Nuclear Physics: BSM

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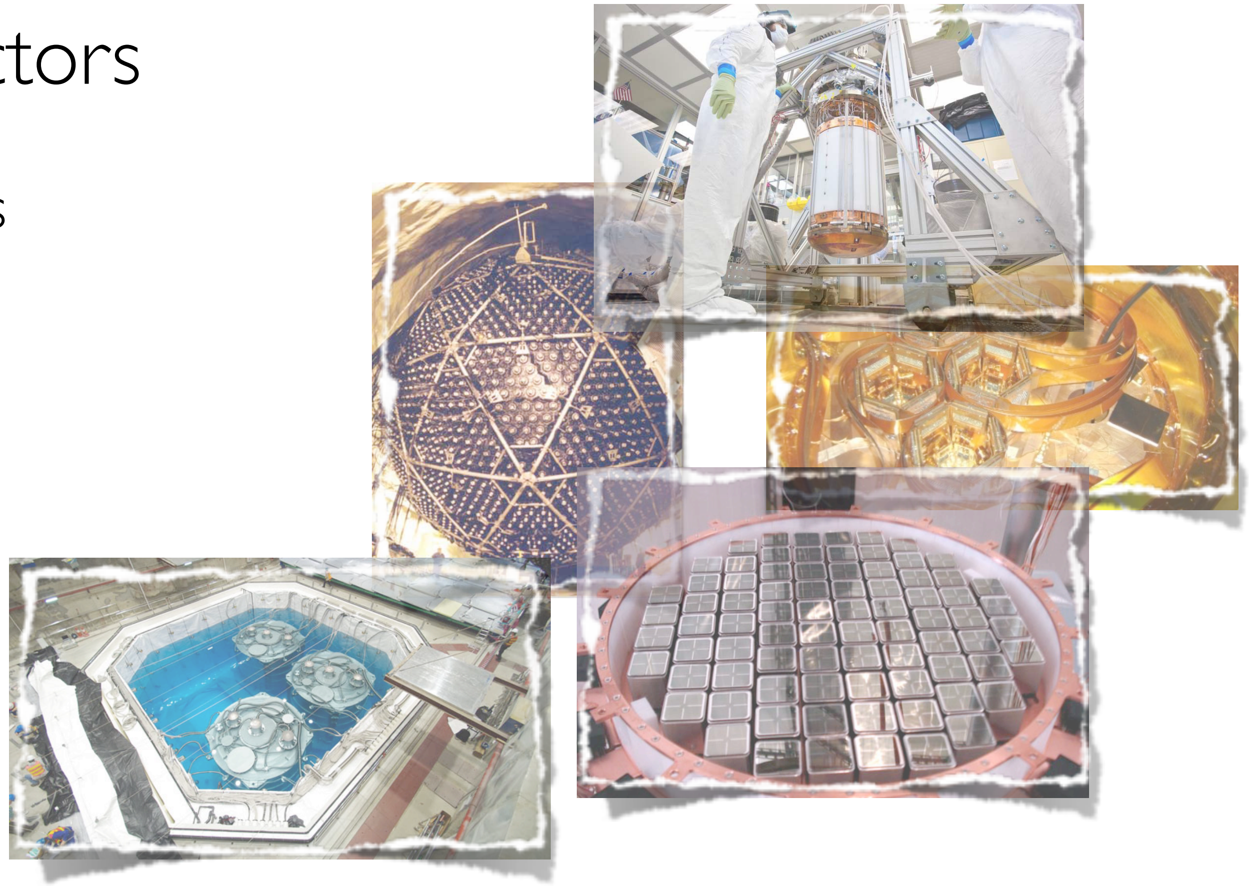
Outline

- Role of NP in search for physics BSM and other rare processes
- Uncertainties in nuclear effects: (un)known (un)knowns
  - Examples: $0\nu\beta\beta$ decay, GT transitions, eA DIS
- Nuclear physics from the SM?
  - Problems and progress
  - Scalar-isoscalar current nuclear matrix elements

Searches for very rare interactions

- Weakness of weak or dark matter interactions with ordinary matter ⇒ big detectors
  - Piles (buckets) of heavy stuff instead of protons
- Specific nuclear transitions sensitive to fundamental symmetries: nuclear environment enhances effect
- Range of nuclei used in detectors
  - Neutrino DIS: NuTeV - steel sheets
  - Solar Neutrinos @ SNO: D_2O
  - Dark matter: Na, Si, Ge, Xe, ...
  - EDM searches: Rn, Hg, Xe, ..
  - $0\nu\beta\beta$ decay: Ge, Ca, Xe, ...

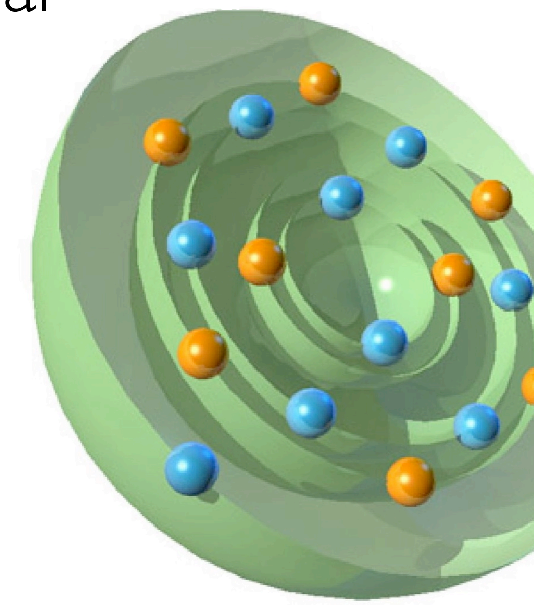


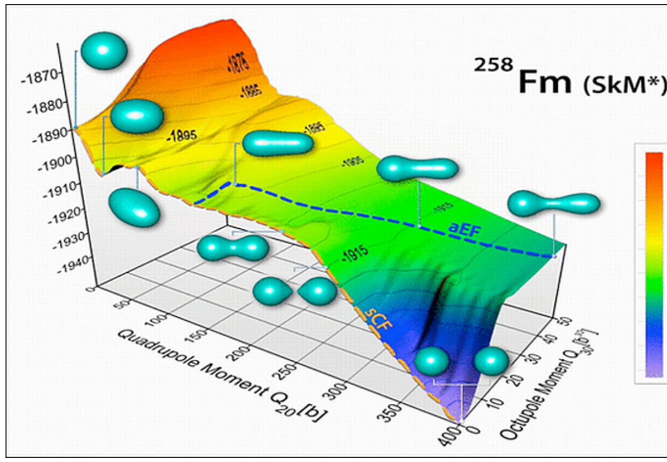
How predictive is nuclear physics?

- NP critical to experimental investigations of these interactions
- Phenomenological: poorly understood from a theoretical perspective
    - Quantifying uncertainties on predictions is difficult
- Ideal experiment: simple nuclei (single isotope) where theory is best understood
    - Study dependence on target
- Reality: single target chosen for a host of reasons

😀 New physics *discovery* can be robust despite NP

😧 Differentiation of new physics no so easy



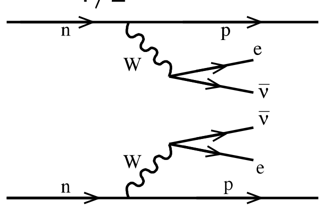


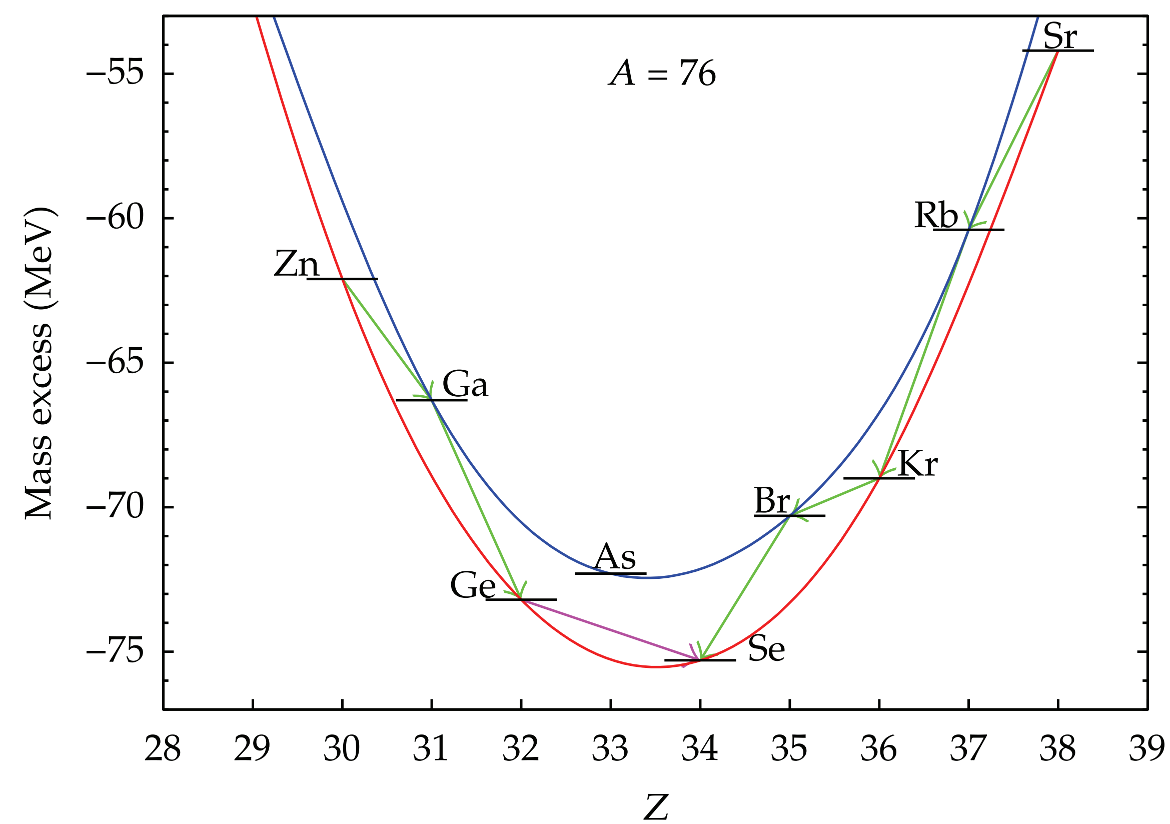
$0\nu\beta\beta$ decay

0νββ decay

- Certain nuclei allow observable ββ decay

$T_{1/2}^{2\nu\beta\beta} \gtrsim 10^{19}$ y





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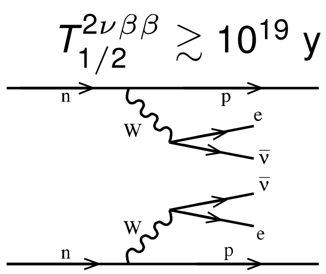

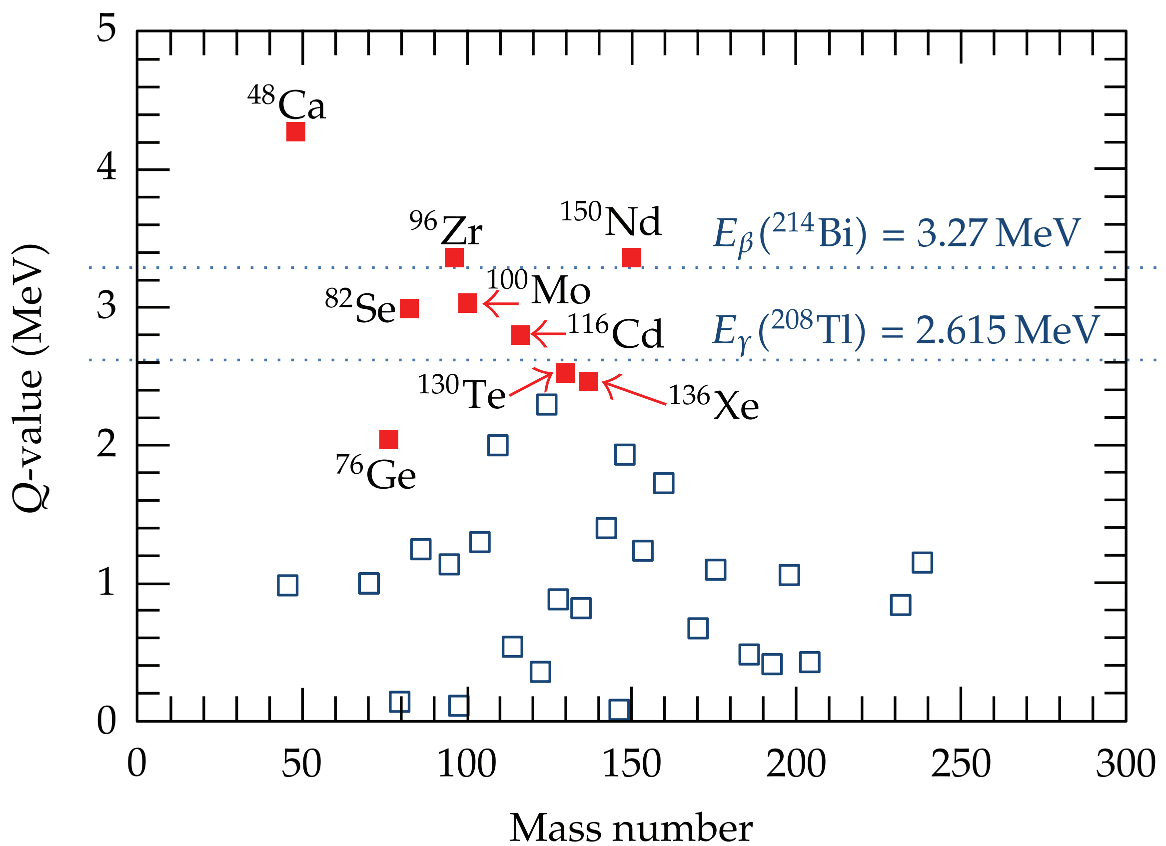

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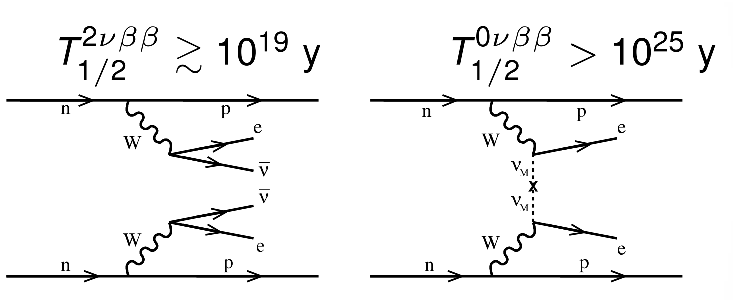
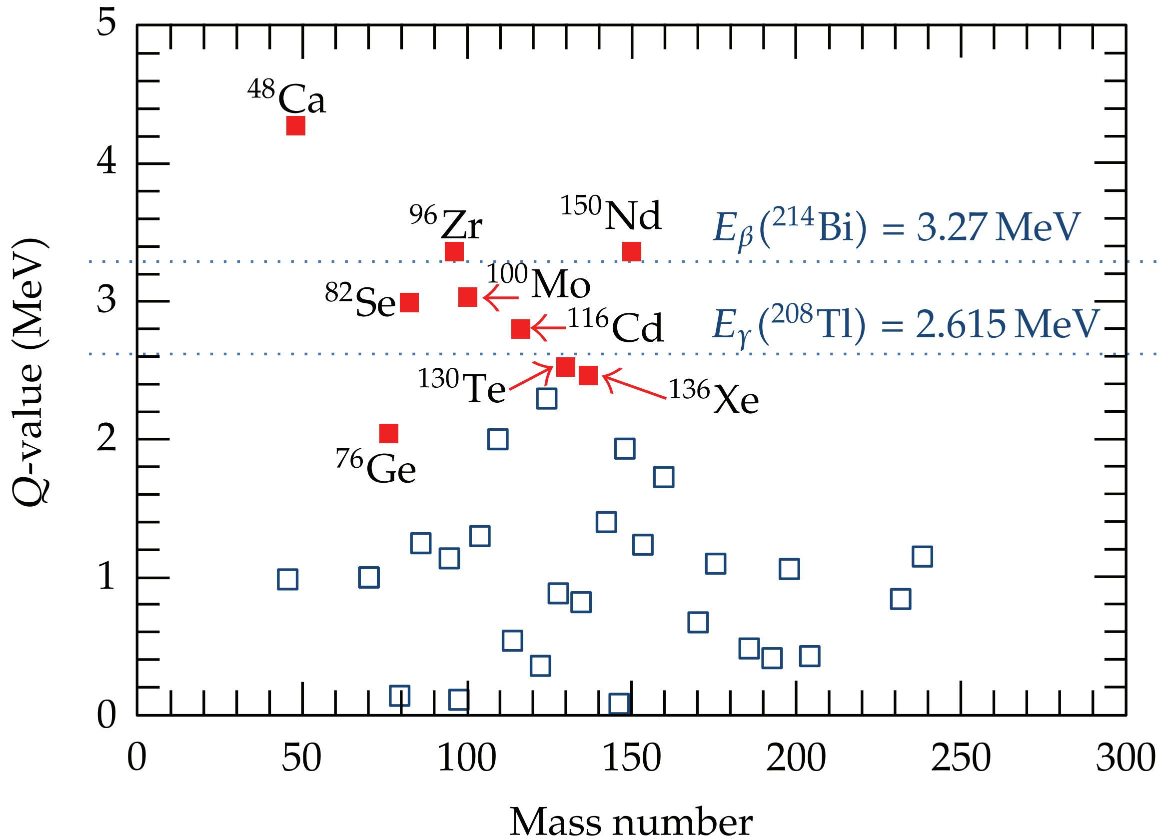
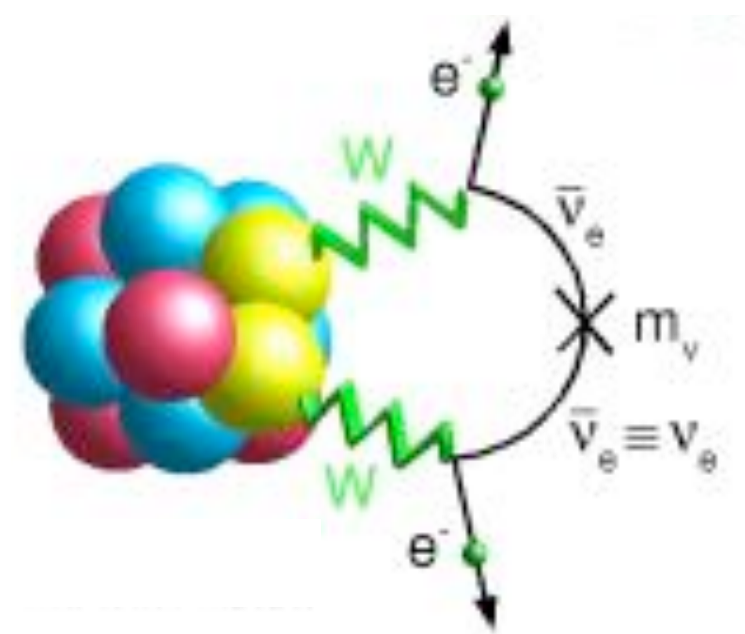


- If neutrinos are massive Majorana fermions 0νββ decay is possible





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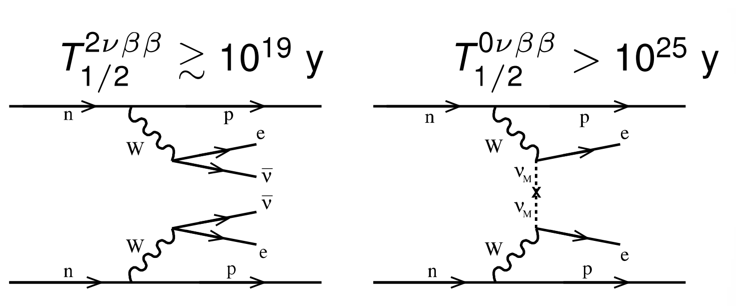
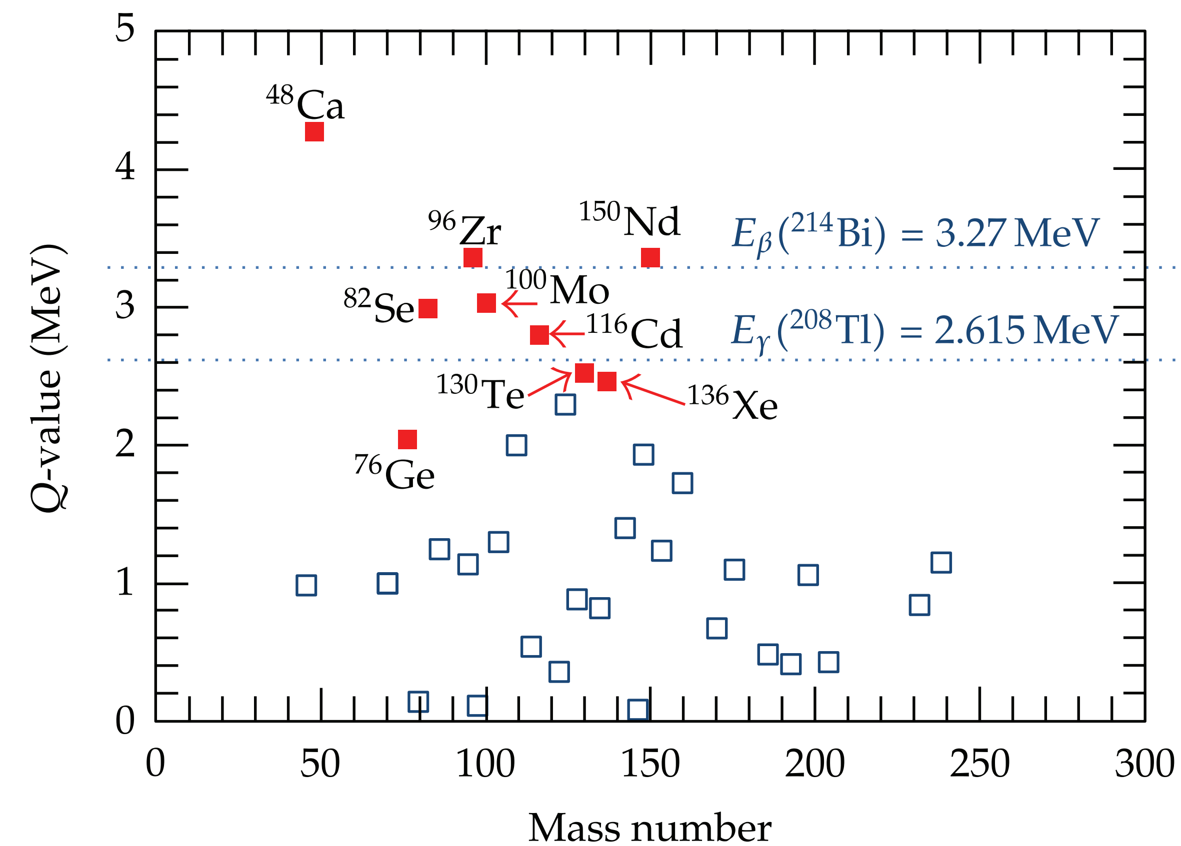
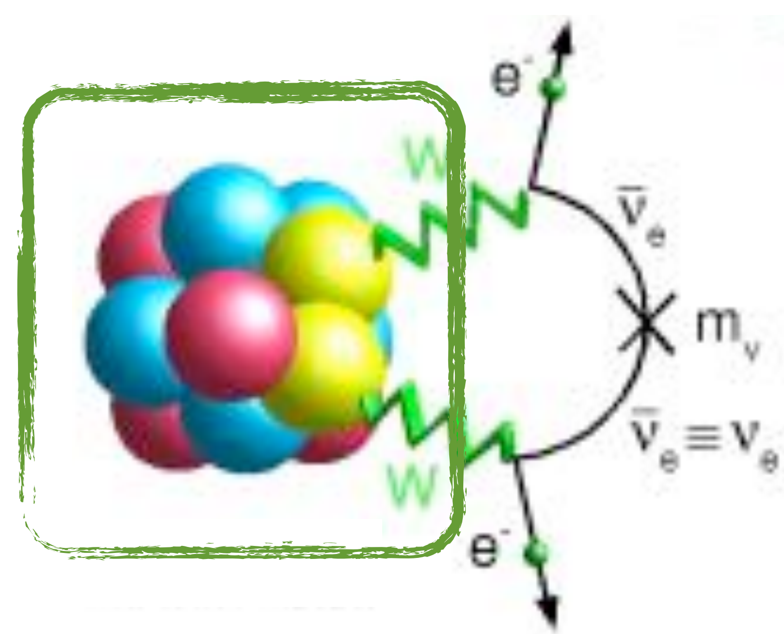


- If neutrinos are massive Majorana fermions 0νββ decay is possible

- Half-life depends critically on the nuclear matrix elements of two weak currents

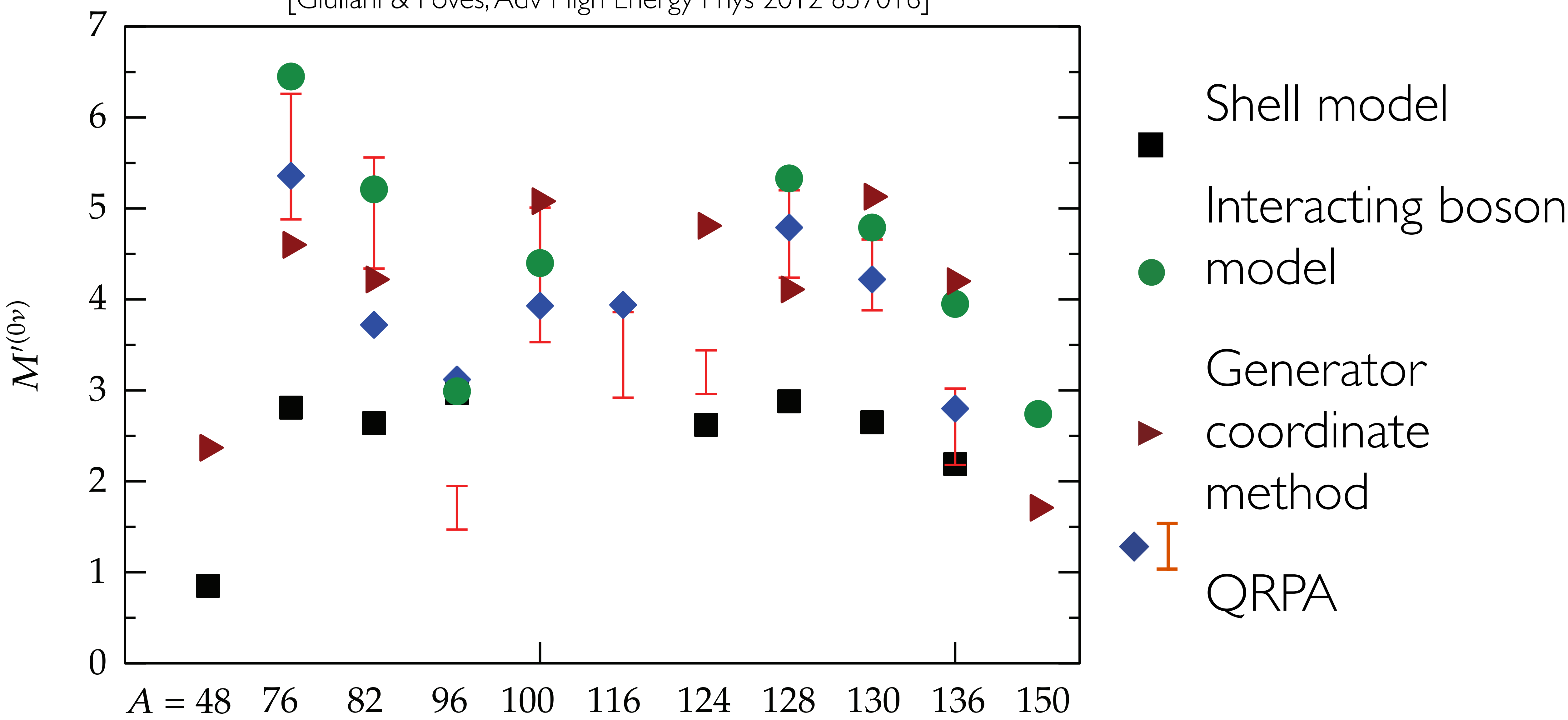
$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2$$





0νββ decay nuclear matrix elements

[Giuliani & Poves, Adv High Energy Phys 2012 857016]

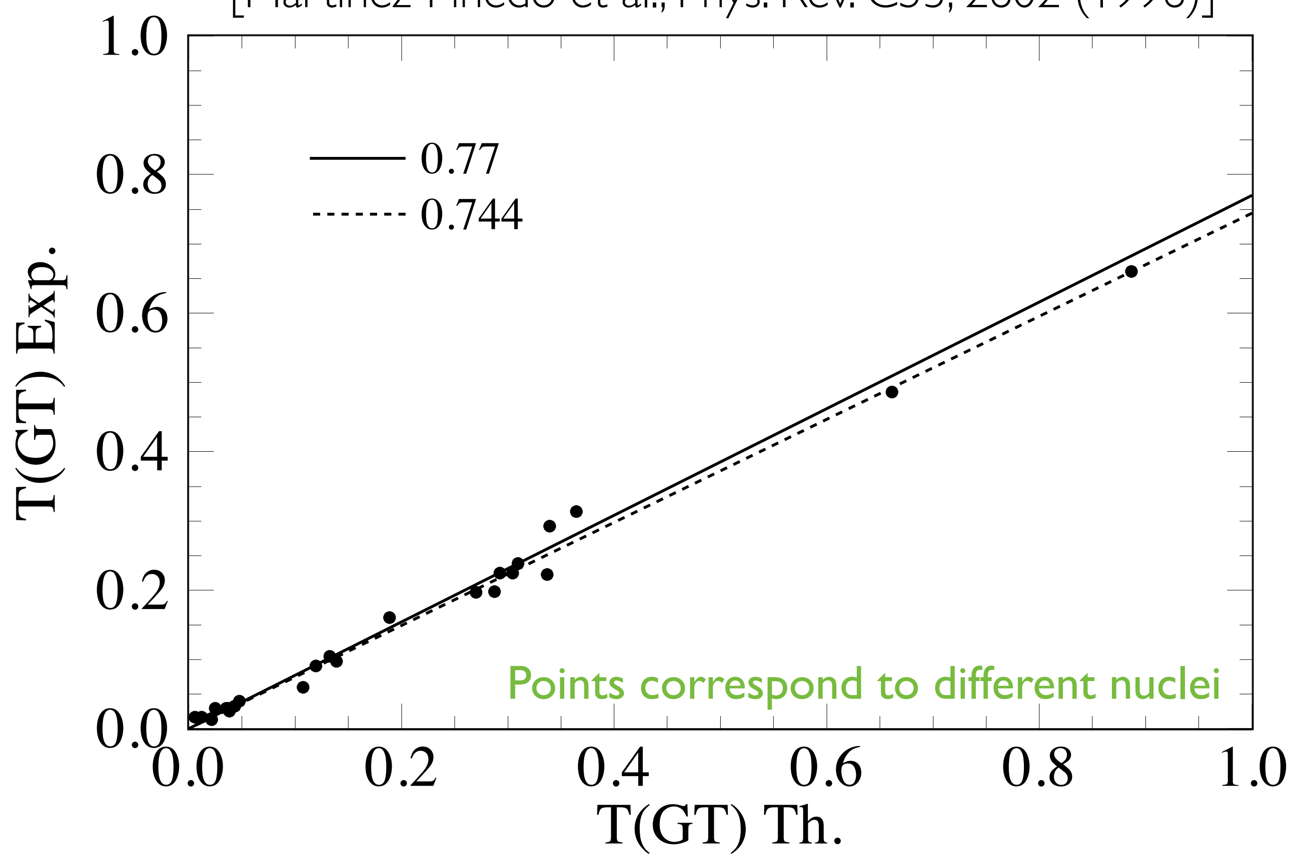


Is the spread of results representative of the true uncertainty?

Gamow-Teller: axial charge in nuclei

- Gamow-Teller transitions in nuclei are a stark example of problems
- Well measured
- Best nuclear structure calculations are systematically off by 20–30%
  - Large range of nuclei (30<A<60) where spectrum is well described
  - QRPA, shell-model,...
  - Correct for it by "quenching" axial charge in nuclei ...

[Martinez-Pinedo et al., Phys. Rev. C53, 2602 (1996)]

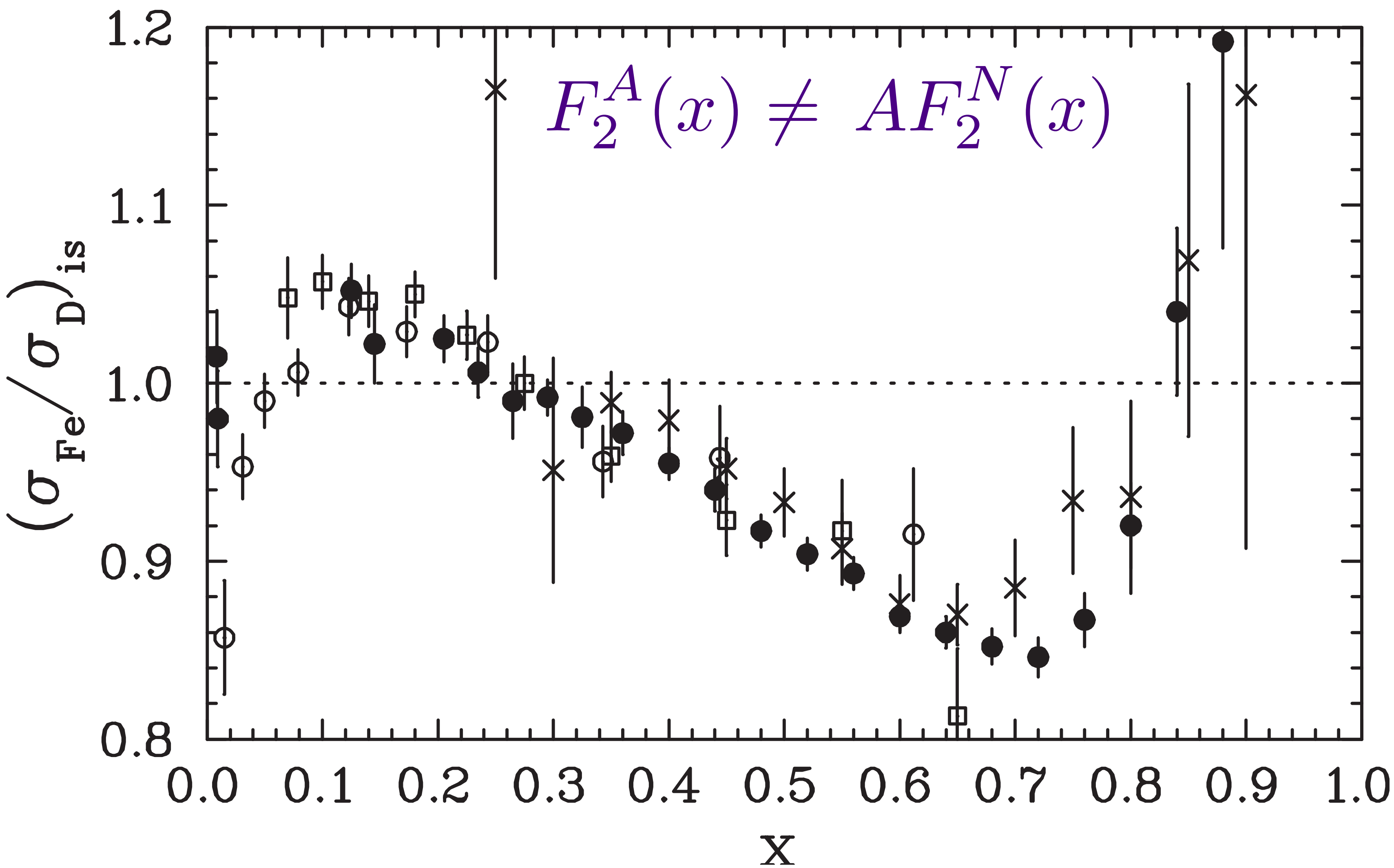


$$T(GT) \sim \sqrt{\sum_f \langle \boldsymbol{\sigma} \cdot \boldsymbol{\tau} \rangle_{i \to f}}$$

$$\langle \boldsymbol{\sigma\tau} \rangle = \frac{\langle f || \sum_k \boldsymbol{\sigma}^k \boldsymbol{t}^k_{\pm} || i \rangle}{\sqrt{2J_i + 1}}$$

The EMC effect

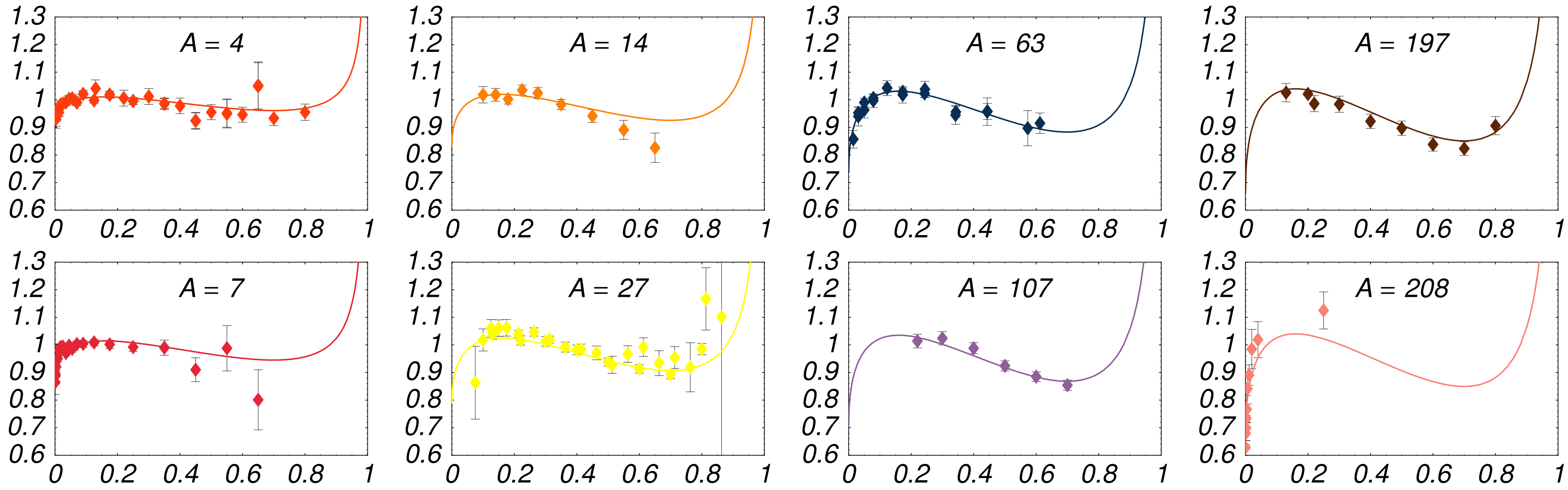
- 1983: DIS on Fe target [EMC]



- Proton structure modified in a nuclear environment

Dependence on A

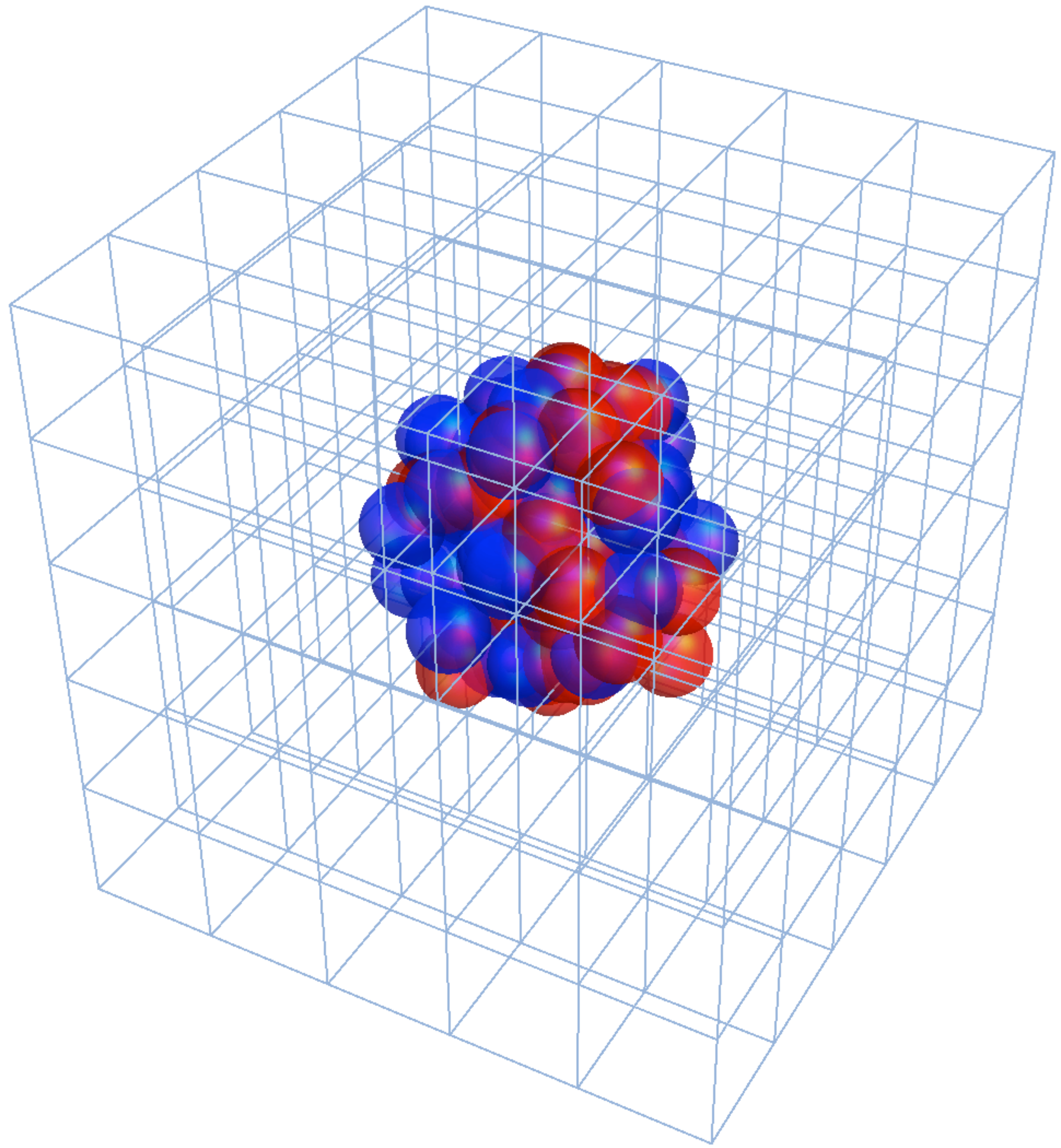
- Large nuclear effects ~ 30%
- Over last 30 years: studies of target dependence



- No convincing microscopic understanding of its origin (EMC = Every Model is Cool)
  - Little predictive power

LQCD to the rescue?

- Nuclear physics is Standard Model physics
  - ... so calculate ab initio!



Nuclei: an (exponentially hard)^2 problem

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$$\stackrel{t\to\infty}{\longrightarrow} \# \exp(-M_{Pb} t)$$

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- Complexity: number of contractions = (A+Z)!(2A-Z)!

$$a_i^\dagger(t_1)a_j^\dagger(t_1)a_j(t_1)a_i(t_1)a_i^\dagger(t_2)a_j^\dagger(t_2)a_j(t_2)a_i(t_2)$$

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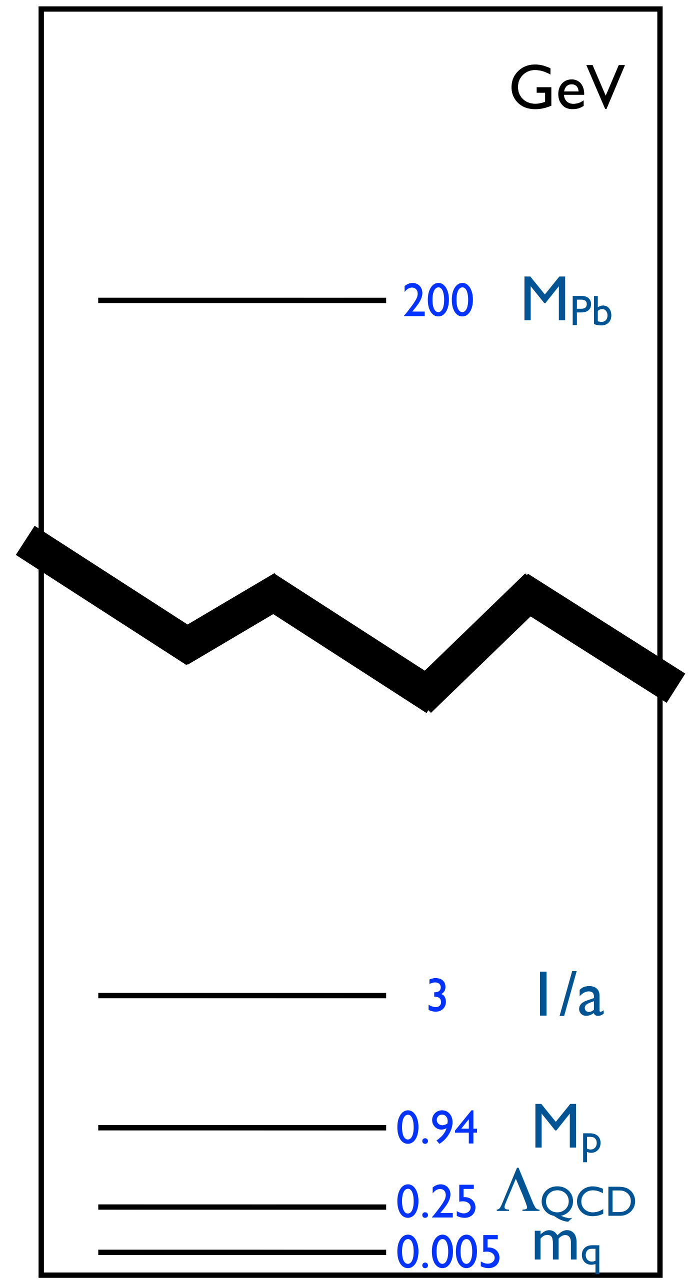
- Dynamical range of scales: requires care with numerical precision



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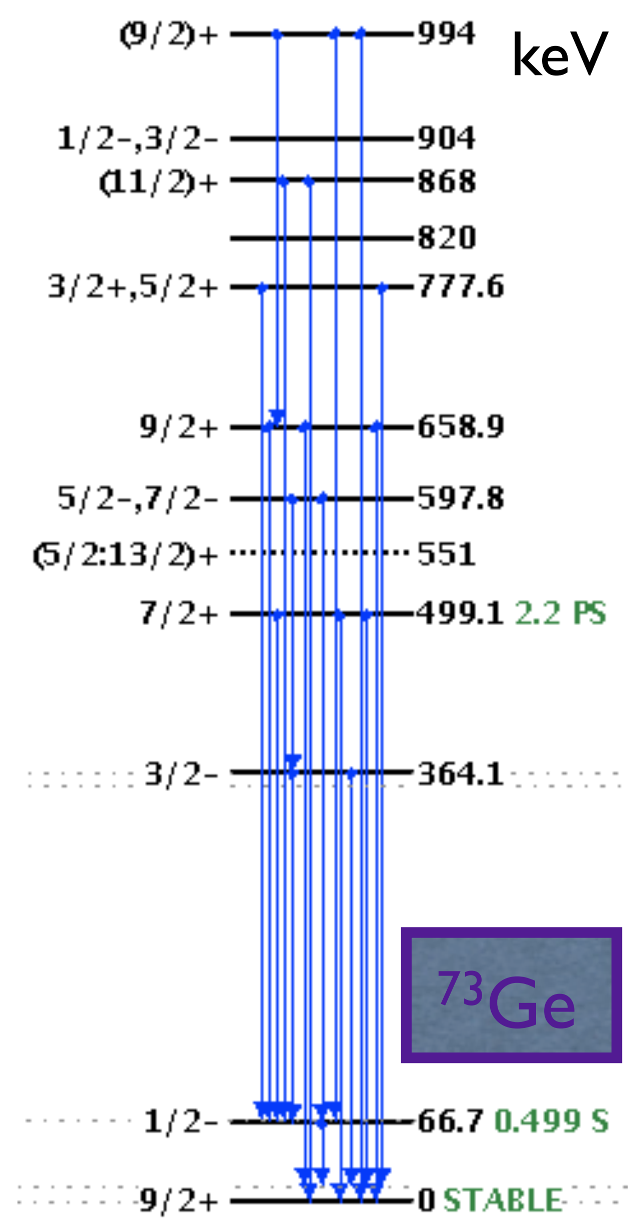

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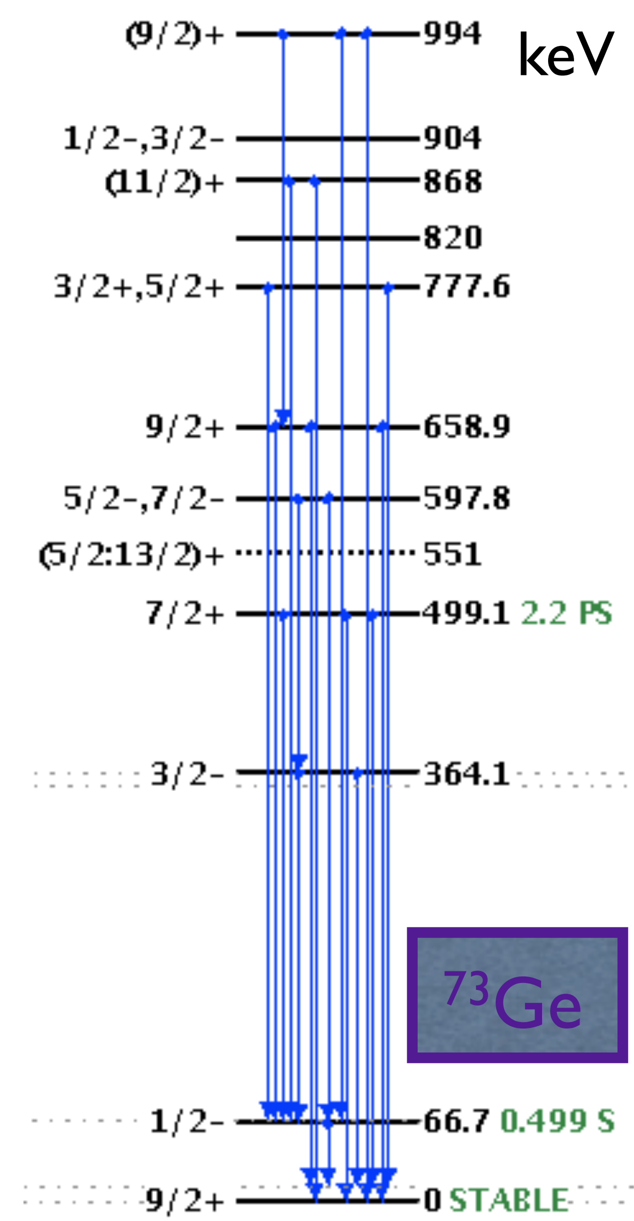
- Importance sampling: statistical noise exponentially increases with A



The trouble with baryons

[Lepage '89]

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- Importance sampling of QCD functional integrals
  ➤ correlators determined stochastically

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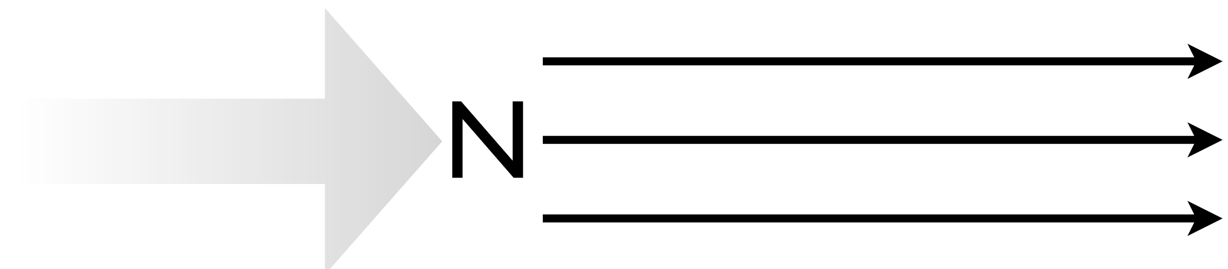

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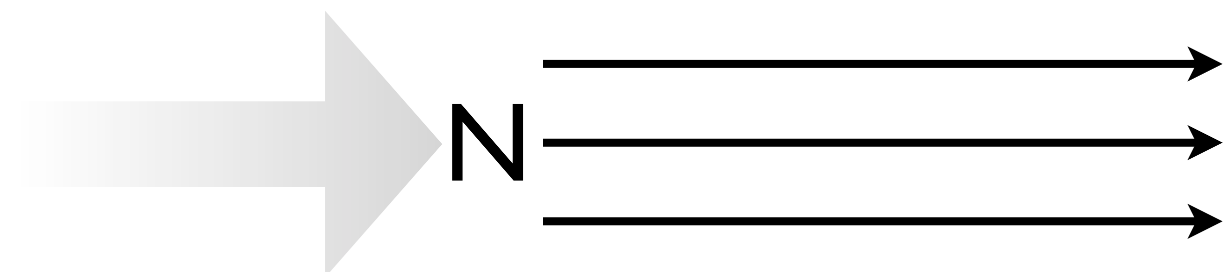

  - Variance determined by

  $$\sigma^2(C) = \langle C C^\dagger \rangle - |\langle C \rangle|^2$$

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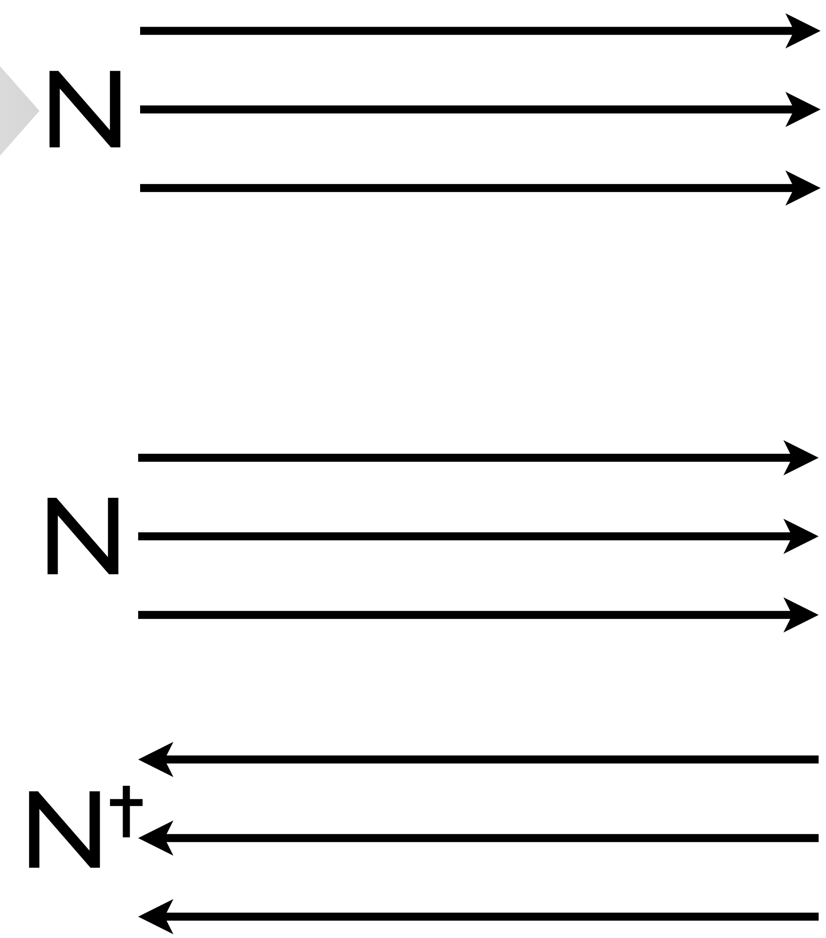

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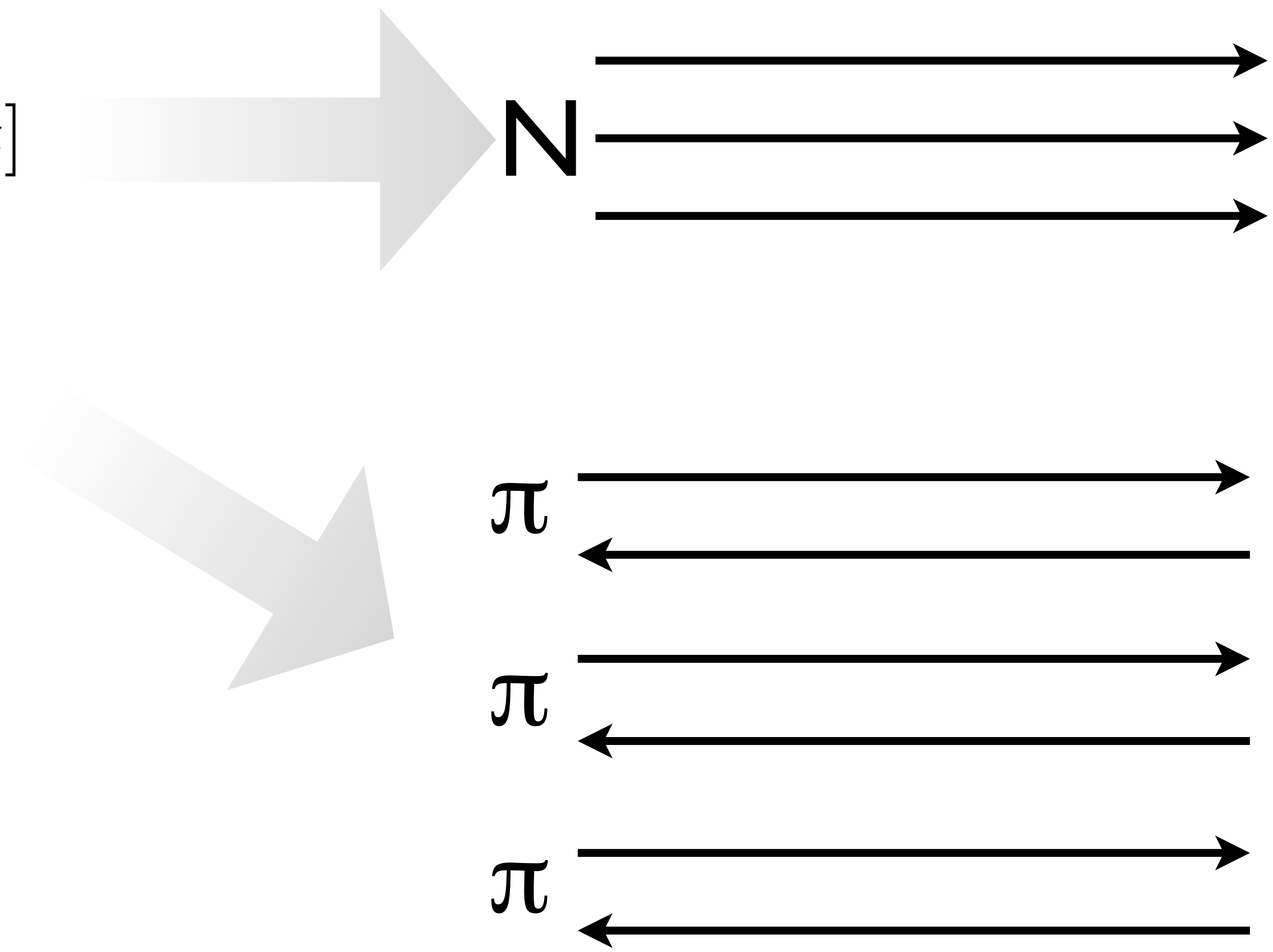

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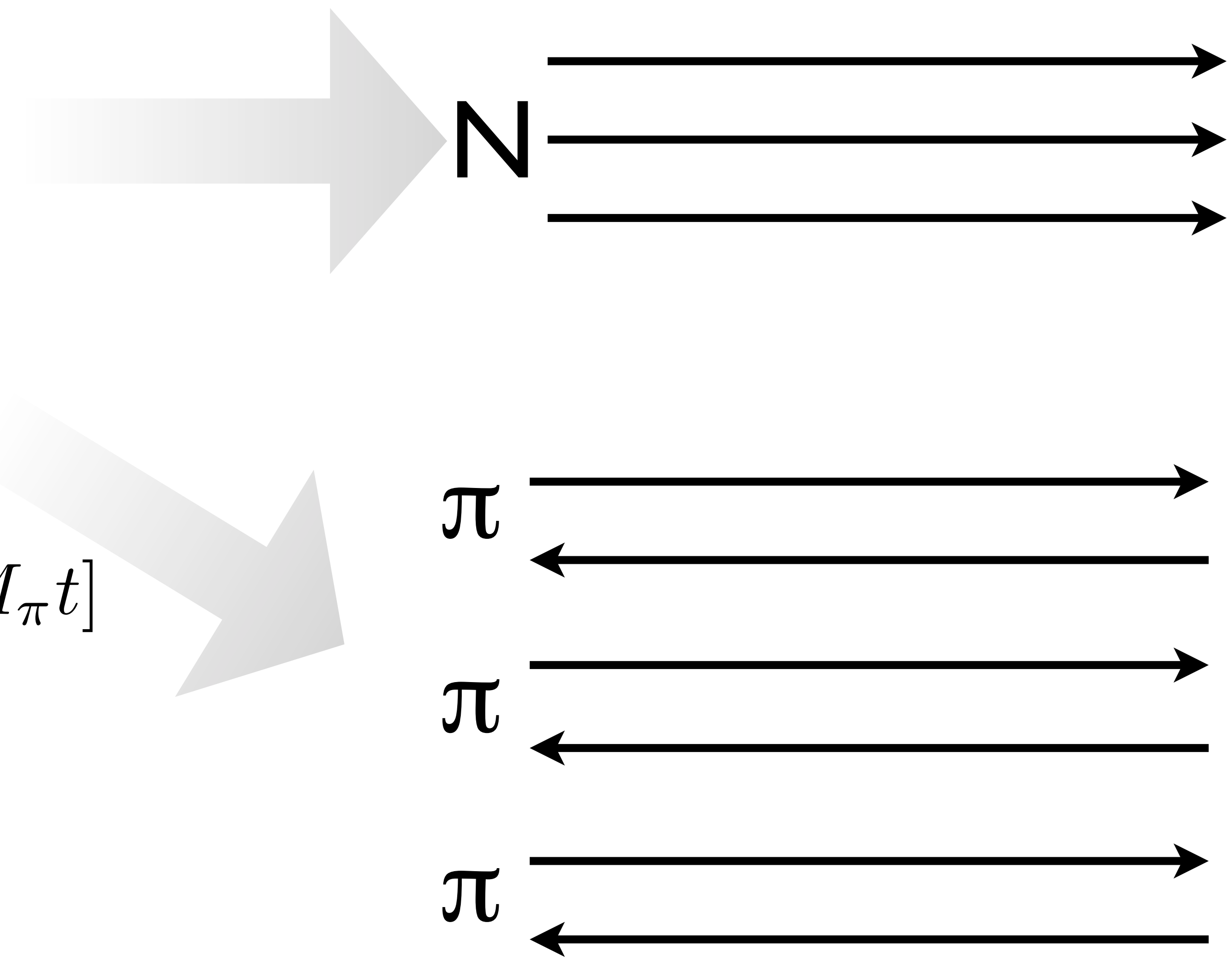

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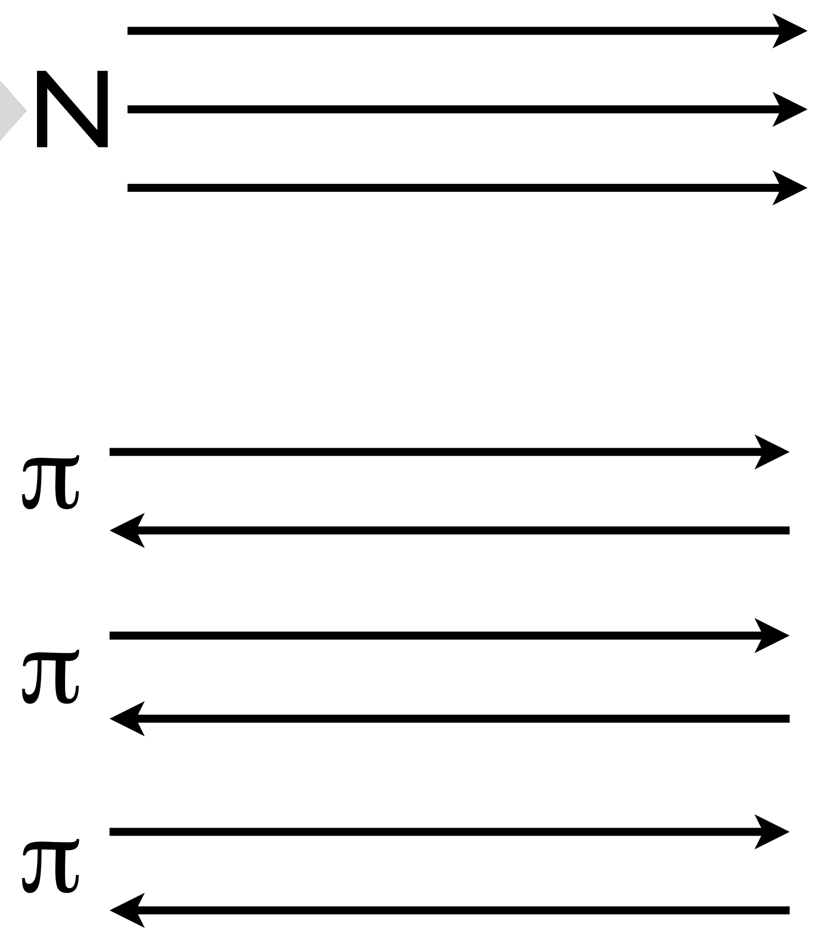

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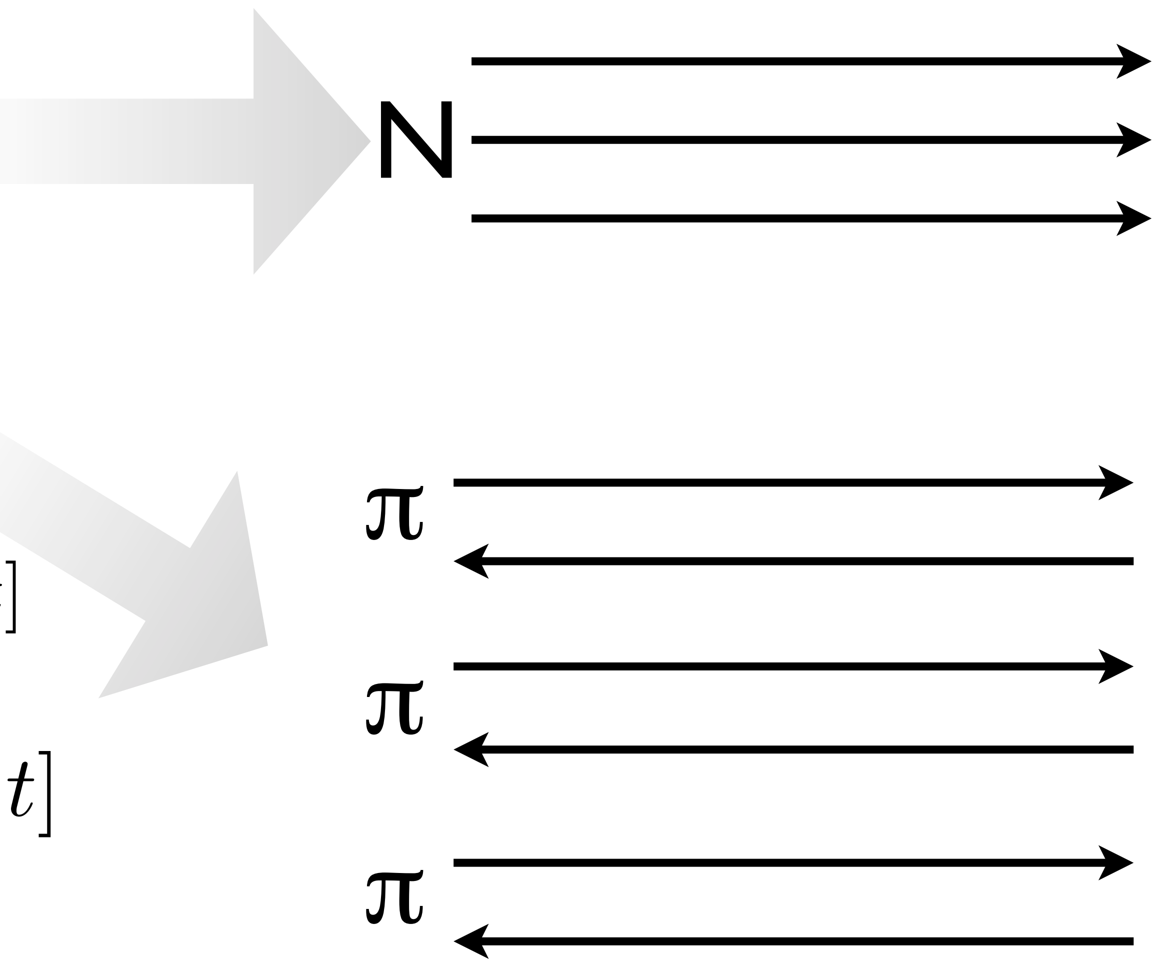

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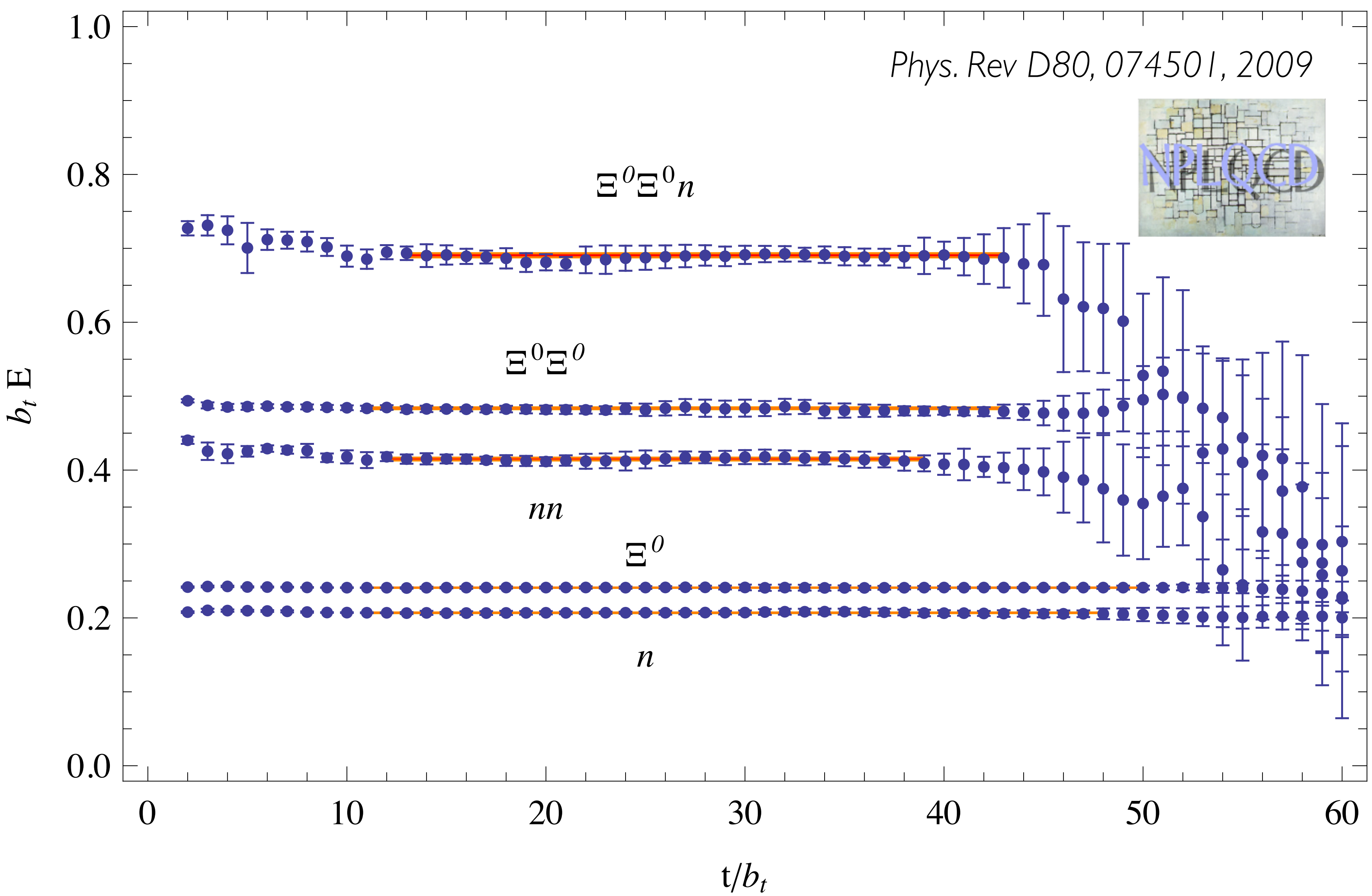
- For nucleus A:

$$\frac{\text{signal}}{\text{noise}} \sim \exp\left[-A(M_N - 3/2 m_\pi) t\right]$$

[Lepage '89]

The trouble with baryons

High statistics study using anisotropic lattices (fine temporal resolution)



@ m_π = 390 MeV

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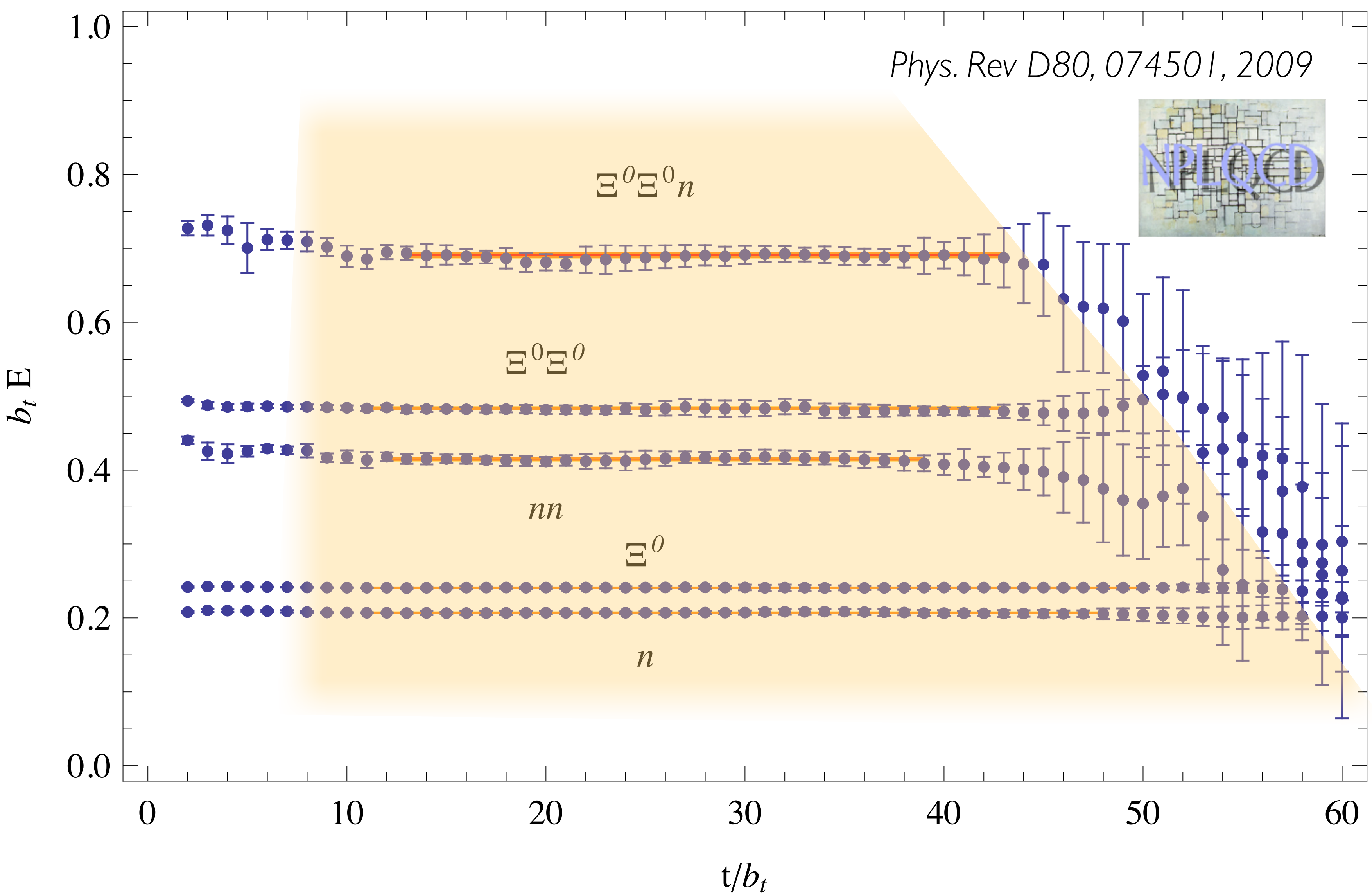

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Golden window of time-slices where signal/noise const

No? trouble with baryons

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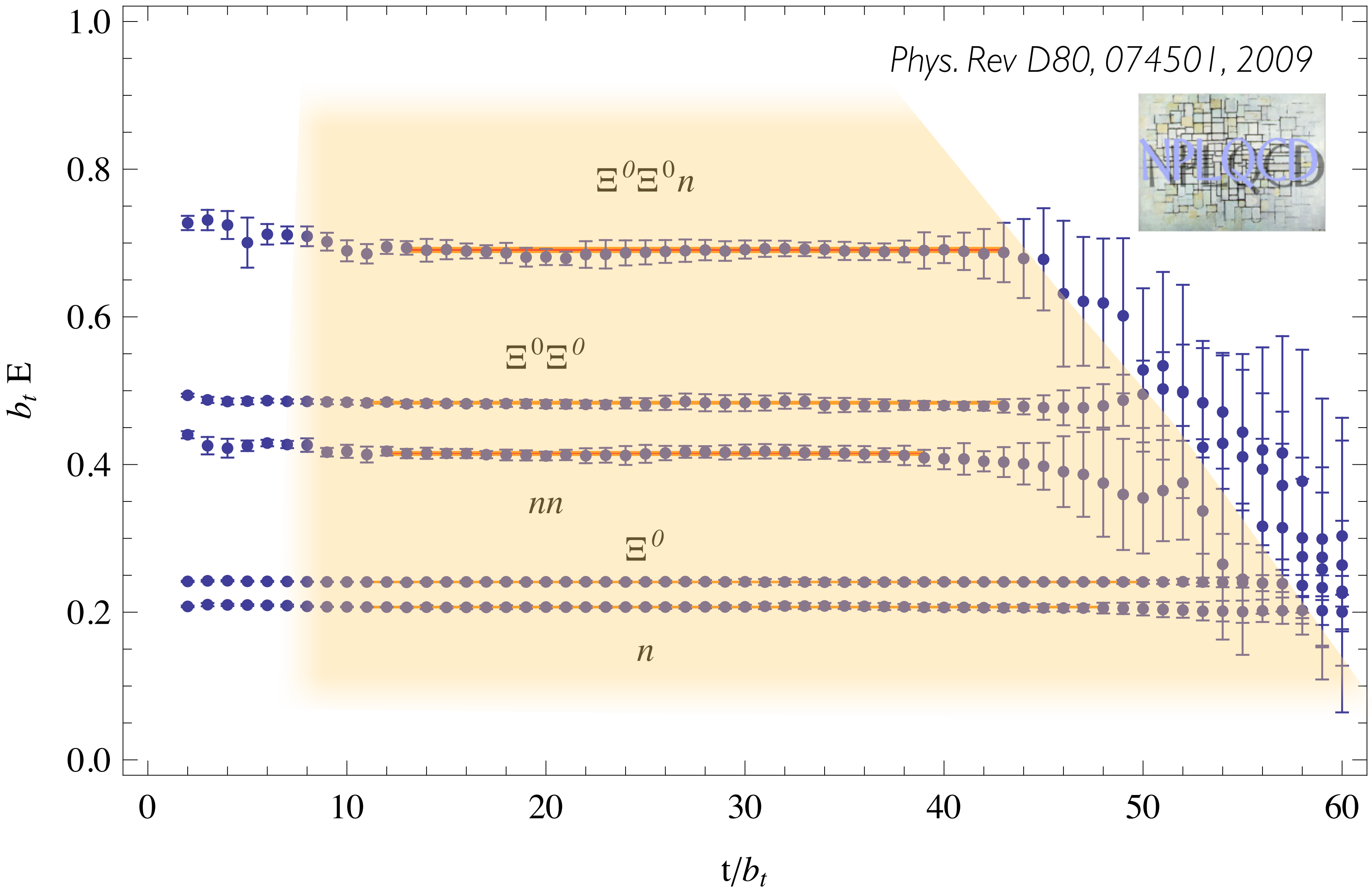

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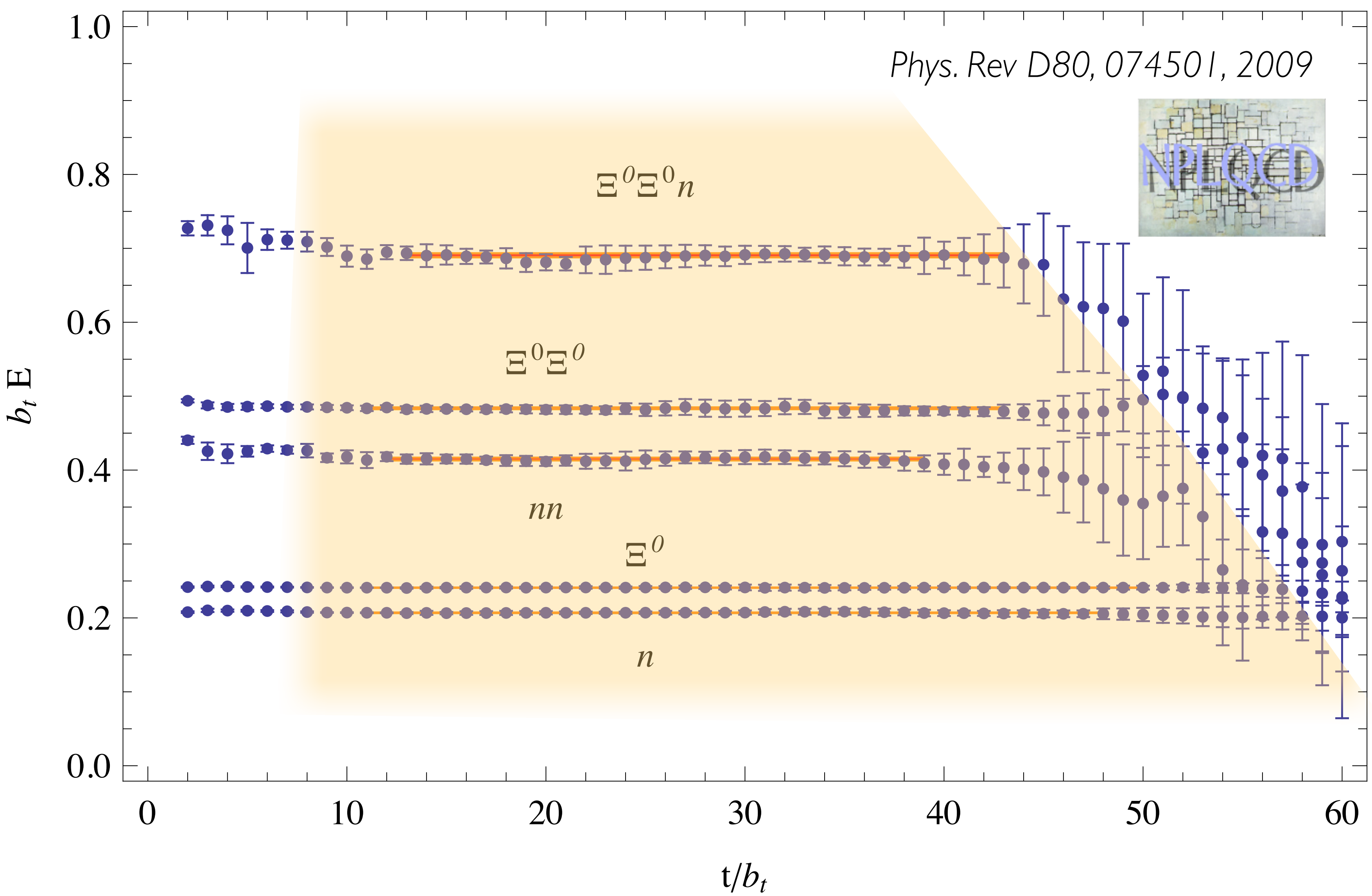

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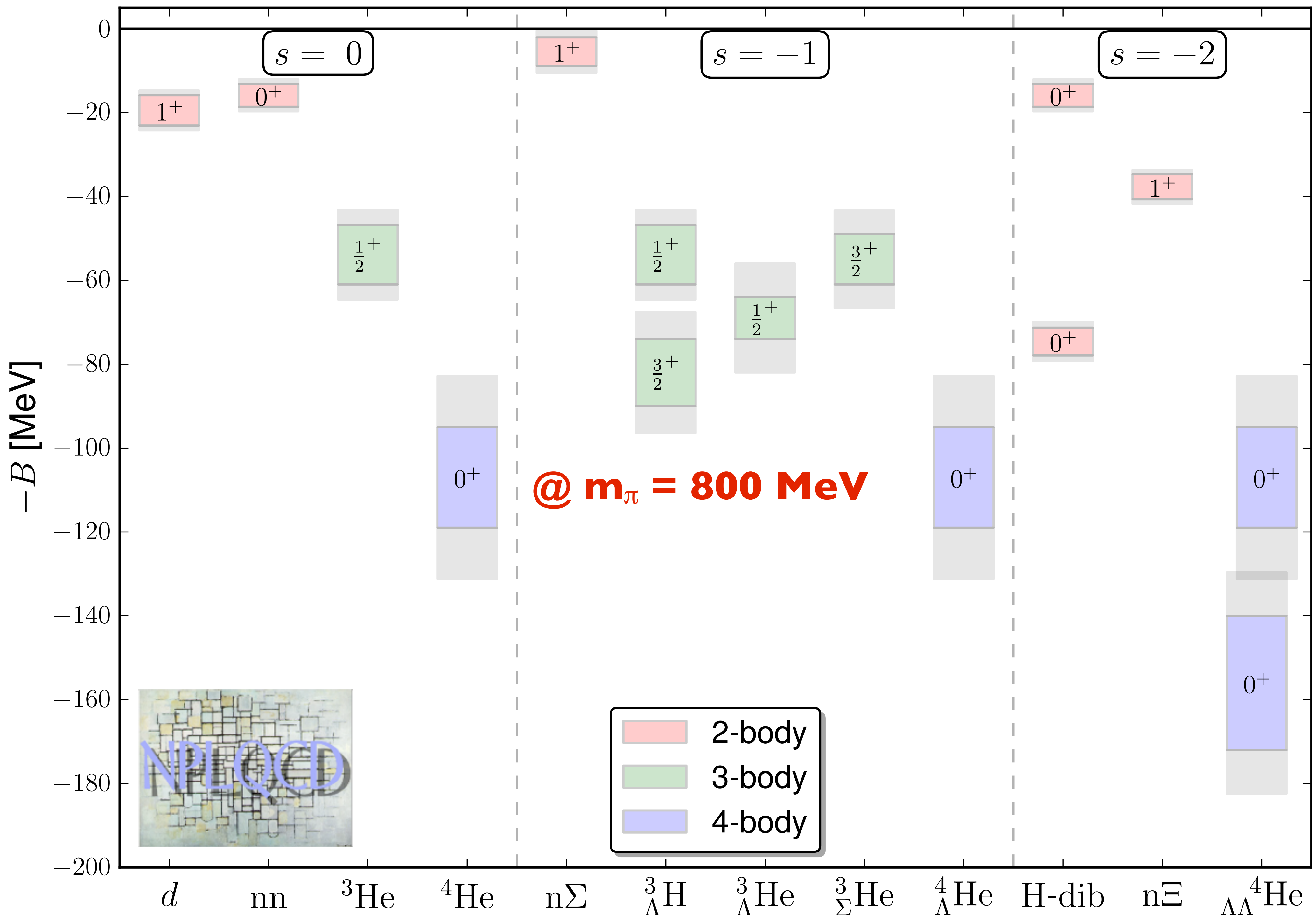
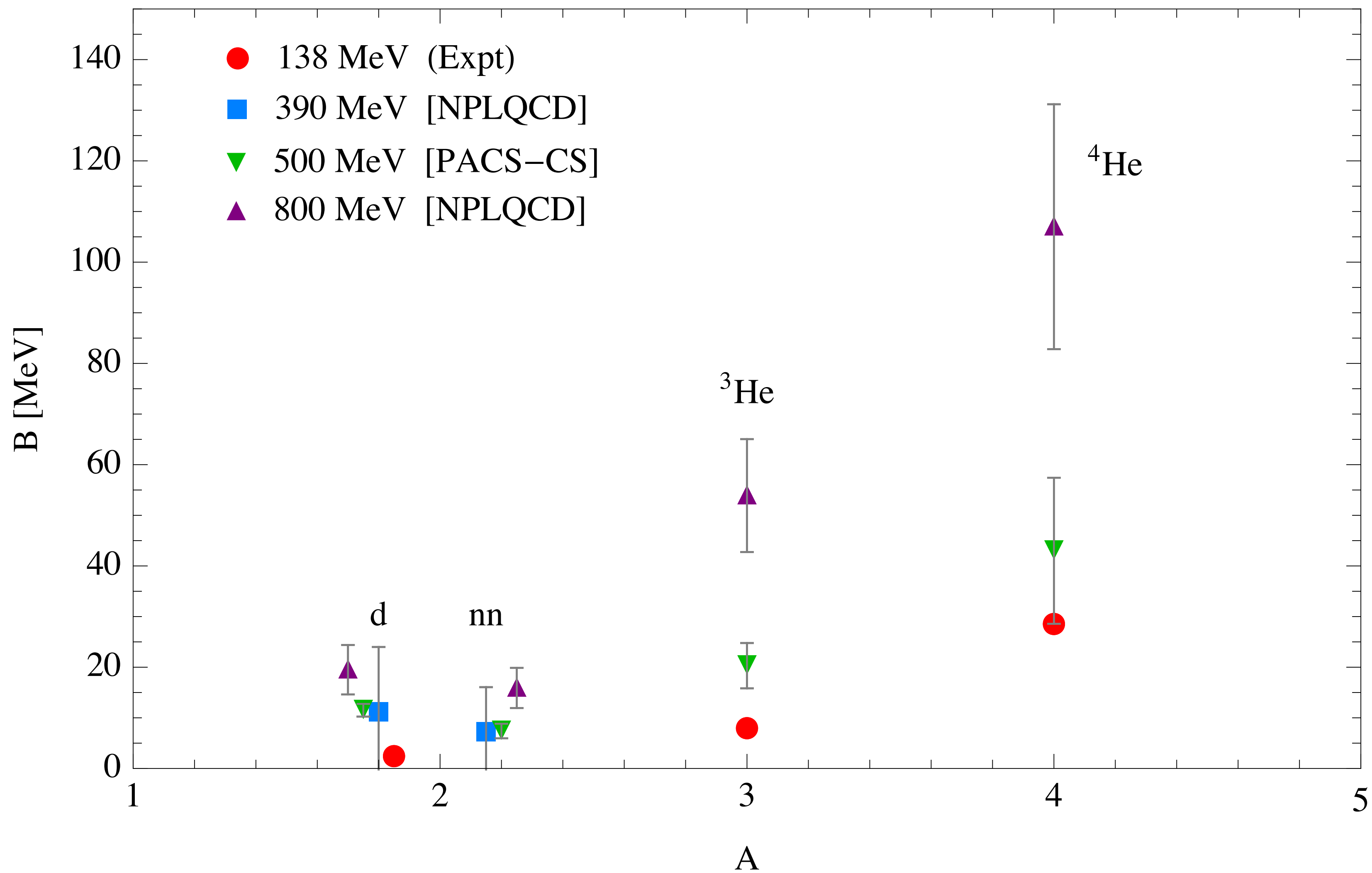
Interpolator choice can be used to suppress noise

Nuclei (A=2,3,4)



NPLQCD Phys.Rev. D87 (2013), 034506

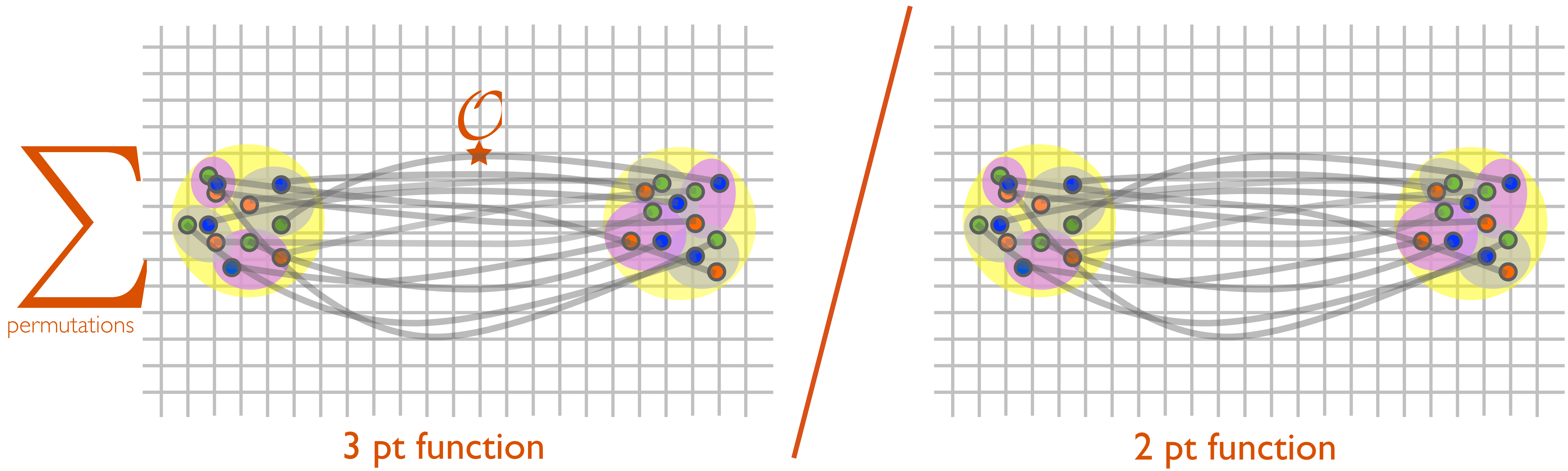
QCD Periodic Table



- Light nuclei (A<6) will be feasible at the physical quark mass in the near future
- Interesting progress with larger nuclei (A=4,8,12,...) but still a major challenge [WD, Orginos Phys.Rev. D87 (2013) 114512]

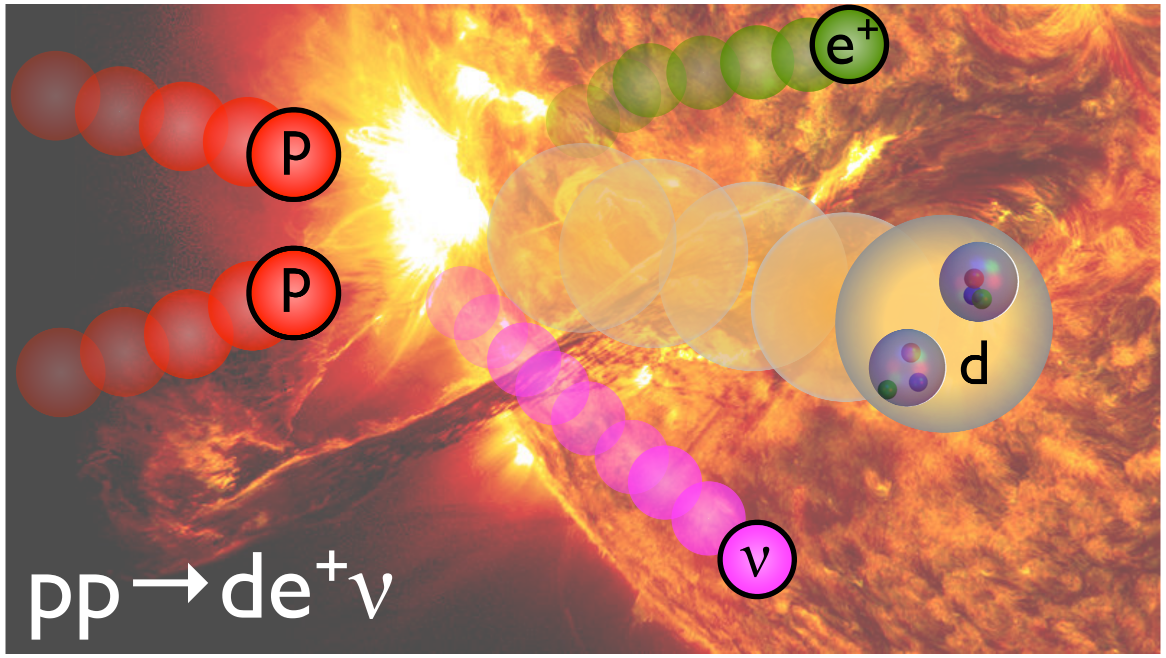
Nuclear matrix elements

- Calculations of matrix elements of currents in light nuclei just beginning
- For deeply bound nuclei, use the same techniques as for single hadron matrix elements



- For near threshold states, need to be careful with volume effects

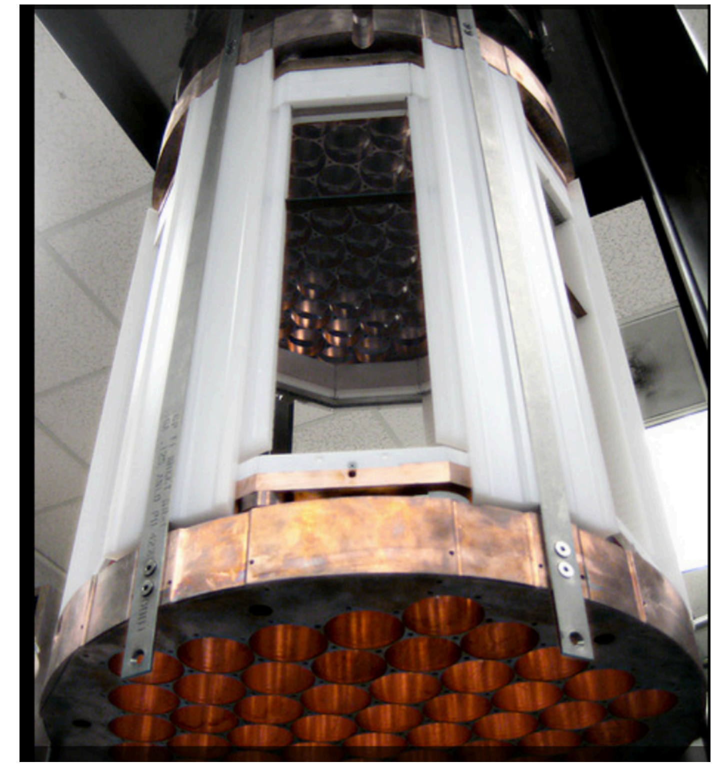
Nuclear matrix elements



1. Axial coupling to NN system
   - pp fusion: "Calibrate the sun"
   - Muon capture: MuSun @ PSI
   - $d\nu \rightarrow n\,n\,e^+$: SNO
2. Twist-2 operators: eg EMC effect

   $\langle N,Z|\bar{q}\gamma_{\{\mu_0}D_{\mu_1}\ldots D_{\mu_n\}}q|N,Z\rangle$
   - Velocity dependent DM interactions
   - Proof of principle (moments of pion PDF in pion gas) [WD, HW Lin 1112.5682]

Nuclear sigma terms

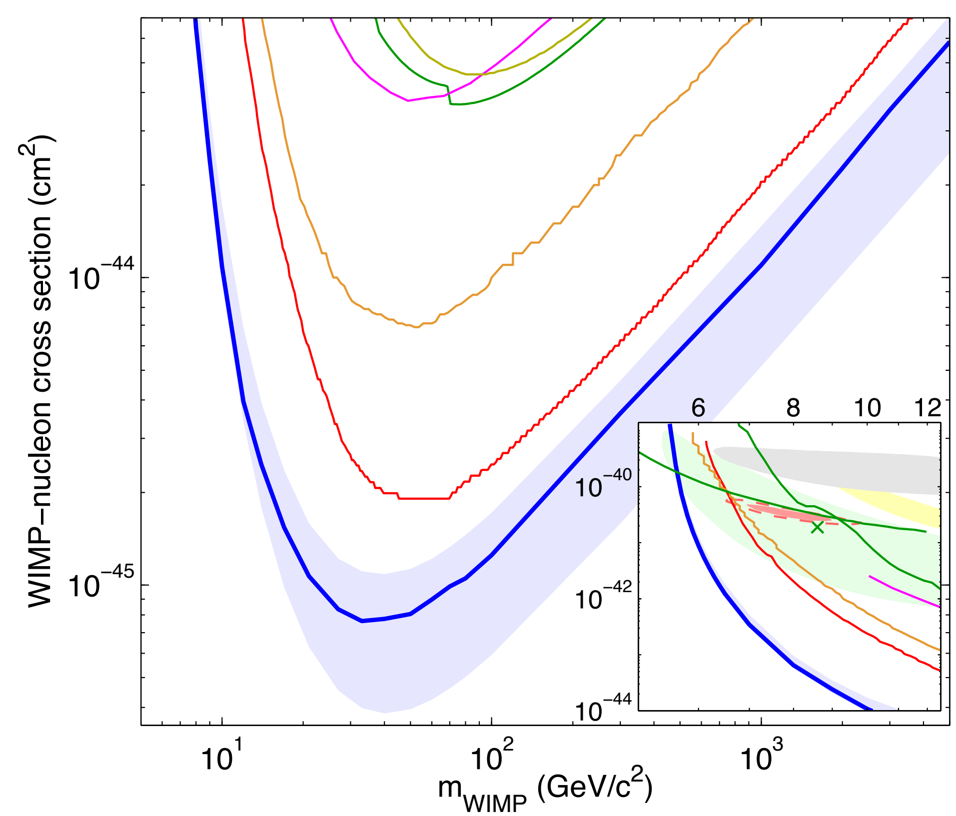


- Dark matter direct detection experiments look for DM interactions with nuclei (Si, Xe, ...)

- One possible interaction is through scalar exchange

$$\mathcal{L} = \frac{G_F}{2} \sum_q a_S^{(q)} (\overline{\chi}\,\chi)(\overline{q}\,q)$$

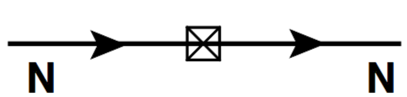
- Accessible via Feynman-Hellman theorem

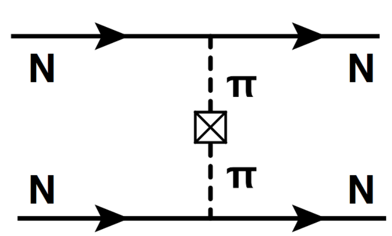


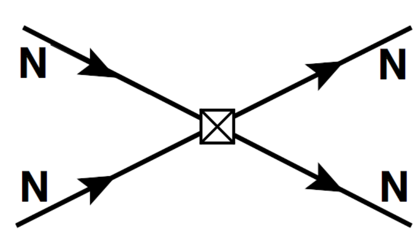
- At hadronic/nuclear level

$$\mathcal{L} \to G_F\, \overline{\chi}\chi \left(\frac{1}{4}\langle 0|\overline{q}q|0\rangle \ \mathrm{Tr}\left[a_S\Sigma^\dagger + a_S^\dagger\Sigma\right] \ + \ \frac{1}{4}\langle N|\overline{q}q|N\rangle N^\dagger N \mathrm{Tr}\left[a_S\Sigma^\dagger + a_S^\dagger\Sigma\right] \right.$$
$$\left. - \ \frac{1}{4}\langle N|\overline{q}\tau^3 q|N\rangle \left(N^\dagger N \mathrm{Tr}\left[a_S\Sigma^\dagger + a_S^\dagger\Sigma\right] \ - \ 4N^\dagger a_{S,\xi} N\right) \ + \ \ldots \right)$$

- Contributions:







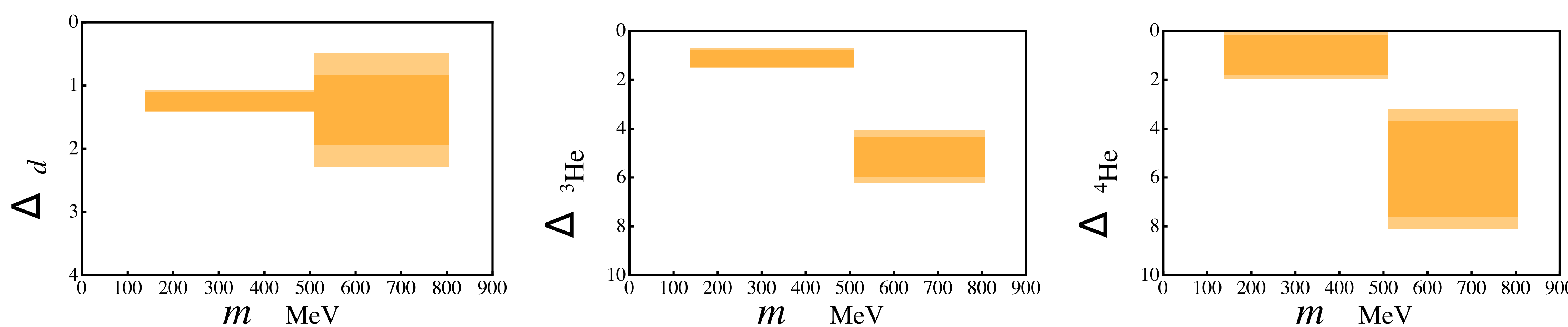
Nuclear sigma terms

- Previous work suggested scalar-isoscalar dark matter couplings to nuclei have O(50%) uncertainty arising from MECs [Prezeau et al 2003]

- Quark mass dependence of nuclear binding energies bounds such contributions

$$\delta\sigma_{Z,N} = \frac{\langle Z,N(\mathrm{gs})|\ \overline{u}u + \overline{d}d|Z,N(\mathrm{gs})\rangle}{A\ \langle N|\ \overline{u}u + \overline{d}d|N\rangle} - 1 \quad = -\frac{1}{A\sigma_N}\frac{m_\pi}{2}\frac{d}{dm_\pi}B_{Z,N}$$

  - Lattice calculations + physical point suggest such contributions are O(10%) or less for light nuclei

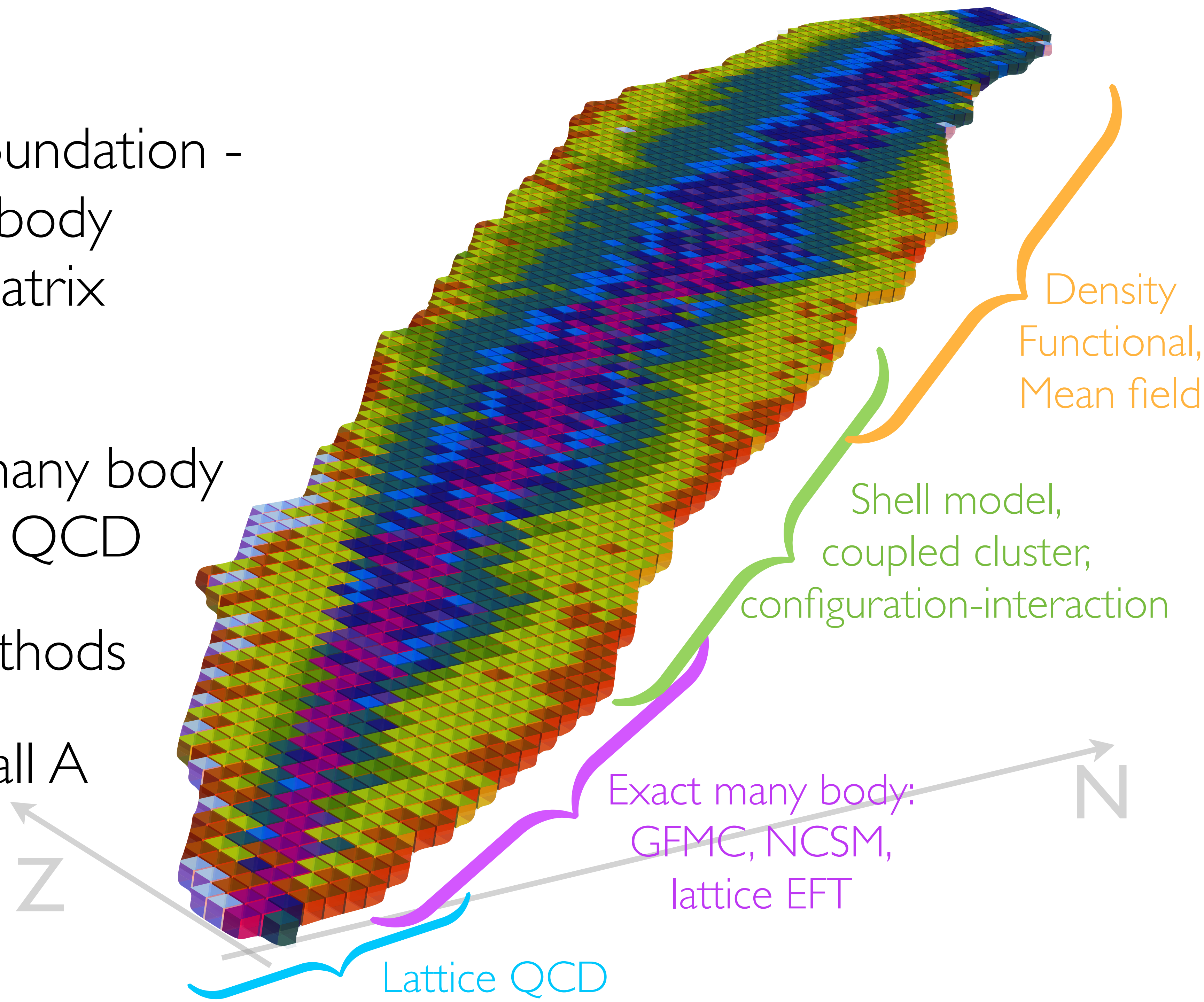


  - Admittedly crude approximation to derivative ... stay tuned

NPLQCD arXiv:1306.6939

Larger nuclei

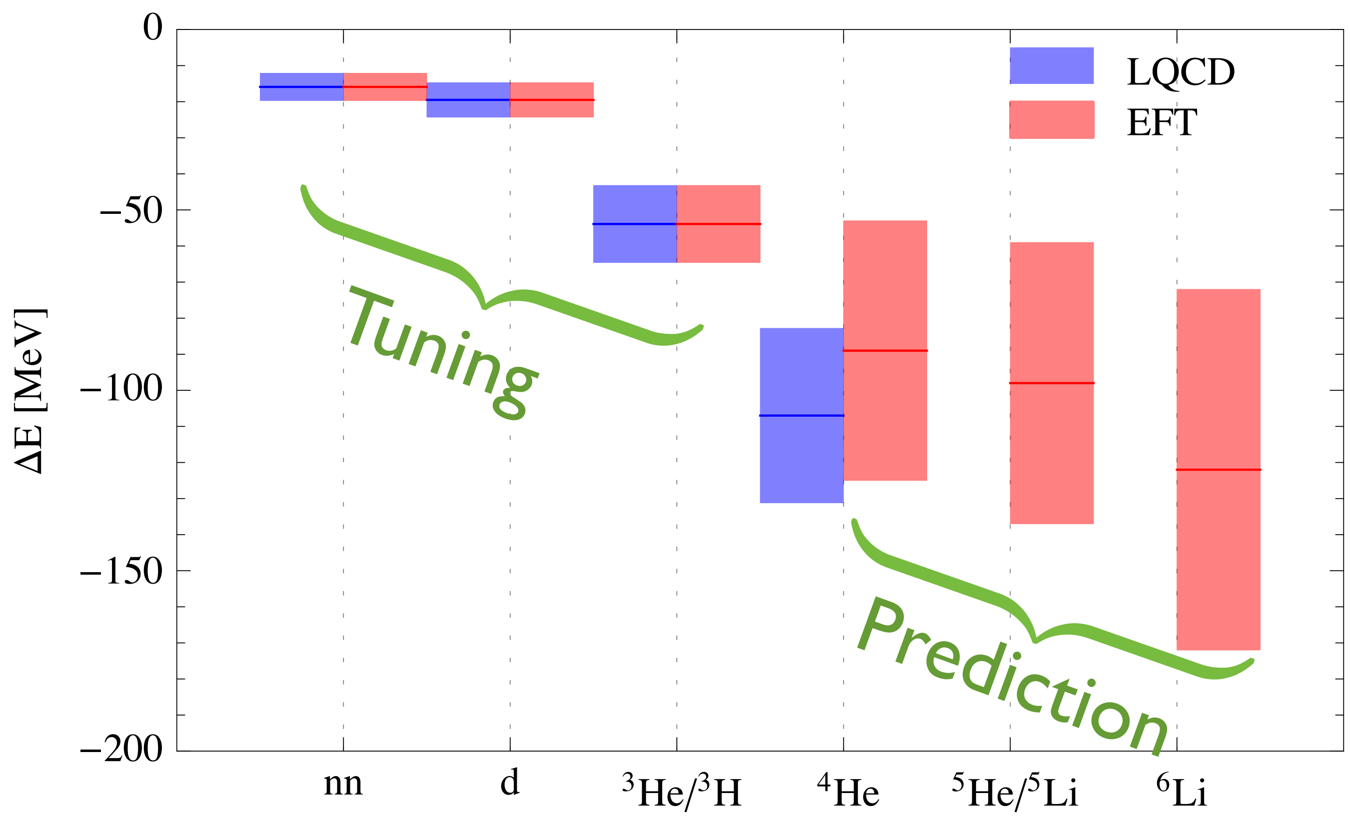
- A path to ab initio nuclear physics:
  - QCD forms a foundation - determines few body interactions & matrix elements
  - Match existing many body techniques onto QCD
  - Hierarchy of methods
- QCD: focus on small A
  - ... for now ...



Heavy quark universe

[Barnea, et al. 1311.4966]

- Already seeing LQCD and nuclear EFT coming together
- For heavy quarks, even spectroscopy requires QCD matching



- Equally important for matrix elements at the physical quark mass

Matrix elements: philosophy

- Provided the hierarchy of higher-body interactions persists into heavy nuclei, power counting of nuclear effective field theory:
  - 1-body currents are dominant
  - 2-body currents are sub-leading and higher-body currents are even less important
- Determine one body contributions from single nucleon/pion systems
- Determine few-body contributions from A=2,3,4...
- Use EFT and many body methods to extend LQCD results to large nuclei

Prospects and Outlook

- Properties and interactions of light nuclei represent an important opportunity for LQCD
    - Direct impact on NP of light nuclei
    - Input to/constraint on nuclear many-body methods can greatly improve NP of searches for BSM physics
    - Stay tuned

[FIN]

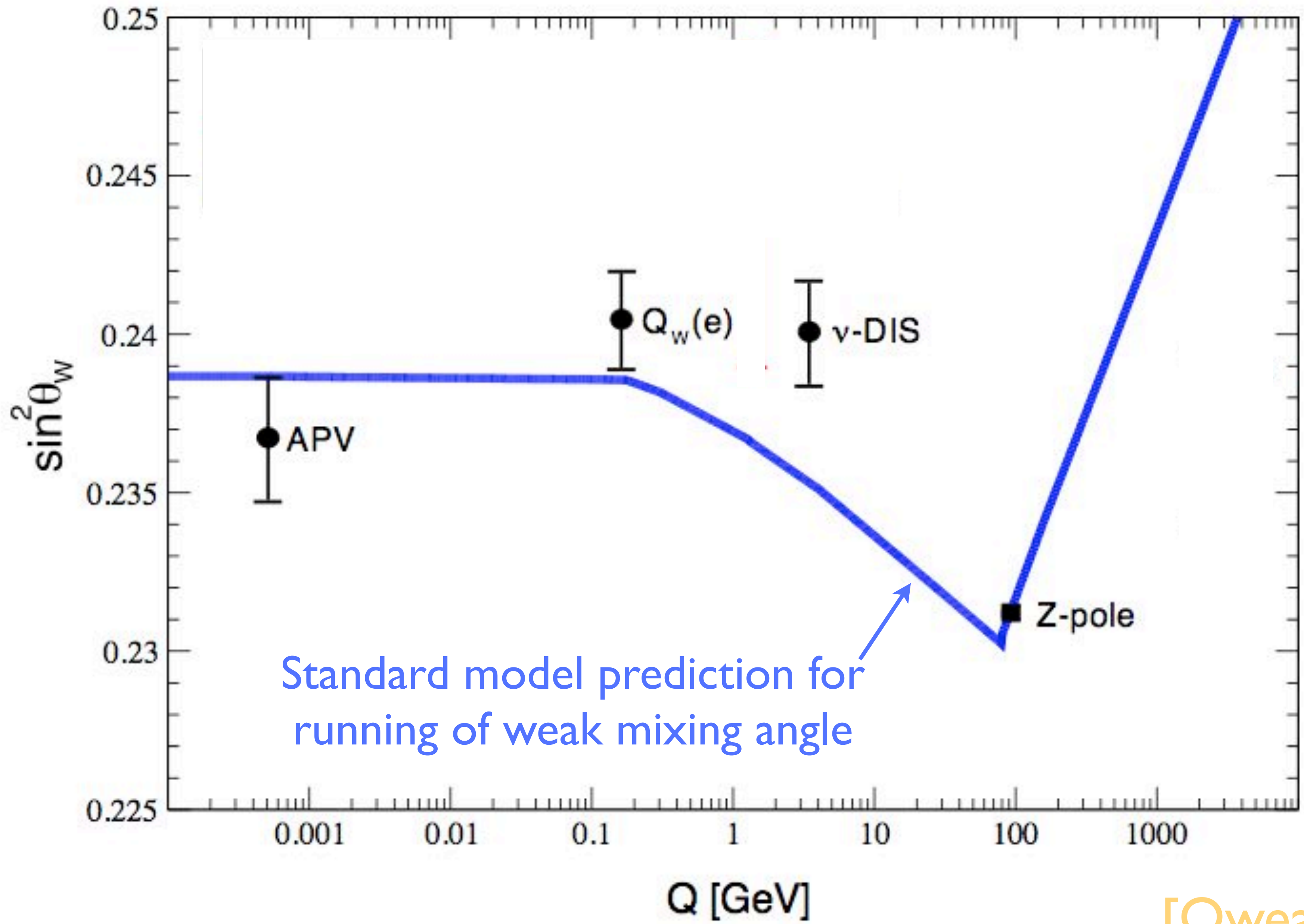
NuTeV anomaly: $\sin^2\theta_W$

- Neutrino deep-inelastic scattering
- Paschos-Wolfenstein relation:

$$R^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\overline{\nu} N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\overline{\nu} N}} = \frac{1}{2} - \sin^2\theta_W$$

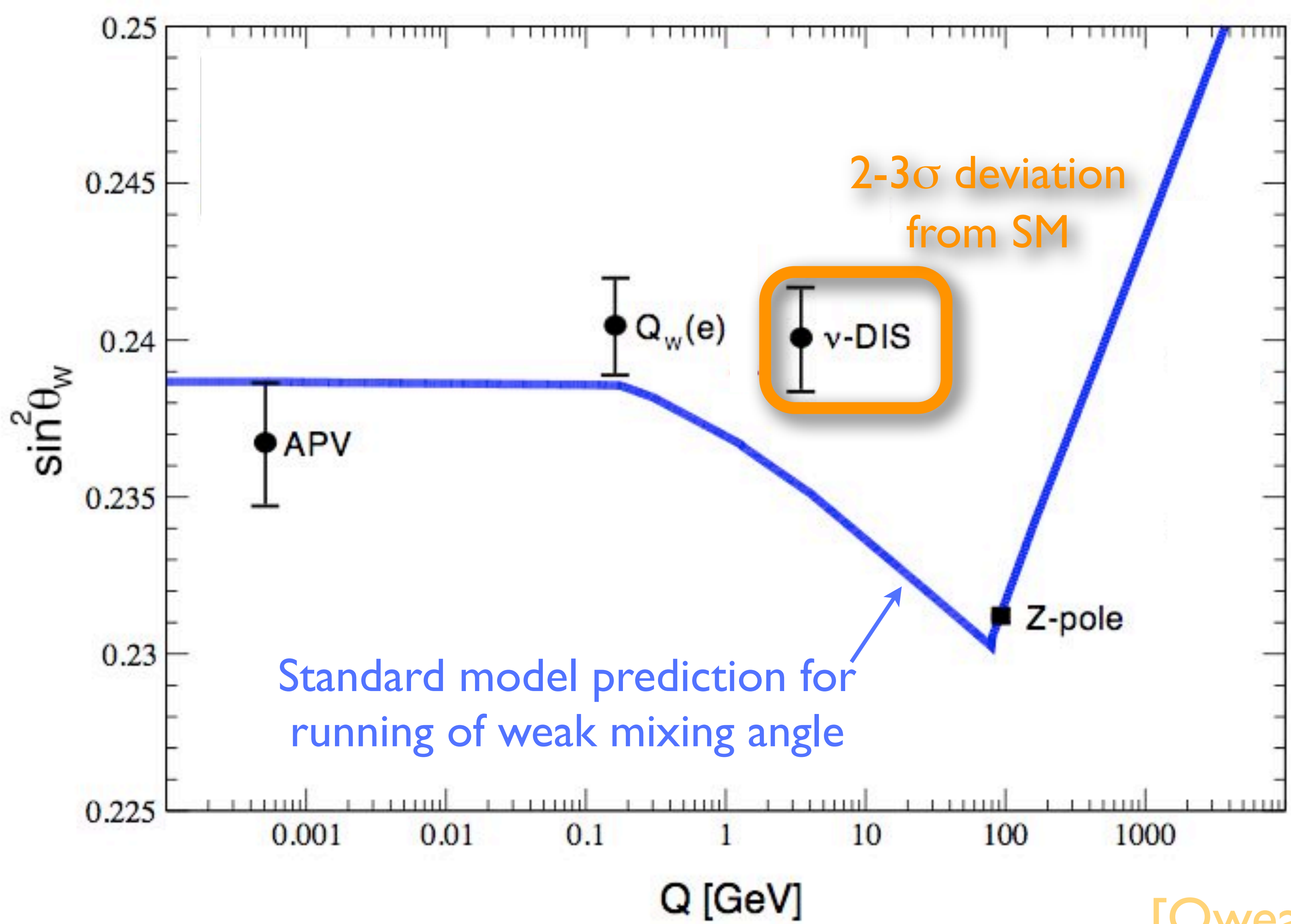
- NuTeV measure CC and NC neutrino scattering on steel target at Fermilab
- Extract the weak mixing angle

NuTeV anomaly: $\sin^2\theta_W$



[Qweak]

NuTeV anomaly: $\sin^2\theta_W$



[Qweak]

NuTeV anomaly: $sin^2\theta_W$

- Corrected Paschos-Wolfenstein relation:

$$R_A^- = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\overline{\nu} A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\overline{\nu} A}} = \frac{1}{2} - \sin^2\theta_W + \epsilon_v + \epsilon_n + \epsilon_s + \epsilon_c$$

Nuclear modifications
Non-isoscalarity
Strange quarks
Charm quarks

- NuTeV take some of this into account

- Many authors find significant reduction in NuTeV significance from hadronic/nuclear physics

EMC for light nuclei

- E03-103 experiment @ JLab
- High precision studies of DIS on light nuclei
- Size of EMC effect vs nuclear density
  - Nontrivial behaviour
- Correlated with strength of short range correlations
  [Weinstein *et al*, PRL. 106 (2011) 052301]