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Quantum Computing for New Physics Searches

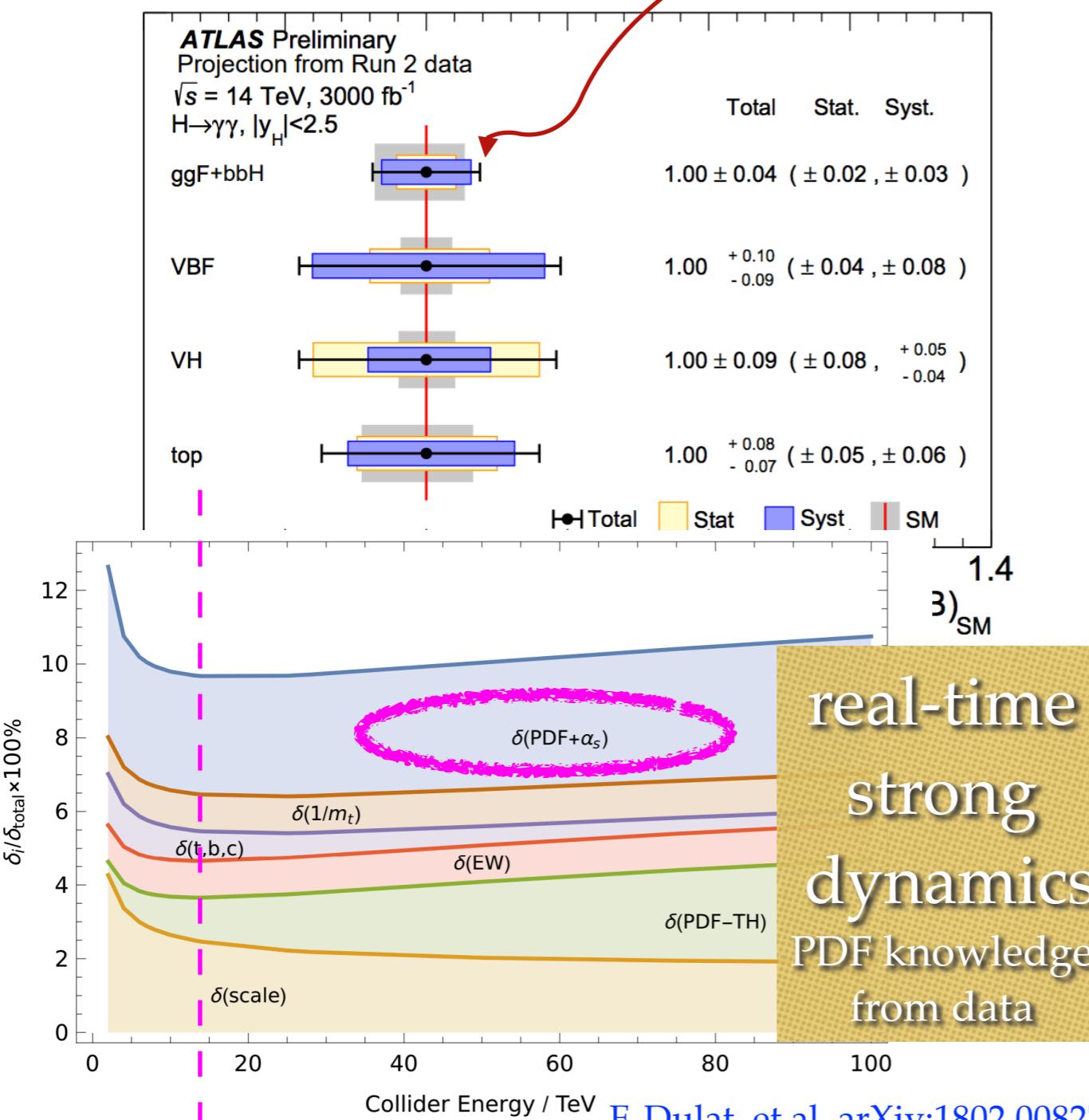
May. 29, 2023 @ “*Beyond the SM from Colliders to the Early Universe*”



Theoretical inputs to colliders

theoretical uncertainties

PDF

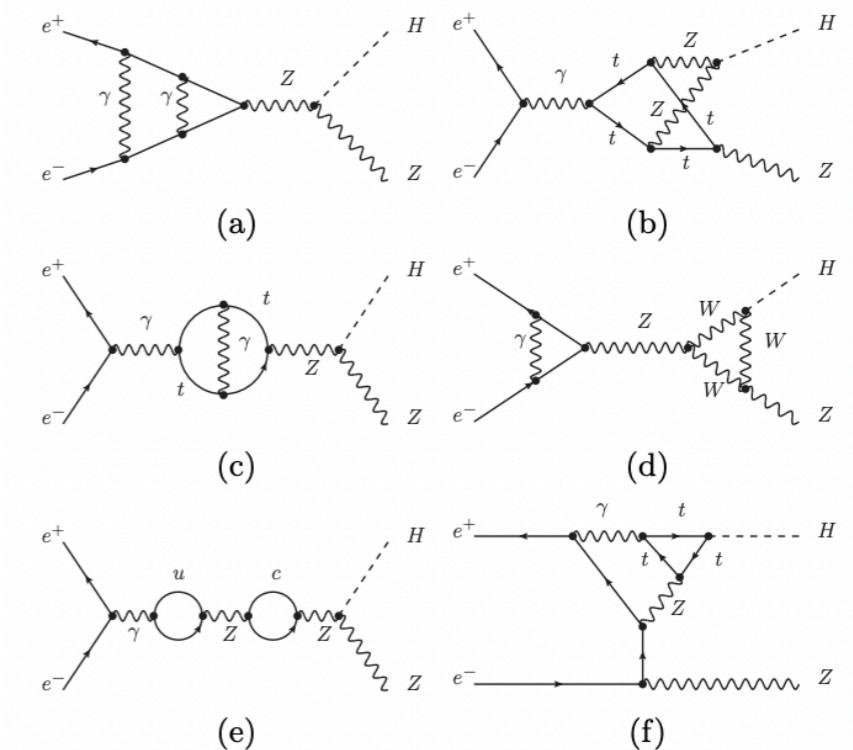


higher order corrections

CEPC : $\sigma(e^+e^- \rightarrow ZH), 0.51\%$

NLO EW
NNLO EW-QCD 1%

complete two loop



F. An, et al, arXiv:1810.09037

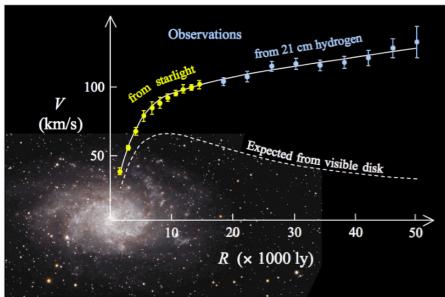
Y. Gong et al., Q. -F. Sun et al.,

X. Chen et al, arXiv: 2209.14953



Puzzles We Encountered

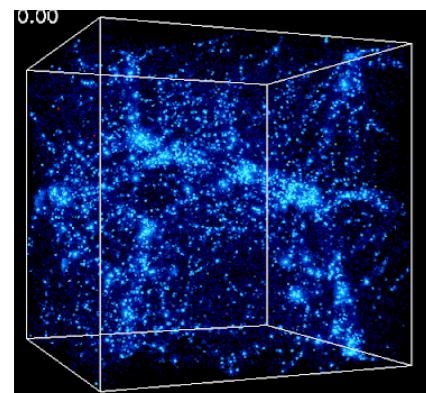
1933-Now
dark matter



rotation curves



bullet cluster



structure formation

$$m_a^2(T)f_a^2 \propto \frac{\partial^2 F(\theta, T)}{\partial \theta^2} |_{\theta=0}$$

lattice non-perturbative
calculations

$$\begin{array}{ccc} F(\theta, T) & \leftarrow & \langle O \rangle = \frac{\sum_{\mathcal{C}} O(\mathcal{C}) W(\mathcal{C})}{\sum_{\mathcal{C}} W(\mathcal{C})} \\ \text{QCD free energy} & & \end{array}$$

Imaginary time problem : $W(\mathcal{C}) \sim \exp(-S(\mathcal{C}))$

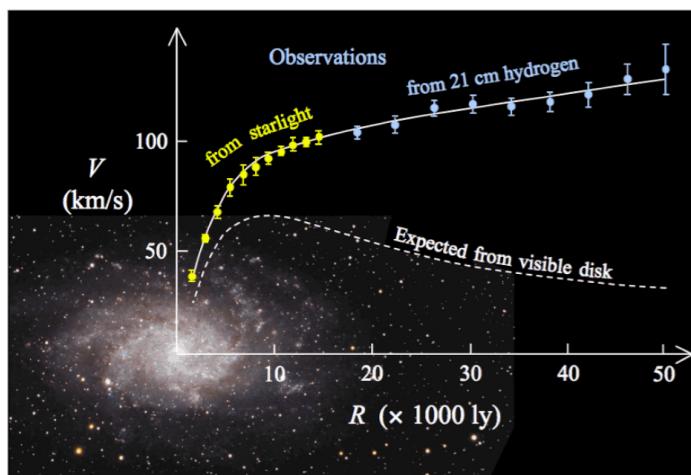
complex $S(\mathcal{C})$ for non vanishing θ

Sign Problem!!!

configuration space \mathcal{C} is exponentially large in system size



1933-Now
dark matter



1940s-Now
baryon
asymmetry



$$\delta m_{SM}^2 \sim -\frac{3y_t^2\Lambda^2}{16\pi^2} + \frac{3g^2\Lambda^2}{16\pi^2} + \frac{3\lambda_{SM}\Lambda^2}{16\pi^2}$$

- WIMP dark matter freeze-out,
- axion dark matter (relic abundance depends on the QCD topological term—**complex action**)

Sakharov
Out of equilibrium
C- and CP-
violation
B-violation

- Composite Higgs (strong dynamics),
- Higgs Precision measurement (higher-order rare processes—**rare events**)

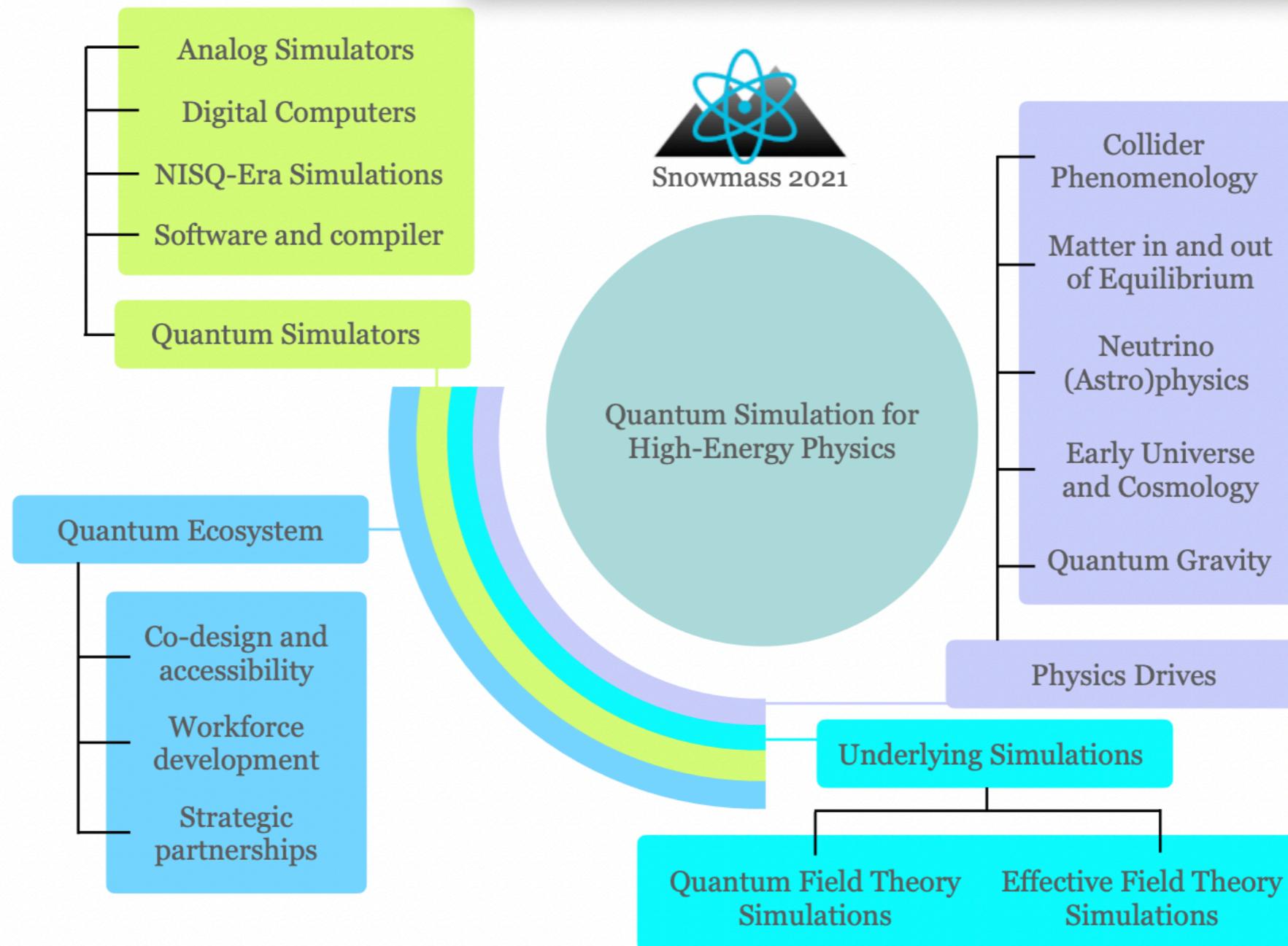
out-of-equilibrium,
non-perturbative
higher order processes,
quantum interference
cannot be solved classically
due to theoretical or computational limitations:

**sign problem or rare events that has
exponential-scaling of the complexity**

$$\langle x | e^{-iHt} | y \rangle = \int \mathcal{D}\phi e^{iS}$$

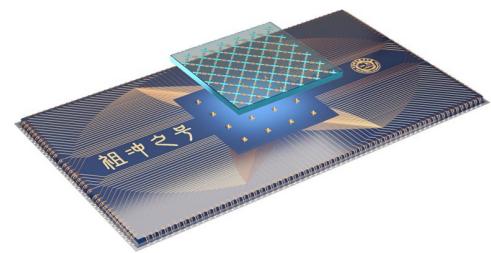
Quantum Simulation for High Energy Physics

Christian W. Bauer,^{1, a} Zohreh Davoudi,^{2, b} A. Baha Balantekin,³ Tanmoy Bhattacharya,⁴ Marcela Carena,^{5, 6, 7, 8} Wibe A. de Jong,¹ Patrick Draper,⁹ Aida El-Khadra,⁹ Nate Gemelke,¹⁰ Masanori Hanada,¹¹ Dmitri Kharzeev,^{12, 13} Henry Lamm,⁵ Ying-Ying Li,⁵ Junyu Liu,^{14, 15} Mikhail Lukin,¹⁶ Yannick Meurice,¹⁷ Christopher Monroe,^{18, 19, 20, 21} Benjamin Nachman,¹ Guido Pagano,²² John Preskill,²³ Enrico Rinaldi,^{24, 25, 26} Alessandro Roggero,^{27, 28} David I. Santiago,^{29, 30} Martin J. Savage,³¹ Irfan Siddiqi,^{29, 30, 32} George Siopsis,³³ David Van Zanten,⁵ Nathan Wiebe,^{34, 35} Yukari Yamauchi,² Kübra Yeter-Aydeniz,³⁶ and Silvia Zorzetti⁵

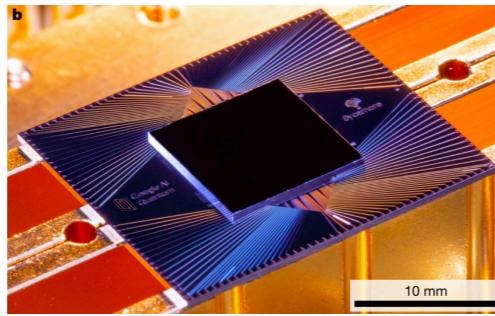


A range of quantum simulators with varying capacity and capability

Superconducting Processor



66 qubits



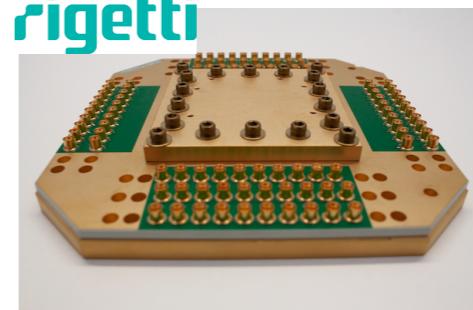
54 qubits



127 qubits

multi-chip quantum processor

rigetti



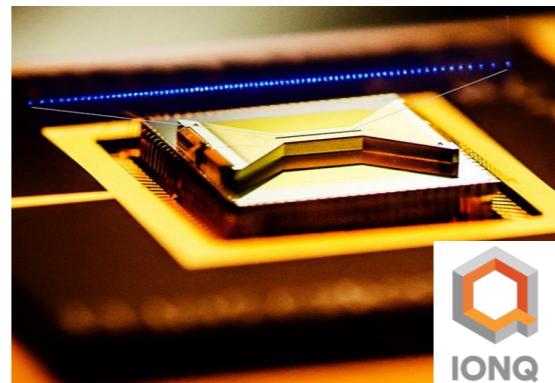
80 qubits

Photon qubits



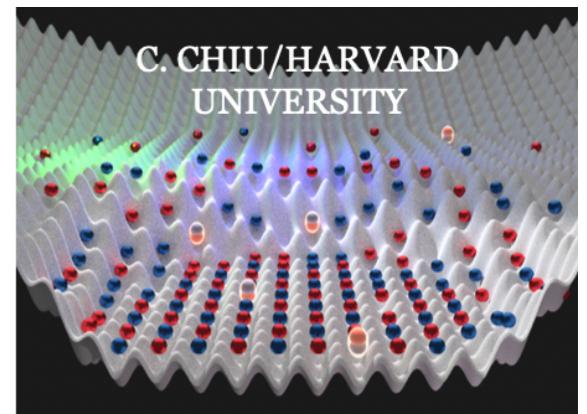
九章- 76 qubits

trapped ion qubits

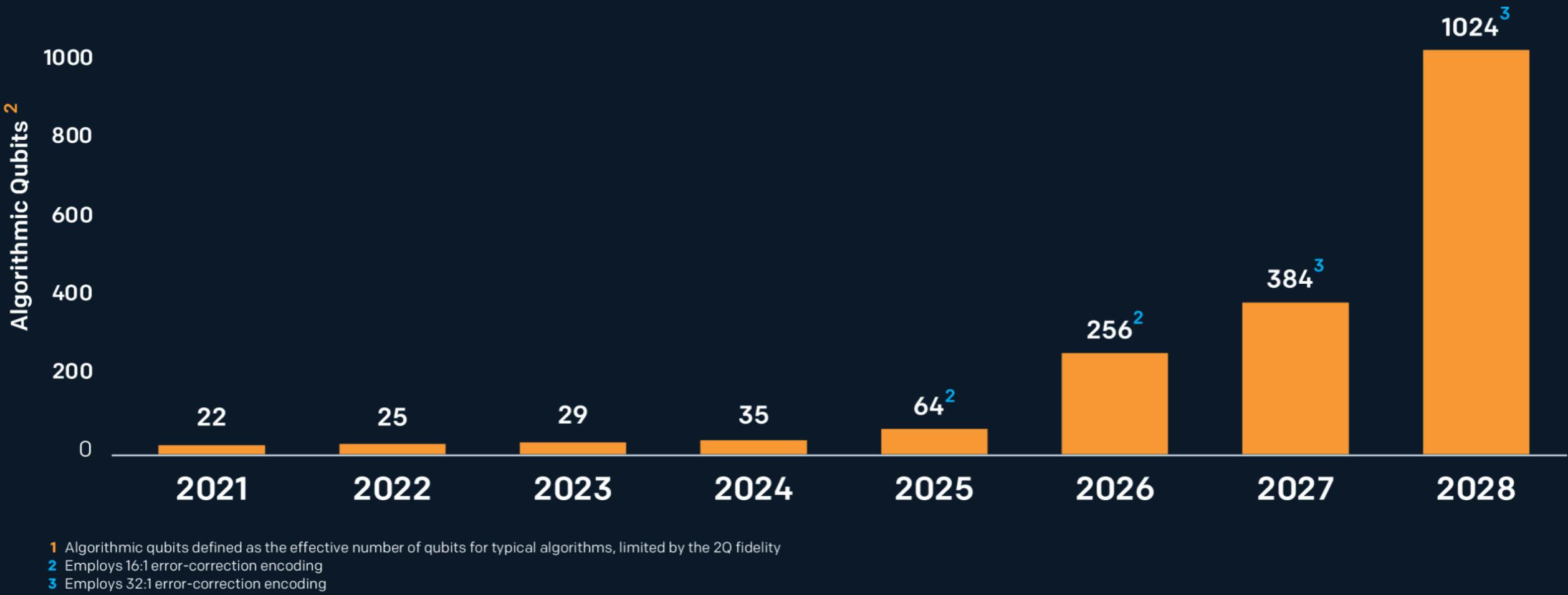


22 qubits

Analog
quantum
simulator



A range of quantum simulators with varying capacity and capability



rapid development
still limited resources

History of LQCD

From Henry Lamm's talk

(1970s) Formulate the problem

quantize a gauge field theory on a discrete lattice in Euclidean space-time,

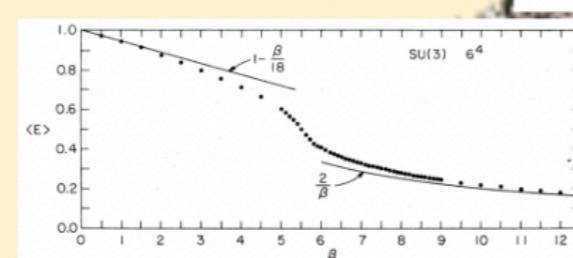
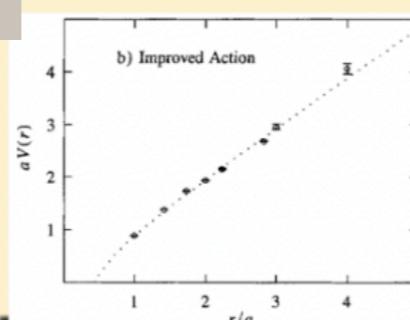
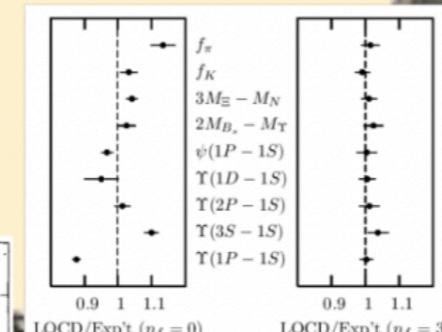
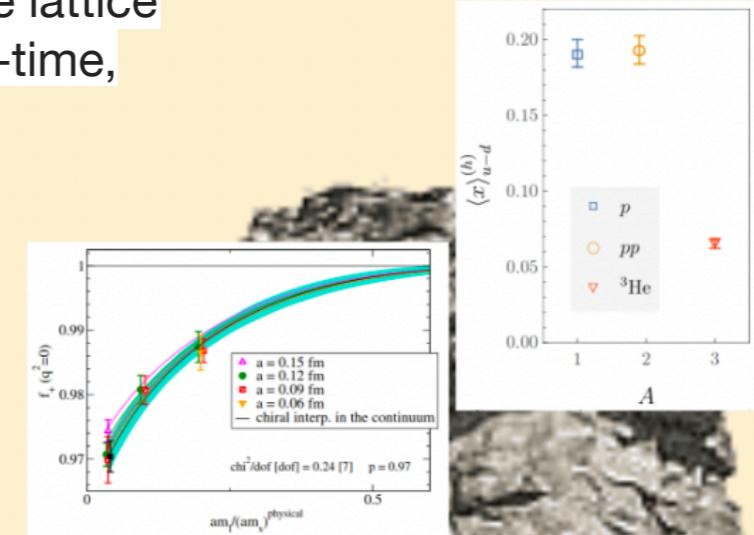
(1980s) Reaching the continuum

(1990s) Reducing lattice artifacts

(2000s) Dynamical Fermions

(2010s) Form Factors, QED

Now: Great Success



Confinement of quarks*

Kenneth G. Wilson

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
(Received 12 June 1974)



History of LQCD

From Henry Lamm's talk

(1970s) Formulate the problem

quantize a gauge field theory on a discrete lattice in Euclidean space-time,

(1980s) Reaching the continuum

(1990s) Re

(2000s) Dy

(2010s) Fo

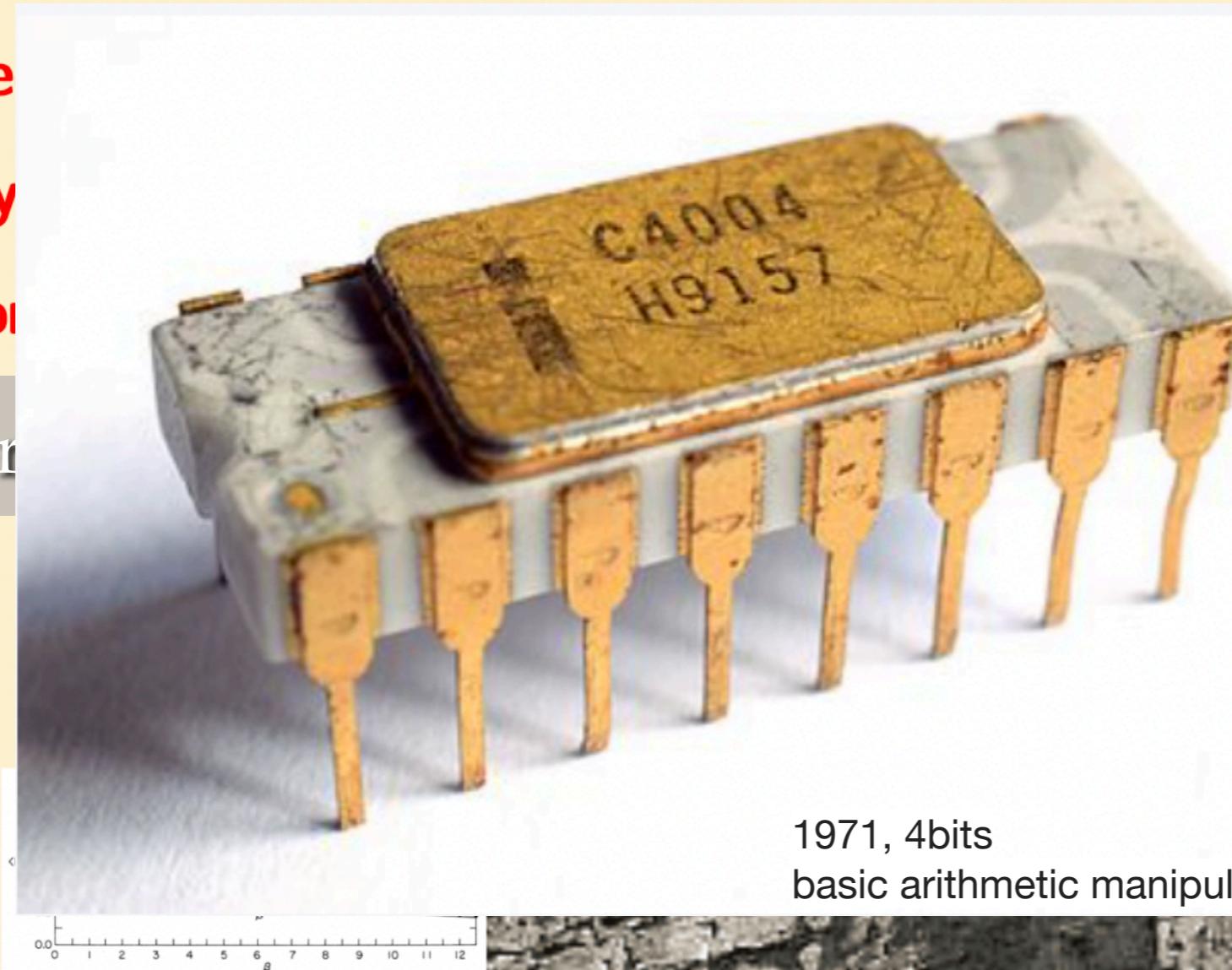
Now: Gr



Confinement of quarks*

Kenneth G. Wilson

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1971, 4bits
basic arithmetic manipulations



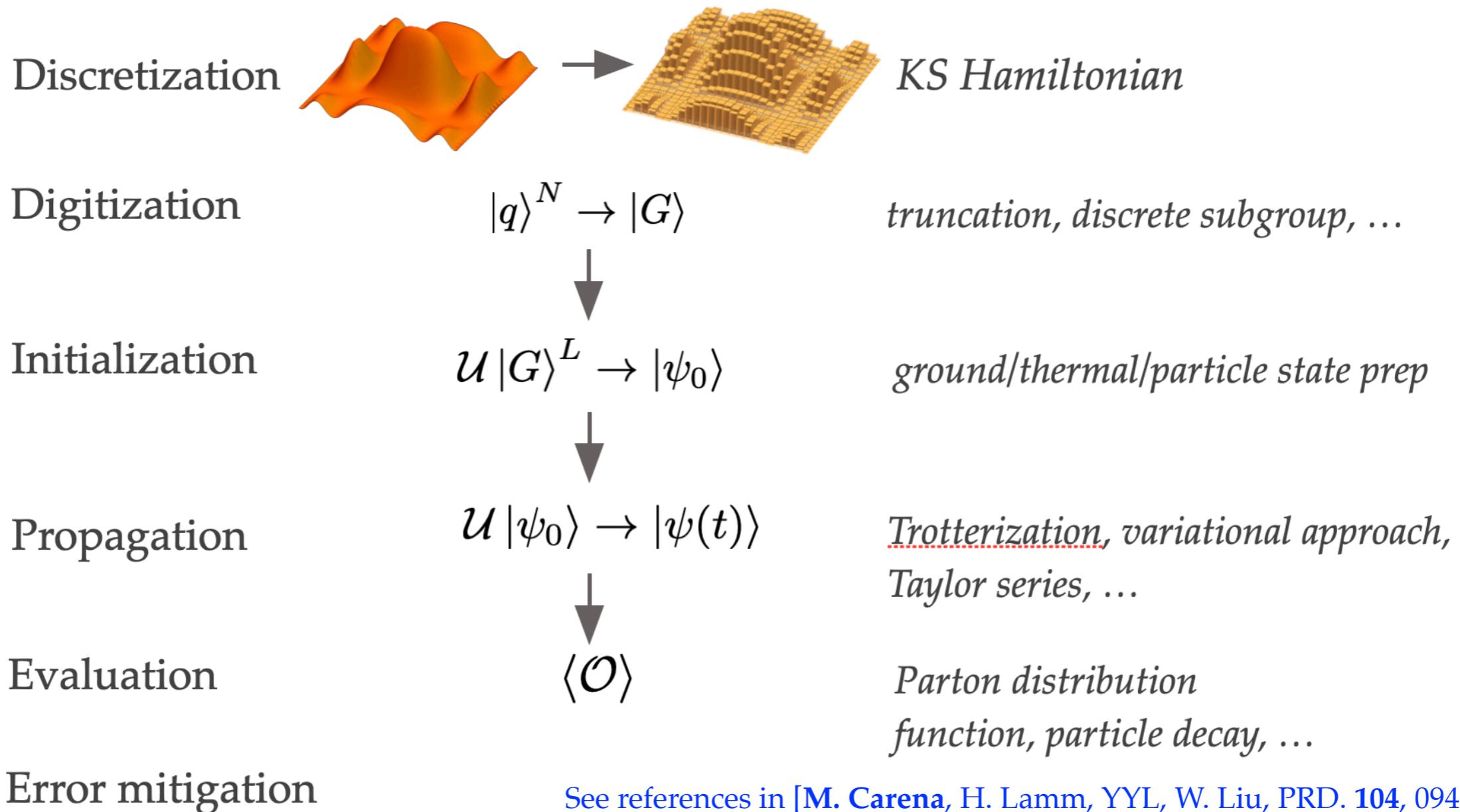
Quantum Simulation for Quantum Field Theory

Bosonic and fermionic DOF,
Dynamical and coupled global and local (gauge) symmetries,
Relativistic - particle number non-conservation,
Nontrivial vacuum state in strongly interacting theories

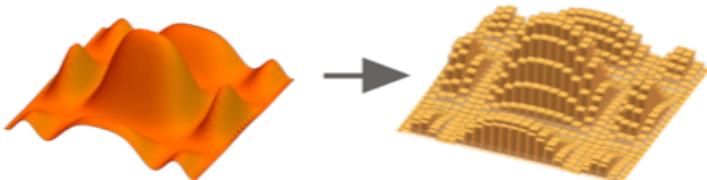
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“Champagne Problems”

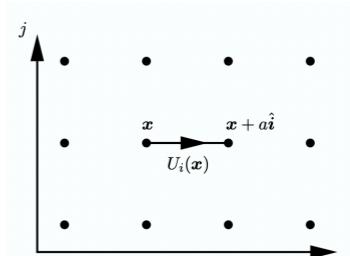


Discretization



infinities in QFT

$$H = \int d^d x \text{Tr} (\mathbf{E}^2 + \mathbf{B}^2) \quad \xrightarrow{\text{gauge invariance}} \quad U_{\square} = \exp \left\{ ig \oint_{\square} A \cdot dx \right\}$$



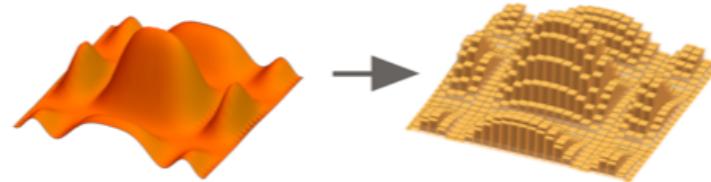
$$U_i(x) = e^{ig \int_a^0 dt A_i(x + t\hat{i})}$$

Kogut and Susskind formulation: [Phys. Rev. D 11, 395 (1975)]

$$H = -t \sum_{\langle xy \rangle} s_{xy} (\psi_x^\dagger U_{xy} \psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x) + m \sum_x s_x \psi_x^\dagger \psi_x + \frac{g^2}{2} \sum_x \mathbf{E}(x)^2 - \frac{1}{4g^2} \sum_{\square} \text{Tr} (U_{\square} + U_{\square}^\dagger)$$

fermion kinetic	fermion mass	energy of electric field	energy of magnetic field
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Discretization



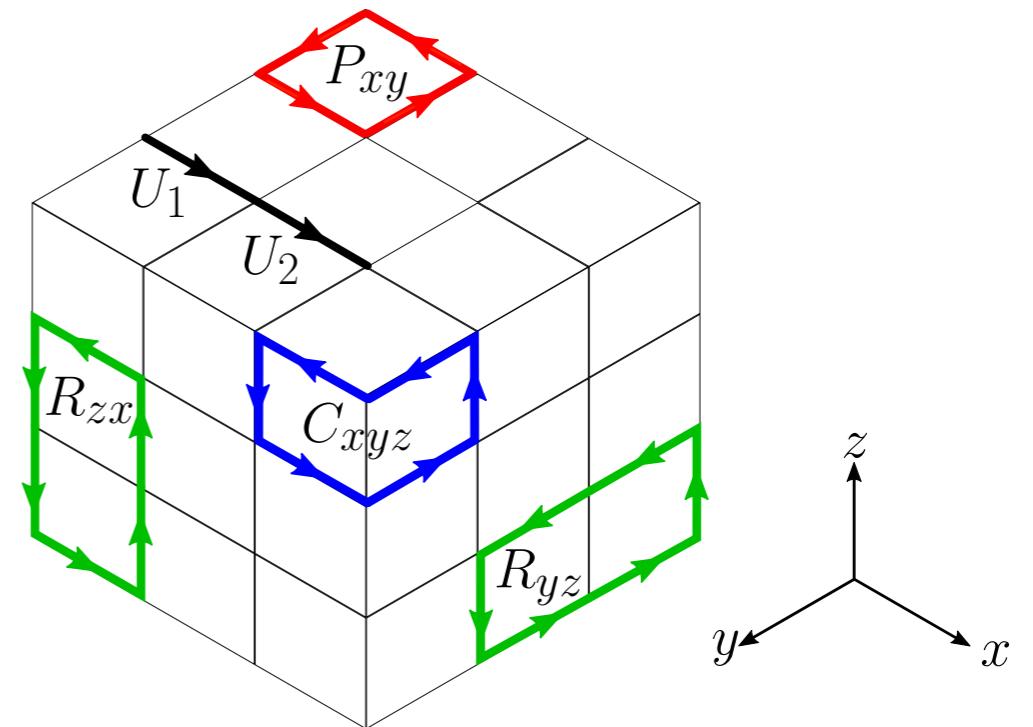
[J. Carlsson, et al, hep-lat/0105018]

$$P_{ij}(x) = 1 - \frac{1}{N} \text{ReTr} \exp \left\{ ig \oint_{\square} A \cdot dx \right\} \approx \frac{g^2 a^4}{2N} \text{Tr} \{ F_{ij}(x) F_{ij}(x) \} + \frac{g^2 a^6}{12N} \text{Tr} \{ F_{ij}(x) (D_i^2 + D_j^2) F_{ij}(x) \} + \dots$$

deviations from the continuum, starts from a^2 error, classical computational resources proportional a^{-k} to for Wilson action

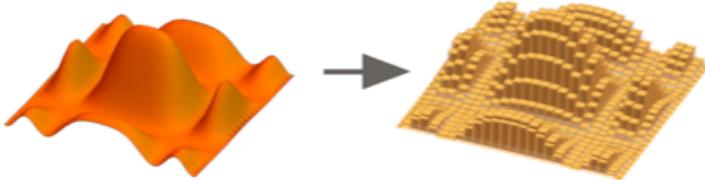
$$R_{ij}(x) = 1 - \frac{1}{N} \text{ReTr} \left\{ \begin{array}{c} \text{square loop with arrows} \\ i \quad j \end{array} \right\} = \frac{4g^2 a^4}{2N} \text{Tr} \{ F_{ij}(x) F_{ij}(x) \} + \frac{4g^2 a^6}{24N} \text{Tr} \{ F_{ij}(x) (4D_i^2 + D_j^2) F_{ij}(x) \} + \dots$$

deviations from the continuum starts from $a^2 g^2$ at quantum level



[M. Carena, H. Lamm, YYL, W. Liu, PRL. 129, 051601]

Discretization



[M. Alford, et al, hep-lat/9507010]
[..., ...]

With improved action,
for Euclidean spacetime
at the same error level,
simulations can be done
with a lattice spacing of
at least 2 larger

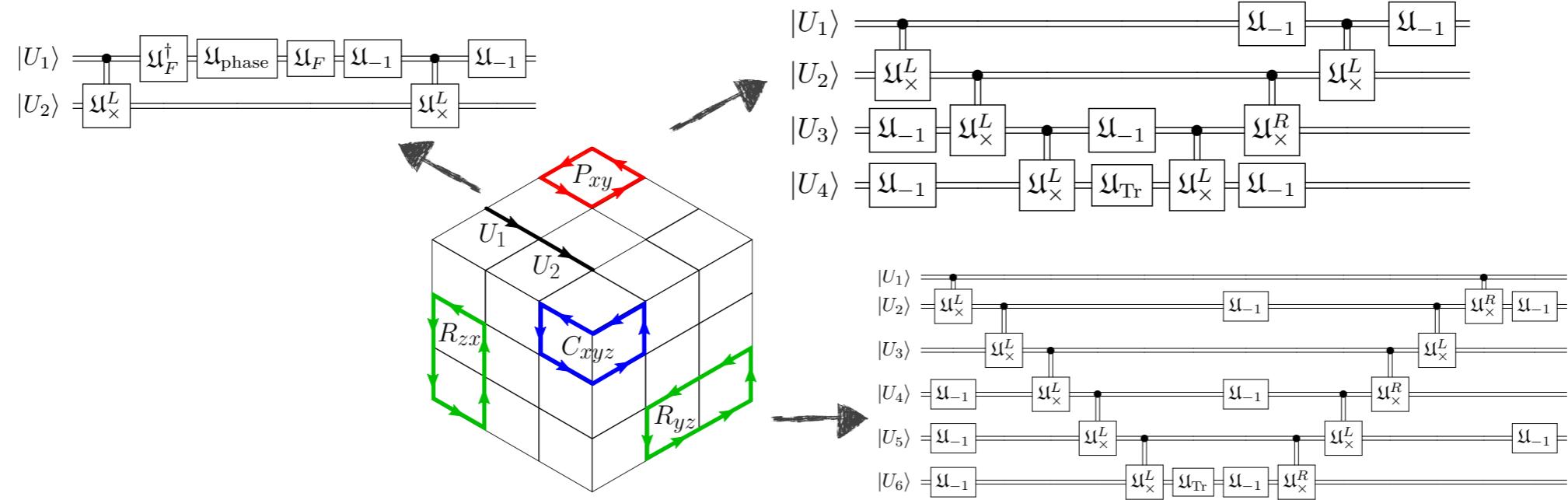
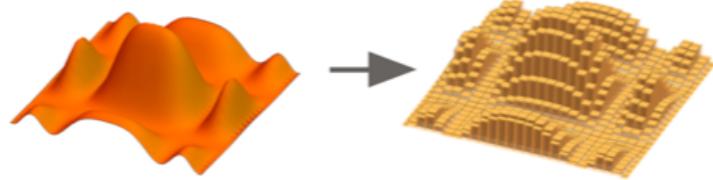
Qubits required

$$N_q \sim \left(\frac{L}{a}\right)^d$$

Only count qubits:
saving us at least 3 years for 3+1d,
assuming number of qubits increases by
a factor of 2 each year on hardware

circuits for improved Hamiltonian need to be designed

Discretization



Gate	$N[\hat{K}_{KS} + \hat{V}_{KS}]$	$N[\hat{K}_{2L} + \hat{V}_{\text{rect}}]$
\mathfrak{U}_F	2	2
$\mathfrak{U}_{\text{phase}}$	1	1
\mathfrak{U}_{Tr}	$\frac{d-1}{2}$	$d - 1$
\mathfrak{U}_{-1}	$3(d - 1)$	$2 + 8(d - 1)$
\mathfrak{U}_x	$6(d - 1)$	$4 + 20(d - 1)$

- # of Gates here for a single trotter is increasing only multiplicatively, could be compensated by the decreasing of links.
- Larger trotter steps, instead could be used for improved Hamiltonian.

Digitization

$$|q\rangle^N \rightarrow |G\rangle$$

infinities in QFT

Kogut and Susskind formulation: [Phys. Rev. D 11, 395 (1975)]

$$H = -t \sum_{\langle xy \rangle} s_{xy} (\psi_x^\dagger U_{xy} \psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x) + m \sum_x s_x \psi_x^\dagger \psi_x + \frac{g^2}{2} \sum_x \mathbf{E}(x)^2 - \frac{1}{4g^2} \sum_{\square} \text{Tr} (U_{\square} + U_{\square}^\dagger)$$

continuous field variables

infinities in QFT

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continuous field variables

rapid development with its own pros and cons

*rate of convergences to the infinite-dimensional theory, resource requirements,
local and global gauge symmetry*

Casimir dynamics, Natalie et al

LSH formalism, Mathur et al, Anishetty et al

Group-element basis and discrete subgroups, Erez et al, Lamm et al, Carena et al

Magnetic or dual representations, Mathur et al, Bauer et al

Tensor renormalization group (character expansion, Fourier series), Meurice et al

Light-front quantization (light-cone instead of fixed time-slicing), Mannheim et al

Quantum link models / qubit regularization (critical point), Brower et al

Matrix models (dimension reduction), Shen et al

Digitization

$$|q\rangle^N \rightarrow |G\rangle$$

infinities in QFT

Kogut and Susskind formulation: [Phys. Rev. D 11, 395 (1975)]

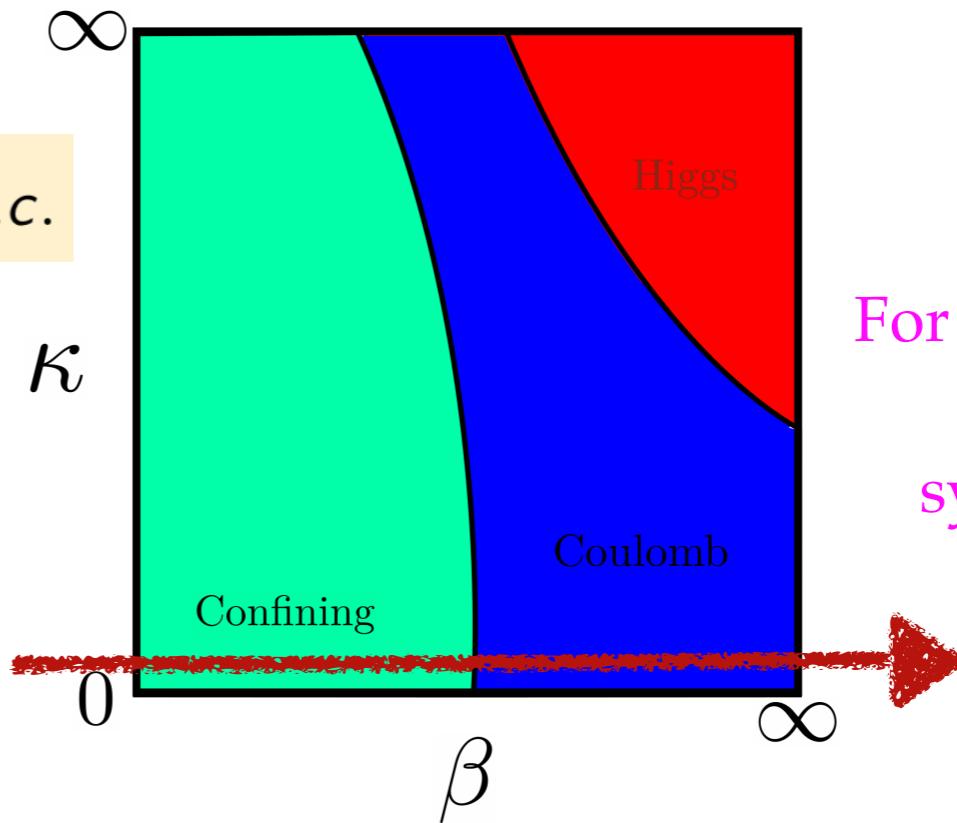
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continuous field variables

Gauge field truncations with discrete group

$$S = \beta \sum \text{Re Tr } U_P + \kappa \sum \phi \cdot D\{U_P\} \cdot \phi^\dagger + c.c.$$

discrete group
continuous group + Higgs
continuum limit for U(1)



For non-abelian
gauge
symmetry?

[M. Carena, H. Lamm, YYL, W. Liu, to be put on the schedule]

[Fradkin, Shenker, PRD. 19. 3682]

infinities in QFT

Kogut and Susskind formulation: [Phys. Rev. D 11, 395 (1975)]

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continuous field variables

Gauss's law operator $G^a(x) = -E_L^a(x) + E_R^a(x-1) + \psi^\dagger(x) T^a \psi(x)$ $G_x^a |P\rangle = 0$

infinities in QFT

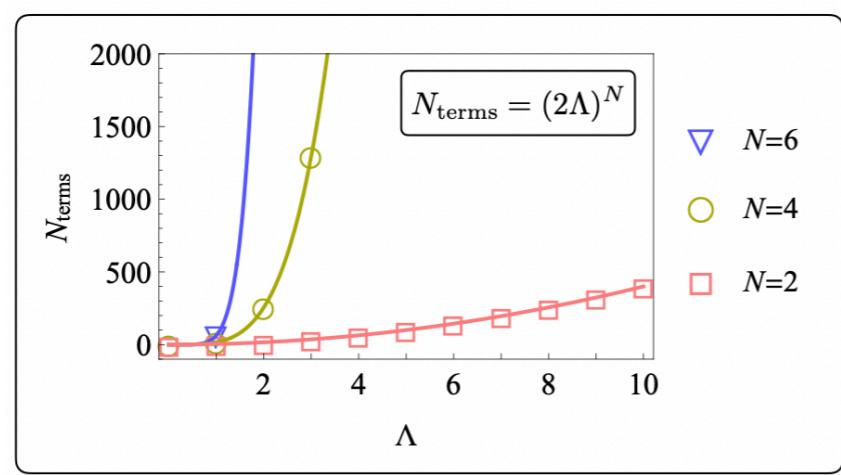
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continuous field variables

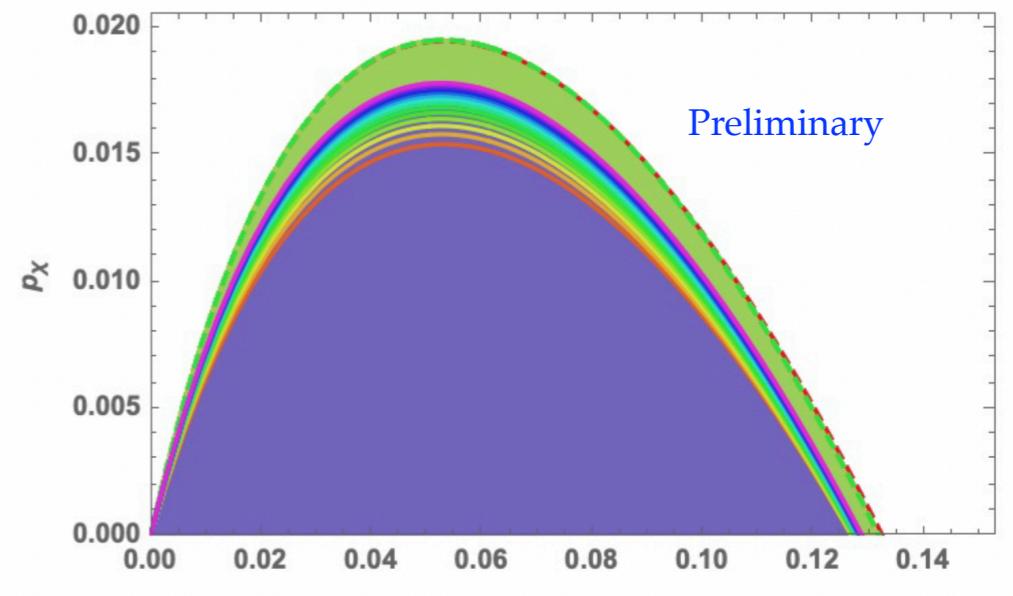
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To present a physical state in the angular momentum basis



Davoudi, Raychowdhury, and Shaw, arXiv:2009.11802 [hep-lat]

Gauge fixing in higher dimensions, and resilience to quantum errors?



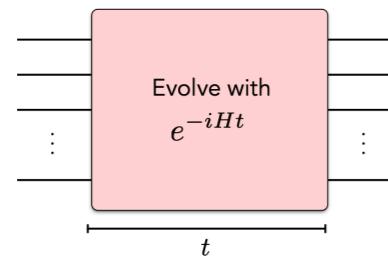
[M. Carena, H. Lamm, YYL, W. Liu, in preparation]

Gauge symmetry used for error corrections, see Halimeh, et al. Lamm, et al. ...

Propagation

$$\mathcal{U} |\psi_0\rangle \rightarrow |\psi(t)\rangle$$

ANALOG



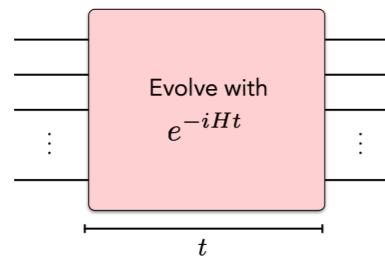
Cold neutral atoms, Trapped ions, Cavity quantum electrodynamics
Superconducting circuits

...

Propagation

$$\mathcal{U} |\psi_0\rangle \rightarrow |\psi(t)\rangle$$

ANALOG

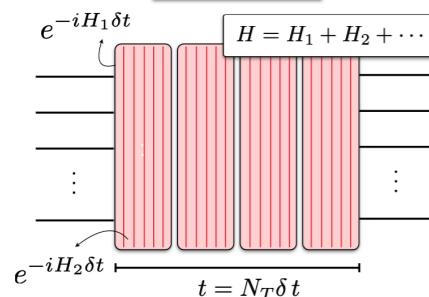


Cold neutral atoms, Trapped ions, Cavity quantum electrodynamics
Superconducting circuits

...

DIGITAL

superconducting qubit/trapped-ion system



building blocks:
one-qubit/two-qubit gate set

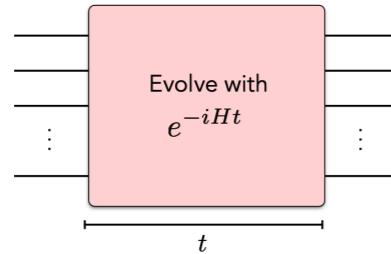
$$||\mathcal{U} - e^{-iHt}|| < \epsilon$$

optimal asymptotically?
overload of resources?
easy implementation?

Propagation

$$\mathcal{U} |\psi_0\rangle \rightarrow |\psi(t)\rangle$$

ANALOG

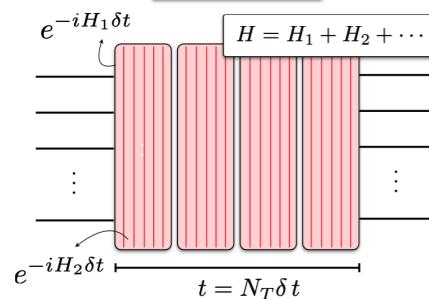


Cold neutral atoms, Trapped ions, Cavity quantum electrodynamics
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DIGITAL

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one-qubit/two-qubit gate set

$$||\mathcal{U} - e^{-iHt}|| < \epsilon$$

optimal asymptotically?
overload of resources?
easy implementation?

Trotter-Suzuki decomposition

$$H = \sum_{l=1}^{\Gamma} H^{(l)}$$

$$\mathcal{U} = \left[\prod_{l=1}^{\Gamma} e^{-itH^{(l)}/r} \right]^r$$

p-th order trotterization: $\mathcal{O}\left(\left(\frac{t}{r}\right)^p\right)$

Errors depends on t and r

No ancillary overhead

Simpler implementation

Taylor series expansion (LCU)

$$e^{-iHt} = (e^{-iHt/r})^r \equiv V^r$$

$$V \approx \tilde{V} = \sum_{k=0}^K \frac{1}{k!} \left(\frac{-iHt}{r} \right)^k$$

$$\mathcal{U} = \tilde{V}^r$$

$$||\tilde{V} - V|| < \epsilon/r$$

K values depends on the aimed errors

Ancillary qubits are needed

Complex circuits implementation

Quantum singular value transformation

$$e^{-iHt} = \cos(Ht) - i \sin(Ht)$$

$$e^{i\phi_0\sigma_z} \prod_{j=1}^k \left(W(x) e^{i\phi_j \sigma_z} \right) = \begin{bmatrix} P(x) & iQ(x)\sqrt{1-x^2} \\ iQ^*(x)\sqrt{1-x^2} & P^*(x) \end{bmatrix}$$

$$W(x) := \begin{bmatrix} x & i\sqrt{1-x^2} \\ i\sqrt{1-x^2} & x \end{bmatrix}$$

Jacobi-Anger expansion for cos and sin

error: truncation order of the expansion

Ancillary qubits are needed

Complex circuits implementation

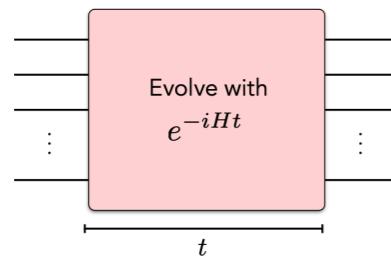
Quantum signal processing, blocking encoding, off-diagonal Hamiltonian expansion, etc...

[PRX Quantum 4 (2023) 2, 027001]

Propagation

$$\mathcal{U} |\psi_0\rangle \rightarrow |\psi(t)\rangle$$

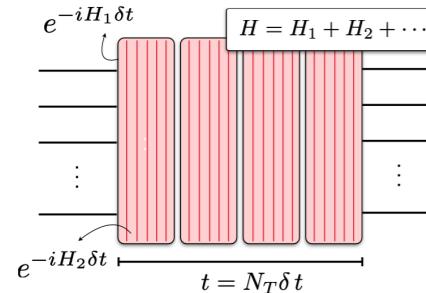
ANALOG



Cold neutral atoms, Trapped ions, Cavity quantum electrodynamics
Superconducting circuits

...

DIGITAL



superconducting qubit/trapped-ion system

building blocks:

one-qubit/two-qubit gate set

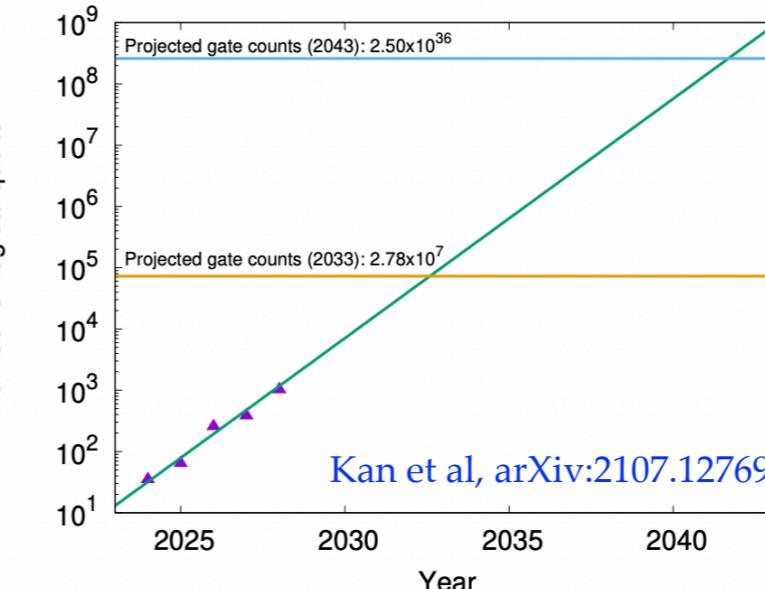
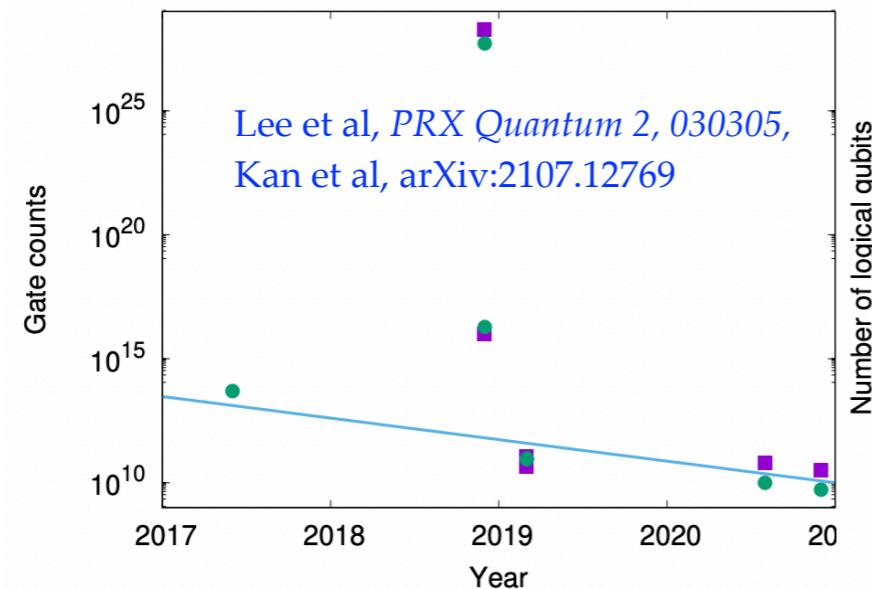
$$||\mathcal{U} - e^{-iHt}|| < \epsilon$$

Trotter-Suzuki decomposition

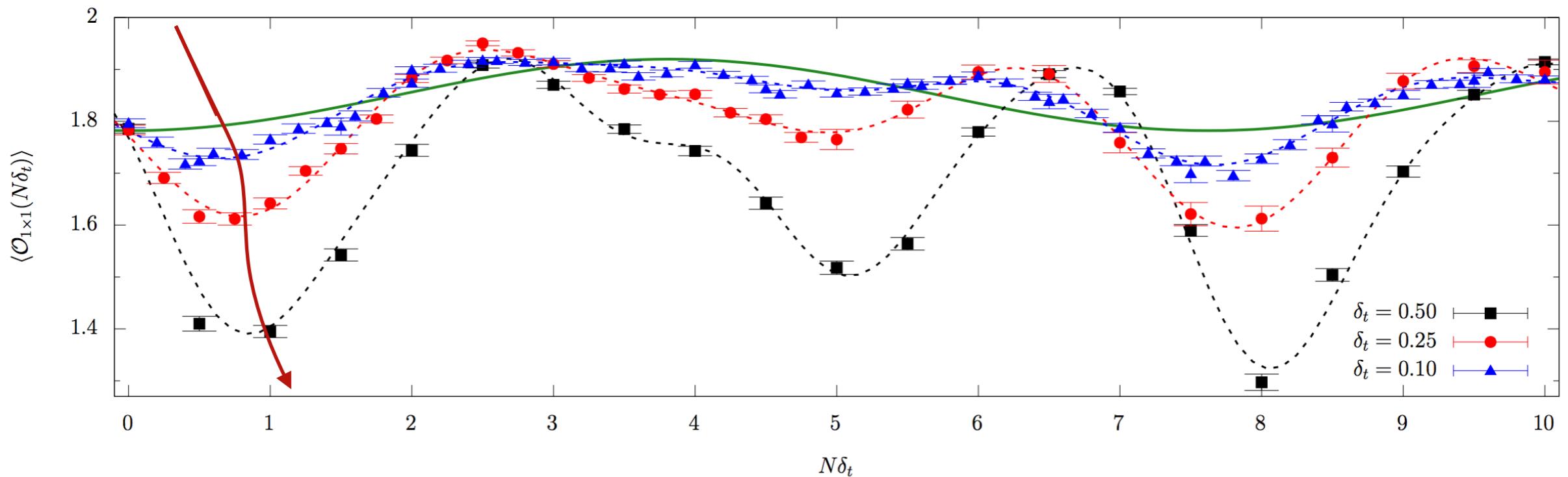
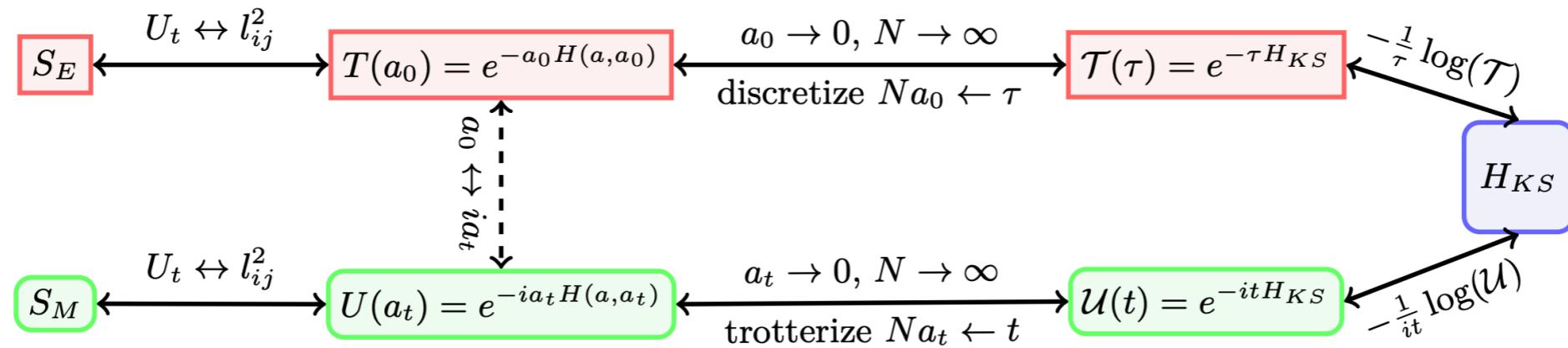
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$$\mathcal{U} = \left[\prod_{l=1}^{\Gamma} e^{-itH^{(l)}/r} \right]^r$$

RESOURCE ESTIMATION AND CIRCUITS CONSTRUCTION IMPROVEMENT



RENORMALIZATION EFFECTS FOR TROTTERIZATION

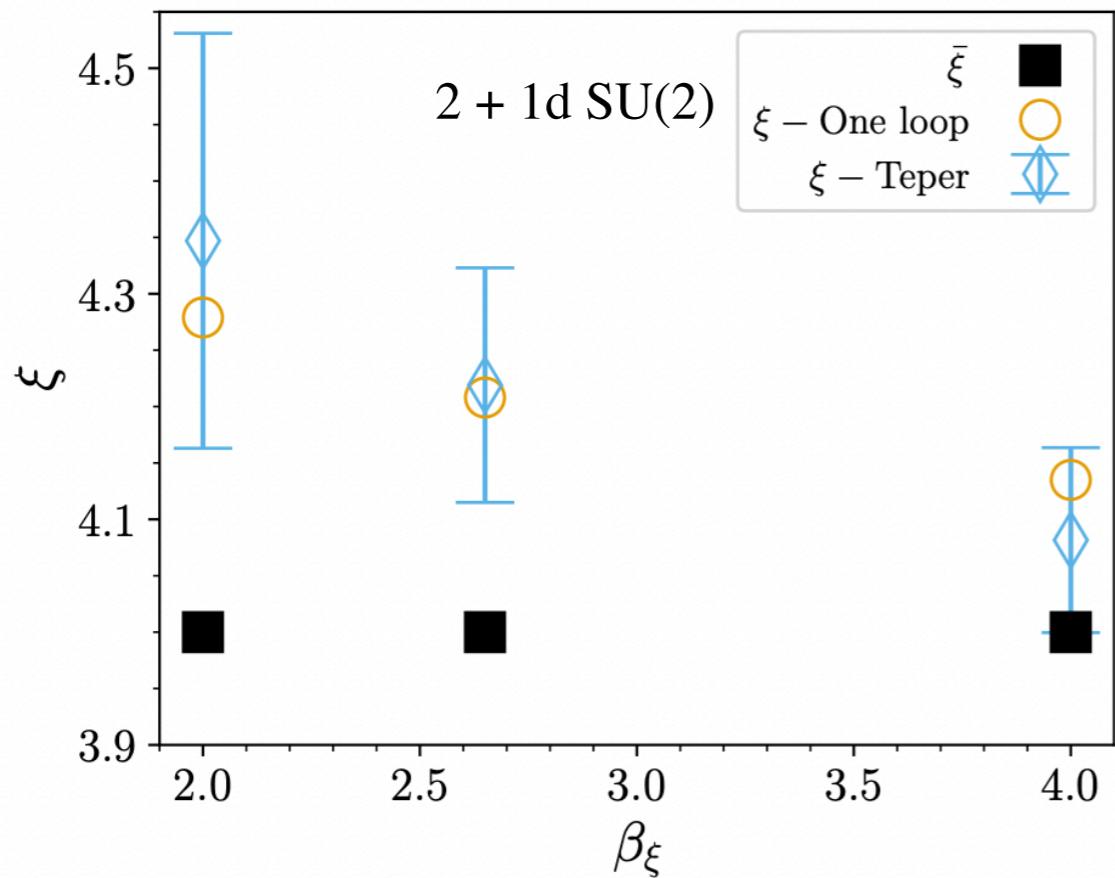


$$T(\delta_\tau, g_H^2) = e^{-\delta_\tau \overline{H}_V/2} e^{-\delta_\tau \overline{H}_K} e^{-\delta_\tau \overline{H}_V/2} \longleftrightarrow U(\delta_t, g_H^2) = e^{-i\delta_t \overline{H}_V/2} e^{-i\delta_t \overline{H}_K} e^{-i\delta_t \overline{H}_V/2}$$

[M. Carena, H. Lamm, YYL, W. Liu, PRD. 104, 094519]

Anisotropic Parameter $\xi = a/a_t$ Renormalization

- numerical results is pretty tedious—saving measurement on the Euclidean side
- Preferred for analytical continuation
- Determine the fixed anisotropic trajectory
- Continuous group agrees quite well with their discrete subgroups



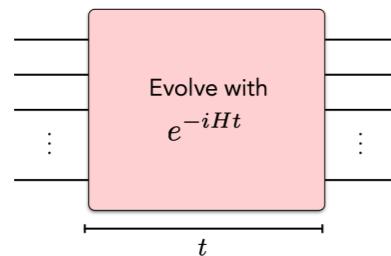
β_ξ	N_s	N_t	$\bar{\xi}$	$\xi_{\text{1-loop}}$	ξ	$SU(2)$ [111]
				$\mathbb{B}\mathbb{I}$		
$D = 3$						
2.00	36	72	2.00	2.097	2.099(1)	...
2.00	12 ^a	60 ^a	4.00	4.278	...	4.35(19)
2.65	16 ^a	64 ^a	4.00	4.207	...	4.22(11)
3.00	36	72	1.33	1.351	1.369(19)	...
4.00	24 ^a	96 ^a	4.00	4.136	...	4.08(9)
$D = 4$						
3.0	36	72	1.33	1.351	1.36(1)	...

[M. Carena, E. Gustafson, H. Lamm, YYL, W. Liu, PRD 106 11, 114504]

Propagation

$$\mathcal{U} |\psi_0\rangle \rightarrow |\psi(t)\rangle$$

ANALOG

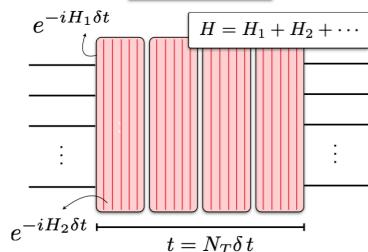


Cold neutral atoms, Trapped ions, Cavity quantum electrodynamics
Superconducting circuits

...

DIGITAL

superconducting qubit/trapped-ion system



building blocks:
one-qubit/two-qubit gate set

$$||\mathcal{U} - e^{-iHt}|| < \epsilon$$

optimally asymptotically?
overload of resources?
easy implementation?

HYBRID METHOD

Casanova et al (2011), Davoudi et al (2021) [trapped ion]

Harmalkar et al (2022) classical preprocessing

Zohar et al (2017), Bender et al (2018) effective interactions

Klco et al (2018), Kokail et al (2019), Atas et al (2021) state preparations

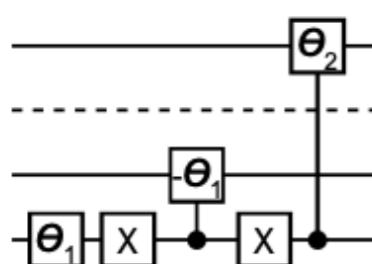
Peruzzo et al (2014), Farhi et al (2014) optimization methods

To reach the observables — How to do ...

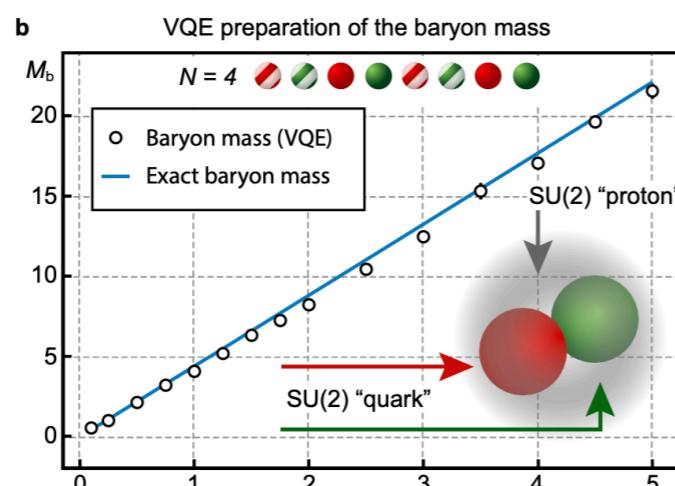
INITIAL STATE PREP

hadronic state, topological vacuum state, thermal state, etc

Hybrid methods with VQE protocols



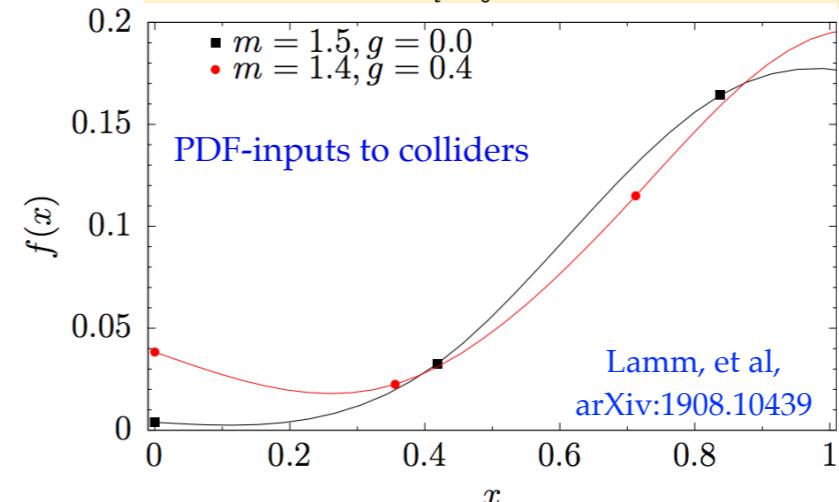
Atas et al, Nat Commun 12, 6499 (2021)



MEASUREMENTS

time-separated correlators, exponentially suppressed process, entanglement, etc

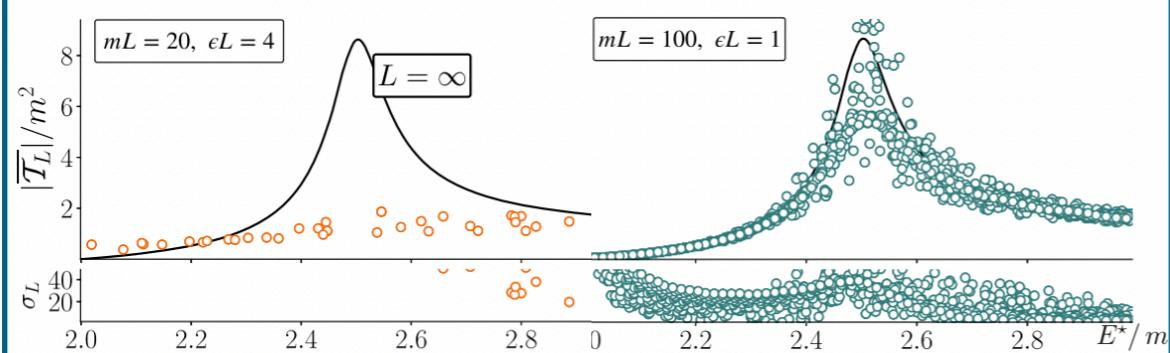
$$\langle \Psi | \mathcal{O}(t) \mathcal{O}(0) | \Psi \rangle = \frac{\partial}{\partial \epsilon_t} \frac{\partial}{\partial \epsilon_0} \langle \Psi | e^{-iHt} e^{-i\mathcal{O}\epsilon_t} e^{iHt} e^{i\mathcal{O}\epsilon_0} | \Psi \rangle$$



SYSTEMATIC UNCERTAINTIES

finite volume effects, truncation errors, convergence rate

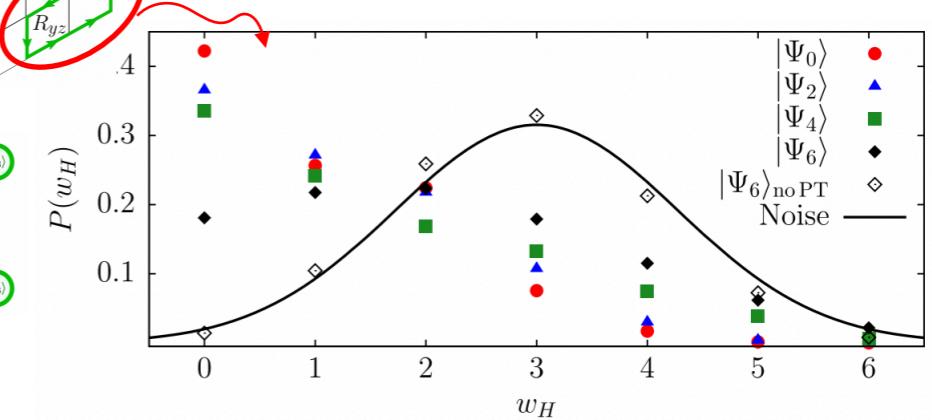
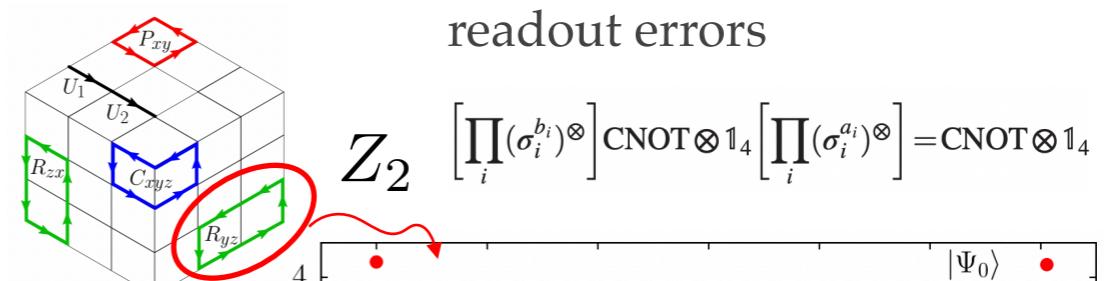
$$i\mathcal{T} = \begin{array}{c} q \\ \swarrow \quad \searrow \\ p_f \quad p_i \end{array}$$



Briceno, PRD 103, 014506 (2021)

ERROR CORRECTIONS

gate error - stochastic and coherent errors
readout errors

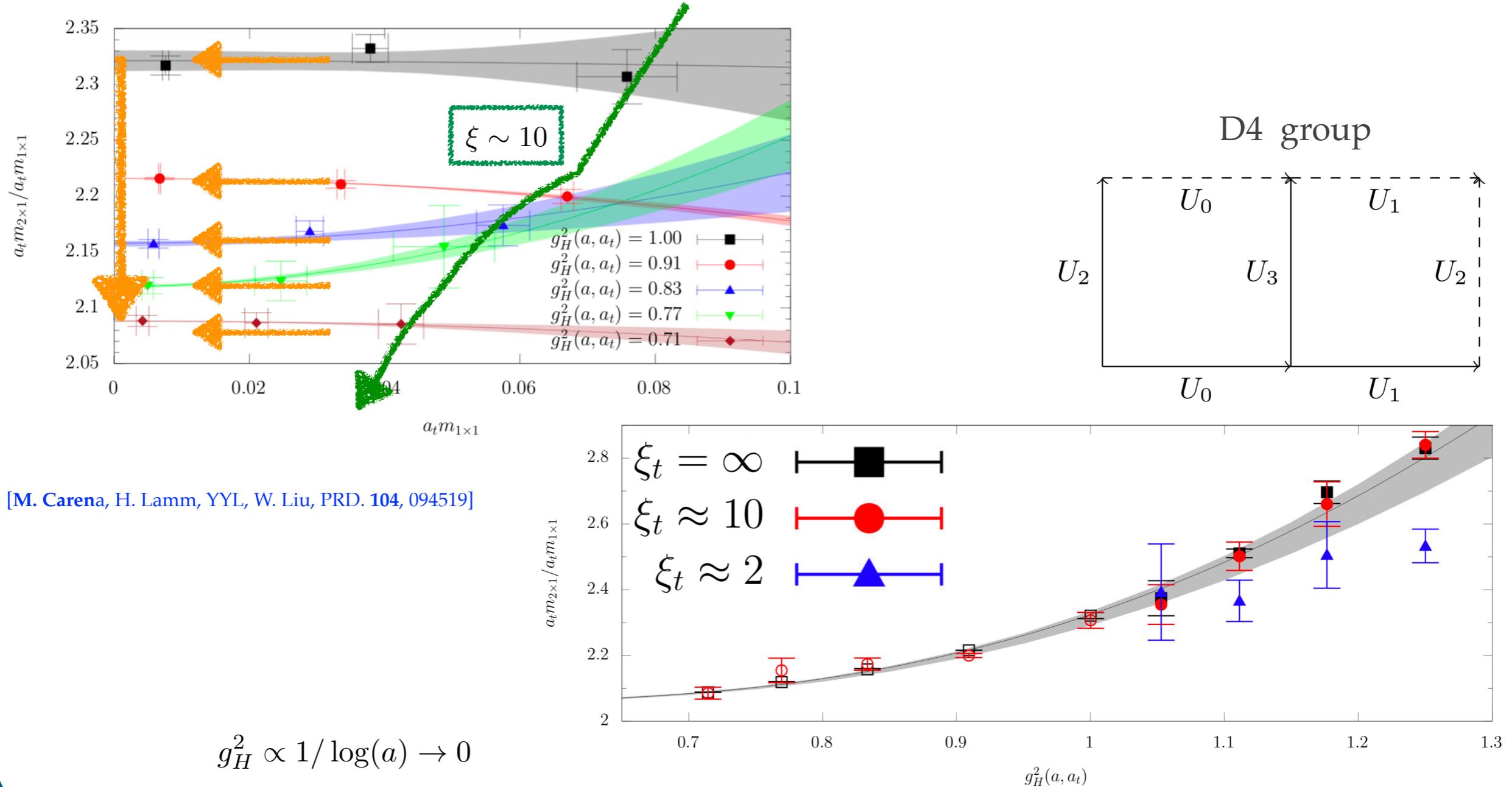


Carena, Lamm, YYL, Liu, PRL 129, 051601

To reach observables in the continuum limit

TRAJECTORY TO THE CONTINUUM LIMIT

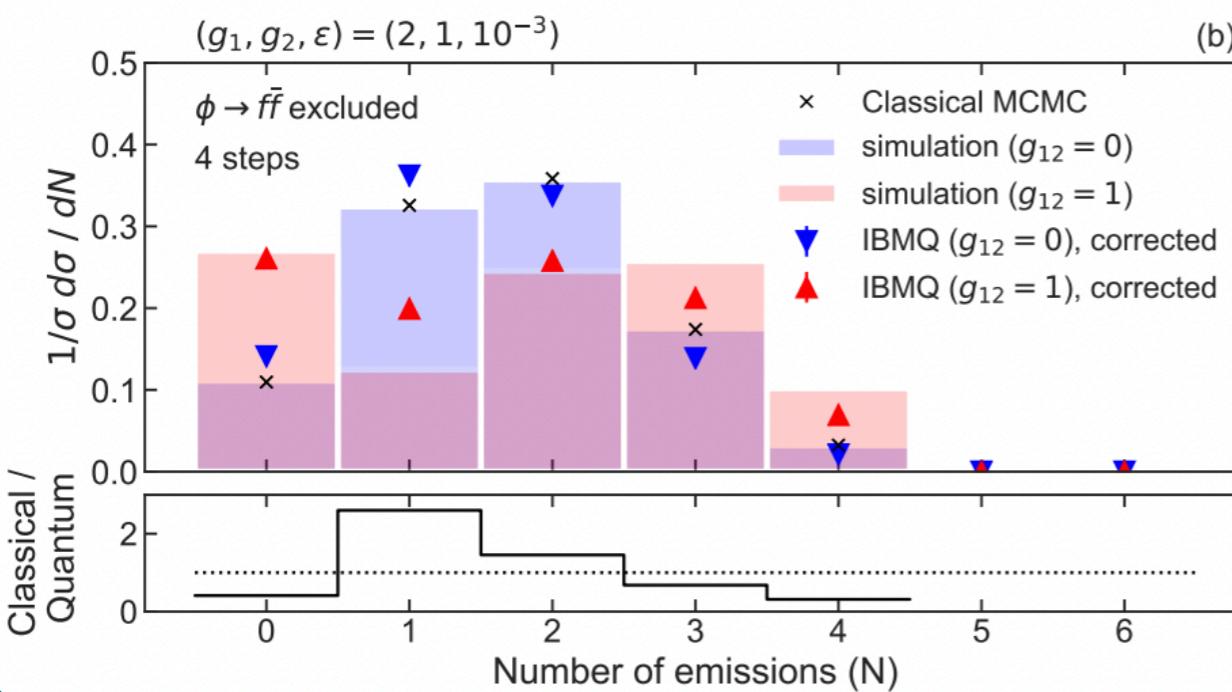
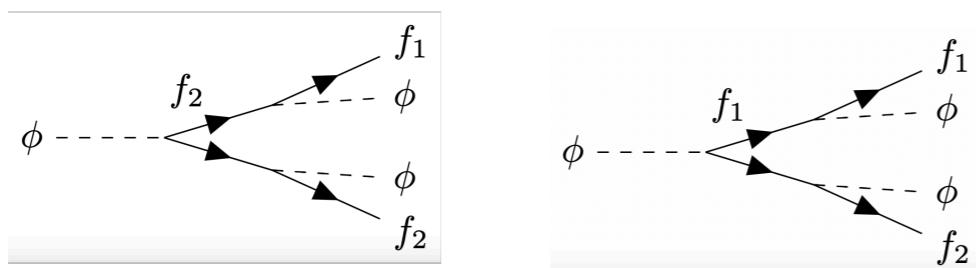
continuum limit: extrapolation to the continuum at $\xi = a/a_t$



Benchmarks

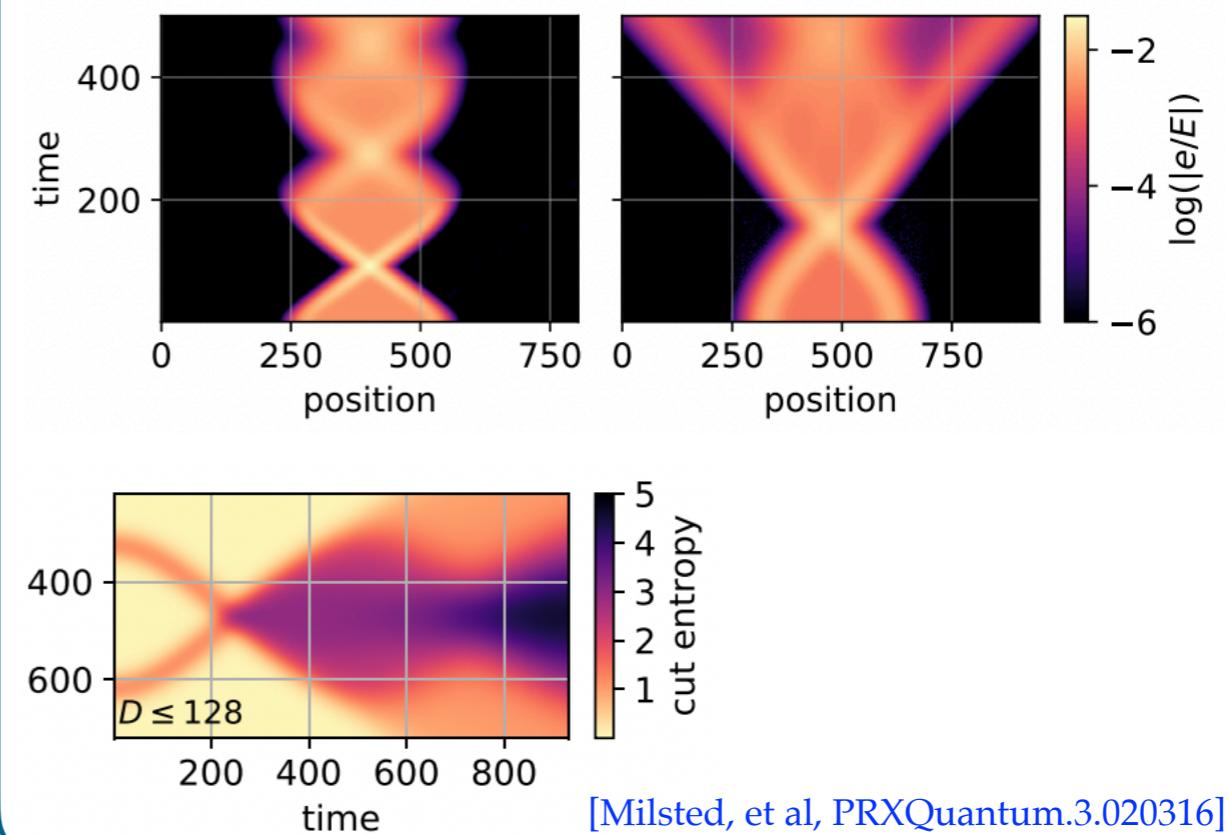
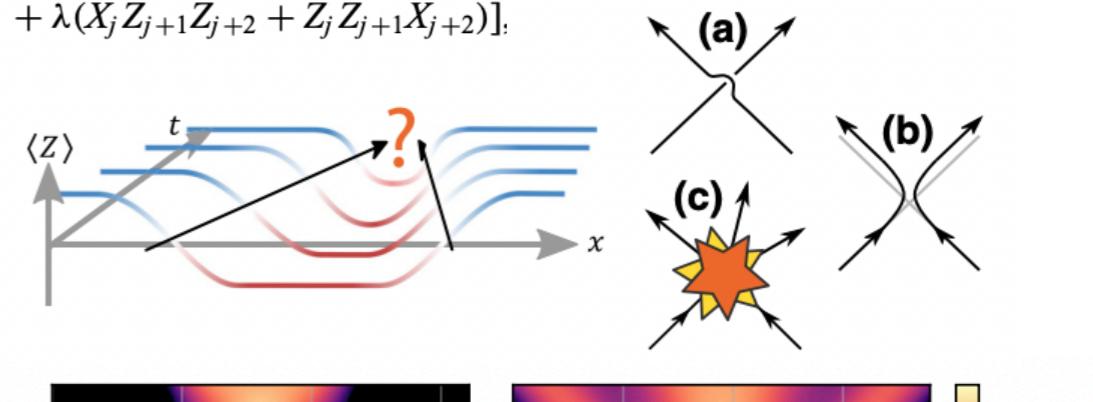
PARTON SHOWERING [arXiv:2102.05044, PRD 103, 076020, PRD 106, 056002,...]

$$\mathcal{L} = \bar{f}_1(i\partial + m_1)f_1 + \bar{f}_2(i\partial + m_2)f_2 + (\partial_\mu \phi)^2 + g_1 \bar{f}_1 f_1 \phi + g_2 \bar{f}_2 f_2 \phi + g_{12} [\bar{f}_1 f_2 + \bar{f}_2 f_1] \phi$$



BUBBLE COLLISION

$$H = \sum_{j=1}^N [-Z_j Z_{j+1} - g X_j - h Z_j + \lambda (X_j Z_{j+1} Z_{j+2} + Z_j Z_{j+1} X_{j+2})],$$

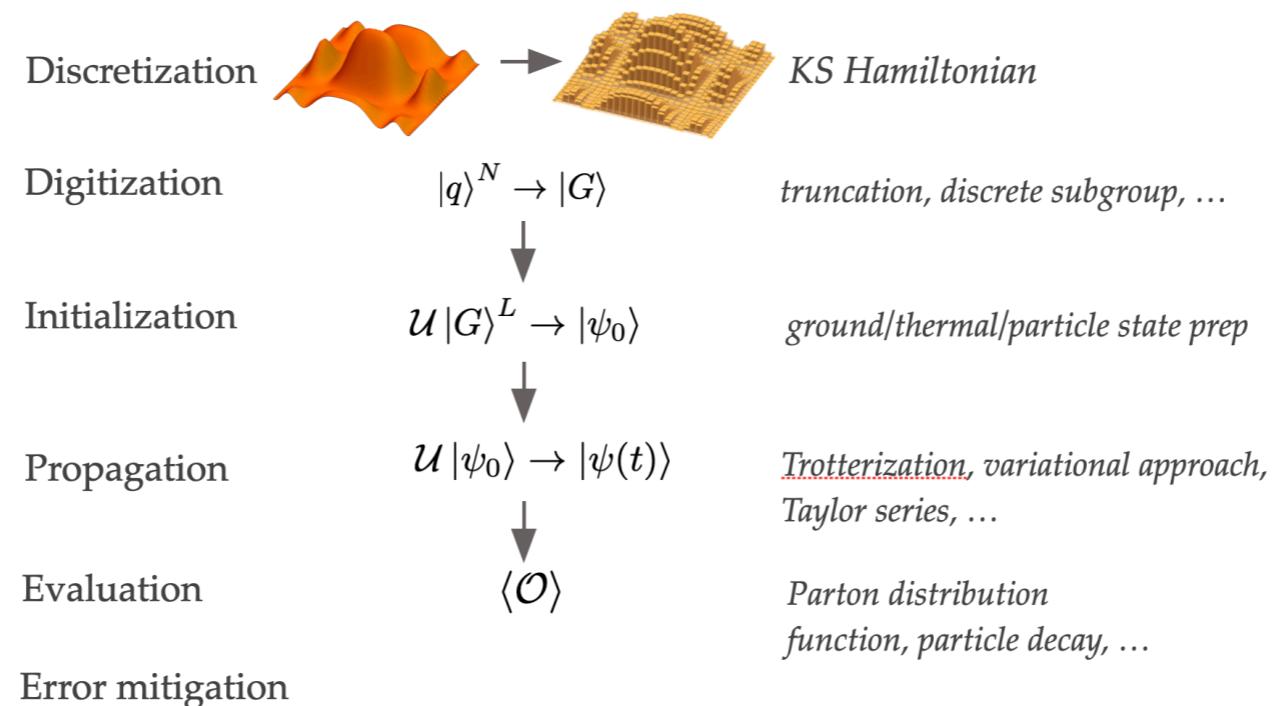


“It is time to go”

SUMMARY and OUTLOOK

Quantum computing can access to quantities in high energy physics which are intractable with classical methods

So many things to do, ... and lots should be done to before scalable noise-resilient ones are available.

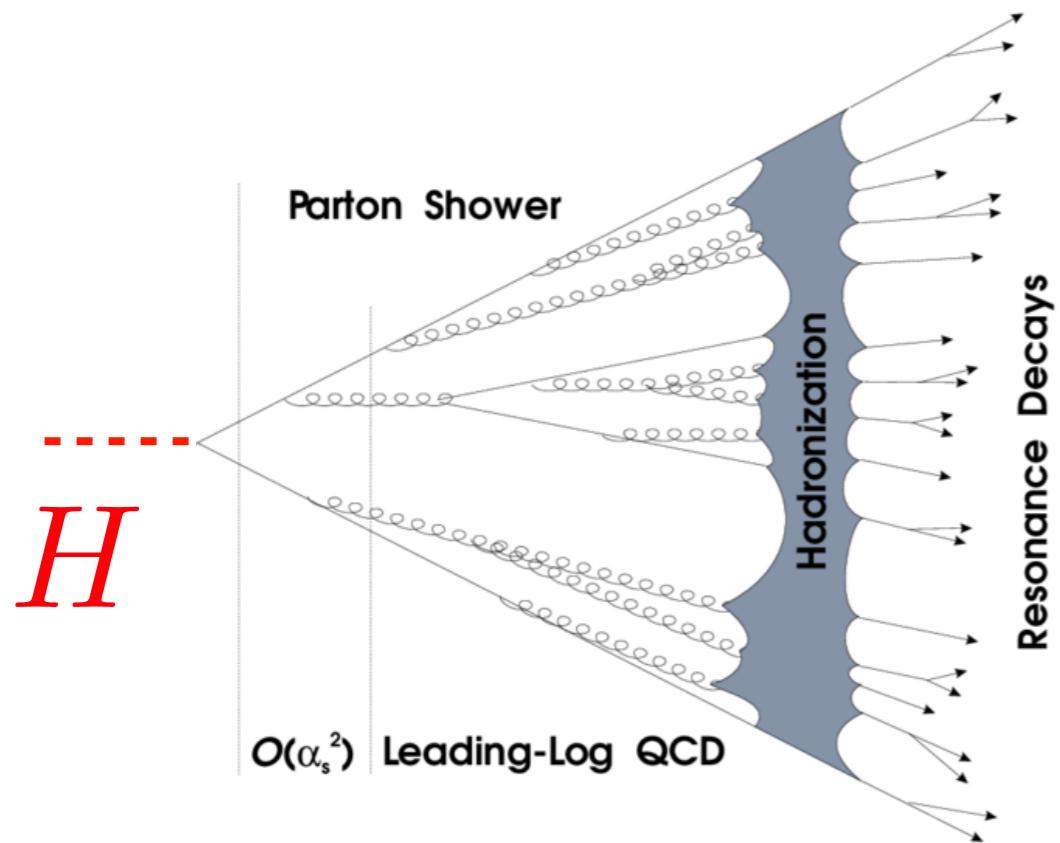


Theory investigations, algorithmic developments, benchmark study, hardware co-design,...

Thank you

BACK UP

Theoretical inputs to colliders



Parton Shower

Long-distance dynamics - dominated by massless modes, high multiplicity final states

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

collinear

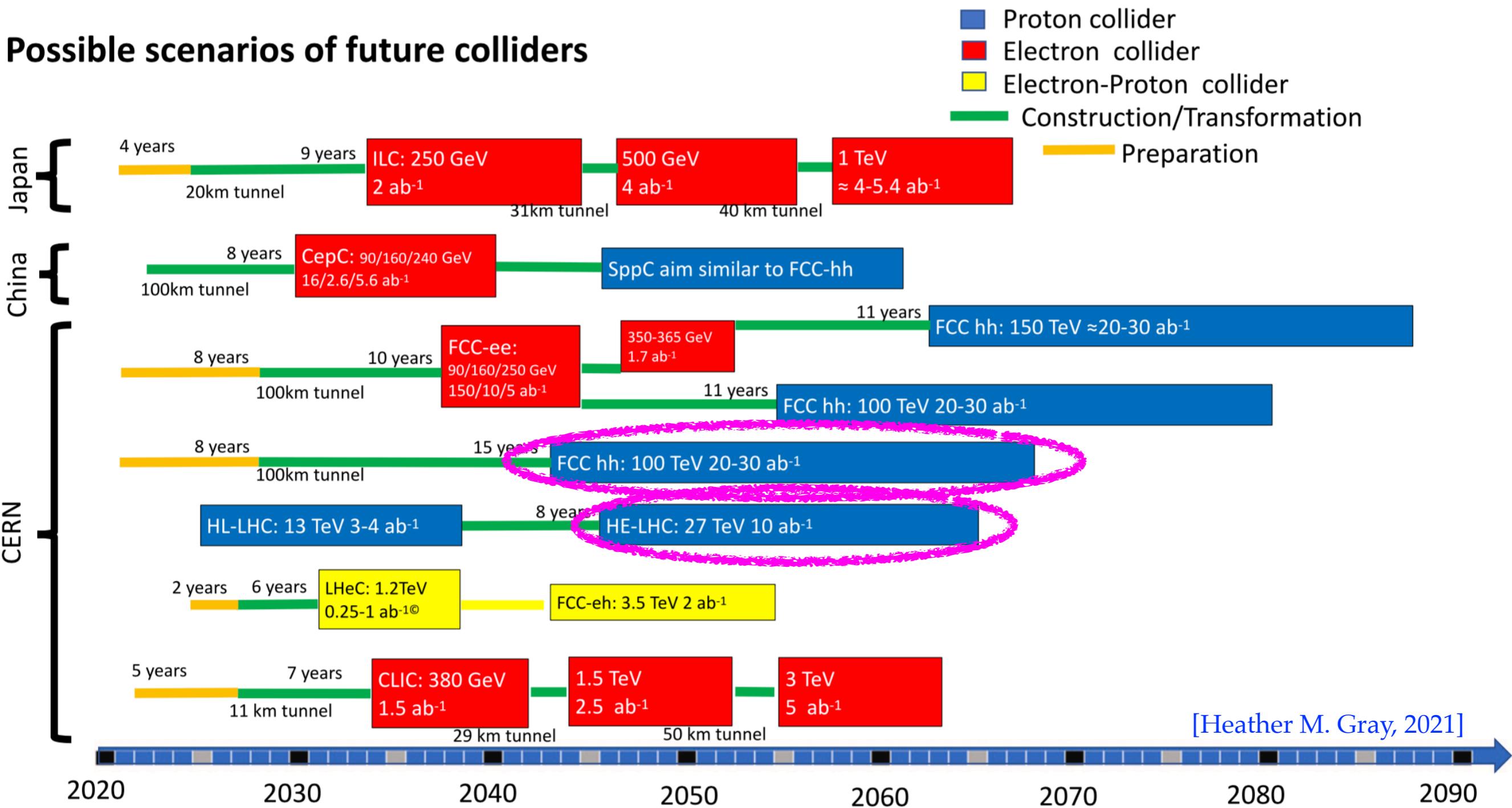
soft

Lattice: in principle, sign problem
State-of-art tech (MCMC):
probability level—interference
not properly included

[arXiv:2102.05044, arXiv: 1904.03196,
PRD 103, 076020, PRD 106, 056002,...]

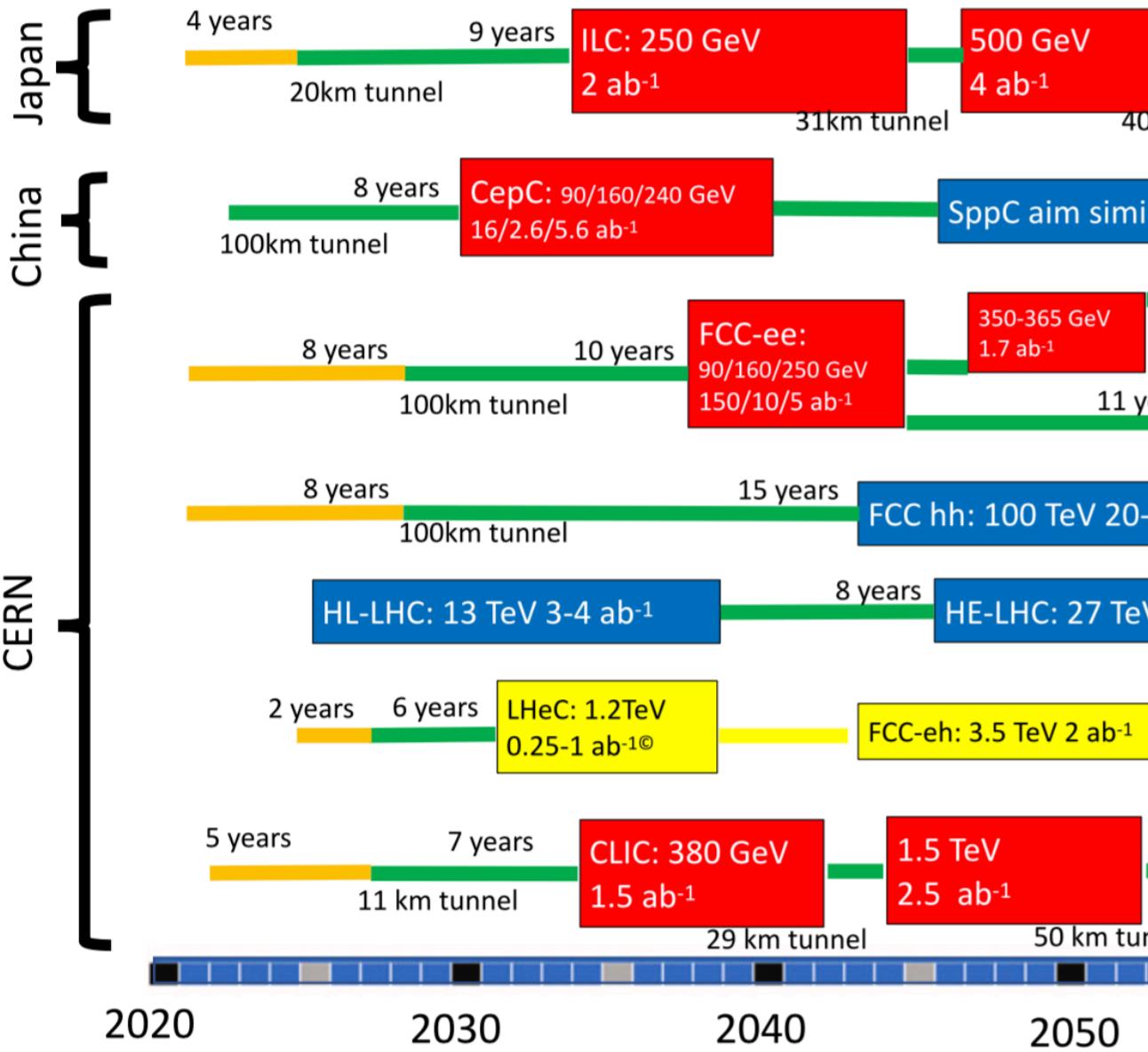
-Now-: precision measurement

Possible scenarios of future colliders



-Now-: precision measurement

Possible scenarios of future colliders



μ (%)	Future Circular Colliders		
	CEPC	FCC-ee	
	240 GeV	240 GeV	365 GeV
unpolarized			
σ_{Zh}	0.005	0.005	0.009
μ_{Zh}^{bb}	0.21 [†]	0.20	0.50
μ_{Zh}^{cc}			0.50
$\mu_{Zh}^{\tau\tau}$			0.80
$\mu_{Zh}^{\mu\mu}$	17.1	19.0	40.0
μ_{Zh}^{WW}	0.98 [†]	1.20	2.60
μ_{Zh}^{ZZ}	5.09 [†]	4.40	12.0
$\mu_{Zh}^{Z\gamma}$	15.0	15.9	—
$\mu_{Zh}^{\gamma\gamma}$	6.84	9.00	18.0
μ_{Zh}^{gg}	1.27 [†]	1.90	3.50

New physics up to 100 TeV can be probed

Quantum Machine Learning

computational complexity improvements, computational speed-ups

Supervised Learning—better separation power?

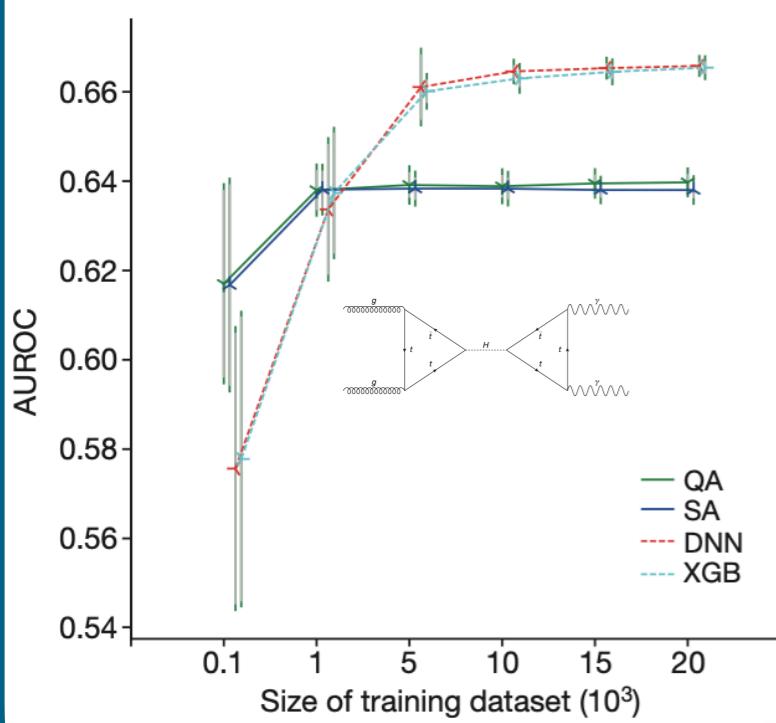
Quantum variational circuits, quantum annealing, QSVM, etc.

Quantum Annealing

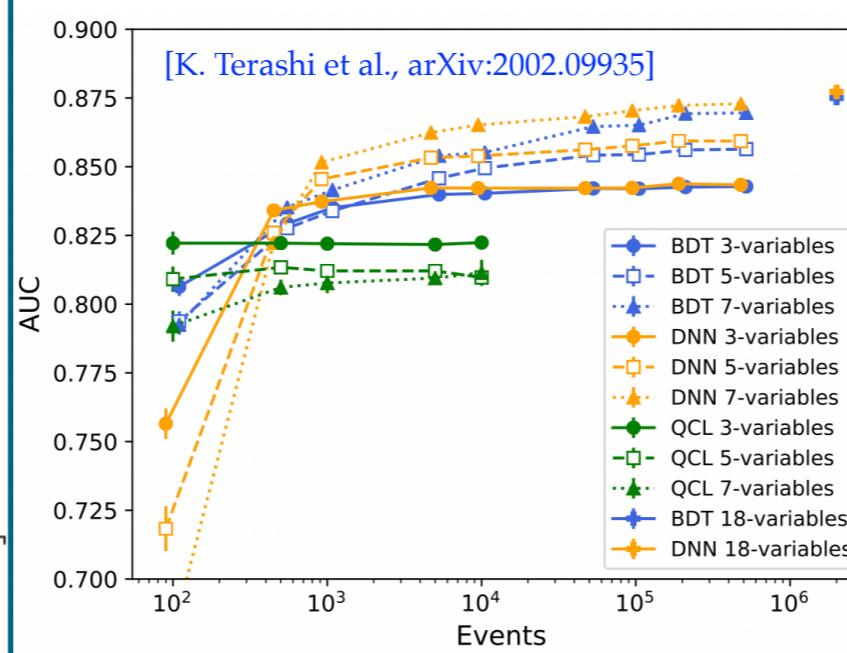
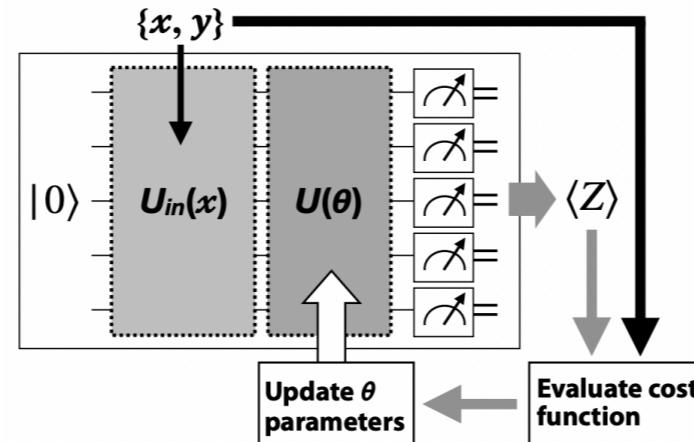
$$C_{ij} = \sum_{\tau} c_i(\mathbf{x}_{\tau}) c_j(\mathbf{x}_{\tau}), \quad C_i = \sum_{\tau} c_i(\mathbf{x}_{\tau}) y_{\tau}$$

$$H = \sum_{i,j} J_{ij} s_i s_j + \sum_i h_i s_i$$

$$R(\mathbf{x}) = \sum_i s_i^g c_i(\mathbf{x}) \in [-1, 1]$$

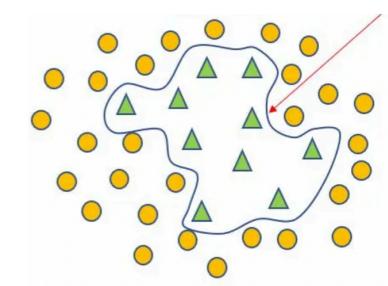
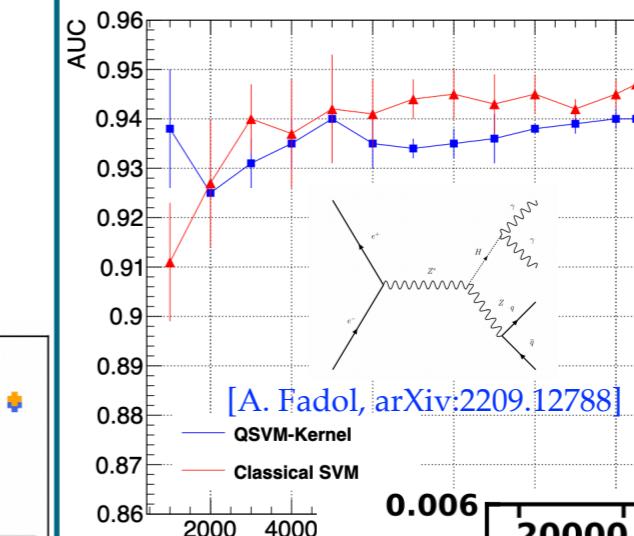


Variational Quantum Approach

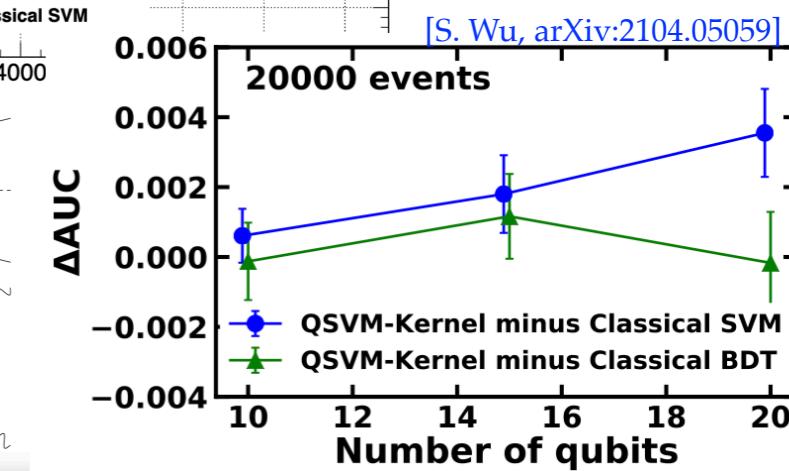


Quantum Support Vector Machine

$$k(\vec{x}_i, \vec{x}_j) = \left| \langle 0^{\otimes N} | \mathcal{U}_{\Phi(\vec{x}_i)}^\dagger \mathcal{U}_{\Phi(\vec{x}_j)} | 0^{\otimes N} \rangle \right|^2$$

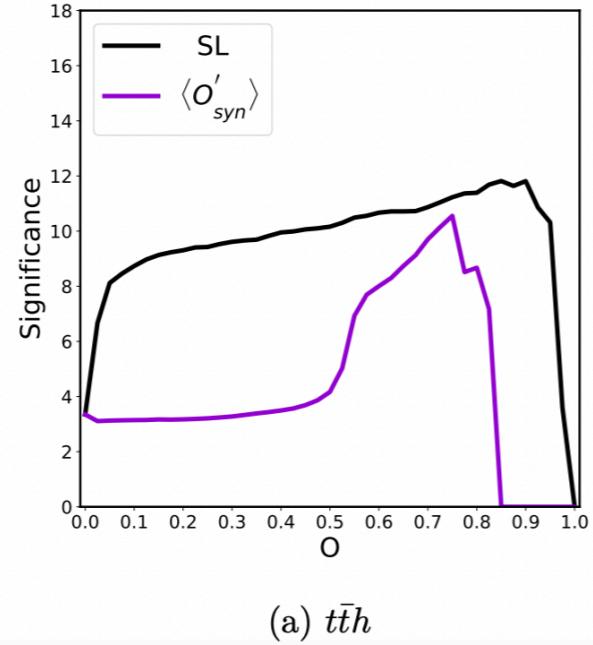
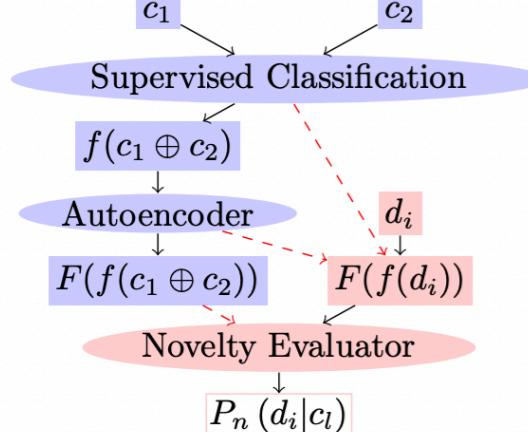


larger sample size?



Quantum Machine Learning - Anomaly detection

ANOMALY DETECTION

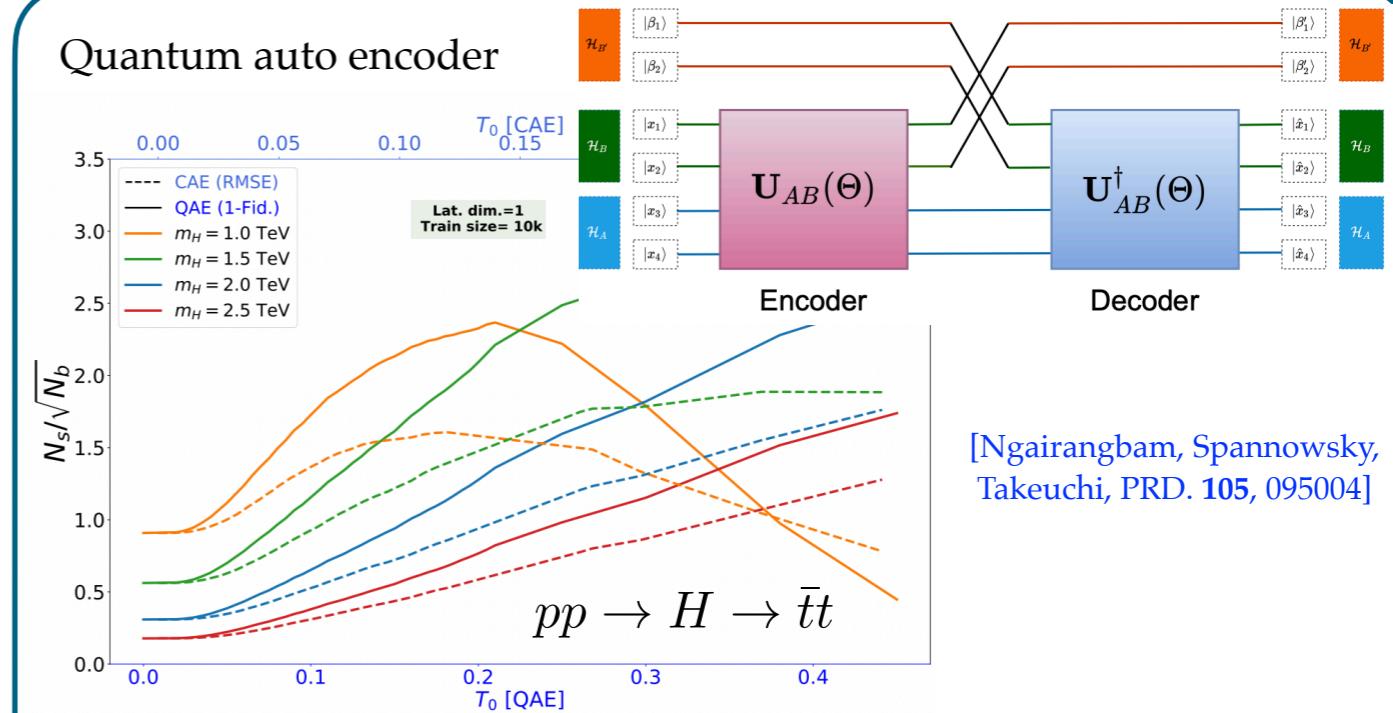


[J. Hajer, YYL, T. Liu, H. Wang, PRD 101 7, 076015]
[X.-H. Jiang, YYL, A. Juste, T. Liu, JHEP 10 (2022) 085]

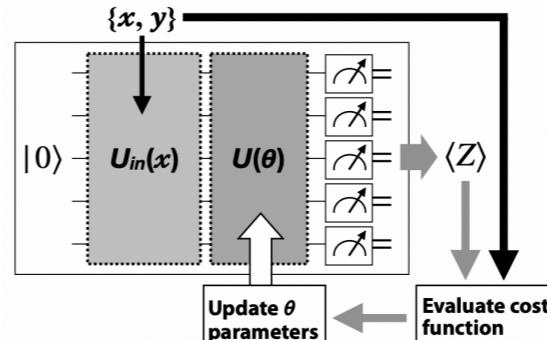
- arXiv:1808.08992: "Searching for New Physics with Deep Autoencoders", Marco Farina, Yuichiro Nakai, and David Shih
- arXiv:1808.08992: "QCD or What?", Theo Heimel, Gregor Kasieczka, Tilman Plehn, and Jennifer M Thompson
- arXiv:1811.10276, "Variational Autoencoders for New Physics Mining at the Large Hadron Collider", Olmo Cerri, Thong Q. Nguyen, Maurizio Pierini, Maria Spiropulu and Jean-Roch Vlimant
- arXiv:1903.02032, "A robust anomaly finder based on autoencoder", Tuhin S. Roy and Aravind H. Vijay
- arXiv:1905.10384, "Adversarially-trained autoencoders for robust unsupervised new physics searches", Andrew Blance, Michael Spannowsky, and Philip Waite
-

QUANTUM ANOMALY DETECTION

Quantum auto encoder



Quantum weakly-supervised learning (bg VS bg + ϵ signal)



[Terashi et al, arXiv:2002.09935]

$pp \rightarrow A \rightarrow B (\rightarrow e^+e^-) C (\rightarrow \mu^+\mu^-)$
3D with 1% Signal

