

- 1 Organizational matters
- 2 Why quantum computing in hadron physics
- 3 Various problems
- 4 Fragmentation functions, and TMDs?
- 5 Particle Physics in Neutron Stars

Two organizational things...

- We are at the seminar room of the theoretical physics department at Complutense
- Back of the room: lanyard id, certificate of assistance, paper & pen
- A coffee break will be served at the end of this corridor
- Drinking water tap just next to the lavatory behind us
- Lunch is at the basement cafeteria: we have a reserved table, each one pays his own.
- Google meet link sent to the same email in your registration



- If you came from out of town, check out the “Faro de Moncloa”, the watchtower in our campus, for great views of the city’s west.

Welcome and Overview of Quantum Computation in Hadron Physics

F.J. Llanes-Estrada (speaker)

J.J. Gálvez-Viruet (PhD@UCM) & M. Gómez-Rocha (UGR)

Universidad Complutense de Madrid, Dept. de Física Teórica and IPARCOS

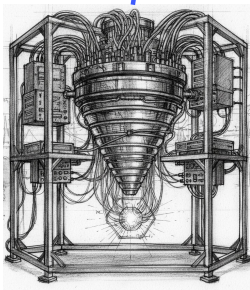
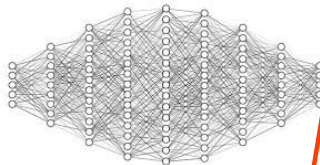
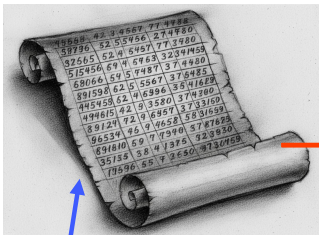
December 18th, 2025

Based on [2510.26293 \[hep-ph\]](#)



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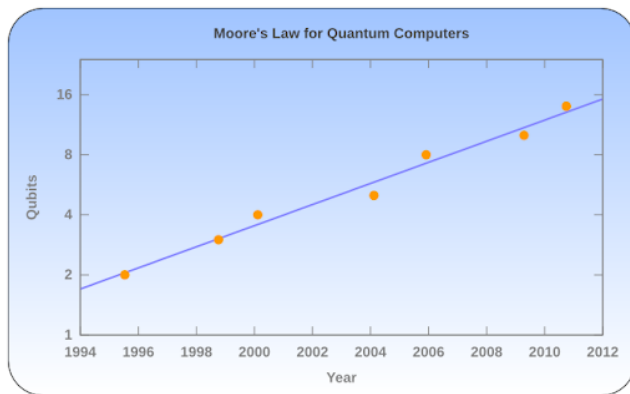
Large data (inductive) vs. large computations (deductive)



$H_{\text{your model}} =$

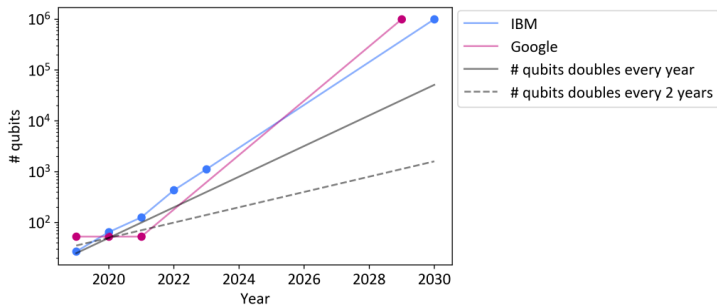
$$\sum_{ijk} \bar{\psi}_i O_j \psi_k + \dots$$

Moore's (Rose's) law working for a long time



(Copyright Hendrik Weimer, <http://www.quantenblog.net/license>)

Moore's (Rose's) law and more



<https://www.quantum.amsterdam/>

And let's not forget

- $2^{\text{\#bits}}$ = size of a representable **number**
- $2^{\text{\#qubits}}$ = size of basis for a **linear space**

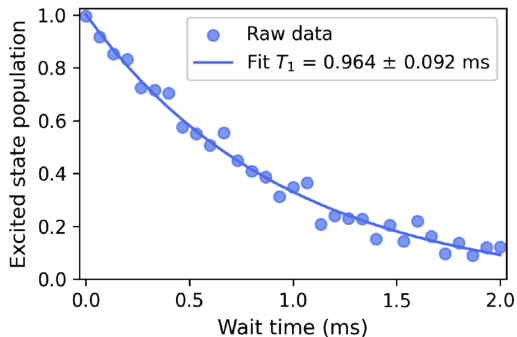
We will need circuits many thousands of layers deep...

- T. Rudolph on photon devices: 10^{-5} done, 10^{-8} achievable, APL Photonics 2, 030901 (2017)
- Quantinuum (trapped ions) claims error rate 10^{-5} - 10^{-10} by 2029.
- If you are on the wifi during my talk ☹, that is typical

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Decoherence time



- Decoherence time hitting the millisecond
- 10^3 gates in that time

Milestone by IQM company

Quantum Simulation Algorithm

- 1 Choose an encoding for the physical states (Here, particles, not fields)
- 2 Initiate the quantum computer memory to $|\psi(0)\rangle$
- 3 Decompose the unitary $U(t) = \exp(-itH/\hbar)$ into elementary gates and evolve $|\psi(t)\rangle = U(t)|\psi(0)\rangle$
- 4 Measure expectation values $\langle\psi(t)|\hat{O}|\psi(t)\rangle$

Minimization algorithm (more traditional many-body)

- 1 Formulate variational space $\{U(\theta_1, \theta_2, \dots, \theta_n)\psi_0\}$
- 2 Calculate $\langle H \rangle$ on quantum computer
- 3 Minimize over θ_i

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Simple calculations at hand

Example: Triply heavy baryons
with QCD Cornell potential

$$V(r) = \frac{\alpha_s}{r} + \sigma r$$

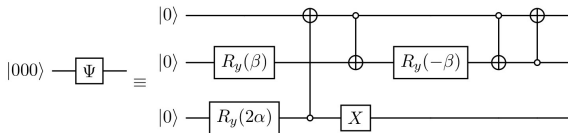
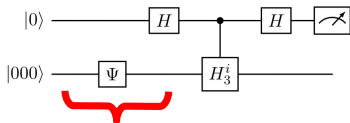


EPJA with
Nicolás Martínez de Arenaza,

Baryon (composition)	$\Omega(bbb)$	$\Omega(bbc)$	$\Omega(bcc)$	$\Omega(ccc)$
This work	14270 \pm 340	11210 \pm 350	8100 \pm 350	4940 \pm 340
Variational pNRQCD	14700 \pm 300	11400 \pm 300	8150 \pm 300	4900 \pm 250
Coulomb variational	14370 \pm 80	11190 \pm 80	7980 \pm 70	4760 \pm 60
QCD sum rules	13280 \pm 100	10460 \pm 110	7443 \pm 150	4670 \pm 150
Quark counting	14760 \pm 180	11480 \pm 120	8200 \pm 90	4925 \pm 90
MIT bag model	14300	11200	8030	4790

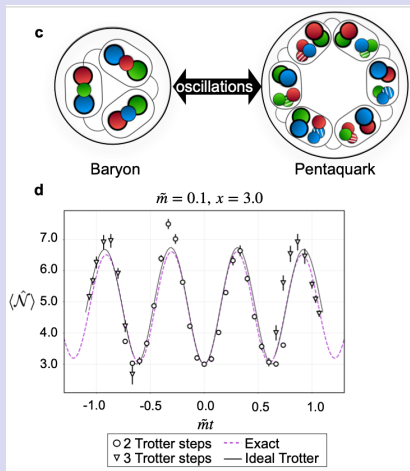
With very few qubits (quantum computer = small diagonalizer)

State preparation & measurement of Hamiltonian



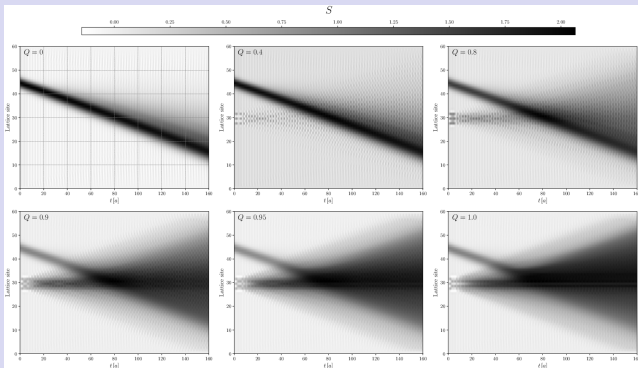
Simple calculations already working...
but Lattice can do it better (for now) at less cost! (forever?)

Time evolution with H_{QCD}



Y. Y. Atas et al. Phys. Rev. Res. 5, 033184 (2023)

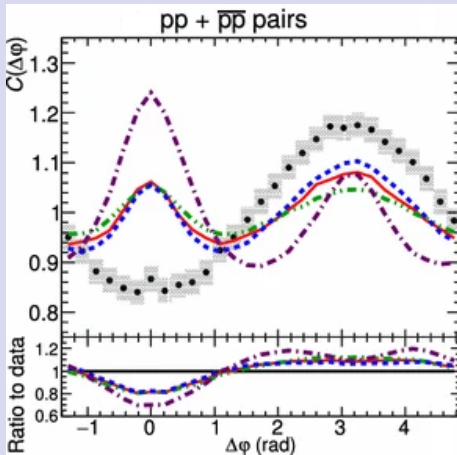
Jet energy loss in Schwinger model



Shows S production for jet+medium, increasing coupling

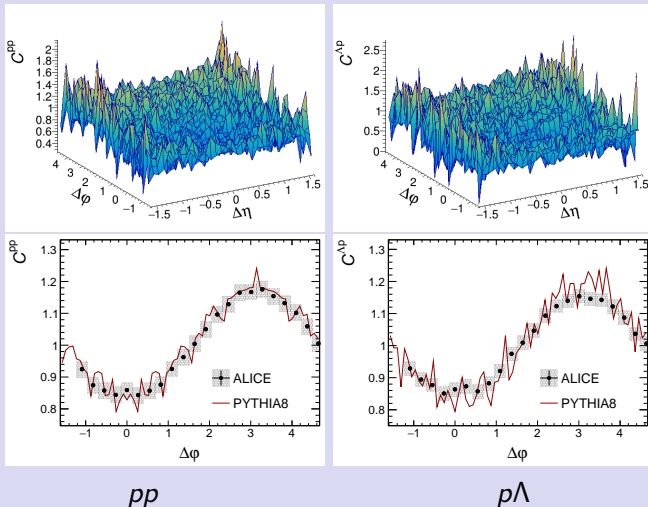
J. Barata and E. Rico, arXiv:2502.17558 [hep-ph]

Monte Carlo generators use classical probability



Gross disagreement at $\varphi = 0$:
Pythia is missing baryon anticorrelations

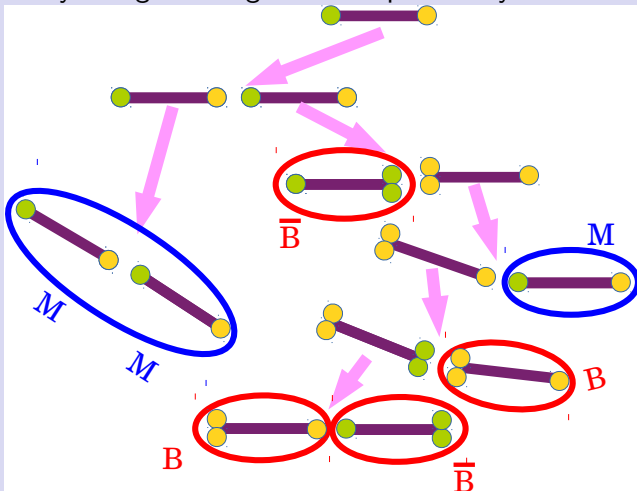
Ad hoc fix: One-baryon policy and All-baryon policy



Brings Pythia 8 in agreement with ALICE data

Rewrite parts of generators for a quantum chip?

Hadronization by string breaking: classical probability

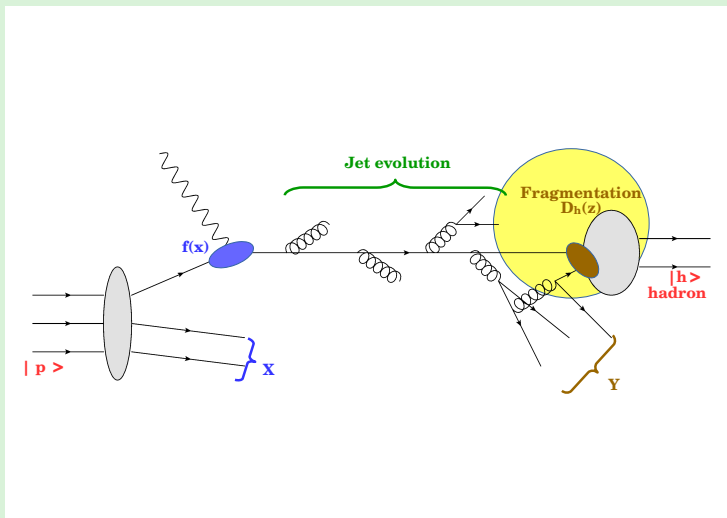


- 1) Separate the baryons;
- 2) How about entanglement/Bell inequalities?

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Fragmentation functions: from quarks to hadrons

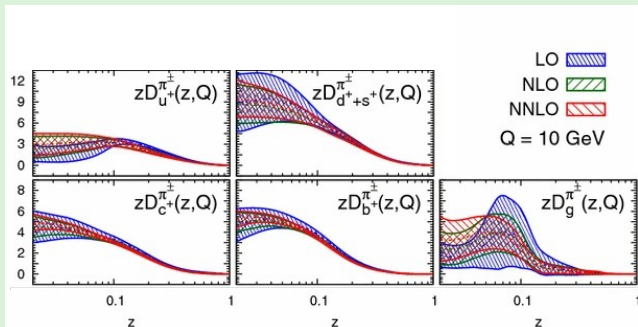


Fragmentation functions: evolution with light-front time

$$D_{(0) h/j}(z) = \frac{\text{Tr}}{4} \left(\gamma^- \times \frac{z}{z^{2\epsilon}} \sum_X \int \frac{dx^+}{2\pi} e^{i(zp^-)x^+} \right. \\ \left. \langle 0 | \psi_j^{(0)}(x) | h, X \rangle_{\text{out}} \langle h, X | \bar{\psi}_j^{(0)}(0) | 0 \rangle \right)$$

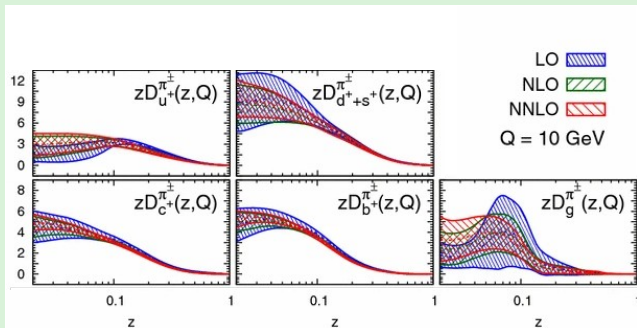
$x := (x^+, 0, 0_\perp)$ Not the simplest lattice computation

Fragmentation functions: normally extracted from data



- See talk by J.J. Gálvez-Viruet later on

Fragmentation functions: normally extracted from data



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Light-front QCD Hamiltonian

n	Sector	1 q \bar{q}	2 gg	3 q \bar{q} g	4 q \bar{q} q \bar{q}	5 gg g	6 q \bar{q} gg	7 q \bar{q} q \bar{q} g	8 q \bar{q} q \bar{q} q \bar{q}	9 gg gg	10 q \bar{q} gg g	11 q \bar{q} q \bar{q} gg	12 q \bar{q} q \bar{q} q \bar{q} g	13 q \bar{q} q \bar{q} q \bar{q} q \bar{q}
1	q \bar{q}													
2	gg													
3	q \bar{q} g													
4	q \bar{q} q \bar{q}													
5	gg g													
6	q \bar{q} gg													
7	q \bar{q} q \bar{q} g													
8	q \bar{q} q \bar{q} q \bar{q}													
9	gg gg													
10	q \bar{q} gg g													
11	q \bar{q} q \bar{q} gg													
12	q \bar{q} q \bar{q} q \bar{q} g													
13	q \bar{q} q \bar{q} q \bar{q} q \bar{q}													

Brody, Pauli & Pinsky, Phys. Rep. 301 (1998) 299

December 18th, 2025 Based on 2510.2

Transverse Momentum extensions

e.g. SIDIS

$$\frac{d\sigma}{dx dy dz d^2P_{hT}} = \frac{2\pi\alpha^2}{Q^2} (1 + (1-y)^2) \sum_q e_q^2 \times$$
$$\int d^2k_T d^2p_T \delta^{(2)}\left(k_T - p_T - \frac{P_{hT}}{z}\right) f_{q/H}(x, k_T) D_{h/q}(z, p_T)$$

$$f_{q/H}(x, k_T) = \int \frac{dz^- d^2z_T}{(2\pi)^3} e^{ixP^+z^- - ik_T \cdot z_T} \langle P | \bar{\psi}(0) \Gamma \mathcal{W}[0, z] \psi(z) | P \rangle \Big|_{\underbrace{z^+ = 0}}$$

(Timelike separation unnatural in lattice QCD –Euclidean formulation!)

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If your goal is to test gravity...

Einstein's equations in General Relativity

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Well tested in vacuo. And in matter? Neutron stars!

$$T_{\mu\nu} \rightarrow \text{diag}(\epsilon, P, P, P) + \underbrace{\tau_{ij}}_{\text{transport}} + \underbrace{\tau_{ij}^{NH}}_{\text{crystalline}} + \dots$$

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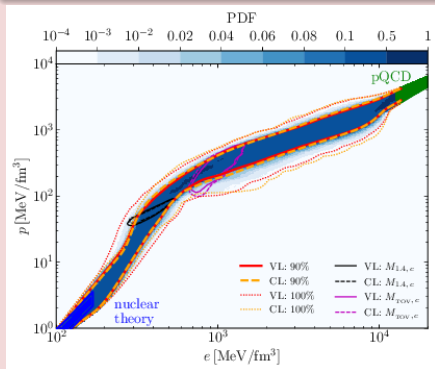
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$$T_{\mu\nu} \rightarrow \text{diag}(\epsilon, P, P, P) + \underbrace{\tau_{ij}}_{\text{transport}} + \underbrace{\tau_{ij}^{NH}}_{\text{crystalline}} + \dots$$

How about extracting the EoS from astrophysics?

Available data

- 1 Maximum neutron star mass
- 2 A few radius estimates
- 3 Upper bound on tidal deformability from aLIGO

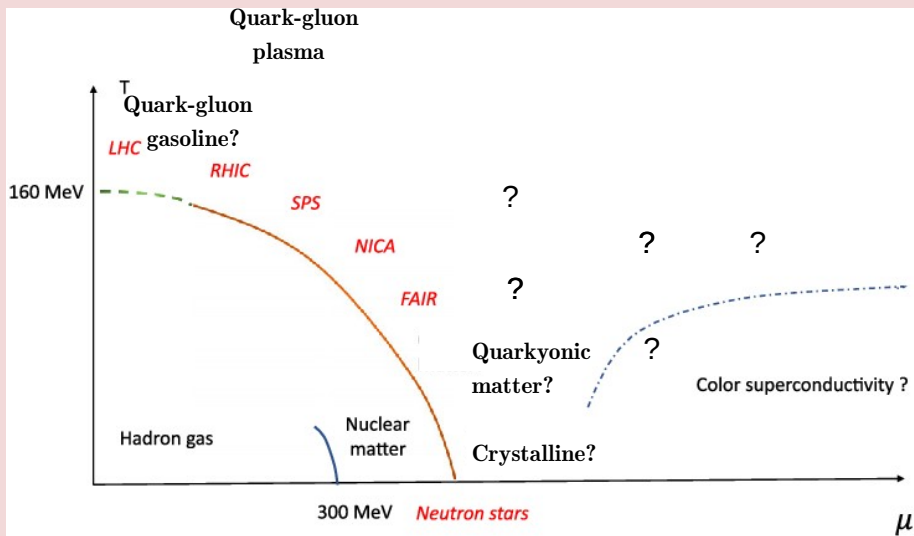


Tighter band

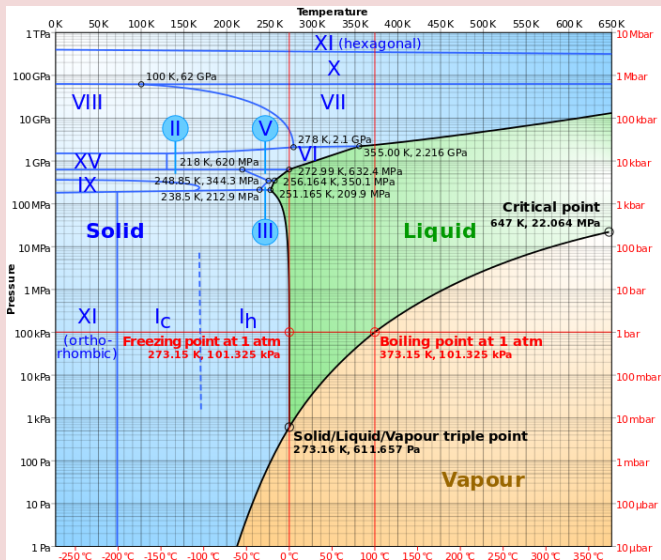
General Relativity assumed!

Inappropriate to test
Modified Gravity

Microscopic physics: QCD phase diagram



Why would it be simpler than water...



- Lattice gauge theory stumbles:
finite chemical potential μ (sign problem)
- Put the QCD EoS on a Quantum Computer (see Nahia's talk later)

- Lattice gauge theory stumbles:
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- Quantum computers would be a great new tool
- Niche problems in hadron physics resisting lattice efforts
- Number of qubits adequate; error rate and decoherence time, not yet
- @ UCM: investigating hadron structure and quark/hadron matter