Inverse problems of indirectly measuring quarks and gluons

Inverse Days 2024

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fame
MATHEMATICS
PHYSICS
COMPUTING

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Overview of topics

- Study of elementary particles is full of inverse problems
- Proton's internal structure: 100+ years of discovery
- Particle accelerator experiments: what do we measure?
- IP1: Scattering off the proton to uncover its structure
- IP2: Scattering off a gluon cloud in the proton
- Future experiments and inverse problems theory

Particle physics is fundamentally inverse problems

The measurement of elementary particles is full of inverse problems:

- The particles are astonishingly small.
    - Hydrogen atom $\sim 10^{-10}$m, proton $\sim 10^{-15}$m, quarks smaller than $\sim 10^{-18}$m.

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- Cannot be freely observed.
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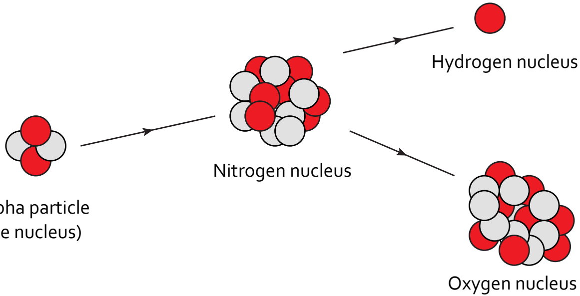
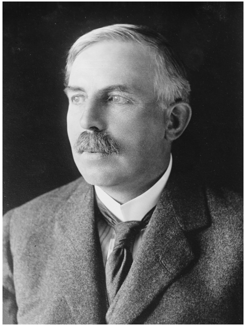
- Often all of the above.

Discovery of the proton in 1919



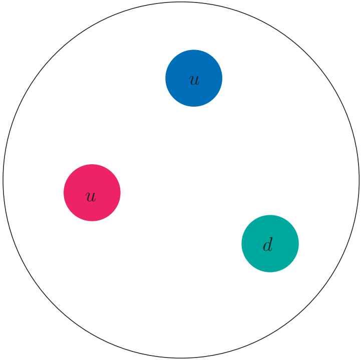
$${}^{4}_{2}\mathrm{He} + {}^{14}_{7}\mathrm{N} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{p}$$



Sir Ernest Rutherford

E. Rutherford, *Collision of α particles with light atoms. An anomalous effect in nitrogen*, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 37.222 (1919) 581–587

100+ years of discovery of the interior of the proton



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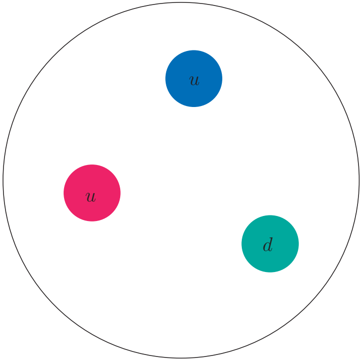

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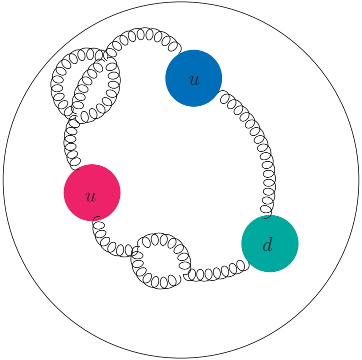

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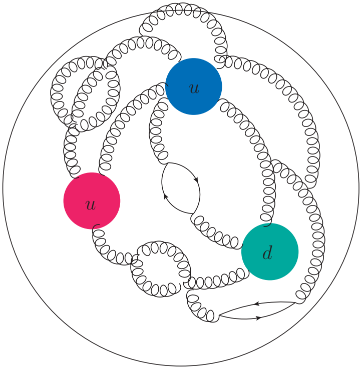

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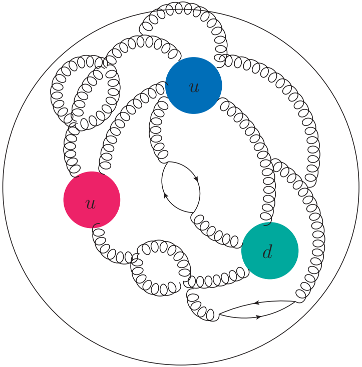

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- Background of sea quarks: momentarily existing quark-antiquark pairs.
- Valence and sea quark densities depend on the energy and size scale: quantified by **parton distribution functions (PDF).**

On-going questions about the proton structure

- Mass composition ($m_p = 1.67262192 \times 10^{-27}$ kg)

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- Gluonic structure and saturation within the proton
- Low-energy structure / quantum wavefunction of the proton

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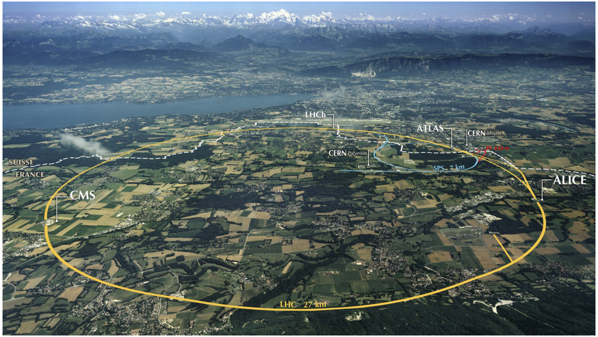
How do we make measurements?

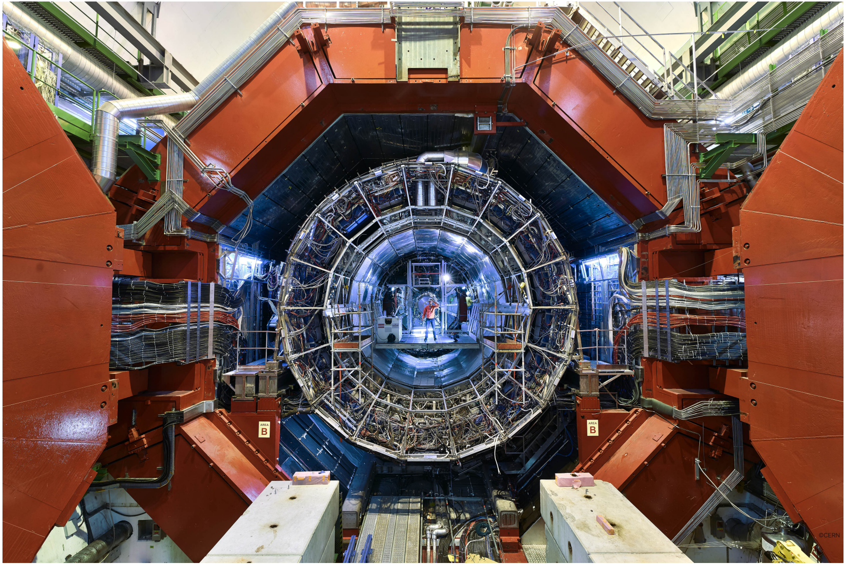
The diameter of a proton is about 1 femtometer (10^{-15} meters), how do we measure its internal structure?

Large Hadron Collider

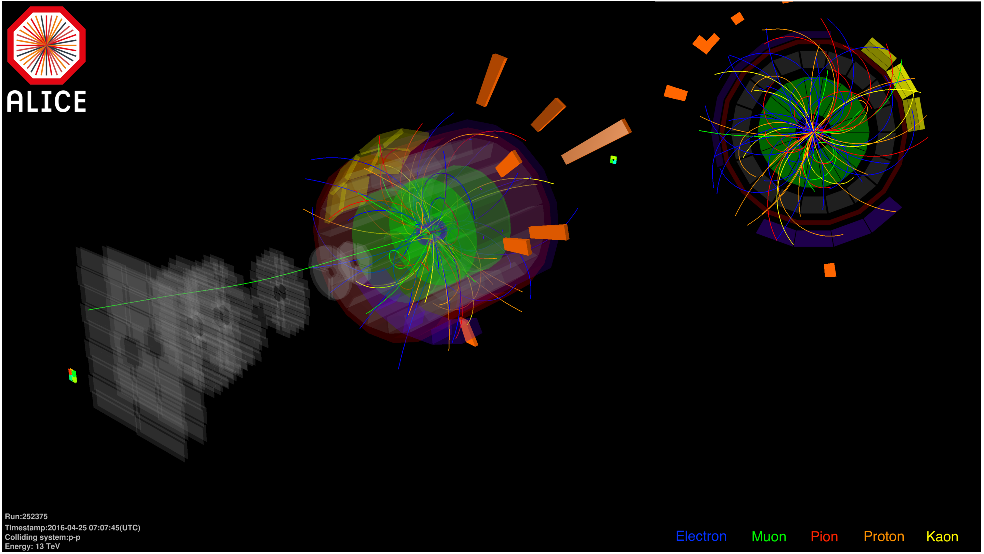


- Located at CERN on the Franco-Swiss border near Geneva.
- LHC circumference is 26659 metres.
- Beam tunnel 100 meters underground on the bedrock for stability and shielding from cosmic rays.

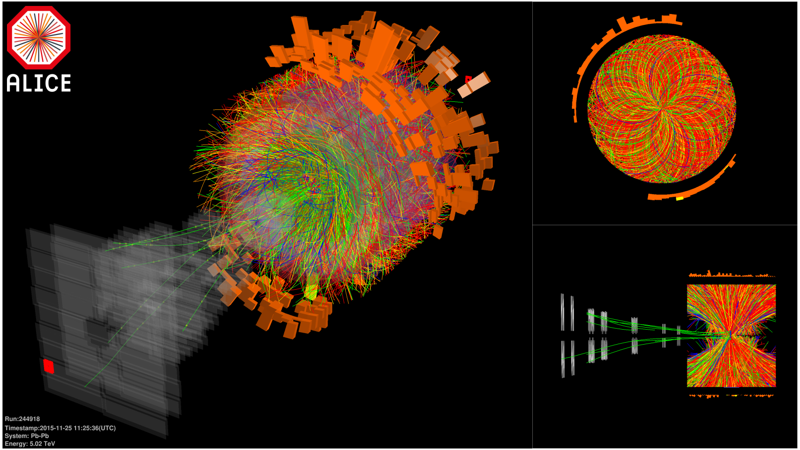
The ALICE detector at CERN



Proton–proton collision at CERN (ALICE)



Lead–lead heavy ion collision at CERN (ALICE)



- $\sim$ 1 billion collisions/s
- generates $\sim$ 1 petabyte of collision data per second (can't save all of it!)[a]
- $\geq$ 100 petabytes/year of filtered data stored (2018)
- $\geq$ 380 petabytes in long-term archival on magnetic tapes (2021)

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[a] `https://information-technology.web.cern.ch/sites/default/files/CERNDataCentre_KeyInformation_Nov2021V1.pdf`

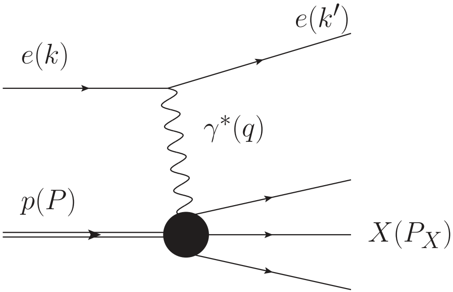
Connecting theory and experiment: cross section

Experiment observes the *reaction frequency*: $W_r = \sigma_r J_a N_b$,

- Reaction frequency W_r = number of scatterings / time
- $J_a = n_a v_{TRF}$ flux of incoming particles in the Target Rest Frame
- N_b = number of target particles in the volume that the projectile beam passes inside the target
- σ_r = "cross section" of the scattering process r.
  - $\sigma_r \propto$ probability of the scattering process r.

$\Longrightarrow$ Cross section is the interface between experiment and theory.

Deep inelastic electron–proton scattering (DIS)



The electron scatters by emitting a virtual photon, which hits a parton in the proton and breaks it apart.

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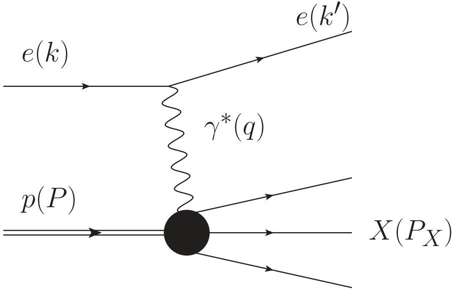

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This is the particle collider analogue of a microscope: we're looking into the proton with a very short wavelength photon, produced by the high-energy electron.

Parton distribution functions in QFT scattering

Proton structure can be described in terms of so-called **parton distribution functions**.

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[2] Peskin & Shroeder, An Introduction to Quantum Field Theory

Parton distribution functions in QFT scattering

Proton structure can be described in terms of so-called **parton distribution functions**. Consider the probability that anything happens in the *ep* collision (inclusive DIS). The corresponding total cross section σ can be written[2]

$$\sigma_{\text{pdf}}^{e^- p \to e^- X}(x, Q) = \left(\sum_{i \in u,d,s,..} f_i(x, Q) e_i^2 \right) \frac{2\pi\alpha s}{Q^4} \left[1 + (1-y)^2 \right],$$

where $x := \frac{Q^2}{2P \cdot q}$ (Bjorken-x), $y := \frac{2P \cdot q}{s}$ (inelasticity), dimensionless variables, $x, y \in [0, 1]$. Momenta P, q, Q and energy $\sqrt{s}$ measured. The sum goes over parton flavors: *up*, *down*, and so on.

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Task is to extract the functions f_i from data. In complete generality one should include also those of antiquarks separately, 12 unknown functions in total.

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Global analysis of all possible scattering data

To constrain all the unknown PDFs, so-called global analysis uses data from multiple scattering processes.

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For example in neutrino-proton DIS the total cross section becomes[3]:

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Recent PDF progress: EPPS21: 2112.12462 [hep-ph], NNPDF4.0: 2109.02653 [hep-ph]

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Recent PDF progress: EPPS21: 2112.12462 [hep-ph], NNPDF4.0: 2109.02653 [hep-ph]
Extension of 'inference-by-fit' to a more rigorous indirect measurement would be of high interest and impact in the field.

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Charm quarks in the proton?

Context: proton has mass $1.67262192 \times 10^{-27}$ kg, charm quark has 2.264×10^{-27} kg.

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Mathematically rigorous analysis of the PDF inverse problem could be impactful, and perhaps help solidify novel discoveries?

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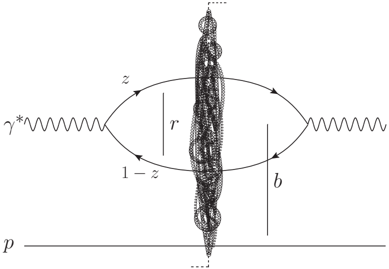
Scattering off the Color Glass Condensate



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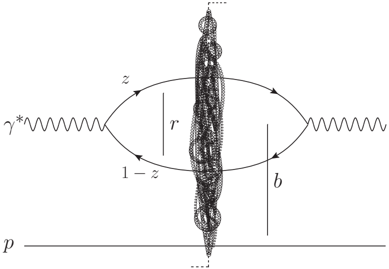

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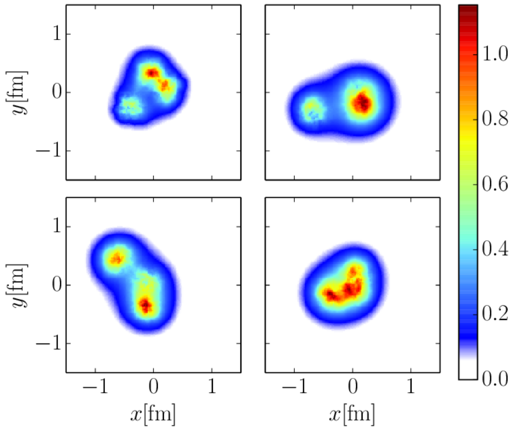
The total cross section ($\sim$ probability of scattering) is the Color Glass Condensate picture:

$$\sigma_{\text{dip.}}^{e^- p \to e^- X}(x, Q) \sim \# \int_0^\infty \sum_{i \in u,d,s,..} \left[f_T^{(i)}(r, Q^2) + \frac{2(1-y)}{1+(1-y)^2} f_L^{(i)}(r, Q^2) \right] N(r, x) \, \mathrm{d}r,$$

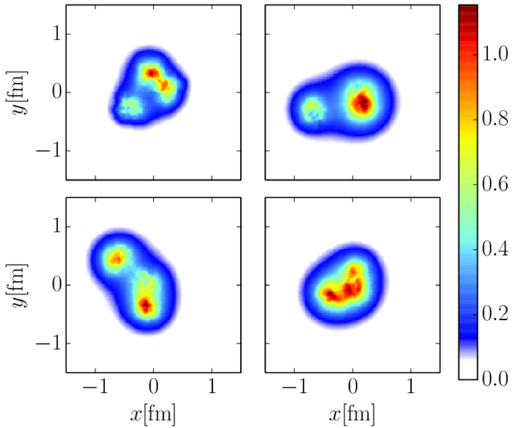
where so-called **dipole amplitude** $N(r,x)$ is the unknown function to be inferred from data. The functions f_T, f_L are known from quantum field theory calculations.

Proton density hot-spots



State-of-the-art proton structure phenomenology[a] is exploring the statistical fluctuations of so-called hot-spots inside the proton.

Proton density hot-spots



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Density profiles are achieved by building a forward model of a proton composed of hot-spots, which is then fit to data to constrain the distribution shape parameters.

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[a] H. Mäntysaari, B. Schenke, Phys.Rev.D 94 (2016) 3, 034042

Actively researched inverse problems in high-energy physics[5]

Particle accelerator experiments (LHC, RHIC, Electron-Ion Collider (2030s), FCC?) study:

- (Nuclear) parton distribution functions
  - EPPS21: 2112.12462 [hep-ph], NNPDF4.0: 2109.02653 [hep-ph]

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- Generalized distributions:
  - Transverse Momentum Distributions (TMD): 1101.5057 [hep-ph], 1507.05267 [hep-ph]
  - Generalized Parton Distributions (GPD): hep-ph/0504030, 0711.2625 [hep-ph]
    - Deconvolution problem: 2104.03836 [hep-ph]

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Layers of PDF, dipole amplitude inverse problem

Task	State-of-the-art	Up-coming, (Under study)
Collider experiments	LHC, RHIC, (HERA)	EIC in the 2030s, (FCC, LHeC)
Physics theory	Precision cross section calculations based on PDFs or the dipole picture.	Generalized Parton Distributions, ever improving precision
Comparison of theory and data	'Global analysis', Bayesian fits, Neural networks	**Inverse problems theory and reconstruction**

Summa summarum

- Particle physics as a field is full of application of inverse problems to study the smallest objects in the universe. There is still much to learn.

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- The high-energy physics community is planning and building next generation colliders to peer deeper into the proton than ever before. EIC begins operation in 2030s, LHC will continue to operate for years to come.

Summa summarum

- Particle physics as a field is full of application of inverse problems to study the smallest objects in the universe. There is still much to learn.
- The high-energy physics community is planning and building next generation colliders to peer deeper into the proton than ever before. EIC begins operation in 2030s, LHC will continue to operate for years to come.
- $\Longrightarrow$ High time to **develop rigorous theory of indirect measurement** for high precision applications in particle physics.
  - Great potential for novel physical discovery!

Thank you for listening!

Questions? Ideas?

Contact:

`henri.j.hanninen@jyu.fi`

`https://hhannine.github.io/`