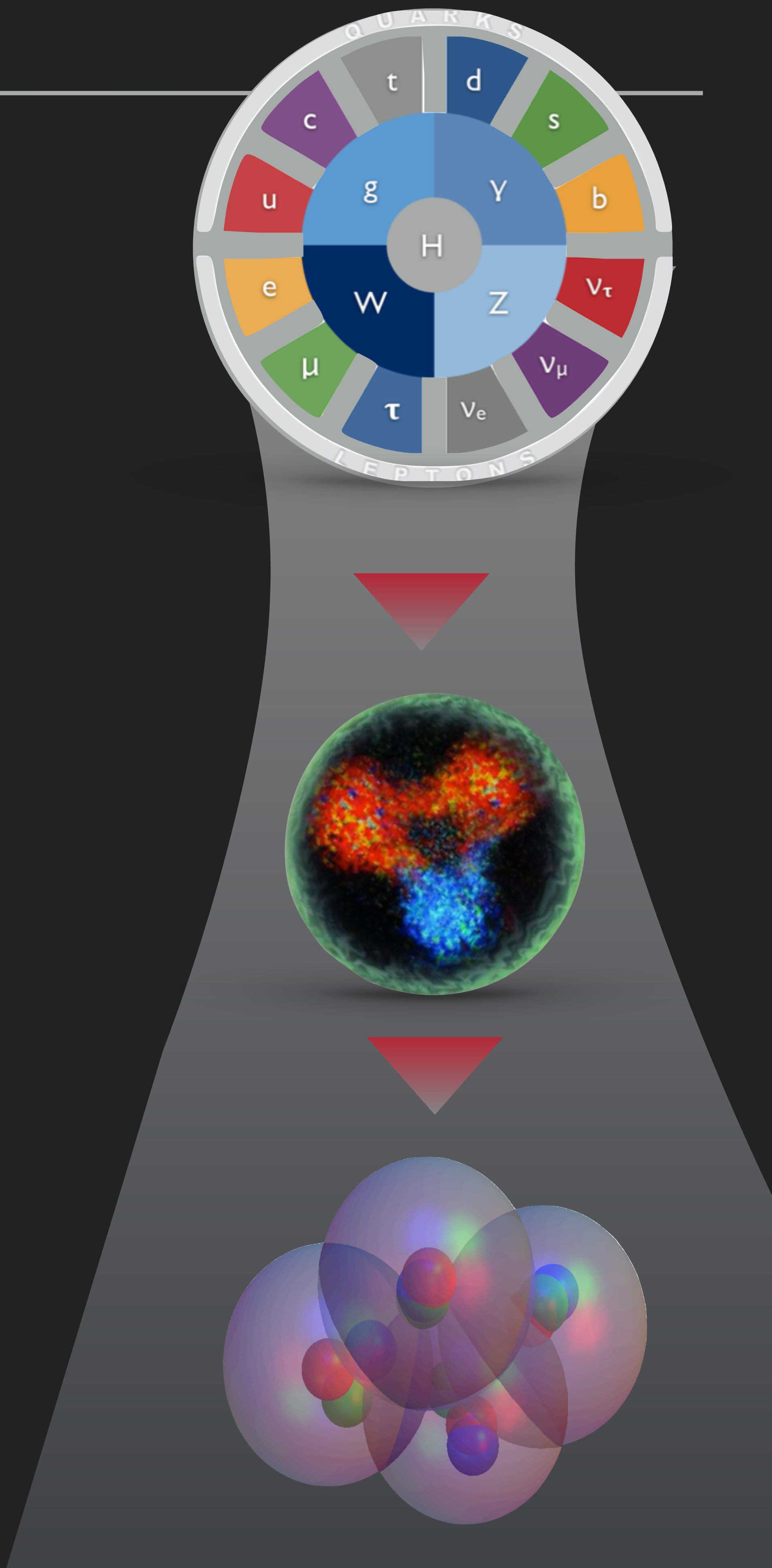
WILL DETMOLD MIT

MATRIX ELEMENTS IN LIGHT NUCLEI

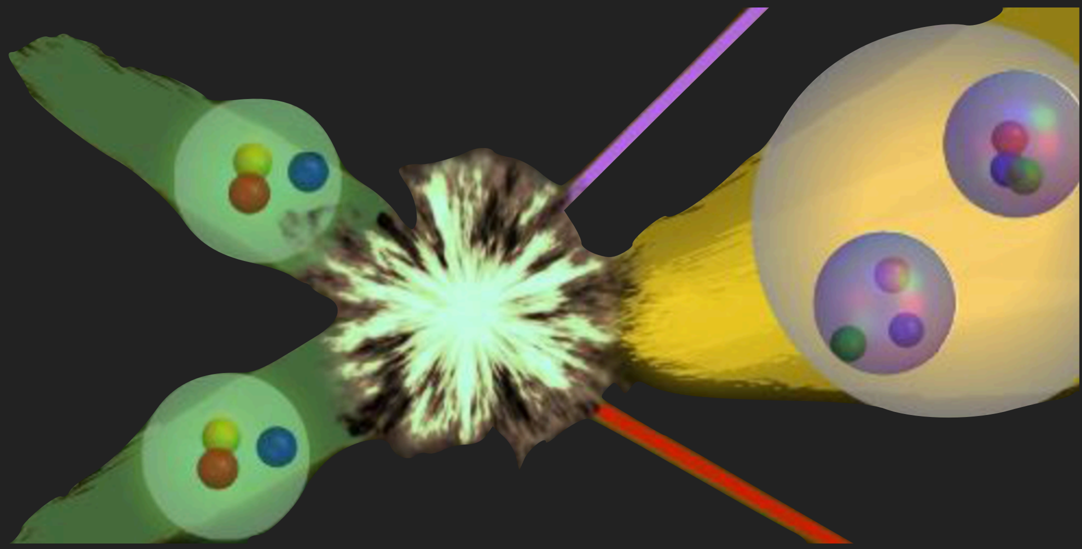
Lattice 2018, East Lansing, July 24th 2018

EMERGENCE OF NUCLEI

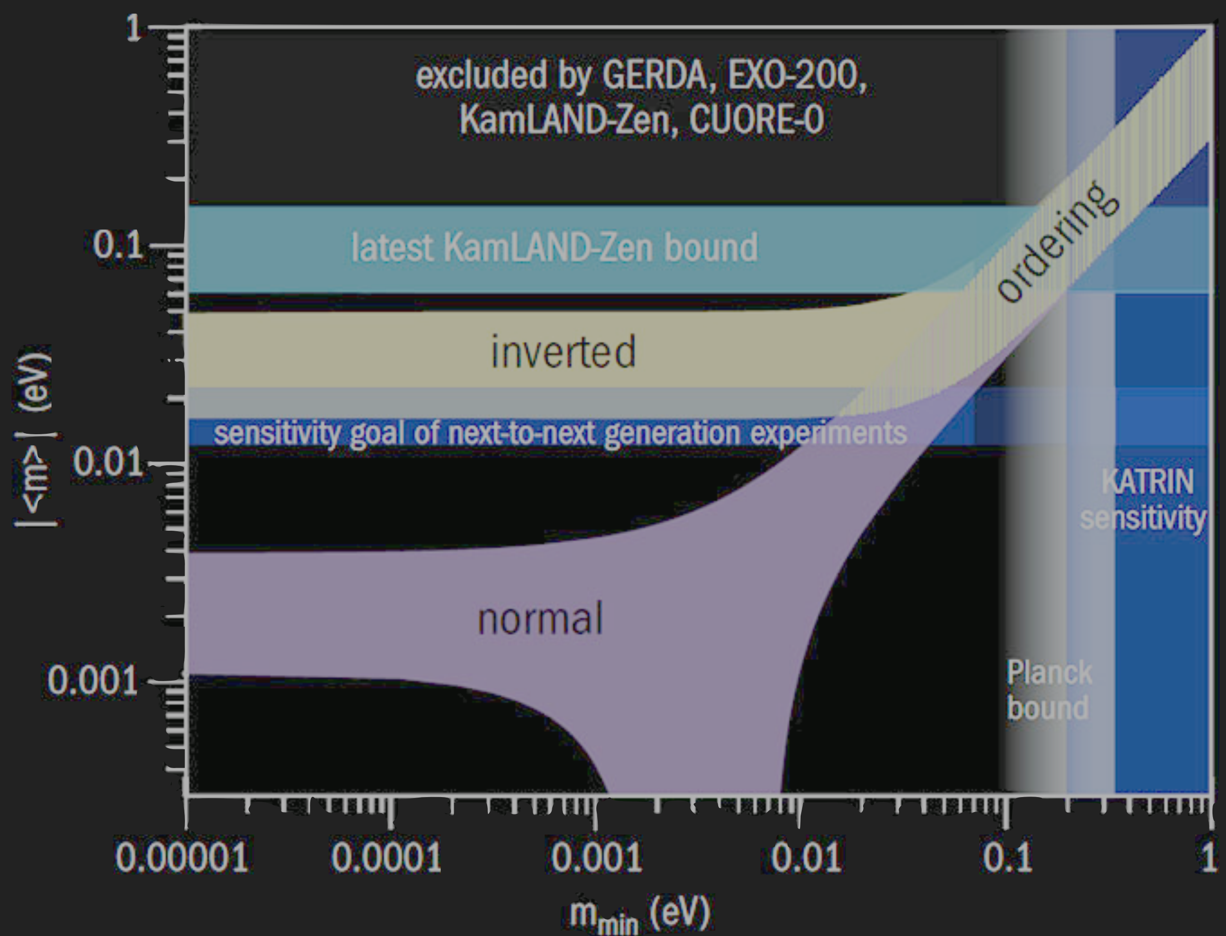
- QCD+EW encodes nuclear physics
- Computational challenge to see QCD produce nuclear physics
- Study emergence of layered complexity of nucleons and nuclei
- Input for intensity frontier experiments
    - Interactions of nuclei with external currents
    - Need lattice QCD calculations



ELECTROWEAK PROCESSES

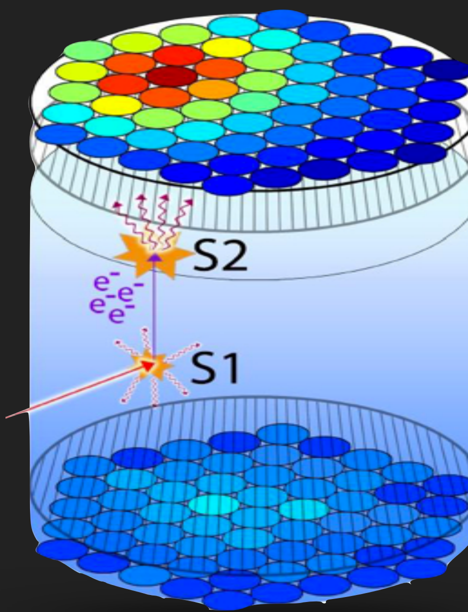


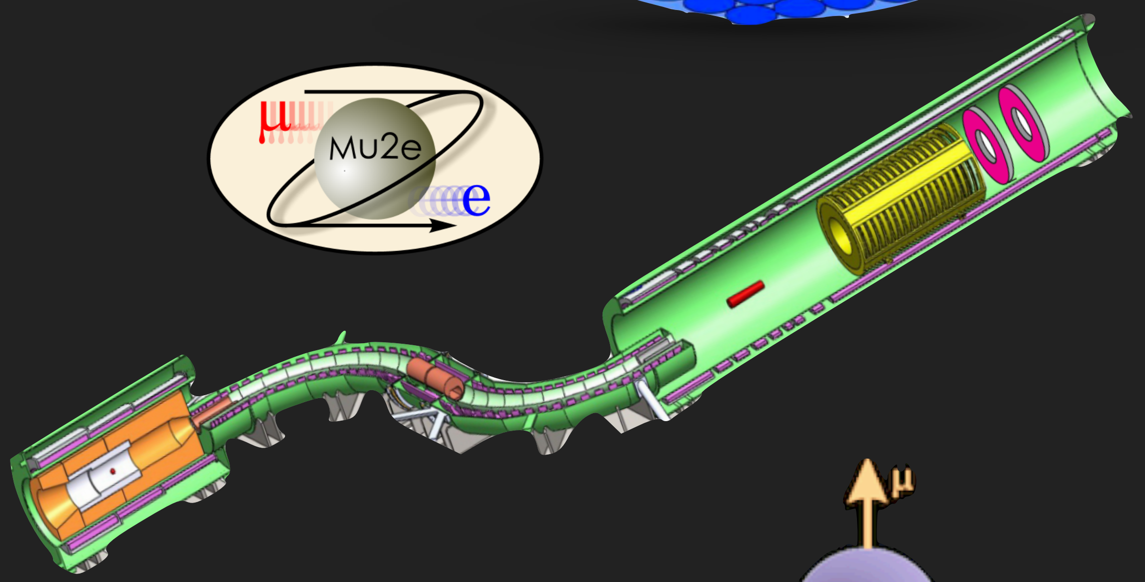
- Electroweak processes in light nuclei
- Tritium decay $\langle {}^3\mathrm{He}|\bar{\mathbf{q}}\gamma_k\gamma_5\tau^-\mathbf{q}|{}^3\mathrm{H}\rangle$
- Proton-proton fusion
- Double-β decay: nn→pp
  - Improve nuclear matrix element uncertainties
- Neutrino-nucleus interactions for long baseline neutrino program

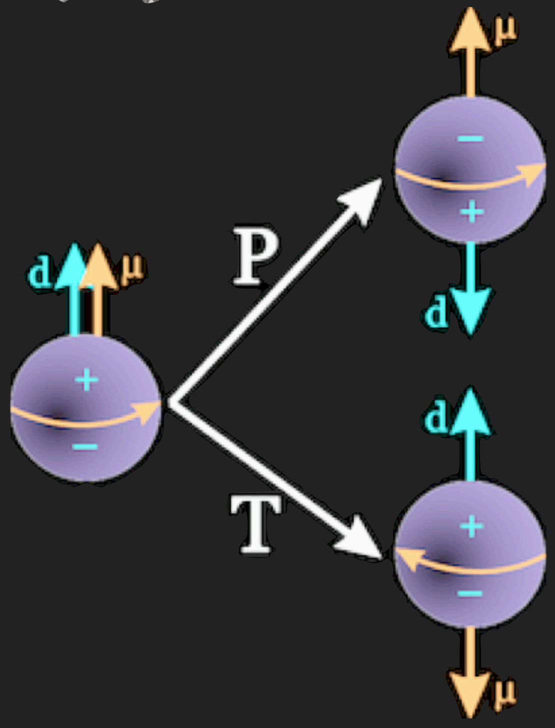


BSM PROCESSES

- Non standard model currents in light nuclei
- Scalar currents
  - Dark matter direct detection
  - Lepton flavour violation: μ2e
  - Precision spectroscopy
- Tensor currents
  - Quark contribution to EDMs of nuclei

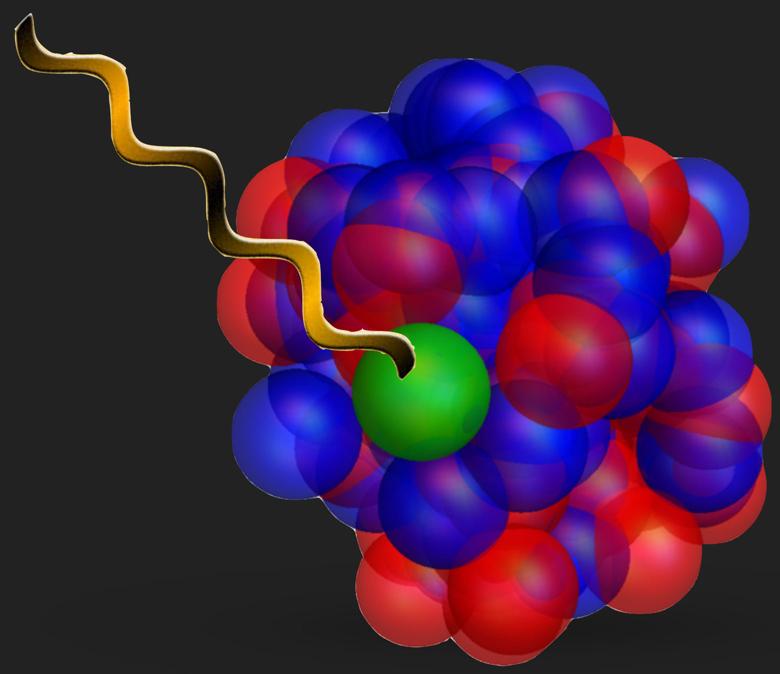


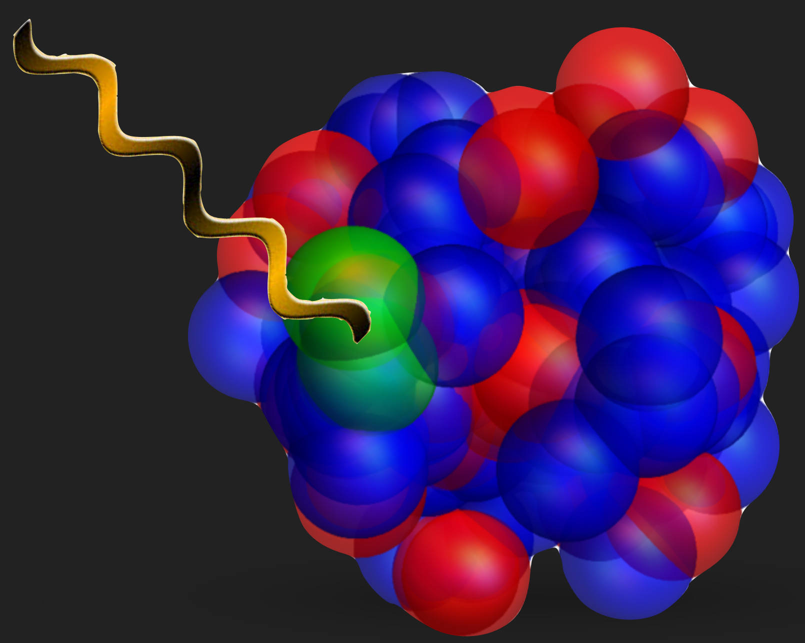




INTERACTIONS WITH NUCLEI

- Coupling of currents to nuclei in nuclear EFT
- One body coupling dominates
  - Determine from nucleon matrix element calculations
- Two nucleon contributions are subleading but non-negligible
  - Study A=2,3,4,.. systems
  - Validate power counting
  - Determine countqerterms

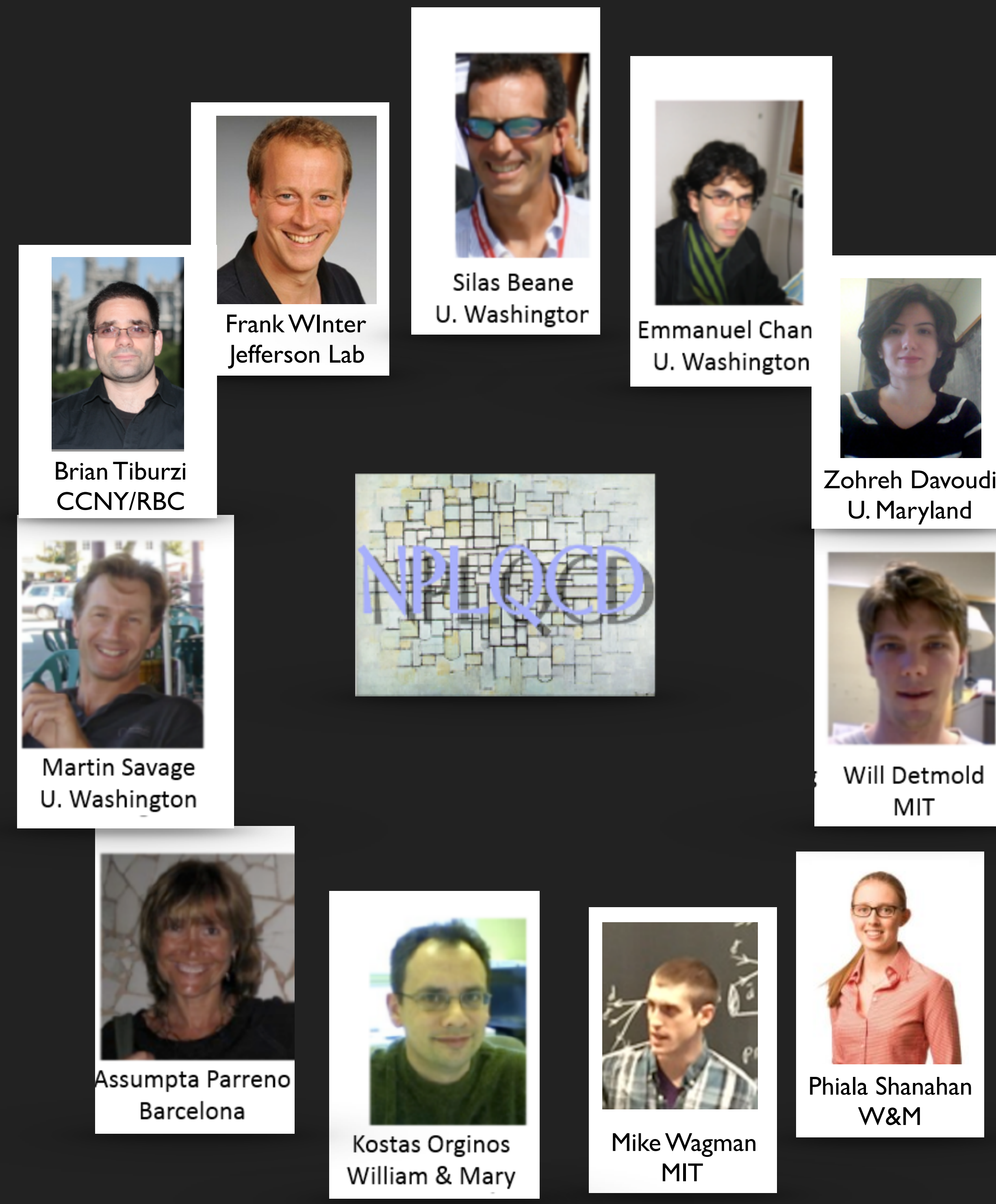




NPLQCD: UNPHYSICAL NUCLEI

- Case study LQCD with unphysical quark masses (m_π~800 MeV, 450 MeV)

1. Spectrum and scattering of light nuclei (A<5) [PRD 87 (2013), 034506]
2. Nuclear structure: magnetic moments, polarisabilities (A<5) [PRL **113**, 252001 (2014), PRL **116**, 112301 (2016)]
3. Nuclear reactions: np→dγ [PRL **115**, 132001 (2015)]
4. Gamow-Teller transitions: pp→deν, $g_A(^3H)$ [PRL **119** 062002 (2017)]
5. Double β decay: pp→nn [PRL **119**, 062003 (2017)]
6. Gluon structure (A<4) [PRD **96** 094512 (2017)]
7. Scalar/tensor currents (A<4) [PRL **120** 152002 (2018)]



+ Arjun Gambhir + David Murphy

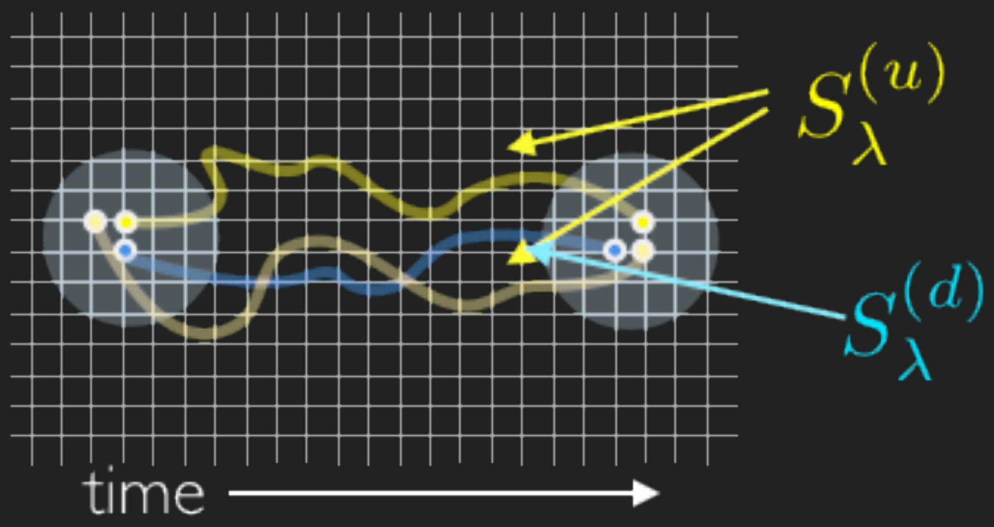
BACKGROUND FIELD APPROACH

- Fixed order background field (axial current as example)
- Construct correlation functions from quark propagators modified in external field

compound propagator   constant

$$S_\lambda^{(q)}(x,y) = S^{(q)}(x,y) + \lambda_q \int dz\, S^{(q)}(x,z)\,\gamma_3\gamma_5\, S^{(q)}(z,y)$$

$$C_{\lambda_u;\lambda_d}(t) =$$

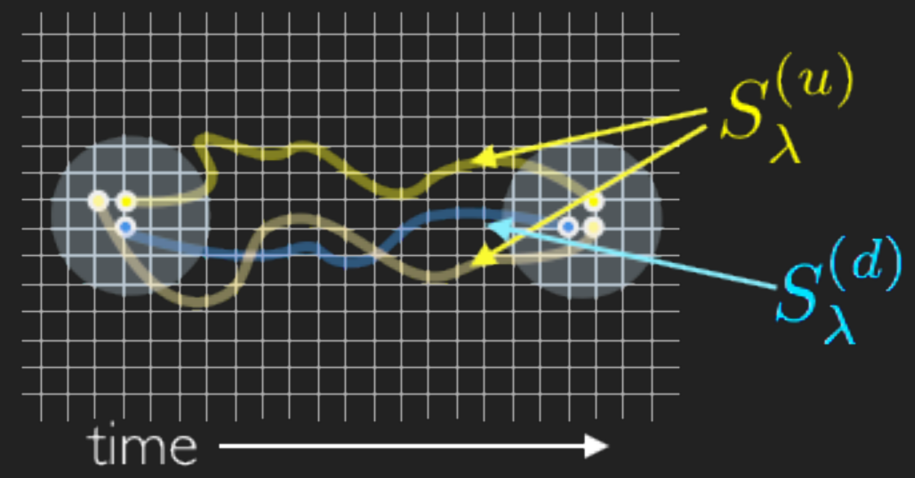


- Linear response gives matrix element

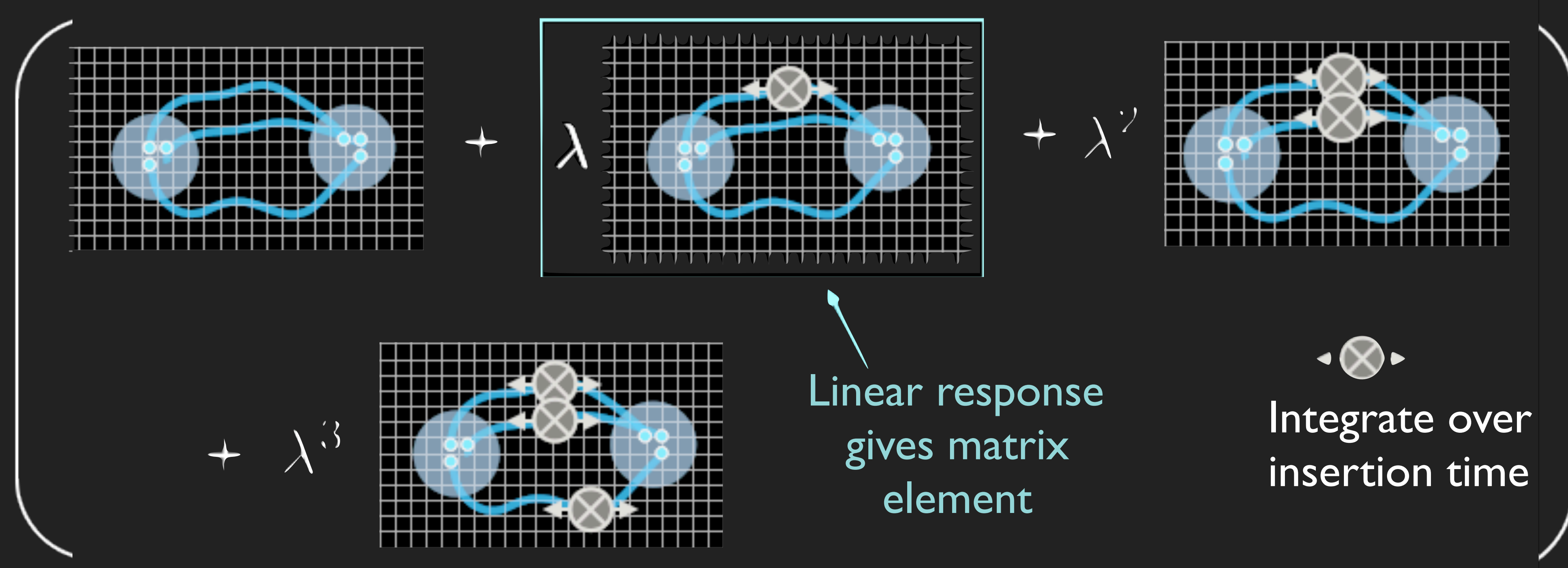
[NPLQCD 1610.04545]

BACKGROUND FIELD APPROACH

$$C_{\lambda_u;\lambda_d}(t) =$$

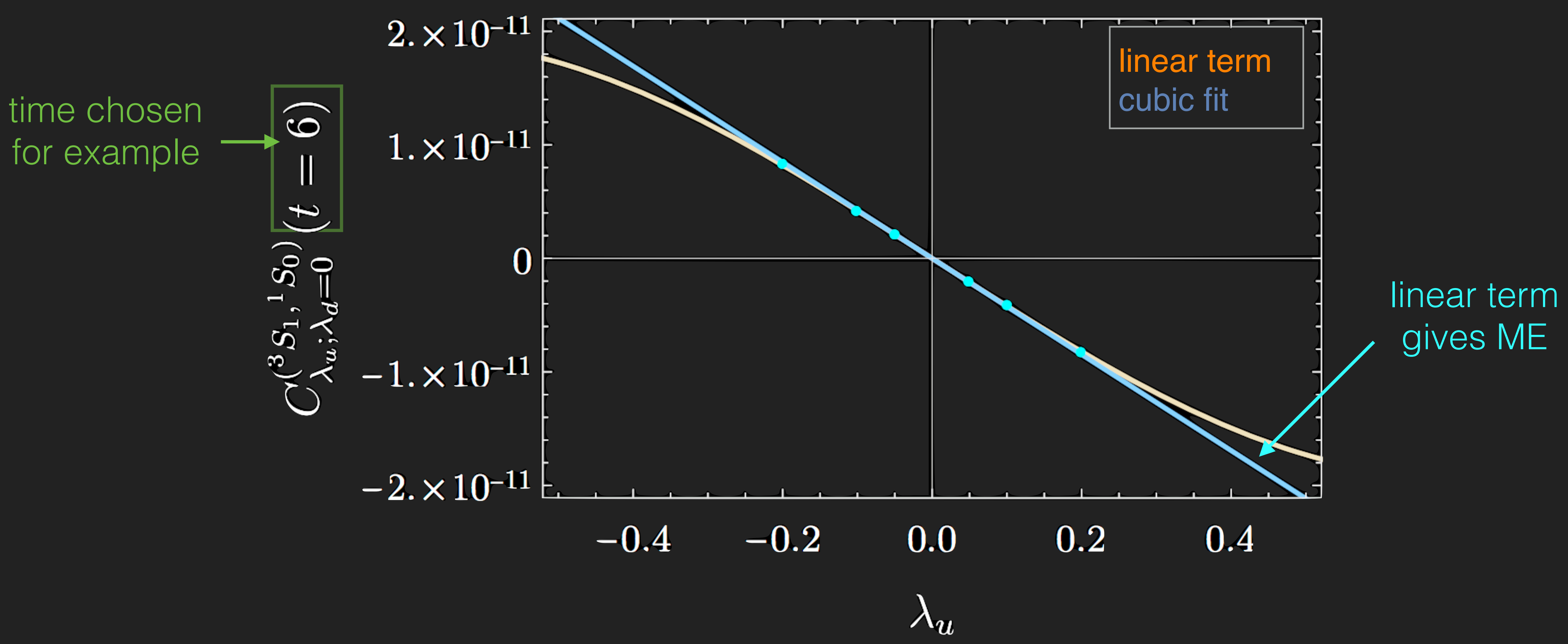


$$C_{\lambda_u;\lambda_d}(t) =$$



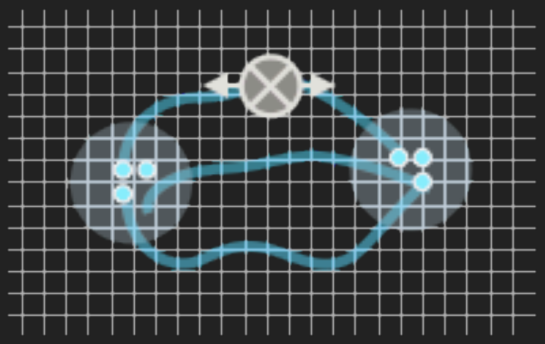
BACKGROUND FIELD APPROACH

- Example: triton correlator formed with background field coupling to u quark



AXIAL BACKGROUND FIELD

$$C_{\lambda_u;\lambda_d}(t)\Big|_{\mathcal{O}(\lambda)} =$$



Implicit sum over current insertion times

- Example: determination of the proton axial charge

$$\begin{aligned} C_{\lambda_u;\lambda_d}(t)\Big|_{\mathcal{O}(\lambda)} &= \sum_{\tau=0}^{t} \langle 0|\chi^\dagger(t) J(\tau)\chi(0)|0\rangle \\ &= \ldots \\ &= Z_0 e^{-M_p t}\left[C + t\,\langle p|A_3^{(u)}(0)|p\rangle + \mathcal{O}(e^{-\delta t})\right] \end{aligned}$$

Uninteresting constant

Excited states

Matrix element

- Time difference isolates matrix element part

$$\left(C_{\lambda_u;\lambda_d}(t+1) - C_{\lambda_u;\lambda_d}(t)\right)\Big|_{\mathcal{O}(\lambda)} = Z_0 e^{-M_p t}\langle p|A_3^{(u)}(0)|p\rangle + \mathcal{O}(e^{-\delta t})$$

PROTON AXIAL CHARGE

- Extract matrix element through linear response of correlators to the background field

- Form ratios to cancel leading time-dependence

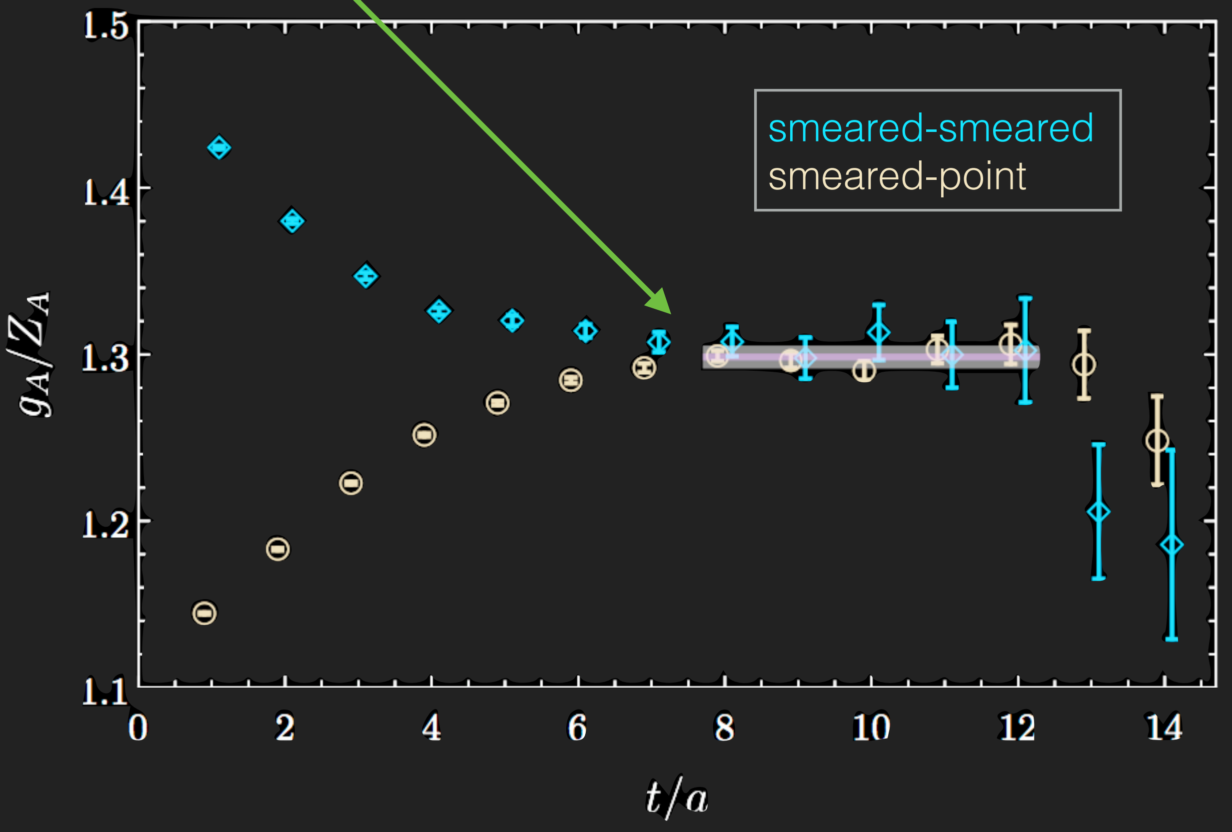
$$R_p(t) = \frac{\left(C^{(p)}_{\lambda_u;\lambda_d=0}(t) - C^{(p)}_{\lambda_u=0;\lambda_d}(t)\right)\Big|_{\mathcal{O}(\lambda)}}{C^{(p)}_{\lambda_u=0;\lambda_d=0}(t)}$$

At late times:

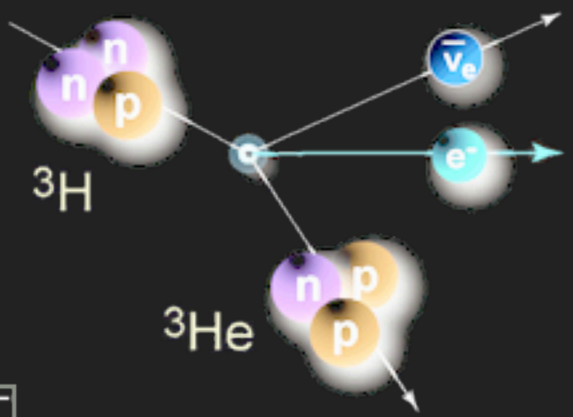
$$R_p(t+1) - R_p(t) \xrightarrow{t\to\infty} \frac{g_A}{Z_A}$$

- Matrix element revealed through "effective matrix elt. plot"

constant fit to plateau region



TRITIUM BETA DECAY



- Tritium decay half life

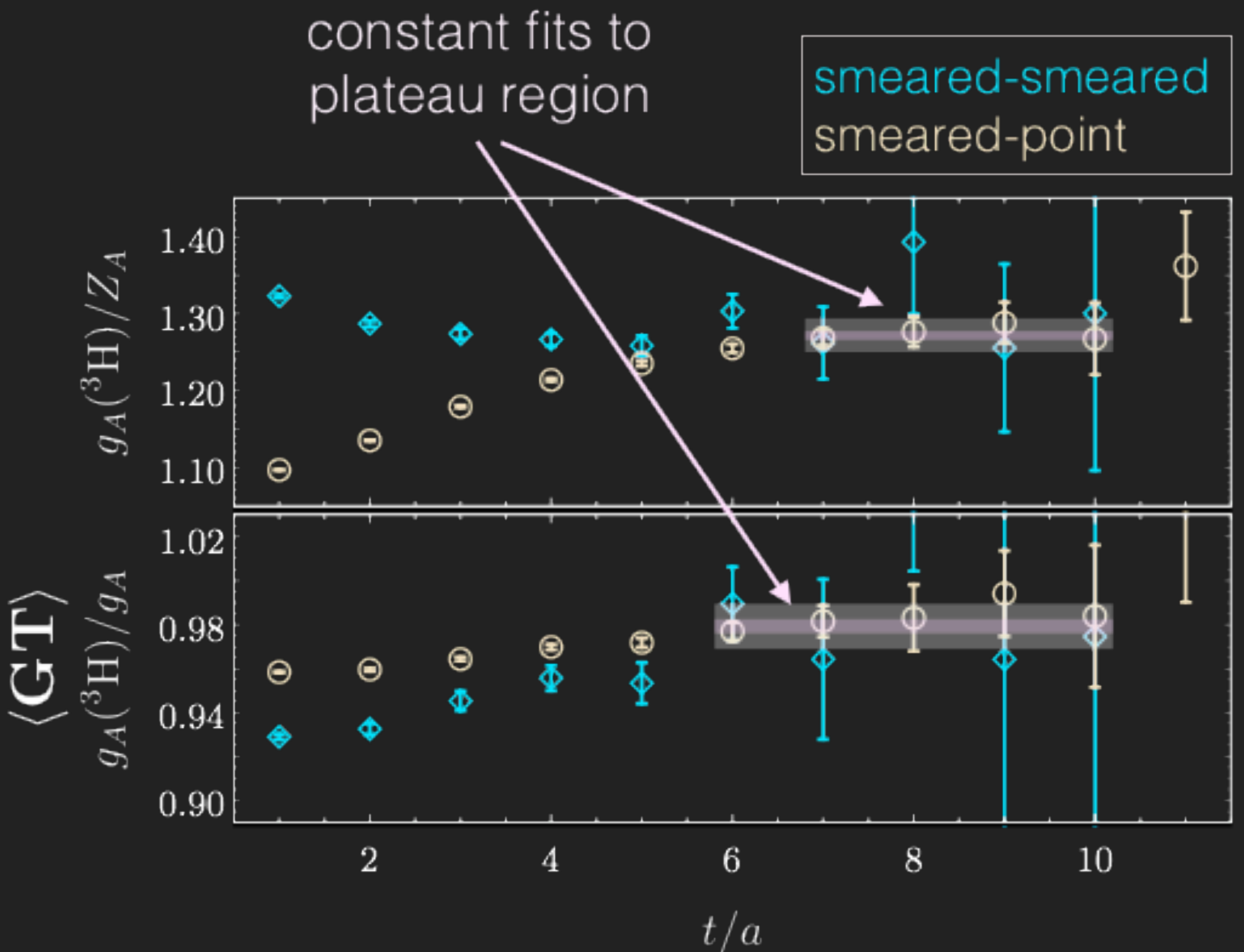
$$\underbrace{\frac{(1+\delta_R)f_V}{K/G_V^2}}_{\text{known from theory or expt.}} \underbrace{t_{1/2}}_{\text{half-life}} = \frac{1}{\underbrace{\langle \mathbf{F} \rangle^2}_{\text{vector ME}} + f_A/f_V\, g_A^2 \underbrace{\langle \mathbf{GT} \rangle^2}_{\text{axial ME}}}$$

- Biggest uncertainty in

$$g_A \langle \mathbf{GT} \rangle = \langle {}^3\mathrm{He} | \bar{\mathbf{q}} \gamma_{\mathbf{k}} \gamma_{\mathbf{5}} \tau^- \mathbf{q} | {}^3\mathrm{H} \rangle$$

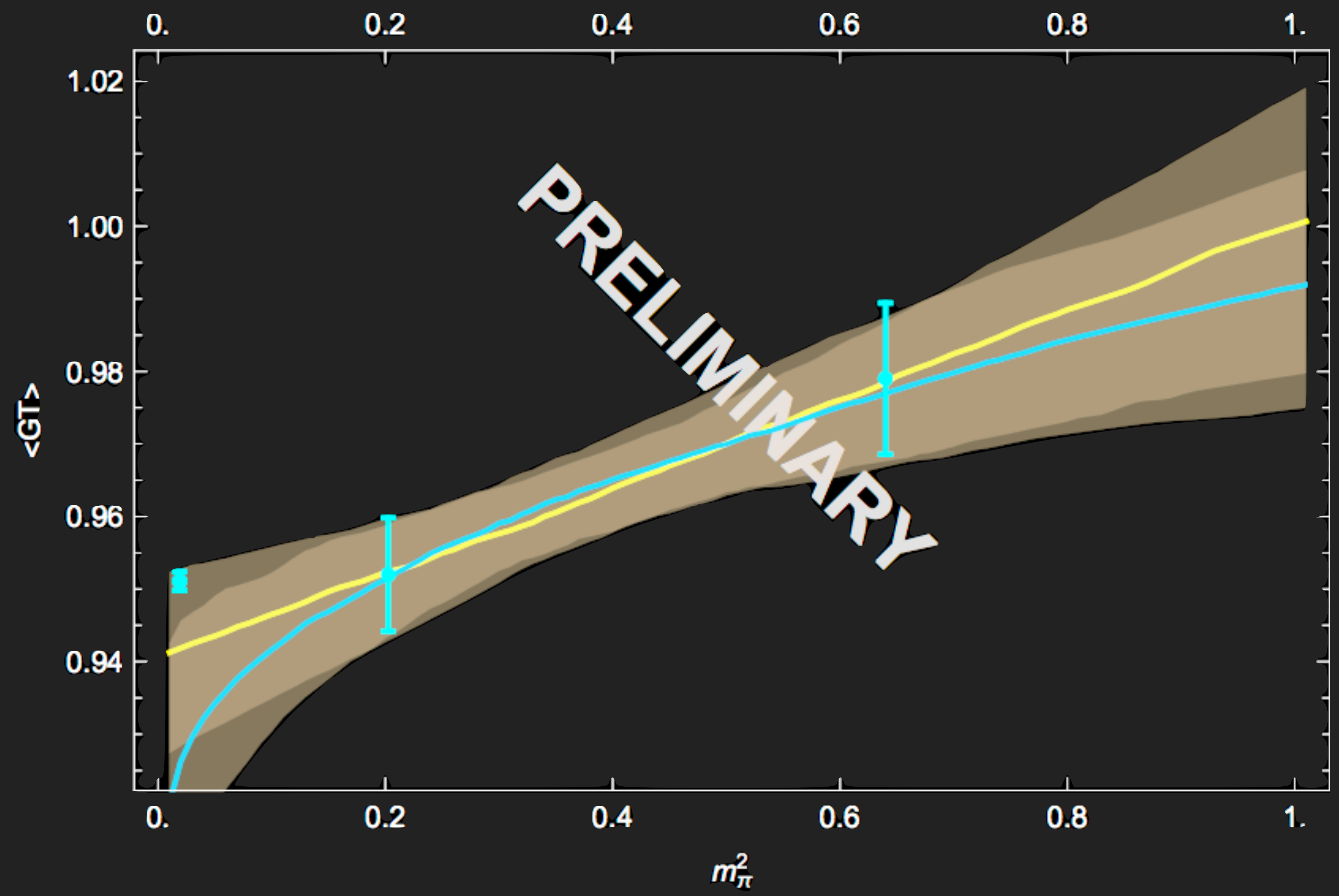
- Form ratios of correlators to cancel leading time-dependence:

$$\frac{\overline{R}_{^3\mathrm{H}}(t)}{\overline{R}_p(t)} \overset{t\to\infty}{\longrightarrow} \frac{g_A(^3\mathrm{H})}{g_A} = \langle \mathbf{GT} \rangle$$



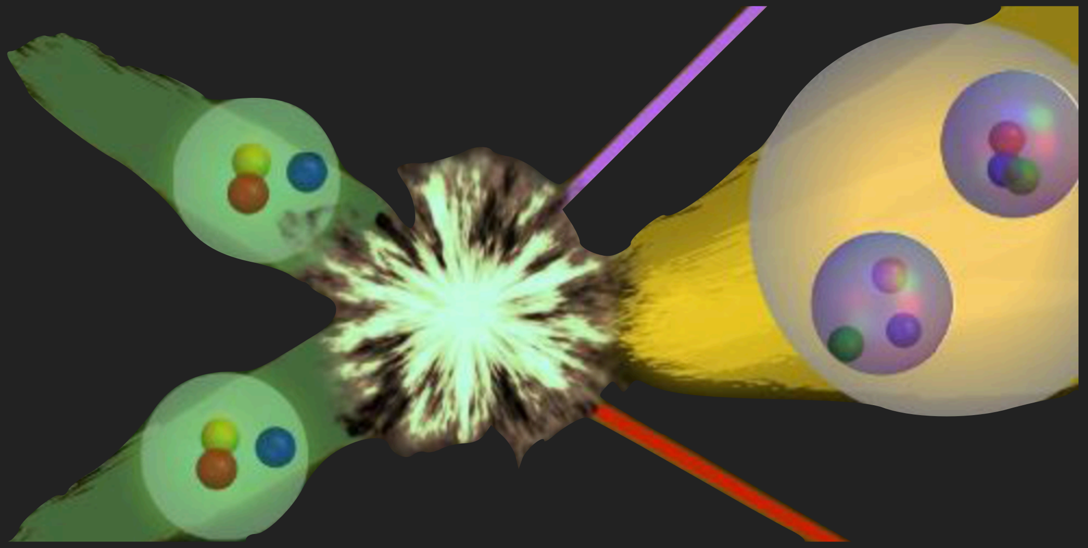
TRITIUM BETA DECAY

- Quark mass dependence (m_π~800,450 MeV)

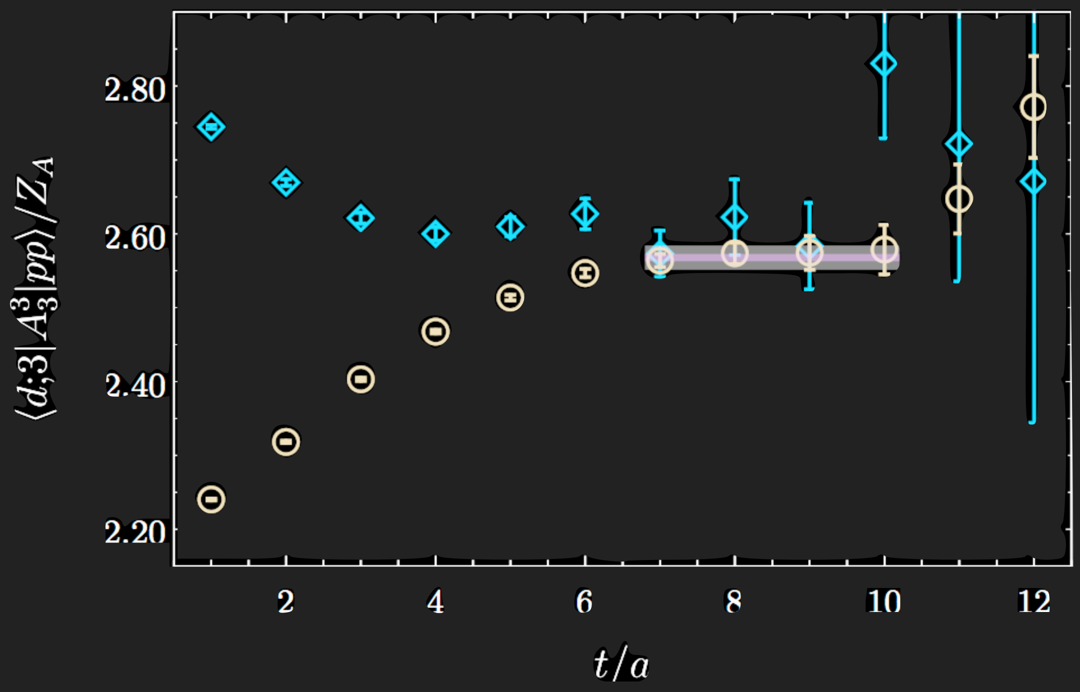


[NPLQCD PRL **119**, 062002 (2017), PRL **119**, 062003 (2017)]

PP FUSION



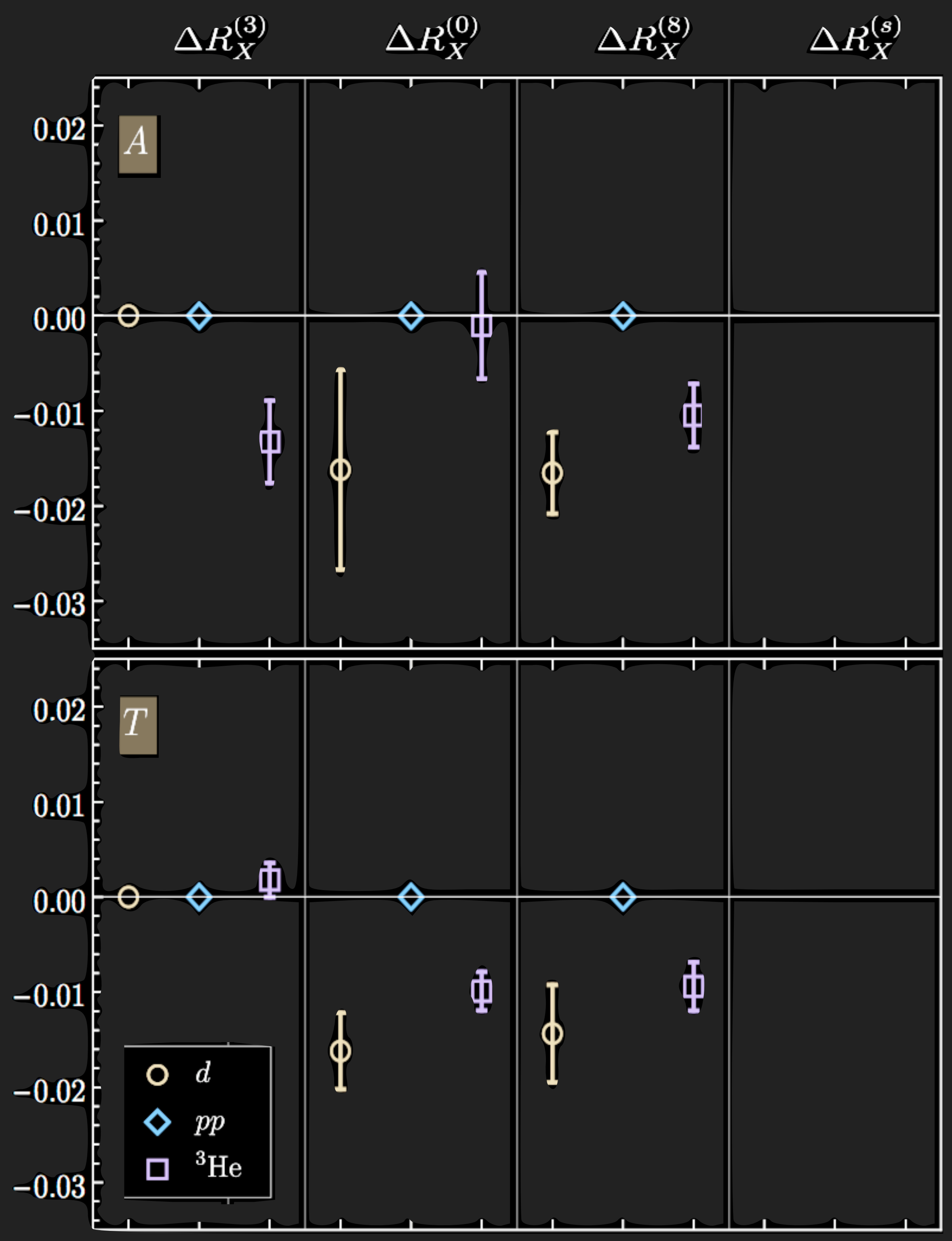
- Axial transition in two nucleon system: pp → de⁺ν, μd→nnν, νd→ppe⁻
- Important EFT contribution form two-body currents
  - First LQCD calculation of pp → deν [NPLQCD PRL **119**, 062002 (2017)]
  - Determines counter-term at similar precision to knowledge from phone
  - Goal: precise prediction for current MuSun experiment



[NPLQCD, PRL **120**, 152002 (2018)]

NUCLEAR EFFECTS

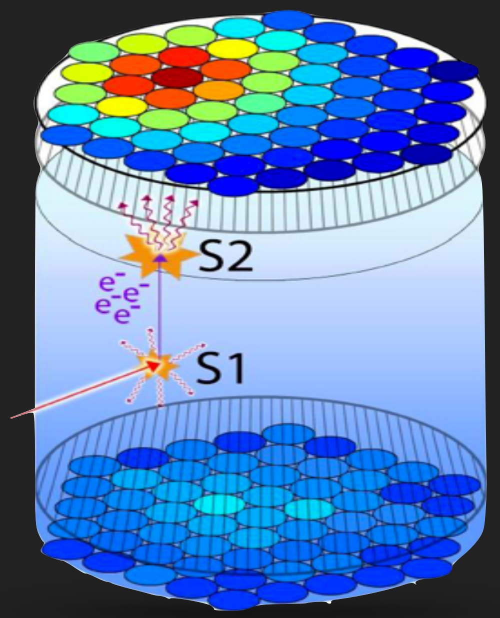
- Background field approach can be used for other types of currents
  - Also for momentum transfer [A. Chambers et al.]
- New study of scalar, axial and tensor quark bilinear
  - Calculate forward limit MEs for A=2,3
  - Disconnected contributions using hierarchical probing [Gambhir et al.]
- Axial and tensor MEs show small nuclear effects

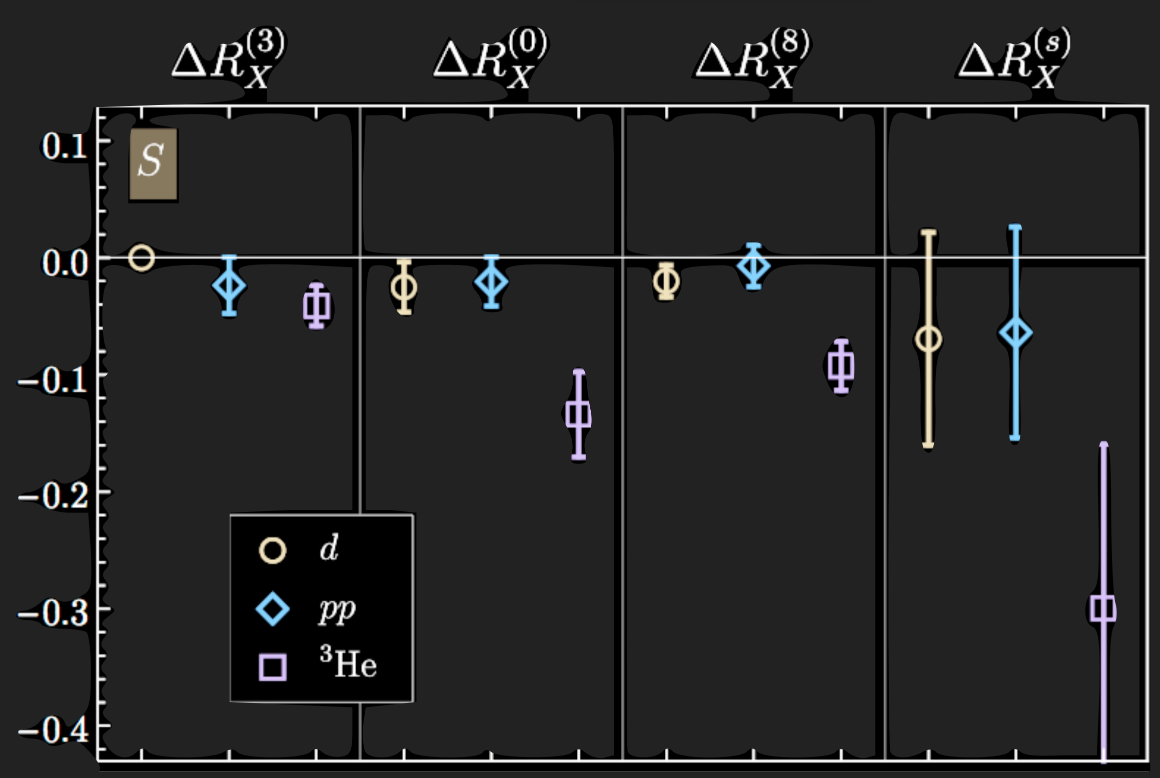


[NPLQCD, PRL **120**, 152002 (2018)]

NUCLEAR EFFECTS

- Scalar MEs
  - See large (~10%) deviation from sum of nucleon MEs for A=3
  - Consequences for larger nuclei used in dark matter detectors?
  - Repeating calculations at lighter quark masses
- Future: second order response give polarisabilities
  - Address questions of nuclear saturation





OUTLOOK

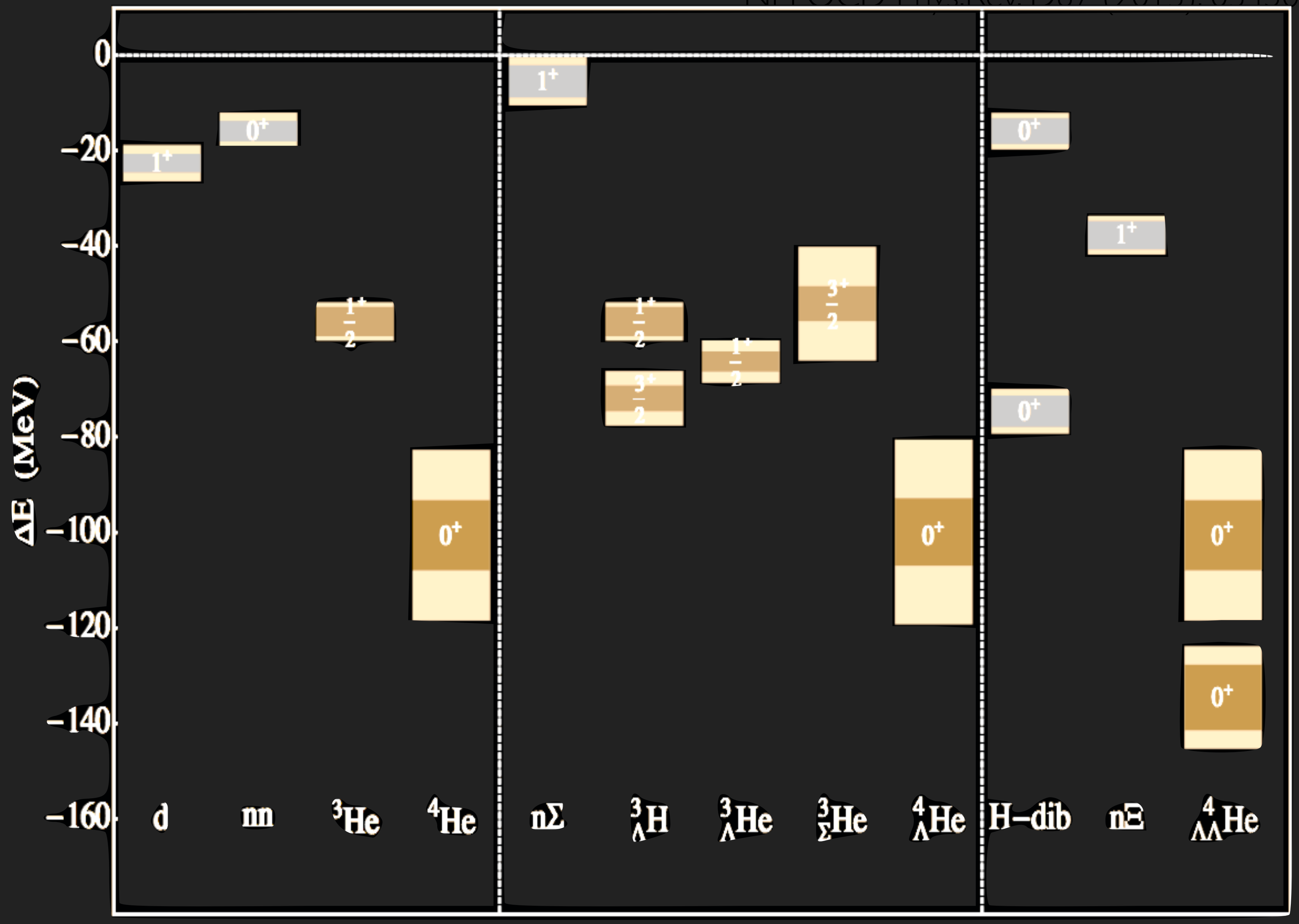
- Nuclei are under study directly from QCD
  - Comprehensive study of matrix elements at heavy quark masses
- Prospect of a quantitative connection to QCD makes this an exciting time for nuclear physics
  - Important role in current and upcoming intensity frontier experimental program
  - Learn many interesting things about the nature of hadrons and nuclei along the way

-FIN-

LIGHT NUCLEI AND HYPERNUCLEI

- Light hypernuclear binding energies @ m_{π}=800 MeV

NPLQCD Phys.Rev. D87 (2013), 034506



NN BOUND STATES

- Potential for fake plateaus? [Iritani et al.]
  - Scattering states combine with relative signs to give negative-shifted flat behaviour
- Very unlikely
- Study at 3 volumes with same source structure
- Negative shifted states
  - Correlators fully consistent at L=24, 32, 48
- Excited state
  - Scales as $1/L^3$ consistent with scattering state