Baryon Number-Violating Amplitudes on a Lattice with Physical Chirally-Symmetric Quarks

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- Neutron-antineutron oscillation amplitudes
    - *Experimental lifetime limits & outlook*
    - *Nucleon model uncertainties*
    - *Hadron masses and energies*
    - *Extraction of matrix elements*
    - *Operator renormalization*

- Proton decay amplitudes
    - *Experimental lifetime limits & outlook*
    - *Effective operators for* $p\to\pi\ell$, $K\ell$ *decays*
    - *Momentum & continuum extrapolations*
    - *Proton decay constants (* $p\to 3\ell$ *)*

- Summary&Outlook

Baryogenesis and Broken Symmetries

Why More Matter > Antimatter? $\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \cdot 10^{-10}$

- Three necessary components [A.Sakharov (1967)] :

proton decay, neutron oscillations

Baryon number-changing interactions

(alternatively, leptogenesis + sphalerons)

neutrinoless beta-decays

Violations of C- and CP-symmetries

(electric dipole moments of p, n, e⁻, nuclei, atoms)

Interactions out of equlibrium

Baryon Number : accidental symmetry of SM, violated by sphalerons

- neutron-antineutron oscillations ($\Delta B=2$)
- proton decay ($\Delta B=1$)

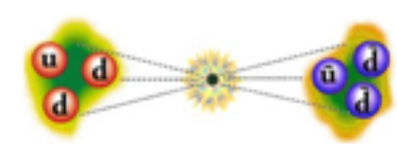
Missing piece of Grand-Unified Theories

Limit on nuclear matter stability?

ΔB=2 Number Violation : n–n̄ Oscillations

Baryon number not conserved ?⇒ (anti)neutrons are not energy eigenstates:

- (n,n̄) Hamiltonian with ΔB=2 $\mathcal{H} = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}^\dagger \begin{pmatrix} M_n + \frac{1}{2}\Delta M & \delta m \\ \delta m & M_n + \frac{1}{2}\Delta M \end{pmatrix} \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$
- n→n̄ transition probability $P_{n\to\bar{n}}(t) \approx \left[\frac{2\delta m}{\Delta M}\right]^2 \sin^2\left[\frac{1}{2}\Delta M\, t\right]$
- If $t \ll (\Delta M)^{-1}$: n→n̄ transition in $\tau_{n\bar{n}} = (2\delta m)^{-1}$
- current limit $\delta m \lesssim (10^8\,\mathrm{s})^{-1} \approx O(10^{-24})\ \mathrm{eV}$

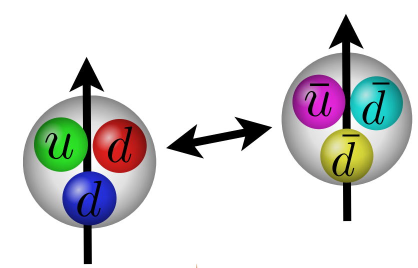


Medium effects dominate $\Delta M \gg \delta m$

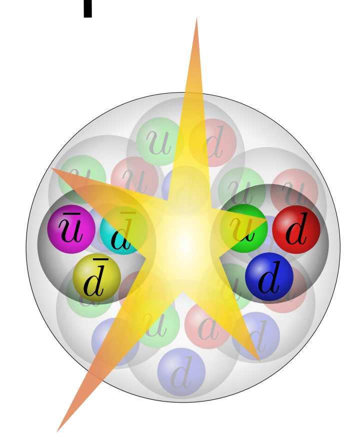
- In vacuum ("quasi-free" n–n̄) B~0.5 Gauss:

  $\Delta M = 2\mu_n B_\oplus \approx 6 \cdot 10^{-12}\ \mathrm{eV}$
- In nuclei :

  $\Delta M \sim O(100\,\mathrm{MeV})$



magnetic moment flip



interactions with nuclear medium

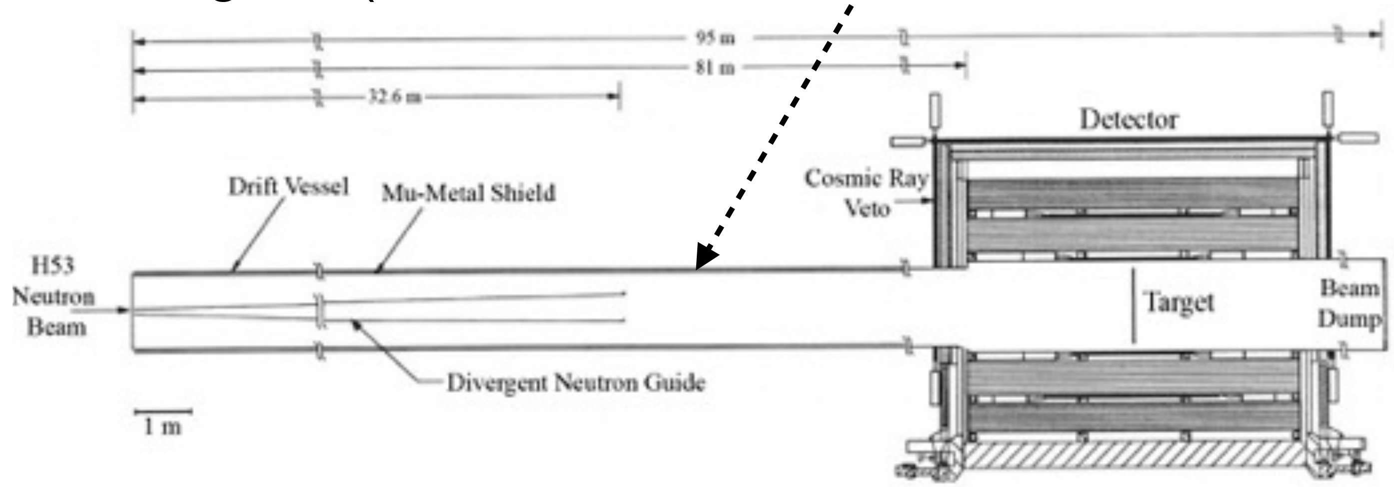
N–N̄ Oscillations: Experimental Status

- "Quasi-free" reactor neutrons
  - ILL Grenoble high-flux reactor [M.Baldo-Ceolin et al, 1994)]

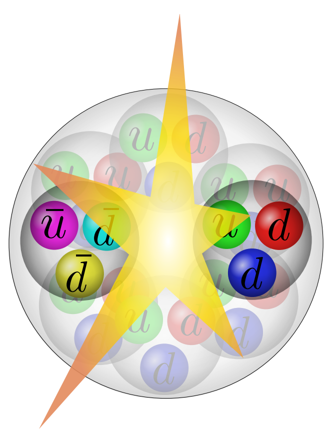
$$\tau_{n\bar{n}} \gtrsim 10^8\ s$$
$$\delta m \lesssim 6 \cdot 10^{-24}\ \text{eV}$$

Mag.field screening for flight ~ $(\Delta M)^{-1} > 1\text{s}$

$$B < (2\mu_n t)^{-1} = 5\ \text{nT} = 10^{-4} B_\oplus$$



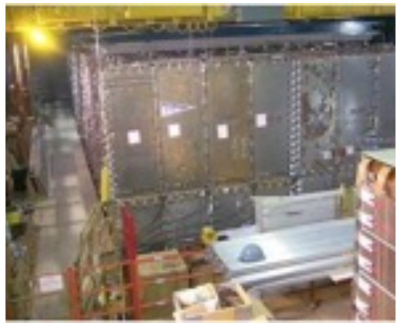
- In nuclei :
  - $\tau(^{56}Fe) \gtrsim 0.72 \cdot 10^{32}$ yr
    $\Longrightarrow \tau_{N\bar{N}} \gtrsim 1.4 \cdot 10^8$ s [Soudan]
  - $\tau(^{16}O) \gtrsim 1.77 \cdot 10^{32}$ yr
    $\Longrightarrow \tau_{N\bar{N}} \gtrsim 3.3 \cdot 10^8$ s [Super-K]
  - $\tau(^{2}H) \gtrsim 0.54 \cdot 10^{32}$ yr
    $\Longrightarrow \tau_{N\bar{N}} \gtrsim 1.96 \cdot 10^8$ s [SNO]



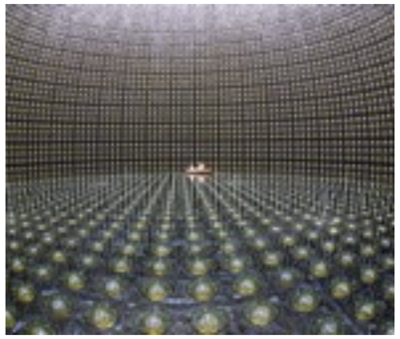
Nuclear decays from (ΔB=2) transitions: suppressed by nuclear medium:

$$T_d = R\tau_{n\bar{n}}^2$$
$$R \sim 10^{23}\ s^{-1}$$

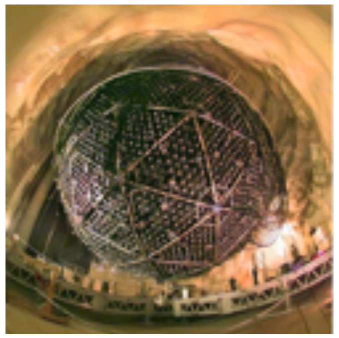
nuclear model uncertainty ~ 10-15% for ^{16}O [E.Friedman, A.Gal (2008)]



Soudan



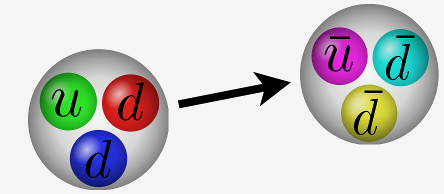
Super Kamiokande



SNO

Sensitivity is limited by atmospheric neutrinos

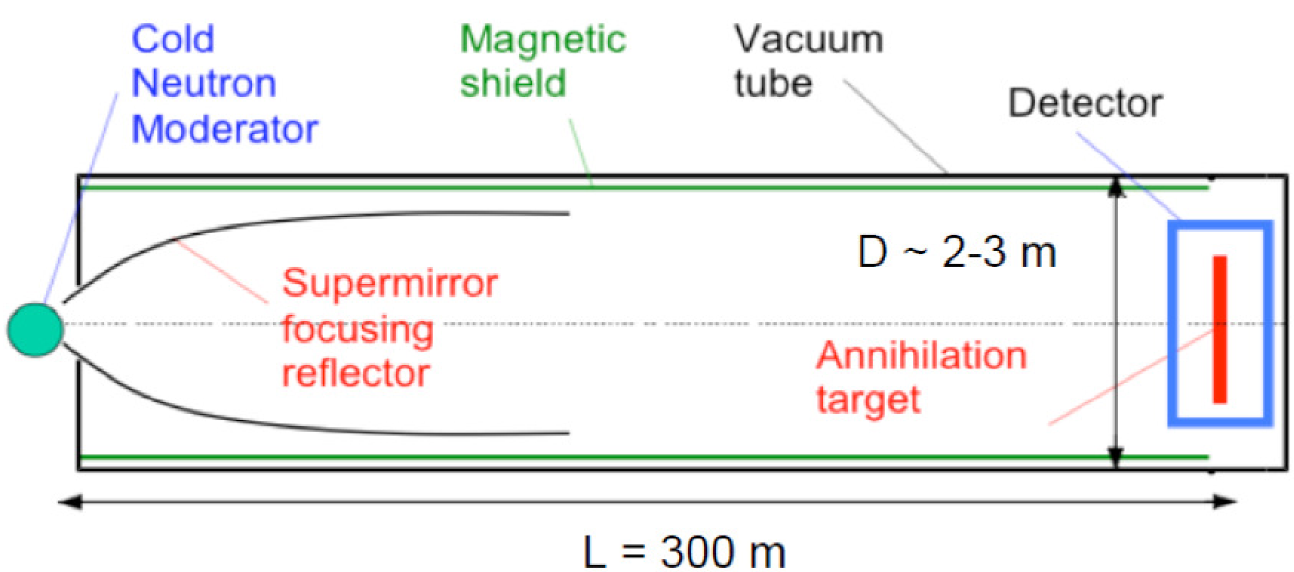
N–N̄: Experimental Outlook



Maximize *Probability of oscillation* ~ $N_n\ (T_{\text{free}})^2$

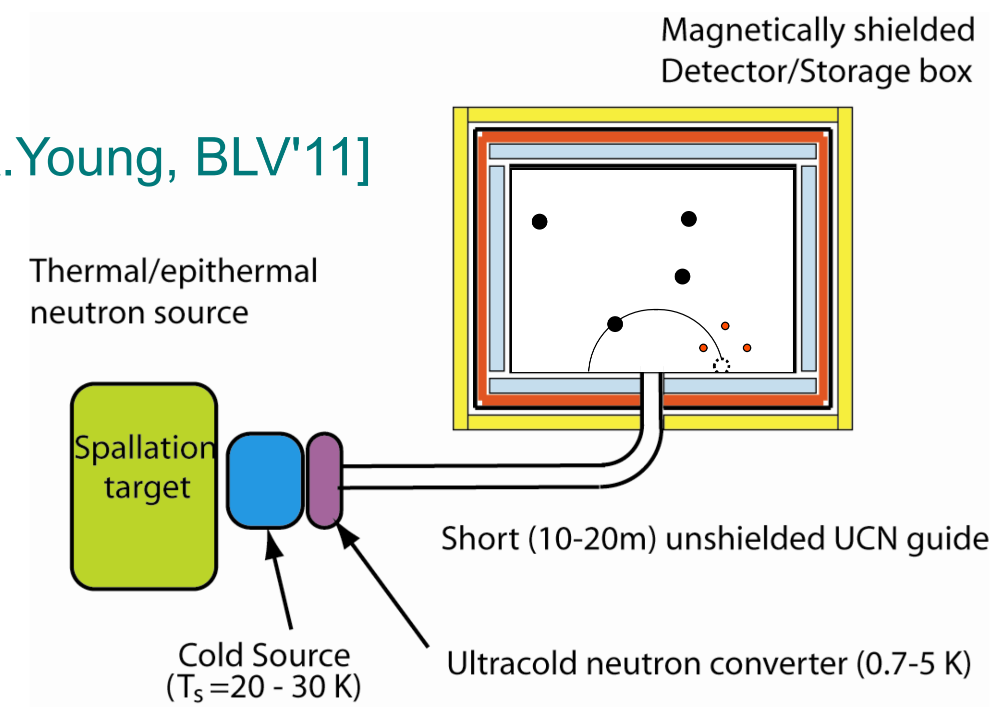
- Shielded beam (similar to ILL):
  Expected sensitivity x**10²-10³** ILL
  $\tau_{n\text{-}\bar{n}} \gtrsim 10^9\text{-}10^{10}$ s
  - ✦ Spallation sources: x12 flux @ESS
  - ✦ Elliptic focussing mirror
  - ✦ Better magnetic shielding (B < 1 nT)

[Phillips et al, arXiv:1410.1100]



- stored ultra-cold neutrons
  $\tau_{n\text{-}\bar{n}} \gtrsim 2.2\cdot10^8$ s

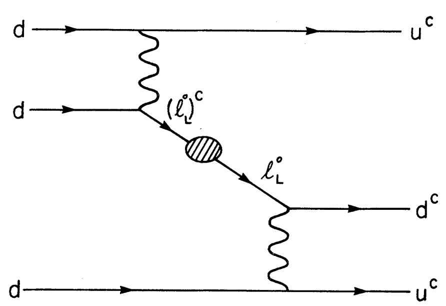
[A.Young, BLV'11]

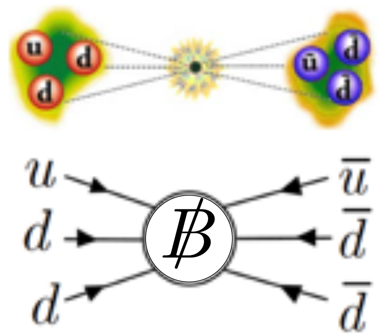


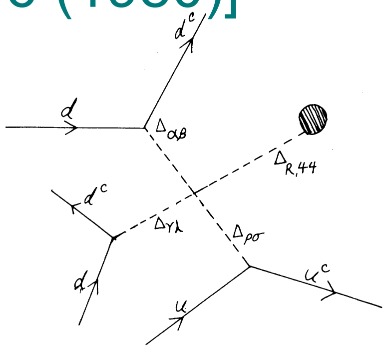
- Further improvements
  - ✦ Larger vessels
  - ✦ Better magnetic shielding (B < 1 nT)
  - ✦ Parabolic floor concentrators
  - ✦ Multiple coherent reflections

BSM Models and QCD Input

- GUT + massive Majorana lepton [T.K.Kuo, S.T.Love, PRL45:93 (1980)]
- partial unification and (B–L) viol. [R.N.Mohapatra, R.E.Marshak, PRL44:1316 (1980)]







Effective *ΔB=2* interaction

$$\mathcal{L}_{\rm eff} = \sum_i \left[c_i \mathcal{O}_i^{6q} + \text{h.c.}\right]$$

oscillation rate

$$(2\tau_{n\bar n})^{-1} = \delta m = -\langle\bar n| \int d^4x\, \mathcal{L}_{\rm eff}\, |n\rangle = -\sum_i \frac{c_i}{M_X^5} \boxed{\langle\bar n|\mathcal{O}_i^{6q}|n\rangle}$$

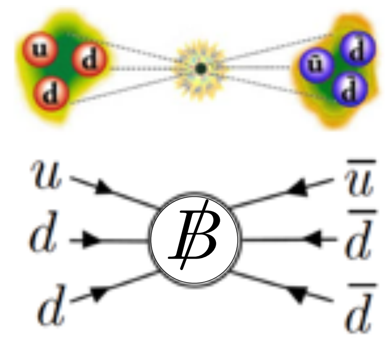
BSM scale suppression
M_X ≳ (200–300) TeV

n–$\bar n$ amplitude from NP QCD $\sim \int d^3x\, (\rho_q)^3$

sensitive to spatial quark distribution

ΔB=2 Operators

Classification of all ΔI=1 6-quark operators



- Light-flavor $SU(2)_f$ multiplets
  [T.Kuo, S.Love, PRL45:93 (1980);
  S.Rao, R.Shrock, PLB116:238 (1982)]
- 2-loop perturbative running
  [Buchoff, Wagman, PRD93:016005(2015)]

$$(q_1 q_2) \doteq (q_1^T C q_2)$$
$$(q_1 q_2)^A \in (\bar{\mathbf{3}}_{\text{color}}, \mathbf{1}_{\text{flavor}})$$
$$(q_1 q_2)^S \in (\mathbf{8}_{\text{color}}, \mathbf{3}_{\text{flavor}})$$

$(\mathbf{1}_L, \mathbf{3}_R)$

$$Q_1 = -4\,(ud)_R^{A_1}\,(ud)_R^{A_2}\,(dd)_R^{S_3}\,T^{A_1A_2S_3}$$
$$Q_2 = -4\,(ud)_L^{A_1}\,(ud)_R^{A_2}\,(dd)_R^{S_3}\,T^{A_1A_2S_3}$$
$$Q_3 = -4\,(ud)_L^{A_1}\,(ud)_L^{A_2}\,(dd)_R^{S_3}\,T^{A_1A_2S_3}$$

$(\mathbf{1}_L, \mathbf{7}_R)$

$$Q_4 = -\frac{4}{5}\left[(uu)(dd) + 4(ud)_R(ud)\right]_{RR}^{S_1S_2}\,(dd)_R^{S_3}\,T^{S_1S_2S_3}$$

$(\mathbf{3}_L, \mathbf{5}_R)$

$$Q_5 = (uu)_R^{S_1}\,(dd)_L^{S_2}\,(dd)_L^{S_3}\,T^{S_1S_2S_3}$$ (not $SU(2)_L$-symmetric)

(and also $\boldsymbol{Q_{6,7}}$ related by Wigner-Eckart thm)

Must have chiral symmetry to protect the operators from mixing

Fundamental Theory: QCD on a Lattice

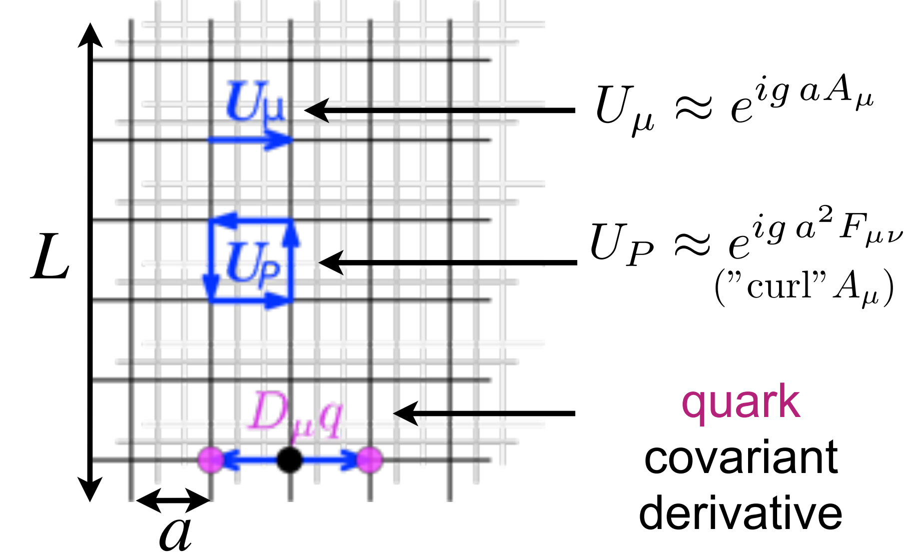
Lattice Field Theory ⇔ Numerical evaluation of the Path Integral

$$\langle q_x \bar{q}_y \ldots \rangle = \int \mathcal{D}\big(Glue\big) \int \mathcal{D}\big(Quarks\big)\; e^{-S_{Glue} - \bar{q}\left(\not{D}+m\right)q}\; \big[\cancel{q_x \bar{q}_y} \ldots\big]$$

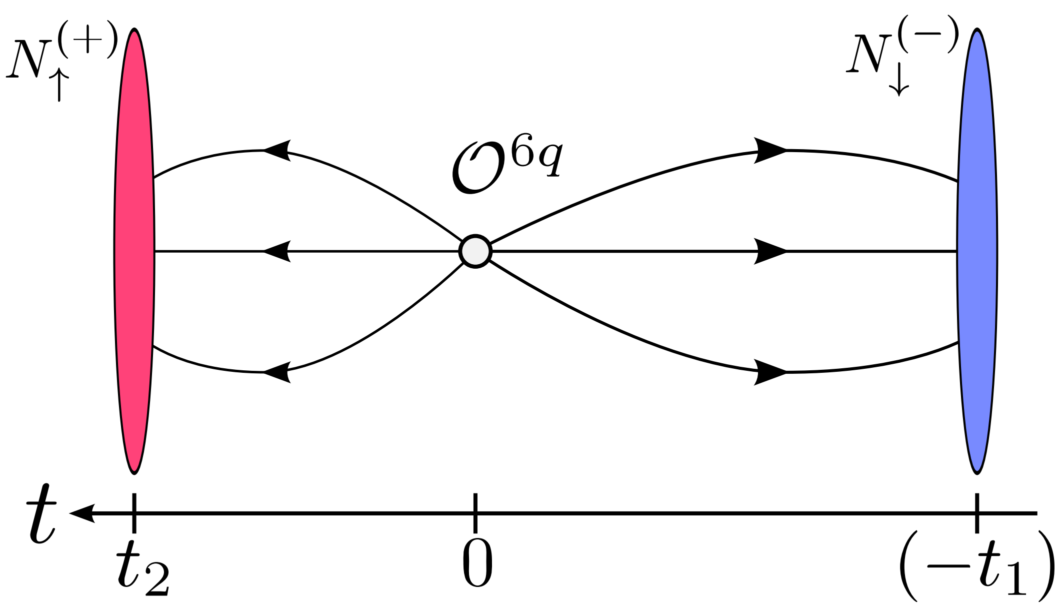
Grassmann integration

$$= \int \mathcal{D}\big(Glue\big)\, \underbrace{e^{-S_{Glue}}\, \mathrm{Det}\big(\not{D}+m\big)}_{\text{Hybrid Monte Carlo sampling of gluon background}}\; \underbrace{\big[\big(\not{D}+m\big)^{-1}_{x,y} \ldots\big]}_{\text{Quark Eqns. of Motion}}$$

QCD on Euclidean 4D lattice



Lattice correlation fcn. for ⟨$\bar{n}$|Q$_\alpha$|n⟩ matrix elements
[M.Buchoff, C.Schroeder, J.Wasem PRD93:016005(2015)]



Systematic effects
- discretization errors
- finite volume
- ~~unphysical heavy pion(quark) mass~~
- ~~chiral symmetry breaking~~
- excited states
- renormalization / $\overline{\mathrm{MS}}$ matching

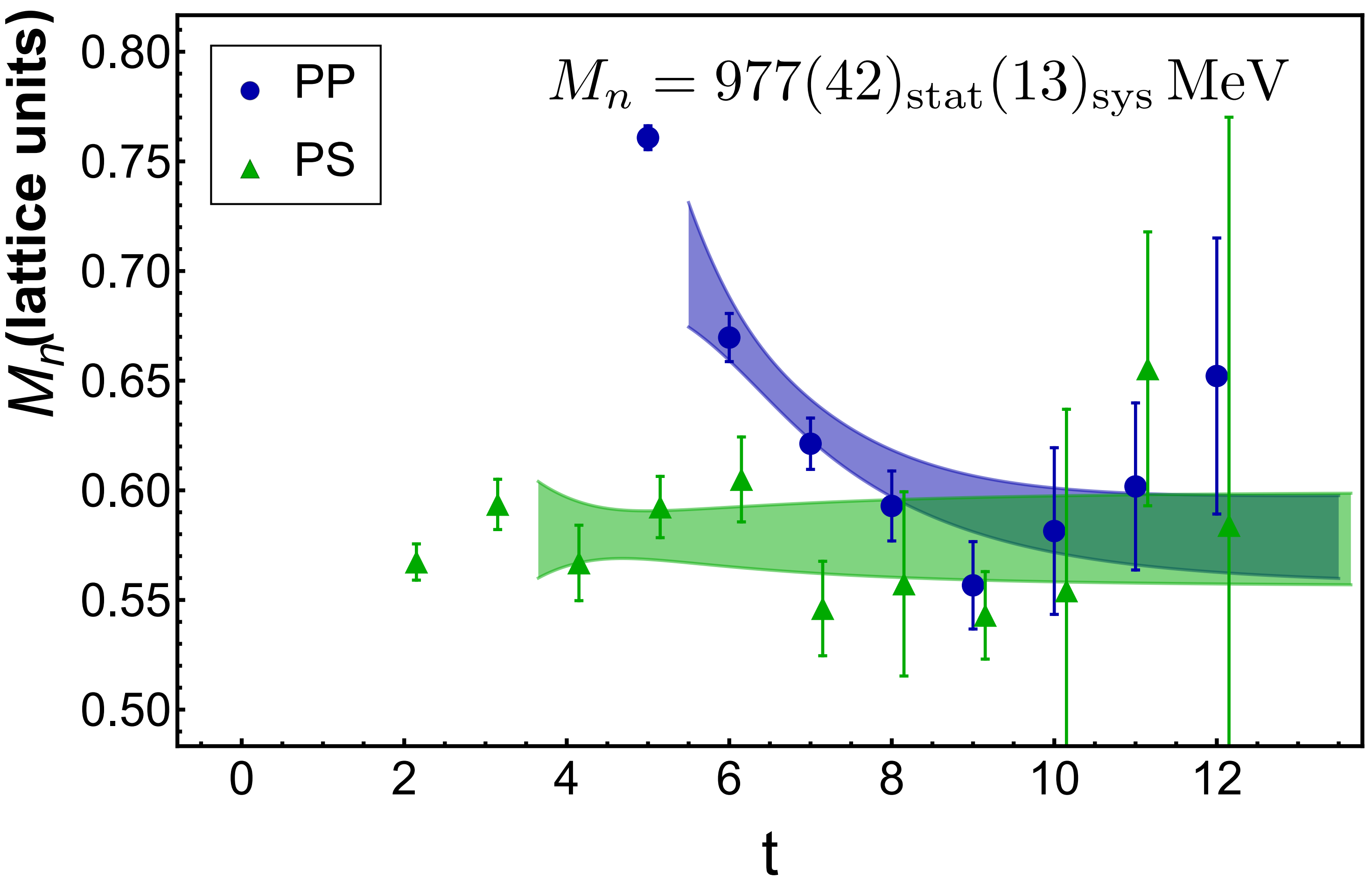
Lattice Details

- Physical quark masses, m_π = 140 MeV
  [T.Blum et al (RBC/UKQCD), PRD93:074505 arXiv:1411.7017]
  - ✦ lattice $48^3 \times 96 = 5.5^3 \times 10.9$ fm
  - ✦ spacing $a = 0.1392(4)$ fm, $\delta(a^{-6}) \approx$ **1.7%**
- chiral (Möbius Domain Wall Fermions)
- 2268 (28 x 81) MC samples

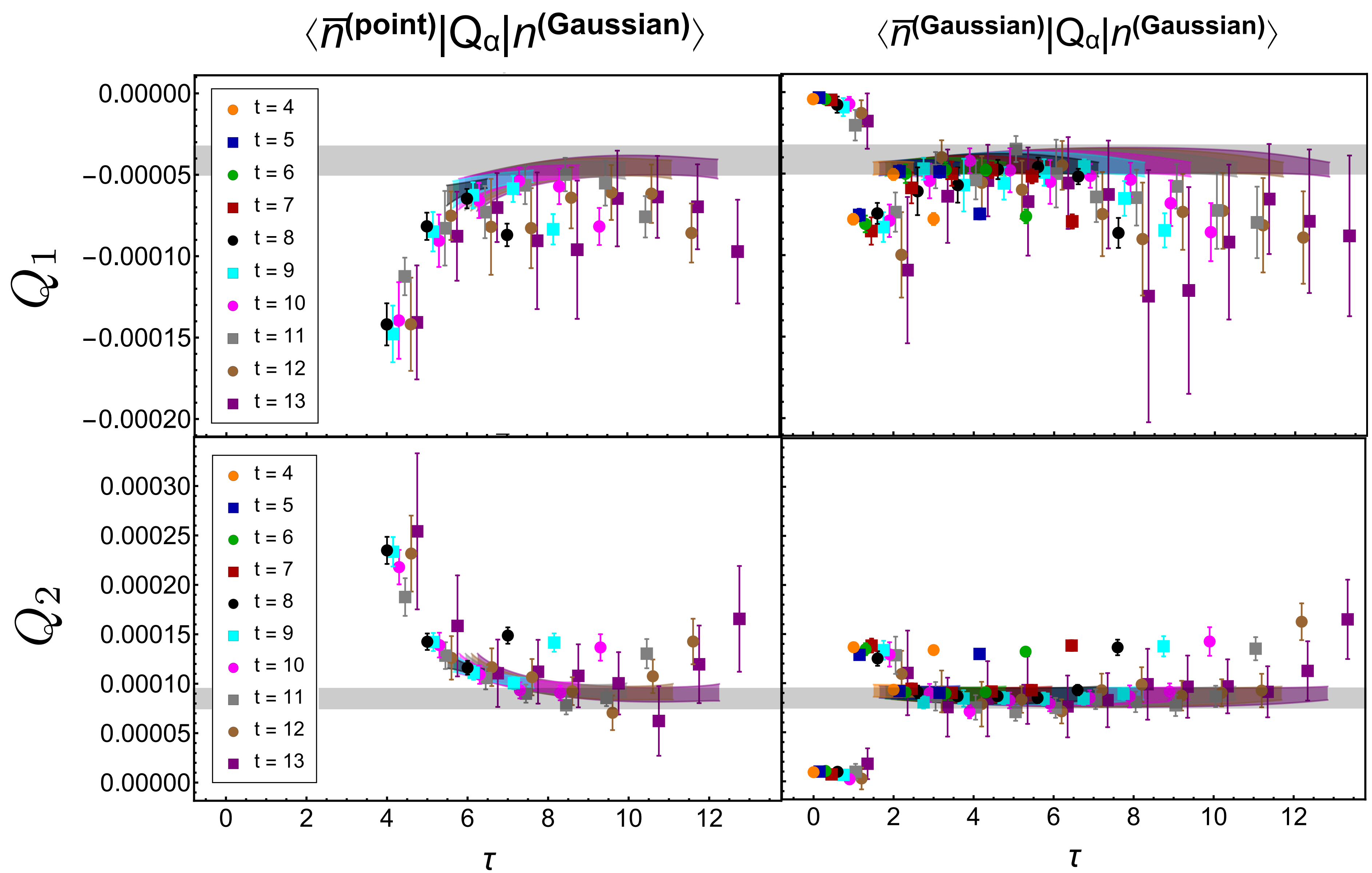
Nucleon effective mass

$$M_n^{\rm eff}(t) = \frac{1}{a}\log\frac{C_{nn}(t)}{C_{nn}(t+a)}$$

- lattice data
- Variational analysis on quark w.f.'s: point-like vs. Gaussian(smeared)
- fits $C_{nn}(t) \sim C_0 e^{-E_0 t} + C_1 e^{-E_1 t}$
  sim. PP+PS with $t \approx 0.5 \ldots 1.5$ fm



n↔n̄ Amplitudes: Ground and Excited States

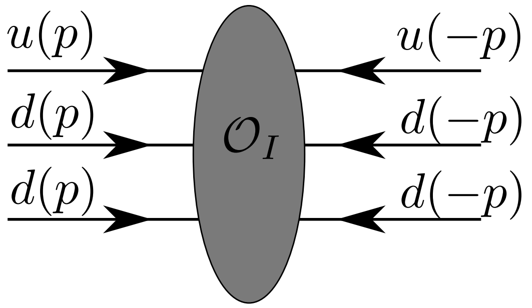


Excited state analysis:

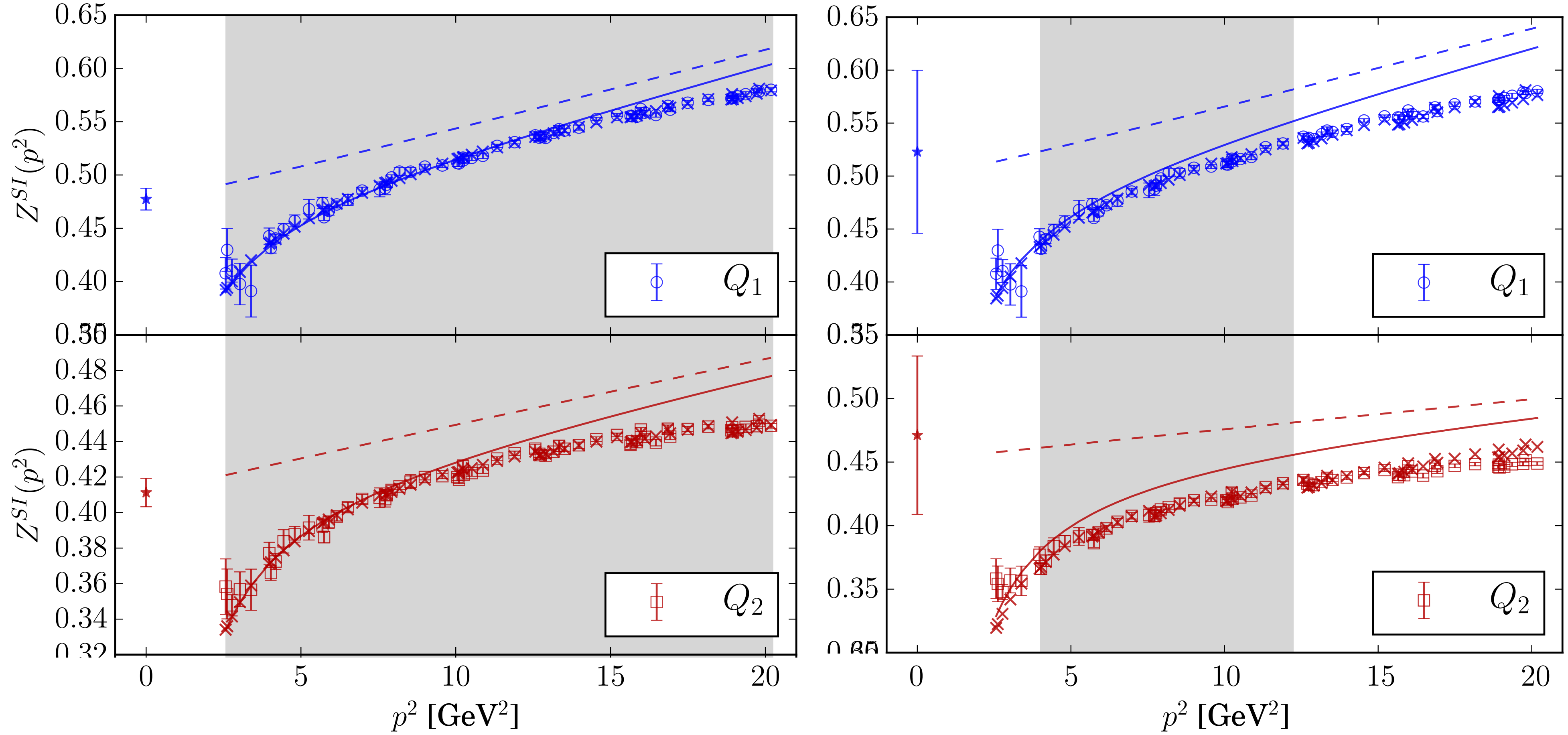
- Variational analysis: point-like vs. Gaussian-like quark w.f.'s in (anti)neutrons
- Data points: ratios of lattice correlators $C_{3pt}(T)/C_{2pt}(T) \to \langle N|Q|\bar{N}\rangle$
- Bands: 2-state fits of lattice data with Tsep ≈ 0.5 ... 1.5 fm
- Variance across fits → systematic uncertainty

Nonperturbative Operator Renormalization

- 6-Quark Green's functions on a lattice
  quark momentum scheme for 2-loop pQCD
  [Buchoff, Wagman PRD93:016005(2015);
  Rinaldi, SS, Wagman, et al PRD99:074510 (2019)]



+ permutations to enforce ***SU*(2)*f***

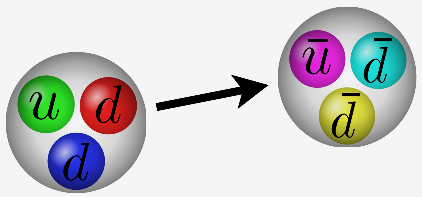


- p-dependence fit:
  (window $\Lambda_{\mathrm{QCD}} \ll p \ll \frac{\pi}{a}$)

$$Z^{SI}(p^2) = Z_{\text{final}} + \underbrace{c_{NP}\frac{\Lambda_{QCD}^2}{p^2}}_{\text{nonpert.}} + \underbrace{c_2(ap)^2 + c_{[4]}\frac{a^4p^{[4]}}{(ap)^2}}_{\text{discretization}}$$

- Variation with p^2 fits ranges, pQCD 1-,2-loop matching → systematic uncertainty

Lattice QCD Result: Enhanced N⇔$\bar{\text{N}}$



Lattice QCD with physical-mass, chiral-symmetric quarks:

x(5-10) larger N-Nbar oscillation vs. nucleon Bag model

[E.Rinaldi, S.S., M.Wagman, et al, PRD99:074510 (2019)]
[E.Rinaldi, S.S., M.Wagman, et al, PRL122:162(2018)]

	$\mathcal{O}^{\overline{MS}}(2\text{ GeV})$	Bag "A"	$\frac{\text{LQCD}}{\text{Bag "A"}}$	Bag "B"	$\frac{\text{LQCD}}{\text{Bag "B"}}$
$[(RRR)_{\mathbf{3}}]$	0	0	–	0	–
$[(RRR)_{\mathbf{1}}]$	45.4(5.6)	8.190	5.5	6.660	6.8
$[R_{\mathbf{1}}(LL)_{\mathbf{0}}]$	44.0(4.1)	7.230	6.1	6.090	7.2
$[(RR)_{\mathbf{1}}L_{\mathbf{0}}]$	-66.6(7.7)	-9.540	7.0	-8.160	8.1
$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]^{(1)}$	-2.12(26)	1.260	-1.7	-0.666	3.2
$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]^{(2)}$	0.531(64)	-0.314	-1.7	0.167	3.2
$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]^{(3)}$	-1.06(13)	0.630	-1.7	-0.330	3.2
	$[10^{-5}\text{ GeV}^{-6}]$	$[10^{-5}\text{ GeV}^{-6}]$		$[10^{-5}\text{ GeV}^{-6}]$	

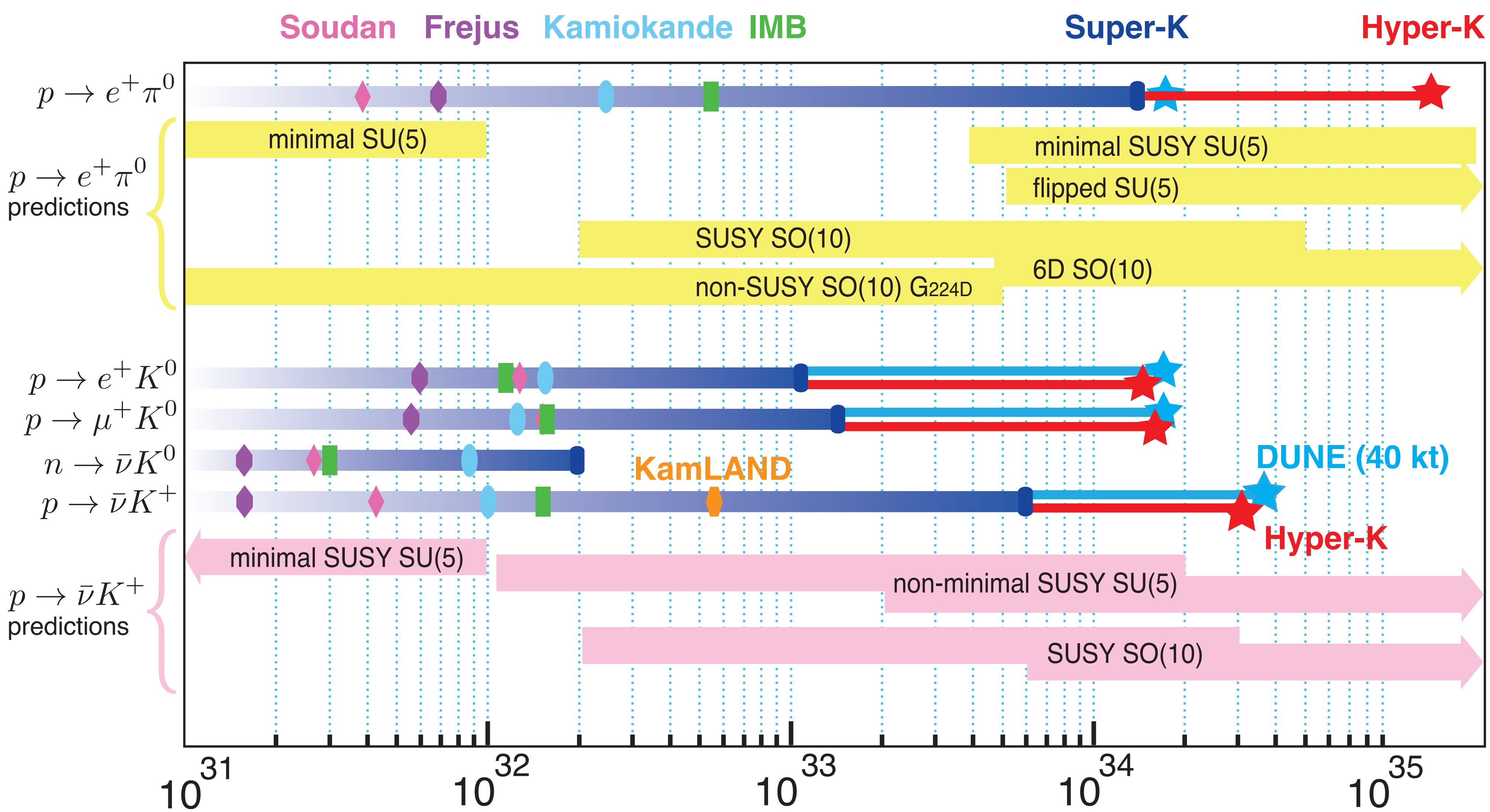
comparison to MIT Bag model [S.Rao, R.Shrock, PLB116:238 (1982)]

Next steps: non-quasi-free oscillation

- full systematic UQ : finite volume, continuum limit
- "crossed" 2-neutron annihilation amplitudes $\langle \text{vac}|O^{6q}|nn\rangle$
- Nuclear medium effects

Searches for Proton Decays

- Missing piece of Grand-Unified Theories
- Limits on stability of nuclear matter

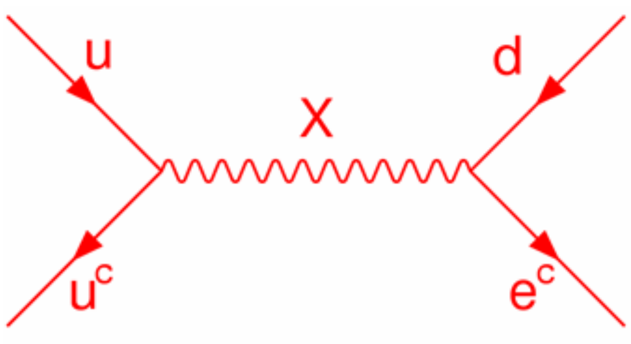


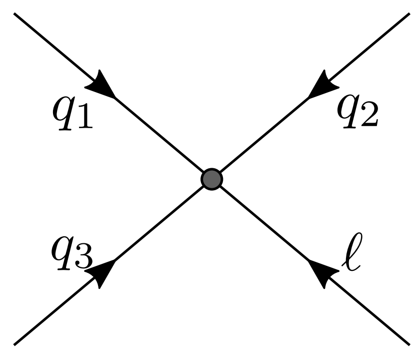
[LBNF and DUNE CDR, R.Acciarri et al (2015)]

- Expect x10 improvement on lifetime limit from Hyper-K and DUNE
- Better sensitivity to $p \to \bar{\nu}K^+$ that affects supersymmetric GUT models

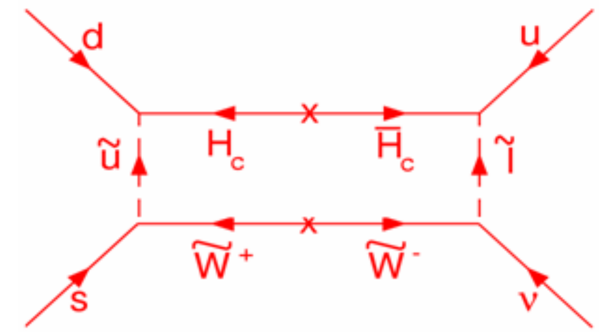
Proton Decay Amplitudes and Rate

ordinary GUT





supersymmetric GUT



- Effective interaction

$$\mathcal{L}_{\rm eff} = \sum_I C_I \mathcal{O}_I \; + \; \text{h.c.}$$

$$\mathcal{O}_I = \epsilon^{abc} (\bar{q}_1^{aC} P_{\chi_I} q_2^b)(\bar{\ell}^C P_{\chi_I'} q_3^c) = \bar{\ell}^C_\alpha \, \mathcal{O}^{3q}_{I,\alpha}$$

$$q_{1,2,3} \in \{u, d, s\} \, , \qquad P_{\chi_I^{(\prime)}} = \frac{1 \pm \gamma_5}{2}$$

- Decay width $p \rightarrow \Pi \bar{\ell}$ $\quad (\Pi = \pi, \mathrm{K}, \eta)$

$$\Gamma(p \to \Pi \bar{\ell}) = \frac{m_N}{32\pi} \left[1 - \left(\frac{m_\Pi}{m_N} \right)^2 \right]^2 \Big| \sum_I C_I W^I_{\bar{\ell}} \Big|^2$$

where $W_{\bar{\ell}} = \Big[W_0 + \underbrace{W_1 \cdot O(m_{\bar{\ell}}/m_N)} \Big]_{q^2 = m^2_{\bar{\ell}}}$

negligible for e^+
≈10% for μ^+

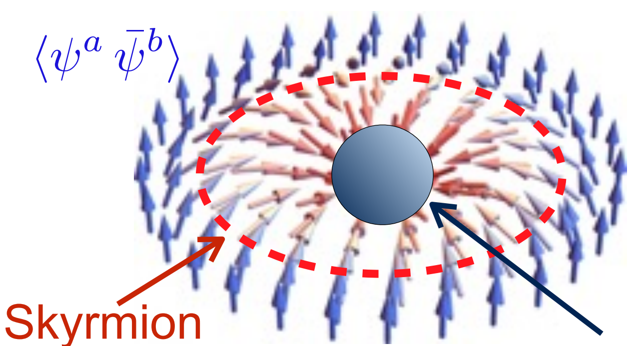
- Decay matrix elements $(W_{0,1})_I$ [S.Aoki et al, PRD62:014506 (2000)]

$$\langle \bar{\ell}(q) \Pi(p) | \mathcal{O}^{\chi'} | N(k) \rangle = \bar{v}^C_{\ell\alpha}(q) \, P_{\chi'} \left[W_0(-q^2) - \frac{i \not{q}}{m_N} W_1(-q^2) \right] u_N(k)$$

Proton Decay Matrix Elements

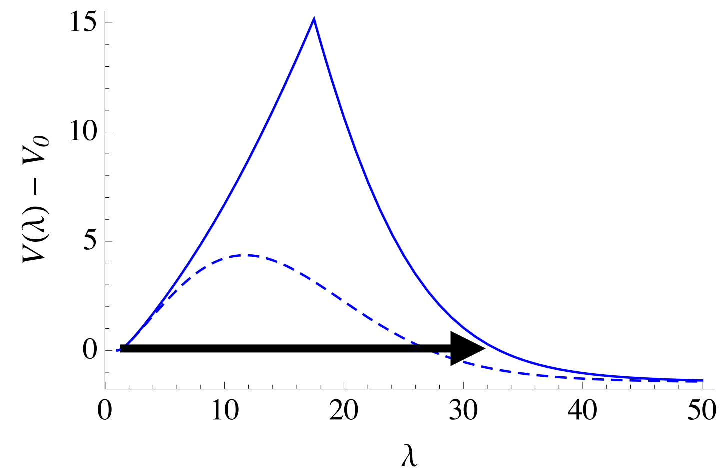
Is proton inherently stable?

Conjecture [A.Martin, G.Stavenga '12]
Topological stability of "Chiral Bag" proton :



Skyrmion
(fig. [Zhang et al])

Free-Quark "Bag"

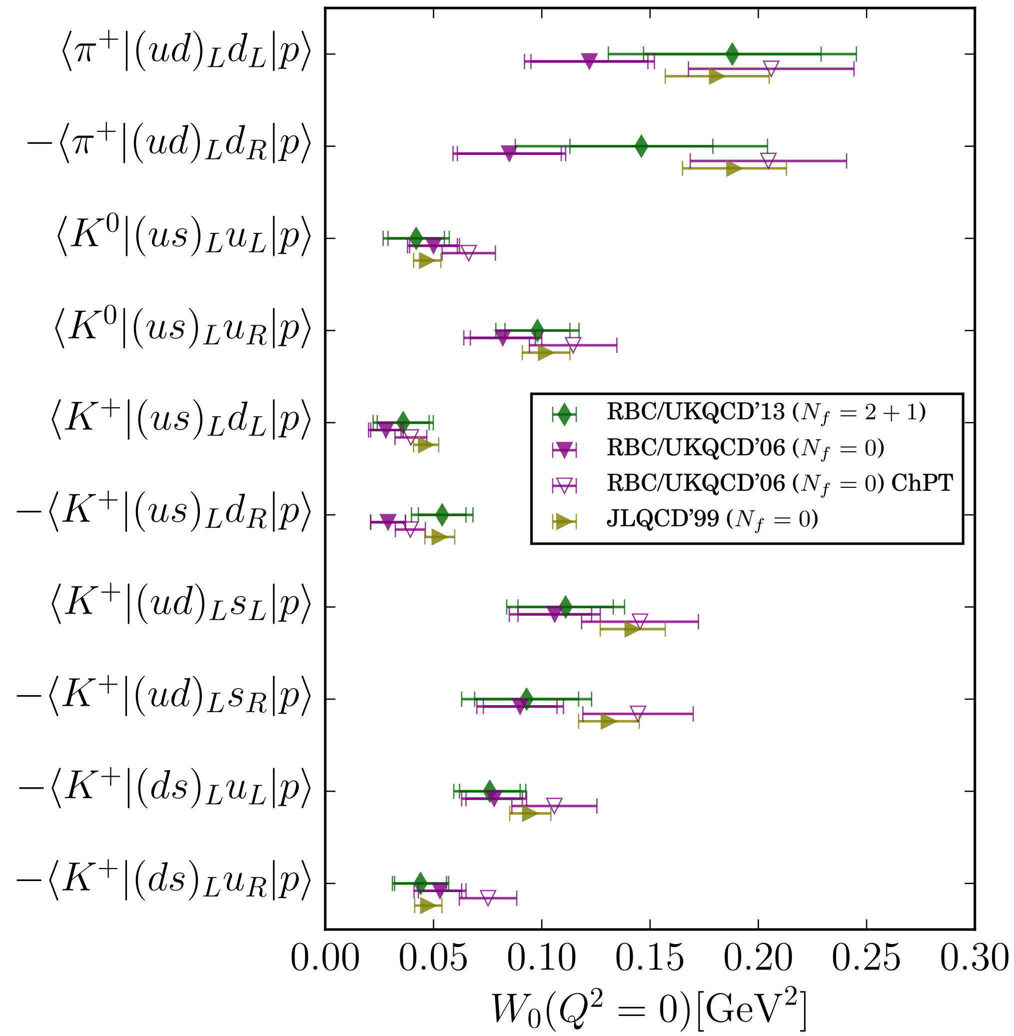


Lattice calculations:

- "direct" $p \to \pi\bar\ell, K\bar\ell$ decay matrix elements
  prior work at mπ ≳300 MeV:[S.Aoki et al (2000)]
  [Y.Aoki et al (2006), (2013), (2017)]
- "indirect" $p \to \textbf{vacuum}$ proton "decay constants"
  + LO-ChPT

Nucleon-to-meson amplitudes
($p \to \pi\bar\ell, K\bar\ell,$ decays)

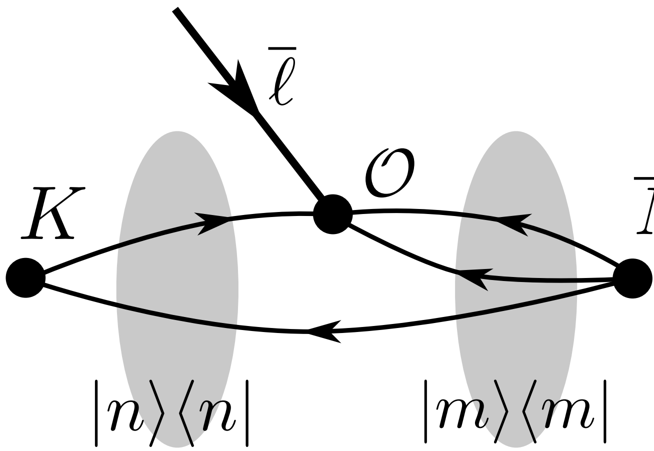
lattice calculations
with $m_\pi \gtrsim 330$ MeV



Topological stability may strongly depend on quark mass , chiral symmetry
$\Longrightarrow$ *Realistic physical-point calculation is necessary*

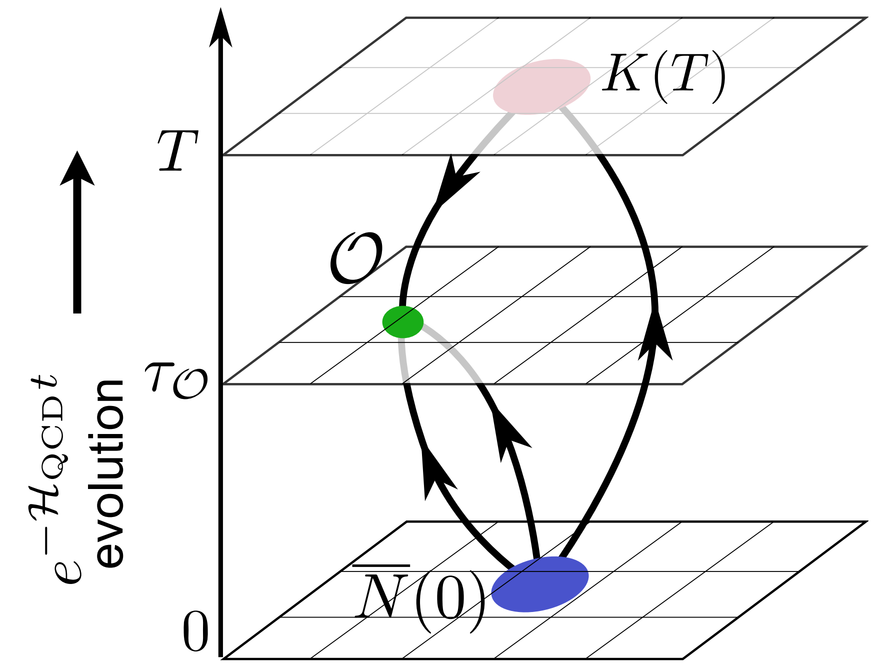
Proton→Meson Correlators in Lattice QCD

$$C_{3\mathrm{pt}}^{K\mathcal{O}N} = \langle K(T)\mathcal{O}(\tau)\overline{N}(0)\rangle =$$



$$= \sum_{m(K),n(N)} Z_m e^{-E_m(T-\tau)} \langle m(K)|\mathcal{O}|n(N)\rangle e^{-E_n\tau} Z_n^*$$

(Fit lattice data with $n,m = 0,1$)

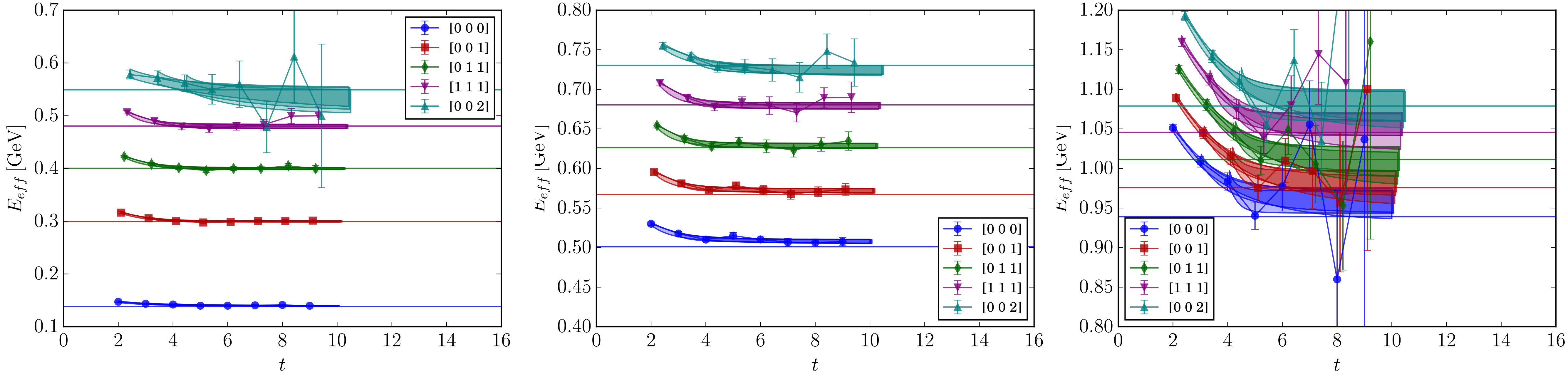


Quark lines = $(\not{D} + m)^{-1} \cdot \psi$

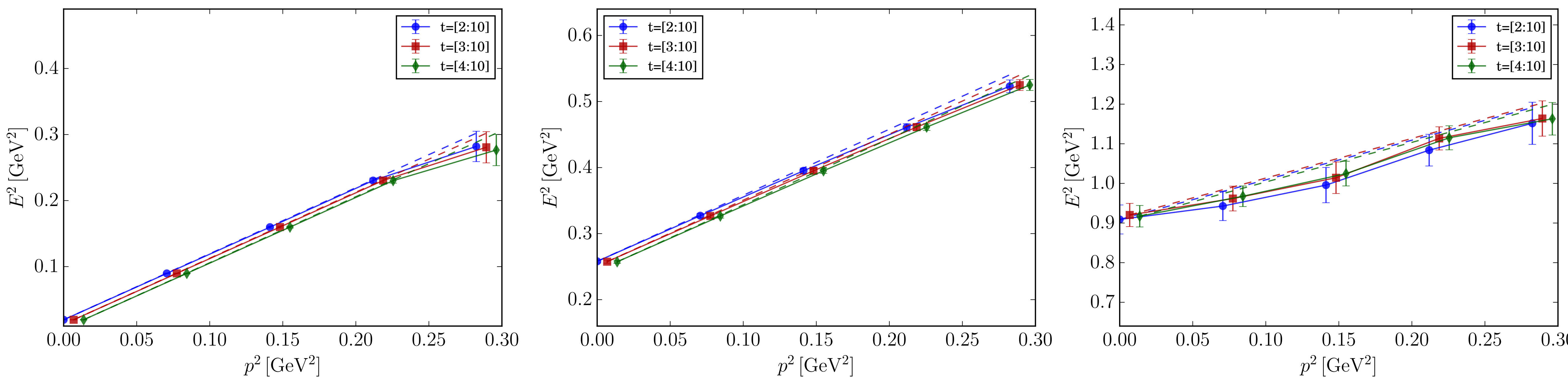
- Two lattice field ensembles:
  - $32^3{\times}64(a{=}0.14\text{ fm})$ [32ID]
  - $24^3{\times}64(a{=}0.20\text{ fm})$ [24ID]
- Chirally-symmetric (Mobius-)Domain Wall fermion action with physical light and strange quark masses
- Iwasaki gauge action+ Dislocation-supp. det.ratio (DSDR)

Proton and Meson Spectrum

- hadron effective energies



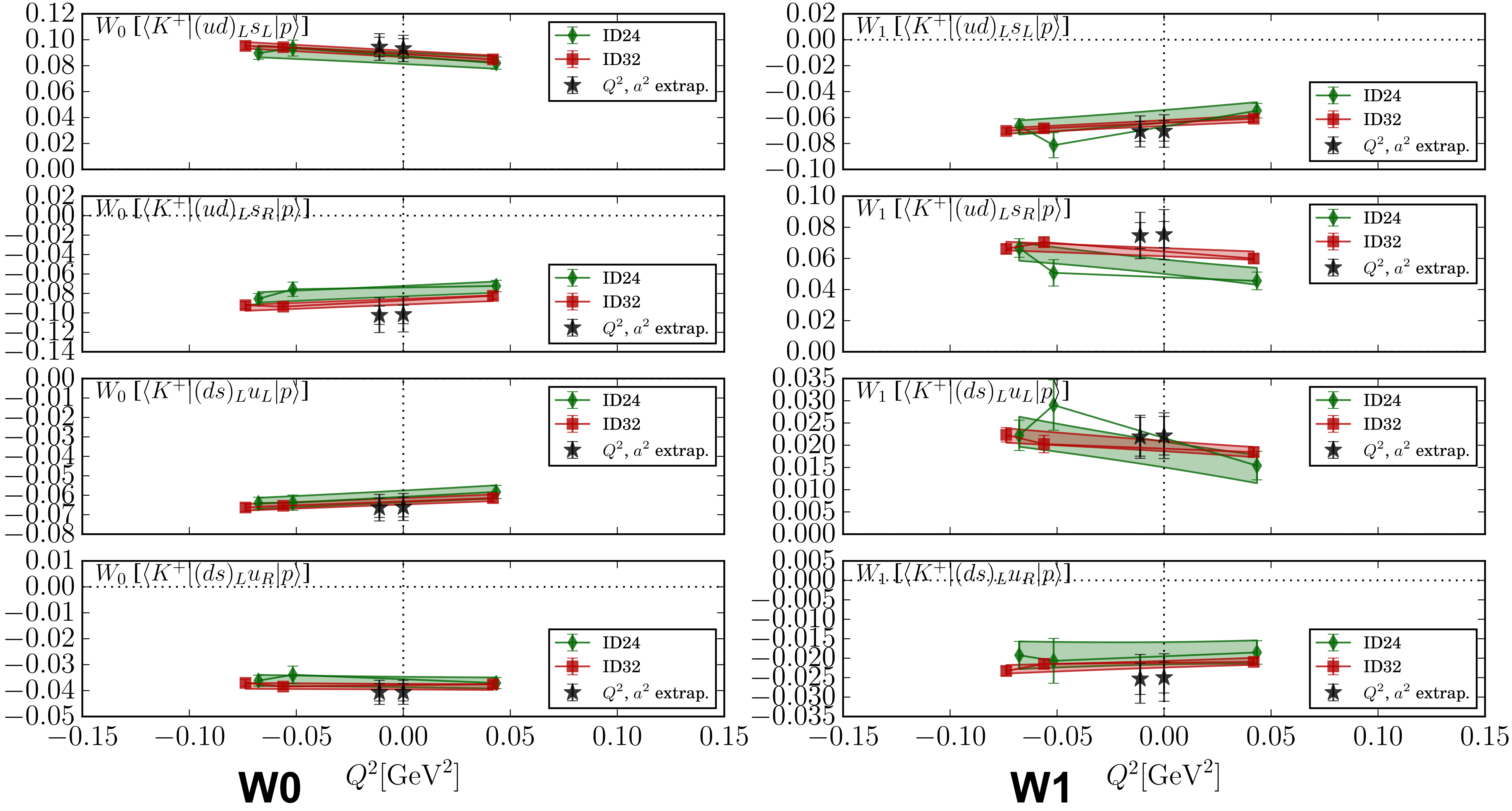
- hadron dispersion relations $E^2(p^2)$



pion **kaon** **nucleon**

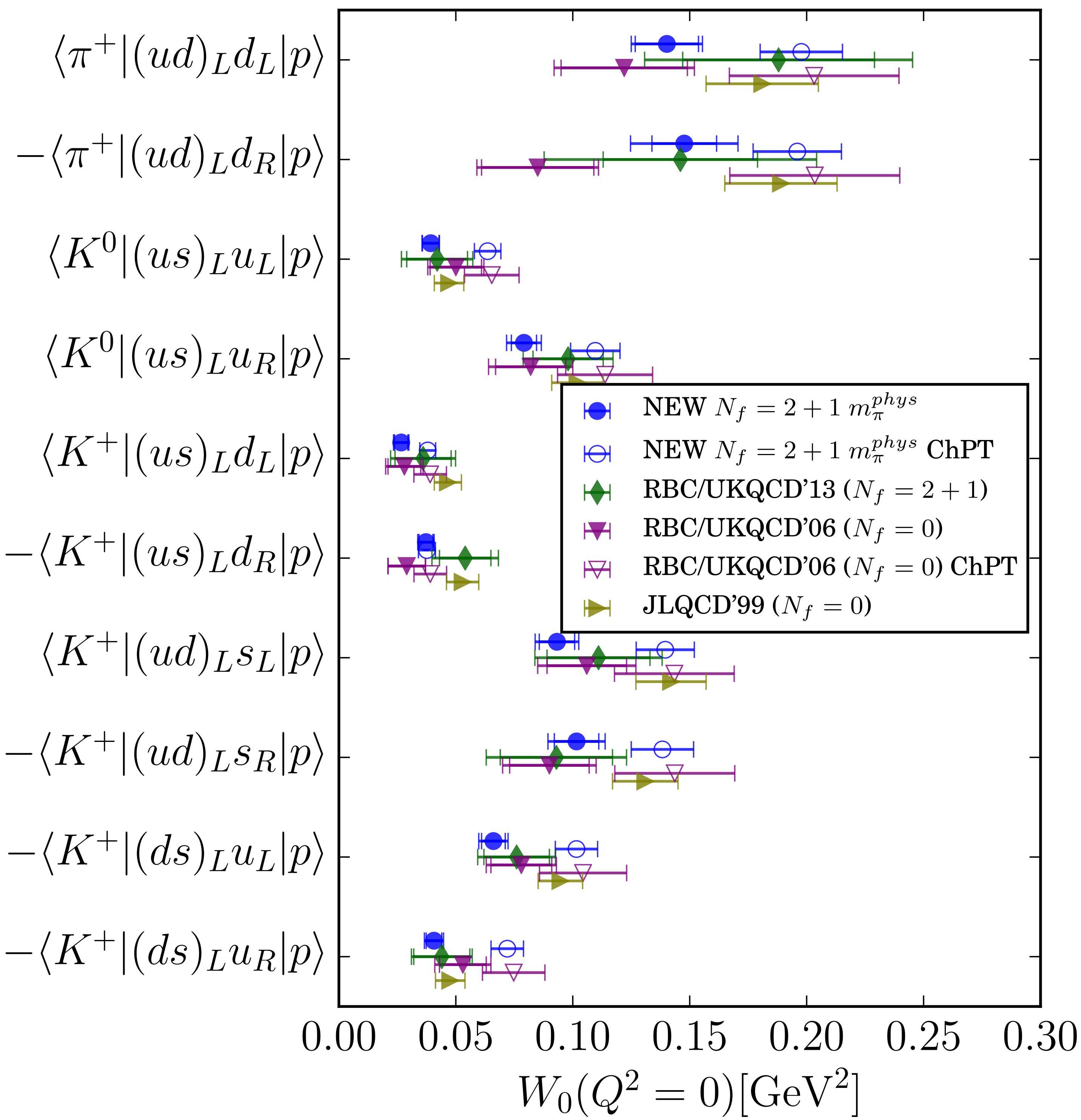
- 24ID ensemble (lattice spacing a=0.20 fm, $a^{-1} \approx 1$ GeV)
- Two-state fits + priors from large-t_{min} one-state fits

Momentum and Continuum Extrapolation



- linear momentum extrapolation $Q^2 \rightarrow m_e^2, m_\mu^2$ to the decay kinematics
- Continuum extrapolation $A(a^2) \sim (A_0 + A_2\, a^2)$; sys.error = $|A_0 - A_{[a=0.14\mathrm{fm}]}|$

Comparison to Previous Work

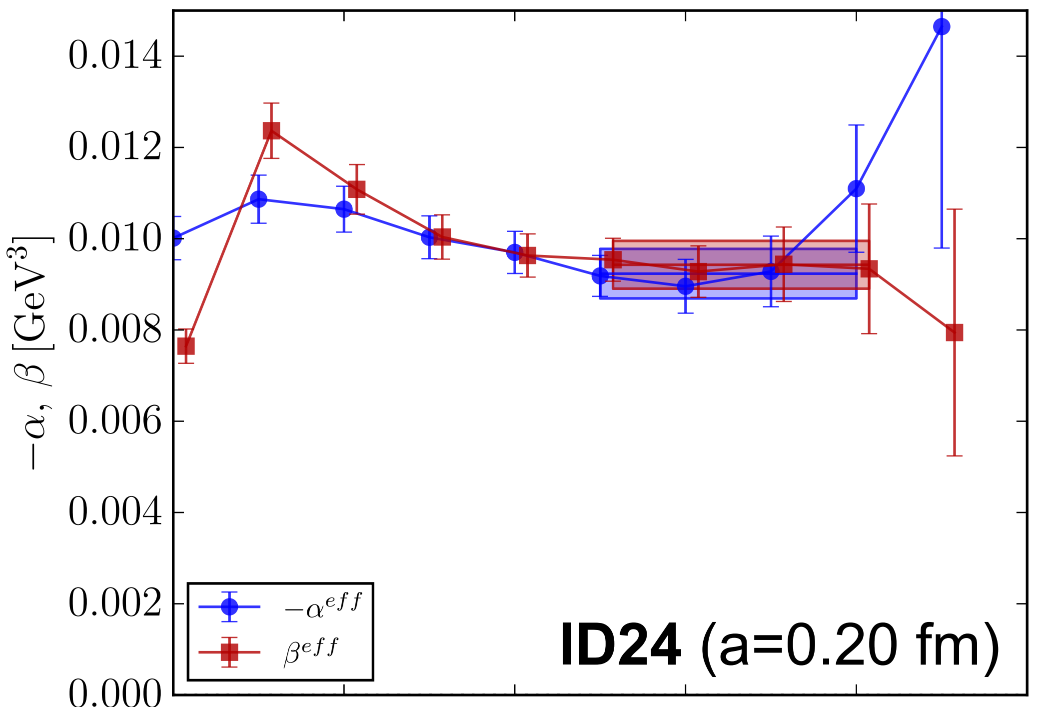


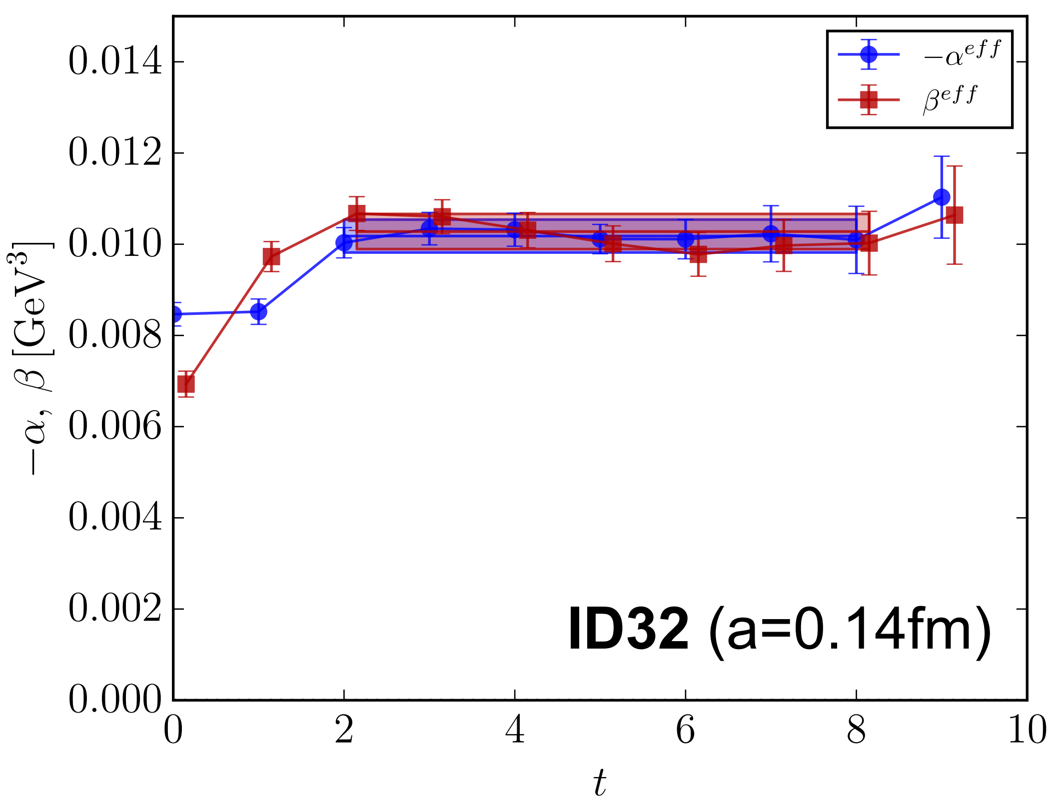
[J. Yoo, SS, et al, PRD105:074501 (2021)]

- New results:
  conservative sys. errors
  (stat+sys) precision ~ 10-20%
- No FVE study, mπ L~3.4
- physical-point results agree with prev. calculations at mπ ≳300 MeV
  [S.Aoki et al (2000)]
  [Y.Aoki et al (2006)]
  [Y.Aoki et al (2013)]

No suppression of nucleon decay due to chiral skyrmion topology

Proton Annihilation Amplitudes

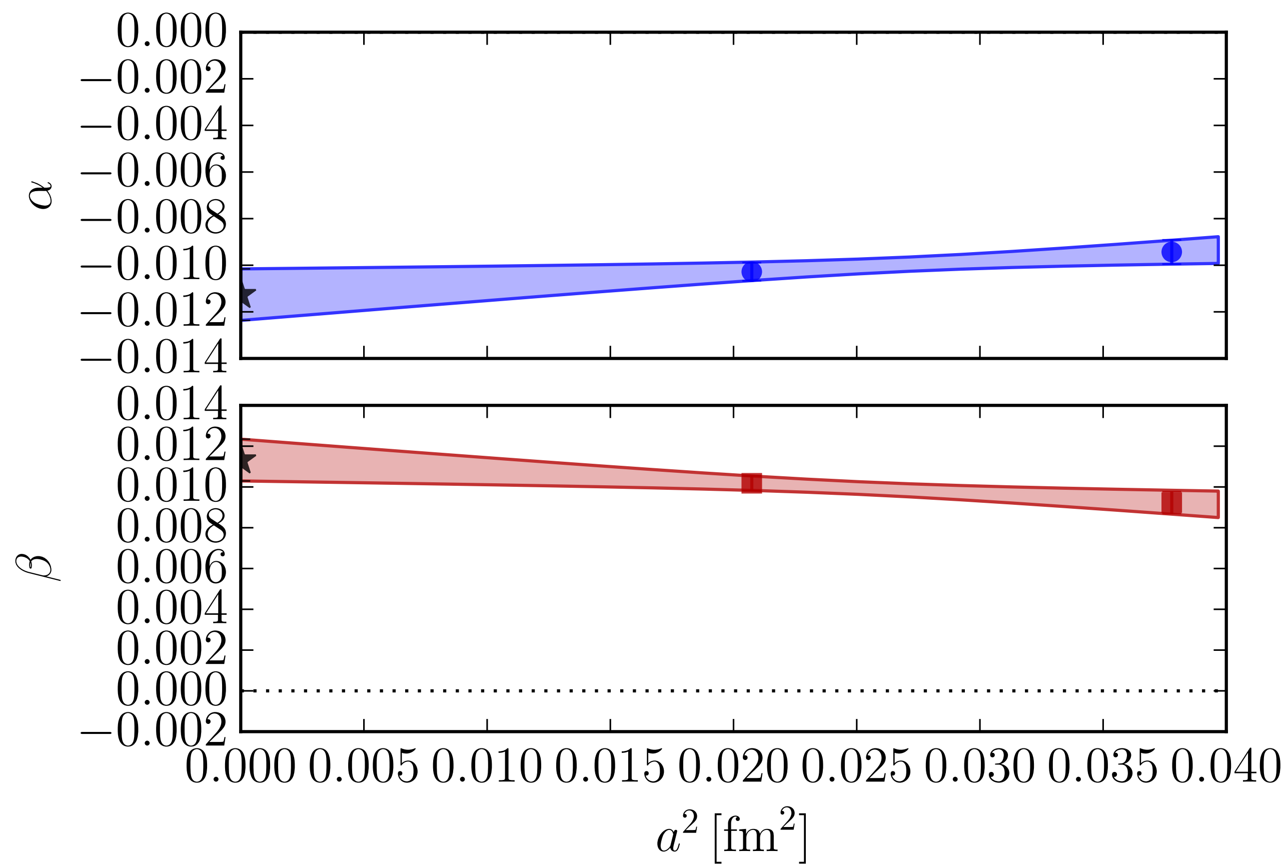




$$\langle \mathrm{vac}|\epsilon^{abc}(\bar{u}^{aC}d^b)_R u^c_L|N\rangle = \alpha\, P_L U_N$$

$$\langle \mathrm{vac}|\epsilon^{abc}(\bar{u}^{aC}d^b)_L u^c_L|N\rangle = \beta\, P_L U_N$$

- $\langle \pi/\mathrm{K}|O^{3q}|N\rangle$ with soft-pion theorem
- nonpert.QCD component of $p \to 3\ell$



Summary & Conclusions

- Amplitudes of quark BNV operators computed in lattice QCD with realistic, chirally-symmetric quarks

- Neutron-antineutron oscillation

  Amplitudes × (6 ... 8) larger than from pheno.models

  Continuum limit study pending

  NEXT: nn→vacuum amplitudes, n→$\bar{n}$ in nuclear medium

- Proton decays p→π/K, p→leptons

  No topological suppression of nucleon decay found; confirm limits on GUTs

  Finer spacing, larger volume calculations desirable

  Need NLO ChPT for p→π/K : cross-check vs. p→vacuum amplitude

  NEXT: p→ρ→$\pi\pi$, p→K→πK amplitudes*

BACKUP

This Work: Lattice Setup

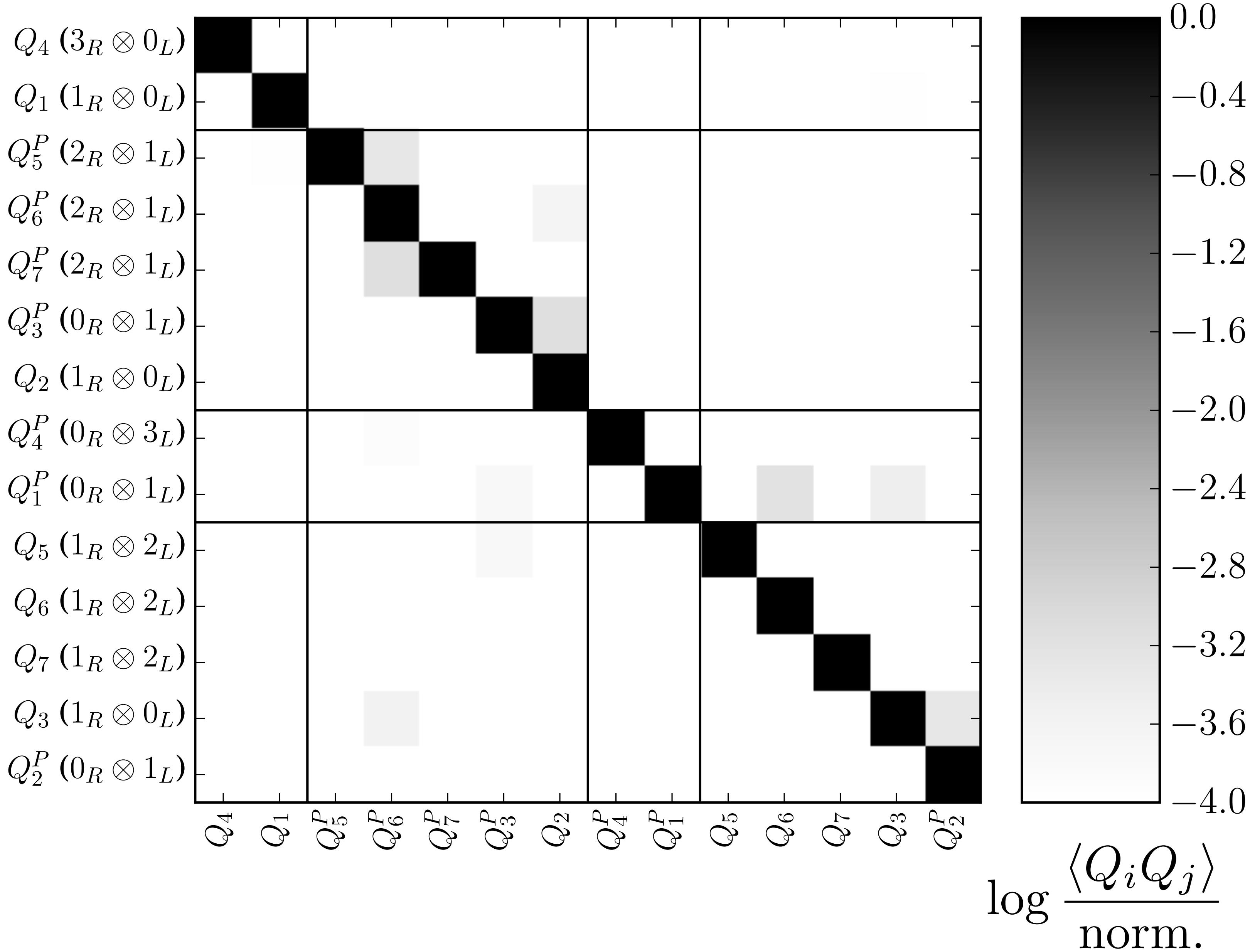
- Two ensembles: [32ID] $32^3 \times 64 (a = 0.14\ \mathrm{fm})$ and [24ID] $24^3 \times 64 (a = 0.20\ \mathrm{fm})$
- Iwasaki gauge action+ Dislocation-supp. det.ratio (DSDR)
- $N_f = 2+1$ Chirally-symmetric (Mobius-)Domain Wall fermion action with physical light and strange quark masses
- Multigrid deflation of z-Mobius operator + AMA
- "Direct" ($p \to \pi, K$ matrix elements) and "Indirect" ($p \to \mathrm{vacuum}$ + ChPT)
- Nonperturbative renormalization
- Two state-fit analysis of π, K, N spectrum and $p \to \pi, K$ matrix elements
- a^2 Continuum extrapolation

	24ID $24^3 \times 64$	32ID $32^3 \times 64$
β	1.633	1.75
a, fm	0.20	0.14
a^{-1}, GeV	1.02	1.37
$m_\pi L$	3.4	3.3
N_{conf}	134	94
N_{samp}	4288	3008

- three kinematic (Q^2) points to interpolate matrix elements to decay kinematic $Q^2 = -(m_{\bar{\ell}})^2$

Π	$\vec{n}_\Pi$	$\vec{n}_N$	$Q^2(\mathrm{GeV}^2)$ (24c)	(32c)
π	[1 1 1]	[0 0 0]	0.010	−0.012
	[1 1 1]	[0 1 0]	0.113	0.095
	[0 0 2]	[0 0 0]	−0.116	−0.140
K	[0 1 1]	[0 0 0]	−0.034	−0.042
	[0 1 1]	[0 1 0]	0.058	0.056
	[0 0 1]	[0 0 0]	0.075	0.074

Nonperturbative Mixing of ⟨n̄|Q|n⟩ Operators

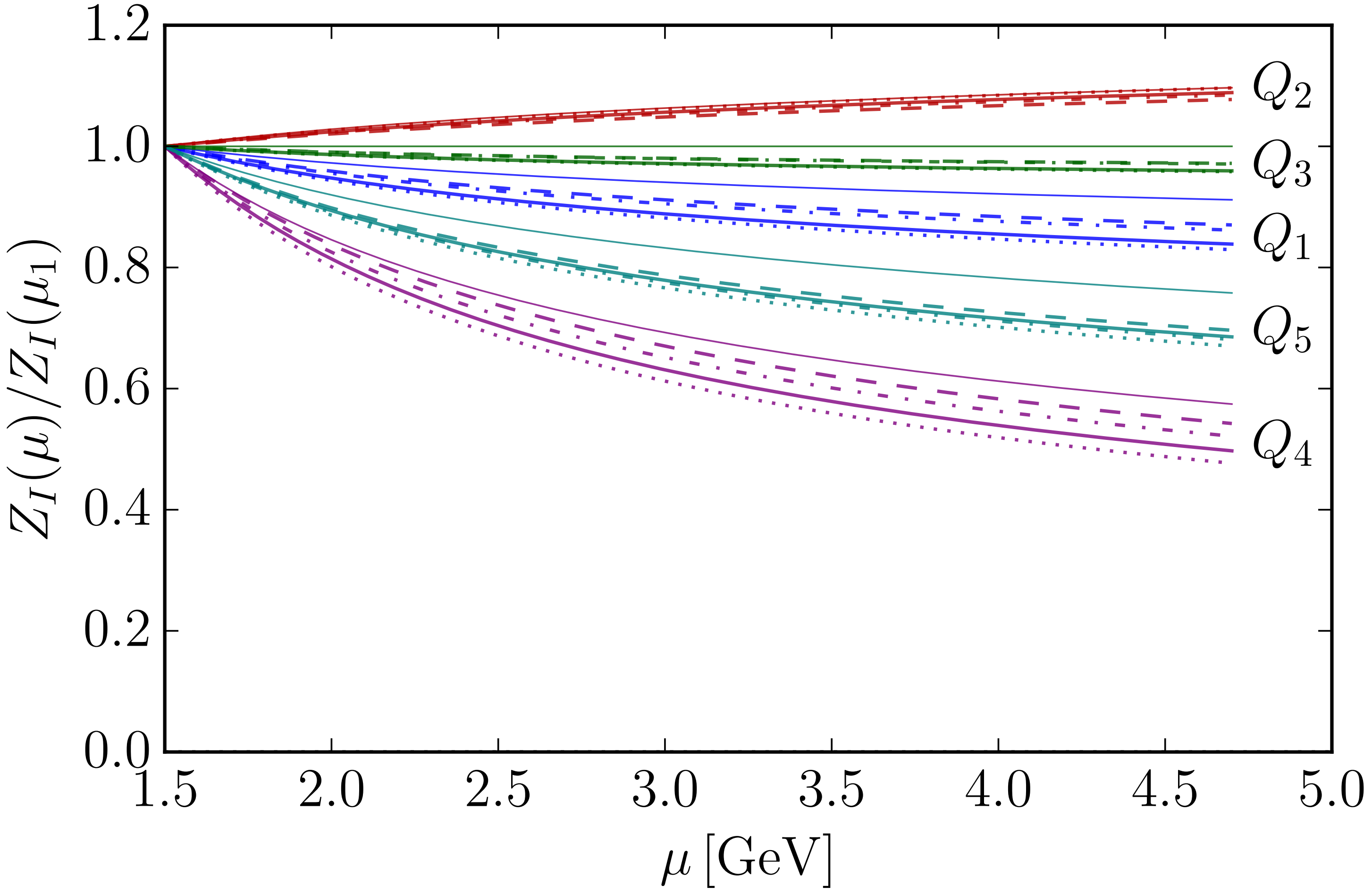


Nonperturbative mixing, normalized by diagonal ⟨Q_i Q_i⟩ correlators

- RI-MOM scheme: N_f=3 (solid) and N_f=4 (dotted)
- MSbar scheme: N_f=3 (dashed) and N_f=4 (dash-dotted)

Negligible mixing due to chiral symmetry of quark action

Perturbative Running of ⟨$\overline{\text{n}}$|Q|n⟩ Operators



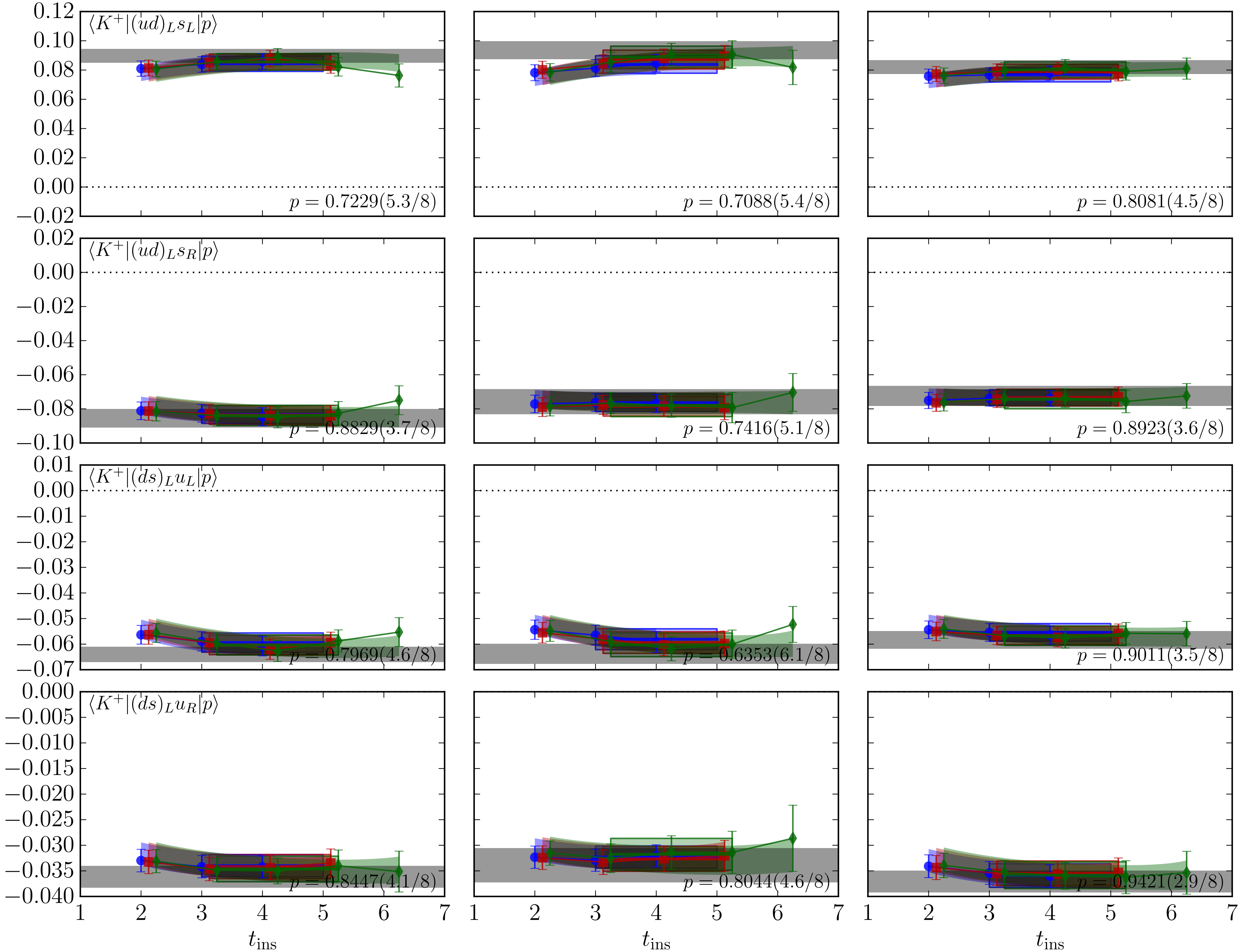
Perturbative running

- RI-MOM scheme: N_f=3 (solid) and N_f=4 (dotted)
- MSbar scheme: N_f=3 (dashed) and N_f=4 (dash-dotted)

Extraction of Matrix Elements

32ID

W₀



- Two-state fits with energies fixed from spectrum fits

Nonperturbative Renormalization

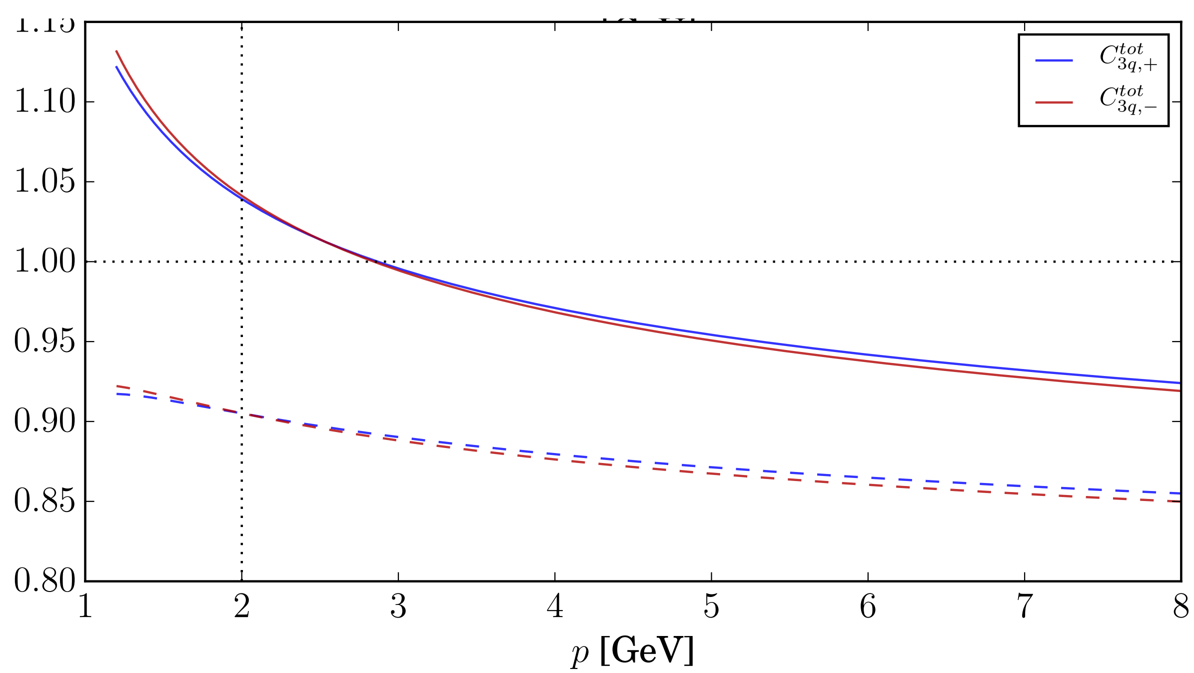
- symmetry-allowed mixing

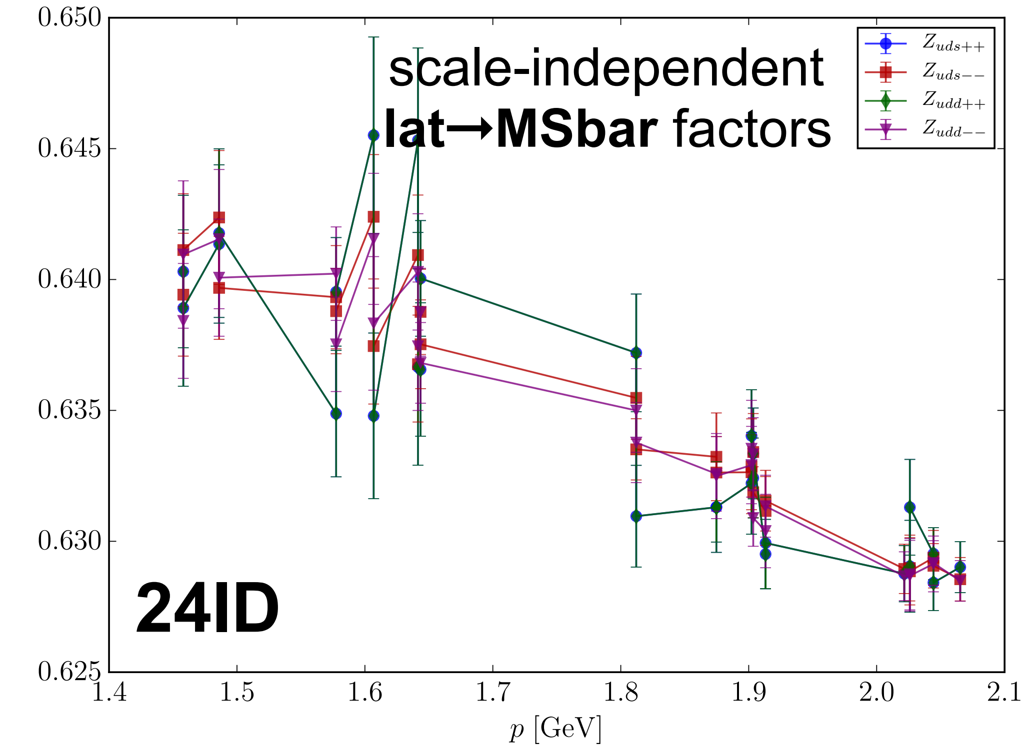
	$\mathcal{S}=-1$	$\mathcal{S}=+1$
$\mathcal{P}=-1$	$SS,\ PP,\ AA$	$VV,\ TT$
$\mathcal{P}=+1$	$SP,\ PS,\ AV$	$VA,\ TQ$

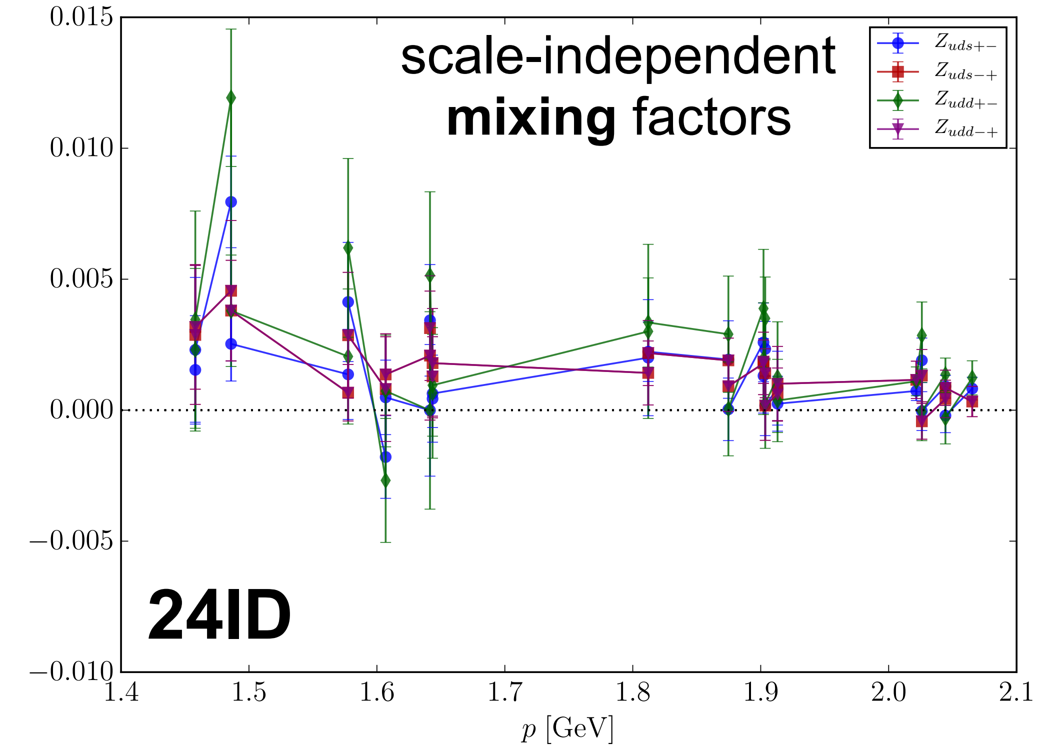
- *symmMOM* scheme : $p+q+r=0,\ \ p^2=q^2=r^2=\mu^2$

$$Z^{3q}_{IK}(\mu)\ \mathrm{Proj}_J\left[\langle\bar q_1(p)\bar q_2(q)\bar q_3(r)\,\mathcal{O}^{3q}_K\rangle_{\mathrm{amp}}\right]=\delta_{IJ}$$

- symmMOM(p)→MSbar(2 GeV) perturbative conversion at $O(\alpha^3)$ [J.Gracey, JHEP09:052 (2012)]







- chiral symmetry suppresses mixing of L⟺R fields & operators