Introduction & History of Nucleon Spin

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The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

http://science.energy.gov/np/reports

RECOMMENDATION:

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Initiatives:

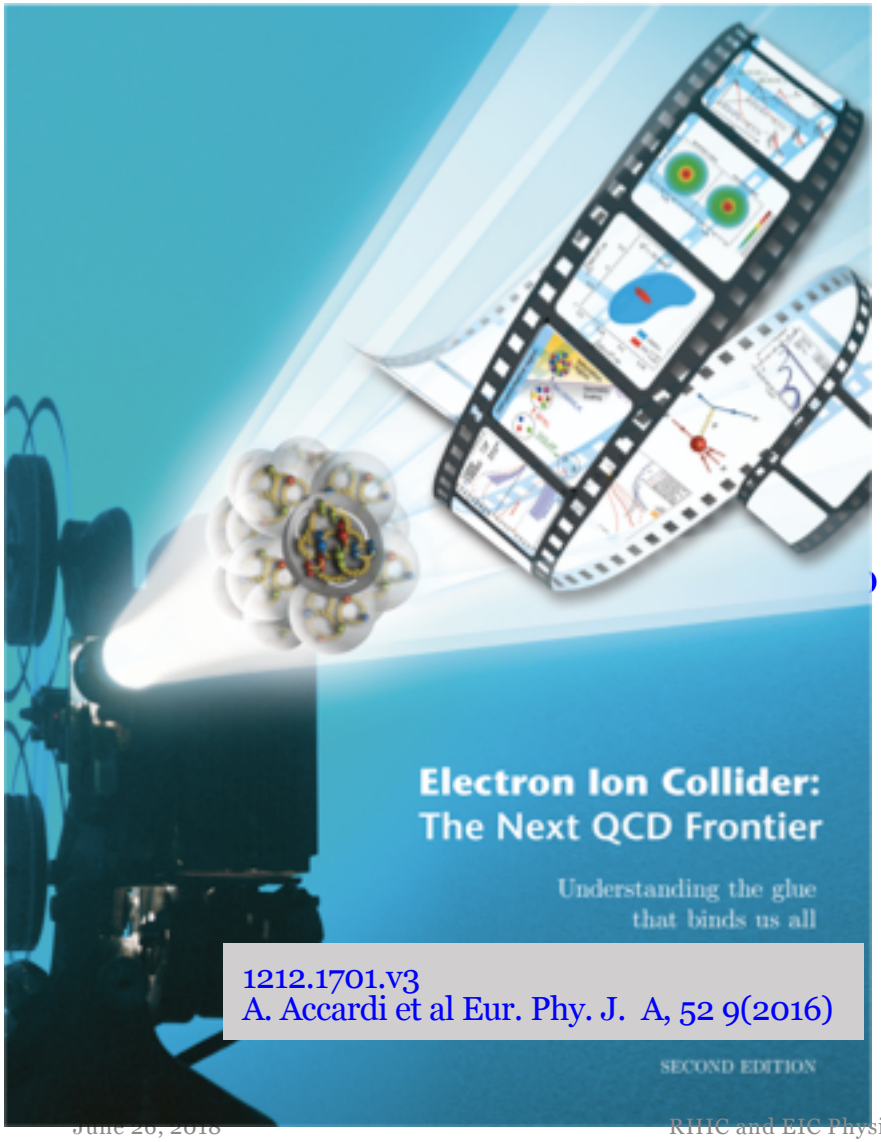
Theory
Detector & Accelerator R&D

$1.1M/year since 2011 for detector R&D

$7.5M/year since 2018 for accelerator realization R&D

The Electron Ion Collider

Two options of realization!



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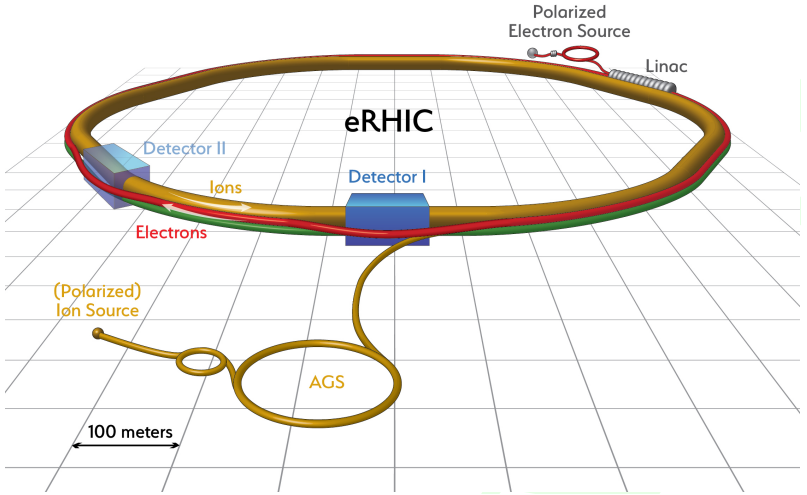
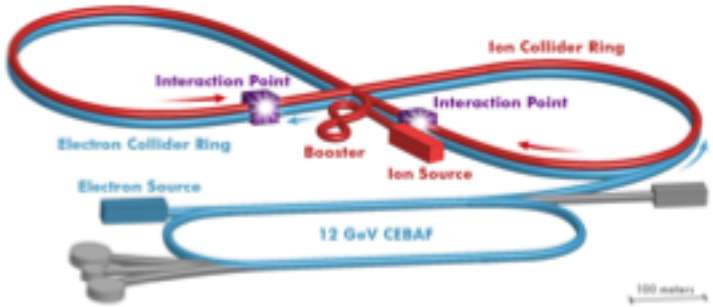
A. Accardi et al Eur. Phy. J. A, 52 9(2016)



Not to scale



Why was such a collider supported, and why is it going forward?

In the following lectures, we will go back 40-50 years and try to understand the origin of ideas and open questions that led us to the Electron Collider, the truly ultimate QCD machine

“spin” is an interesting and fundamental property in nature

Always full of surprises!

1955
Bohr & Pauli

Trying to understand
The tippy top toy

1900's a Century of Spin Surprises!

- Stern Gehrlach Experiment (1921)
  - Space quantization associated with direction
- Goudshmidt and Uhlenbeck (1926)
  - Atomic fine structure and electron spin
- Stern (1933)
  - Proton's anomalous magnetic moment : 2.79 (proton not a point object)
- Kusch (1947)
  - Electron's anomalous magnetic moment: 1.00119 (electron a point object)
- Yale-SLAC Experiment (Prescott et a.)
  - Electroweak interference in polarizded e-D scattering
- European Muon Collaboration (EMC) (1988)
  - The Nucleon Spin Crisis (now – a puzzle)

20th Century was a *Century of Spin Surprises!*

In fact, it has noted by :

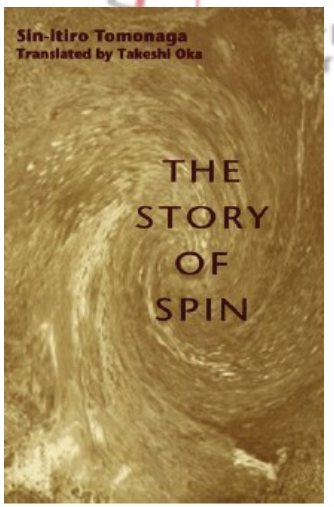
Prof. Elliot Leader (University College London) that

"Experiments with spin has killed more theories in physics, than any other physical property"

Prof. James D. Bjorken (SLAC), jokingly, that

"If theorists had their way, they would ban all experiments involving spin"

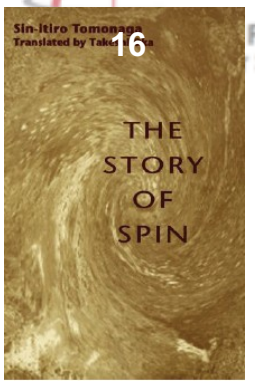
Brief history of spin:



- Measurement by Stern and Gerhlach (1922) "How a bad cigar helped reorient atomic physics" Physics Today
- *https://physicstoday.scitation.org/doi/full/10.1063/1.1650229*

- Introduced as a fundamental observable of sub-atomic physics by Goudshmidt and Uhlenbeck (1926)
  - P. Ehrenfest (reviewed the paper):
  - *"This is a good idea. Your idea may be wrong, but since both of you are so young without any reputation, you would not loose anything making a stupid mistake"*

- Other principle players in this drama:
  - Bohr-Sommerfield, Pauli, Dirac…. All in the 1920's



Story of Proton spin:

- Begins in 1927:
  - Hund, rotational part of specific heat of H_2 molecule
  - Hori: observed the band spectrum of H_2
  - Dennison: resolves the discrepancy between their results and concludes in a paper June 16, 1927 that:

Proton is a fermion of spin ½

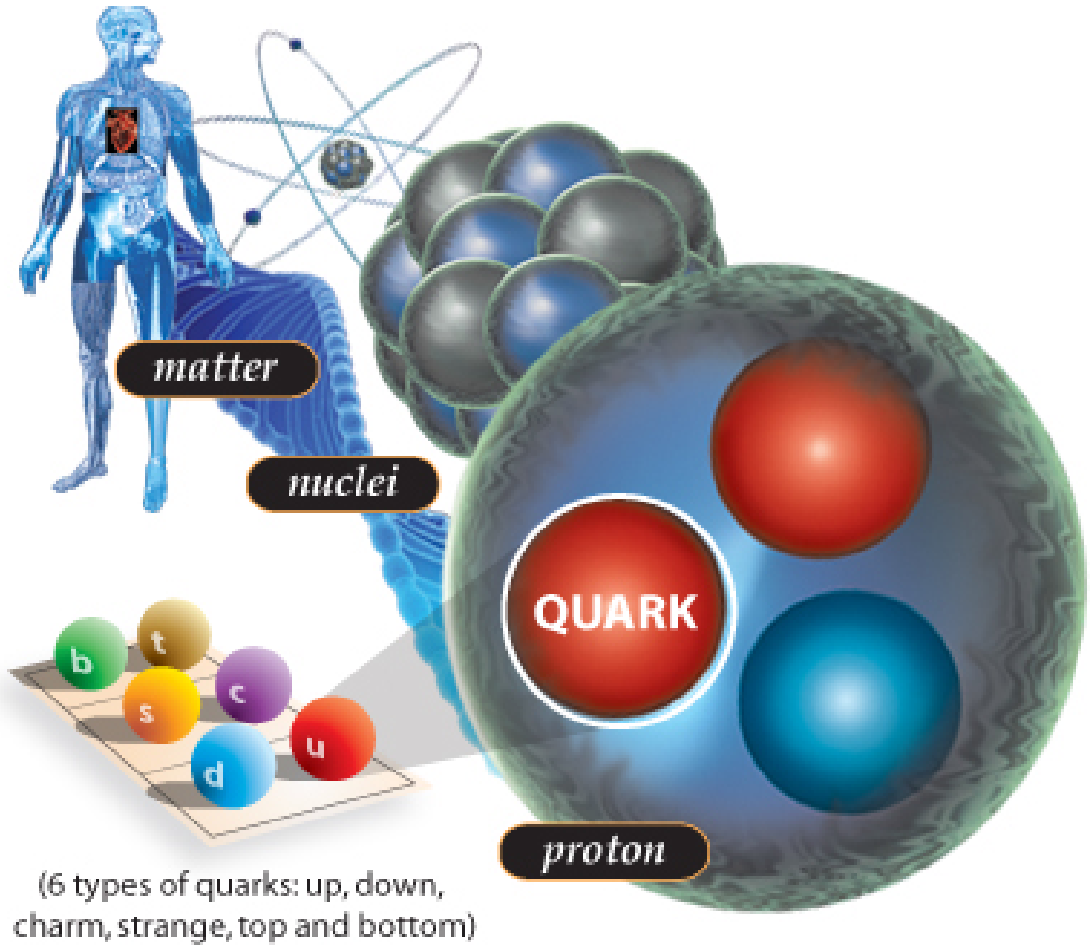
Today we know proton is a very complicated object:

Composite of quarks, gluons

It's spin (= ½) could get contributions from quarks, gluons and their possible orbital motion

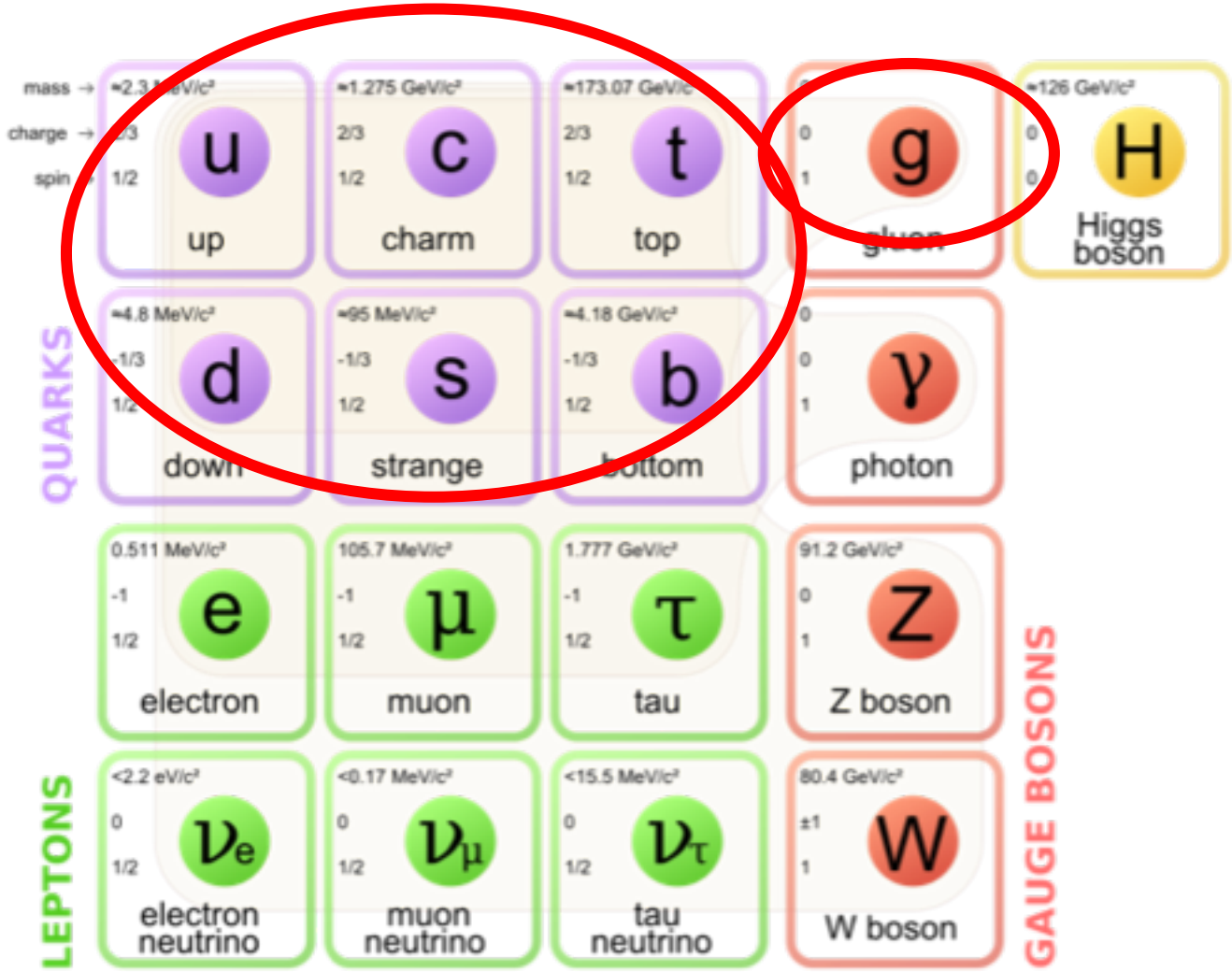
Would it not be cool to look inside the Proton?

Inside the proton… the fundamental particles that make… you, me and every thing around us….



The Standard Model of physics

Theory of *almost* everything



QED vs. QCD

- Quantum Electro-Dynamics (QED)
  - Electric charges : 2 types + & -
  - Electrons, protons carry electric charge
  - Interactions mediated by massless "photons" γ
  - Photons are electrically neutral → no electromagnetic charge!

  Charge Carriers in QED is Chargeless!

- Quantum Chromo-Dynamics (QCD)
  - Color charges : 3 types → red, blue, green ➔ Never seen separately
  - Interactions between quarks mediated by massless "gluons" → "g"
  - Quarks carry electric AND color charge
  - Gluons are electrically neutral but carry color charge!

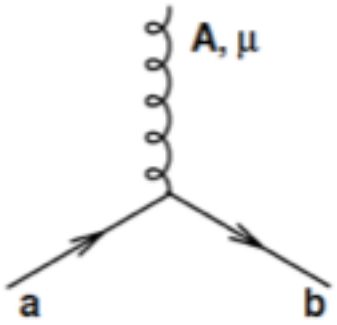
  Charge Carrier in QCD is Charged!

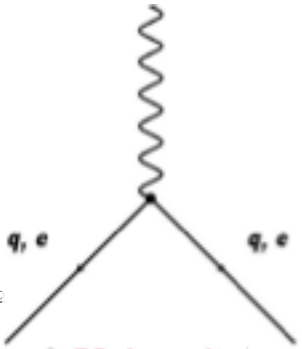
What distinguishes QCD from QED?

QED is mediated by photons (γ) which are charge-less

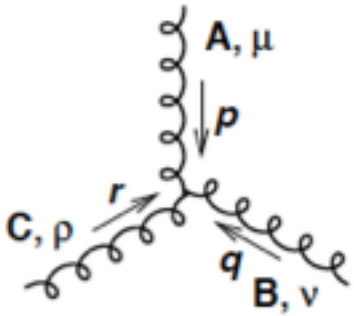
QCD is mediated by gluons (g), also charge-less but *are* colored!

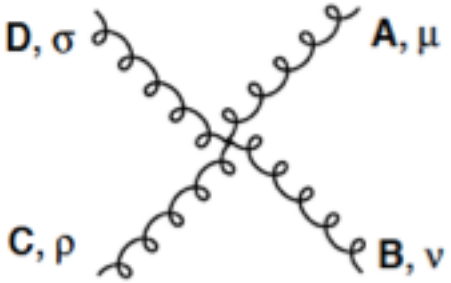
In QCD & g → γ in QED





Only in QCD

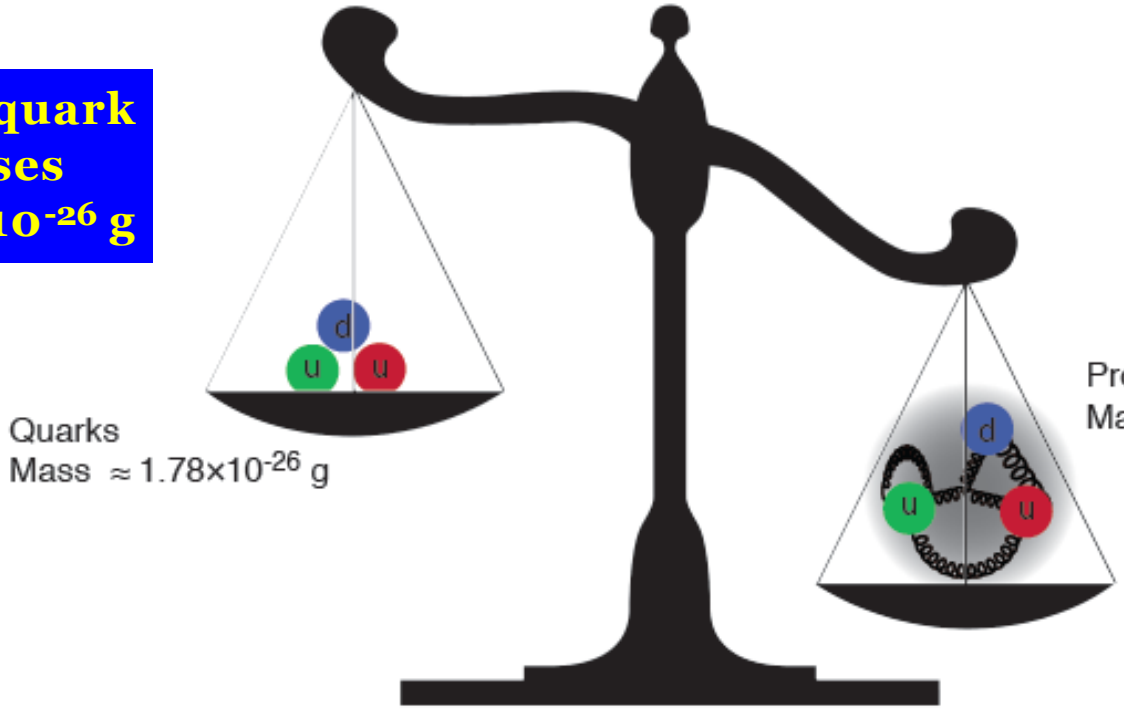




The Color-Interactions create mass!!!!

The mass miss-understanding

Sum of quark masses = 1.8 x 10^{-26} g



Proton mass 168 x 10^{-26} g

$M = E/C^2$

The Higgs ["God particle"] is responsible for **quark** masses ~ 1-2% of the proton mass.

Gluons are massless…yet their interaction are responsible for (nearly all) the mass of visible matter

All known hadrons and mesons are made up of "quarks & anti-quarks"

They are bound together by gluons…

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Some facts about Protons, Quarks & QCD

- Quarks do not exist in isolation, neither can gluons…
  - Always coupled to anti-quarks (to form mesons) or triplets to form Hadrons/Baryons
- Have spin ½ …. Always! No quarks with any other "spin"

- Protons always have spin ½ (well known ~100 years)
  - Undergraduate table top experiments show this these days
- Proton's charge is always +1
- Neutron is the neutral particle charge is always 0, and spin is ½

In these lectures:

We will ask many questions about "spin" of subatomic particles.

We will ask many questions about the behavior of gluons in hadrons and nuclei.

We will ask many questions about differences and similarities between nucleons and nuclei.

We will ask many questions about experimental methods.

There will be overlap and repetition to emphasize the connectedness of many topics through the role of spin, gluons and nuclei/nucleon's structure and dynamics that we intend to experimentally observe

The lectures will cover:

QCD and 1 D picture at high energy of a hadron

- Introduction : Lecture 1 A
- Discovery of Spin Crisis, spin rules, and history : Lecture 1 B
- Discovery of parton dynamics beyond 1-Dimention : Lecture 1 C

RHIC Spin program and inventing Collider Techniques and Tools

- From fixed target to RHIC , and polarized RHIC : Lecture 2

Need for DIS in Collider mode:

- The Science of Electron Ion Collider : Lecture 3
  - Nucleon Spin
  - Interactions amongst nucleons in nuclei
  - Effect of high density gluonic states

Status of the Electron Ion Collider

- Status and plans : Lecture 4 , a discussion: Lecture 4

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