第十四届全国粒子物理学术会议

高能物理和量子物理交叉

曹庆宏

北京大学物理学院
北京大学高能物理研究中心

会议主题：人工智能、量子信息、量子计算在粒子物理、核物理和宇宙学等学科前沿的应用

第28届LHC Mini-Workshop报告

2024年7月9日-10日

人工智能

罗民兴：Some observations on AI assited theoretical studies

马滟青：人工智能回顾及愚见

机器学习

马伯强：Application of machine learning method with cosmic photons

李　亮：高能物理的下一场革命：从深度学习走向通用人工智能

李．靖：HEP ML Lab: an end-to-end framework for machine learning application in high energy physics

郭禹辰：Using machine learning to optimize the measurements of anomalous gauge couplings

朱永峰：Jet Origin Identification & Quantum-based Jet Clustering

量子计算

李英英：HEP Opportunities in the Quantum Computing Era

刘晓辉：Partonic Collinear Structure by Quantum Computing

杨冀翀：Using machine learning method suitable for quantum computing in the phenomenological study of new physics

量子信息

肖明磊：Emergent Symmetry from Entanglement Suppression

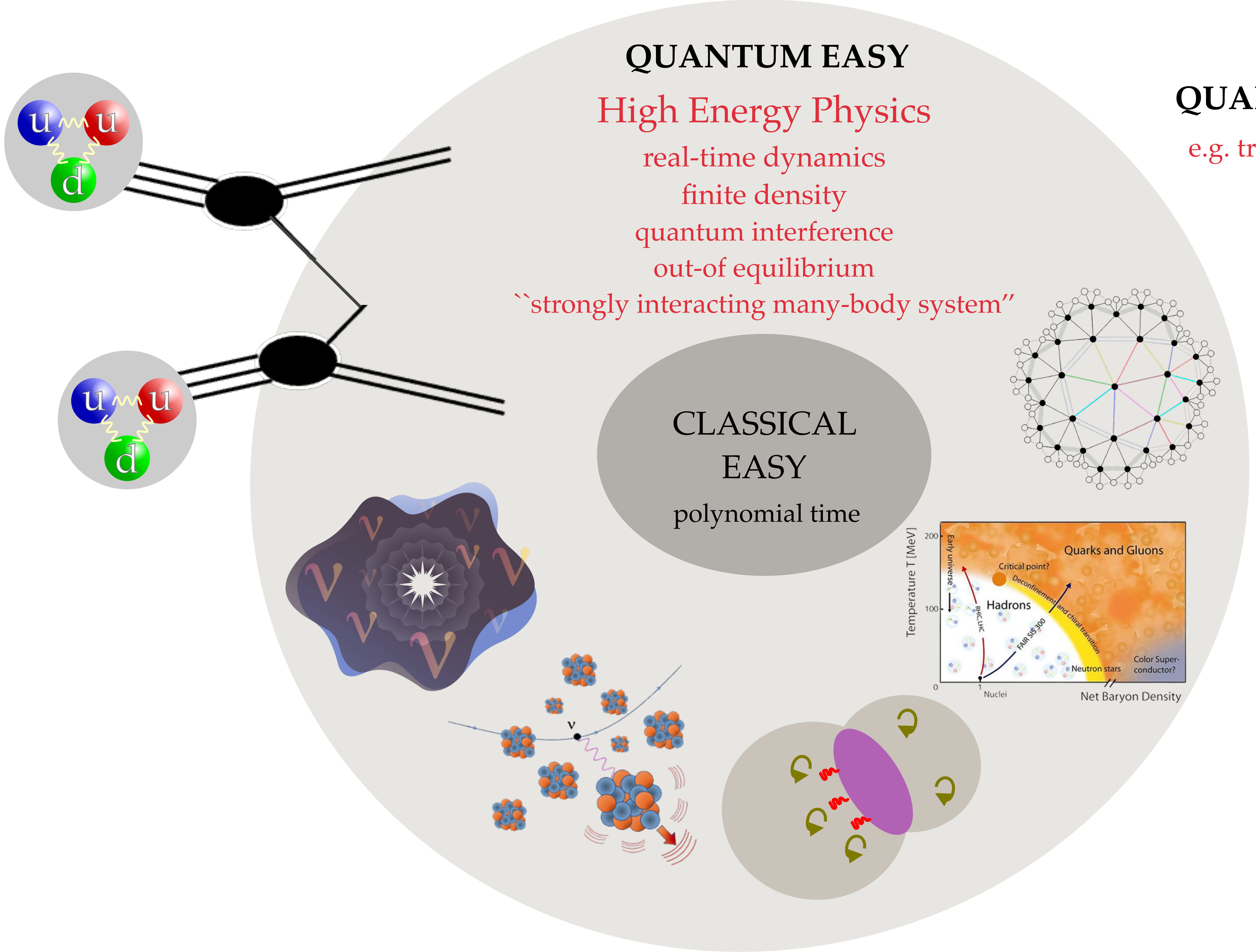
施　郁：Quantum Entanglement in High Energy Physics

程　焜：Quantum Entanglement at High-energy Colliders

量子计算

1、量子计算

李英英



QUANTUM EASY

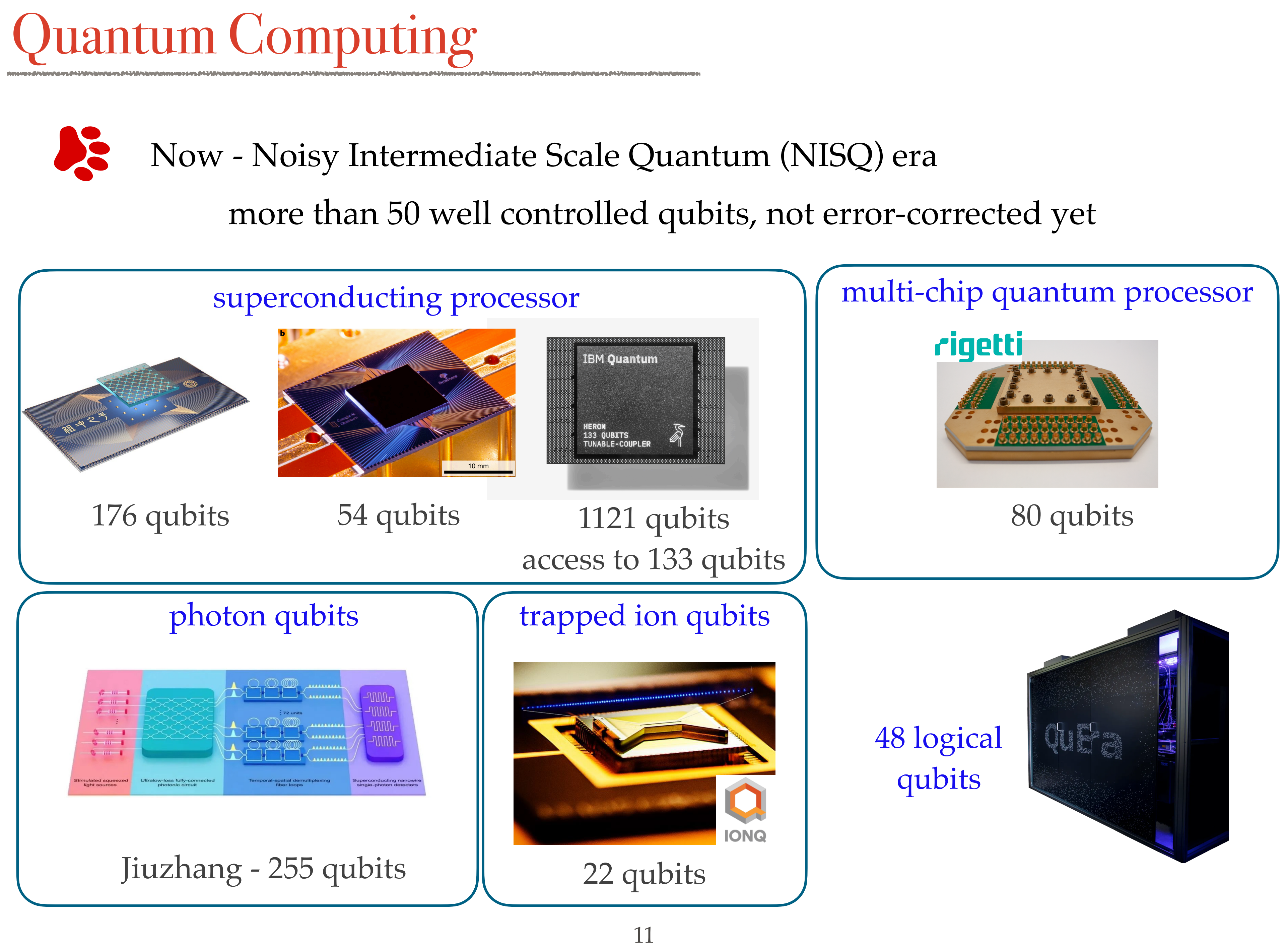
High Energy Physics

real-time dynamics
finite density
quantum interference
out-of equilibrium
``strongly interacting many-body system''

CLASSICAL
EASY
polynomial time

QUANTUM HARD

e.g. traveling salesmen
problem



Quantum Computing

Now - Noisy Intermediate Scale Quantum (NISQ) era
more than 50 well controlled qubits, not error-corrected yet

superconducting processor
176 qubits
54 qubits
1121 qubits
access to 133 qubits

multi-chip quantum processor
80 qubits

photon qubits
Jiuzhang - 255 qubits

trapped ion qubits
22 qubits

48 logical
qubits

11

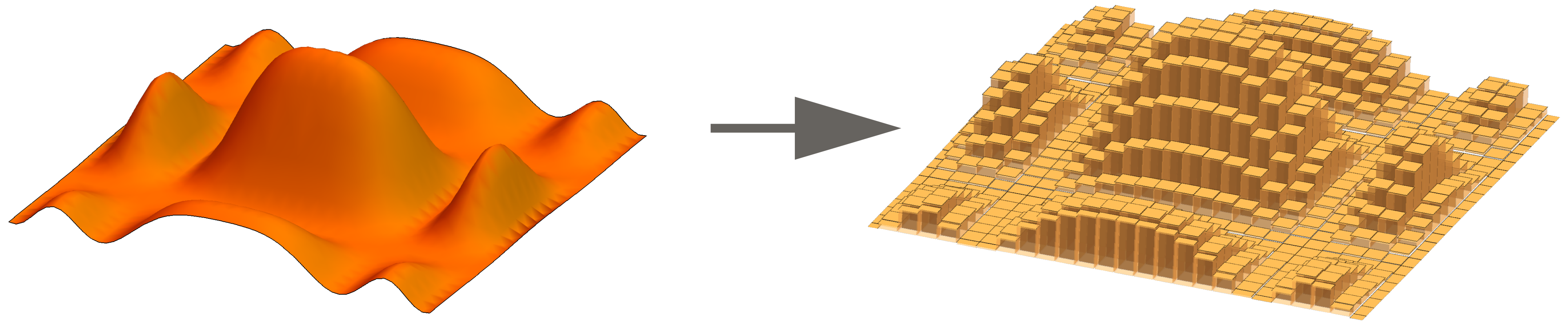
Problems in HEP that are beyond classical easy but are
``QUANTUM EASY''

Quantum Computing for HEP

[Jordan, Lee, Preskill, 2011]

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

Discretization



infinities in space

Carena, Lamm, YYL, Liu,
Gustafson, Water,…

Digitization

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

infinities in field variables

Bauer, Davoudi, Gustafson, Meurice,
Lamm, YYL, Savage,…

Initialization

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

ground/thermal/bound state prep

Karsen, Davoudi, Lawrence, YYL, Xu, Liu, Xing…

Propagation

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

efficiency of time evolutions

Davoudi, Gustafson, YYL, Stryker, Wang, Zohar…

Evaluation

$$\langle \mathcal{O} \rangle$$

parton distribution function,

Lamm, Liu, Yamauchi, Xing…

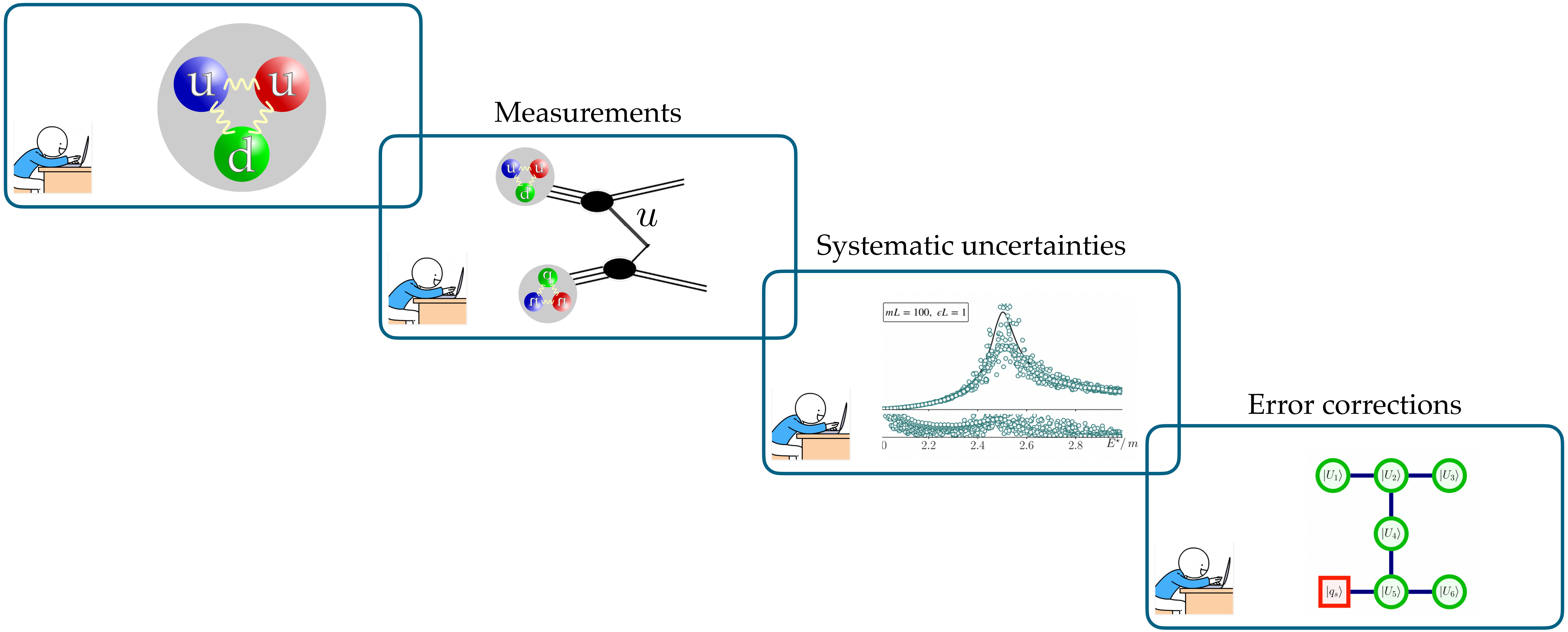
Error mitigation/corrections

gauge symmetry for error corrections

Bauer, Carena, Halimeh, Lamm, YYL,…

To reach the observables — How to do…

详见李英英老师报告



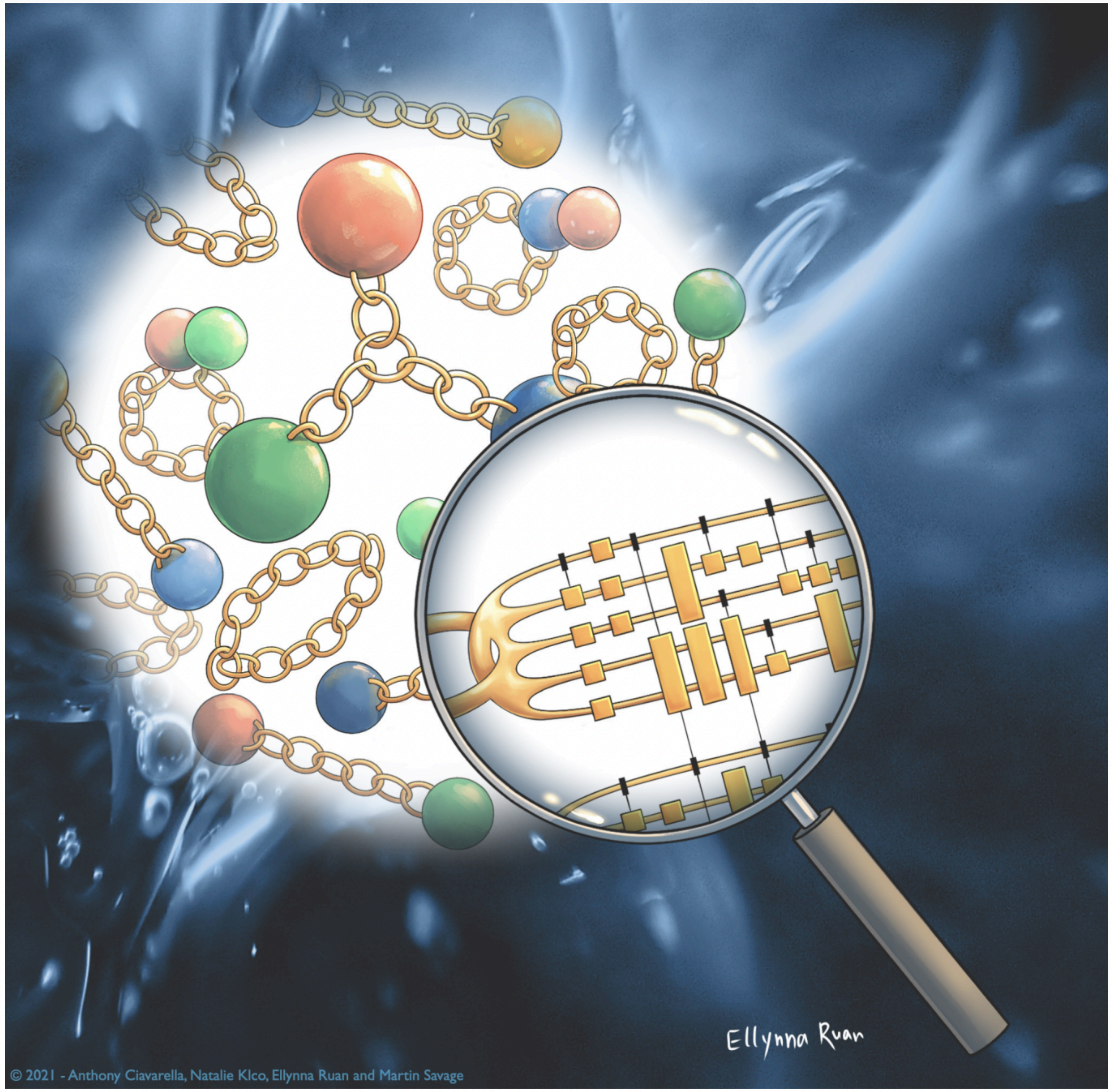
State preparation

Measurements

Systematic uncertainties

Error corrections

and reach the continuum limit



Partonic Collinear Structure by Quantum Computing

第28届**LHC Mini Workshop**

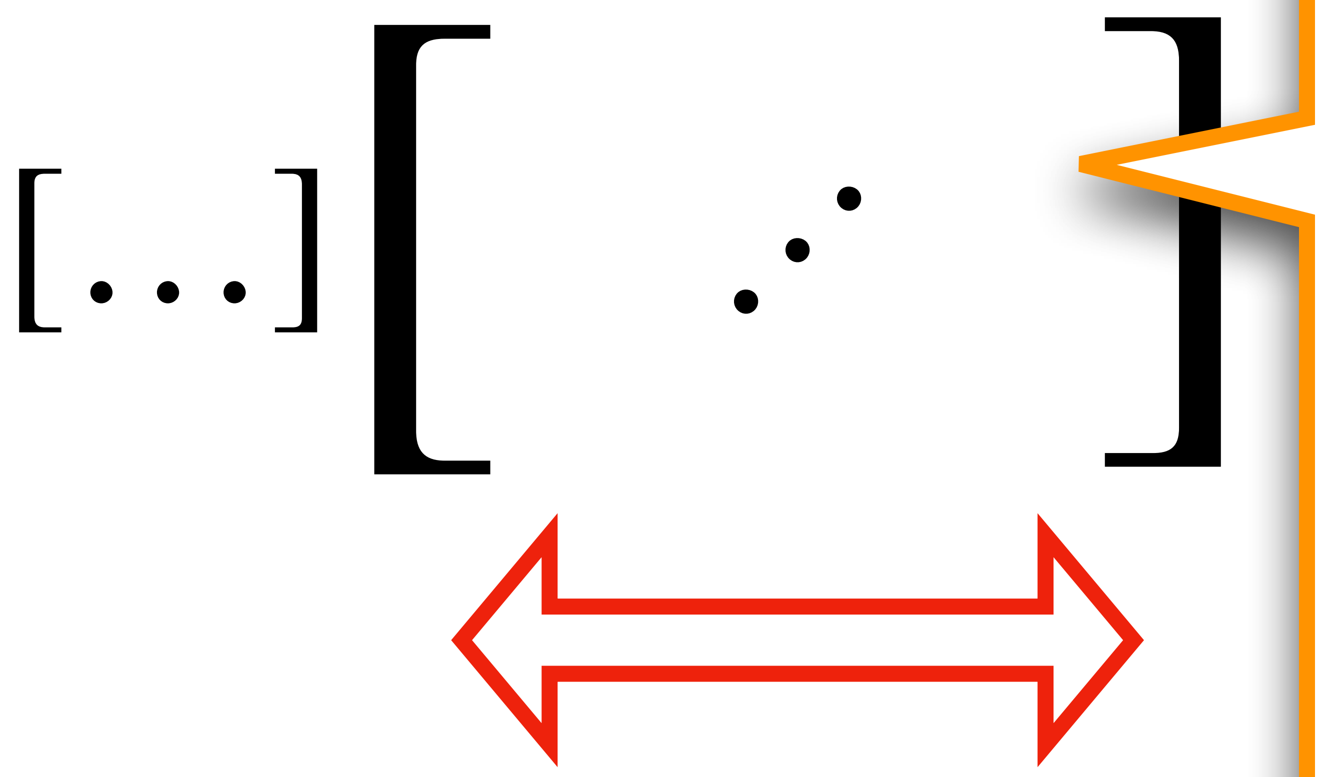
刘晓辉

北京師範大學
BEIJING NORMAL UNIVERSITY

Quantum Computing for HEP

In HEP, we are dealing with n-pt correlates, i.e. S-matrix

$$\langle \mathrm{out} | e^{-iH[\psi]t} | \mathrm{in} \rangle$$



$$[\dots] \left[\;\; \iddots \;\; \right]$$

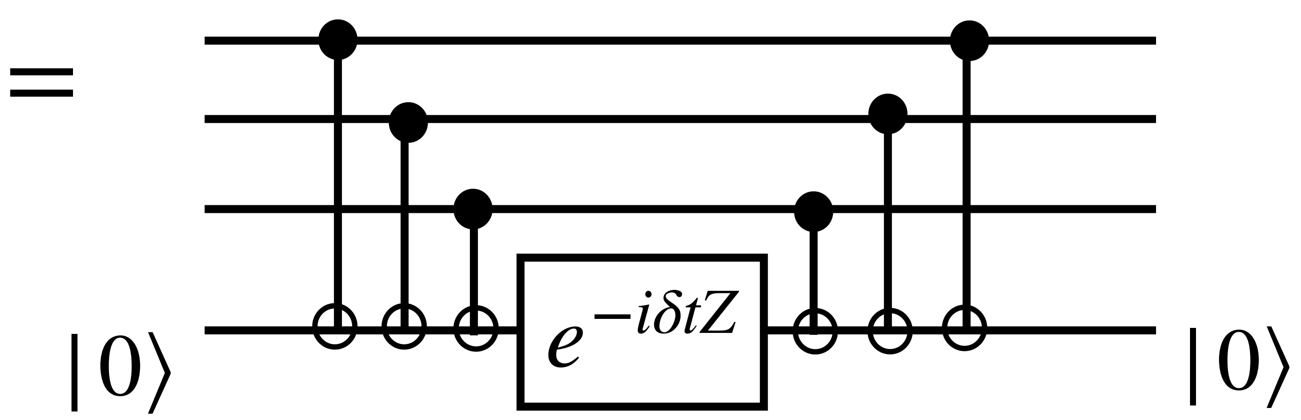
$$\dim = (n_\psi)^{n^{D_{sp}}}$$

decompose to a set of gates, evolution much cheaper

e.g. $H = Z_1 \otimes Z_2 \otimes Z_3$ $\qquad e^{-iHt} \approx \lim_{\delta t \to 0, N \to \infty} \left[e^{-iH\delta t} \right]_N$ Trotter, 1959

Use the fact that $|\phi_1\rangle|\phi_2\rangle \dots |0\rangle \to |\phi_1\rangle|\phi_2\rangle \dots |\phi_1 \oplus \phi_2 \dots\rangle$

$$e^{-iH\delta t} =$$



Others can be realized similarly

e.g. by using $e^{-i\delta t X_1 \otimes Z_2 \otimes \dots} = H_1 e^{-i\delta t Z_1 \otimes Z_2 \otimes \dots} H_1$

Quantum computing: reasonable size and operations (scales logarithmically)

Jordan, Lee, Preskill, Science 336, 1130-1133 (2012)

A toy model: Map QFT on to a qubits+gates system

$$\mathscr{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi + g(\bar{\psi}\psi)^2$$ (no gauge, 1+1)

Gross, Neveu, 1974

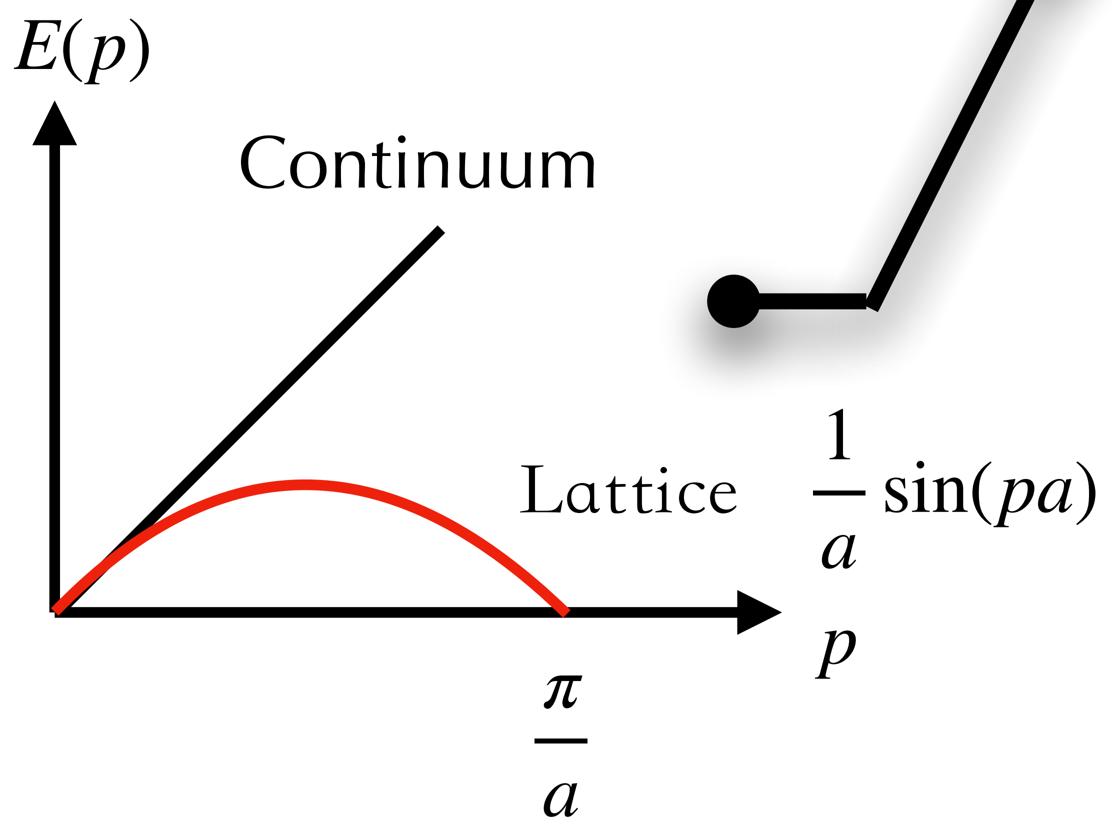
$$f(x) = \int dz^- e^{-ixM_h z^-} \langle h | \bar{\psi}(z^-)\gamma^+\psi(0) | h \rangle = \int dz^- e^{-ixM_h z^-} \langle h | e^{iHz}\bar{\psi}(0, -z)e^{-iHz}\gamma^+\psi(0) | h \rangle$$

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \rightarrow \begin{pmatrix} \phi_{2n} \\ \phi_{2n+1} \end{pmatrix}$$

Staggered fermion,
Put different fermion components, flavors on different sites

$$\phi_n = \prod_{i<n} Z_i (X + iY)_n$$

Jordan-Wigner

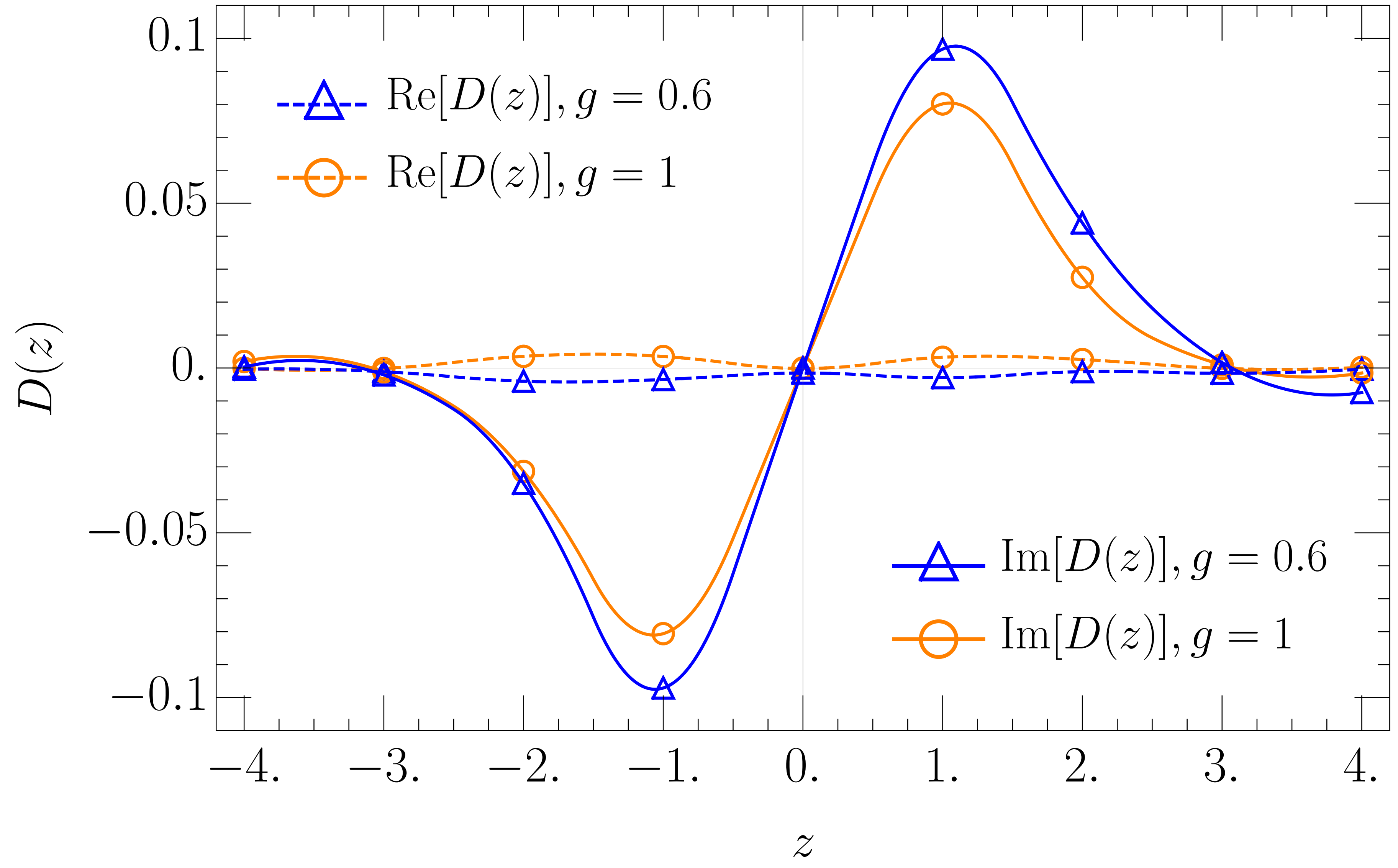


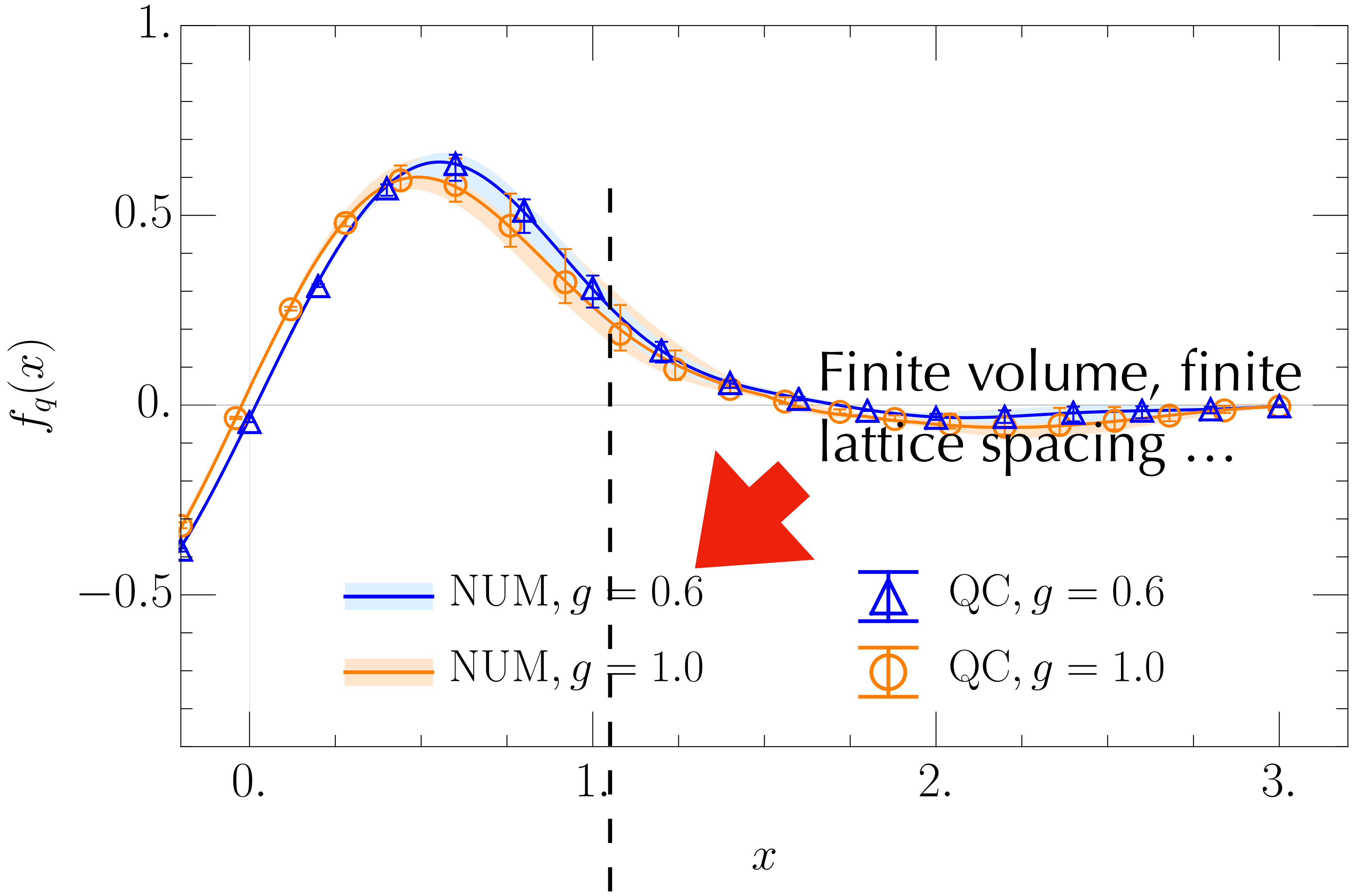
Fermion doubling!!

fields will be represented by a set of gates.

Li, et al, PRD letter 22

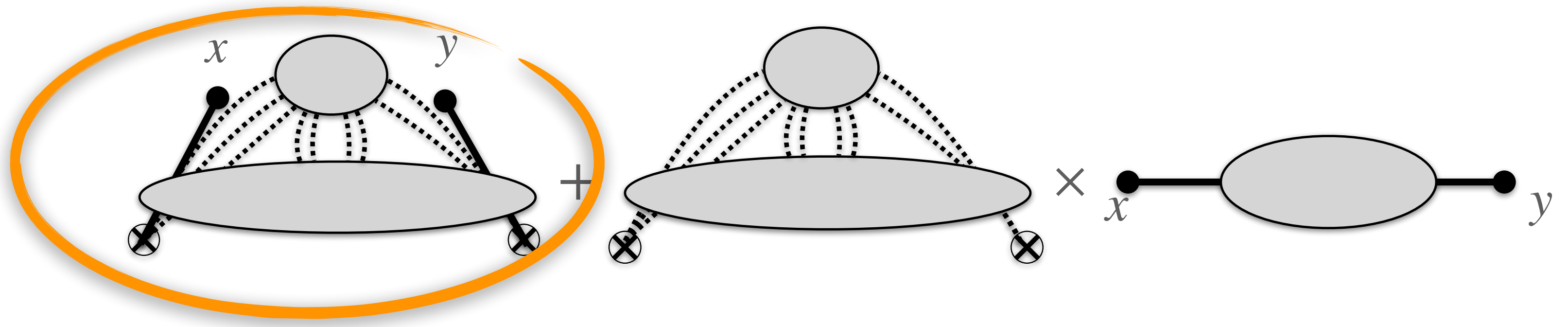
A toy model: Results





Finite volume, finite lattice spacing …

$${}_H\langle h\,|\,T[\psi_H(x)\,\psi_H(y)]\,|\,h\rangle_H =$$



$$f(x) \to \sum_{i,j}\sum_{z}\frac{1}{4\pi}e^{-ixM_h z}\langle h\,|\,e^{iHz}\phi^{\dagger}_{-2z+i}e^{-iHz}\phi_j\,|\,h\rangle$$

Li, et al, PRD letter 22

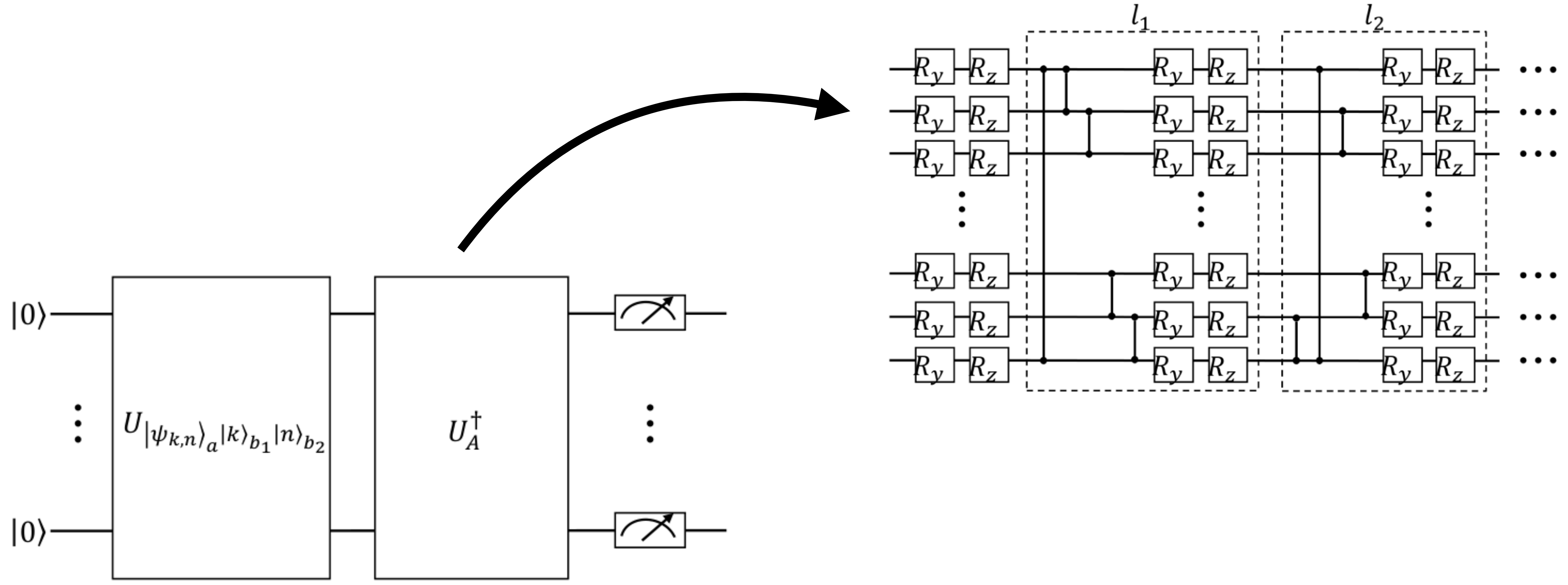
量子计算在模式识别中的作用

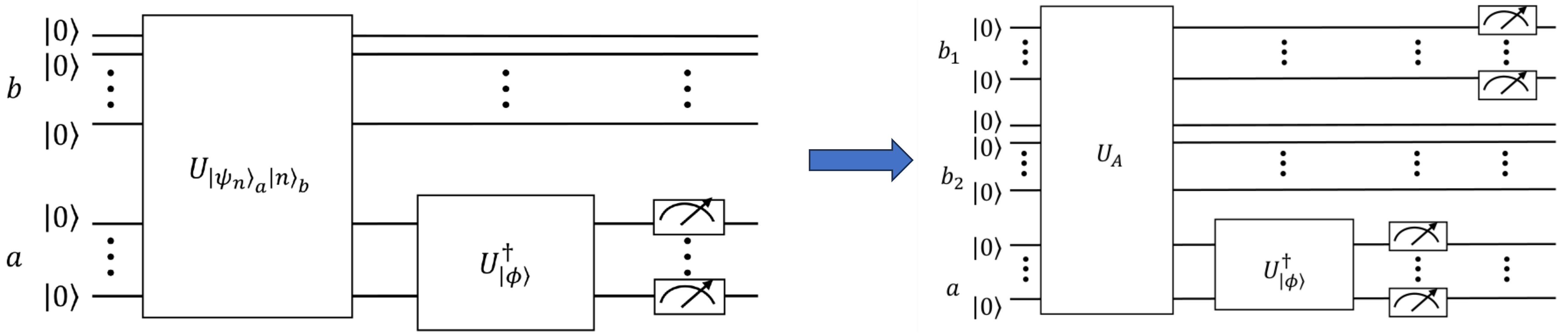
Using machine learning method suitable for quantum computing in the phenomenological study of new physics

Ji-Chong Yang
(yangjichong@lnnu.edu.cn)

In preparation, collaborator: Chong-Xing Yue

Variational quantum classifier





量子信息

粒子物理散射和衰变过程中的纠缠

Quantum Entanglement in High Energy Physics

Yu Shi (施郁)

2024.7.9.

28th LHC MiniWorkshop

Quantum Entanglement at High-energy Colliders

Kun Cheng 程焜
28th Mini-workshop on the frontier of LHC

粒子物理散射和衰变过程中的纠缠

Bell non-locality

∩

Quantum Steering

∩

Quantum Entanglement

∩

Quantum Discord

Fabbrichesi et al,
PRL 127, 161801(2021)

Afki et al,
PRL 130, 11801(2023)

Afki et al,
EPJP 136, 907(2021)

Afki et al,
PRL 130, 11801(2023)

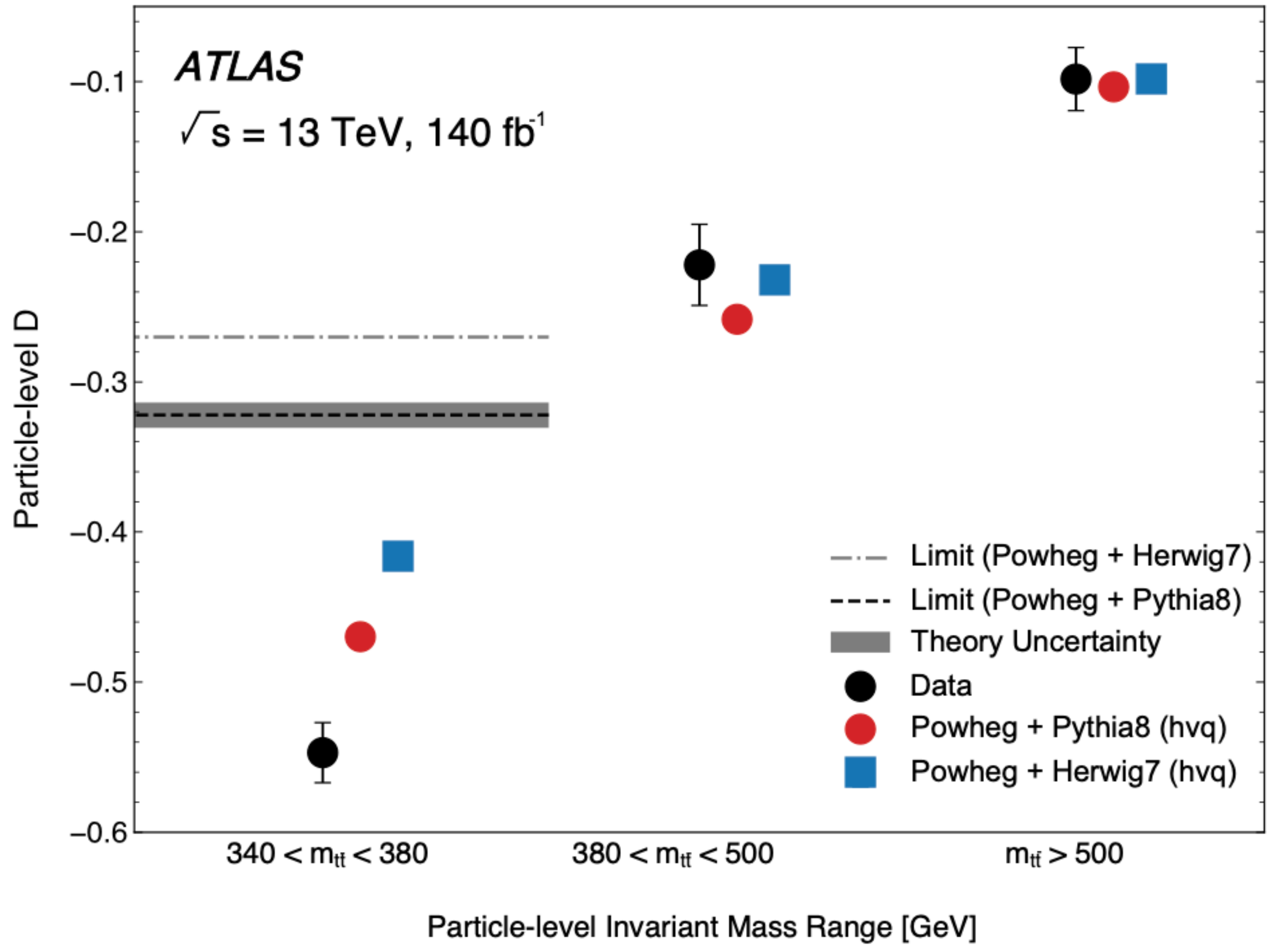


Fig: $D < -1/3$ indicates entanglement
[ATLAS, 2311.07288]

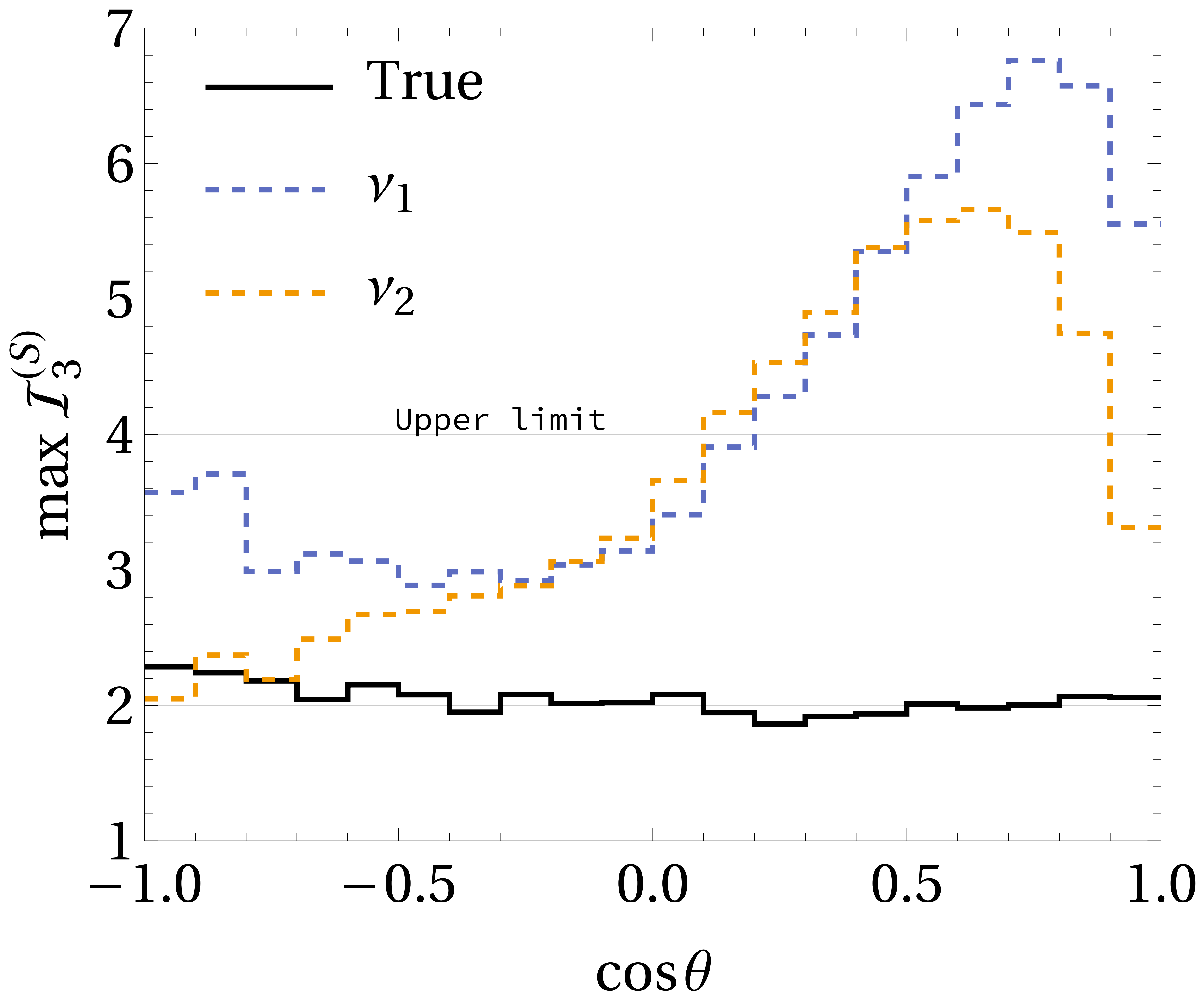
- **Test the principle of QM at the highest energy we can achieve**
- **The entanglement between fundamental particles: sensitive to NP?**
- **The entanglement of unstable particles: some new properties?**
- ***More than spin correlation***

贝尔不等式破坏的检验

希格斯工厂上的W玻色子对产生过程

- $W^{\pm}$的衰变：
  - 轻子衰变道：100%自旋关联可知自旋投影方向，但伴随中微子丢失能量；
  - 强子衰变道：没有丢失能量，但无法确定自旋投影方向（无法测量夸克电荷）
- 唯象学困难：若利用自旋关联确定$W^{\pm}$的自旋投影方向，需要$W^{\pm}$均轻子衰变，此时末态有两个中微子，无法重建$W^{\pm}$的四动量（重根）。

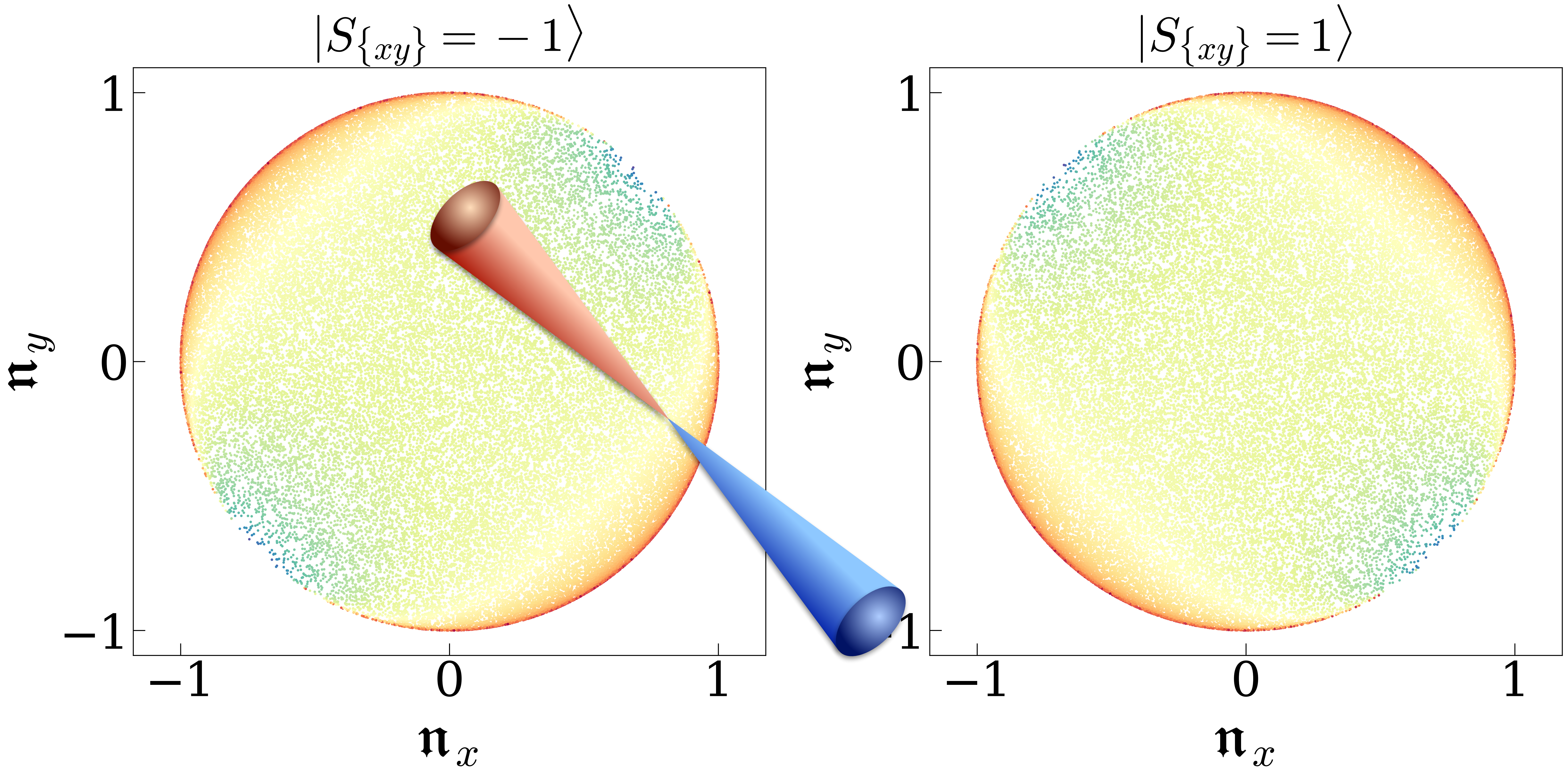
错误选取中微子动量将导致“超越”量子力学的结果



贝尔不等式破坏的检验

希格斯工厂上的W玻色子对产生过程

- 新贝尔观测量：W^+玻色子在其静止系中的自旋状态和W^-玻色子在其静止系中的线偏振状态。
- 好处：W^+玻色子轻子衰变，W^-玻色子强子衰变，末态可重建。



$$\vec{\epsilon}_{|S_{\{xy\}}=-1\rangle} = \frac{1}{\sqrt{2}}(1,1,0),$$
$$\vec{\epsilon}_{|S_{\{xy\}}=1\rangle} = \frac{1}{\sqrt{2}}(1,-1,0),$$
$$\vec{\epsilon}_{|S_{\{xy\}}=0\rangle} = (0,0,1),$$

详见张昊的报告

Emergent Symmetry from Entanglement Suppression

Ming-Lei Xiao

Sun Yat-Sen University

with M. Carena, I. Low, and C.E. Wagner [arXiv:2209.00198]

July 9, 2024 @ **28th Mini-workshop on the frontier of LHC, Tonghua**

It from (qu)bit

J. A. Wheeler: Every it—every particle, every field of force, even the space-time continuum itself— derives its function, its meaning, its very existence entirely—even if in some contexts indirectly— from the apparatus-elicited answers to yes-or-no questions, binary choices, bits.

it	from	(qu)bit
Symmetry		**Entanglement**
Black Hole		Complexity
(OTOC) Correlation		Quantum Chaos
Holography		Error-Correcting Code
⋮		⋮

Information-theoretic properties may provide insights on the origin of physical principles.

Two-Higgs-Doublet Model

Two flavors of $SU(2)_L$ doublet $\Phi_a = (\underbrace{\Phi^+_{a=1,2}}_{p_{\uparrow,\downarrow}}, \underbrace{\Phi^0_{a=1,2}}_{n_{\uparrow,\downarrow}})$.

$$\begin{aligned}\mathcal{V}(\Phi_1,\Phi_2) &= m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right] \\ &+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+ \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + h.c.\right] .\end{aligned}$$

Consider tree-level scattering $\mathcal{S}(\Phi_a^+,\Phi_b^0 \to \Phi_c^+,\Phi_d^0) \equiv 1 + iM_{ab,cd}\delta^{(4)}(p)$

Unbroken Phase: $$M_{ab,cd} = \begin{array}{cc} \begin{pmatrix} \lambda_1 & \lambda_6^* & \lambda_6^* & \lambda_5^* \\ \lambda_6 & \lambda_3 & \lambda_4 & \lambda_7^* \\ \lambda_6 & \lambda_4 & \lambda_3 & \lambda_7^* \\ \lambda_5 & \lambda_7 & \lambda_7 & \lambda_2 \end{pmatrix} & \begin{array}{c} 11 \\ 12 \\ 21 \\ 22 \end{array} \\ \begin{array}{cccc} 11 & 12 & 21 & 22 \end{array} & \end{array}$$

Carena, Low, Wagner and **Xiao** [2307.08112]

Entanglement suppression in the broken phase impose constraints even on the spectrum, leading to the maximal symmetry in 2HDM.

Enhanced Symmetry in the Unbroken Phase

The Bose symmetry for the s-wave amplitude imposes $\vec{\alpha} = \vec{\beta} = \vec{r}$

Enhanced Symmetry: $SO(2)$ **rotation along** $\vec{r}$

Redefine $\Phi'_a = U_a{}^b\Phi_b$ such that $U \in SU(2)$ brings $\vec{r} \parallel \hat{z}$.

$$\mathcal{V}(\Phi'_1,\Phi'_2) = \cdots + \frac{\lambda'_1}{2}(\Phi'^\dagger_1\Phi'_1)^2 + \frac{\lambda'_2}{2}(\Phi'^\dagger_2\Phi'_2)^2 + \lambda_3(\Phi'^\dagger_1\Phi'_1)(\Phi'^\dagger_2\Phi'_2)$$

- $\Phi'_{1,2}$ may have independent phase symmetries $e^{i\phi_0}$ and $e^{i\phi_z\sigma^z}$.
- In the original basis, $U^{-1}e^{i\phi_z\sigma^z}U$ is the new $SO(2)$ rotation around $\vec{r}$.

Emergent Maximal Symmetry

A last chance: if the two charged scalars H_1^+ and H_2^+ are degenerate

$$P_1^s = P_2^s \ , \ P_1^u = P_2^u \quad \Rightarrow \quad m_{H^+}^2 = 0, \ Y_2 = -\frac{Z_3}{2}v^2 \ ,$$

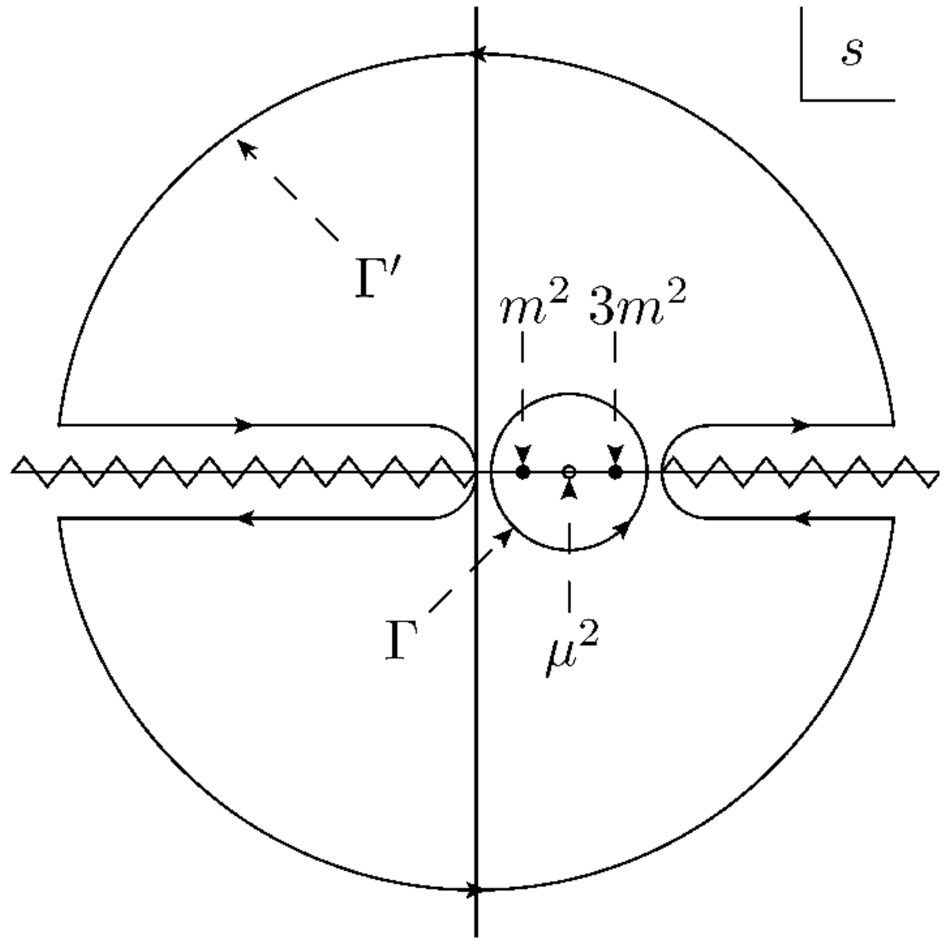
we only need the combinations $M_1^s + M_2^s$ and $M_1^u + M_2^u$ to satisfy the entanglement suppression condition!

$$\begin{pmatrix} Z_1^2 + Z_6^2 & Z_1Z_6 & (Z_1+Z_3)Z_6 & Z_6^2 \\ Z_1Z_6 & Z_6^2 & Z_6^2 & 0 \\ (Z_1+Z_3)Z_6 & Z_6^2 & Z_6^2 + Z_3^2 & Z_3Z_6 \\ Z_6^2 & 0 & Z_3Z_6 & Z_6^2 \end{pmatrix} \Rightarrow Z_1 = Z_3 \text{ and } Z_6 = 0$$

The resulting potential: $\mathcal{V} = \frac{Z_1}{2}\left[H_1^\dagger H_1 + H_2^\dagger H_2 - \frac{v^2}{2}\right]^2$ has $SO(8)$ symmetry!

Positivity from elastic scattering

$$A_{2\to2}(s,t=0) = c_0 + c_2 s^2 + c_4 s^4 + \cdots$$



[Cheung, Remmen,1601.04068]

- ✦ Analyticity: $$f = \frac{1}{2\pi i}\oint_\Gamma \mathrm{d}s\,\frac{A(s,0)}{(s-\mu^2)^3}$$
- ✦ Unitarity + Locality: $$A(s,0) < \mathcal{O}(s\ln^2 s)$$

$$f = \frac{1}{2\pi i}\oint_\Gamma \mathrm{d}s\,\frac{A(s,0)}{(s-\mu^2)^3} = \frac{1}{2\pi i}\left(\int_{-\infty}^{0} + \int_{4m^2}^{\infty}\right)\mathrm{d}s\,\frac{\mathrm{Disc}A(s,0)}{(s-\mu^2)^3}$$

IR

Calculable in EFT

UV

Disc > 0 by optical theorem + (s-u) crossing

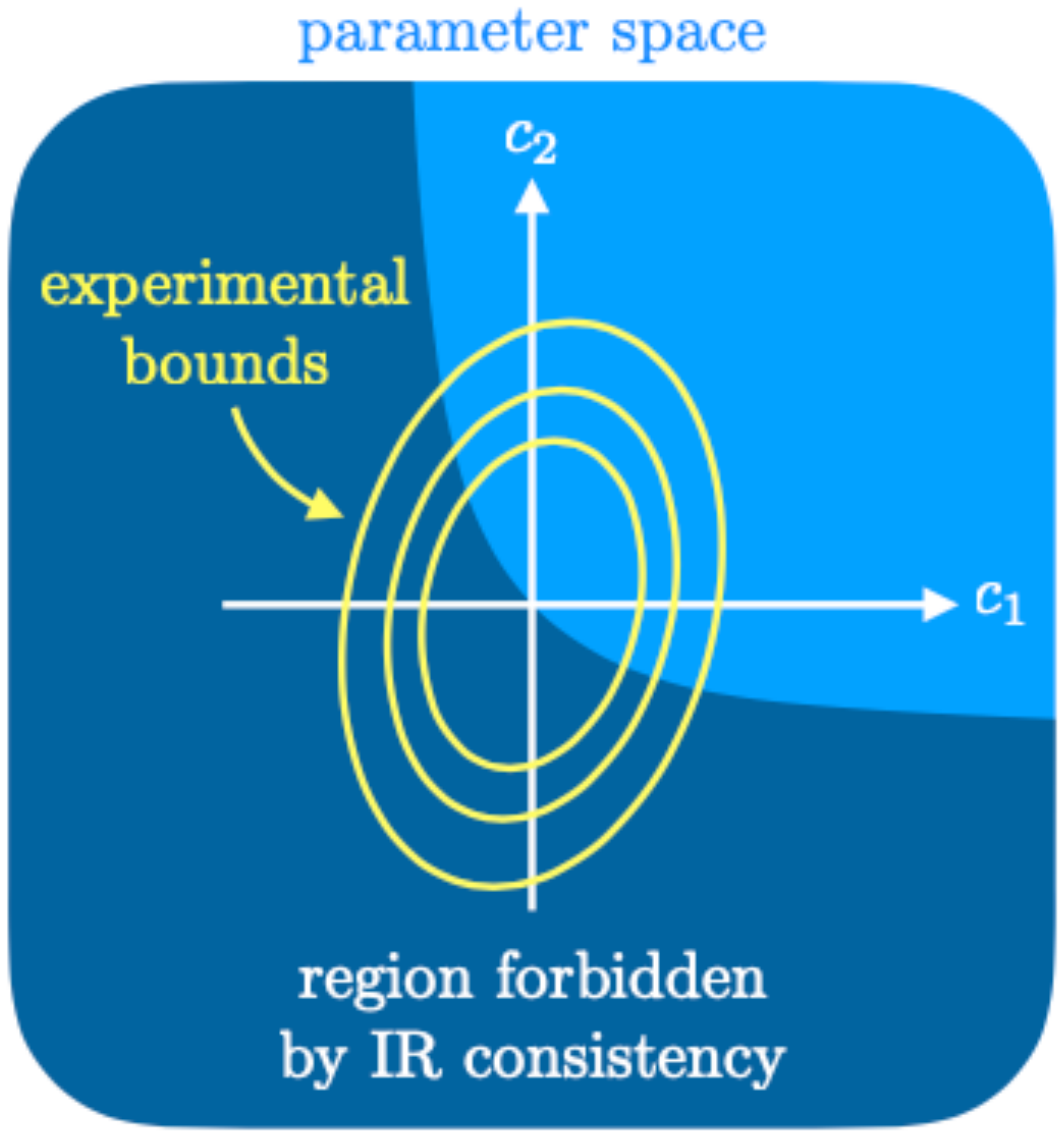
$$A_{2\to2}(s,t=0) = c_0 + \boxed{c_2 s^2} + c_4 s^4 + \cdots$$

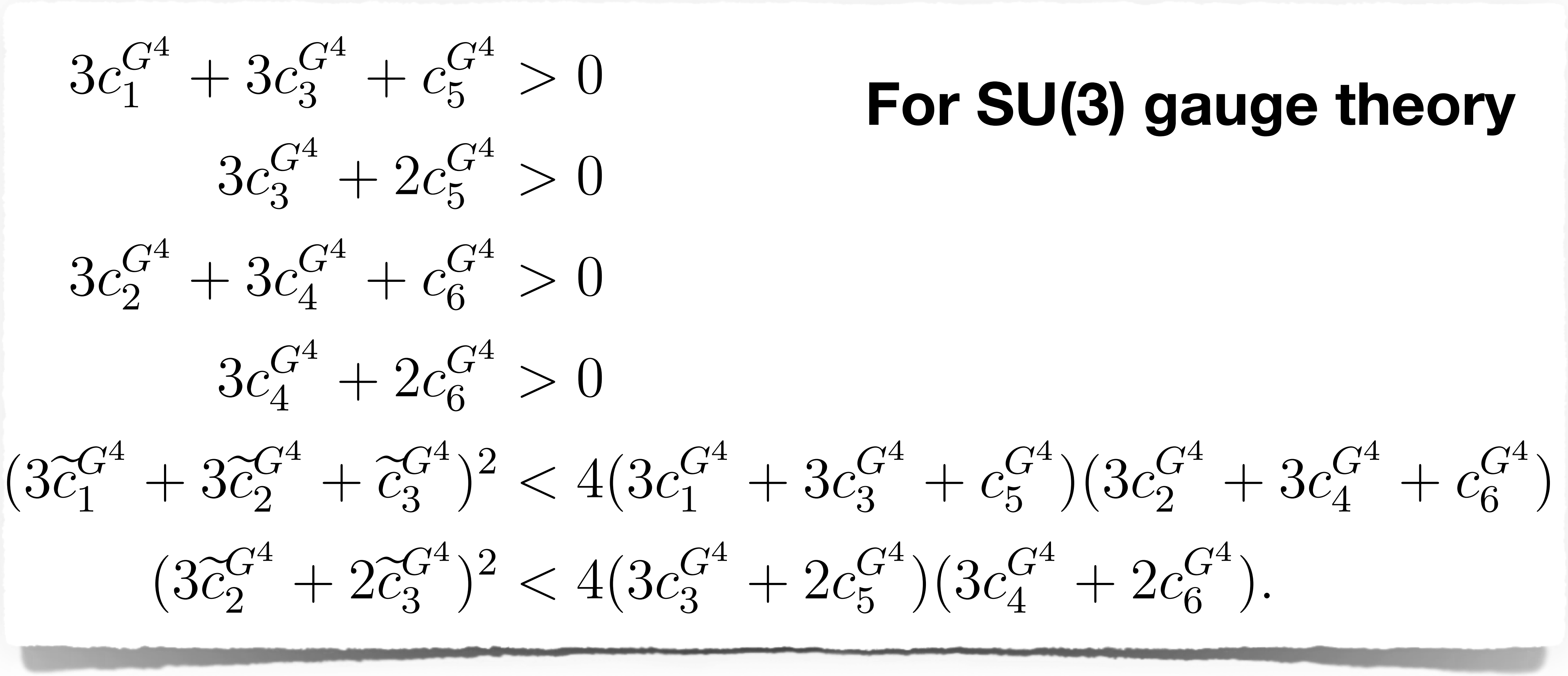
Positivity bounds in SM EFT

Dim-8 operators in $SU(N)$ gauge theory

$\mathcal{O}_1^{F^4}$	$(F^aF^a)(F^bF^b)$
$\mathcal{O}_2^{F^4}$	$(F^a\widetilde{F}^a)(F^b\widetilde{F}^b)$
$\mathcal{O}_3^{F^4}$	$(F^aF^b)(F^aF^b)$
$\mathcal{O}_4^{F^4}$	$(F^a\widetilde{F}^b)(F^a\widetilde{F}^b)$
$\mathcal{O}_5^{F^4}$	$d^{abe}d^{cde}(F^aF^b)(F^cF^d)$
$\mathcal{O}_6^{F^4}$	$d^{abe}d^{cde}(F^a\widetilde{F}^b)(F^c\widetilde{F}^d)$
$\mathcal{O}_7^{F^4}$	$d^{ace}d^{bde}(F^aF^b)(F^cF^d)$
$\mathcal{O}_8^{F^4}$	$d^{ace}d^{bde}(F^a\widetilde{F}^b)(F^c\widetilde{F}^d)$
$\widetilde{\mathcal{O}}_1^{F^4}$	$(F^aF^a)(F^b\widetilde{F}^b)$
$\widetilde{\mathcal{O}}_2^{F^4}$	$(F^aF^b)(F^a\widetilde{F}^b)$
$\widetilde{\mathcal{O}}_3^{F^4}$	$d^{abe}d^{cde}(F^aF^b)(F^c\widetilde{F}^d)$
$\widetilde{\mathcal{O}}_4^{F^4}$	$d^{ace}d^{bde}(F^aF^b)(F^c\widetilde{F}^d)$

Remmen, Rodd, 1908.09845





$$3c_1^{G^4} + 3c_3^{G^4} + c_5^{G^4} > 0$$
$$3c_3^{G^4} + 2c_5^{G^4} > 0$$
$$3c_2^{G^4} + 3c_4^{G^4} + c_6^{G^4} > 0$$
$$3c_4^{G^4} + 2c_6^{G^4} > 0$$
$$(3\tilde{c}_1^{G^4} + 3\tilde{c}_2^{G^4} + \tilde{c}_3^{G^4})^2 < 4(3c_1^{G^4} + 3c_3^{G^4} + c_5^{G^4})(3c_2^{G^4} + 3c_4^{G^4} + c_6^{G^4})$$
$$(3\tilde{c}_2^{G^4} + 2\tilde{c}_3^{G^4})^2 < 4(3c_3^{G^4} + 2c_5^{G^4})(3c_4^{G^4} + 2c_6^{G^4}).$$

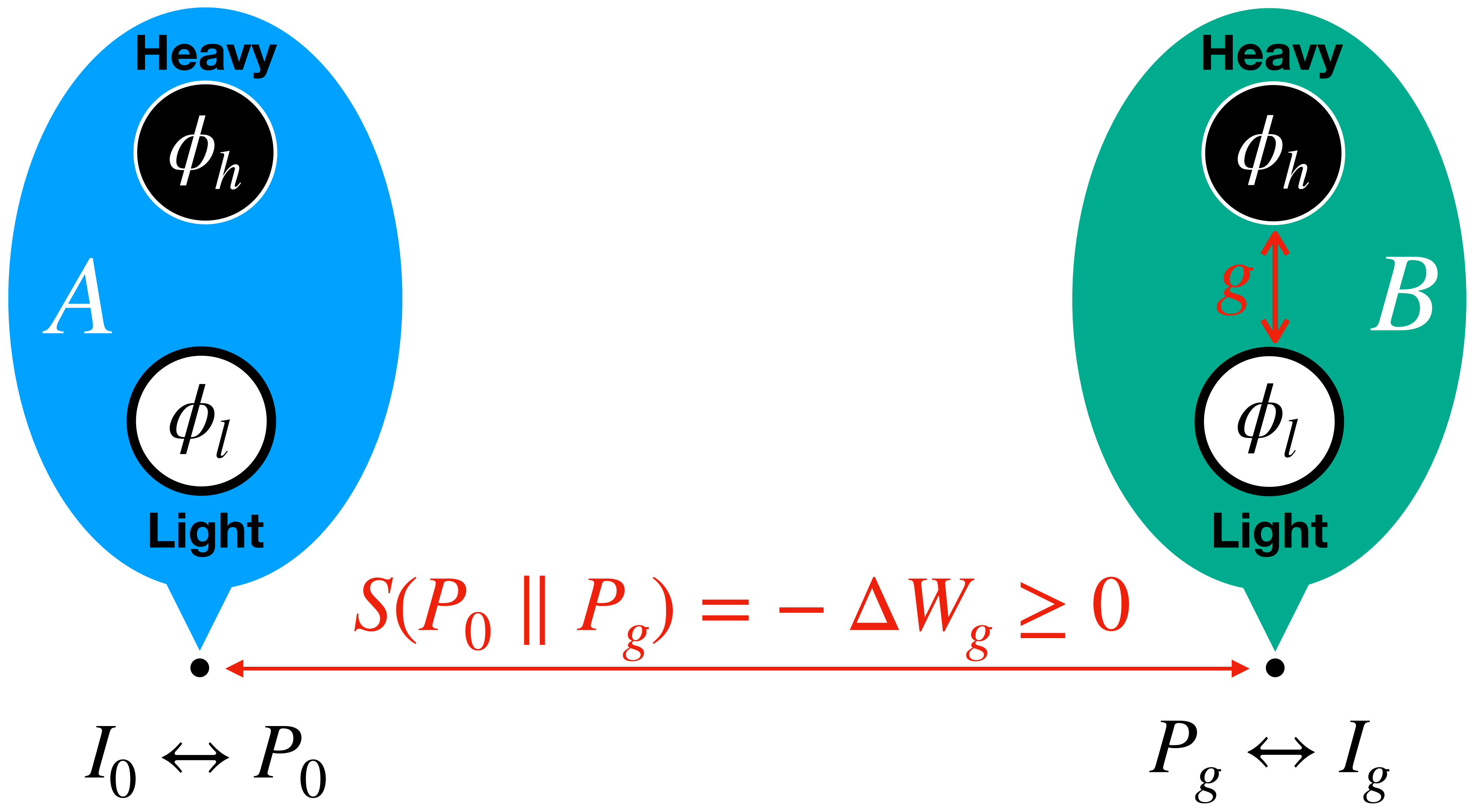
For SU(3) gauge theory

Relative entropy

We defined a distance between two different theories in the approach of information theory

QHC, Ueda, PhysRevD.108.025011

QHC, Kan, Ueda, JHEP07(2023)111)



$S(P_0 \parallel P_g) = -\Delta W_g \geq 0$

$I_0 \leftrightarrow P_0$

$P_g \leftrightarrow I_g$

I_0 **without interaction b/w heavy and light**

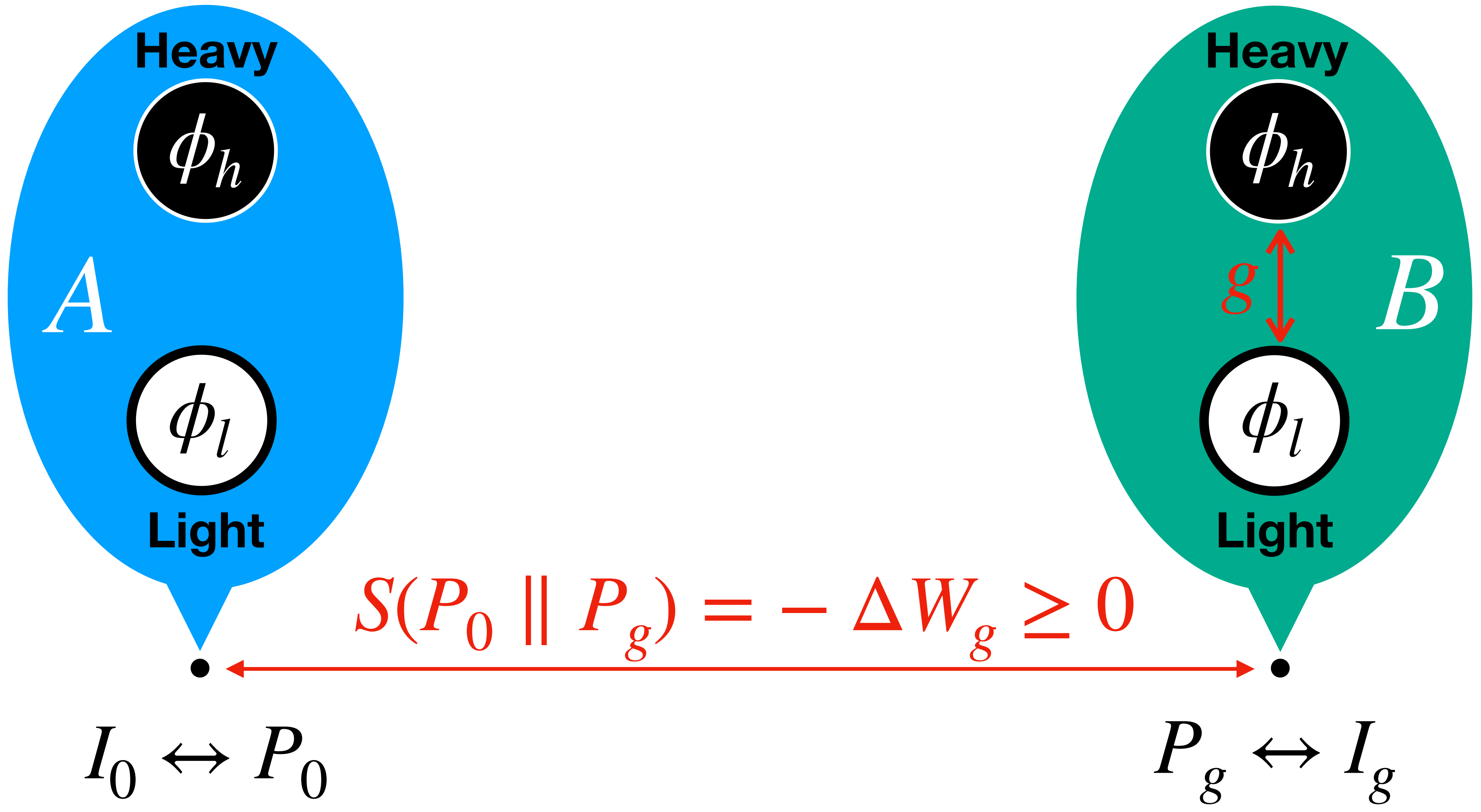
$I_g = I_0 + g \cdot I_I$ **with the interaction**

Distance defined by relative entropy

$$S\left(P_0 || P_g\right) = \int d\left[\phi_h\right]\left(P_0 \ln P_0 - P_0 \ln P_g\right) \geq 0$$

$$P_0 = e^{-I_0}/Z_0 \qquad P_g = e^{-I_g}/Z_g$$

Non-negativity of relative entropy



U(1) and SU(2) bounds are the same as positivity bounds from unitarity and causality

- $U(1)_Y$:

$$c_1^{B^4} \geq 0, \quad c_2^{B^4} \geq 0, \quad 4c_1^{B^4}c_2^{B^4} \geq (\tilde{c}_1^{B^4})^2,$$

- $SU(2)_L$:

$$c_1^{W^4} + c_3^{W^4} \geq 0, \quad c_2^{W^4} + c_4^{W^4} \geq 0, \quad 4(c_1^{W^4} + c_3^{W^4})(c_2^{W^4} + c_4^{W^4}) \geq (\tilde{c}_1^{W^4} + \tilde{c}_2^{W^4})^2,$$

We show that the positive distance yields

- **Positivity bounds on SMEFT dim-8 gauge bosonic operators**
- **WGC-like behavior in extremal relation holds in wide class of black holes**
- **Any UV theory violating second law of thermodynamics yields pathological EFTs**

SU(3) bounds are stronger than positivity bounds from unitarity and causality

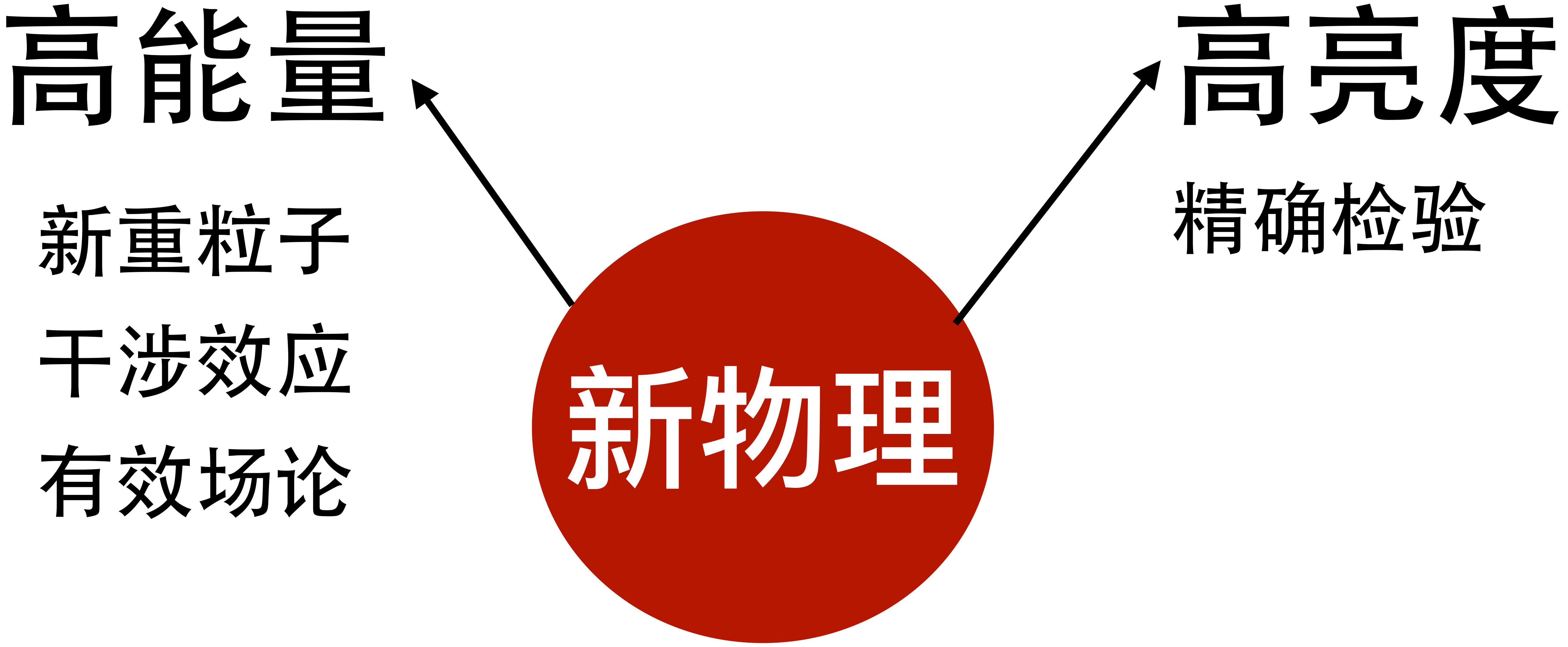
- $SU(3)_C$:

$$2c_1^{G^4} + c_3^{G^4} \geq 0, \quad 3c_2^{G^4} + 2c_5^{G^4} \geq 0,$$

$$4(3c_1^{G^4} + 3c_3^{G^4} + c_5^{G^4})(3c_2^{G^4} + 3c_4^{G^4} + c_6^{G^4}) \geq (3\tilde{c}_1^{G^4} + 3\tilde{c}_2^{G^4} + \tilde{c}_3^{G^4})^2$$

$$4(3c_3^{G^4} + 2c_5^{G^4})(3c_4^{G^4} + 2c_6^{G^4}) \geq (3\tilde{c}_2^{G^4} + 2\tilde{c}_3^{G^4})^2$$

结论



高能量

新重粒子
干涉效应
有效场论

新物理

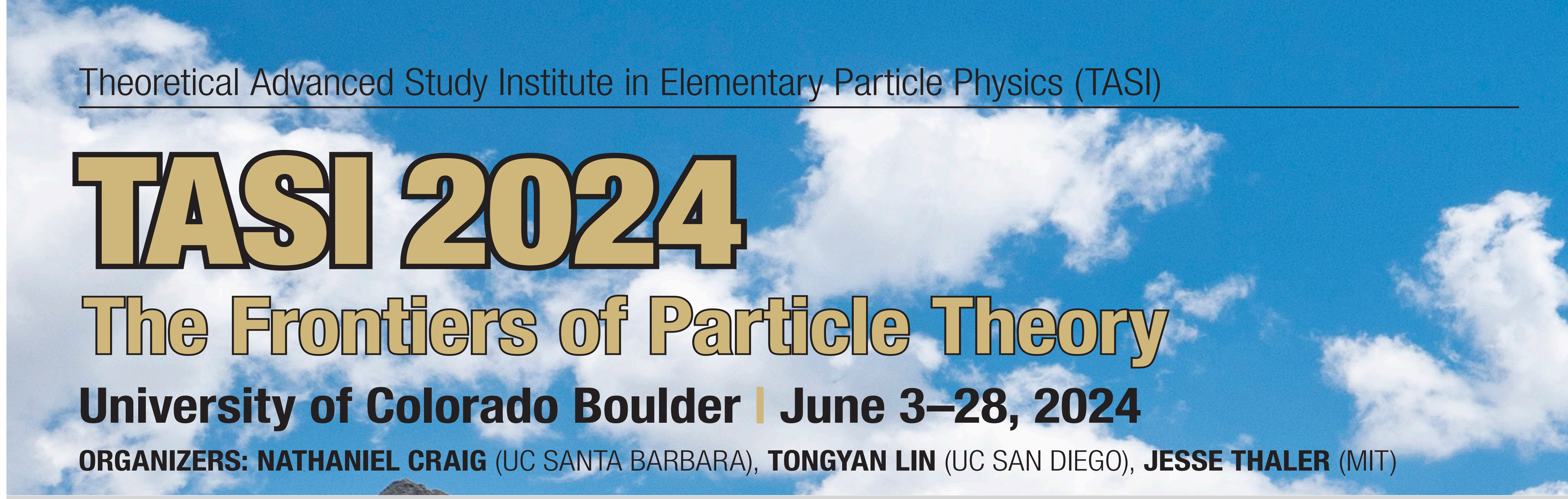
高亮度

精确检验

新技术和新视角

人工智能和高能物理的结合
量子计算和场论的结合
量子信息和高能物理的结合

谢谢！



Theoretical Advanced Study Institute in Elementary Particle Physics (TASI)

TASI 2024

The Frontiers of Particle Theory

University of Colorado Boulder | June 3–28, 2024

ORGANIZERS: NATHANIEL CRAIG (UC SANTA BARBARA), **TONGYAN LIN** (UC SAN DIEGO), **JESSE THALER** (MIT)

V. Cirigliano: The Subatomic Realm: Standard Model and Beyond
Z. Davoudi: **Quantum Computing for Quantum Field Theories**
V. Domcke: Discovery Opportunities with Gravitational
J. Halverson: **Physics4ML**
S. Hoeche: From Amplitudes to Cross Sections
L. Knox: The Invisible Universe: LambdaCDM and Beyond
S. Li: Neutrino Physics in the Era of Data
M.McCullough: In Pursuit of New Paradigms
P. Meade : Accelerating into the Future
I. Moult: Conformal Field Theory for Particle Physics
B. Nachman: **Machine Learning at Colliders**
J. Parra-Martinez: Scattering Amplitudes and Effective Field Theory
K. Schutz: Astrophysical Probes of Fundamental Physics
P. Shanahan: Lattice Gauge Theory: Applications and Advances
K. V. Tilburg: Dark Sectors and Small Scale Experiments
C. Weniger: **Statistics and Machine Learning**
T.-T. Yu: Dark Matter: Evidence and Opportunities