Studying hadrons and nuclei with electromagnetic processes: Experimental overview

Christine A. Aidala
University of Michigan

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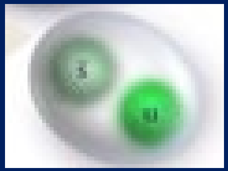
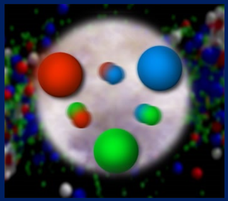
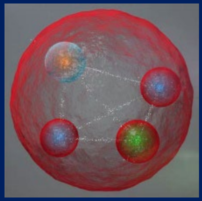
(One way of dividing up) Areas of study in QCD

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

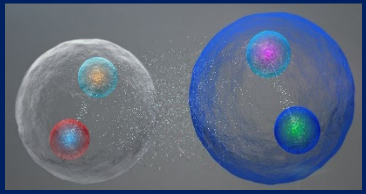
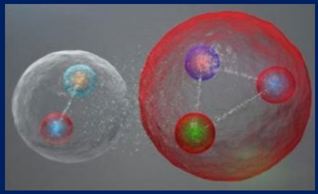
Structure/Properties of QCD matter

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

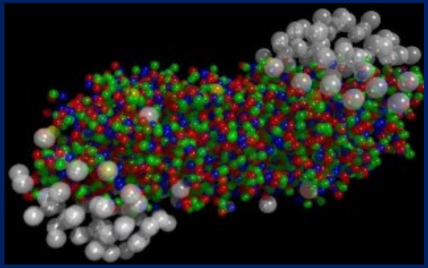





- Bound states of bound states: Nuclei, neutron stars, other hadronic molecules?



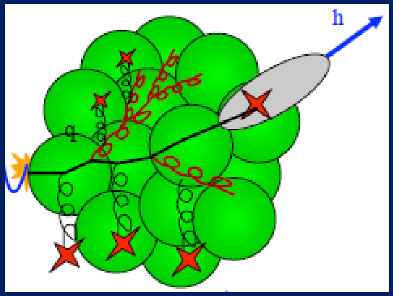



- Deconfined states: Quark-gluon plasma



Formation of states of QCD matter

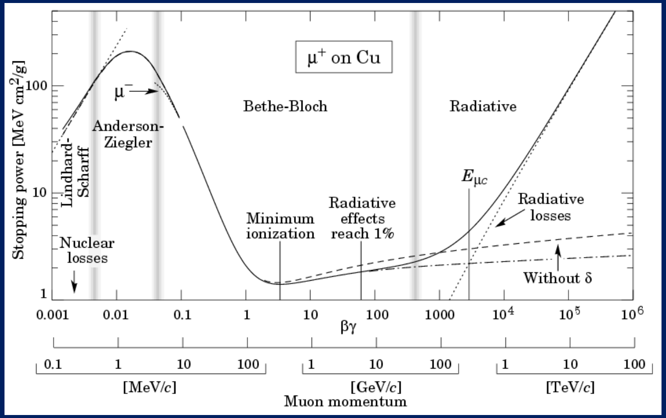
- Bound state formation mechanisms
- Formation of bound states of bound states
- Equilibration of quark-gluon plasma
- Time scales of hadronization/equilibration
- Modification of hadronization in different environments



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? Or simply a hadronic environment rather than e+e-?

Interactions within QCD

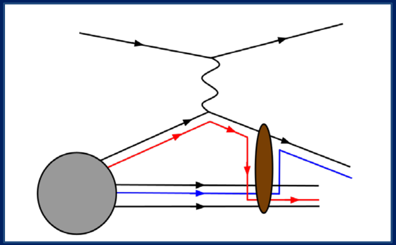
- Quark and gluon energy loss in cold and hot QCD matter
  - What is the analog of the Bethe-Bloch curve for QCD rather than electromagnetism?

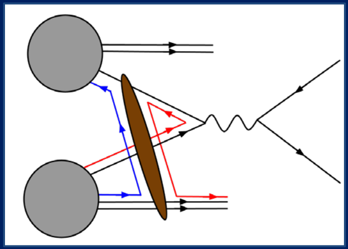


Electromagnetic energy loss of muons passing through copper

- Quantum interference and phase shifts
  - E.g. quantum interference effects in hadronization
    - One quark or gluon → multiple hadrons
    - Multiple quarks or gluons → one hadron

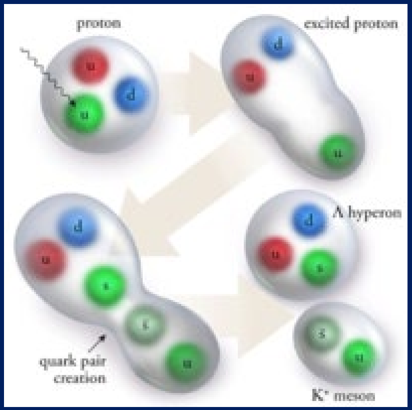
- Color charge flow effects in scattering processes
  - Process-dependent spin-momentum correlations in hadrons
  - Quantum entanglement of quarks across colliding hadrons





Sivers TMD PDF sign change in SIDIS vs. Drell-Yan

Complexity and richness of QCD: Confinement



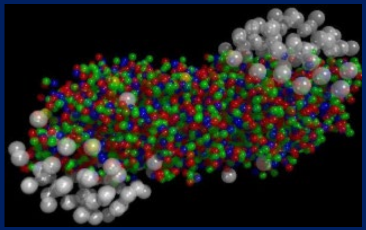
CLAS Collaboration
PRL 113, 152004 (2014)

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

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

High-energy collisions: Tools to study QCD

- Need high (enough) energies to
  - Access subnuclear distance scales
  - Form new states of QCD matter



- High energies also
  - Allow use of perturbative theoretical tools
  - Provide access to new probes, e.g. heavy quarks, Z and W bosons

High-energy collisions: Complementary 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^-??

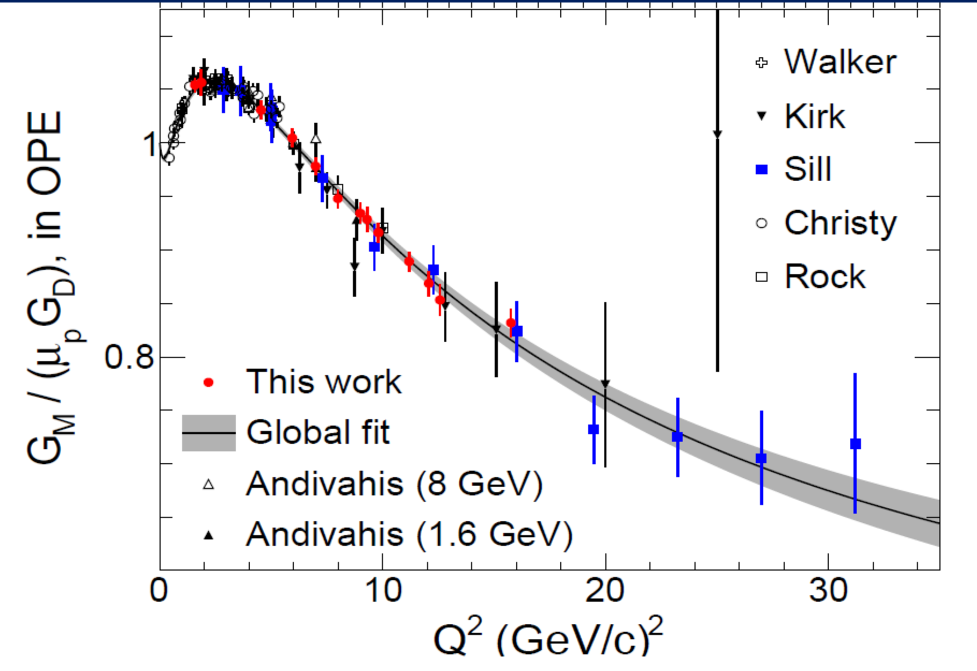
*Electromagnetic interactions with nucleons and nuclei to study hadronic **structure/properties***

- *Elastic* scattering using electron or muon beams
  - Virtual photon sensitive to overall charge distribution
  - Electric and magnetic form factors
  - Electric charge radius
- JLab, MUSE at PSI, AMBER, …

*Electromagnetic interactions with nucleons and nuclei to study hadronic **structure/properties***

- *Elastic* scattering using electron or muon beams

Effective proton magnetic form factor



M.E. Christy et al., PRL 128, 102002 (2022)

*Electromagnetic interactions with nucleons and nuclei to study hadronic **structure/properties***

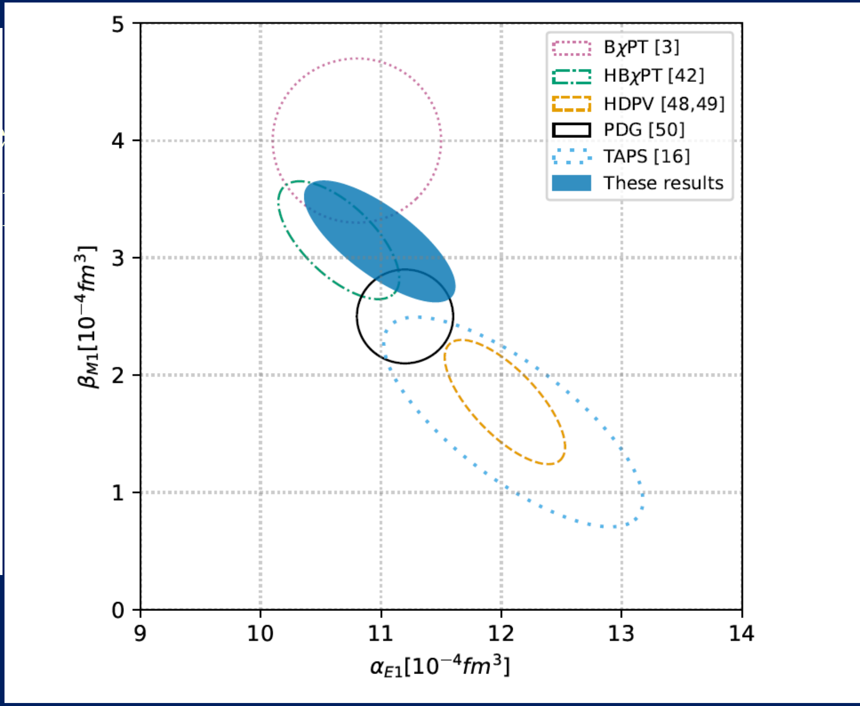
- *Elastic or inelastic nucleon Compton scattering* using photon beams
  - Electromagnetic field couples to distribution of charge and magnetization inside the nucleon
  - Can polarize photon beam and/or target
  - Nucleon scalar and spin polarizabilities
  - Photoproduction of pions – investigate origins of isospin symmetry breaking
- HIγS at TUNL, MAMI/MESA at Mainz,…

Electromagnetic interactions with nucleons and nuclei to study hadronic ***structure/properties***

- *Elastic or inelastic nucleon Compton scattering* using photon beams

A2, PRL 128, 132503 (2022)

FIG. 3: Results of α_{E1} vs β_{M1} for the proton, obtained from different experiments and theories. The extraction from our data is depicted as blue full ellipse. The loosely dotted azure ellipse shows the result from the TAPS collaboration [16]. The dotted purple circle is the BχPT prediction [3], the green dashed-dotted curve is the extraction within HBχPT [42], and the orange dashed curve is the bootstrap-based fit using DR [48, 49]. The black circle shows the values quoted by the PDG [50]. The Baldin sum rule constraint was used in the present extraction, as well as in those from TAPS, HBχPT, and HDPV. All contours correspond to 1σ level.



Electric and magnetic polarizabilities of the proton

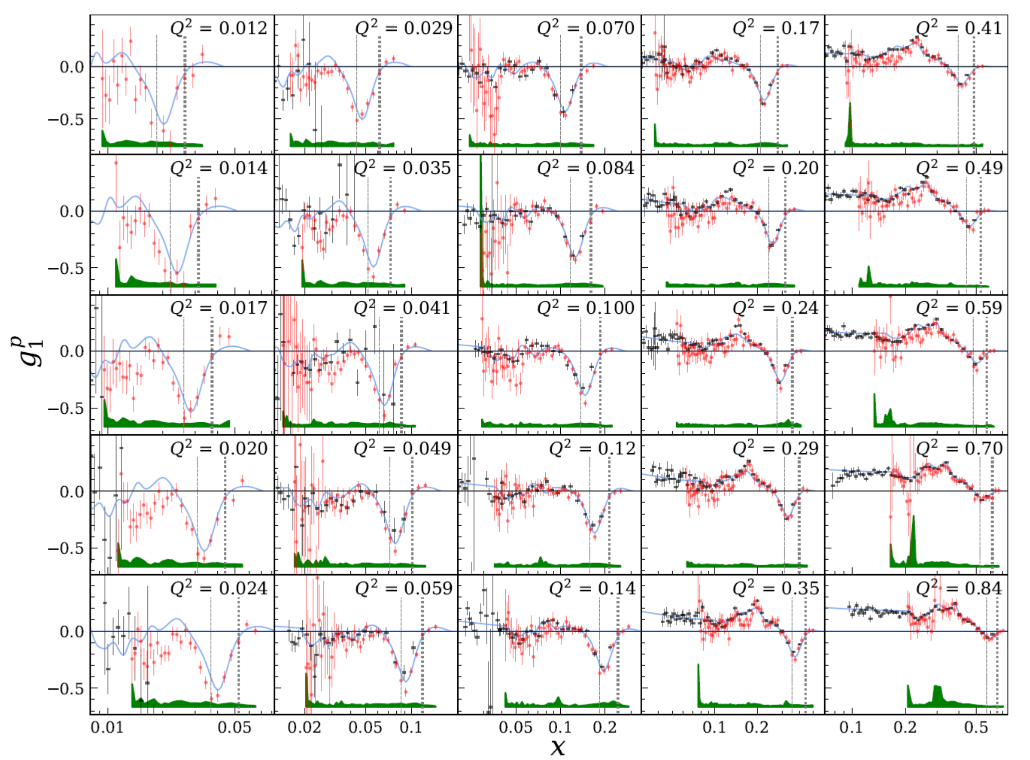
*Electromagnetic interactions with nucleons and nuclei to study hadronic **structure/properties***

- *Deep-inelastic scattering* (DIS) using electron or muon beams
- *Inclusive* DIS—measure only scattered lepton
  - For $Q^2 \geq \sim$1-2 GeV^2, sufficient resolution to access individual quarks through coupling between virtual photon and electrically charged quarks
  - Indirectly access gluon distributions through Q^2 scaling violations
  - Nucleon structure functions and parton distribution functions (PDFs)
    - Polarized nucleon → polarized structure functions
  - Also nuclear PDFs
- JLab, COMPASS/AMBER, …

Electromagnetic interactions with nucleons and nuclei to study hadronic ***structure/properties***

- *Deep-inelastic scattering* (DIS) using electron or muon beams
- *Inclusive* DIS—measure only scattered lepton

Final archival CLAS results on proton longitudinal spin structure function g_1^p at low Q^2



CLAS, PRC 111, 035202 (2025)

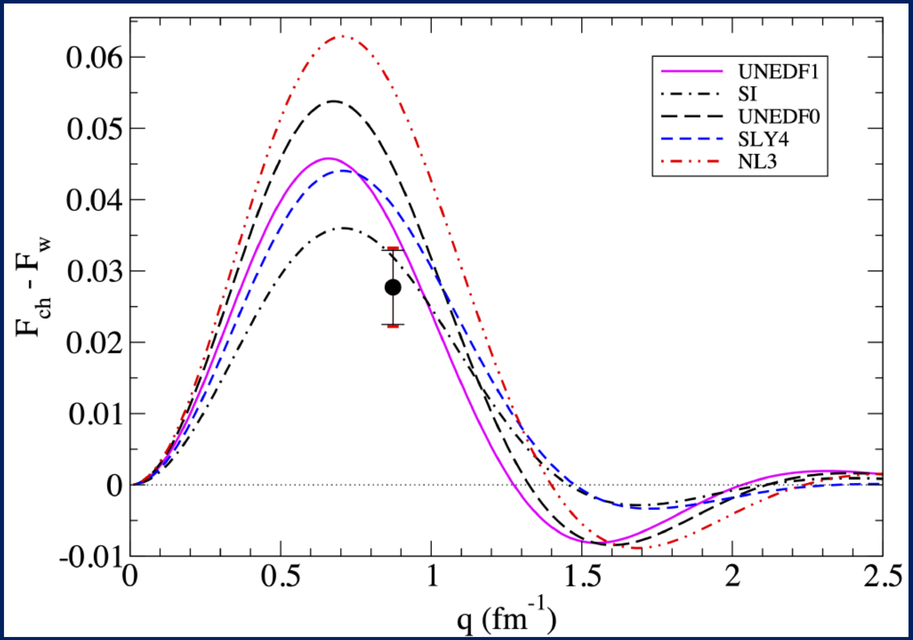
Electromagnetic interactions with nucleons and nuclei to study hadronic ***structure/properties***

- *Parity-violating elastic or inelastic scattering* using electron beams
  - Use interference between virtual photon and virtual Z^0 boson
  - Weak structure of nucleons and nuclei
  - Neutron skin thickness of nuclei
- JLab, Mainz, …

Electromagnetic interactions with nucleons and nuclei to study hadronic ***structure/properties***

- *Parity-violating elastic or inelastic scattering* using electron beams

Charge minus weak form factor of ^{48}Ca as a function of momentum transfer, measured in elastic scattering of longitudinal polarized electrons



CREX, PRL 129, 042501 (2022)

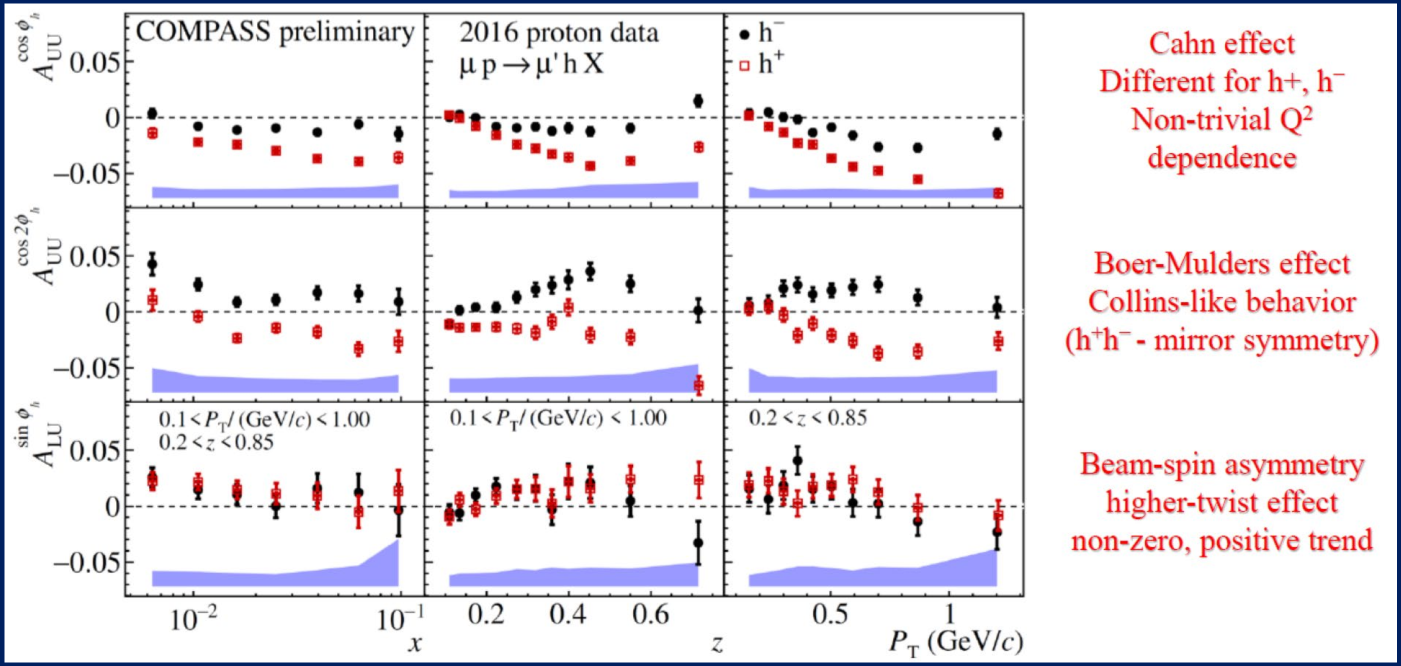
Electromagnetic interactions with nucleons and nuclei to study hadronic ***structure/properties***

- *Semi-inclusive* DIS using electron or muon beams
  - Measure scattered lepton and one or more products of the collision
  - Keep more info (e.g. momentum direction of produced hadron, species of produced hadron), so can access more details of structure
  - Can also polarize lepton and/or nucleon—defines yet another direction in the interaction
  - Transverse-momentum-dependent (TMD) PDFs—polarized and unpolarized
    - Sivers and Boer-Mulders PT-odd TMD PDFs—probe spin-momentum correlations in the nucleon, but also probe QCD ***interactions*** in the overall scattering process
  - Sullivan process—measure structure of pion or kaon
  - Short-range nucleon-nucleon correlations in nuclei
- JLab, COMPASS/AMBER, HERA, …

Electromagnetic interactions with nucleons and nuclei to study hadronic ***structure/properties***

- *Semi-inclusive* DIS using electron or muon beams
  - Measure scattered lepton and one or more products of the collision

SIDIS angular modulations for a muon beam on an unpolarized proton target. Can access spin-momentum correlations for spin of quark in unpolarized proton via $\cos 2\phi$ modulation.



COMPASS, Spin 2025 talk by F. Tessarotto

Electromagnetic interactions with nucleons and nuclei to study hadronic ***structure/properties***

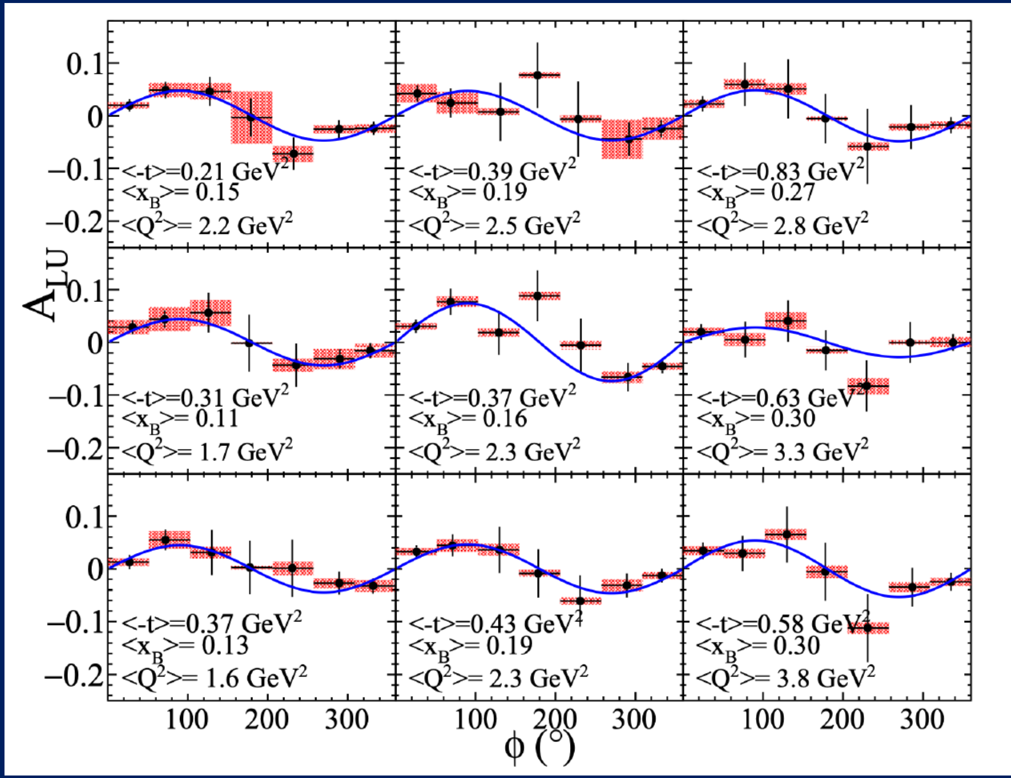
- *Exclusive* DIS using electron or muon beams
  - Measure scattered lepton and *all* products of the collision—access different details of structure
    - Deeply virtual Compton scattering, deeply virtual meson production
  - Virtual photon couples to electrically charged quarks
  - Or virtual photon fluctuates into a $q\bar{q}$ dipole and can also interact with gluons
  - Can also polarize lepton and/or nucleon—defines yet another direction in the interaction
  - Generalized Parton Distributions
    - Spatial distributions of partons within nucleon
    - Energy-momentum tensor within nucleon
- JLab, COMPASS/AMBER, …

Electromagnetic interactions with nucleons and nuclei to study hadronic ***structure/properties***

- *Exclusive* DIS using electron or muon beams
  - Measure scattered lepton and *all* products of the collision—access different details of structure

Neutron DVCS beam-spin asymmetry, sensitive to imaginary part of GPD E, related to angular momentum of quarks inside neutron.

CLAS, PRL 133, 211903 (2024)

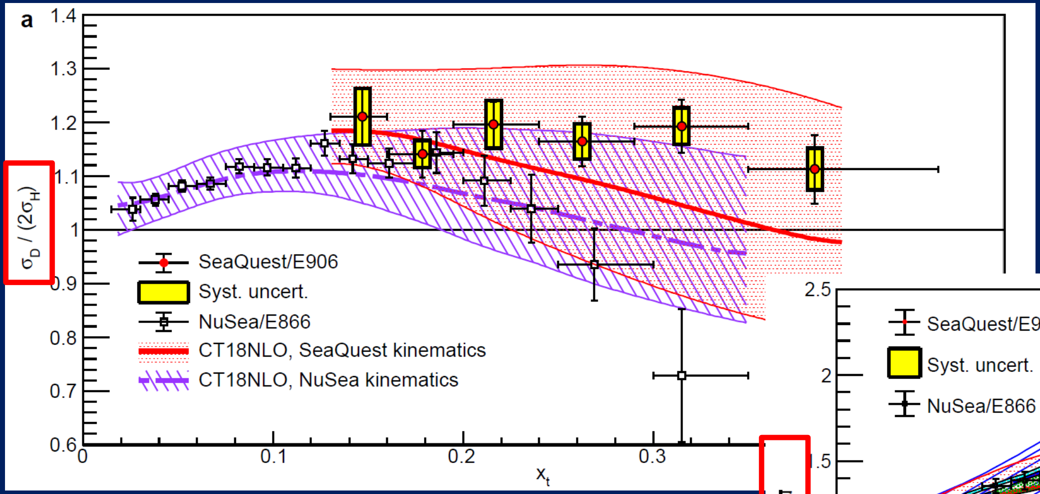


Produced *electromagnetic probes to study hadronic* ***structure/properties***

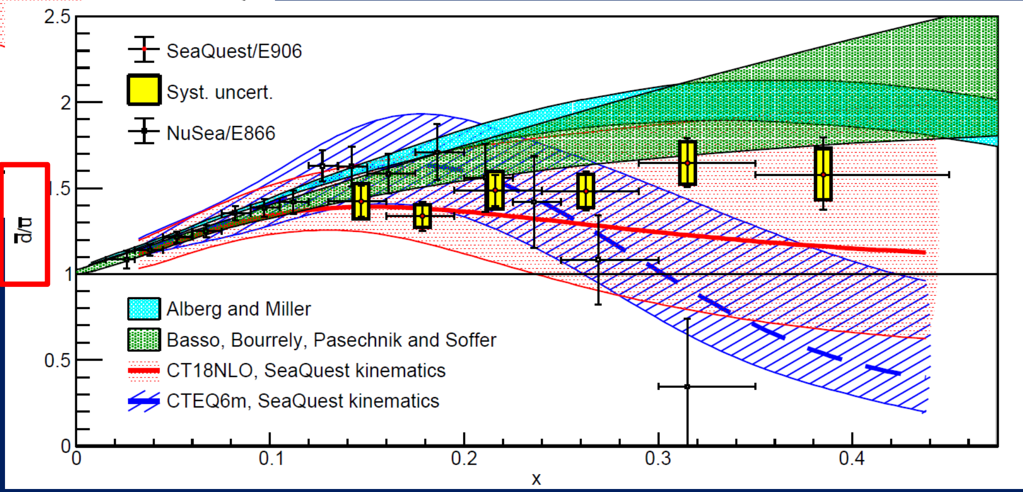
- Hadron-hadron collisions: *Quark-antiquark annihilation to lepton pairs* (Drell-Yan)
  - Probe quark and *antiquark* PDFs
  - With pion or kaon beams, direct measurement of pion and kaon PDFs
  - Can also probe ***interactions***—e.g. incoming parton energy loss in cold nuclear matter using Drell-Yan on nuclei
- SeaQuest/SpinQuest at Fermilab, COMPASS/AMBER, RHIC, LHC,…

Produced *electromagnetic probes to study hadronic* ***structure/properties***

- Hadron-hadron collisions: *Quark-antiquark annihilation to lepton pairs* (Drell-Yan)



Drell-Yan ratio for $p + d$ to scaled $p + p$, providing evidence for an excess of antidown-to-antiup quarks persisting to $x \sim 0.45$.



SeaQuest, Nature 590, 561 (2021)

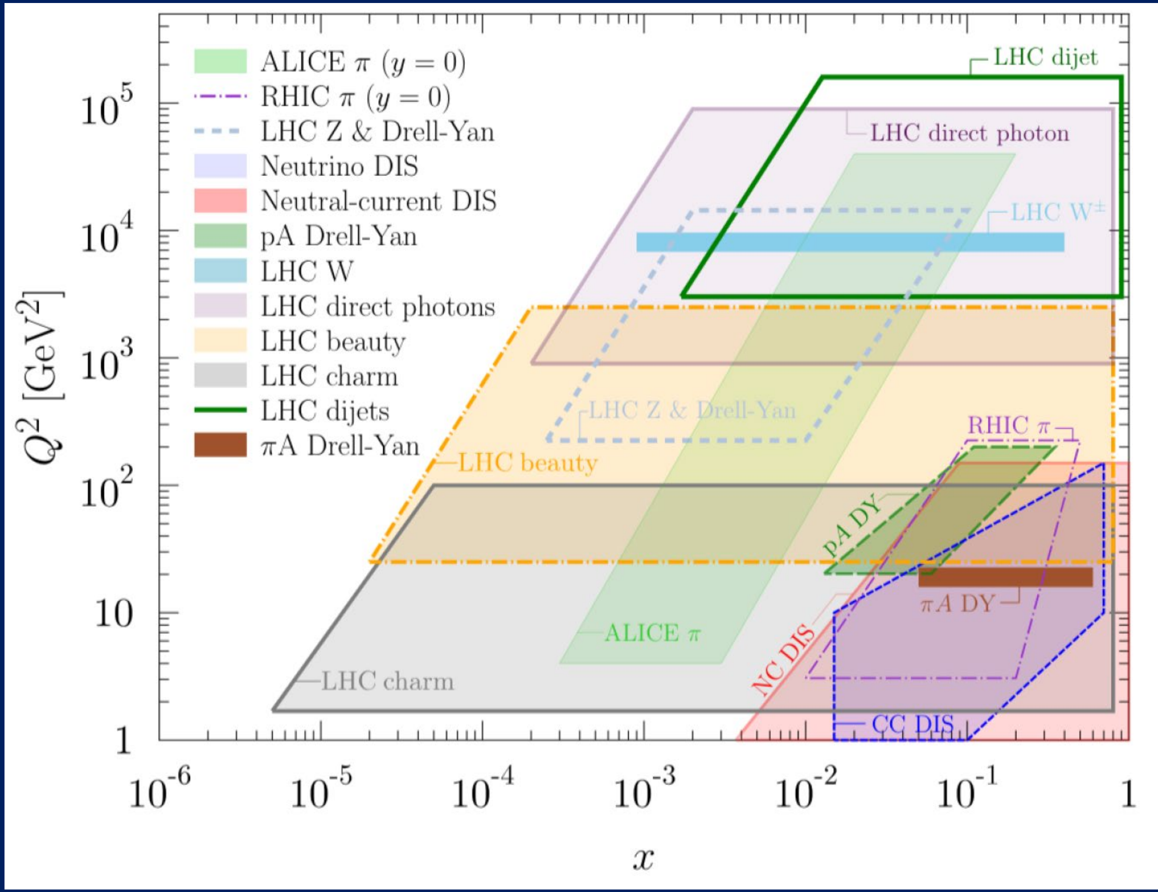
Produced *electromagnetic probes to study hadronic* ***structure/properties***

- Hadron-hadron collisions: *Direct photon production*
  - Probe quark and gluon PDFs in nucleons or nuclei via quark-gluon Compton scattering
    - Also in polarized nucleons
  - Calibration probe to study structure and properties of quark-gluon plasma—exits hot nuclear medium without interacting strongly
  - Thus also indirectly used to probe ***interactions***—e.g. energy lost by a back-to-back hard-scattered parton as it traverses the hot nuclear medium
- RHIC, LHC

Produced *electromagnetic probes to study hadronic* ***structure/properties***

- Hadron-hadron collisions: *Direct photon production*

Overview of $x - Q^2$ coverage for data input to nuclear PDF fits



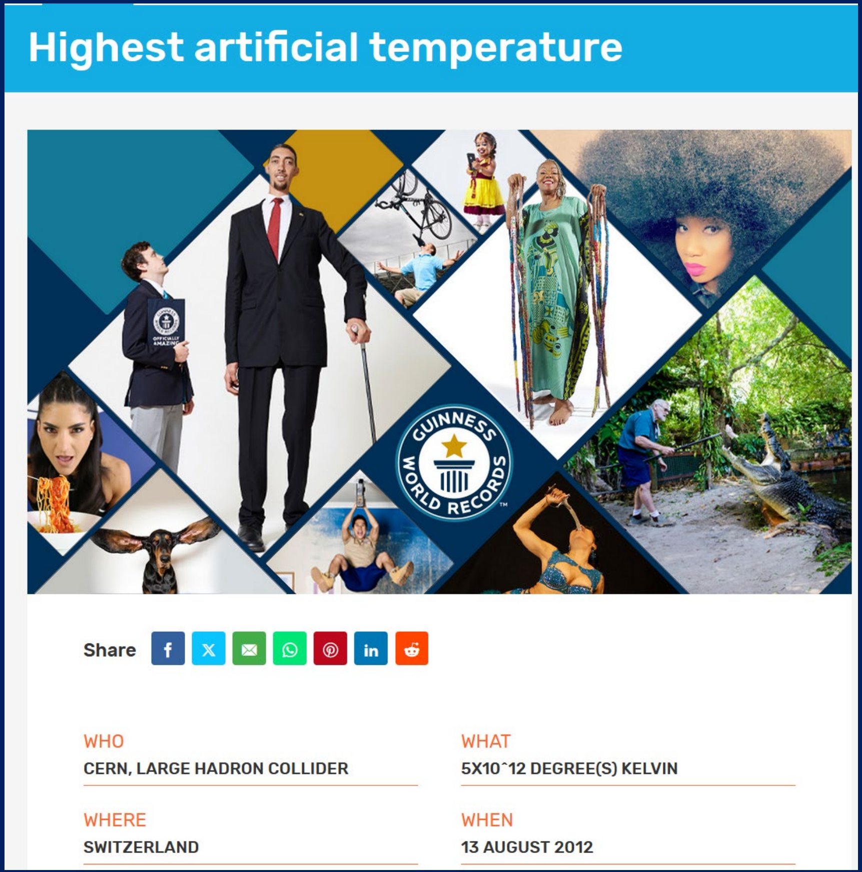
Ann. Rev. Nucl. Part. Sci. 74, 49 (2024)

Produced *electromagnetic probes to study hadronic* ***structure/properties***

- Low-energy nucleus-nucleus collisions: *gamma spectra for nuclear spectroscopy*
  - Nuclear structure and reactions
  - Nuclear astrophysics
- Lots of facilities worldwide, with recent large investments in FRIB at Michigan State U.

Produced *electromagnetic probes to study hadronic* ***structure/properties***

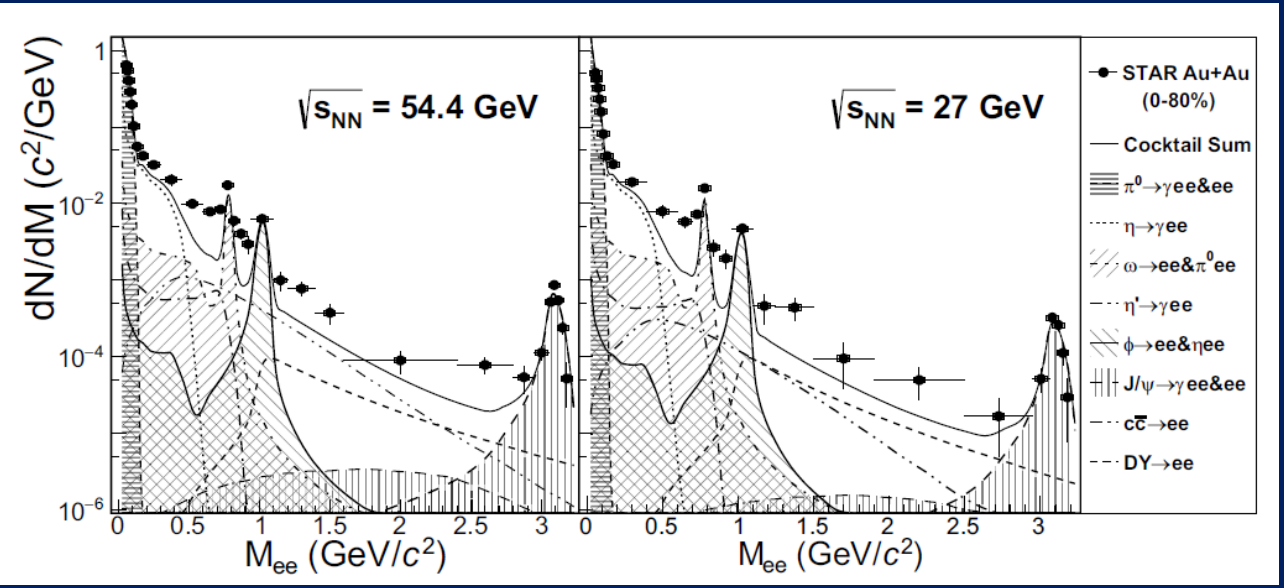
- Hadron-hadron collisions: *Thermal photon or dilepton production*
  - Measure temperature of produced quark-gluon plasma
- RHIC, LHC



Produced** electromagnetic probes to study hadronic **structure/properties

- Hadron-hadron collisions: *Thermal photon or dilepton production*

Thermal dileptons from different energy Au+Au collisions published by STAR earlier this month! Helps map out the QCD phase diagram.



STAR, Nat. Comm. 16, 9098 (2025)

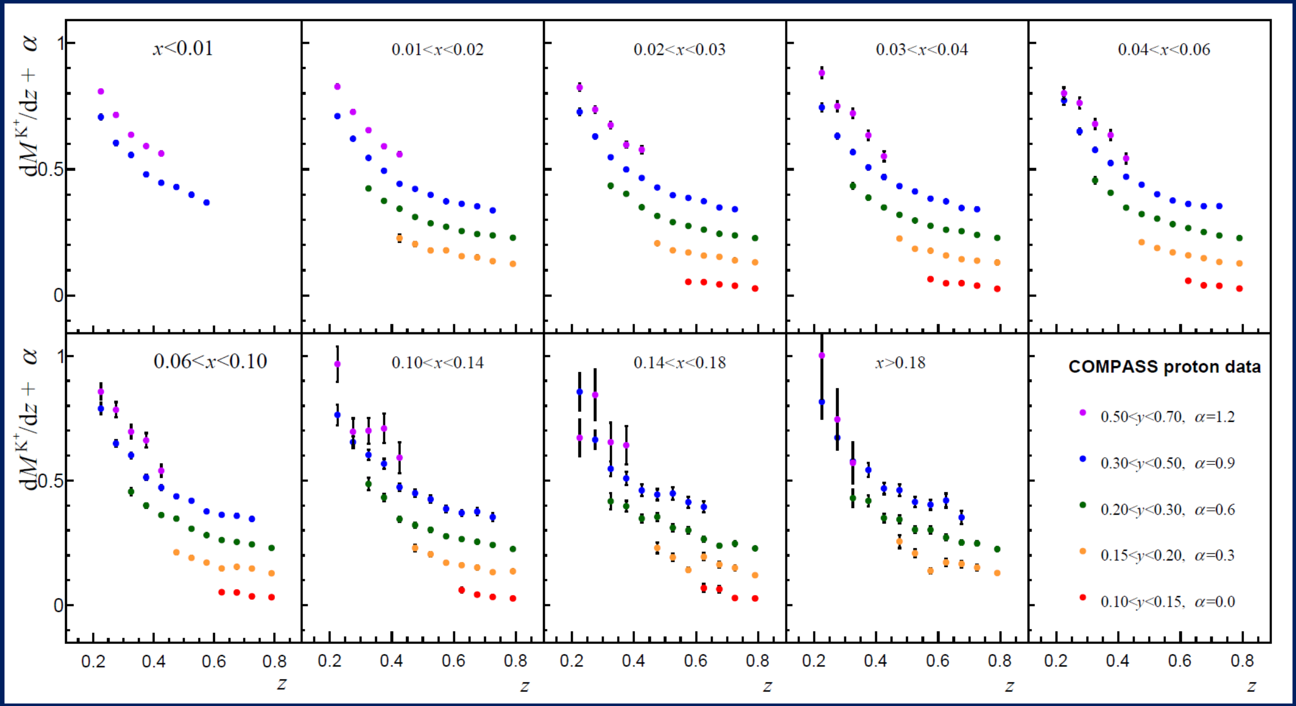
Electromagnetic beams to study ***produced hadrons and hadronization***

- *Semi-inclusive DIS*—measure scattered lepton and at least one final-state hadron
  - Valuable for parton flavor separation of collinear fragmentation functions
  - TMD fragmentation functions, e.g. unpolarized, Collins TMD FF (polarized scattered quark) or polarizing TMD FF (polarized produced hadron)
  - Dihadron interference fragmentation function (polarized scattered quark)
- COMPASS/AMBER, JLab

Electromagnetic beams to study ***produced hadrons and hadronization***

- *Semi-inclusive DIS*—measure scattered lepton and at least one final-state hadron

K^+ multiplicities vs. fragmentation momentum fraction z in bins of Bjorken x and inelasticity. Will improve parton flavor dependence of collinear kaon fragmentation functions.



COMPASS, PRD 112, 012002 (2025)

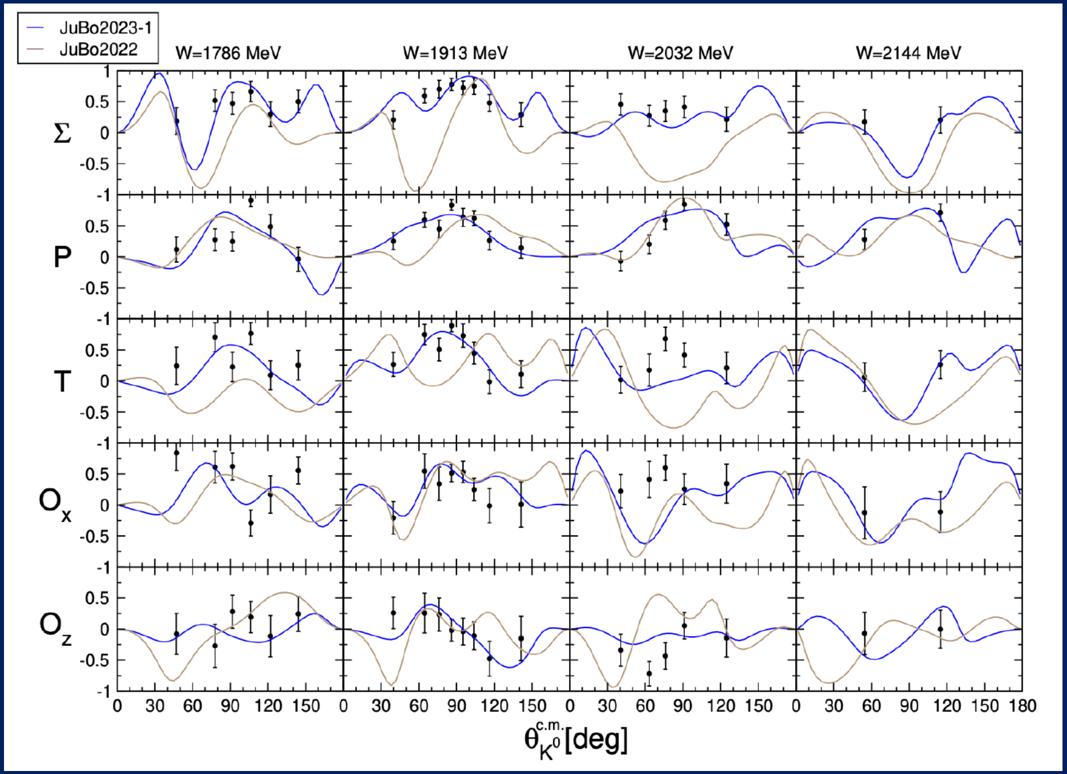
Electromagnetic beams to study ***produced hadrons and hadronization***

- *Electron, muon, or photon beams on nucleons or nuclei for hadron spectroscopy*
- JLab, COMPASS/AMBER, Bonn, SPring-8,…

Electromagnetic beams to study ***produced hadrons and hadronization***

- *Electron, muon, or photon beams on nucleons or nuclei for hadron spectroscopy*

Photoproduction of the Σ^+ hyperon using linearly polarized photons.



CLAS, PRC 111, 025204 (2025)

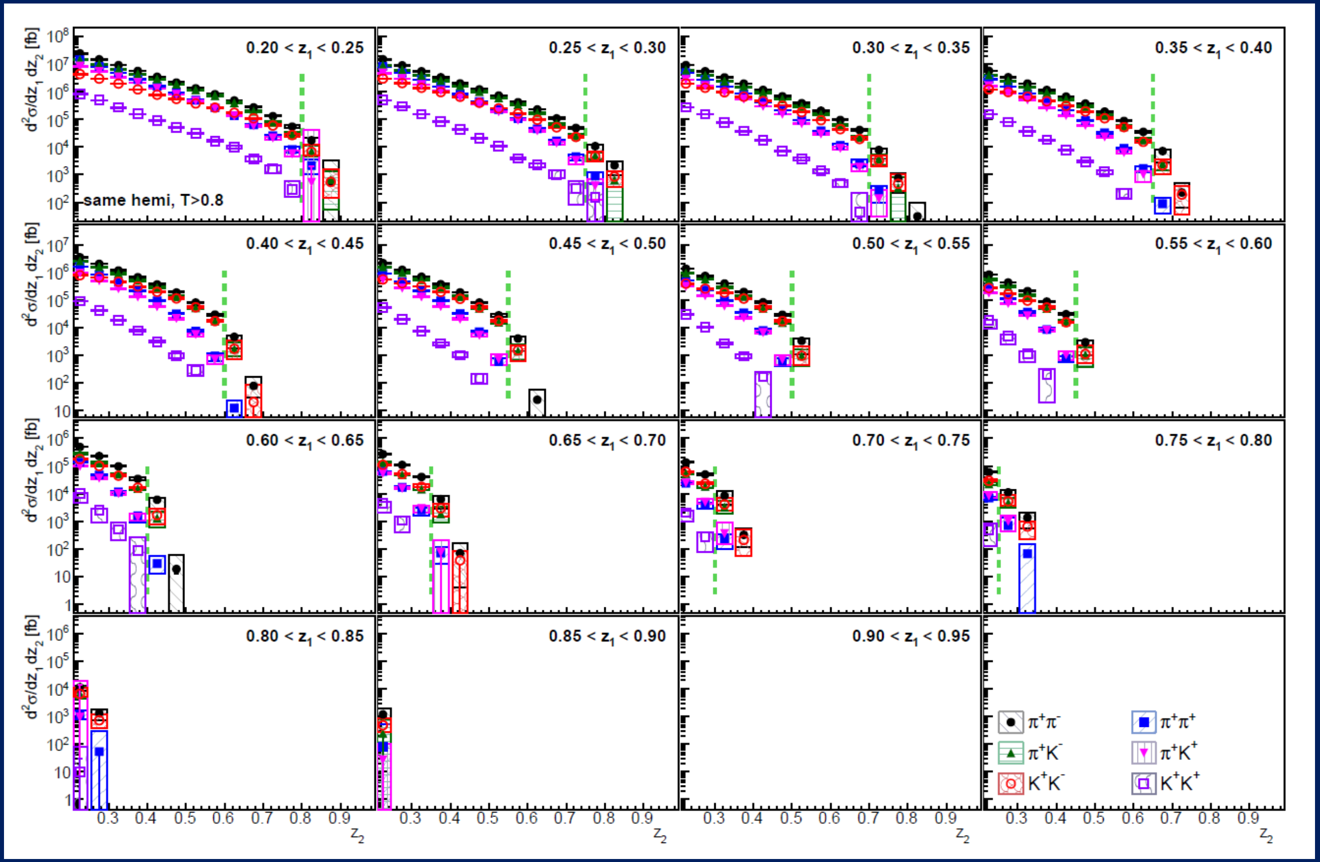
Electromagnetic beams to study ***produced hadrons and hadronization***

- *Electron-positron annihilation to hadrons*
  - Isolate hadronization processes
  - Access collinear and TMD fragmentation functions, including spin-dependent FFs
  - Also hadron spectroscopy
- Belle, Belle 2, BES III, BaBar

Electromagnetic beams to study ***produced hadrons and hadronization***

- *Electron-positron annihilation to hadrons*

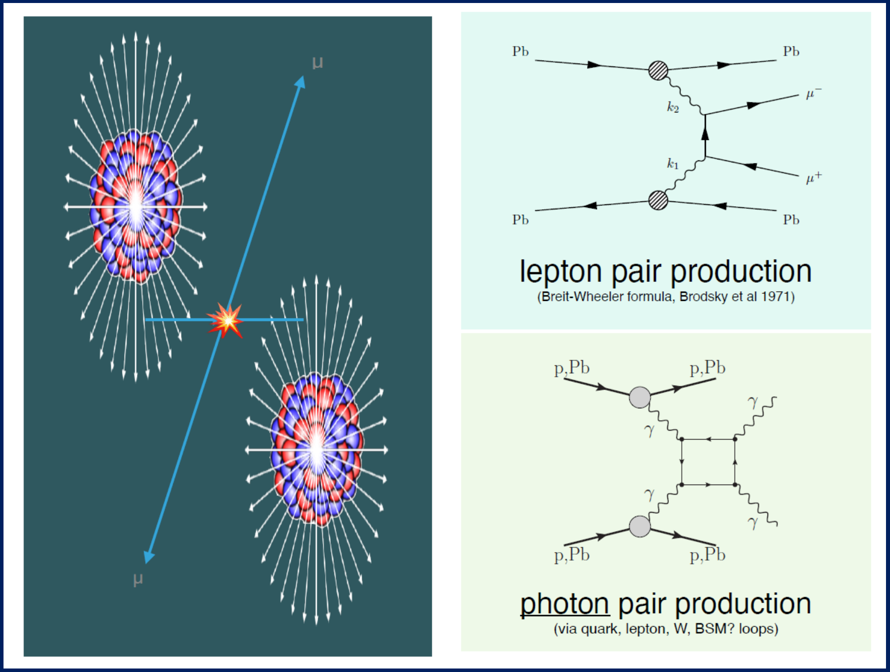
Dihadron fragmentation functions for $\pi^+\pi^-$, $\pi^+\pi^+$, π^+K^-, π^+K^+, K^+K^-, K^+K^+, probing correlations in hadronization.



Belle,
PRD 101, 092004 (2020)

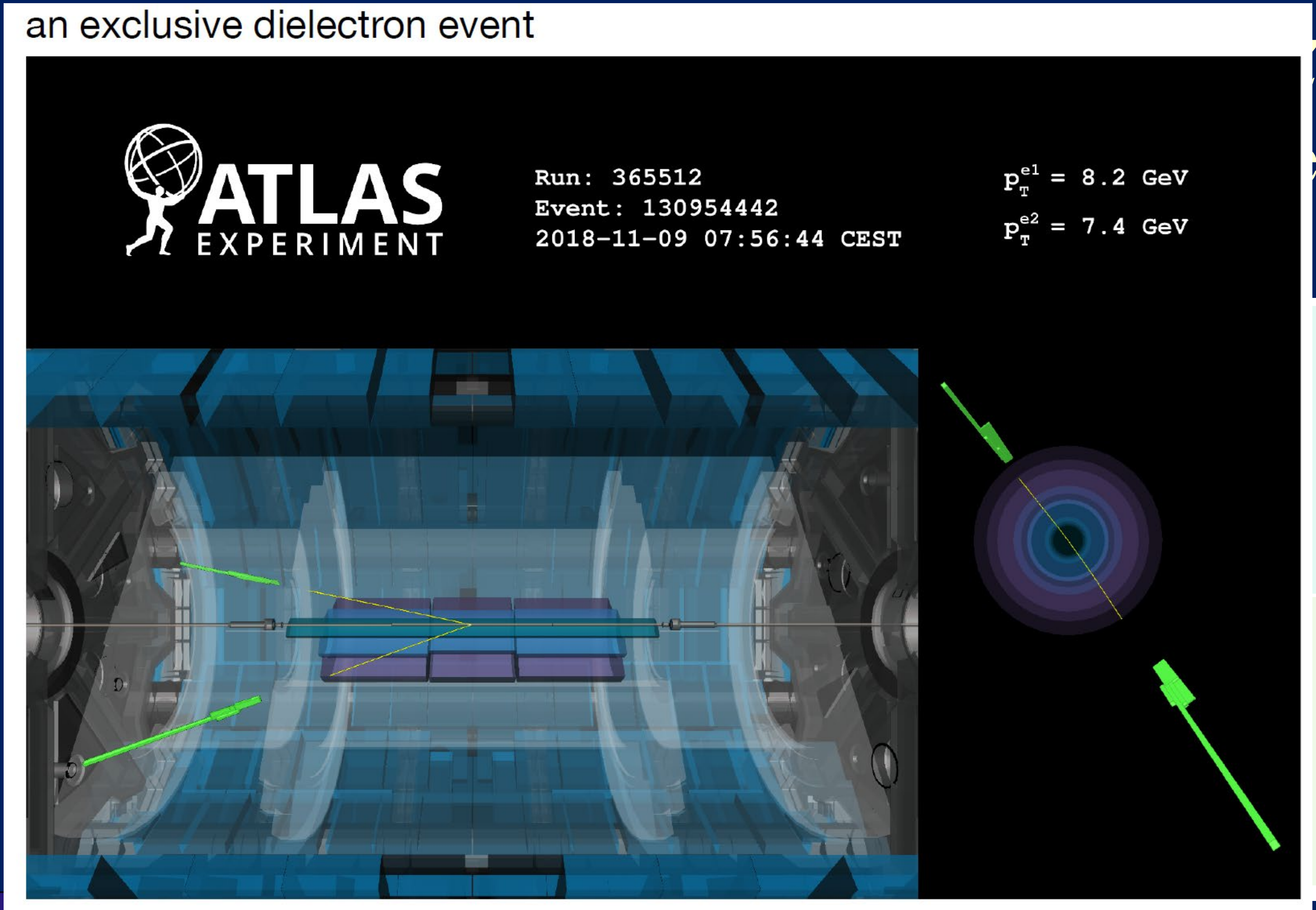
Electromagnetic field interactions in ultraperipheral hadron-hadron collisions

- Strong electromagnetic field of large-*Z* nucleus interacts with other beam hadron/nucleus or with other beam's field
  - Photonuclear processes
  - Light-by-light scattering!
- RHIC, LHC



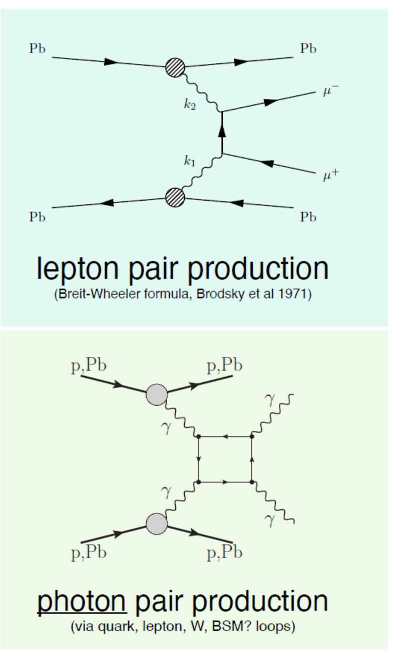
P. Steinberg, DIS 2025

Electromagnetic field interactions in ultraperipheral hadron-hadron collisions



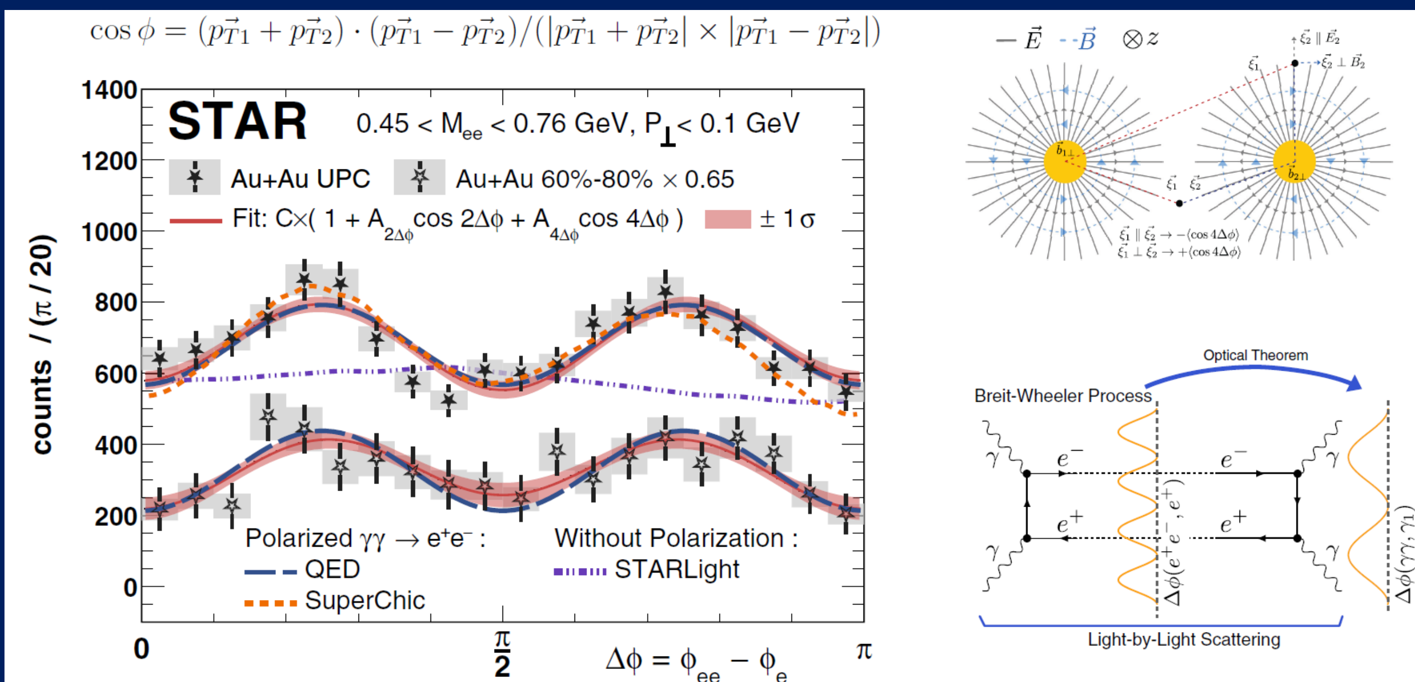
nucleus

us or



Electromagnetic field interactions in ultraperipheral hadron-hadron collisions

- Strong electromagnetic field of large-*Z* nucleus interacts with other beam hadron/nucleus or with other beam's field



Linear polarization of photons leads to azimuthal modulation of produced dielectron!

STAR, PRL 127, 052032 (2021)

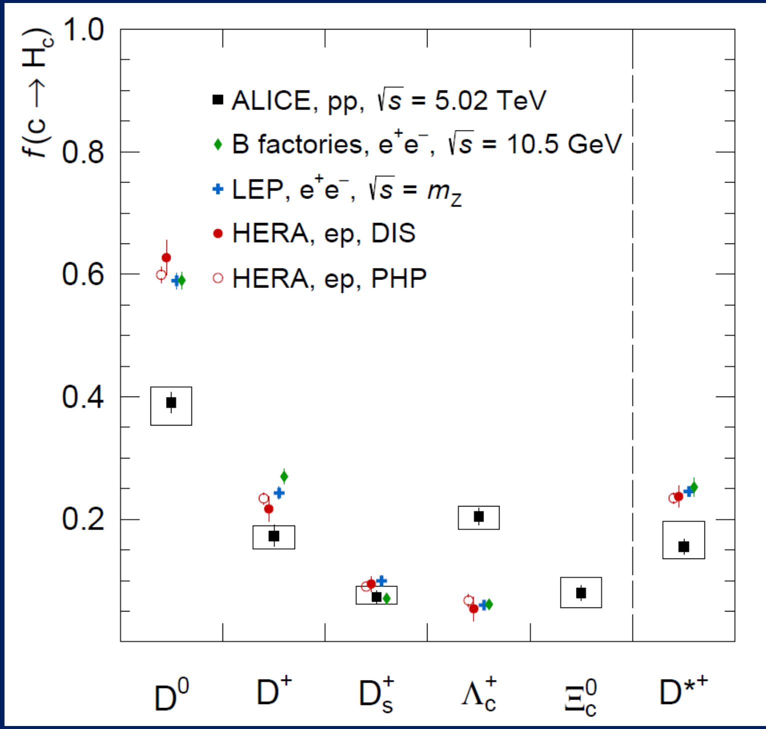
QED ***comparisons*** *to inform our understanding of QCD*

- Compare leading-order QED and QCD processes to study *universality* of theoretical objects describing hadron structure (PDFs) and hadronization (fragmentation functions)
  - Process-dependence of PT-odd TMD PDFs describing spin-momentum correlations in the nucleon—opposite sign in SIDIS vs. Drell-Yan
  - Predicted TMD-factorization breaking in hadron-hadron collisions with at least one measured final-state hadron
    - Explicitly due to non-Abelian nature of QCD
    - Partons become color entangled *across* incoming hadrons!
  - Differences in charm hadron production in e+e- vs. proton-proton

*QED **comparisons** to inform our understanding of QCD*

- Compare leading-order QED and QCD processes to study *universality* of theoretical objects describing hadron structure (PDFs) and hadronization (fragmentation functions)

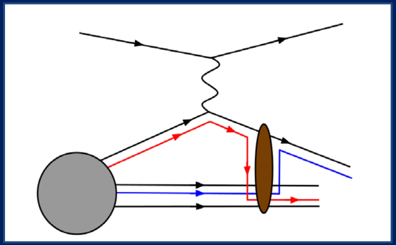
Charm quark fragmentation fractions to charm hadrons in pp in comparison to e^+e^- and ep. Increased baryon production in pp.

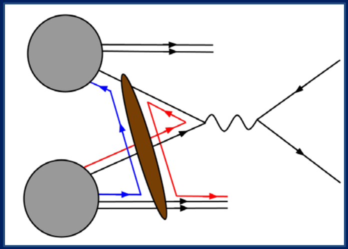


ALICE, PRD 105, L011101 (2022)

*QED **analogs** to inform our understanding of QCD **interactions***

- Predicted process-dependent sign change for PT-odd Sivers TMD PDF is not specific to QCD
  - Only need a gauge-invariant QFT that admits bound states → also in QED!
- Pros of investigating in QED:
  - Perturbative at low energies—PT-odd spin-momentum correlations in atomic bound states are calculable
  - QED measurements are extremely precise
  - Could be tested experimentally with tabletop devices
- But—α_{em} small, so might be a small effect

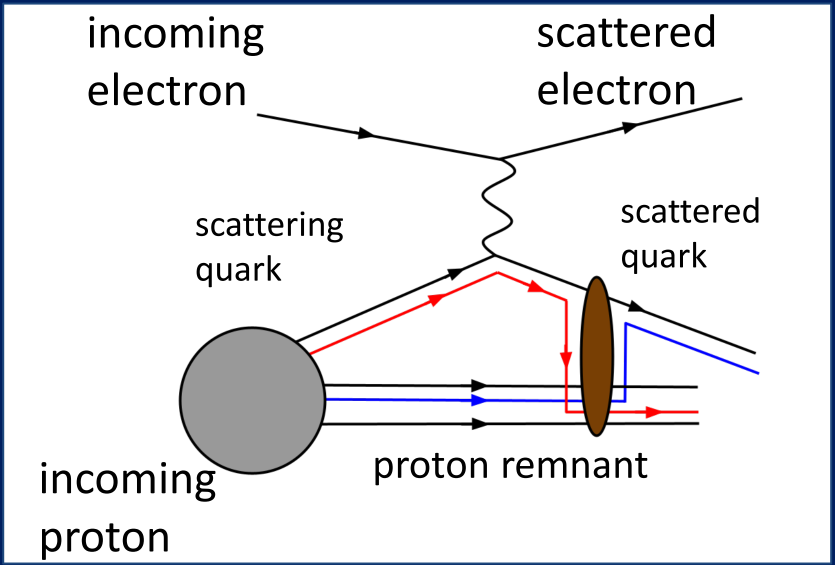




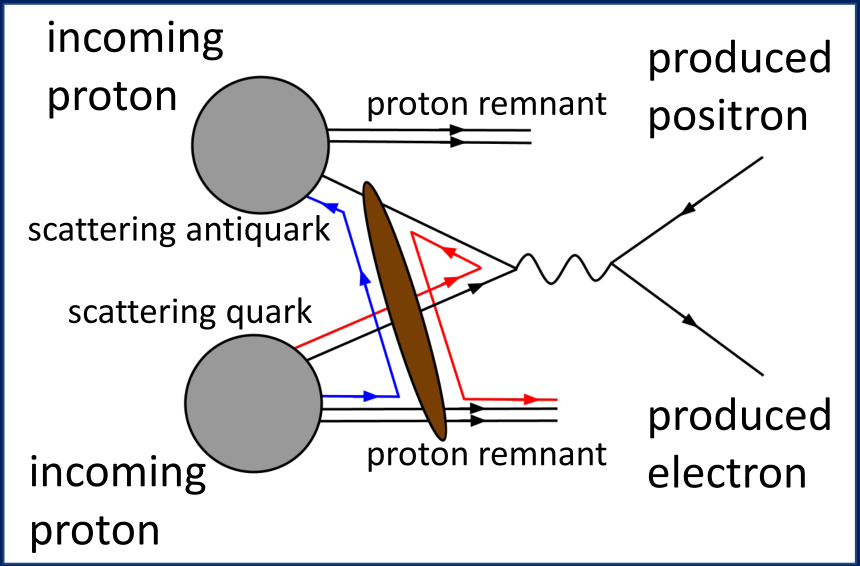
Ongoing work with A. Signori, D. Manna, A. Bacchetta, and Bachelor's students A. Minotti, A. Perron Cabus

Process-dependent PT-odd spin-momentum correlations in hadronic bound states

Deep-inelastic lepton-nucleon scattering: Final-state gluon exchange

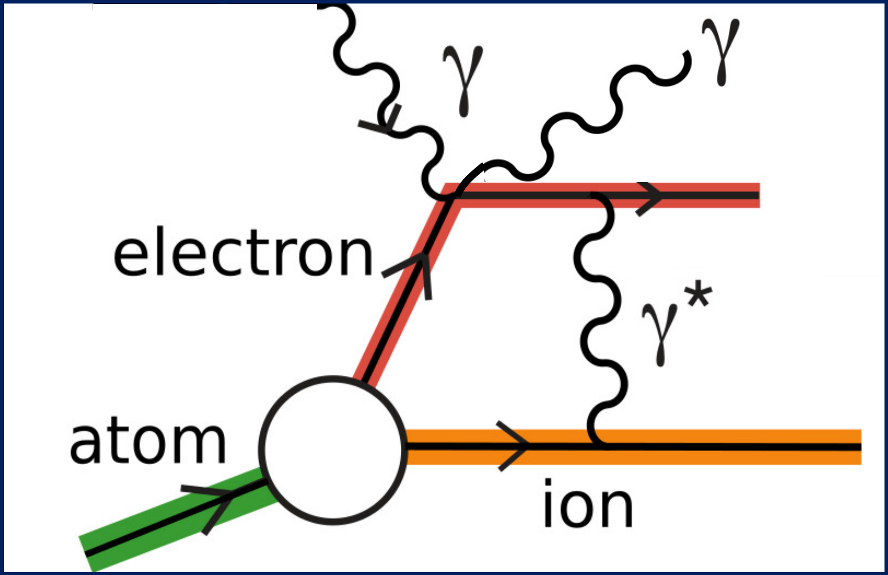


Quark-antiquark annihilation to leptons: Initial-state gluon exchange



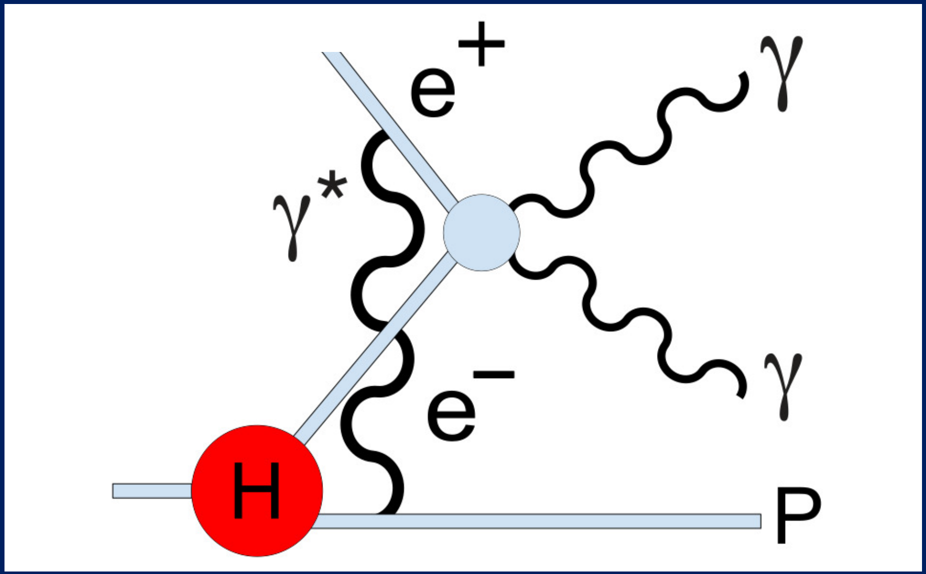
Process-dependent *PT-odd spin-momentum correlations in atomic bound states*

Photo-ionization: Final-state photon exchange



Measure angular distribution of scattered photon and ionization electron w.r.t. angular momentum $\vec{J}$ of atom

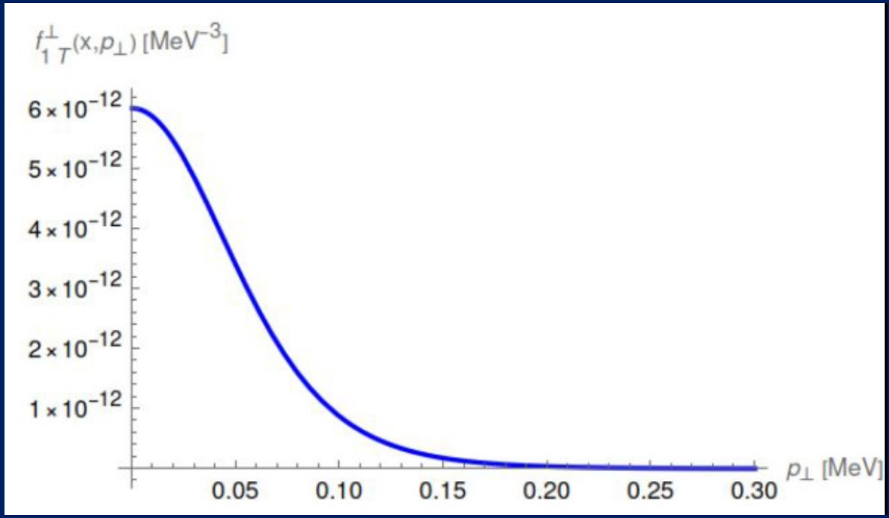
Annihilation to photons: Initial-state photon exchange



Measure angular distribution of photon pair w.r.t. angular momentum $\vec{J}$ of atom

*QED **analogs** to inform our understanding of QCD **interactions***

- Performed photoionization (atomic Compton scattering) calculations for singly ionized ^{4}He—scalar nucleus
- Asymmetry for this ion ~10^{-12}
- May be enhanced in other ions
  - Hope to inspire further work!



Stepping back—so why do we use electromagnetic probes to study objects with internal color structure??

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Electromagnetic probes are and will continue to be essential and versatile tools in studying hadrons, nuclei, and QCD!

Extra

Electromagnetic beams to study

Search for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ at Belle II

Belle II

Confirm $\Upsilon(10753)$ existence

- New measurement confirms previous Belle result: cross section is peaking near 10.75 GeV.

	Belle + Belle II (MeV)	Belle (MeV)
$M_{\Upsilon(10753)}$	$10756.6 \pm 2.7 \pm 0.9$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
$\Gamma_{\Upsilon(10753)}$	$29.0 \pm 8.8 \pm 1.2$	$35.5^{+17.6+3.9}_{-11.3-3.3}$

- Results are consistent with the Belle results.
- Uncertainties are improved by a factor of two from previous Belle results.

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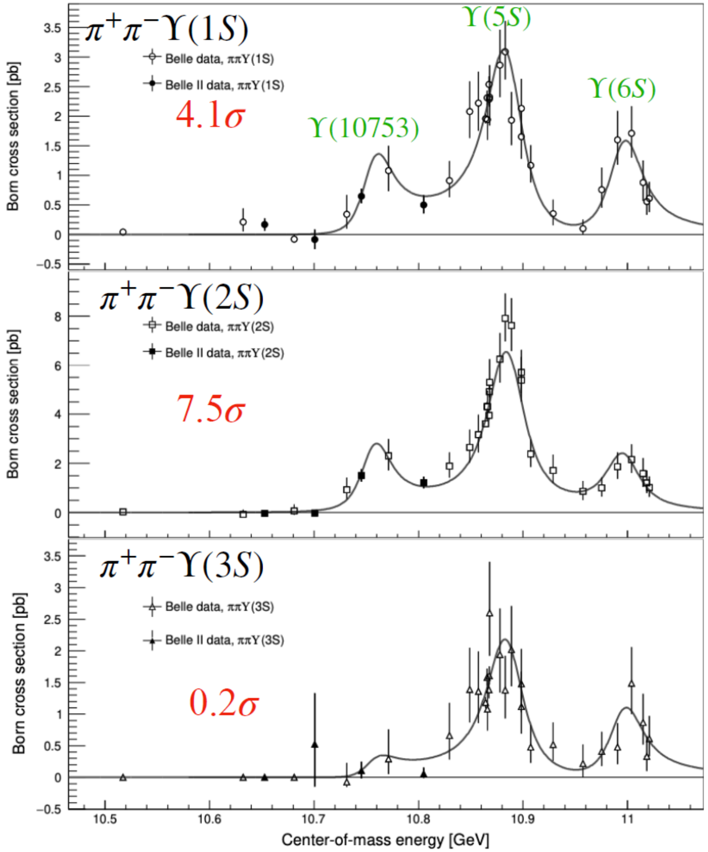
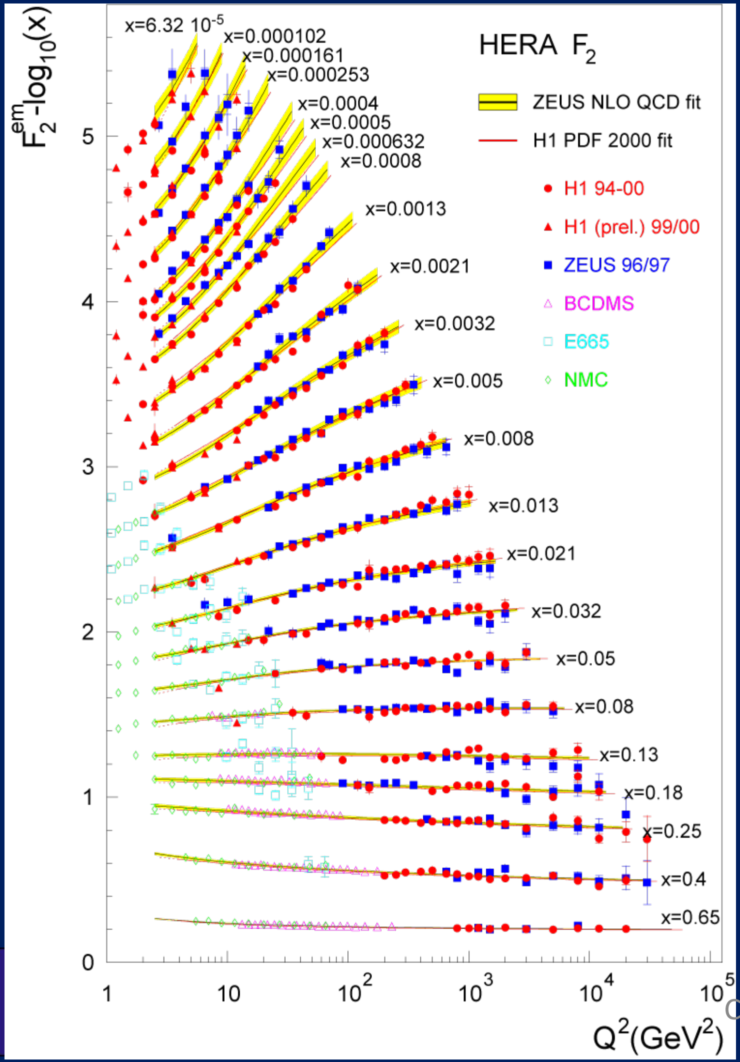


How do we understand the visible matter in our universe in terms of the quark and gluon degrees of freedom of quantum chromodynamics?

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

Accessing gluons with an electroweak probe

$$\text{DIS}: \quad \frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$



Access the gluons in DIS via scaling violations:

$dF_2/d\ln Q^2$ and linear DGLAP evolution in $Q^2 \rightarrow G(x,Q^2)$

OR

Via F_L structure function

OR

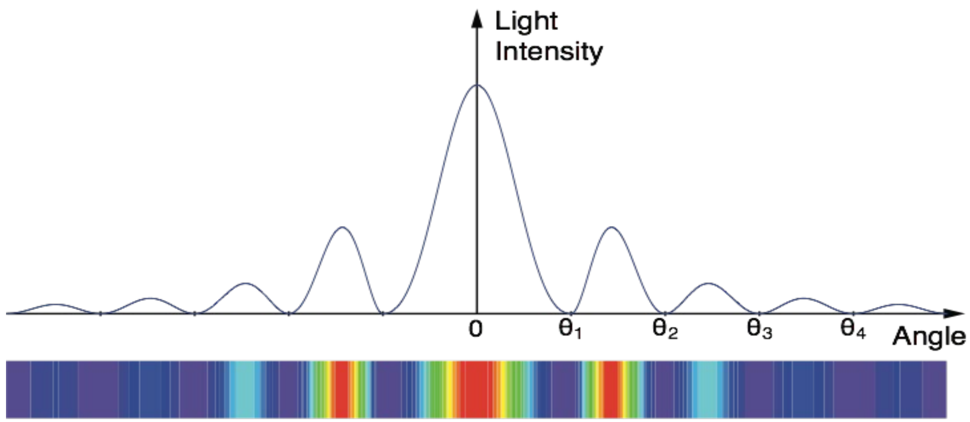
Via dihadron production

OR

Via diffractive scattering

Imaging spatial structure of quarks in nuclei: Diffraction

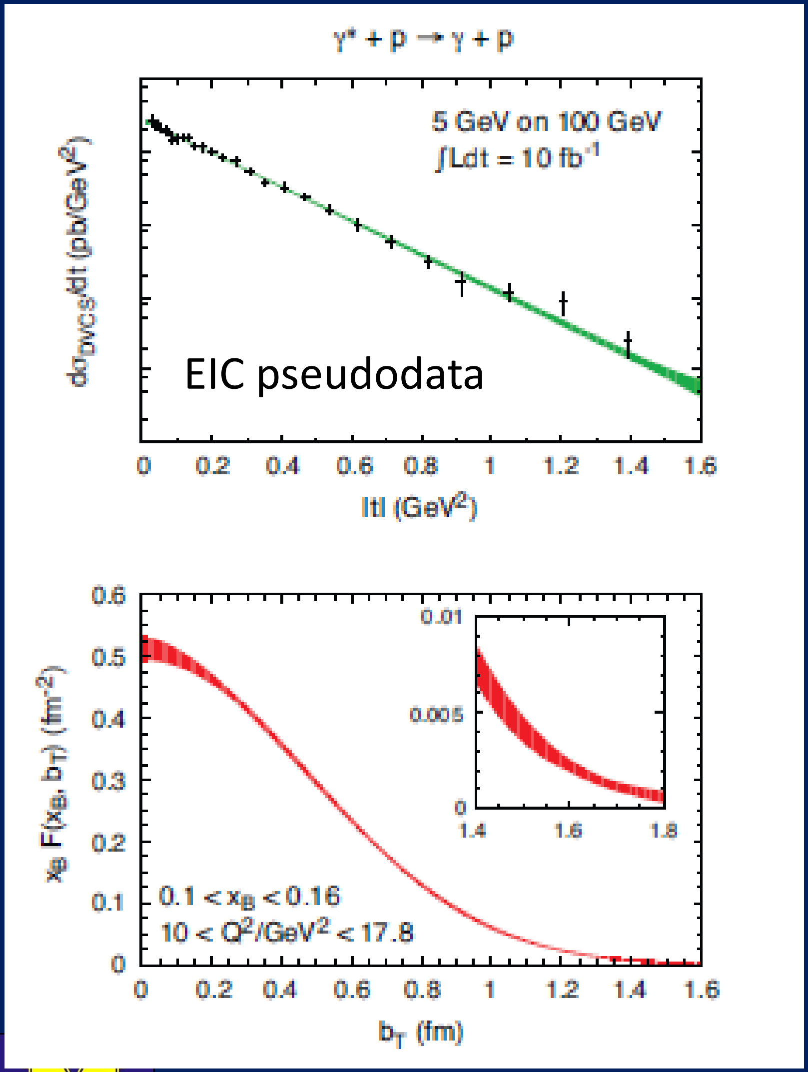
Diffraction pattern from monochromatic plane wave incident on a circular screen of fixed radius

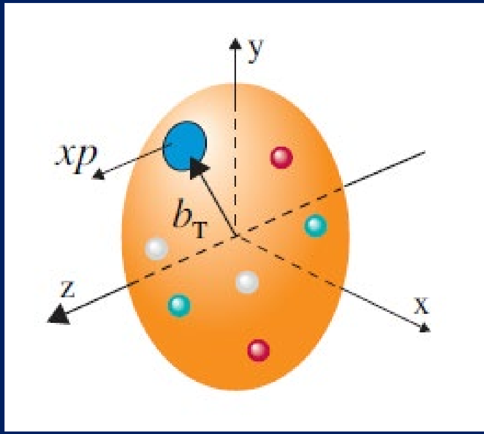


From E. Aschenauer

- 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

Partonic spatial structure of nuclei: Diffraction





Goal: Cover wide range in *t*.
Fourier transform → impact-parameter-space profiles.
Obtain *b* profile from slope vs. *t*.

Note: To probe spatial distributions, can also use Bose-Einstein correlations (HBT) in e+A to probe spatial extent of particle production region, as in hadron-hadron collisions

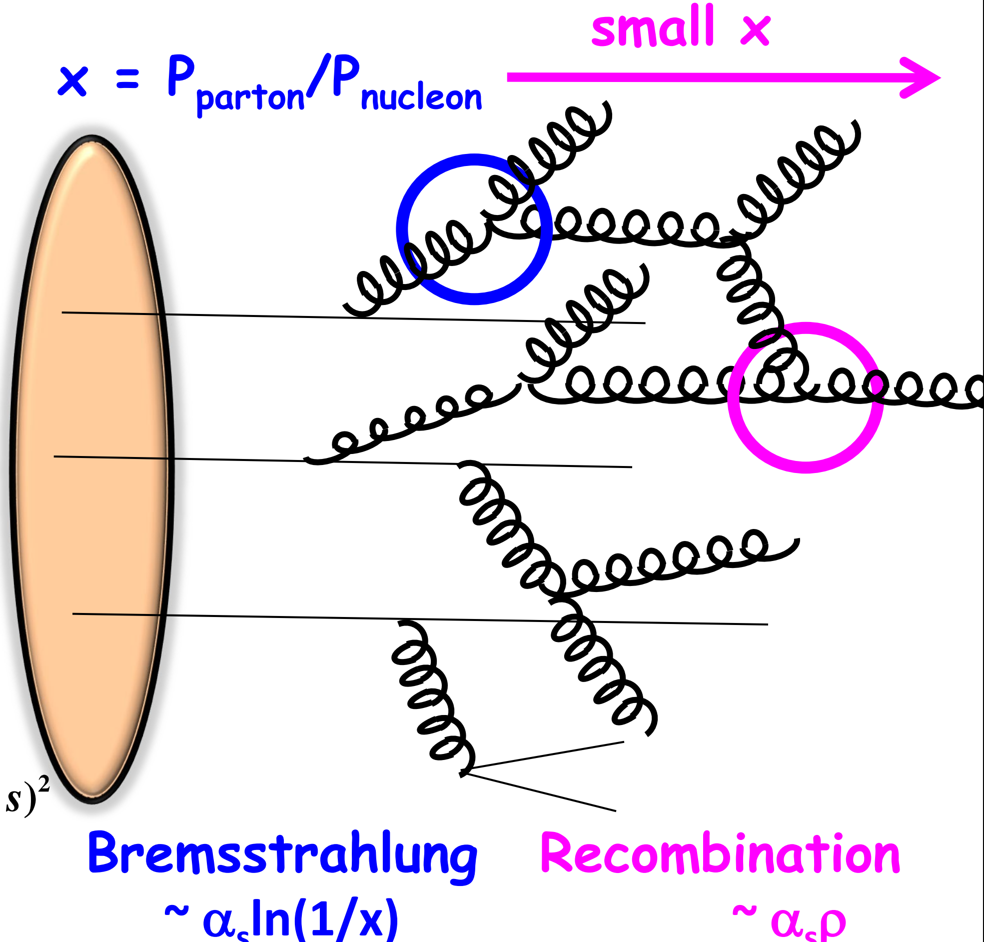
Gluon saturation

At small x linear evolution gives strongly rising $g(x)$ – but must be bounded!

BK/JIMWLK non-linear evolution includes recombination effects → saturation

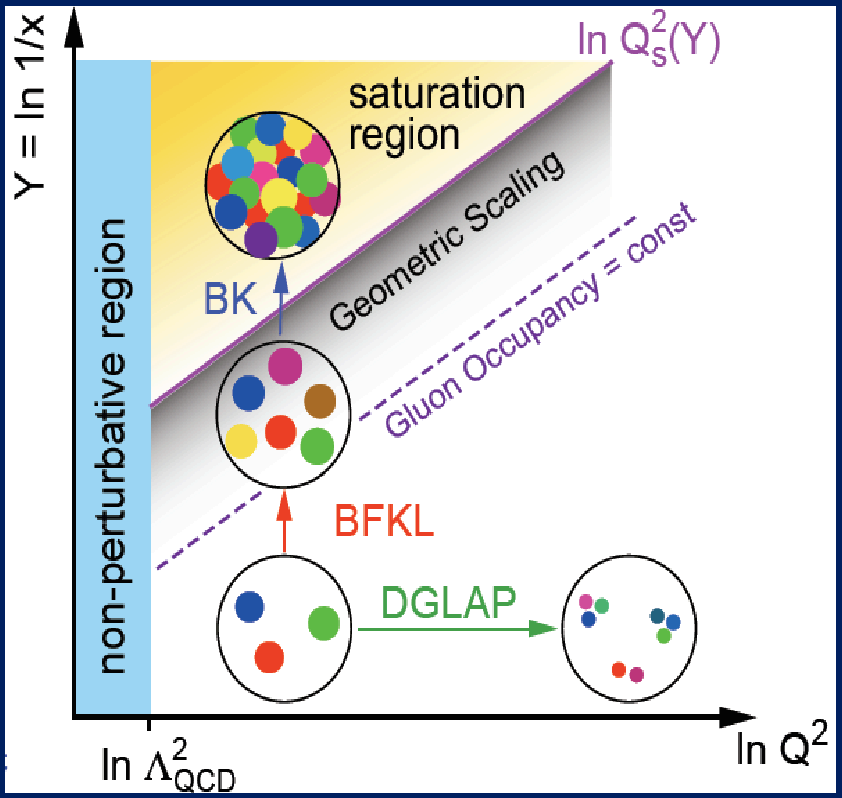
- Dynamically generated scale
  Saturation Scale: $Q^2_s(x)$
    - Increases with energy or decreasing x
- Scale with $Q^2/Q^2_s(x)$ instead of x and Q^2 separately

$$\sigma_{tot} = \frac{\pi}{m_\pi^2}(\ln s)^2$$

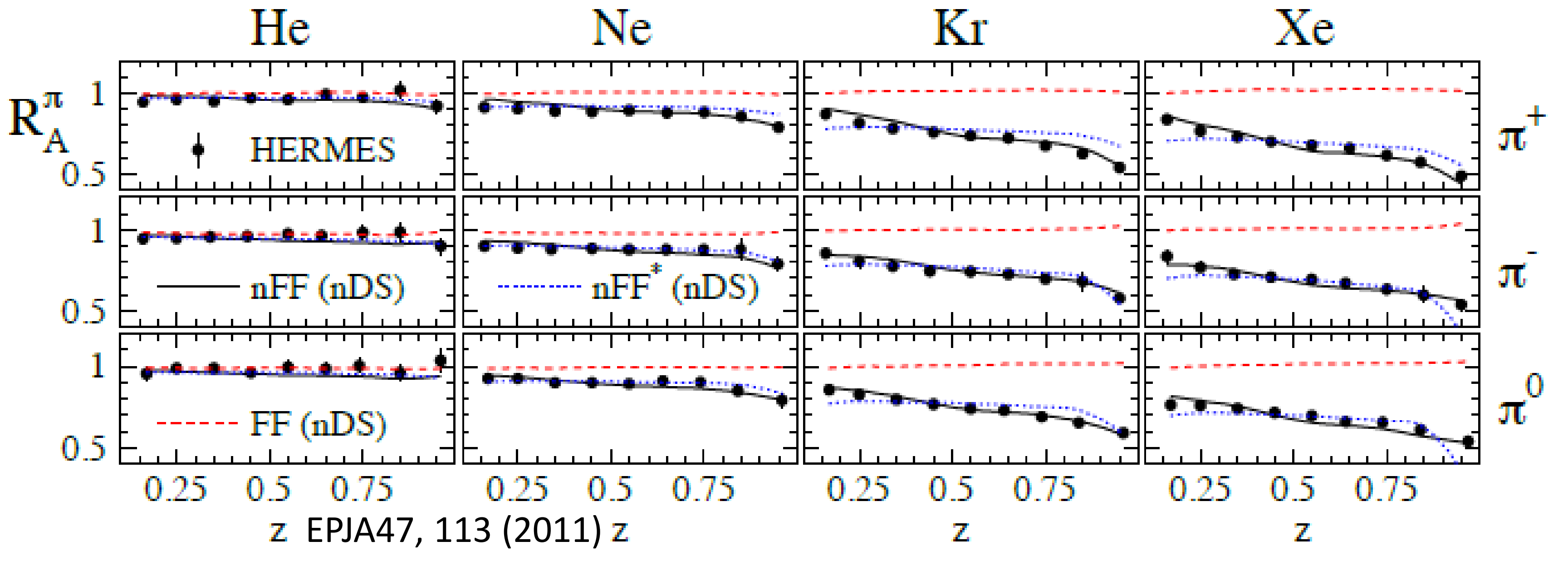


Diffraction to study universal state of gluonic matter: Gluon saturation

- In addition to probing spatial structure, diffraction is one way to probe gluon saturation within nuclei



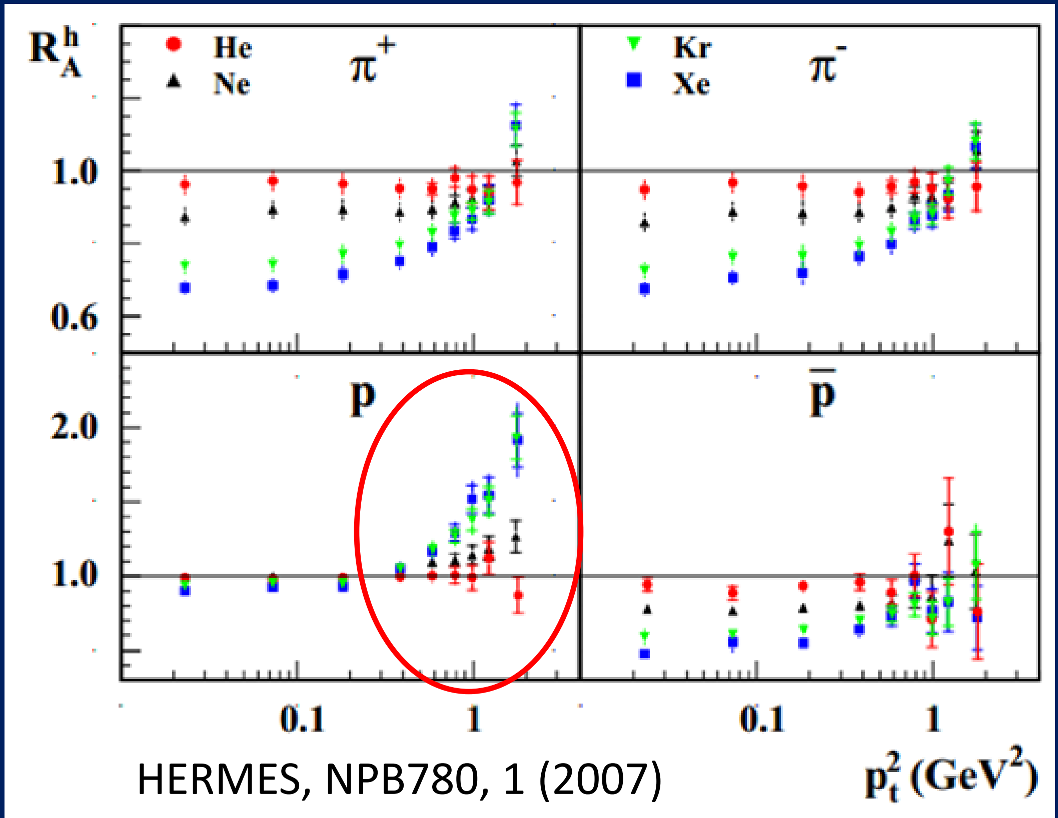
Formation of QCD bound states: Nuclear modification of fragmentation functions



As in A+A and p+A, fragmentation functions are modified in e+A with respect to e+p, e.g. suppression of pion production

Formation of QCD bound states: Hadronization in higher-density partonic environments

- Evidence for baryon enhancement also in e+A!
- Baryon enhancement in A+A, p+A, e+A suggests mechanism(s) other than "vacuum fragmentation"
- Binding of nearby partons in phase space?



HERMES, NPB780, 1 (2007)

Comprehensive studies of hadronization as well as of propagation of color charges through nuclei possible at EIC

High-energy collisions: Control

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

- 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, sensitivity to system properties

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Some aspects we *select* rather than control

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