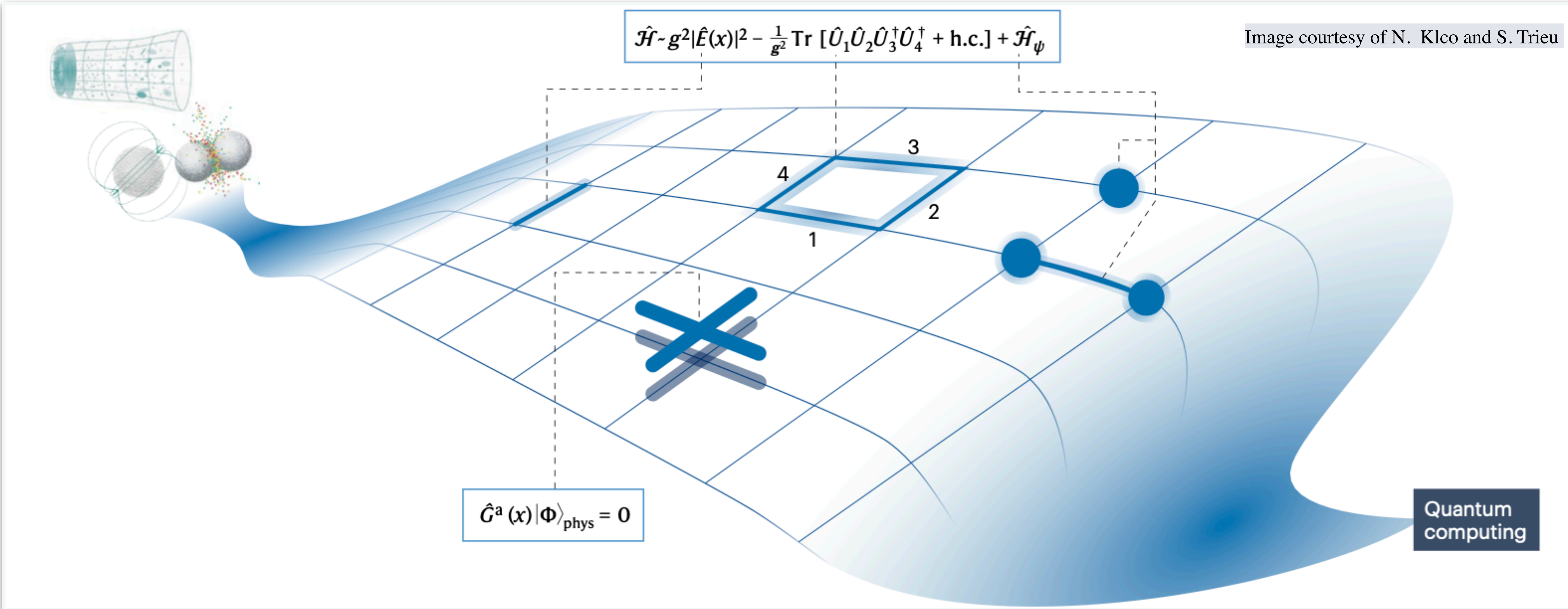


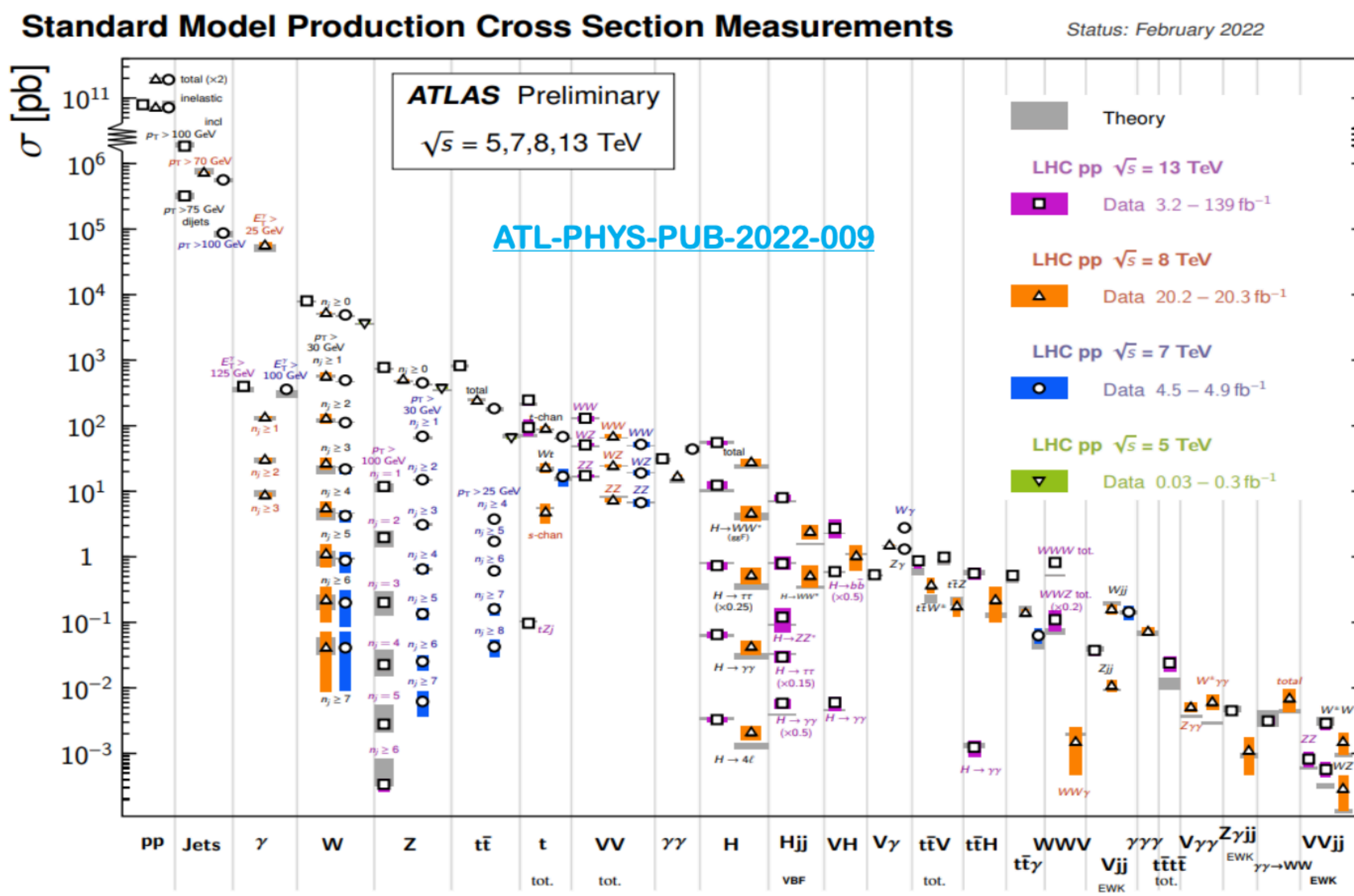
Image courtesy of N. Klco and S. Trieu

Quantum Frontiers in High Energy Physics

Ying-Ying Li
李英英

Era of precision physics

- **High-precision data**
  - Many observables probed at precent level precision
- **QCD cor. requirement**
  - Most processes: N2LO
  - Many processes: N3LO
  - Some processes: N4LO
  - A few processes: N5LO



- **A "billion-dollar project"**
  - LHC cost about 10 billion dollars
  - It is waste of money unless having high-precision computation

Courtesy of Yan-Qing Ma

微扰量子场论

History of one-loop FIs computation

- **Analytical results up to 4 points**

Scalar One Loop Integrals
Gerard 't Hooft (Utrecht U.), M.J.G. Veltman (Utrecht U.) (Nov, 1978)
Published in: *Nucl.Phys.B* 153 (1979) 365-401

- **Numerical stable version, implemented in FF package**

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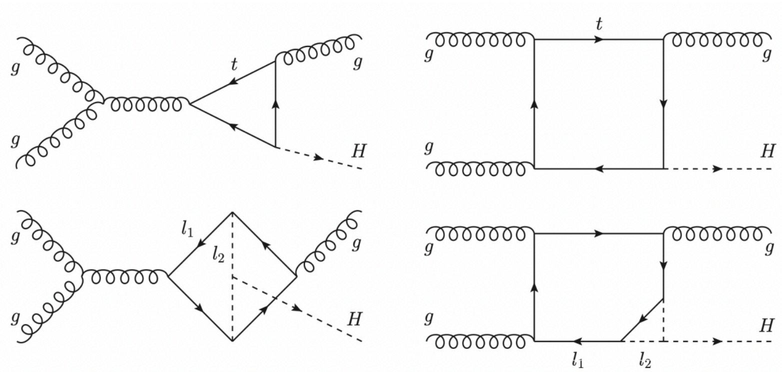
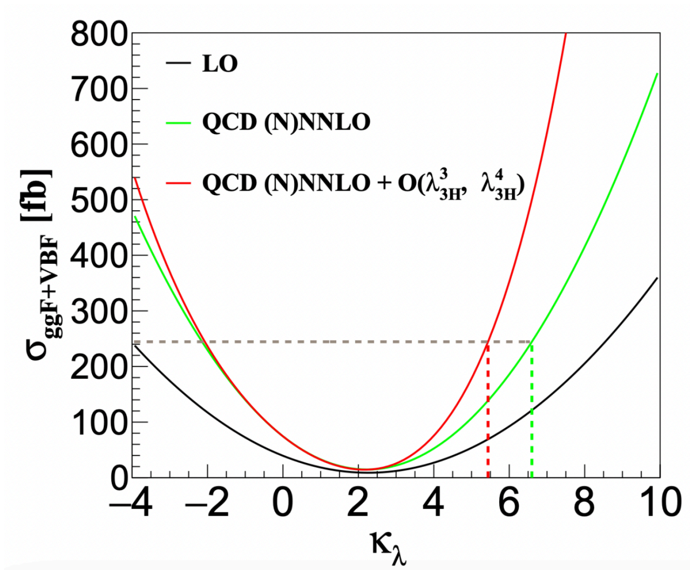
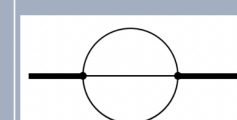
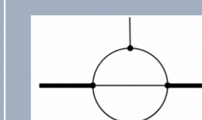
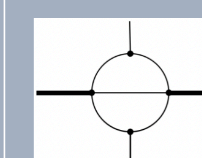
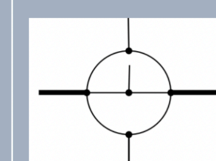
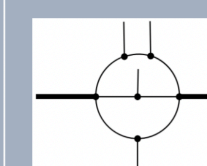




From 1970s

Courtesy of Yan-Qing Ma

Order \ Legs	2→1	2→2	2→3	2→4	2→5	2→6
NLO	★★★	★★★	★★★	★★★	★★★	★★★
N2LO	★★★	★★	★	?	?	
N3LO	★★	★	?			
N4LO	★	?				
N5LO	?					

					
DCT/pt (ms)	0.12	0.19	0.47	2.73	7.89
Total time (CPU)	<1min	<1min	<3min	3min	12h

微扰量子场论

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Scalar One Loop Integrals

Gerard 't Hooft (Utrecht U.), M.J.G. Veltman (Utrecht U.) (Nov, 1978)

Courtesy of Yan-Qing Ma

Legs / Order	2→1	2→2	2→3	2→4	2→5	2→6

Quantum algorithm for Feynman loop integrals

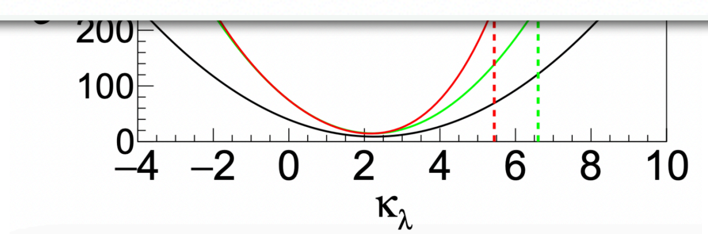
[arXiv:2105.08703]

Selomit Ramírez-Uribe,[a,b,c] Andrés E. Rentería-Olivo,[a] Germán Rodrigo,[a] German F. R. Sborlini[d,a] and Luiz Vale Silva[a]

Variational quantum eigensolver for causal loop Feynman diagrams and directed acyclic graphs

[arXiv:2210.13240]

Giuseppe Clemente,[1,*] Arianna Crippa,[1,†] Karl Jansen,[1,‡] Selomit Ramírez-Uribe,[2,3,4,§] Andrés E. Rentería-Olivo,[2,¶] Germán Rodrigo,[2,**] German F. R. Sborlini,[5,6,††] and Luiz Vale Silva[2,‡‡]



From 1970s

微扰量子场论

Courtesy of Yan-Qing Ma

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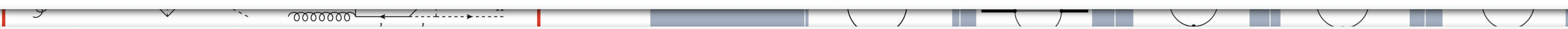

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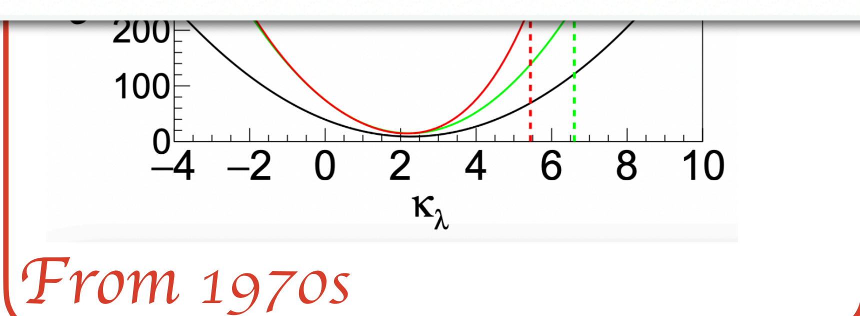

All order perturbative calculations: convergence?

微扰量子场论

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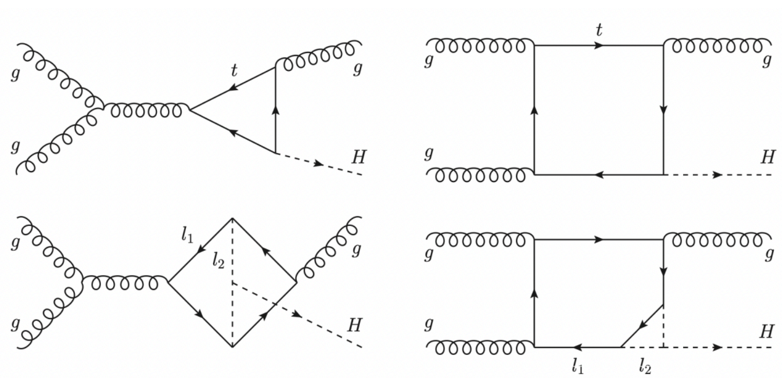
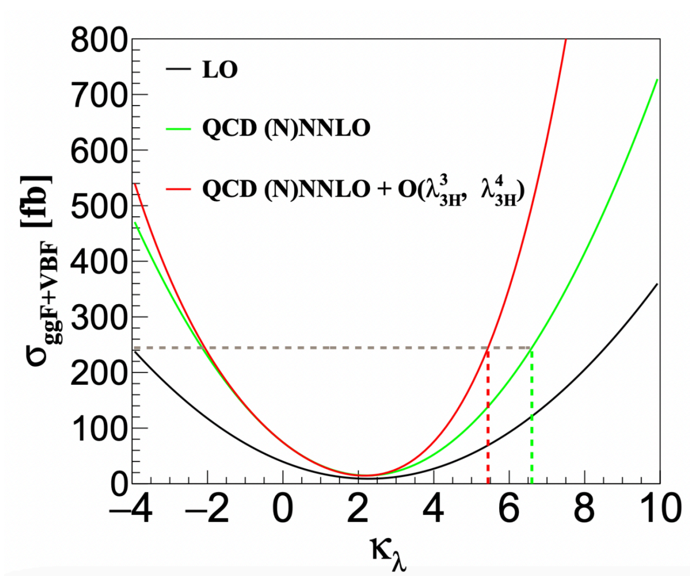
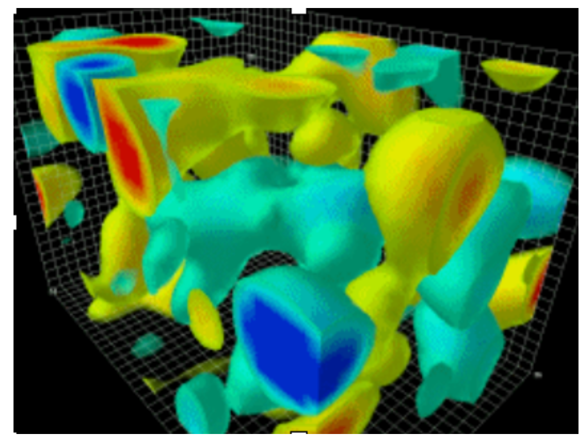




From 1970s

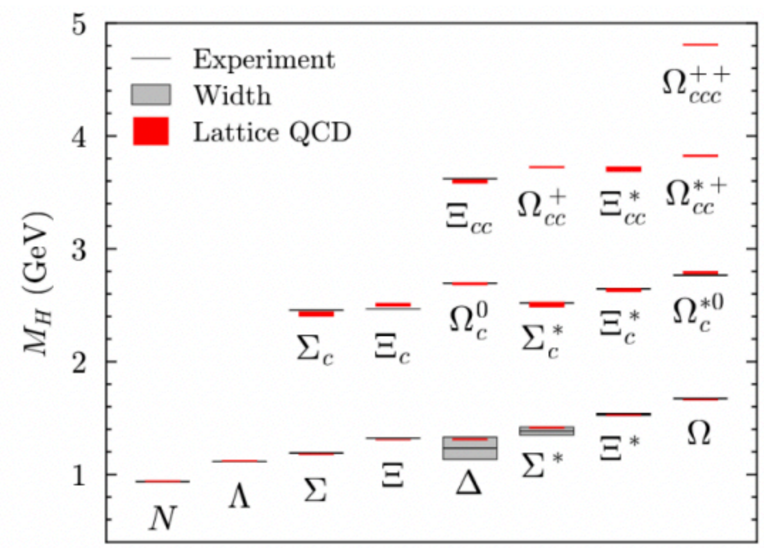
非微扰量子场论

经典格点计算 — 欧氏时空



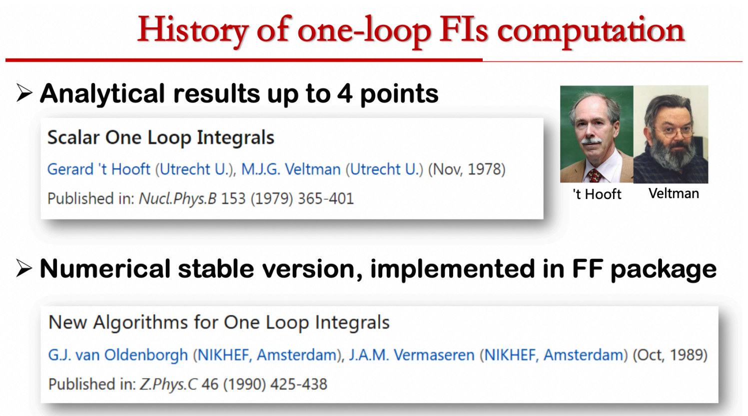
$$W(\mathcal{C}) \sim \exp(-S(\mathcal{C}))$$

$$\langle O \rangle = \frac{\sum_{\mathcal{C}} O(\mathcal{C}) W(\mathcal{C})}{\sum_{\mathcal{C}} W(\mathcal{C})}$$

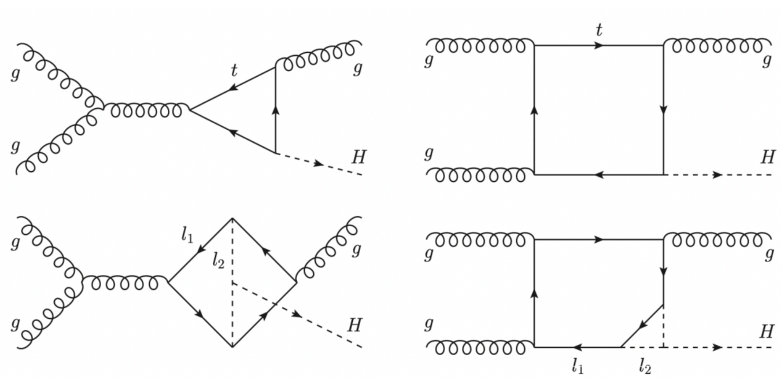


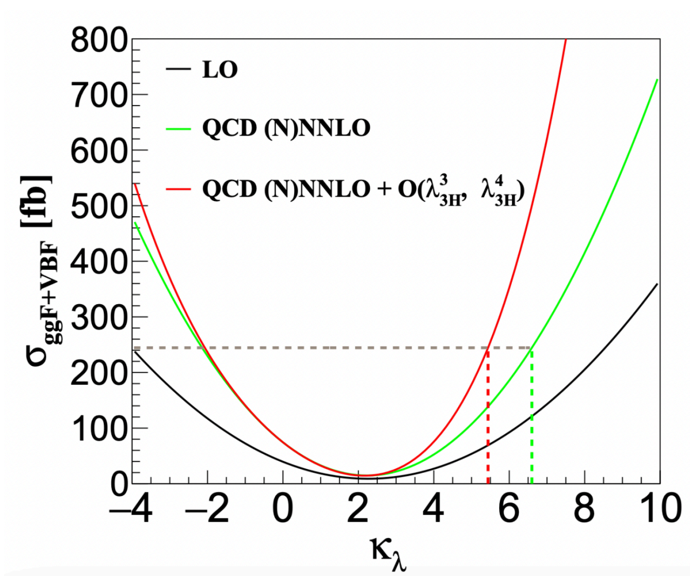
From 1970s

微扰量子场论



Courtesy of Yan-Qing Ma





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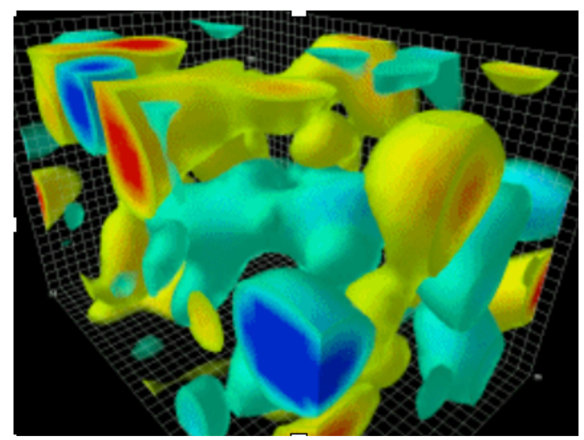

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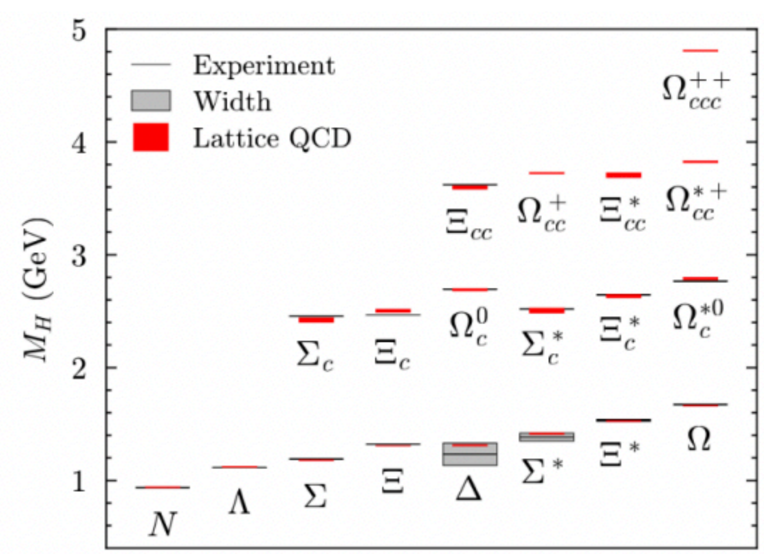
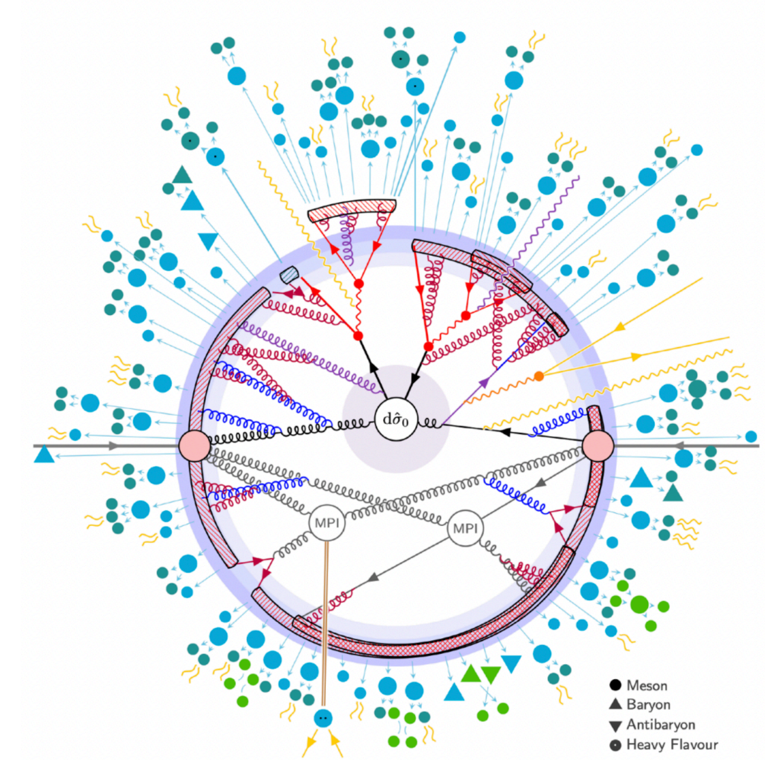
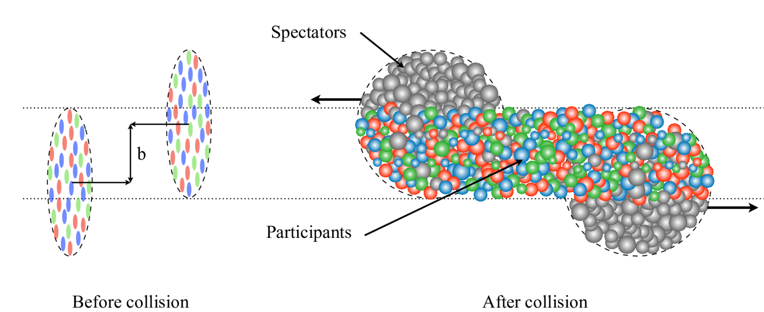


From 1970s

非微扰实时动态过程?



From PYTHIA 8.3



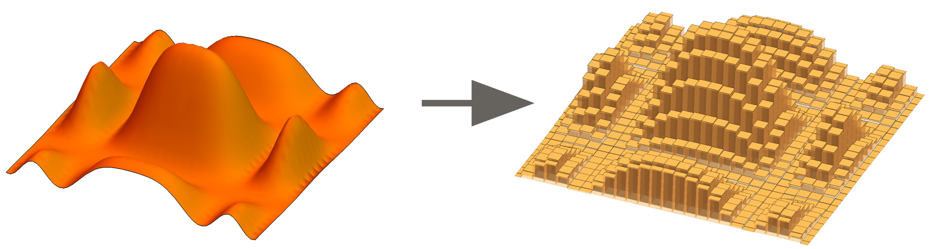
QGP, 有效温有限密?

非微扰量子场论

实时动态过程, 有限温有限密, ...

格点非微扰计算 — 闵氏时空

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



$$\mathrm{dim} H \propto |G|^{N_V}$$

所需经典比特数: $N_b \propto |G|^{N_V}$

(*CLASSICAL HARD*)

From 1970s Phys. Rev. D 11, 395 (1975) KS Hamiltonian

非微扰量子场论

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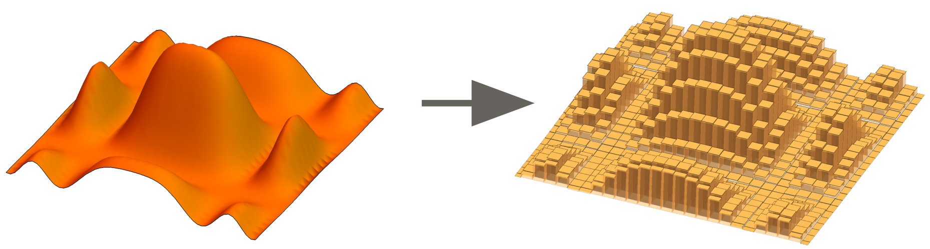

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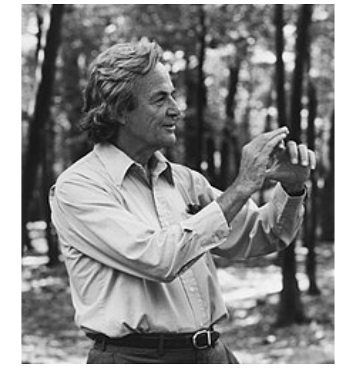
From 1970s   Phys. Rev. D 11, 395 (1975) KS Hamiltonian

1982 “nature isn’t classical”



所需量子比特数: $N_q \propto N_V \log |G|$

(*QUANTUM EASY*)

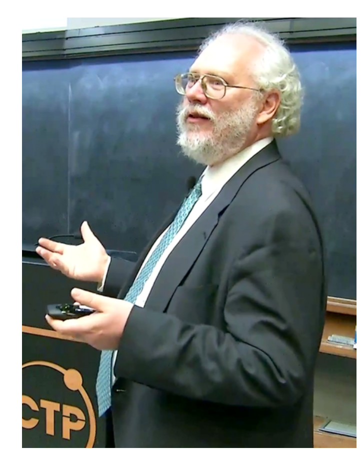
1996 - Seth LIoyd

Universal Quantum Simulators

Seth Lloyd

Feynman's 1982 conjecture, that quantum computers can be programmed to simulate any local quantum system, is shown to be correct.

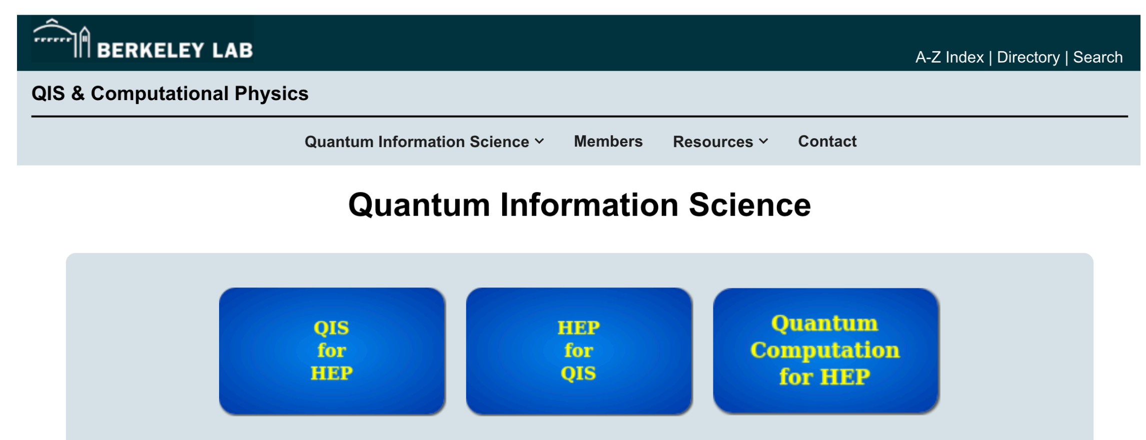
1990s Quantum Threshold Theorem



Quantum Computing for HEP

Brookhaven
Argonne
Oak Ridge
LBNL
Fermilab

1 **(h) Quantum Information Science for High Energy Physics Research**



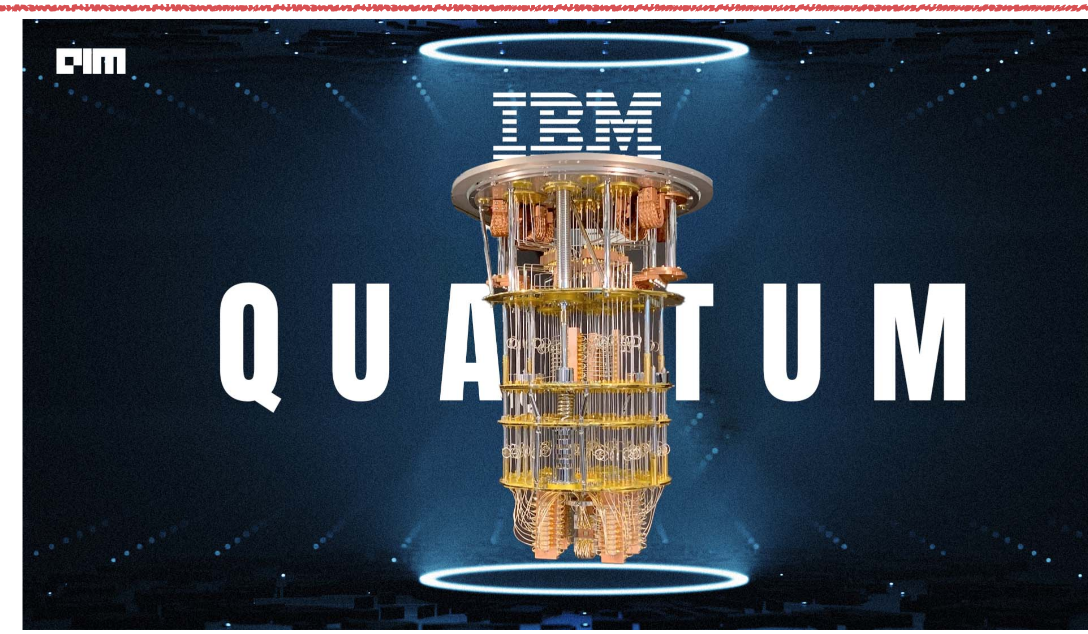
HEP-QIS QuantISED program is aligned with the ``Science First'' driver for the national QIS program

Quantum Computing for HEP

2. **Quantum simulation and information processing:** Applications to QCD1 (Quantum Chromo Dynamics), non-perturbative dynamics using lattice QFT and more, map of quantum field theories onto quantum devices, use of well-controlled quantum systems to simulate or reproduce the behaviour of less accessible many-body quantum phenomena, noise and error control by investigations of Hilbert-space truncation mitigations.

DESY. QUANTUM | Center for Quantum Technology and Applications

"offers the fascinating opportunity to solve problems which are extremely hard or even impossible to address on conventional computers"



… chart future for use of quantum computing in particle physics

Quantum Computing for HEP

[*PRX Quantum* 4, 027001 (2023)]

Quantum Simulation for High Energy Physics

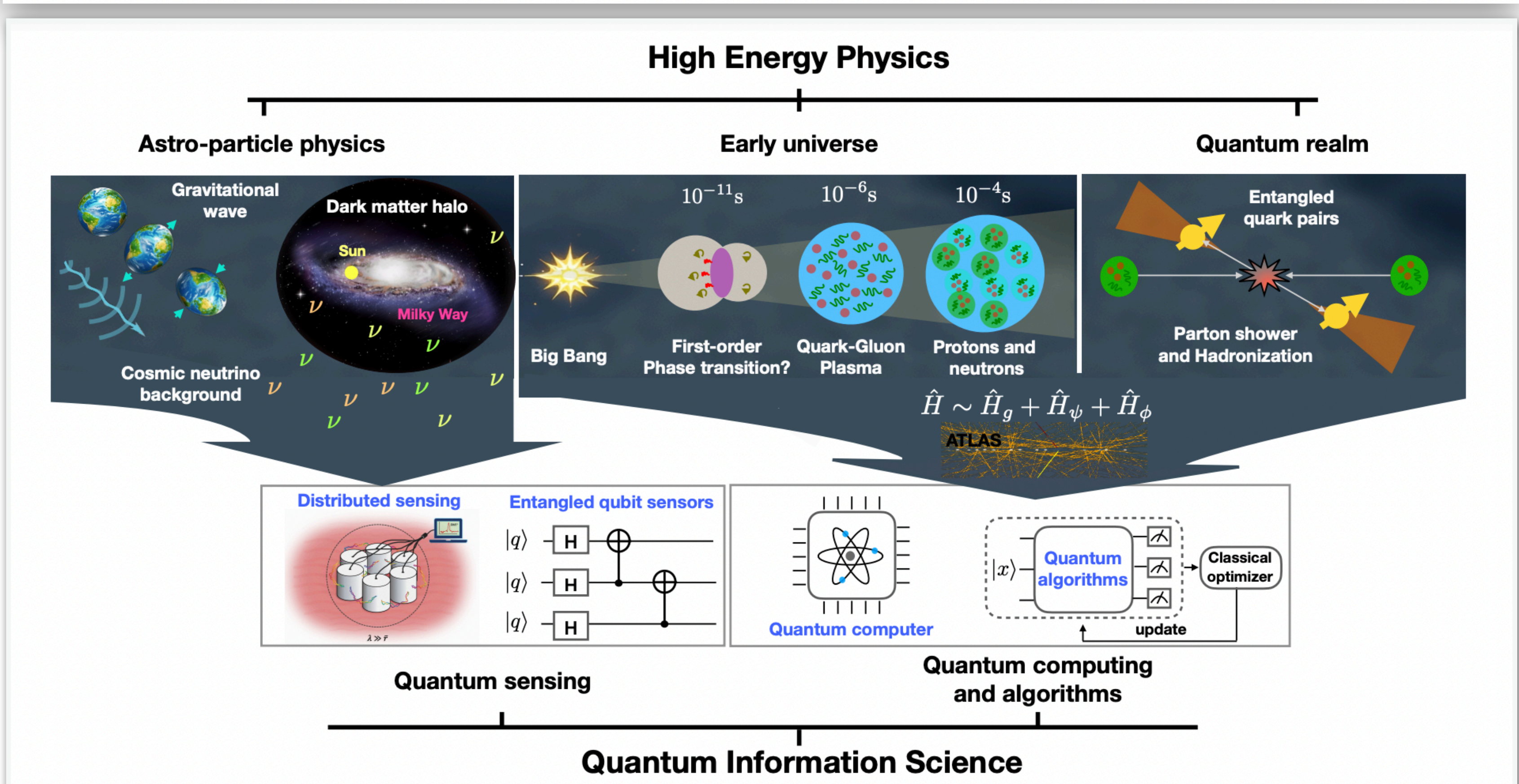
Christian W. Bauer,[1,a] Zohreh Davoudi,[2,b] A. Baha Balantekin,[3] Tanmoy Bhattacharya,[4] Marcela Carena,[5,6,7,8] Wibe A. de Jong,[1] Patrick Draper,[9] Aida El-Khadra,[9] Nate Gemelke,[10] Masanori Hanada,[11] Dmitri Kharzeev,[12,13] Henry Lamm,[5] Ying-Ying Li,[5] Junyu Liu,[14,15] Mikhail Lukin,[16] 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 Zorzetti[5]

[*arXiv:2411.11294*]

USTC-ICTS/PCFT-24-47

Quantum Frontiers in High Energy Physics

Yaquan Fang,[1,2] Christina Gao,[3] Ying-Ying Li,[4,5] Jing Shu,[6,7,8] Yusheng Wu,[9] Hongxi Xing,[10,11,12] Bin Xu,[6] Lailin Xu,[9] and Chen Zhou[6]



Quantum Simulations for HEP

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

[Jordan, Lee, Preskill, 2011]

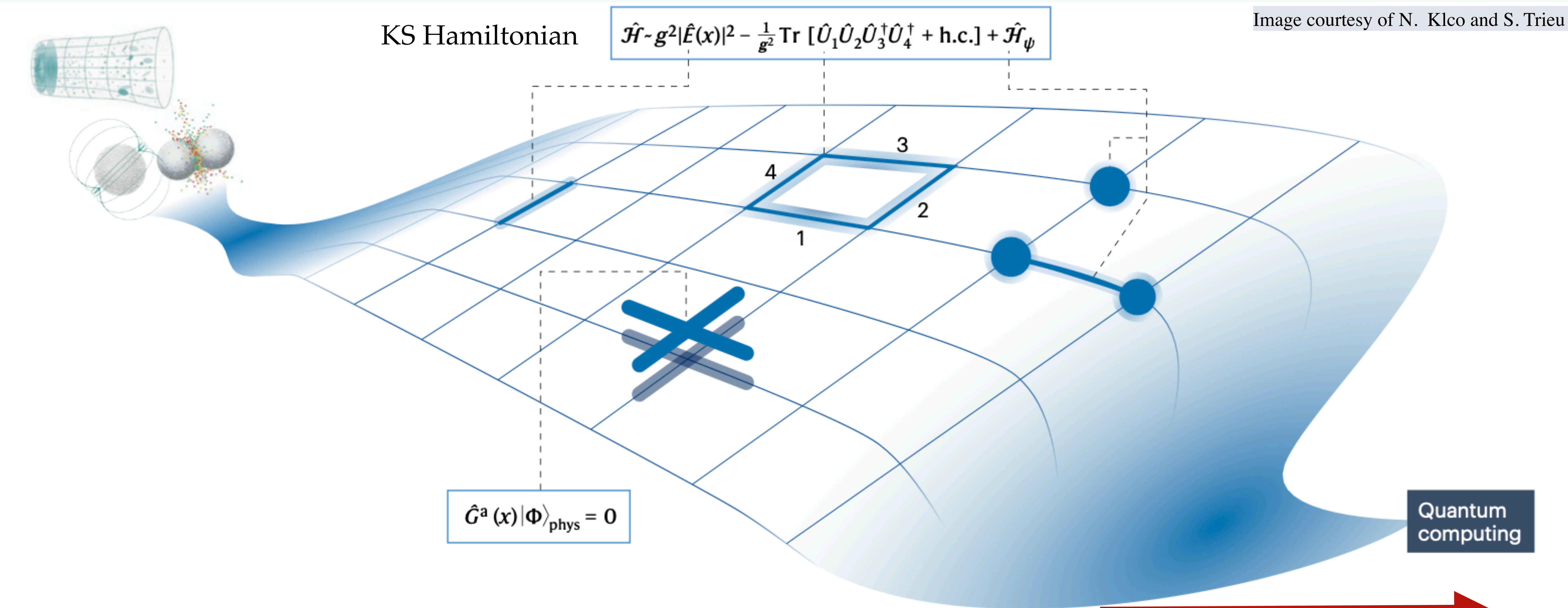


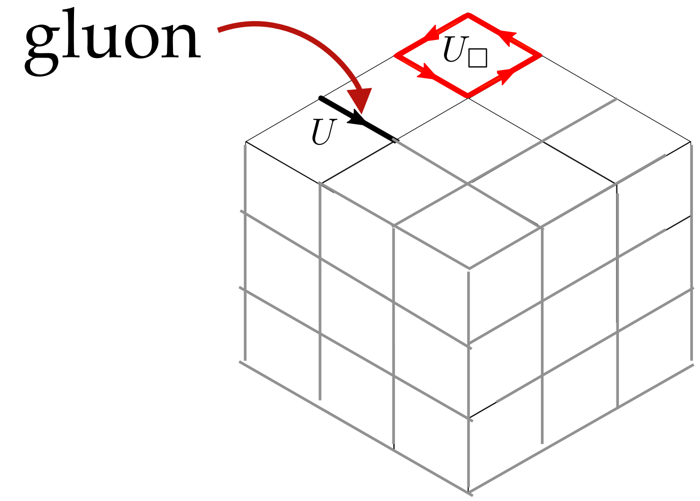
Image courtesy of N. Klco and S. Trieu

Gauge field and quark field DOF to qubits

time evolution to quantum gates

数字化

场的自由度无限



方法&向量空间:举例

Kogut-Susskind Formulation

— Irrep / angular momentum basis: *Byrnes, Yamamoto, Zohar, Burrell, et al*

— Group-element basis: *Carena, Lamm,* **YYL**, *Liu, Zohar, et al.*

— Mixed basis: *Bauer, D'Andrea, Freytsis, Grabowska*

— Large N truncations: *Bauer, Ciavarella*

— Continuous-Variable quantum computing: *Abel, Spannowsky, Williams, et al.*

***Gauge magnets*/Quantum link models:** *Wiese, Chandrasekhara, et al.*

Casimir variables: *Klco, Savage, Stryker, Ciavarella*

Schwinger boson formulations: *Mathur, Anishetty, Raychowdhury, et al*

Loop-string-hadron formulation: *Raychowdhury, Stryker, Davoudi, Kadam, et al.*

Qubit models: *Chandrasekhara, Singh, et al.*

Dual/rotor formulations: *Kaplan, Stryker, Haase, et al.*

q-deformed Kogut-Susskind: *Zache, Zoller et al*

Dual/rotor formulations: *Kaplan, Stryker, Haase, Dellantonio, et al.*

理论发展和算法仍处于非常初级的阶段

数字化 $|q\rangle^N \to |G\rangle$ infinities in QFT

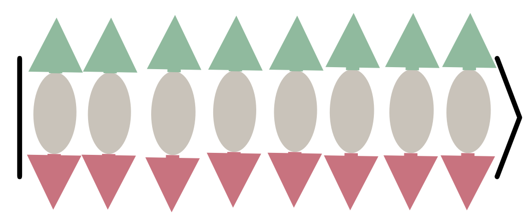
离散子群

$$|U\rangle = \left\{ \begin{pmatrix} \alpha & -\overline{\beta} \\ \beta & \overline{\alpha} \end{pmatrix} : \ \alpha, \beta \in \mathbb{C}, |\alpha|^2 + |\beta|^2 = 1 \right\} \rightarrow |U\rangle = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \middle| a, b, c, d \in \mathbf{F}_3, ad - bc \equiv 1 \pmod 3 \right\}$$

3-sphere

块编码方法: BT

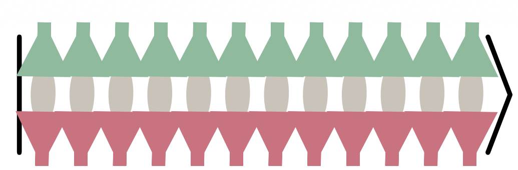
$$|U\rangle =$$



块编码方法: BI

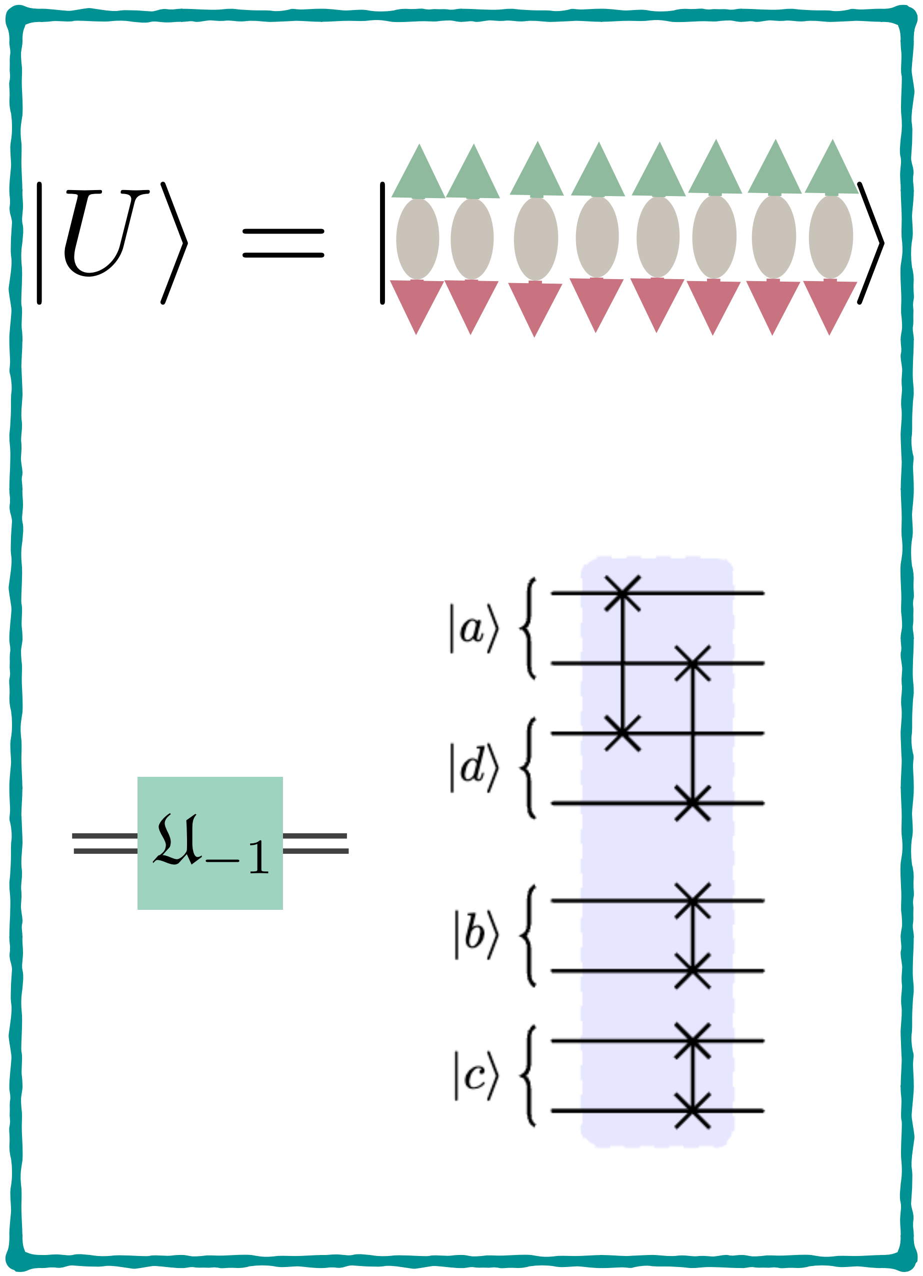
$$|U\rangle = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \middle| a, b, c, d \in \mathbf{F}_5, ad - bc \equiv 1 \ \mathrm{mod}(5) \right\}$$

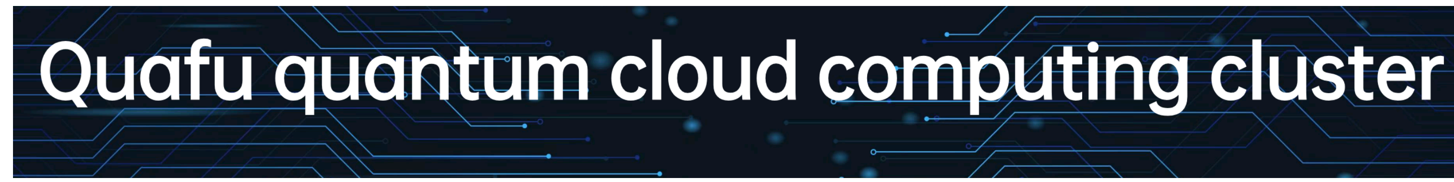
$$|U\rangle =$$

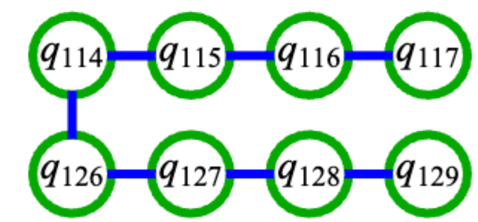


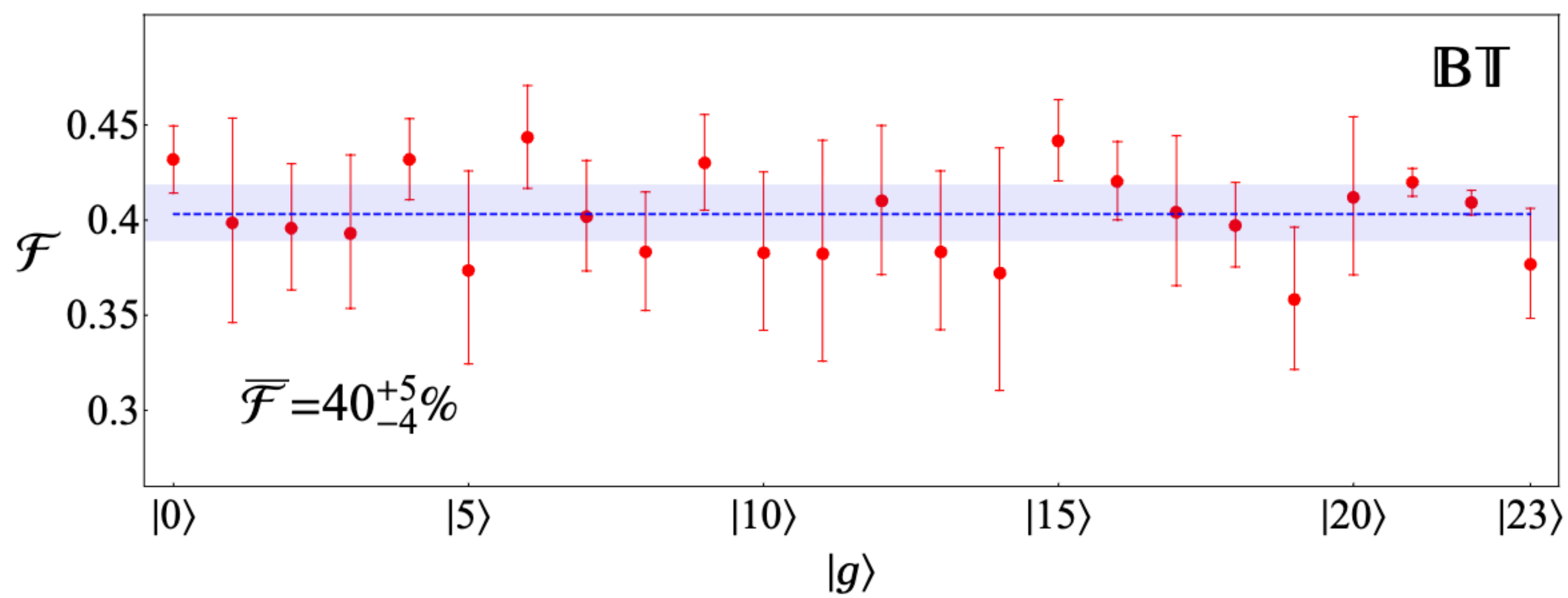
[Lamm,**YYL**, Shu, Wang, Bin, PRD **110**, 054505]

数字化 $|q\rangle^N \to |G\rangle$ infinities in QFT









[Lamm, **YYL**, Shu, Wang, Bin, PRD **110**, 054505]

- 在量子平台上实现了SU(2)规范场取逆的动力学演化。

Now - Noisy Intermediate Scale Quantum (NISQ) era

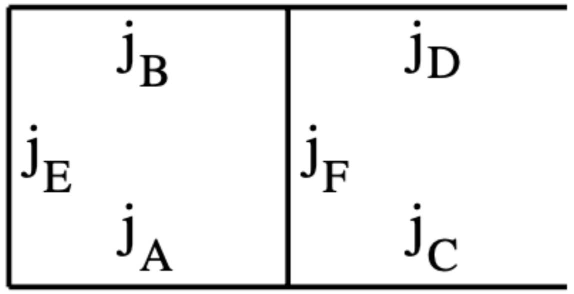
With $\mathcal{O}(100)$ well controlled qubits, not error-corrected yet

Physics Benchmarks

Physics Benchmarks – Fragmentation Dynamics

2+1D SU(2) Gauge Theories

$$\hat{H} = \frac{g^2}{2}\left(\sum_{i=\text{links}} \hat{E}_i^2 - 2x \sum_{i=\text{plaquettes}} \hat{\Box}_i\right)$$



$$\langle\psi|\sum_i \hat{E}_i^2|\psi\rangle = \sum_{i=A}^{L} j_i(j_i+1)$$

$$|\psi\rangle = |j_A, m_A, m'_A\rangle\,|j_B, m_B, m'_B\rangle \ldots |j_L, m_L, m'_L\rangle$$

Physics Benchmarks – Fragmentation Dynamics

2+1D SU(2) Gauge Theories

$$\hat{H} = \frac{g^2}{2}\left(\sum_{i=\text{links}} \hat{E}_i^2 - 2x \sum_{i=\text{plaquettes}} \hat{\square}_i\right) \qquad \langle\psi|\sum_i \hat{E}_i^2|\psi\rangle = \sum_{i=A}^{L} j_i(j_i+1)$$

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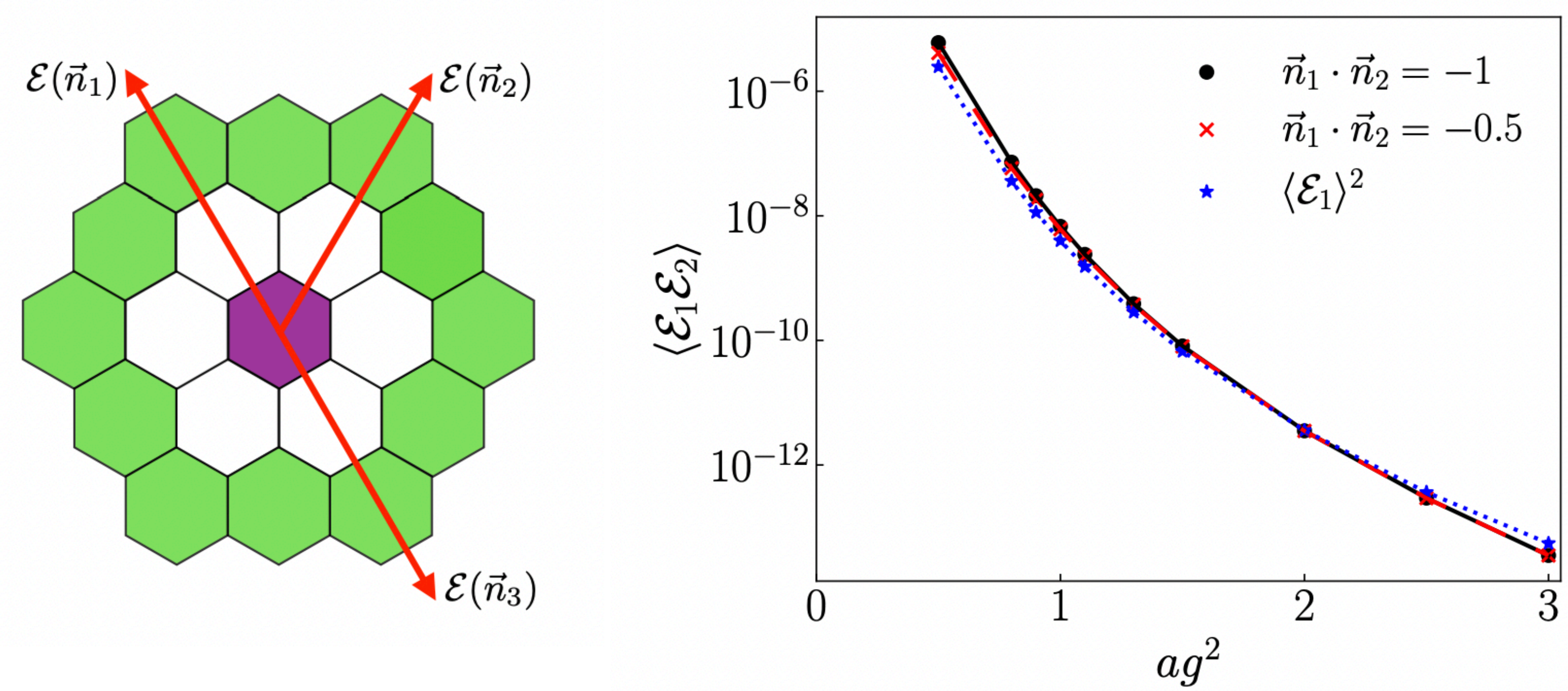
$$j_{\max} \leq \frac{1}{2}$$

Gauss's Law

Including modes of higher j values to approach continuous field limit



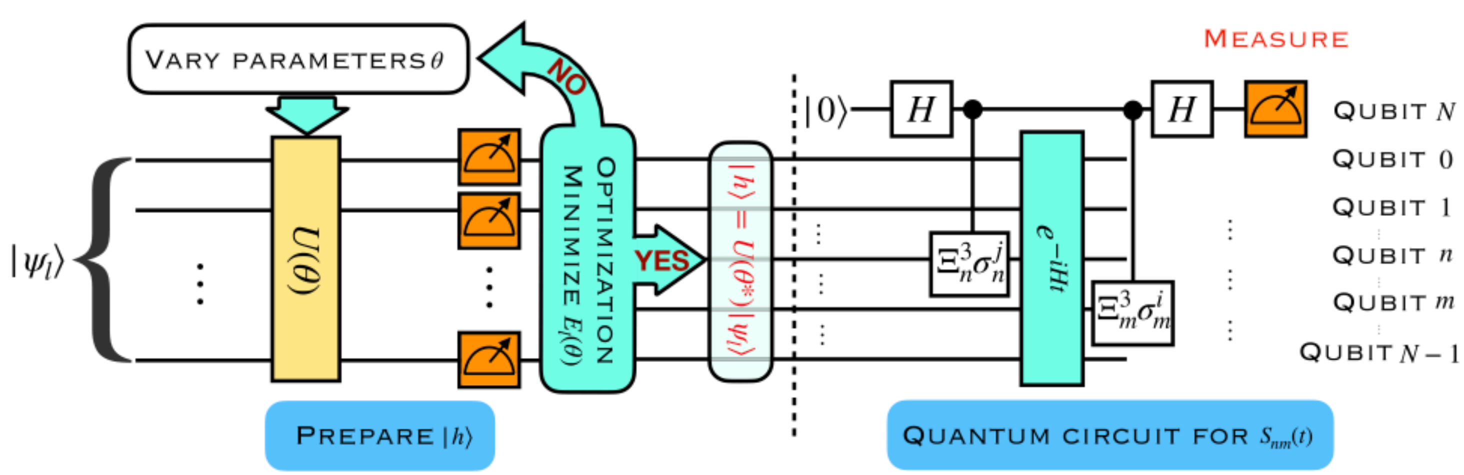
[Lee, Turro, Yao, arXiv:2409.13830]

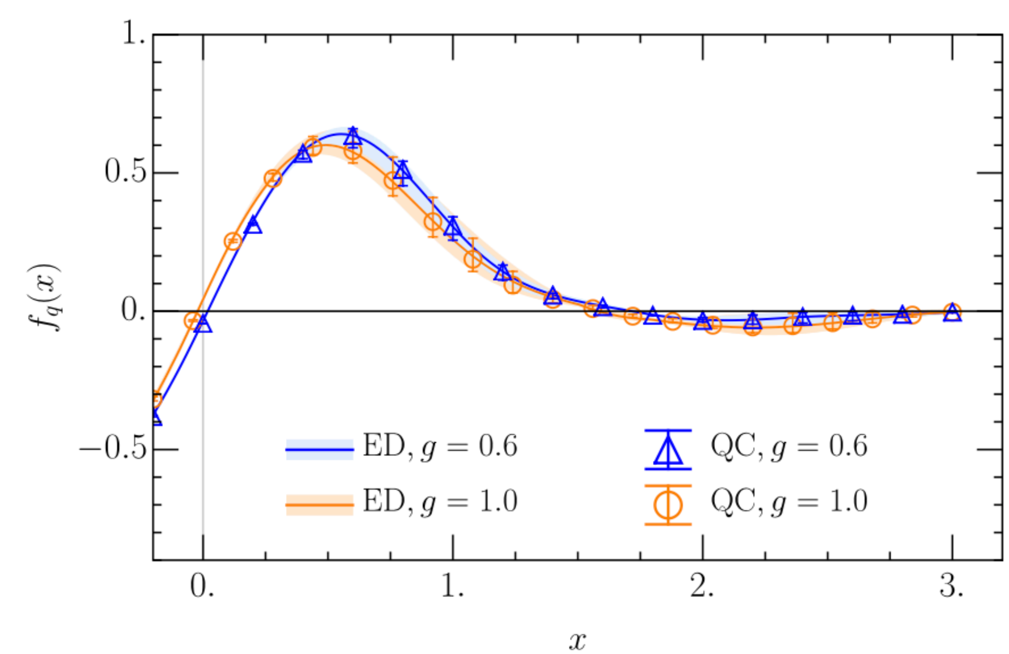
Physics Benchmarks – PDF

1+1D Nambu-Jona- Lasinio model

$$\mathcal{L} = \bar{\psi}_\alpha (i\gamma^\mu \partial_\mu - m_\alpha)\psi_\alpha + g(\bar{\psi}_\alpha \psi_\alpha)^2,$$

$$f_{q/h}(x) = \int \frac{dz}{4\pi} e^{-ixM_h z} \times \langle h| e^{iHt} \bar{\psi}(0,-z) e^{-iHt} \gamma^+ \psi(0,0) |h\rangle$$





[Tianyin Li, et al., PHYS. REV. D 105, L111502 (2022)]

Quantum Machine Learning

computational complexity improvements, computational speed-ups

Supervised Learning—better separation power?

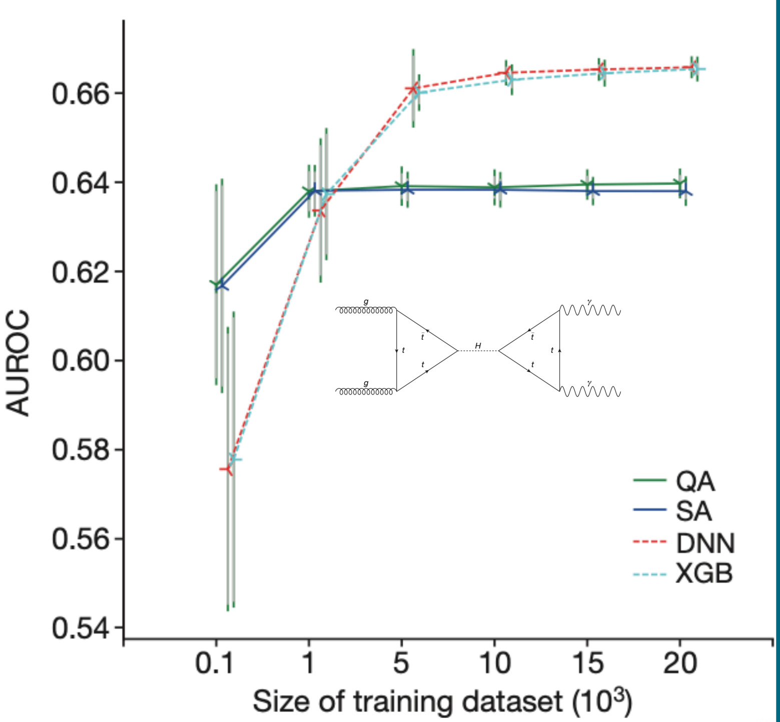
Quantum variational circuits, quantum annealing, QSVM, etc.

Quantum Annealing

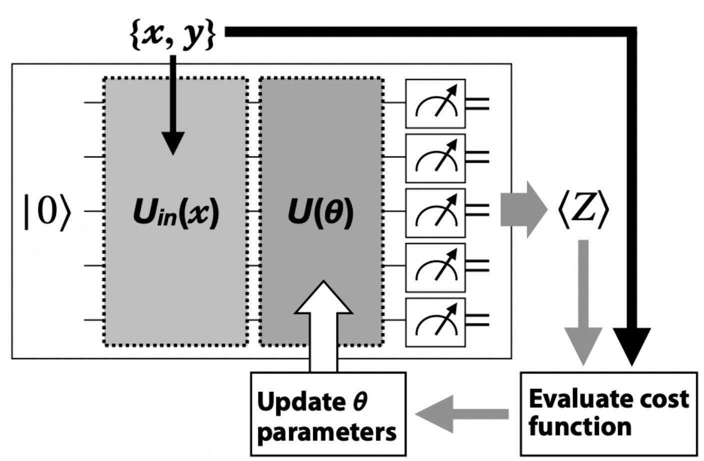
$$C_{ij} = \sum_{\tau} c_i(\boldsymbol{x}_\tau) c_j(\boldsymbol{x}_\tau), \quad C_i = \sum_{\tau} c_i(\boldsymbol{x}_\tau) y_\tau$$

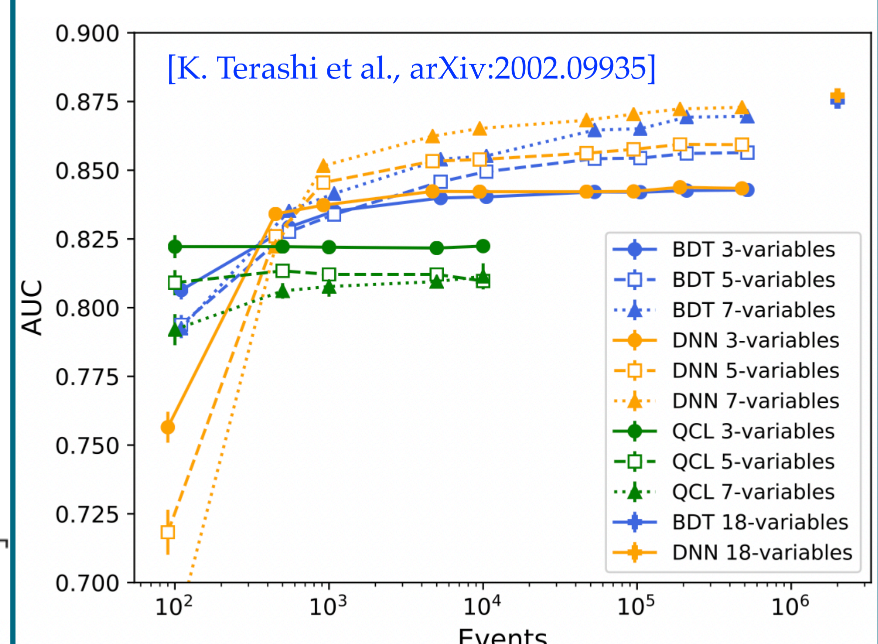
$$H = \sum_{i,j} J_{ij} s_i s_j + \sum_i h_i s_i$$

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



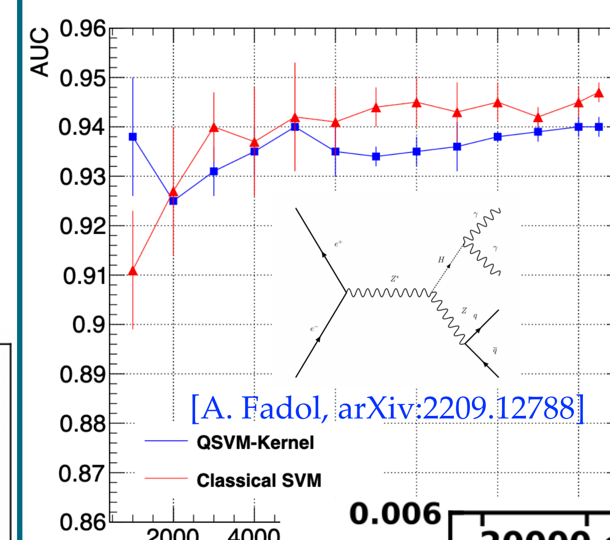
Variational Quantum Approach

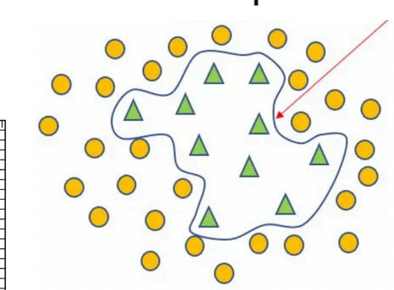




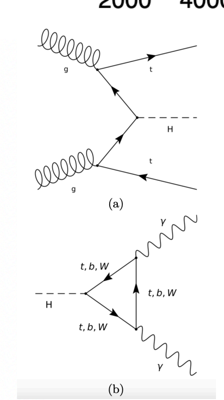
Quantum Support Vector Machine

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

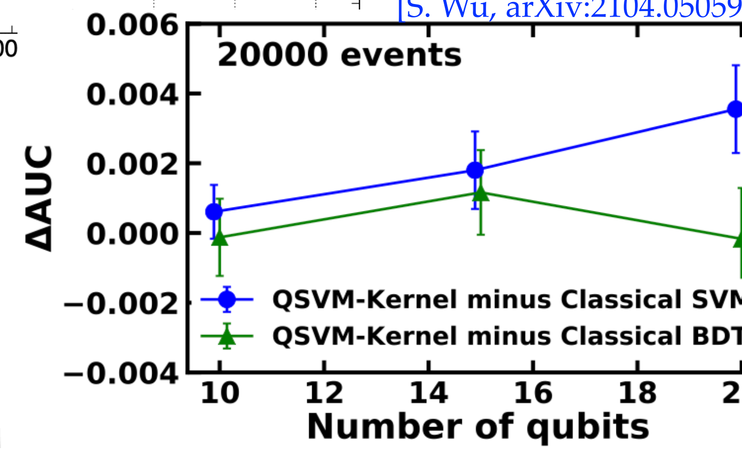




larger sample size?

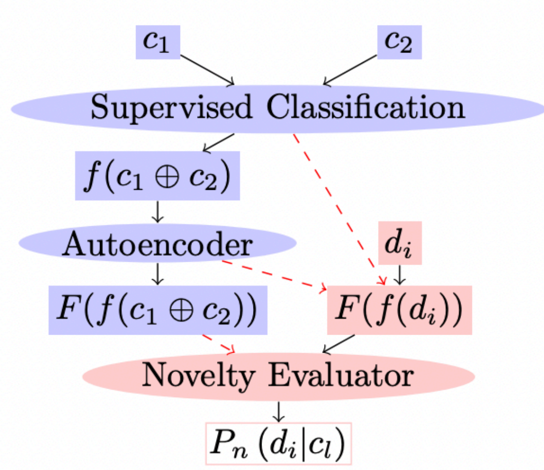


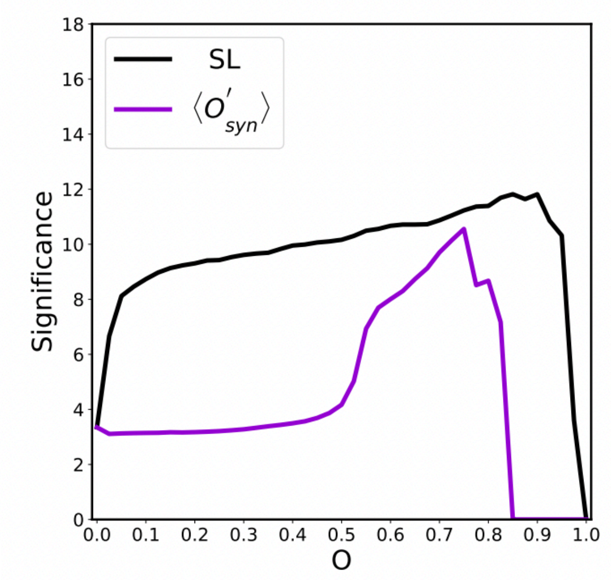
[S. Wu, arXiv:2104.05059]



Quantum Machine Learning - Anomaly detection

ANOMALY DETECTION





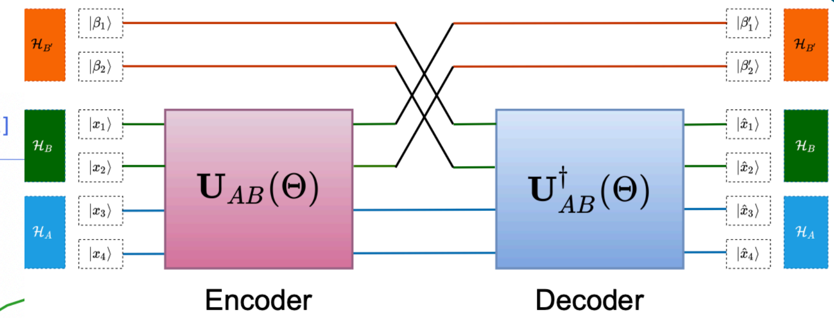
(a) $t\bar{t}h$

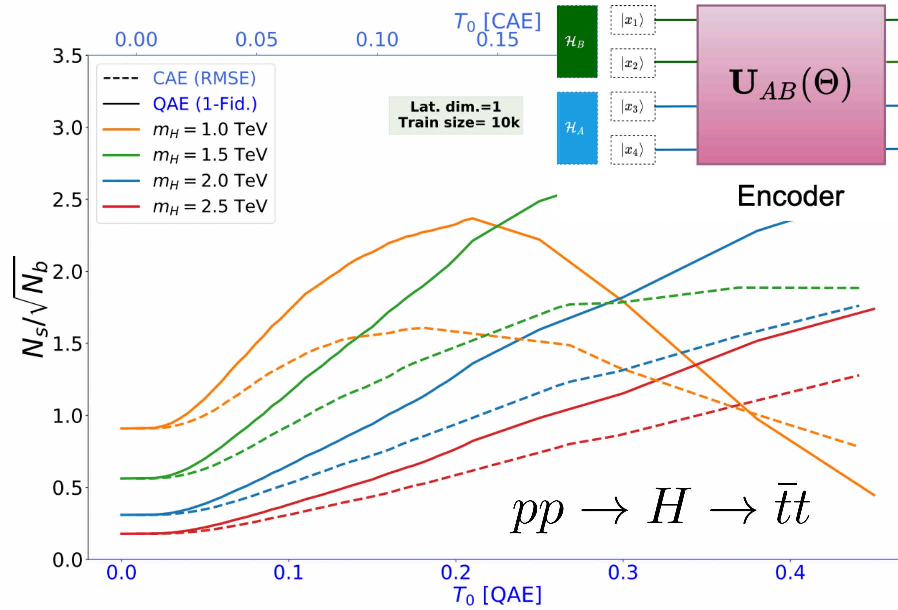
[J. Hajer, **YYL**, T. Liu, H. Wang, *PRD* 101 7, 076015]
[X.-H. Jiang, **YYL**, A. Juste, T. Liu, JHEP 10 (2022) 085]

- 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 Spiropulua 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

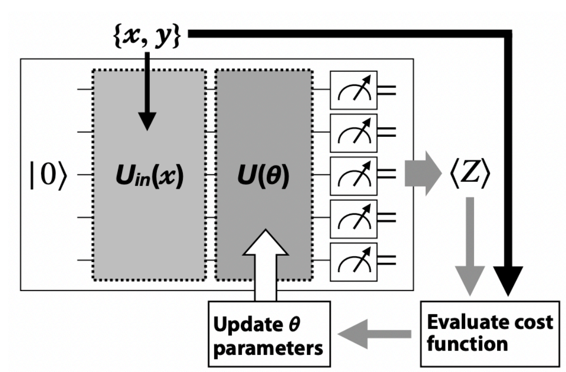
Quantum auto encoder





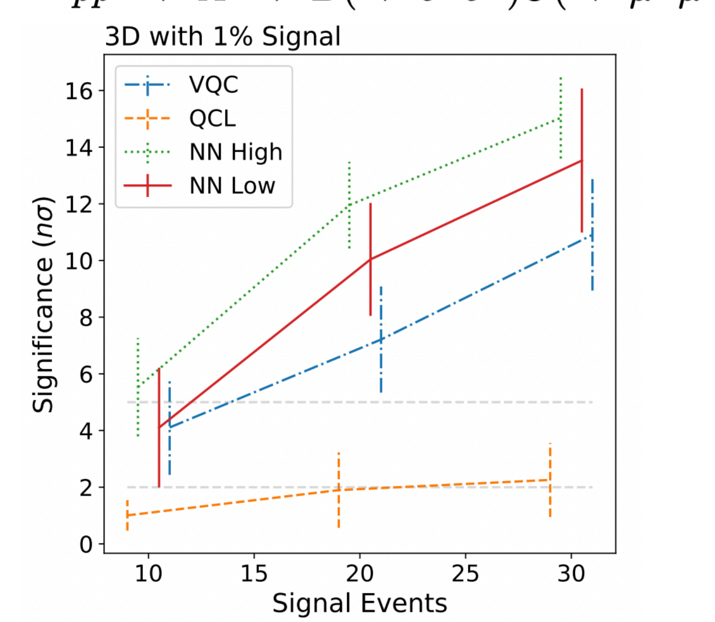
[Ngairangbam, Spannowsky, Takeuchi, PRD. **105**, 095004]

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



[Terashi et al, arXiv:2002.09935]

$pp \to A \to B(\to e^+e^-)C(\to \mu^+\mu^-)$

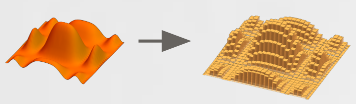


[Alvi, Bauer, Nachman, arXiv:2206.08391]

“Quantum potential for High Energy Physics!”

(2030s) narrow down the framework with

- systematic studies of errors from digitization —— phase diagrams with spontaneous symmetry breaking, and for improved H
- hardware co-design —— qudits for blocking encodings and the redundancies
- improving algorithms —— efficient quantum circuits based on qudits
- benchmark studies —— HEP case calculations for experiments
- …



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

↓

$\mathcal{U}\,|G\rangle^L \rightarrow |\psi_0\rangle$

↓

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

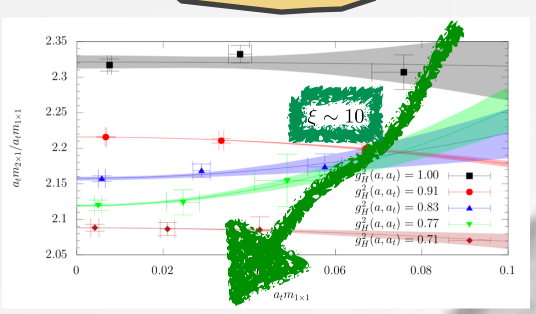
↓

$\langle \mathcal{O} \rangle$

S. P. Jordan,
K. S. M. Lee,
J. Preskill

2011-

various methods



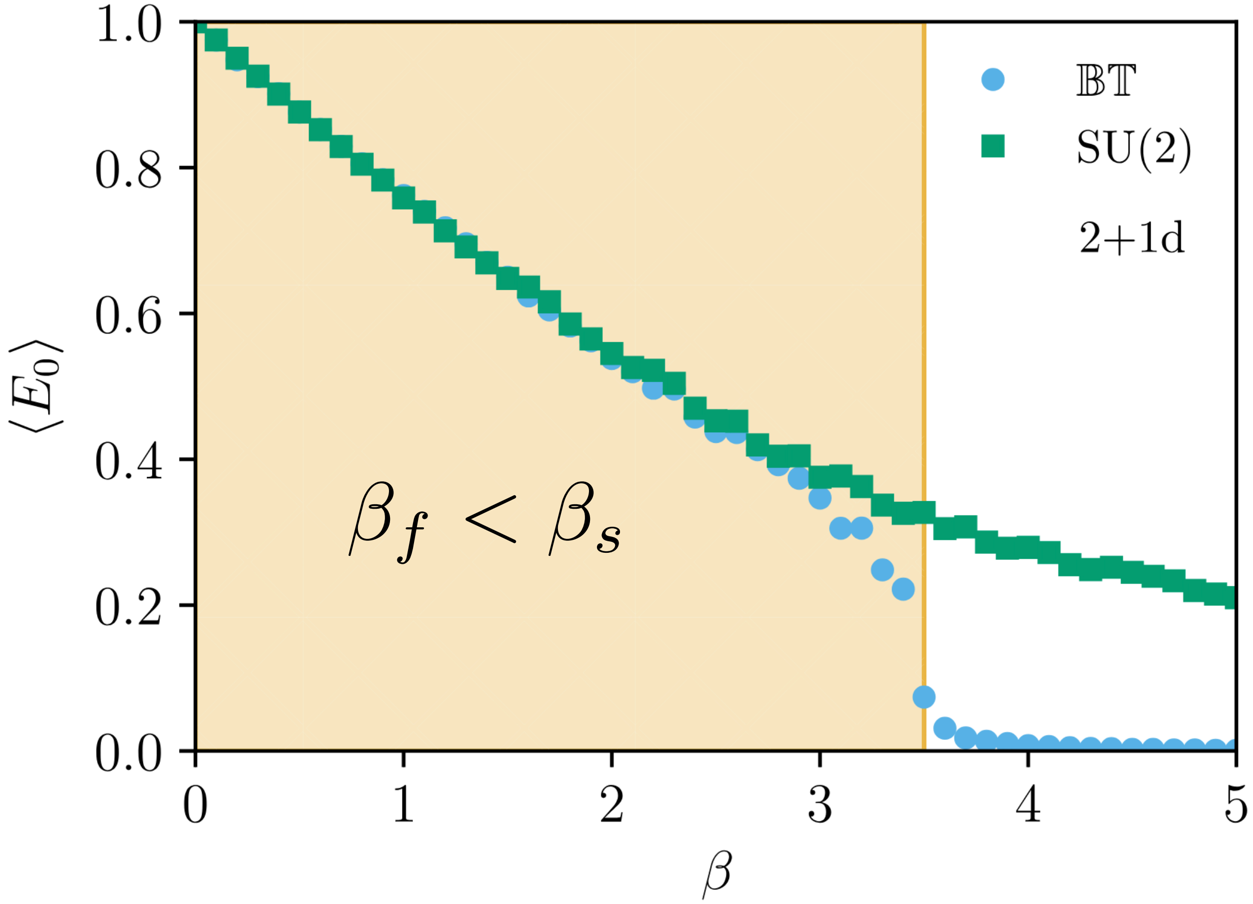
2020 -

2030s -

Thank you

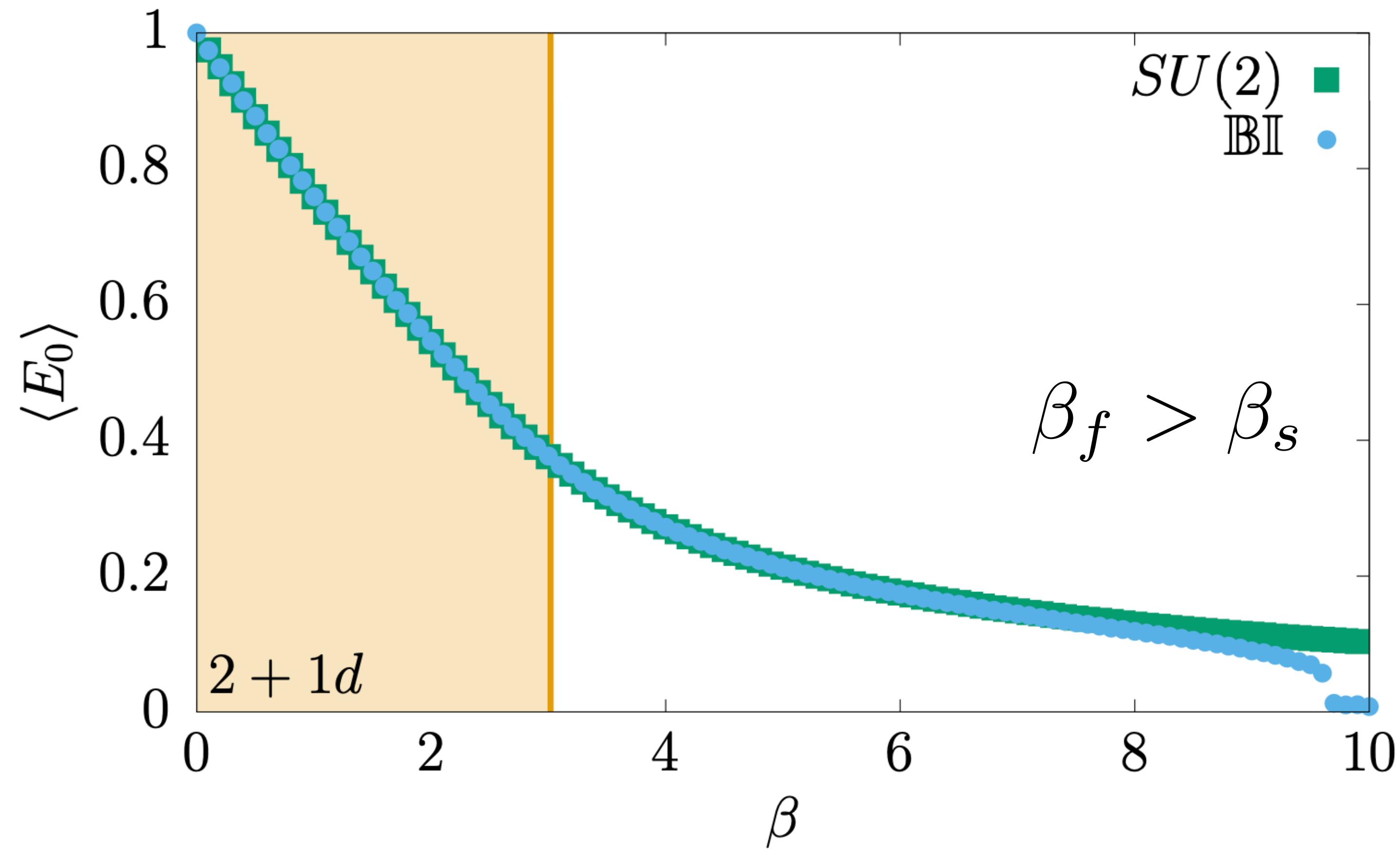
数字化 $|q\rangle^N \rightarrow |G\rangle$ infinities in QFT

[Gustafson, Lamm, Lovelace, Mush, PRD **106**, 114501]



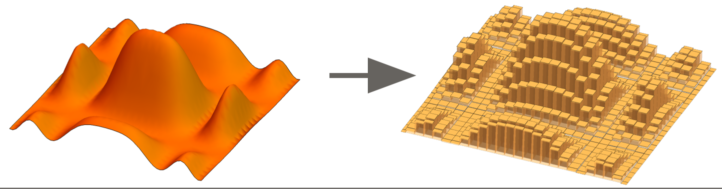
量化/改进误差的系统方法?

[Lamm,**YYL**, Shu, Wang, Bin, PRD **110**, 054505(2024)]



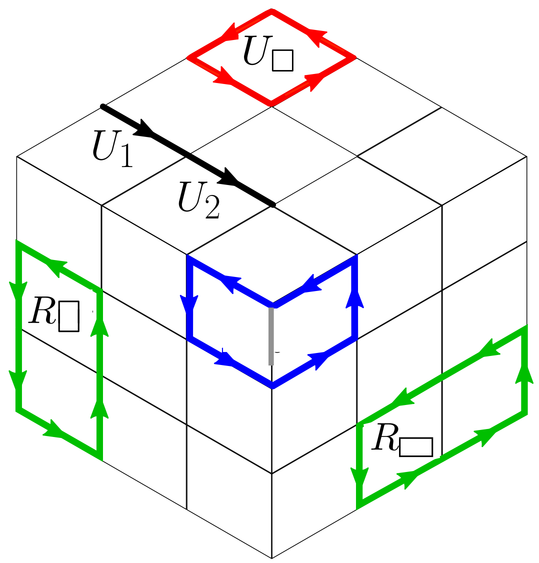
In the Scaling Regime:
较大的离散子群可以降低模拟SU(2)规范场的系统误差

离散化

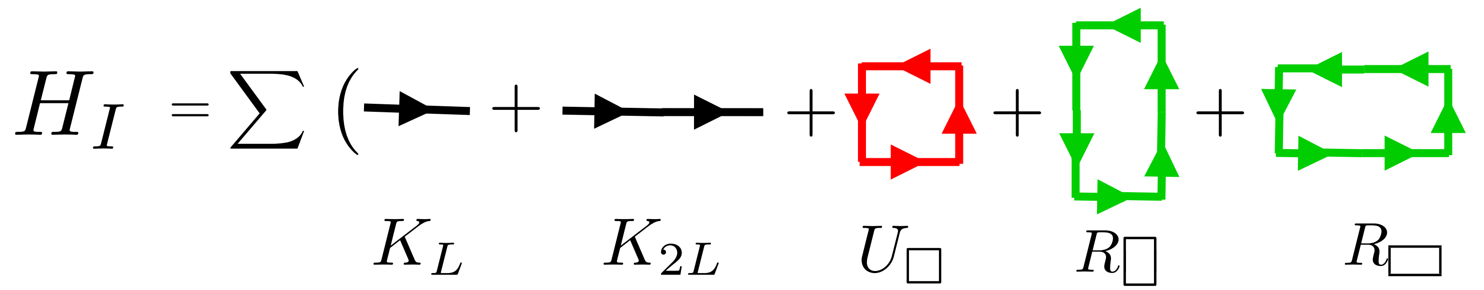


infinities in QFT

$$K_{2L} = E_i(\mathbf{x})U_i(\mathbf{x})E_i(\mathbf{x}+a\mathbf{i})U_i^\dagger(\mathbf{x})$$

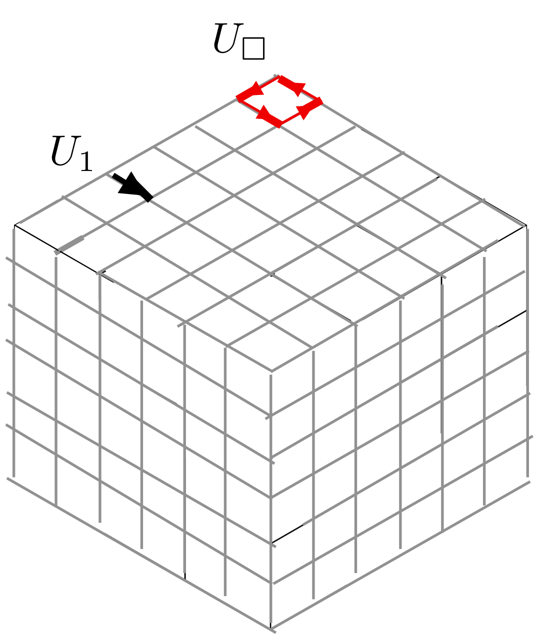


改进哈密顿量



量子线路

$$\langle U_1', U_2' | \mathcal{U}_{K_{2L}} | U_1, U_2 \rangle = \delta_{U_1'U_2', U_1U_2} \langle U_1' | e^{i\theta K_{L_1}} | U_1 \rangle$$



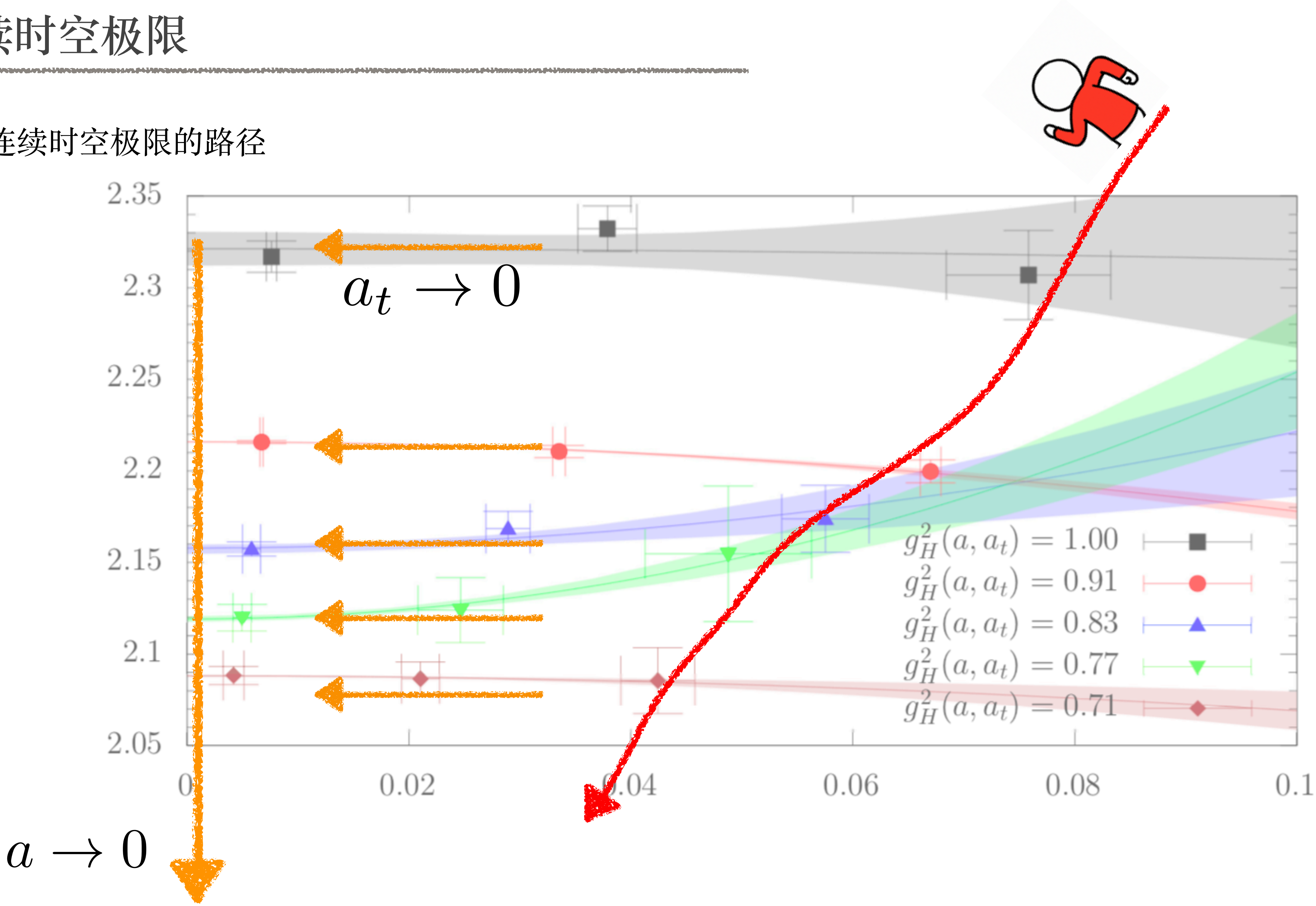
改进动能项保持群元素乘积不变!

约化成领头阶动能项的量子线路

[Carena, Lamm, **YYL**, Liu, PRL. **129**, 051601]

连续时空极限

取连续时空极限的路径



continuous
space-time limit

[Carena, Lamm, **YYL**, Liu, PRD. **104**, 094519]