Title: Quantum Information Meets Particle Physics

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Subject: Cosmology, Particle Physics, Strong Gravity

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Quantum Information Meets Particle Physics

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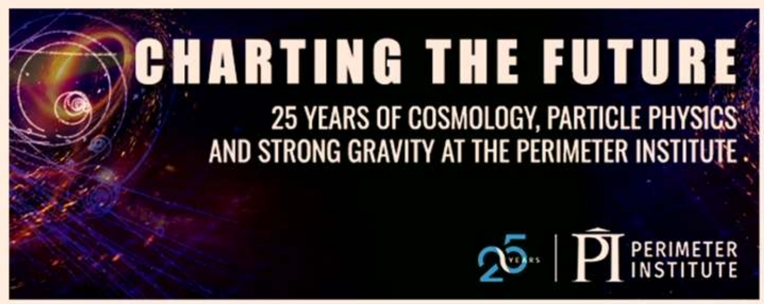
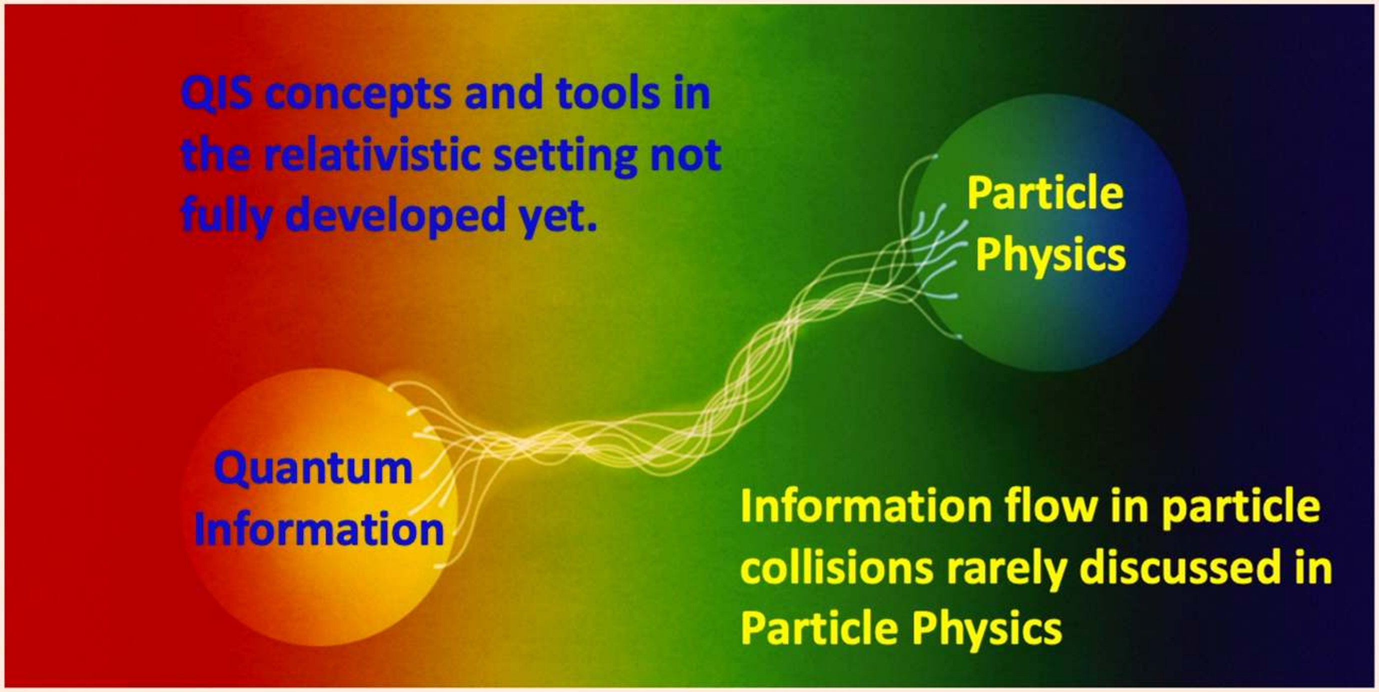


Quantum Mechanics + Information Theory + Relativity



Entanglement is the most prominent feature of Quantum:

- It refers to the situation where a measurement on a subsystem will improve our knowledge on the rest of the system.

- A quantum state of a system is entangled if it cannot be written as a tensor-product state of its subsystems.

Consider a system of two spin-1/2 particles.

- $|\uparrow\downarrow\rangle \equiv |\uparrow\rangle \otimes |\downarrow\rangle$ is an unentangled state:
  Measurement of one spin would not change the outcome of the other.

- $(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$ is an entangled state:
  Measurement of the first spin would collapse the state into $|\uparrow\downarrow\rangle$ or $|\downarrow\uparrow\rangle$, which consequently determines the second spin.

John Wheeler famously claimed:

It from bit : "All things physical are information-theoretic in origin"

INFORMATION, PHYSICS, QUANTUM: THE SEARCH FOR LINKS

John Archibald Wheeler * †

Abstract

This report reviews what quantum physics and information theory have to tell us about the age-old question, How come existence? No escape is evident from four

winnowing: **It from bit**. Otherwise put, every **it** — every particle, every field of force, even the spacetime 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 [52], **bits**.

Three topics at the intersection of Quantum Information and Particle Physics:

- An information-theoretic origin of symmetry
- An area law for entanglement entropy in particle scatterings
- Quantum computational advantage in fundamental forces

Symmetry is among the most fundamental principles in physics:

Chen-Ning Yang famously coined the phrase --
Symmetry dictates Interaction.

- Lorentz invariance →
  Special Relativity
- General coordinate invariance →
  General Relativity
- Gauge invariance →
  QCD and Electroweak theory.

An Information-theoretic Origin of Symmetry

In condensed matter physics, the Landau paradigm:

Phases of matter are represented by their symmetries and whether they are spontaneously broken or not.

- Gapless degrees of freedom → Goldstone modes
- Locus of critical points → Enhanced (emergent) symmetries
- Ginzburg-Landau theory gives a macroscopic description.

But what is the origin of symmetry?

Can symmetry be the outgrowth of more fundamental principles?

Can symmetry come from qubit?

Recent efforts to understand the origin of symmetry from the information-theoretic perspective have uncovered intriguing insights:

- Extremization (minimization or maximization) of entanglement entropy in particle interactions lead to enhanced symmetries.
- Examples encompass both non-relativistic (low-energy QCD) and fully relativistic (two-Higgs-doublet models) systems.
- The observation applies to qubits (spin-1/2) and qudits (spin-3/2).

Emergent symmetries in low-energy QCD (not transparent in the QCD Lagrangian):

- Schrodinger symmetry (non-relativistic conformal invariance):

$$\text{boosts:} \quad \vec{x}\,' = \vec{x} + \vec{v}\,t \ , \ \ t' = t \ ,$$

$$\text{scale:} \quad \vec{x}\,' = \vec{x} + s\vec{x} \ , \ \ t' = t + 2st \ ,$$

$$\text{conformal:} \quad \vec{x}\,' = \vec{x} - ct\vec{x} \ , \ t' = t - ct^2 \ ,$$

Hagen and Niederer, 1972

- Wigner's SU(4) Spin-flavor symmetries for protons and neutrons

$$N = \begin{pmatrix} p_\uparrow \\ p_\downarrow \\ n_\uparrow \\ n_\downarrow \end{pmatrix} \qquad N \to \mathcal{U}N \ , \quad \mathcal{U} \in SU(4)$$

E. P. Wigner (1934)

Let's consider non-relativistic, S-wave scattering of a neutron and a proton:

- Treat them as two qubits -- Alice (neutron) and Bob (proton)

- The S-matrix can be decomposed into ${}^{1}S_{0}$ and ${}^{3}S_{1}$ channels
  → there are two phase shifts: δ_0 and δ_1 , respectively.

- Rotational invariance and Unitarity then uniquely fix the S-matrix:

$$S = e^{2i\delta_0}\,\frac{(1-\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})}{4} + e^{2i\delta_1}\,\frac{(3+\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})}{4}$$

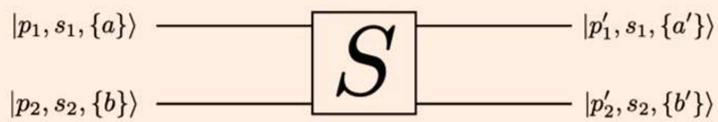
Spin-projector into ${}^{1}S_{0}$ channel

Spin-projector into ${}^{3}S_{1}$ channel

- In the scattering process the S-matrix acts on the IN-state:

$$|\mathrm{out}\rangle = S\ |\mathrm{in}\rangle$$

- For 2-to-2 scattering of spin-1/2 fermions, the S-matrix can be viewed as a two-qubit quantum logic gate acting on the spin-space:



- Can characterize the ability of the S-matrix to generate entanglement from unentangled initial states.

- Entanglement is a property of the quantum state. But we are more interested in the ability of a *quantum-mechanical operator* (i.e. the S-matrix) to entangle.

- However, there is a subtlety here, as the amount of entanglement generated by an operator could depend on the initial state.

- The "entanglement power" deals with this issue is by averaging over the initial states:

$$E(U) = \overline{E(U\,|\psi_1\rangle \otimes |\psi_2\rangle)},$$

For quibts, the average is over the Bloch sphere.

It is a measure of the ability of an operator *U* to generate entanglement on product states.

- A minimally entangling operator has *E*(*U*) = 0, i.e.,

$$|\ \ \rangle \otimes |\ \ \rangle \xrightarrow{U} |\ \ \rangle \otimes |\ \ \rangle$$

It turns out there are two and only two minimally entangling operators, which in the computational basis, $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$

$$\mathbf{1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \qquad \mathrm{SWAP} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} .$$

Identity gate: do nothing.
SWAP gate: interchange the qubits.

$$\mathrm{SWAP} \sim -1 \quad \text{as} \quad [\mathrm{SWAP}]^2 = 1$$

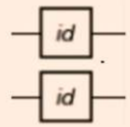
In terms of Pauli matrices,

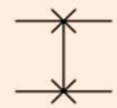
$$\mathrm{SWAP} = (1 + \boldsymbol{\sigma} \cdot \boldsymbol{\sigma})/2 \,, \qquad \boldsymbol{\sigma} \cdot \boldsymbol{\sigma} \equiv \sum_a \boldsymbol{\sigma}^a \otimes \boldsymbol{\sigma}^a \,.$$

Low, Mehen: 2104.10835

Re-write the S-matrix in terms of quantum logic gates,

$$S = \frac{1}{2}\left(e^{2i\delta_1} + e^{2i\delta_0}\right)\mathbf{1} + \frac{1}{2}\left(e^{2i\delta_1} - e^{2i\delta_0}\right)\ \mathrm{SWAP},$$

$$S = \frac{1}{2}\left(e^{2i\delta_1} + e^{2i\delta_0}\right)$$ 

$$+ \ \frac{1}{2}\left(e^{2i\delta_1} - e^{2i\delta_0}\right)$$ 

Conditions for the S-matrix to minimize entanglement:

1. $S = 1$ if $\delta_0 = \delta_1$ ➡ SU(4) spin-flavor symmetry
2. S = SWAP if $|\delta_0 - \delta_1| = \pi/2$ ➡ Schrodinger symmtery

Low, Mehen: 2104.10835

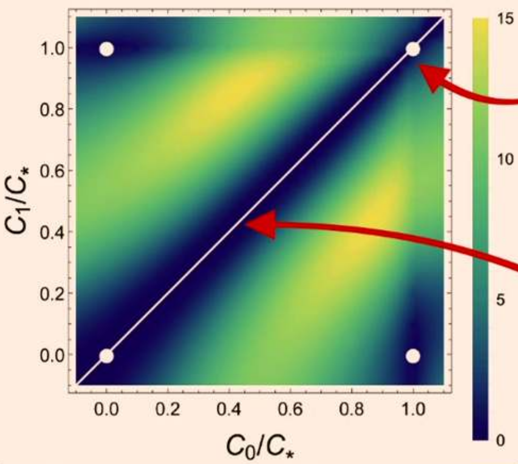
This observation was first made by the Seattle group in 1812.03138:

$$\mathcal{L}_6 = -\tfrac{1}{2}C_S(N^\dagger N)^2 - \tfrac{1}{2}C_T(N^\dagger \vec{\sigma} N)^2$$

$$^1S_0: \quad \bar{C}_0 = (C_S - 3C_T)$$

$$^3S_1: \quad \bar{C}_1 = (C_S + C_T)$$

$$\mathcal{E}(\hat{\mathbf{S}}) = \frac{1}{6}\,\sin^2\left(2(\delta_1 - \delta_0)\right)$$



Conformal fixed points (zero or infinite scattering lengths, $\delta_i = 0, \pi/2$)

$SU(4)_{\text{Wigner}}$ symmetry line ($\delta_0 = \delta_1$)

INSTITUTE for NUCLEAR THEORY D. B. Kaplan ACP: "In Pursuit of New...Paradigms" 3/30/19

Slide by D.B. Kaplan

We have observed similar correlations between entanglement minimization and the appearance of enhanced symmetries in several other systems:

- 2-to-2 scattering of spin-1/2 octet baryons. (Liu, Low, Mehen: 2210.12085)
- 2-to-2 scattering of spin 3/2 decuplet baryons. (Hu, Sone, Guo, Hyodo, Low: 2506.08960)
- Exotic mesons (four-quark bound states) in X(3872) and $T_{cc}(3875)^+$. (Hu, Chen, Guo: 2404.05958.)
- 2-to-2 scattering of Higgs bosons in two-Higgs-doublet models. (Carena, Low, Wagner and Xiao: 2307.08112)

We are in pursuit of a new paradigm:

Can symmetry be the outgrowth of more fundamental principles?

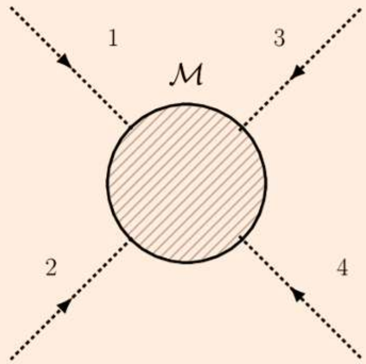
- **Several "data points" are very suggestive, but we don't yet have a precise statement on what the "new principle" is.**

- **Can spontaneously broken symmetries be understood/defined in a similar fashion ?**

  → Can we classify phases of matter from the information-theoretic perspective?

We are interested in the quantum correlations in 2-to-2 scattering of distinguishable particles in the S-matrix formalism:

A B → A B



$$|\text{out}\rangle \equiv S|\text{in}\rangle \qquad S = 1 + iT$$

$$\langle \{k_\mathrm{f}\}, f_\mathrm{f}|T|\{k_\mathrm{i}\}, f_\mathrm{i}\rangle$$
$$= (2\pi)^4 \delta^4 \left(\sum k_\mathrm{f} - \sum k_\mathrm{i} \right) M_{f_\mathrm{i}, f_\mathrm{f}}(\{k_\mathrm{i}\}; \{k_\mathrm{f}\})$$

We construct the bipartite system as

$$\mathcal{H}_\mathrm{AB} = \mathcal{H}_\mathrm{A} \otimes \mathcal{H}_\mathrm{B}$$

$$\mathcal{H}_{A/B} = \mathcal{H}_\mathrm{kinematic} \otimes \mathcal{H}_\mathrm{flavor}$$

Kinematic = momentum and mass
Flavor = everything non-kinematic (could be spin!)

For now, we assume

- A pure initial state
- No entanglement between the incoming momenta
- No entanglement between momentum and flavor quantum numbers
- Allow possible entanglement among flavors

In QFT textbooks it is customary to employ momentum eigenstates for the incoming particles.

$$\langle p|q\rangle = (2\pi)^3\, 2E_p\, \delta^3(\vec{p}-\vec{q})$$

But then $\qquad \rho = |p\rangle\langle p| \qquad \mathrm{Tr}\ \rho = \langle p|p\rangle \ \propto\ \delta^3(0)$

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One possibility is to introduce finite-volume regularization:

$$\delta^3(0) = \int d^3x \ \longrightarrow \ V$$

We will instead introduce wave packets, which is really how we do the experiment!

$$|\text{in}\rangle = \sum_{i,\bar{i}} \Omega_{i\bar{i}} |\psi_{\text{A}}\rangle \otimes |i\rangle \otimes |\psi_{\text{B}}\rangle \otimes |\bar{i}\rangle$$

$$|\psi_{\text{A/B}}\rangle = \int_p \psi_{\text{A/B}}(p)\, |p\rangle, \qquad \int_p \equiv \int \frac{d^3\vec{p}}{(2\pi)^3 \sqrt{2E_p}}$$

$$\langle\psi|\psi\rangle = \int \frac{d^3\vec{p}}{(2\pi)^3}\; |\psi(p)|^2 = 1$$

The initial density matrix is now properly normalized:

$$\rho^{\text{i}} = |\text{in}\rangle\langle\text{in}|$$

$$\text{tr}\rho^{\text{i}} = \langle\text{in}|\text{in}\rangle = \langle\psi_{\text{A}}|\psi_{\text{A}}\rangle\langle\psi_{\text{B}}|\psi_{\text{B}}\rangle = 1$$

We will need an explicit form of wave packet to carry out the calculation.

Finite plane wave limit for wave packets:

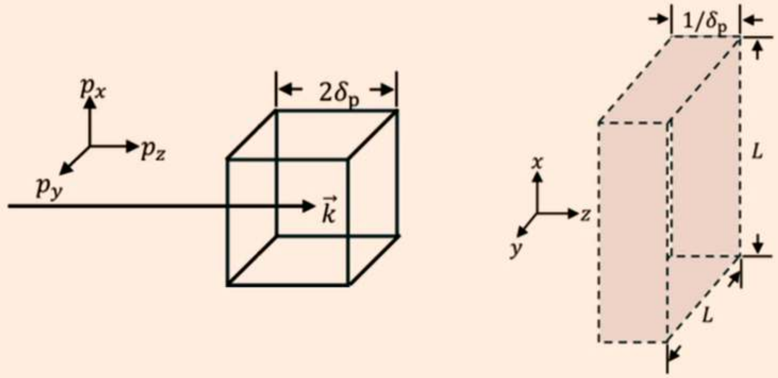
- For any wave packet, we will take the limit that the momentum space wave function is localized about a definitive momentum.

- In the strict limit of momentum eigenstate, the position wave function is a plane wave with an infinite extent

  → **this is not how the experiment is conducted.**

- Instead we will take a “finite” plane wave limit where the transverse dimension of the wave packet is much larger than the longitudinal dimension.

An example: a wave packet that is approximately uniform in the transverse plane in the position space:



(a) In momentum space (b) In position space

L[2] characterizes the transverse size of the wave packet in position space!

The finite plane wave limit is

$$\delta_\mathrm{p}/|\vec{k}| \to 0 \ , \qquad \delta_\mathrm{p} L \gg 1$$

In the position space it looks like a ”square pancake”, as we expect the longitudinal direction to be “Lorentz contracted.”

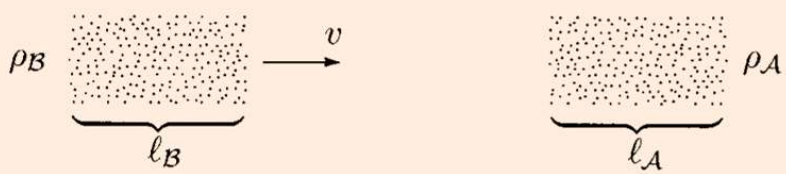
After carefully set up a wave packet formalism to compute the cross section and entanglement entropy in the finite plane wave,

we are going to compute everything to the leading order in $\delta_{\rm p}/|\vec{k}|$

After expanding around the finite plane wave limit,

$$\mathcal{P}_{\rm el} \ = \ \langle {\rm in}|T^\dagger P_{\rm AB} T|{\rm in}\rangle = \frac{\sigma_{\rm el}}{L^2} + \mathcal{O}({\delta_{\rm p}}^5/|\vec{k}|^5).$$

There's an intuitive understanding of this result. Let's go back to Chapter 4 in Peskin and Schroeder:



$$\sigma \equiv \frac{\text{Number of scattering events}}{\rho_{\mathcal{A}}\,\ell_{\mathcal{A}}\,\rho_{\mathcal{B}}\,\ell_{\mathcal{B}}\,A}$$

We are scattering only two particles head on, so

$$\rho_{\mathcal{A}}\ell_{\mathcal{A}}A = \rho_{\mathcal{B}}\ell_{\mathcal{B}}A = 1\ , \quad A = L^2\ , \quad N_{\rm inel} = \mathcal{P}_{\rm inel}$$

Using this result, when the initial state is unentangled in both momentum and flavors, the entanglement entropy between particle A and particle B is

$$\mathcal{E}_2^{\mathrm{f}} = 2\frac{\sigma_{\mathrm{el}}}{L^2} + \mathcal{O}(\delta_{\mathrm{p}}{}^5/|\vec{k}|^5)\,,$$

In plain English:

The entanglement entropy is the cross section in unit of the transverse size of the wave packet.

A few comments are in order:

- To create quantum correlations (entanglement) in the final state, "something" must occur.

  (The "1" in S = 1 +i T can't create entanglement}

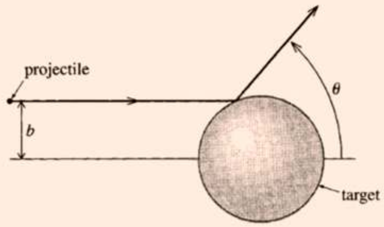
- The physical observable characterizing the probability of "something" happens is cross-section!

- The "non-trivial" outcome is that the entanglement entropy is **linearly** proportional to the cross-section.

- Dimensional analysis dictates the dimensionless ratio (cross-section)/L^2. (In a different regularization scheme, it's less clear what this ratio is.)

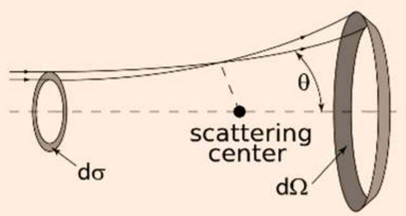
Dual interpretations of the cross section:

- It is an effective area characterizing the strength of interaction when two particles collide:



$$\sigma = \pi r^2$$

- Quantum-mechanically, it is a probability measure of a specific process taking place.



This is an area law: Entropy ~ Area

- It is also natural to wonder if other "area laws" can also be interpreted as some sort of "scattering cross sections"?

The celebrated Bekenstein-Hawking formula for black hole entropy:

$$S_{BH} = \frac{A}{4G_N} = \frac{\pi R^2}{L_{\mathrm{P}\ell}^2}$$

$$\boxed{A = 4\pi R^2; \quad G_N = L_{\mathrm{P}\ell}^2}$$

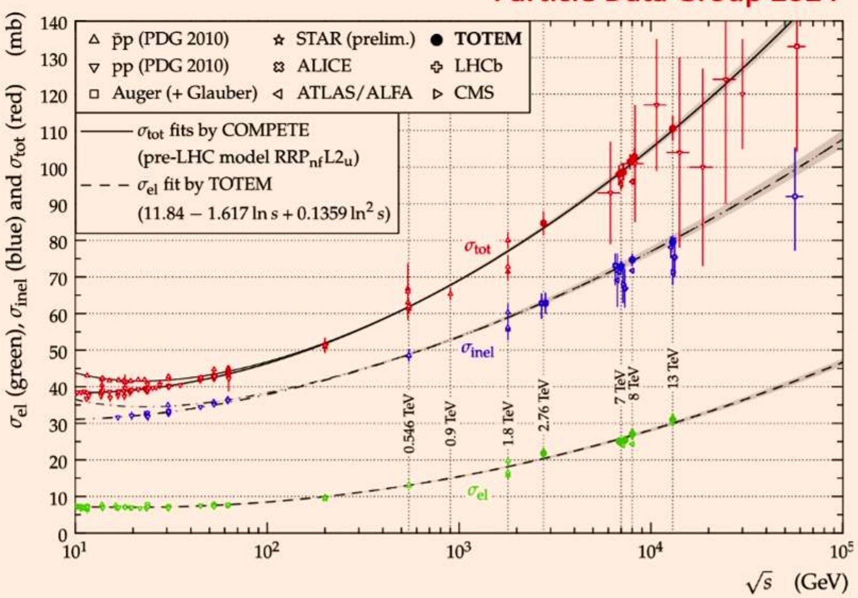
Instead of the surface area of the event horizon, the formula can be written as

$$\text{Entropy} = \frac{\text{Cross} - \text{Sectional Area of the Black Hole}}{\text{Transverse Area of Wave Packets}}$$

Is there a calculation one can do?

- **Total and elastic cross sections are known to increase with respect to energy:**

Particle Data Group 2024



- Froissiart and Martin showed there's a universal bound on the total cross section:

$$\sigma_{\text{tot}} \leq \log^2 s$$

With entropy and energy, one can define a "temperature"

Thermodynamic laws in particle scattering?

Quantum Computational Advantage in Fundamental Forces

Liu, Low, Yin: 2502.17550; 2503.03098.