frontier in QIS theory for QCD, HEP, and beyond

from entanglement to parton densities

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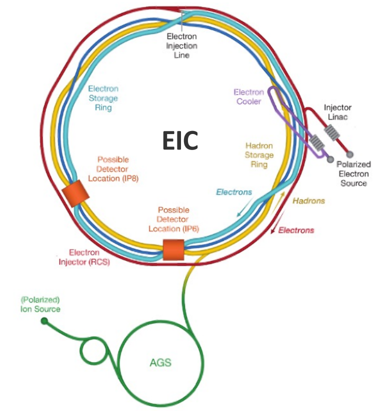
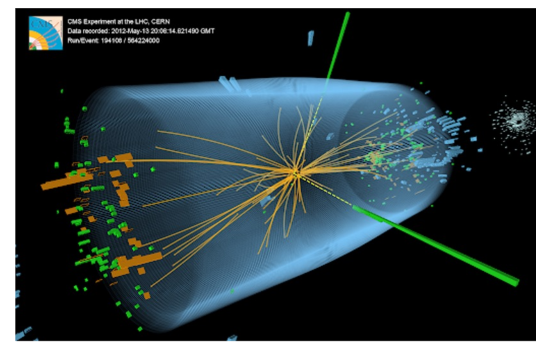
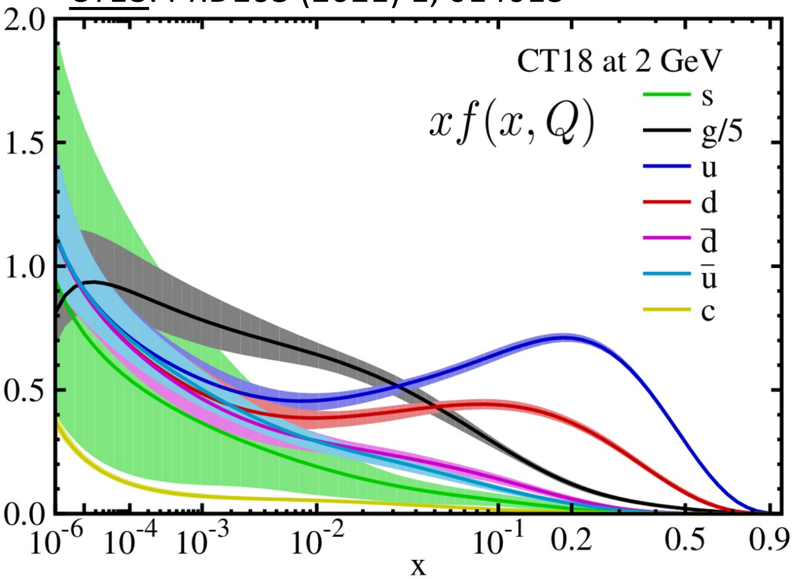
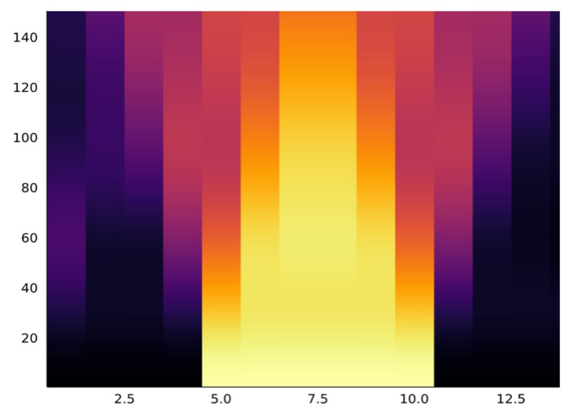
CTEQ





CT18: PRD**103** (2021) 1, 014013

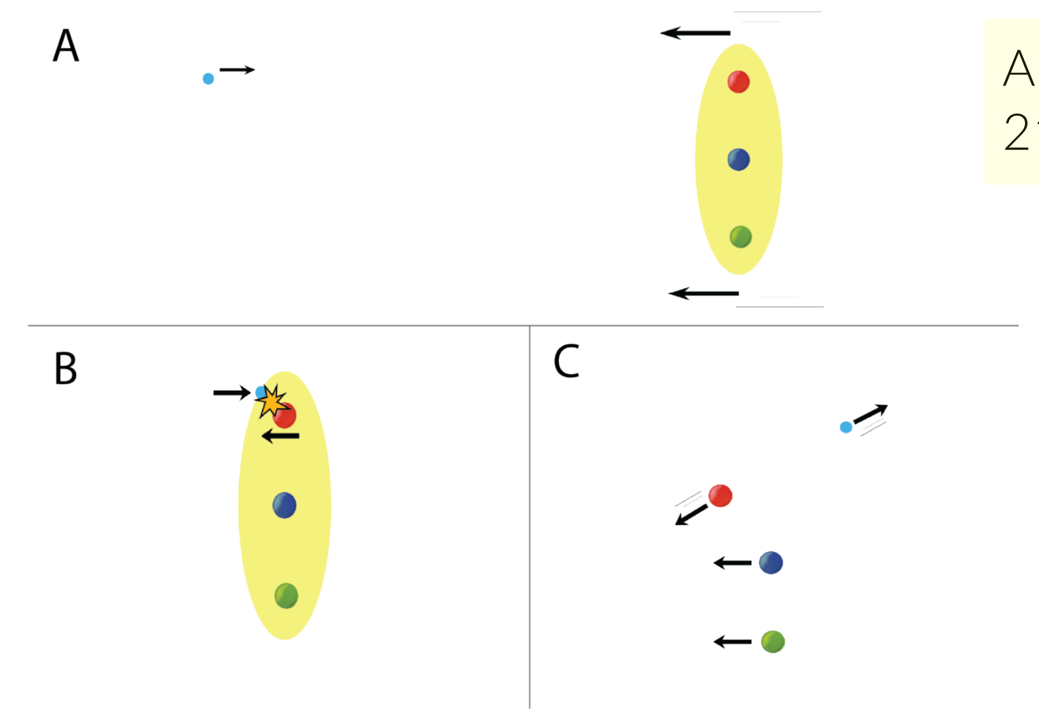




fundamental physics in a quantum-information language

→ broad reimagining of HEP in QIS terms is underway; <u>applies to QCD</u>

- ‘simplest’ scenario – factorization in DIS exploits a **sequential, semi-classical** picture of scattering interaction



Aidala and Rogers, 2108.12319 [quant-ph]

external lepton interacts with <u>one</u> constituent quark (leading twist) at short distance (B); fragments fly away asymptotically (C); only lepton observed

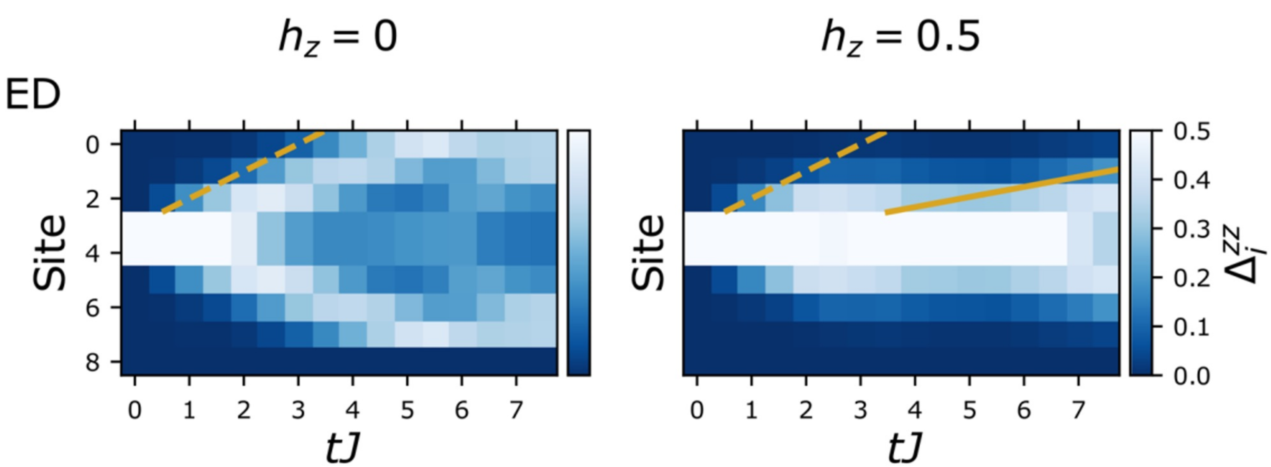
confinement dynamics from (simplified) model Hamiltonians

Vovrosh, Knolle: Nature (2021) 11:11577

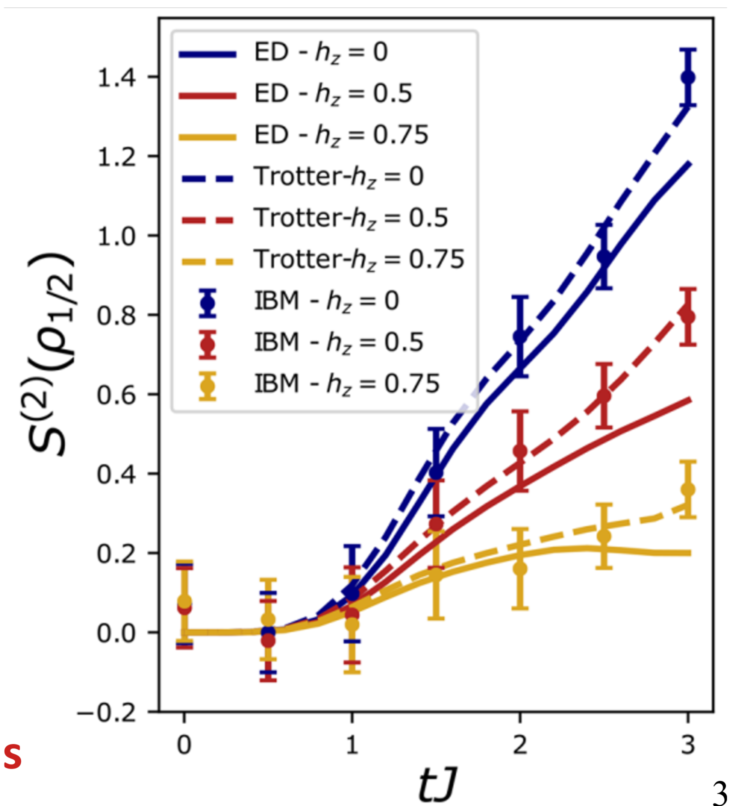
- e.g., confinement in 2-fermion systems; Transverse-Field Ising Model:

$$H = -J\left\{\sum_{i=0}^{L-2}\sigma_i^z\sigma_{i+1}^z + h_x\sum_{i=0}^{L-1}\sigma_i^x + h_z\sum_{i=0}^{L-1}\sigma_i^z\right\} \qquad h_x = 0.5$$

- quark-antiquark → mesons; examine "binding" effects as external potential varied



de-confined confined



- sample system config → evaluate Réyni entropy

entropy suppression signals confinement at long times

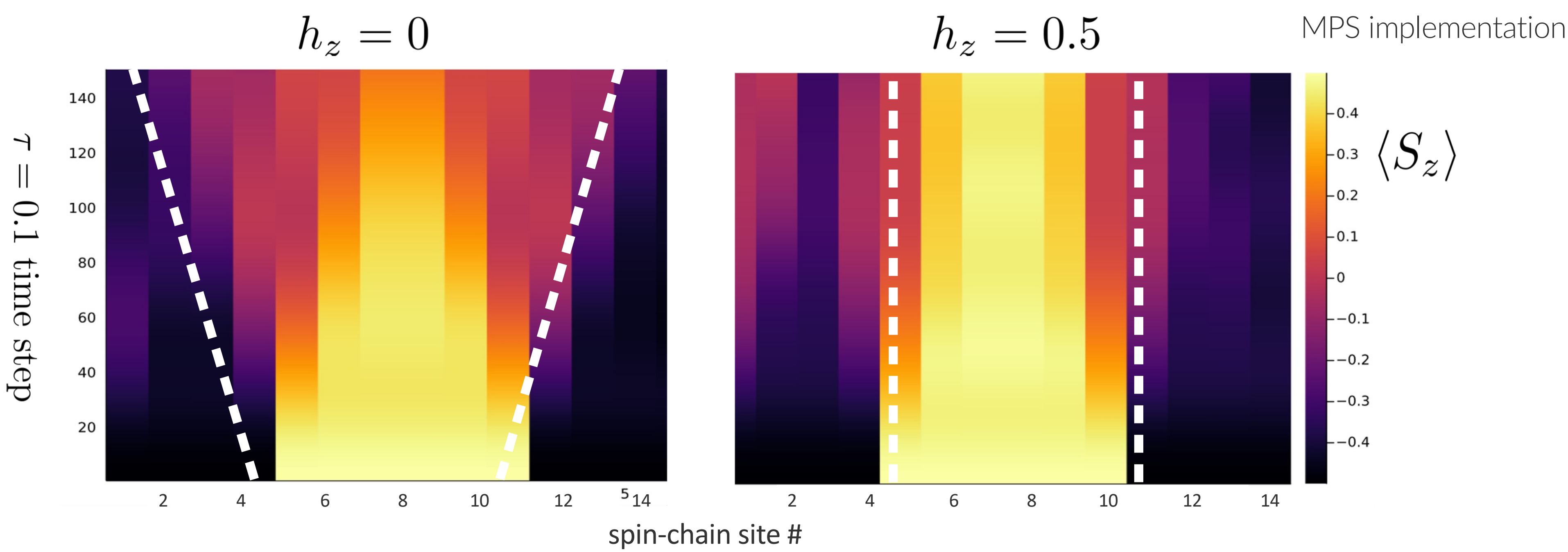
tensor network simulation is informative

- build initial understanding: Matrix Product States (MPS) with Tensor Networks

$$H = -J\left\{\sum_{i=0}^{L-2}\sigma_i^z\sigma_{i+1}^z + h_x\sum_{i=0}^{L-1}\sigma_i^x + h_z\sum_{i=0}^{L-1}\sigma_i^z\right\}$$

Khor, Kurkcuoglu, TJH, Perdue, Klich

2312.08601 [quant-ph]



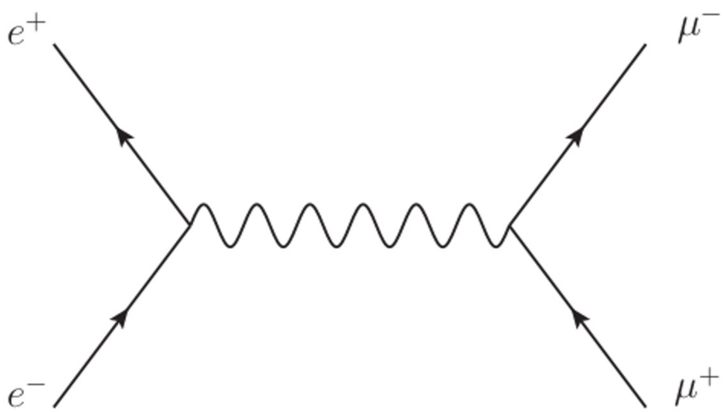
→ explore model space; rapidly compute many metrics (Réyni entropy, arbitrary order, ...)

relations among symm breaking, entanglement entropy, confining dynamics in QCD-like systems

entanglement in fundamental 2 → 2 scattering

- many contemporary HEP studies explore utility of MaxEnt to connect properties of specific systems to structure, dynamics

Cervera-Lierta, SciPost Phys. 3, 036 (2017)



$$\mathcal{M}_{RL} \sim \alpha_{RL}|RR\rangle + \beta_{RL}|RL\rangle$$
$$+\gamma_{RL}|LR\rangle + \delta_{RL}|LL\rangle$$

$$\Delta = 2|\alpha\delta - \beta\gamma| \text{ (concurrence)}$$

→ represent entanglement in 2 → 2 scattering via *concurrence*; examine conditions maximum entanglement place on couplings

→ is there a connection between MaxEnt and fundamental symmetries?

- photon-electron interactions *without* gauge symmetry: MaxEnt → QED

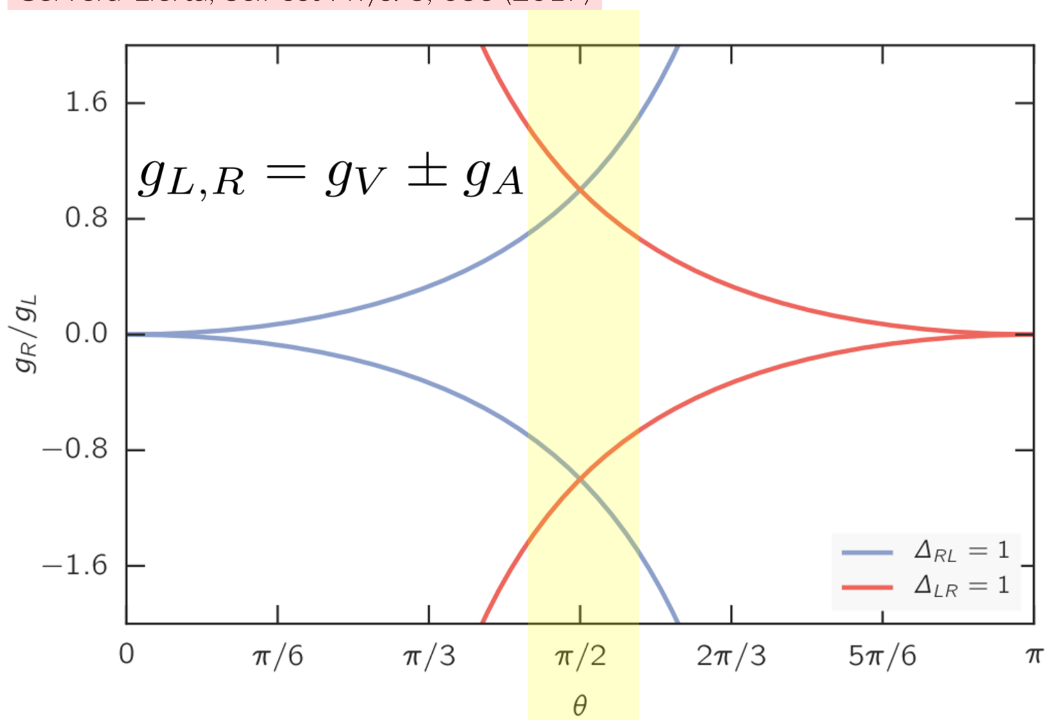
entanglement in fundamental 2 → 2 scattering

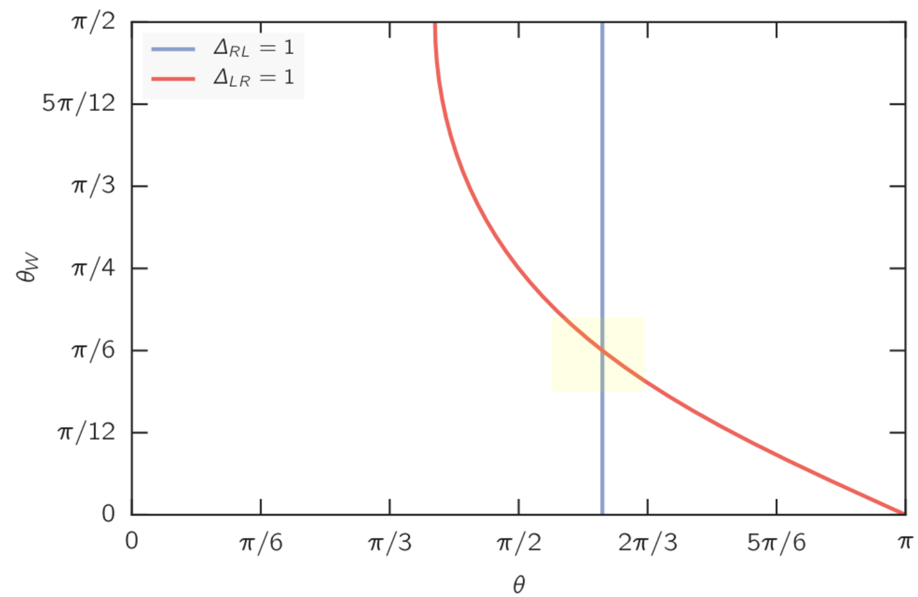
- this method can be extended to the electroweak sector

  → consider weak scattering mediated by *Z* exchange: $e^- e^+ \to \mu^- \mu^+$

$$c_Z^f = i \frac{g}{\cos\theta_W} \gamma^\mu \left(g_V^f - g_A^f \gamma^5 \right)$$

Cervera-Lierta, SciPost Phys. 3, 036 (2017)



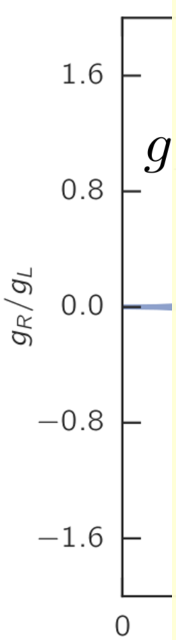


- MaxEnt realized for $g_L = g_R \to g_A = 0$ (QED) OR $g_V = 0,\ \sin^2\theta_W = 1/4$

entanglement in fundamental 2 → 2 scattering (ii)

- this method can be extended to the electroweak sector

  → consider weak scattering mediated by Z exchange



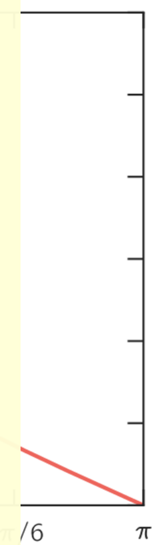
- **very suggestive** → MaxEnt can serve as a constraining principle;

  …reflects fundamentally quantum nature of these processes…

- extendable to other HEP pheno., QCD bound states

  → *n.b.:* conclusions will shift at higher orders

  → top sector is an obvious application



- analogous concurrences, Bell's inequality tests possible in top sector

→ high **QCD accuracy** is essential to robustness of QM tests

Entanglement and Bell Inequality Before Integration

Purdue Top Entanglement Workshop, October 2023: Yoav Afik

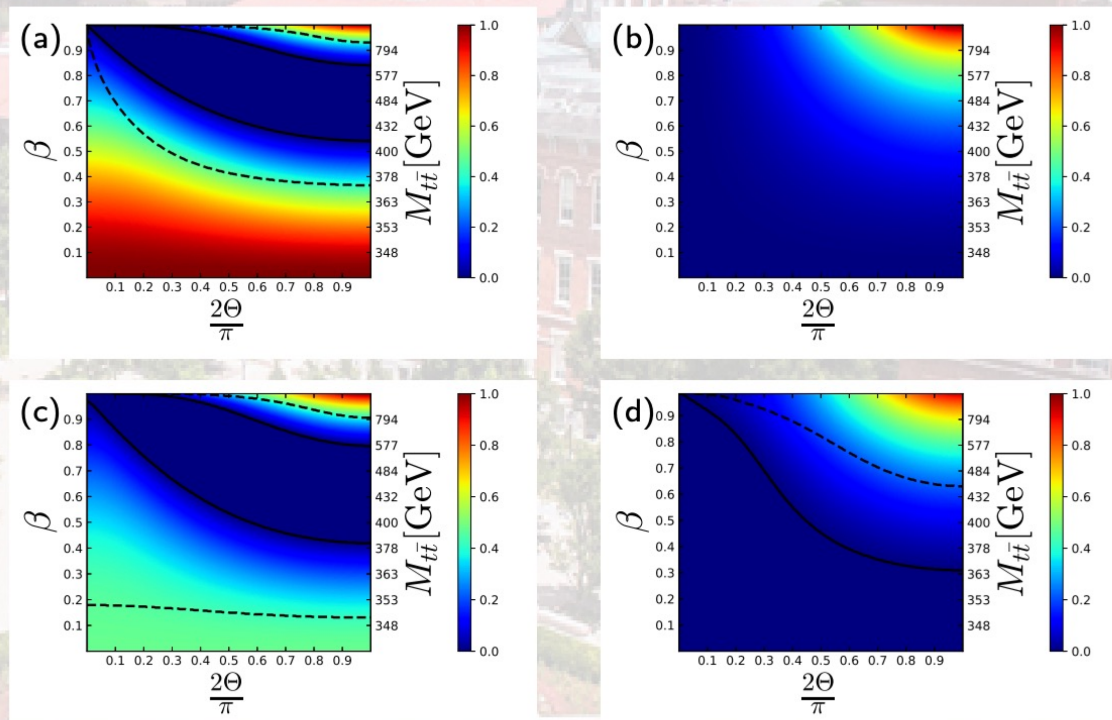
a) $gg \to t\bar{t}$ Concurrence.

b) $q\bar{q} \to t\bar{t}$ Concurrence.

c) Full LHC $\rho(M_{t\bar{t}}, \hat{k})$ Concurrence.

d) Full Tevatron $\rho(M_{t\bar{t}}, \hat{k})$ Concurrence.

- Solid line: entanglement boundary; Dashed line: Bell non-locality boundary.



- It is possible to control the $gg/q\bar{q}$ fraction by further selections ($\beta_{t\bar{t}}$), see Aguilar-Saavedra, Casas, EPJC (2022).

back up

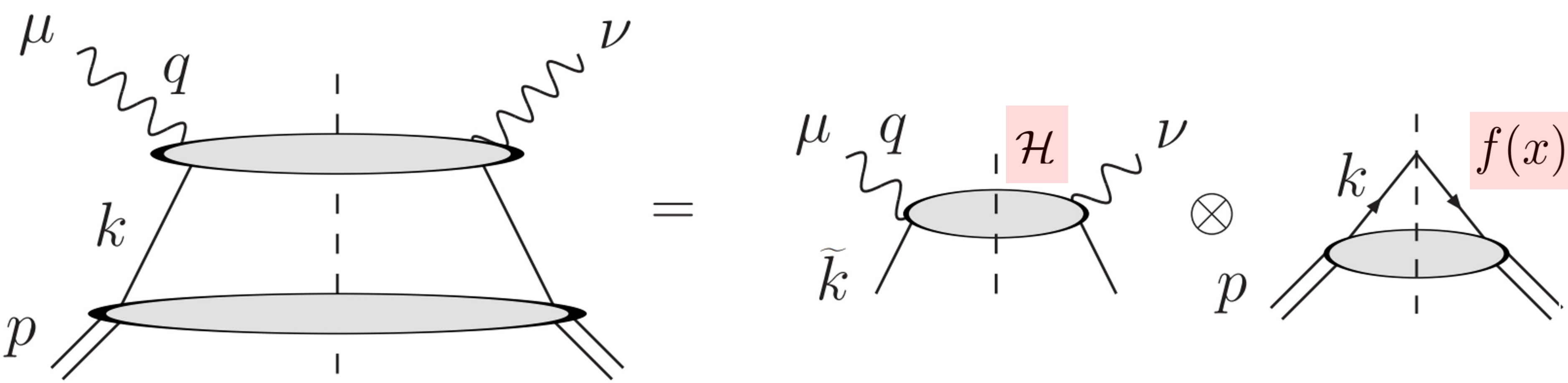
fully inclusive processes: DIS

$$d\sigma \sim W^{\mu\nu}(p,q) = \frac{1}{8\pi}\int d^4z\, e^{-iq\cdot z}\langle p|J^{\dagger\mu}(z)J^{\nu}(0)|p\rangle$$

- previous picture implies scale separation; resolution into subprocesses with classical, probabilistic interpretation

$$W^{\mu\nu}(p,q) = \sum_f \int \frac{dx}{x}\,\mathcal{H}_f^{\mu\nu}(\widetilde{k},q)\,\varphi_{f/N}(x,Q^2,m_N^2) + O(\Lambda^2/Q^2)$$

$$\longrightarrow \quad \boxed{d\sigma = \mathcal{H}\otimes f(x)}$$



→ systematic breakdown of coherence; power-suppressed corrections: residual entanglement; <u>complicated in less inclusive processes</u>