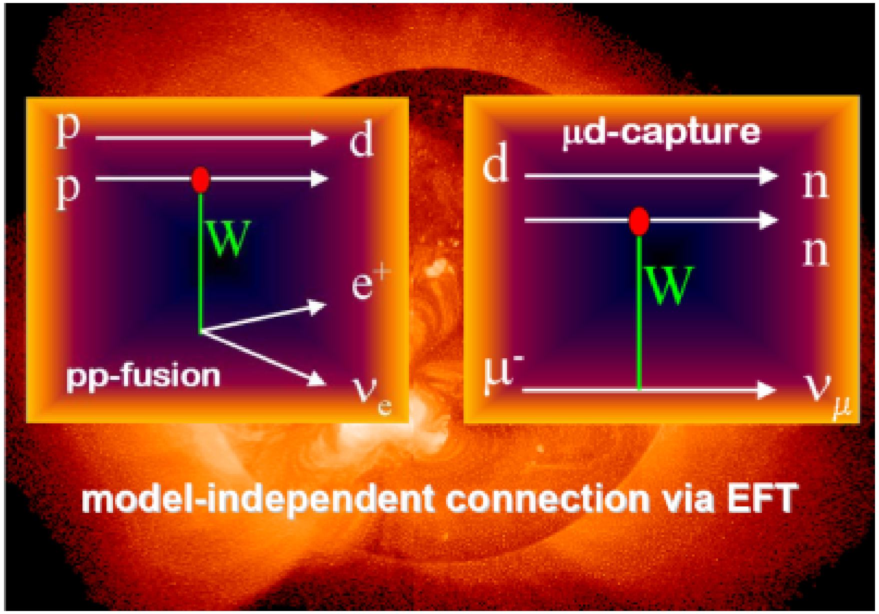
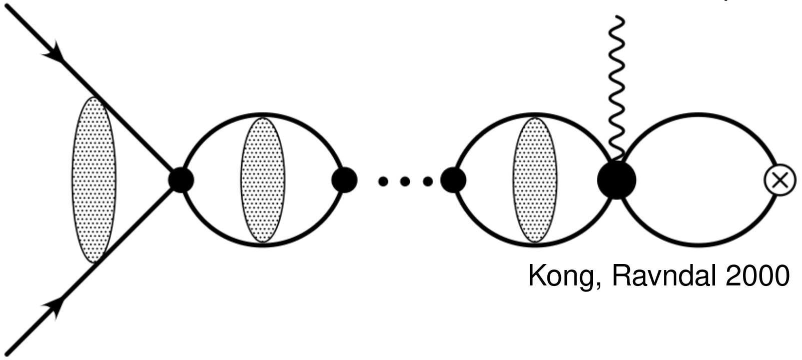
A preview from NPLQCD

Weak Nuclear Reactions

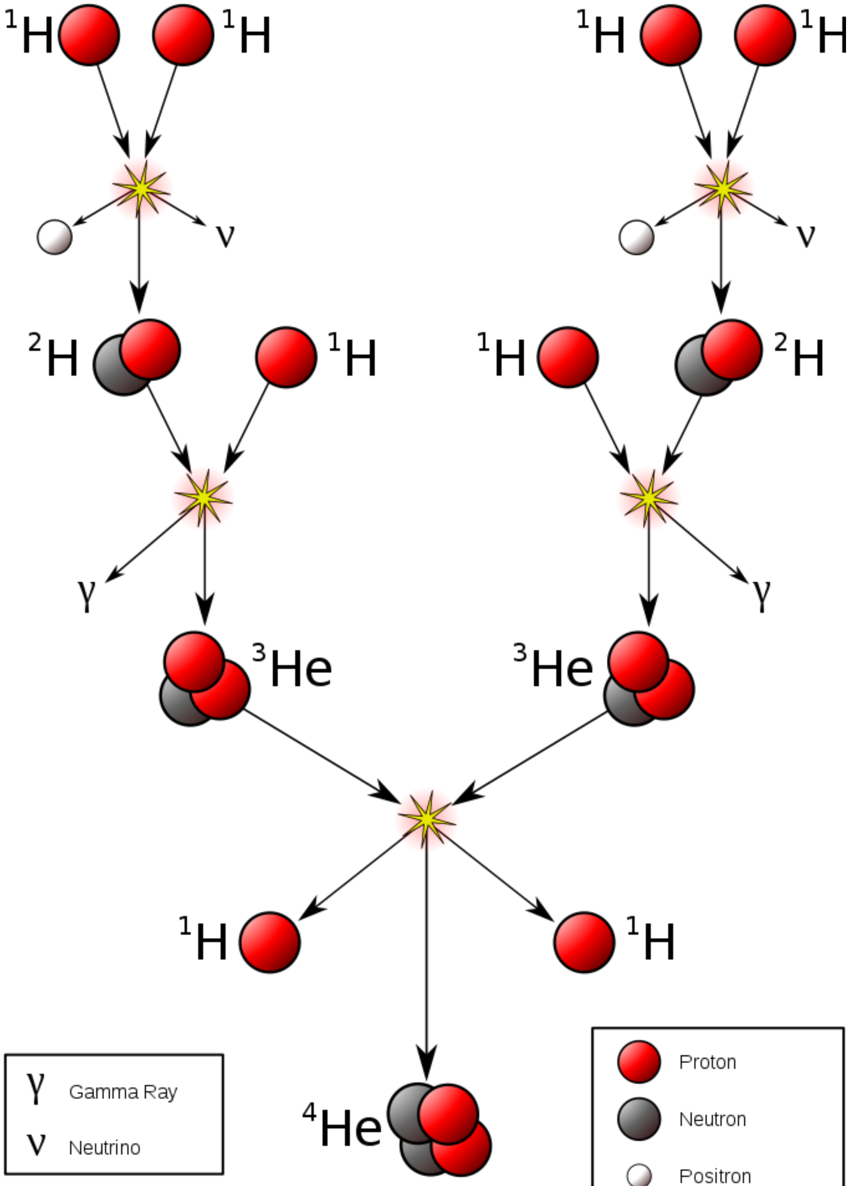


Mu Sun Experiment

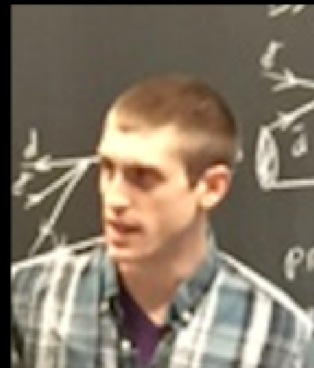
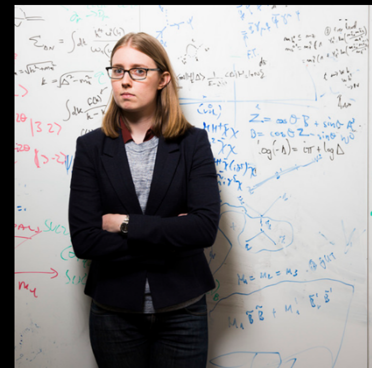


Kong, Ravndal 2000

See talks by
Saori Pastore last week
Hermann Krebs yesterday



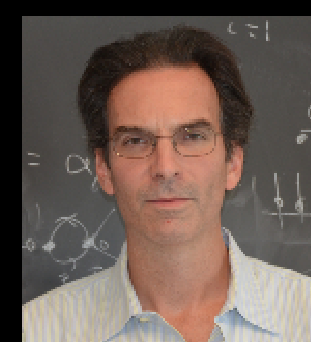
https://commons.wikimedia.org/wiki/File:FusionintheSun.svg

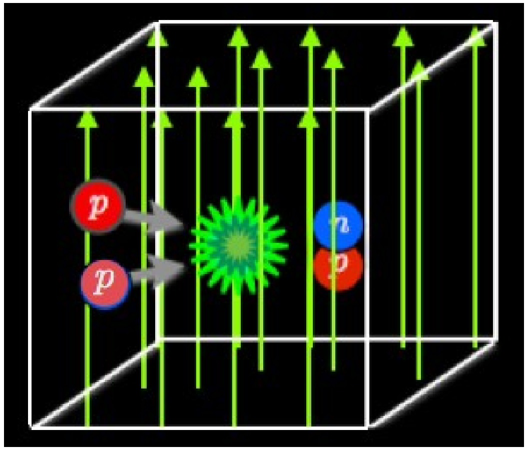


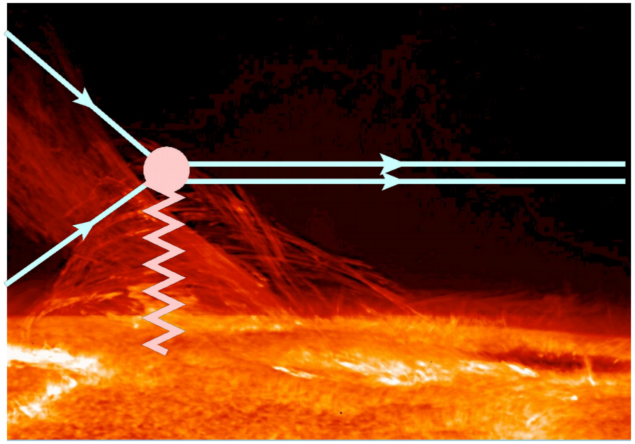

NPLQCD



Proton-Proton Fusion and Tritium Beta-Decay from Lattice QCD



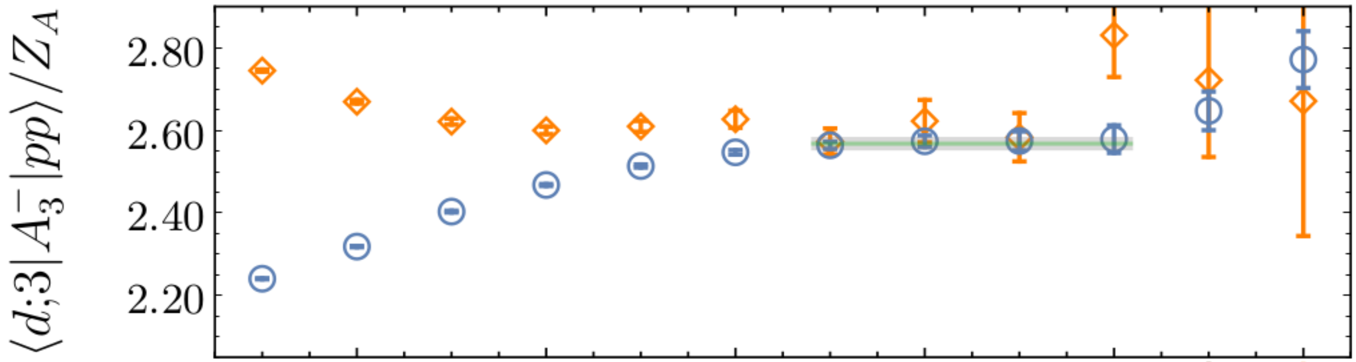


$$\frac{g_A(^3H)}{g_A} = 0.979(3)(10)$$

$$m_\pi \sim 800 \text{ MeV}$$

$$L_{1,A} = 3.9(0.1)(1.0)(0.3)(0.9) \text{ fm}^3$$

$$\Lambda(0) = 2.6585(6)(72)(25)$$



m_q extrapolation uncertainty

800 MeV NPLQCD ensembles with compound propagator background axial fields

Neutron-Antineutron Matrix Elements and Renormalization

Michael Wagman (UW/INT)

Frontiers in Nuclear Physics, KITP

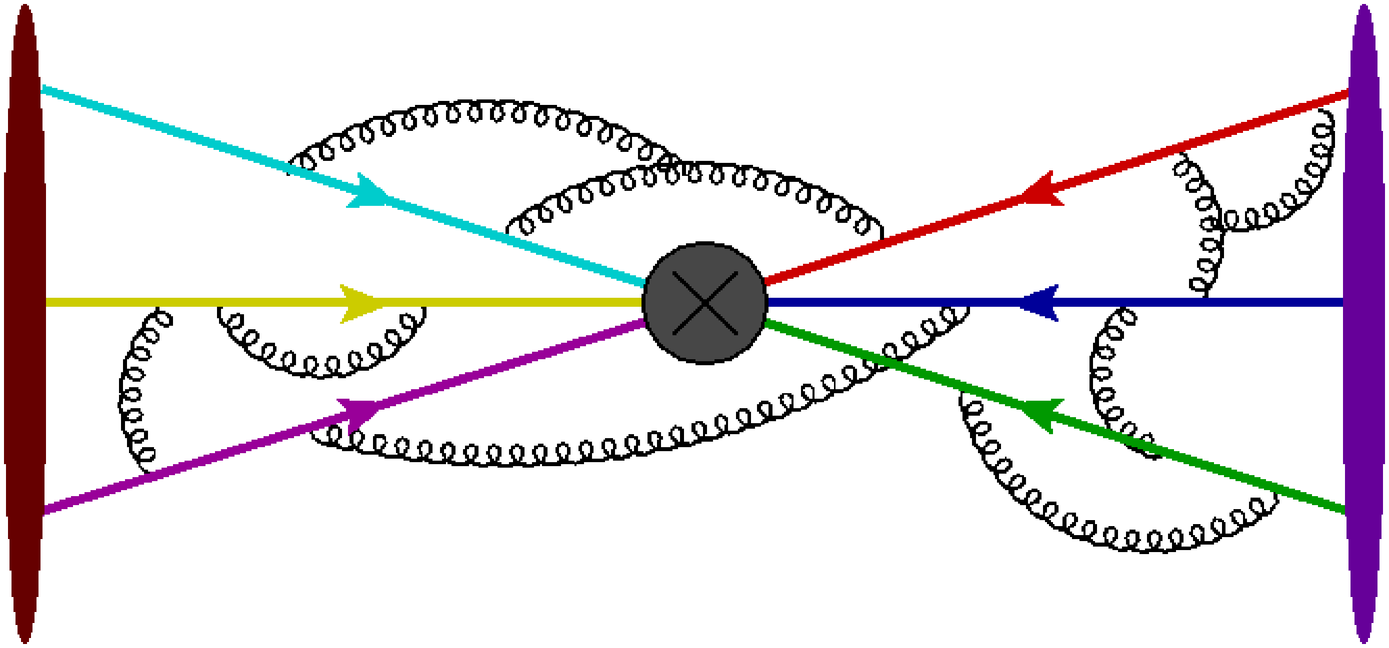
with Michael Buchoff, Enrico Rinaldi, Chris Schroeder, and Joseph Wasem (LLNL), and Sergey Syritsyn (Jefferson Lab/Stony Brook)

Neutron-Antineutron Oscillations

$n\bar{n}$ violates fundamental symmetries of baryon number and $B - L$, sensitive to different physics than proton decay

Testable signature of possible BSM baryogenesis mechanisms explaining matter-antimatter asymmetry

See Rabindra Mohapatra's conference talk



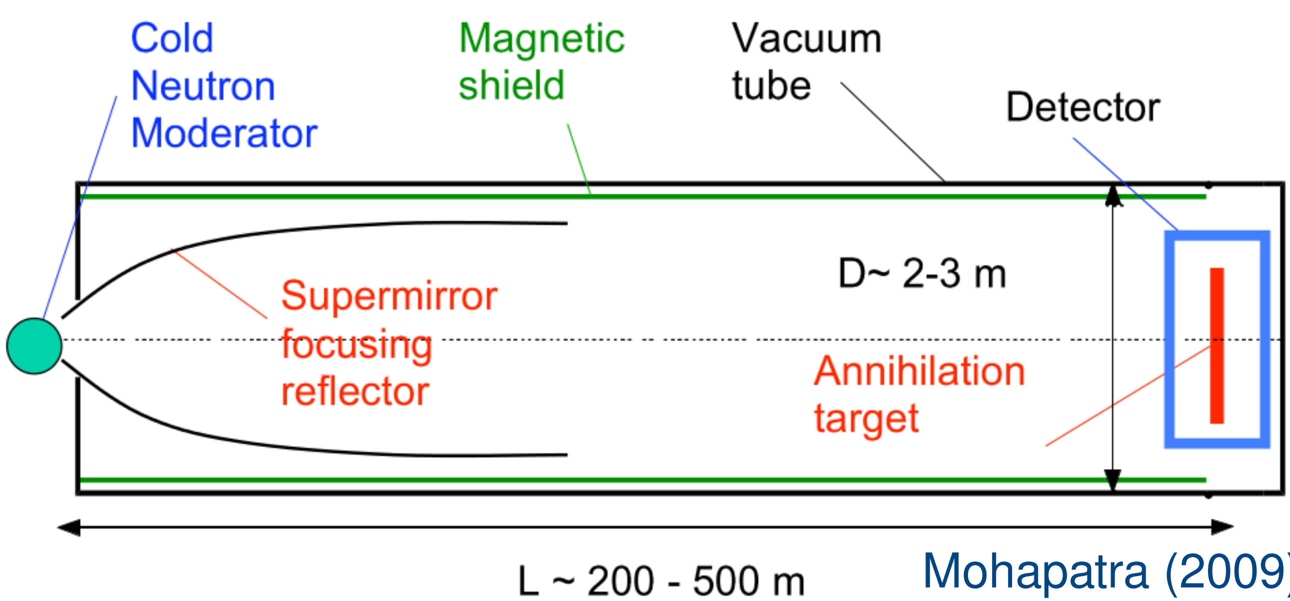
Neutron-Antineutron Phenomenology

Similarities to kaon, neutrino oscillations

$$P_{n\bar{n}}(t) = \sin^2(t/\tau_{n\overline{n}})e^{-\Gamma_n t} \qquad \frac{1}{\tau_{n\overline{n}}} = < \bar{n}|H_{n\bar{n}}|n >$$

Magnetic fields, nuclear interactions modify transition rate

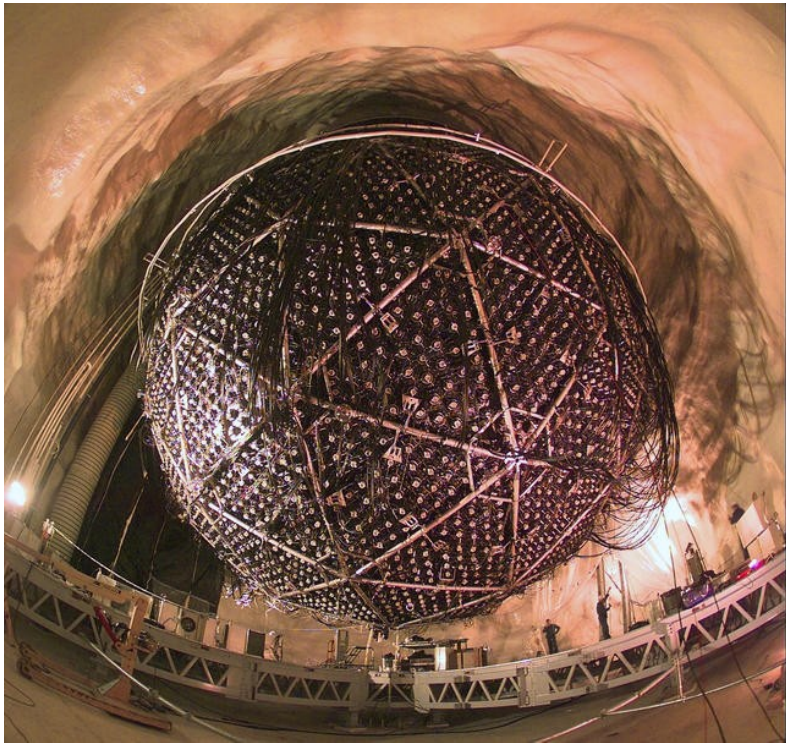
See Susan Gardner's talk



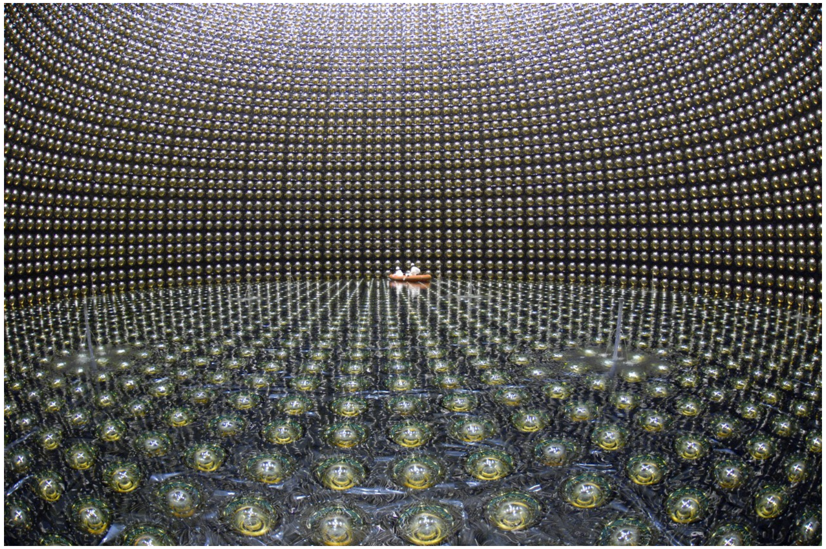
Mohapatra (2009)

Experimental Constraints

ILL: $\tau_{n\bar{n}} > 2.7$ years



SNO: $\tau_{n\bar{n}} > 5.7$ years (preliminary)



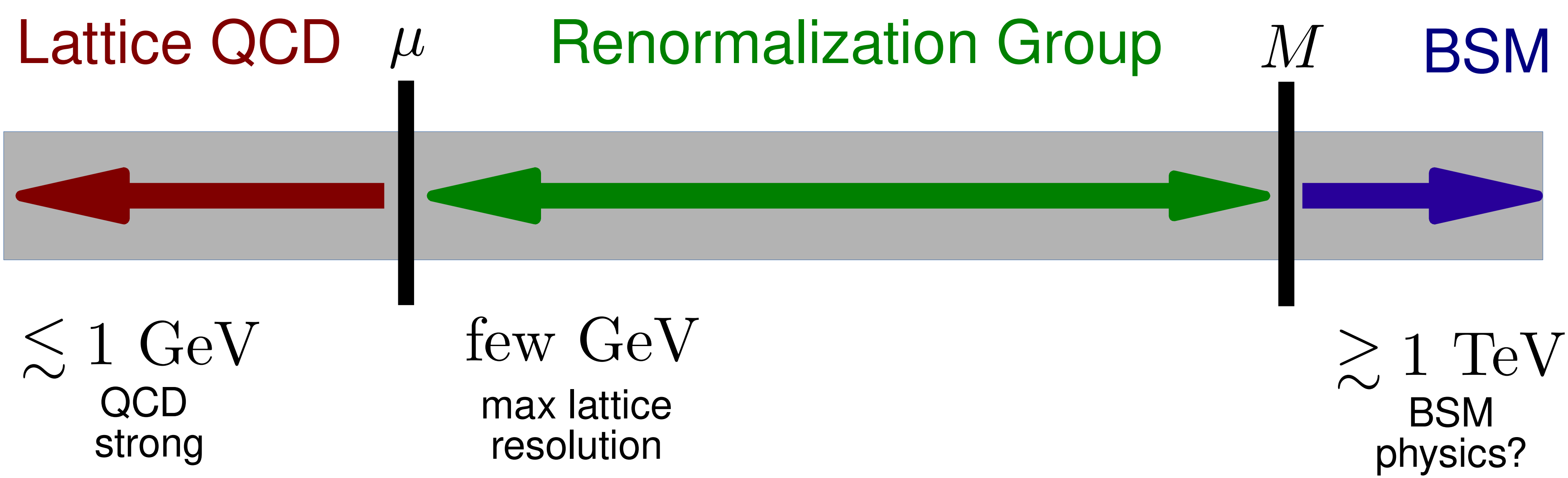
Super K: $\tau_{n\bar{n}} > 11$ years

Experimental Outlook

European Spallation Source could have 1000 times ILL sensitivity, probe 30 times higher $\tau_{n\bar{n}}$ within next decade

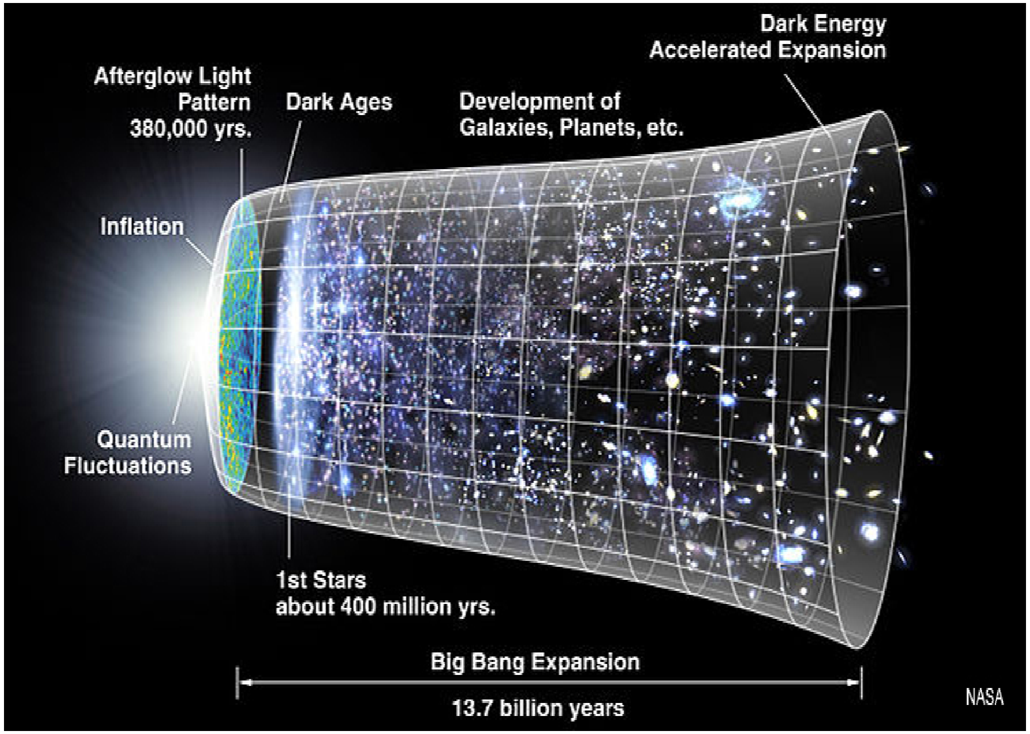
Neutron-Antineutron Theory: The Standard Model and Beyond

Theory must make robust predictions for $\tau_{n\bar{n}}$ to reliably interpret the constraints from these experiments



Matter-Antimatter Asymmetry

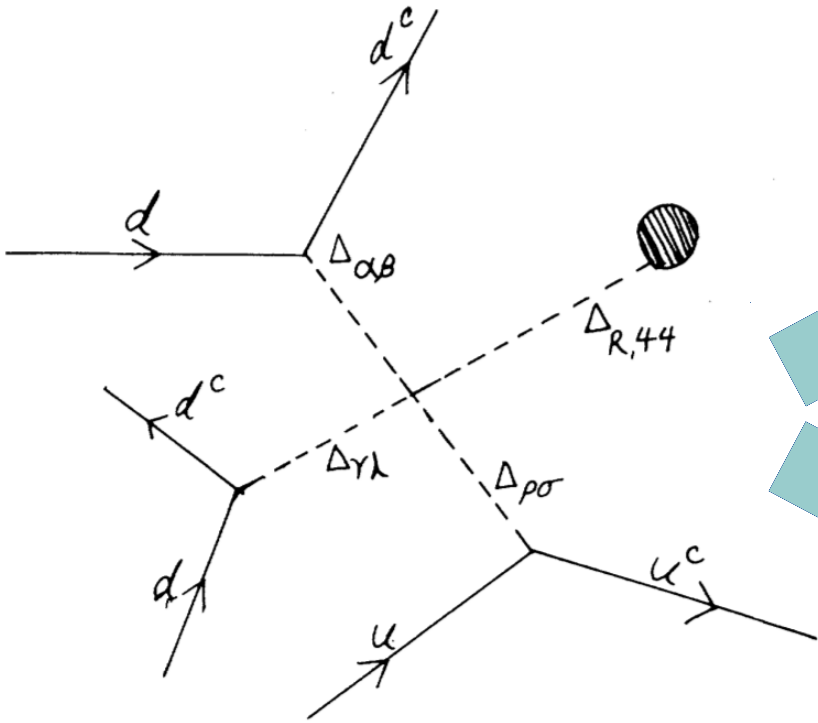
Sakharov conditions for generating baryon asymmetry:
B, *C,* and *CP* violation out of thermal equilibrium



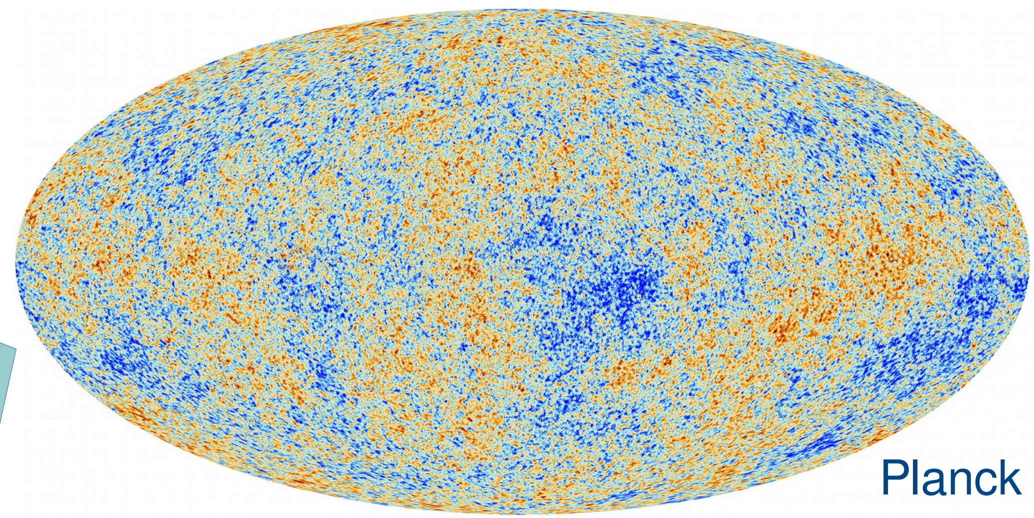
Standard Model meets necessary conditions, but predicts much smaller asymmetry

Baryogenesis

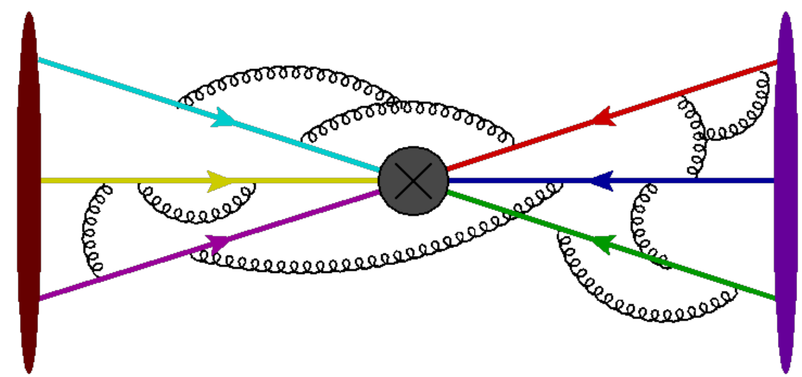
Baryon asymmetry and $n\bar{n}$ produced by same interactions in several BSM theories



Mohapatra and Marshak (1980)



Planck

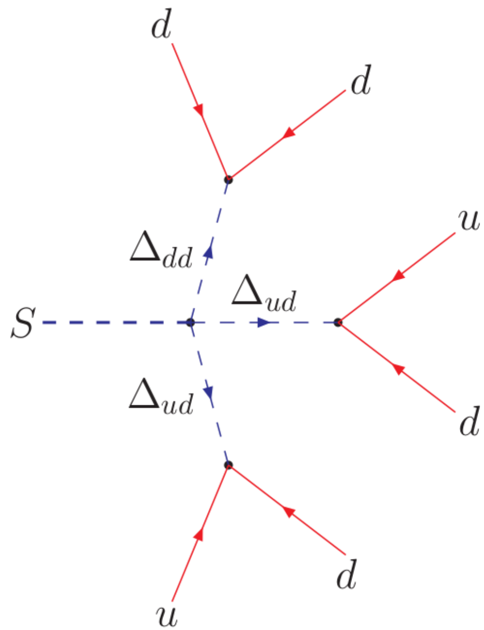


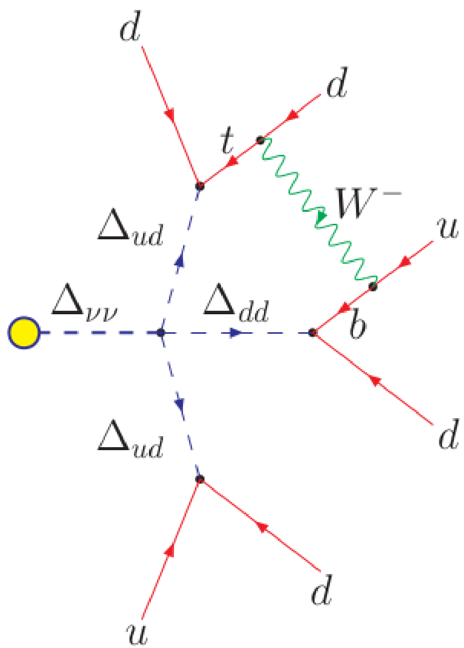
Post-Sphaleron Baryogenesis

Baryogenesis via higher-dimensional stays in equilibrium later, washes away pre-existing asymmetry

Post-sphaleron baryogenesis in e.g. left-right symmetric theories predicts a theoretical upper bound on $\tau_{n\overline{n}}$

Babu, Dev, Fortes, and Mohapatra (2013)





Six-Quark Operators

SM effective theory describes $n\bar{n}$ with six-quark operators

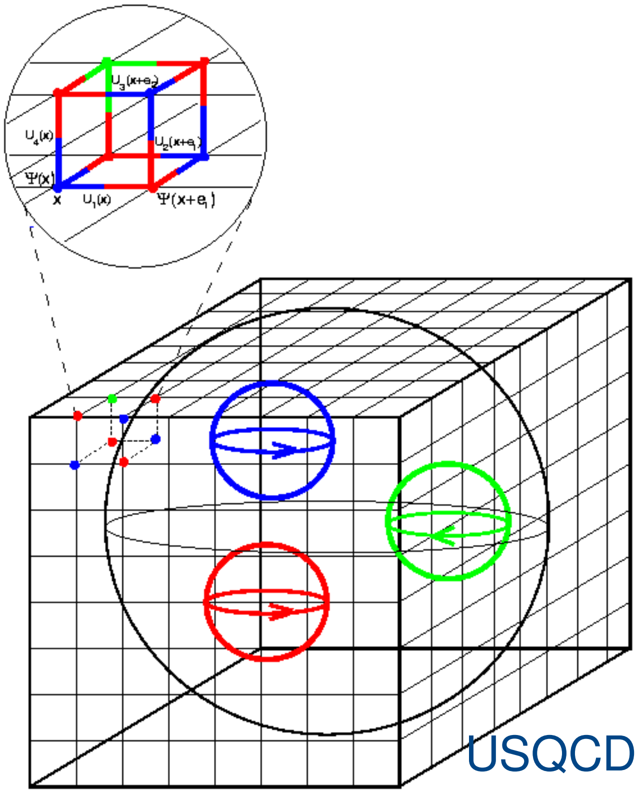
$$\mathcal{H}_{n\bar{n}} = \sum_I C_I^{\overline{\mathrm{MS}}}(M) Q_I^{\overline{\mathrm{MS}}}(M) \qquad Q_I \sim uudddd$$

BSM theories predict coefficients at high scales

Early estimates of six-quark matrix elements in MIT bag model

Rao and Shrock (1984)

Lattice QCD needed for reliable connection between BSM predictions and experimental constraints on $\tau_{n\bar{n}}$



$$\psi = \begin{pmatrix} u \\ d \end{pmatrix}$$

Chiral Operator Basis

$$Q_1 = (\psi C P_R i\tau^2 \psi)(\psi C P_R i\tau^2 \psi)(\psi C P_R i\tau^2 \tau^+ \psi) T^{AAS} = \mathcal{D}_R \mathcal{D}_R \mathcal{D}_R^+ T^{AAS}$$

Isospin 3

Not SM gauge invariant

Redundant in $D = 4$

Chiral Basis	Fixed-Flavor Basis	Chiral Tensor Structure	Chiral Irrep
Q_1	$\mathcal{O}^3_{RRR}$	$\mathcal{D}_R\mathcal{D}_R\mathcal{D}_R^+ T^{AAS}$	$(\mathbf{1}_L, \mathbf{3}_R)$
Q_2	$\mathcal{O}^3_{LRR}$	$\mathcal{D}_L\mathcal{D}_R\mathcal{D}_R^+ T^{AAS}$	$(\mathbf{1}_L, \mathbf{3}_R)$
Q_3	$\mathcal{O}^3_{LLR}$	$\mathcal{D}_L\mathcal{D}_L\mathcal{D}_R^+ T^{AAS}$	$(\mathbf{1}_L, \mathbf{3}_R)$
Q_4	$4/5\ \mathcal{O}^2_{RRR} + 1/5\ \mathcal{O}^1_{RRR}$	$\mathcal{D}_R^{33+} T^{SSS}$	$(\mathbf{1}_L, \mathbf{7}_R)$
Q_5	$\mathcal{O}^1_{RLL}$	$\mathcal{D}_R^-\mathcal{D}_L^{++} T^{SSS}$	$(\mathbf{5}_L, \mathbf{3}_R)$
Q_6	$\mathcal{O}^2_{RLL}$	$\mathcal{D}_R^3\mathcal{D}_L^{3+} T^{SSS}$	$(\mathbf{5}_L, \mathbf{3}_R)$
Q_7	$2/3\ \mathcal{O}^2_{LLR} + 1/3\ \mathcal{O}^1_{LLR}$	$\mathcal{D}_R^+\mathcal{D}_L^{33} T^{SSS}$	$(\mathbf{5}_L, \mathbf{3}_R)$
$\widetilde{Q}_1$	$1/3\ \mathcal{O}^2_{RRR} - 1/3\ \mathcal{O}^1_{RRR}$	$\mathcal{D}_R\mathcal{D}_R\mathcal{D}_R^+ T^{SSS}$	$(\mathbf{1}_L, \mathbf{3}_R)$
$\widetilde{Q}_3$	$1/3\ \mathcal{O}^2_{LLR} - 1/3\ \mathcal{O}^1_{LLR}$	$\mathcal{D}_L\mathcal{D}_L\mathcal{D}_R^+ T^{SSS}$	$(\mathbf{1}_L, \mathbf{3}_R)$

Chiral symmetry provides a basis with no operator mixing

Tiburzi (unpublished), Buchoff, MW (2015)

Regularization-Independent Renormalization

RI-MOM scheme: hold vertex functions Λ_I fixed to tree-level values at chosen reference scale μ (momentum subtraction)

Martinelli et al (1995)

$\mathcal{P}_I$ projector defined for each tree-level operator → $[\mathcal{P}_I \Lambda_J(\mu)] = \delta_{IJ}$

Buchoff, MW (2014)

Vertex function should preserve chiral symmetry Syritsyn (2015)

$$
\begin{aligned}
[\Lambda_I]^{\alpha\beta\gamma\delta\eta\zeta}_{ijklmn}(p) = {} & \frac{1}{5}\left\langle Q_I(0)\,\bar{u}^\alpha_i(p)\bar{u}^\beta_j(p)\bar{d}^\gamma_k(p)\bar{d}^\delta_l(-p)\bar{d}^\eta_m(-p)\bar{d}^\zeta_n(-p)\right\rangle\Big|_{amp} \\
& + \frac{3}{5}\left\langle Q_I(0)\,\bar{u}^\alpha_i(p)\bar{u}^\beta_j(-p)\bar{d}^\gamma_k(p)\bar{d}^\delta_l(p)\bar{d}^\eta_m(-p)\bar{d}^\zeta_n(-p)\right\rangle\Big|_{amp} \\
& + \frac{1}{5}\left\langle Q_I(0)\,\bar{u}^\alpha_i(-p)\bar{u}^\beta_j(-p)\bar{d}^\gamma_k(p)\bar{d}^\delta_l(p)\bar{d}^\eta_m(p)\bar{d}^\zeta_n(-p)\right\rangle\Big|_{amp}
\end{aligned}
$$

Perturbative Renormalization

$$\mathcal{H}_{n\bar{n}} = \sum_I C_I^{\overline{\rm MS}}(M) Q_I^{\overline{\rm MS}}(M) = \sum_I C_I^{\overline{\rm MS}}(M) U_I(M,\mu) Q_I^{\rm RI}(\mu)$$

One-loop running: Caswell, Milutinovic, and Senjanovic (1983)

$$U_I(M,\mu) = \left(\frac{\alpha_s(\mu)}{\alpha_s(M)}\right)^{-\gamma_I^{(0)}/2\beta_0} \left[1 - r_I^{(0)}\frac{\alpha_s(\mu)}{4\pi} + \left(\frac{\beta_1\gamma_I^{(0)}}{2\beta_0^2} - \frac{\gamma_I^{(1)}}{2\beta_0}\right)\frac{\alpha_s(\mu)-\alpha_s(M)}{4\pi} + O(\alpha_s(\mu)^2)\right]$$

One-loop matching

Buchoff, MW (2015)

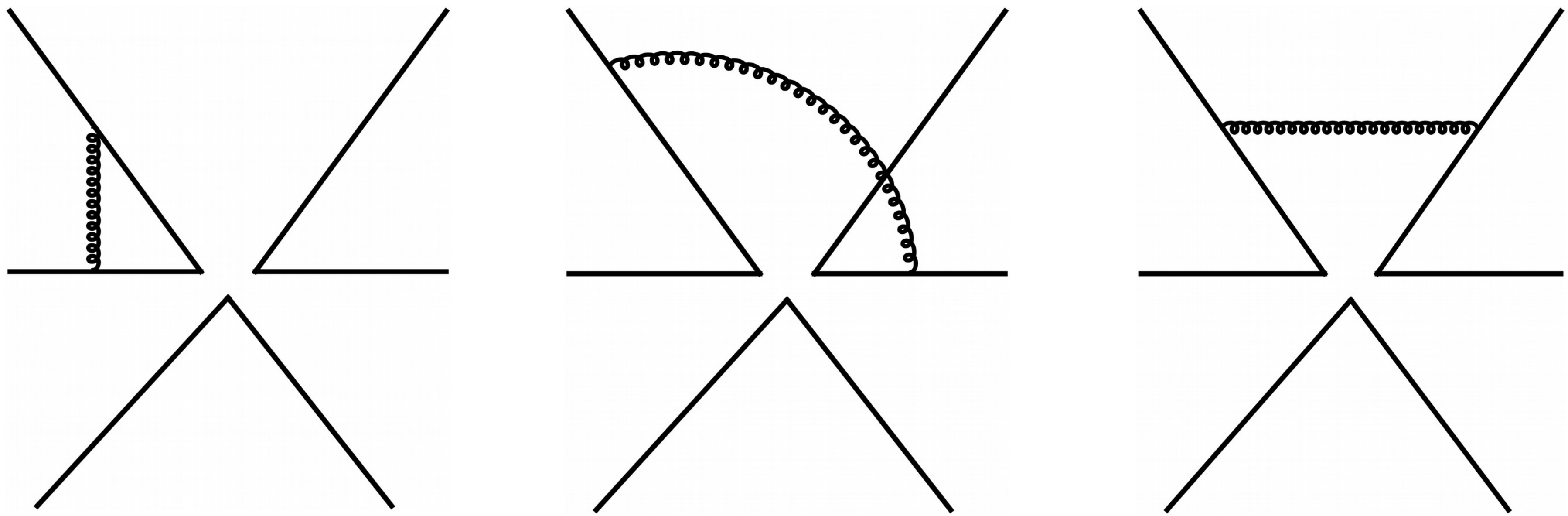
Two-loop running,
needed for $\alpha_s(\mu)$ accuracy

Buchoff, MW (2015)

Negligible

One-Loop Matching

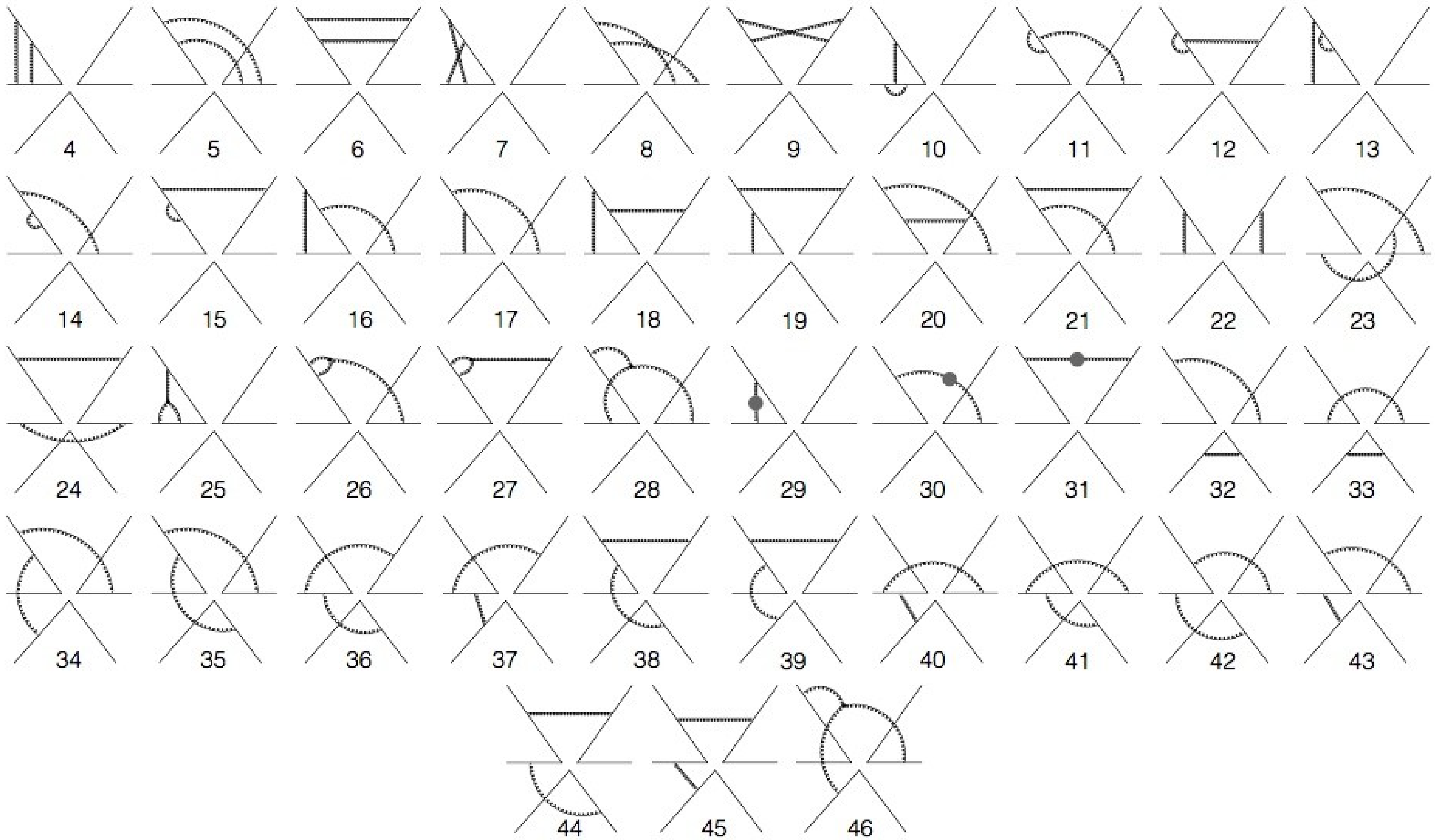
15 one-loop diagrams in 3 topologies



Same topologies appear in four-quark weak matrix elements and proton decay

Two-Loop Running

350 two-loop diagrams. Evanescent operators introduce complications

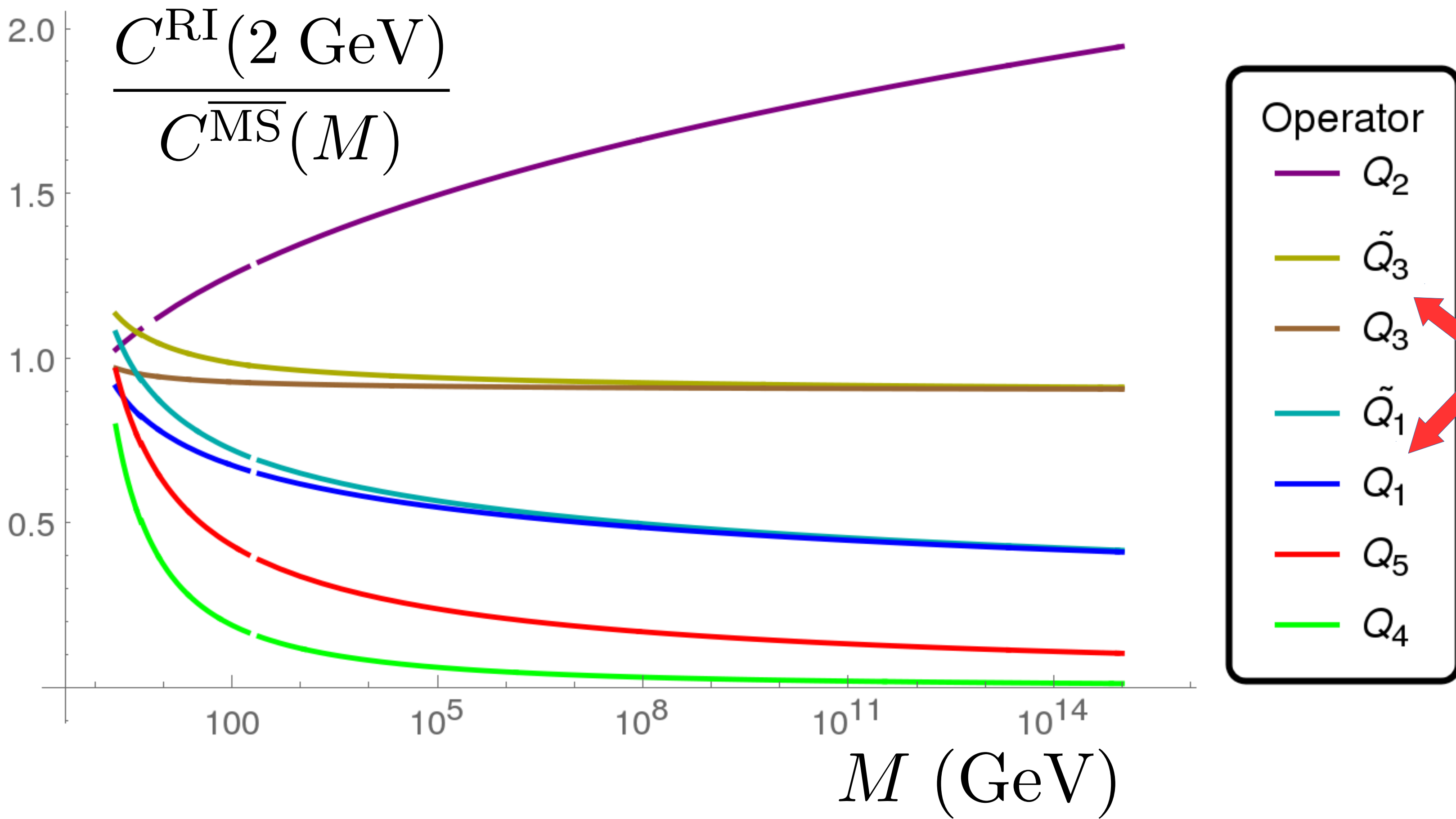


Includes all diagram topologies needed for two-loop running of any operator built from spin singlet diquarks

Perturbative Renormalization

Two-loop corrections $< 26\%$ at $\mu = 2\ \mathrm{GeV}$ perturbative matching under control

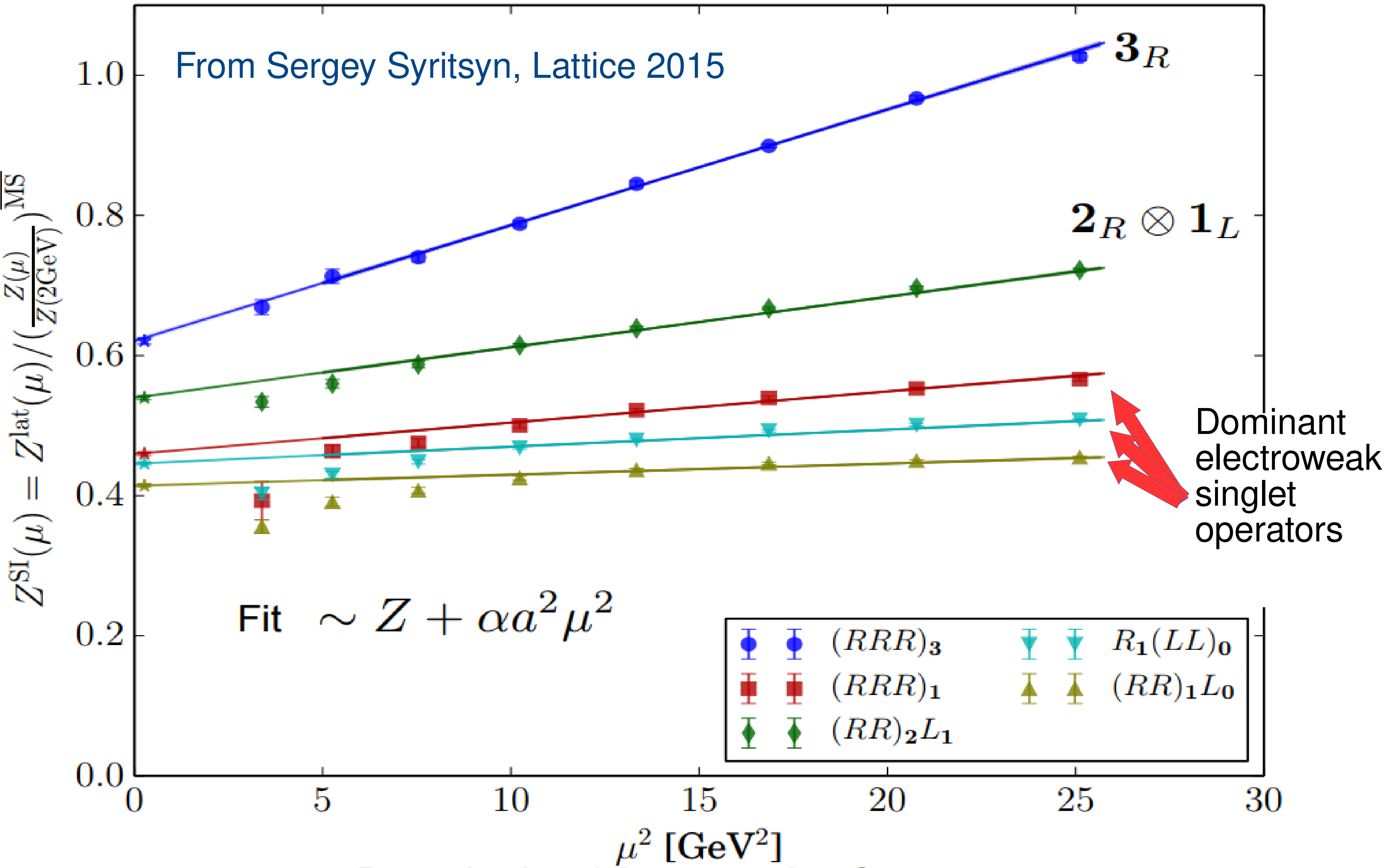
Operator renormalization effects significant



Fierz-conjugate operators differ in $\overline{\mathrm{MS}}$ by $O\left(\alpha_s(M)\right)$

Non-Perturbative Renormalization

NPR complete, lattice artifacts small for most important operations



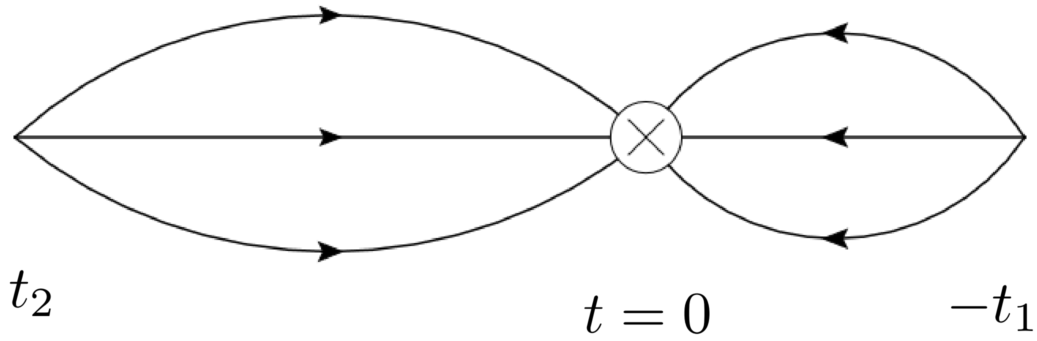
Lattice QCD Matrix Elements

LQCD matrix elements calculated from ratios of three-point to two-point correlation functions at large Euclidean time separations

$$< N_{\uparrow}^{(+)}(t_2) Q_I(0) N_{\downarrow}^{(-)}(-t_1) > \to \; Z_n Z_{\overline{n}} e^{-M_n(t_1+t_2)} < n|Q_I|\overline{n} >$$

Operator insertions at all time separations calculable from single point-to-all propagator

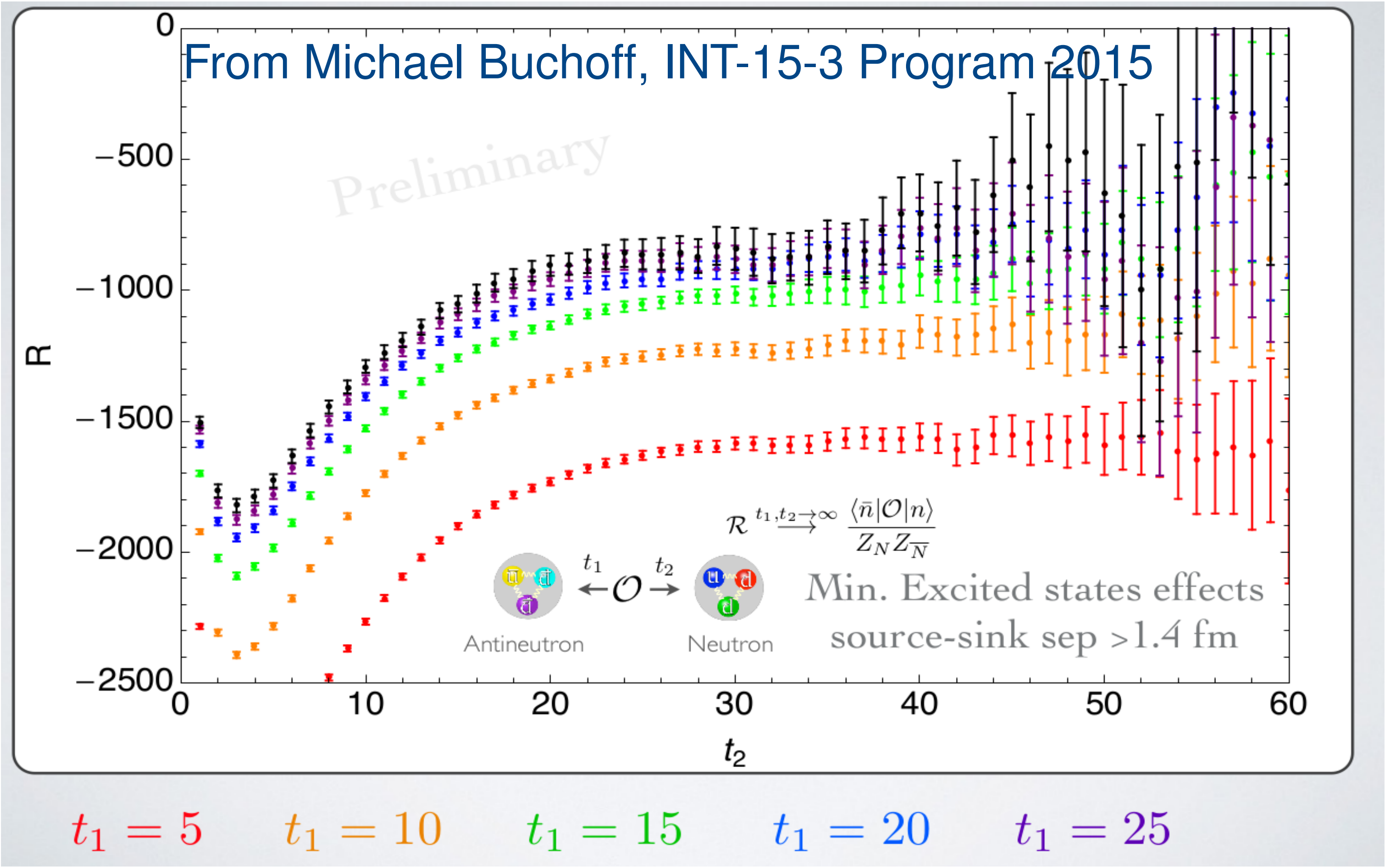
No disconnected diagrams



Exploratory LQCD Studies

Exploratory anisotropic Wilson calculation:

Buchoff, Schroeder, Wasem (2012)

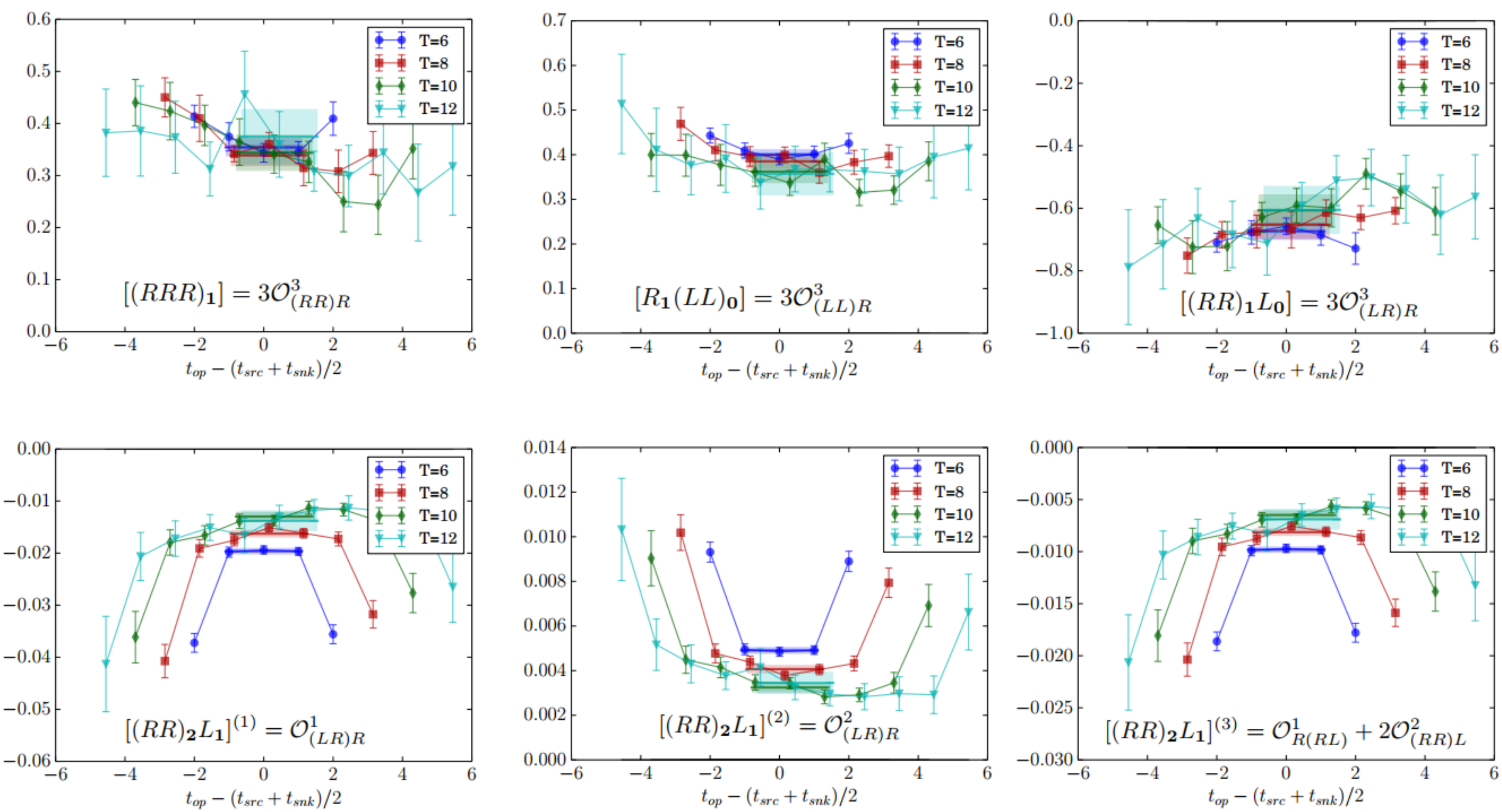


$a \sim 0.125$ fm $\qquad m_\pi \sim 390$ Mev $\qquad V = 20^3 \times 256$

Physical Point LQCD

Domain wall fermion calculation with RBC/UKQCD configurations

Syritsyn, Buchoff, Schroeder, Wasem (2015)



From Sergey Syritsyn, Lattice 2015

$a \sim 0.123$ fm $\qquad m_\pi \sim 140$ Mev $\qquad V = 48^3 \times 96$

Physical Point LQCD Results

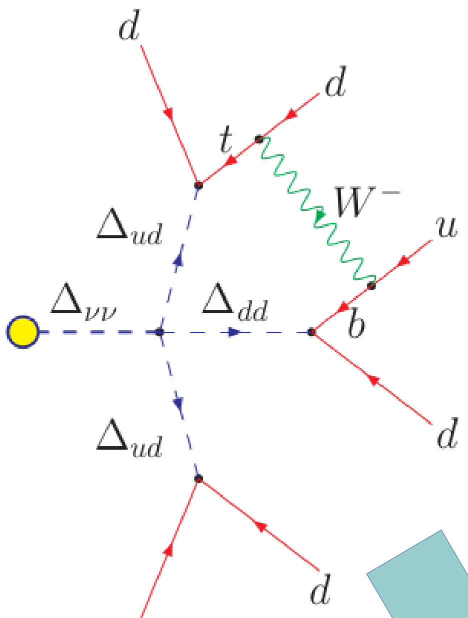
	$Z(\text{lat} \to \overline{MS})$	$\mathcal{O}^{\overline{MS}(2\text{ GeV})}[10^{-5}\text{GeV}^6]$	Bag "A"	$\frac{\text{LQCD}}{\text{Bag "A"}}$	Bag "B"	$\frac{\text{LQCD}}{\text{Bag "B"}}$
$[(RRR)_3]$	0.62(12)	0	0	–	0	–
$[(RRR)_1]$	0.454(33)	45.4(5.6)	8.190	5.5	6.660	6.8
$[R_1(LL)_0]$	0.435(26)	44.0(4.1)	7.230	6.1	6.090	7.2
$[(RR)_1L_0]$	0.396(31)	-66.6(7.7)	-9.540	7.0	-8.160	8.1
$[(RR)_2L_1]^{(1)}$	0.537(52)	-2.12(26)	1.260	-1.7	-0.666	3.2
$[(RR)_2L_1]^{(2)}$	0.537(52)	0.531(64)	-0.314	-1.7	0.167	3.2
$[(RR)_2L_1]^{(3)}$	0.537(52)	-1.06(13)	0.630	-1.7	-0.330	3.2

Preliminary physical point results presented at Lattice 2015, final stages of the calculation underway with results to appear soon

Syritsyn, Buchoff, Schroeder, Wasem (2015)

Buchoff, Rinaldi, Schroeder, Syritsyn, MW, Wasem – *in preparation*

Phenomenological Applications



Babu et al (2013)

	$Z(\text{lat} \to \overline{MS})$	$\mathcal{O}^{\overline{MS}(2\text{ GeV})}[10^{-5}\text{GeV}^6]$	Bag "A"	$\frac{\text{LQCD}}{\text{Bag "A"}}$	Bag "B"	$\frac{\text{LQCD}}{\text{Bag "B"}}$
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Syritsyn, Buchoff, Schroeder, Wasem (2015)
Buchoff, Rinaldi, Schroeder, Syritsyn, MW, Wasem – *in preparation*

$$\tau_{n\bar{n}}^{ILL} \geq 0.86 \times 10^8 \text{ s}$$
$$\tau_{n\bar{n}}^{ESS} \sim 2.7 \times 10^9 \text{ s}$$

$$\tau_{n\bar{n}}^{224,PSB} \leq (1.5 \pm 0.2) \times 10^{10} \text{ s}$$

Phenomenological studies needed to determine constraints of proposed ESS experiments on all BSM models of interest, e.g. Calibbi, et al (2016) for $\not{R}$ SUSY + bag model predictions

Summary

Low-energy $\mathrm{n\bar{n}}$ Hamiltonian relatively simple

– Three electroweak singlet operators in isospin limit, distinct chiral irreps

Experimental reach higher than expectated

– QCD matrix elements 5-10 times larger than bag model estimates for electroweak singlet operators

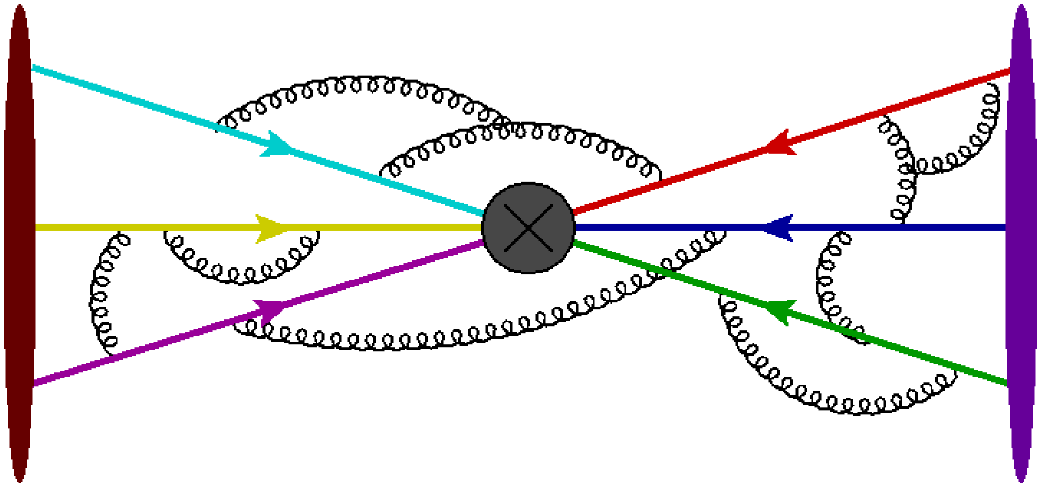
Operator color-flavor structure matters

– Different sign anomalous dimensions among electroweak singlet operators

– Non-singlet matrix elements 1-2 orders of magnitude smaller than singlets

Concrete BSM predictions including final LQCD results essential to assess reach of proposed ESS experiments

– Can post-sphaleron baryogenesis models be definitively tested at ESS?



Exciting days ahead for $n\overline{n}$, stay tuned!