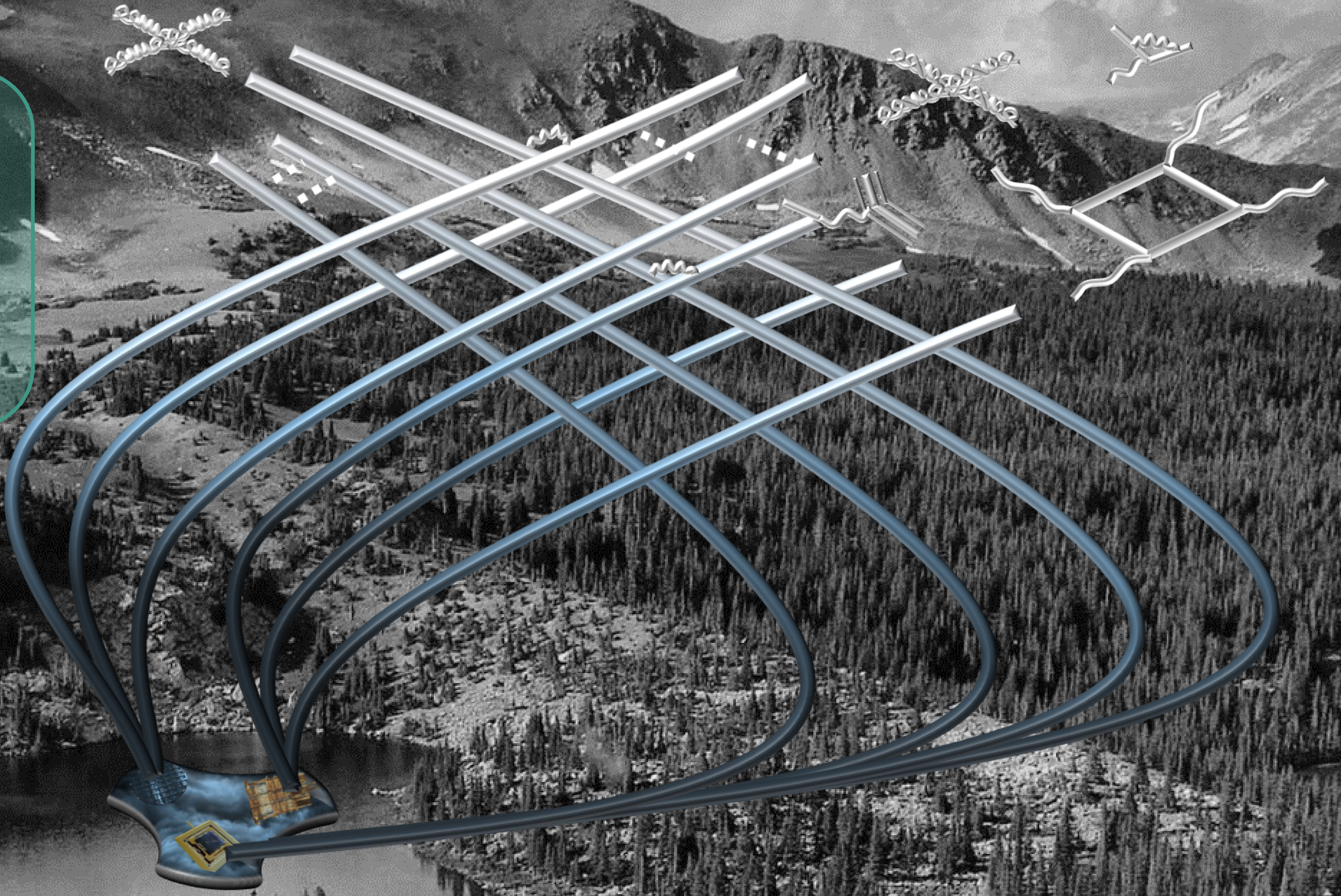
Quantum Simulation for Lattice Gauge Theories

APS Topical Group on Hadronic Physics
Sacramento, California. April 15th 2021

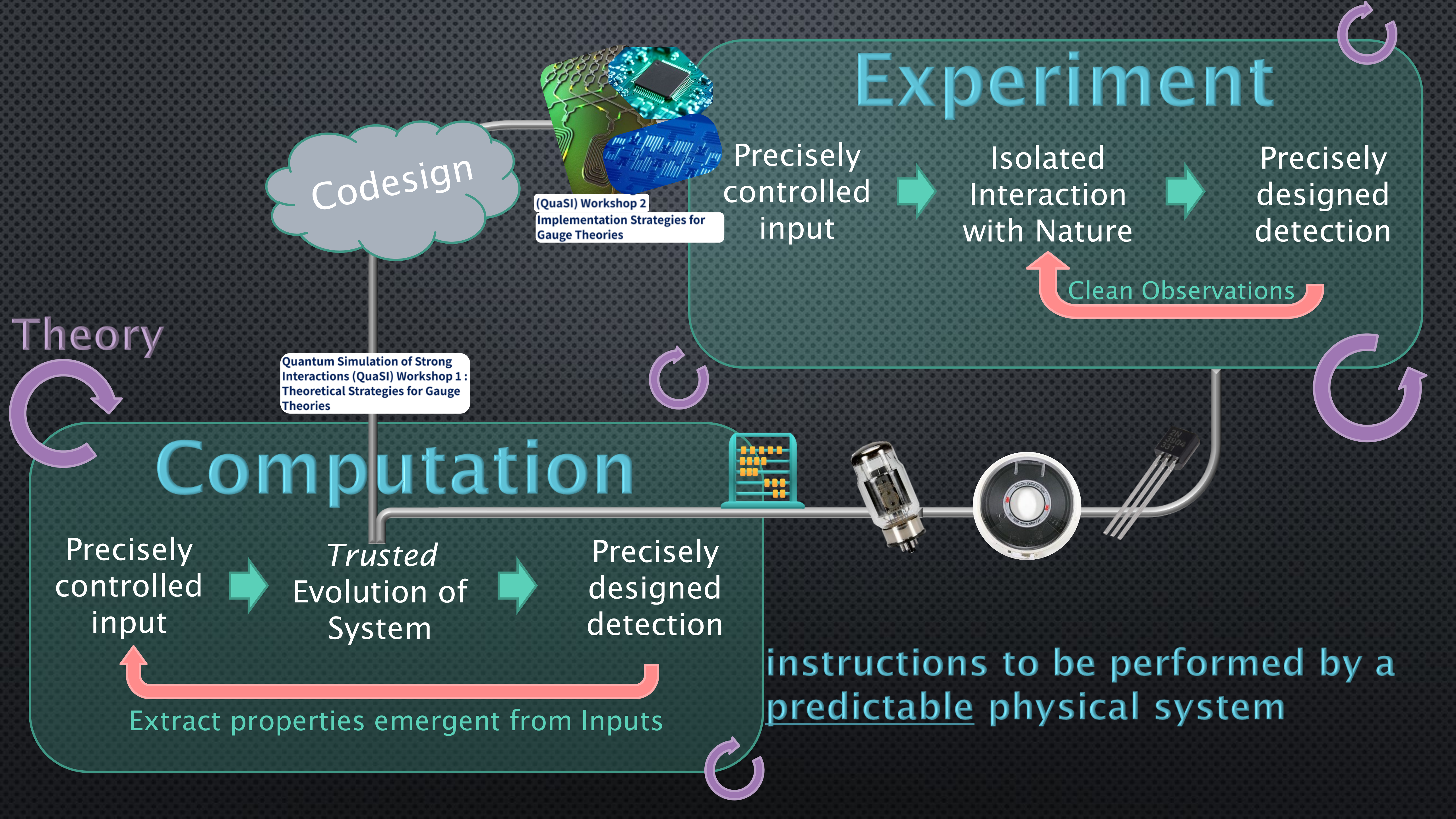


Natalie Klco

IQIM

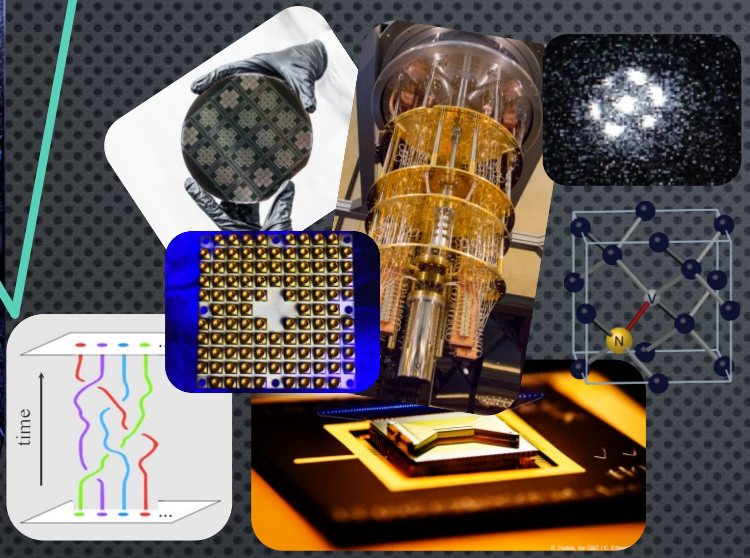
CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

BURKE INSTITUTE



Experiment
Precisely controlled input
Isolated Interaction with Nature
Precisely designed detection
Clean Observations
Codesign
(QuaSI) Workshop 2
Implementation Strategies for Gauge Theories
Theory
Quantum Simulation of Strong Interactions (QuaSI) Workshop 1 : Theoretical Strategies for Gauge Theories
Computation
Precisely controlled input
Trusted Evolution of System
Precisely designed detection
Extract properties emergent from Inputs
instructions to be performed by a predictable physical system

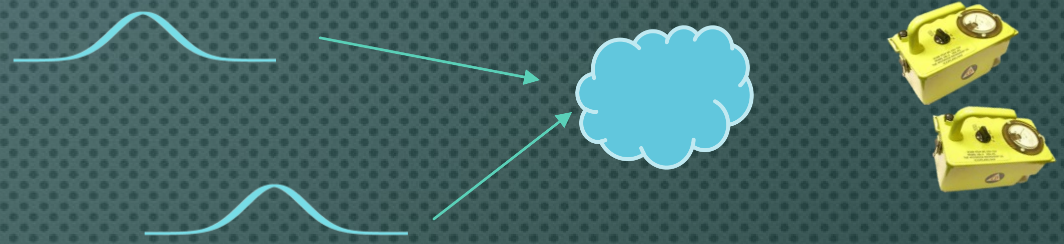
Where is the line?



Quantum Computation of Scattering in Scalar Quantum Field Theories

Stephen P. Jordan (NIST, Wash., D.C. and Caltech), Keith S.M. Lee (Pittsburgh U. and Caltech), John Preskill (Caltech)

Published in: Quantum Information and Computation 14, 1014-1080 (2014), *Quant.Inf.Comput.* 14 (2014) 1014-1080



Simulating collider physics on quantum computers using effective field theories

Christian W. Bauer* and Benjamin Nachman†

Marat Freytsis‡

arXiv:2102.05044v1

$$\sigma = H \otimes J_1 \otimes \cdots \otimes J_n \otimes S$$

$$\langle X | \mathrm{T}[Y_n\, Y_{\bar{n}}^\dagger] | \Omega \rangle$$

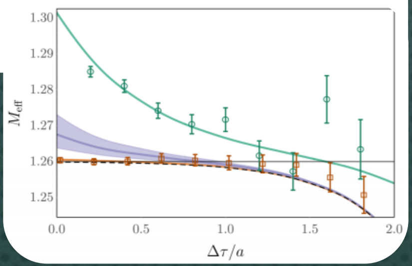
Wilson Line in Gauge Field

Soft Function

Accelerating Lattice Quantum Field Theory Calculations via Interpolator Optimization Using Noisy Intermediate-Scale Quantum Computing

A. Avkhadiev, P. E. Shanahan, and R. D. Young

Phys. Rev. Lett. **124**, 080501 – Published 26 February 2020

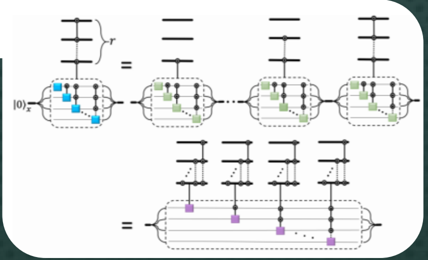


Q projection → C state creation/annihilation

Fixed-point quantum circuits for quantum field theories

Natalie Klco and Martin J. Savage

Phys. Rev. A **102**, 052422 – Published 30 November 2020



C snapshots → Q state prep

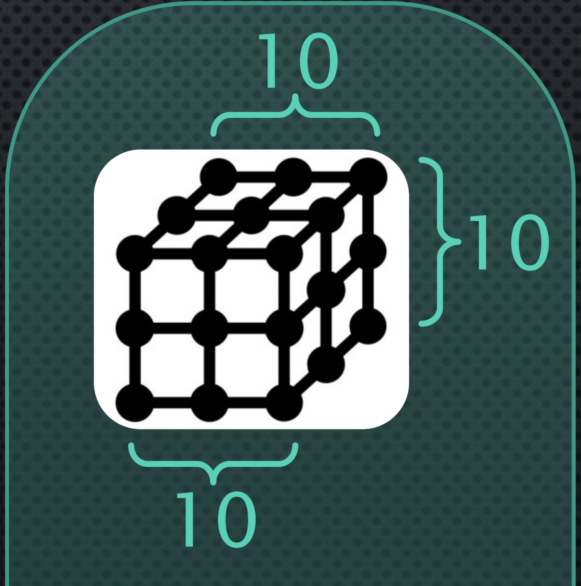
$$\alpha \left| \text{Analog}\ \substack{\text{Computation} \\ \text{via Simile}} \right\rangle + \left| \text{Digital}\ \substack{\text{Discrete} \\ \text{Universal Gates}} \right\rangle$$

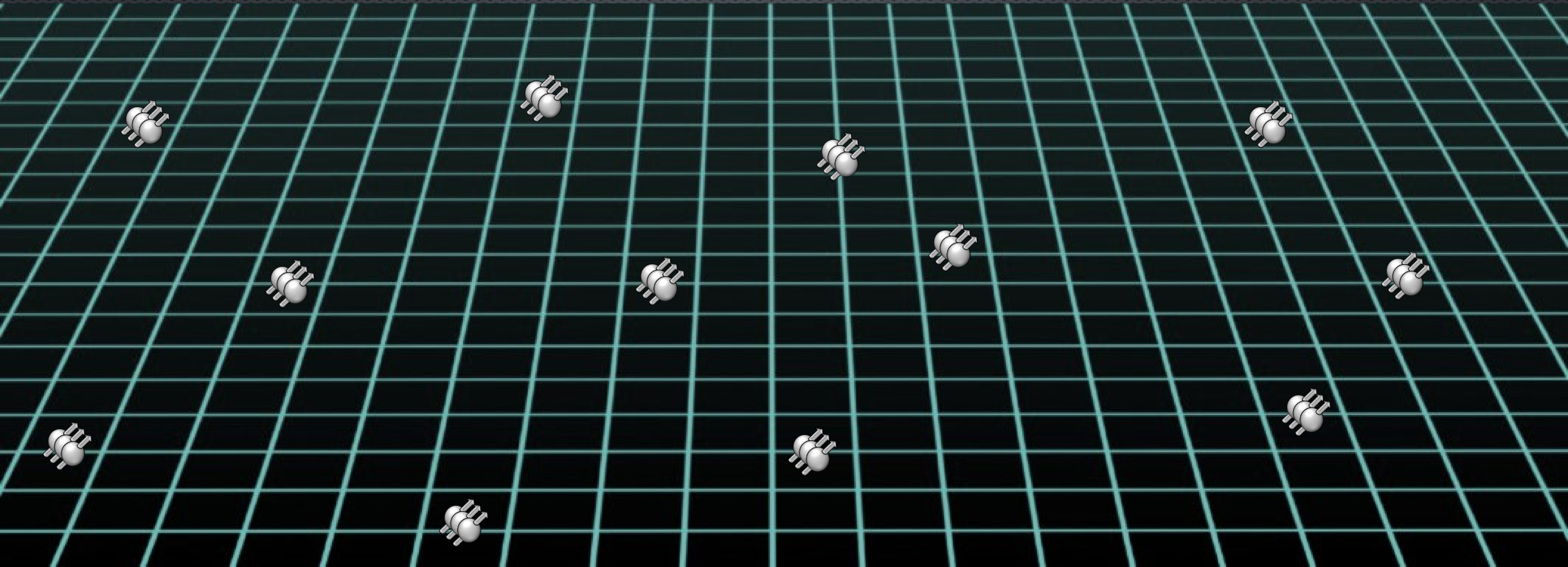
Subatomic dynamics from atomic scale interactions

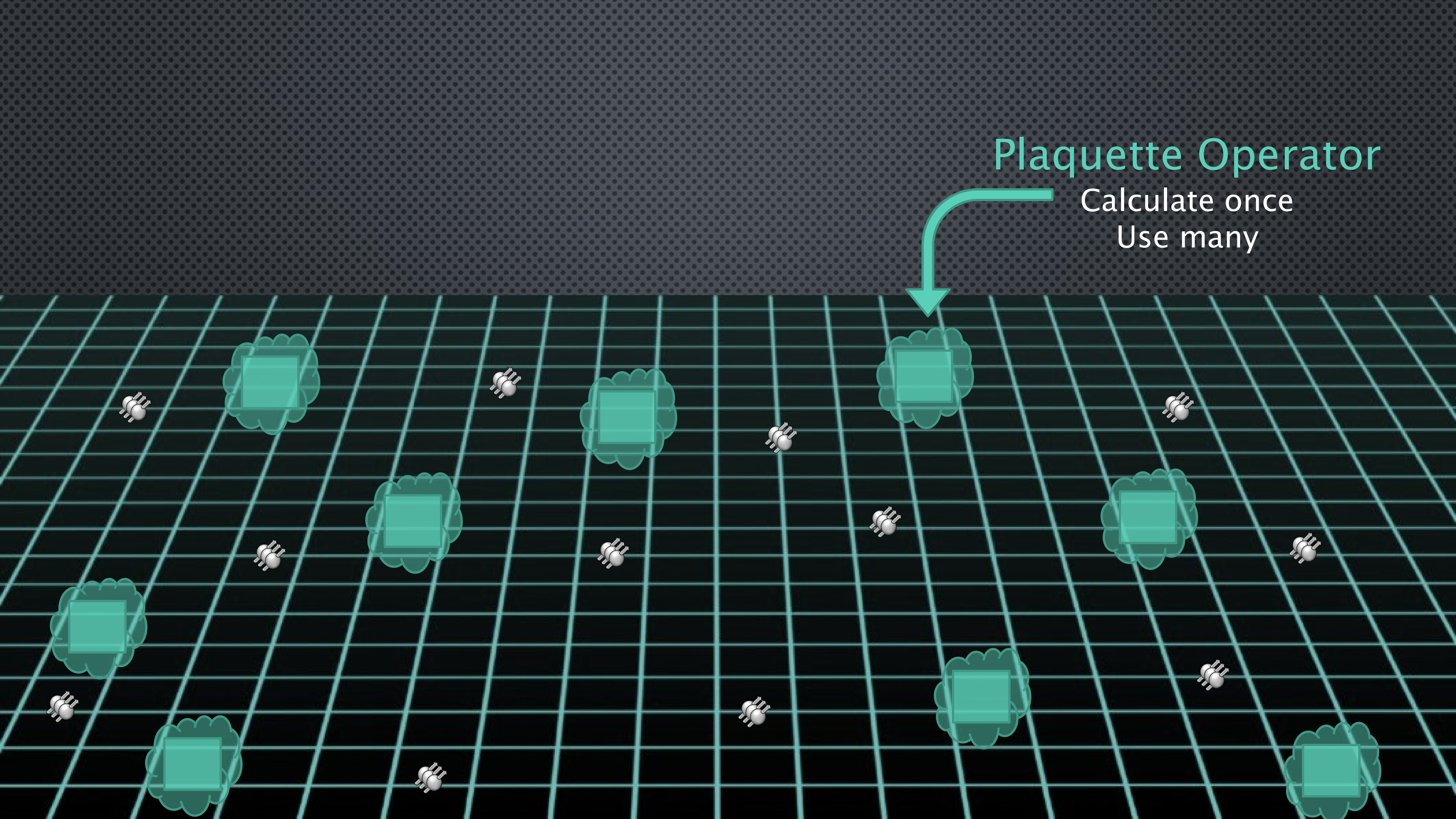
Intersimulatability

A Trailhead for Quantum Simulation of SU(3) Yang-Mills Lattice Gauge Theory in the Local Multiplet Basis

Anthony Ciavarella, Natalie Klco, Martin J. Savage






Plaquette Operator
Calculate once
Use many

Byrnes and Yamamoto

Phys. Rev. A 73 (2006) 022328

$$\hat{H} = \frac{g^2}{2a^{d-2}} \sum_{b,\text{links}} |\hat{\mathbf{E}}^{(b)}|^2 + \frac{1}{2a^{4-d}g^2} \sum_{\text{plaquettes}} \left[6 - \hat{\Box}(\mathbf{x}) - \hat{\Box}^\dagger(\mathbf{x}) \right]$$

CGs through poly-overhead Operator construction

$$|j,m\rangle_{\text{reg}} |\tfrac{1}{2}, \Delta m\rangle_{\text{reg}} \to \sum_{J=|j-1/2|}^{j+1/2} \langle J, M | j, m; \tfrac{1}{2}, \Delta m\rangle |J, M = m + \Delta m\rangle_{\text{reg}}$$

Bacon, Chuang, Harrow (2006)

CGs introduced as gate rotation angles, classically precomputed*

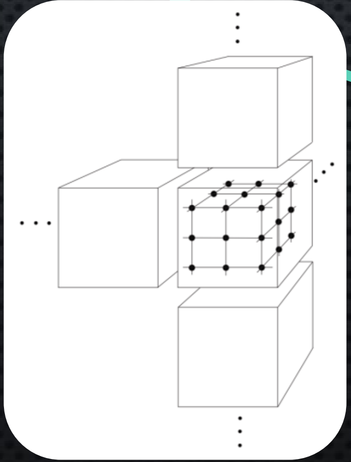
Local Hilbert Space

$$|p, q, T_L, T_L^z, Y_L, T_R, T_R^z, Y_R\rangle$$

$$\begin{aligned} T_i &= \{0, \tfrac{1}{2}, \ldots, \tfrac{1}{2}(p+q)\}, \\ T_i^z &= \{-\tfrac{1}{2}(p+q), -\tfrac{1}{2}(p+q) + \tfrac{1}{2}, \ldots, \tfrac{1}{2}(p+q)\}, \\ Y_i &= \{-\tfrac{1}{3}(q+2p), -\tfrac{1}{3}(q+2p) + \tfrac{1}{3}, \ldots, \tfrac{1}{3}(p+2q)\}, \end{aligned}$$

Tensor indices

$$T^{a_1 a_2 \ldots a_{\Lambda p}}_{b_1 b_2 \ldots b_{\Lambda q}}$$



Integrate Local Gauge Space

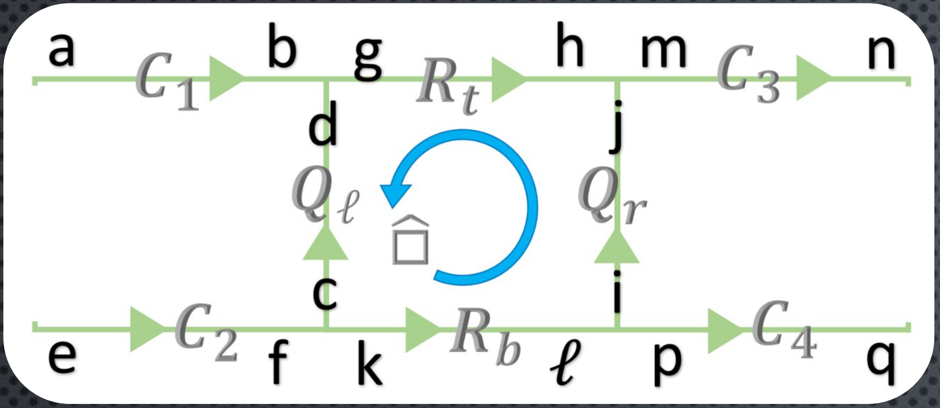
$$|p, q\rangle = |\mathbf{R}\rangle$$

$|0,0\rangle = |1\rangle$
$|1,0\rangle = |3\rangle$
$|0,1\rangle = |\bar{3}\rangle$
$\vdots$

$1D$ SU(2): Bañuls, Cichy, Cirac, Jansen, Kühn. (2017)
$1D_\Box$ SU(2): Klco, Stryker, Savage. (2020)

modifications

*Poly-time algorithm for fixed rank
De Loera, McAllister (2005)



Wavefunction

Sum over local orientations

$$\left| \begin{pmatrix} \mathbf{C}_1, \mathbf{R}_t, \mathbf{C}_3 \\ \mathbf{Q}_\ell, \mathbf{Q}_r \\ \mathbf{C}_2, \mathbf{R}_b, \mathbf{C}_4 \end{pmatrix} \right\rangle = \frac{1}{\dim(\mathbf{Q}_\ell)\dim(\mathbf{Q}_r)} \sum_{all} |\mathbf{C}_1, a, b\rangle |\mathbf{Q}_\ell, c, d\rangle |\mathbf{C}_2, e, f\rangle |\mathbf{R}_t, g, h\rangle |\mathbf{Q}_r, i, j\rangle |\mathbf{R}_b, k, \ell\rangle |\mathbf{C}_3, m, n\rangle |\mathbf{C}_4, p, q\rangle$$

$$\underbrace{\langle \mathbf{C}_1, b, \overline{\mathbf{R}}_t, g | \overline{\mathbf{Q}}_\ell, d\rangle_{\Gamma_1} \langle \mathbf{R}_t, h, \overline{\mathbf{C}}_3, m | \overline{\mathbf{Q}}_r, j\rangle_{\Gamma_2} \langle \mathbf{C}_2, f, \overline{\mathbf{R}}_b, k | \mathbf{Q}_\ell, c\rangle_{\Gamma_3} \langle \mathbf{R}_b, \ell, \overline{\mathbf{C}}_4, p | \mathbf{Q}_r, i\rangle_{\Gamma_4}}_{\text{Tied together with Vertex CGs}}$$

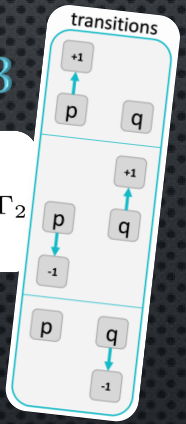
Local Irreps

Possible Multiplicities in SU(3)

e.g., $8 \otimes 8 \otimes 8$

Link Operator

e.g., $r = 3$



$$\hat{U}^{\mathbf{r}}_{\alpha,\beta} |\mathbf{R}, a, b\rangle = \sum_{\oplus \mathbf{R}', \vec{\Gamma}} \sum_{a'b'} \sqrt{\frac{\dim(\mathbf{R})}{\dim(\mathbf{R}')}} |\mathbf{R}', a', b'\rangle \; \langle \mathbf{R}, a, \mathbf{r}, \alpha | \mathbf{R}', a'\rangle_{\Gamma_1} \langle \mathbf{R}', b' | \mathbf{R}, b, \mathbf{r}, \beta\rangle_{\Gamma_2}$$

Pair of link CGs

Magnetic Matrix Element

$$\left\langle \begin{pmatrix} \mathbf{C}_1, \mathbf{R}'_t, \mathbf{C}_3 \\ \mathbf{Q}'_\ell, \mathbf{Q}'_r \\ \mathbf{C}_2, \mathbf{R}'_b, \mathbf{C}_4 \end{pmatrix} \middle| \hat{\square} \middle| \begin{pmatrix} \mathbf{C}_1, \mathbf{R}_t, \mathbf{C}_3 \\ \mathbf{Q}_\ell, \mathbf{Q}_r \\ \mathbf{C}_2, \mathbf{R}_b, \mathbf{C}_4 \end{pmatrix} \right\rangle =$$

$$\sqrt{\frac{\dim(\mathbf{R}_t)\dim(\mathbf{R}_b)}{\dim(\mathbf{R}'_t)\dim(\mathbf{R}'_b)\dim(\mathbf{Q}_\ell)\dim(\mathbf{Q}_r)\dim(\mathbf{Q}'_\ell)^3\dim(\mathbf{Q}'_r)^3}}$$

$$\sum \langle \mathbf{C}_1, b, \overline{\mathbf{R}}_t, g | \overline{\mathbf{Q}}_\ell, d\rangle_{\Gamma_1} \langle \mathbf{R}_t, g, \overline{\mathbf{3}}, \delta | \mathbf{R}'_t, g'\rangle_{\Gamma_2} \langle \mathbf{Q}'_\ell, d' | \mathbf{Q}_\ell, d, \overline{\mathbf{3}}, \delta\rangle_{\Gamma_3} \langle \overline{\mathbf{Q}}'_\ell, d' | \mathbf{C}_1, b, \overline{\mathbf{R}}'_t, g'\rangle_{\Gamma_4}$$

$$\sum \langle \mathbf{R}_t, h, \overline{\mathbf{C}}_3, m | \overline{\mathbf{Q}}_r, j\rangle_{\Gamma_5} \langle \mathbf{Q}'_r, j' | \mathbf{Q}_r, j, \mathbf{3}, \gamma\rangle_{\Gamma_6} \langle \mathbf{R}'_t, h' | \mathbf{R}_t, h, \overline{\mathbf{3}}, \gamma\rangle_{\Gamma_7} \langle \overline{\mathbf{Q}}'_r, j' | \mathbf{R}'_t, h', \overline{\mathbf{C}}_3, m\rangle_{\Gamma_8}$$

$$\sum \langle \mathbf{C}_2, f, \overline{\mathbf{R}}_b, k | \mathbf{Q}_\ell, c\rangle_{\Gamma_9} \langle \mathbf{R}_b, k, \mathbf{3}, \alpha | \mathbf{R}'_b, k'\rangle_{\Gamma_{10}} \langle \mathbf{Q}_\ell, c, \overline{\mathbf{3}}, \alpha | \mathbf{Q}'_\ell, c'\rangle_{\Gamma_{11}} \langle \mathbf{Q}'_\ell, c' | \mathbf{C}_2, f, \overline{\mathbf{R}}'_b, k'\rangle_{\Gamma_{12}}$$

$$\sum \langle \mathbf{R}_b, \ell, \overline{\mathbf{C}}_4, p | \mathbf{Q}_r, i\rangle_{\Gamma_{13}} \langle \mathbf{R}'_b, \ell' | \mathbf{R}_b, \ell, \mathbf{3}, \beta\rangle_{\Gamma_{14}} \langle \mathbf{Q}_r, i, \mathbf{3}, \beta | \mathbf{Q}'_r, i'\rangle_{\Gamma_{15}} \langle \mathbf{Q}'_r, i' | \mathbf{R}'_b, \ell', \overline{\mathbf{C}}_4, p\rangle_{\Gamma_1}$$

4+4+8 = 16

➡ Identify Vertex Factors

SU(2)

Klco, Savage, Stryker (2019)

$$\langle \chi_{\ldots, j_\ell^{t,b}, q_{\ell f}, j_{af}^{t,b}, q_{rf}, j_r^{t,b}, \ldots} | \hat{\Box} | \chi_{\ldots, j_\ell^{t,b}, q_{\ell i}, j_{ai}^{t,b}, q_{ri}, j_r^{t,b}, \ldots} \rangle =$$

$$\times \begin{Bmatrix} j_\ell^t & j_{ai}^t & q_{\ell i} \\ \frac{1}{2} & q_{\ell f} & j_{af}^t \end{Bmatrix} \begin{Bmatrix} j_\ell^b & j_{ai}^b & q_{\ell i} \\ \frac{1}{2} & q_{\ell f} & j_{af}^b \end{Bmatrix} \begin{Bmatrix} j_r^t & j_{ai}^t & q_{ri} \\ \frac{1}{2} & q_{rf} & j_{af}^t \end{Bmatrix} \begin{Bmatrix} j_r^b & j_{ai}^b & q_{ri} \\ \frac{1}{2} & q_{rf} & j_{af}^b \end{Bmatrix}$$

$$|j, m, m'\rangle \rightarrow |j\rangle$$

6j vertex factors

SU(3)

$$\left\langle \chi \begin{pmatrix} \mathbf{C}_1, \mathbf{R}_t', \mathbf{C}_3 \\ \mathbf{Q}_\ell', \mathbf{Q}_r' \\ \mathbf{C}_2, \mathbf{R}_b', \mathbf{C}_4 \end{pmatrix} \middle| \hat{\Box} \middle| \chi \begin{pmatrix} \mathbf{C}_1, \mathbf{R}_t, \mathbf{C}_3 \\ \mathbf{Q}_\ell, \mathbf{Q}_r \\ \mathbf{C}_2, \mathbf{R}_b, \mathbf{C}_4 \end{pmatrix} \right\rangle =$$

$$\begin{Bmatrix} \overline{\mathbf{R}}_t & \mathbf{C}_1 & \overline{\mathbf{Q}}_\ell \\ \mathbf{3} & \mathbf{1} & \mathbf{3} \\ \overline{\mathbf{R}}_t' & \mathbf{C}_1 & \overline{\mathbf{Q}}_\ell' \end{Bmatrix} \begin{Bmatrix} \mathbf{R}_t & \overline{\mathbf{C}}_3 & \overline{\mathbf{Q}}_r \\ \overline{\mathbf{3}} & \mathbf{1} & \overline{\mathbf{3}} \\ \mathbf{R}_t' & \overline{\mathbf{C}}_3 & \overline{\mathbf{Q}}_r' \end{Bmatrix} \begin{Bmatrix} \overline{\mathbf{R}}_b & \mathbf{C}_2 & \mathbf{Q}_\ell \\ \overline{\mathbf{3}} & \mathbf{1} & \overline{\mathbf{3}} \\ \overline{\mathbf{R}}_b' & \mathbf{C}_2 & \mathbf{Q}_\ell' \end{Bmatrix} \begin{Bmatrix} \mathbf{R}_b & \overline{\mathbf{C}}_4 & \mathbf{Q}_r \\ \mathbf{3} & \mathbf{1} & \mathbf{3} \\ \mathbf{R}_b' & \overline{\mathbf{C}}_4 & \mathbf{Q}_r' \end{Bmatrix}$$

$$|R, T_L, T_L^Z, Y_L, T_R, T_R^Z, Y_R\rangle \rightarrow |R\rangle$$

"9R" vertex factors

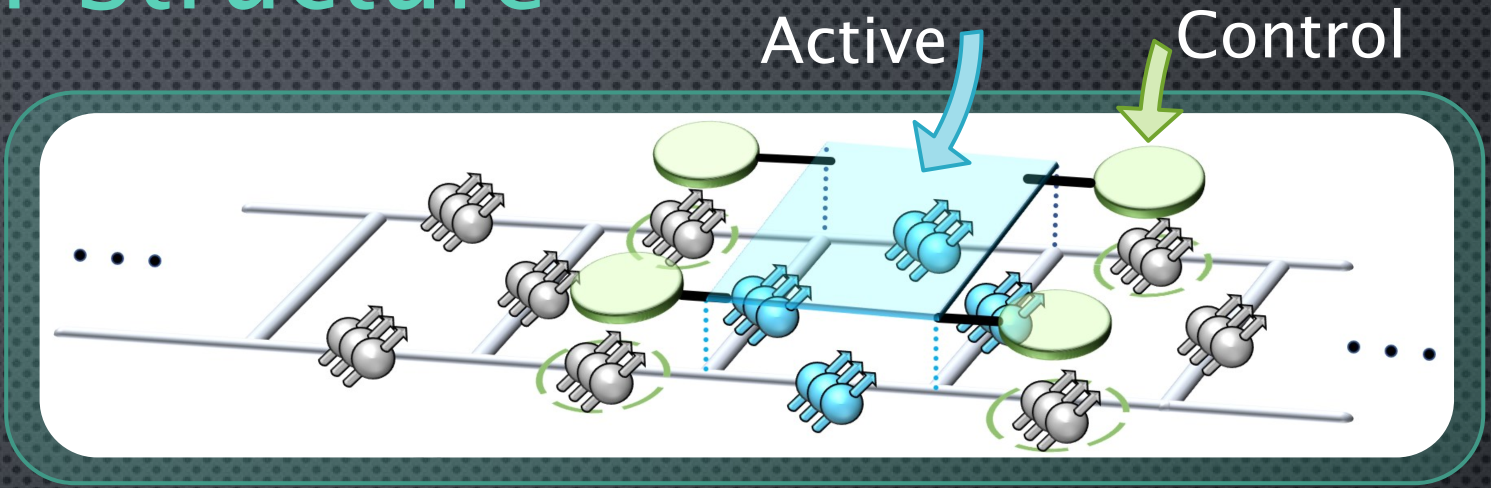
$$\begin{Bmatrix} \mathbf{A} & \mathbf{B} & \mathbf{C} \\ \mathbf{3} & \mathbf{1} & \mathbf{3} \\ \mathbf{D} & \mathbf{B} & \mathbf{E} \end{Bmatrix} = \sum \langle \mathbf{D}, y', \mathbf{B}, x | \mathbf{E}, q' \rangle_{\Gamma_1} \langle \mathbf{A}, y, \mathbf{B}, x | \mathbf{C}, q \rangle_{\Gamma_2} \langle \mathbf{A}, y, \mathbf{3}, c | \mathbf{D}, y' \rangle_{\Gamma_3} \langle \mathbf{C}, q, \mathbf{3}, c | \mathbf{E}, q' \rangle_{\Gamma_4}$$

SU(N)

Classical Integration of Local Gauge Space

Plaquette Operator Structure

$1D_{\square}$:



4 control registers

2D:

8 control registers

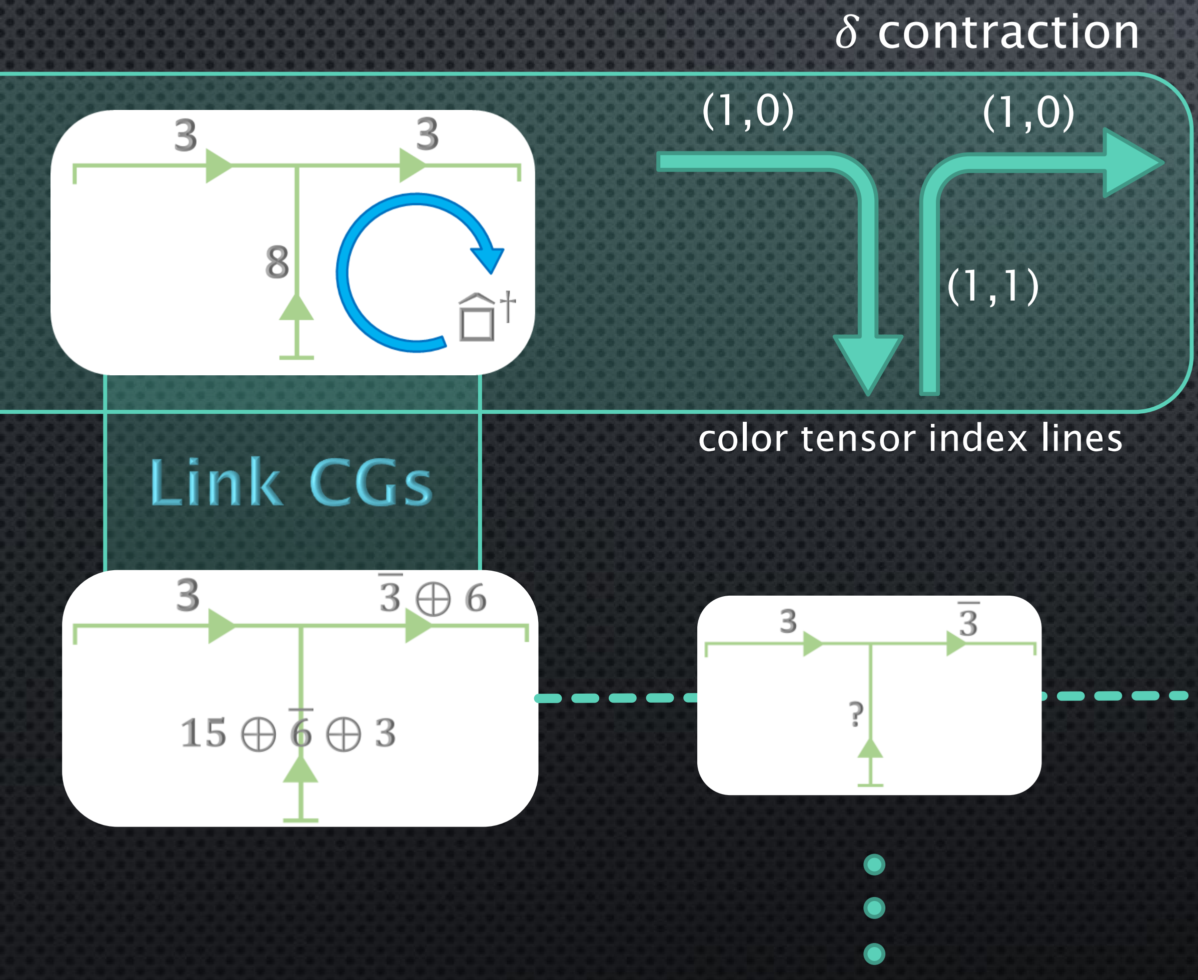
D: 4D control registers

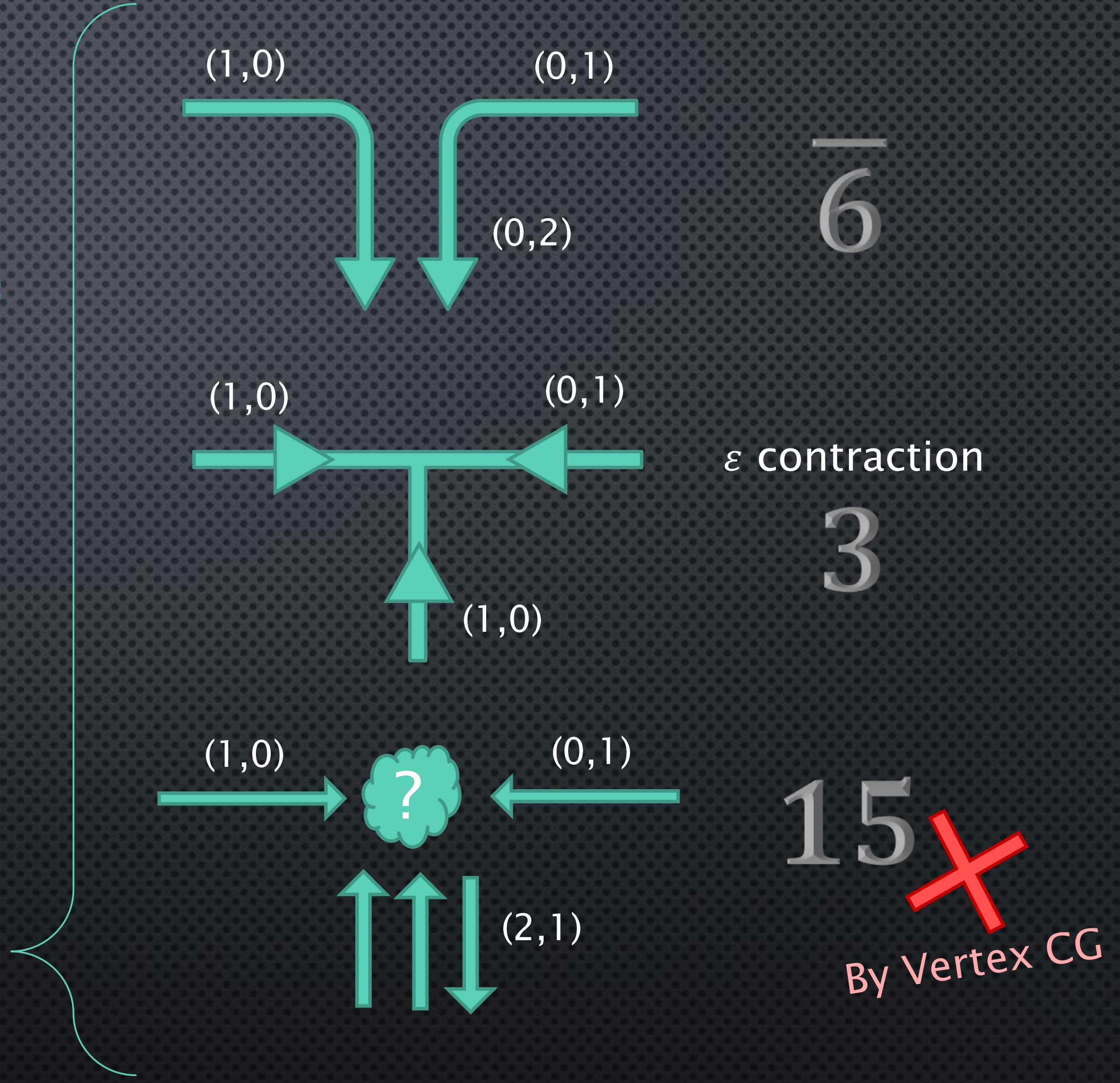
Consolidated into 4 virtual link insertions

Vertex CGs

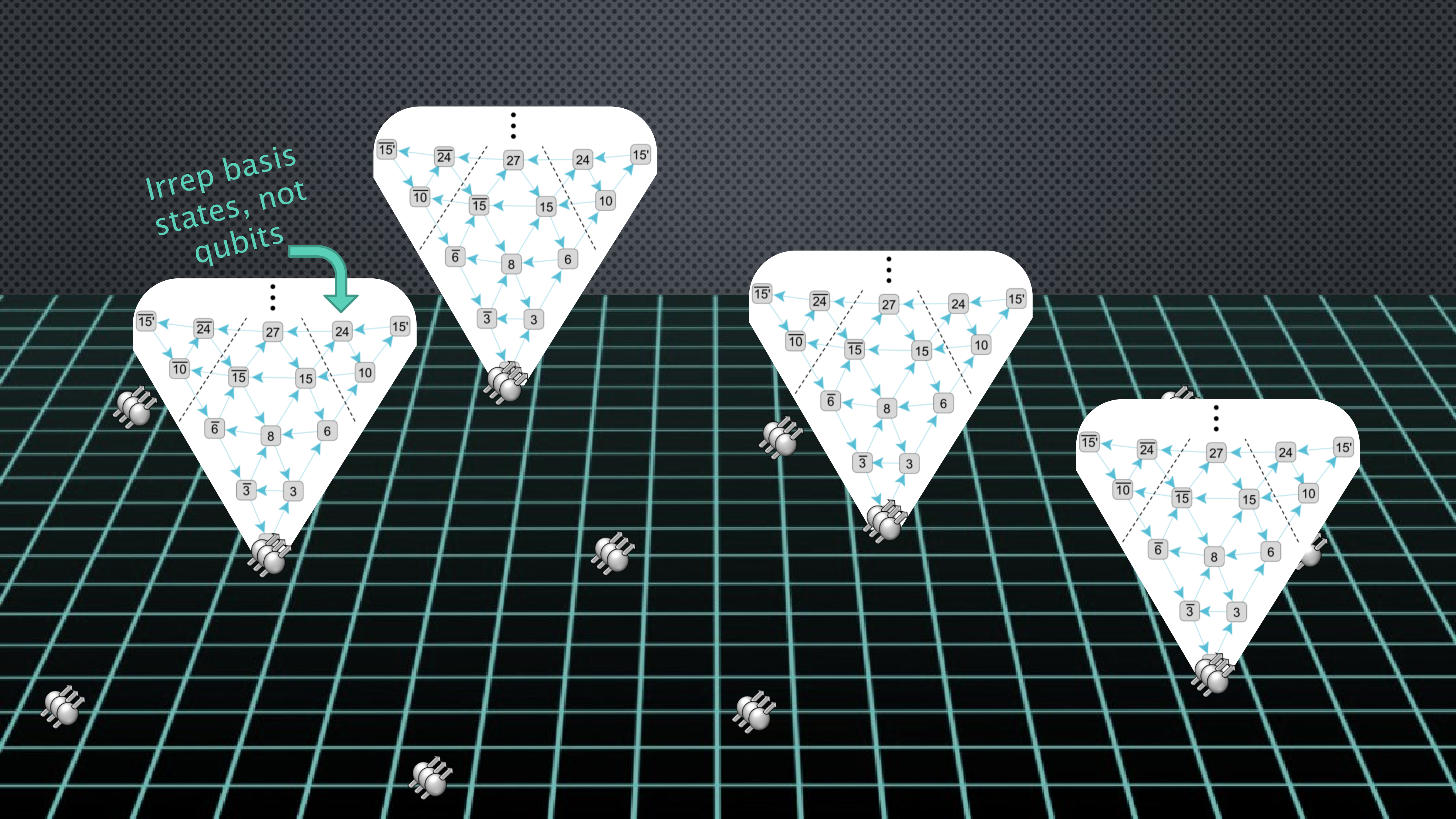
$$|\psi_{3pt}\rangle \sim \sum_{b,g,d,\Gamma} \langle \mathbf{C}_1, b, \overline{\mathbf{R}}_t, g | \overline{\mathbf{Q}}_\ell, d\rangle_\Gamma \; |\mathbf{C}_1, a, b\rangle |\mathbf{Q}_\ell, c, d\rangle |\mathbf{R}_t, g, h\rangle$$

Absent in unstructured Qubit Hilbert Space

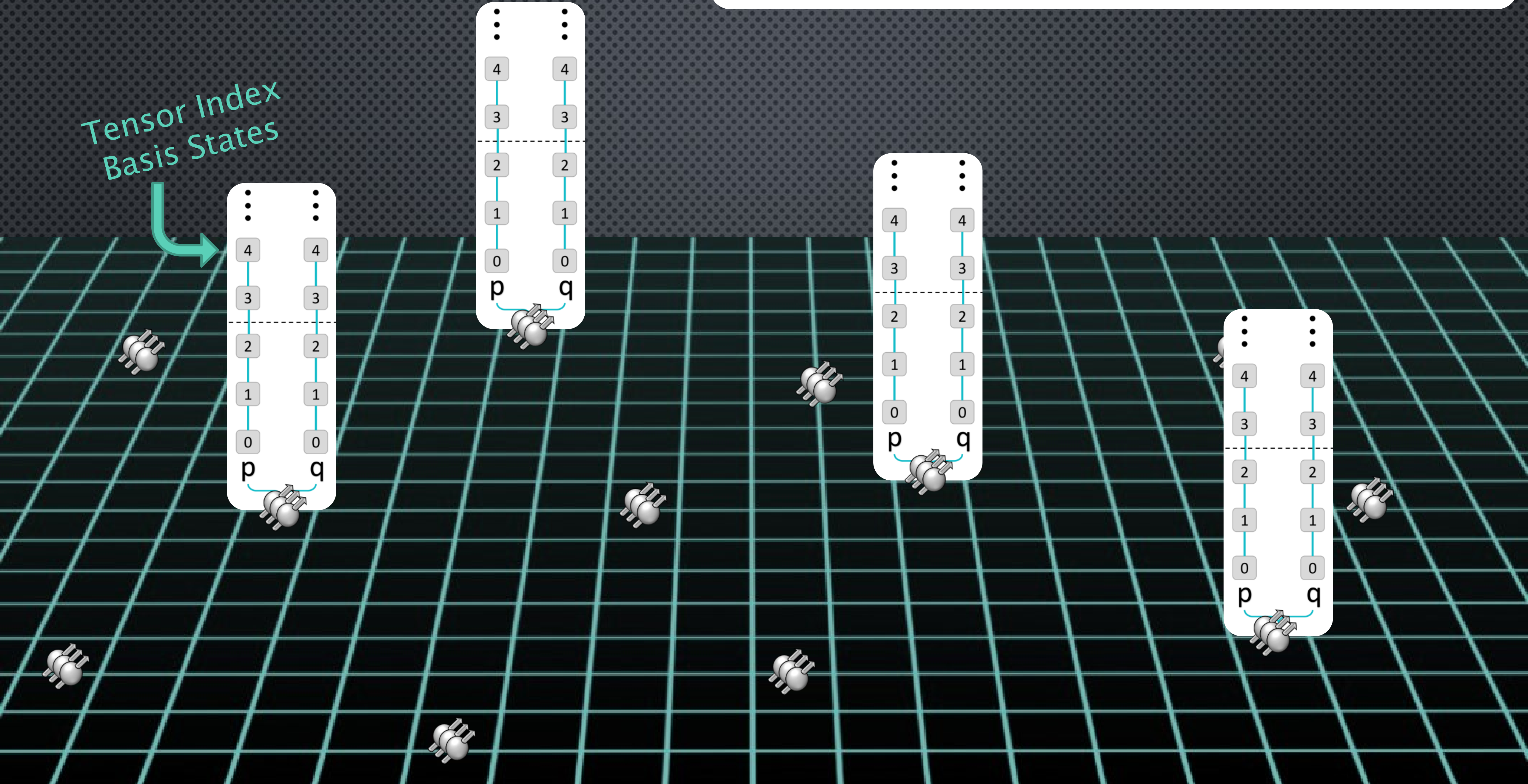




Controls incorporate Vertex CGs into operator
Gauge-Violating states in Hilbert Space!


Irrep basis states, not qubits
$\overline{15'}$ $\overline{24}$ 27 24 15'
$\overline{10}$ $\overline{15}$ 15 10
$\overline{6}$ 8 6
$\overline{3}$ 3

$$(p,q)\otimes(1,0)=(p+1,q)\oplus(p-1,q+1)\oplus(p,q-1)$$



$$(p,q)\otimes(1,0)=(p+1,q)\oplus(p-1,q+1)\oplus(p,q-1)$$

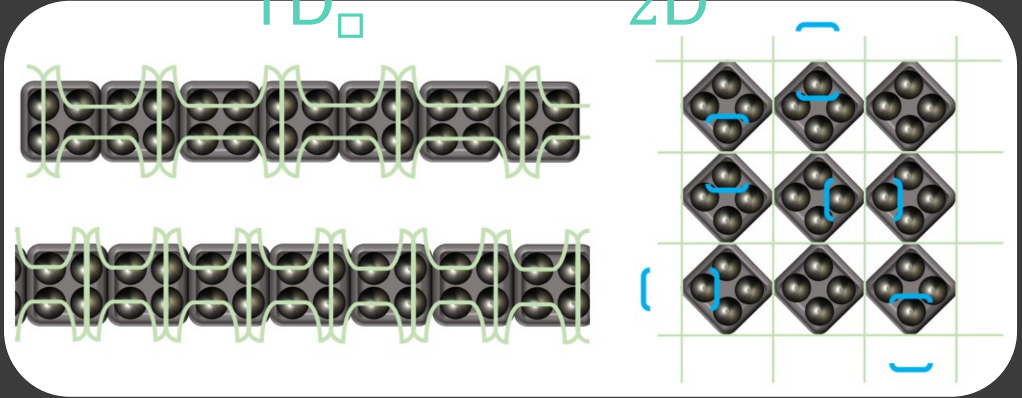
Flexibility for Codesign with existing and developing hardware

e.g., SRF cavities, Ions, Superconducting Circuits, …

1D 2D

(p,q):

(p,q), ⬡ mix:



Global Basis

$$|\Psi\rangle = \sum c\left(\vec{R}\right)|\vec{R}\rangle$$

- Classical Preprocessing of Hilbert Space.

Scalability Unknown

- Project into Local and Global Symmetry Sectors

Economical use of Hilbert space
Errors incapable of violating symmetry

- Non-local distribution of lattice-local information

One plaquette

Hilbert space ~
Link Hilbert space

$$|\mathbf{R}\rangle = \frac{1}{\dim(\mathbf{R})^2} \sum_{\alpha,\beta,\gamma,\delta} |\mathbf{R},\alpha,\beta\rangle_1 |\mathbf{R},\beta,\gamma\rangle_2 |\mathbf{R},\gamma,\delta\rangle_3 |\mathbf{R},\delta,\alpha\rangle_4$$

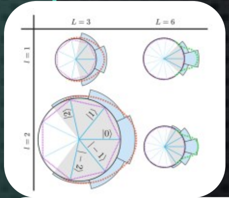
SU(2)

$$\hat{H} = \frac{g^2}{2} \sum_{\text{a,links}} |\mathbf{E}^a|^2 + \frac{1}{2g^2}\left(4 - \hat{\Box} - \hat{\Box}^\dagger\right)$$

$$\nabla_j^2 \psi(j) + \left(g^2 E - \frac{1}{2} g^4 j(j+1)\right)\psi(j) = 0$$

$$\psi \to e^{-\frac{g^2}{2\sqrt{2}}(j+\frac{1}{2})^2}$$

Gaussian Convergence
in “color” space

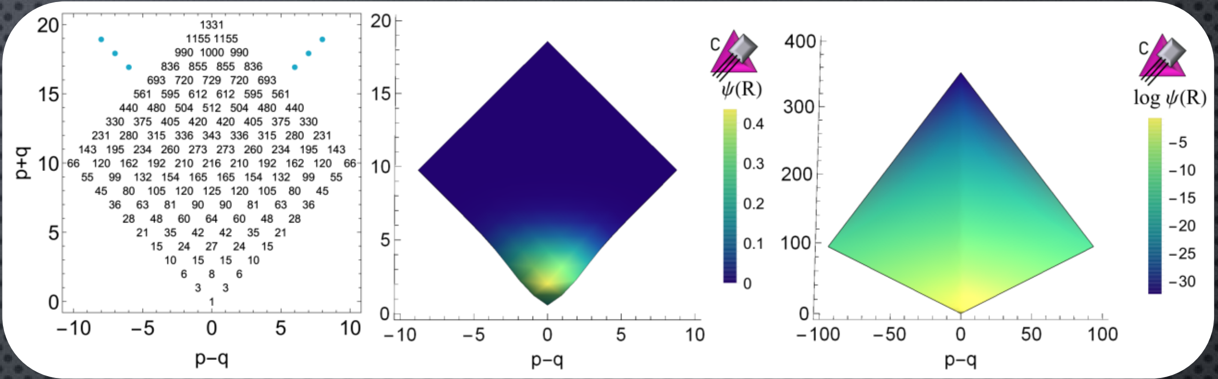


A resource efficient approach for quantum and classical simulations of gauge theories in particle physics

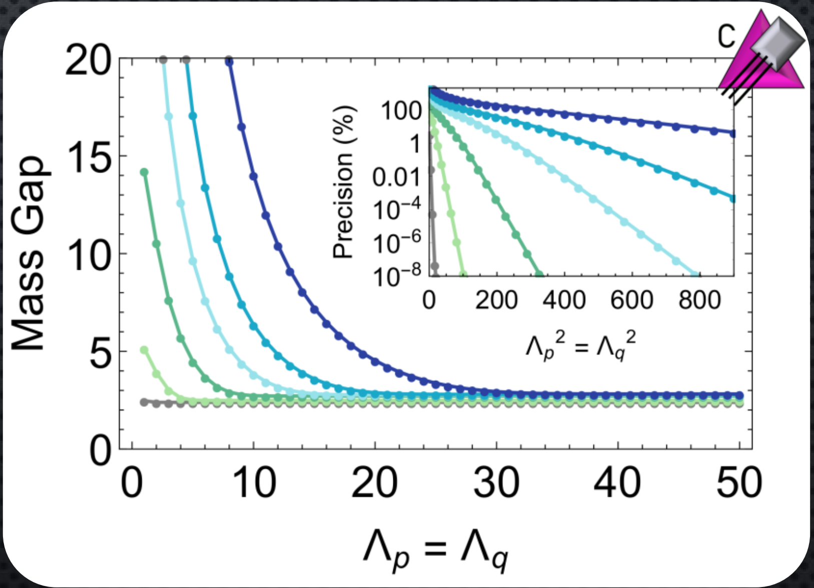
Jan F. Haase[1,2], Luca Dellantonio[1,2], Alessio Celi[3,4], Danny Paulson[1,2], Angus Kan[1,2], Karl Jansen[5], and Christine A. Muschik[1,2,6]

SU(3)

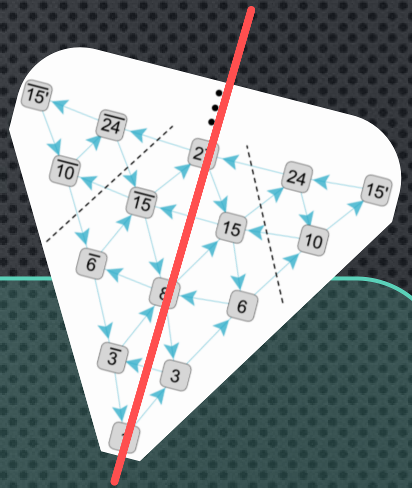
Wavefunction



Observables



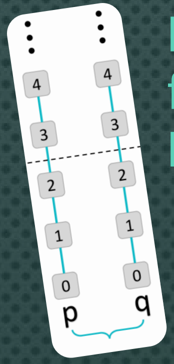
Color-Parity Symmetry



$$\hat{H} = \frac{g^2}{2}\sum_{b,\text{links}}|\hat{\mathbf{E}}^{(b)}|^2+\frac{1}{2g^2}\left(6-\hat{\Box}-\hat{\Box}^\dagger\right)$$

Distinct Sectors
Trivial vacuum +

$$|R^+\rangle = \frac{1}{\sqrt{2}}\left[\,|R\rangle+|\bar{R}\rangle\,\right]$$



Decomposition for Dynamics

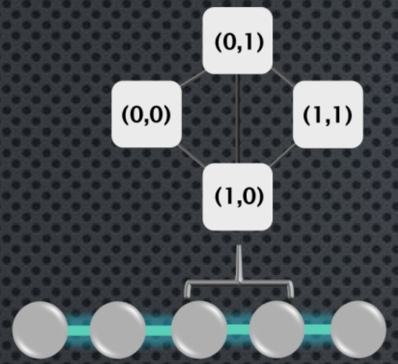
~~Pauli~~
Binary and Gray Encoding

Polynomial Time Evolution

$$\hat{\Box}+\hat{\Box}^\dagger = \left(\hat{B}_n+\hat{B}_n^\dagger\right)\otimes\mathbb{I}+\mathbb{I}\otimes\left(\hat{B}_n+\hat{B}_n^\dagger\right)+\hat{B}_n\otimes\hat{B}_n^\dagger+\hat{B}_n^\dagger\otimes\hat{B}_n$$

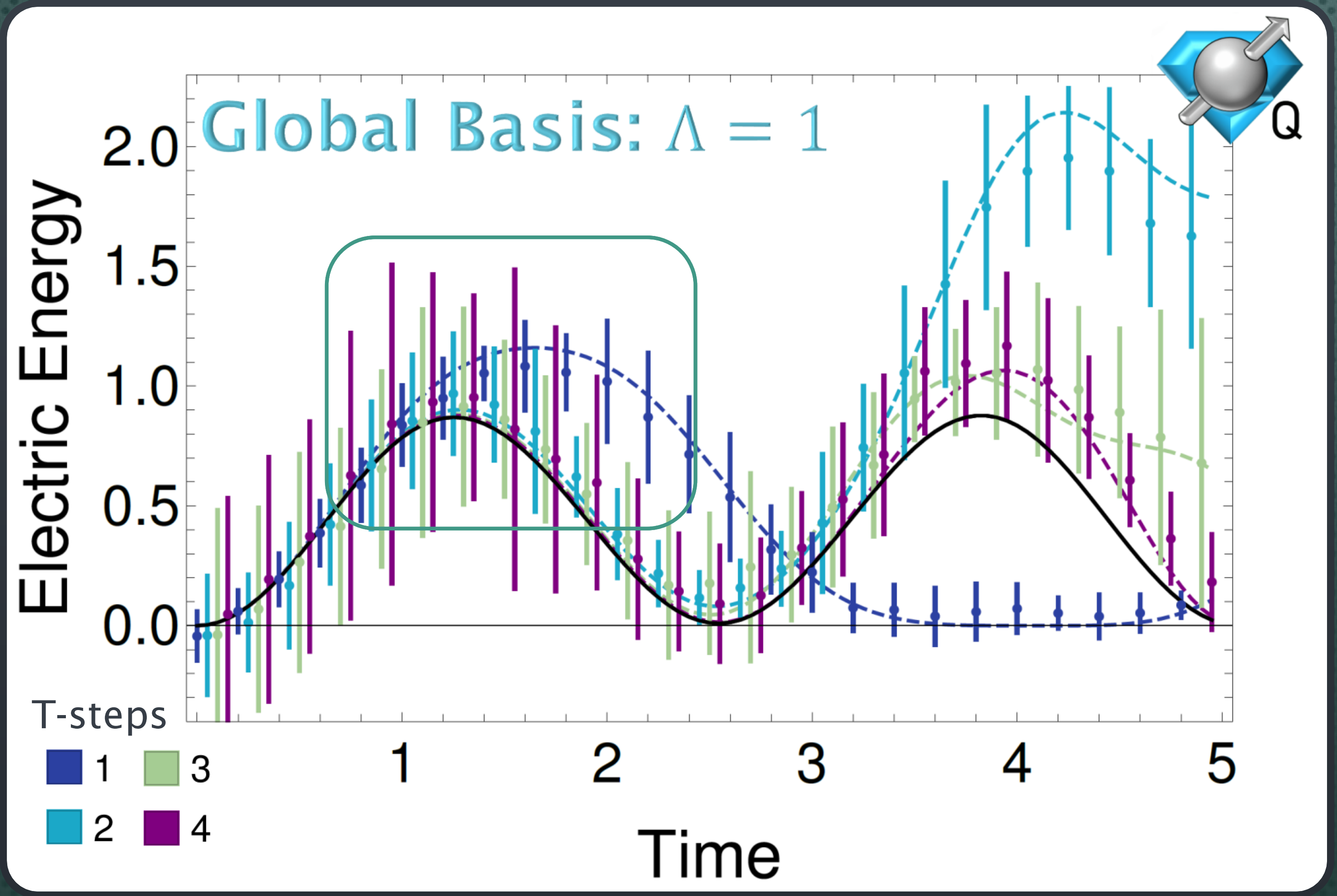
$$= \sum_{j=1}^{n^2+2n}\hat{O}_j+\hat{O}_j^\dagger$$

2-Level unitary

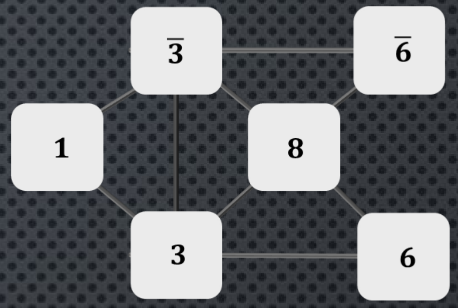


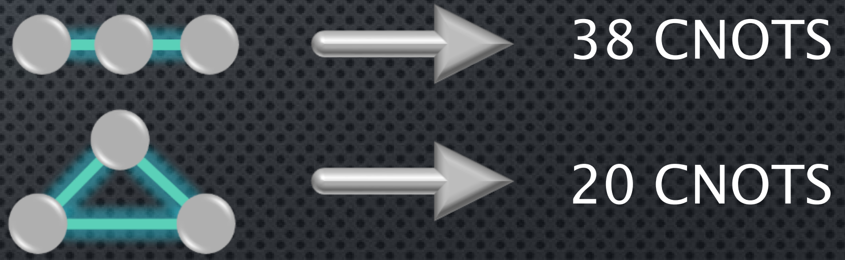
Confidence Intervals:

- CNOT extrapolation
- Measurement calibration matrix inverse
- Majority voting (aux. qubits)



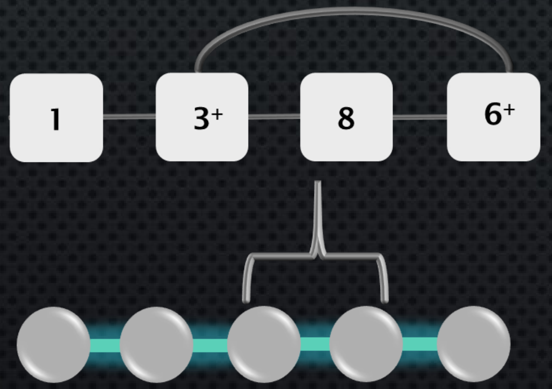
Global Basis: $|R_{max}| = 6$



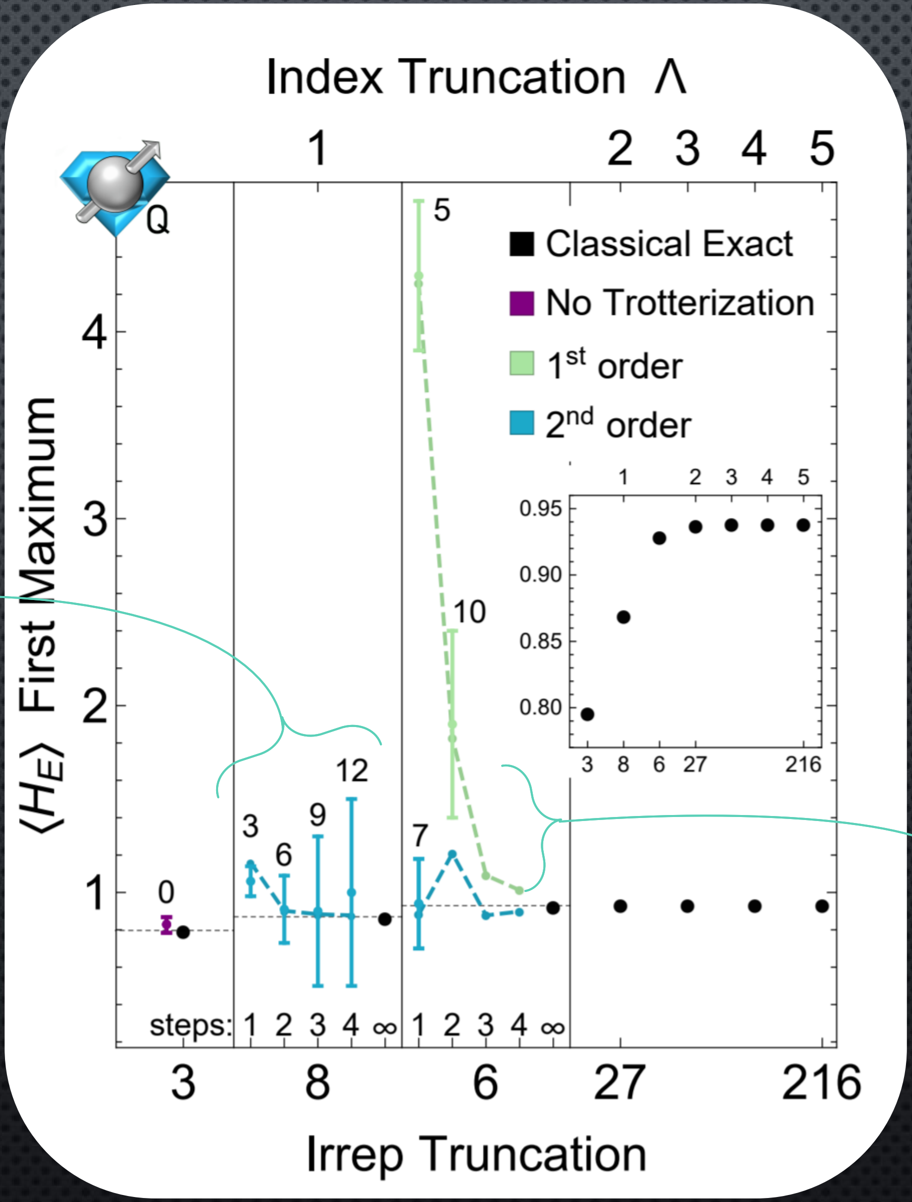


CP projection

T-order	CNOTs
1	5
2	7



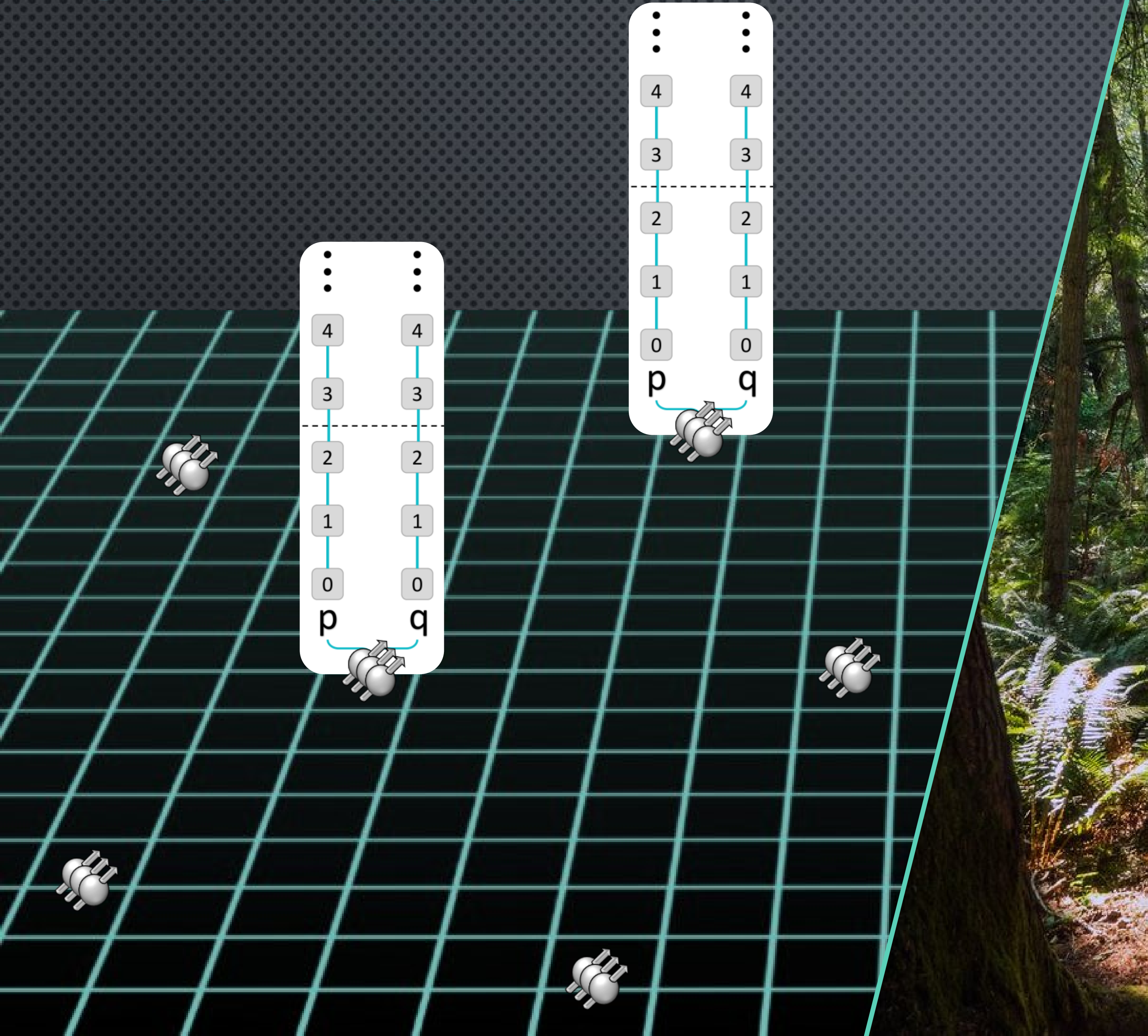
Dynamical Peak Benchmarks

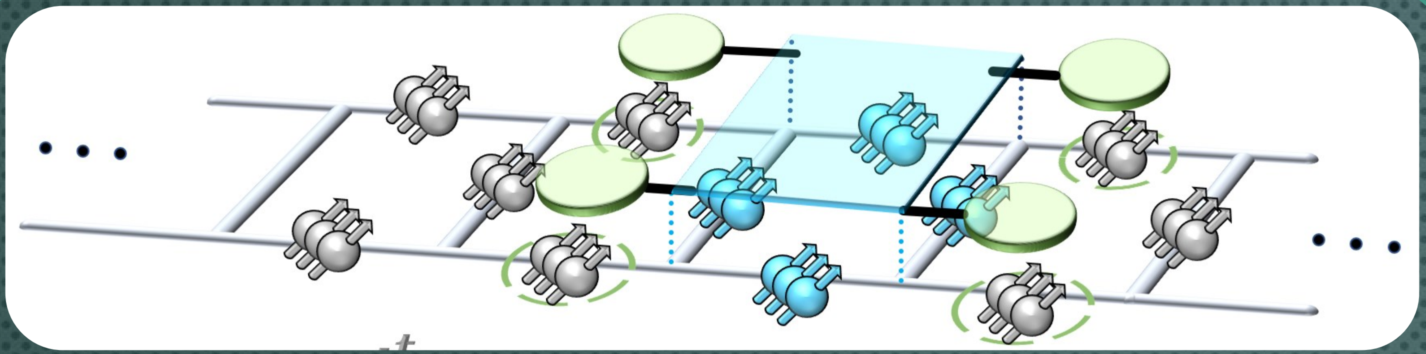


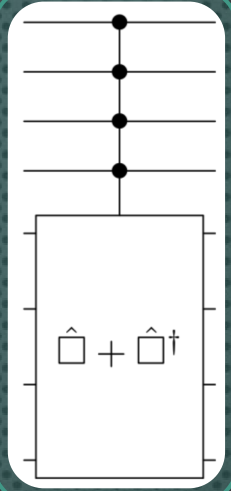
Theory-Experiment tradeoff

Trotter Order vs Steps

Local Basis







Gauge Variant Completion

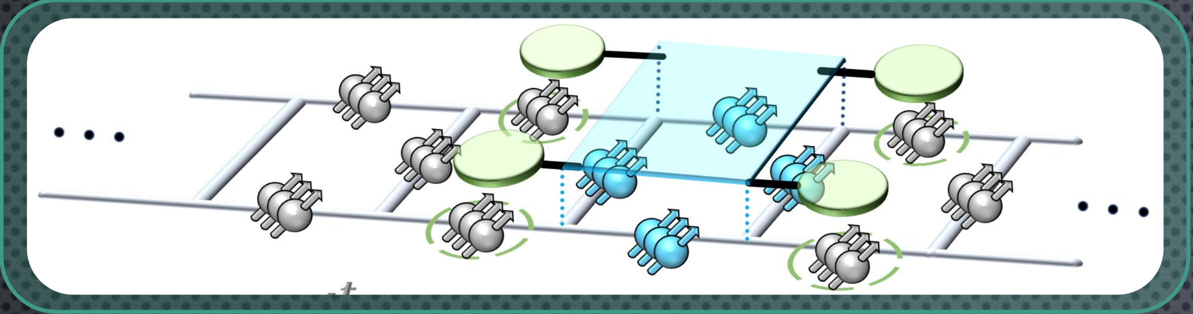
phys ↔ phys ✓

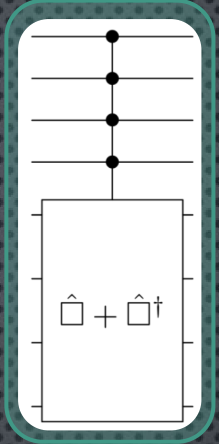
phys ↔ unphys **0**

unphys ↔ unphys **Free!**

SU(2): “human neural network” for low Λ “color” truncation

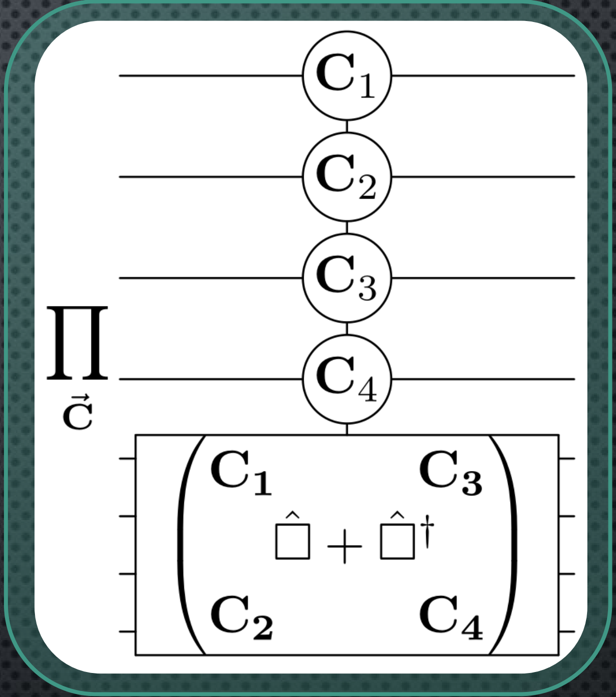
SU(3): systematic construction. Human understandable.





Magnetic time evolution expanded in *Gauge Invariant* product of operators organized by control sectors, $\vec{C}$

(No Trotter errors between control sectors)



2-Level unitaries

$$\begin{pmatrix} \mathbf{3} & & \bar{\mathbf{3}} \\ & \hat{\Box}+\hat{\Box}^\dagger & \\ \bar{\mathbf{3}} & & \mathbf{3} \end{pmatrix} = \exp\left[-i\alpha\left(\frac{1}{3}\mathcal{X}_{12}\mathcal{X}_{01}\mathcal{X}_{12}\mathcal{X}_{01} + \frac{1}{3\sqrt{3}}\mathcal{X}_{02}\mathcal{X}_{12}\mathcal{X}_{01}\mathcal{X}_{02} + \frac{1}{3\sqrt{3}}\mathcal{X}_{01}\mathcal{X}_{02}\mathcal{X}_{02}\mathcal{X}_{12}\right)\right]$$

Gauge Invariant
Matrix Element

Trotterization with Givens

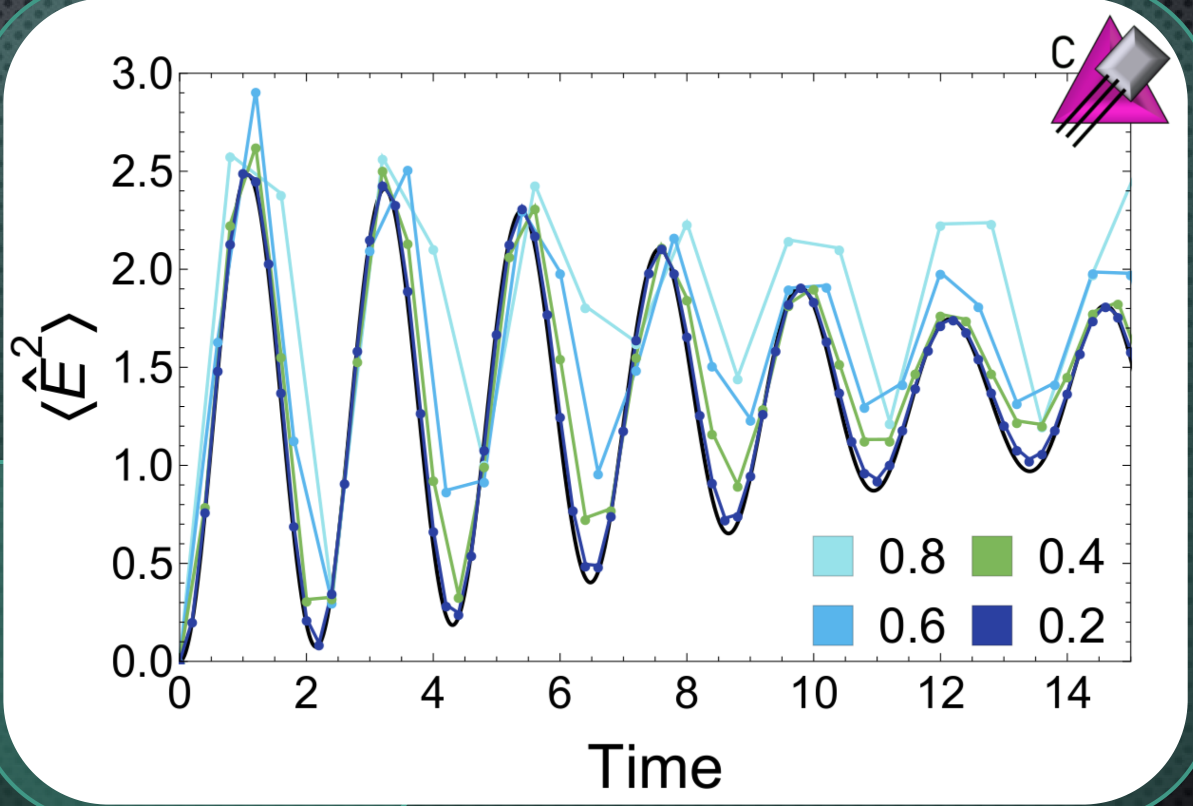
Preserves Gauge Invariance and Color Parity

$$\exp\left[-i\alpha\begin{pmatrix}\mathbf{3} & & \mathbf{3}\\ & (\hat{\Box}+\hat{\Box}^\dagger) & \\ \bar{\mathbf{3}} & & \bar{\mathbf{3}}\end{pmatrix}\right] \rightarrow$$

$$\left(\exp\left[-i\frac{\alpha}{3}\mathcal{X}_{12}\mathcal{X}_{02}\mathcal{X}_{12}\mathcal{X}_{01}\right]\exp\left[-i\frac{\alpha}{9}\mathcal{X}_{02}\mathcal{X}_{01}\mathcal{X}_{01}\mathcal{X}_{02}\right]\exp\left[-i\frac{\alpha}{3}\mathcal{X}_{01}\mathcal{X}_{12}\mathcal{X}_{02}\mathcal{X}_{12}\right]\right)\otimes\Lambda_1\otimes\Lambda_2\otimes\Lambda_1\otimes\Lambda_2$$

- Each unitary operator is associated with a physical plaquette transition
- Coefficients determined from matrix elements between gauge-invariant states

Two PBC Plaquettes {1, 3, 3bar}

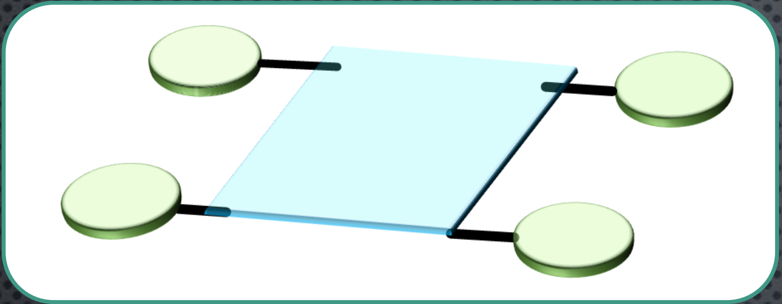


Black: global ++ basis (4 dim)

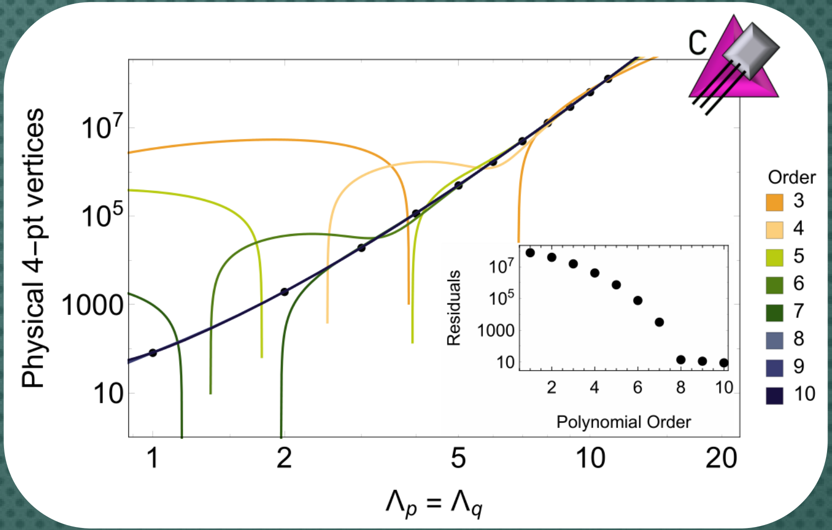
Colors: local qudit basis ($3^6 = 729$ dim, 27 cGivens)

Scaling

4-pt $\lesssim$ control sectors $\sim \Lambda^8$



Gauss's law constraint does not reduce the asymptotic polynomial scaling.



$\Lambda_p = \Lambda_q$	dimensions	physical states	matrix elements	elements/states
1	$(\mathbf{1},\mathbf{3})$	81	81	1
1	$(\mathbf{1},\mathbf{3},\mathbf{8})$	529	1,018	1.92
2	$(\mathbf{1},\mathbf{3},\mathbf{8},\mathbf{6})$	5,937	19,594	3.30
2	$(\mathbf{1},\mathbf{3},\mathbf{8},\mathbf{6},\mathbf{15})$	59,737	419,316	7.02
2	$(\mathbf{1},\mathbf{3},\mathbf{8},\mathbf{6},\mathbf{15},\mathbf{27})$	139,317	1,049,931	7.54
3	$(\mathbf{1},\mathbf{3},\mathbf{8},\mathbf{6},\mathbf{15},\mathbf{27},\mathbf{10})$	509,271	4,001,111	7.86
3	$(\mathbf{1},\mathbf{3},\mathbf{8},\mathbf{6},\mathbf{15},\mathbf{27},\mathbf{10},\mathbf{24})$	2,008,297	24,648,819	12.27

- Potential non-zero matrix element per physical state constant: $3^4 = 81$
- Limited by Gauss' Law
- Givens rotations $\sim \Lambda^{16}$

Retain exponential color space convergence?

EFT for inclusion of "hot" links?

Field

Quantum d.o.f.

Quantum Simulation of Strong Interactions (QuaSI) Workshop 1 : Theoretical Strategies for Gauge Theories

Position space lattice

Momentum Mode Lattice

Loop, String, Hadron Excitations

Eigenbasis of Field Operator

Gauge Field Integration in (1+1)

Hybrid/Analog Representation

Orbifold Lattice

Irreducible Representations

Local Free-Field Eigenstates

Group Space Decimation

Link Models/Qubit Regularization

Magnetic Basis

Discrete Subgroups

Mesh Digitization

Light-Front Formulations

Initialization

Ground States

Local wave packets

connectivity

gates

Time Evolution

Coherence times

Measurement Procedure

Detector Design

Entanglement Structures

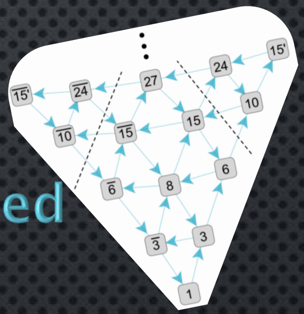
Summary

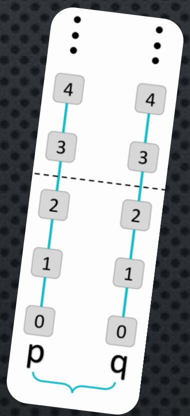
- Multiplet basis integrated over the local gauge space. Qubit requirements:

$$\#\ qubits \sim 2L^D \log_2(\Lambda_p + 1)$$

L = 10, D = 3, Λ = 1 → 2,000 logical qubits
1,000 ops/plaquette

- Implementation of Global basis





- Gauge Invariant Time Evolution organized by local link qudit structure

- Flexibility for Codesign with existing and developing hardware

1D 2D

(p,q):

(p,q), ⬡ mix: