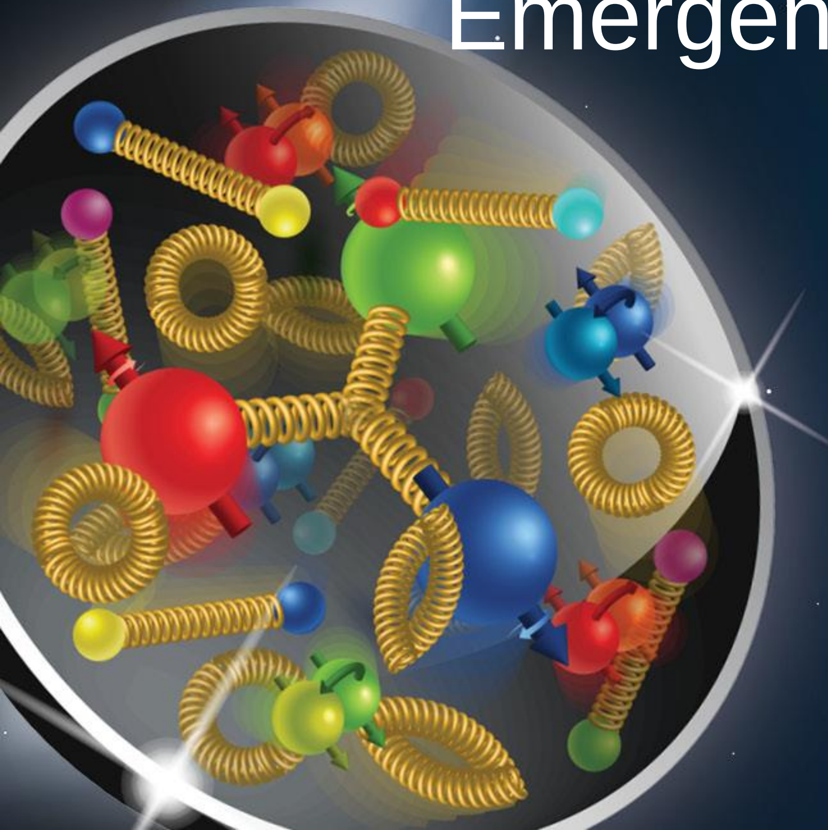
Experimental Prospects to Study the Emergence of Mass and Structure



Rolf Ent (Jefferson Lab)

Revealing Emergent Mass Through Studies of Hadron Spectra and Structure

ECT* Trento, September 12-16, 2022

Electron Ion Collider

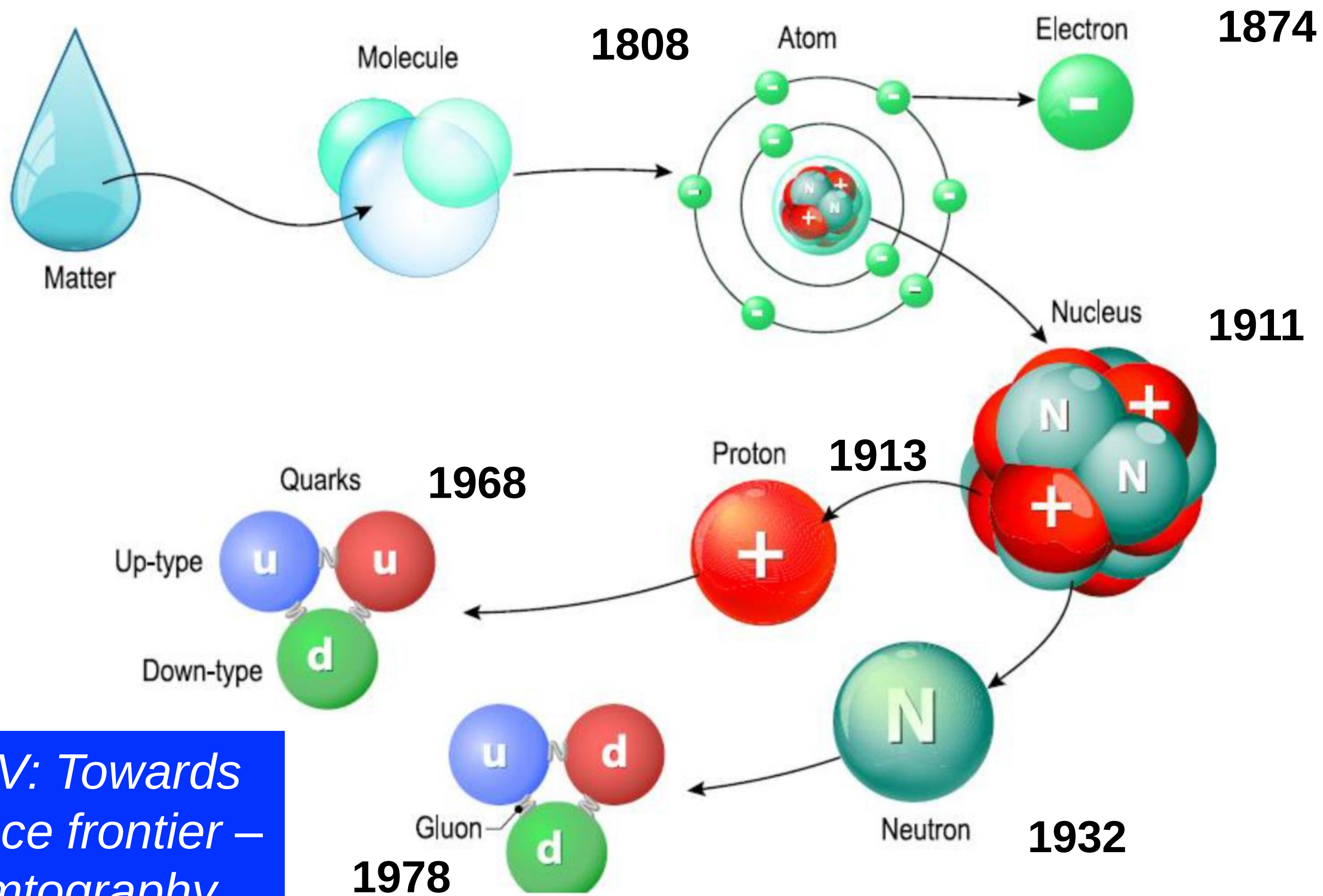
BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY Office of Science

Outline

A lighthearted experimentalist talk as start of the workshop…

- The Quest to Understand the Fundamental Structure of Matter:
  3D Sub-Atomic Structure: Nuclear Femtography
- 21st Century View of the Fundamental Structure of the Proton:
  The Emergence of Mass and Structure
- Jefferson Lab 12 GeV and Beyond Prospects
- The US-Based Electron-Ion Collider (EIC) and Status
- Artistic View of Proton Structure Based on 1D Data → On to Reality!

The Quest to Understand the Fundamental Structure of Matter

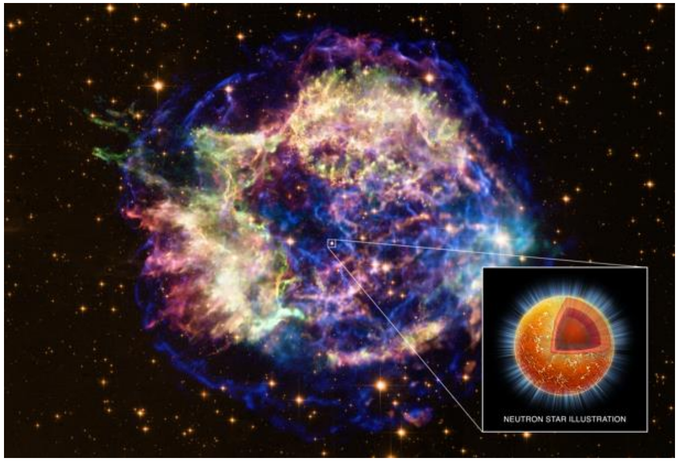


JLab 12 GeV: Towards a new science frontier – Nuclear Femtography

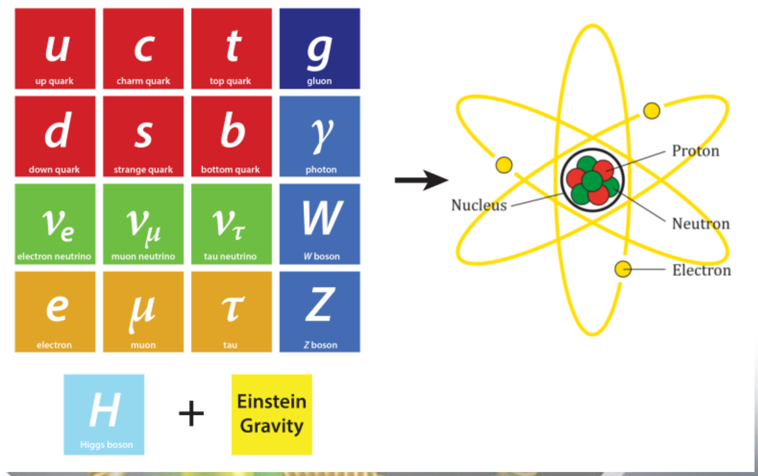
*EIC: Understanding the Glue that Binds Us All - **Without gluons, there would be no nucleons, no atomic nuclei… no visible world!***

Standing on a bathroom scales tells us our weight, i.e., quantifies our mass.

During an MRI scan explicit use is made of the spin (or magnetic moment) of a nucleus.



Around us, in the visible world, we see a large variety of structures of nuclear matter.



All the matter in the visible universe is understood in terms of subatomic particles and their constituents and interactions.

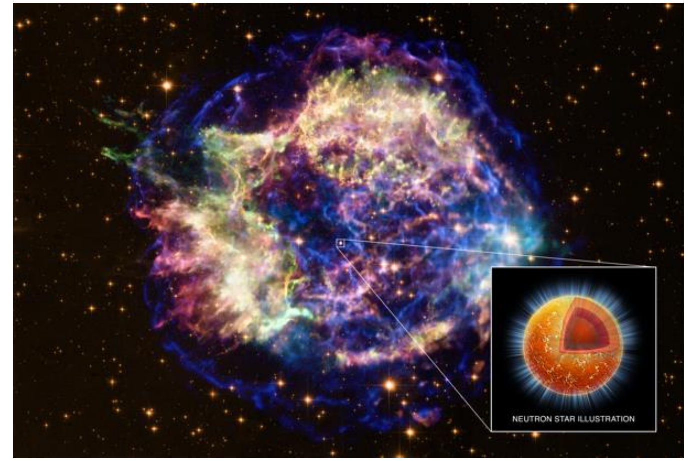
The Standard Model of Physics explains the fundamental structure of the visible matter in terms of quarks, gluons and their interactions.

These particles, interacting together, make up protons and neutrons, which along with electrons, in turn, make up more familiar atoms. This leads to mass, MRI, and visible structure.

What if there were would not be Gluons and Quark-Gluon Interactions?

Your mass, and the mass of the visible world, would drop by over an order of magnitude

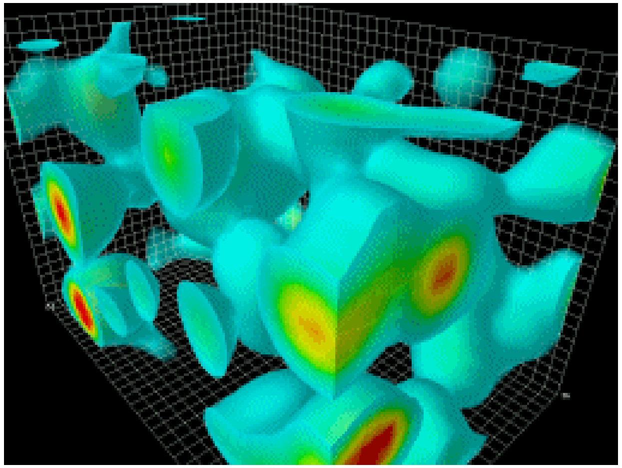
The signals from MRI scans would be reduced by a factor of five.



There would be no protons, no neutrons, no atomic nuclei … no visible world!

How is this possible? → Deep dive inside the world of the proton

When we enter the quantum world, particles are confined to small volumes

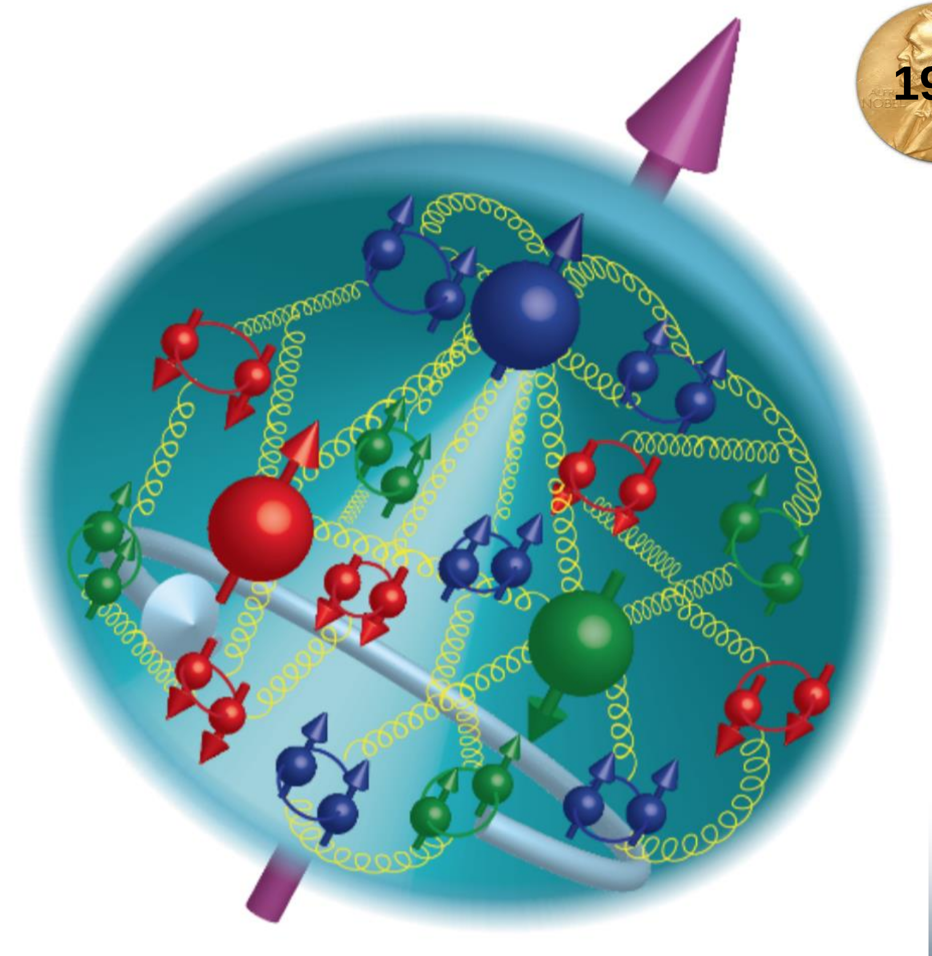


Because of Quantum Mechanics

- Particles move at near lightspeed; everything is in continual motion.
- Particles are created and annihilated
- Even the vacuum fluctuates!

21st Century View of the Fundamental Structure of the Proton

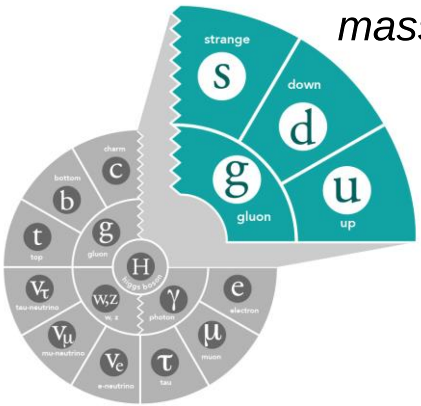
- Elastic electron scattering determines charge and magnetism of nucleon
- Approx. sphere with <r> ≈ 0.85 Fermi
- The proton contains quarks, as well as dynamically generated quark-antiquark pairs and gluons.
- Quark and gluon momentum fractions (in specific Infinite Momentum Frame) are well mapped out.
- The proton spin and mass have large contributions from the quark-gluon dynamics.



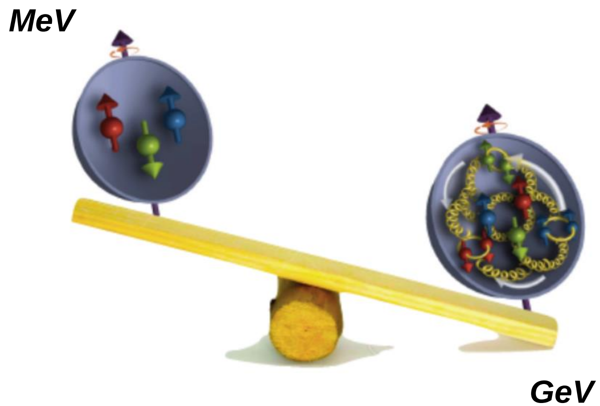
In fact, the proton mass and structure emerge from the quark-gluon dynamics

Mass of the Proton, Pion, Kaon

Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions.



“Mass without mass!”



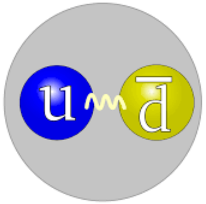
Proton

Quark structure: uud
Mass ~ 940 MeV (~1 GeV)
Most of mass generated by dynamics.

Gluon rise discovered by HERA e-p

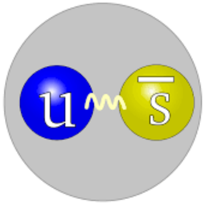
Pion

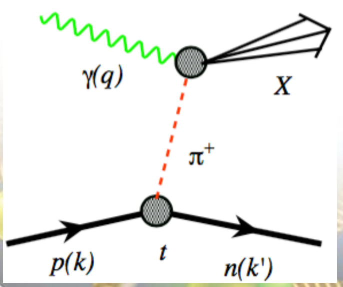
Quark structure: ud
Mass ~ 140 MeV
Exists only if mass is dynamically generated.
Empty or full of gluons?



Kaon

Quark structure: us
Mass ~ 490 MeV
Boundary between emergent- and Higgs-mass mechanisms.
More or less gluons than in pion?





For the proton the EIC will allow determination of an important term contributing to the proton mass, the so-called “QCD trace anomaly”

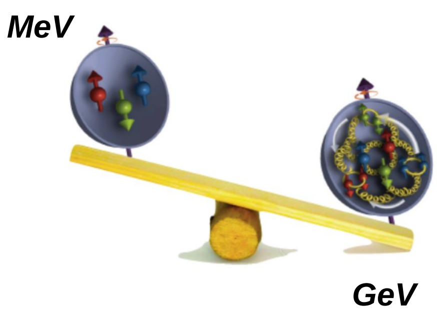
For the pion and the kaon the EIC will allow determination of the quark and gluon contributions with the Sullivan process.

A.C. Aguilar et al., Pion and Kaon structure at the EIC, arXiv:1907.08218, EPJA 55 (2019) 190.
J. Arrington et al., Revealing the structure of light pseudoscalar mesons at the EIC, arXiv:2102.11788.

The Incomplete Proton: Mass Puzzle

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

- Proton mass:



Relativistic motion — Quantum fluctuation

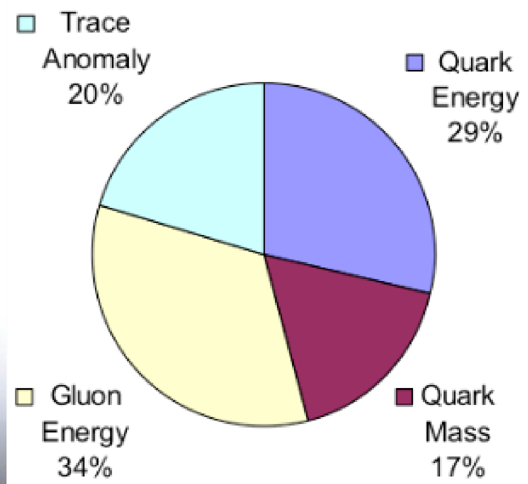
$$M = E_q + E_g + \chi_{m_q} + T_g$$

Quark Energy — Gluon Energy — Quark Mass — Trace Anomaly

Ji PRL 1995

Ji 1995 (proton): c_{mq} = small, E_q = ¾M <xq> (m), E_g = ¾ M <xg> (m), T_g = ¼ M

Early Lattice:
(Keh-Fei Liu)

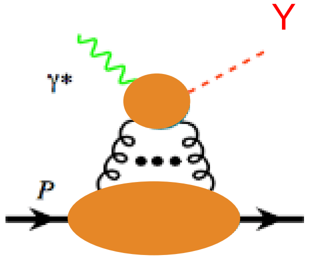


Present Lattice:
(C. Alexandrou)

c_{mq} ~ 20%
E_q ~ 30% (MSbar, at 2 GeV)
E_g ~ 32% (MSbar), at 2 GeV)
T_g ~ 20%

Elastic Υ production near threshold at an EIC

At an EIC a study of the <u>Q^2 dependence</u> in the threshold region is possible (J/Ψ also)

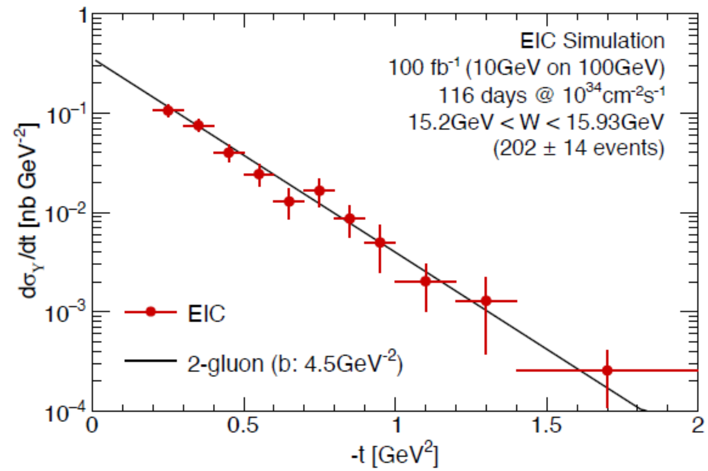


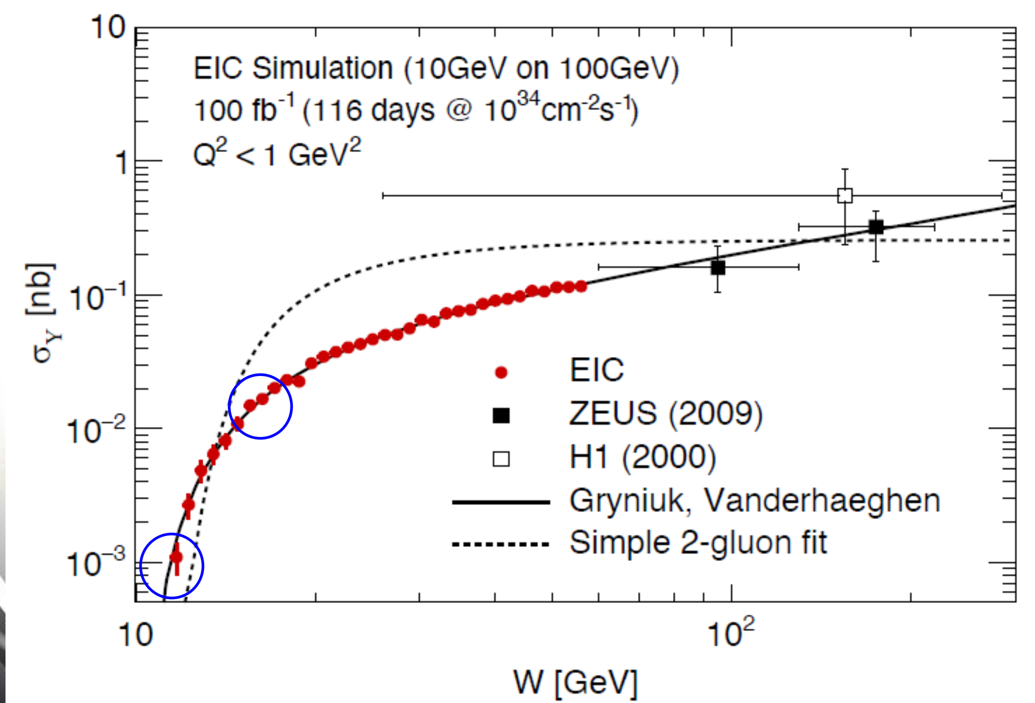
S. Joosten,
Z-E. Meziani

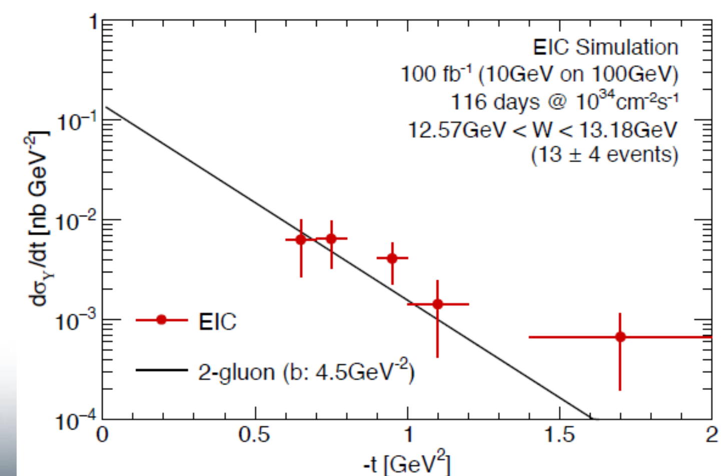
Low W → trace anomaly
Large W → Gluon GPDs

(see arXiv:1802.02616)

t distribution







JLab12 and EIC: Constraining the Vacuum Contribution to the Proton Mass

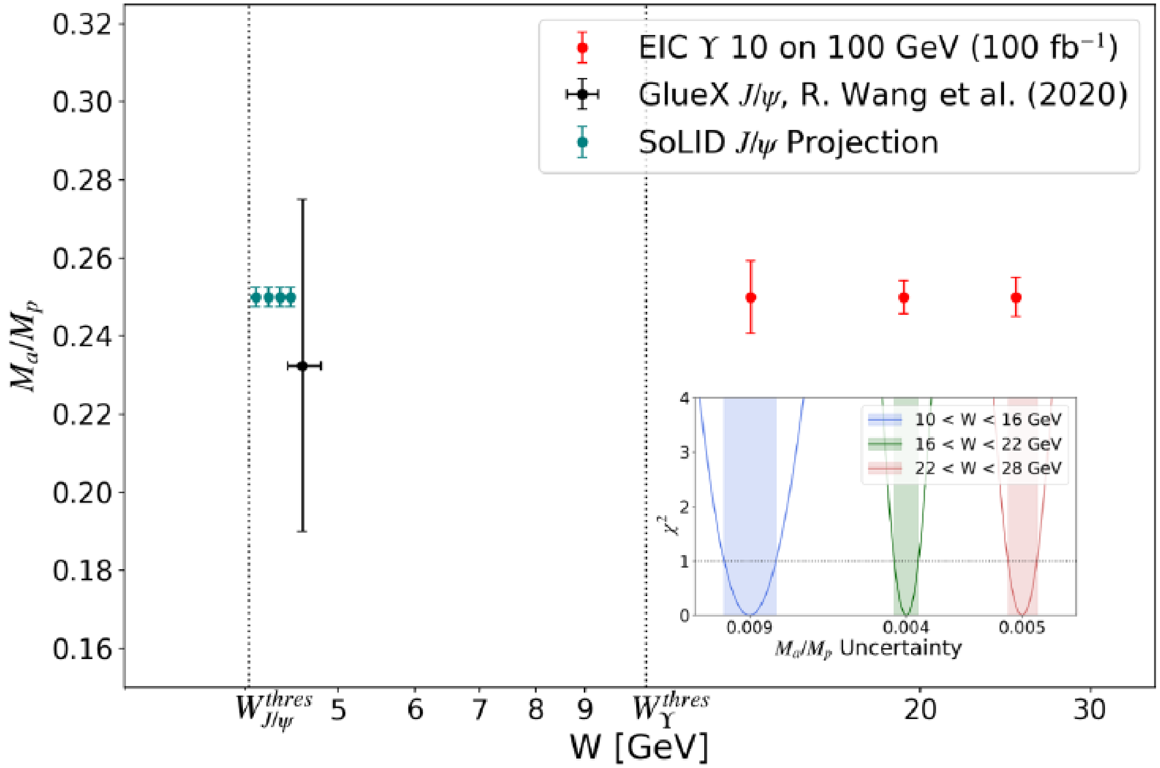


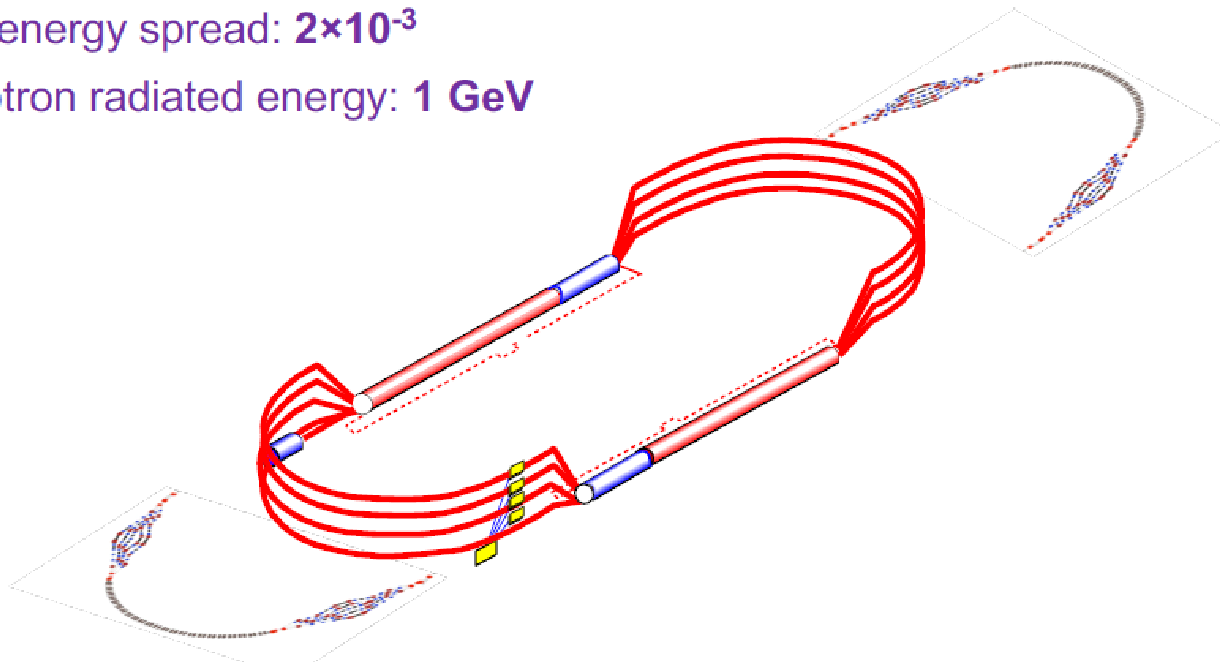
Figure 7.26: Projection of the trace anomaly contribution to the proton mass (M_a/M_p) with Υ photoproduction on the proton at the EIC in 10 × 100 GeV electron/proton beam-energy configuration. The insert panel illustrates the minimization used to determine the uncertainty for each data point. The black circles are the results from the analysis of the GlueX J/ψ data [191], while the dark green circles correspond the JLab SoLID J/ψ projections. The Υ projections were generated following the approach from Ref. [192] with the lAger Monte Carlo generator [193].

JLab-20+: Unique Science at the Luminosity Frontier

FFA CEBAF with CBETA-like Arcs

Synchrotron Radiation impact on beam quality

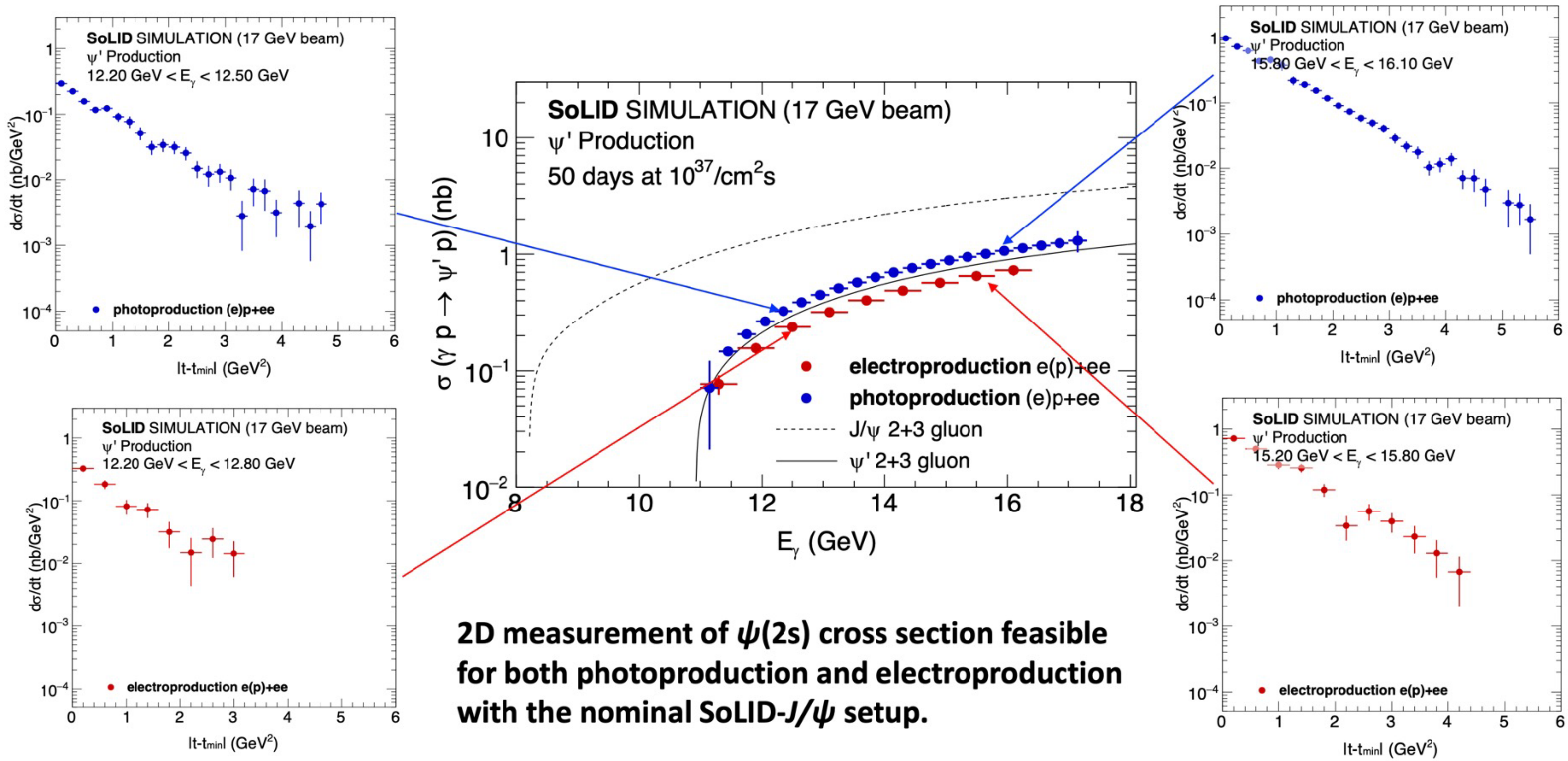
- Net transverse emittance dilution (normalized): **60 mm mrad** at 23 GeV, β = 20 m $\rightarrow$ σ = 150 microns
- Net natural energy spread: **2×10^{-3}**
- Net synchrotron radiated energy: **1 GeV**



Capitalizing on recent innovations enabled by accelerator science and technology, a cost-effective energy upgrade of the 12-GeV CEBAF at Jefferson Lab to a 20+ GeV facility has become feasible. Such an upgrade would permit a worldwide unique nuclear science program with fixed targets at the luminosity frontier, roughly five decades above that possible with a collider.

JLab20+: Further Prospects for Constraining the Vacuum Contribution to the Proton Mass

Example Plot – S. Joosten



2D measurement of $\psi(2s)$ cross section feasible for both photoproduction and electroproduction with the nominal SoLID-J/ψ setup.

JLab at higher energies would enable a comparative study of J/Ψ and Ψ' production at threshold as complementary probe and constrain model assumptions.

Mass of the Proton, Pion, Kaon – the Chiral Limit

- The chiral limit gives us understanding and can act as consistency check
- But the pion mass is not zero, it is 140 MeV

[Jianwei Qiu:]

- Good mass decomposition should work for the proton, pion, (the kaon), …

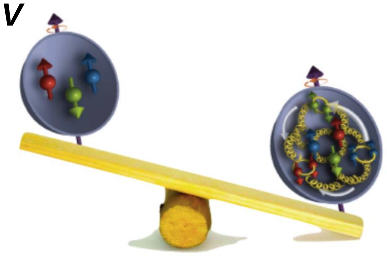
$$\langle P(p)|T^{\mu}_{\mu}|P(p)\rangle = M_p^2 \sim (938\,\mathrm{MeV})^2$$
$$\langle \pi(p)|T^{\mu}_{\mu}|\pi(p)\rangle = M_\pi^2 \sim (139\,\mathrm{MeV})^2$$
$$\langle K(p)|T^{\mu}_{\mu}|K(p)\rangle = M_K^2 \sim (497\,\mathrm{MeV})^2$$

- A decomposition is valuable iff individual terms can be measured or calculated independently with controllable approximations

The Incomplete Hadron: Mass Puzzle

- Pion mass:

MeV



0.1 GeV

$$M = \underbrace{E_q + E_g}_{\text{Relativistic motion}} + \underbrace{\chi m_q + T_g}_{\text{Quantum fluctuation}}$$

Relativistic motion

Quantum fluctuation

Quark Energy

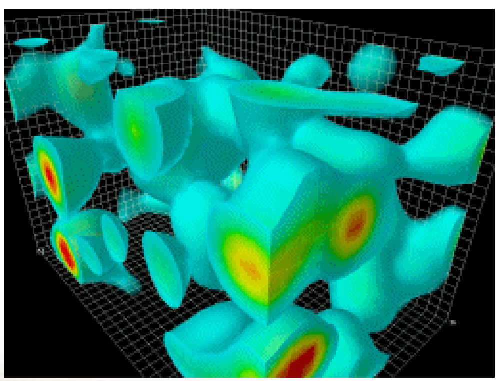
Gluon Energy

Quark Mass

Trace Anomaly

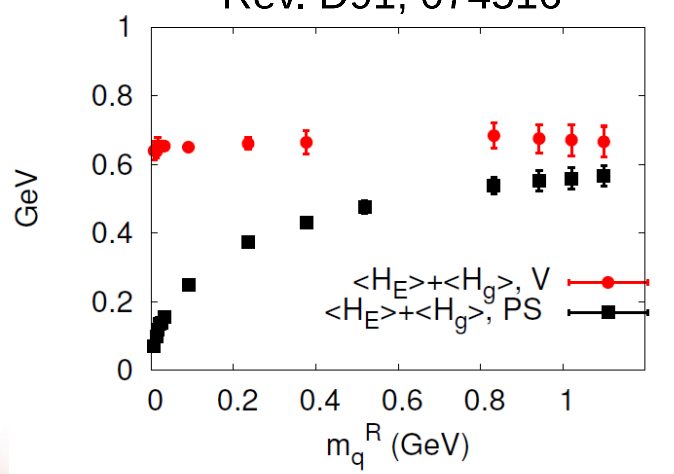
Ji 2021 (pion): c_{mq} ~ 1/2 M, E_q = 3/8 M <xq> (m), E_g = 3/8 M <xg> (m), T_g = 1/8 M

Ji 1995



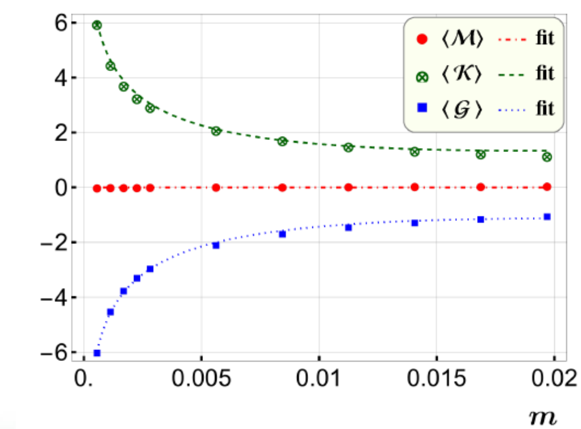
In chiral limit, all terms vanish, and pion's gluon structure becomes like vacuum

Yang et al, Phys. Rev. D91, 074516



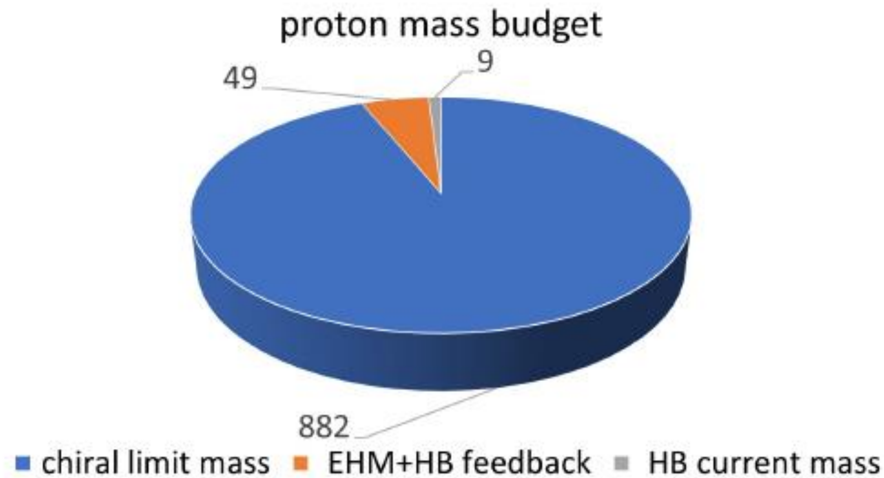
The combined quark/glue energy contribution to the PS/V meson mass

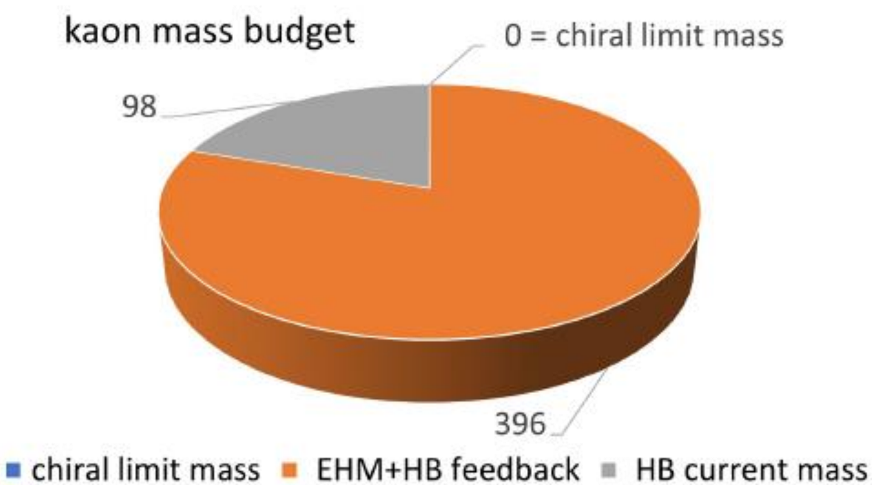
Yu Jia et al., Phys. Rev. D98, 074024

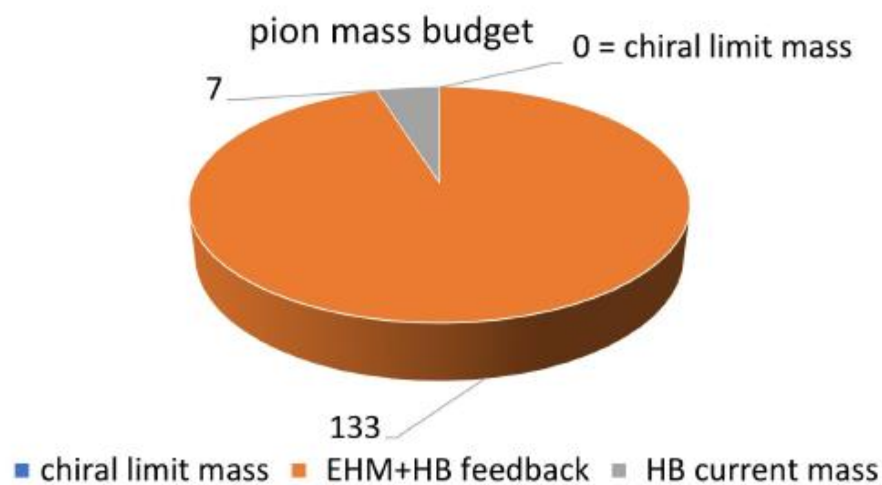


In 2D QCD the quark and gluon contributions diverge and bear opposite sign, upon summing the GOR relation holds

Mass of the Proton, Pion, Kaon – Mass Budget







Rapid acquisition of mass is effect of gluon interactions

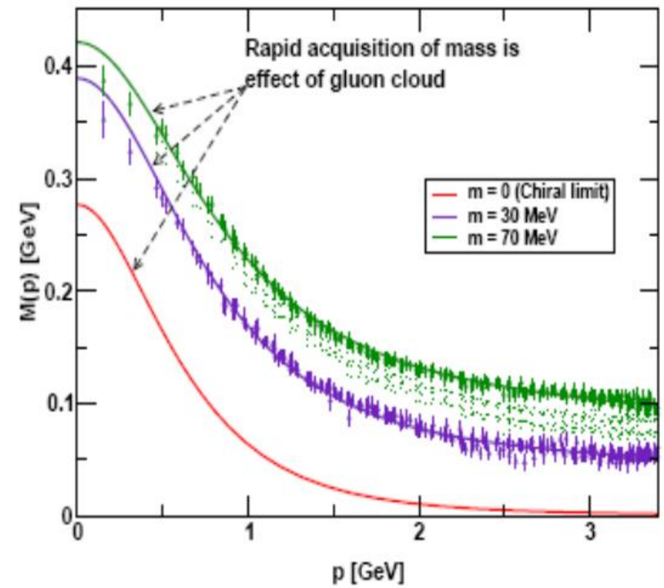
$$S_F(p) = \frac{\mathcal{F}(p)}{\not p - \mathcal{M}(p)}$$

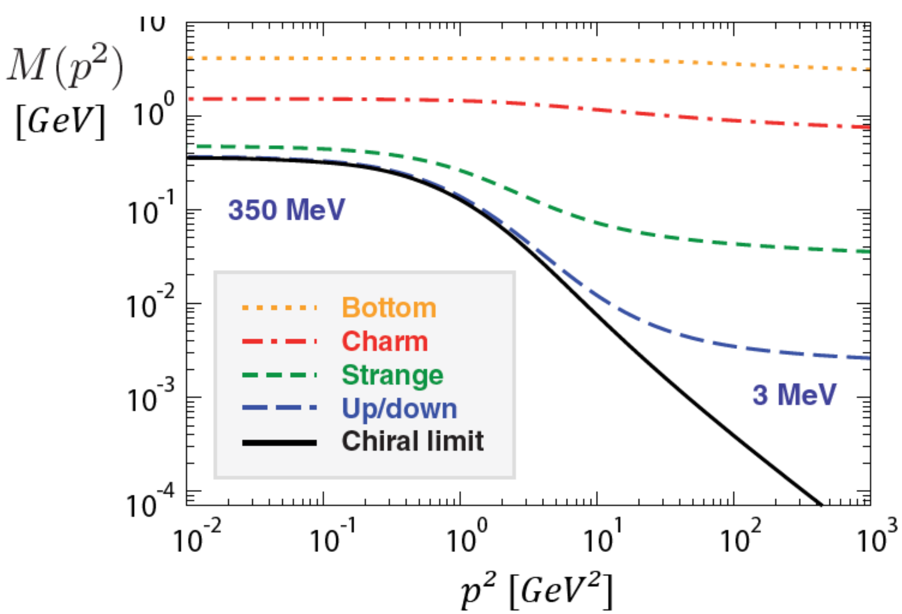
wavefunction renormalisation

mass function

$$S_F(p)^{-1} = \not p - m_0 - \frac{\alpha}{4\pi} \int d^4k \, \gamma_\mu \, S_F(k) \, \Gamma_\nu(k,p) \, \Delta^{\mu\nu}(q)$$

DSE and Lattice Results



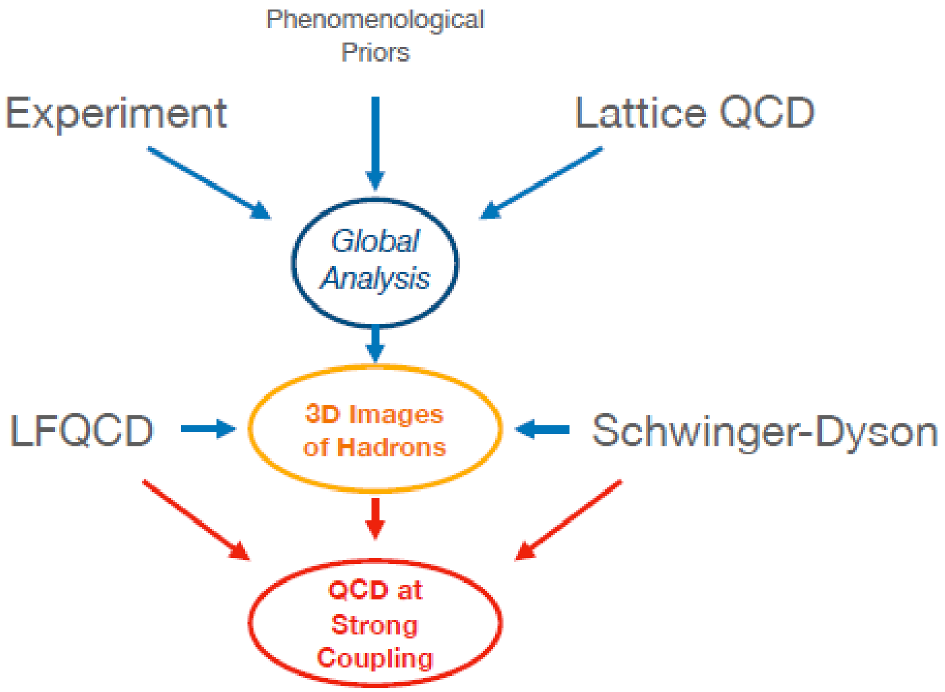


Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions. Higgs mechanism hardly plays a role.

The strange quark is at the boundary - both emergent-mass and Higgs-mass generation mechanisms are important.

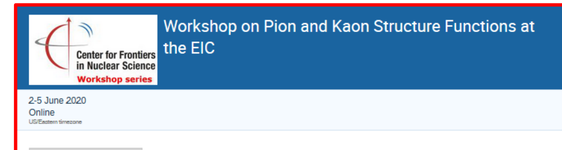
Emergent Mass and Structure – a Beautiful Synergy of Experiment, QCD Phenomenology and Lattice QCD

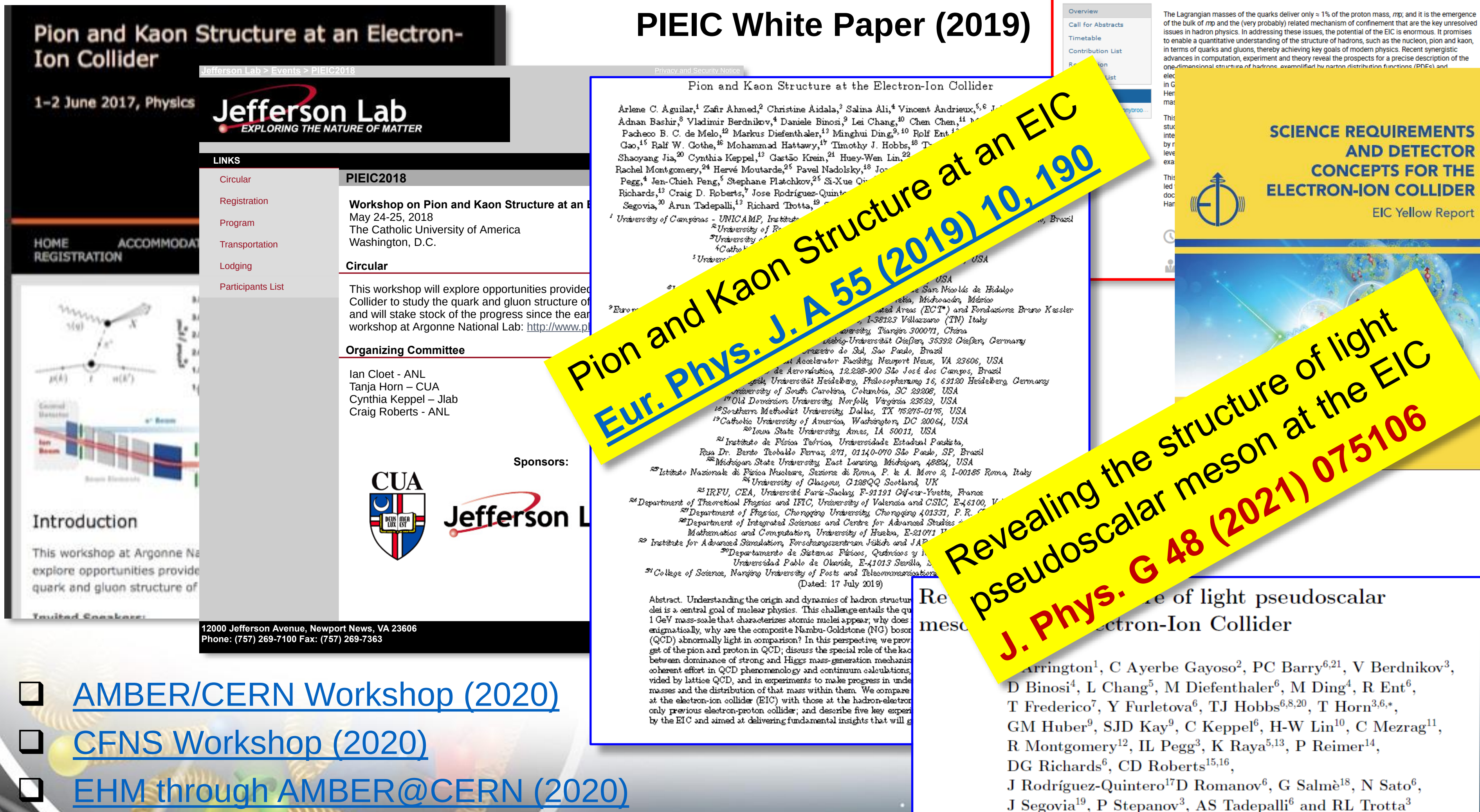
Context: much work has been done by large group of theorists and experimentalists in the context of EIC-related workshops ("Pion and Kaon Structure at the EIC"), an EIC white paper, and a sub-group on meson structure as part of the EICUG Yellow Report initiative. This group continues to meet, with emphasis on the synergy.



Pion and Kaon Structure at the EIC – History

- PIEIC Workshops hosted at ANL (2017) and CUA (2018)
- ECT* Workshop: Emergent Mass and its Consequences (2018)



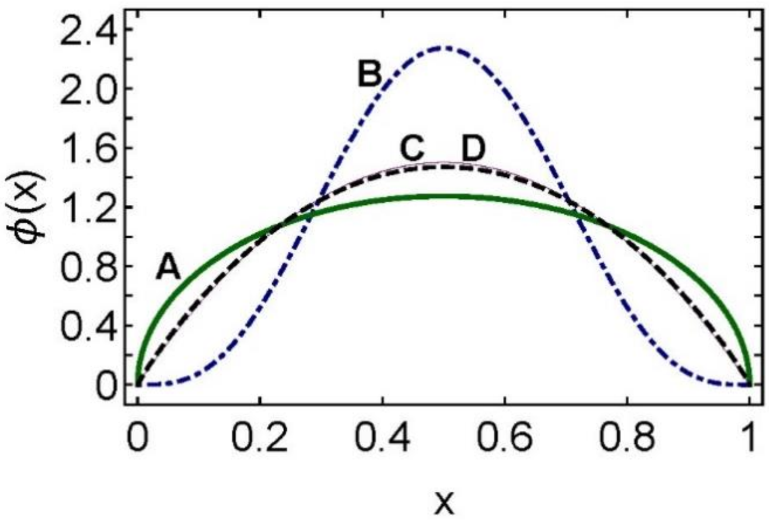


- AMBER/CERN Workshop (2020)
- CFNS Workshop (2020)
- EHM through AMBER@CERN (2020)
- **ECT* Workshop in 2021 (remote) & 2022**

Example of Strong Synergy with QCD Continuum

Emergent- versus Higgs-Mass Generation

Twist-2 PDA at Scale z = 2 GeV



Unfortunately, experimental signatures of the exact PDA form are, in general, difficult.

A solid (green) curve – pion ⇐ emergent mass is dominant;

B dot-dashed (blue) curve – η_c ⇐ primarily, Higgs mass generation;

C solid (thin, purple) curve – conformal limit result, 6x(1 - x); and

D dashed (black) curve – "heavy-pion", i.e., a pion-like pseudo-scalar meson (~η_s) in which the valence-quark current masses take values corresponding to a strange quark ⇐ the border, where emergent and Higgs mass generation are equally important.

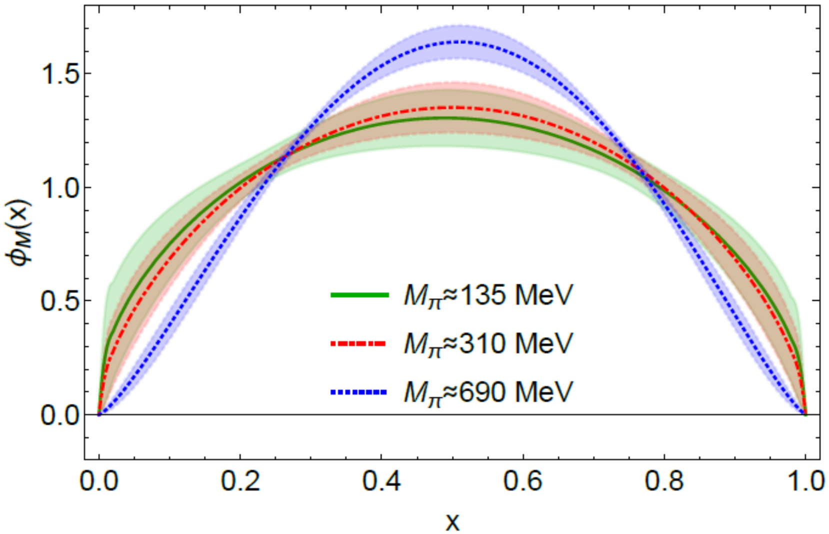
- In the limit of infinitely-heavy quark masses, the Higgs mechanism overwhelms every other mass generating force, and the PDA becomes a δ-function at x = ½.
- The sufficiently heavy η_c meson (**B**), feels the Higgs mechanism strongly.
- The PDA for the light-quark pion (**A**) is a broad, concave function, a feature of emergent mass generation.

Example of Strong Synergy with Lattice QCD

Huey-Wen Lin et al.

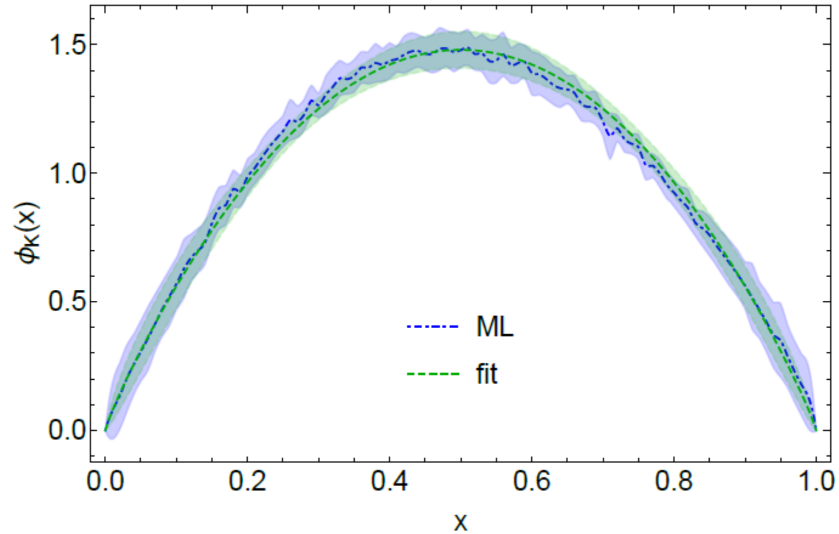
Parton distribution amplitudes

Pion at two different pion masses & extrapolated to the physical mass



As the pion mass decreases, the distribution amplitude gets broader

Fit to lattice data for kaon, and using machine learning approach



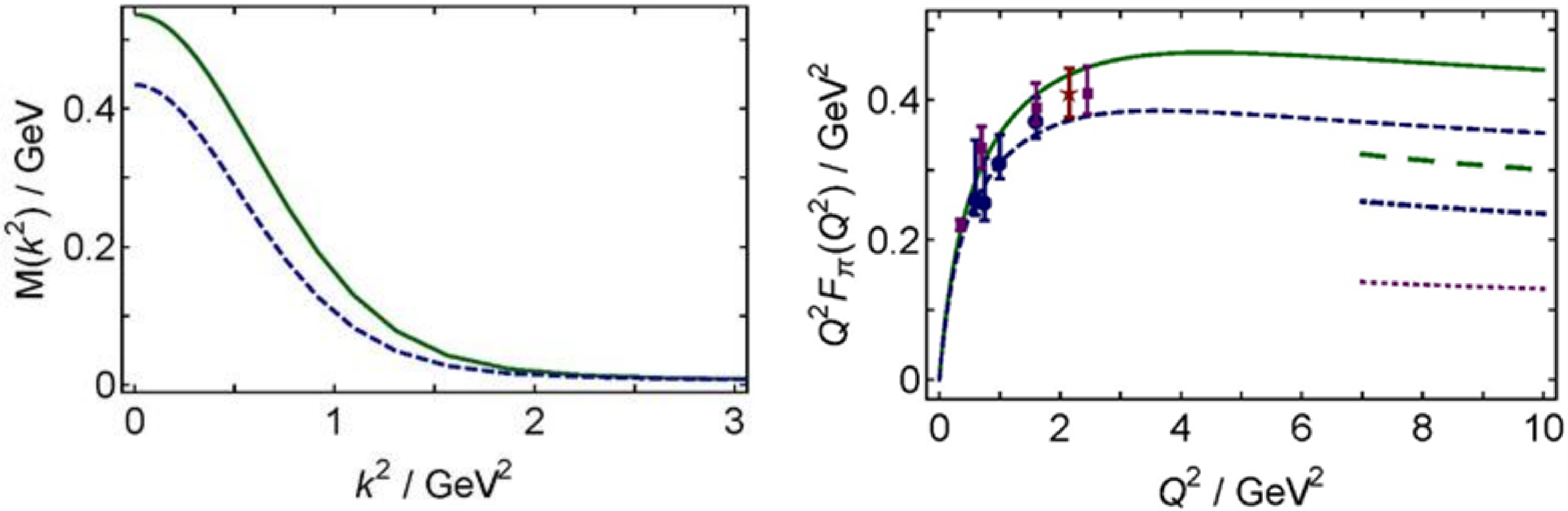
Note the slight asymmetry in the distribution amplitude around x = 0.5

Calculations using meson-boosted momentum at P_z = 1,.73 GeV and renormalized at 2 GeV in MS-bar scheme

Example of Strong Synergy with QCD Continuum

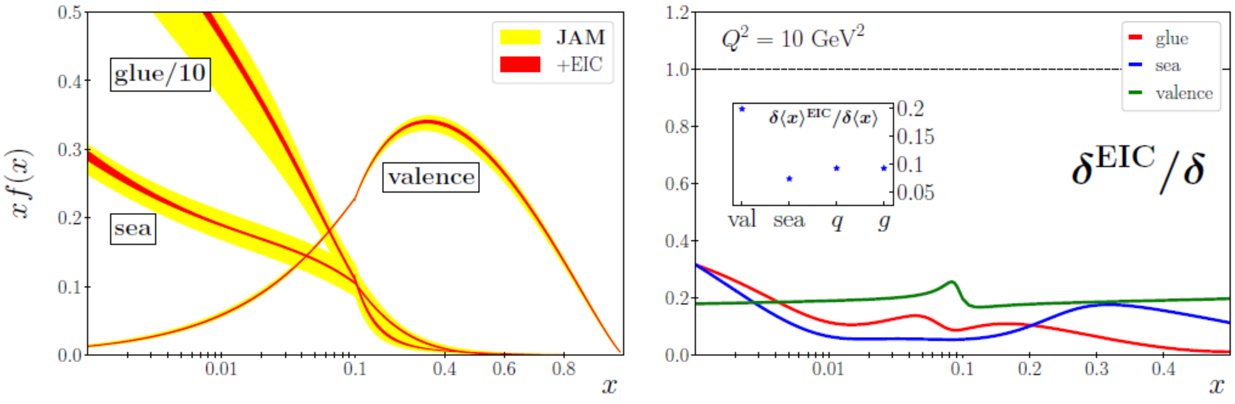
Pion Form Factor and Emergent Mass

Muyang Chen, Craig Roberts



Left panel. Two dressed-quark mass functions distinguished by the amount of DCSB: emergent mass generation is 20% stronger in the system characterized by the solid green curve, which describes the more realistic case. Right panel. $F_\pi(Q^2)$ obtained with the mass function in the left panel: r_π = 0.66 fm with the solid green curve and r_π = 0.73 fm with the dashed blue curve. The long-dashed green and dot-dashed blue curves are predictions from the QCD hard-scattering formula, obtained with the related, computed pion PDAs. The dotted purple curve is the result obtained from that formula if the conformal-limit PDA is used, $\phi(x)=6x(1-x)$.

Strong Synergy of Experiment and Phenomenology – Reduction of Pion 1-D Structure Information by EIC



Work by Tanja Horn, Richard Trotta, Garth Huber, Stephen Kay

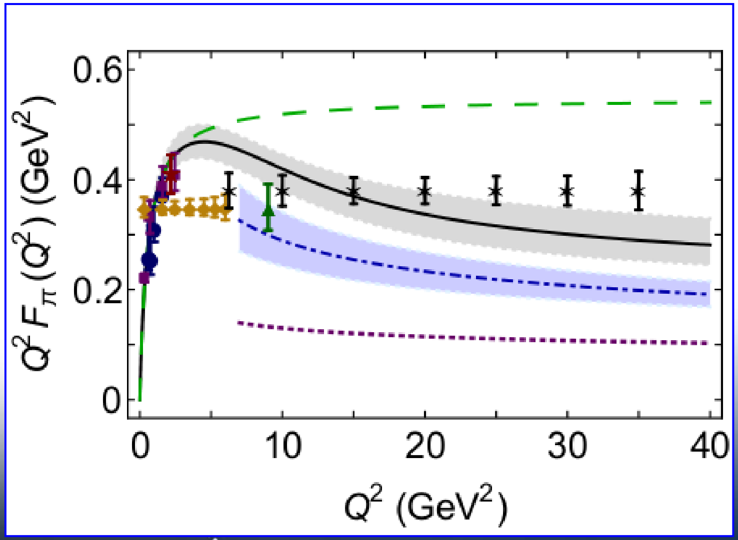
From EIC Yellow Report, P. Barry, W. Melnitchouk, N. Sato et al.

Figure 7.24: Left: Comparison of uncertainties on the pion valence, sea quark and gluon PDFs before (yellow bands) and after (red bands) inclusion of EIC data. Right: Ratio of uncertainties of the PDFs with EIC data to PDFs without EIC data, δ^{EIC}/δ, for the valence (green line), sea quark (blue) and gluon (red) PDFs, assuming 1.2% systematic uncertainty,

Pion form factor measurement projections at EIC

- ❑ Assumed 5 GeV(e^-) x 100 GeV(p) with an integrated luminosity of 20 fb^{-1}/year, and similar luminosities for d beam data

*From A.C. Aguilar et al., EPJ A **55** (**2019**) 10, 190*

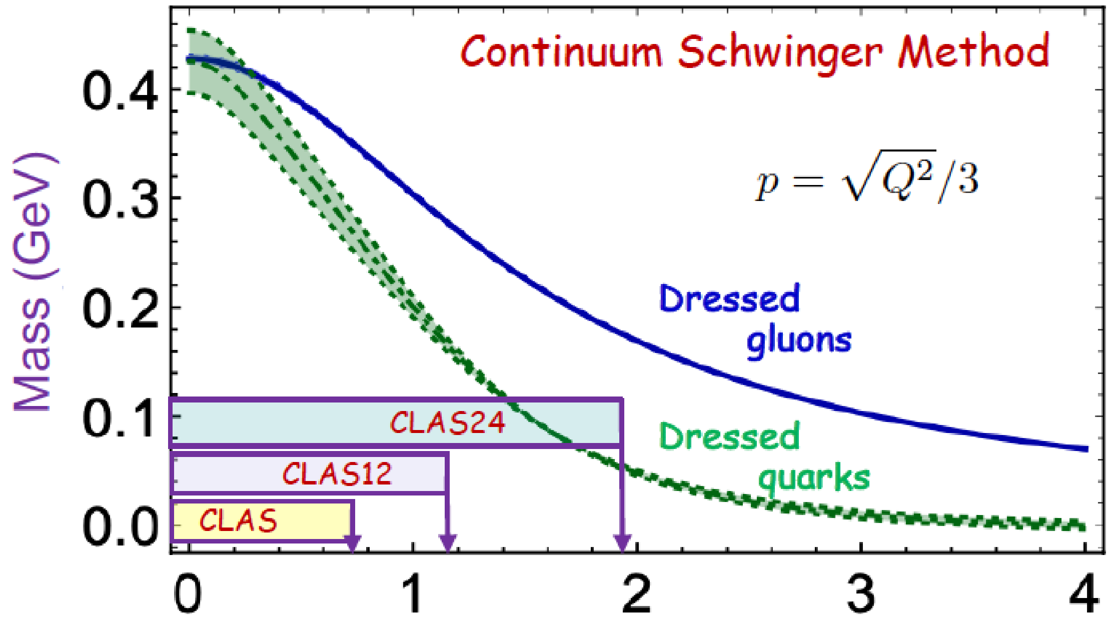


JLab20+: Example of Strong Synergy with Experiment

Emergence of Hadron Mass: Concept from Continuum Schwinger Method (CSM) vs. the Results from CLAS6-CLAS12-CLAS20+ on N Electroexcitation*

A successful description of the pion and nucleon elastic FFs, and the electrocouplings of the D(1232)3/2$^+$ and N(1440)1/2$^+$ resonances of different structure has been achieved ***with the same dressed quark/gluon mass functions***

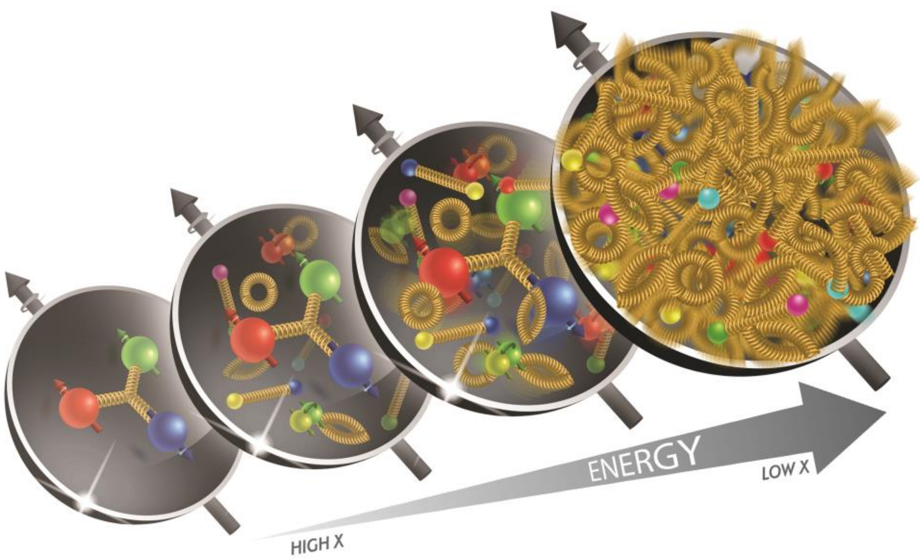
Example Plot for JLab energy extension – V. Mokeev

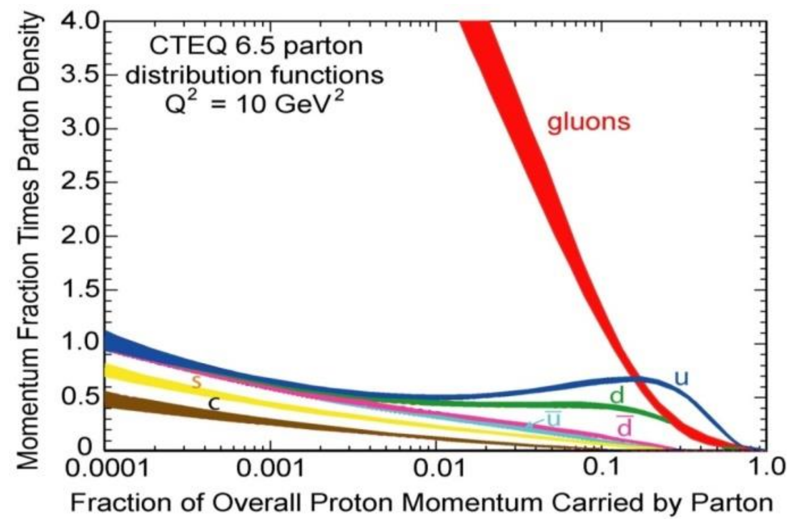


Running Dressed Quark/Gluon Masses from CSM
C.D. Roberts, Symmetry 12, 1468 (2020)

QCD Landscape Explored by EIC

Strong QCD dynamics creates many-body correlations between quarks and gluons
→ structure of nuclear matter emerges



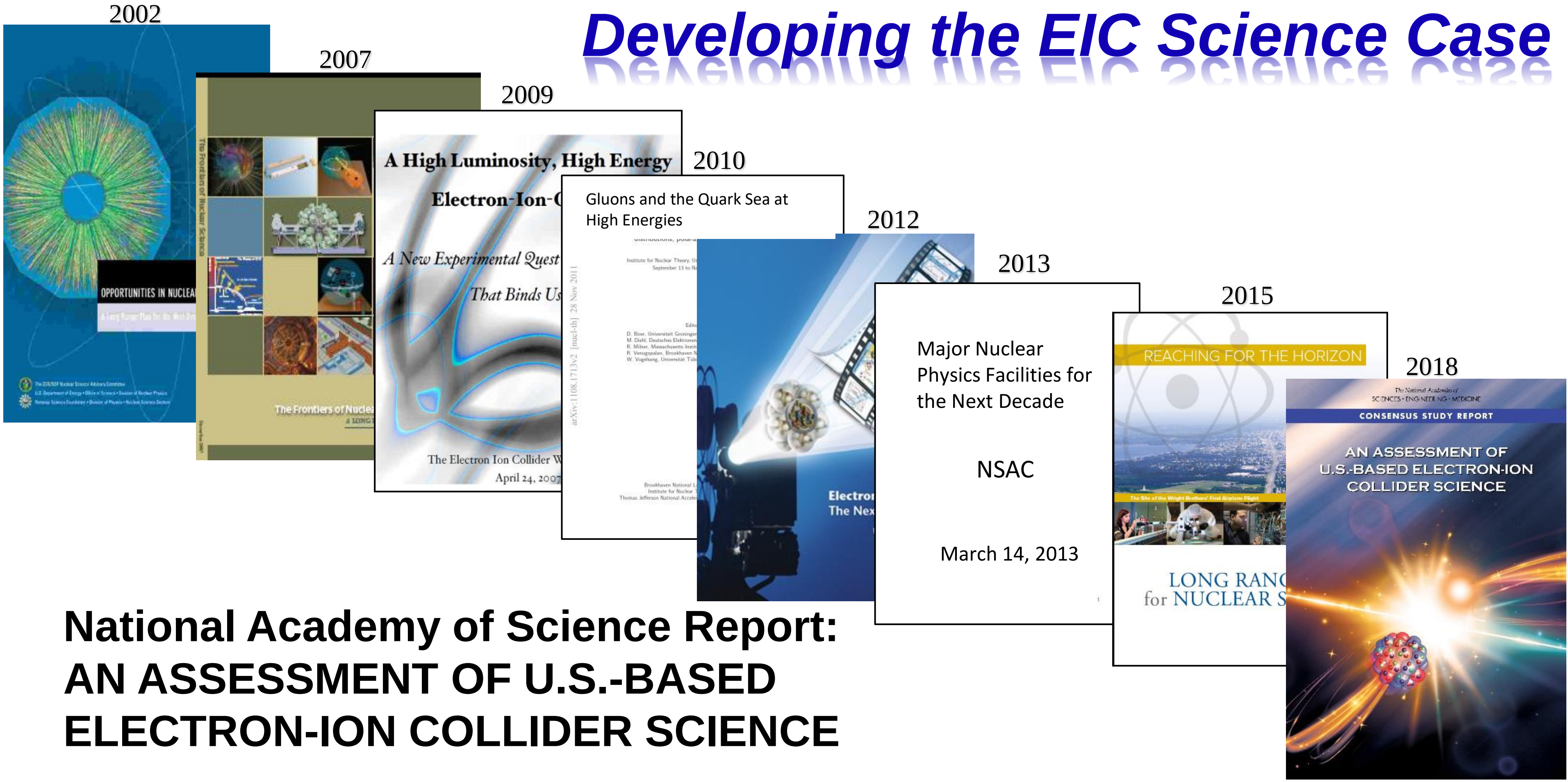


Longitudinal (1D) Momentum Fraction x

Explore QCD landscape over large range of resolution (Q^2) and quark/gluon density (1/x)

- EIC needed as microscope to explore the region from where a proton is (mostly) an up-up-down quark system to the gluon dominated region.
- Heavy nuclei critical to explore high-density gluon matter.

Developing the EIC Science Case

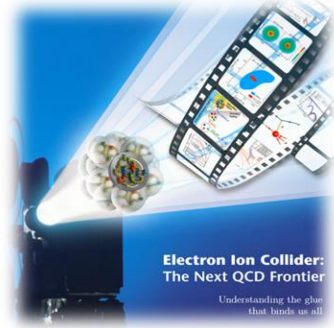


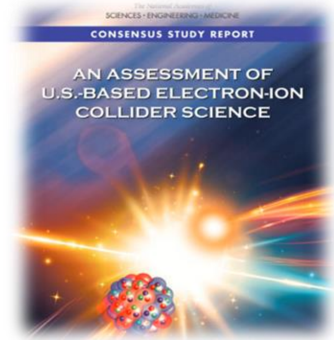
National Academy of Science Report:
AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE

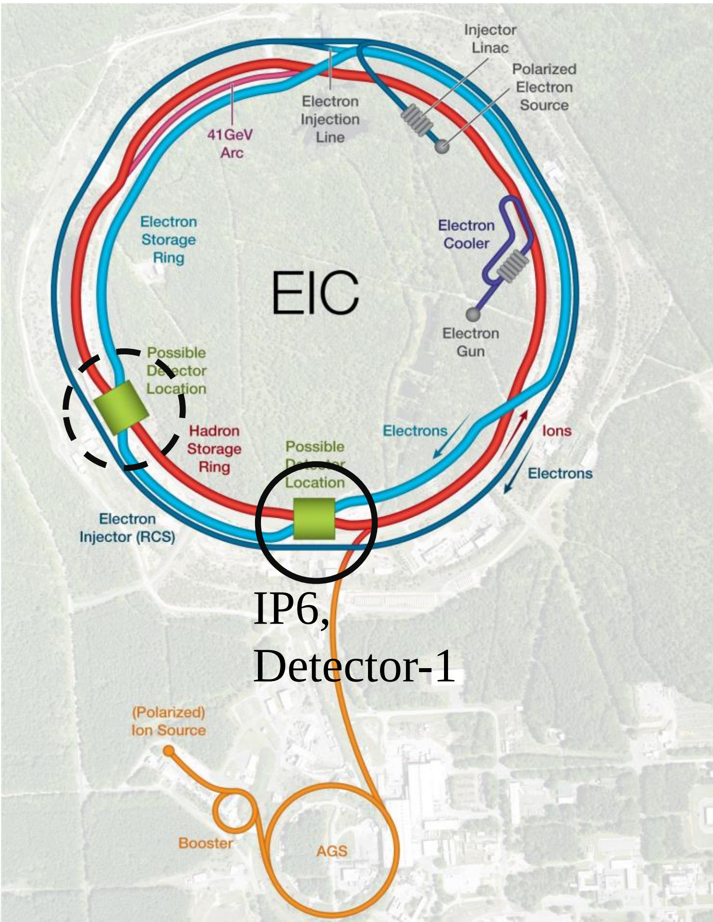
"An EIC can uniquely address three profound questions About nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- **How does the mass of the nucleon arise?**
- **How does the spin of the nucleon arise?**
- **What are the emergent properties of dense systems of gluons?"**

EIC Scope







Project Design Goals

- High Luminosity: L= $10^{33} – 10^{34} cm^{-2} sec^{-1}$, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

p/A beam → ← e beam

p: 41 GeV, 100 to 275 GeV

e: 5 GeV to 18 GeV

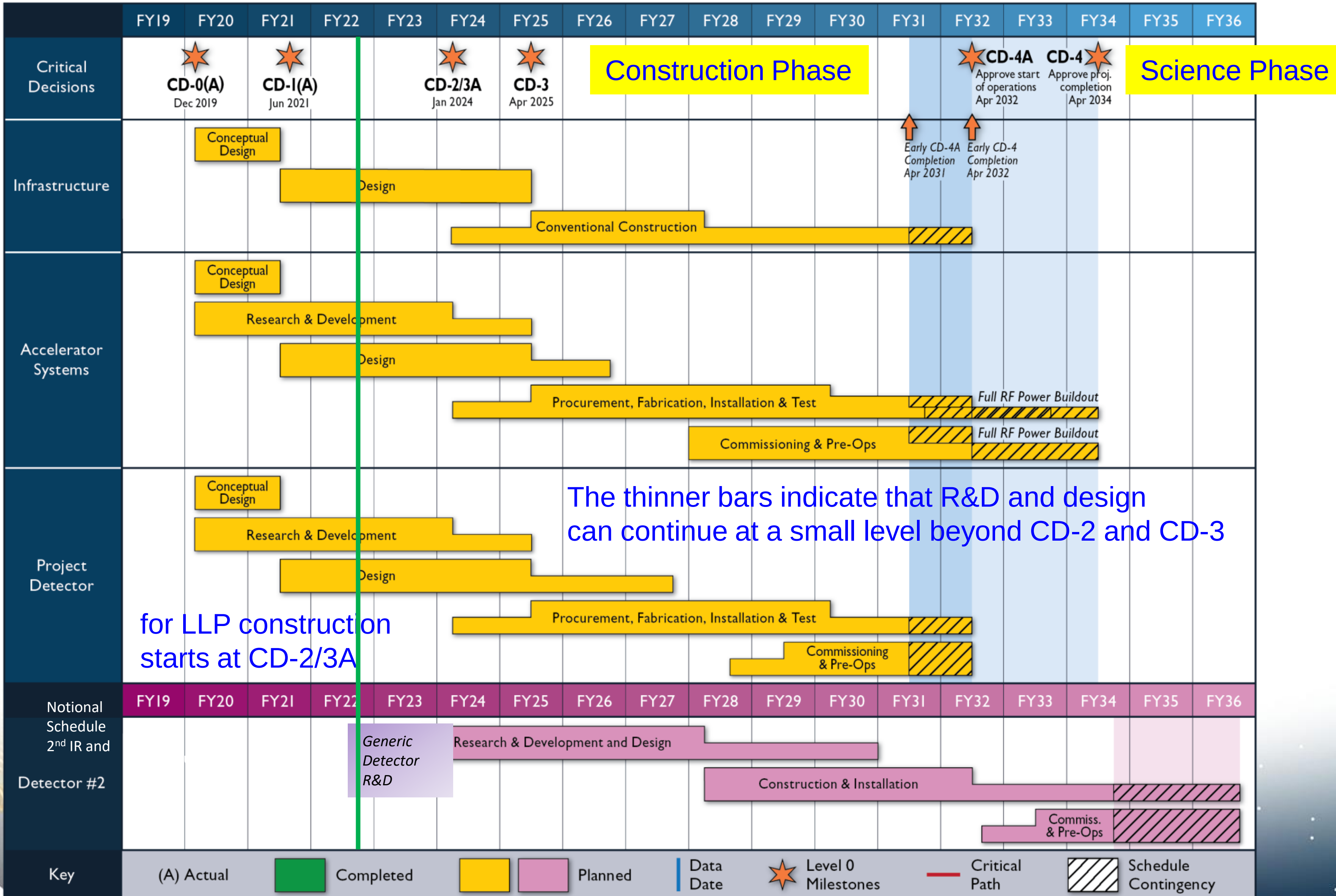
Experimental Program Preparation

- Year-long EIC User Group driven EIC Yellow Report activity
  - Science Requirements and Detector Concepts for the EIC
  - arXiv:2103.05419 – 358 citations (09/07/22)
  - Appeared as once volume in Nucl.Phys.A 1026 (2022) 122447
- Drives the requirements of EIC detectors

BNL and TJNAF Jointly Leading Efforts Towards Experimental Program		
2020	Call for Expressions of Interest (EOI) https://www.bnl.gov/eic/EOI.php	May 2020
	EOI Responses Submitted	November 2020
	Assessment of EOI Responses	On-going
2021	Call for Collaboration Proposals for Detectors https://www.bnl.gov/eic/CFC.php	March 2021
	BNL/TJNAF Proposal Evaluation Committee	Spring 2021
	Collaboration Proposals for Detectors Submitted	December 2021
✔	Decision on Project Detector – “ECCE”	March 2022
	Guide process to joint “Detector-1” Collaboration	Spring 2022
	EPIC Collaboration* Formed – 160 institutions	July 2022

*Merger of two large ATHENA and ECCE proposals

High Level EIC Reference Schedule



Latest EIC Budget News

From DOE/NP:
"… with the passage of the Inflation Reduction Act (IRA), the Office of Nuclear Physics anticipates providing an additional $10 million OPC and $100 million TEC of FY 2022 funds for the Electron-Ion Collider project."

(This is separate from FY23 funding - still in congressional appropriations phase.

- *The reference plan for FY2023 is $90M.*
- *House Mark for FY2023 is $35M TEC, plus additional OPC would be close to $70M total.*
- *Senate Mark for FY2023 is $50M TEC, plus additional OPC could be close to $90M total.*
- *Pending CHIPS+/USICA/COMPETES authorizes $90M for EIC in FY2023 and $181M in FY2024.)*

From Jim Yeck:
"There is an important phase change in the EIC project underway as a consequence of the Inflation Reduction Act (IRA) and the DOE plan to provide significant IRA funding to the EIC project."
…
"Our short-term objective is to secure CD-2/3a at the earliest possible date and we are fortunate that DOE will provide the funds we require through both IRA funding and the traditional annual appropriations process. We will work with DOE and our partners to secure CD-2/3a approval in early calendar 2024."

High-Level Message: The DOE funding to ensure CD-2/3A timeline (baselining, start of long-lead procurement items) seems secured. Start of construction (CD-3) in 2025 seems also likely.

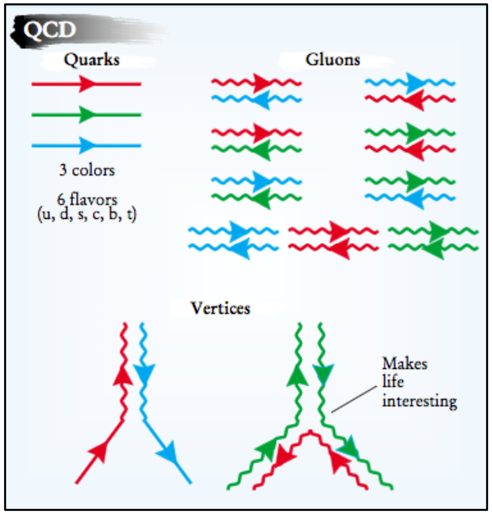
→ A Game Changer!

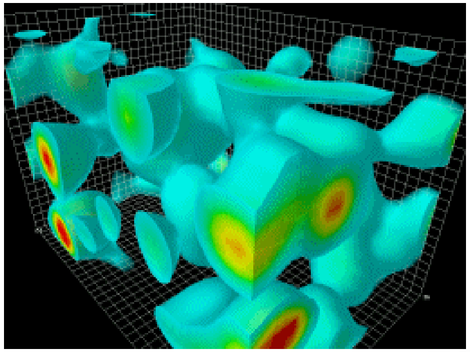
Uniqueness of EIC

- **EIC will be unique facility worldwide**: there is no equivalent of the EIC science capabilities *due to its versatility in energies, polarization, and ion species*.
- Global competition can exist in subsets of the EIC science, e.g.:
  - Ideas for an Electron-Ion Collider in China (EicC) which would operate at center-of-mass energies similar as COMPASS@CERN.
  - Annual ongoing workshops related to adding a high-energy electron beam to interact with LHC beams at CERN (LHeC).
- In addition, several programs have natural complementarity:
  - Consideration to add a fixed-target spin program at the LHC – LHCspin (@LHCb).
  - The AMBER experiment at CERN mainly emphasizing the valence and sea quark regions with pion and kaon beams.
  - Ultraperipheral and heavy-ion reactions at CERN/LHC to constrain low-x behavior.
  - (within the US) The polarized RHIC pp and pA program, addressing universality questions in QCD.
  - (within the US) The Jefferson Lab fixed-target program at high luminosity (12 GeV and energy extension), adding crucial data in the strongly-interacting valence quark region.

JLab (12/20+) and EIC: 21st Century Laboratories of Emergence of Mass and Structure in QCD

- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons
- Gluons carry ~50% of the proton's momentum, a significant fraction of the nucleon's spin, and are essential for the dynamics of confinement
- Properties of hadrons – composite systems of quarks and gluons – are emergent phenomena and inextricably tied to the properties of the QCD vacuum. Striking examples besides confinement are spontaneous symmetry breaking and anomalies
- The nucleon-nucleon forces emerge from quark-gluon interactions: how this happens remains a mystery

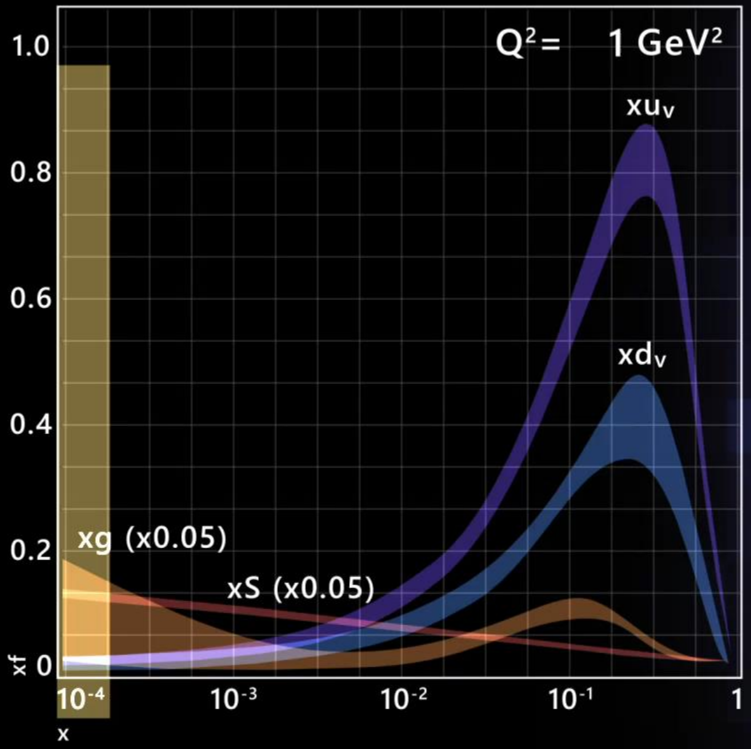




- The goal is to provide us with an understanding of the internal structure of the proton and more complex atomic nuclei that is comparable to our knowledge of the electronic structure of atoms, which lies at the heart of modern technologies

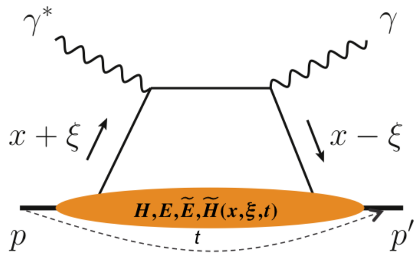
Proton Structure – Artistic Visualization

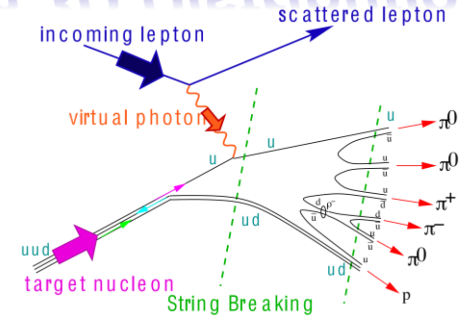
James LaPlante (Sputnik Animation), Richard Milner (MIT), Rolf Ent (JLab)



Note that this strategically stops at x ~ 0.3…

We Need Realty: Extension to Proton 3D Distributions





$f(\xi, b_T)$

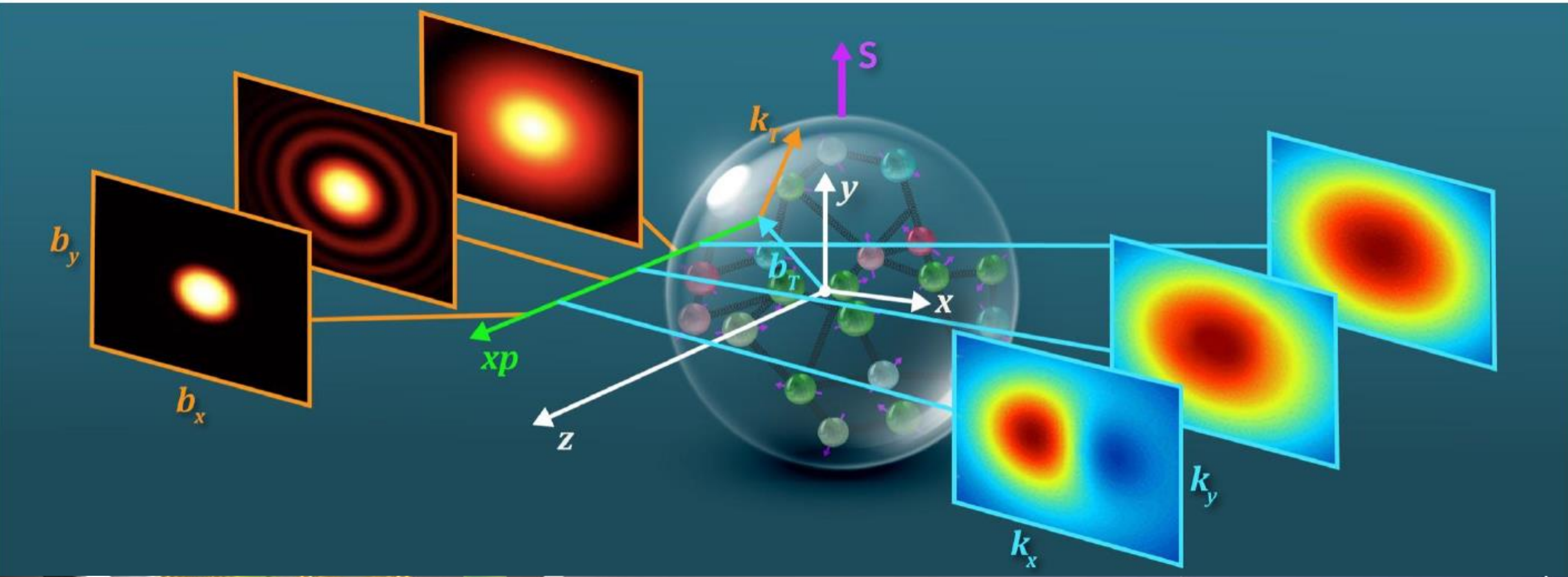
Impact parameter distribution -> **GPDs**

$f(\xi)$

PDFs

$f(\xi, k_T)$

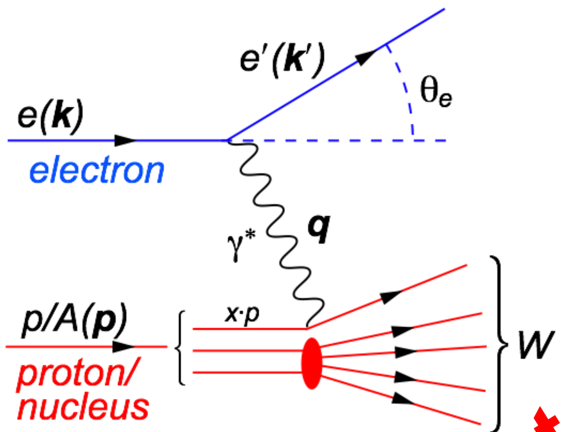
Transverse momentum distribution -> **TMDs**

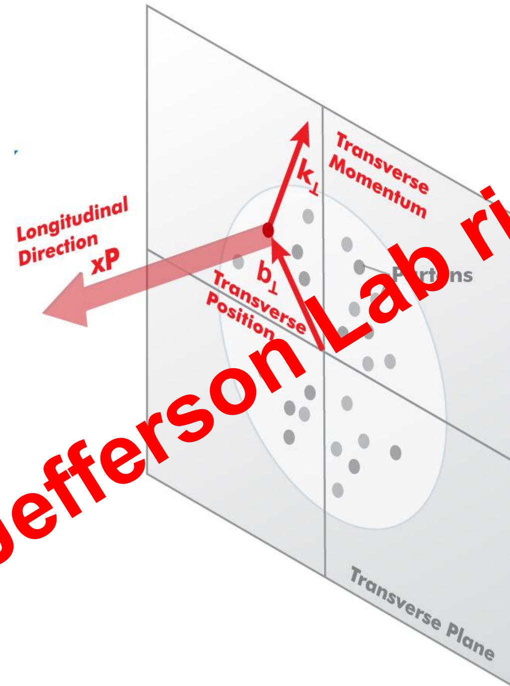


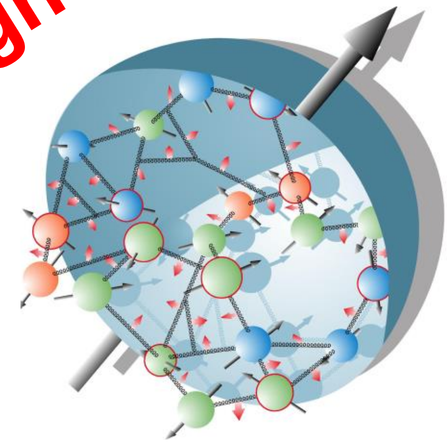
3D Structure of Nucleons and Nuclei

$s = xyQ^2$,
$s = 4E_eE_p$

- ***s:*** center-of-mass energy squared
- ***x*:** the fraction of the nucleon's momentum carried by the struck quark (0 < x < 1)
- ***Q^2*:** resolution power
- ***y:*** inelasticity







Underway at Jefferson Lab right now!

need energy range to unambiguously resolve partons over wide range in x and Q^2 → versatile center-of-mass energy energy √s: 20 – 140 GeV

need to resolve parton quantities (k_t, b_t) of order a few hundred MeV in the proton → high luminosity needed: 10^{33}-10^{34} (and high polarization needed)

k_T, b_T (~100 MeV)

Proton and Ion Beam ~100 GeV

Backup

EIC Timeline – What Is Coming

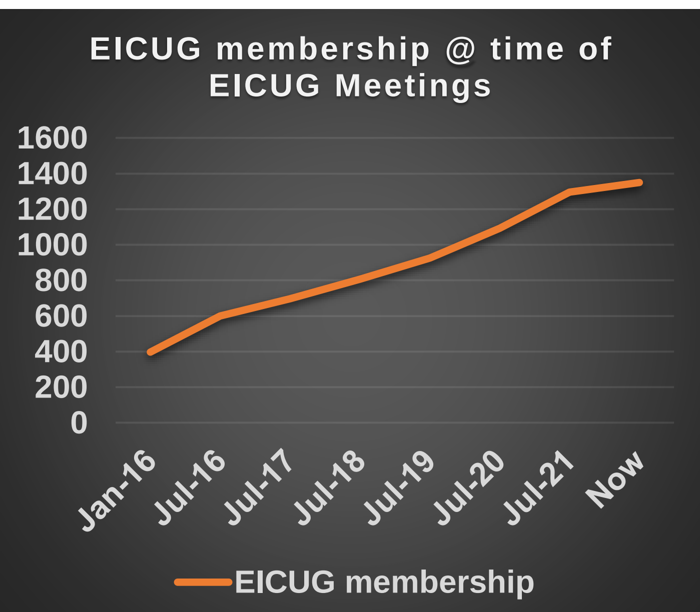
CD-0 approval	December 19, 2019
Community-wide Yellow Report effort	Dec. 2019 – Feb. 2021
CD-1 review (includes CDR)	January 26-29, 2021
Call for Collaboration Proposals for Detectors	March 6, 2021
CD-1 approval	June 29, 2021
DOE/OPA Status Review	October 19-21, 2021
Status Update to Federal Project Director	June 28-30, 2022, @BNL
Cost and Schedule Event(s)	May-June 2022
Technical Subsystem Reviews	January – December 2022
OPA Status Review	Jan. 30 – Feb. 2, 2023
Preliminary Design Complete & Review	May 2023
Final Design/Maturity Readiness for CD-3A Items	May 2023
CD-2/3A review (expectation), requires pre-TDR	~October 2023
CD-2/3A (expectation)	~January 2024
CD-3 review (expectation)	~January 2025
CD-3 (expectation), requires TDR	~April 2025

Worldwide Interest in EIC

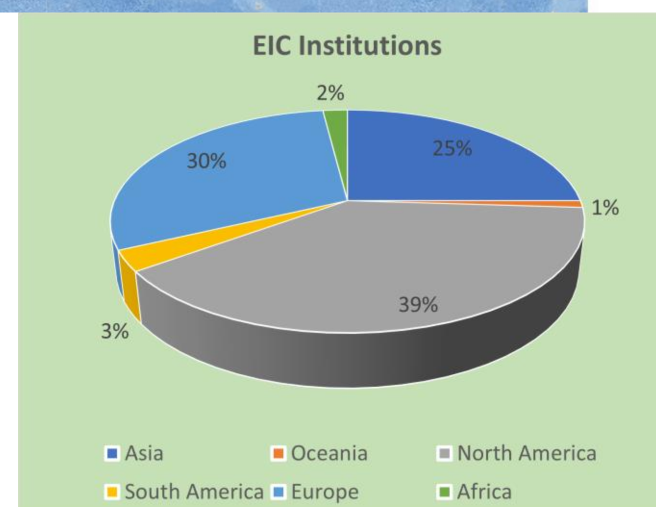
The EIC Users Group:
https://eicug.github.io/

Formed 2016 –
- **1349 collaborators,**
- **36 countries,**
- **266 institutions as of July 20, 2022.**

Strong and Growing International Participation.



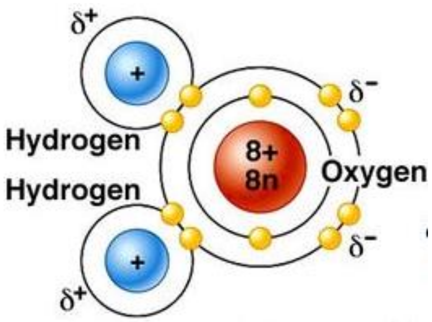
Annual EICUG meeting
2016 UC Berkeley, CA
2016 Argonne, IL
2017 Trieste, Italy
2018 Washington, DC
2019 Paris, France
2020 Miami, FL
2021 VUU, VA & UCR, CA
2022 Stony Brook U, NY
2023 Warsaw, Poland



Nuclear Femtography – Subatomic Matter is Unique

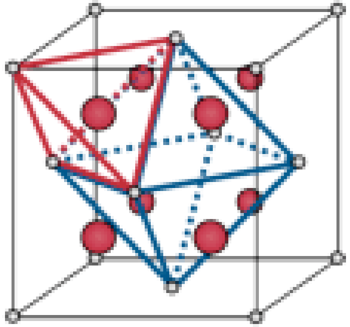
Most known matter has localized mass and charge centers – vast "open" space

Molecule:



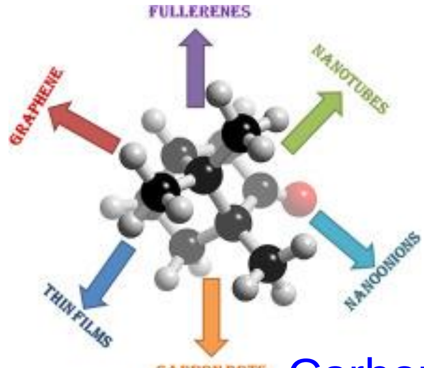
"Water"

Crystal:



Rare-Earth metal

Nanomaterial:



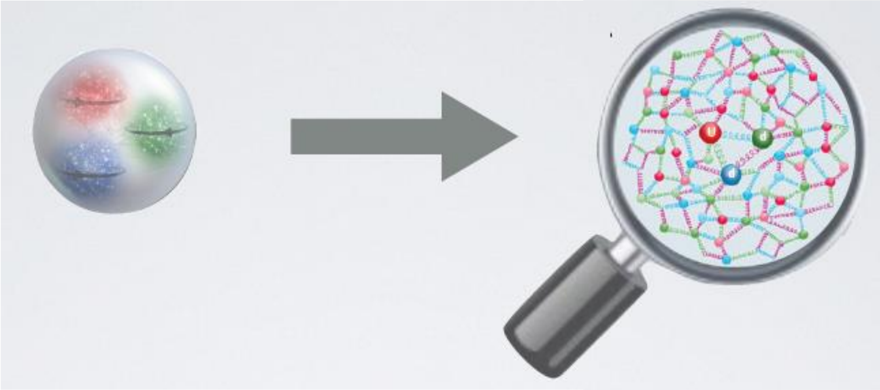
Carbon-based

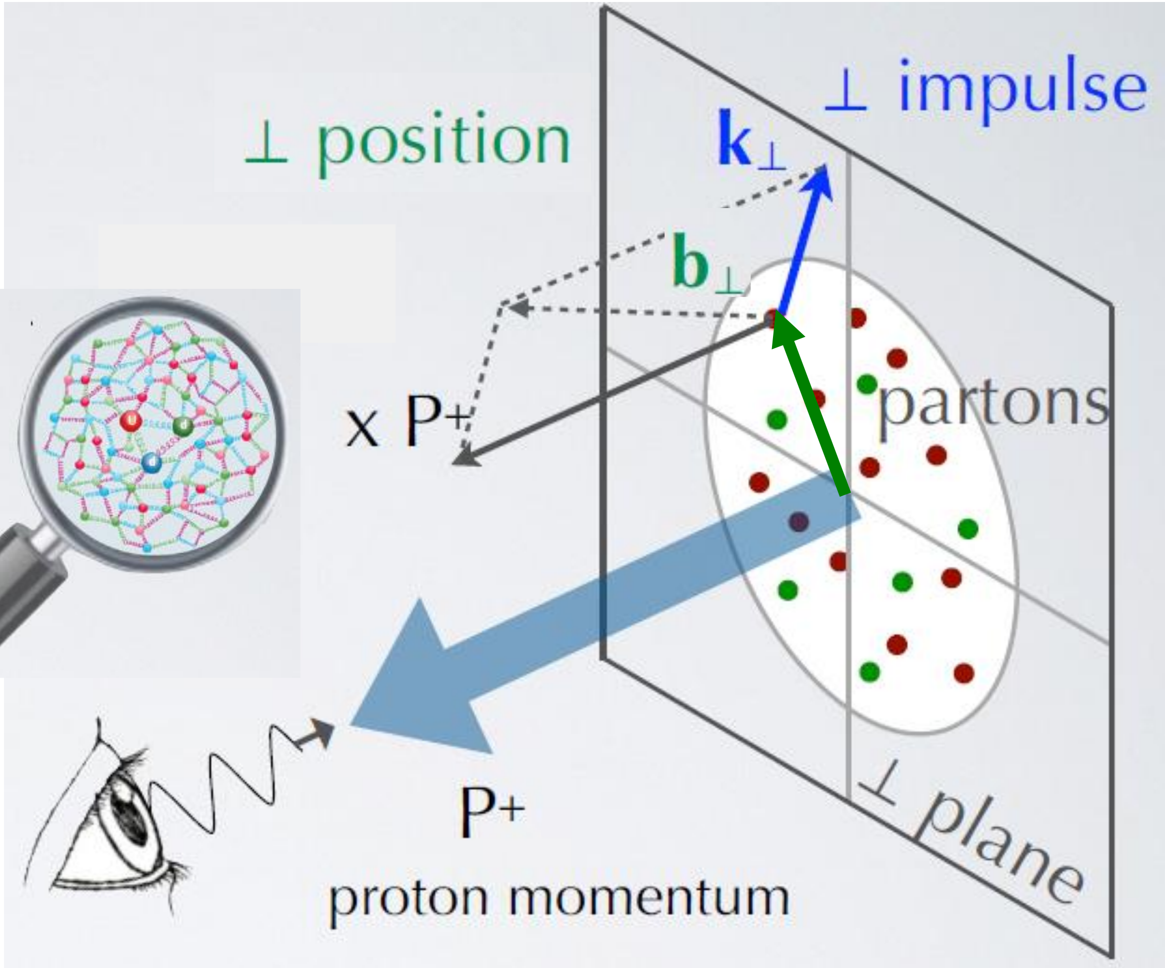
Not so in nuclear matter! – unlike the more familiar molecular and atomic matter, the interactions and structures are inextricably mixed up in protons and other forms of nuclear matter, and the observed properties of nucleons and nuclei, such as mass & spin, emerge out of this complex system.

Imaging Physical Systems is Key to New Understanding

Nuclear Femtography - Imaging

In other sciences, imaging the physical systems under study has been key to gaining new understanding.





Structure mapped in terms of
$\mathbf{b}_T$ = transverse position
$\mathbf{k}_T$ = transverse momentum

Also information on orbital angular momentum: **r** x **p**

Exploring the 3D Nucleon Structure

- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
  - High luminosity, large acceptance experiments with polarized beams and targets.
  - Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions.

- **Deep Exclusive Scattering (DES)** cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) x at a transverse location $\mathbf{b_T}$.

- **Semi-Inclusive Deep Inelastic Scattering (SIDIS)** cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum ($\mathbf{k_T}$) of a parton and transverse momentum (p_T) created during the [parton → hadron] fragmentation process.

PDFs → Nuclear Femtography

3D Structure of Nucleons and Nuclei

$s = xyQ^2$,
$s = 4E_eE_p$

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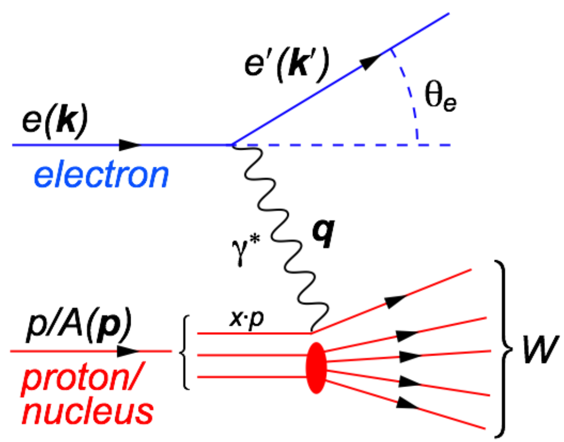

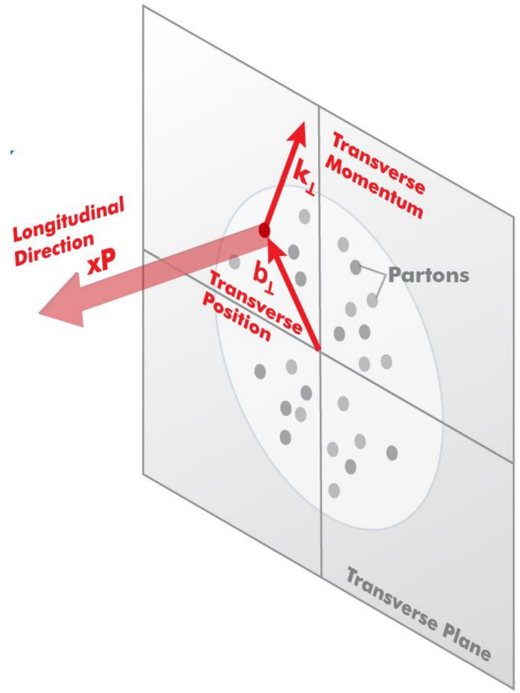

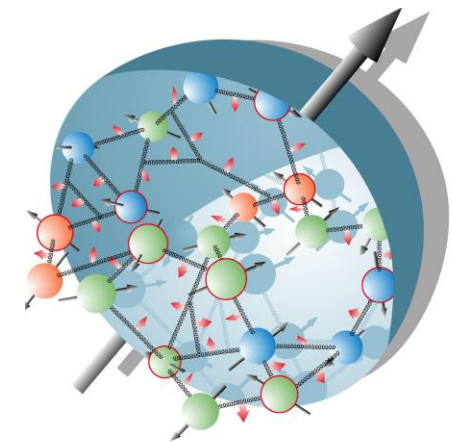

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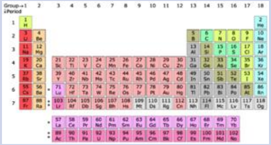
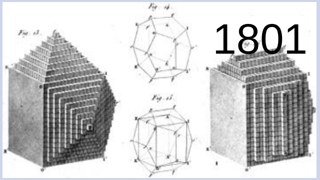
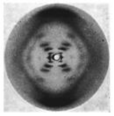
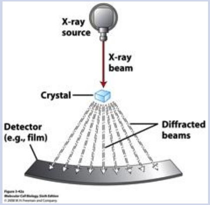
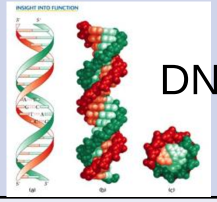
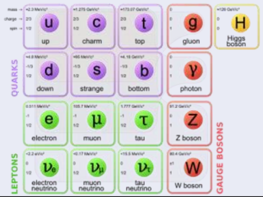
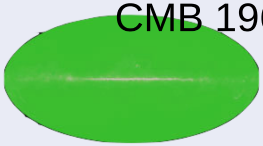
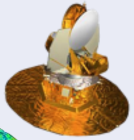
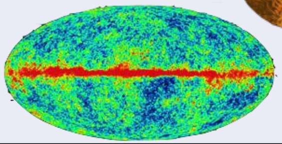
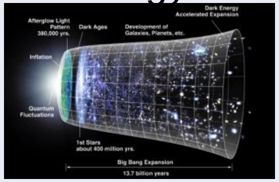
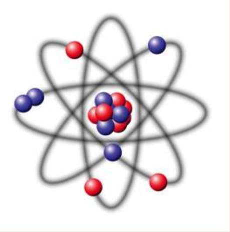
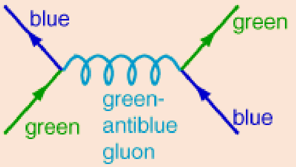
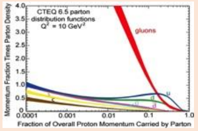
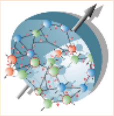
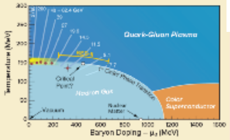
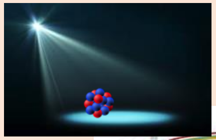
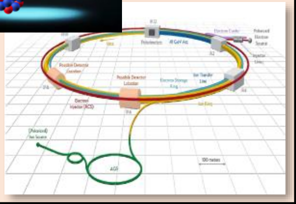
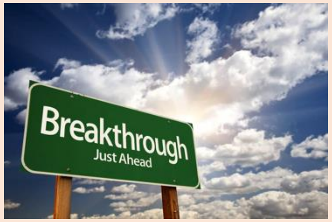
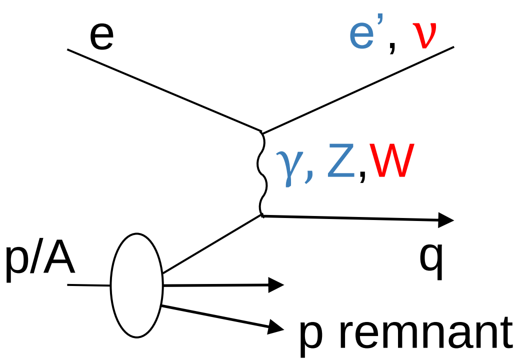
k_T, b_T (~100 MeV)

Proton and Ion Beam ~100 GeV

Imaging Physical Systems is Key to New Understanding

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure  1801	X-ray Diffraction (~1920)  	Solid state physics Molecular biology  DNA
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark energy. Structure CMB 1965 	Large Scale Surveys CMB Probes (~2000)  	Precision Observational Cosmology 
Nuclei and Nucleons 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{QCD} = \overline{\psi}(i\partial\!\!\!/ - gA\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$ 	Non-perturbative QCD. Structure 2017   	Electron-Ion Collider (~2030)  	Structure & Dynamics in QCD 

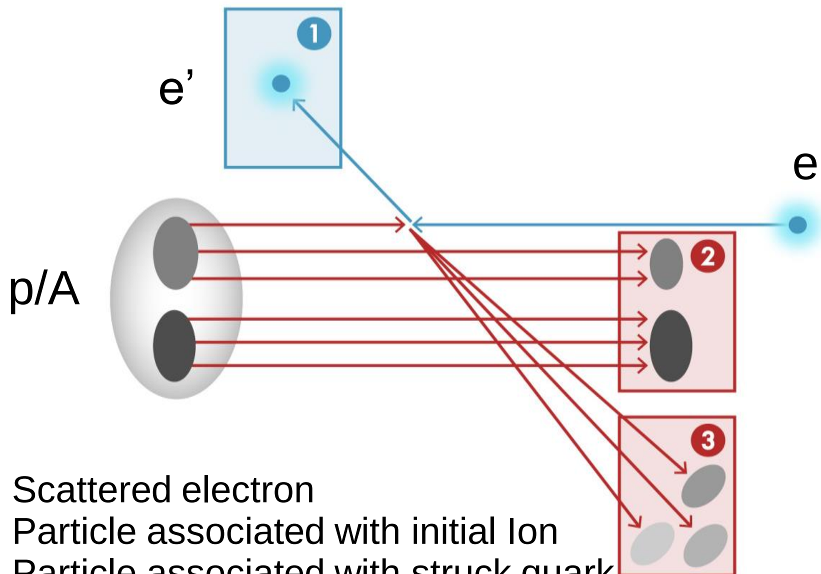
Detector Integration Challenge of the EIC



Aim of EIC is 3D nucleon and nuclear structure beyond the longitudinal description.

This makes the requirements for the machine and detector different from all previous colliders.

"Statistics"=Luminosity × Acceptance



1. Scattered electron
2. Particle associated with initial Ion
3. Particle associated with struck quark (or associated gluon)

EIC Physics demands ~100% acceptance for all final state particles (including particles associated with initial ion)

Ion remnant is particularly challenging

- not a usual concern at colliders
- at EIC integrated from the start with a highly integrated (and complex) detector and interaction region scheme.

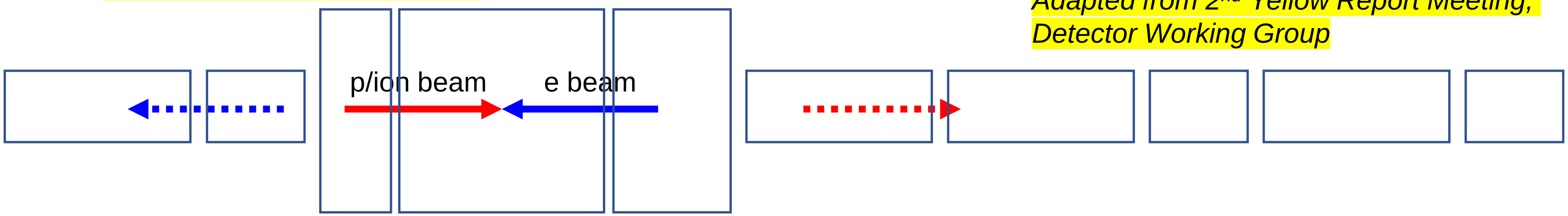
Cartoon/Model of the Extended Detector and IR

- EIC physics covers the entire region (backward, barrel/central, forward)
- The detector requirements differ in these regions due to the EIC asymmetry
- Many EIC science processes rely on excellent scattered electron detection and excellent and fully integrated forward detection scheme

p: 41 GeV, 100 to 275 GeV

e: 5 GeV to 18 GeV

Adapted from 2nd Yellow Report Meeting, Detector Working Group



far-backward e-detection	e final-focus quads	"Central detector", includes e-endcap, barrel, and p/ion endcap detectors	forward dipole incl. h detection	Ion final-focus quads	forward dipole	far-forward h-detection	far-forward h-detection
Low-Q^2 spectroscopy		Inclusive Structure Functions, TMDs, heavy flavors and jets, electrons for GPDs	GPDs/DVCS, tagging, diffraction, high-medium t			Baryon decay π/K structure evaporated n	GPDs, tagging, diffraction, lowest-t
GEMs Diamond detectors?		Vertex and Tracking detectors, particle identification detectors, calorimetry detectors, muon detectors, etc.	Si/GEMs Roman pots, e/γ calorim.			GEMs Roman pots e/γ calorim.	Roman pots ZDCs

physics examples

detector examples

Electron-Ion Collider

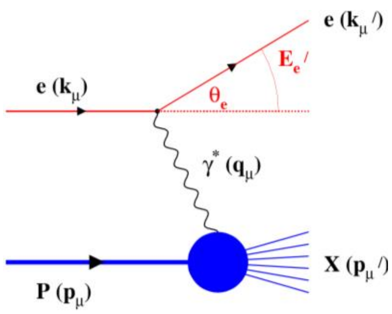
What is Needed Experimentally?

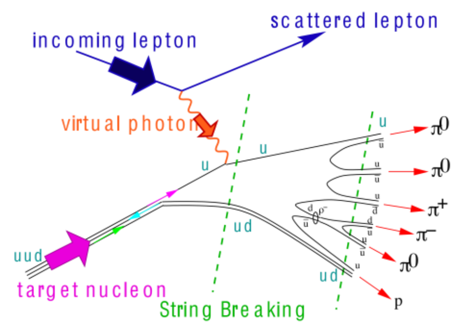
experimental measurements categories to address EIC physics:

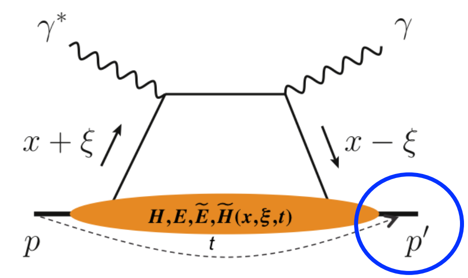
Parton Distributions in nucleons and nuclei

Spin and Flavor structure of nucleons and nuclei | **Tomography Transverse Momentum Dist.**

QCD at Extreme Parton Densities - Saturation | **Tomography Spatial Imaging**







inclusive DIS

- measure scattered electron
- multi-dimensional binning: x, Q^2
  → reach to lowest x, Q^2 impacts Interaction Region design

semi-inclusive DIS

- measure scattered electron and hadrons in coincidence
- multi-dimensional binning: x, Q^2, z, p_T, Θ
  → particle identification over entire region is critical

exclusive processes

- measure all particles in event
- multi-dimensional binning: x, Q^2, t, Θ
- proton p_t: 0.2 - 1.3 GeV
  → cannot be detected in main detector
  → strong impact on Interaction Region design

$\int Ldt$: 1 fb^{-1} — 10 fb^{-1} — 10 - 100 fb^{-1}

machine & detector requirements

EIC General Purpose Detector: Concept