Probing the structure of matter at hadron colliders

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22nd Conference of Czech and Slovak Physicists

Techical University Liberec

September 2026

Co-funded by the European Union

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Structure of Matter - Atomism

For behold whenever
The sun's light and the rays, let in, pour down
Across dark halls of houses: thou wilt see
...
For thou wilt mark here many a speck, impelled
By viewless blows, to change its little course,
And beaten backwards to return again,
Hither and thither in all directions round.
...
Thus motion ascends from the primevals on,
And stage by stage emerges to our sense.

Lucretius, De rerum natura, Book II, 114-141, c. 55 BC
trans. W. E. Leonard (1916)

Lucretius (c. 99-55 BC)
poetic exposition of Epicurean atomism

↓

Epicurus (341-270 BC) - developed Democritean atomism

↓

Democritus (c. 460-370 BC)
comprehensive atomistic theory

↓

Leucippus (5th century BC) - founder of Greek atomism

Leucippus and Democritus

- matter consists of **indivisible particles** - **atomoi**
- atoms move in **empty space** - **the void**
- atoms differ in shape and arrangement
- change comes from atomic motion and rearrangement

Overview

Historical prelude

- atomism and the idea of indivisible constituents
- patterns, symmetries, and structure of matter

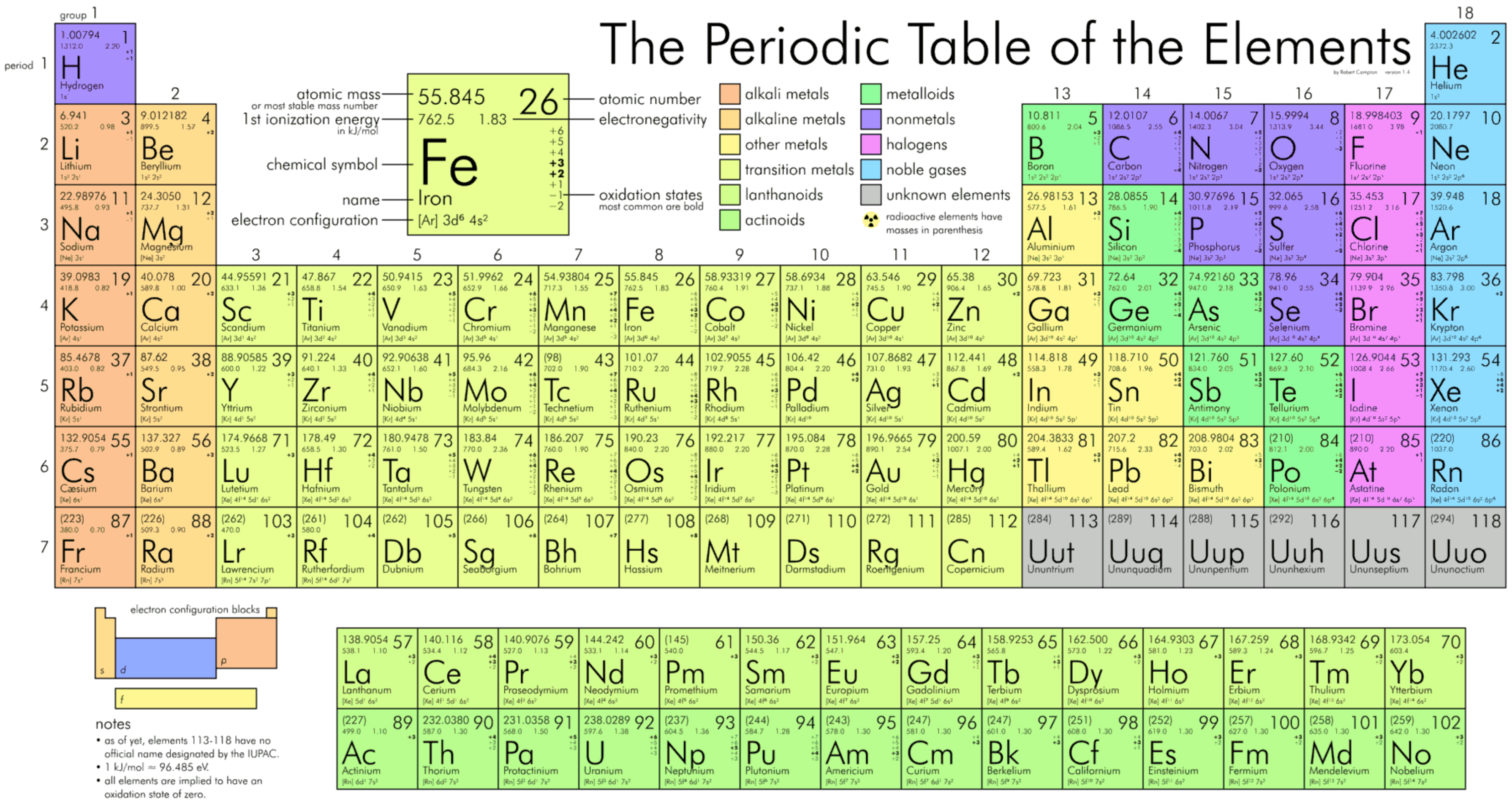
Road to quarks

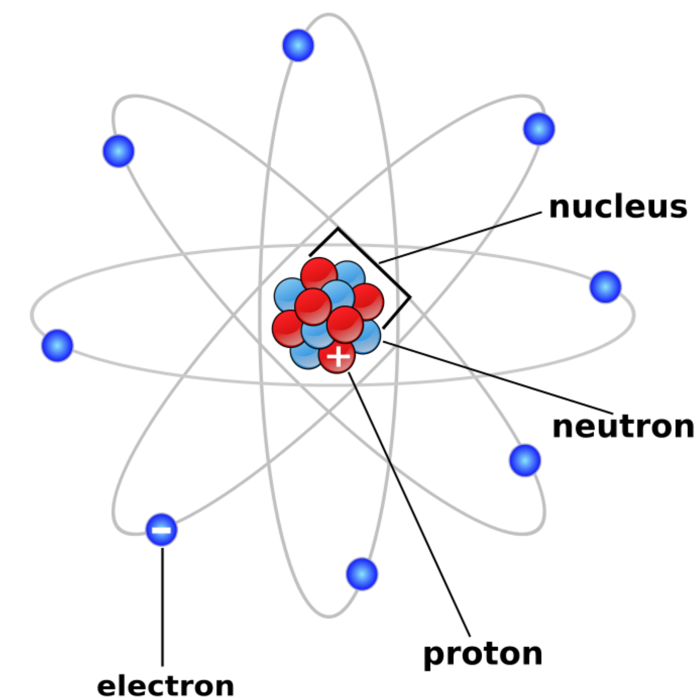
- historical milestones of our understanding of proton structure
- Rutherford scattering, DIS at SLAC, parton model, parton distribution functions and QCD

Jets at hadron colliders and structure of proton

- jet production at Tevatron and LHC experiments
- concentrate on presentation of my research and research of my colleagues

Periodic table of elements (Mendeleev 1869)





http://www.wpclipart.com/

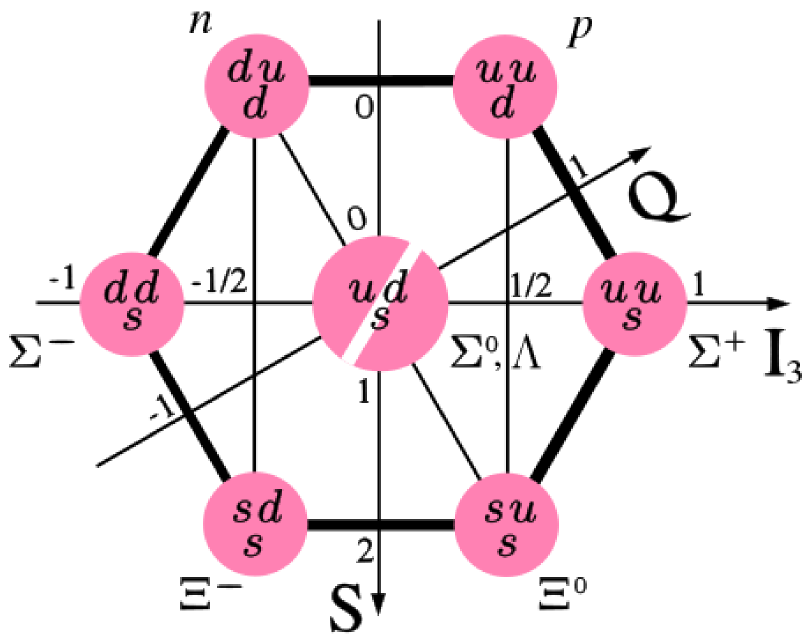
Took some time to understand what is behind the symmetries in the table

Experiment: discovery of electron (Thompson, 1897), atomic nucleus (Rutherford, 1910)

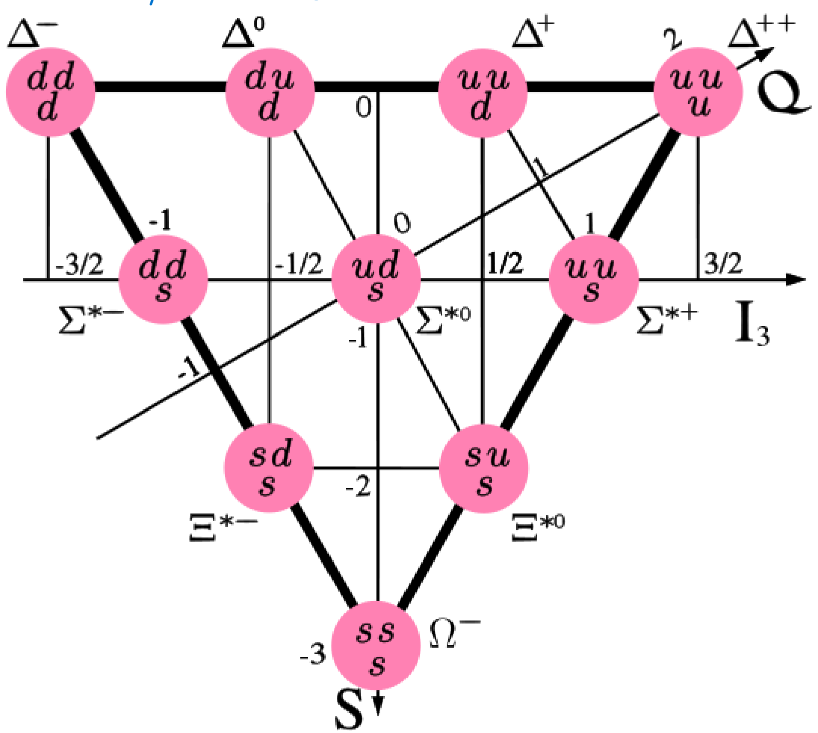
Theory: electrodynamics (Maxwell 1861-1862), quantum mechanics (Schrödinger 1926)

Periodic table of hadrons - quark model

Spin $1/2$ baryons



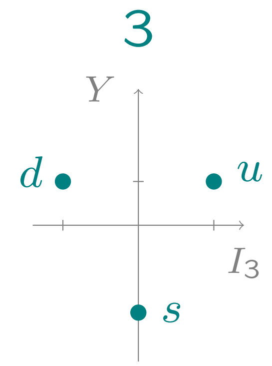
Spin $3/2$ baryons

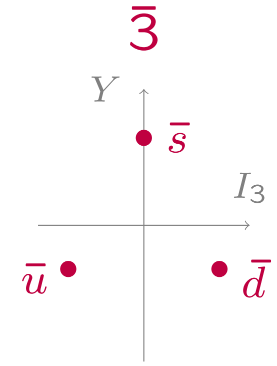


Gell-Mann

Zweig

1961-1962





- hadrons form SU(3) multiplets
  two conserved quantum numbers
  isospin (I_3) and **strangeness** (S)
- baryons (fermions) - qqq
  - proton: uud
- mesons (bosons) - $q\bar{q}$
- prediction of new particles and their properties $(m,\ \mu)$

CERN, July 1962

Experiment: Is it possible to see individual quarks?

Theory: The nature of interactions between quarks?
Are quarks elementary particles?

Looking inside the proton

- we need light with high enough energy: Heisenberg relation of uncertainty $\Delta x \Delta p \geq \hbar/2$
- natural units where $\hbar = c = 1$. Connection with SI units through $\hbar c \sim 200$ MeV $\cdot$ fm

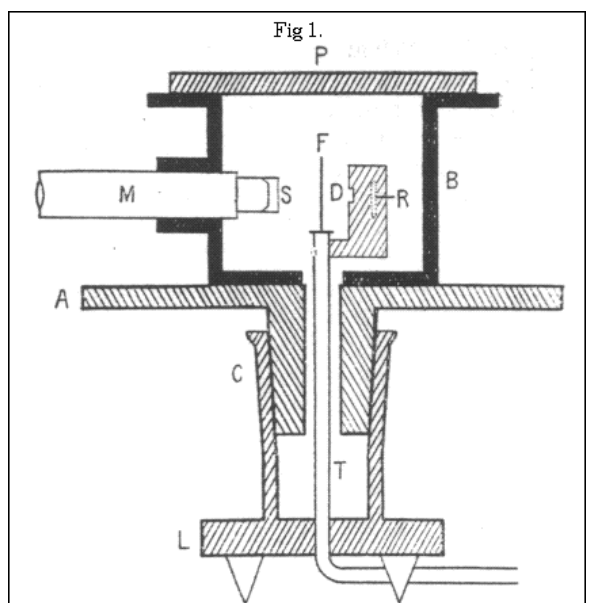
$E_\gamma \sim 2\,\mathrm{eV}$ $\qquad$ $E_\gamma \sim 2\,\mathrm{MeV}$

$100\,\mathrm{nm}$ $\qquad$ 100 fm

light source: Sun $\qquad$ α particles from ^{88}Ra

Science Museum, London (CC BY-SA)

Pasteur's microscope



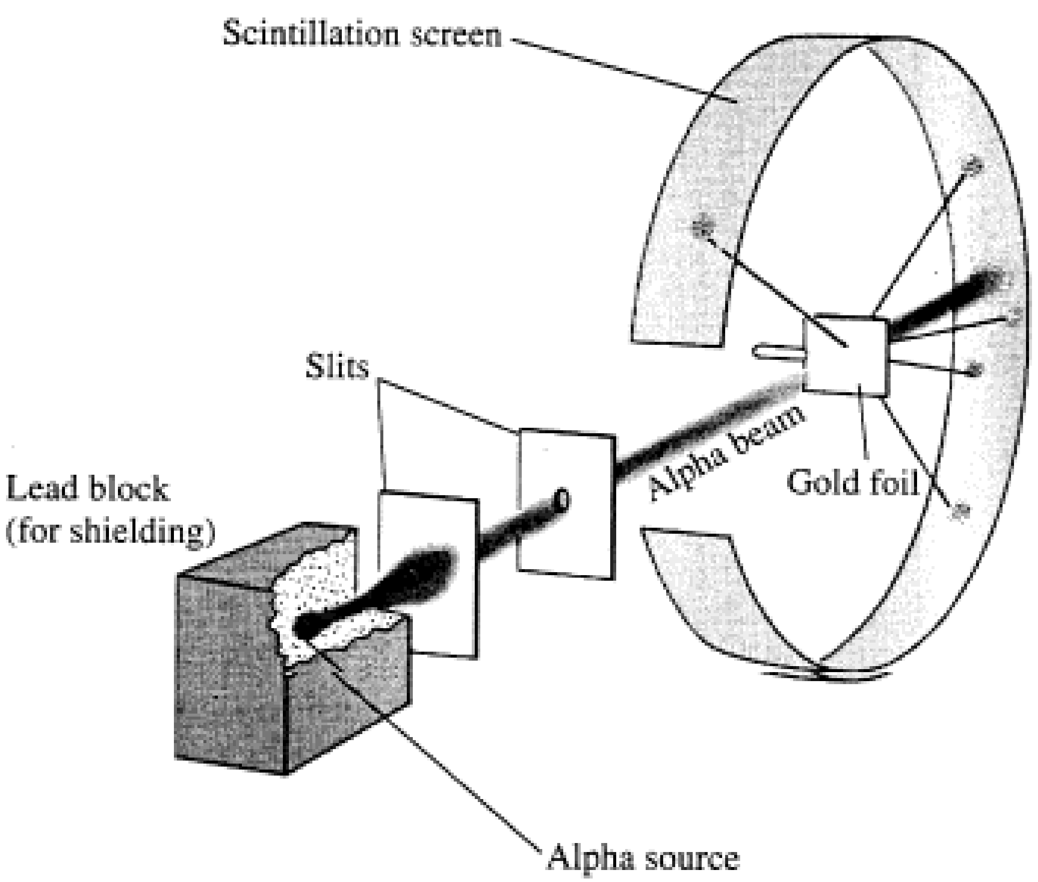
Geiger, Marsden (1913)

Rutherford experiment

$R_{Au} < 30$ fm

Rutherford experiment - atomic nucleus

- scattering of α particles on gold foil
- angular distribution corresponded to a scattering on a point-like charge
- $E_\alpha = 7.86$ MeV $\Rightarrow$ positive charge is localized in a sphere with $R < 30$ fm

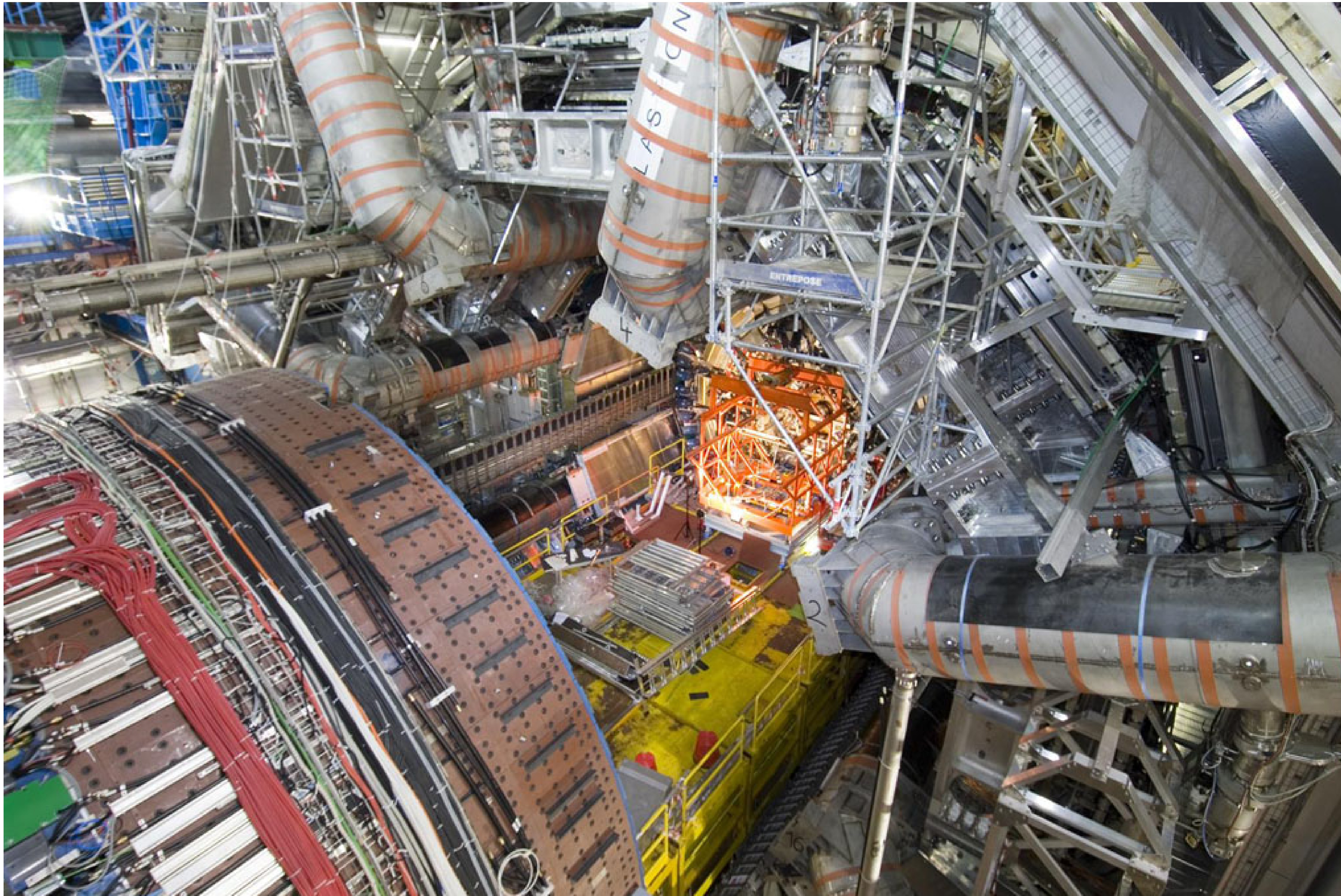


Marsden and Rutherford, Manchester University

- first particle physics experiment
- experimental setup could fit on a table
- nowadays collider experiments are basically of the same nature

  beam - target (second beam) - detector
- just a little bit sophisticated and a little bit larger

Detector ATLAS at LHC



Construction of detector ATLAS

Cross section

Cross section (σ) - a measure of the likelihood of a given interaction or process

Experiment - $N = \sigma \mathcal{L}_{\text{int}}$

- number of observed events $=$ cross section $\times$ integrated luminosity

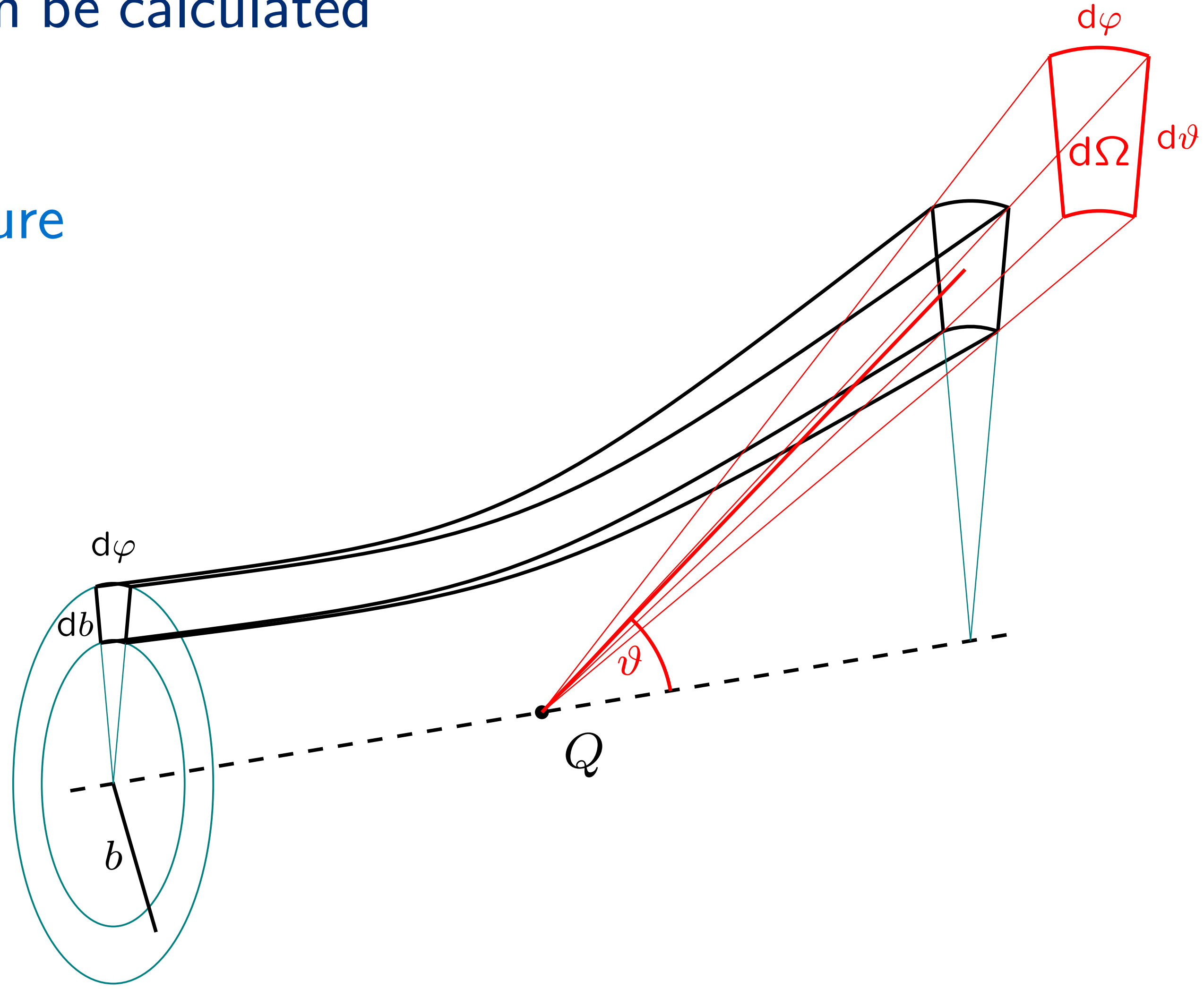
Theory

- for a given interaction potential, the cross section can be calculated
- in both classical and quantum mechanics

$$\left[N \to \sigma_{\text{meas}} \quad \text{vs.} \quad \sigma_{\text{theory}}(\text{model})\right] \quad \Rightarrow \quad \text{structure}$$

Rutherford scattering on point-like Coulomb charge

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{E^2 \sin^4 \frac{\vartheta}{2}}$$



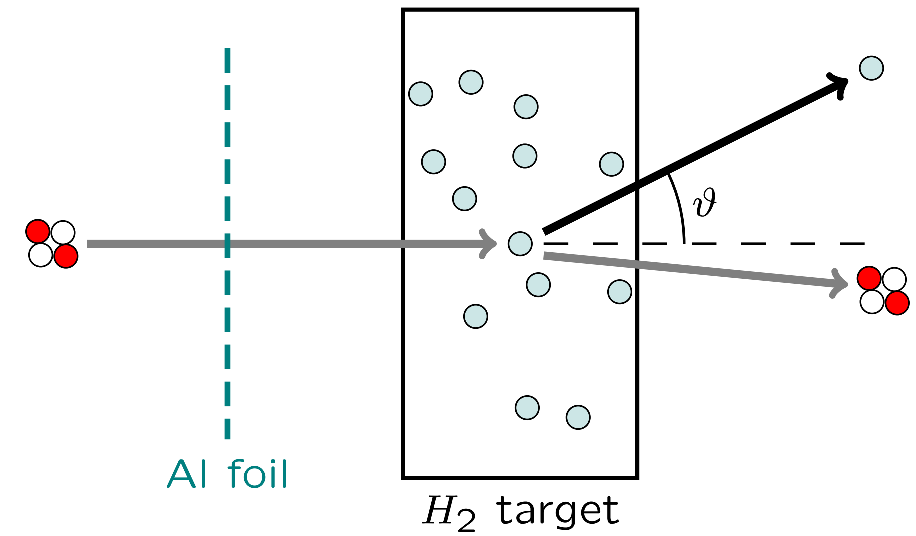
Rutherford scattering - from size of nucleus to nuclear forces

TABLE II.

Variation of Scattering with Angle. (Collected results.)

I. Angle of deflexion, ϕ.	II. $\frac{1}{\sin^4 \phi/2}$	III. Silver. Number of scintillations, N.	IV. Silver. $\frac{N}{\sin^4 \phi/2}$	V. Gold. Number of scintillations, N.	VI. Gold. $\frac{N}{\sin^4 \phi/2}$
150°	1·15	22·2	19·3	33·1	28·8
135	1·38	27·4	19·8	43·0	31·2
120	1·79	33·0	18·4	51·9	29·0
105	2·53	47·3	18·7	69·5	27·5
75	7·25	136	18·8	211	29·1
60	16·0	320	20·0	477	29·8
45	46·6	989	21·2	1435	30·8
37·5	93·7	1760	18·8	3300	35·3
30	223	5260	23·6	7800	35·0
22·5	690	20300	29·4	27300	39·6
15	3445	105400	30·6	132000	38·4
30	223	5·3	0·024	3·1	0·014
22·5	690	16·6	0·024	8·4	0·012
15	3445	93·0	0·027	48·2	0·014
10	17330	508	0·029	200	0·0115
7·5	54650	1710	0·031	607	0·011
5	276300	...	...	3320	0·012

H. Geiger and E. Marsden (1913) Philosophical Magazine 25, 604-623



Gold and Silver foils

- agrees with point-like Coulomb scattering
- $E_\alpha = 7.9$ MeV $\quad \Rightarrow r_{\text{min}} \sim 30$ fm

$\Rightarrow \quad R_{\text{nucleus}} < 30$ fm

Hydrogen target

- E_α controlled by passing through Al foils of different thicknesses
- increase of scattering above Coulomb expectation at the highest energies
- α and proton approach to few fm
- onset of non-Coulomb

$\Rightarrow$ evidence for a new short-range interaction

(Chadwick and Bieler interpretation,
Rutherford interpreted the result as a sign of α particle substructure)

E. Rutherford (1919) Philosophical Magazine 37, 537-561

J. Chadwick and E. S. Bieler (1921) Philosophical Magazine 42, 923-940

Looking inside the proton

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$E_\gamma \sim 2\,\mathrm{eV}$ | $E_\gamma \sim 2\,\mathrm{MeV}$ | $E_\gamma \sim 200\,\mathrm{MeV}$

100 nm | 100 fm | 1 fm

light source: Sun | α particles from ^{88}Ra | electrons from linear accelerators

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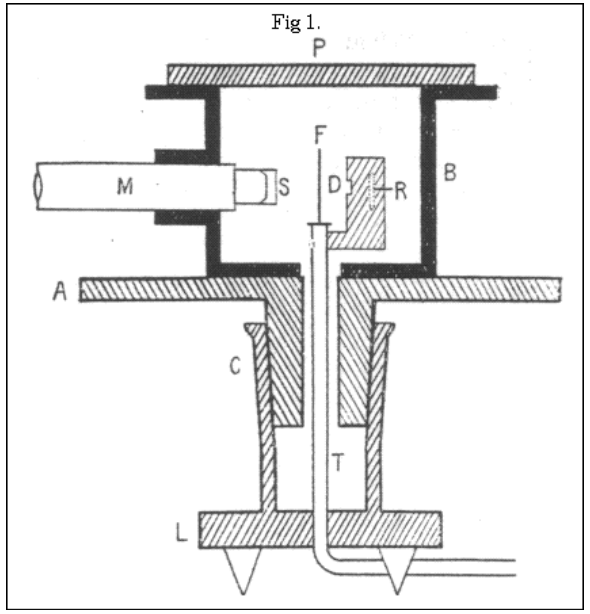
Pasteur's microscope



Geiger, Marsden (1913)

Rutherford experiment

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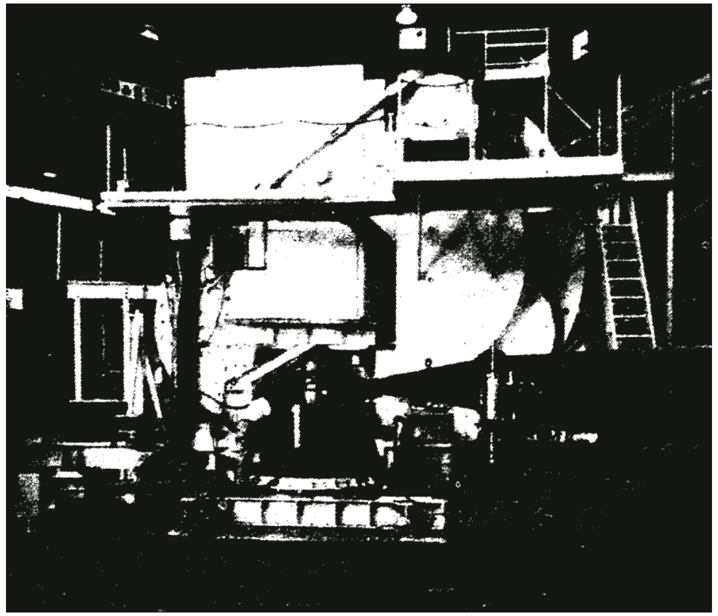
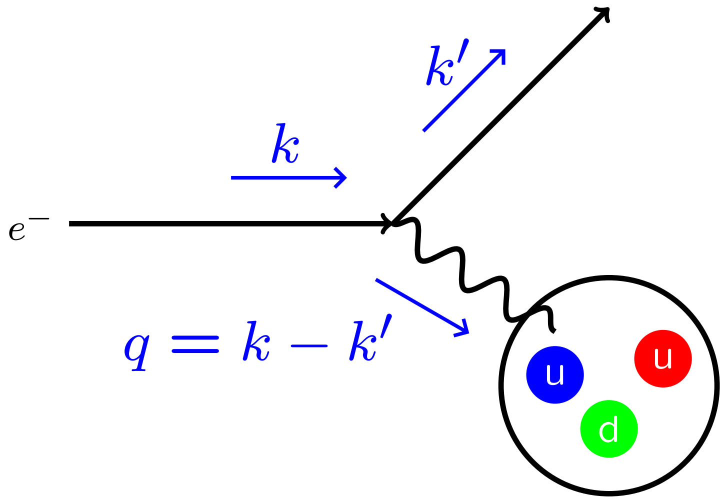


Hofstadter's Nobel Prize lecture (1961)

ep elastic scattering

$R_{\text{proton}} \sim 0.8$ fm

Elastic scattering and proton size

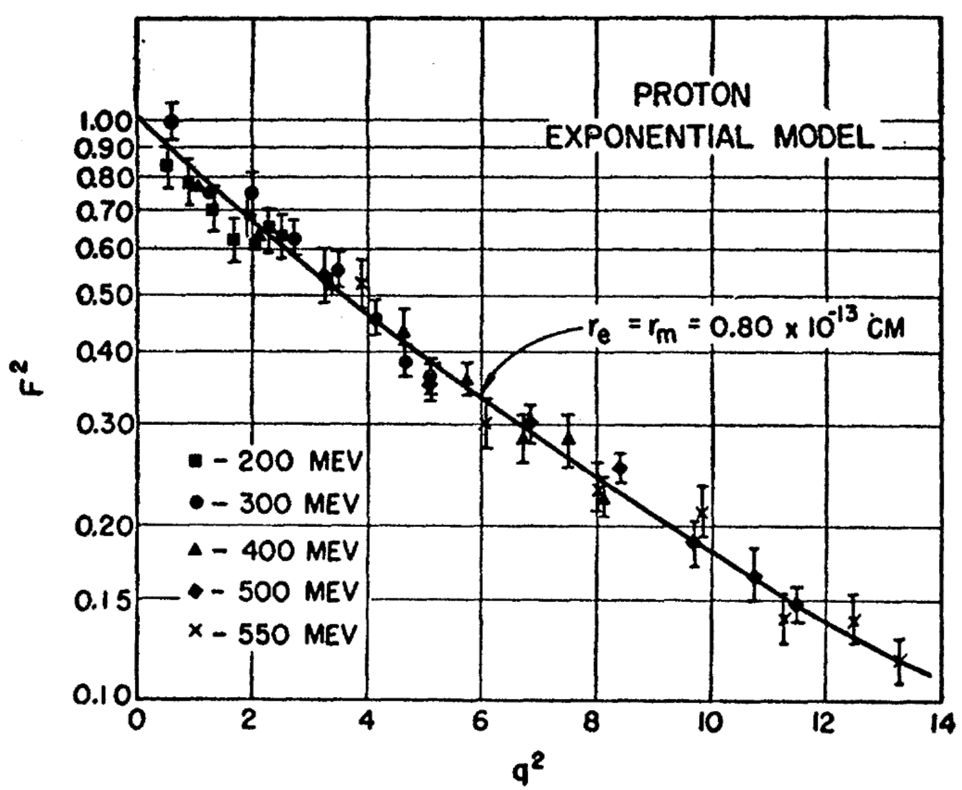


$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{\text{point-like}}}{d\Omega} |F(\vec{q})|^2$$

- $F(\vec{q})$ - form factor

$$F(\vec{q}) = \frac{1}{Q_{\text{tot}}} \int d\vec{x} \varrho(\vec{x}) e^{-i\vec{x}\cdot\vec{q}}$$

- in relativistic scattering, photon virtuality q^2 replaces $|\vec{q}|^2$



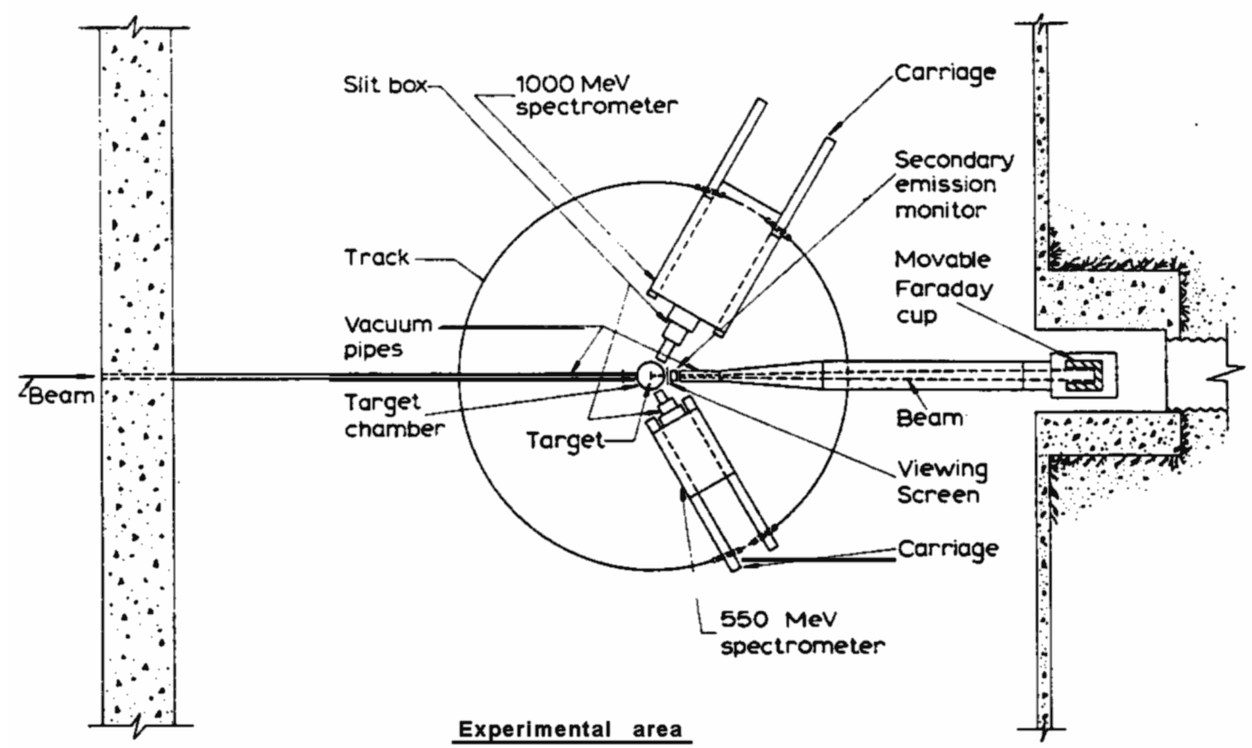
Chambers and Hofstadter, Phys. Rev. 103 (1956), 1454-1464

Robert Hofstadter 1956

- conceptually the same experiment as Rutherford's in addition, measurement of electron momentum
- energy of electron beams up to 550 MeV
- sufficient for the first measurement of the proton size

$$r_{\text{proton}} \approx 0.8 \text{ fm}$$

- not enough to see proton structure



from R. Hofstadter Nobel prize lecture, 1961

Looking inside the proton

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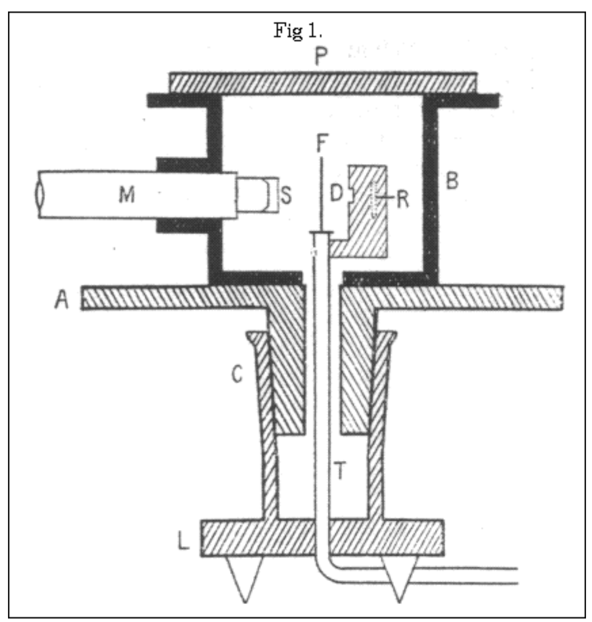
$100\,\mathrm{nm}$ | 100 fm | 1 fm

light source: Sun | α particles from ^{88}Ra | electrons from linear accelerators

Science Museum, London (CC BY-SA)

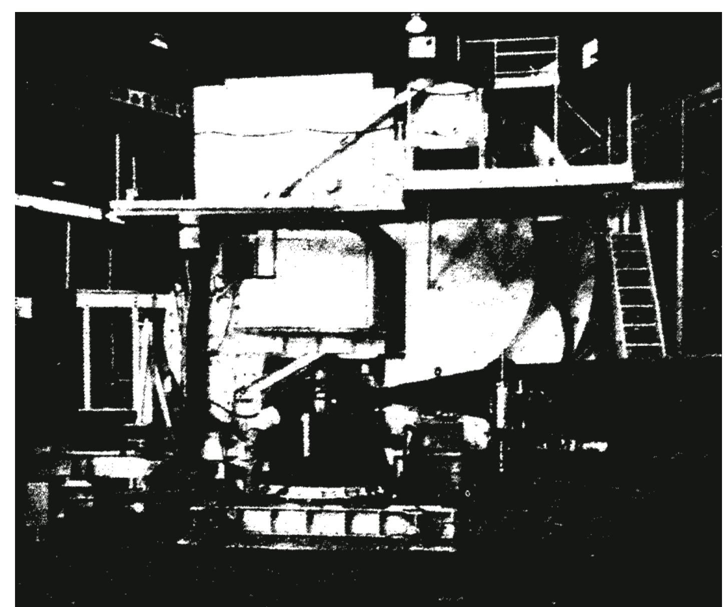
Pasteur's microscope



Geiger, Marsden (1913)

Rutherford experiment

$R_{Au} < 30$ fm



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Looking inside the proton

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- natural units where $\hbar = c = 1$. Connection with SI units through $\hbar c \sim 200$ MeV · fm

$E_\gamma \sim 2\,\text{eV}$ — 100 nm

$E_\gamma \sim 2\,\text{MeV}$ — 100 fm

$E_\gamma \sim 200\,\text{MeV}$ — 1 fm

$E_\gamma \sim 20\,\text{GeV}$ — 0.01 fm

light source: Sun

α particles from ^{88}Ra

electrons from linear accelerators

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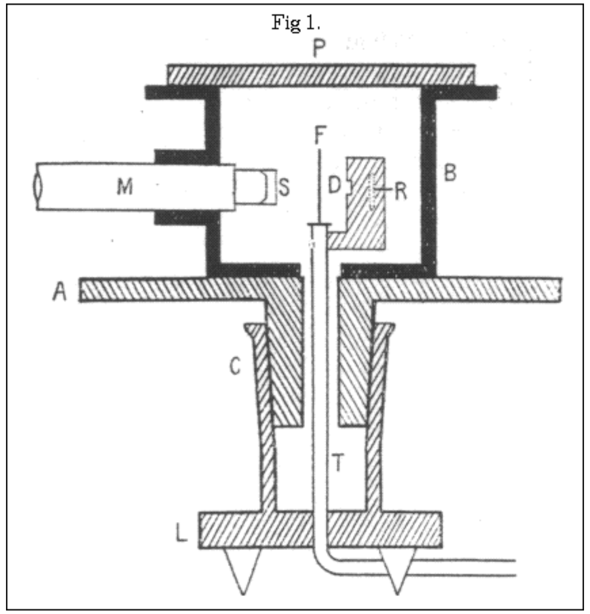
Pasteur's microscope



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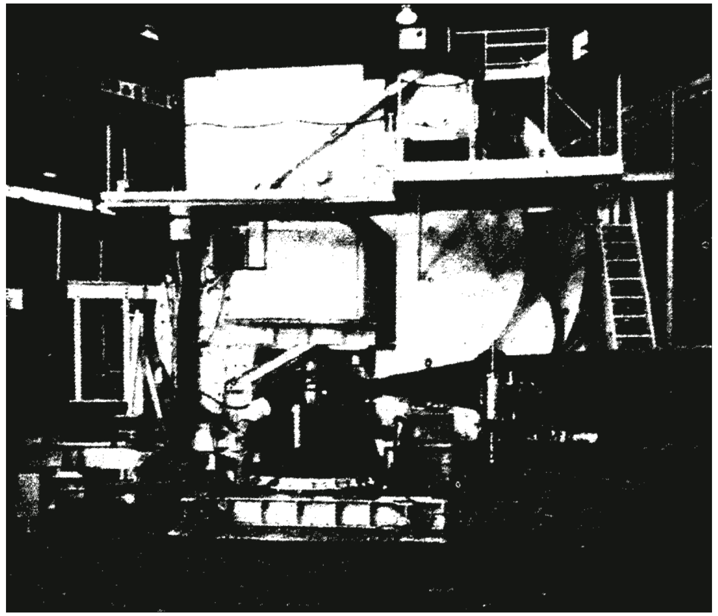

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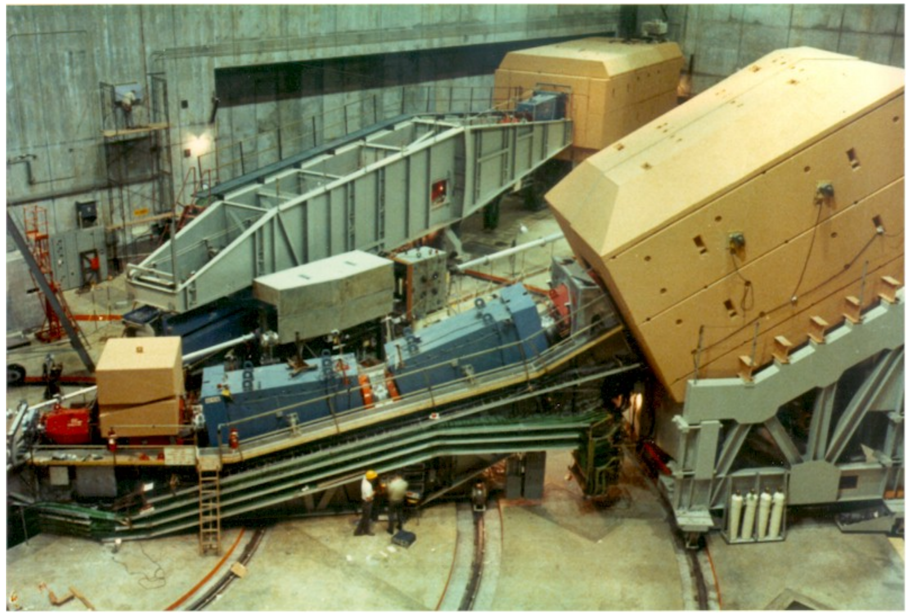


Experimental area at SLAC (1968)

ep deep inelastic scattering (DIS)

proton structure

DIS at SLAC - proton structure

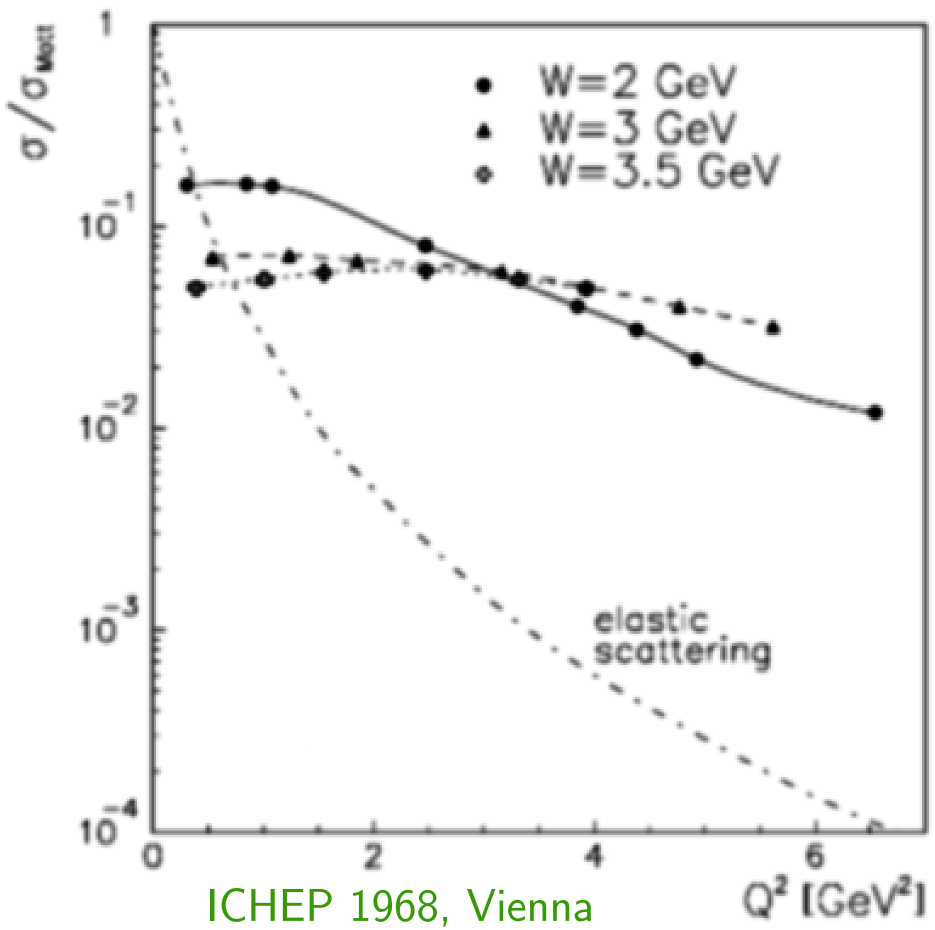
SLAC founded in 1962

3km long linear accelerator

electrons up to 20 GeV

Stanford Linear Accelerator Center

Ratio to the scattering on a point-like proton



ICHEP 1968, Vienna

W - measure of inelasticity

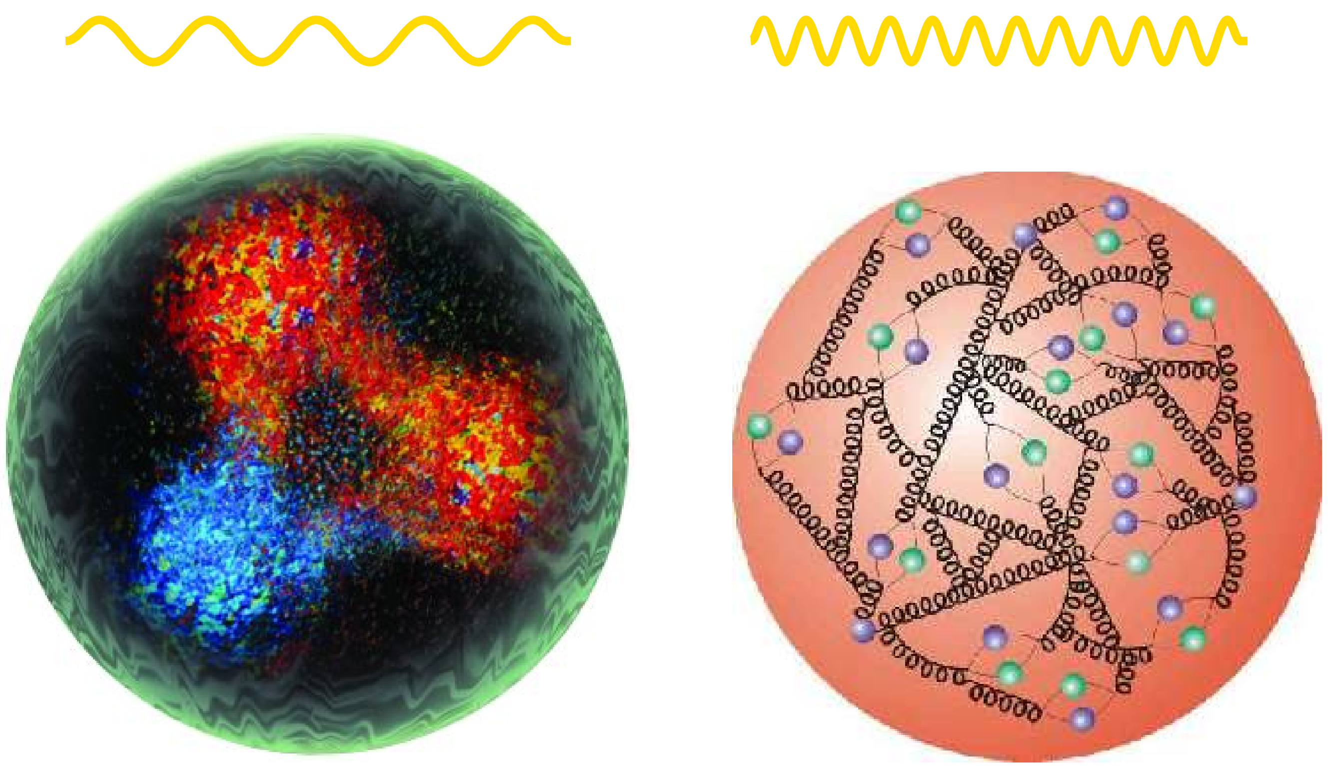
Photon virtuality $Q^2 = -q^2 = -E_\gamma^2 + |\vec{p}_\gamma|^2$

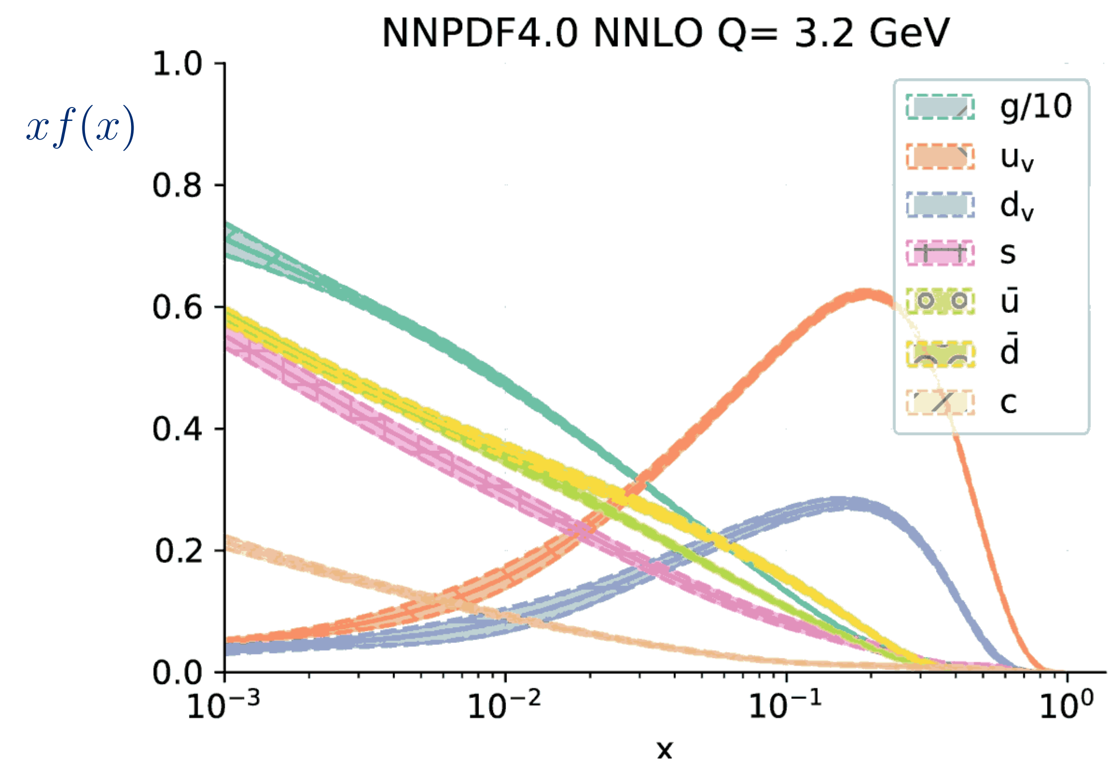
Parton model (Feynman 1968)

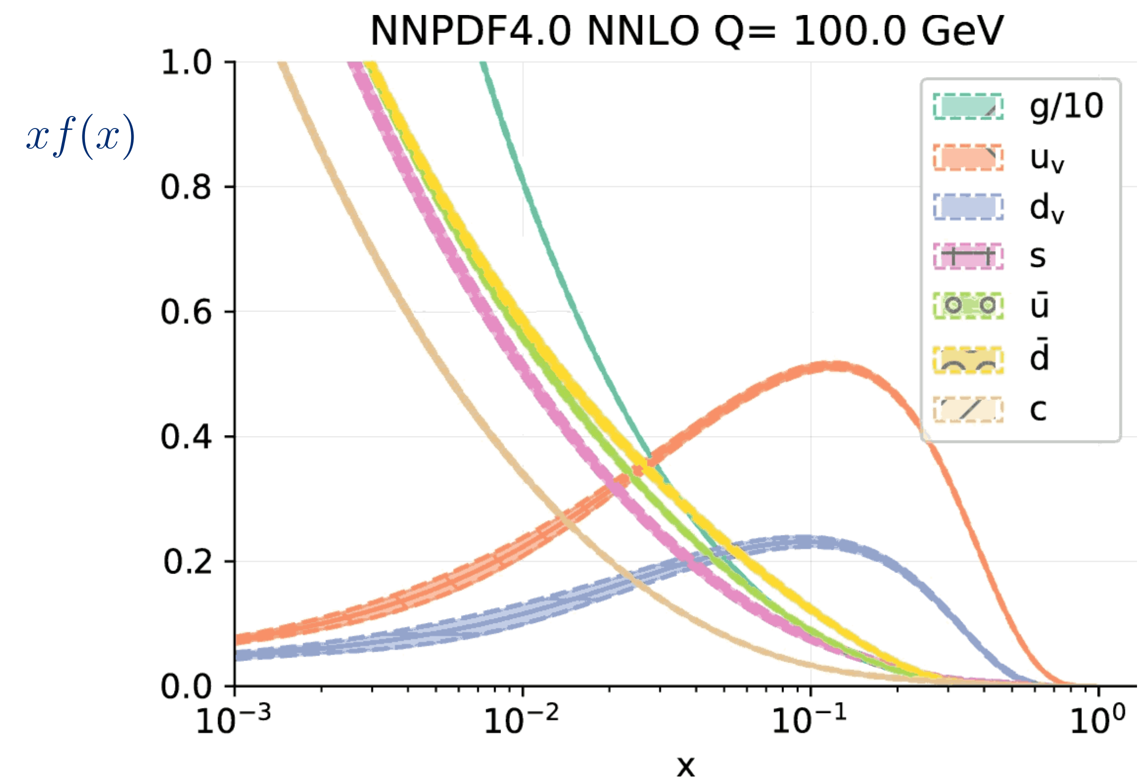
- proton behaves in DIS as a bag of almost free point-like particles - **partons**
- **parton distribution functions** $f_A(x)$ - number of partons of type A carrying longitudinal fractional momentum of proton x;

  not calculable, determined from data, universal

Parton Distribution Functions (PDF)







- partons - quarks and gluons
- not-perturbative, but universal
- from global fits to various data
  - DIS - from HERA
  - νDIS - can distinguish q and $\bar{q}$
  - jets - direct access to gluon PDF
- PDFs depend on energy scale of the process
  - this scale dependence is described by QCD

Quantum Chromodynamics - theory of interactions between quarks

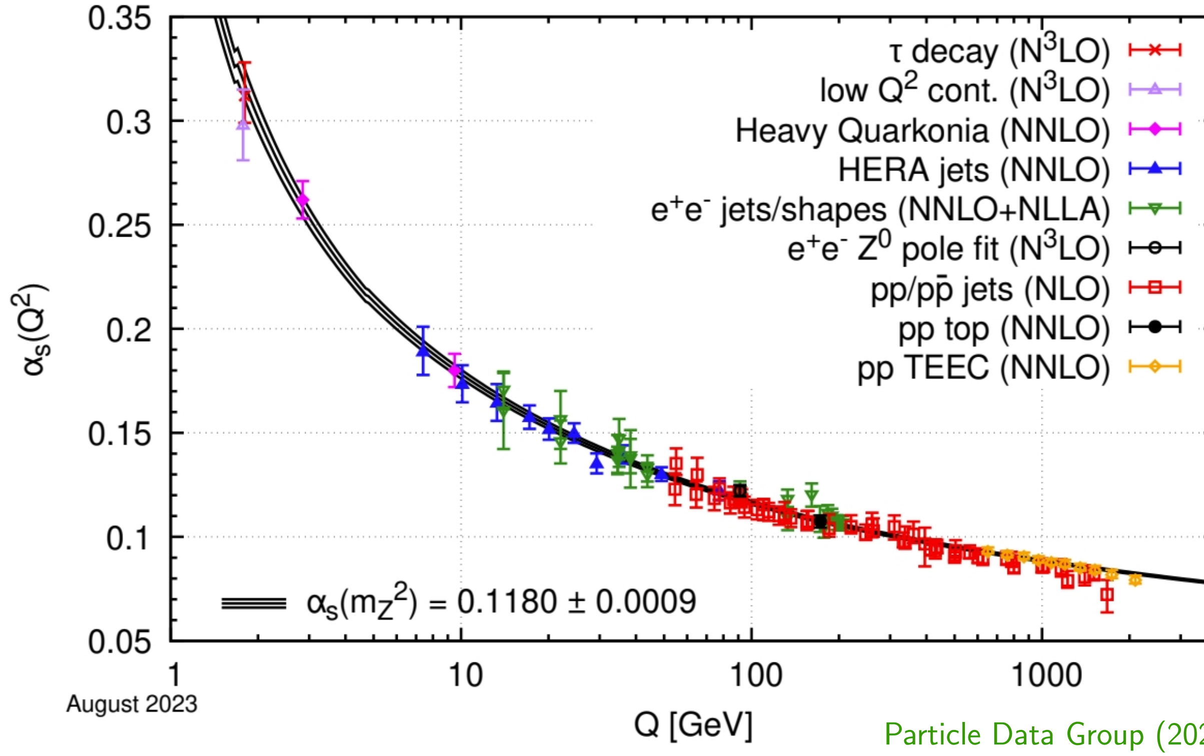
- Theory that gives confinement at 1 fm scale while almost free constituents at smaller distances
- Gross, Wilczek, Politzer (1973)

Quantum Chromodynamics (QCD)

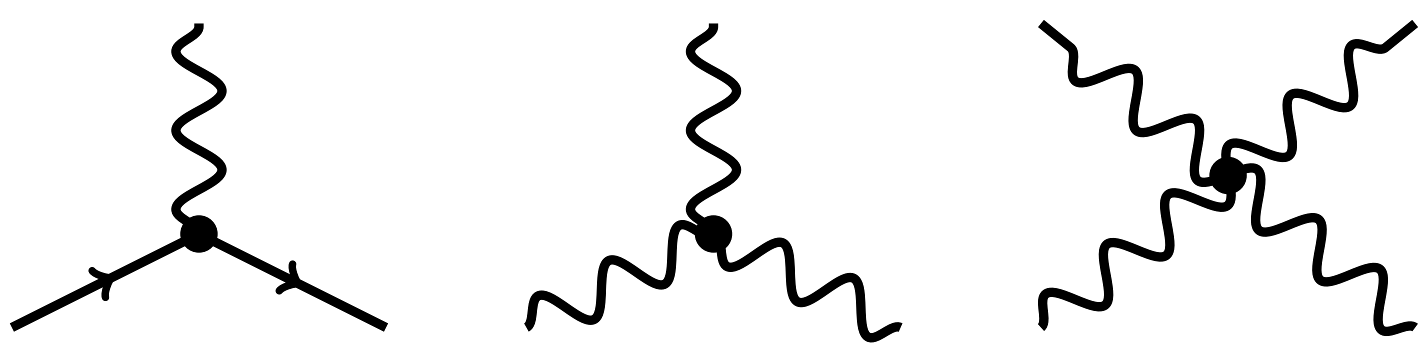
- theory of strong interaction between quarks
- local SU(3) gauge symmetry
- with conserved charge - **color**

- **gluons** - mediators of strong interaction
massless, carry the charge of strong interaction

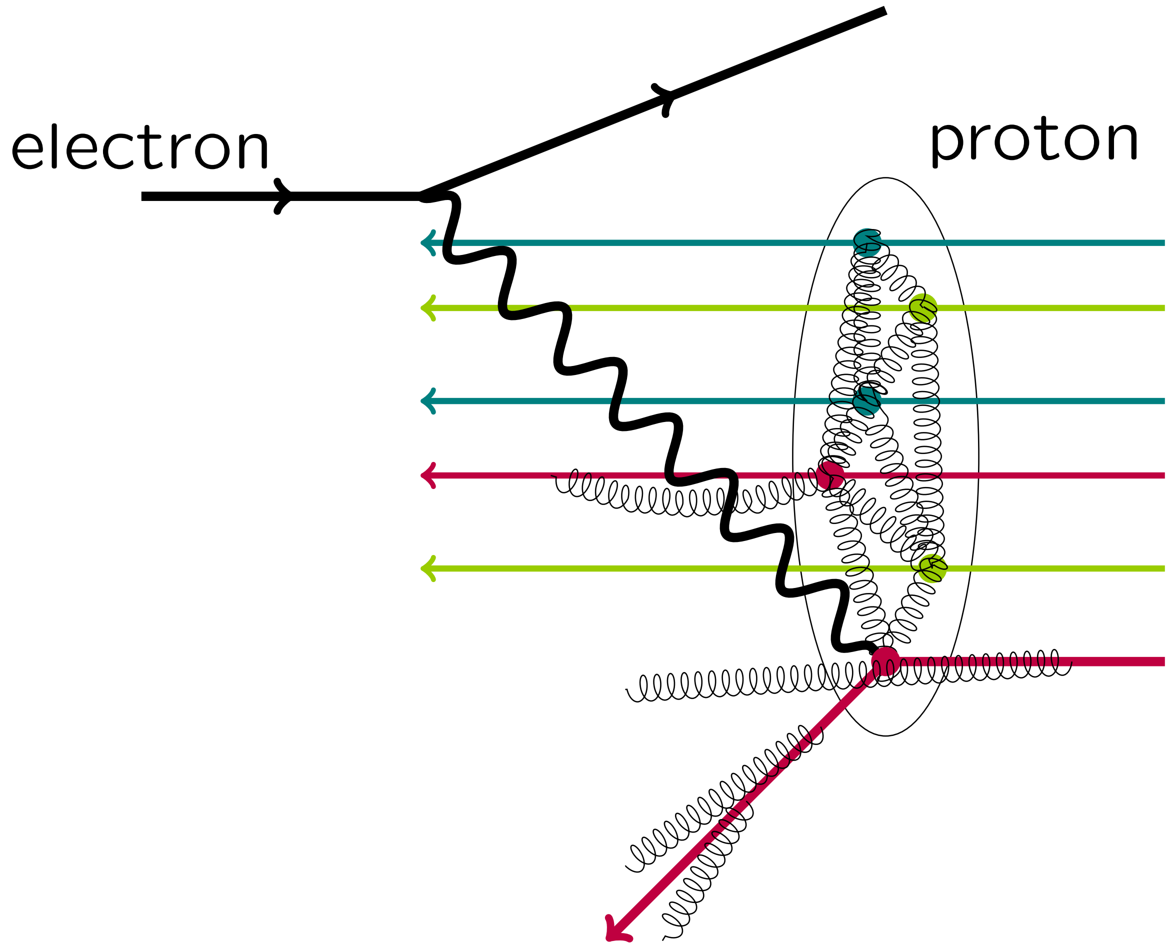
Running of strong coupling α_S



Particle Data Group (2024)



Quark confinement and jets

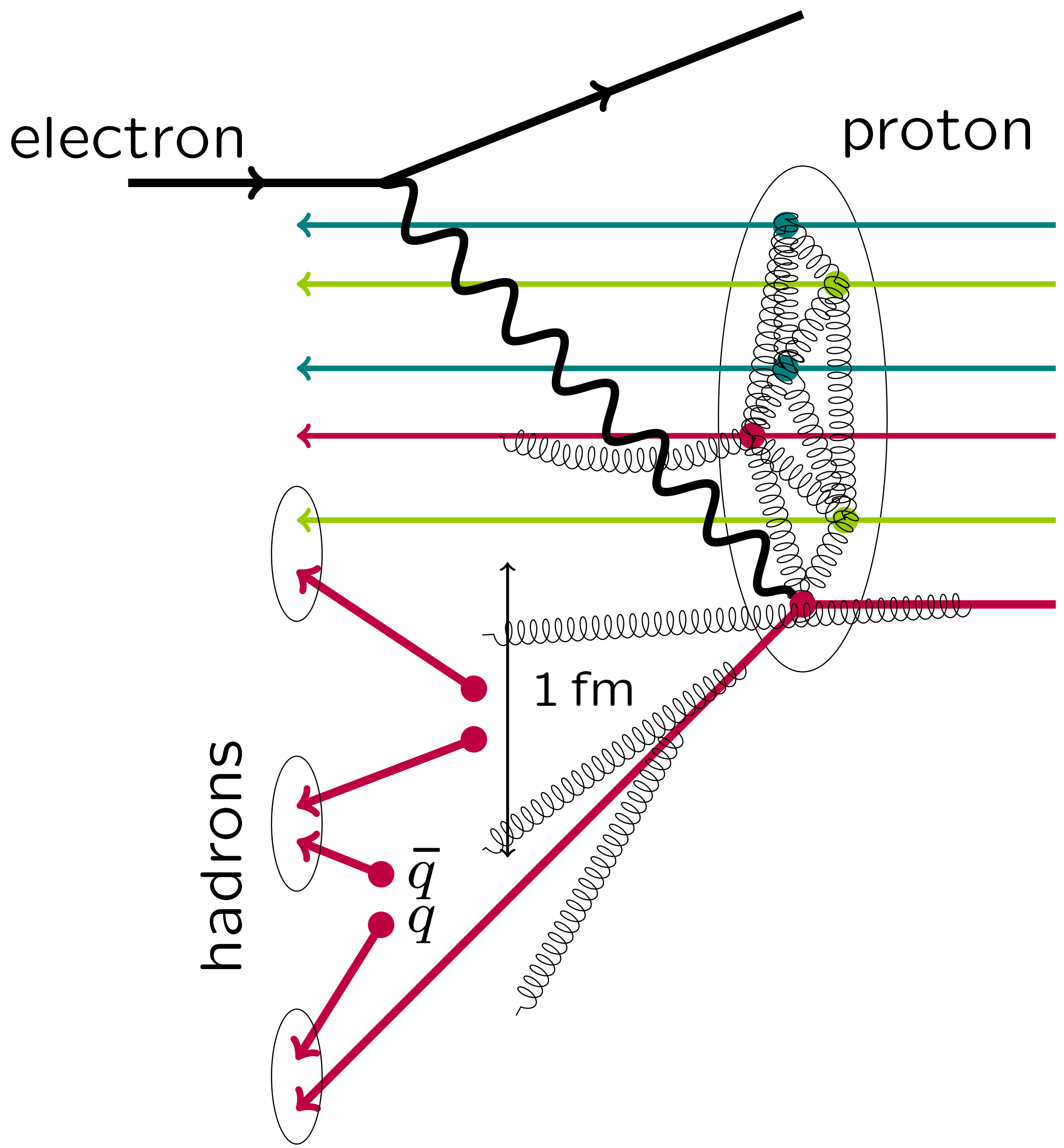


What happens with the kicked-out parton?

Parton shower

- as in QED, an accelerated strong charge radiates
- as in QED, radiation mostly in the direction of motion
- pQCD can be applied to describe this radiation

Quark confinement and jets



What happens with the kicked-out parton?

Parton shower

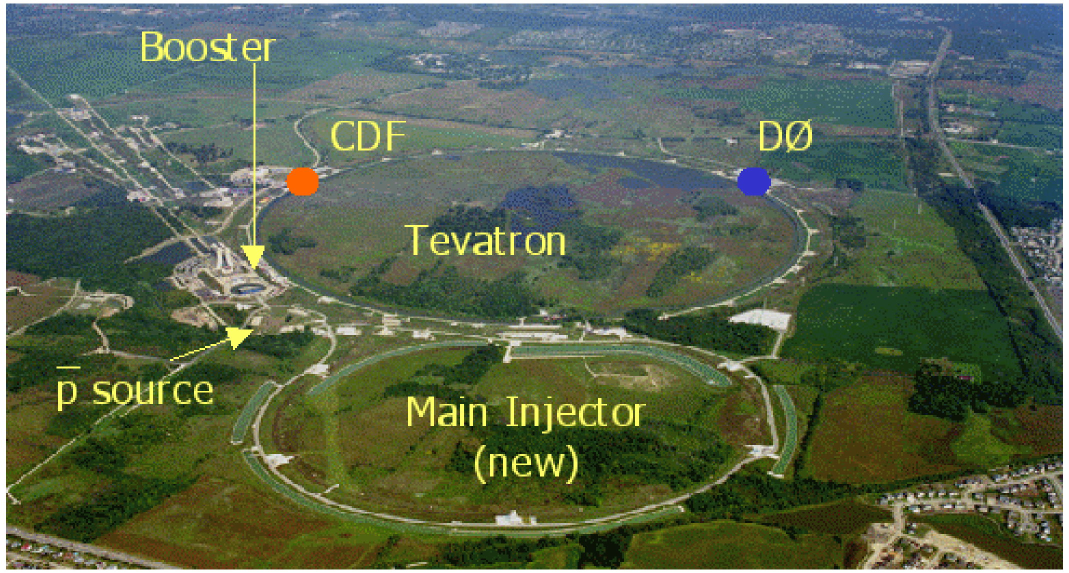
- as in QED, an accelerated strong charge radiates
- as in QED, radiation mostly in the direction of motion
- pQCD can be applied to describe this radiation

Hadronization

- once the distance between charges reaches 1 fm
- enough energy in the field to create quark anti-quark (color anti-color) pairs
- neutral (colorless) clusters are formed
- process continues until there is no free color left
- non-perturbative process - we have only models

- we observe strongly collimated spray of particles in the direction of kicked-out parton - **jets**

Hadron colliders - the largest microscopes in the world

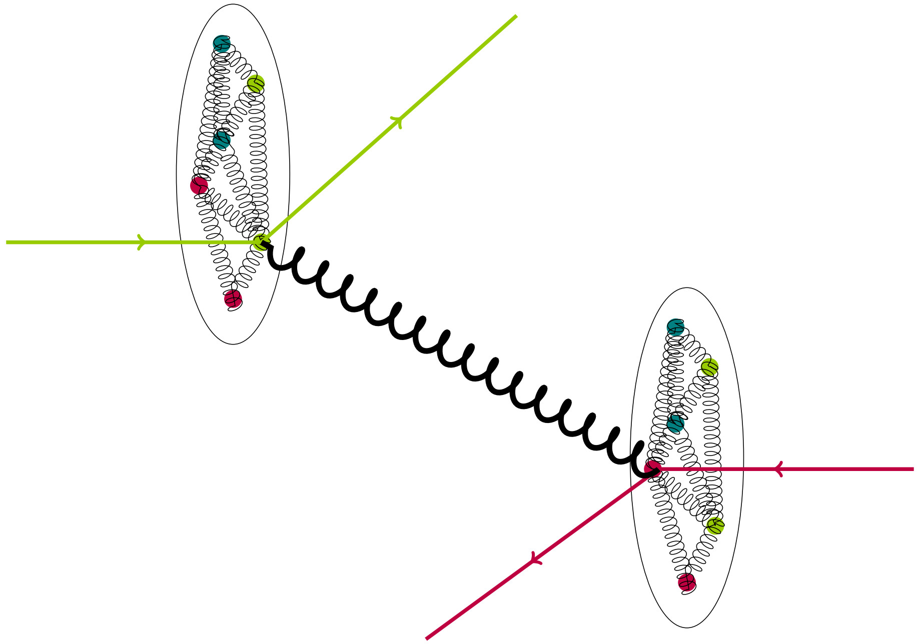


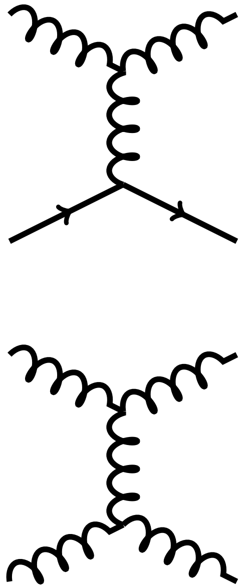
TEVATRON at Fermilab (Run2: 2001-2011)

- $p + \bar{p}$ at $\sqrt{s} = 1.96$ TeV

LHC at CERN (from 2010)

- $p + p$ at $\sqrt{s} = 13.6$ TeV



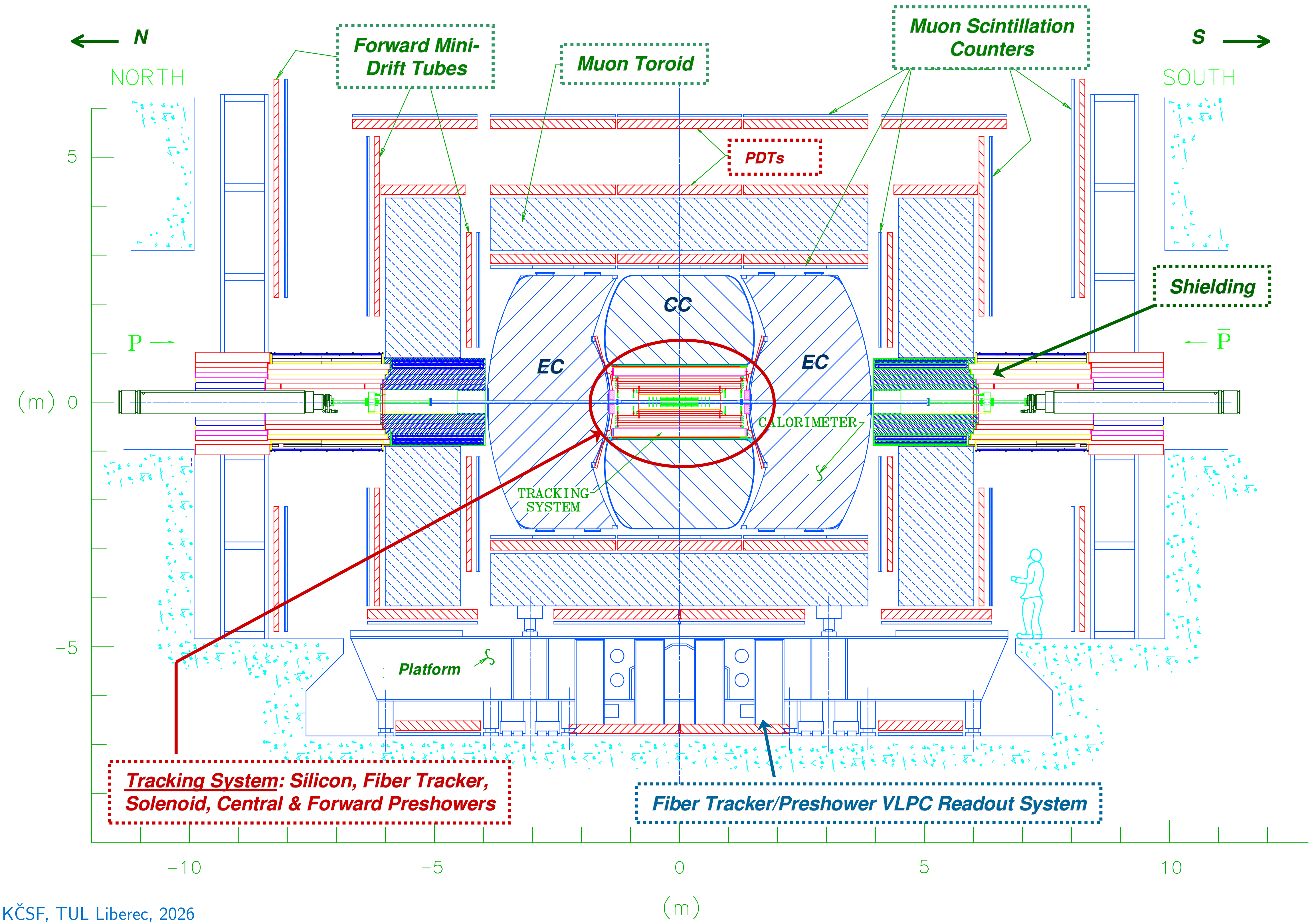


- gluon instead of photon
- more fundamental processes $(qq \to qq,\ qg \to qg,\ gg \to gg)$
- production rate (cross section), $[\sigma] = \mathrm{m}^2$, $1\,\mathrm{b} = 10^{-28}\mathrm{m}^2$

$$\sigma_X = \sum_{abcd}^{flavors} \int \mathrm{d}x_1 \int \mathrm{d}x_2 f_a(x_1) f_b(x_2) \sigma(ab \to cd) D(cd \to X)$$

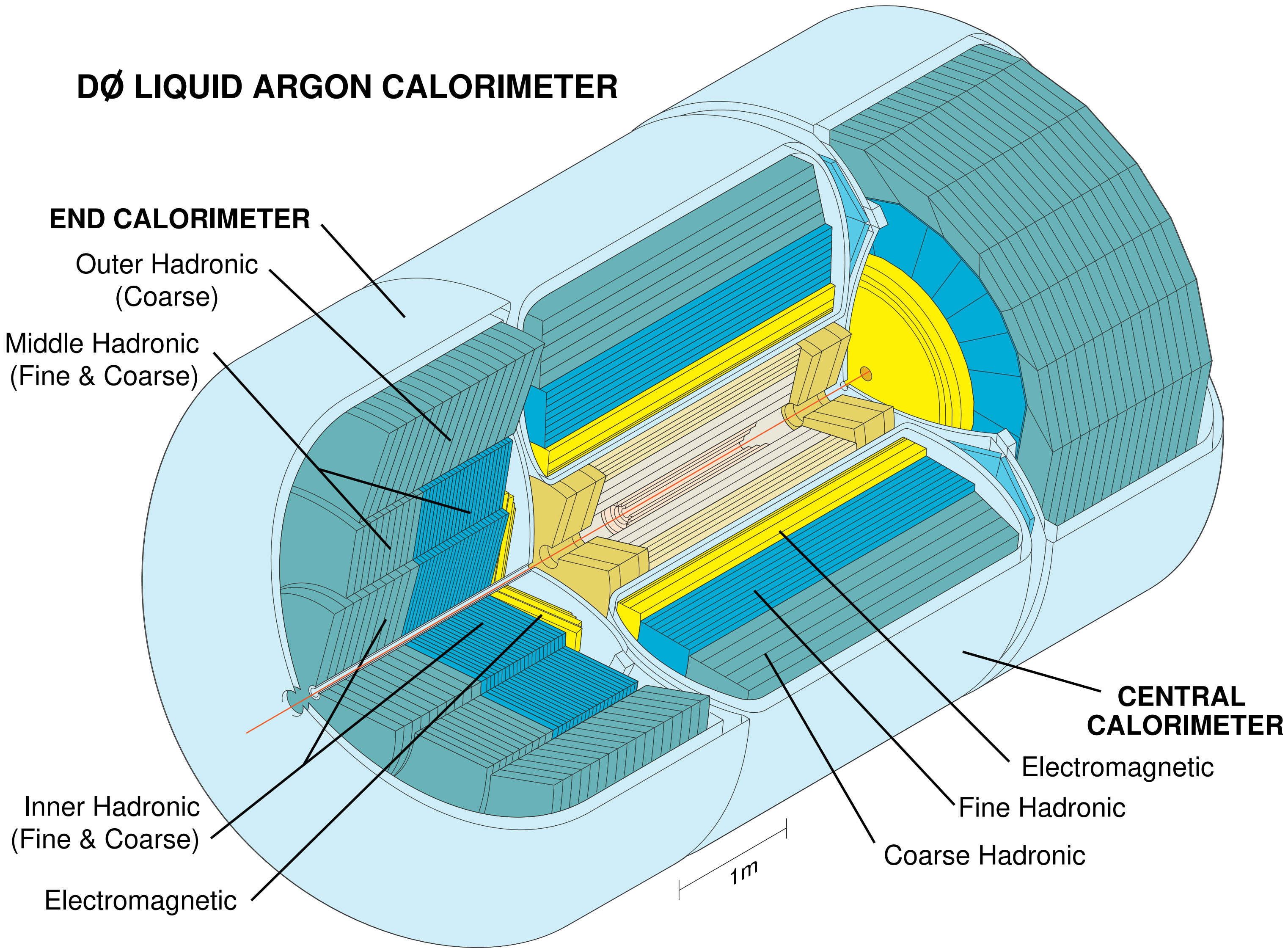
$N = \sigma \mathcal{L}$, luminosity (particle flux) $[\mathcal{L}] = \mathrm{m}^{-2}$

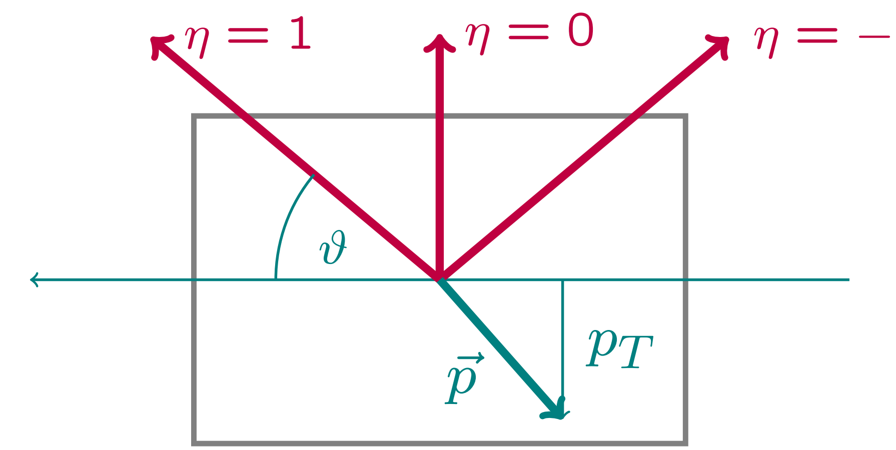
DØ Detector



N
S
NORTH
SOUTH
Forward Mini-Drift Tubes
Muon Toroid
Muon Scintillation Counters
PDTs
Shielding
CC
EC
EC
P
$\overline{\text{P}}$
CALORIMETER
TRACKING SYSTEM
Platform
(m)
5
0
−5
−10
−5
0
5
10
(m)
Tracking System: Silicon, Fiber Tracker, Solenoid, Central & Forward Preshowers
Fiber Tracker/Preshower VLPC Readout System

DØ Calorimeter





Calorimeter - the key detector component for jets

- absorbs and measures the energy of almost all particles
- exceptions: muons and neutrinos
- segmented in depth, azimuthal angle (ϕ), and pseudorapidity (η)

Coordinates

- beam - z-axis, polar angle ϑ

Boost invariant quantities

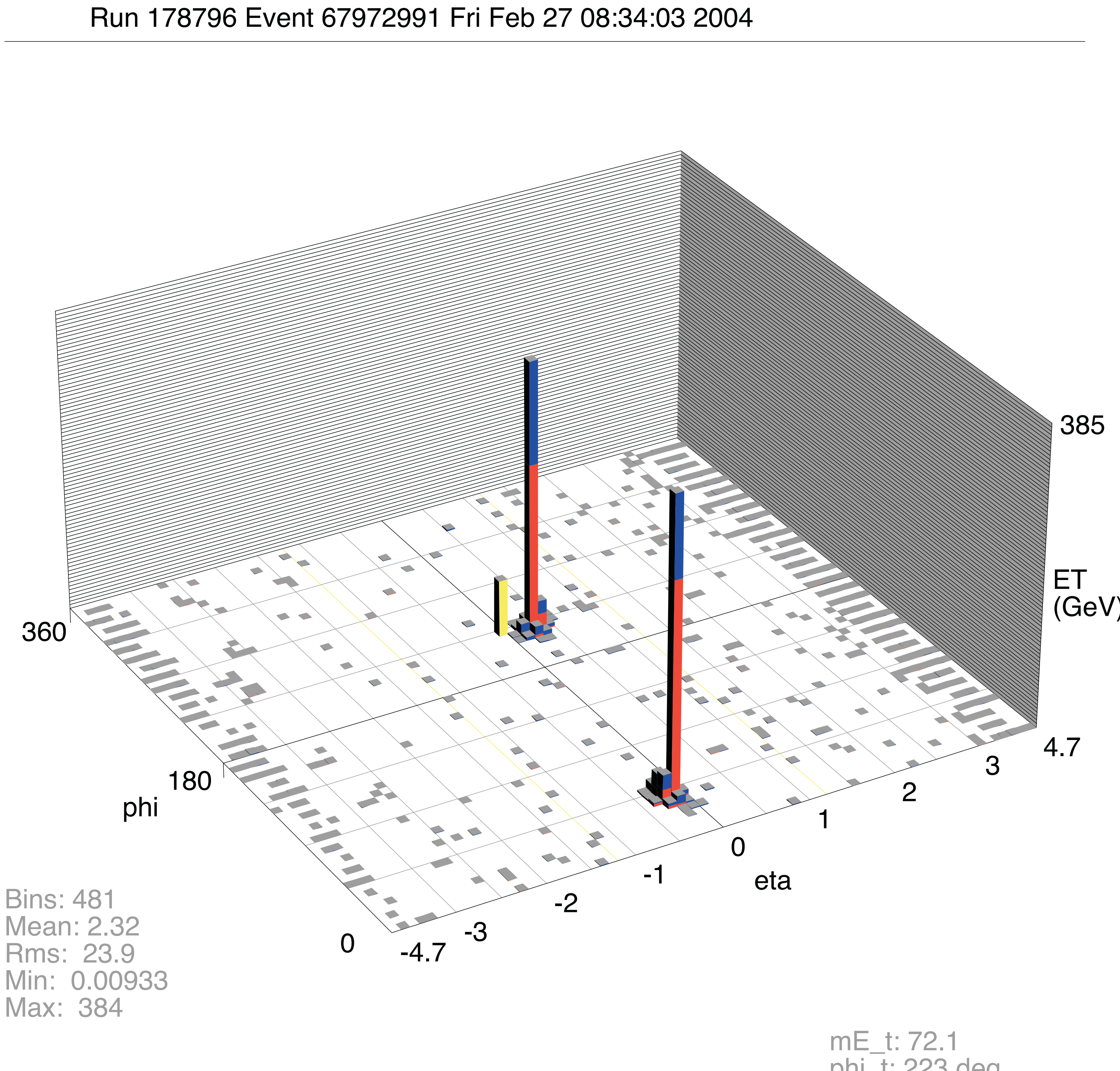
- CMS of parton collision moves along beam axis
- azimuthal angle φ, transverse momentum p_T
- **rapidity** (y)

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

- **pseudorapidity** $\eta = -\ln \tan (\vartheta/2)$

  $y \approx \eta$ for $m \to 0$

Jets at DØ experiment



Dijet event at DØ, $p_{T jet} \sim 600$ GeV

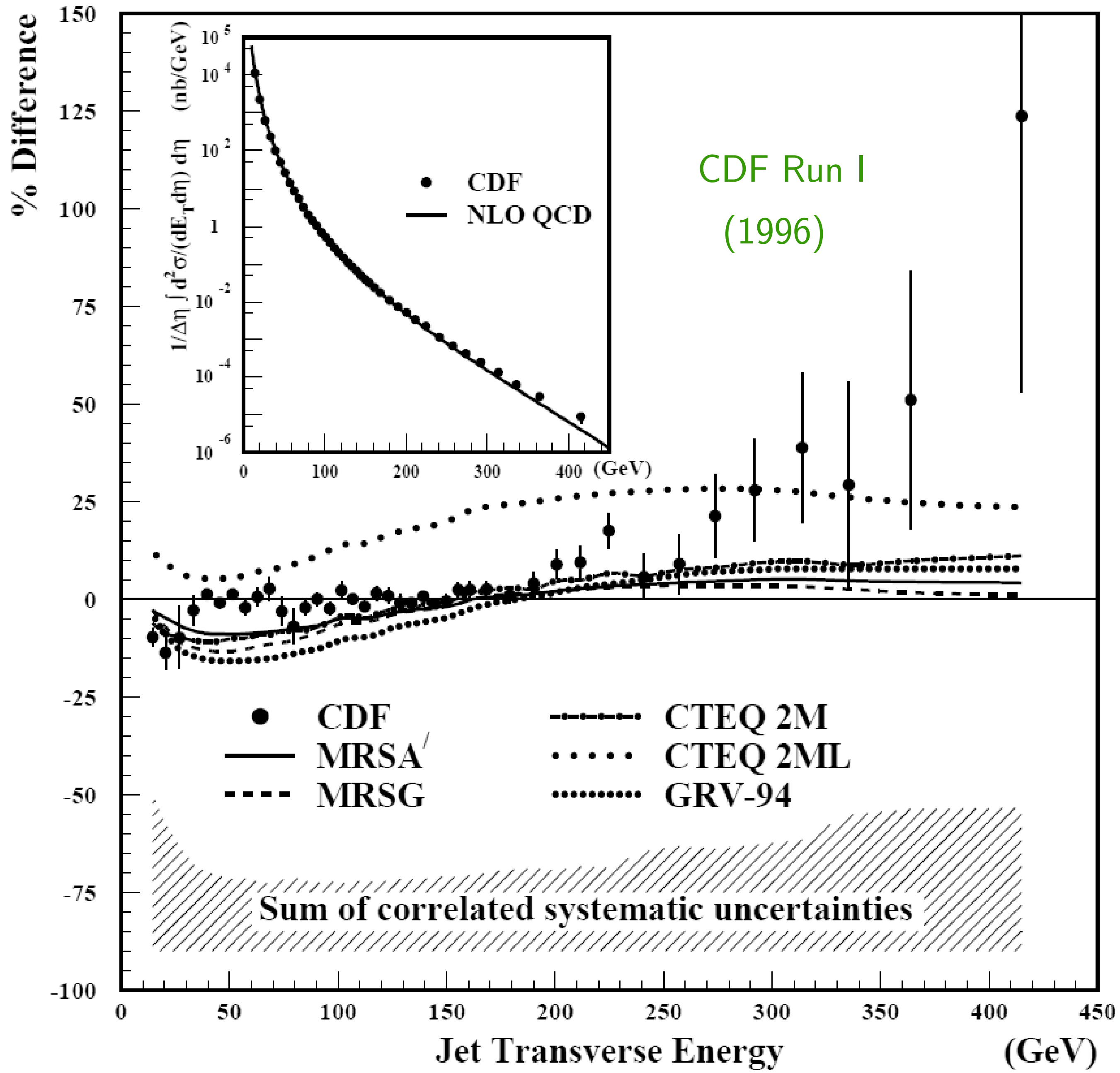
- high energetic jets quite narrow
- quite striking events
- usually produce in pairs balanced in p_T
  - more complicated final states common
- still need a good definition of jet
  - need to work at experiment
  - and theory as well
  - these are non-trivial requirements

Jet algorithm

- DØ: cone in $R = \sqrt{\Delta^2\varphi + \Delta^2\eta} < 0.7$
- at LHC: iterative clustering

- Jets are reconstructed proxies for high-energy partons

Jet production at the Tevatron - Run I



PRL77 (1996) 438

- excess over QCD at high jet transverse energies
- similar situation as in Rutherford experiment with H_2

New physics?


Chicago Tribune
February 8, 1996
Fermilab's 'Preons': Bad Math Or A Profound Find?
As Basic Matter, Quarks Superseded Atoms — Now A Flash Of Energy May Shake Up Physics

The Washington Post
February 18, 1996
Inside the Indivisible: Quarks Collide With Theories

created by ChatGPT (based on real articles)

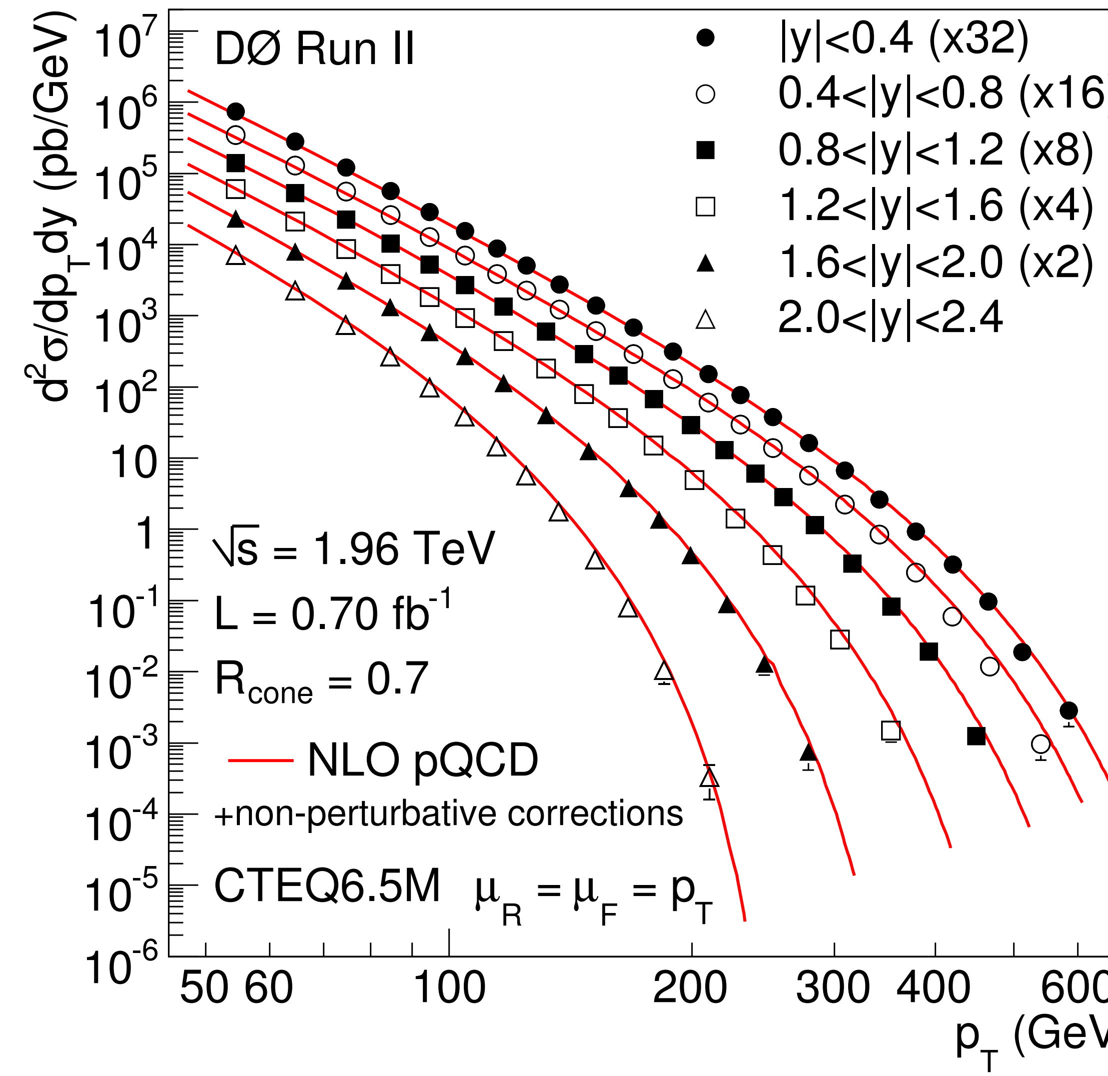
Or more boring explanation?

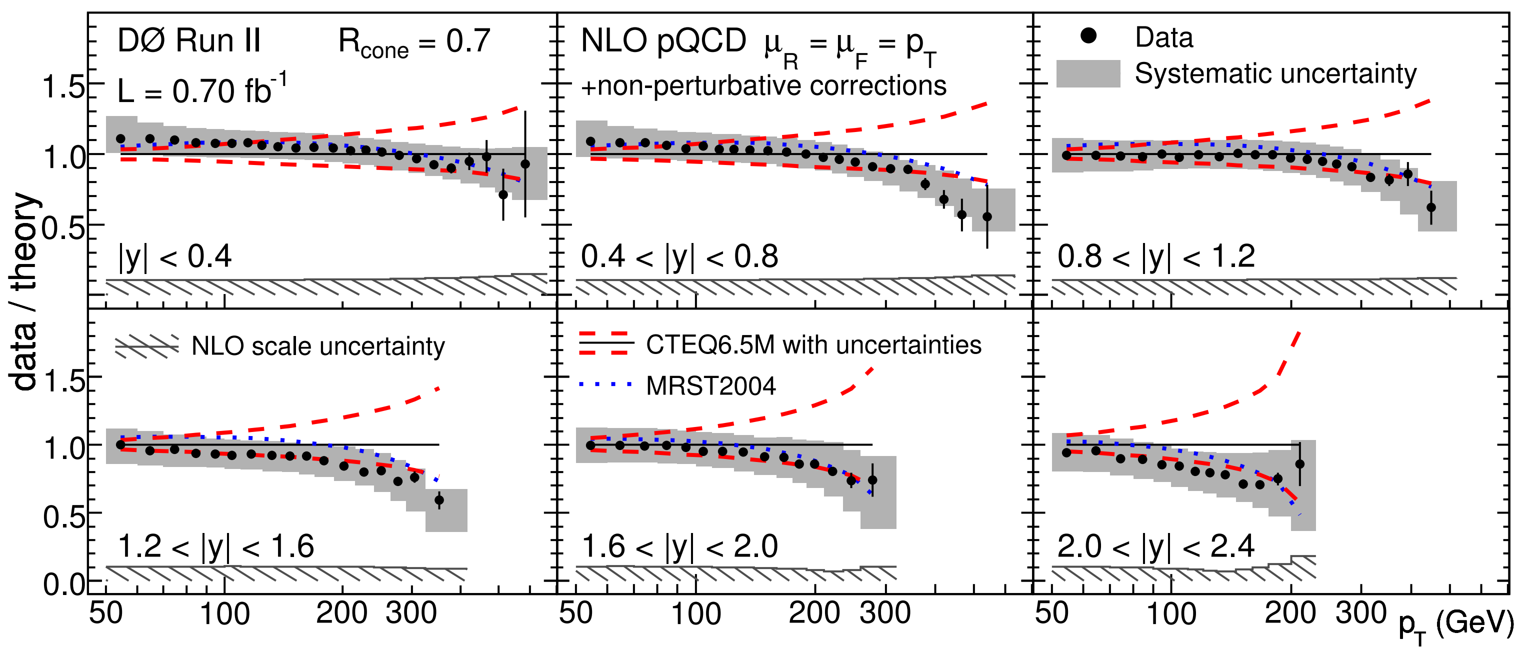
(more gluons in proton would do it)

- This result motivated my choice of PhD thesis and my jet measurements in DØ Run II

Jet production at the Tevatron - Run II

- about twice the precision of Run I
  (took us several years to understand the detector at the 1% level)
- $7\times$ more data (luminosity)
- improved jet algorithm
- improved PDFs (mostly from HERA)
- excellent agreement with QCD
- no sign of quark substructure down to scale of $\sim 10^{-3}$ fm
- data used in the following PDF fits (gluon PDF)

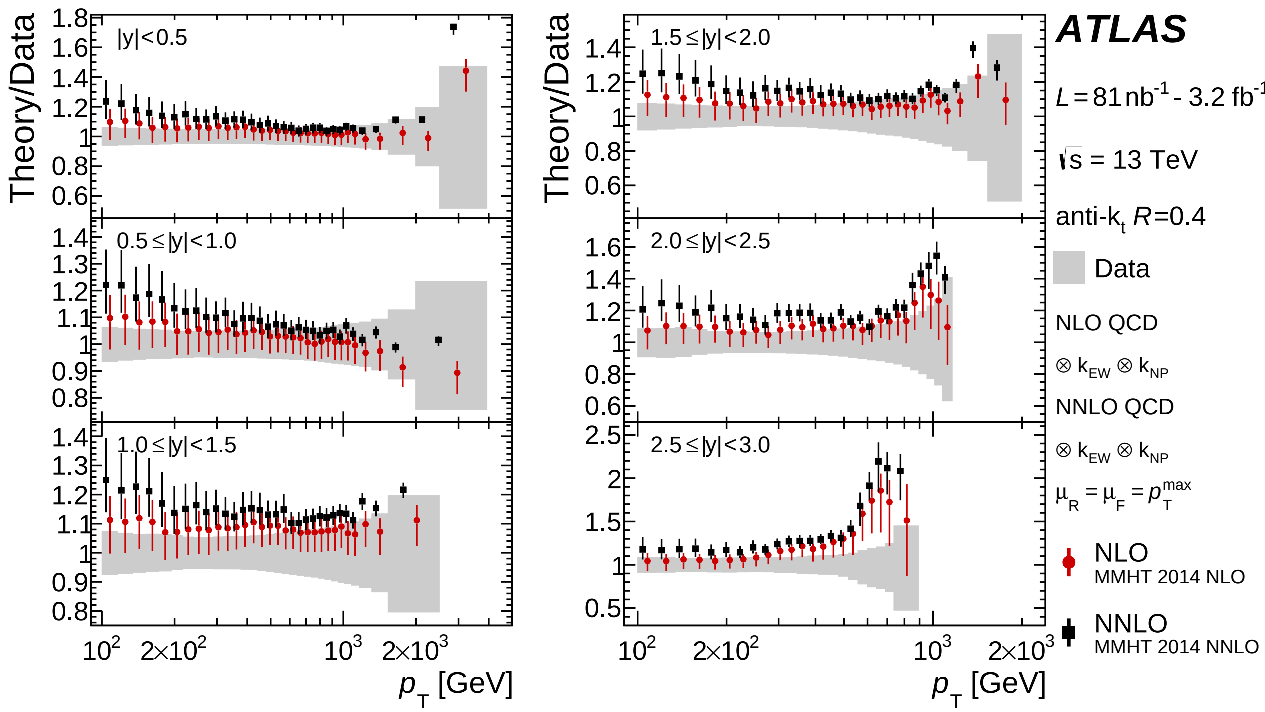




PRL101 (2008) 062001
PRD85 (2012) 052006

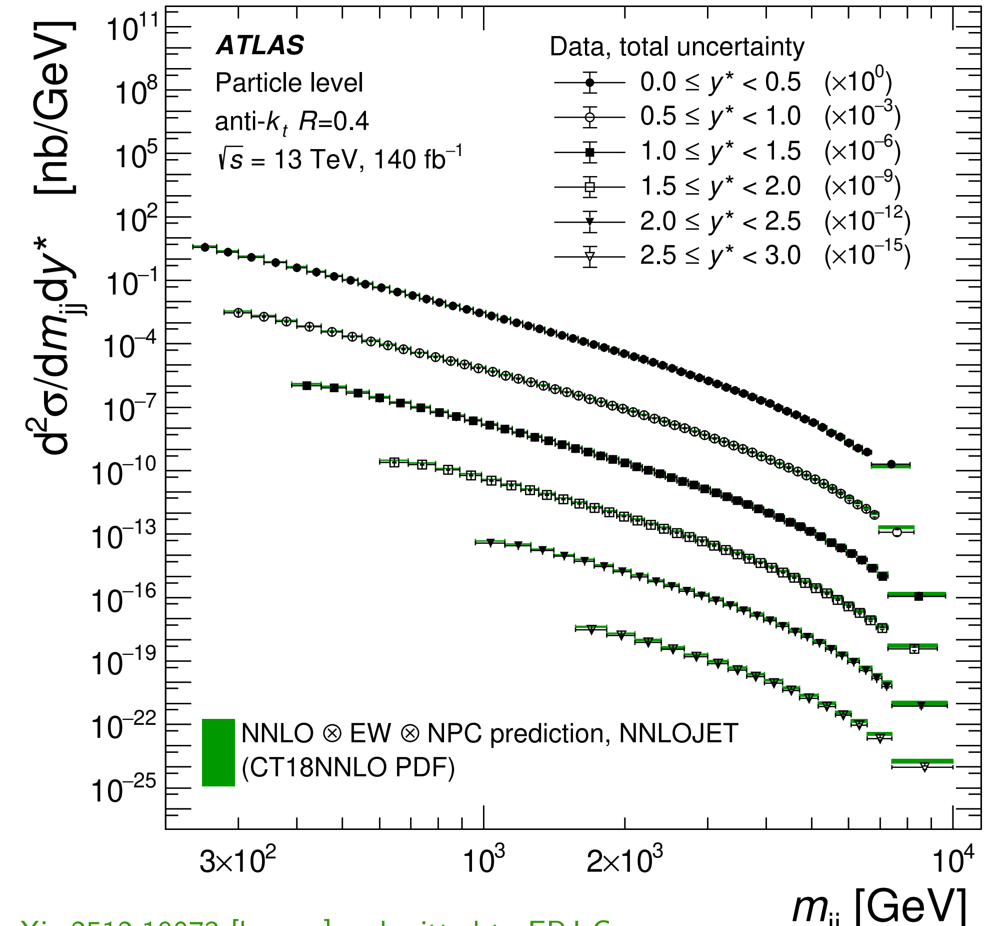
Jet production at LHC

Jet inclusive spectrum at 13 TeV



JHEP 05 (2018) 195

Dijet mass spectrum at 13 TeV



arXiv:2512.19073 [hep-ex], submitted to EPJ C

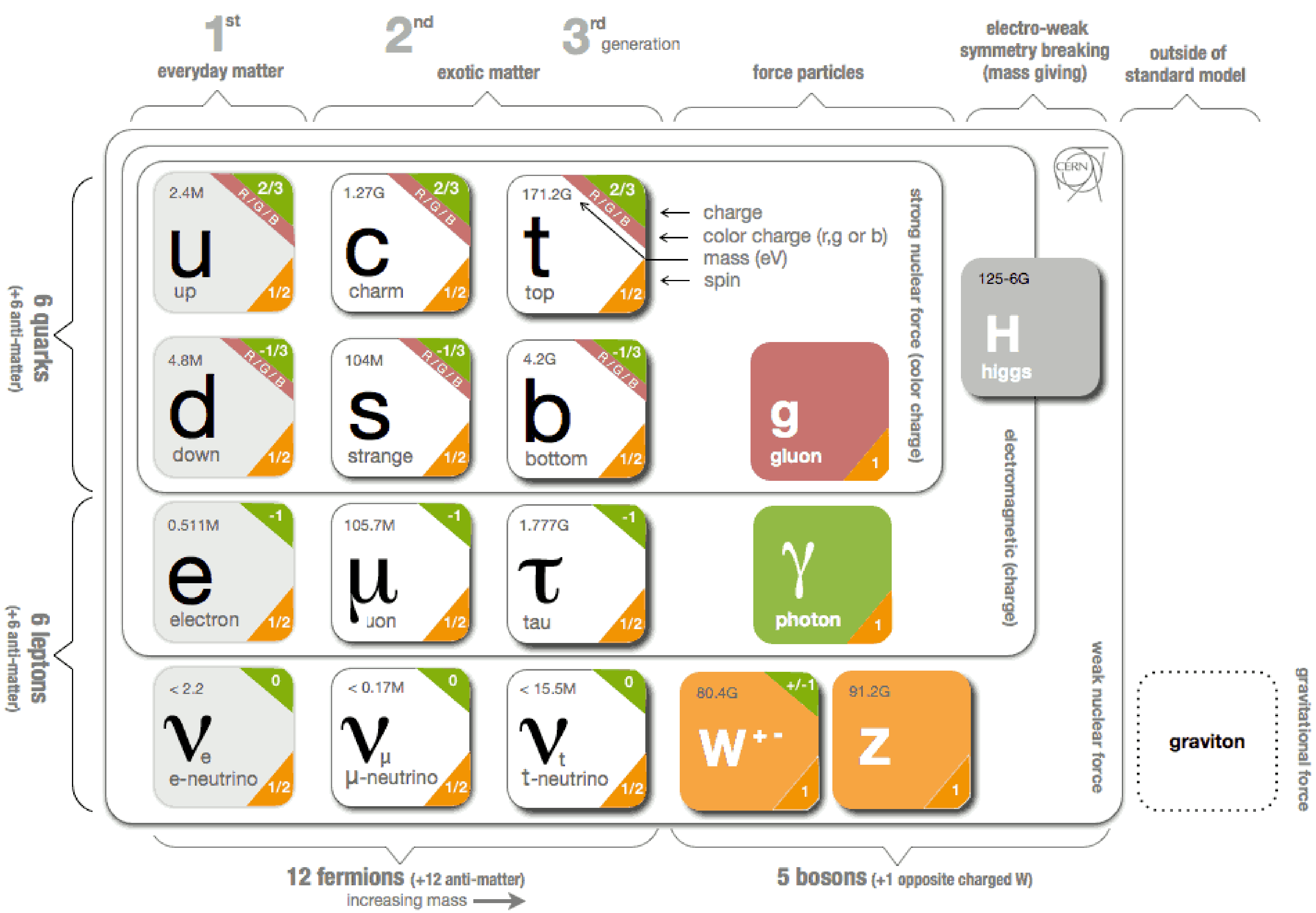
- only early 13 TeV ATLAS data published
  - full Run 2 luminosity measurement in preparation
  - strong involvement of Czech groups (CTU, CU, FZU)
- QCD works at least up to 2 TeV scales
  - improved theory, NNLO QCD

- work of colleagues from CTU
- $m_{\mathrm{jj}}^2 = (P_1 + P_2)^2$ - invariant dijet mass
- $y^\star = \frac{|y_1 - y_2|}{2}$ - related to the scattering angle $\vartheta^\star$ in the CMS of colliding partons

- quarks: no deviation from point-like behaviour to $\sim 10^{-4}$ fm

  electron: direct limit $r_e < 2.8 \times 10^{-4}$ fm from Bhabha scattering Phys. Rev. D62 (2000) 076005

Periodic table of particle physics - Standard Model



Standard Model (SM)

gauge symmetry: $U(1) \otimes SU(2) \otimes SU(3)$

electro-weak strong

+ Higgs mechanism

- Same questions
  - What is behind this simple structure?
  - Can we see this new physics beyond SM experimentally?
  - What kind of theory is behind?
- Only hints
  - Dark matter and energy
  - Neutrino masses
- Many ideas
  - SUSY, strings, extra dimensions, . . .

Future: searching for physics beyond the Standard Model

LHC (now) $\rightarrow$ HL-LHC (2030-2040) $\rightarrow$ FCC? (2045+)

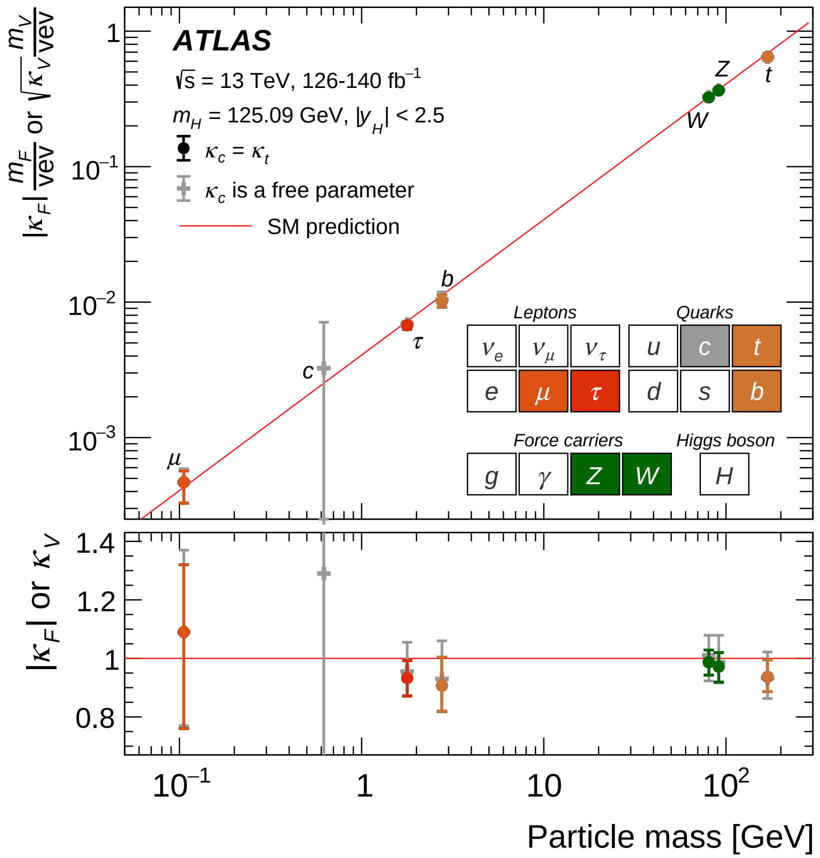
Direct searches

- look for a new particle / resonance / new process
- ideal case: unmistakable direct signal

Precision measurements

- test increasingly precise SM predictions
- look for small but significant deviations
- deviations may point to the scale or type of new physics
- already at the HL-LHC, PDF and α_s uncertainties will become a major limitation for many precision measurements and their sensitivity to new physics

  (e.g. precision measurements of Higgs couplings to SM particles)

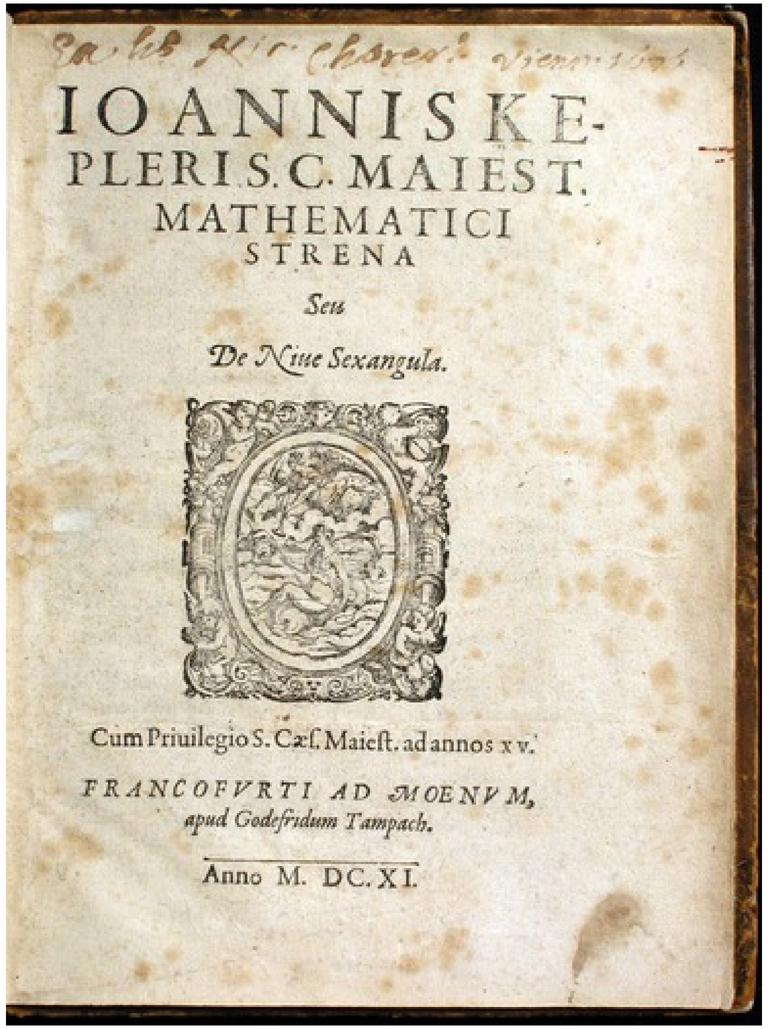


e-Print: 2608.07332 [hep-ex]

> Jet physics plays a dual role at hadron colliders: a direct probe of new physics and a tool for precision measurements across SM.

Backup

Symmetries and structure of matter



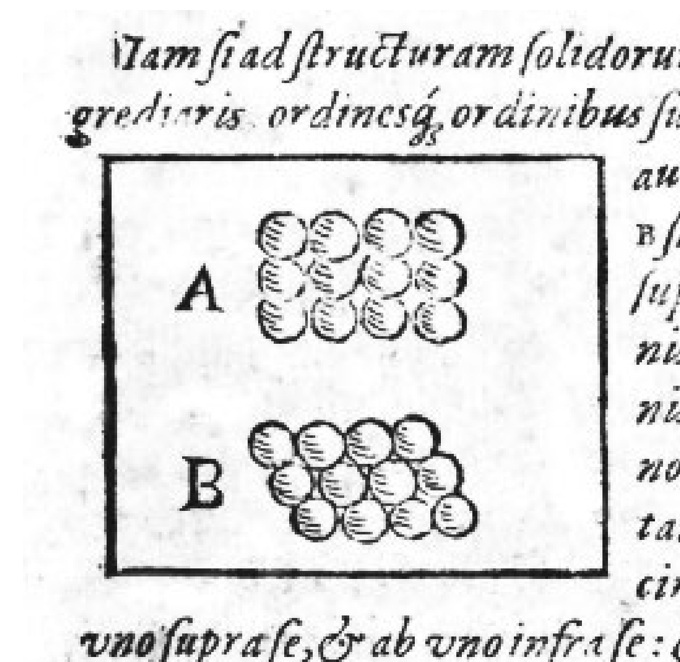
IOANNIS KE-
PLERI S.C. MAIEST.
MATHEMATICI
STRENA
Seu
De Nive Sexangula.

Cum Priuilegio S. Cæs. Maiest. ad annos XV.
FRANCOFVRTI AD MOENVM,
apud Godefridum Tampach.
Anno M. DC. XI.

Bentley 1902

- Kepler's New Year's pamphlet on snowflakes

  Strena Seu De Nive Sexangula (1611)
- the first(?) scientific treatise on crystallography
- hexagonal symmetry of snowflakes is connected with the way how to arrange spheres in space
  - packing with hexagonal symmetry is the most dense one



- took almost 400 years to prove the Kepler's conjecture (1999, Hales)
  - first thoughts about connection between symmetry and structure of matter?
  - regularity/patterns - often a sign of a simpler internal structure
- Thomas Harriot - packing of cannonballs, correspondence with Kepler (1606-1607)