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C²QA

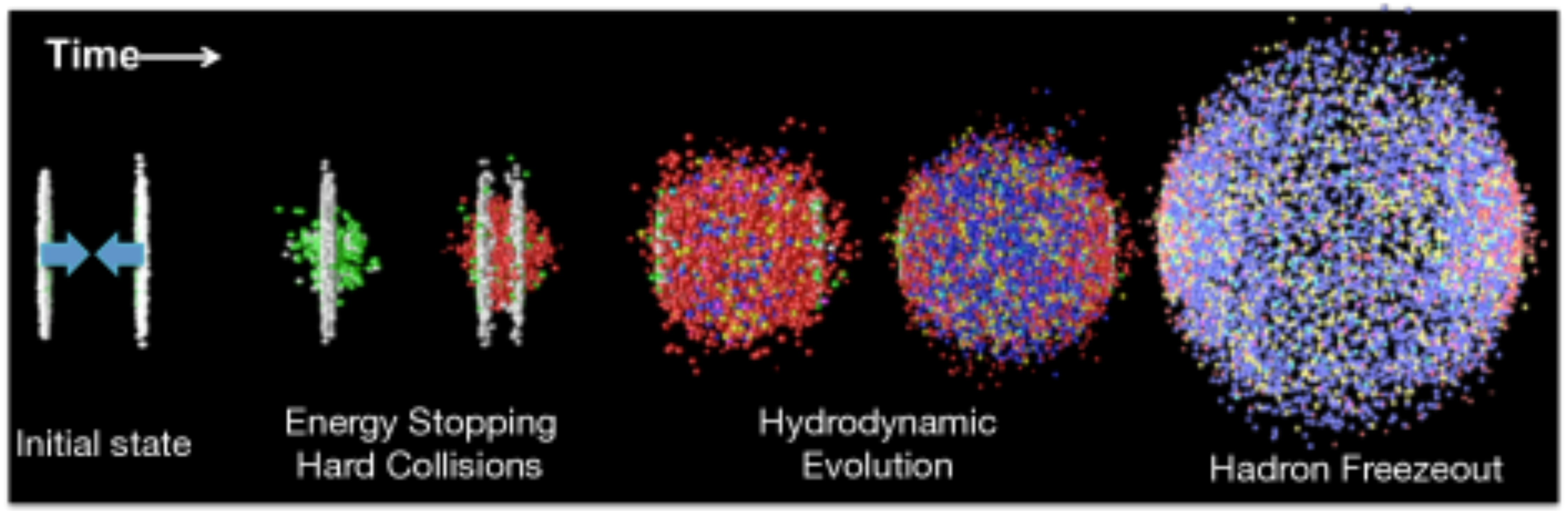
HEP in the new quantum era

7th September 2022, QNP2022

João Barata, BNL

Based on: 2208.06750, with M. Li, X. Du, W. Qian, C. Salgado

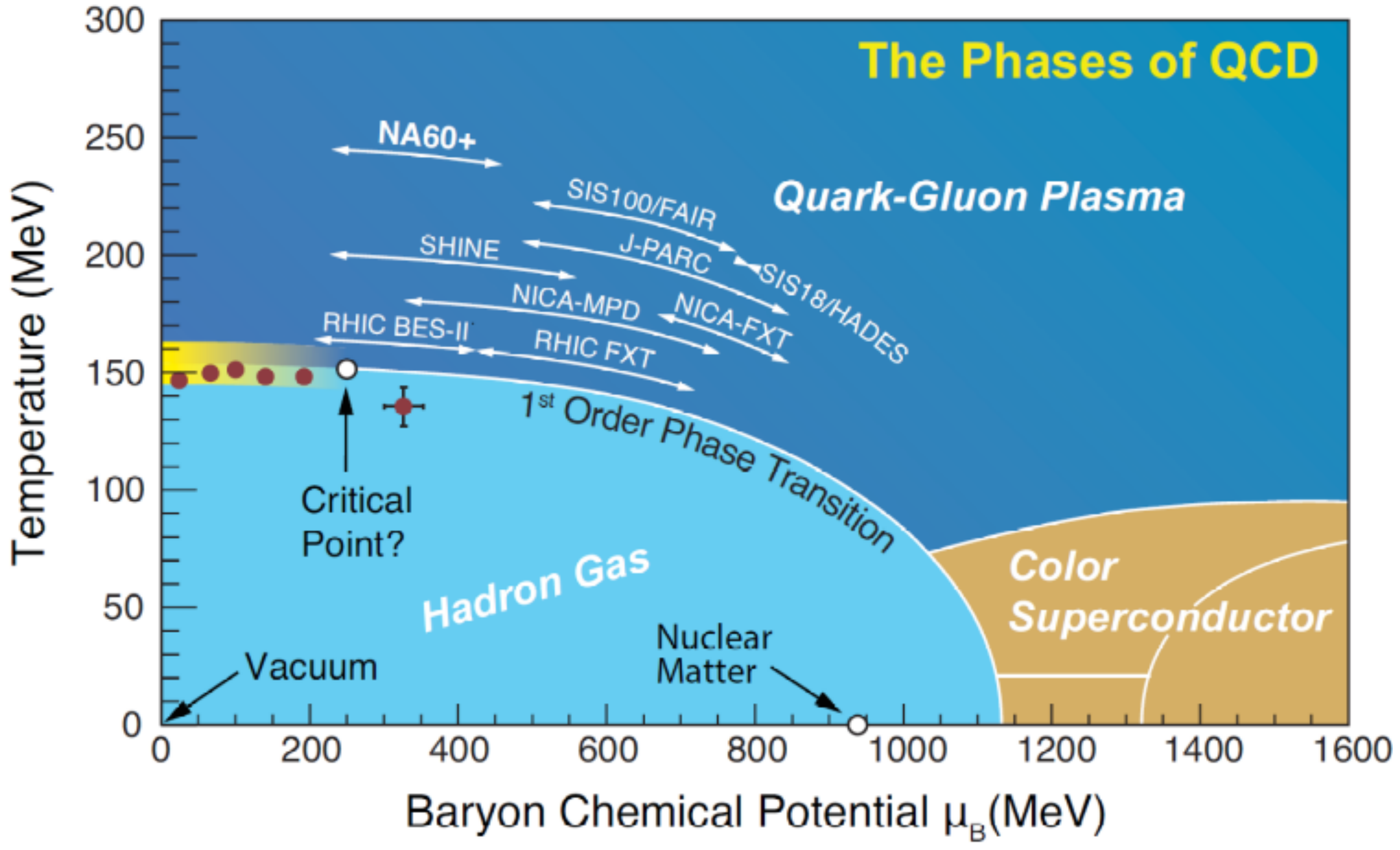
Why Quantum computing?



Simulating Physics with Computers

Richard P. Feynman

"Nature isn't classical
... and if you want to make a simulation of Nature,
you'd better make it quantum mechanical,
and by golly it's a wonderful problem,
because it doesn't look so easy."



What is Quantum computing?

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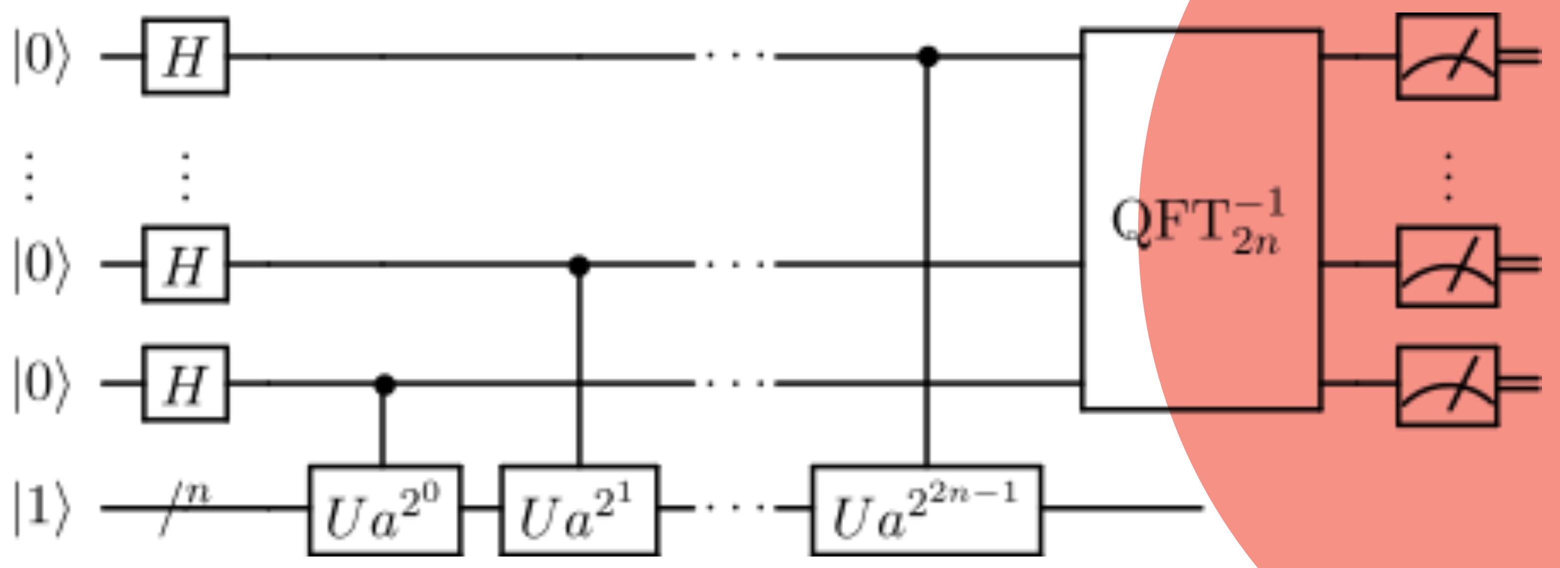
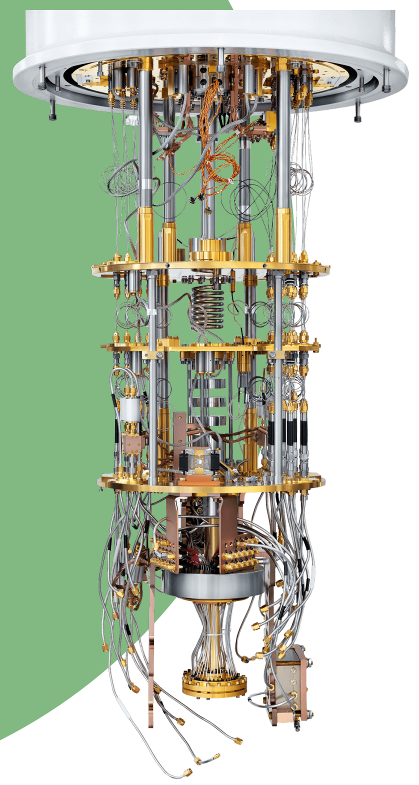
Quantum algorithms



Quantum devices



D-Wave The Quantum Computing Company™

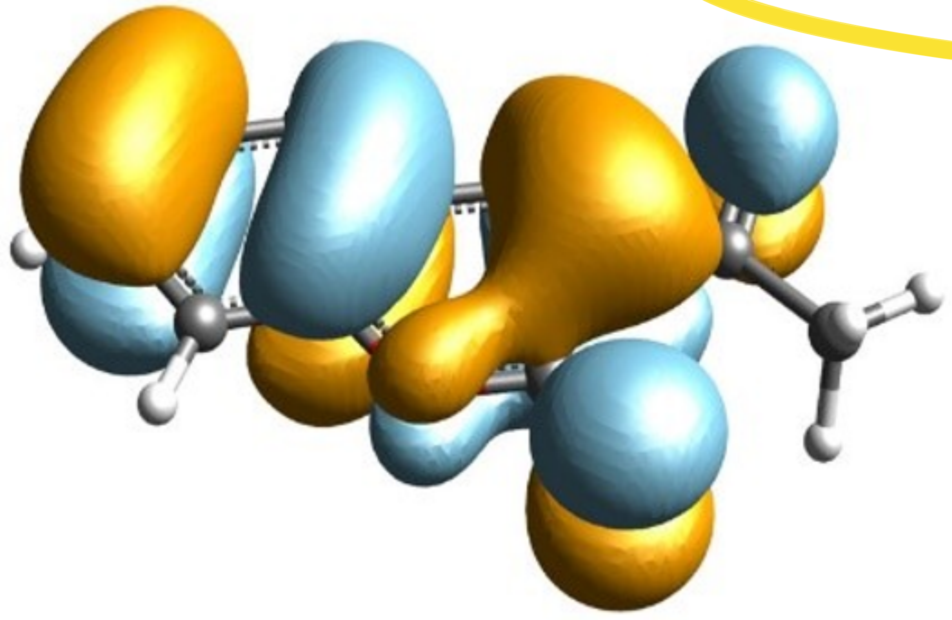
Microsoft Quantum Computer

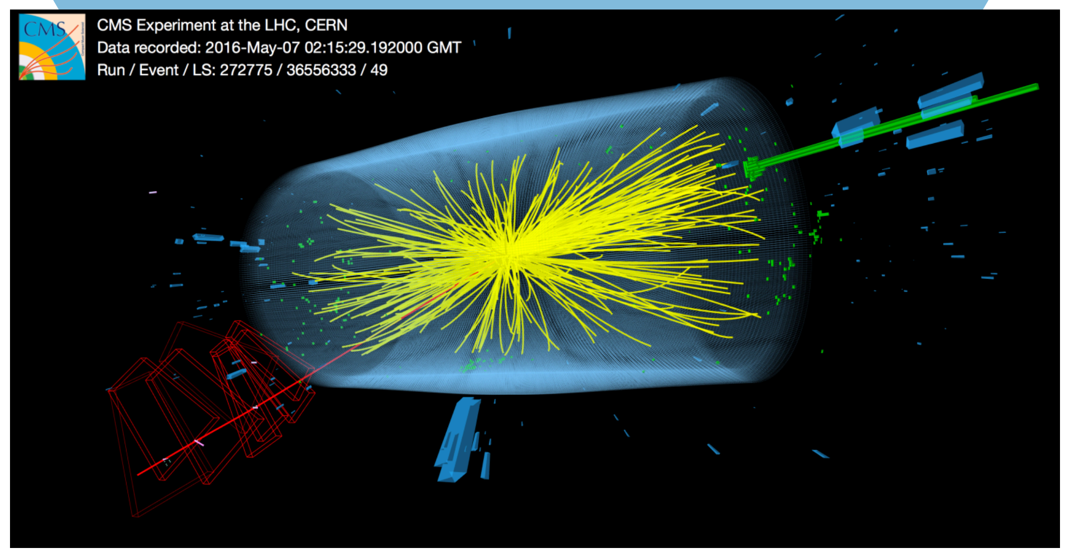
rigetti

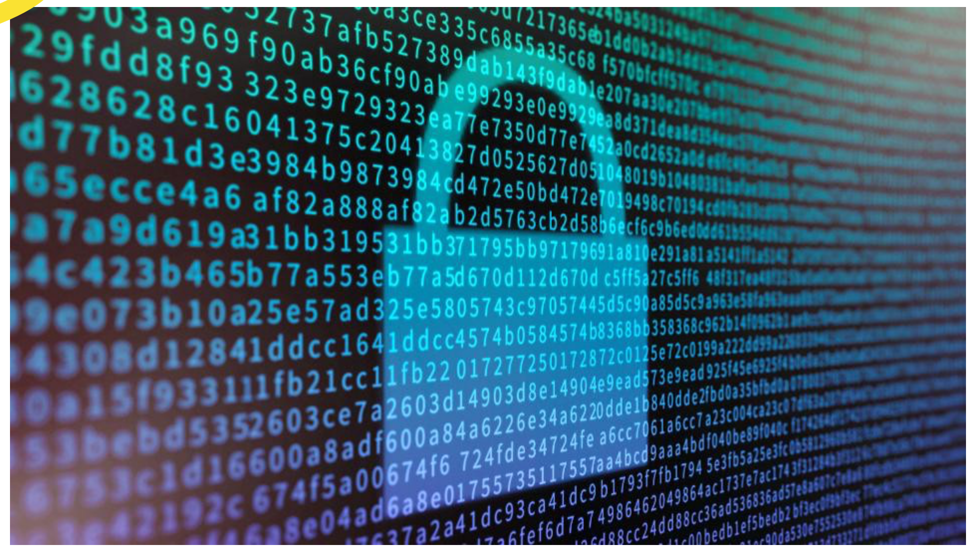
IBM Q

IONQ

Quantum problems





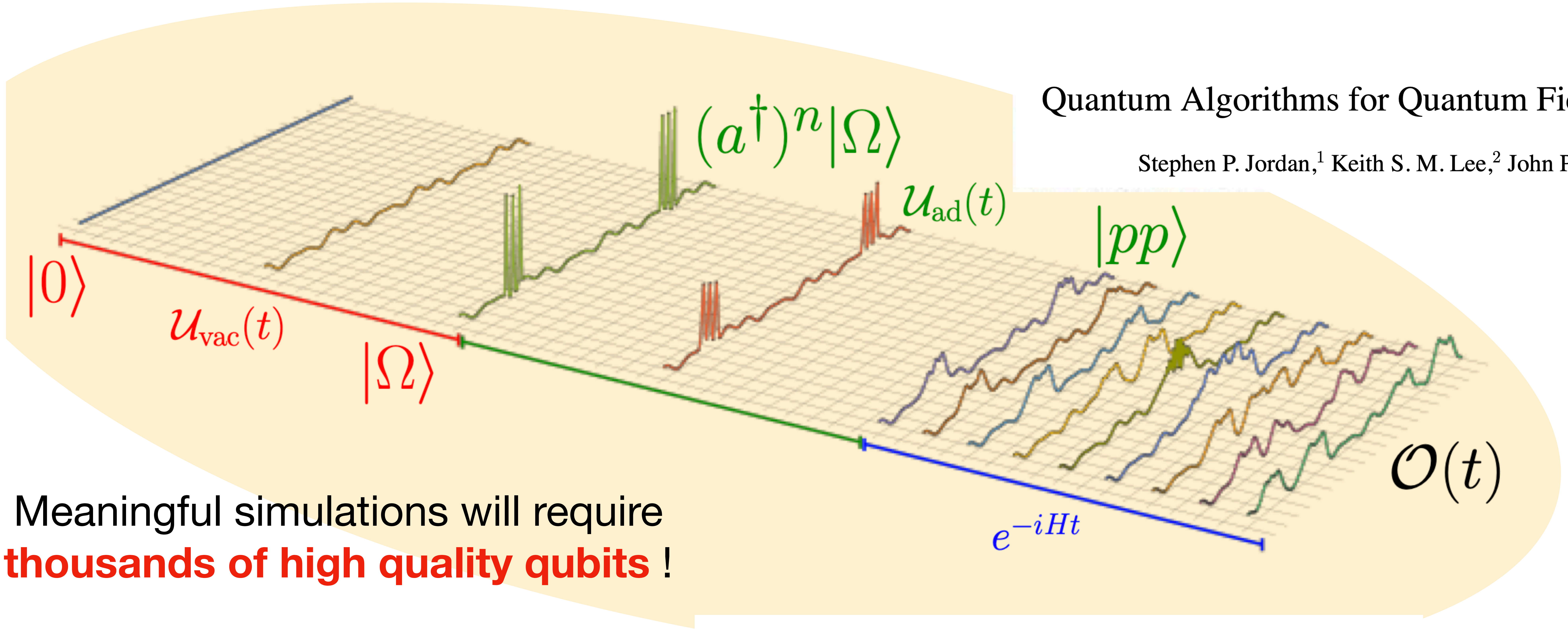


Some recent works on quantum computing applications for HEP

Disclaimer: I will focus on work more relevant for jet physics in vacuum and in heavy ions

Quantum computing for HEP: ab initio QFT simulation

Quantum computers can, in principle, **simulate scattering** events ab initio



Quantum Algorithms for Quantum Field Theories

Stephen P. Jordan,[1] Keith S. M. Lee,[2] John Preskill[3]

Meaningful simulations will require **thousands of high quality qubits** !

Figure by H. Lamm

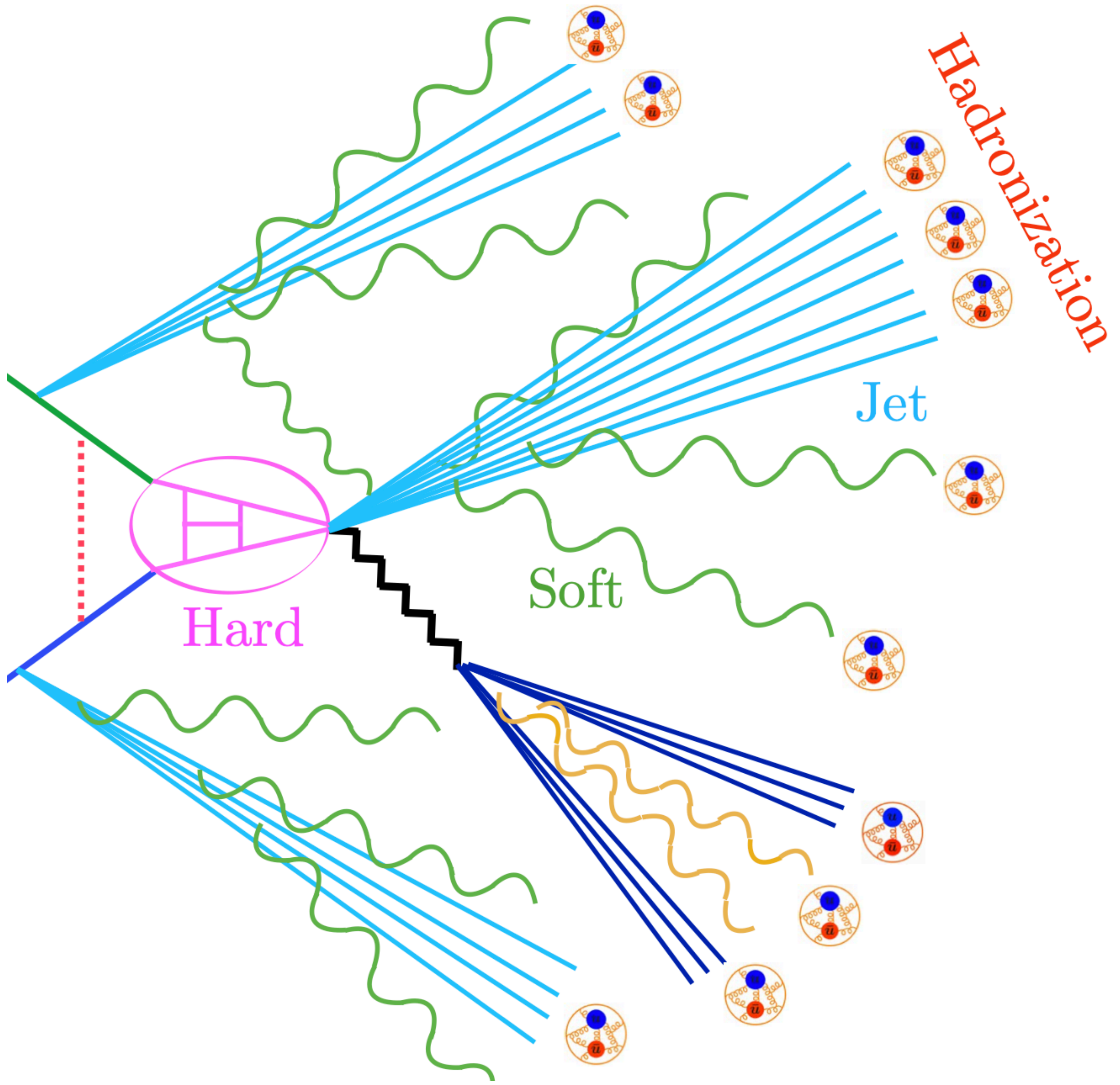
Can we use QCs to tackle smaller problems?

Quantum computing for HEP: EFT approach

Full simulation is expensive, but the problem can be decomposed into several pieces

e.g. EFTs allow to explore the **low energy sector** in a first principle manner (no modeling)

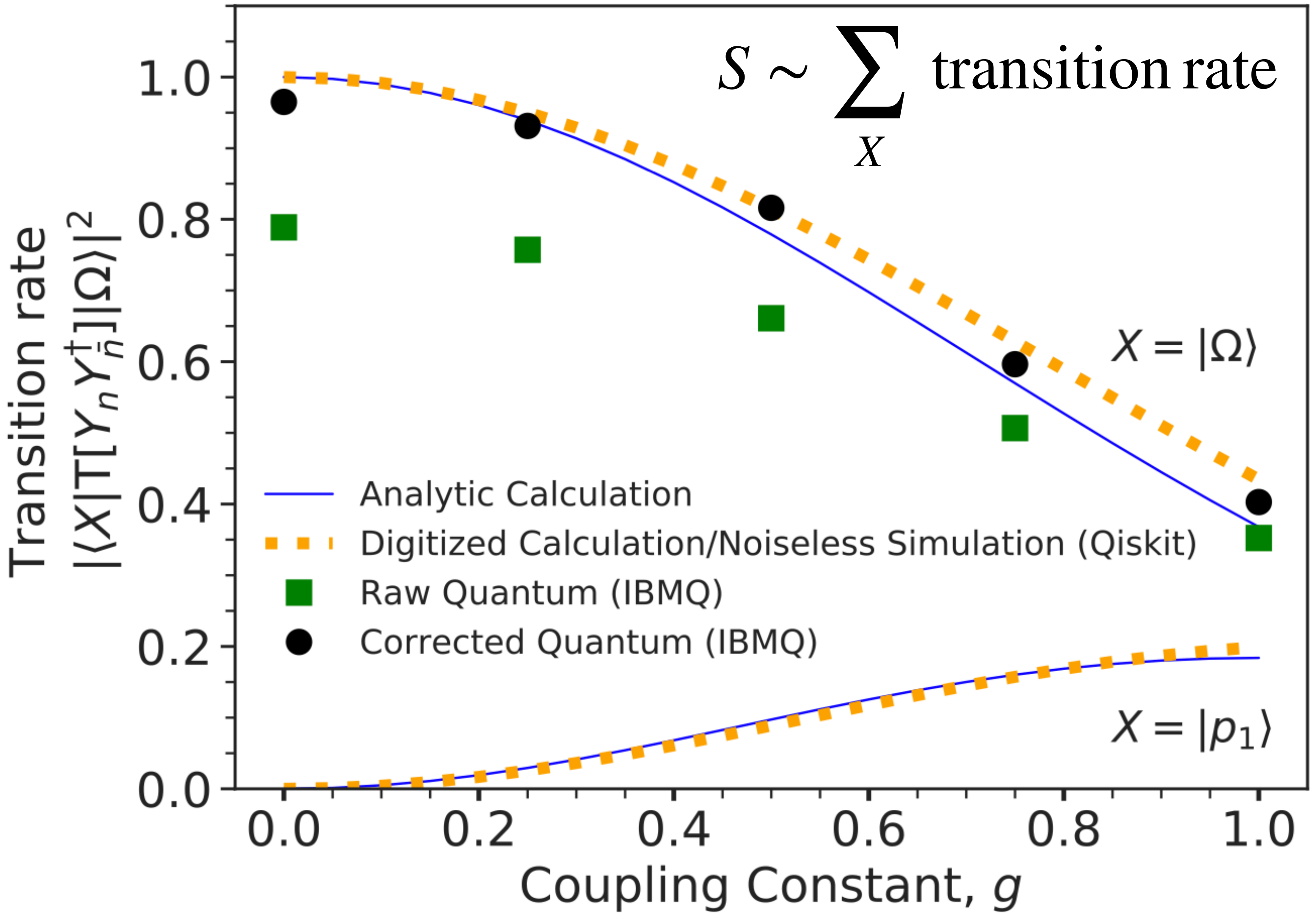
$$\sigma = H \otimes J_1 \otimes \cdots \otimes J_n \otimes S$$



Simulating collider physics on quantum computers using effective field theories

Christian W. Bauer* and Benjamin Nachman†
Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Marat Freytsis‡
NHETC, Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854, USA and Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA



Quantum computing for HEP: fragmentation

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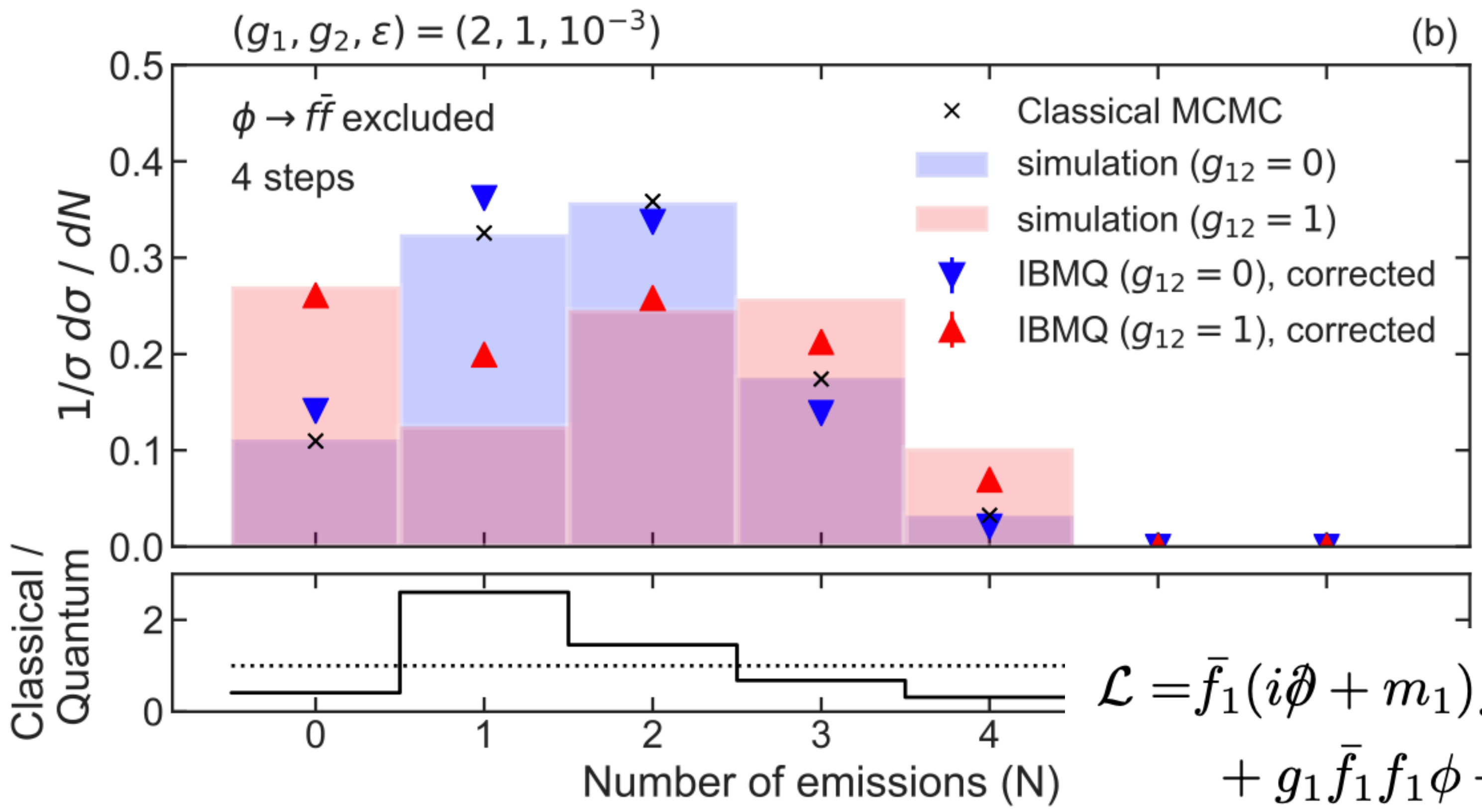
Still for the low energy sector, away from $\Lambda_{\rm QCD}$, **parton showers can also get quantum improvement**



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

A quantum algorithm for high energy physics simulations

Benjamin Nachman,[*] Davide Provasoli,[†] and Christian W. Bauer[‡]
Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Wibe A. de Jong[§]
Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

(Dated: December 30, 2019)

$$\mathcal{H} = \mathcal{H}_C \otimes \mathcal{H}_P$$

$$U = S \cdot (C \otimes I)$$

$$U_c = \begin{pmatrix} \sqrt{1 - P_{jk}} & \sqrt{P_{jk}} \\ \sqrt{P_{jk}} & \sqrt{1 - P_{jk}} \end{pmatrix}$$

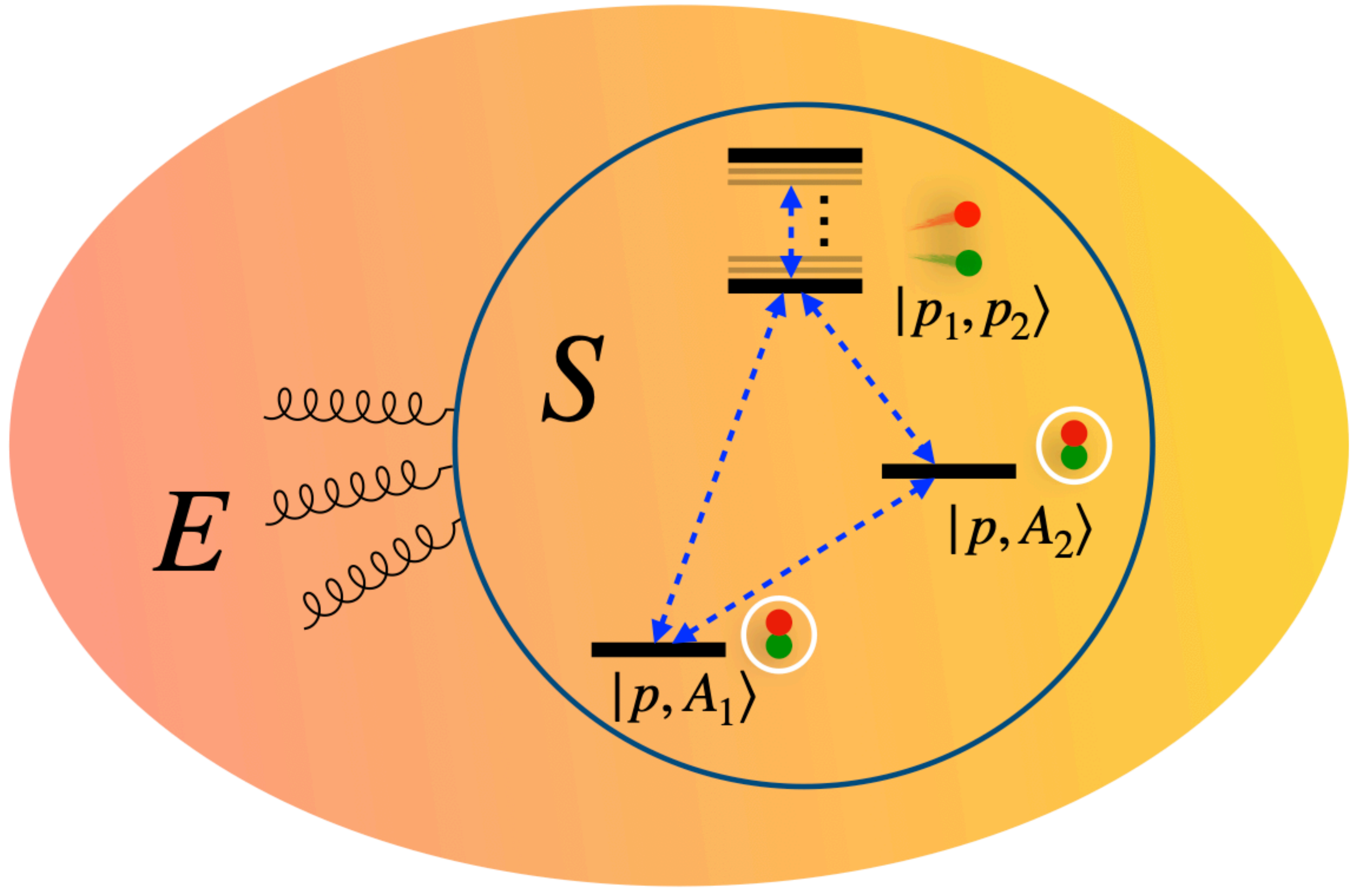
A quantum walk approach to simulating parton showers

Khadeejah Bepari,[a] Sarah Malik,[b] Michael Spannowsky[a] and Simon Williams[c]

All parton shower histories are in a superposition state

Quantum computing for HEP: evolution in media

For heavy ions physics, QC can be used to tackle **real time evolution in the medium …**



Quantum simulation of open quantum systems in heavy-ion collisions

Wibe A. de Jong,[1,*] Mekena Metcalf,[1,†] James Mulligan,[2,3,‡]
Mateusz Płoskoń,[2,§] Felix Ringer,[2,¶] and Xiaojun Yao[4,**]

[1] *Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[2] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[3] *Physics Department, University of California, Berkeley, CA 94720, USA*
[4] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

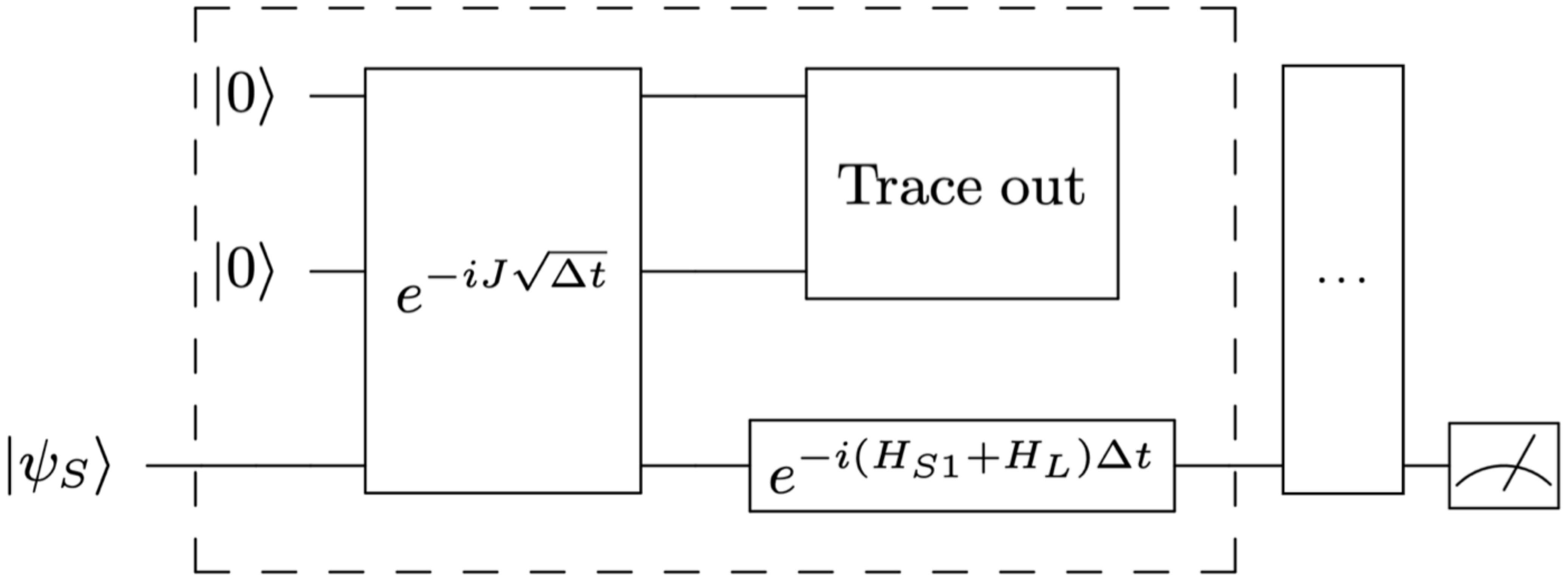
(Dated: September 9, 2021)

Quantum algorithms for transport coefficients in gauge theories

Thomas D. Cohen,[1,*] Henry Lamm,[2,†] Scott Lawrence,[3,‡] and Yukari Yamauchi[1,§]
(NuQS Collaboration)

[1] *Department of Physics, University of Maryland, College Park, MD 20742, USA*
[2] *Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
[3] *Department of Physics, University of Colorado, Boulder, CO 80309, USA*

(Dated: April 6, 2021)



… or compute transport coefficients

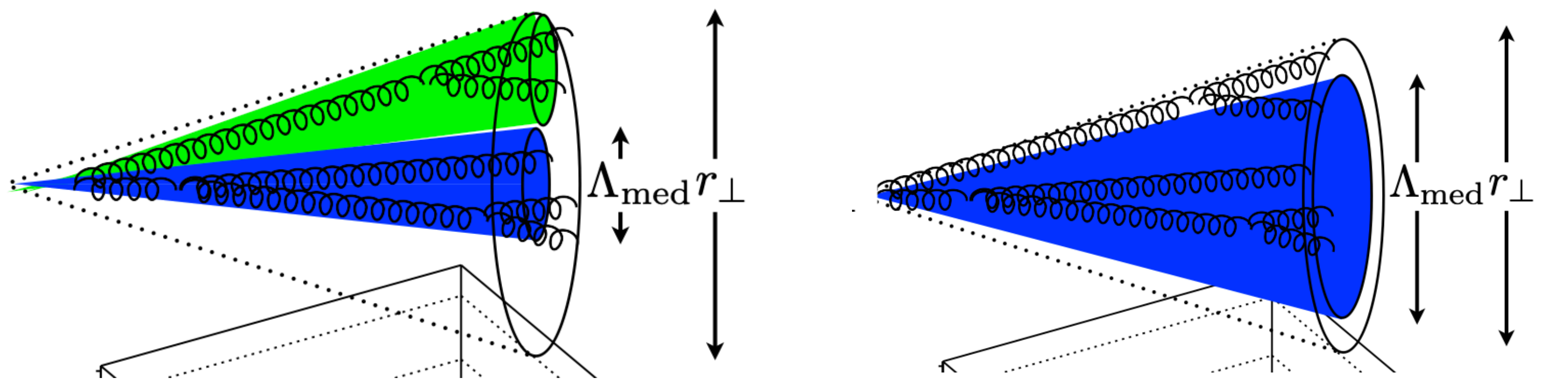
Quantum computing for jet quenching

2104.04661, 2208.06750

Why quantum computing for jets in medium?

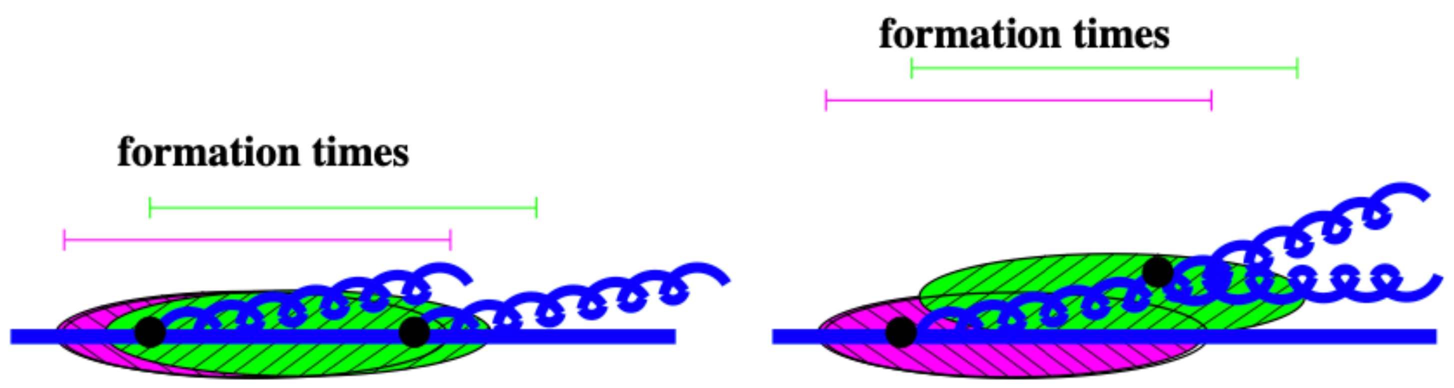
Many of the pheno relevant effects in jet quenching have a quantum origin

See talk by A. Soto-Ontoso

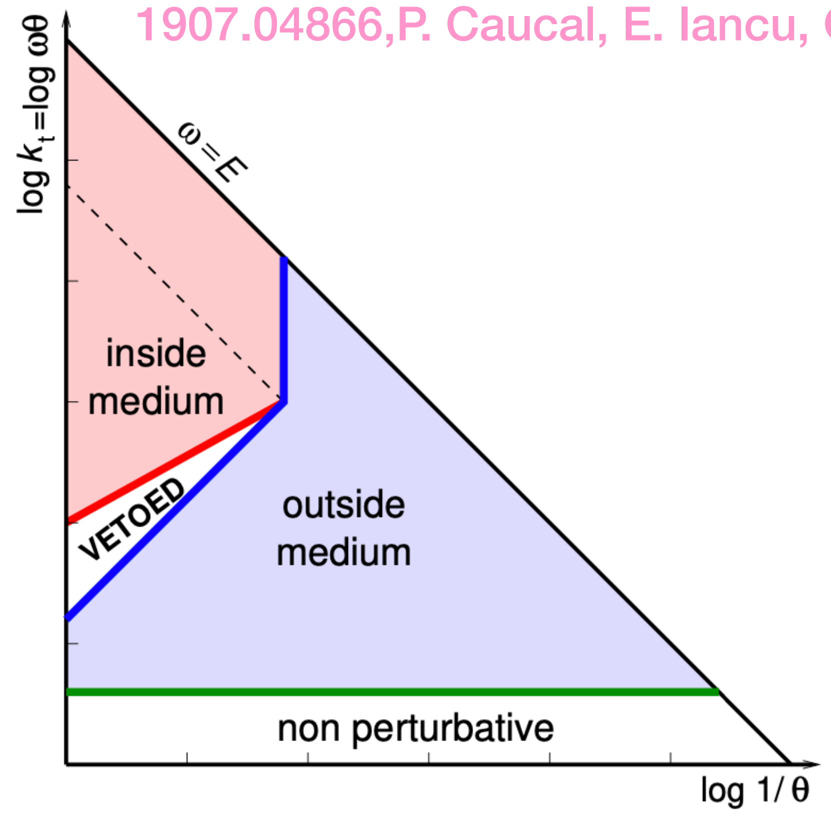


1210.7765, J. Casalderrey-Solana , Y. Mehtar-Tani, C.Salgado, K. Tywoniuk

1501.04964, P. Arnold, S. Iqbal



1907.04866,P. Caucal, E. Iancu, G. Soyez



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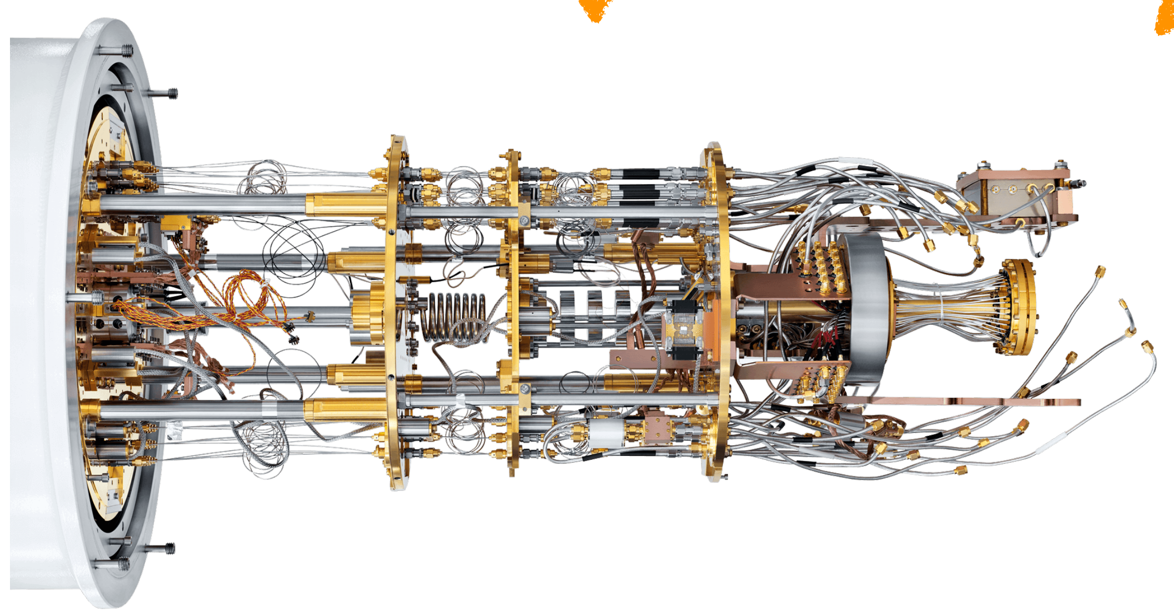

Jet quenching in a QC: a possible approach

2104.04661 with C. Salgado

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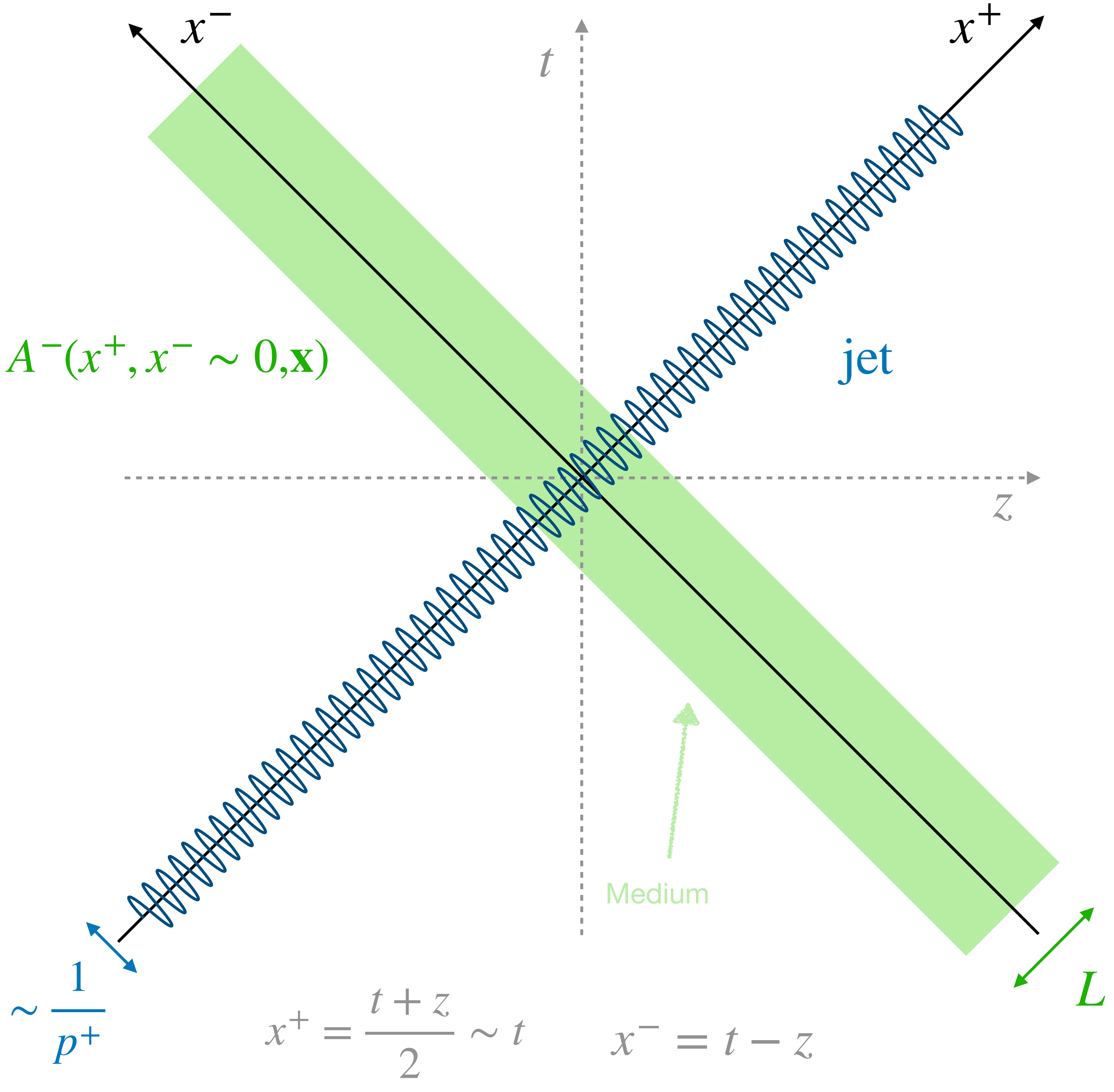


Integrating out x^- the **quark propagator** satisfies

$$\left(i\partial_t + \frac{\partial_{\boldsymbol{x}}^2}{2\omega} + g\mathcal{A}^-(t, \boldsymbol{x}) \cdot T\right) G(t, \boldsymbol{x}; 0, \boldsymbol{y}) = i\delta(t)\delta(\boldsymbol{x} - \boldsymbol{y})$$

Parton evolution is equivalent to **2+1d non-rel. QM**

$$\mathcal{H}(t) = \underbrace{\frac{\boldsymbol{p}^2}{2\omega}}_{\text{p-space}} + \underbrace{g\mathcal{A}^-(t, \boldsymbol{x}) \cdot T}_{\text{x-space}} = \mathcal{H}_K + \mathcal{H}_{\mathcal{A}}(t)$$

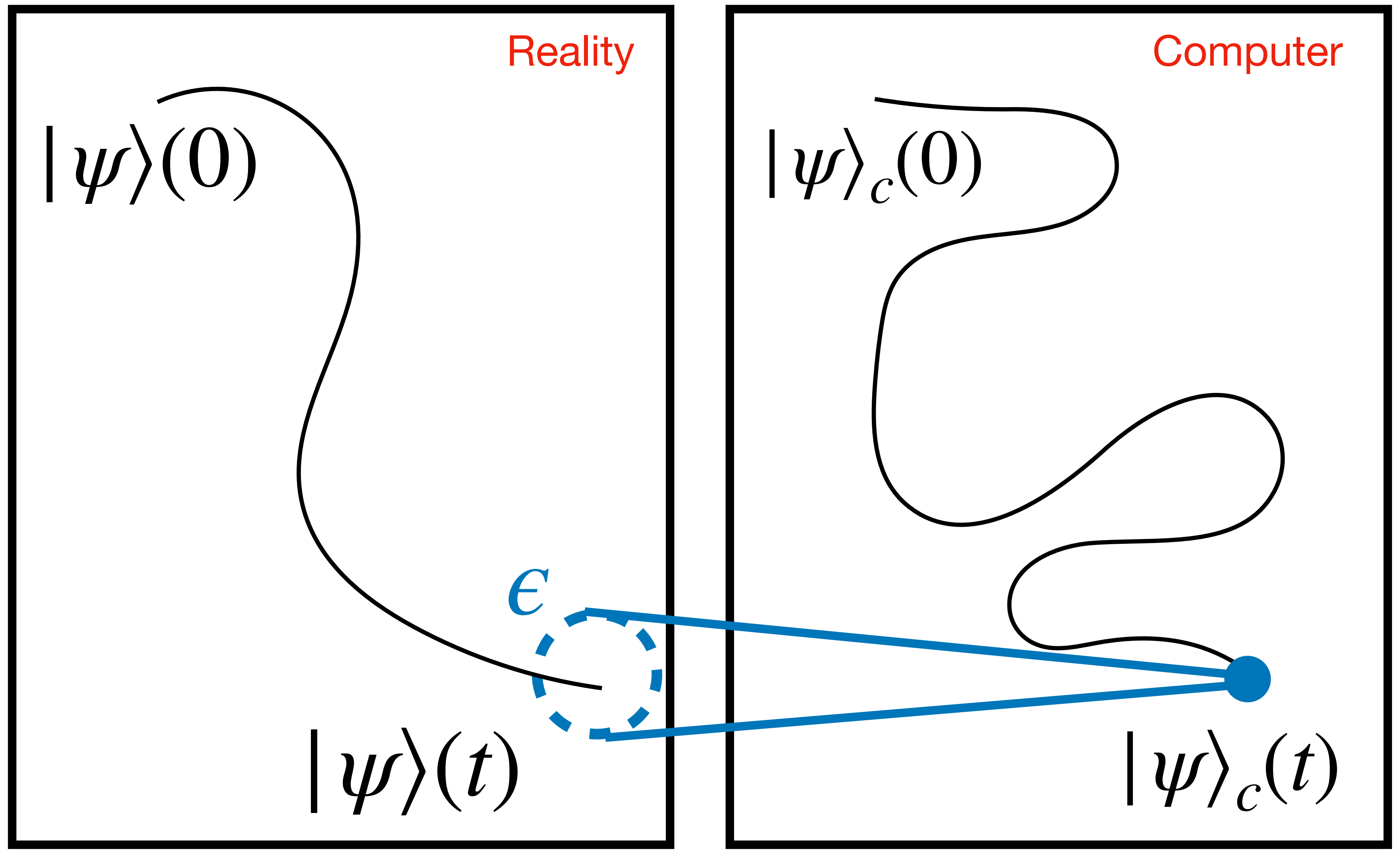
Consider the **simplest** case:

1. $|q\rangle$ Fock space only
2. $T = 1$
3. Stochastic background (hybrid approach)

The quantum simulation algorithm

QComputers can **efficiently** simulate real time evolution ruled by:

$$|\psi\rangle(t) = \exp(-iHt)|\psi\rangle(0)$$



The **5** main steps of the **Quantum Simulation Algorithm**:

1. Provide $H = \sum_k H_k$ and $\psi(0)$
2. Encode the physical d.o.f's in terms of qubits and decompose H_k in terms of gates
3. Prepare the initial wave function from a fiducial state $(|0\rangle^{\otimes n_{\text{qubits}}})$
4. Time evolve according to $\exp(-iHt)$
5. Implement a measurement protocol

Set up the algorithm

2104.04661 with C. Salgado

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1. Provide $H = H_K + H_A(t)$ and $\psi(0) = \psi(\mathbf{p} = 0)$ ✓ + ensemble of $\{A, p_A\}$

2. Encode the physical d.o.f's in terms of qubits and write H in terms of gates

   Introduce 2d spatial lattice with $N_s = 2^{n_Q}$ sites per dimension

$$|\mathbf{x}\rangle = |x_1, x_2\rangle = a_\perp |n_1, n_2\rangle$$

   such that

$$H = \frac{\boldsymbol{P}^2}{2E} + gA(t, \boldsymbol{X}) \cdot T = H_K + H_A(t)$$

$a_\perp$
Lattice spacing

$$\hat{P}|p\rangle = p|p\rangle \qquad \hat{X}|x\rangle = x|x\rangle \qquad x, p \in \mathbb{Z}$$

3. Prepare the initial wave function from a fiducial state ($|0\rangle^{\otimes n_{\text{qubits}}}$) ✓

Set up the algorithm

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4. Time evolve according to U

Assuming that field is static we use

$$U(L_\eta;0) = \prod_{k=1}^{N_t} U(x_k^+; x_{k-1}^+) \longrightarrow U(x_k^+ + \delta x^+; x_k^+) \approx U_K(\delta x^+)\, U_A(\delta x^+, x_k^+)$$

$$\equiv \exp\left\{-i\delta x^+ \frac{\hat{\boldsymbol{p}}^2}{2p^+}\right\} \exp\left\{-ig\delta x^+ \hat{A}_a^-(x_k^+) T^a\right\}$$

Implement operators with a Fourier Transform in between

$$\exp\left\{-i\delta x^+ \frac{\hat{\boldsymbol{p}}^2}{2p^+}\right\} \quad |\psi_{\mathbf{p}}\rangle \qquad |\mathbf{p}\rangle \xrightarrow{\text{qFT}} |\mathbf{x}\rangle \qquad \exp\left\{-ig\delta x^+ \hat{A}_a^-(x_k^+) T^a\right\} \quad |\psi_{\mathbf{x}}\rangle$$

Set up the algorithm

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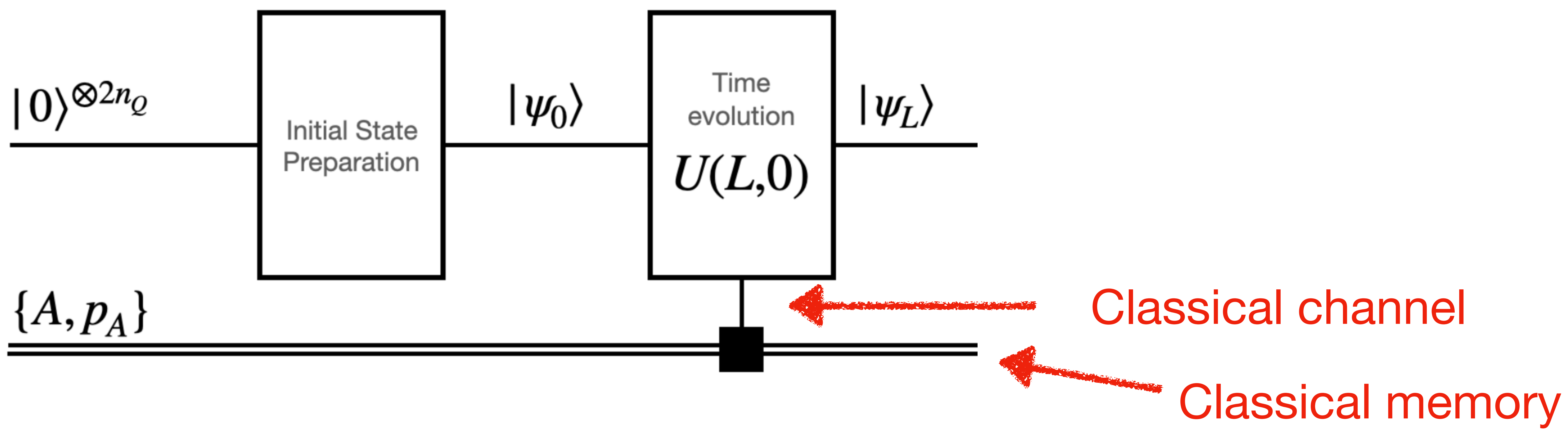
4. Time evolve according to U

Field insertions require probing the field value. This is done classically



Requires $\mathcal{O}(N_{\text{states}})$ field evaluations; **Ok for resolving parton evolution**

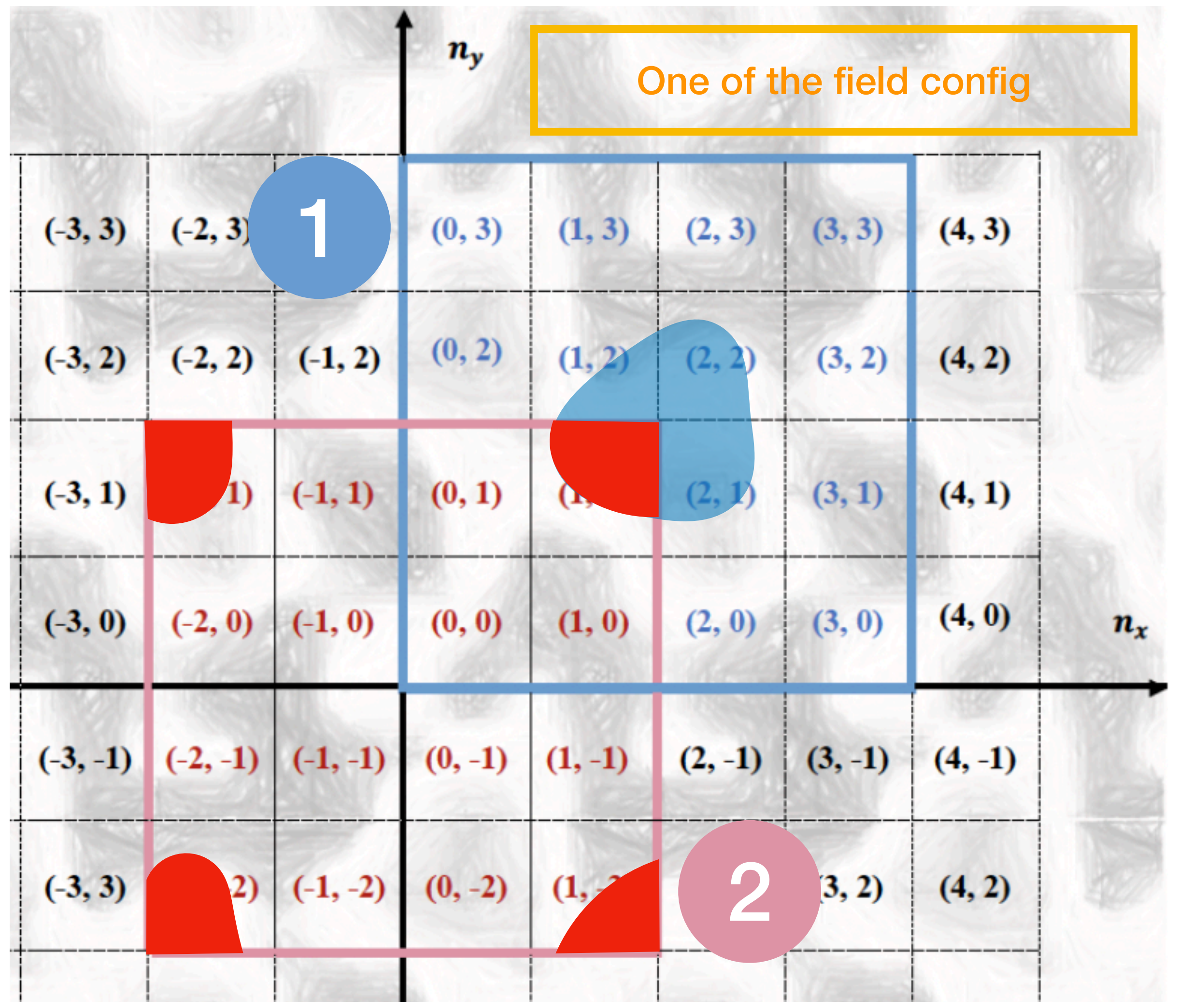
Major limitation of the approach due to classical treatment of medium

Can be made more efficient with further discretization of the field values

Numerical results

Set up:

1. $T = 1$ (no colors) mostly
2. Static brick of length 10 fm
3. 5/6 qubits per spatial dimension (1024/4096 states in total).



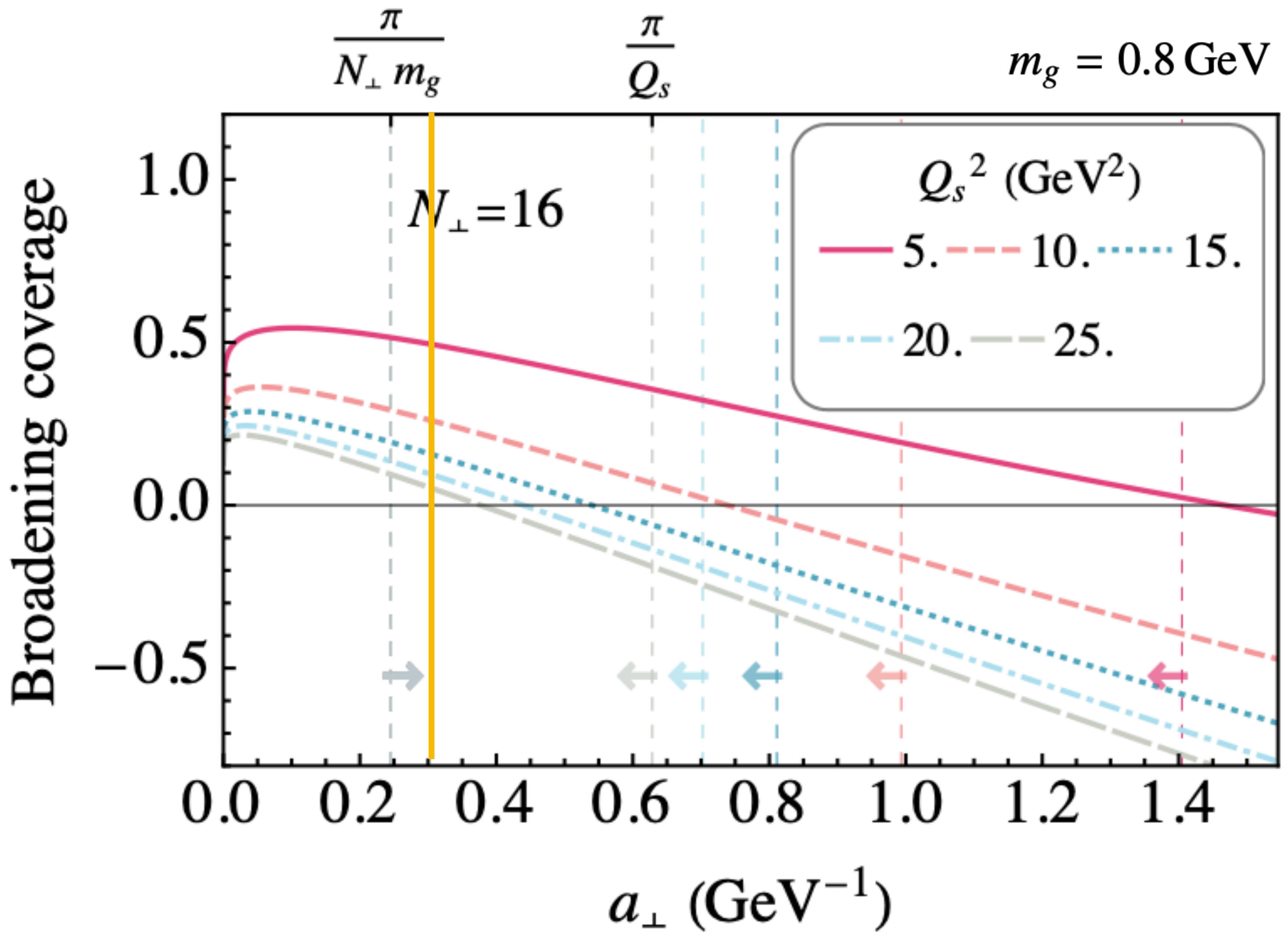
4. We use 5 field configurations. These are determined by lattice spacing and the field strength

Determined by saturation scale: $g^2\tilde{\mu} = \sqrt{\frac{2\pi Q_s^2}{C_F L_\eta}}$

Determined by lattice saturation conditions:

$$\frac{\pi}{N_\perp m_g} \ll a_\perp \ll \frac{\pi}{Q_s}$$ (relevant physical region is covered)

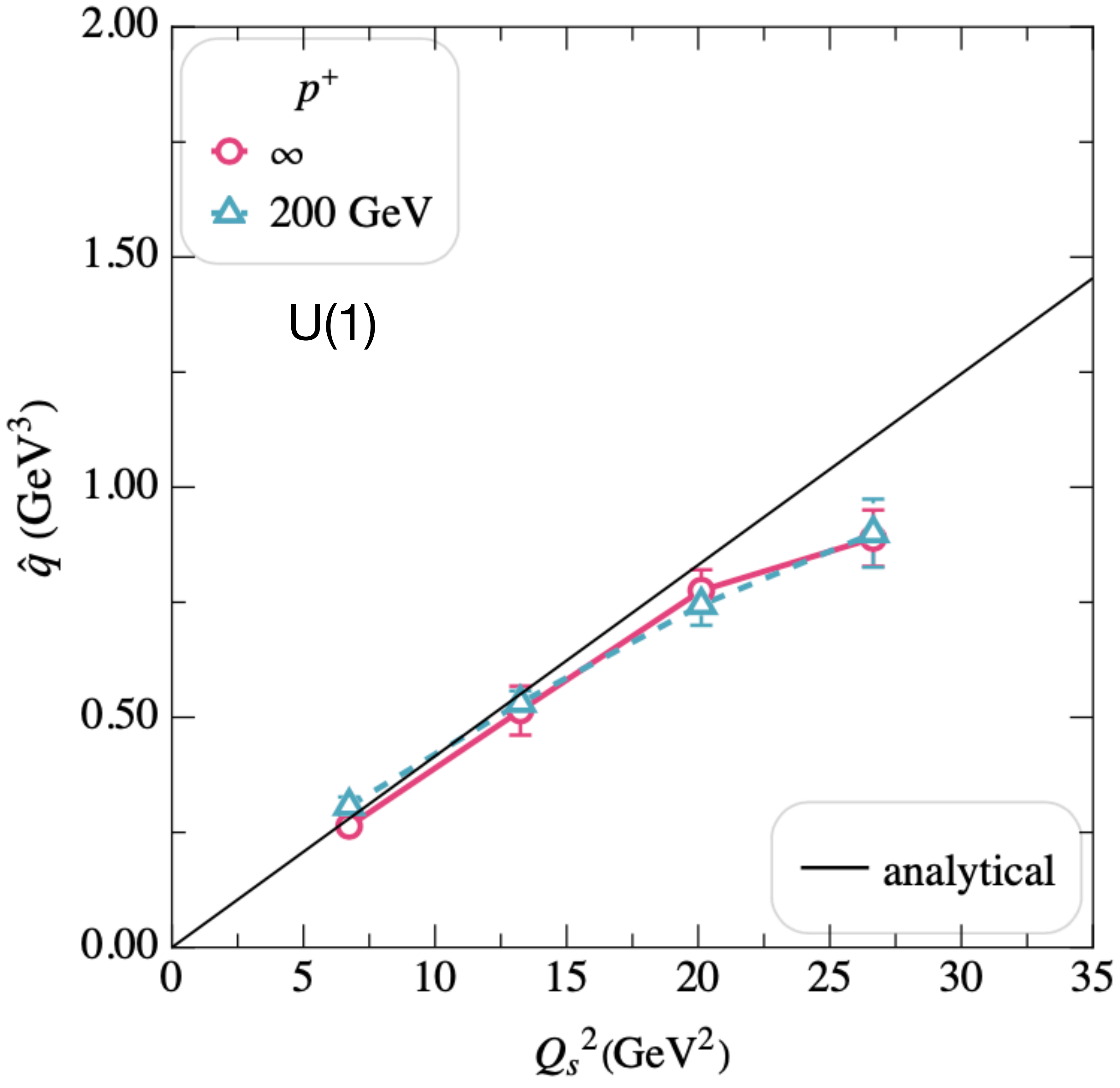
$$a_\perp^2 Q_s^2 < \frac{4\pi^2}{3}\left[\log\left(\frac{1}{a_\perp^2 m_g^2/\pi^2}+1\right) - \frac{1}{1+a_\perp^2 m_g^2/\pi^2}\right]^{-1}$$ (edge effects are absent)



Numerical results

The jet quenching parameter on the lattice is easily obtained analytically:

$$\hat{q} = \frac{1}{t}\int_{p,x,y} p^2 e^{-ip\cdot(y-x)} \langle\langle \mathcal{W}^\dagger(y)\mathcal{W}(x)\rangle\rangle = g^2 \langle\langle \nabla_x \mathcal{A}(0)\cdot\nabla_x\mathcal{A}(0)\rangle\rangle = \frac{g^4}{4\pi} C_F \tilde{\mu}^2 \left\{ \log\left(1+\frac{\frac{\pi^2}{a_\perp^2}}{m_g^2}\right) - \frac{1}{1+\frac{a_\perp^2 m_g^2}{\pi^2}} \right\}$$



In accordance with expected result w/wo kinetic terms

Deviation at large saturation values due to lattice

Numerical results

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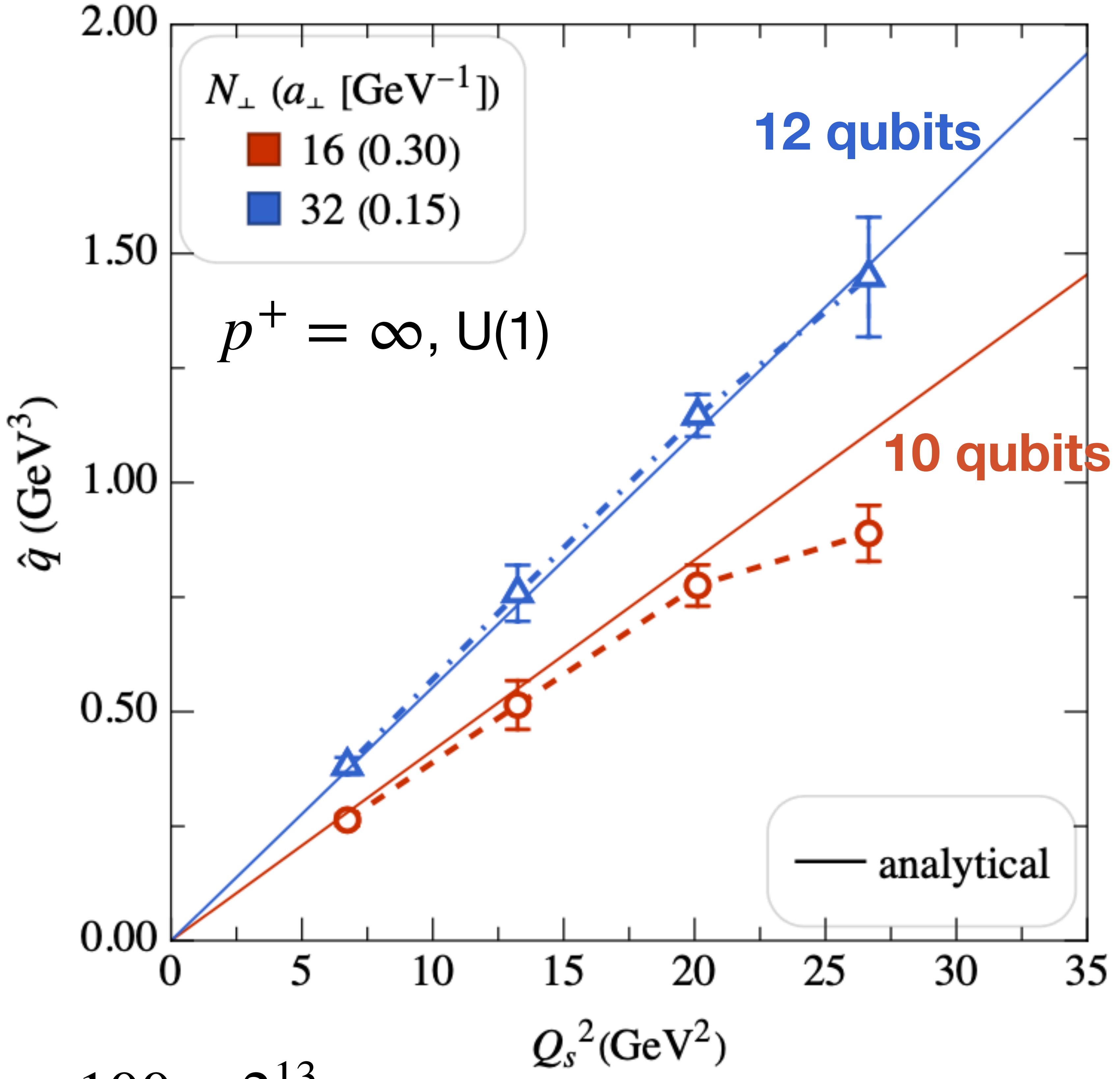
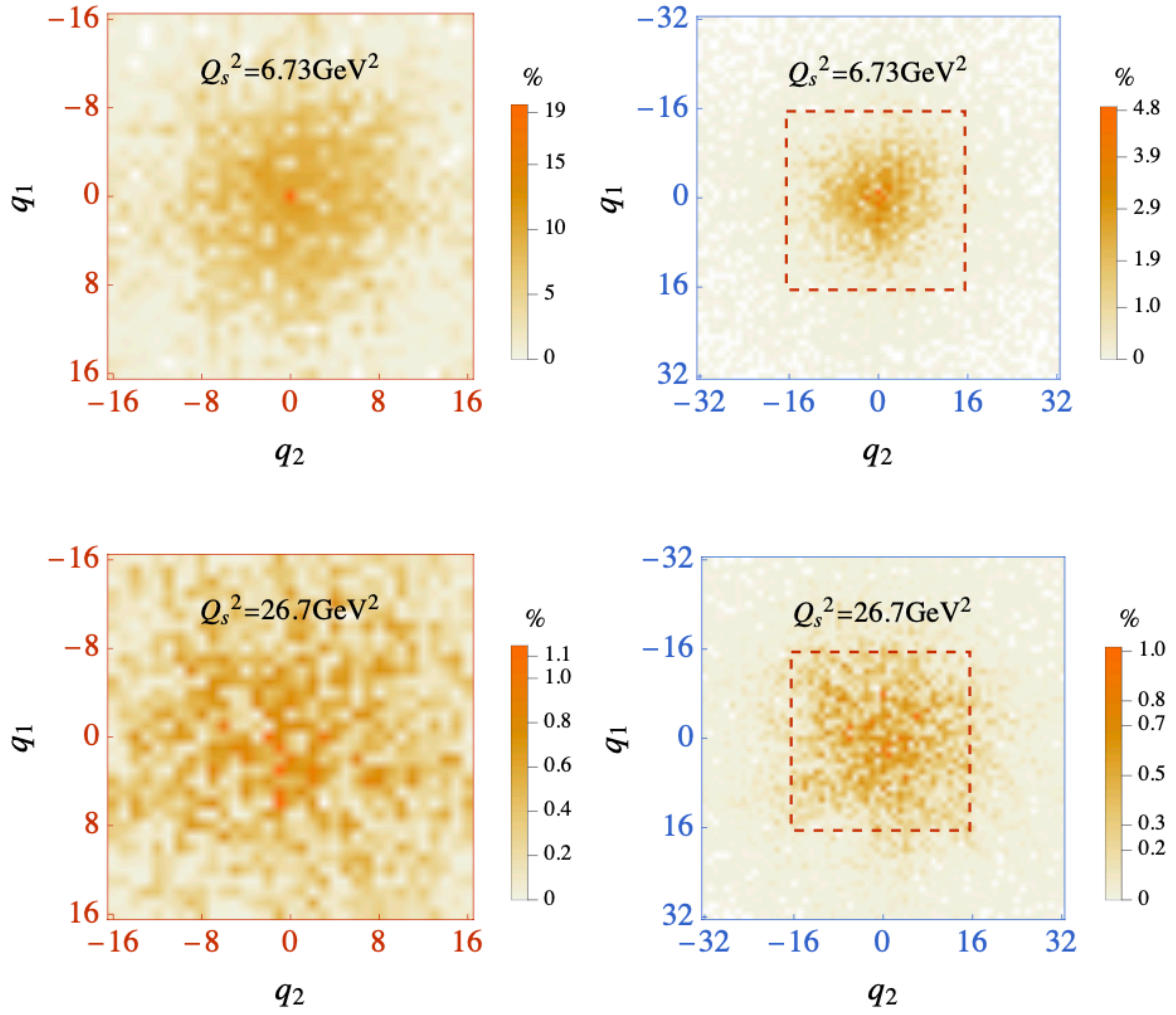
Same result but for two different lattices at infinite jet energy



shots=100×2^{13}



Numerical results

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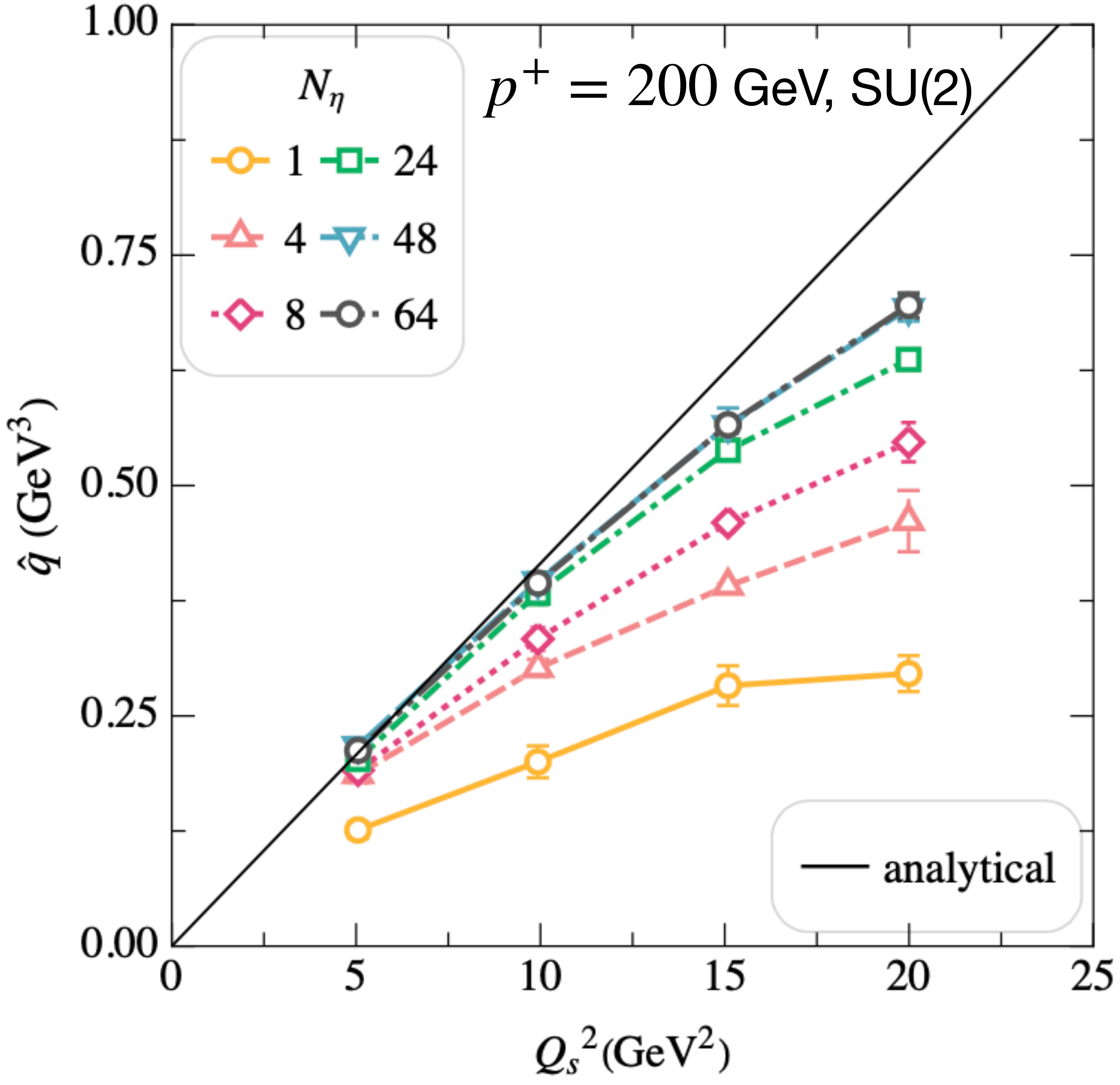
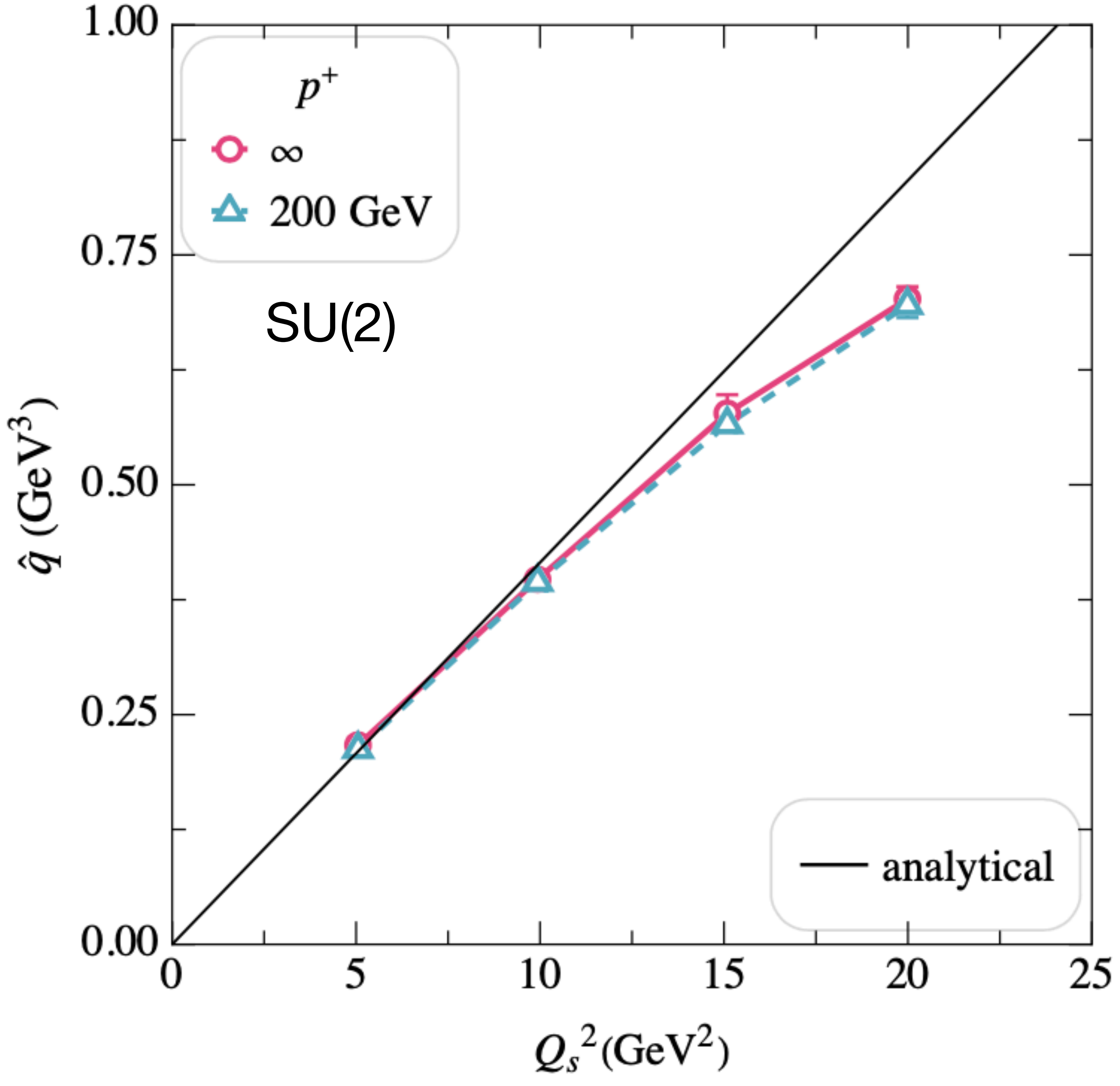
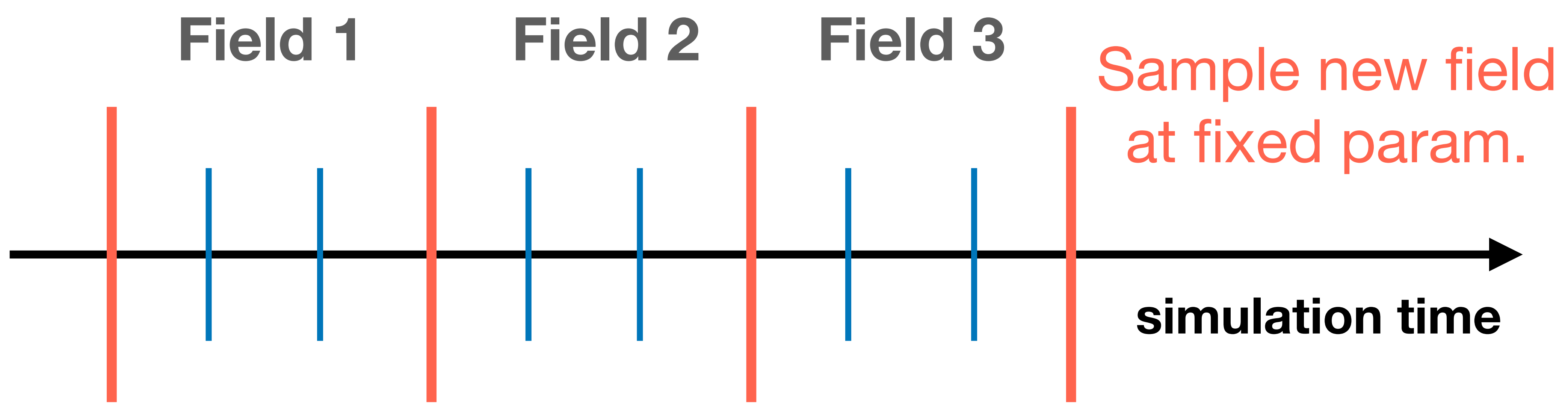
Same results but for a SU(2) background





Random medium leads to emergent time dependence

$$\langle\langle \rho_a(x^+, \boldsymbol{x})\rho_b(y^+, \boldsymbol{y})\rangle\rangle = g^2\mu^2(\boldsymbol{x})\delta_{ab}\delta^2(\boldsymbol{x}-\boldsymbol{y})\delta(x^+ - y^+)$$

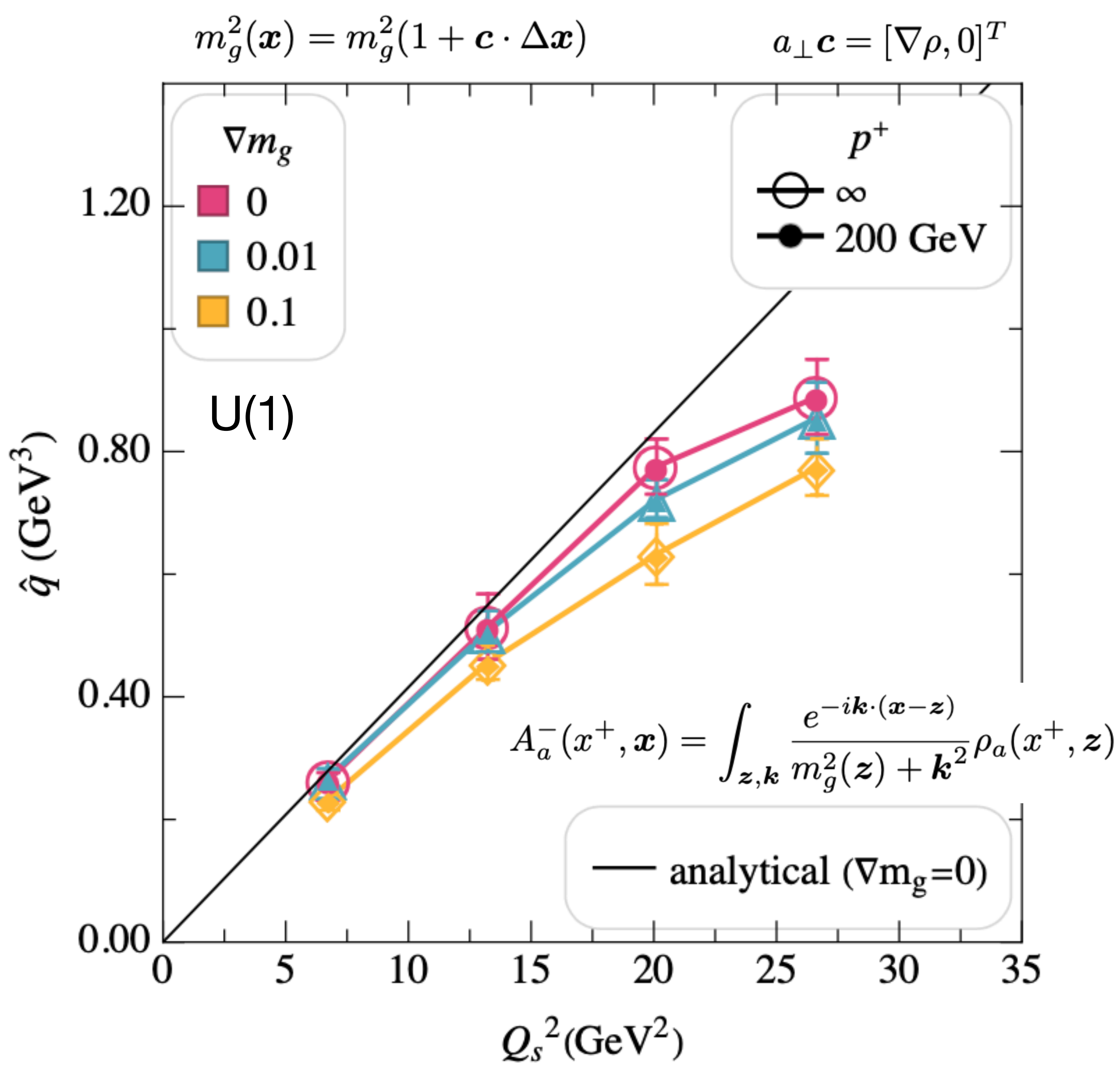


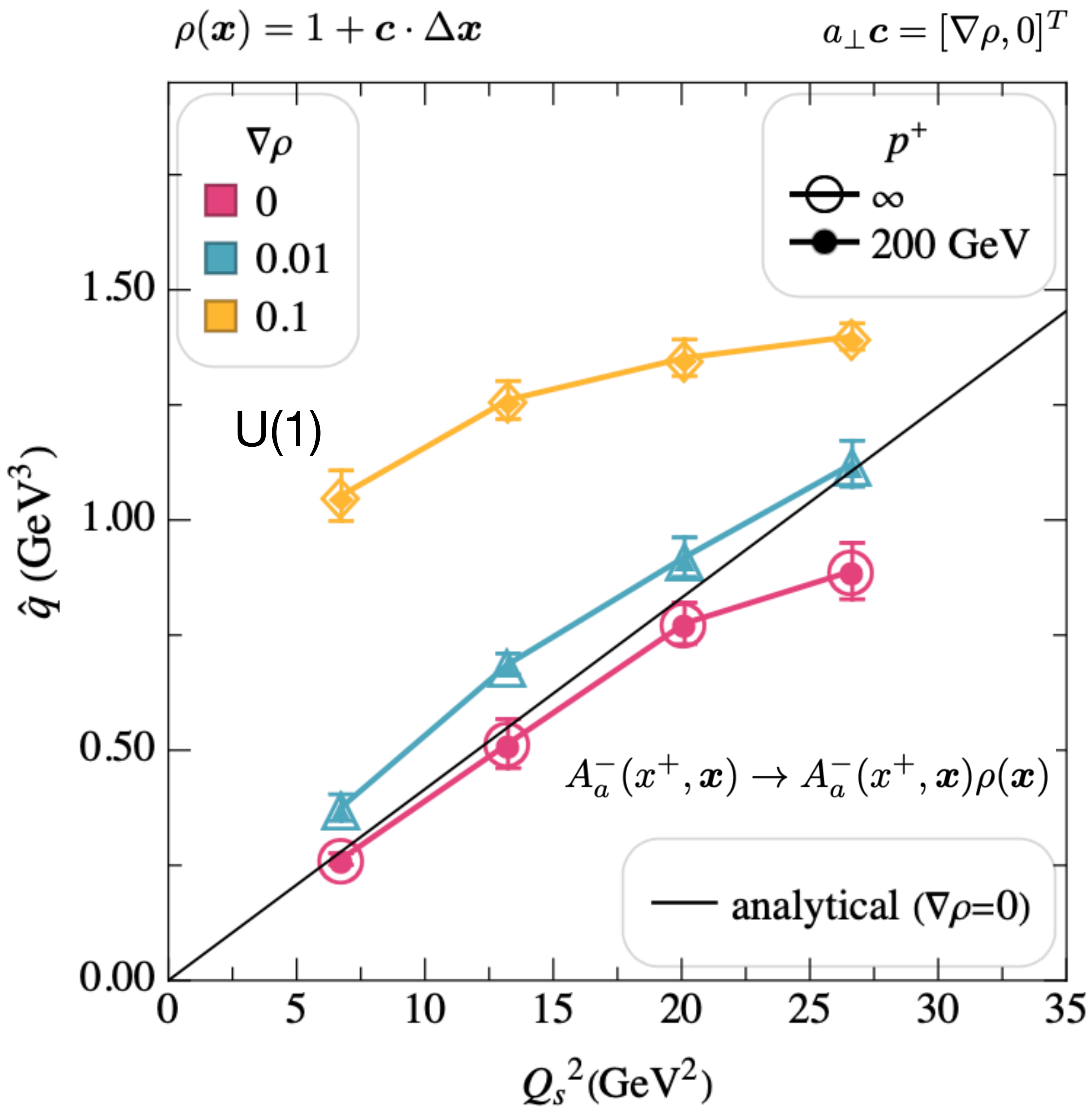
Product formula decomposition

Numerical results

2208.06750 with C. Salgado, M. Li, X. Du, W. Qian

also ongoing J.B. , A. Sadofyev, X.-N. Wang





Energy independent terms might give sizable contribution !

Numerical results

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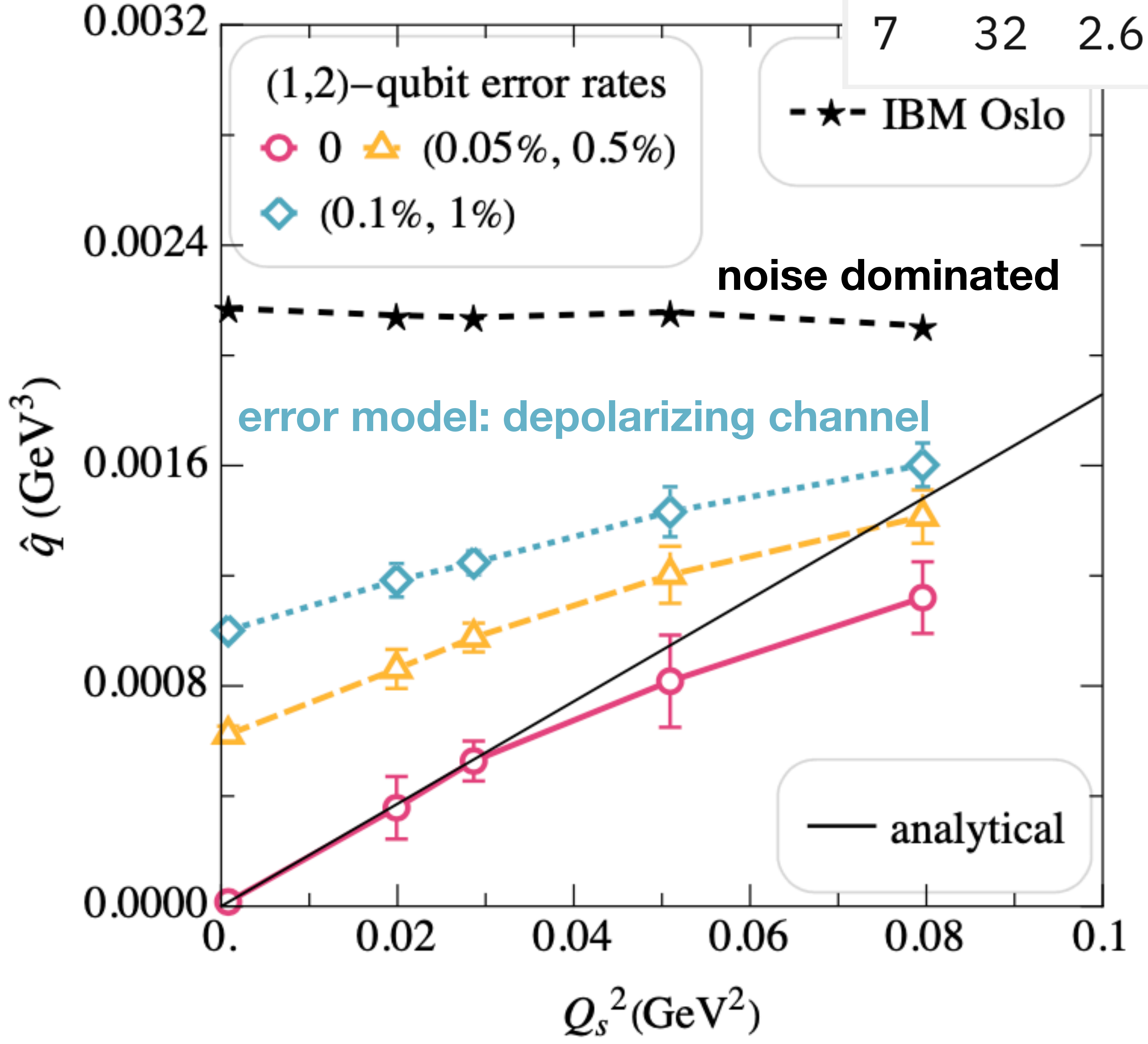
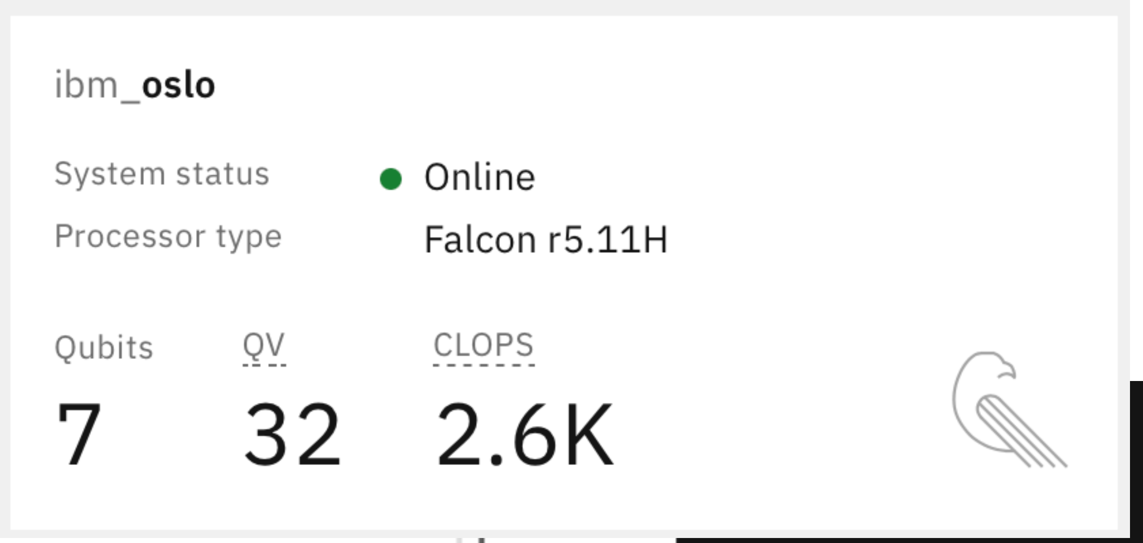
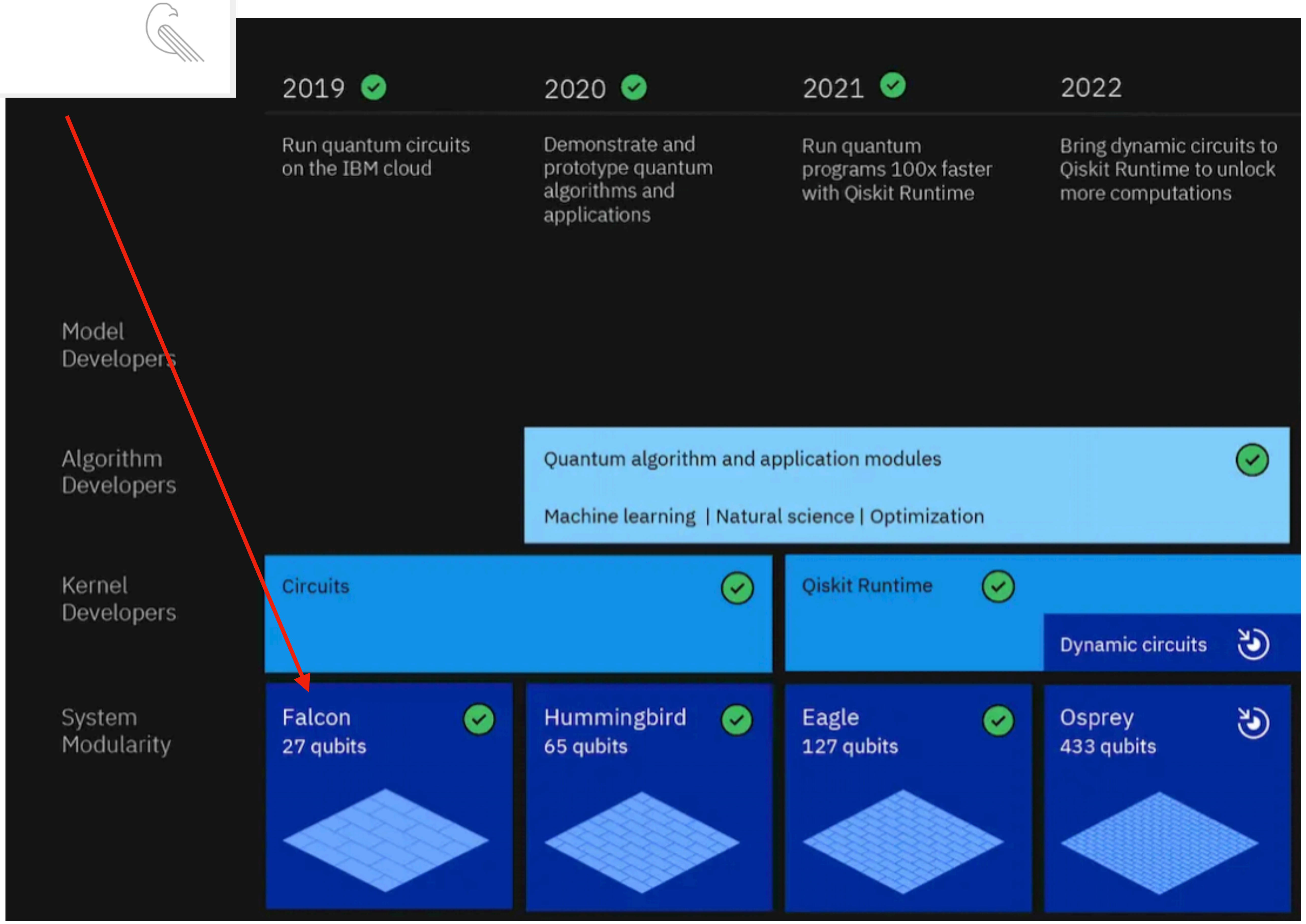




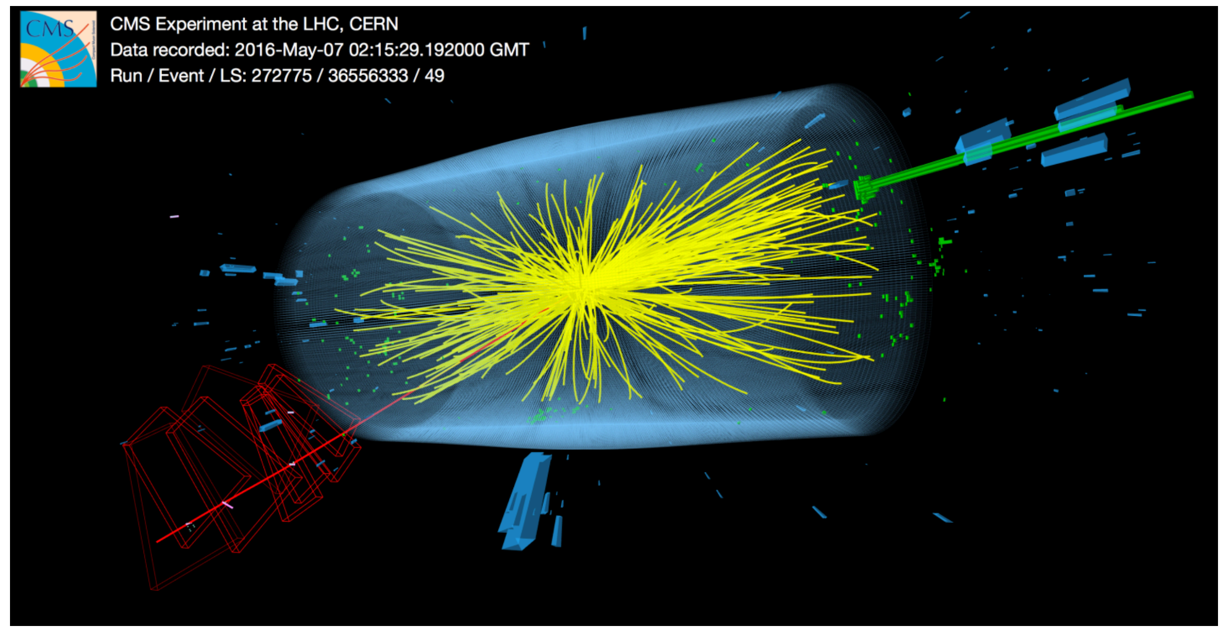


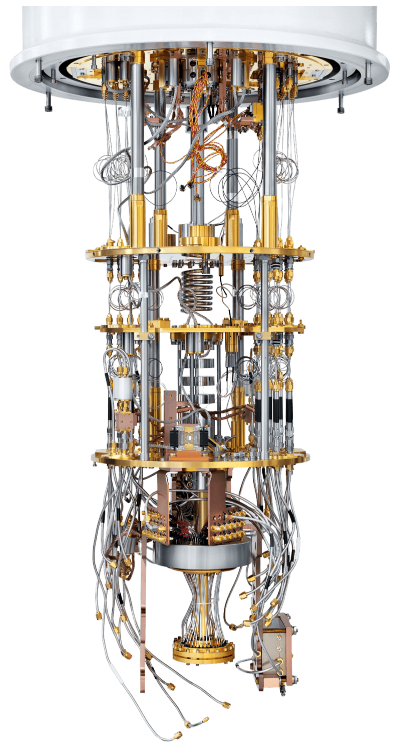
Available but not free

Prototype

Conclusion and Outlook

- Quantum computing applications to HEP are still in their infancy





- For jet quenching, the study of LPM physics can be better understood using these machines in the future

$$|\psi\rangle = c_1|q\rangle + c_2|qg\rangle + c_3|qgg\rangle + \cdots$$