Directions in Hadron Physics (Experiment)

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EINN 2023, Paphos, October 31 – November 4, 2023

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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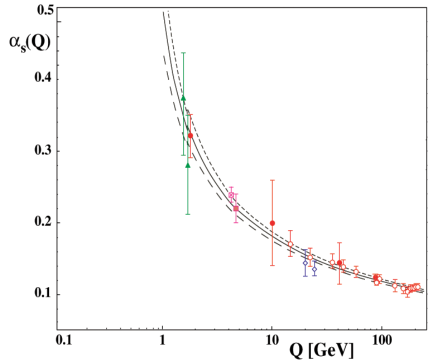
The Fundamental Structure of Visible Matter

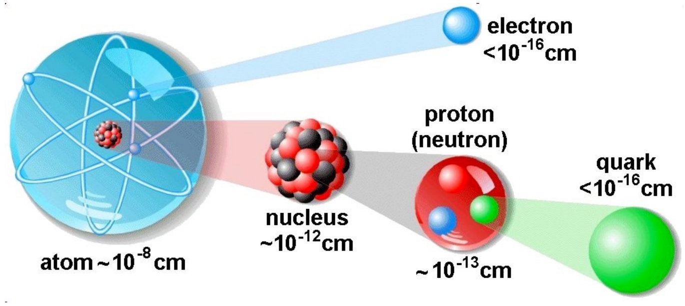
- How does QCD generate the spectrum and structure of conventional and exotic hadrons?
- How do the mass and spin of the nucleon emerge from the quarks and gluons inside and their dynamics?
- How are the pressure and shear forces distributed inside the nucleon?
- How does the quark–gluon structure of the nucleon change when bound in a nucleus?
- How are hadrons formed from quarks and gluons produced in high-energy collisions?

Hadron properties and structure
Nuclei and QCD
Hadronization: forming QCD bound states
Spectrum of excited hadrons



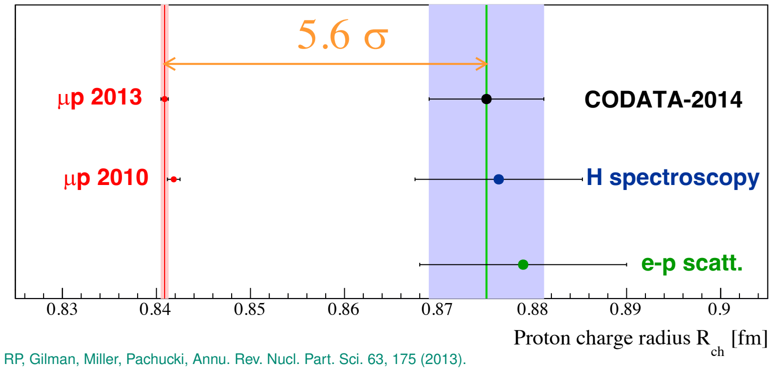
https://science.osti.gov/-/media/np/nsac/pdf/202310/NSAC-LRP-2023-v12.pdf
https://arxiv.org/abs/2303.02579

Disclaimer: not a review talk, not a summary talk, refs: NSAC LRP report, QCD Town Meeting and the whitepaper; I apologize in advance if your favorite topic is not included.

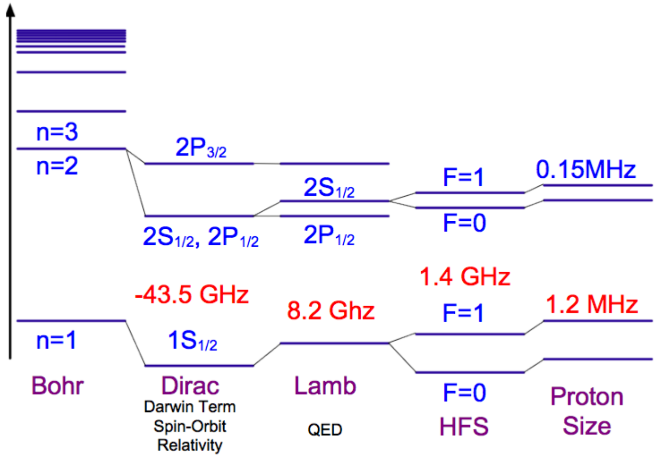


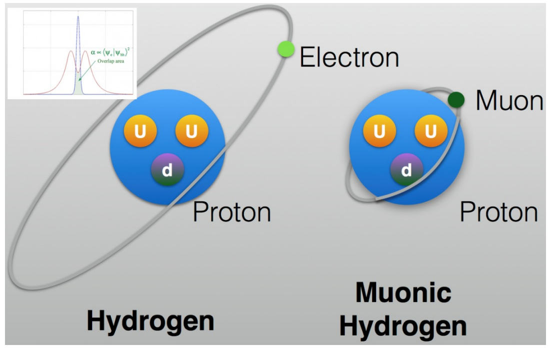
Size of the Proton: Charge Radius and the puzzle

- Proton charge radius:
  1. A fundamental quantity for proton
  2. Important for understanding how QCD works
  3. An important physics input to the bound state QED calculation, affects muonic H Lamb shift ($2S_{1/2} - 2P_{1/2}$) by as much as 2%, and critical in determining the Rydberg constant



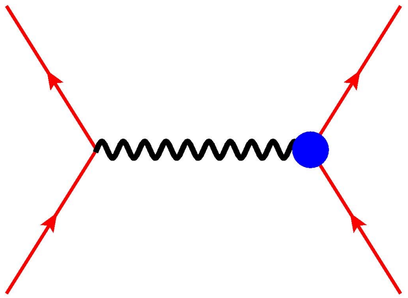
RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).





- Methods to measure the proton charge radius:
  1. Hydrogen spectroscopy (atomic physics)
     - ➢ Ordinary hydrogen
     - ➢ Muonic hydrogen
  2. Lepton-proton elastic scattering (nuclear physics)
     - ➢ *ep* elastic scattering (like PRad)
     - ➢ ***μ****p* elastic scattering (like MUSE, AMBER)

➢ Important point: the proton radius measured in lepton scattering is defined in the same way as in atomic spectroscopy (G.A. Miller, 2019)



$$\sqrt{<r^2>} = \sqrt{-6\frac{dG(q^2)}{dq^2}\Big|_{q^2=0}}$$

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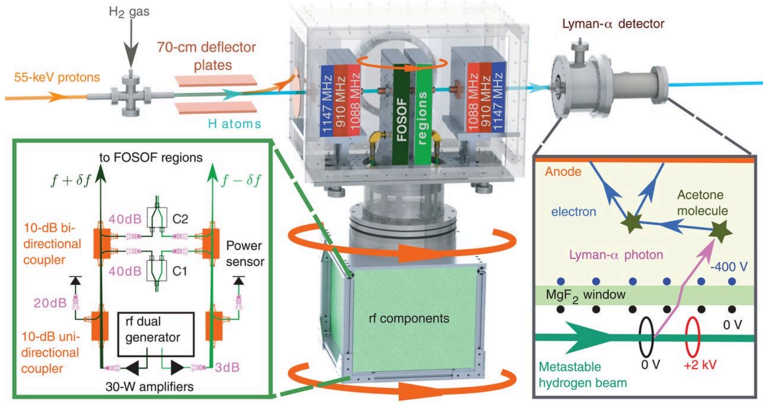
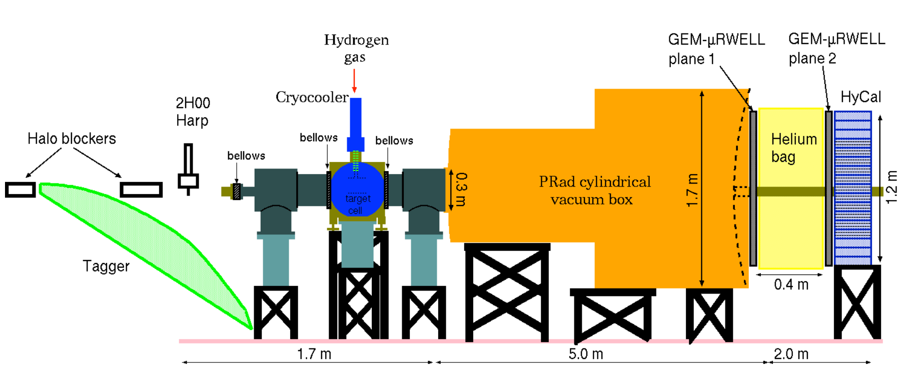
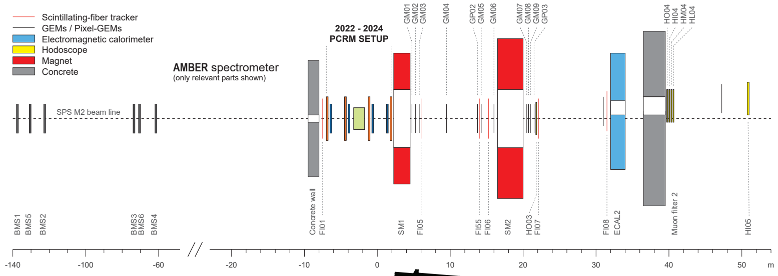
Nucleon EM form factors covered by Z.-E. Meziani, A. Puckett @EINN2023

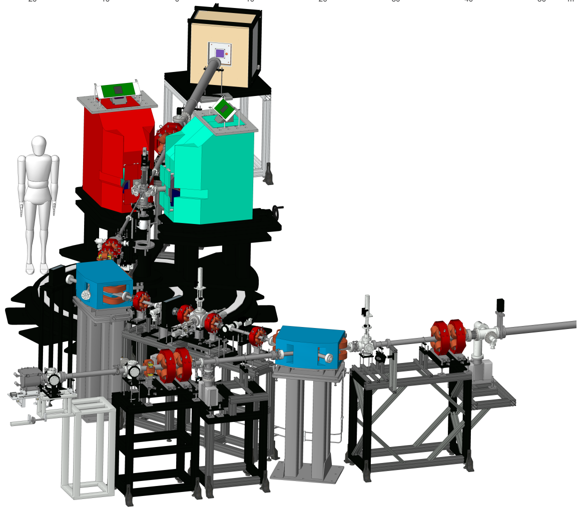
World-wide effort in Nuclear and Atomic Physics on Proton Charge Radius

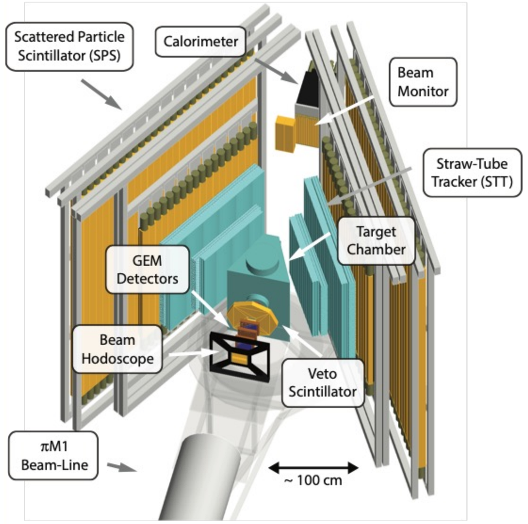


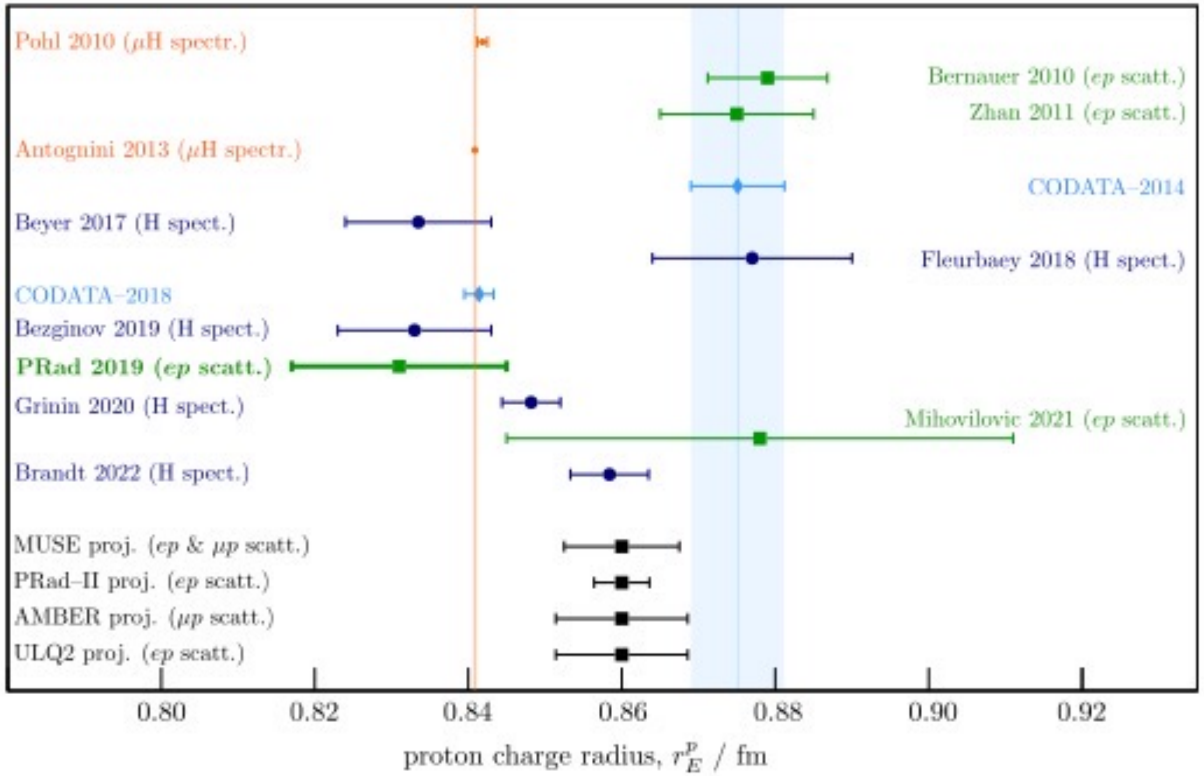
PRad-II Experimental Setup (Side View)

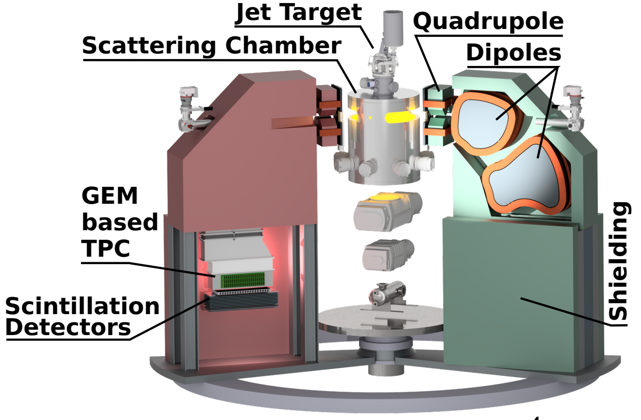












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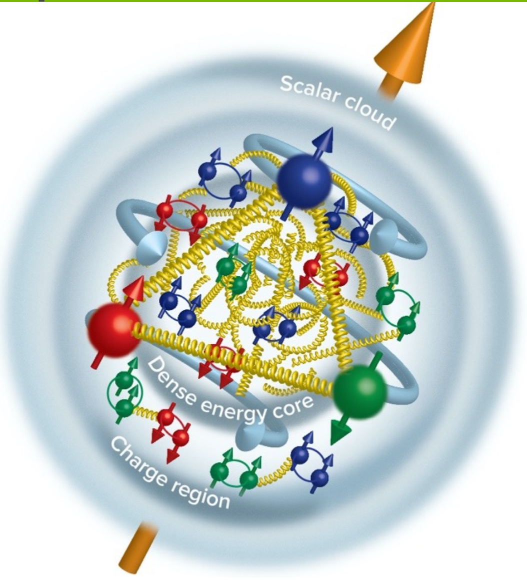
Gao & Vanderhaeghen Rev. Mod. Phys. 94, 015002 (2022)

Meziani, Denig, Quintans EINN2023

FIRST EXTRACTION OF GLUONIC SCALAR/MASS RADIUS OF THE NUCLEON

A picture of three zones?



B. Duran *et al*., Nature 615, 813 (2023)

Definition of gluonic mass and scalar radius

$$\langle r_m^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}|_{t=0} - 6\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

$$\langle r_s^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}|_{t=0} - 18\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

Theoretical approach GFF functional form	χ^2/n.d.f	m_A (GeV)	m_C (GeV)	$C_g(0)$	$\sqrt{\langle r_m^2\rangle_g}$ (fm)	$\sqrt{\langle r_s^2\rangle_g}$ (fm)
Holographic QCD Tripole-tripole	0.925	1.575±0.059	1.12±0.21	-0.45±0.132	0.755±0.067	1.069±0.126
GPD Tripole-tripole	0.924	2.71±0.19	1.28± 0.50	-0.20 ± 0.11	0.472±0.085	0.695±0.162
Lattice Tripole-tripole		1.641± 0.043	1.07± 0.12	-0.483± 0.133	0.7464±0.055	1.073±0.114

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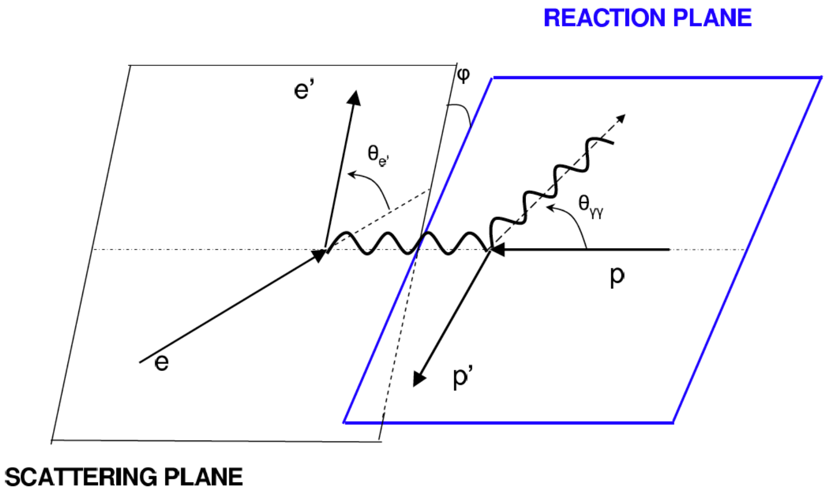
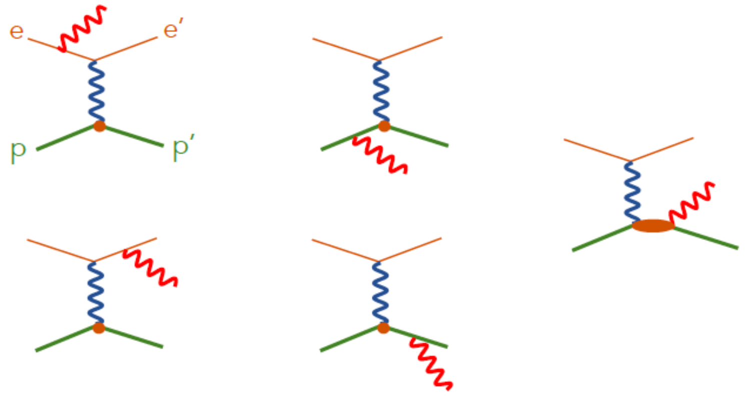
Zein-Eddine Meziani, Spin 2023 Symposium; S. Joosten, D. Pefkou, EINN2023

Virtual Compton Scattering and Proton Polarizability Radii



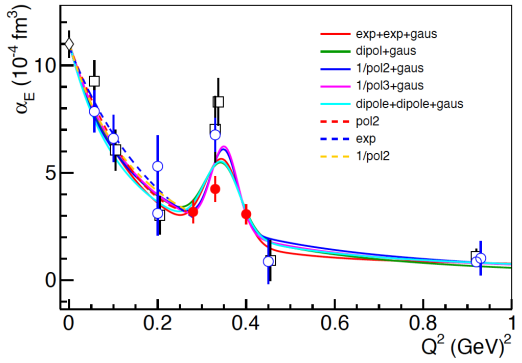


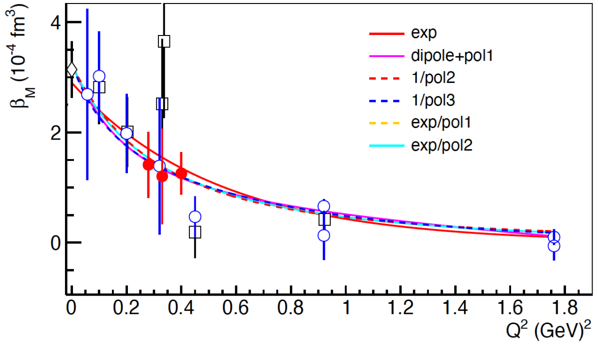
Bethe-Heitler Born VCS non-Born VCS

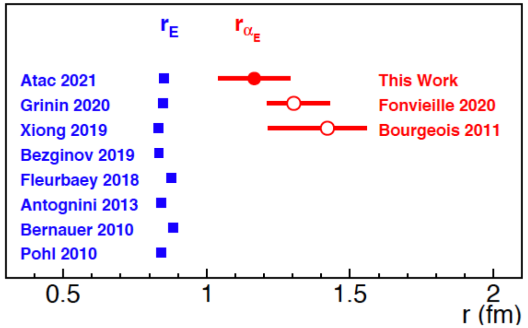
Elastic FFs **Generalized polarizabilities**

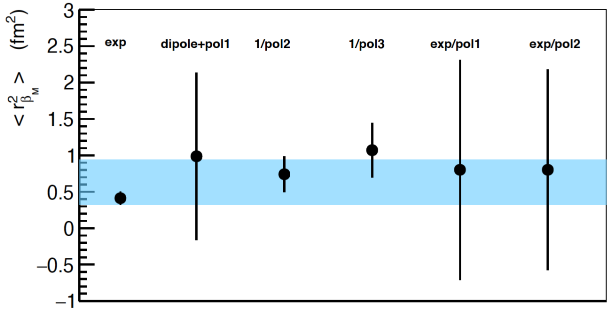
$$\langle r^2_{\alpha_E}\rangle = \frac{-6}{\alpha_E(0)} \cdot \frac{d}{dQ^2}\alpha_E(Q^2)\Big|_{Q^2=0}$$

$$\langle r^2_{\beta_M}\rangle = \frac{-6}{\beta_M(0)} \cdot \frac{d}{dQ^2}\beta_M(Q^2)\Big|_{Q^2=0}$$









$$\langle r^2_{\alpha_E}\rangle = 1.36 \pm 0.29\ \mathrm{fm}^2$$

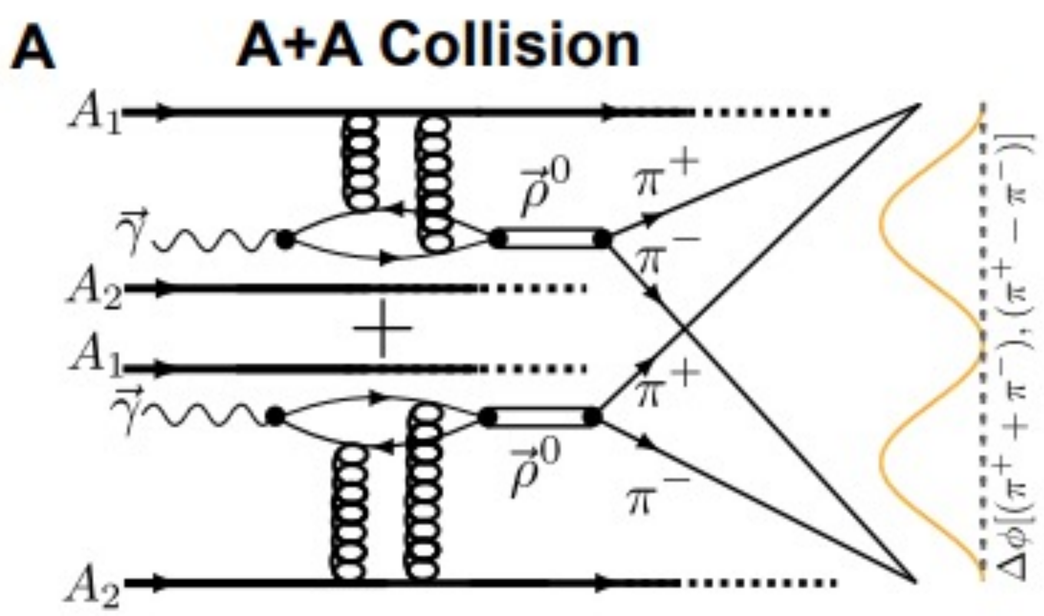
$$\langle r^2_{\beta_M}\rangle = 0.63 \pm 0.31\ \mathrm{fm}^2$$

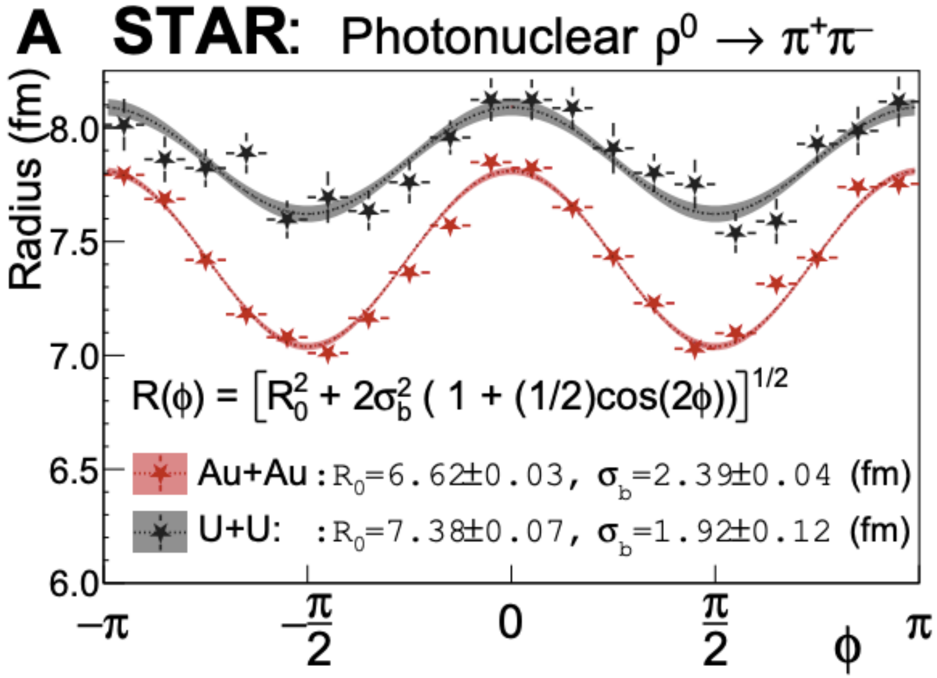
R. Li *et al.*, Nature 611, 265 (2022)

Real Compton Scattering experiments at Mainz and HIγS and nucleon EM and spin polarizabilities

Nikos Sparveris, Spin 2023 Symposium and EINN 2023

Tomography of Ultra-relativistic Nuclei with Gamma + A Collisions





Quantum interference enabled nuclear tomography:

- A novel approach to extract the strong-interaction nuclear radii, which were found to be larger than the nuclear charge radii

2204.01625, Science Advances 9 (2023) 3903

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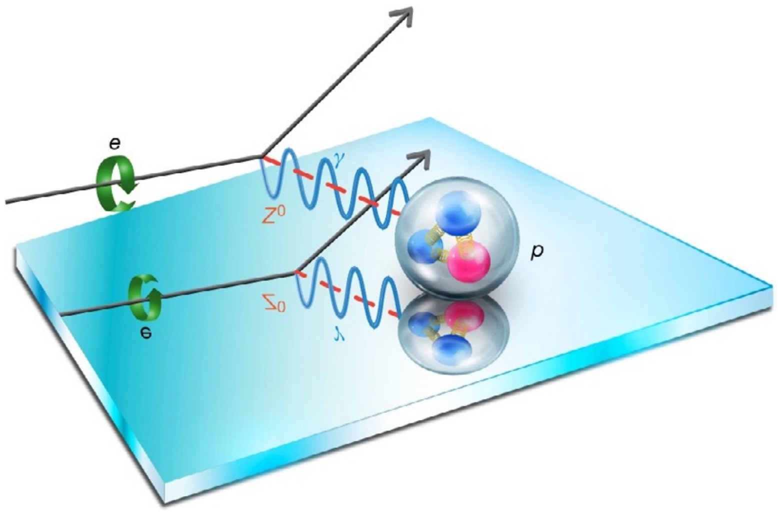
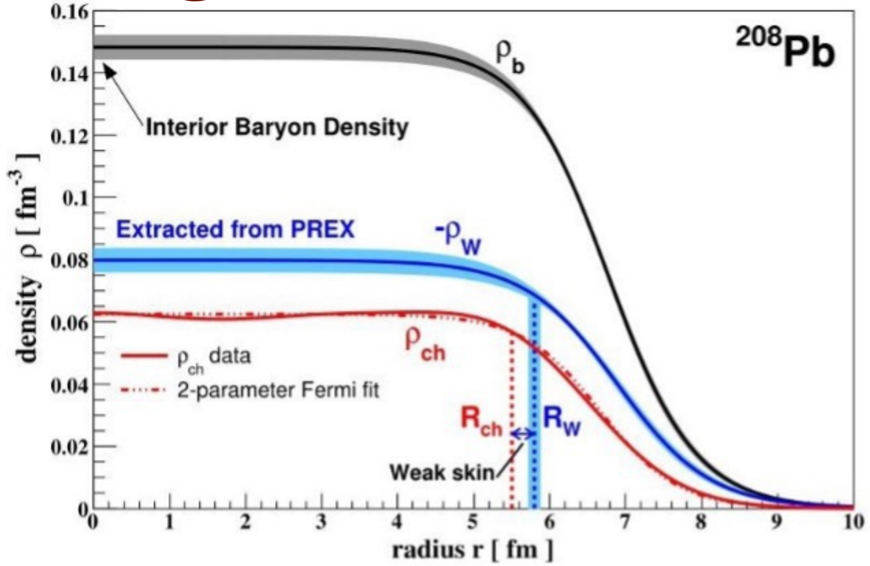
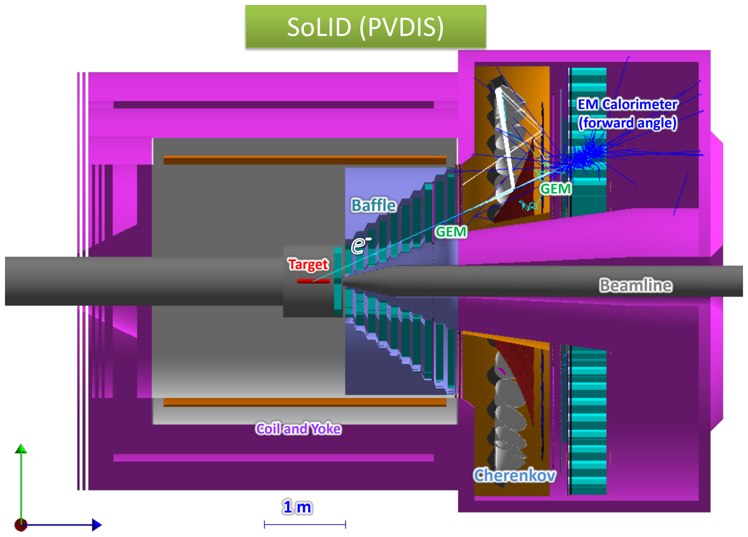
Parity-Violating Electron Scattering

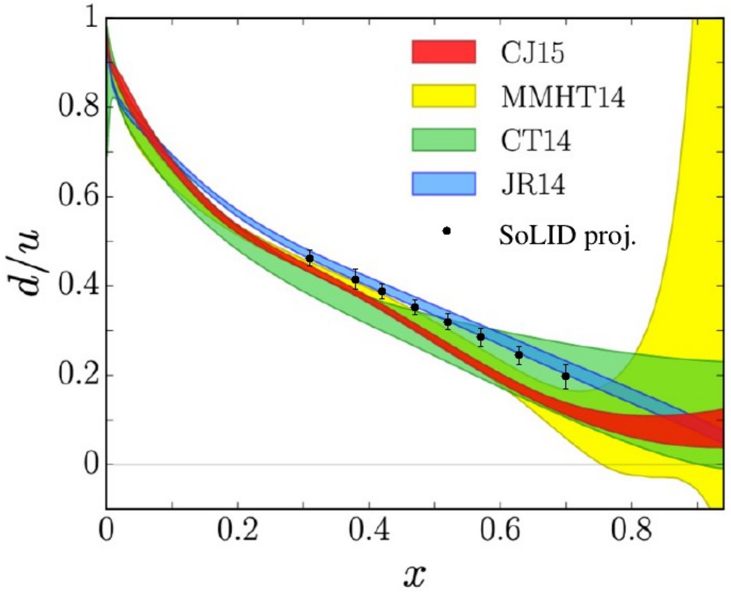


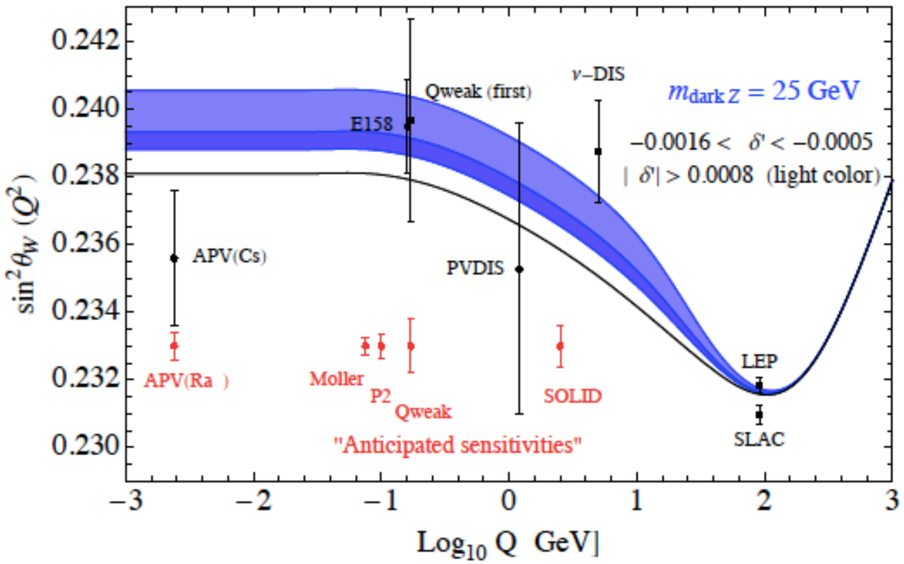
Powerful experimental technique impacting hadron physics, nuclear structure, neutron stars, Standard Model (SM) tests and beyond SM searches



D. Adhikari *et al.* (PREX Collaboration) Phys. Rev. Lett. **126**, 172502 (2021)







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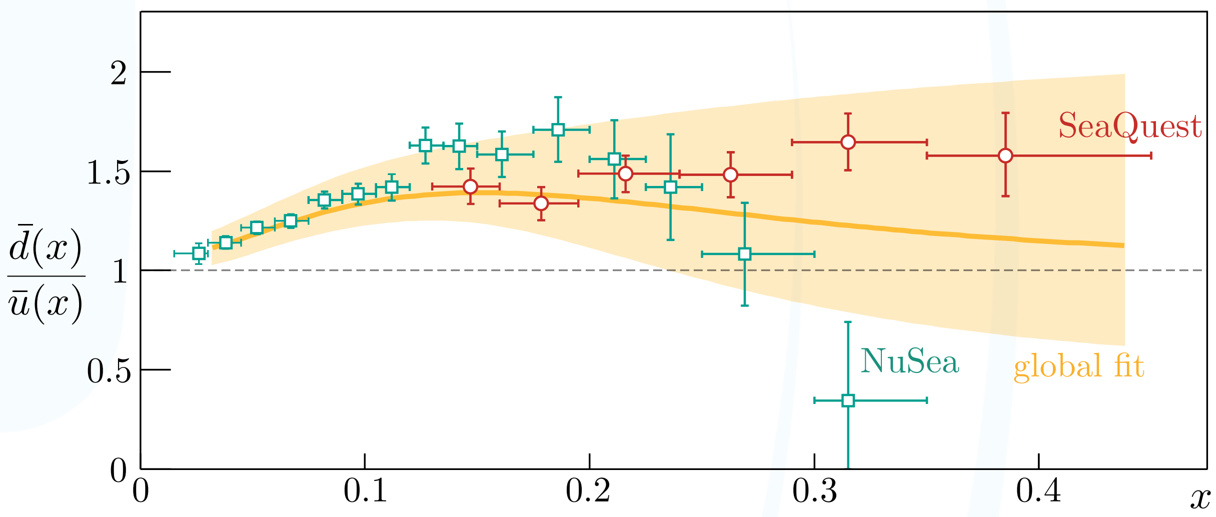
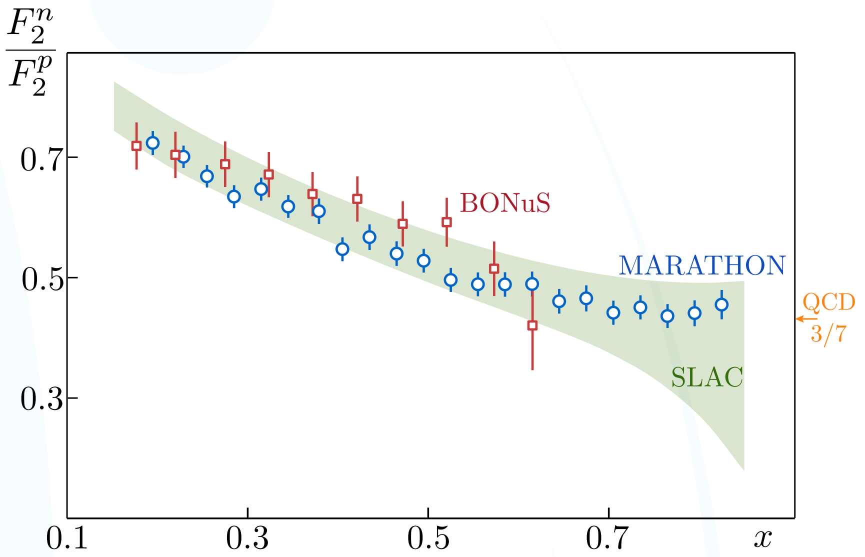
A. Denig on P2@MESA, EINN2023

HOW ARE QUARKS DISTRIBUTED IN THE NUCLEON?

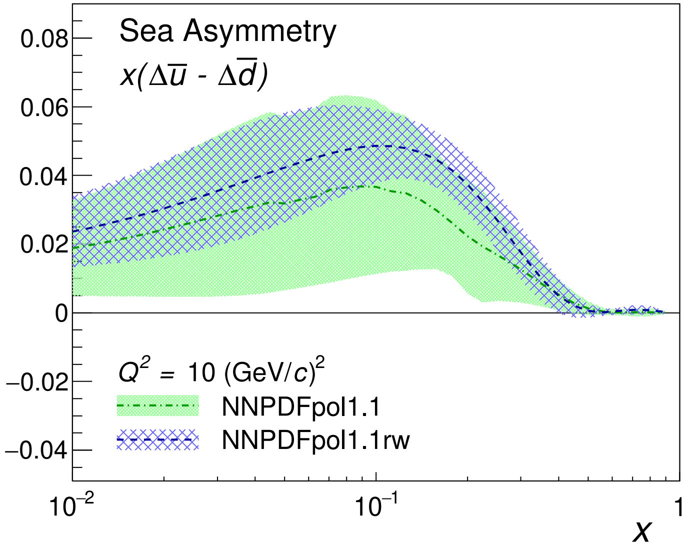


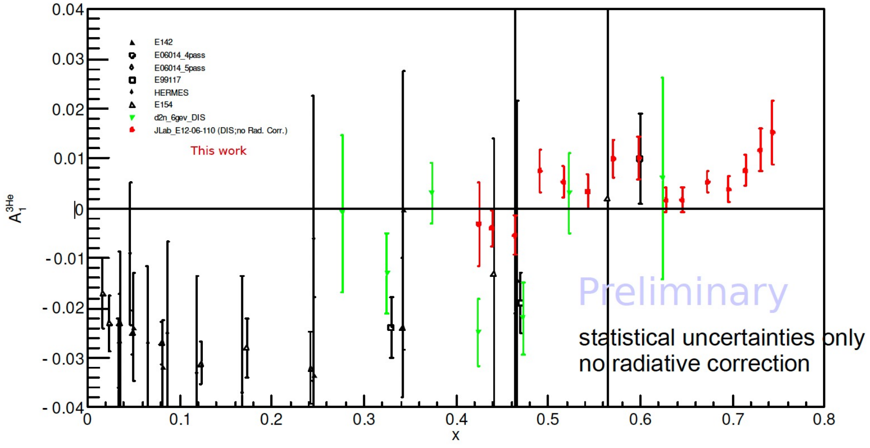
J. Dove *et al.*, *Nature* **590**, 561 (2021)



D. Abrams *et al.*, PRL **128**,132003 (2022), BoNus12 results
Future SoLID model independent extraction of d(x)/u(x) from PVDIS (previous slide)

Complementary informatio from RHIC from W- and Z-bosons production in proto proton (pp) collisions, and polarized sea from W production from pol. pp collisions

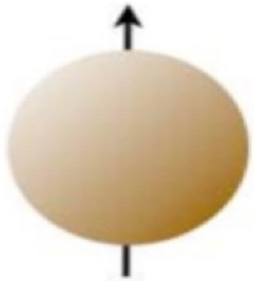




• Credit to Mingyu Chen (UVA)

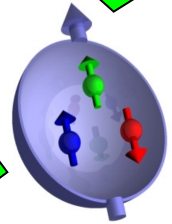
Meziani, Diehl, Mukherjee, Nadolsky@EINN2023

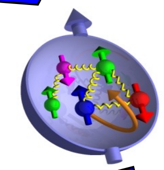
The nucleon spin puzzle



Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$





Quark helicity
Best known

$$\frac{1}{2}\int dx\left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

$$\sim 30\%$$

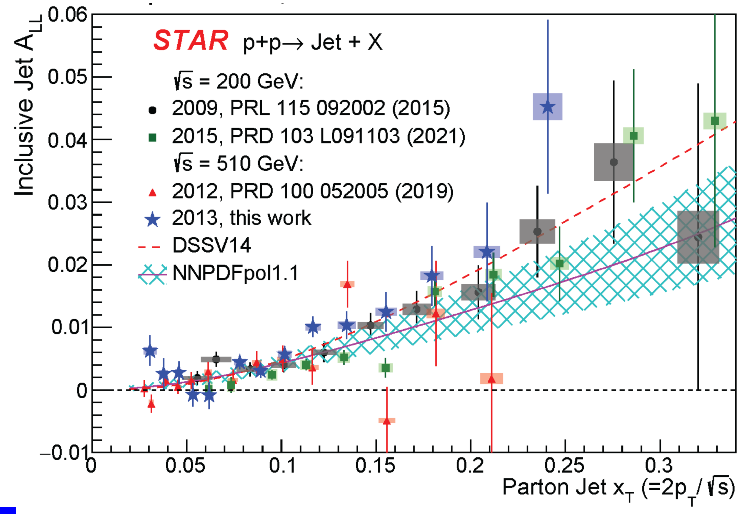
Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$

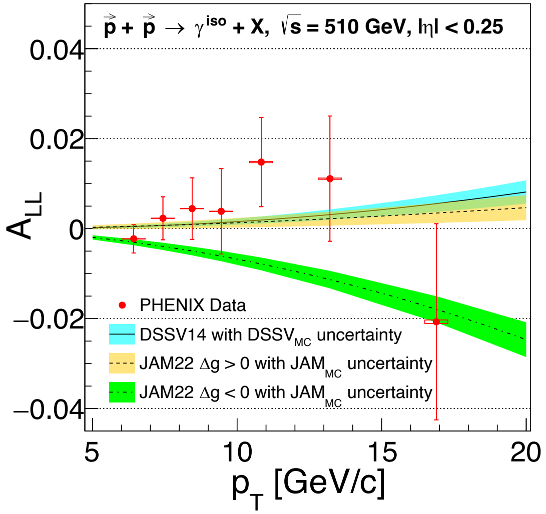
Orbital Angular Momentum of quarks and gluons
Little known

Net effect of partons' transverse motion?

PRD 105 (2022) 092011



PHENIX PRL 130 (2023) 2519201



JLab spin physics highlights:
Spin structure in valence quark region
Generalized spin sum rules and polarizabilities
Tests of χEFT and LQCD calculations

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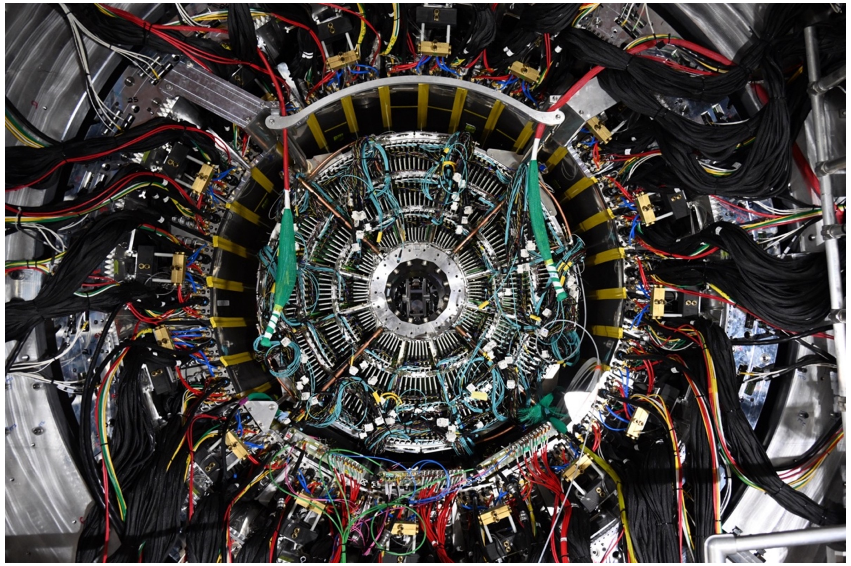
C. Riedl, W. Vogelsang@EINN2023 and others

Spin Physics with sPHENIX

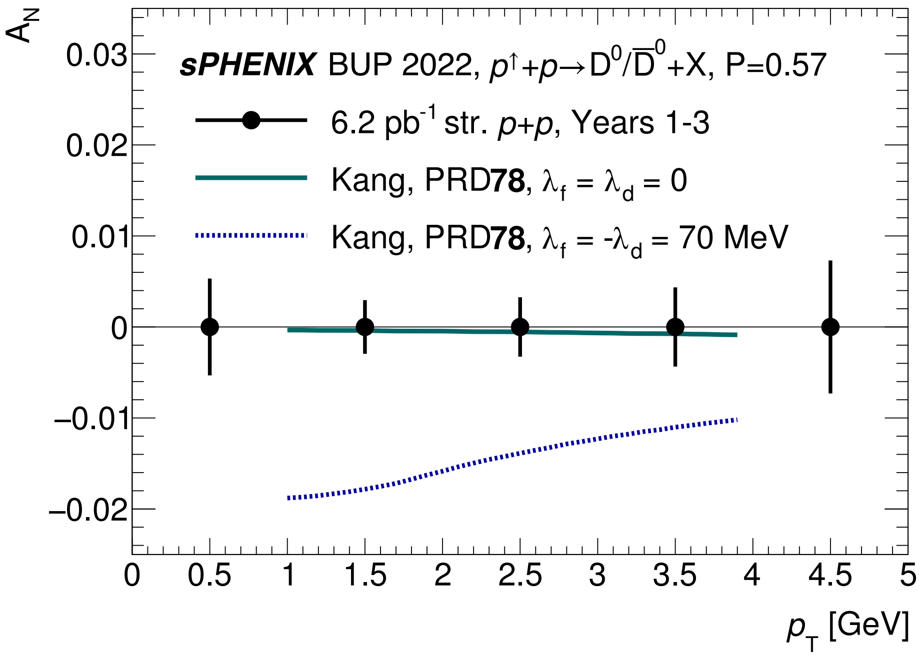
First direct photon A_N extracted at RHIC by PHENIX PRL 127, 162001 (2021)

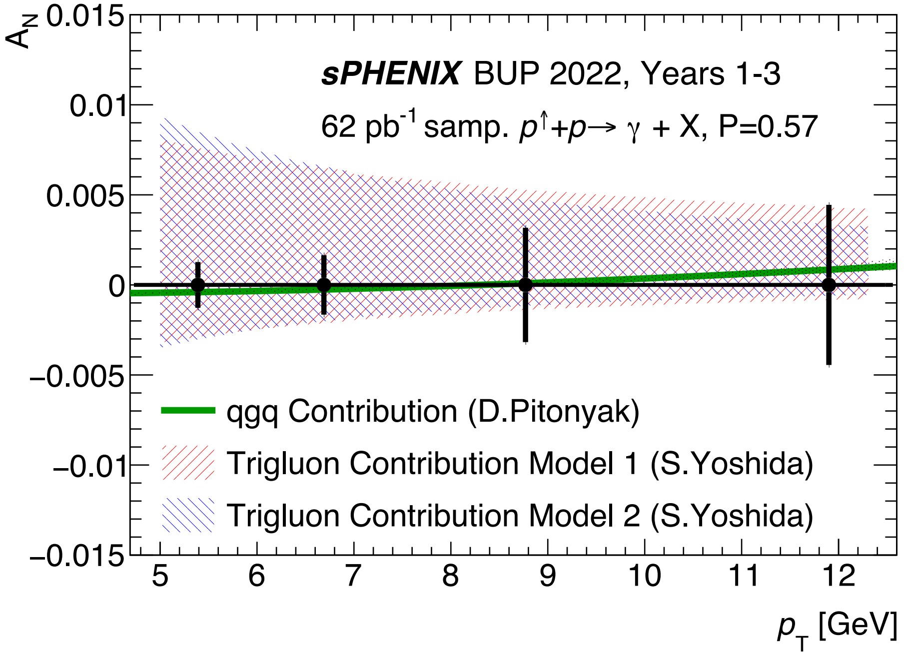
- Mostly sensitive to initial state effects (no fragmentation) → quark-gluon and gluon-gluon correlation functions
- Power to constrain gluon-gluon correlation function as well

Measurement of A_N of heavy-flavor decay electrons by PHENIX Phys. Rev. D **107**, 052012 (2023), probe tri-gluon correlations



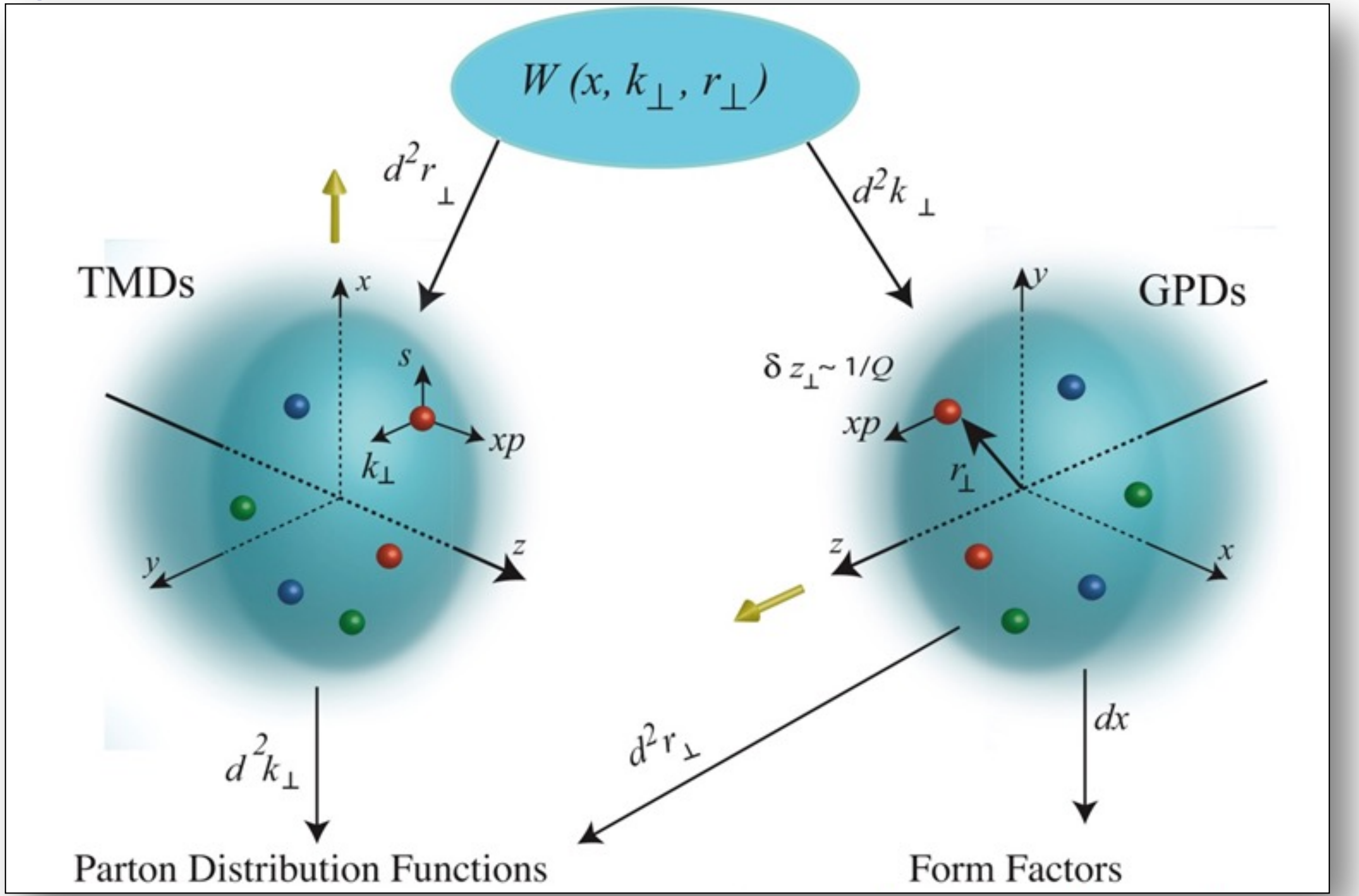
★ enabled by streaming readout





Nucleon Structure from 1D to 3D & orbital motion

5-D Wigner distribution



Nucleon EM form factors core 12-GeV program at JLab, covered by Z.-E. Meziani

Generalized parton distribution (GPD)

Transverse momentum dependent parton distribution (TMD)

Image from J. Dudek et al., EPJA 48,187 (2012)

X.D. Ji, PRL91, 062001 (2003); Belitsky, Ji, Yuan, PRD69,074014 (2004)

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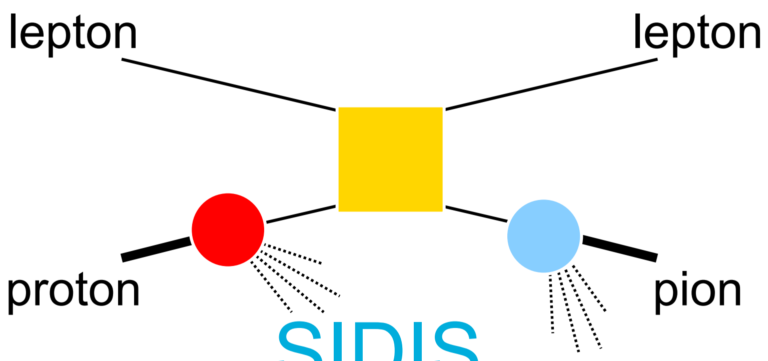
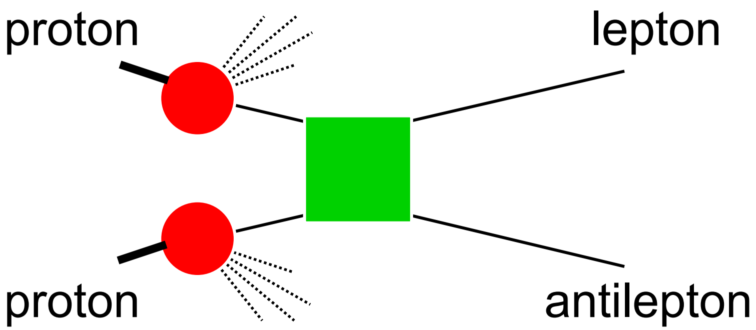
Constantinou, Meziani, Diehl, Metz, Riedl, Surrow at EINN2023, and others

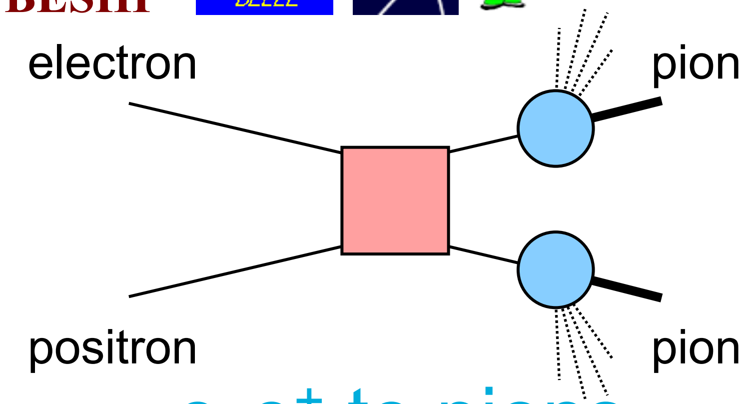
Access TMDs through Hard Processes



SIDIS



Drell-Yan



$e^{-}e^{+}$ to pions

- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

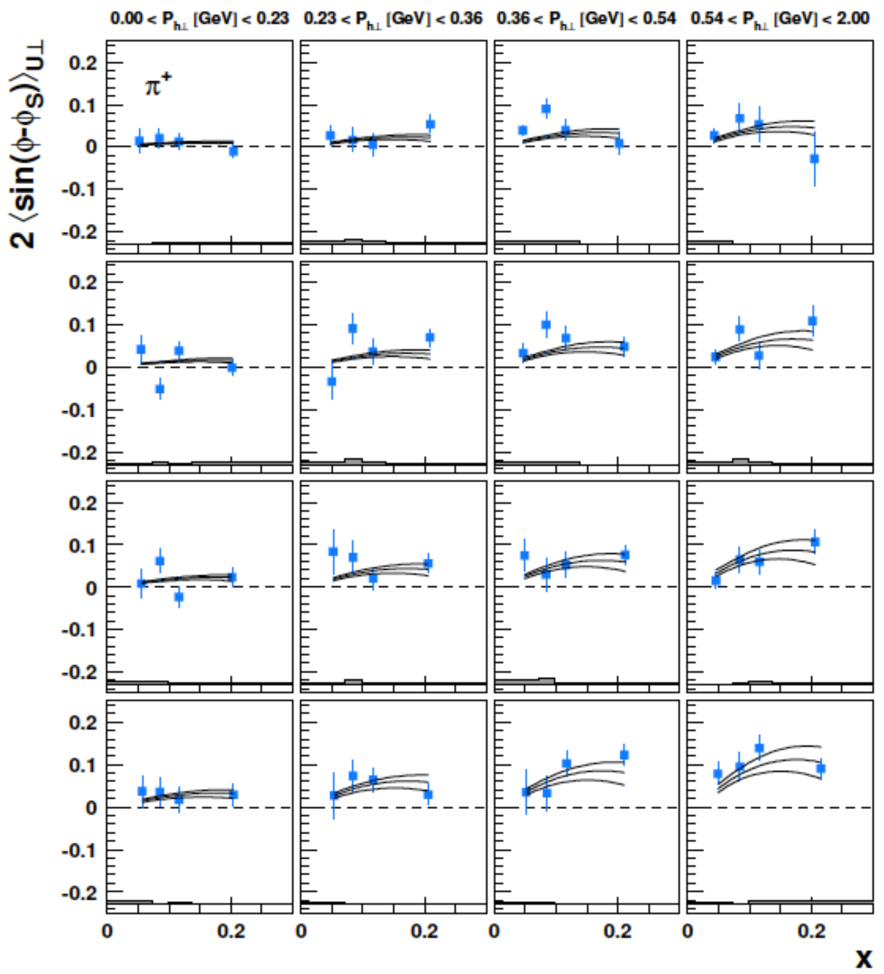
$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

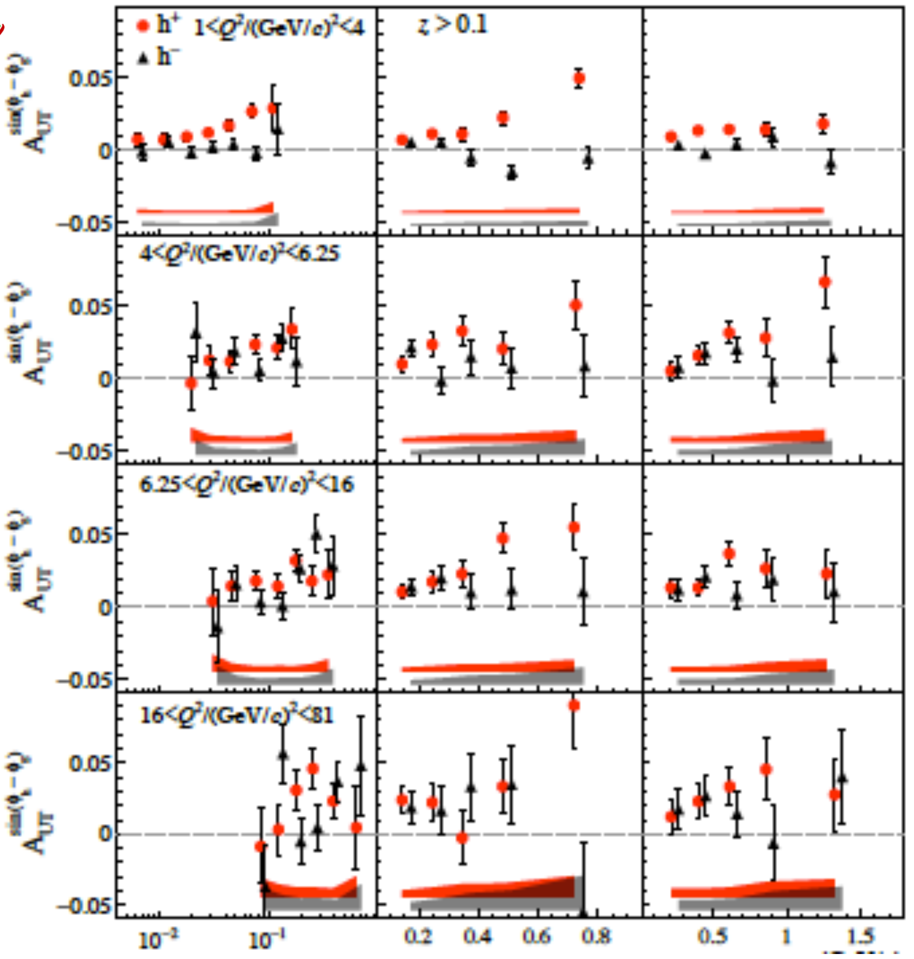
Several talks at EINN2023

Pioneering Studies by HERMES and COMPASS

Multi-dimensional binning with precision – reduces systematics, constrain models, forms of TMDs, disentangle correlations, isolate phase-space region with large signal strength (HERMES, COMPASS)



A. Airapetian et al., arXiv:2007.07755



C. Adolph et al. PLB 770, 138 (2017)

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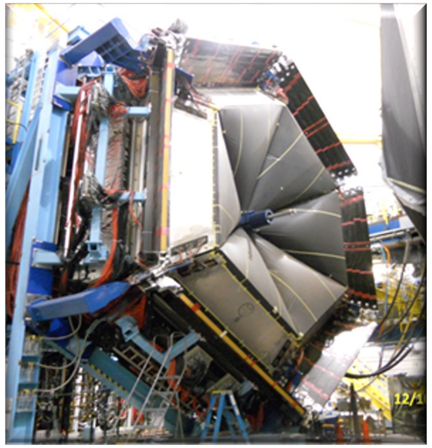
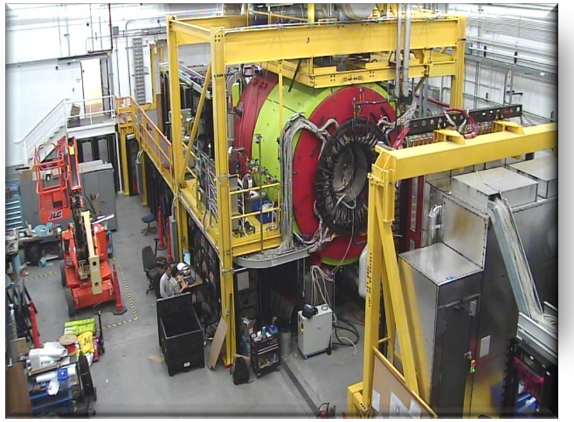
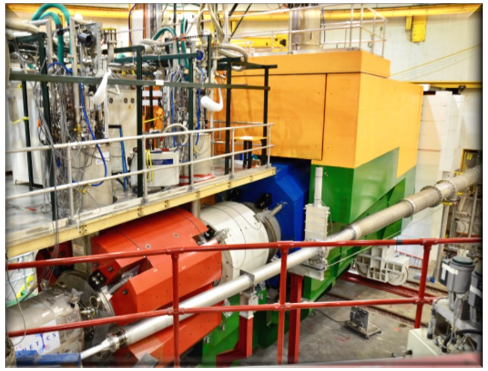
JLab 12 GeV Scientific Capabilities



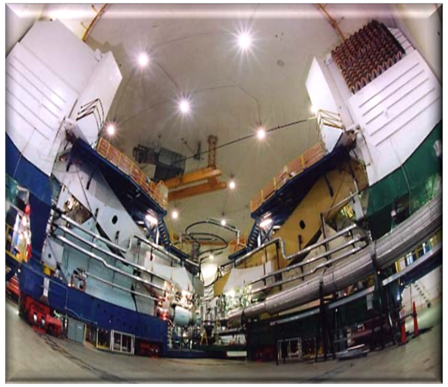


Hall D – exploring origin of confinement by studying exotic mesons

Hall B – understanding nucleon structure via generalized parton distributions and transverse momentum distributions



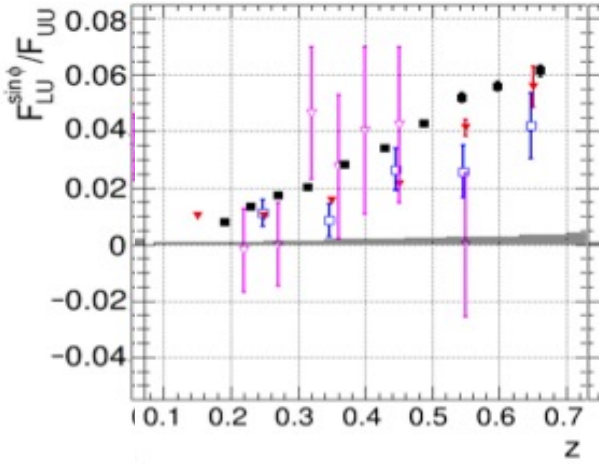
Hall C – precision determination of valence quark properties in nucleons and nuclei

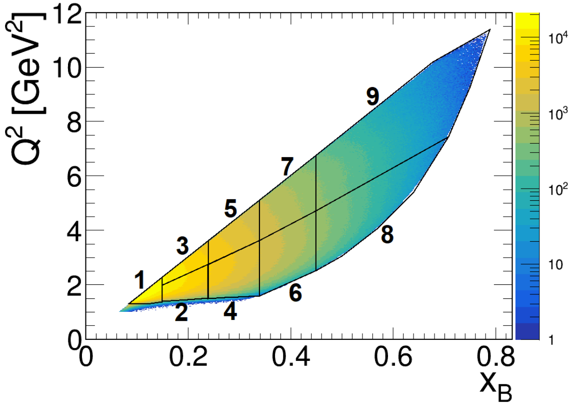


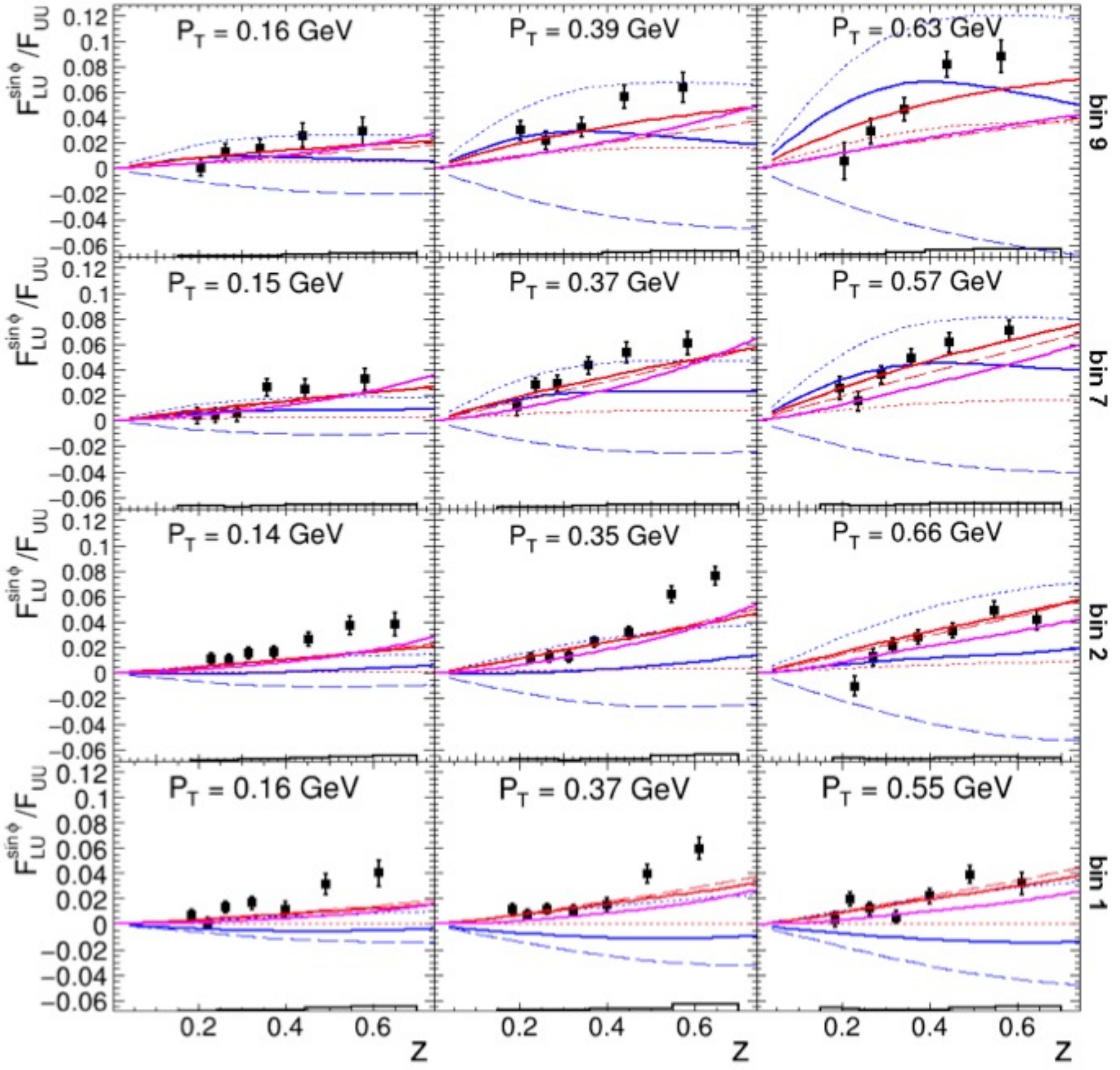
Hall A – short range correlations, form factors, hyper-nuclear physics, future new experiments (e.g., SoLID and MOLLER)

State-of-the-art from CLAS 12

multi-dimensional binning with precision – reduces systematics, constrain models, forms of TMDs, disentangle correlations, isolate phase-space region with large signal strength (CLAS12)







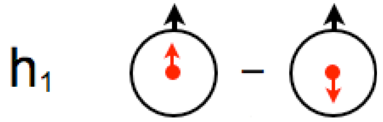
First multidimensional, high precision measurements of semi-inclusive π+ beam single spin asymmetries from the proton over a wide range of kinematics

S. Diehl *et al.* (CLAS Collaboration), Phys. Rev. Lett. **128**, 062005

SoLID@JLab:QCD at the Intensity Frontier

Transversity and Tensor Charge

Transversity distribution



(Collinear & TMD)

- Chiral-odd, unique for the quarks
- No mixing with gluons, simpler evolution effect
- Tensor charge:

$$\langle \mathrm{P,S}|\overline{\psi}_q i\sigma^{\mu\nu}\psi_q|\mathrm{P,S}\rangle = g_T^q \overline{u}(\mathrm{P,S}) i\sigma^{\mu\nu} u(\mathrm{P,S})$$

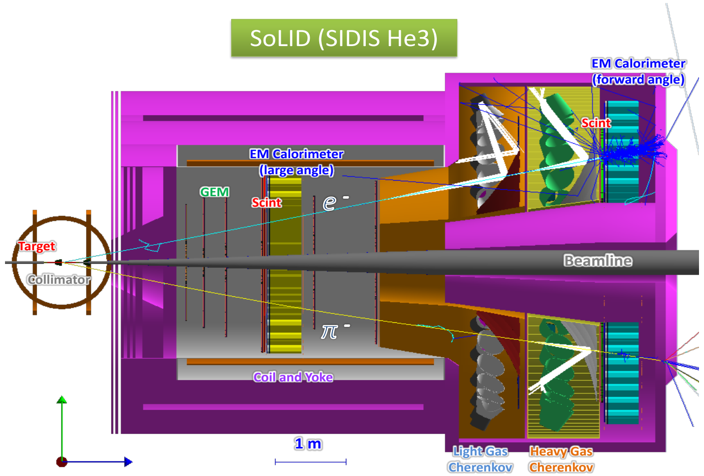
$$g_T^q = \int_0^1 \left[h_1^q(x) - h_1^{\overline{q}}(x)\right] dx$$

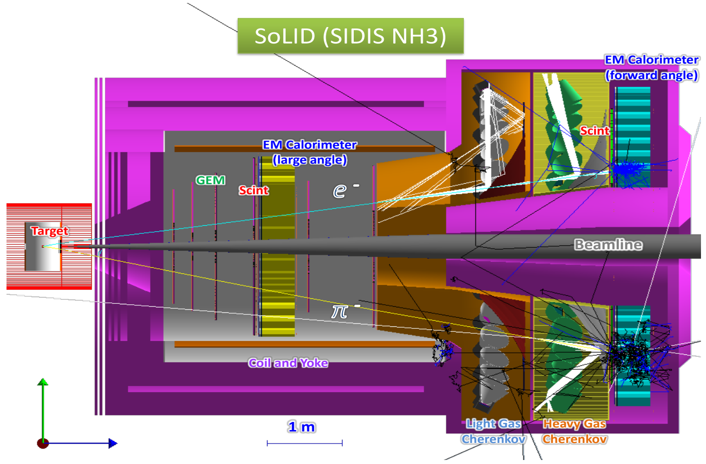
A fundamental QCD quantity dominated by valence quarks; Precisely calculated on the lattice

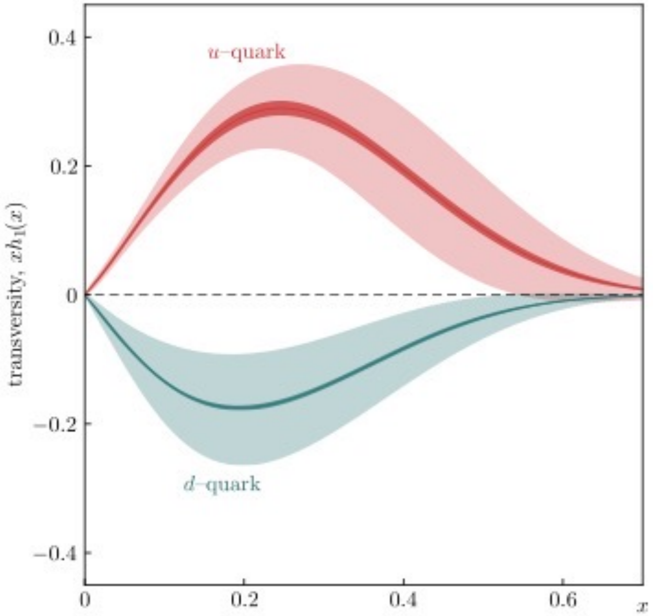
Global analysis including LQCD (PRL 120 (2018) 15, 152502

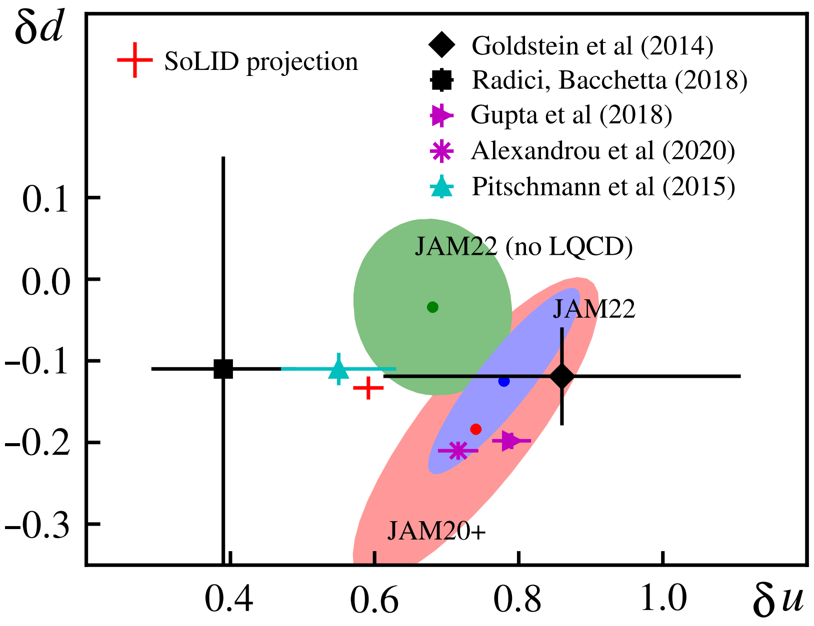
J. Cammarota et al, PRD 102, 054002 (2020) (JAM20+

L. Gamberg et al., arXiv:2205.00999 (JAM22)





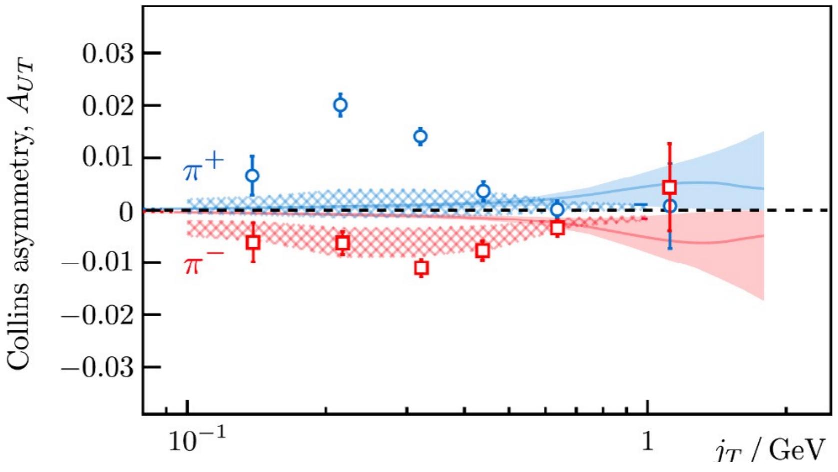




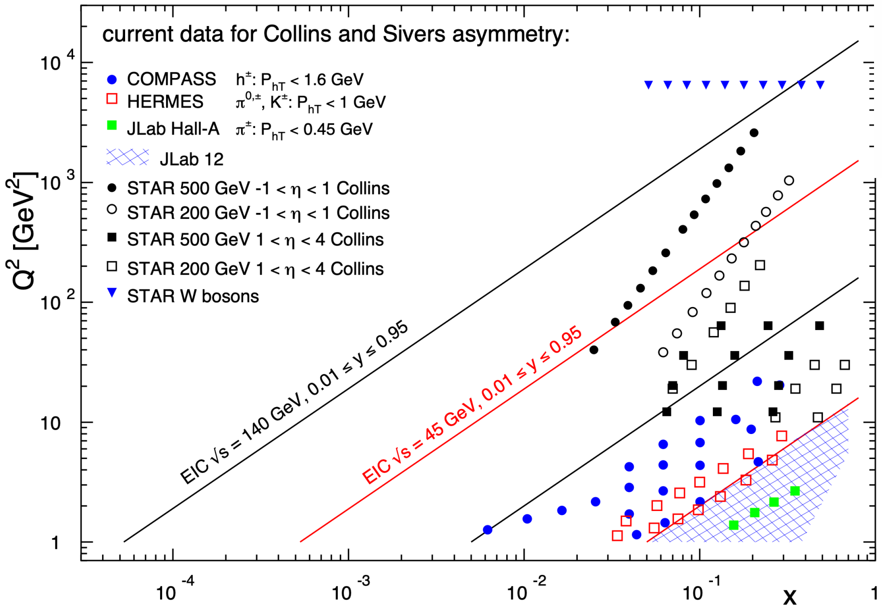
Brookhaven National Laboratory

A. Metz, G. Koutsou, B. Surrow@EINN2023

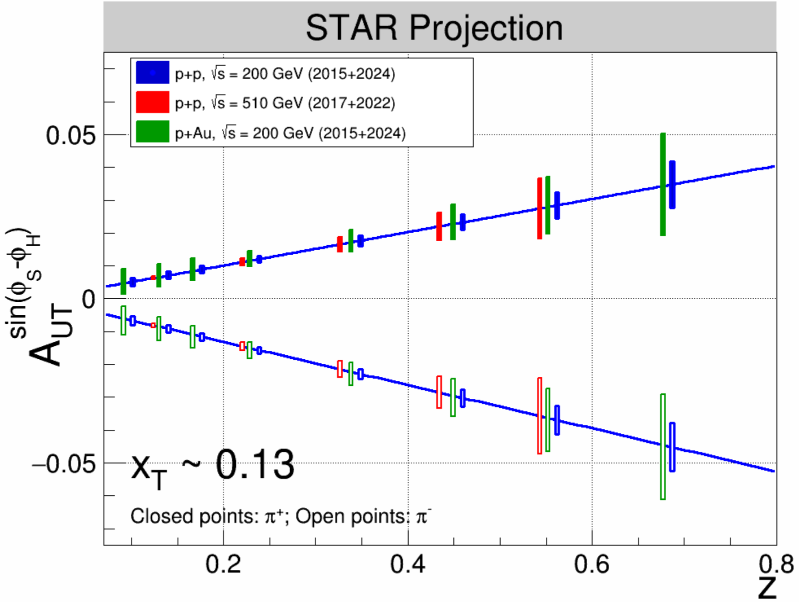
TMD Physics: STAR and forward upgrade

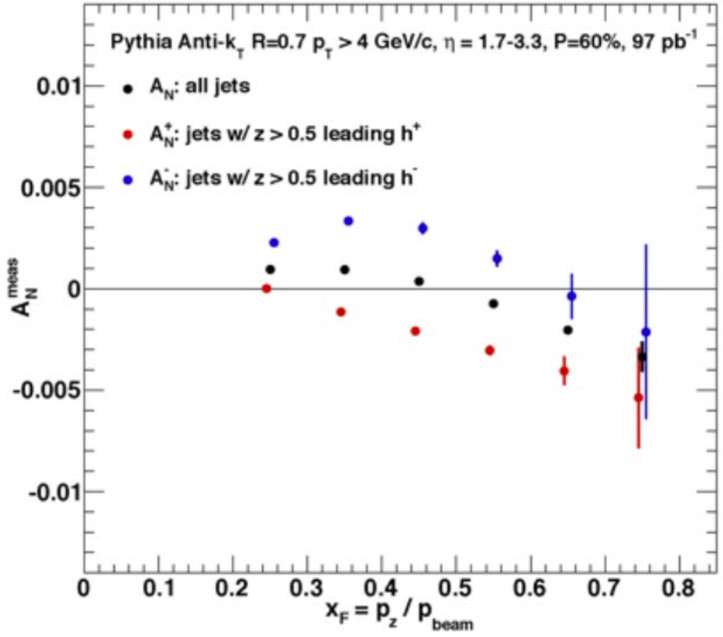


PRD106 (2022) 72010



improved PID, extended η coverage by iTPC





First observation of non-zero Sivers asymmetry in dijet production

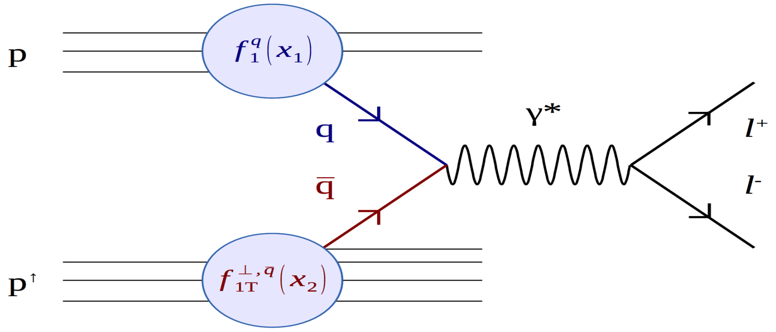
Precision measurements at both energies probe TMD evolution and provide important cross-checks and essential x-Q2 overlap with EIC

RHIC Run-24 will reduce uncertainties at 200 GeV by a factor of 2, enabling the most sensitive universality test with EIC data

Polarized Drell-Yan @ SpinQuest

Measure Drell-Yan azimuthal asymmetry to extract sea quark Sivers:

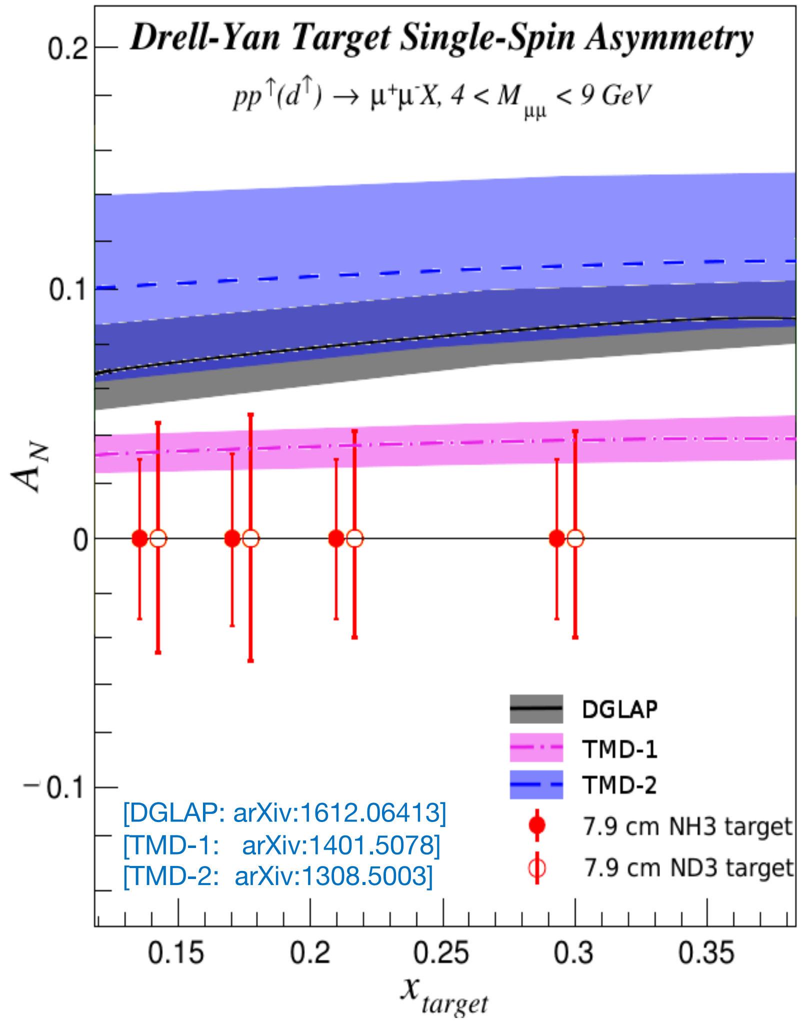
$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}$$



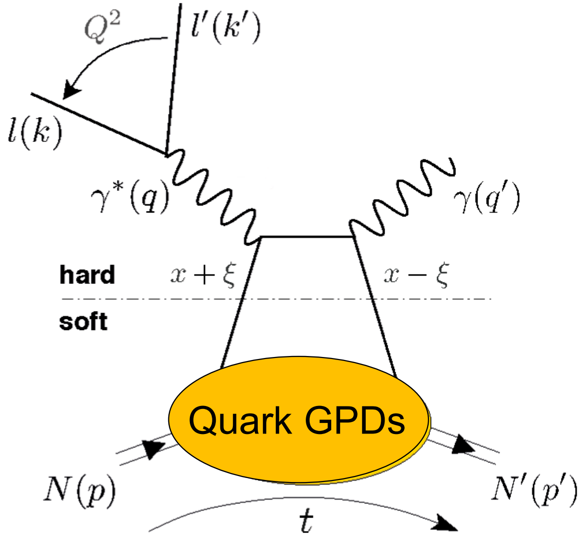
Two-year runtime:

- Add solid NH3 target, upstream for lower X_t
- Proton on target: 1.4 x 10^{18}

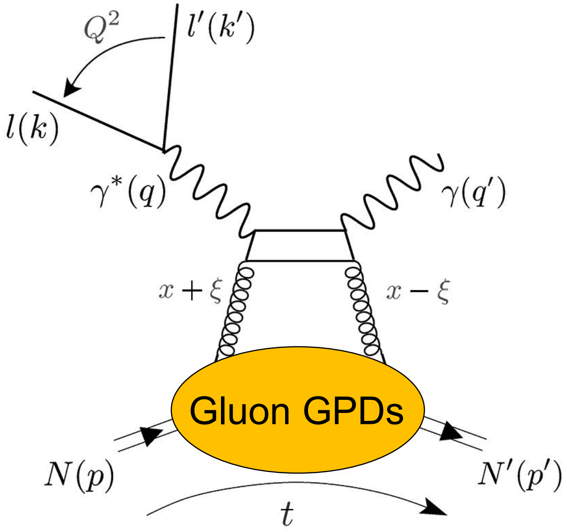
Anticipated Sensitivity



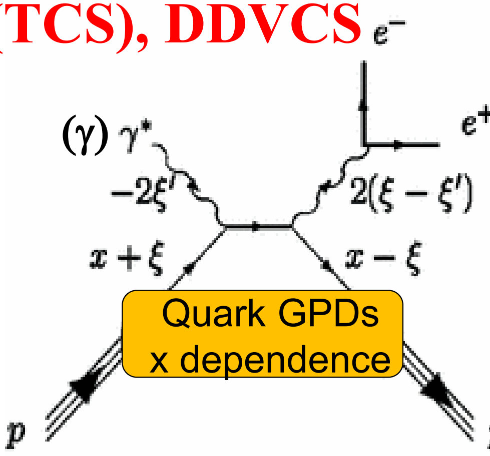
Exclusive reactions giving access to GPDs



DVCS

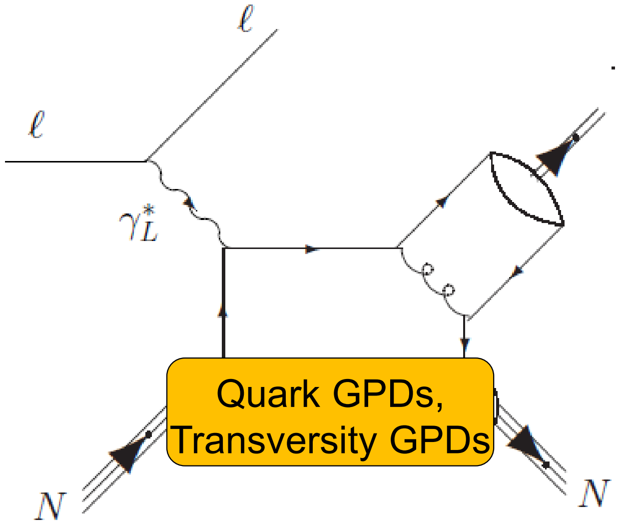


(TCS), DDVCS

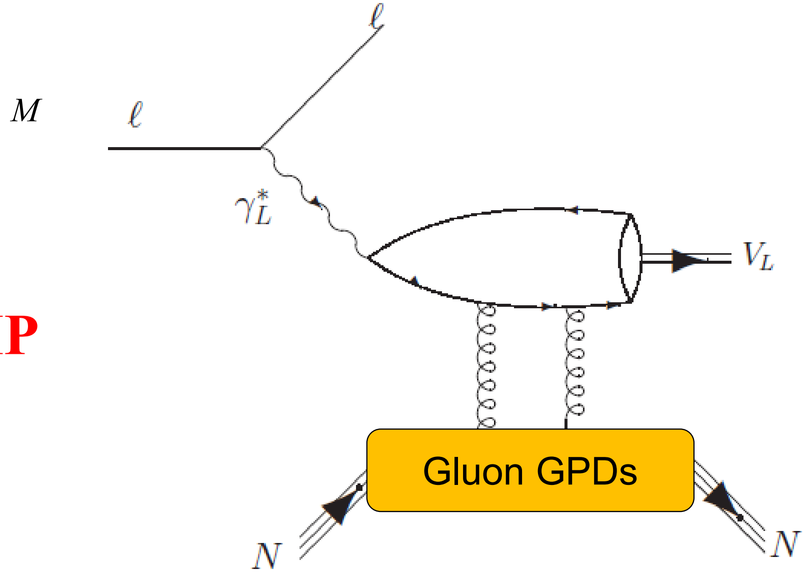


Voutier, Riedl@EINN2023

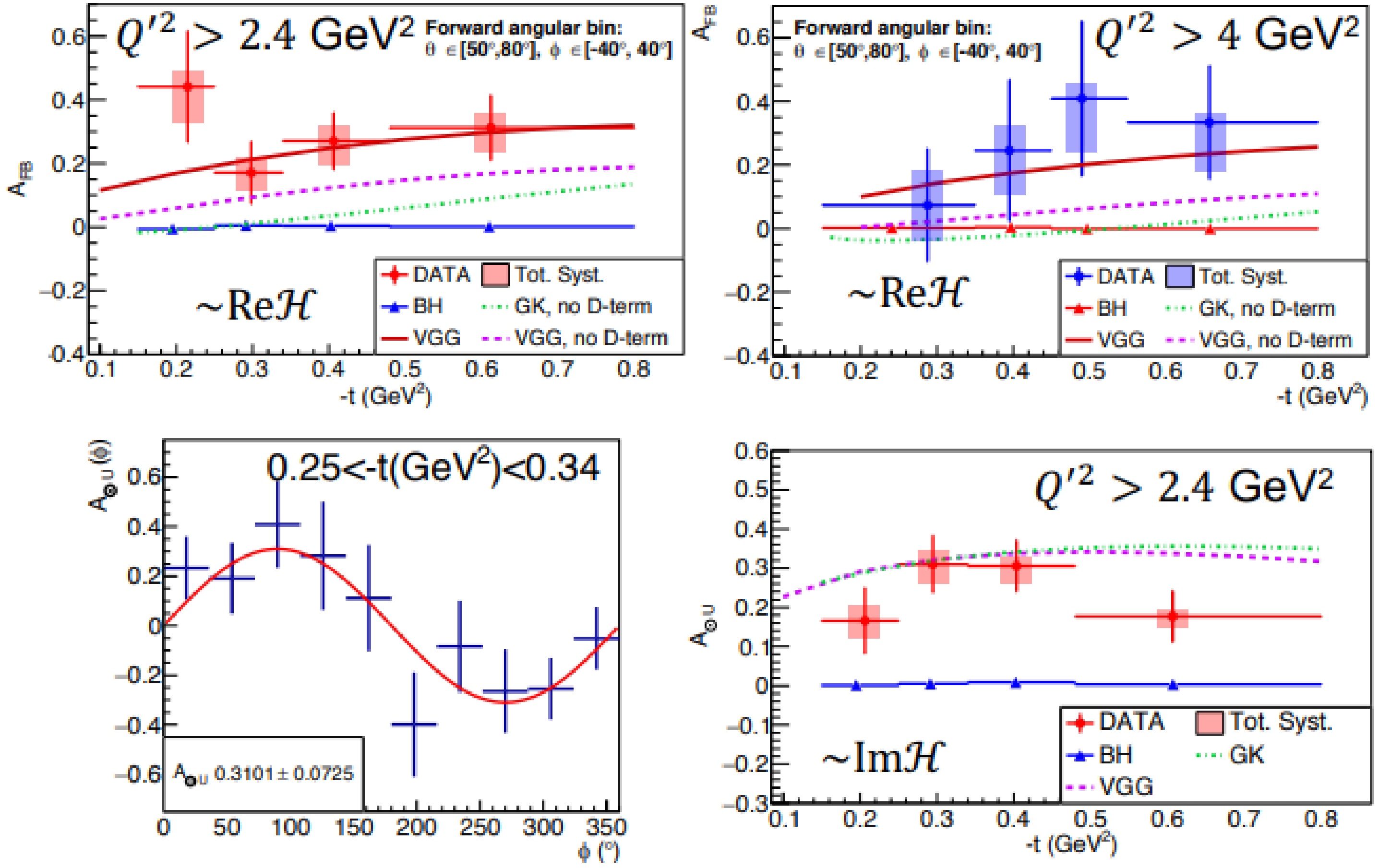
Constantinou, Diehl, Metz, Meziani, and others



DVMP



First-ever measurement of Timelike Compton Scattering (CLAS12)



P. Chatagnon et al. (CLAS), Phys. Rev. Lett. 127 (2021) ***Talk by P. Chatagnon***

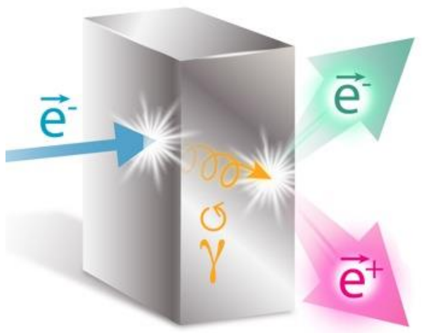
γp→γ*p→(e')e⁺e⁻p

- Quasi-real photo-production (Q^2~0)
- The beam helicity asymmetry of TCS accesses the imaginary part of the CFF in the same way as in DVCS and probes the universality of GPDs
- The forward-backward asymmetry is sensitive to the real part of the CFF → direct access to the Energy-Momentum Form Factor $d_q(t)$ (linked to the D-term) that relates to the mechanical properties of the nucleon (quark pressure distribution)
- This measurement proves the importance of TCS for GPD physics.
- Limits: very small cross section → high luminosity is necessary for a more precise measurement
- Imminent doubling of statistics thanks to data reprocessing with improved reconstruction

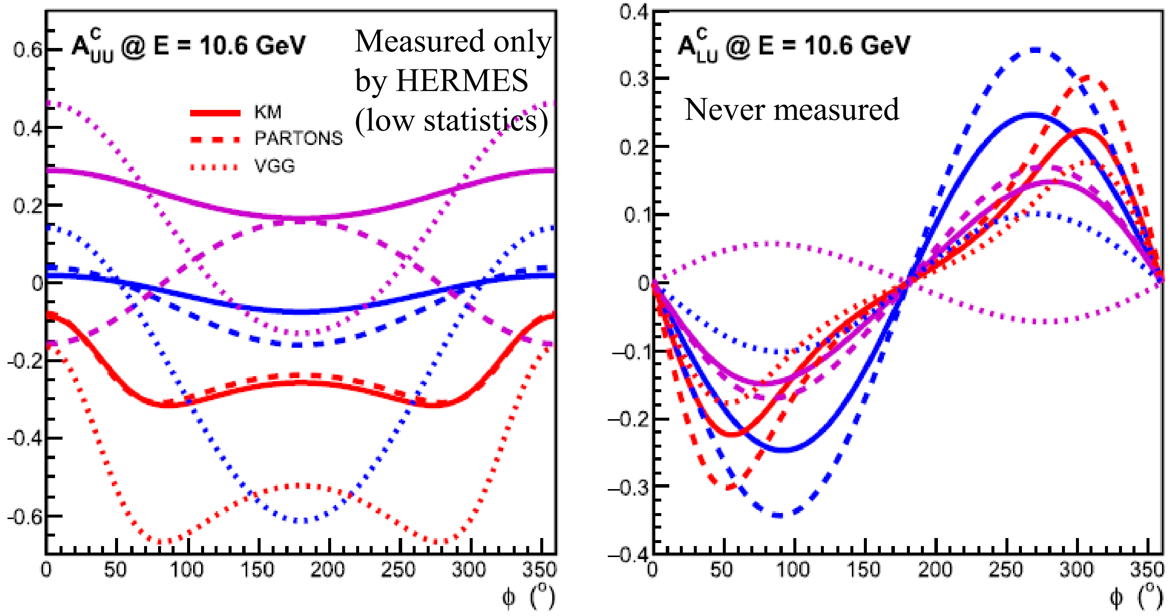
Perspectives: polarized positrons beam for Jefferson Lab

Physics Motivations:
- Two-photon physics
- **Generalized parton distributions**
- Neutral and charged current DIS
- Charm production
- Neutral electroweak coupling
- Light Dark Matter search
- Charged Lepton Flavor Violation

- Publication of the **EPJ A Topical Issue about "An experimental program with positron beams at Jefferson lab", Eur. Phys. J. A 58 (2022) 3, 45**
- 5 positron-based proposals, two of which on DVCS (CLAS12, Hall C) recently Conditionally Approved by JLab PAC51



PePPO: proof-of-principle for a polarized positron beam
PRL 116 (2016) 214801



Model predictions for 2 out of the 3 proposed pDVCS observables

Impact of positron pDVCS projected data on the extraction of ReH via global fits: major reduction of relative uncertainties

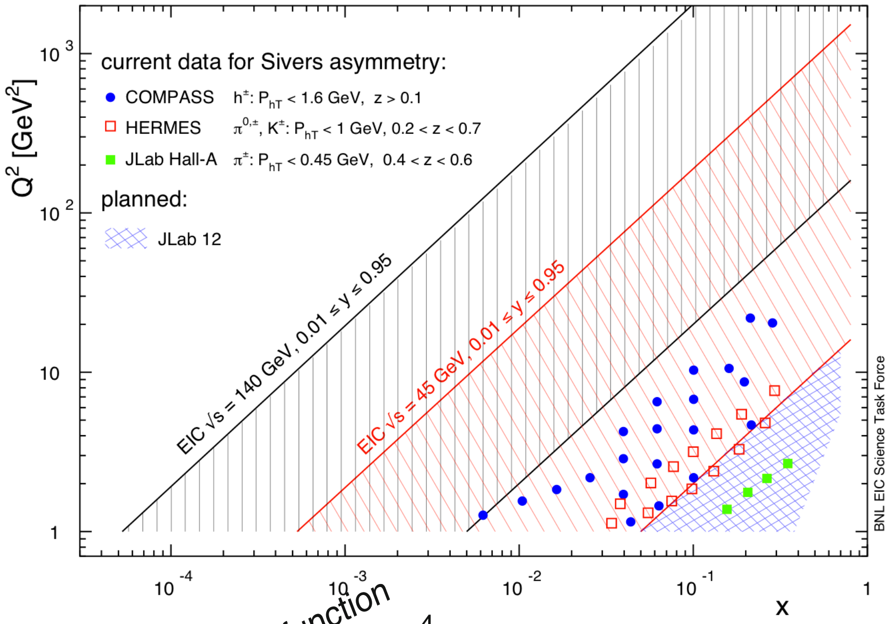
R&D ongoing
Possible timeline: >2030

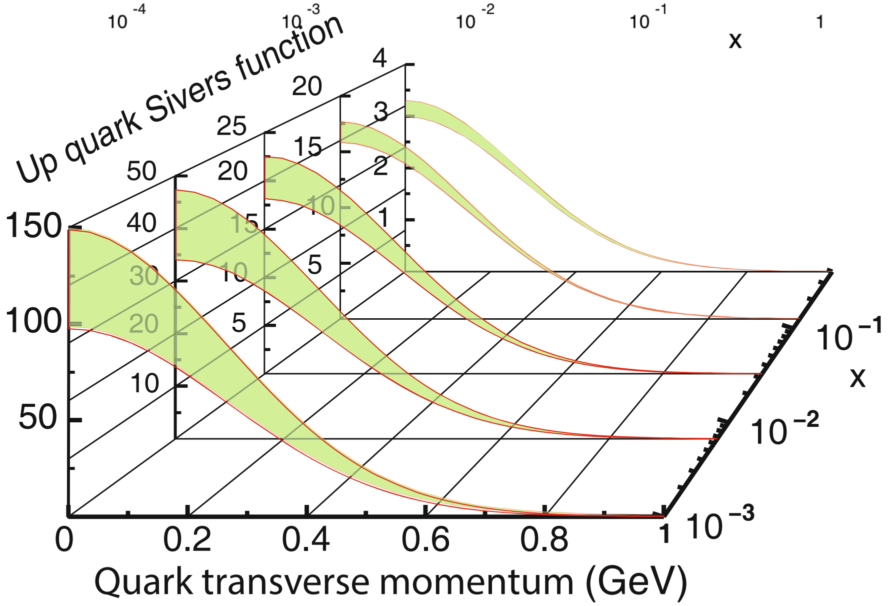
Talk by J. Grames

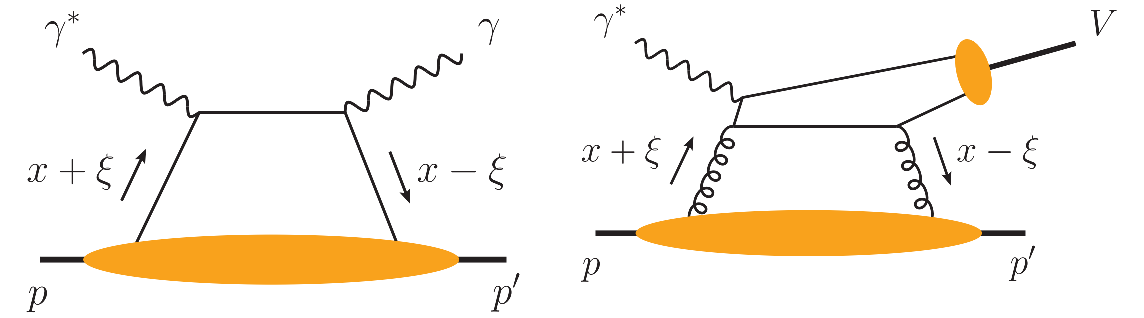
Talk by A. Schmidt

Brookhaven National Laboratory

Tomography of the nucleon @ EIC

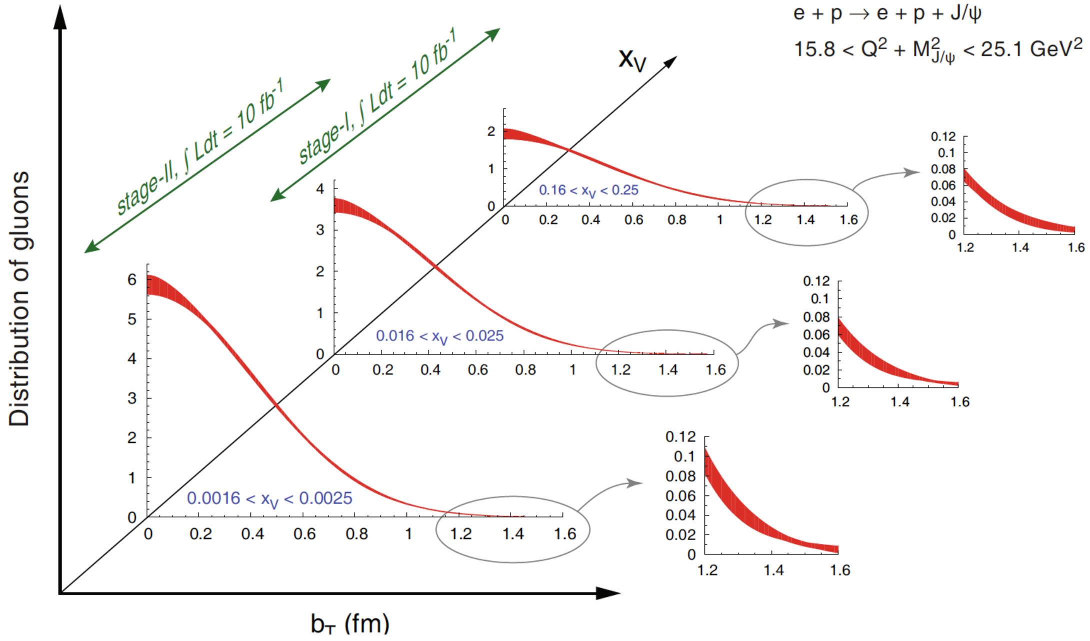






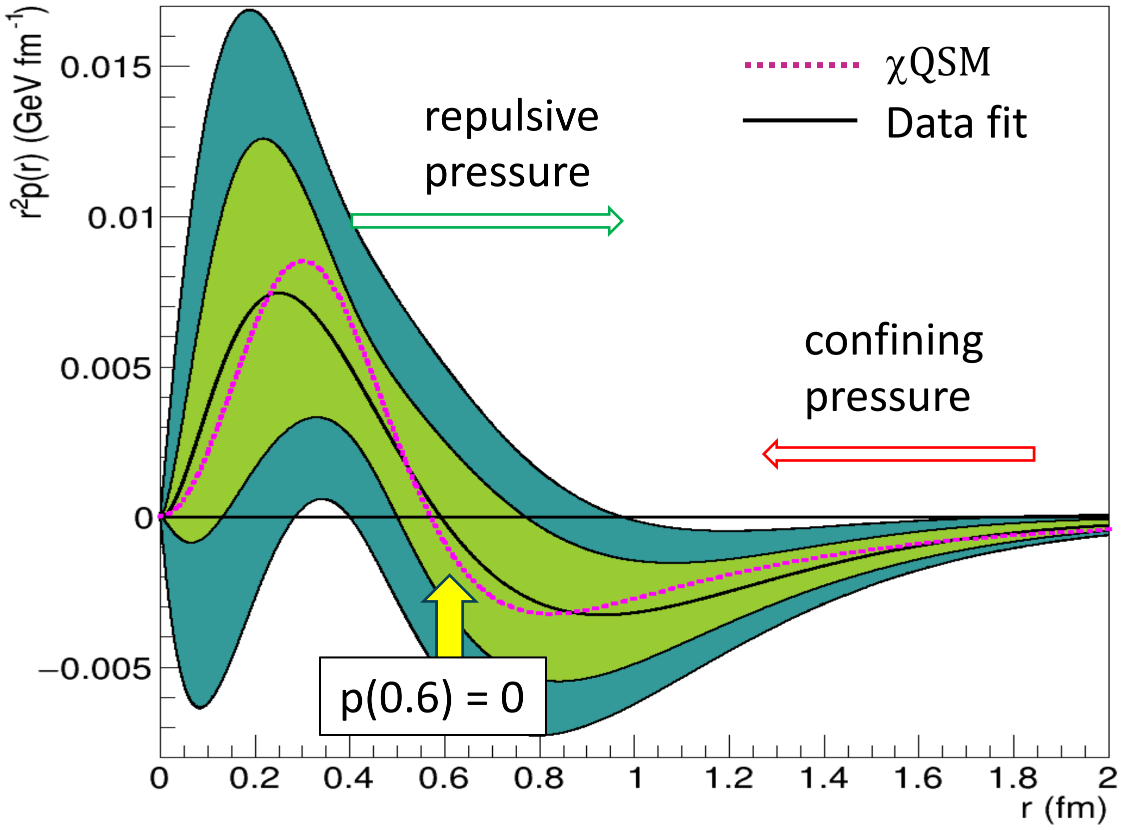
Fourier transform of momentum transferred
= |t| = p-p' → Spatial distribution

0.03 < |t| < 1.6 GeV² 0.2 < |t| < 1.6 GeV² 0.03 < |t| < 0.65 GeV²



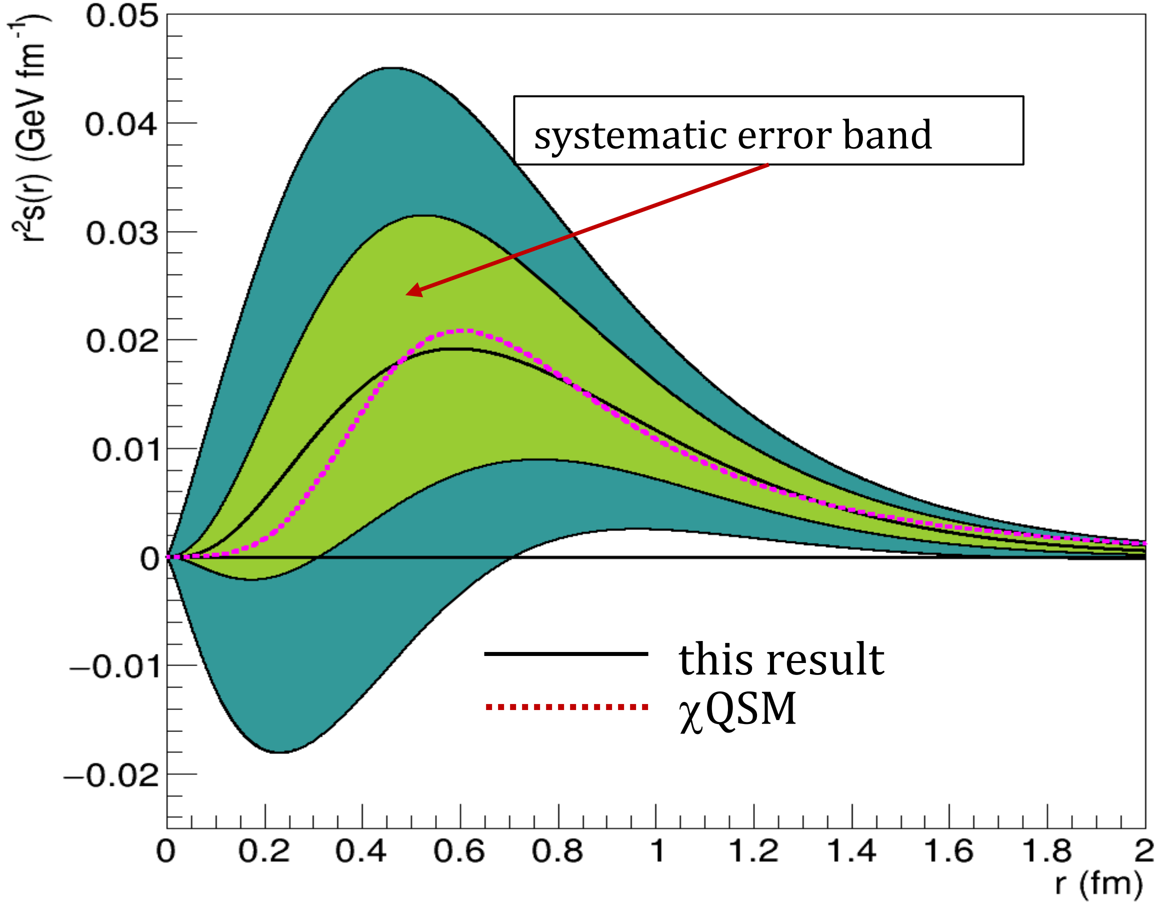
Pressure and Shear Stress on Quarks in the Proton

M. Polyakov, PL B555 (2003) 57



V.B., L. Elouadrhiri, F.X. Girod, Nature 557 (2018) 7705, 39

Shear stress $r^2 s^Q(r)$

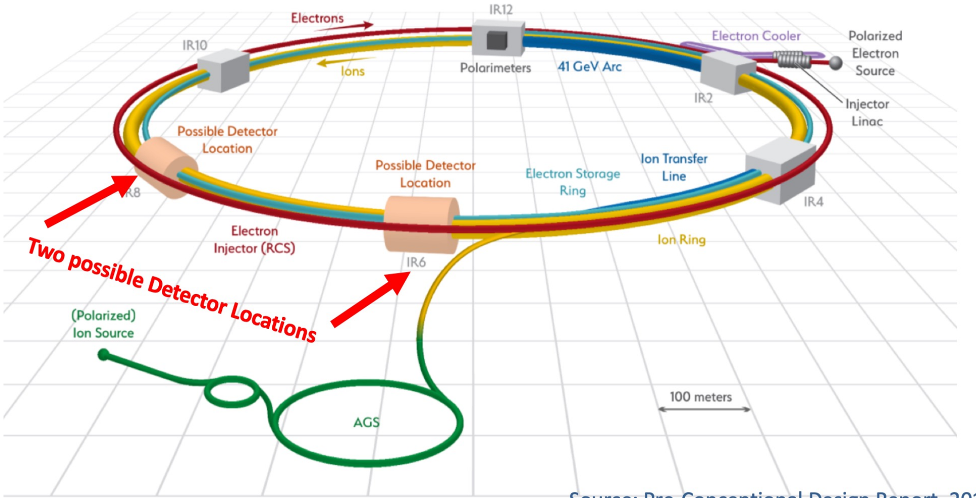


DVCS is a suitable probe of gravitational properties of particles!

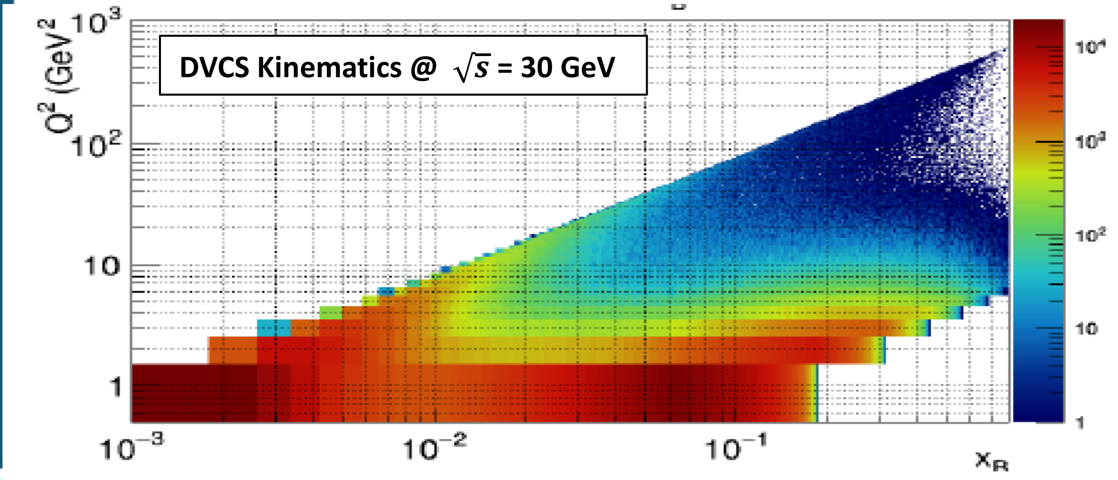
The 2γ field couples to the EMT as gravity does, with many orders of magnitude greater strength.

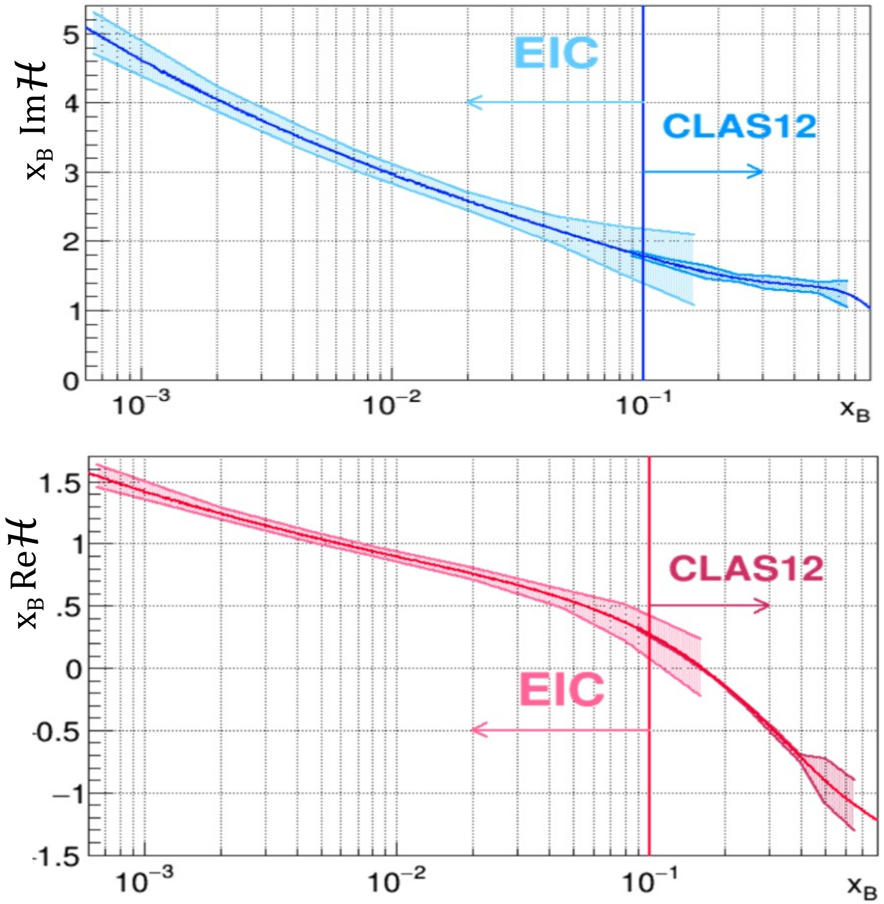
GFF studies at the Electron Ion Collider

CFF $\mathcal{H}$(x,t) extraction at EIC kinematics with integrated luminosity of 200 fb^{-1} w/ polarized electrons and polarized protons.



Source: Pre-Conceptional Design Report, 2019



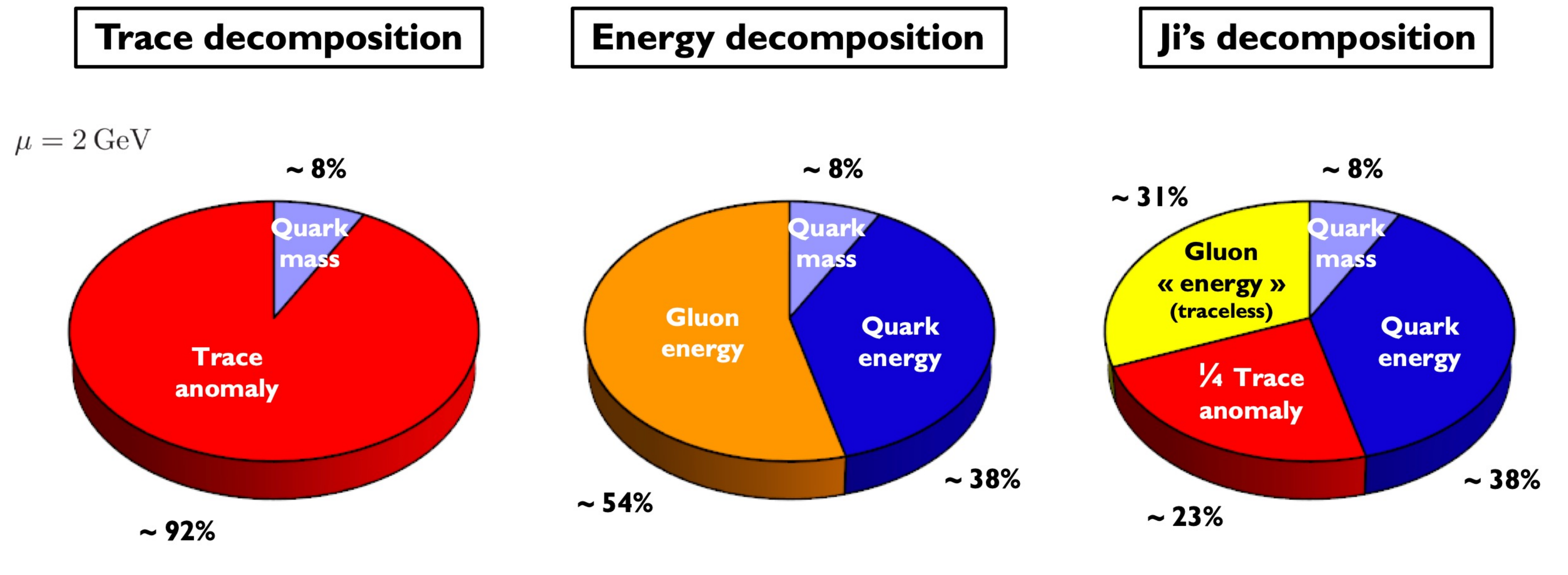


Prog. Part. Nucl. Phys. 131 (2023) 104032, e-Print: [2211.15746](2211.15746)

Credit: F.X. Girod

DIFFERENT MASS DECOMPOSITIONS

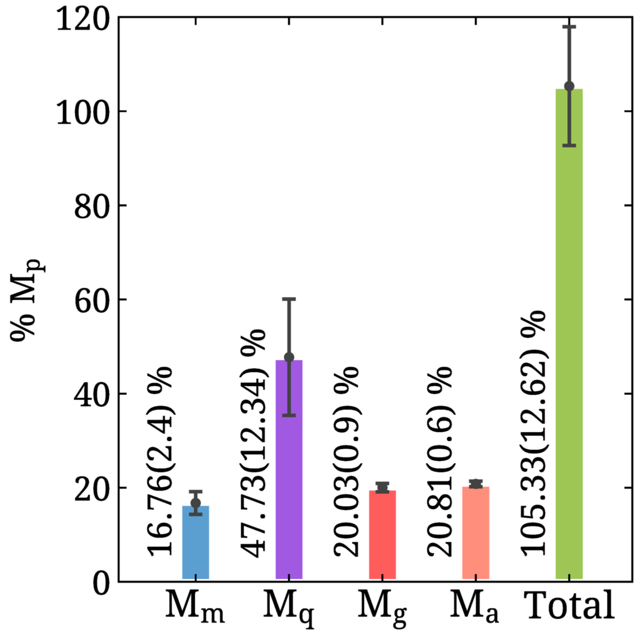
Proton Mass budget decompositions C. Lorcé (from 2022 INT workshop)



Relies on virial theorem

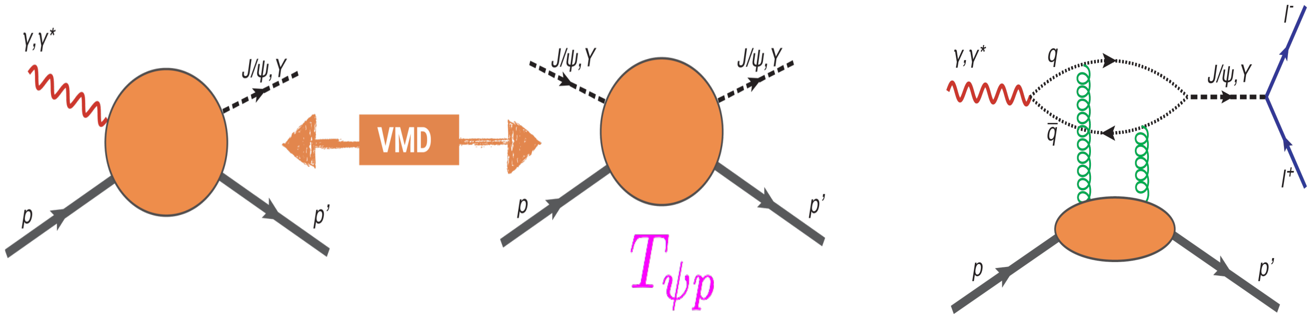
Independent of virial theorem

Motivated by virial theorem



C. Alexandrou et al., (ETMC), PRL 119, 142002 (2017)
Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)

From Cross section to the Trace Anomaly



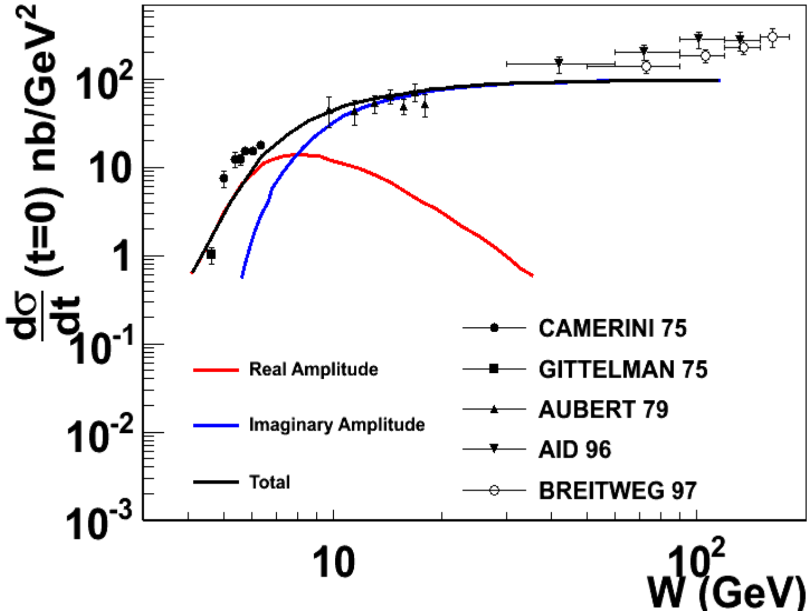
$$\gamma^* + N \to N + J/\psi$$

Heavy quark – dominated by two gluons

$$\langle P|T^\alpha_\alpha|P\rangle = 2P^\alpha P_\alpha = 2M_p^2$$

$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0) = \frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2 \frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

$$\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0) = \frac{1}{64\pi}\frac{1}{m_\psi^2(\lambda^2-m_N^2)}|\mathcal{M}_{\psi N}(s,t=0)|^2$$



- **VMD relates photoproduction cross section to quarknium-nucleon scattering amplitude**
- **Imaginary part** is related to the total cross section through optical theorem
- **Real part contains the conformal (trace) anomaly;** Dominates the near threshold region and constrained through dispersion relation
- D. Kharzeev (1995); Kharzeev, Satz, Syamtomov, and Zinovjev EPJC,9, 459, (1999); Gryniuk and Vanderhaeghen, PRD94, 074001 (2016)

Y. Hatta et al., PRD 98 no. 7, 074003 (2018)
Y. Hatta et al., 1906.00894 (2019)

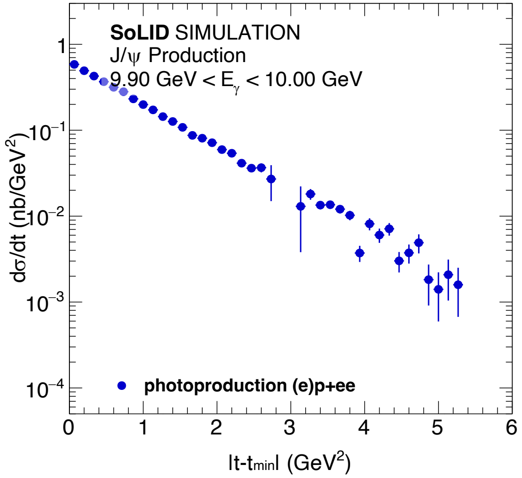
K. Mamo & I. Zahed Phys. Rev. D 101, 086003 (2020)
R. Wang, J. Evslin and X. Chen, Eur. Phys. J. C **80**, no.6, 507 (2020)

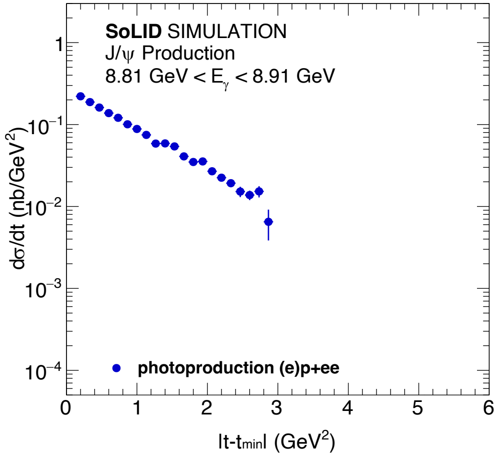
A measurement near threshold could allow access to the trace anomaly

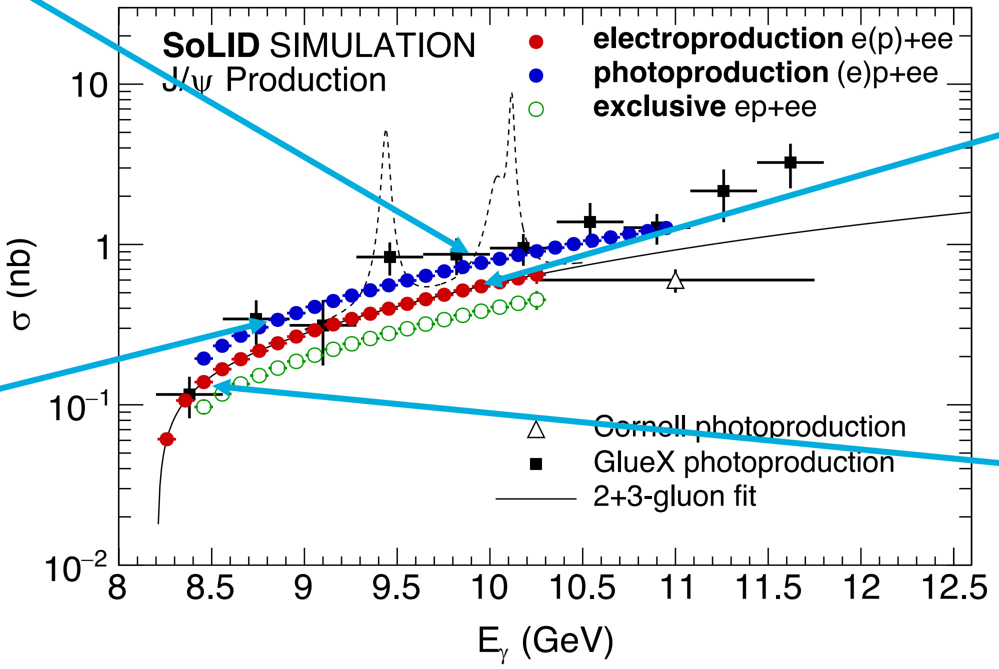
GlueX new data highlight reaction mechanism

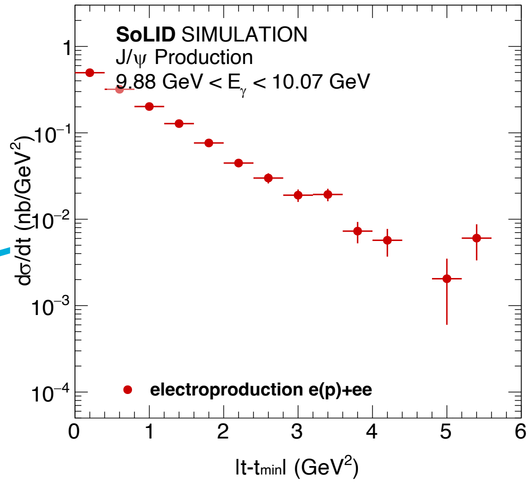
Brookhaven National Laboratory

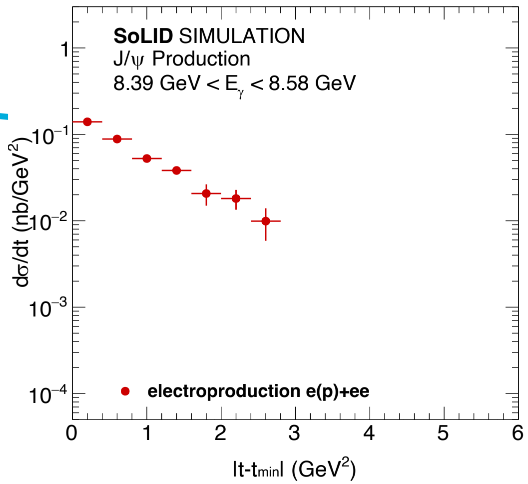
J/Ψ Experiment E12-12-006 @ SoLID





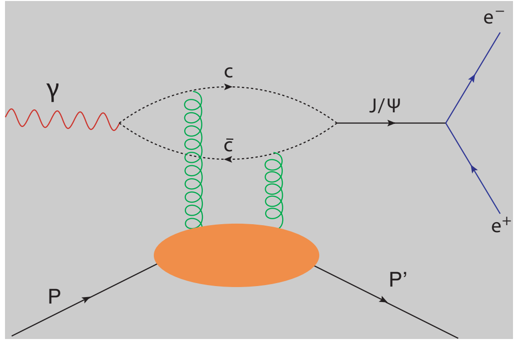






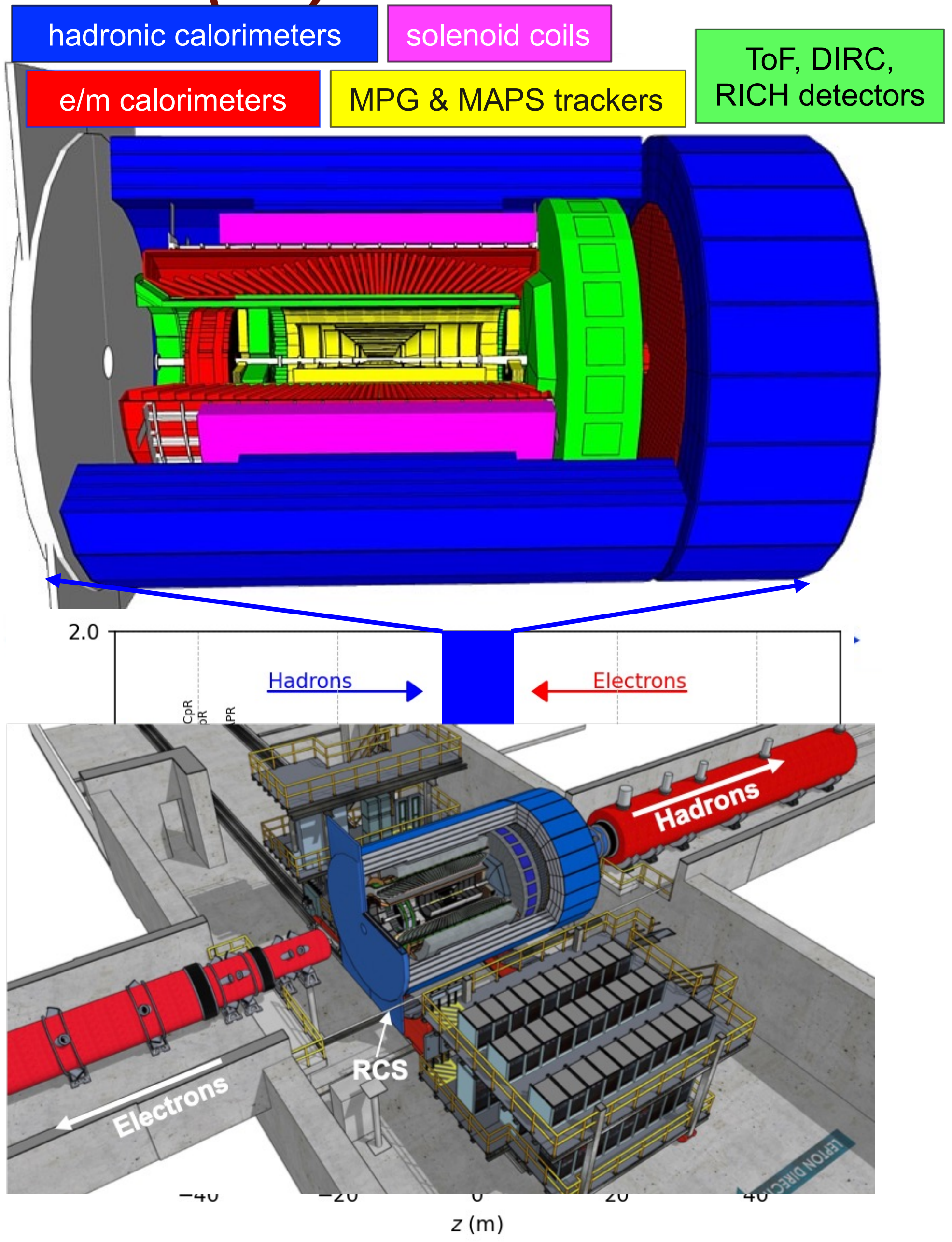
Sensitivity at threshold at about 10^{-3} nb!

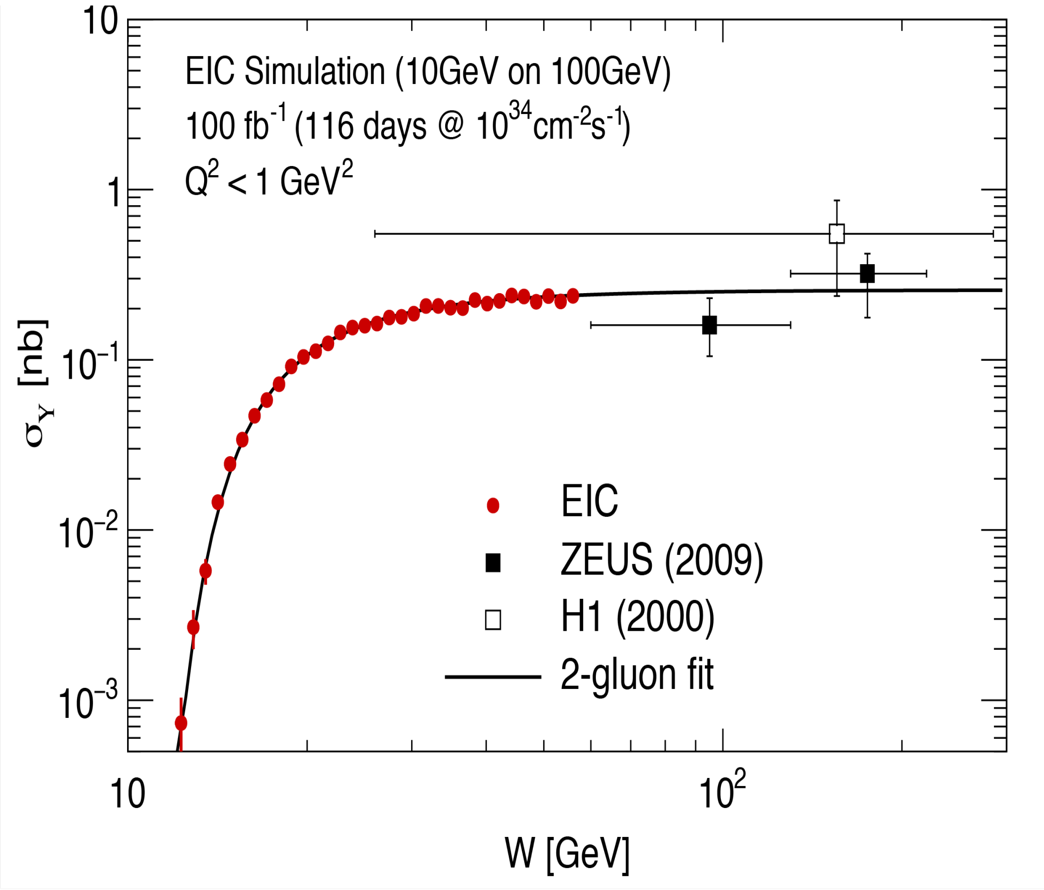
GlueX, PRC**108**, 025201 (2023)
B. Duran *et al.*, Nature **615**, 813 (2023)



Meziani, Joosten
EINN2023

Υ(1S) Production at EIC





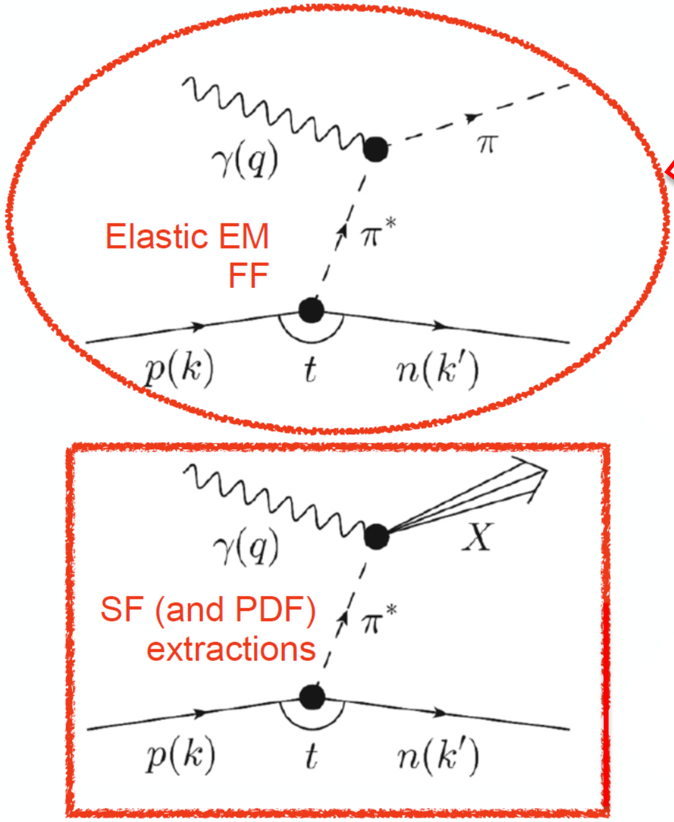
Υ(1S) production at EIC has lower theoretical uncertainties, and provides extra channel to study universality while J/ψ at SoLID has better statistical precision

Gryniuk, Joosten, Meziani, and Vanderhaeghen, PRD 102, 014016 (2020)

Pion/Kaon Structure at Jefferson Lab 12 GeV+ and EIC

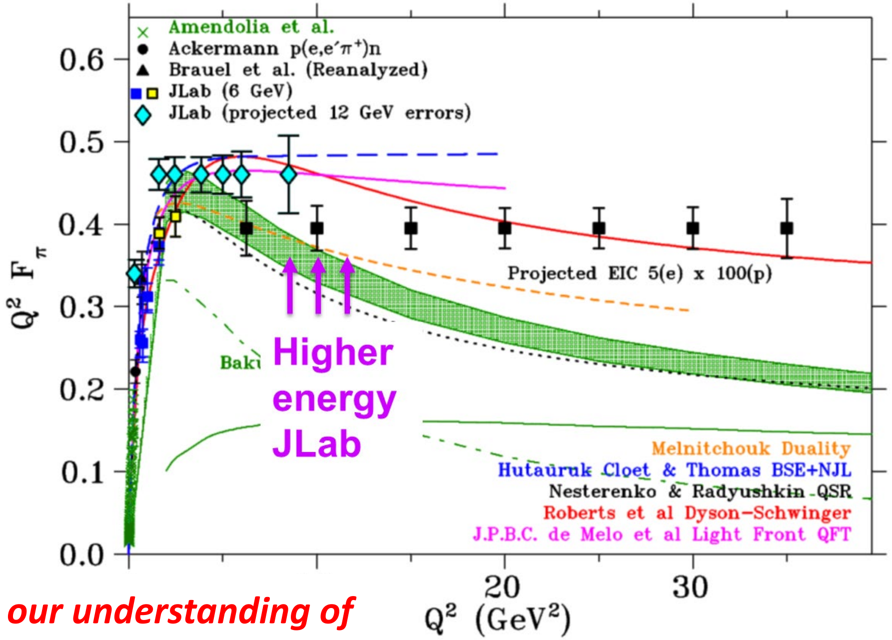
Sullivan

Hard scattering from virtual meson cloud of nucleon



Pion/Kaon elastic EM Form Factor

- Informs how emergent mass manifests in the wave function



Understanding pion/kaon is vital to our understanding of hadron structure and dynamic generation of hadron mass

3

AMBER science questions

There are two bearing columns of the facility:

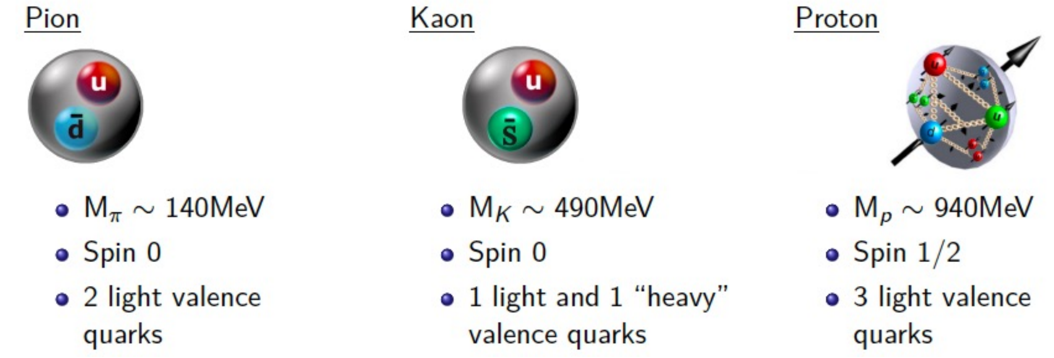
1. **Phenomenon of the Emergence of the Hadron Mass**
2. Proton spin (largely addressed by COMPASS and others, Phase-2)

EHM:

How does the all visible matter in the universe come about and what defines its mass scale?

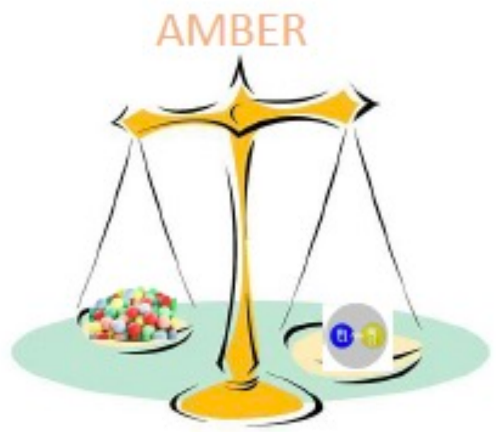
Unfortunately, the Higgs-boson discovery (even if extremely important) does NOT help to answer the question:

- ✓ The Higgs-boson mechanism produces only a small fraction of all visible mass
- ✓ The Higgs-generated mass scales explain neither the "huge" proton mass nor the 'nearly-masslessness' of the pion



Higgs generated masses of the valence quarks:

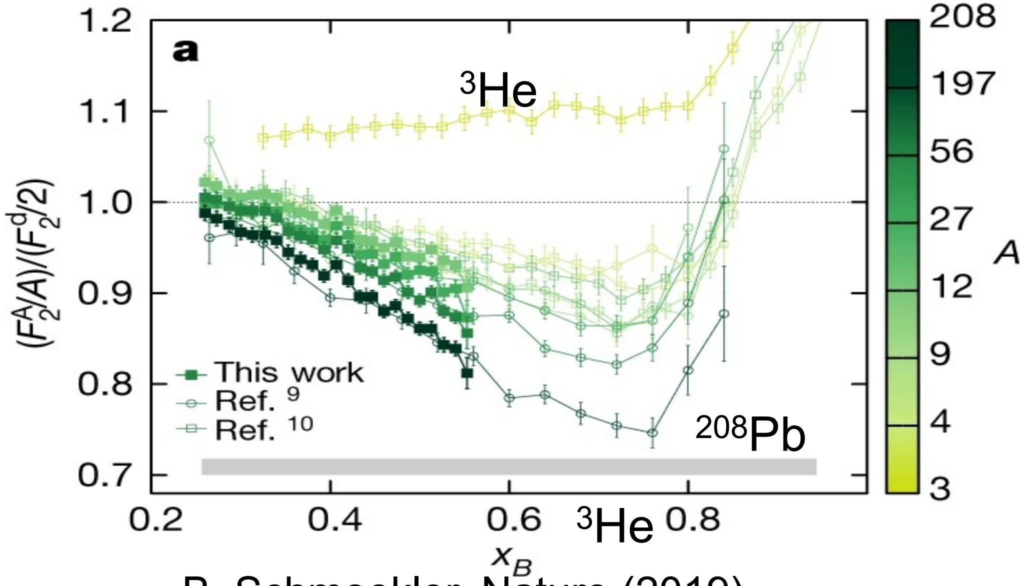
$M_{(u+d)}$ ~ 7 MeV $M_{(u+s)}$ ~ 100 MeV $M_{(u+u+d)}$ ~ 10 MeV



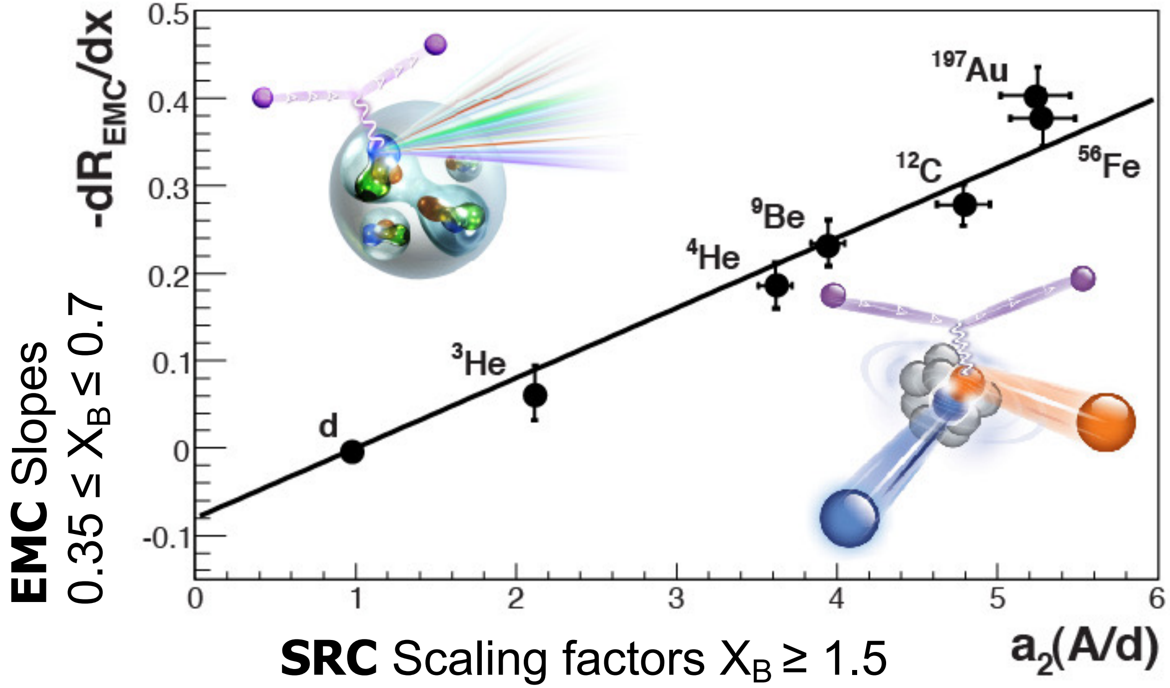
As Higgs mechanism produces a few percent of visible mass, Where from the rest comes?

C. Quintans at EINN2023

Nuclei and QCD – *How does the quark–gluon structure of the nucleon change when bound in a nucleus?* EMC effect

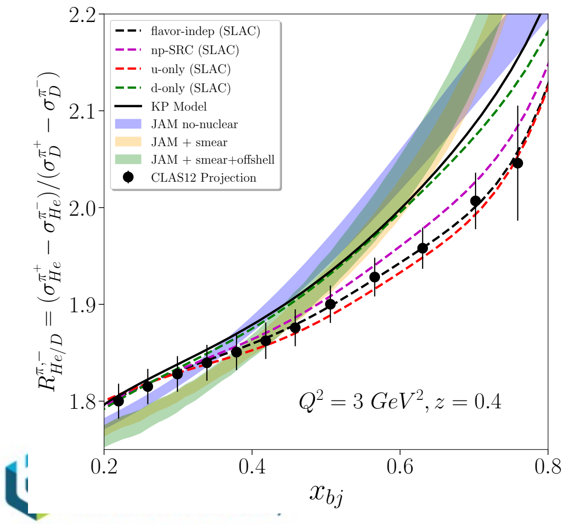


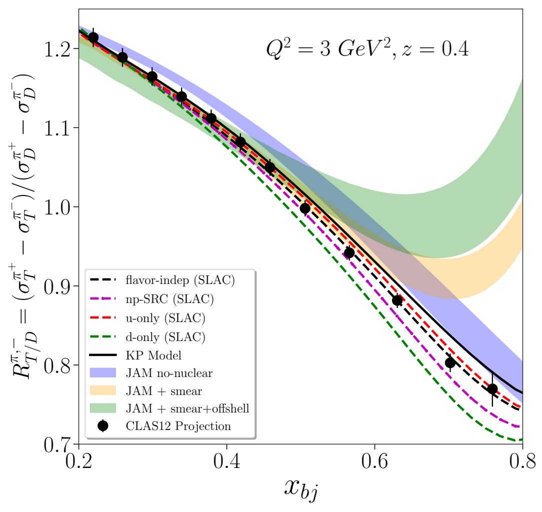
B. Schmookler, Nature (2019)



SRC Scaling factors $X_B \geq 1.5$

Probe Flavor EMC effect using SIDIS





Hen et al, RMP **89**, 045002 (2017)

SRC data from Fomin et al

EMC data from Gomez et al and Seely et al

Weinstein et al, PRL**106**, 052301 (2011)

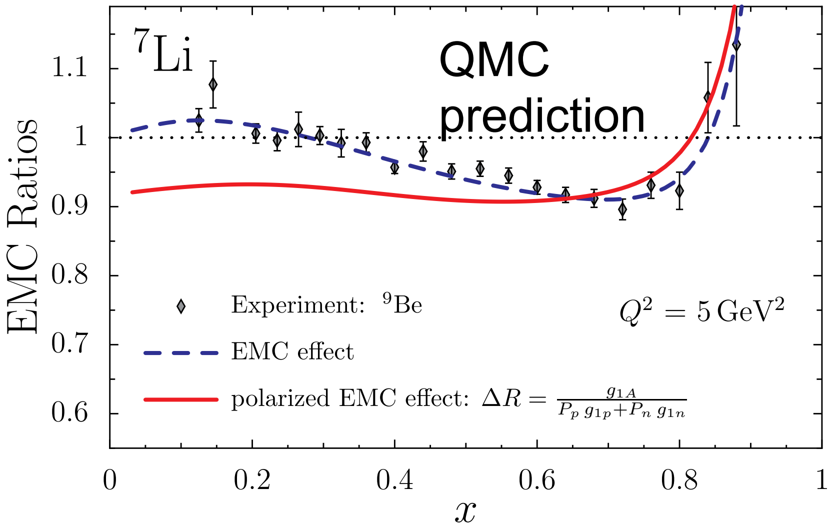
Hen et al, PRC**85**, 047301 (2012)

K. Tu@EINN2023

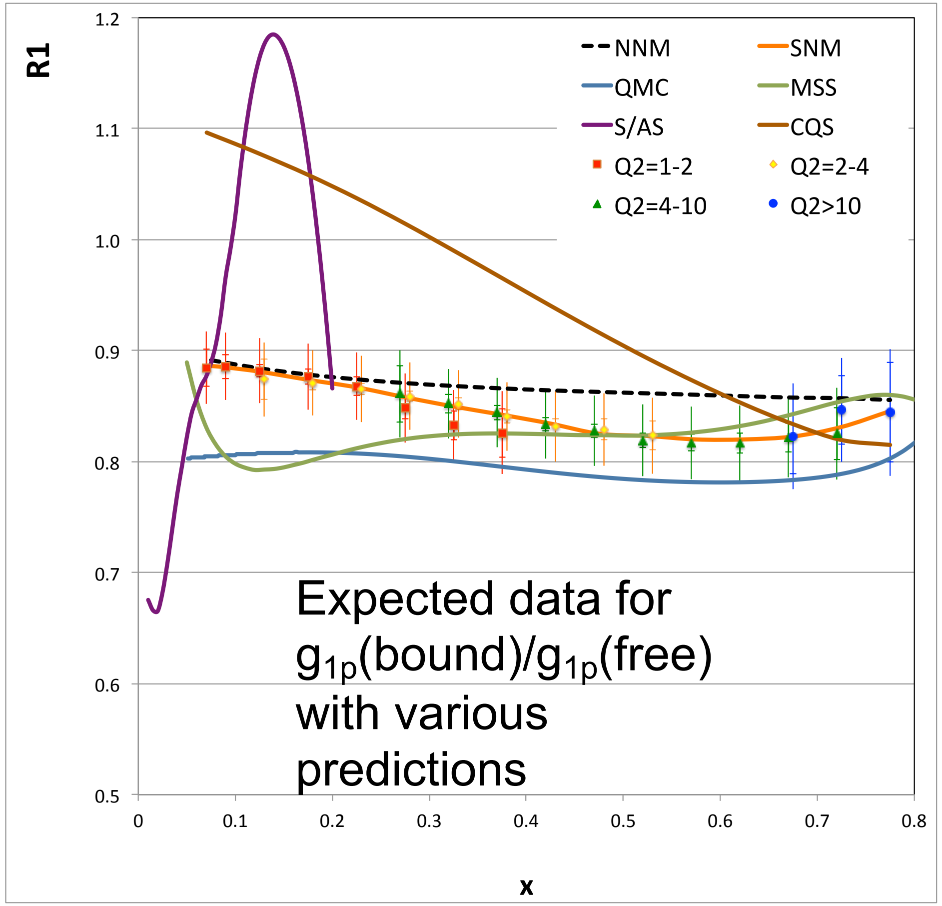
Polarized EMC effect: $^7\overrightarrow{Li}(\vec{e}, e')$ DIS

Is the valence nucleon modified?

- Most EMC experiments average over **all** nucleons
- Measure modification of **polarized** structure function g_{1p} on a single valence nucleon!



$\Delta\sigma$ Ratio $\propto [N^+ - N^-](^7Li) / [N^+ - N^-](p)$



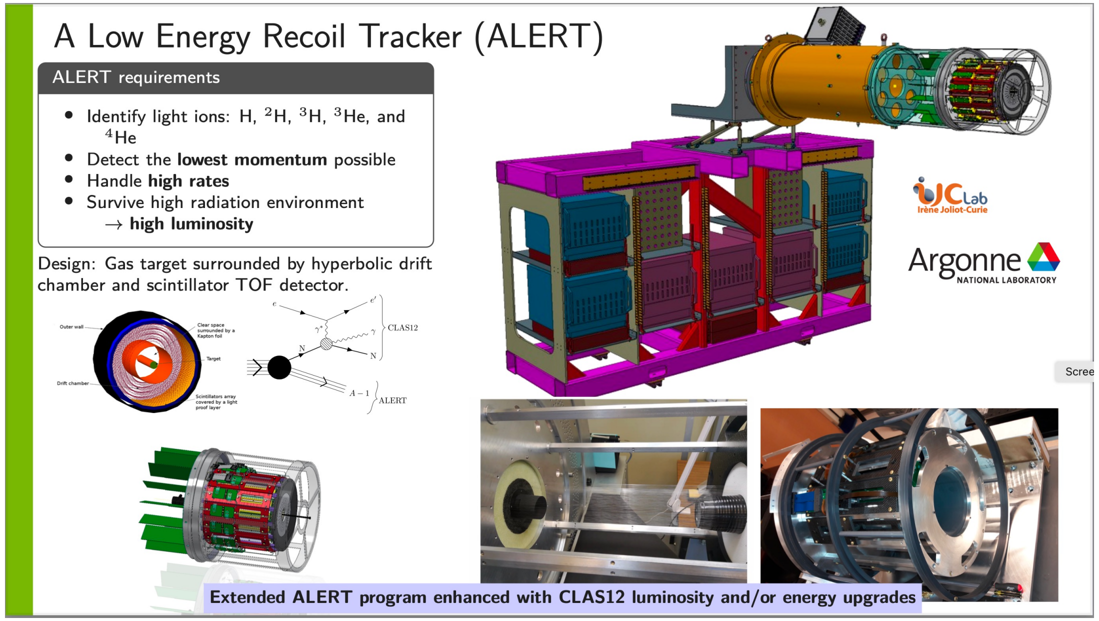
NNM = Shell model (p 87% pol.)
SNM = Standard Nuclear Model (convolution w/out change in medium; equiv. to SRC model)
QMC = Mean Field (Quark-Meson Coupling)
MSS (rescaling/modified sea scheme)
S/AS = Shadowing / Antishadowing (Guzey/Strikman)
CQS = Chiral Quark Soliton (Smith/Miller)

Larry Weinstein at QCD Townhall Meeting September 2022

(CLAS12 Run Group G)

The ALERT Run Group

A comprehensive program to study nuclear effects with CLAS12



Measurements	Particles detected	Targets	Beam time request	Luminosity*
ALERT Commissioning	p, d, ^{4}He	H and He	5 days	Various
Tagged EMC	p, ^{3}H, ^{3}He	^{2}H and He	20 + 20 days	3.10^{34} cm^{-2}s^{-1}
Tagged DVCS	p, ^{3}H, ^{3}He	^{2}H and He	20 + 20 days	3.10^{34} cm^{-2}s^{-1}
Nuclear GPDs	^{4}He	He	extra 10 days on He	6.10^{34} cm^{-2}s^{-1}
Additional Topics	p, d, ^{3}H, ^{3}He	^{2}H and He	20 + 20 + (10) days	$3(6).10^{34}$ cm^{-2}s^{-1}
TOTAL			55 days	

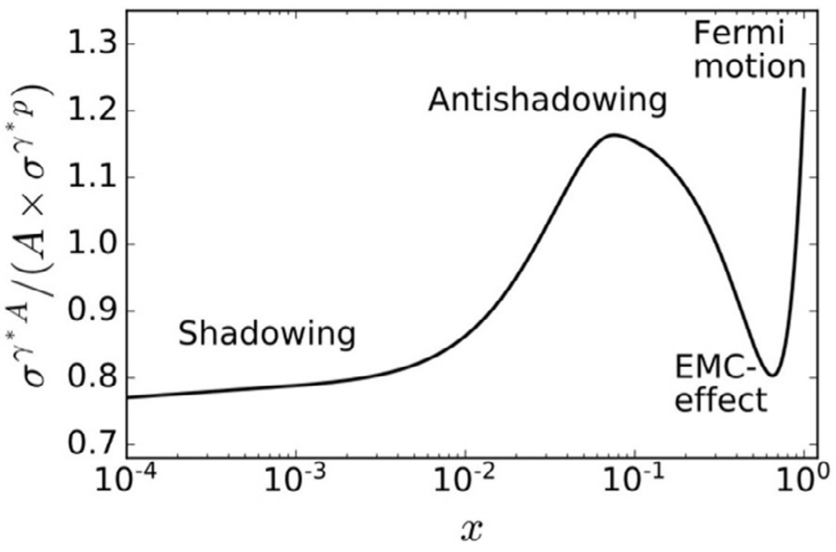
Tagged EMC – address key questions about the EMC effect

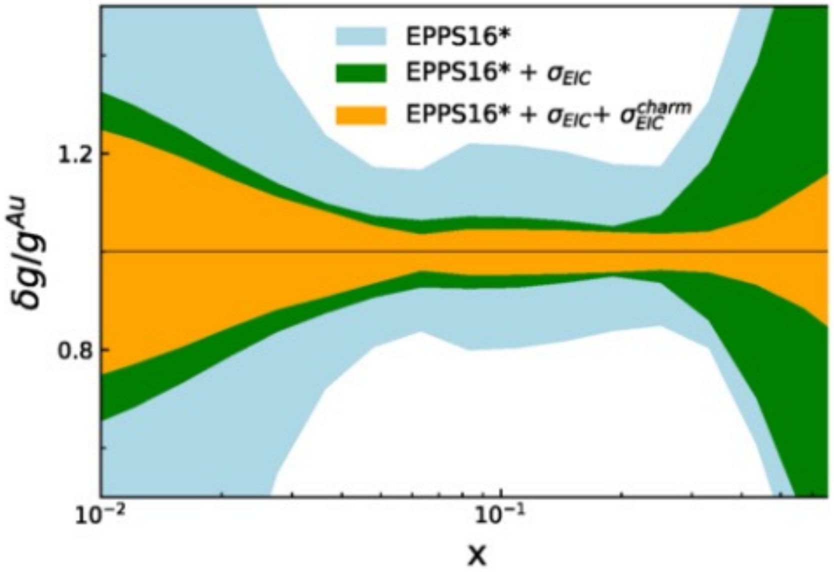
Tagged GPDs – directly compare quark and gluon radii

Tagged DVCS – connect partonic and nucleonic modifications

Natural extension of ALERT Physics into small-x in the EIC era

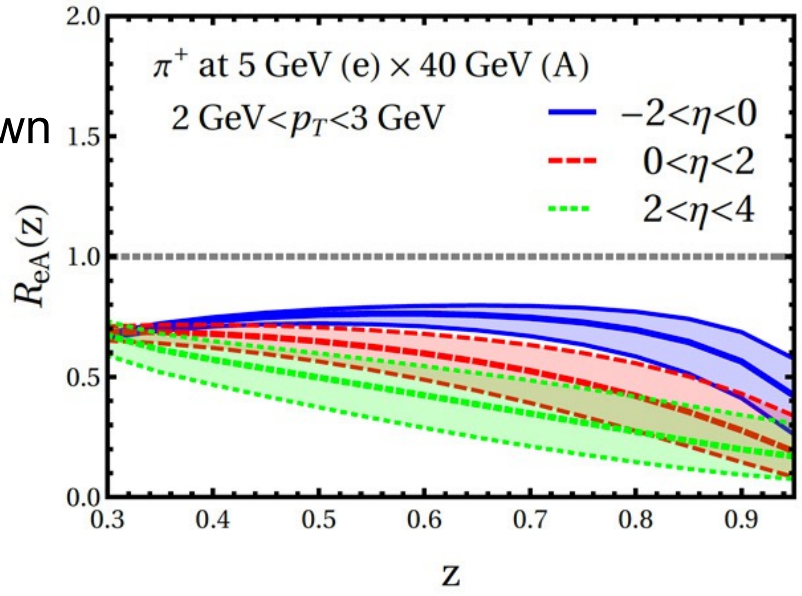
Nuclei and QCD at the EIC

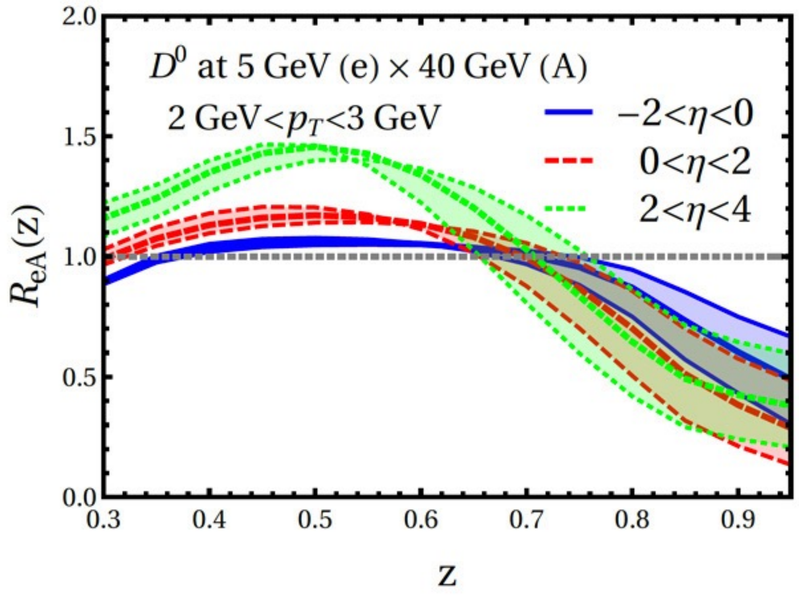




Uncertainty bands gluon density (Au)

Relative particle production eA vs ep, pions (left), shown largest suppression @EIC

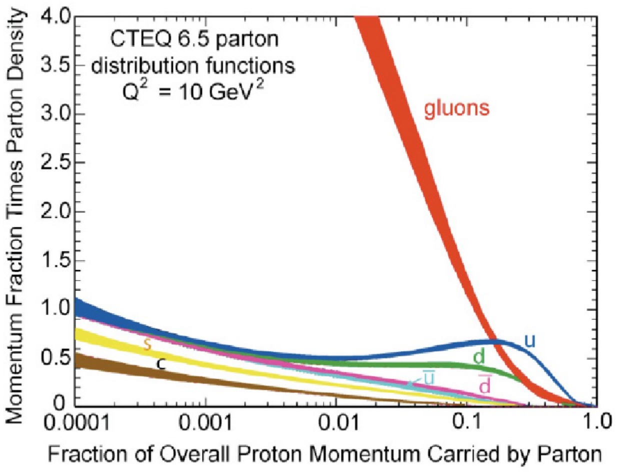


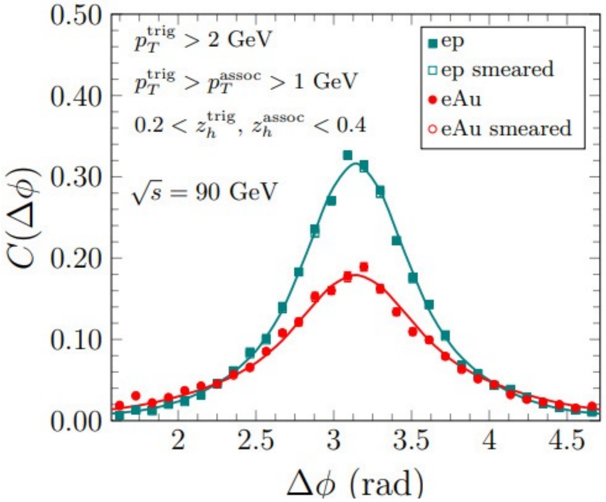


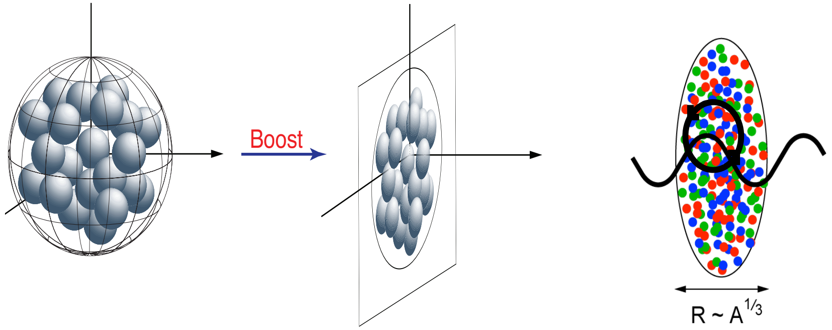
Heavy flavor Mesons (right): differentiate hadronization models

Brookhaven National Laboratory

Low x physics with nuclei

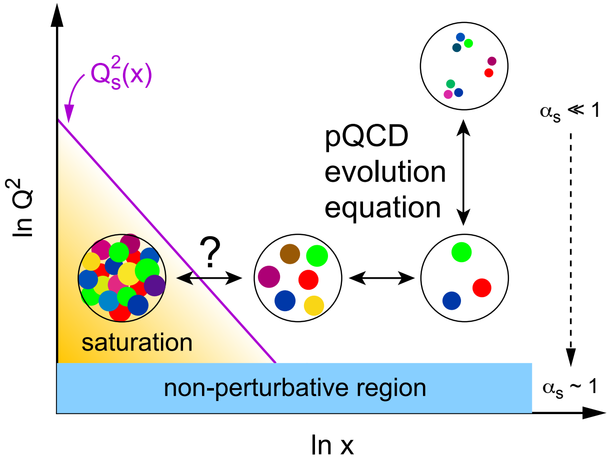






$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

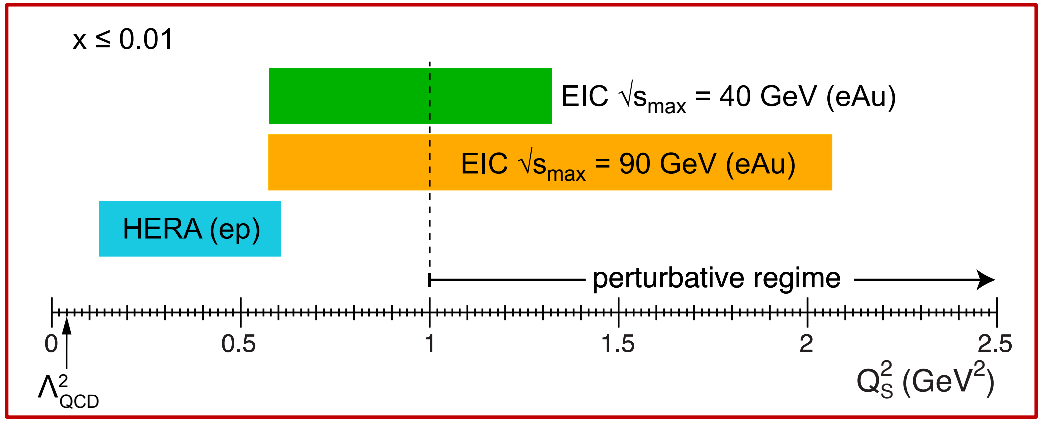
$L \sim (2m_N x)^{-1} > 2\ R_A \sim A^{1/3}$



A saturation model prediction for EIC measurement of hadron–hadron correlation function C versus their azimuthal angular separation Δϕ for electron–proton and electron–gold collisions

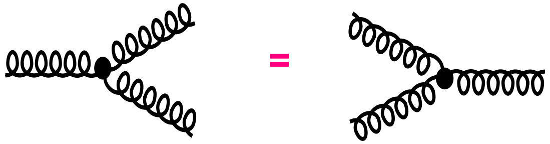
300 GeV

Accessible range of saturation scale $Q_s{}^2$ at the EIC with e+A collisions.
arXiv:1708.01527



gluon emission

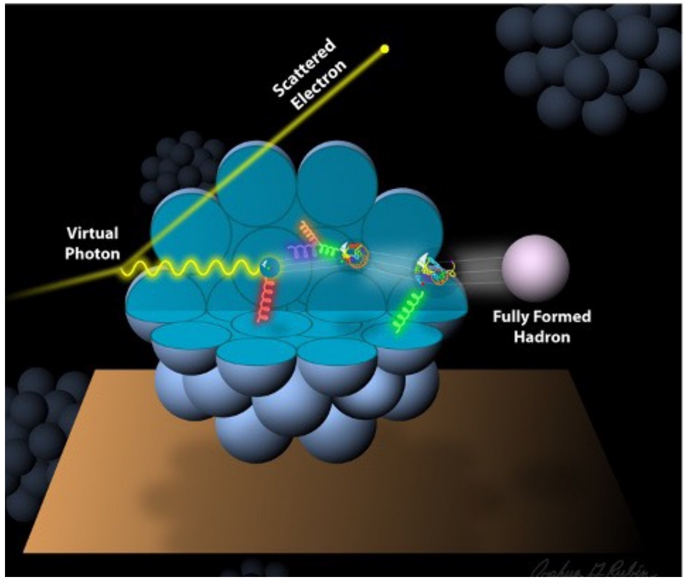
gluon recombination



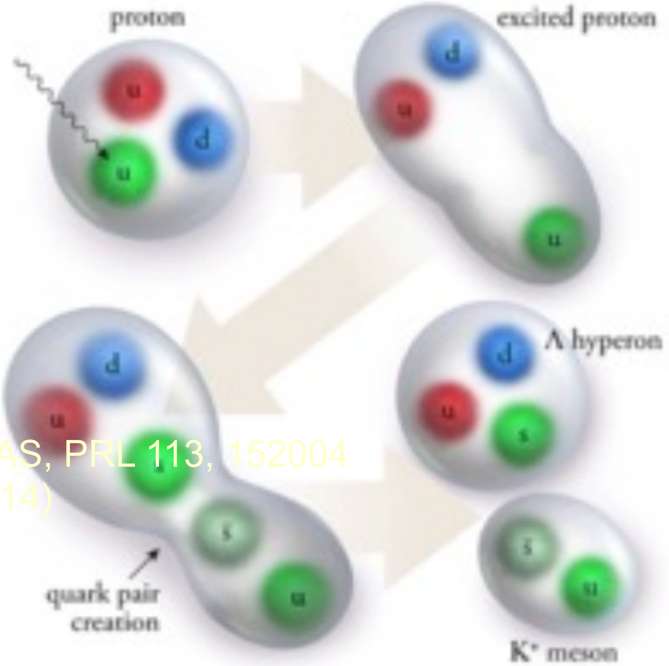
At Q_s

A. Accardi *et al.*, EPJA **52**, 268 (2016)

Formation of QCD bound states: Different mechanisms of hadronization



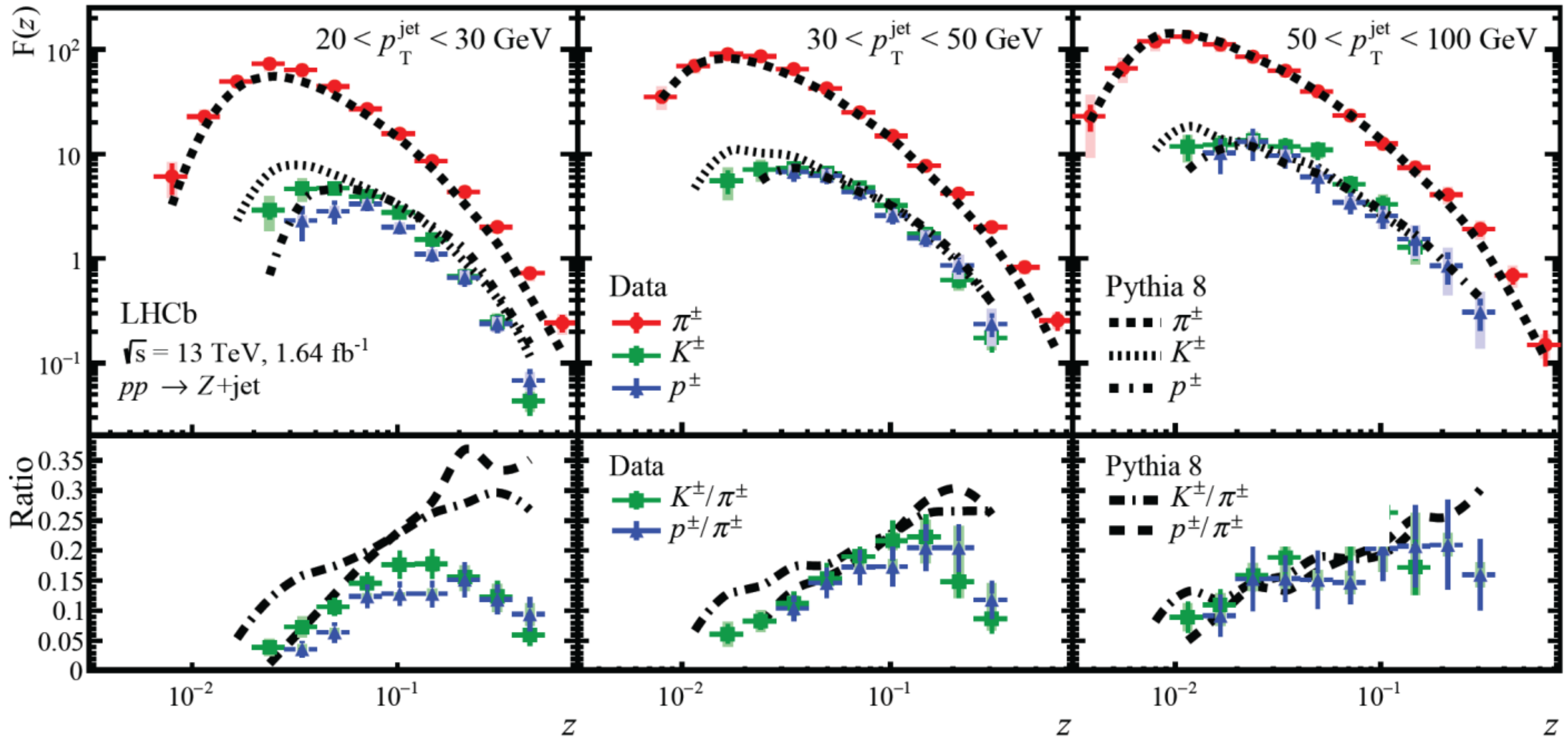
- High-energy limit of “string-breaking” or “cluster” pictures
- Coalescence/recombination of partons nearby in phase space
- Threshold production
- Production via decay from other hadrons
- …?



CLAS, PRL 113, 152004 (2014)

C. Riedl, R. Seidl @EINN2023

Identified hadron-in-jet fragmentation functions

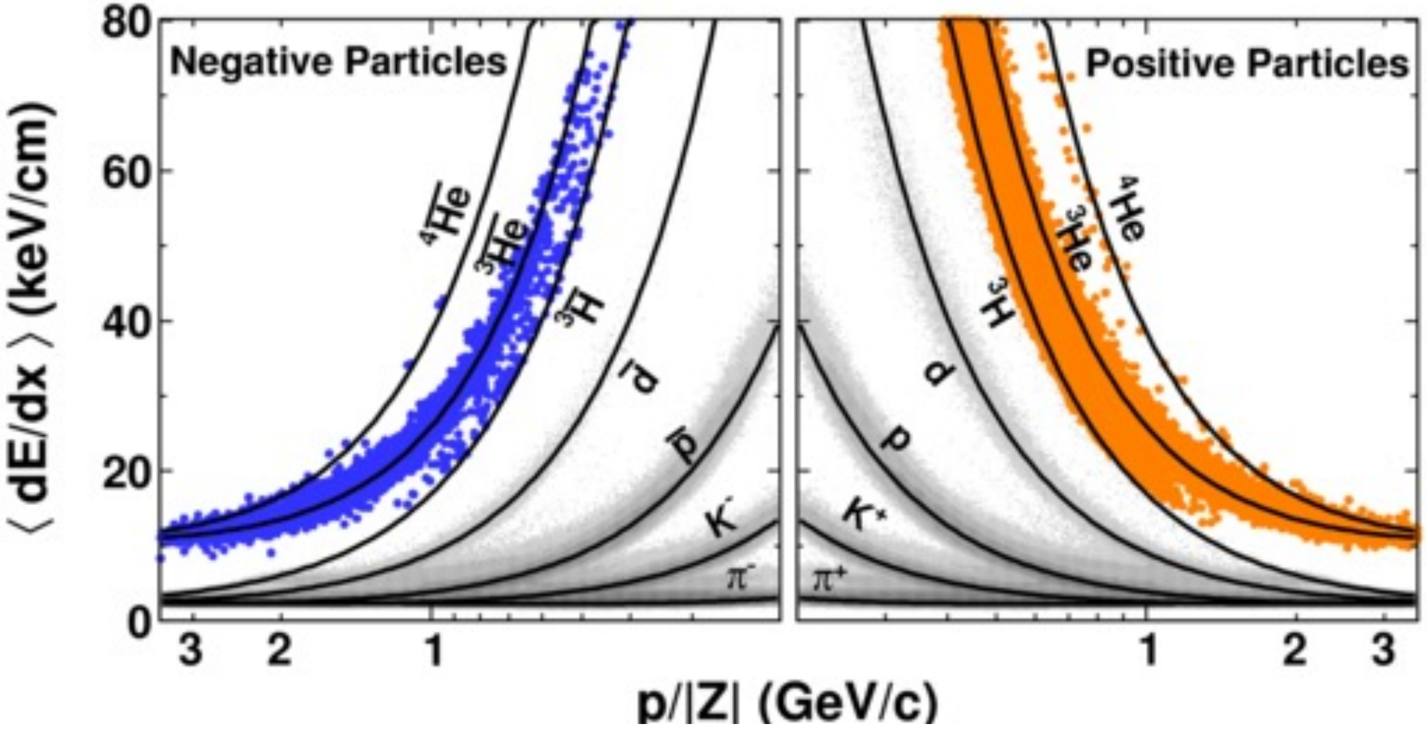


R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D **108**, L031103

Hadron-in-jet theory developments + measurements offer new opportunities

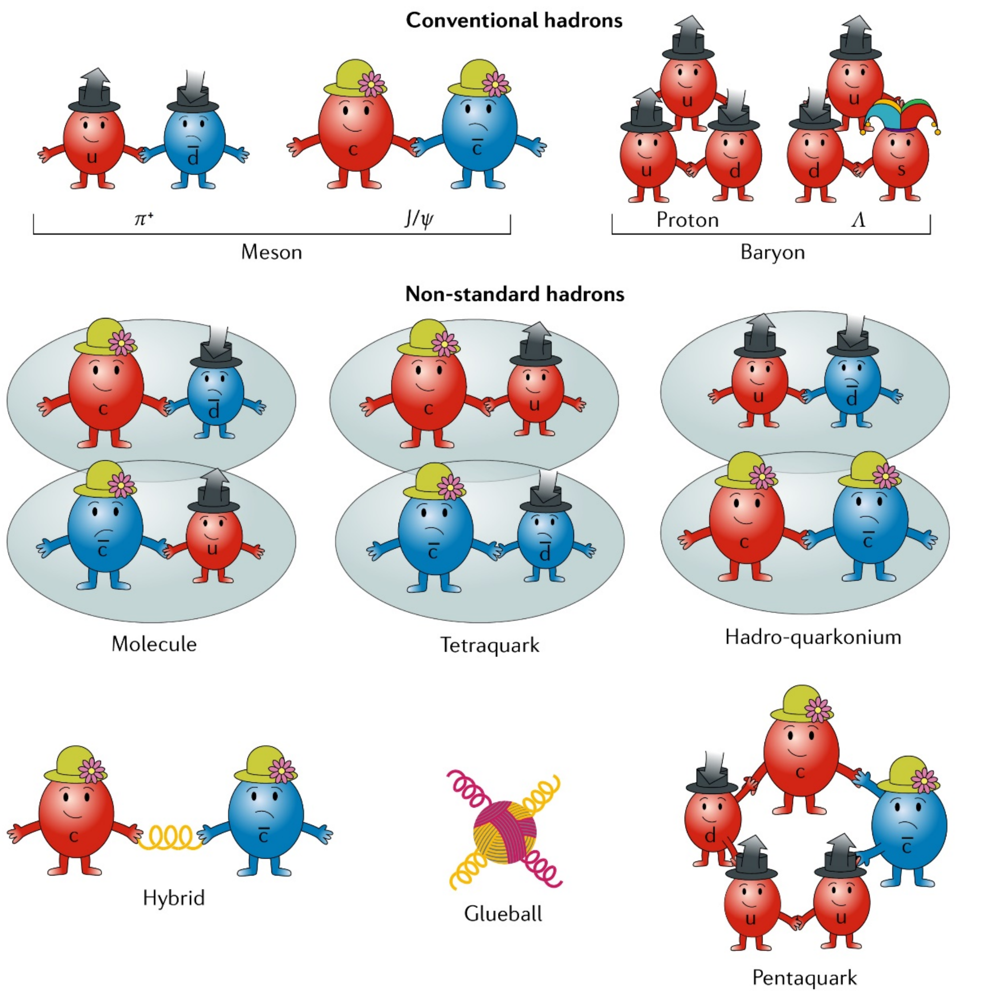
R. Seidl@EINN2023

Bound states of hadronic bound states: Creating (anti)nuclei!

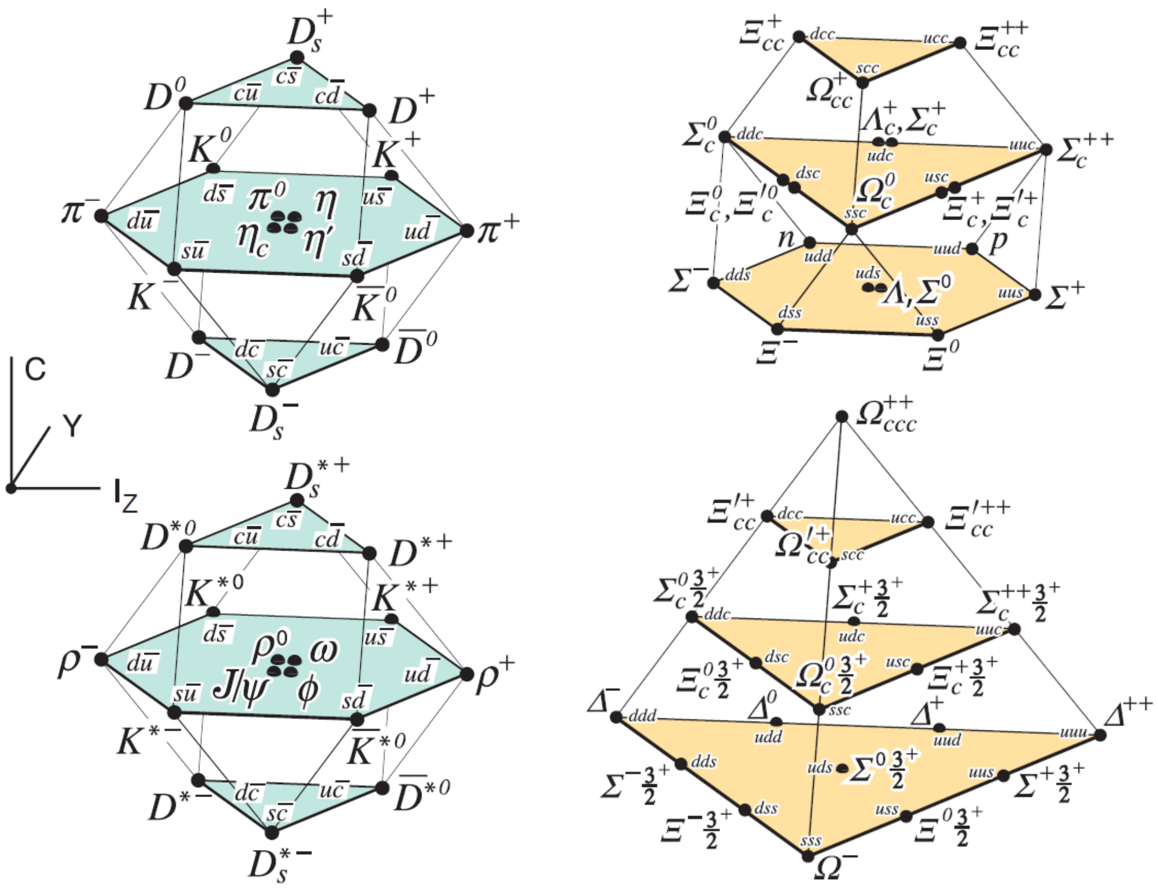


Are any of the recently discovered tetraquarks and pentaquarks hadronic molecules?
What can we learn about hadron structure and/or hadronization from these exotic hadrons?

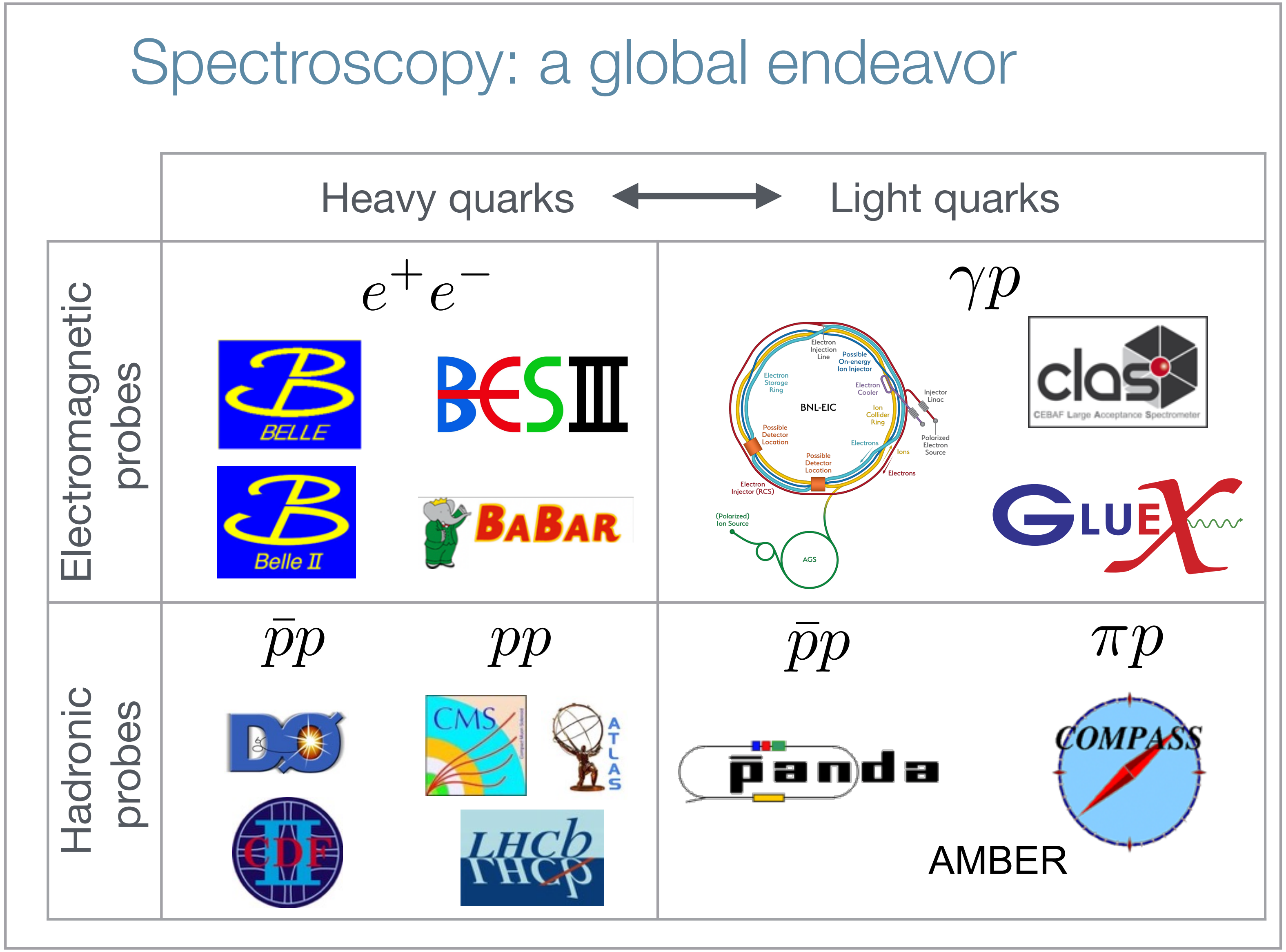
Hadrons: conventional & exotic



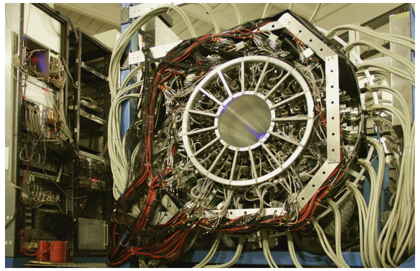
CZY & S. L. Olsen, *Nature Reviews Physics* **1**, 480 (2019)



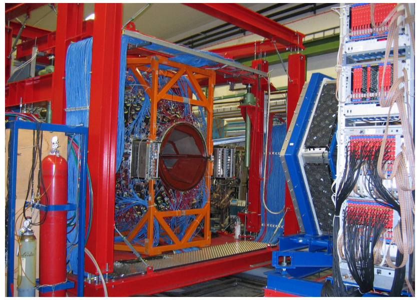
SU(4) multiplets of mesons & baryons



CBELSA/TAPS (ELSA),



CBALL (MAMI),



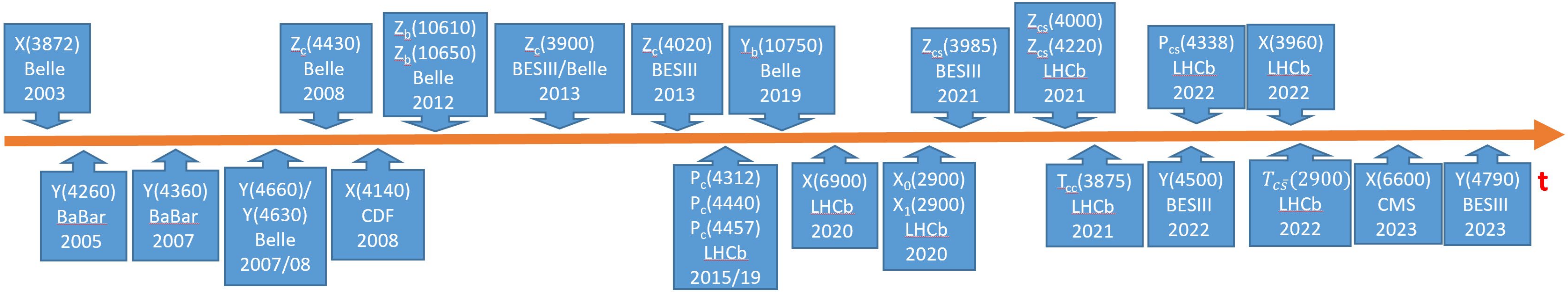
LEPS (Spring-8), BGOOD (El
GRAAL (ESRF),

⇔ polarized beam,
polarized target

Results from photoproduction do now enter the PDG and determine the properties of baryon resonances! Observation of new baryon resonances (U. Thoma @Erice School 2023)

A. D'Angelo, B. Briscoe, C. Quintans@EINN2023

- Lots of states with heavy quarks (c, b) and exotic properties were observed since the discovery of the X(3872) in 2003!
- They are candidates of hadronic molecules, hybrids, and multiquark states.



Z_Q: I=1 & a $Q\bar{Q}$ pair
P_Q: I=1/2 & a $Q\bar{Q}$ pair
Y: $J^{PC}=1^{--}$
$T_{QQ'}$: tetraquark state
X: other states

New spectrum emerges although more effort is needed to understand the nature of them.

Photoproduction of XYZ states

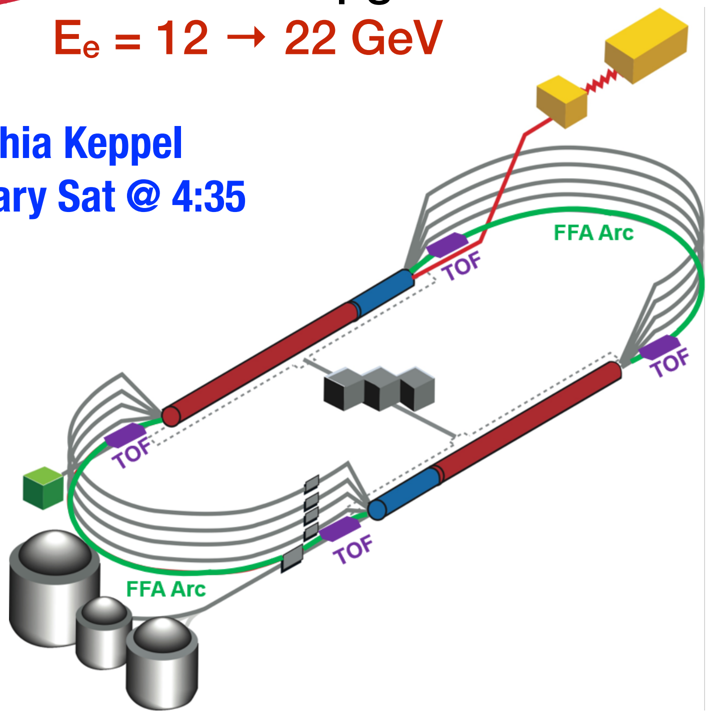
Future

Complementary access to charmonium photoproduction with higher energy facilities

Jefferson Lab upgrade:

E_e = 12 → 22 GeV

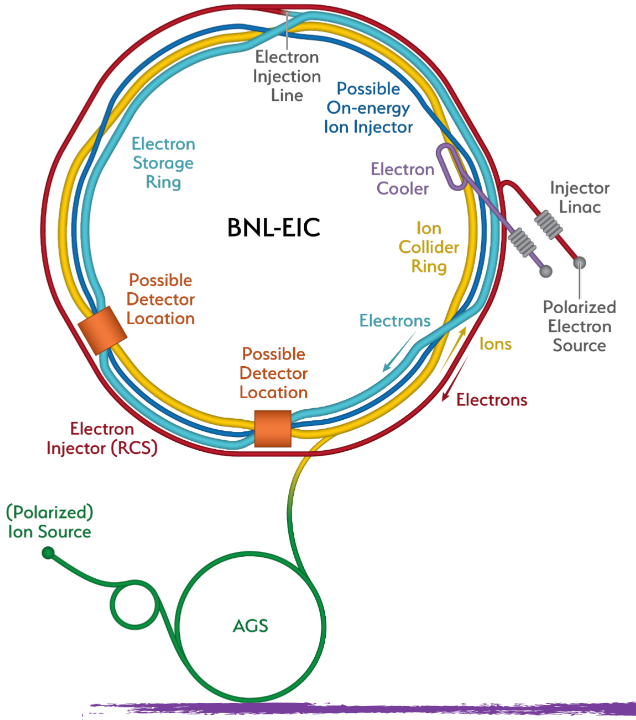
Thia Keppel
Plenary Sat @ 4:35



$$\sqrt{s}_{\gamma p} = 1.5 \ - \ 6.5 \text{ GeV}$$

$$\mathscr{L}_{ep} = 10^{35} - 10^{37} \ cm^{-2}s^{-1}$$

Electron Ion Collider (EIC)



$$\sqrt{s}_{\gamma p} = 5 \ - \ 141 \text{ GeV}$$

$$\mathscr{L}_{ep} = 10^{34} \ cm^{-2}s^{-1}$$

The Electron-Ion Collider

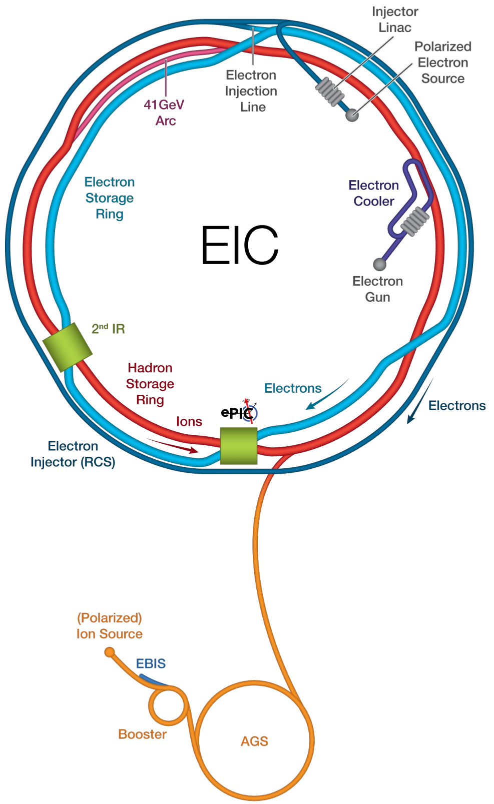
Polarized electrons colliding with polarized protons, polarized light ions, and heavy ions will allow us to study sea-quarks and gluons to understand:

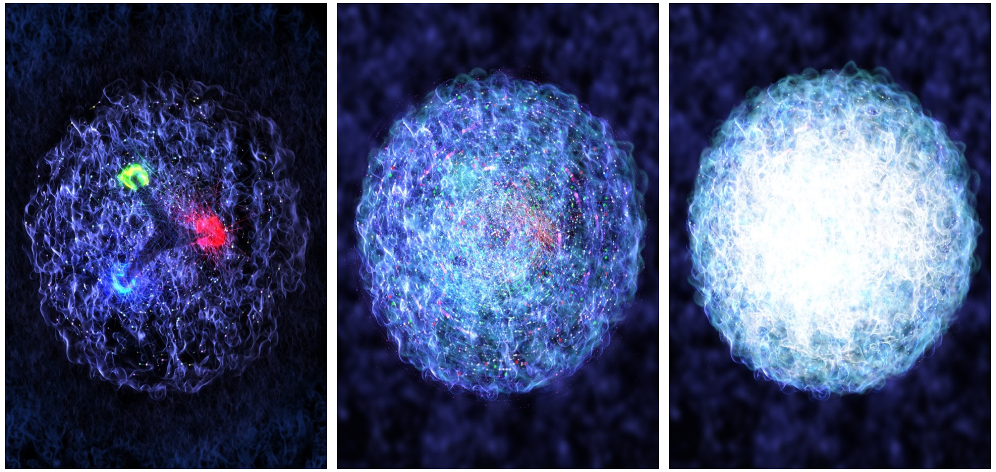
- mass and spin of the proton.
- spatial and momentum distribution of low-x partons
- Possible gluon saturation
- modifications of parton distribution functions when a nucleon is embedded in a nucleus
- hadron formation

The EIC is a partnership between BNL and Jefferson Lab.

Project is aiming for CD2/3 in 2025

ePIC detector design is advanced. Significant international support and participation (160+ institutions, 24 countries).





Major discovery potential!

Thank you for your time and attention!

Brookhaven National Laboratory is supported by the U.S. Department of Energy's Office of Science. Duke part of the research is supported by DOE Contracts No. DE-FG02-03ER41231

Thank many from whom I "borrowed" slides, many speakers at this conference, and many involved in the 2023 NSAC LRP and 2022 QCD Town Meeting