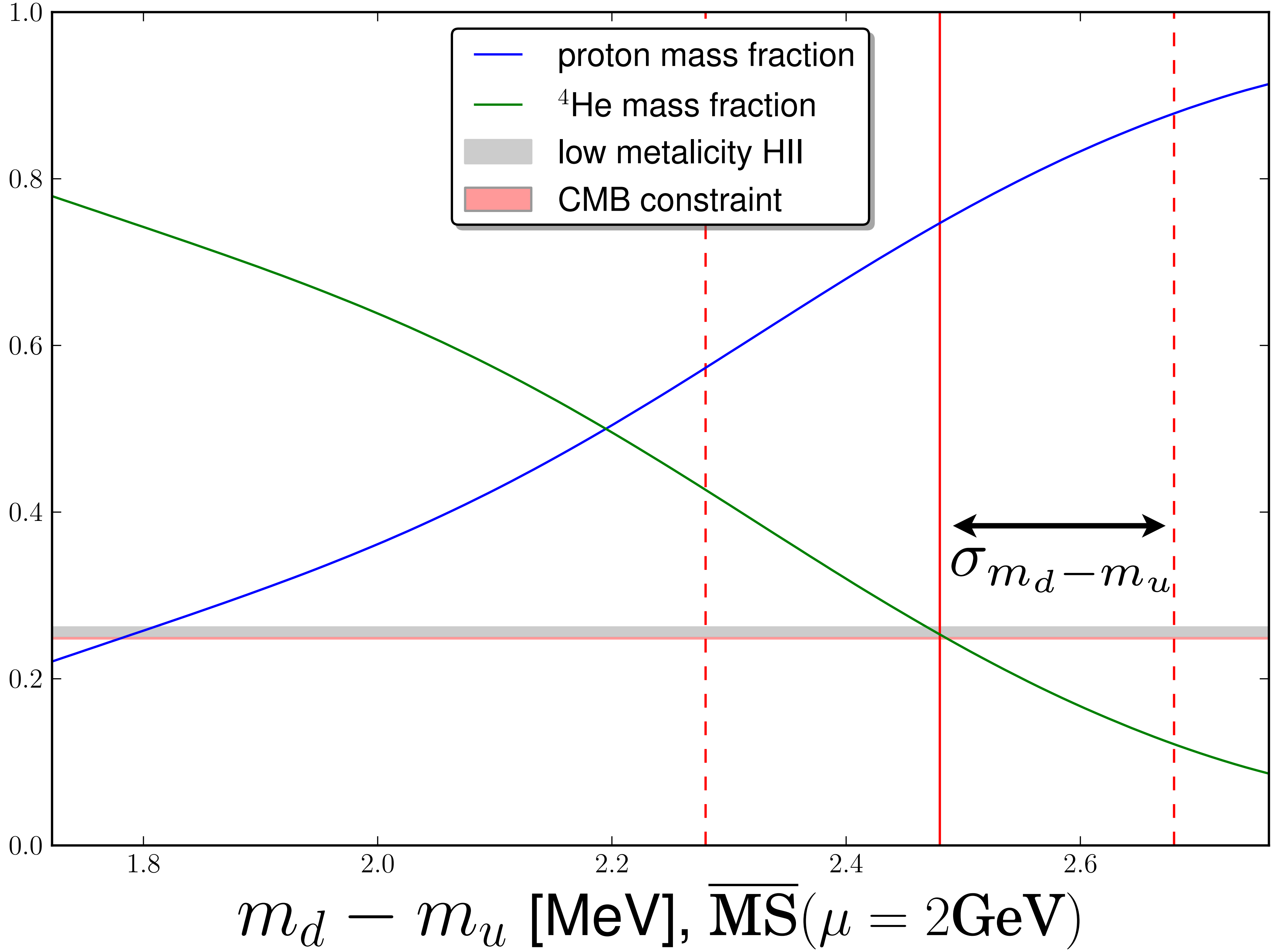
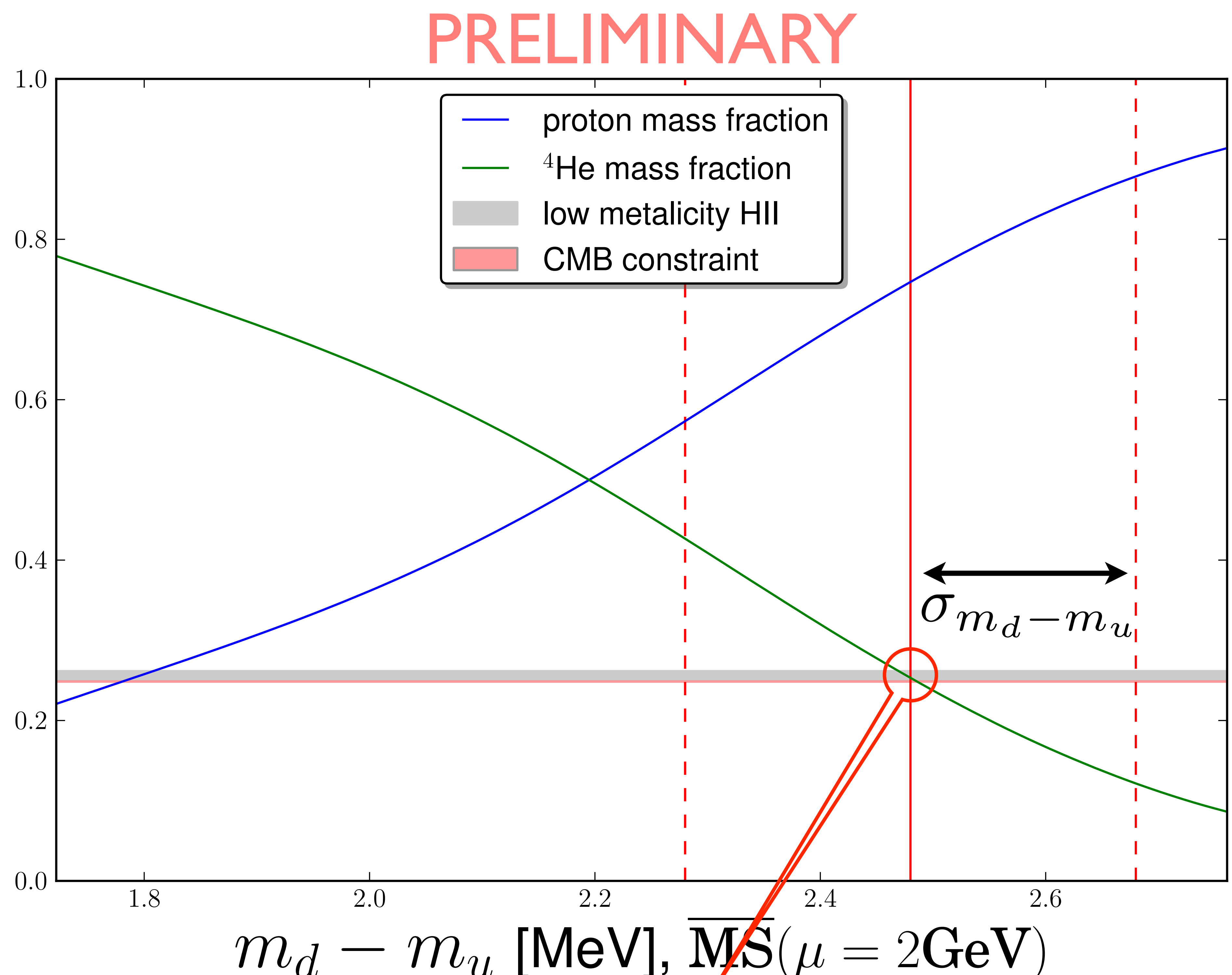
PRELIMINARY



Lattice QCD

Big Bang Nucleosynthesis and $M_n - M_p$

P. Banerjee, T. Luu,
S. Syritsyn AWL



Lattice QCD

A precise determination of α + BBN can constrain $m_d - m_u$

$\delta M_{n-p}^{m_d - m_u} \equiv \alpha(m_d - m_u)$ *connect the quarks with the cosmos*

Conclusions

- After decades of dedicated effort, lattice QCD is now a tool for reliably computing basic QCD observables

- The challenges of extending these calculations to observables relevant to nuclear physics mean it will still be a few years before lattice QCD can make the same impact

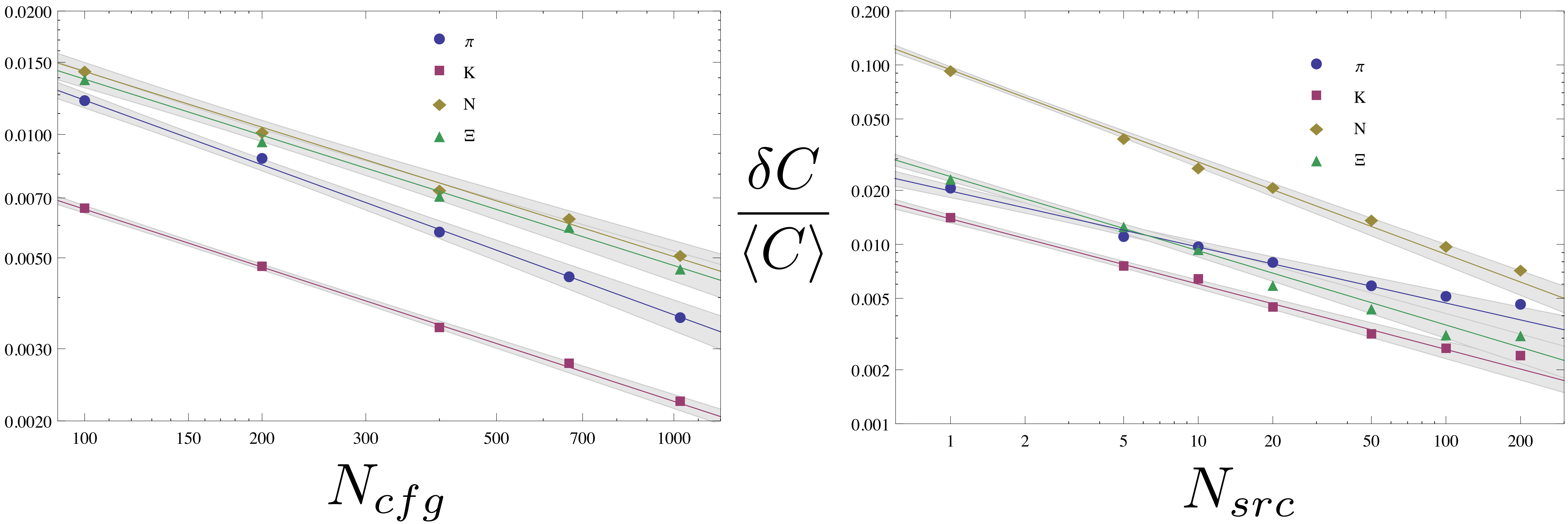
- We are beginning to see the role lattice QCD can play in making a quantitative connection between the quarks and the cosmos - stay tuned!

- Many more things to come
  - hyperon-nucleon interactions
  - hadronic parity violation
  - direct dark matter detection
  - nuclear EDMs
  - ...


Thank You!

Methods and Results

NN Interactions $^1S_0$



$$\frac{\delta C}{\langle C \rangle} = A(N_{cfg})^b$$

$$b^N_{cfg} = -0.45(2)$$

$$\frac{\delta C}{\langle C \rangle} = A(N_{src})^b$$

$$b^N_{src} = -0.51(9)$$

NPLQCD PRD 79 (2009)
arXiv:0903.2990

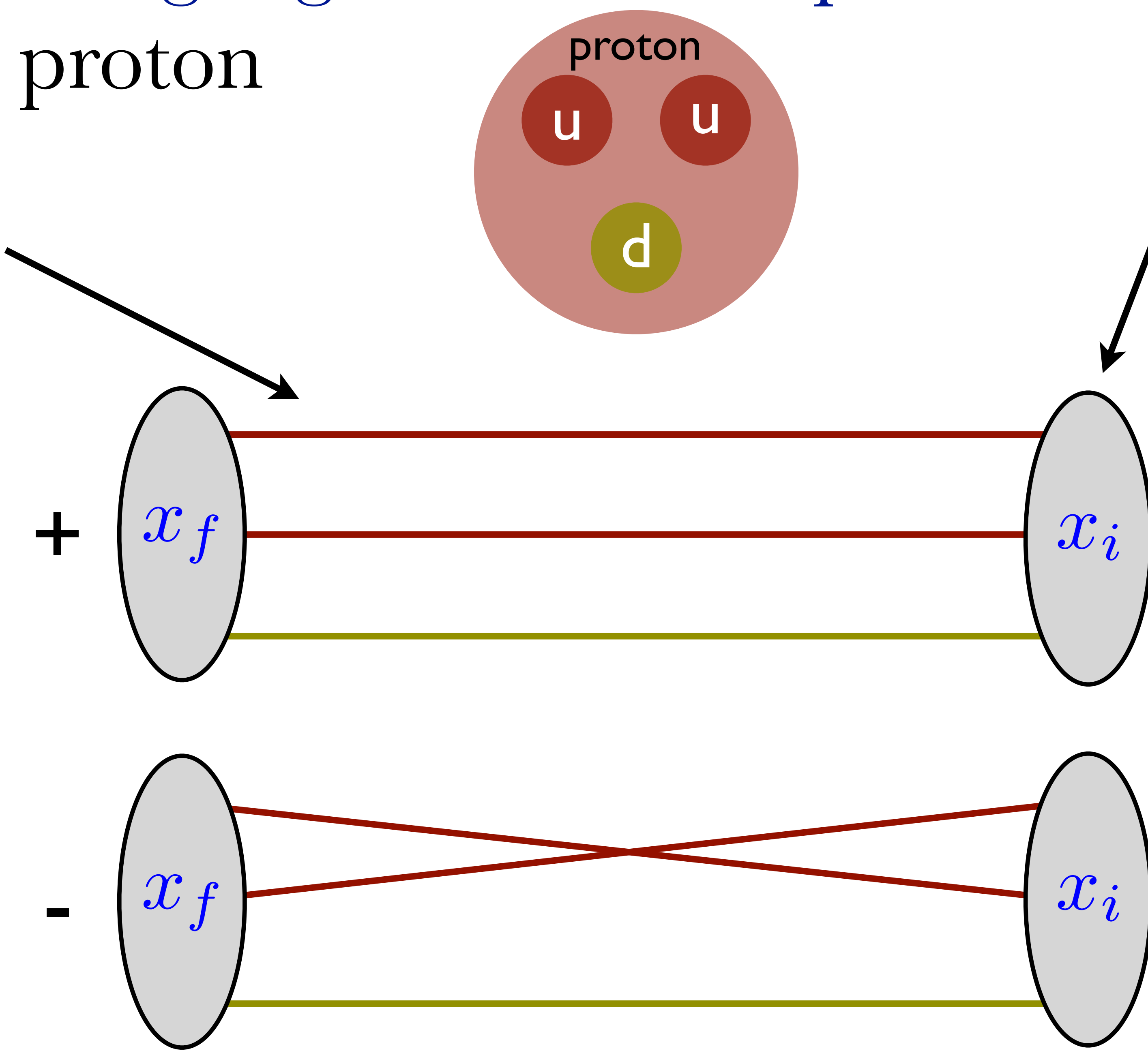
Given a set of gauge fields - one performs *measurements*

consider a proton

D_W^{-1}

quark propagator

"wave functions"

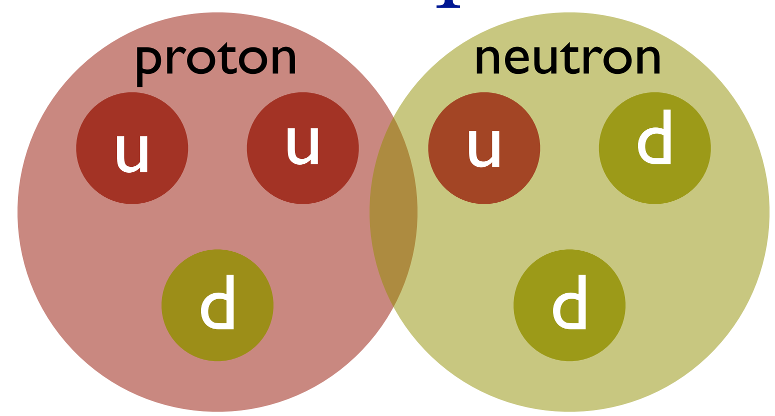


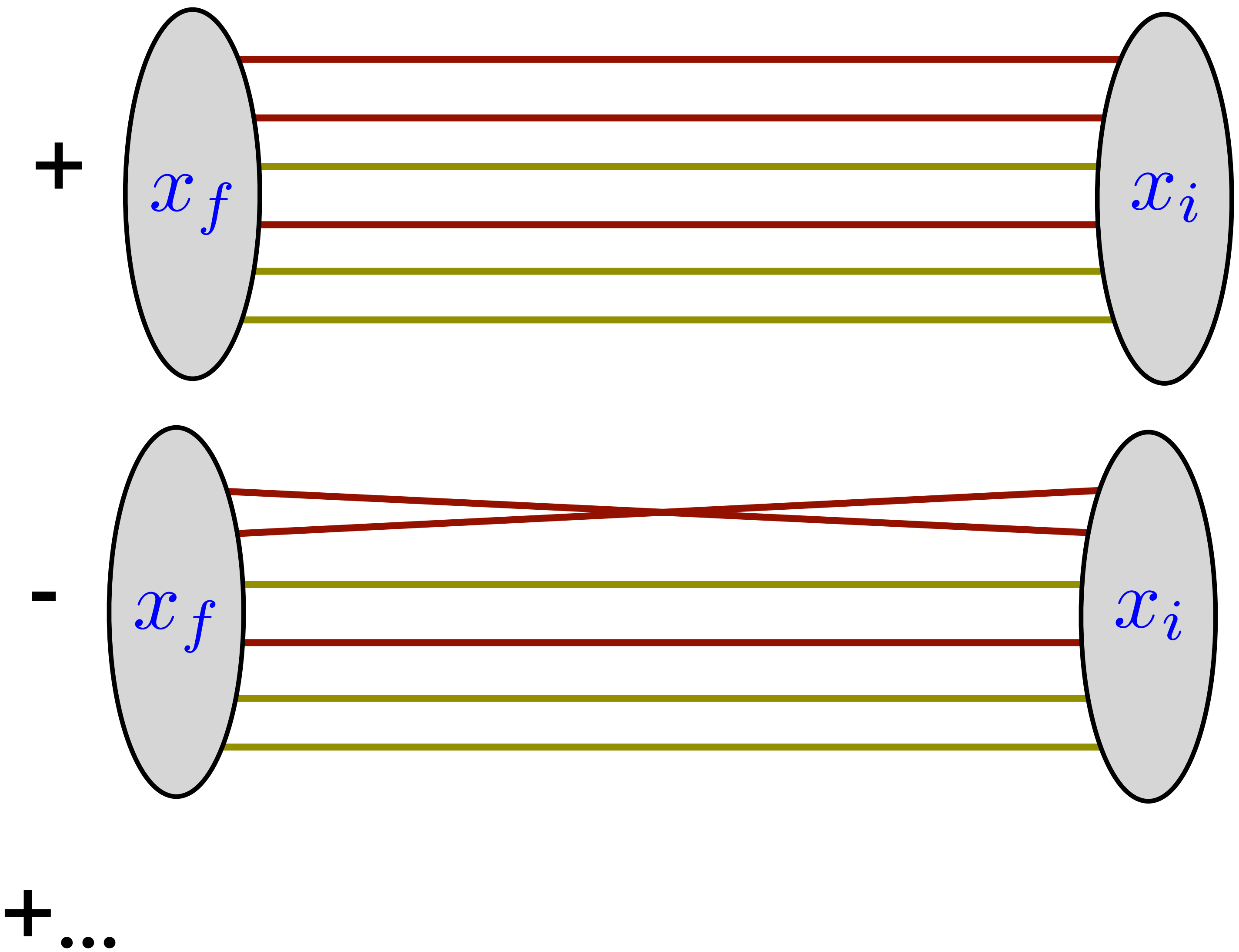
$2! \times 1! = 2$
contractions

quark-exchange diagrams are source of fermion sign problem

Given a set of gauge fields - one performs *measurements*

consider a deuteron



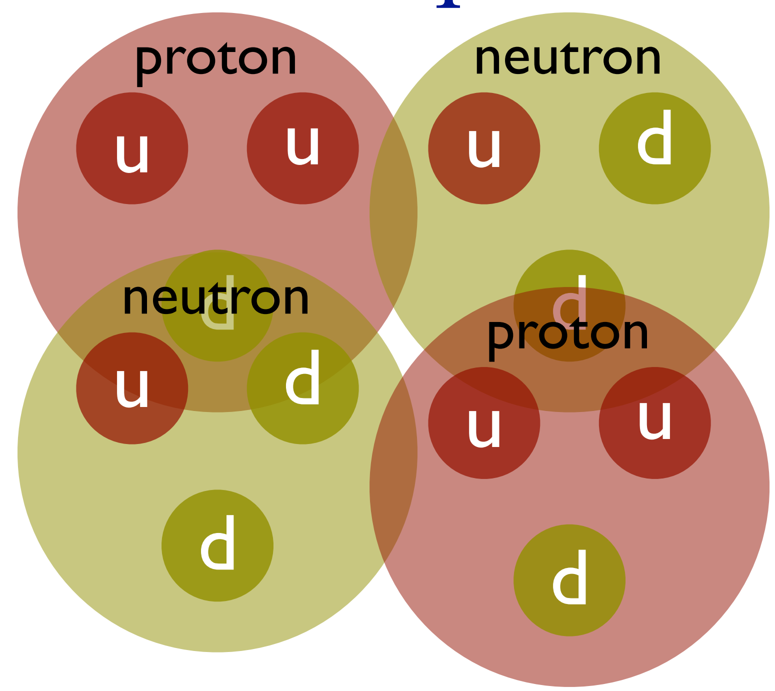


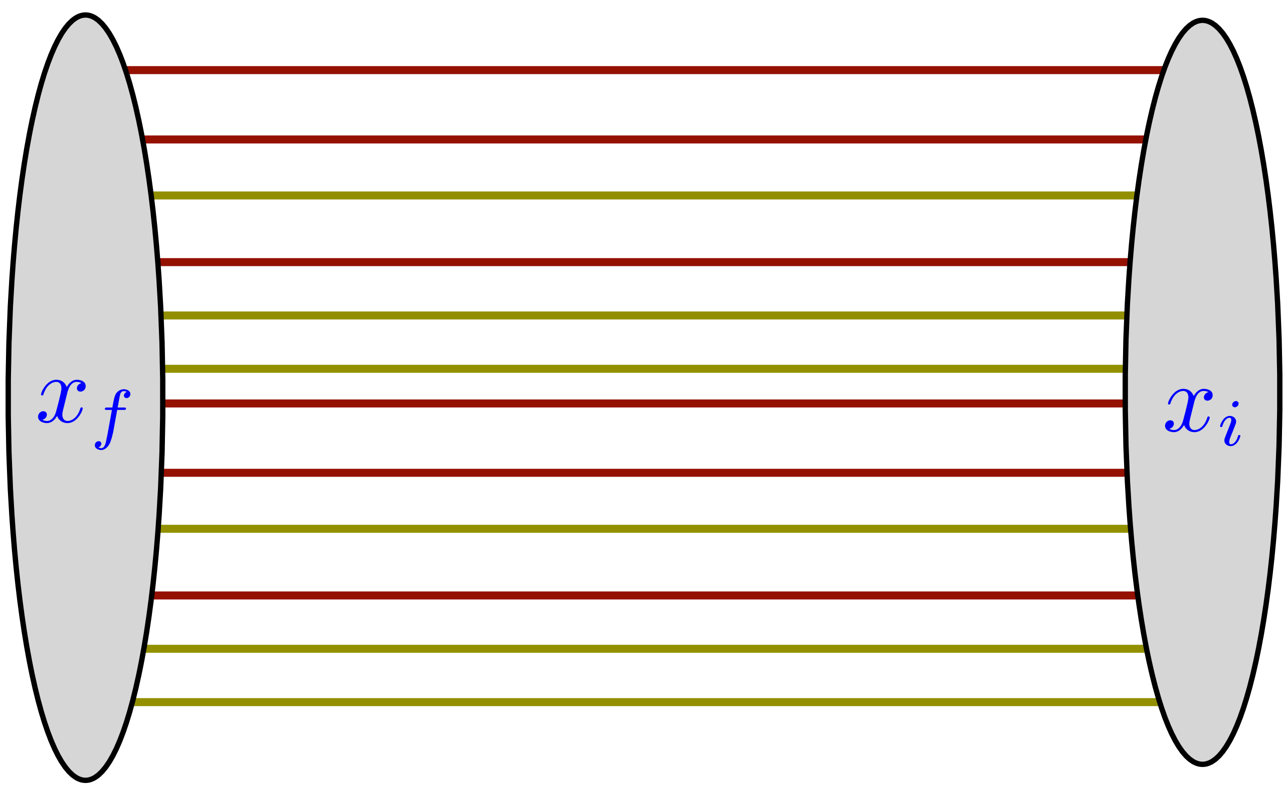
$3! \times 3! = 36$

contractions

Given a set of gauge fields - one performs *measurements*

consider a ^{4}He





+...

$$6! \times 6! = 518400$$

contractions

Not entirely fair - lots of symmetry to reduce the number of contractions

the point is these contraction costs are quite significant

T. Doi and M. Endres, Comp. Phys. Comm. 184 (2013)
W. Detmold and K. Orginos, PRD 87 (2013)
J. Günther, B.C. Toth and L.Varnhorst PRD 87 (2013)