*Photonuclear reactions and strong-field QED at hadron-hadron and electron-hadron colliders**

**And some other assorted thoughts*

Christine A. Aidala
Physics Department
University of Michigan

Nuclear Physics Under the Low-Energy, High-Intensity Frontier
ECT* Trento
August 12, 2026

Some overarching questions in the medium- and high-energy nuclear physics communities

How do we understand nucleons, nuclei, and their interactions in terms of the quark and gluon degrees of freedom of quantum chromodynamics (QCD)?

How can studying QCD systems teach us more about fundamental aspects of QCD as a theory?

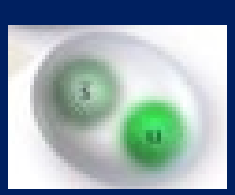
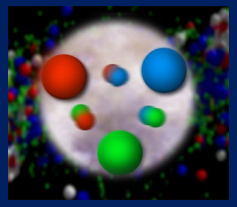
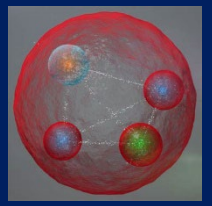
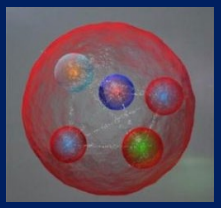
How can high-energy nuclear interactions be used to probe other physics?

(One way of dividing up) Areas of study in QCD

- *Structure/properties* of QCD matter
- *Formation* of states of QCD matter
- *Interactions* within QCD

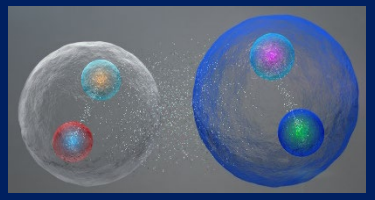
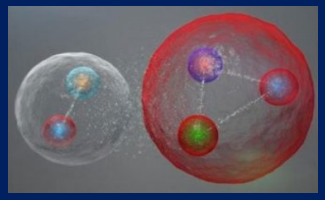
Structure/Properties of QCD matter

- Bound states: Mesons, baryons, also tetraquarks, pentaquarks, sexaquarks?

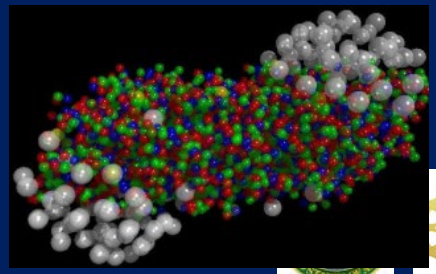





- Bound states of bound states: Nuclei, neutron stars, other hadronic molecules?



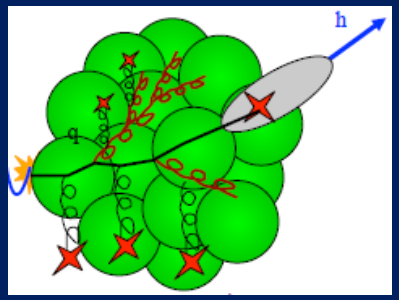



- Deconfined states: Quark-gluon plasma



Formation of states of QCD matter

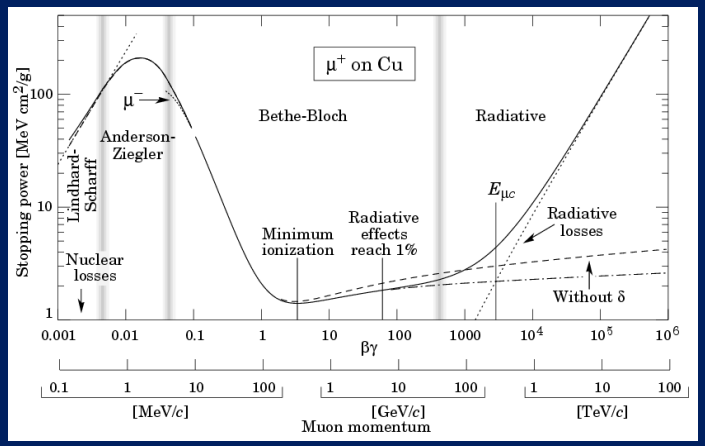
- Bound state formation mechanisms
- Formation of bound states of bound states
- Equilibration of quark-gluon plasma
- Time scales of hadronization/equilibration
- Modification of hadronization in different environments



Knock a quark out of a free proton vs. a nucleus—how is new bound state formation from the scattered quark affected by the presence of the nucleus?

Interactions within QCD

- Quark and gluon energy loss in cold and hot QCD matter
  - What is the analog of the Bethe-Bloch curve for QCD rather than electromagnetism?

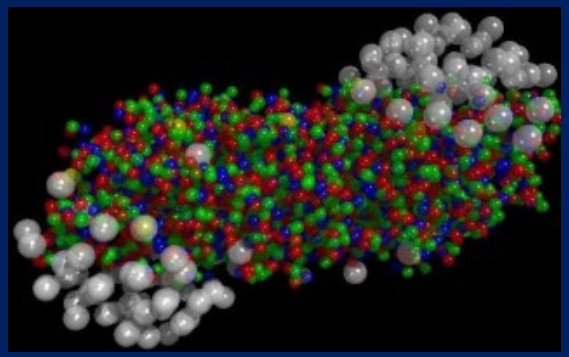


Electromagnetic energy loss of muons passing through copper

- Color charge flow effects in scattering processes
  - Process-dependent spin-momentum correlations in hadrons
  - Quantum entanglement of quarks across colliding hadrons

High-(enough)-energy collisions: Tools to study QCD

- Not energy-frontier research! But sufficiently high energies allow
  - Access to subnuclear distance scales
    - Proton radius ~10^{-15} m → E > ~1 GeV
  - Form new states of QCD matter, e.g. quark-gluon plasma



  - Use of perturbative theoretical tools
  - Access to different probes, e.g. heavy quarks (charm and bottom), Z and W bosons

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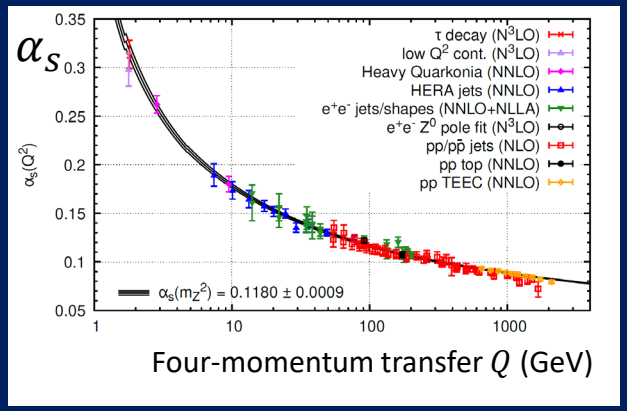

Particle Data Group, 2023

  - Use of perturbative theoretical tools
  - Access to different probes, e.g. heavy quarks (charm and bottom), Z and W bosons

Complementary collision systems

Can study QCD via

- Hadron-hadron collisions: proton-proton, proton-nucleus, nucleus-nucleus, antiproton-proton, pion-nucleus, …

- Lepton-or photon-hadron collisions: e/μ/γ-proton, e/μ/γ-nucleus, ν-nucleus

- Lepton-lepton collisions: e^+-e^-, future μ^+-μ^-??

- Photon-photon collisions?

Nuclear physics and control: Tabletop experiments for giants

Much of nuclear physics is carried out at accelerator facilities—fixed-target or collider—but the spirit is very different from much of particle physics, which focuses on the energy and/or intensity frontier

The more aspects of the collisions we can control/manipulate, the more powerful our tools are to address questions in nuclear physics

- Collision species → state of matter to be studied, geometry, path length, quark flavor/isospin, electroweak vs. strong interactions
- Energy → distance/time scales, probes accessible, states of matter
- Polarization → spin-spin and spin-momentum correlations in QCD systems or in hadronization

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Some aspects we *select* rather than control

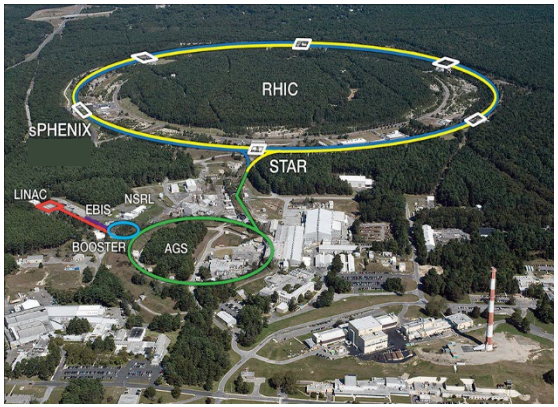
- Overlap of colliding nuclei, final-state produced particles and their kinematics, …

Nuclear physics and control: Tabletop experiments for giants

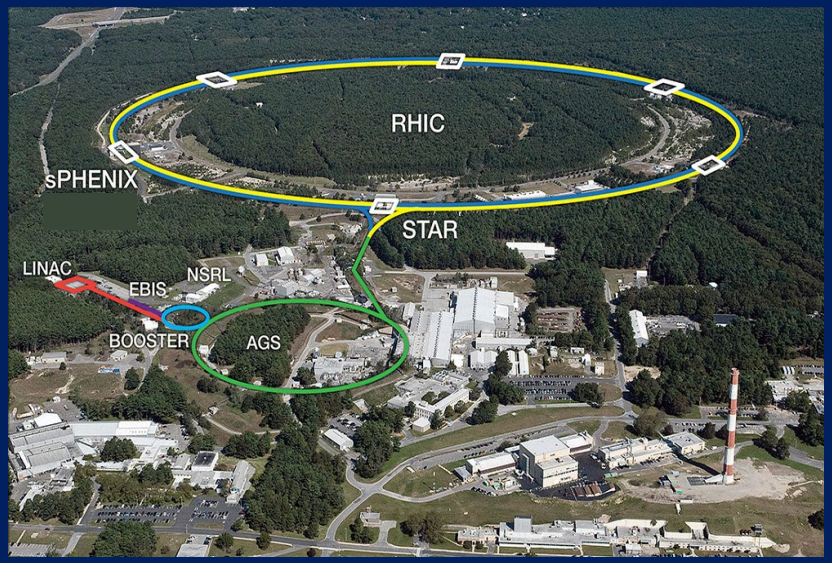
The more aspects of the collisions we can control/manipulate, the more powerful our tools

Relativistic Heavy Ion Collider—a wide range of collision species and energies have been run!

Collision Species	Collision Energies (GeV)
p↑+p↑	510, 500, 200, 62.4
p+Al	200
p+Au	200
d+Au	200, 62.4, 39, 19.6
^{3}He+Au	200
Cu+Cu	200, 62.4, 22.5
Cu+Au	200
Ru+Ru	200
Zr+Zr	200
Au+Au	200, 130, 62.4, 56, 39, 27, 19.6, 15, 11.5, 7.7, 5, ...
U+U	193



My own facilities: RHIC and the LHC





- Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab
  - ***Polarized*** proton beams 31.2-255 GeV (62.4-510 GeV c.m. energy)
  - Nuclear beams from deuterons to uranium 3.85-100 GeV/nucleon (7.7-200 GeV/nucleon c.m. energy)
- Large Hadron Collider at CERN
  - Proton beams up to 6.8 TeV (13.6 TeV c.m. energy)
  - Pb beams up to 2.68 TeV/nucleon (5.36 TeV/nucleon c.m. energy)

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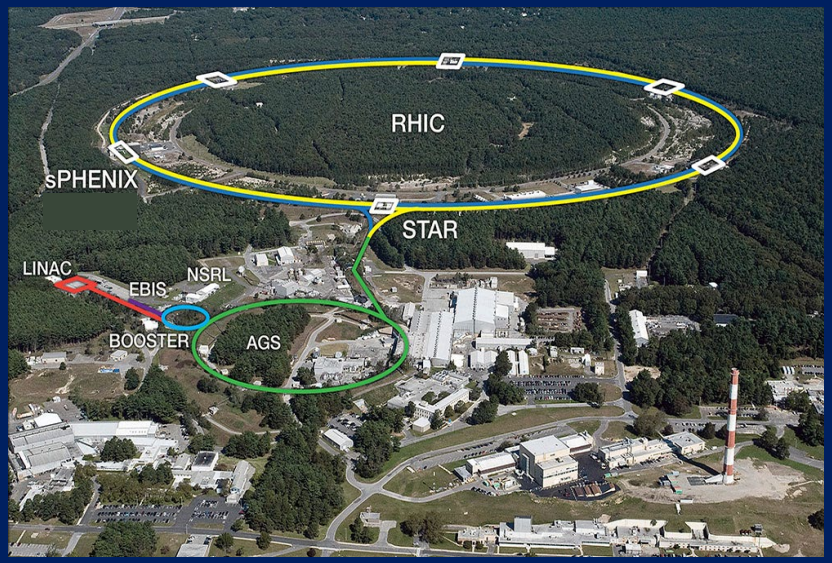

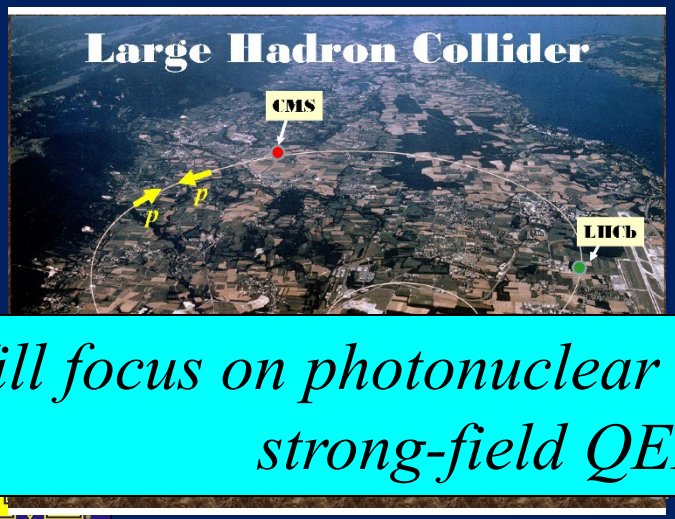

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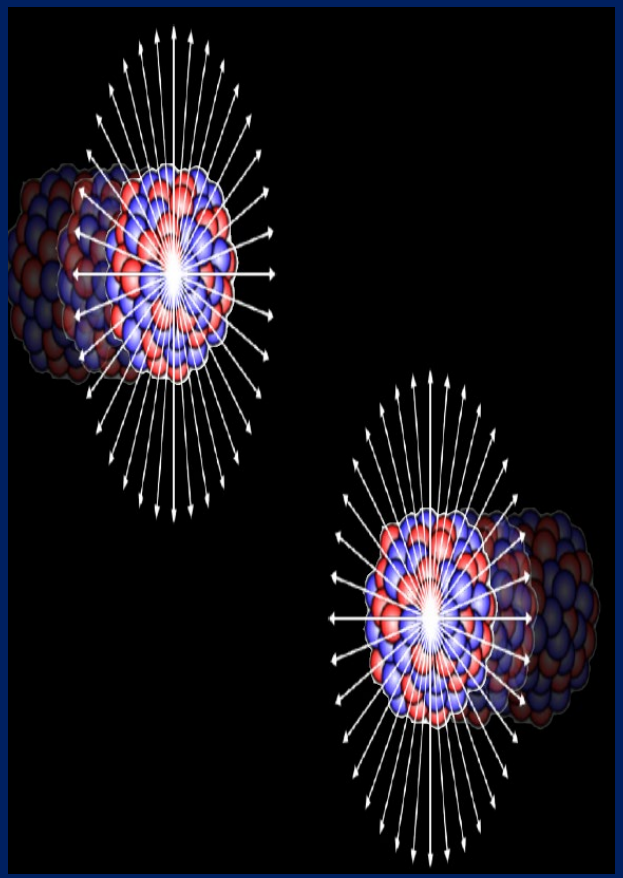
Will focus on photonuclear reactions and strong-field QED

Large nuclei stripped of all electrons moving at highly relativistic speeds create large electromagnetic fields!

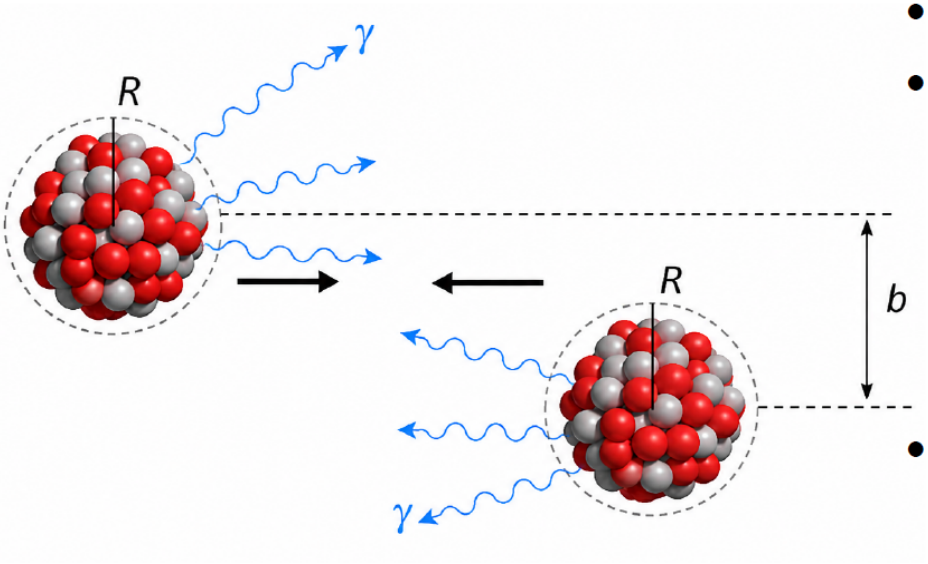


What can we do with them?

See also Snowmass 2021 Letter of Interest: *New opportunities at the photon energy frontier* - https://arxiv.org/pdf/2009.03838

P. Steinberg, DIS 2025

Ultraperipheral nuclear collisions



- Stripped heavy ion have strong EM fields of **B ~ O(10^{15}) T**
- In target frame, highly boosted projectile emitting photons (intensity ≈ Z^2):
  - propagate almost in the **direction of the emitter**
  - are almost **real**, $Q^2 < (\hbar/R)^2$, like a free plane wave
  - **linearly polarized**
- Collisions with **impact parameter b > 2R** where the hadronic interaction is highly suppressed

- **Hadron collider is turned to a photon-hadron or photon-photon collider**

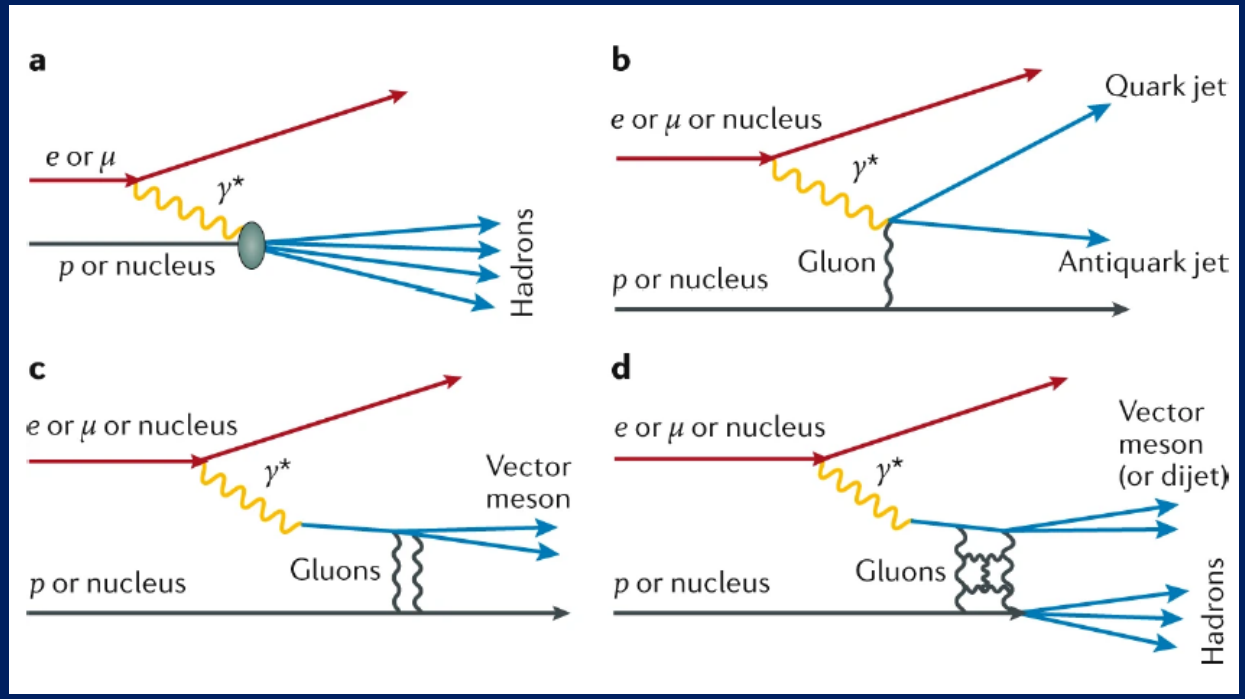
	AuAu RHIC	PbPb LHC
Eγ (target)	0.6 TeV	500 TeV
Wγp	24 GeV	700 GeV
γγ max	6 GeV	200 GeV

4

Minjung Kim, DIS 2026

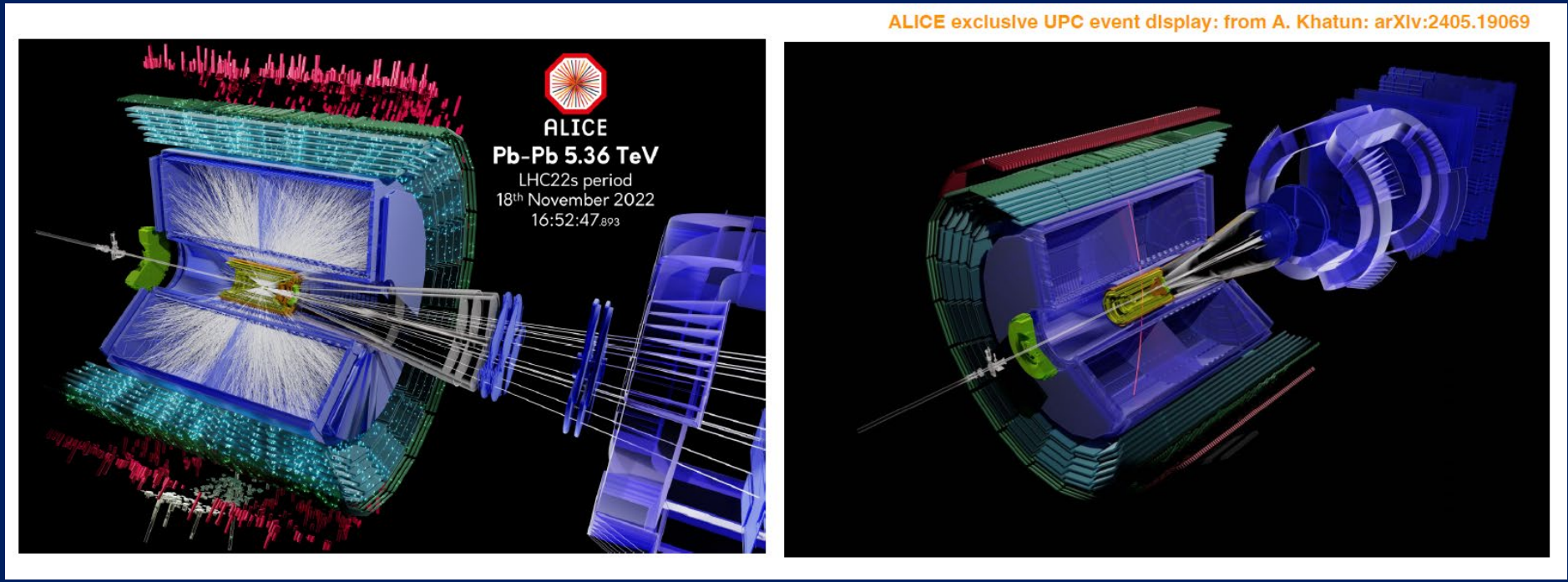
Photon-induced interactions with target proton or nucleus

With quantum numbers $J^{PC} = 1^{--}$, photon preferentially fluctuates into a vector meson



Minjung Kim, DIS 2026

Photoproduced vector meson at LHC ALICE experiment

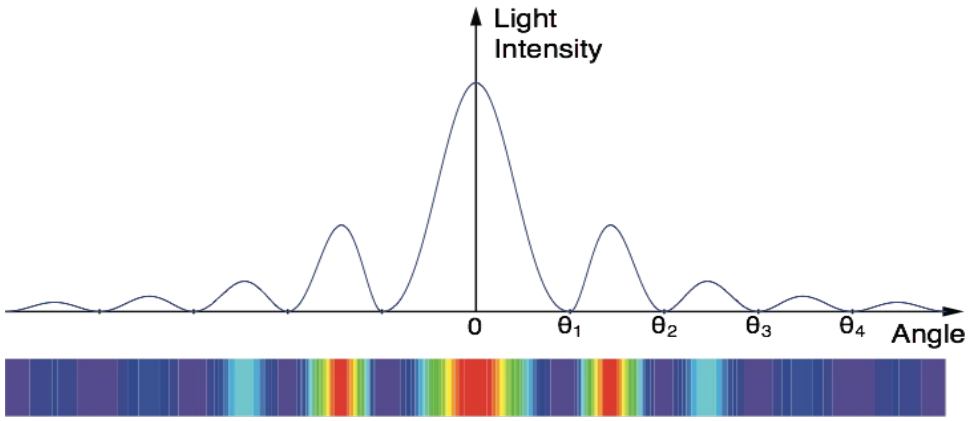


Typical Pb+Pb collision event display

Ultraperipheral collision event display – almost empty detector

Imaging spatial structure of quarks or gluons in nuclei: Diffraction

Diffraction pattern from monochromatic plane wave incident on a circular screen of fixed radius



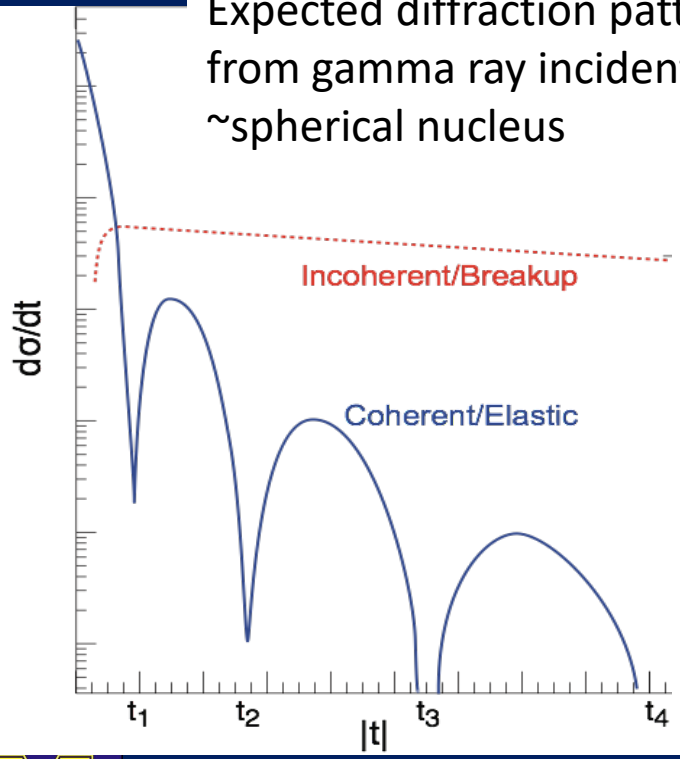
From E. Aschenauer

- X-ray diffraction used to probe spatial structure of atomic crystal lattices
  - Measure in momentum space, Fourier transform to position space
- Nuclear distance scales → Need gamma ray diffraction!
  - Again measure diffractive cross section in momentum space (Mandelstam *t*), Fourier transform to position space

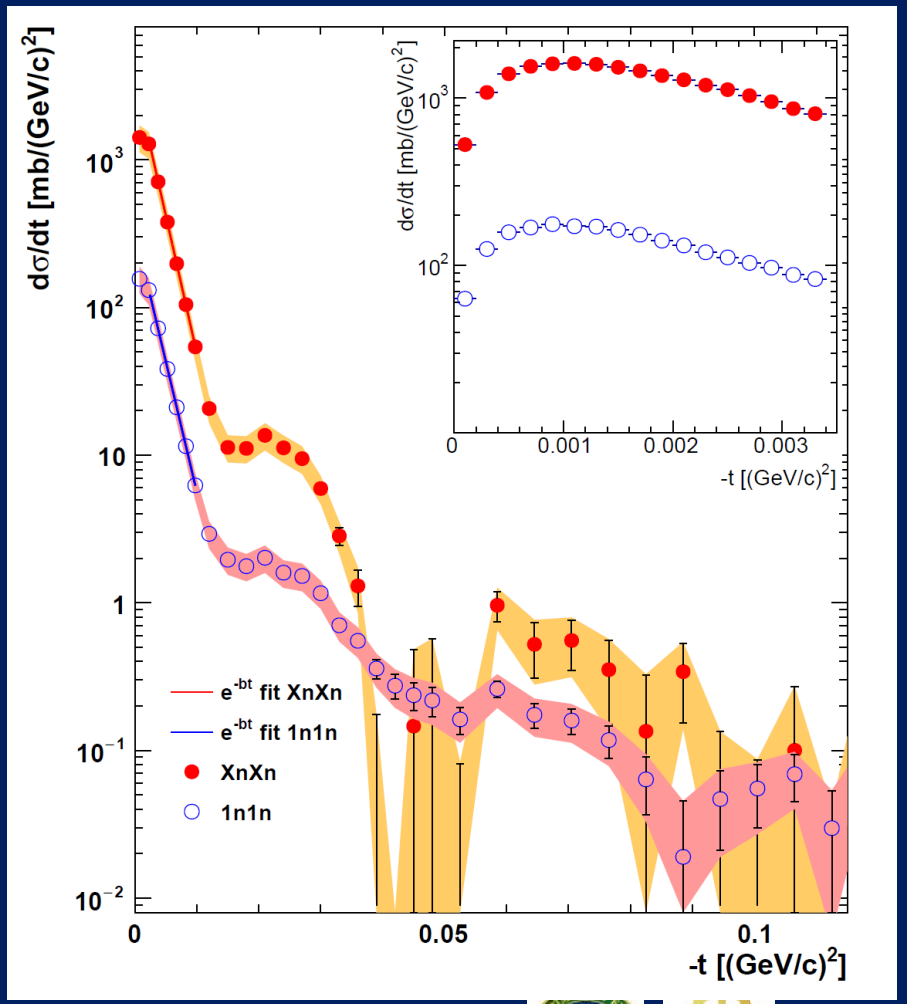
Spatial imaging of nucleons and nuclei

Exclusive vector meson production in nucleus-nucleus collisions can be used to perform spatial imaging of quarks or gluons in nuclei

Expected diffraction pattern from gamma ray incident on ~spherical nucleus



Coherent ρ^0 photoproduction in Au+Au
STAR, PRC96, 054904 (2017)



Modern alchemy via electromagnetic dissociation

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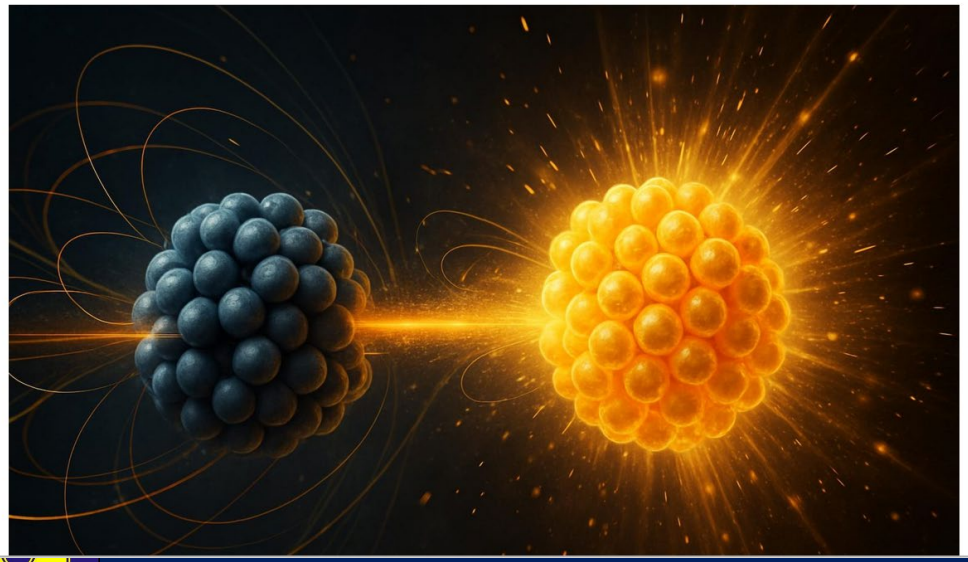

Pb → Au via electromagnetic dissociation

Modern alchemy via electromagnetic dissociation

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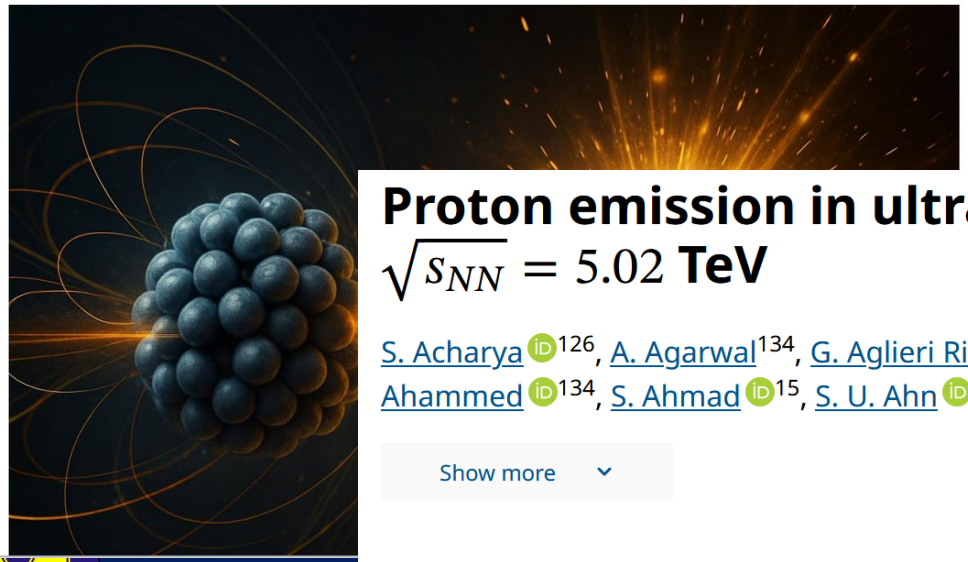


Pb → Au via electromagnetic dissociation

Proton emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

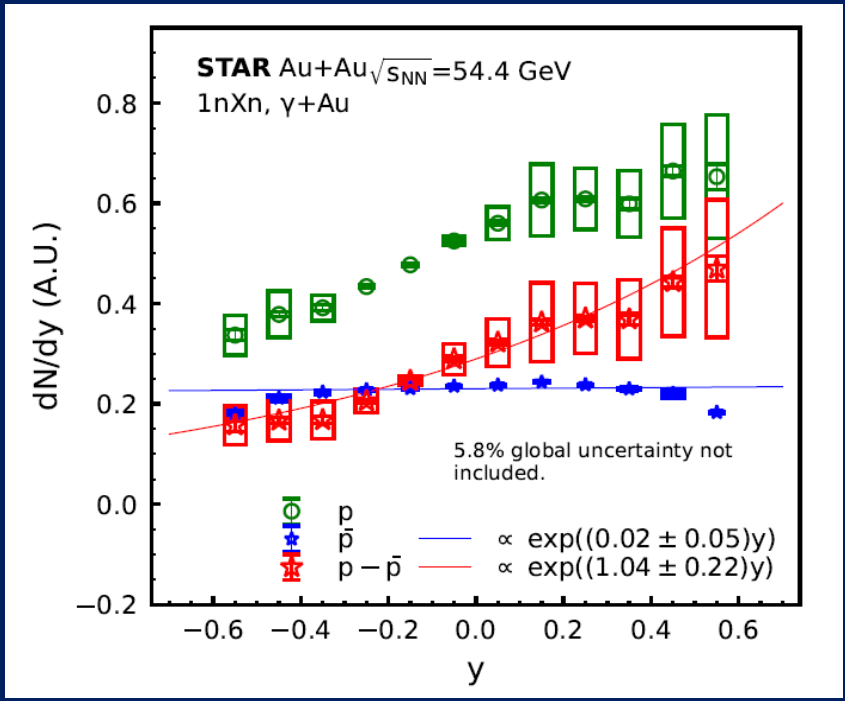
S. Acharya[126], A. Agarwal[134], G. Aglieri Rinella[32], L. Aglietta[24], M. Agnello[29], N. Agrawal[25], Z. Ahammed[134], S. Ahmad[15], S. U. Ahn[71] *et al.* (ALICE Collaboration)

Show more

Phys. Rev. C **111**, 054906 – **Published 7 May, 2025**

Photonuclear collisions to study whether valence quarks or "baryon junctions" carry baryon quantum number

- Study proton, antiproton, and net (proton – antiproton) distribution in rapidity (angle) from "clean" photonuclear reactions

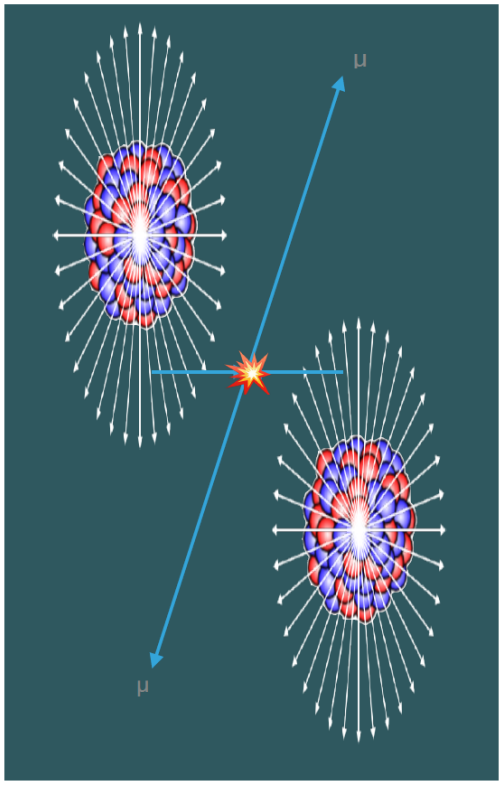


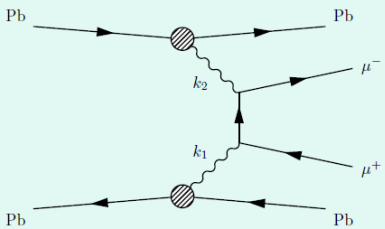
https://arxiv.org/pdf/2408.15441, accepted by Science

Electromagnetic field interactions in ultraperipheral nucleus-nucleus collisions

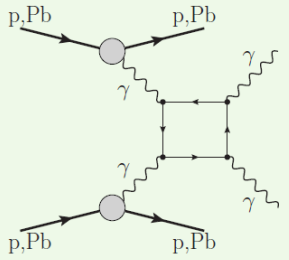
- Light-by-light scattering!
- Observed at RHIC, LHC

P. Steinberg, DIS 2025



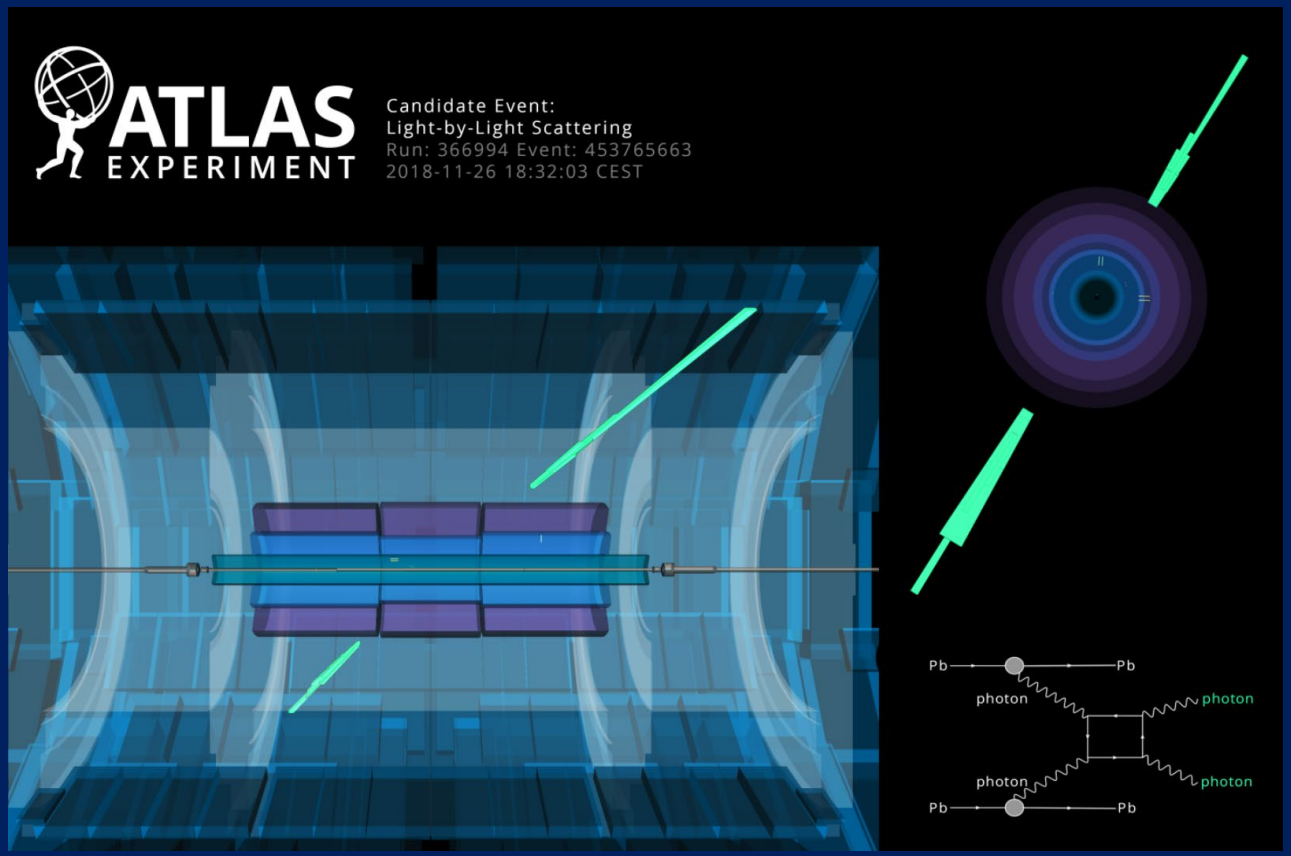


lepton pair production
(Breit-Wheeler formula, Brodsky et al 1971)



photon pair production
(via quark, lepton, W, BSM? loops)

Electromagnetic field interactions in ultraperipheral nucleus-nucleus collisions



Pb+Pb → $\gamma + \gamma$

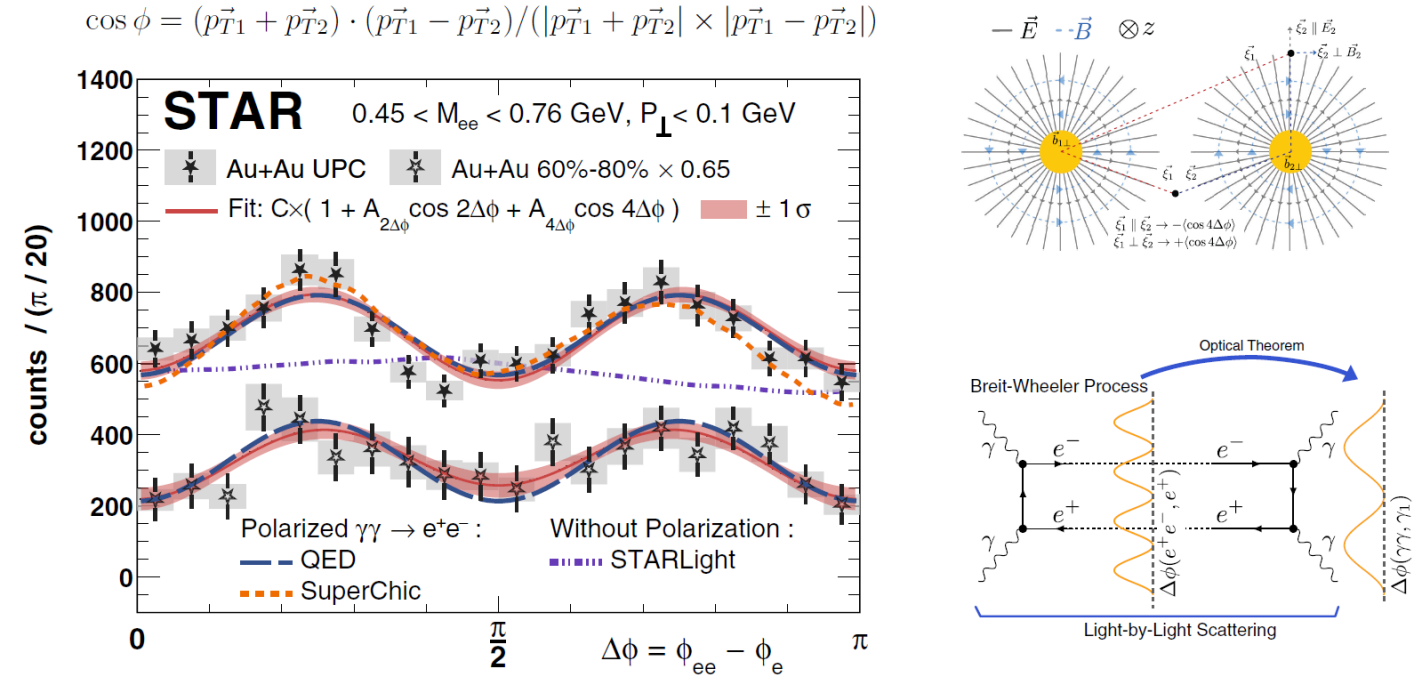
P. Steinberg, DIS 2025

Light-by-light scattering at the LHC

See e.g.
ATLAS:
Nature Phys. 13, 852 (2017),
JHEP 03, 243 (2021)

CMS:
PLB 797, 134826 (2019),
JHEP 08, 006 (2025)

Electromagnetic field interactions in ultraperipheral nucleus-nucleus collisions



Linear polarization of photons leads to azimuthal modulation of produced $e^+ + e^-$

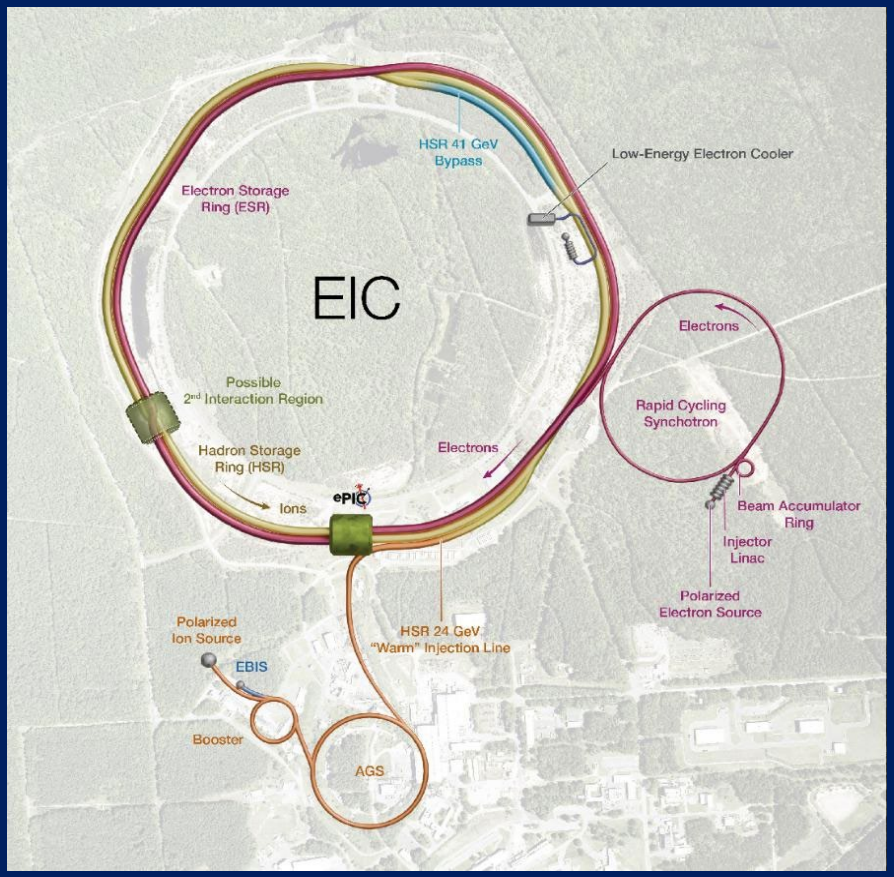
Au+Au → $e^+ + e^-$

STAR Collaboration at RHIC, PRL 127, 052032 (2021)

Looking ahead: The Electron-Ion Collider at BNL

After >25 years, RHIC completed operations on Feb 6, and construction of the Electron-Ion Collider has started

First data expected 2035

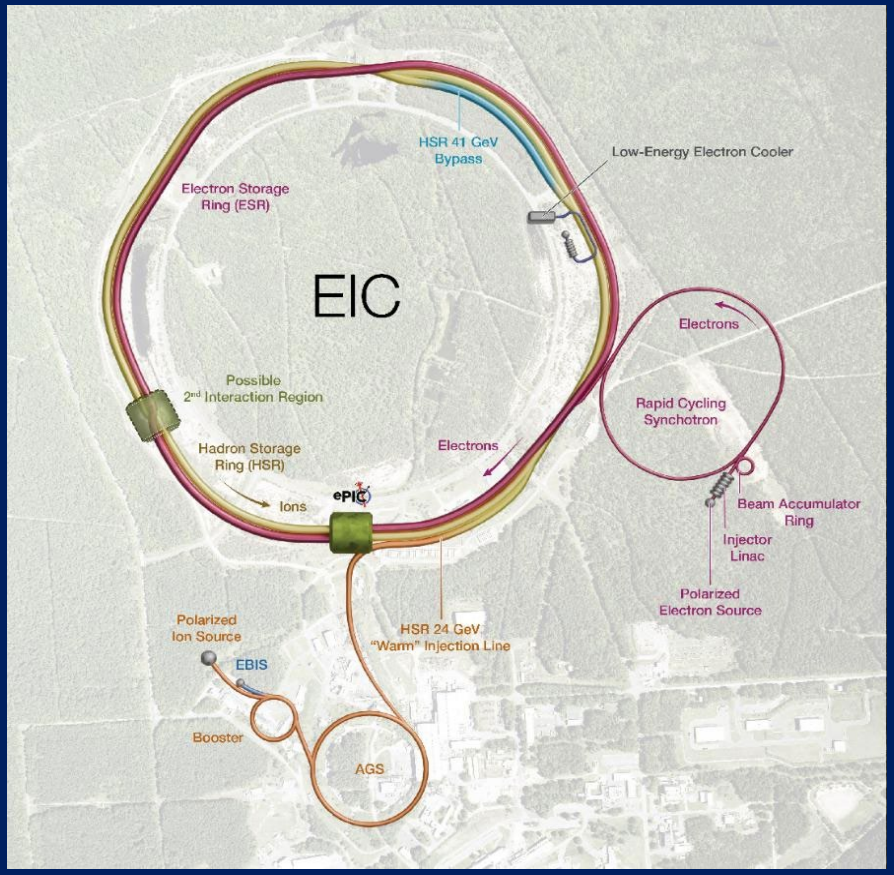


Protons: 41, 100 – 275 GeV

Electrons: 5 – 10 GeV (upgradable to 18 GeV)

Looking ahead: The Electron-Ion Collider at BNL

- Highly polarized electron (~70%) and proton (~70%) beams
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium
  - Including polarized ^{3}He and possibilities for polarized deuterons!
- Variable $e + p$ center-of-mass energies from ~20-100 GeV



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EIC User Group

www.eicug.org



Electron-Ion Collider User Group:
Currently >1500 members from 313 institutions in 43 countries.
(~25% theorists, ~10% accelerator physicists,
~65% experimentalists)

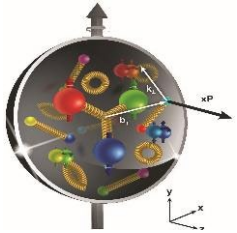
EIC science pillars



SPIN



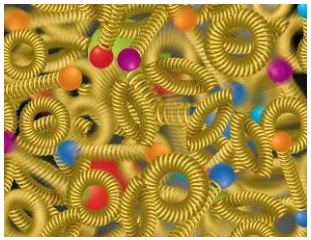
MASS



3D-Imaging



QCD in Nuclei



Dense Gluon Systems

(National Academies of Sciences, Medicine, and Engineering, 2018 Consensus Study Report)

Key science questions:

How does a nucleon acquire mass?

How does the spin of the nucleon arise from its elementary quark and gluon constituents?

What are the emergent properties of dense systems of gluons?

Stepping back: What are the various reasons we use electromagnetic probes to study objects with internal color structure?

- Often for the interactions with *electrically* charged quark constituents of hadrons and nuclei
  - Probe is real or virtual photon, or the EM field

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- Sometimes (also) explicitly want fact that EM probes *don't* interact with color charge—calibration, or simply "clean" probe that's easier to calculate/has fewer complications.
- Sometimes want direct comparison of QED and QCD processes to study features unique to the non-Abelian nature of QCD

Stepping back: What are the various reasons we use electromagnetic probes to study objects with internal color structure?

- Often for the interactions with *electrically* charged quark constituents of hadrons and nuclei
  - Probe is real or virtual photon, or the EM field
- Sometimes for the fact that a *virtual* photon can fluctuate into a quark-antiquark pair and interact with gluons directly
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- Sometimes want direct comparison of QED and QCD processes to study features unique to the non-Abelian nature of QCD
- Can use thermal photons or dileptons to measure the temperature of a quark-gluon plasma!
- Inverting probe and object of study—can use nuclei to study strong-field QED!

Some potential connections to other talks, and other thoughts…

Some just from the last two days, in the spirit of Jerry's request to include ideas that aren't mature!

Laser-accelerated beams

- Few-GeV electron or proton beams valuable as test beams to develop detector technology for particle and (medium- and high-energy) nuclear physics
- There are relatively few such facilities worldwide!
  - Fermilab Test Beam Facility (https://ftbf.fnal.gov/beam-overview/) – primary beam 120 GeV protons, secondary beams of pions, muons, or electrons down to ~1 GeV
  - CERN – see e.g. info at https://web.infn.it/EURO-LABS/cern-ta/
  - DESY – electron, positron, and photon beams - https://particle-physics.desy.de/e252106/
  - SLAC Linac to End Station A (LESA) beam plans to provide 8 GeV electrons starting in 2027, having recognized a critical need for more test beam facilities!
    - Sep 2025 workshop https://indico.slac.stanford.edu/event/9874/
    - S30XL/LESA beam aims for plasma-accelerated electrons

Laser-accelerated beams

- Laser-accelerated beams could also provide additional or complementary(?) facilities to emulate space radiation environments with various ions
  - At Brookhaven National Lab, NASA Space Radiation Lab uses conventional acceleration techniques (https://www.bnl.gov/nsrl/about.php)

Beams of all ions from protons to thorium, ranging in energy from 50 MeV to 1500 MeV (ion species dependent), and extracted from the Booster accelerator with masses and energies similar to the cosmic rays encountered in space

Laser-accelerated beams

- Multi-GeV center-of-mass energy electron-neutron scattering possible someday??
  - Quark-gluon structure of neutrons only measured via bound neutrons (deuterons and helium-3)
  - Many phenomenological extractions *assume* the neutron is the exact isospin mirror of the proton, which is only an approximation. As we obtain more and more precise measurements of quark distributions in nucleons, in particular 3D momentum distributions, the breaking of this approximation will be more relevant
  - So future measurements with free neutron beams would be extremely valuable!

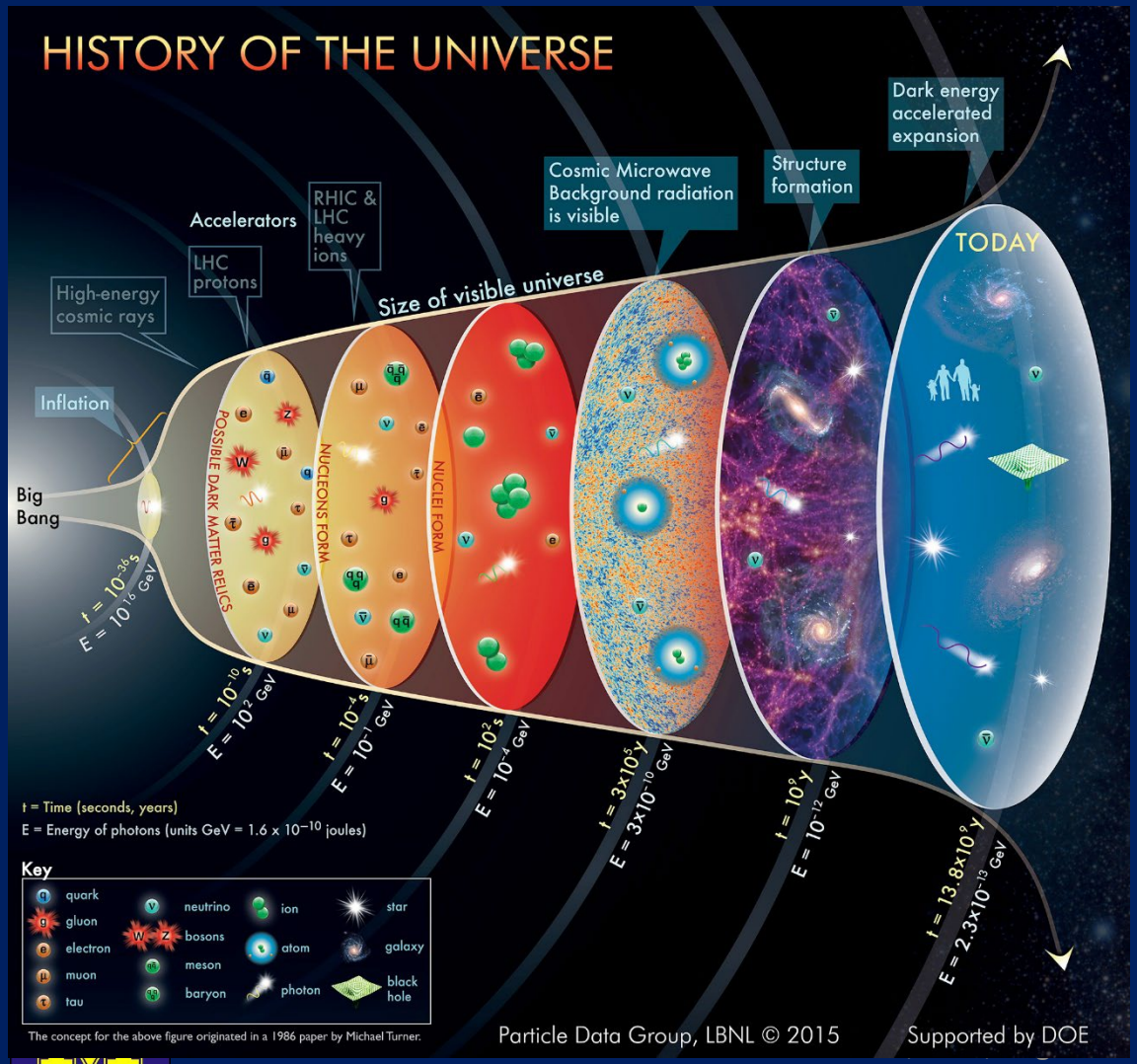
Laser-accelerated beams

- *The science case for an intermediate energy advanced and novel linear collider facility* – whitepaper submitted to Snowmass 2021 – J. Inst. 19, T01010 (2024) and https://arxiv.org/pdf/2203.08425
  - Discusses opportunities at a 20-100 GeV center-of-mass e^+e^- collider facility using plasma-accelerated beams

Laser-accelerated beams and nuclear physics opportunities using ~1-150 MeV photons or electrons?

- High Intensity Gamma-Ray Source (HIGS) at Duke University- https://tunl.duke.edu/research/our-facilities – nearly mono-energetic, polarized gamma-ray beams from 1-100 MeV (Compton backscattering)
- MESA at Mainz - https://www.kernphysik.uni-mainz.de/en/accelerator-mesa-experiments/ - Up to 155 MeV electrons
- Complementary opportunities for nuclear physics at similar energies using laser-accelerated beams??

Extreme nuclear matter: Quark-gluon plasma



- For first ~10 μs – energy densities too high for quark bound states to form → quark-gluon plasma
- Can recreate in lab with high-energy nuclear collisions!

Extreme nuclear matter: Quark-gluon plasma

- Hottest temperature in the known universe: ~10^5 times hotter than typical astrophysical temperatures

$$T \sim \frac{\Lambda_{QCD}}{k_B} = 200 \text{ MeV} = 2.3 \times 10^{12} \text{ K}$$

- Highest pressure in the known universe: ~10^{18} times higher than typical astrophysical pressures

$$P \sim \frac{\Lambda_{QCD}^4}{(\hbar c)^3} = (200 \text{ MeV})^4 = 3.2 \times 10^{34} \text{ Pa}$$

- Largest magnetic field in known universe: ~10^3-10^5 times larger than the field of magnetars

$$B \sim 4.8 \times 10^{14} \text{ T (RHIC)}, 1.4 \times 10^{16} \text{ T (LHC)}$$

Extreme nuclear matter: Quark-gluon plasma

- Hottest temperature in the known universe: ~10^5 times hotter than typical astrophysical temperatures

Possible to study photon vortices in these collisions??
What kind of observables would we need??

Similarly possible in the cleaner environment of ultrapheripheral nuclear collisions??

- [illegible] her

$$P \sim \frac{\quad}{(\hbar c)^3} = (200\ \mathrm{MeV}) = 3.2 \times 10^{\quad}\ \mathrm{Pa}$$

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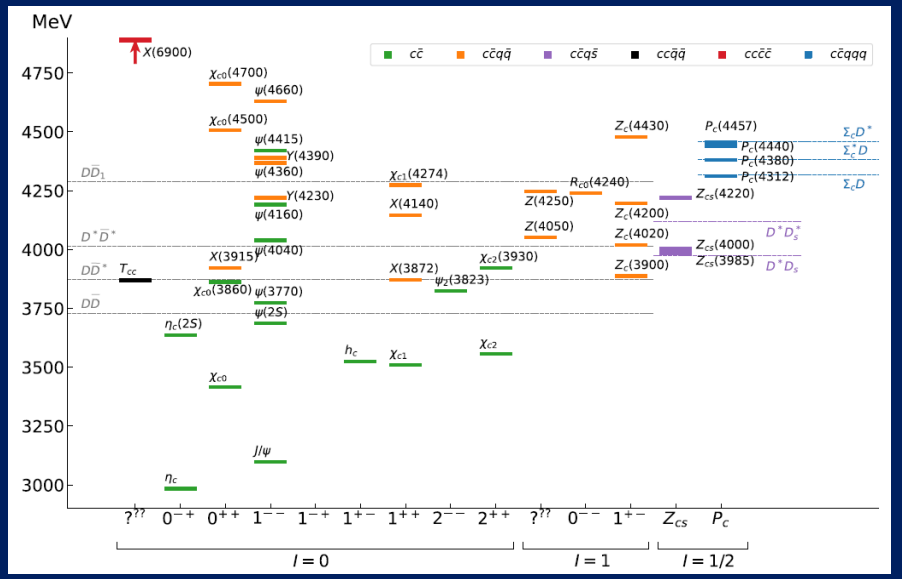
Twisted photons for hadron spectroscopy??

- Similar to atoms and nuclei, quark bound states have many energy levels with different quantum numbers → hadron spectroscopy
  - Unlike atomic and nuclear spectroscopy, same quark combination in a different state has a different mass and is generally considered a different particle, sometimes with a completely different name
- Can do hadron spectroscopy with e.g. collisions of $e^+ + e^-$ (BESIII, Belle II), $\gamma + p$ (GlueX), e^- or $\mu^- + p$ (COMPASS/AMBER), or $p + p$ (LHCb)
  - Different quantum numbers of incoming particles facilitate production of hadrons with different quantum numbers



V. Crede, Hadron spectroscopy: Experimental overview - https://arxiv.org/abs/2608.00191

Twisted photons for hadron spectroscopy??

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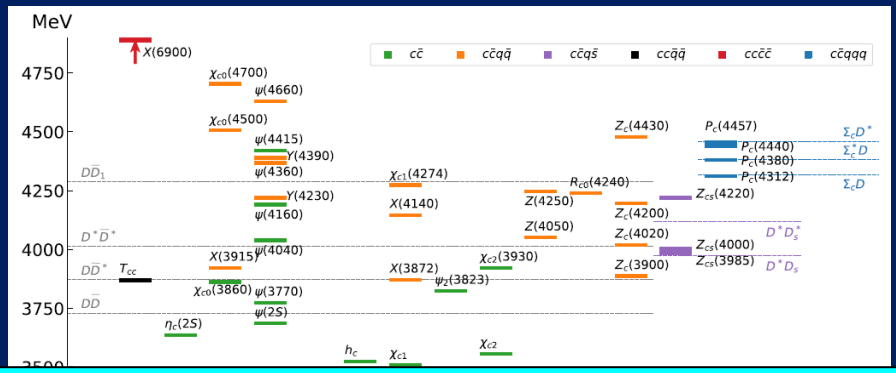
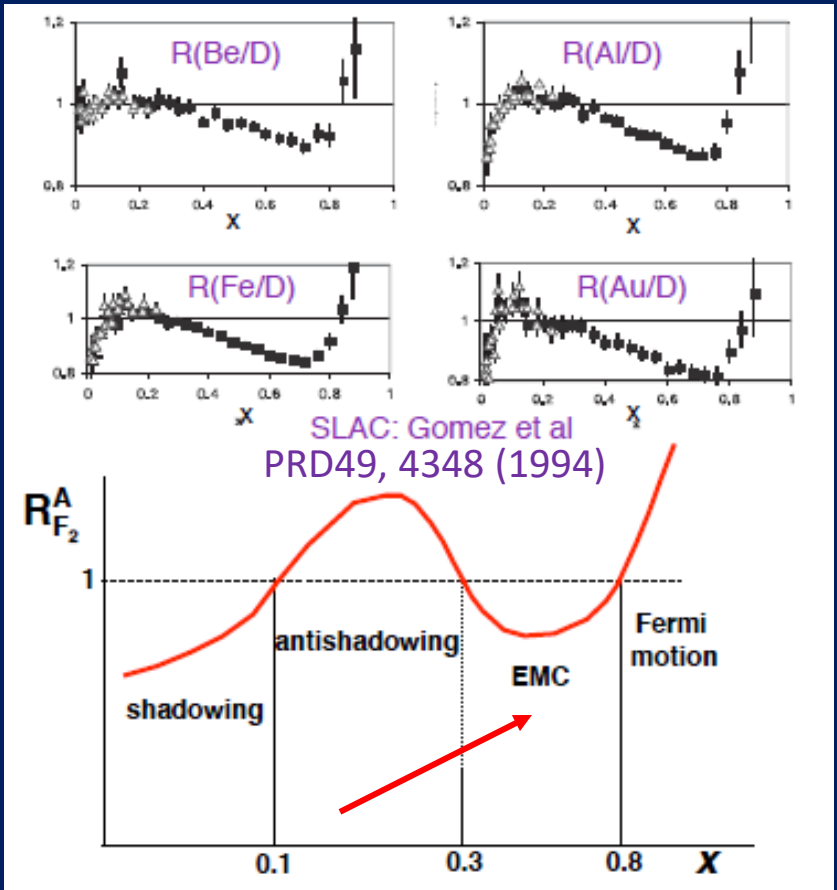


In principle, a twisted photon beam with a given total angular momentum would make it much more efficient to produce given hadrons. Would need center-of-mass energies of at least hundreds of MeV...

Imaging momentum structure of quarks in nuclei: Not just superimposed protons and neutrons

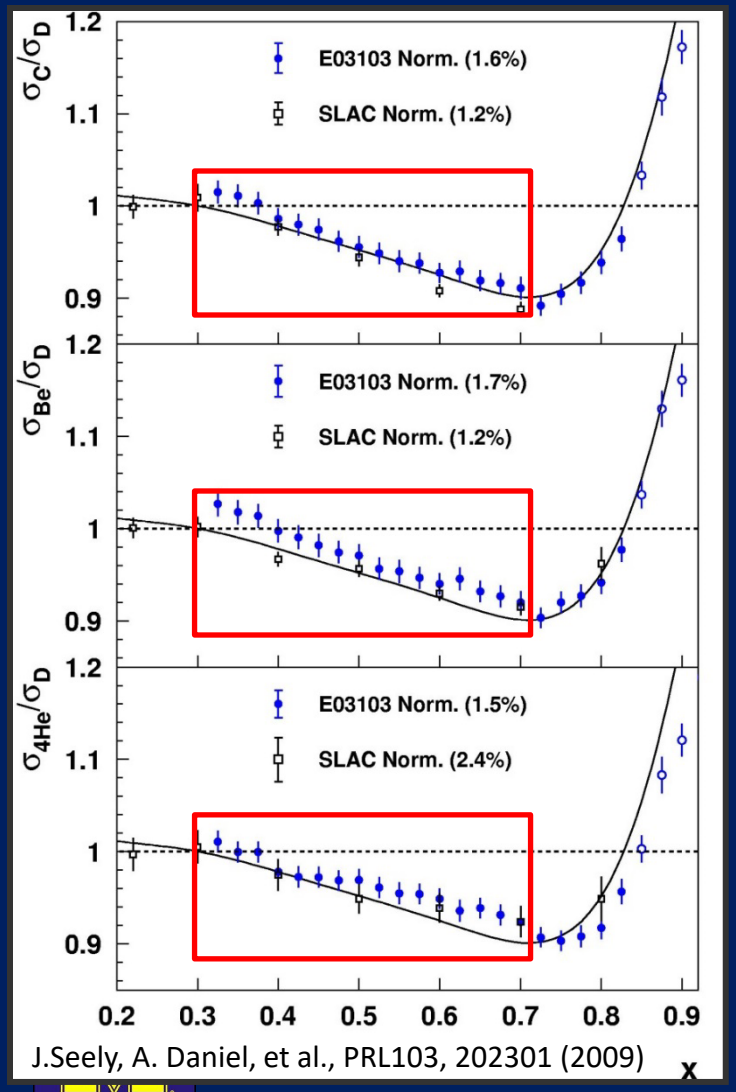


Discovered by European Muon Collaboration (EMC), Phys. Lett. B123, 275 (1983)

$$R_A \equiv \frac{1}{A}\frac{F_{2A}}{F_{2N}} \neq 1$$

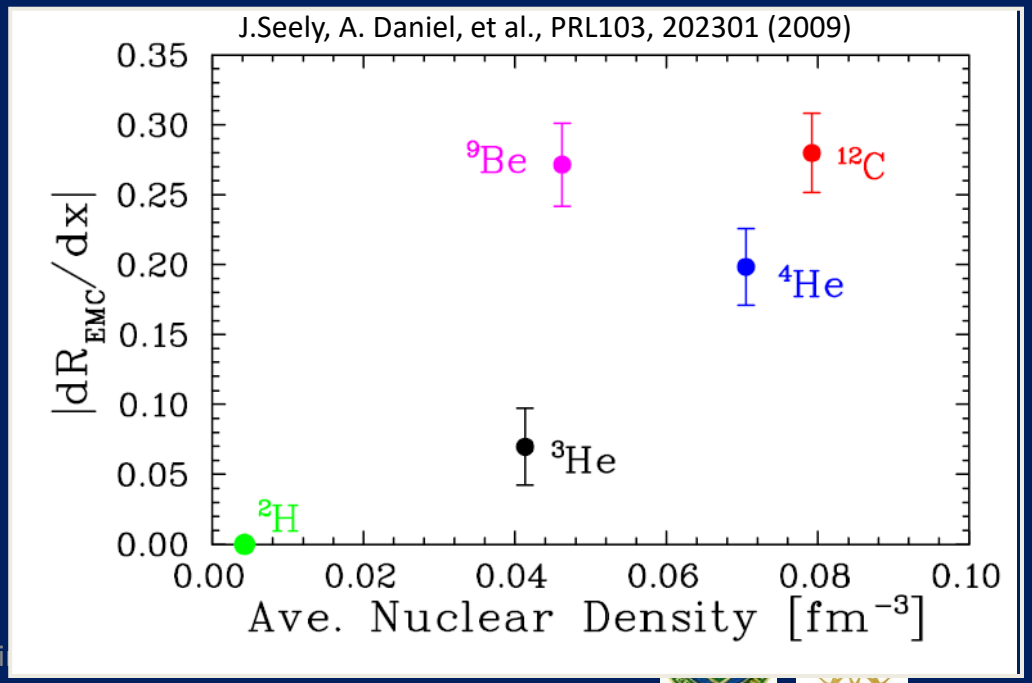
- Ratio of cross section for e-nucleus compared to scaled e-proton collisions, shown vs. quark momentum fraction x
- Regions of both enhancement and depletion—still lots to understand in detail!

Imaging momentum structure of quarks in nuclei: "EMC effect" and local density



J.Seely, A. Daniel, et al., PRL103, 202301 (2009)

- Fit slope of ratios for $0.3<x<0.7$; compare across nuclei
- EMC slope doesn't scale with A or with avg nuclear density…



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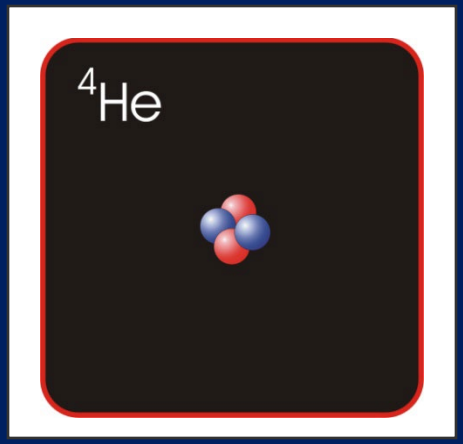
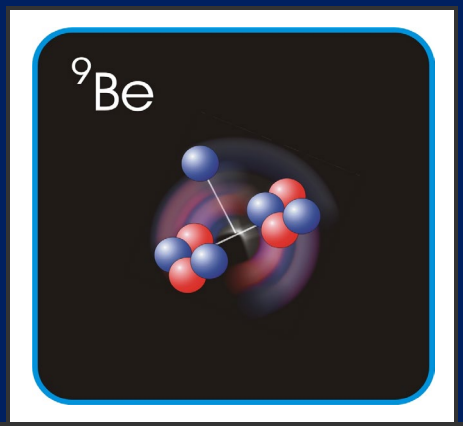
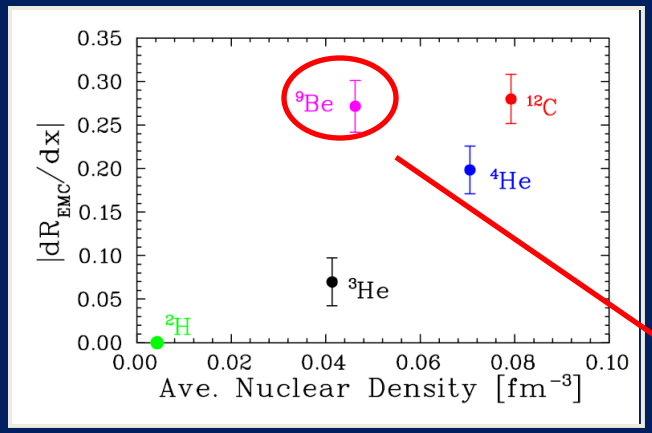
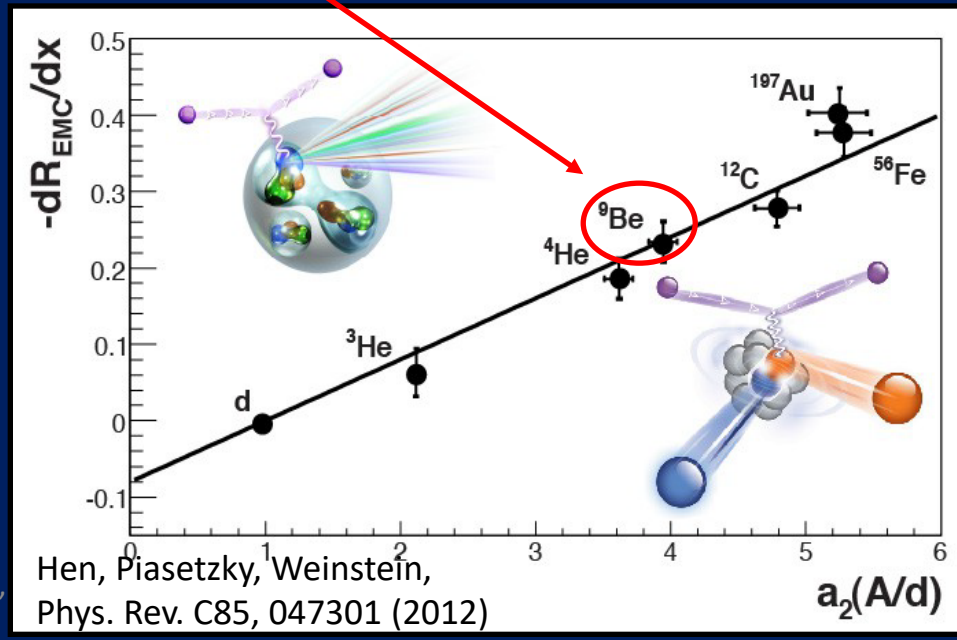






But appears to scale with local density!

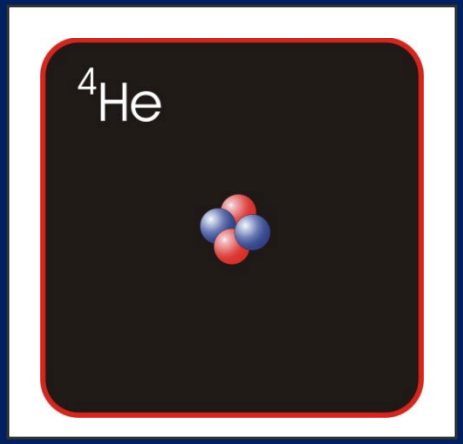


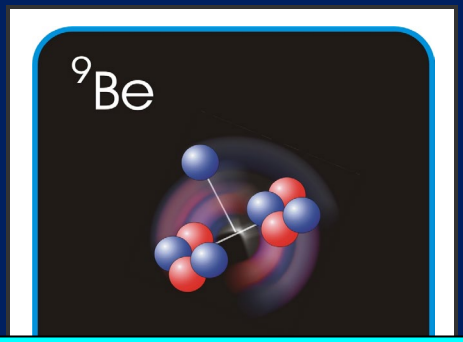
Density determined from *ab initio* few-body calculation

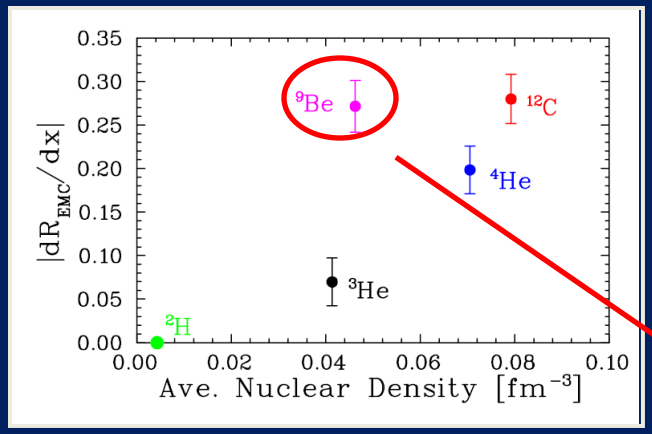
S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)

Hen, Piasetzky, Weinstein, Phys. Rev. C85, 047301 (2012)

Imaging momentum structure of quarks in nuclei: "EMC effect" and local density







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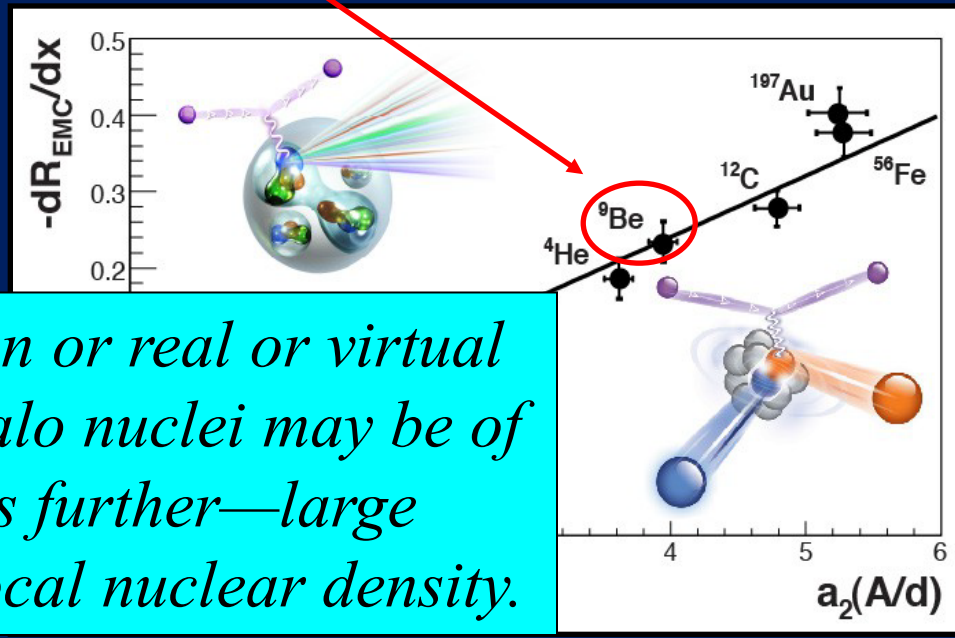


Deep-inelastic scattering (electron or real or virtual photon energy > ~1 GeV) off of halo nuclei may be of particular interest to study this further—large difference between average and local nuclear density.

Summary

- High-power lasers and high-energy collider facilities offer complementary opportunities to study photonuclear reactions and strong-field QED
- Multi-GeV laser-accelerated beams hold the potential for various short- and long-term opportunities in particle and medium- and high-energy nuclear physics
- Possible links between QCD physics and other topics covered here as well

Extra

Facilities: Beam-on-fixed-target



Lower c.m. energies but higher luminosities—liquid and solid targets *much* denser than a second beam

- Continuous Electron Beam Facility (CEBAF) at Jefferson Lab
  - Electron beam up to 12 GeV on polarized and unpolarized proton and nuclear targets
- AMBER at CERN
  - Secondary beam line: $\mu^{\pm}$ 90-180 GeV, $\pi^{\pm}, K^{\pm}, p, \bar{p}$ 60-250 GeV

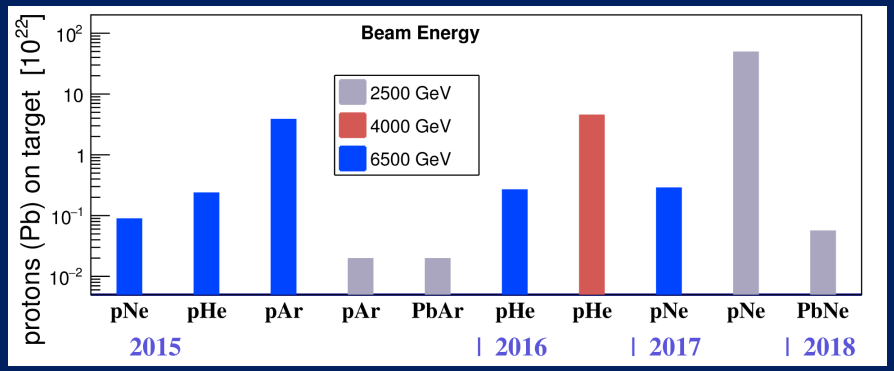


AMBER
Apparatus for Meson and Baryon Experimental Research

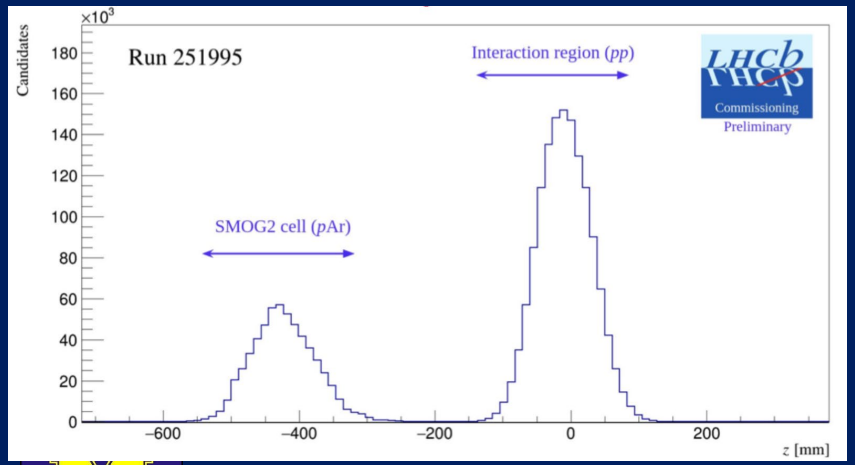
Facilities: Fixed-target programs at colliders!



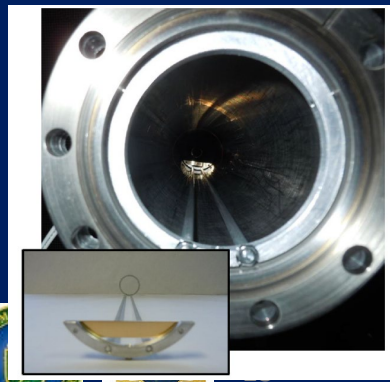
Allow different energies and nuclear species combinations



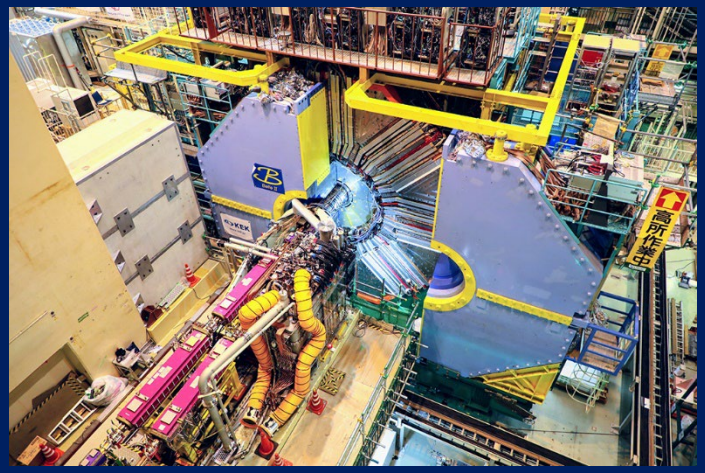
- LHCb System for Measuring Overlap with Gas (SMOG)
  - SMOG 2 gas target cell installed 2020
  - Run simultaneously w/collider mode



- STAR (RHIC at BNL) fixed-target program for beam energy scan
  - 1.93 g/cm2 gold target
  - Dedicated running

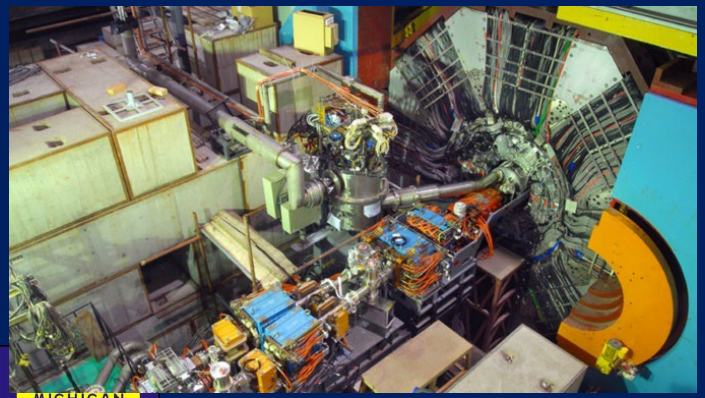


Facilities: Electron-positron collider experiments



Study QCD bound state (hadron) production via electron-positron annihilation to an outgoing quark and antiquark

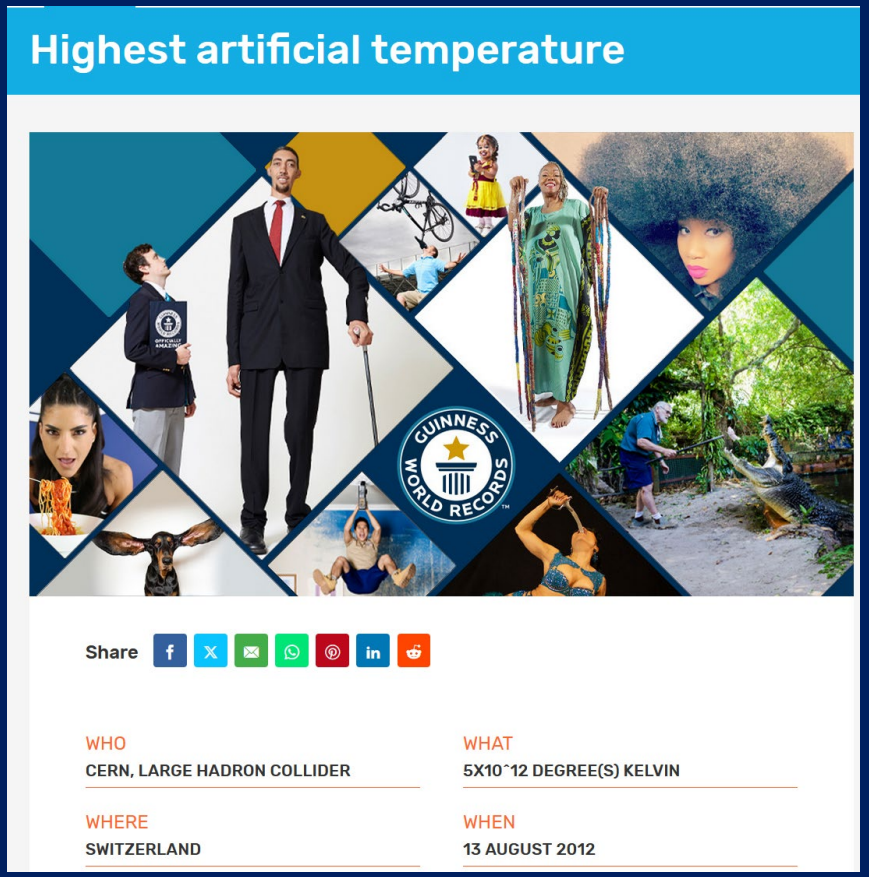
- Belle II at KEK in Japan
  - 10.58 GeV c.m. energy (study bottom quark bound states)



- BESIII at IHEP in China
  - 1.84-4.95 GeV c.m. energy (study charm quark bound states)

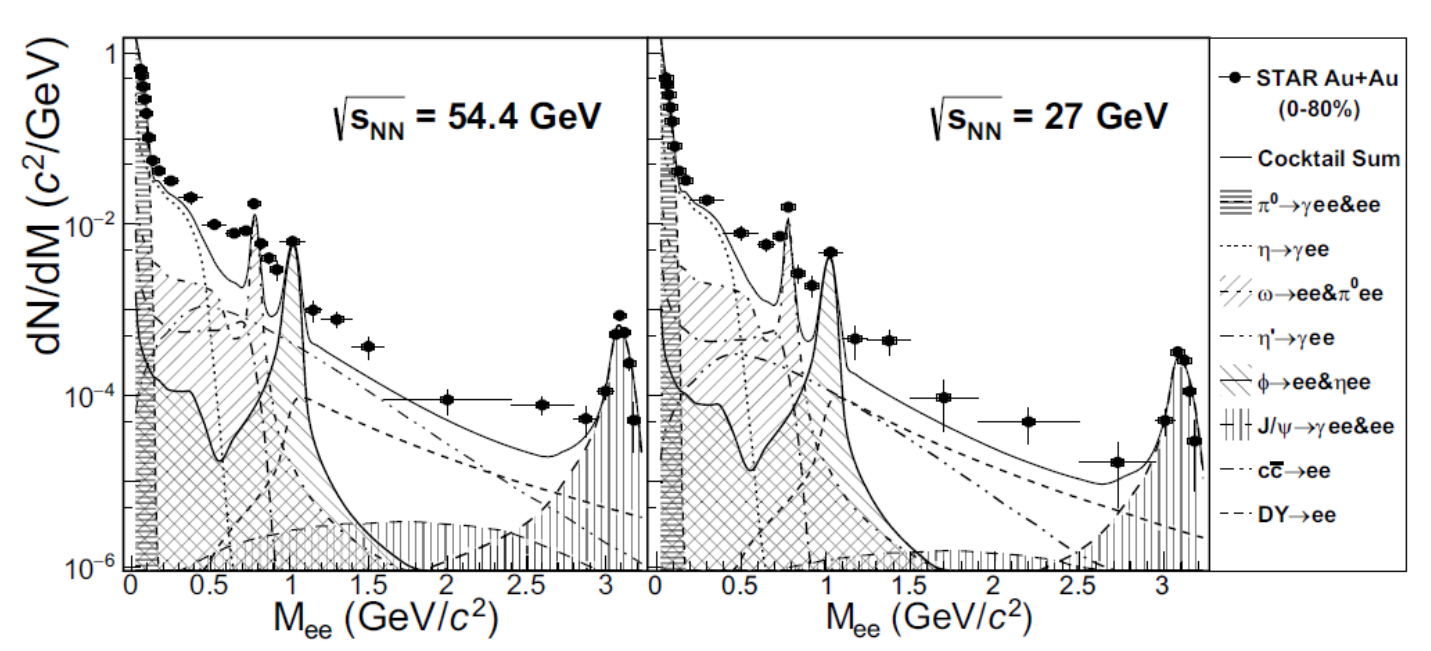
Extreme nuclear matter: Quark-gluon plasma

Measure temperature of quark-gluon plasma via thermal photons or thermal dielectrons



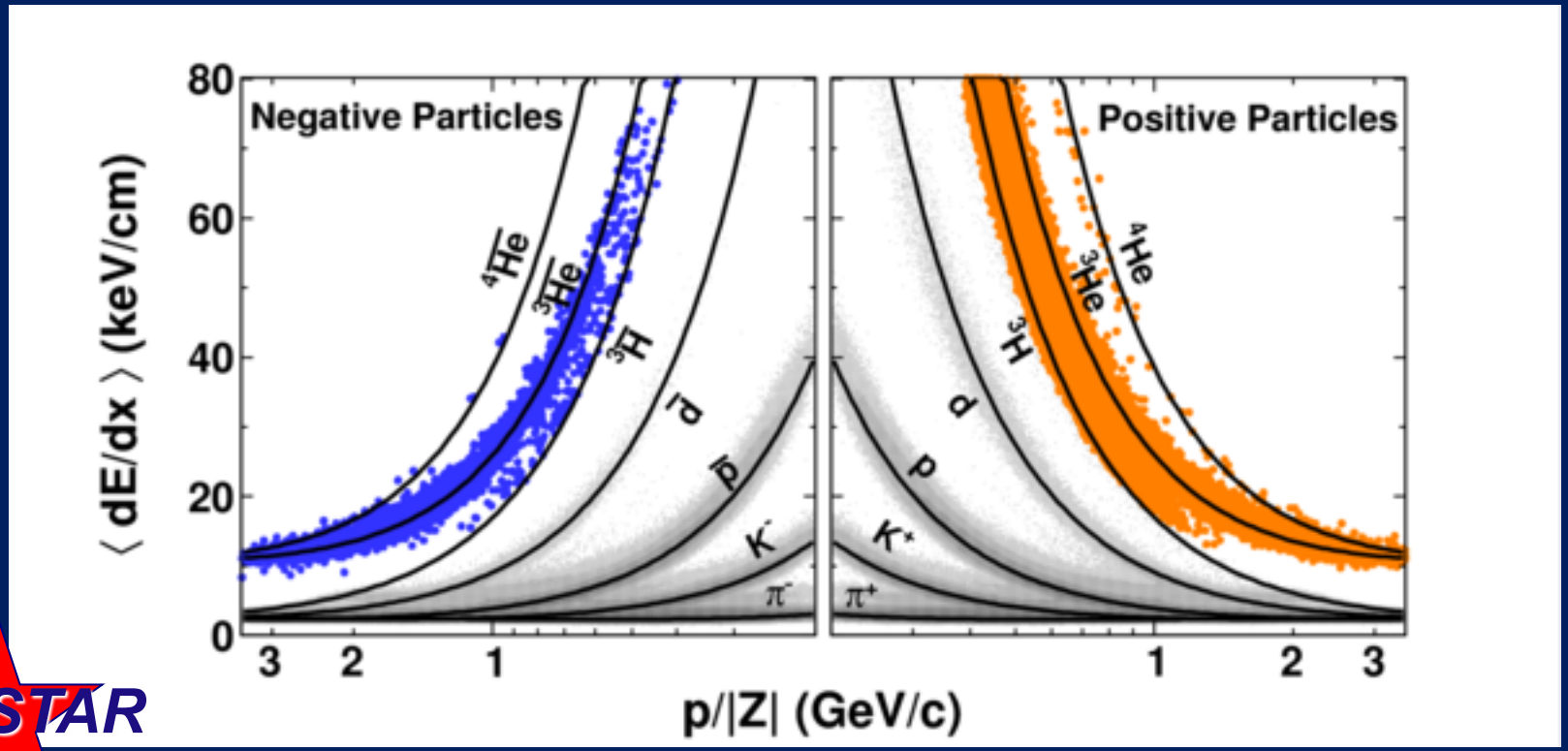
Extreme nuclear matter: Quark-gluon plasma

STAR Collaboration at RHIC, Nat. Comm. 16, 9098 (2025)



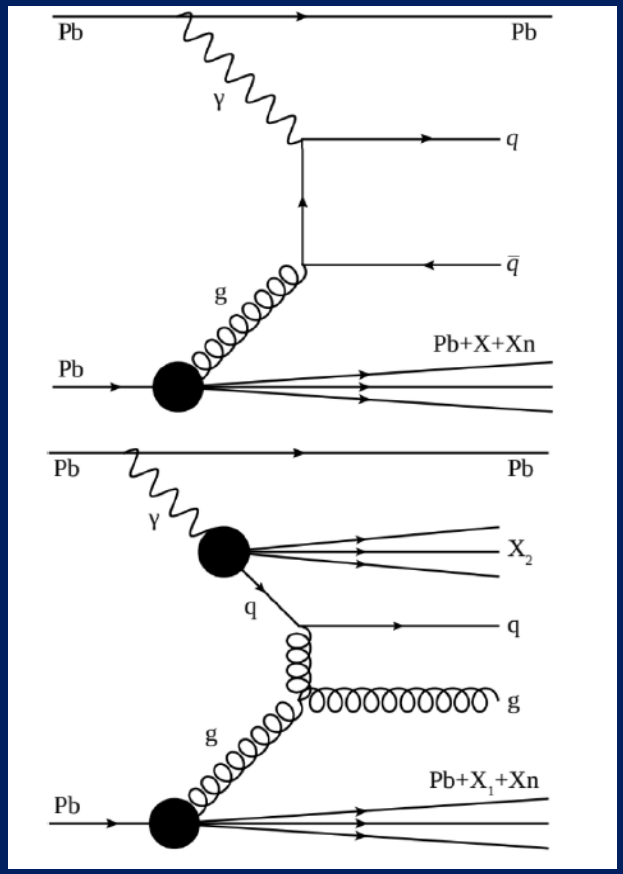
Recent thermal dielectron measurement from lower-energy Au+Au collisions

From quark-gluon plasma to (anti-!) nucleosynthesis

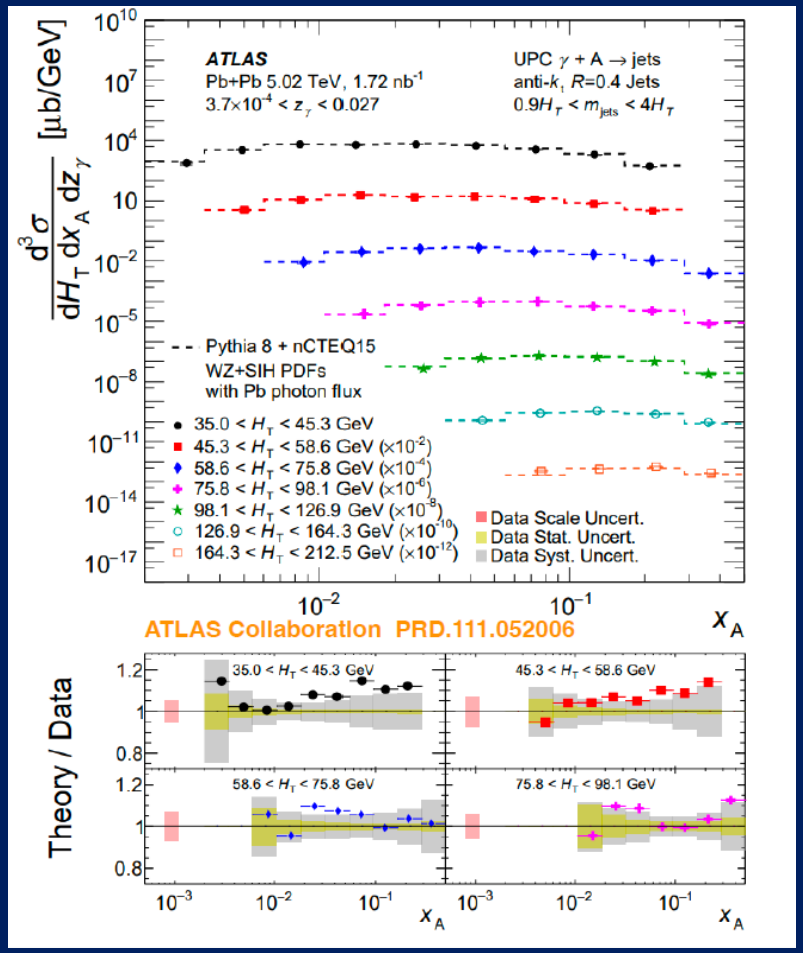


STAR Collaboration at RHIC, Nature 473, 353 (2011)

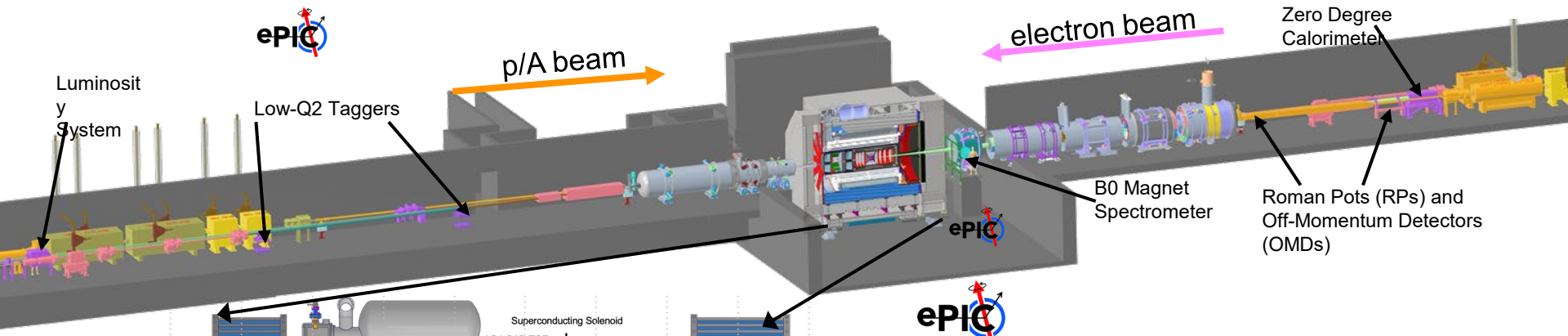
Photonuclear dijet production

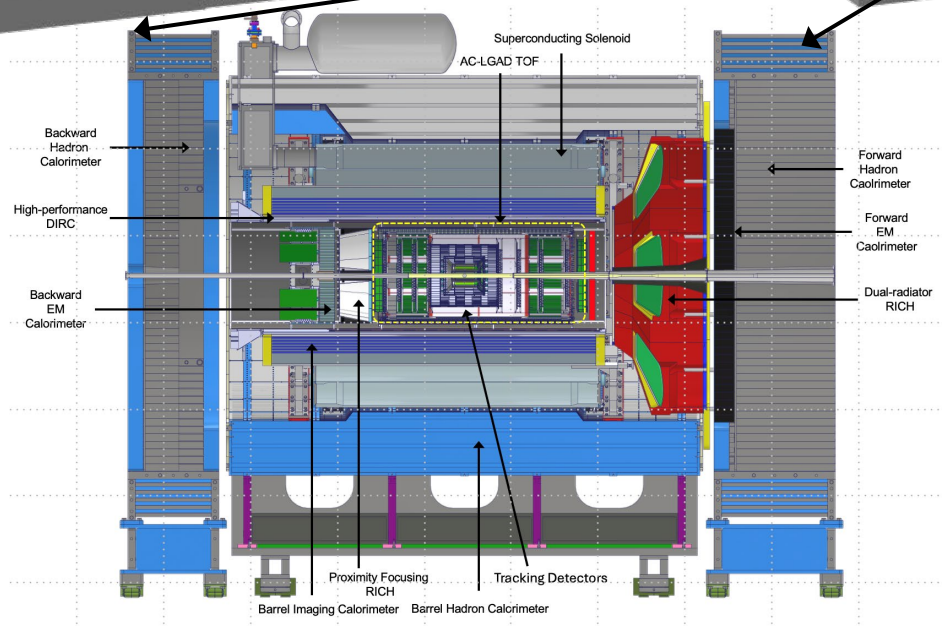


B. Gilbert



ePIC – The EIC State-of-the-Art General-Purpose Detector





ePIC

26 subsystems over ± 40 m

to measure particle momenta, energy and particle type

- 3 electromagnetic calorimeters
- 3 hadronic calorimeters
- Silicon and Multi-pattern gas detectors
- 3 RICH detector + time-of-flight
- 7 Auxiliary detectors (Si + HCal + ECals)
- electron and hadron polarimetry

Integration, Installation and Infrastructure

Non-Beam Commissioning

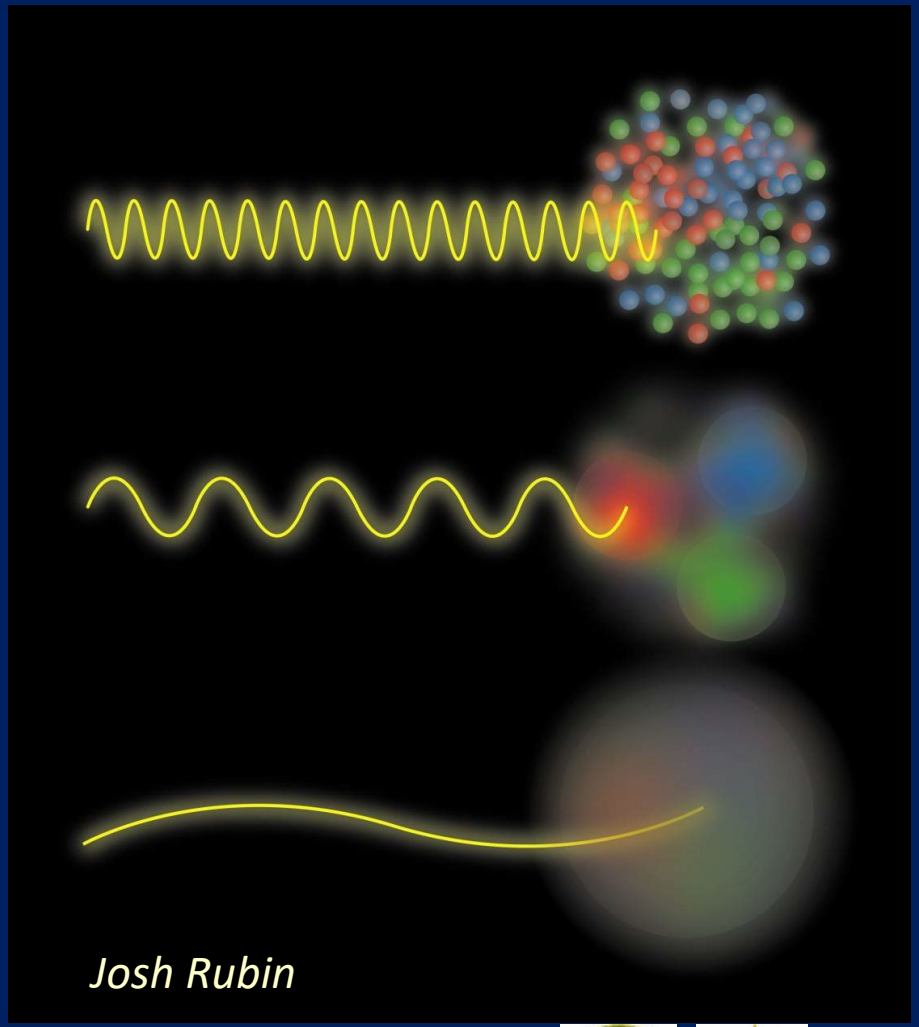
Highest scientific flexibility

→ fully streaming readout electronics and data acquisition

→ integration AI/ML capabilities from the start

The proton as a "laboratory" for studying QCD

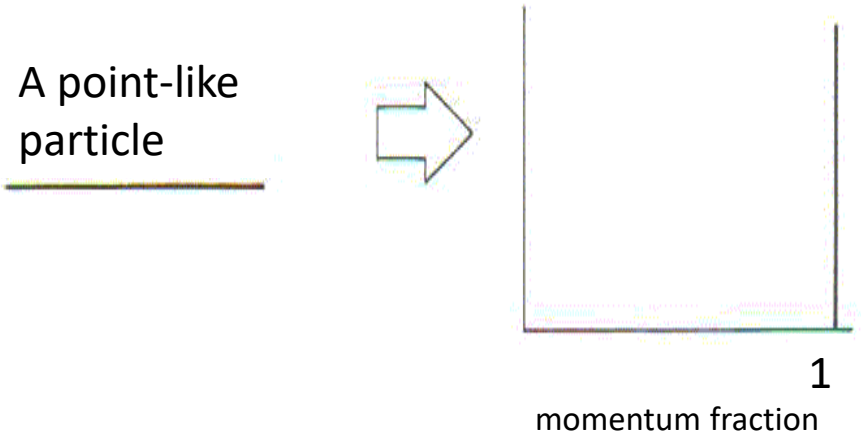
- Proton: simplest stable QCD bound state
- Different energy scales offer information on different aspects of proton internal structure



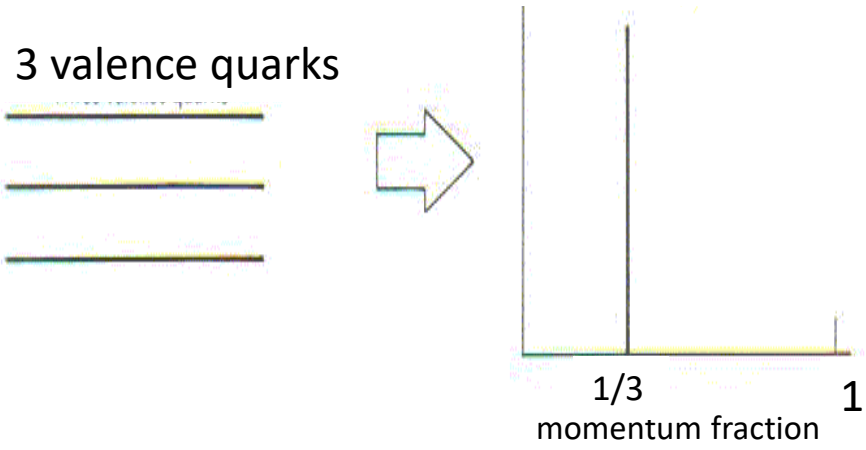
Quark distribution functions inside the proton: The language we've developed (so far!)

What momentum fraction would the scattering particle carry if the proton were made of …

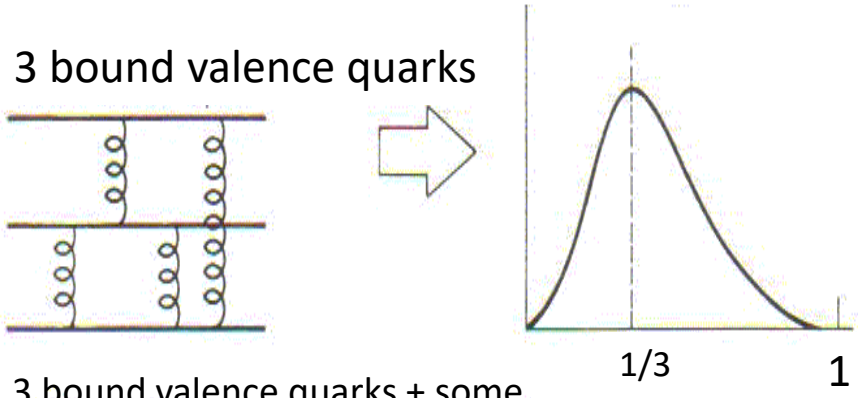
A point-like particle



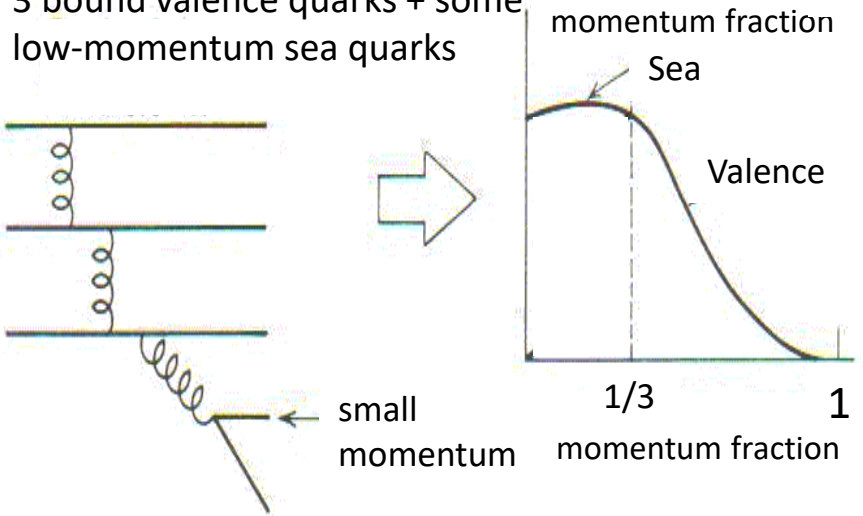
3 valence quarks



3 bound valence quarks



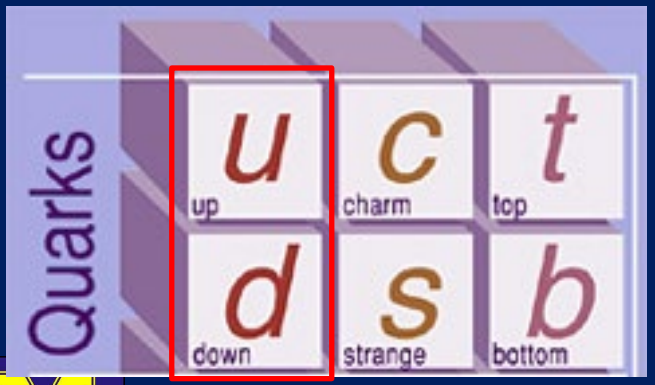
3 bound valence quarks + some low-momentum sea quarks

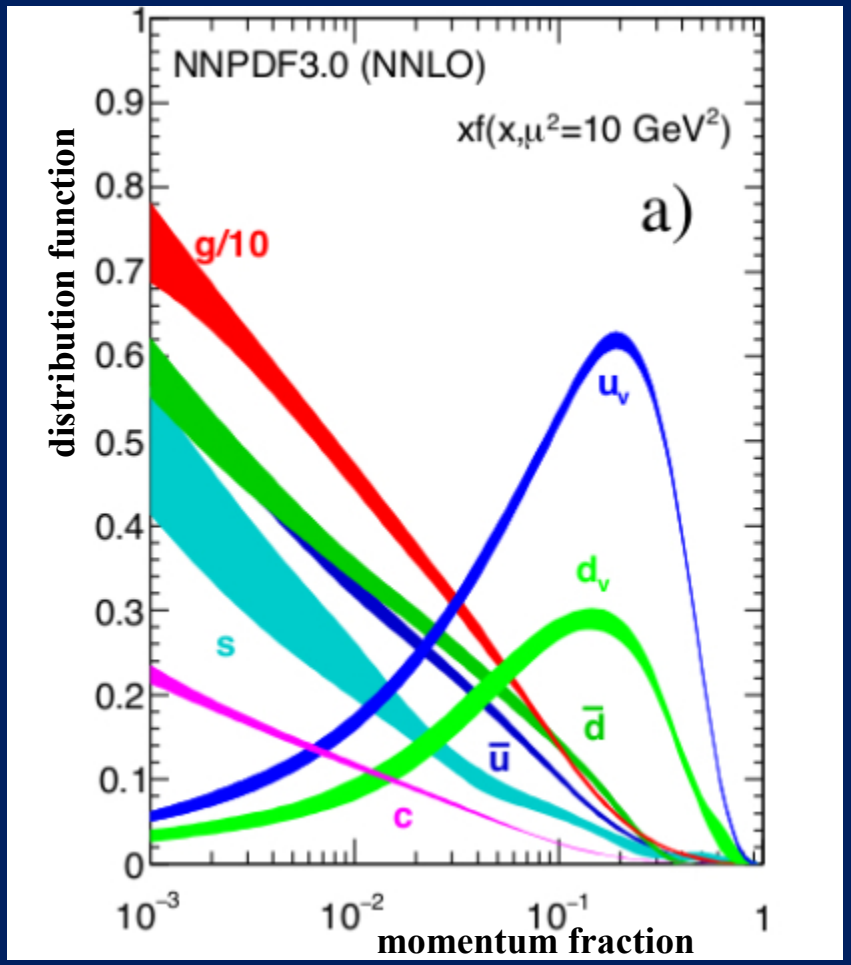


Halzen and Martin, "Quarks and Leptons", p. 201

What have we learned in terms of this picture by now?

- Up and down quark "valence" distributions peaked ~1/3
- Lots of sea quark-antiquark pairs and even more gluons!





EPJ C76, 647 (2016)

Mapping out the quark-gluon structure of the proton

What does the proton look like in terms of the quarks and gluons inside it?

- *Position*
- *Momentum*
- *Spin*
- *Flavor*
- *Color*

Vast majority of past five decades focused on *1-dimensional* momentum structure. Since 1990s starting to consider transverse components . . .

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Polarized protons first studied in 1980s. How angular momentum of quarks and gluons add up still not well understood!

Mapping out the quark-gluon structure of the proton

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Good measurements of flavor distributions in valence region. Flavor structure for sea quarks still yielding surprises.

Mapping out the quark-gluon structure of the proton

What does the proton look like in terms of the quarks and gluons inside it?

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- *Momentum*
- *Spin*
- *Flavor*
- *Color*

Theoretical and experimental concepts to describe and access position only born in mid-1990s. Pioneering measurements over past ~15 years.

Mapping out the quark-gluon structure of the proton

What does the proton look like in terms of the quarks and gluons inside it?

- *Position*
- *Momentum*
- *Spin*
- *Flavor*
- *Color*

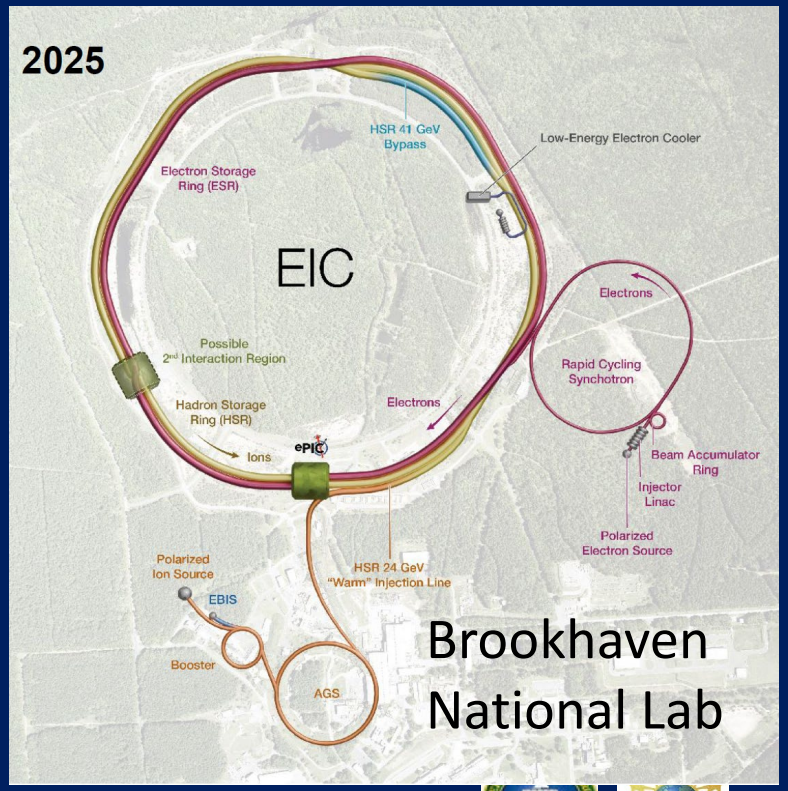
Accounted for theoretically from beginning of QCD, but more detailed, potentially observable effects of color flow have come to forefront in last ~decade . . .

Next-generation QCD facility: The Electron-Ion Collider

Key science questions:

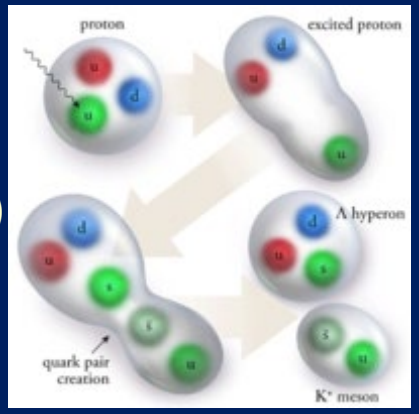
- *How does a nucleon acquire mass?*
- *How does the spin of the nucleon arise from its elementary quark and gluon constituents?*
- *What are the emergent properties of dense systems of gluons?*

Site selection at Brookhaven National Lab announced Jan 2020. DOE Critical Decision 1 granted 2021, Critical Decision 3A granted 2024. First data planned 2035.



Complexity and richness of QCD: Confinement

CLAS Collaboration
PRL 113, 152004 (2014)



- QCD theory: Quarks and gluons
- QCD experiment: QCD bound states

- Always an interplay between parton vs. bound-state descriptions, reductionist vs. emergent pictures