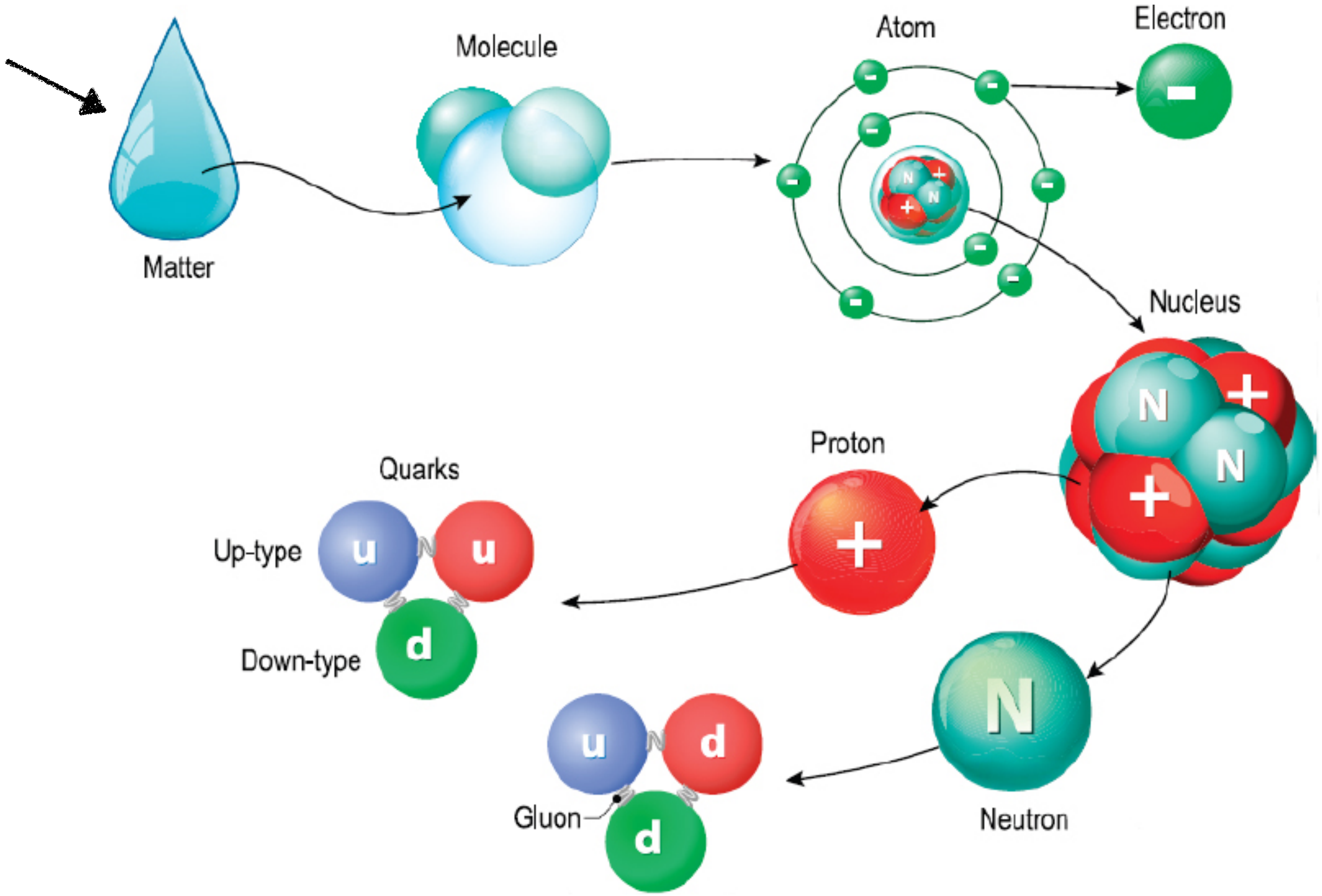
Exploring the Structure of Hadrons at the Intensity Frontier

Rachel Montgomery (University of Glasgow)

On behalf of many from the UK and International JLab Communities …

IOP Nuclear Physics Conference 2025
University of Manchester

What are we made of?

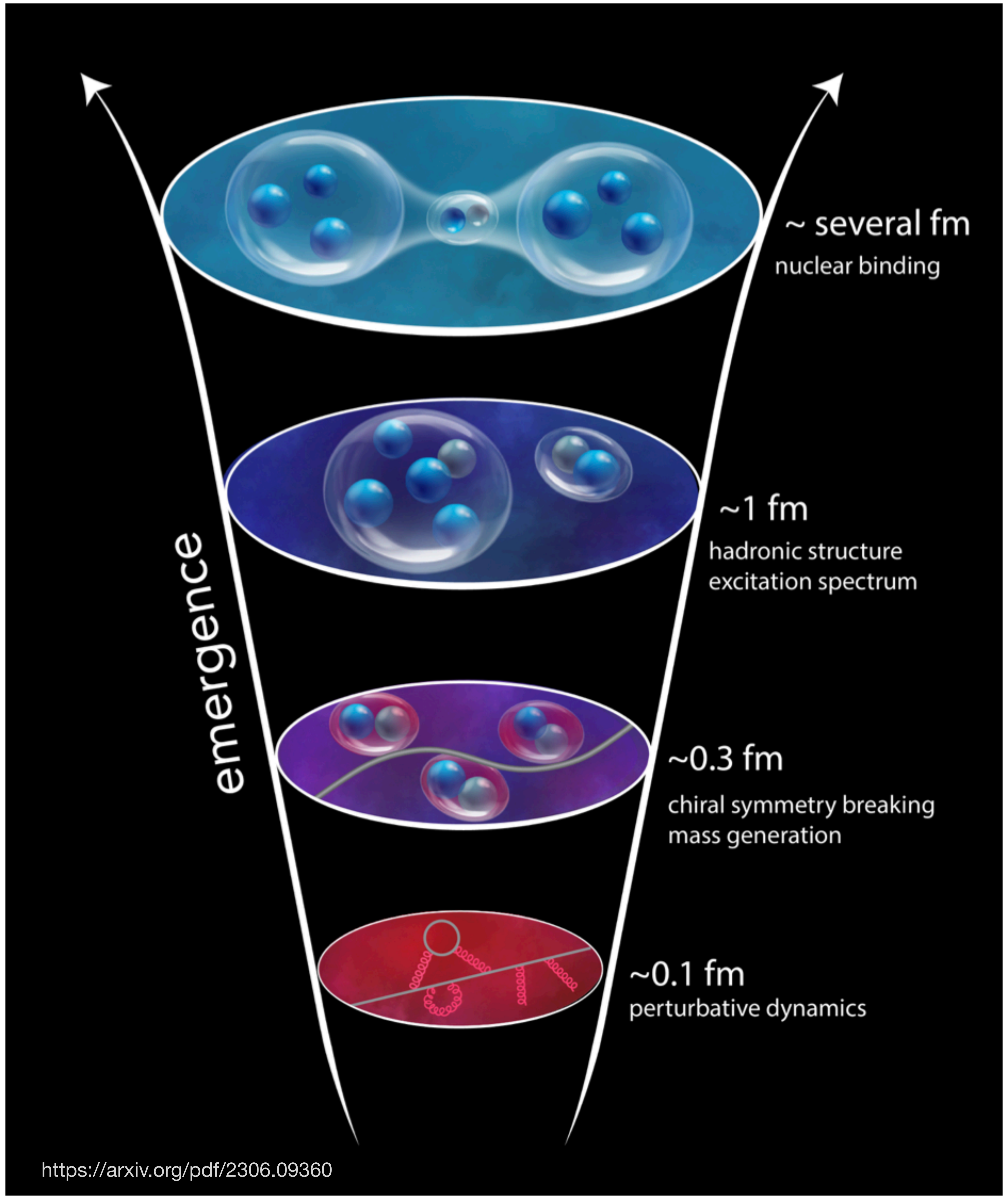


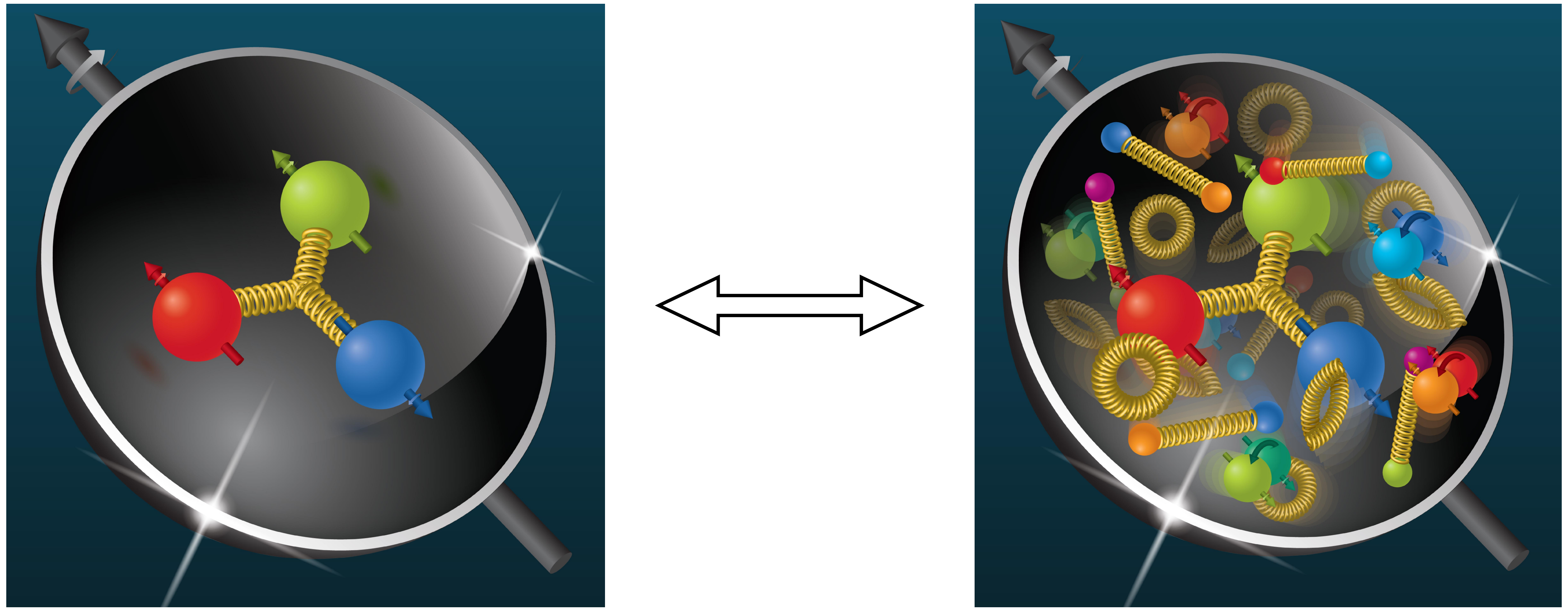
Nuclei responsible for almost all visible matter in Universe

We still strive to fully understand how quarks and gluons are arranged inside the nucleon

Microcosm of Hadrons

Emergence of structure in QCD





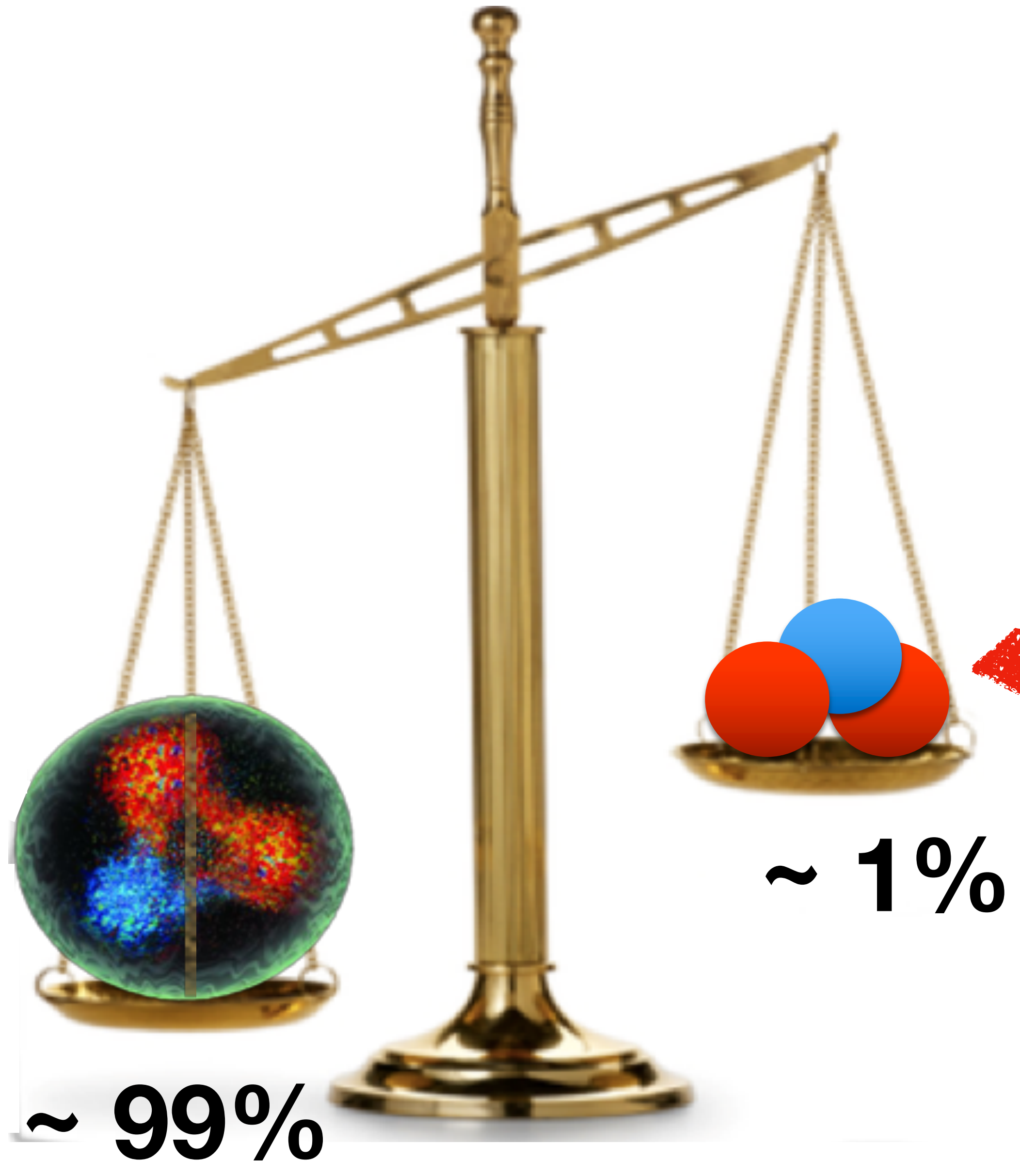
- Quarks/gluons confined in nuclear matter by strong force, mediated by gluons

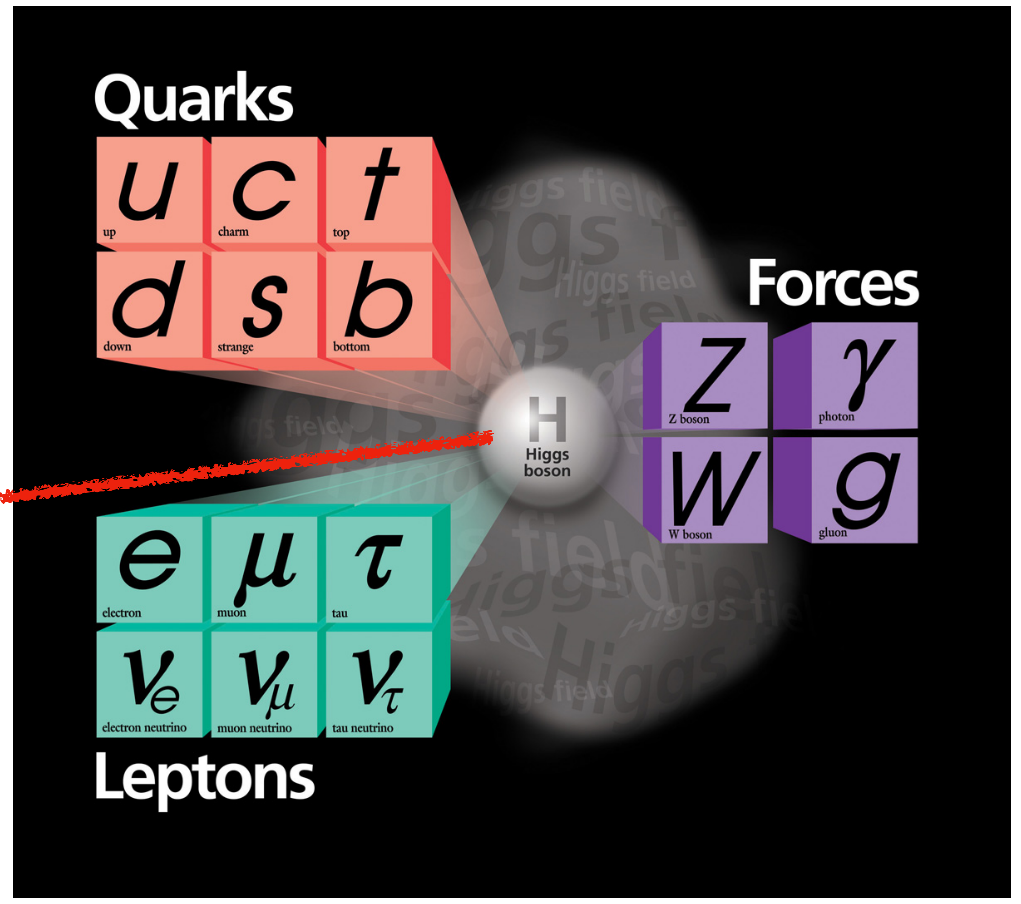
- QCD - theory describing strong interaction
- Many aspects of strong force not understood

- Picture inside hadrons is dynamic
  - Short distances → asymptotic freedom
  - Long distances i.e. hadronic scale → confinement → why?

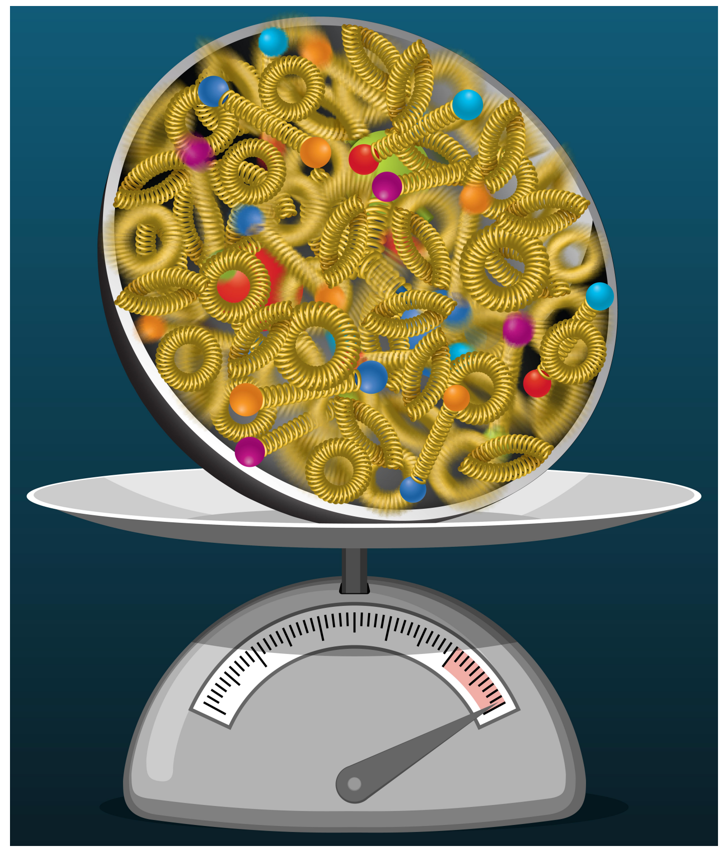
- Understanding dynamics of strong interaction crucial to understand everyday properties of matter e.g. mass / spin

Nucleon Mass Enigma

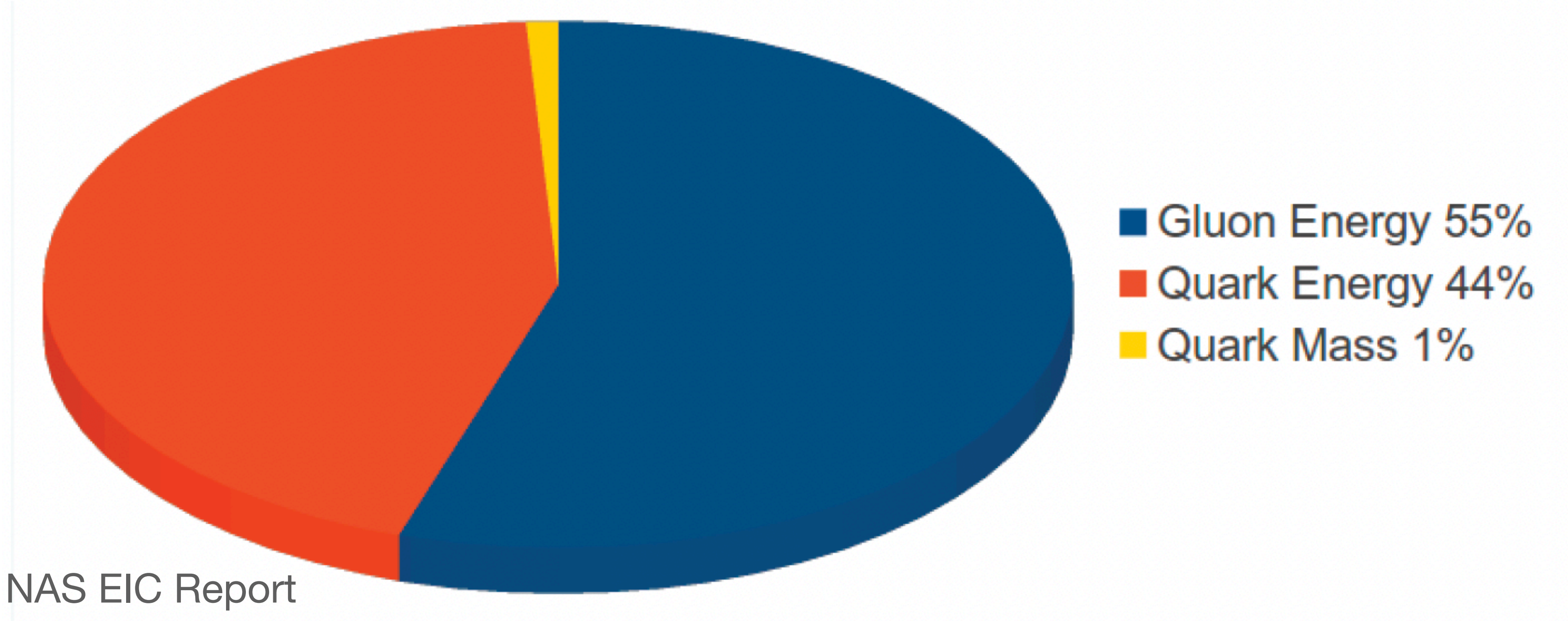




	Observed Mass	Higgs Mass
Proton (uud)	~ 1000 MeV	~10 MeV



Nucleon mass budget

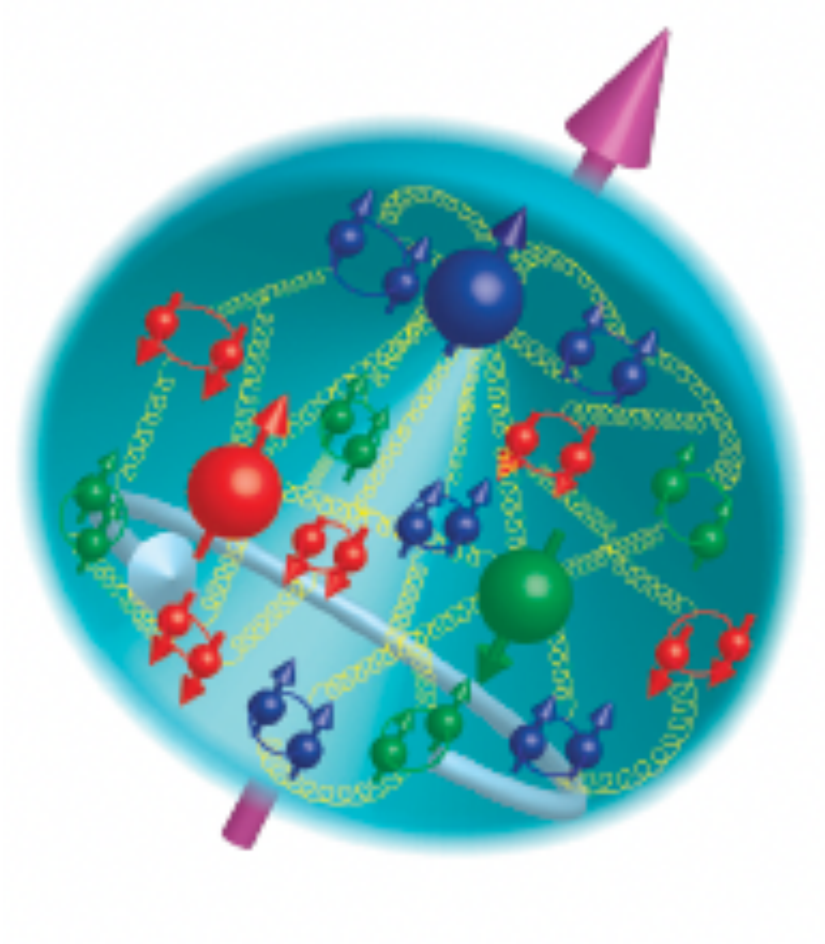


- Nucleon unexpectedly *heavy*

- Quark masses generated by Higgs only ~1% of nucleon mass!
- Gluons are massless

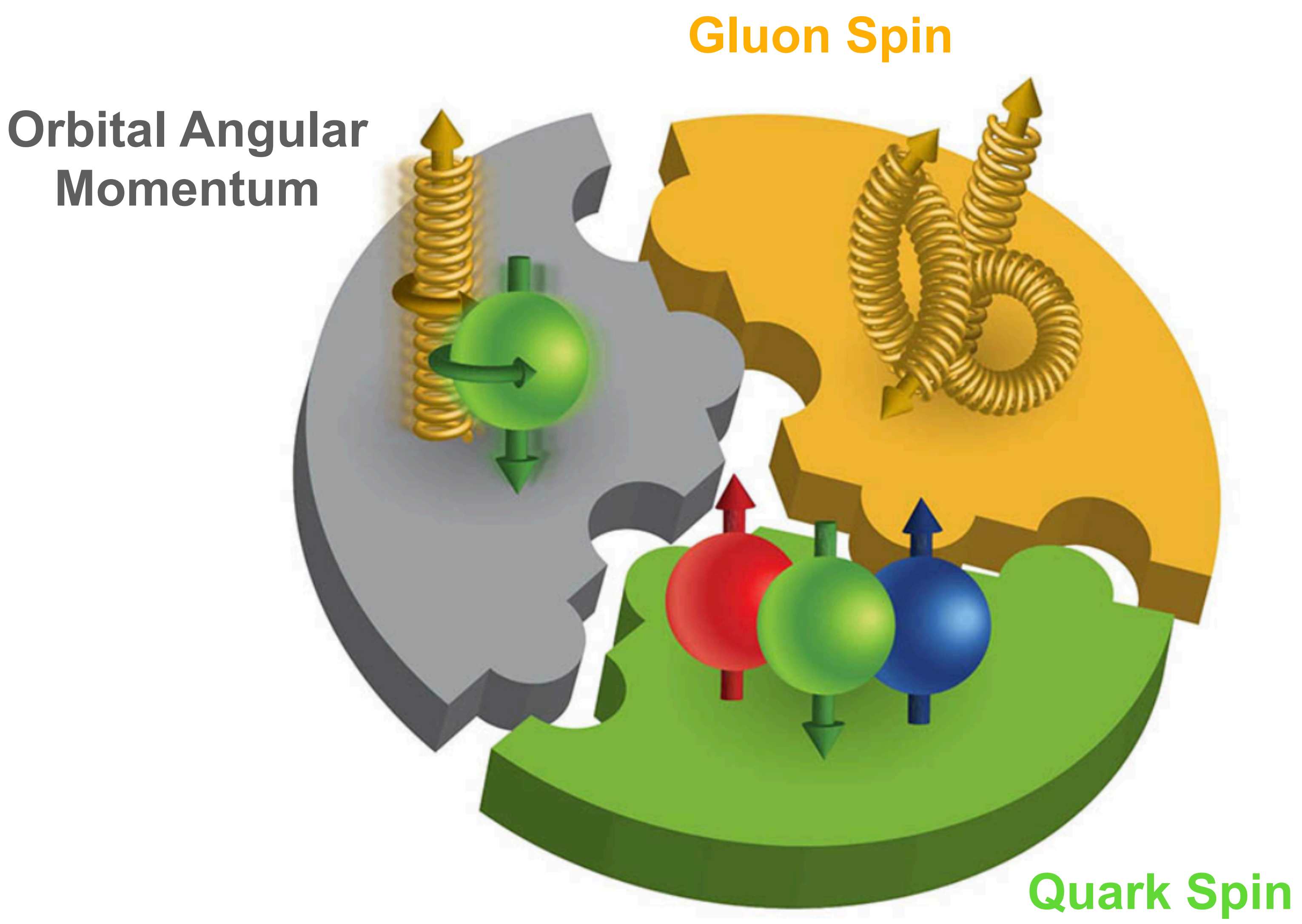
- ~99% of nucleon's mass due to quantum fluctuations of sea quark $q\bar{q}$ pairs, gluons, and energy associated with quarks moving close to speed of light within it

Nucleon Spin Puzzle



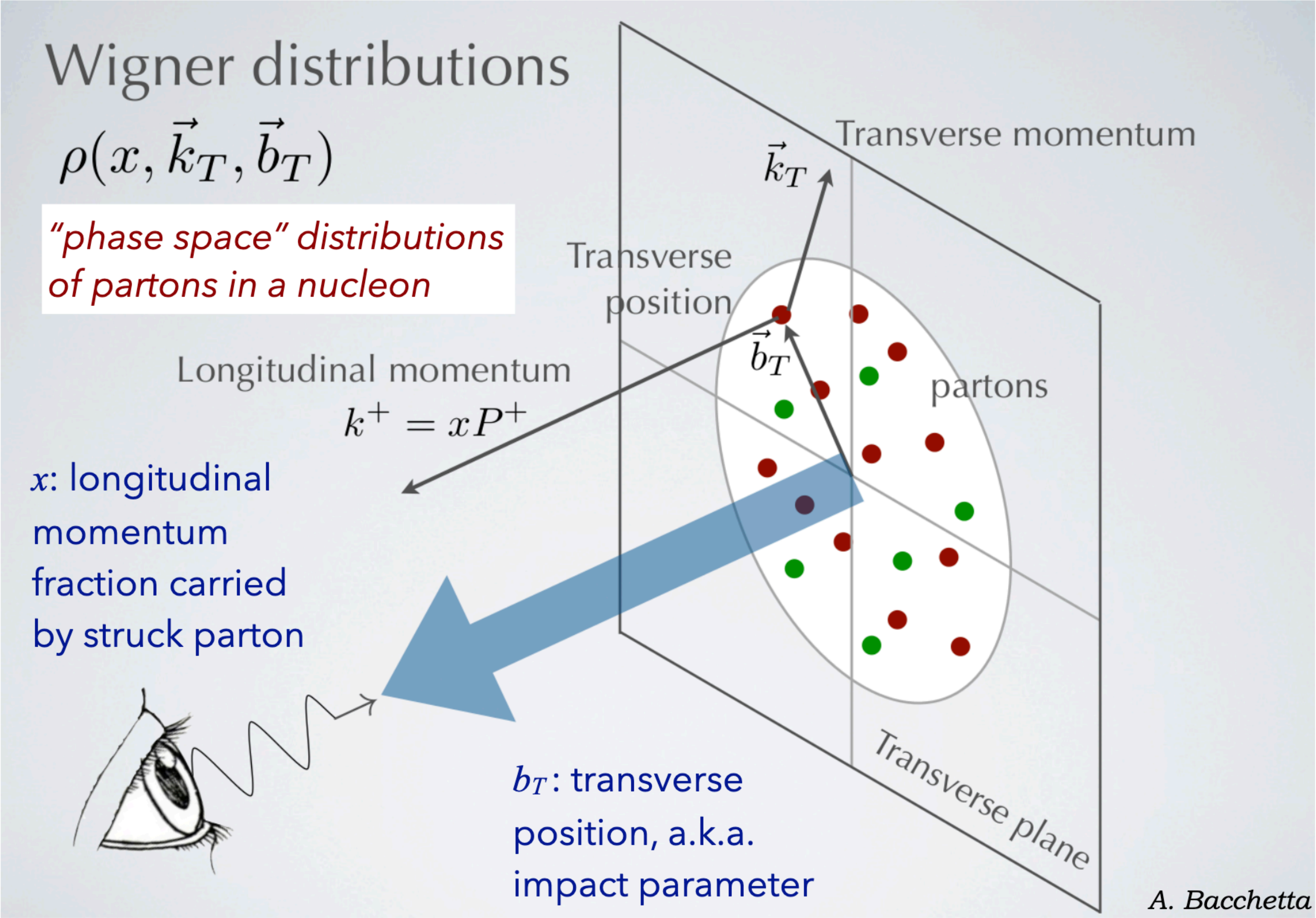
- Proton spin appears as 1/2
- Spins of its components should sum to this
- Only a small fraction carried by valence quarks

- How does nucleon's spin originate from quarks and gluons, and their interactions?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \left(\sum L_q^z + L_g^z\right)$$

Quark Spin | Gluon Spin | Orbital Angular Momentum

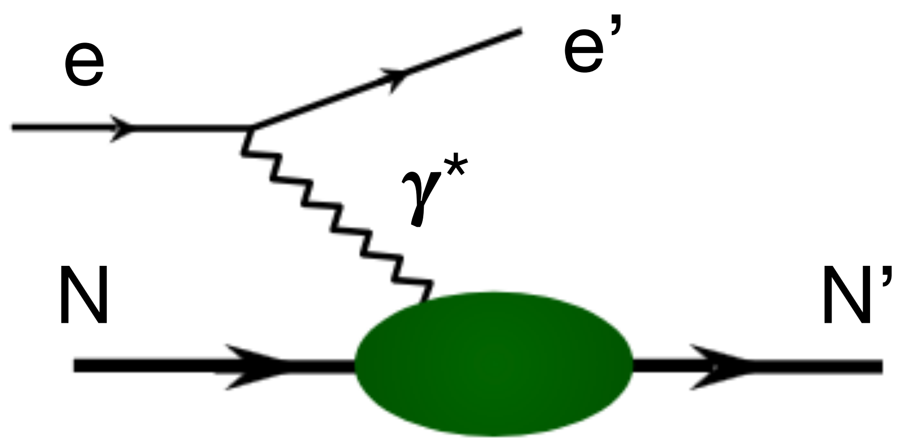


Our goal: understand distributions of partons inside hadrons - how they are located and how they move

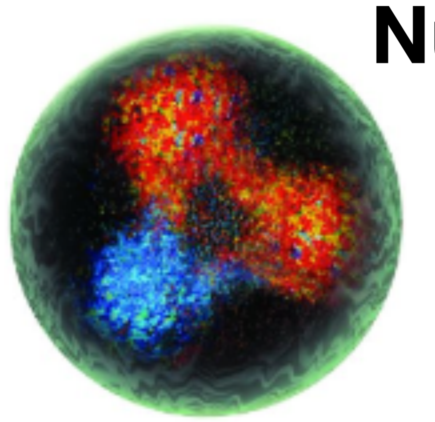
Integrals of Wigner distributions measured via lepton scattering

Pros: electromagnetic interaction → unmatched precision

Challenges: Small cross sections



Hadron Tomography

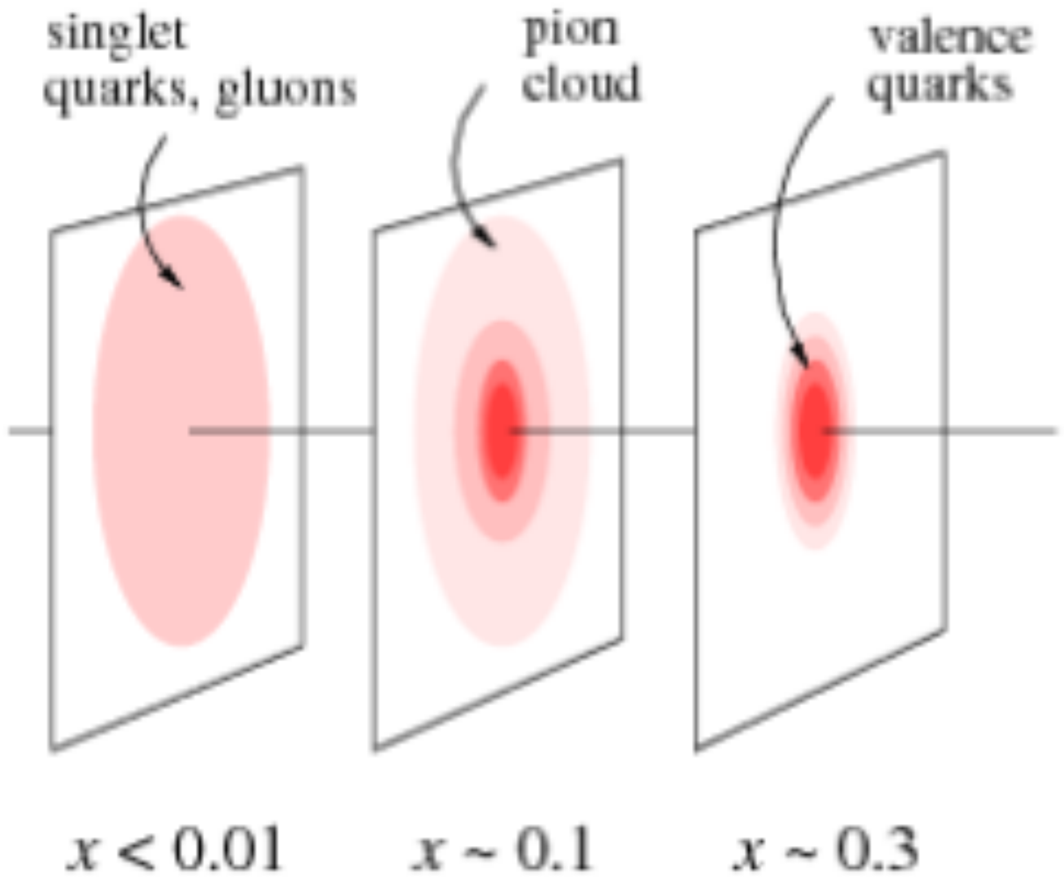


Nucleon

Wigner Function: full phase space parton distribution of the nucleon

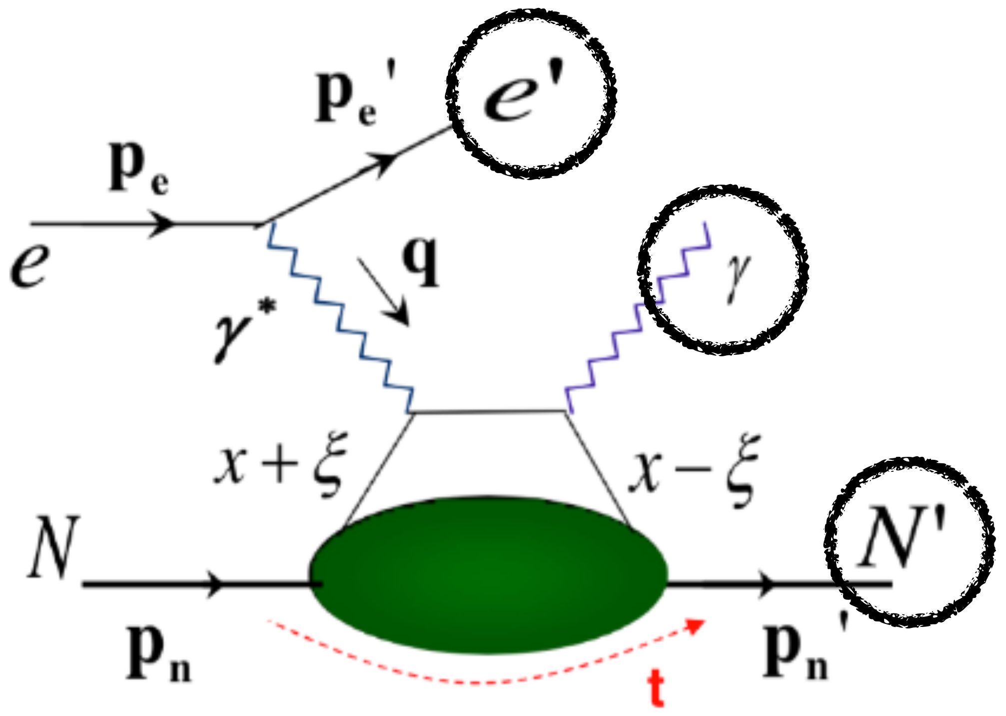
$\int d^2k_T$

$\int d^2b_T$

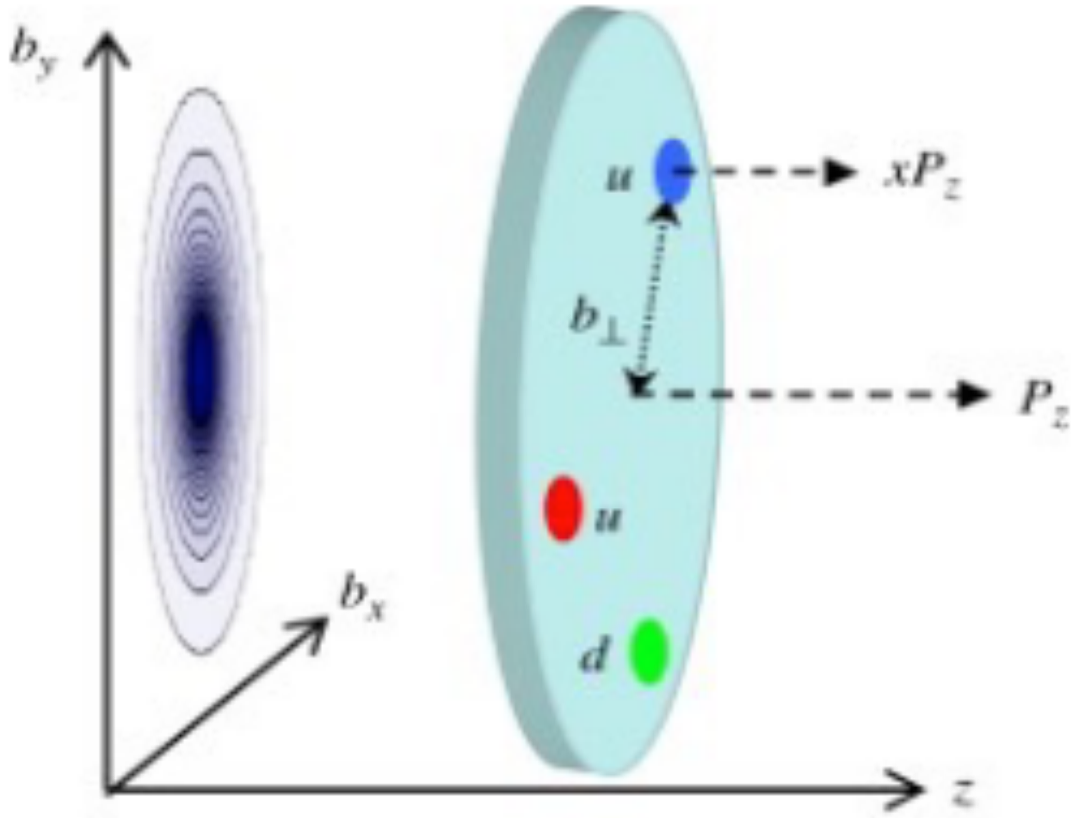


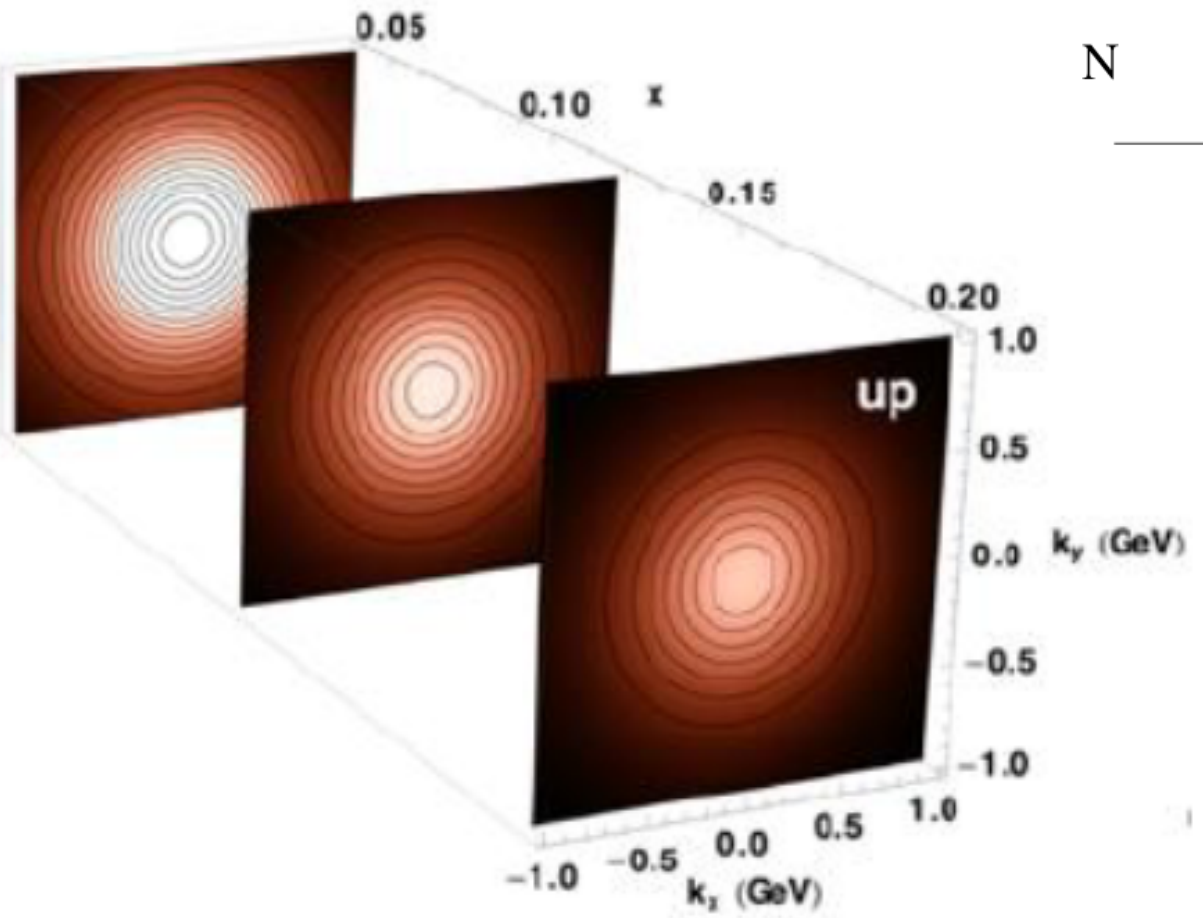
Coordinate Space $f(x,b_T)$:

Generalised Parton Distributions (GPDs)



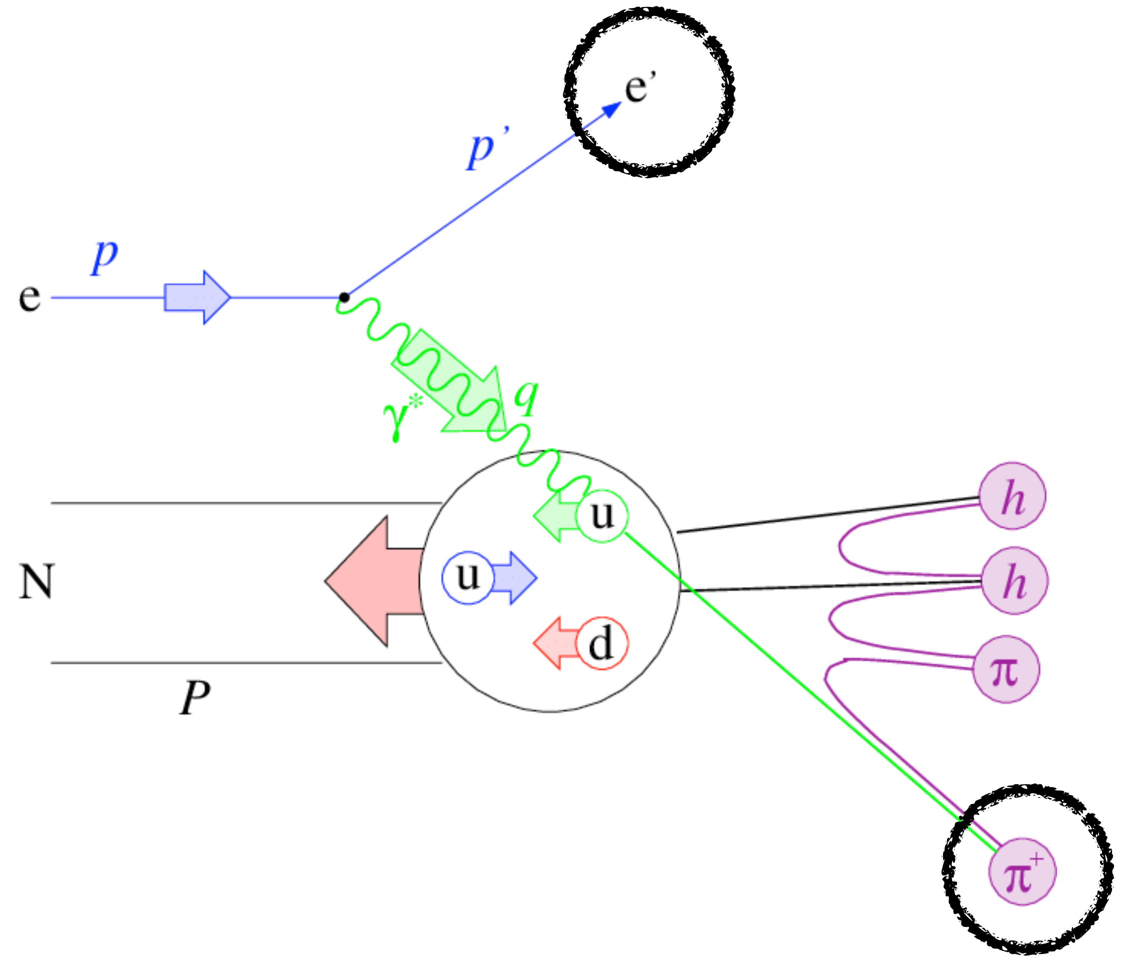
Deeply virtual exclusive reactions





Momentum Space $f(x, k_T)$:

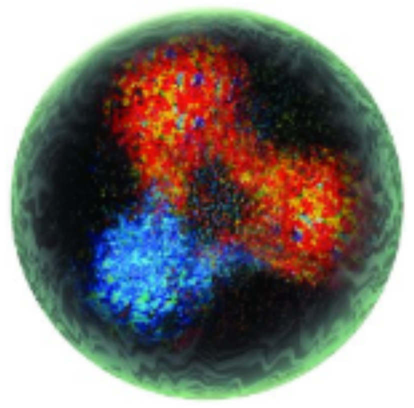
Transverse Momentum Dependent Distribution Functions (TMDs)



Semi-inclusive deep inelastic scattering

Hadron Tomography

Nucleon



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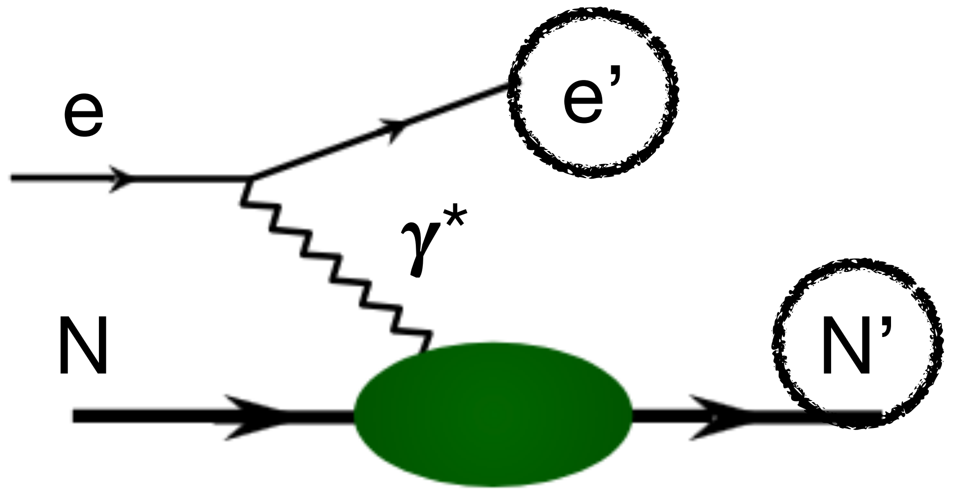
Generalised Parton Distributions (GPDs)

$\int dx$

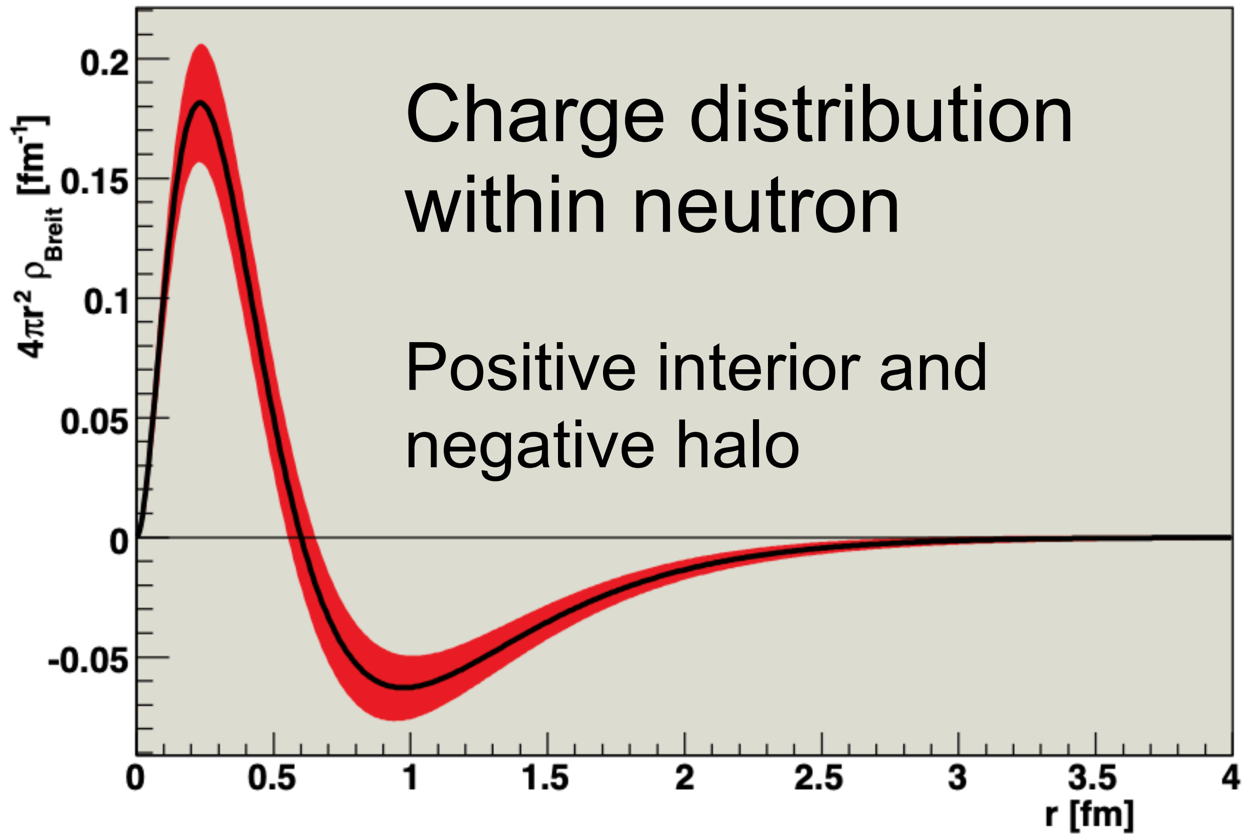
Electromagnetic Form Factors eg G_E, G_M

Access transverse charge/current densities

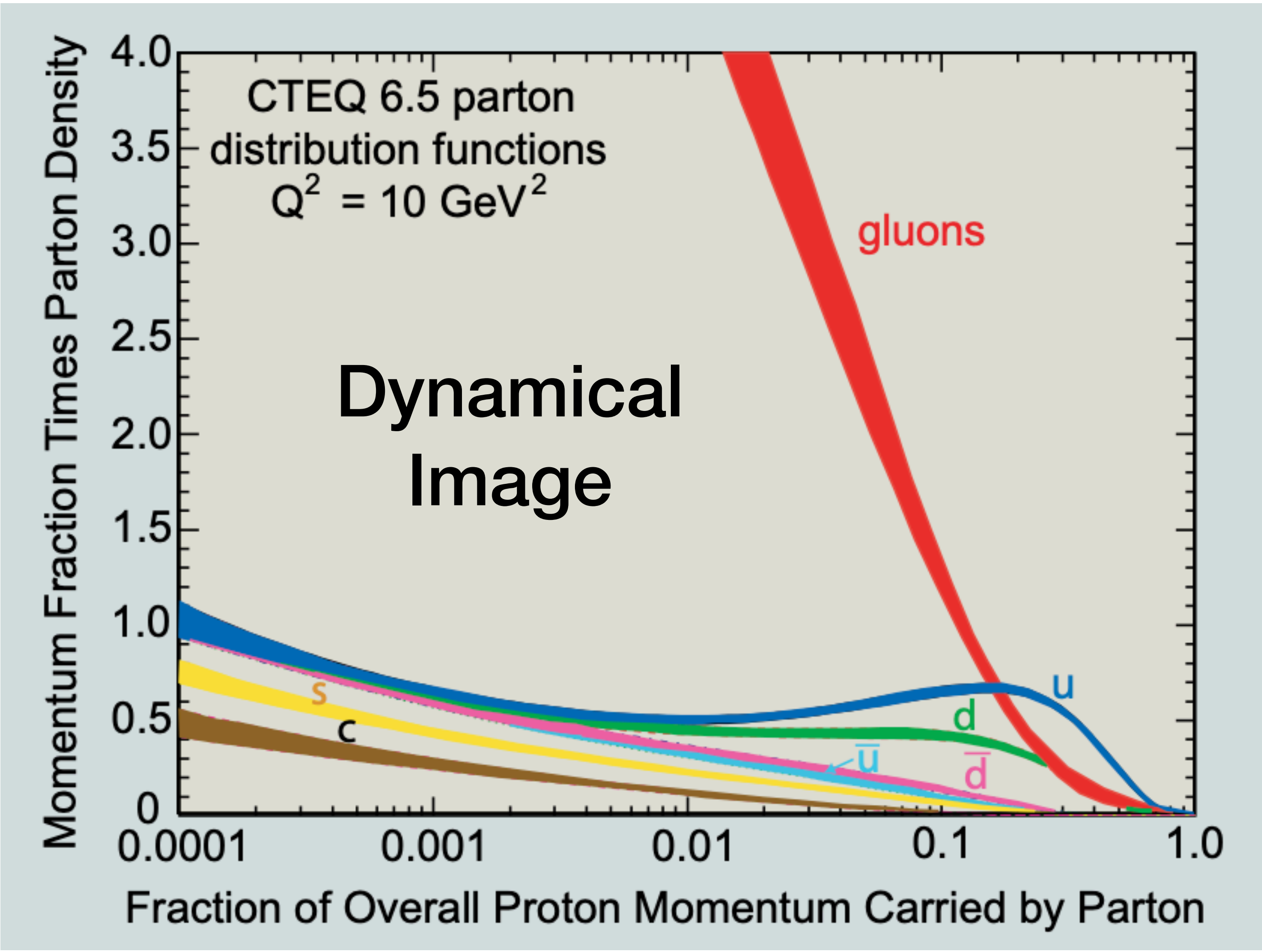


Exclusive Elastic scattering

DOE/NSF NSAC, arXiv:0809.3137v1



arXiv:0809.3137v1 [nucl-ex]

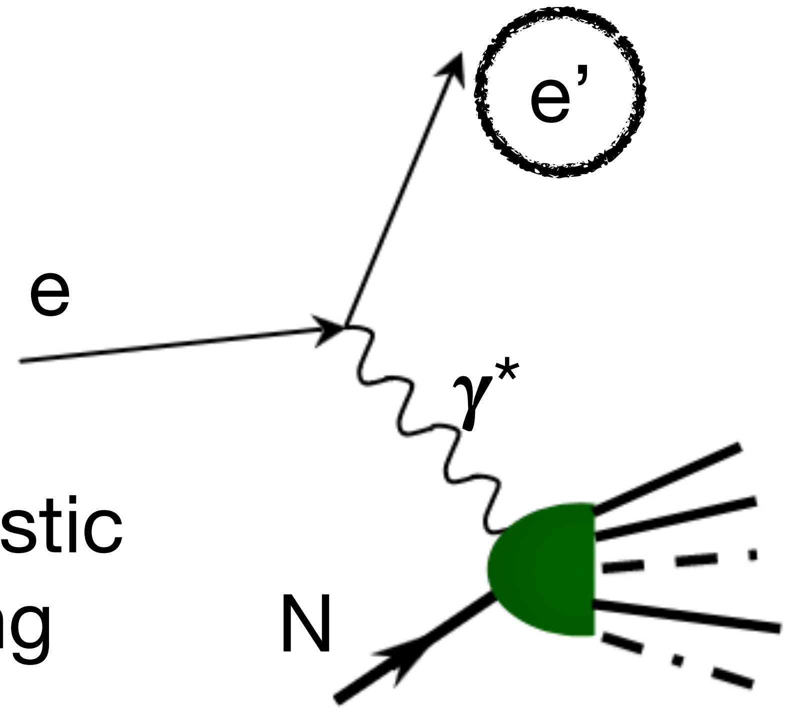


Transverse Momentum Dependent Distribution Functions (TMDs)

$\int k_T$

Parton Distribution Functions

Number densities of different partons as a function of x



Deep Inelastic Scattering

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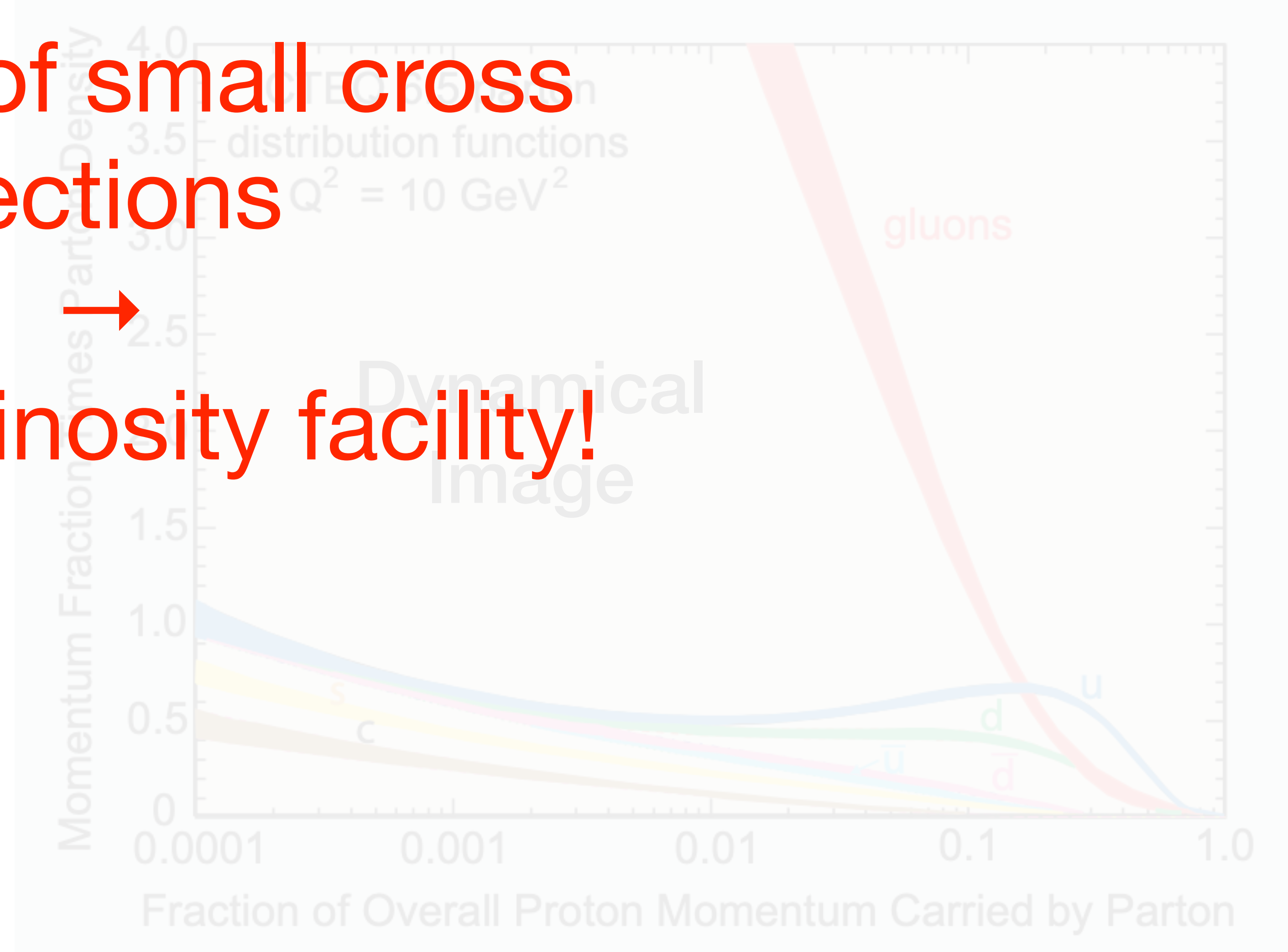


Dynamical Image

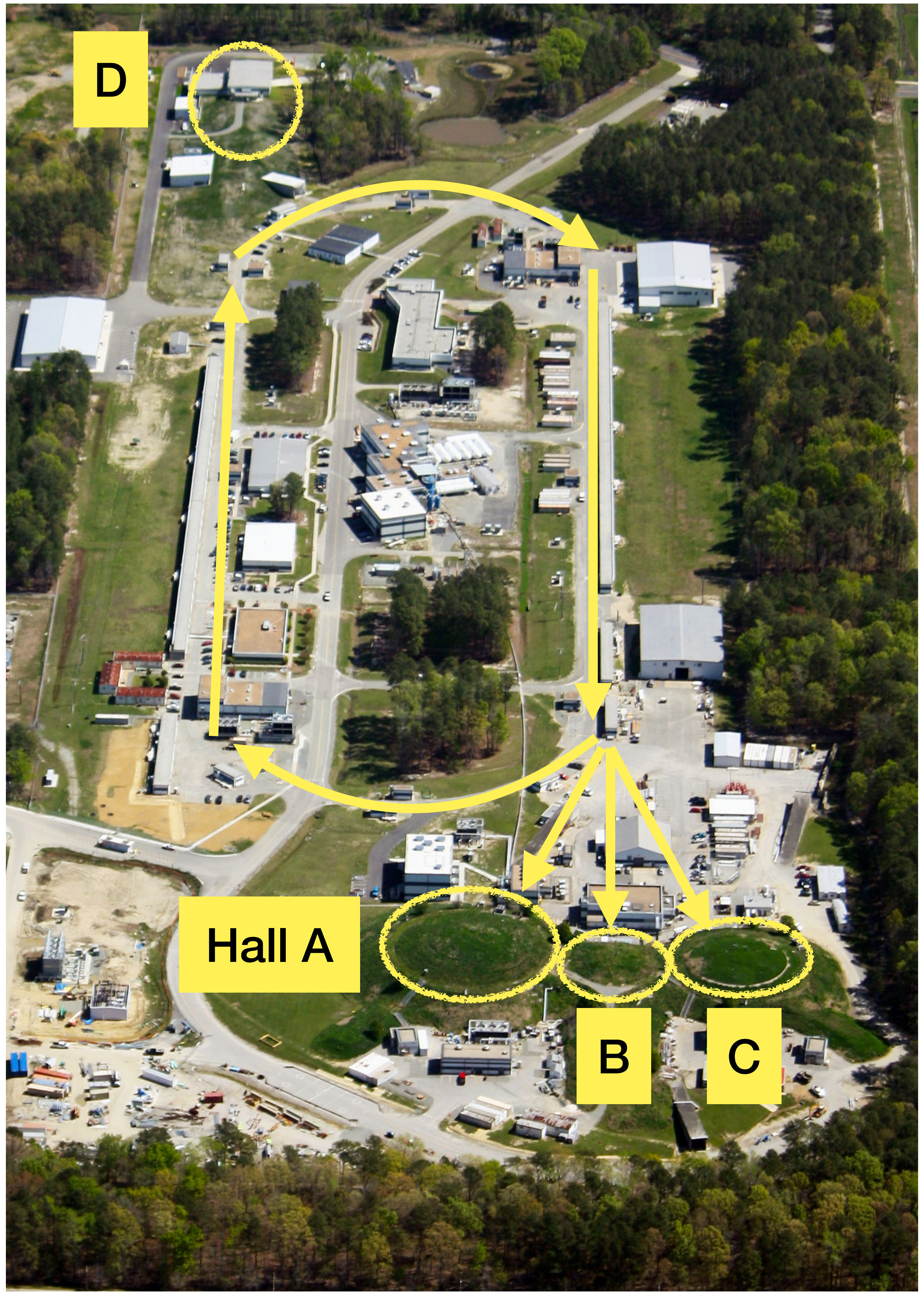
Deep Inelastic Scattering

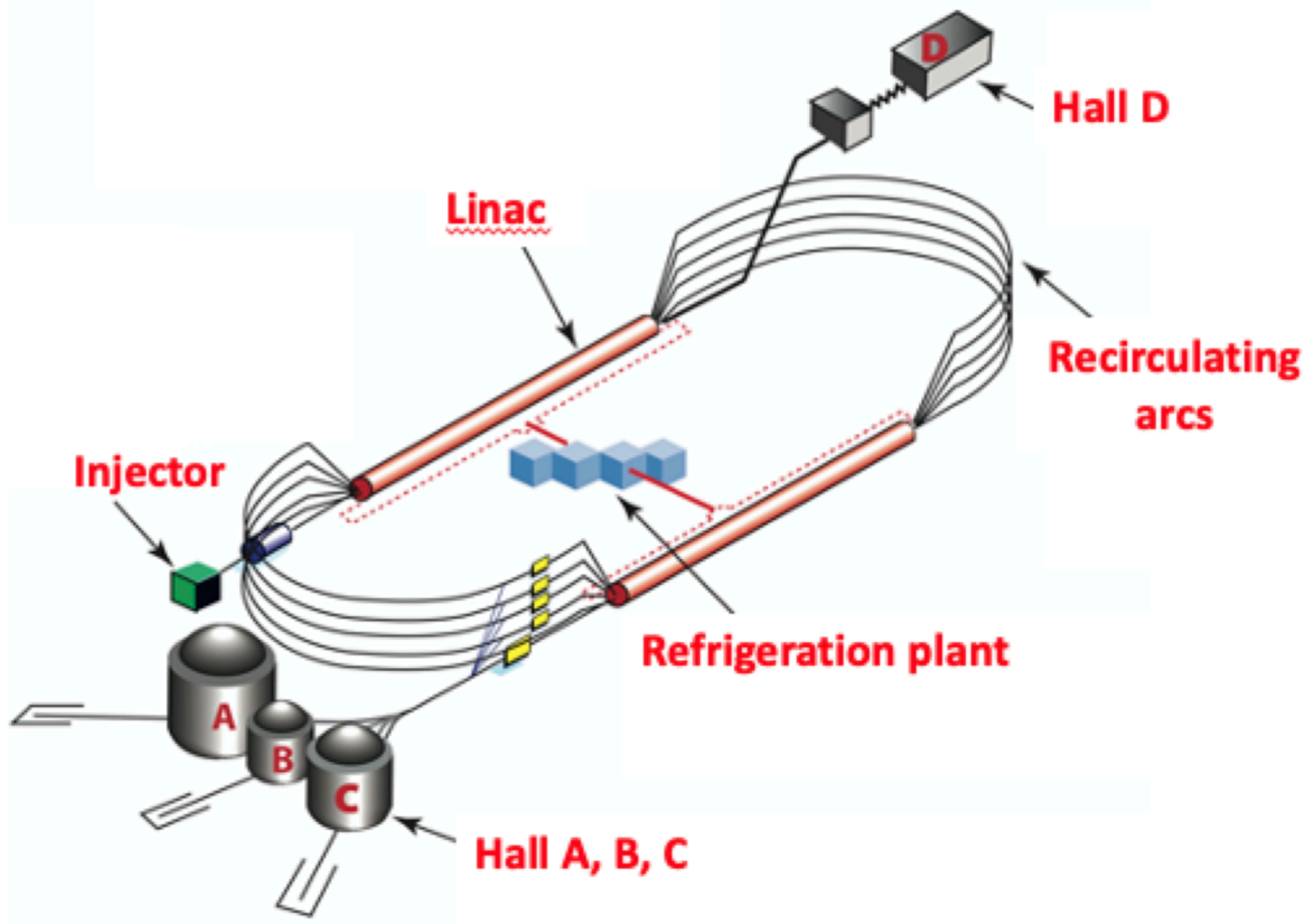
Need multi-dimensional binning of small cross sections

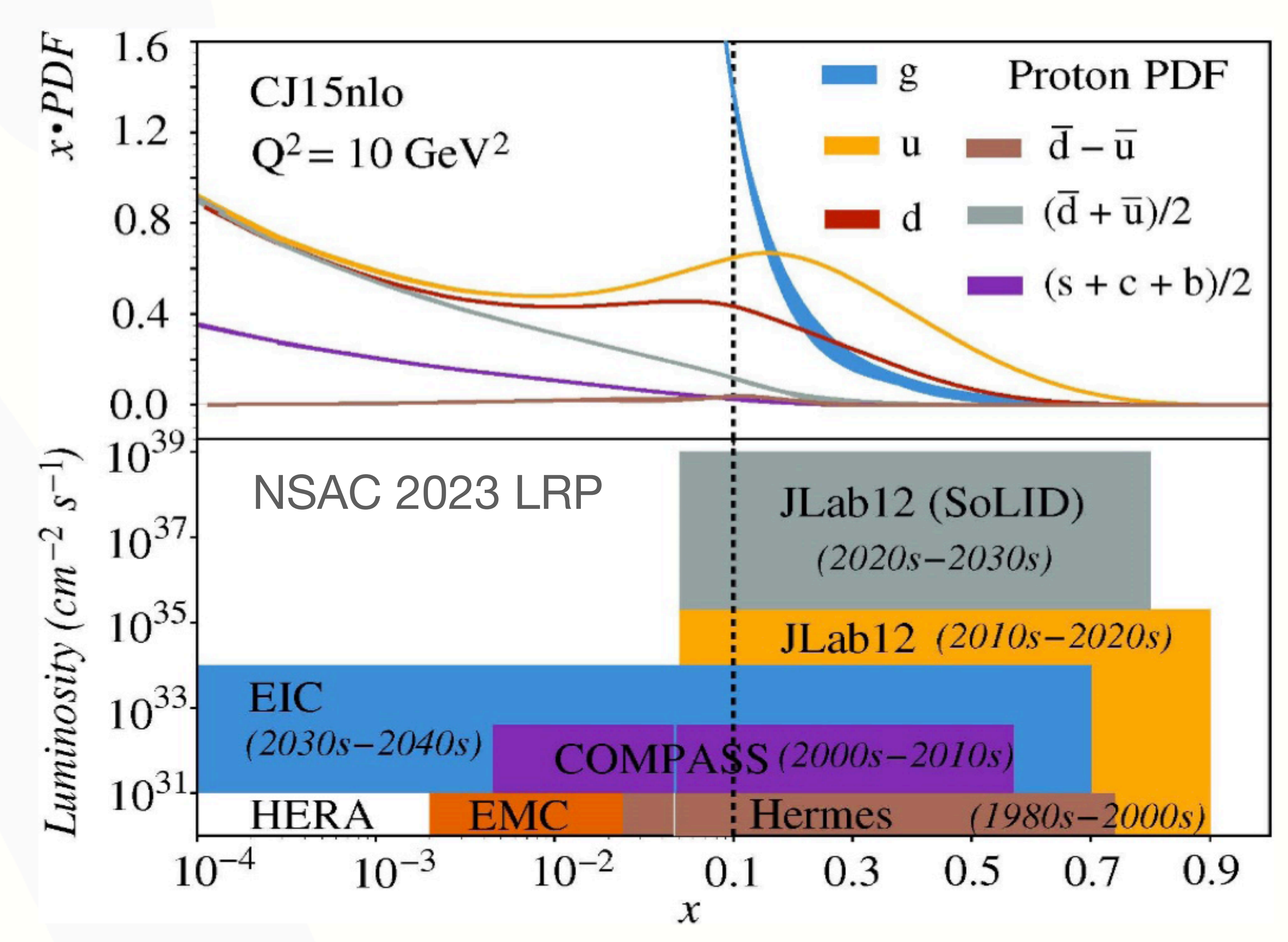
→

High luminosity facility!

Jefferson Lab (JLab)





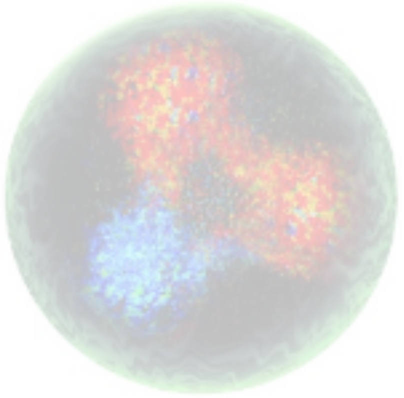


- Glasgow and York active in STFC funded research at JLab
- DOE national laboratory housing CEBAF
  - Continuous Electron Beam Accelerator Facility
  - High power superconducting radio frequency electron accelerator
  - World's highest intensity and highest precision multi-GeV electron beam
  - Highly polarised beam delivered to four halls simultaneously
  - Up to: 12 GeV for D, 11 GeV for A, B, C
  - Fixed target experiments, with polarised beam and polarised targets

World's premier facility for lepton scattering in valence region

Hadron Tomography

Nucleon



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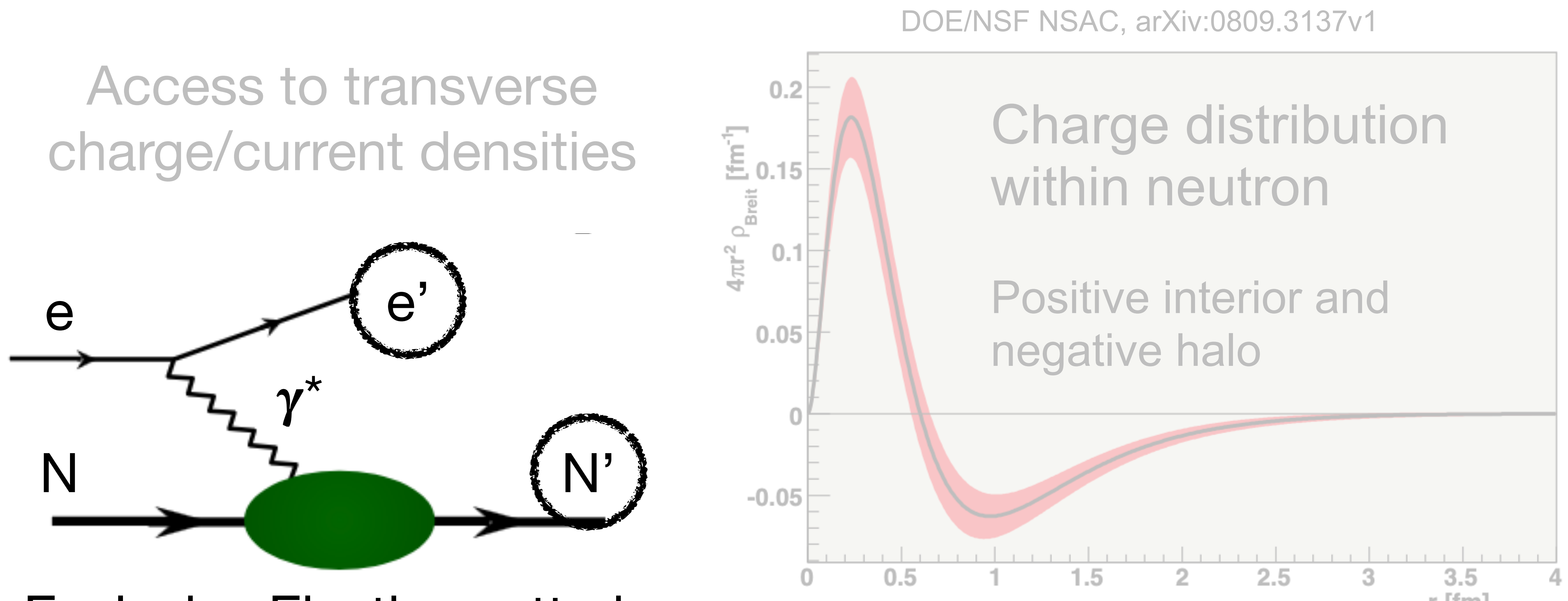
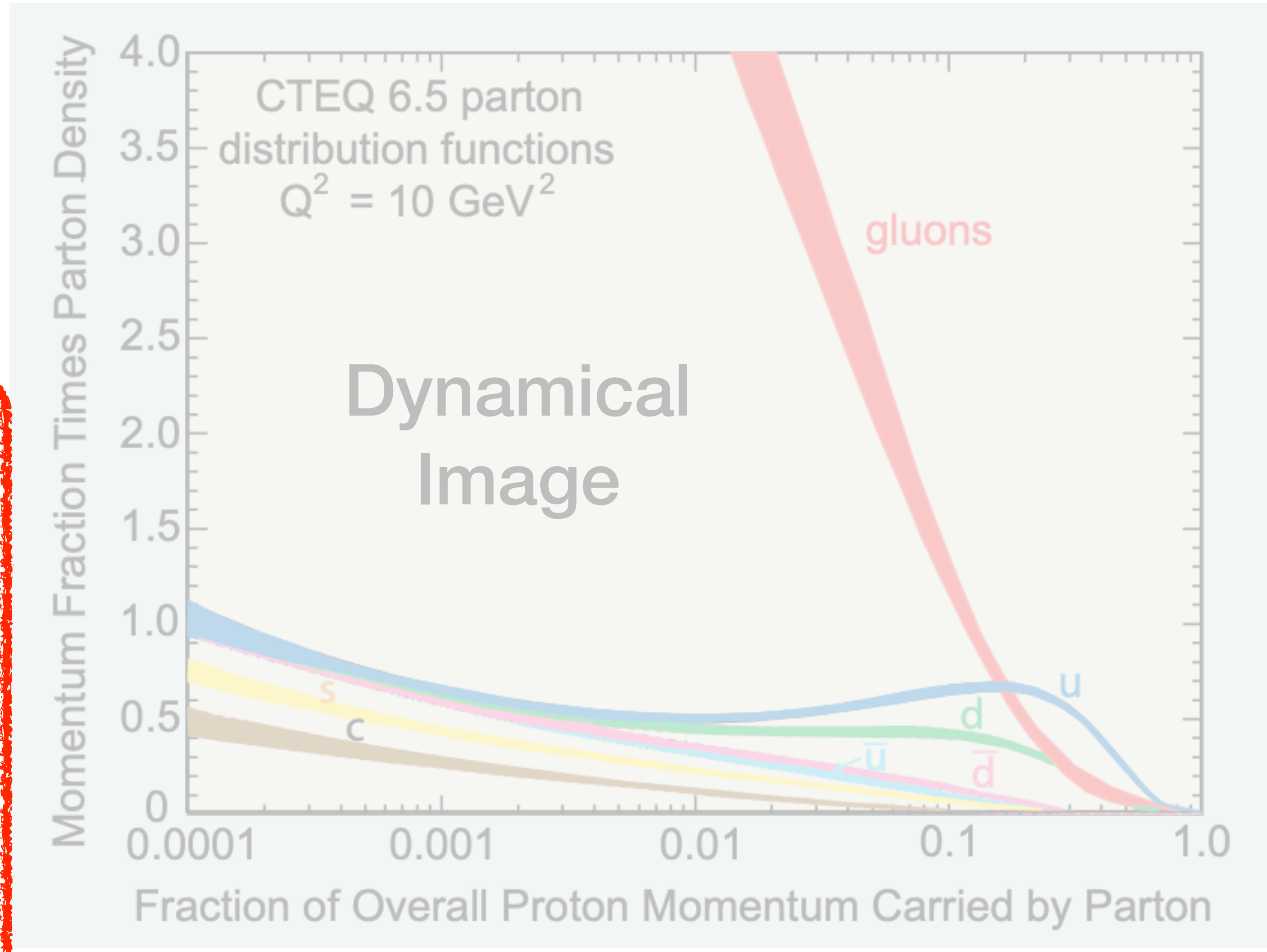


Exclusive Elastic scattering

arXiv:0809.3137v1 [nucl-ex]



Exclusive structure example

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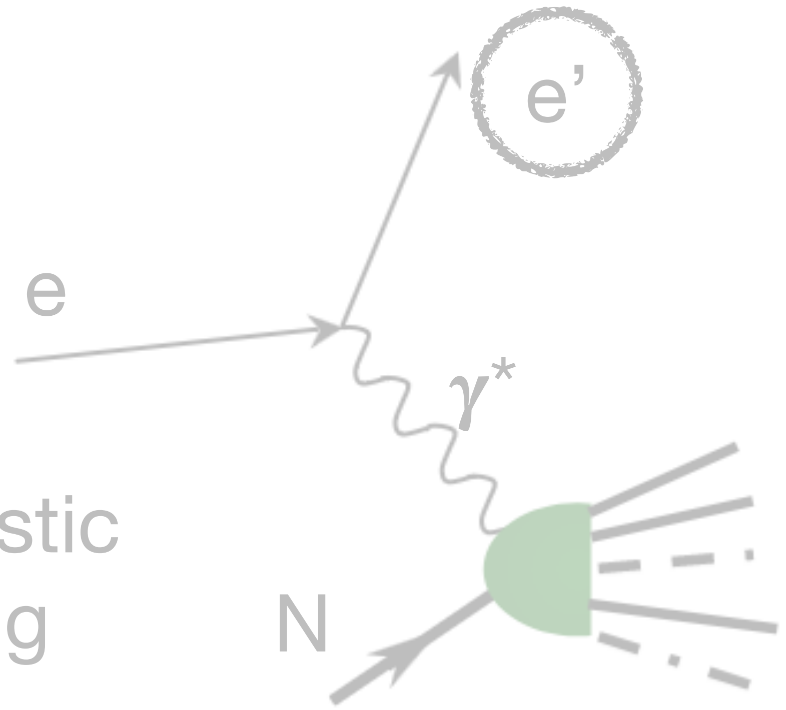
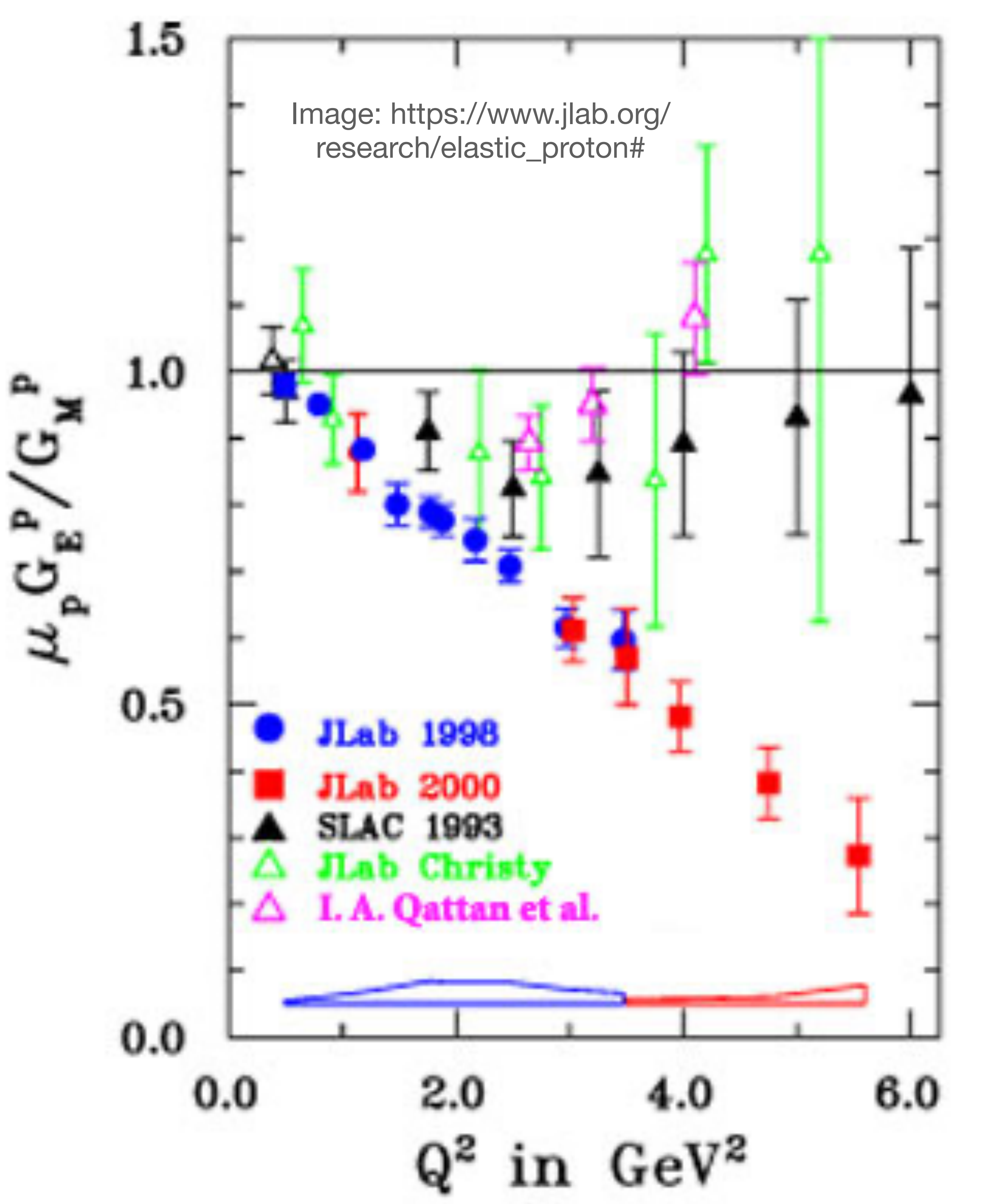
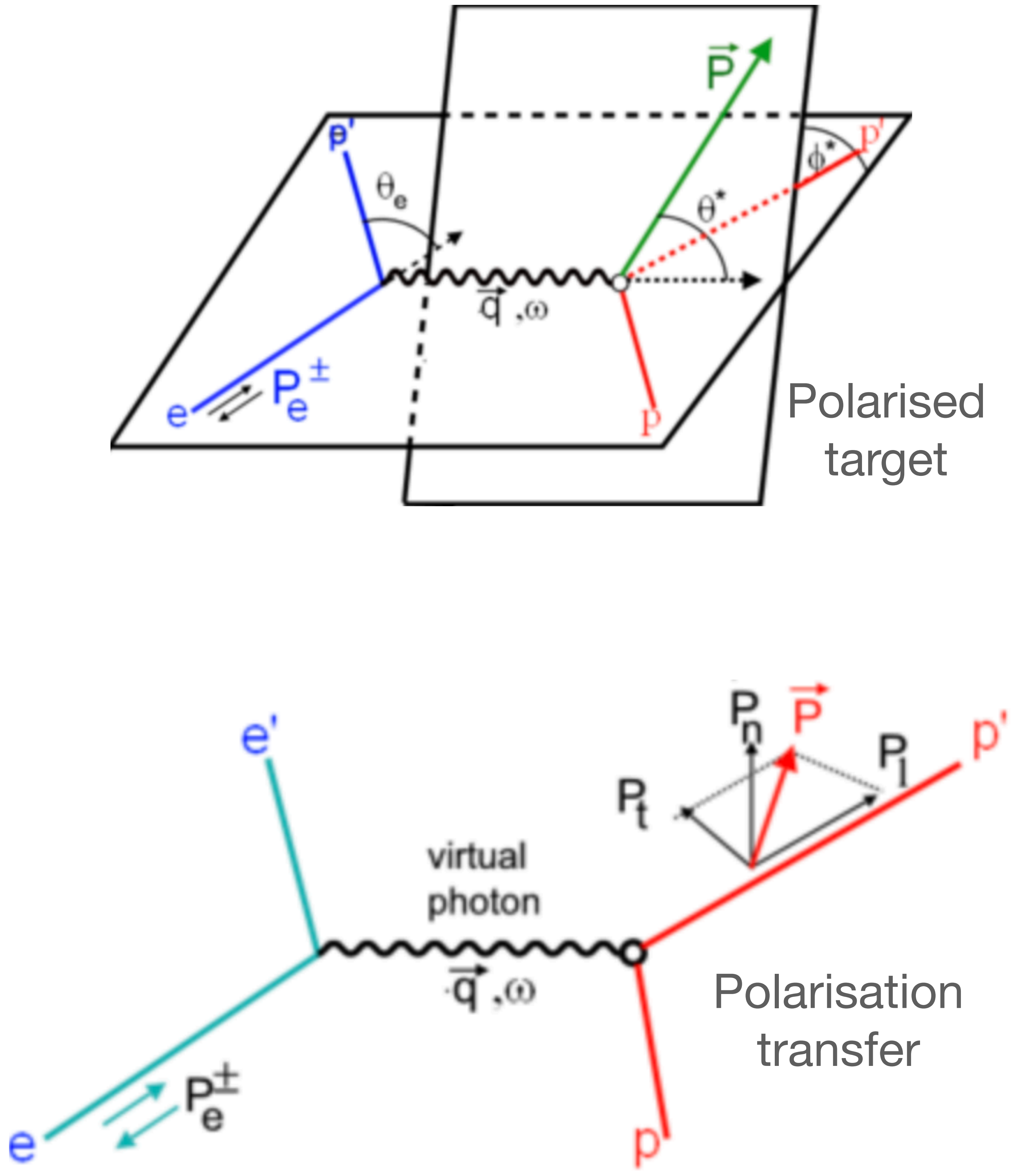


Deep Inelastic Scattering

Electromagnetic Form Factors





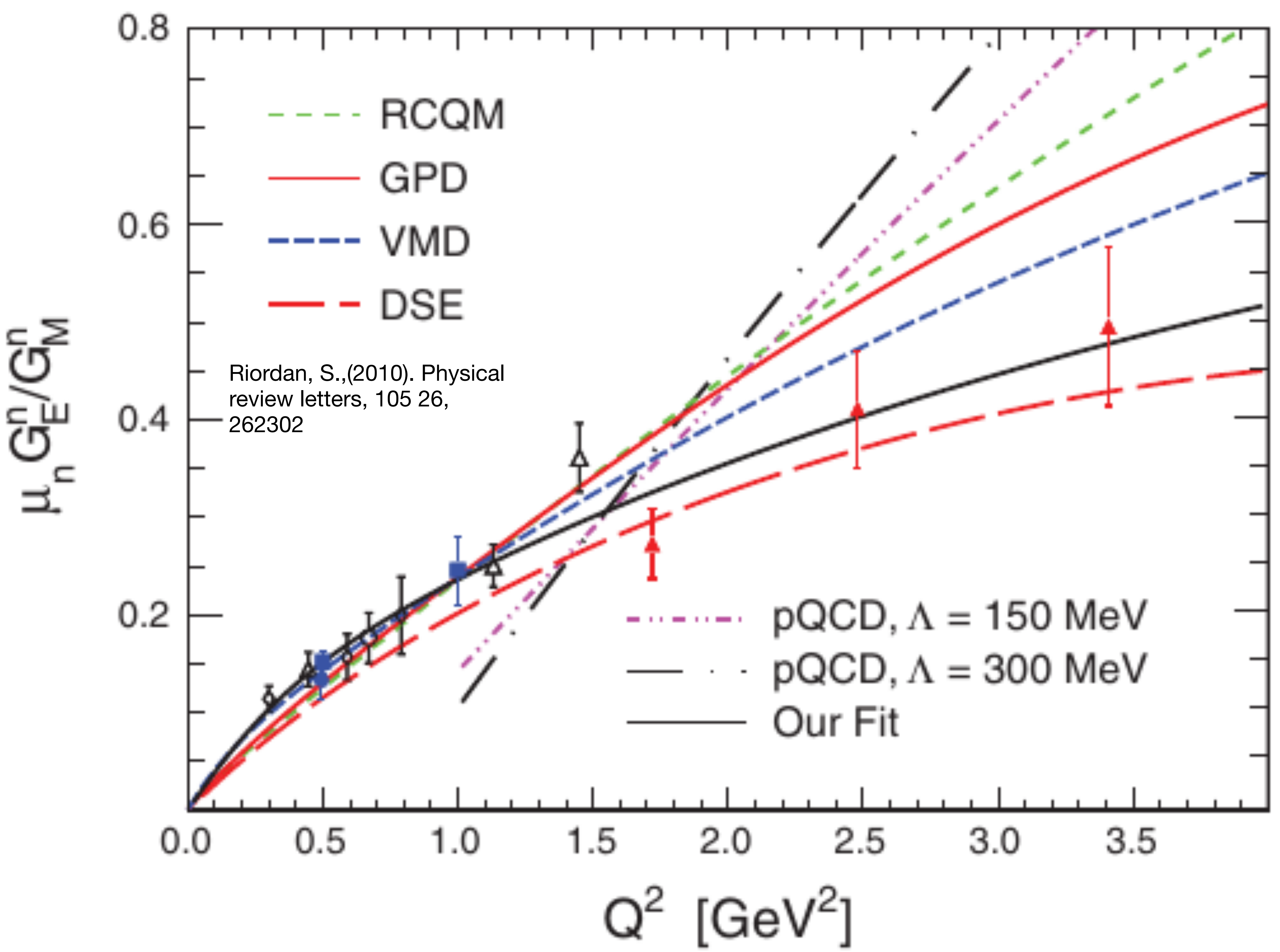
- A flagship in JLab's hadron structure program
- One of the most fundamental parameterisations of nucleon's internal structure
  - Access transverse distributions of electric charge and magnetic moment
- Increasingly precise measurements and access to polarisation observables at JLab have dramatically altered our understanding of nucleon structure at high Q^2
- e.g. extracting ratio G_E^p/G_M^p from double polarisation methods didn't observe scaling behaviour measured via Rosenbluth
  - Orbital angular momentum
  - Two-photon exchanges (or higher orders)
  - Sparked a new era of FF studies at Jlab

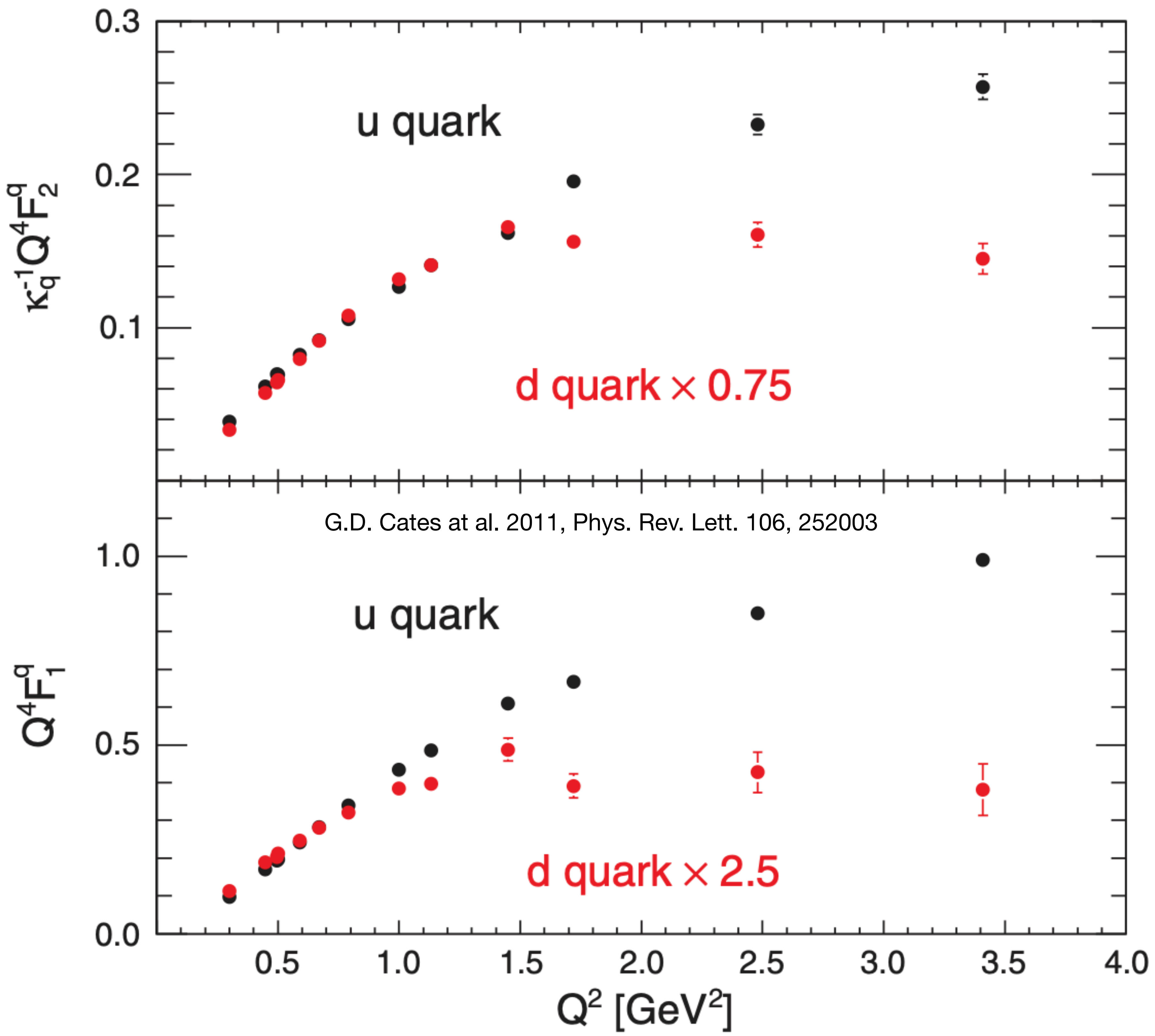
$$\frac{d\sigma}{d\Omega} = \sigma_{\text{Mott}} \frac{E'}{E_0} \left\{ (F_1)^2 + \tau \left[2 (F_1 + F_2)^2 \tan^2(\theta) + (F_2)^2 \right] \right\}$$

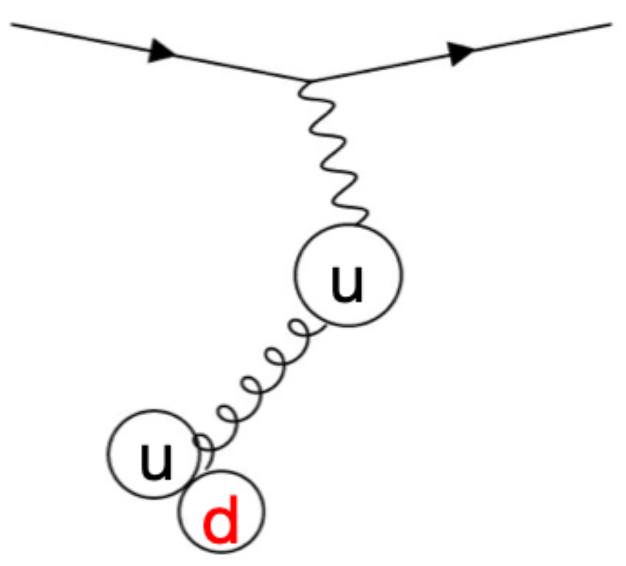
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \times \left[G_E^2 + \frac{\tau}{\epsilon} G_M^2 \right] / (1+\tau)$$

$$G_E = F_1 - \tau F_2$$
$$G_M = F_1 + F_2$$

Electromagnetic Form Factors







- High Q^2 measurements extremely challenging due to tiny cross sections inversely dependent on Q^2
  - Especially neutron
- Key insights into QCD and nucleon structure is revealed in Q^2 evolution of FF

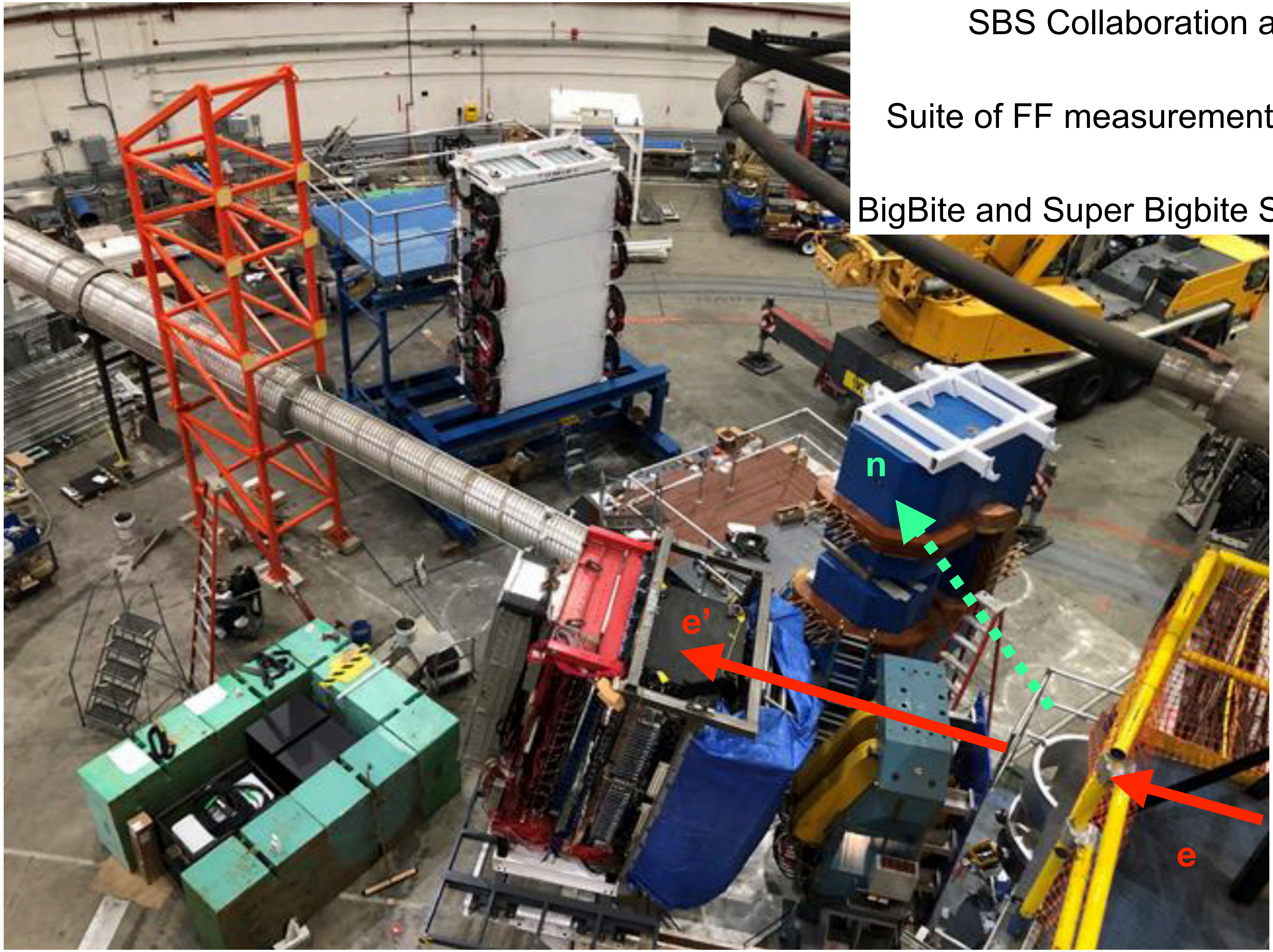
- e.g. JLab neutron G_E^n/G_M^n results → first ever quark flavour decomposition of FF, revealing differences in scaling between u and d quarks
  - Theory hints to di-quark correlations

Super Bigbite Spectrometer (SBS)

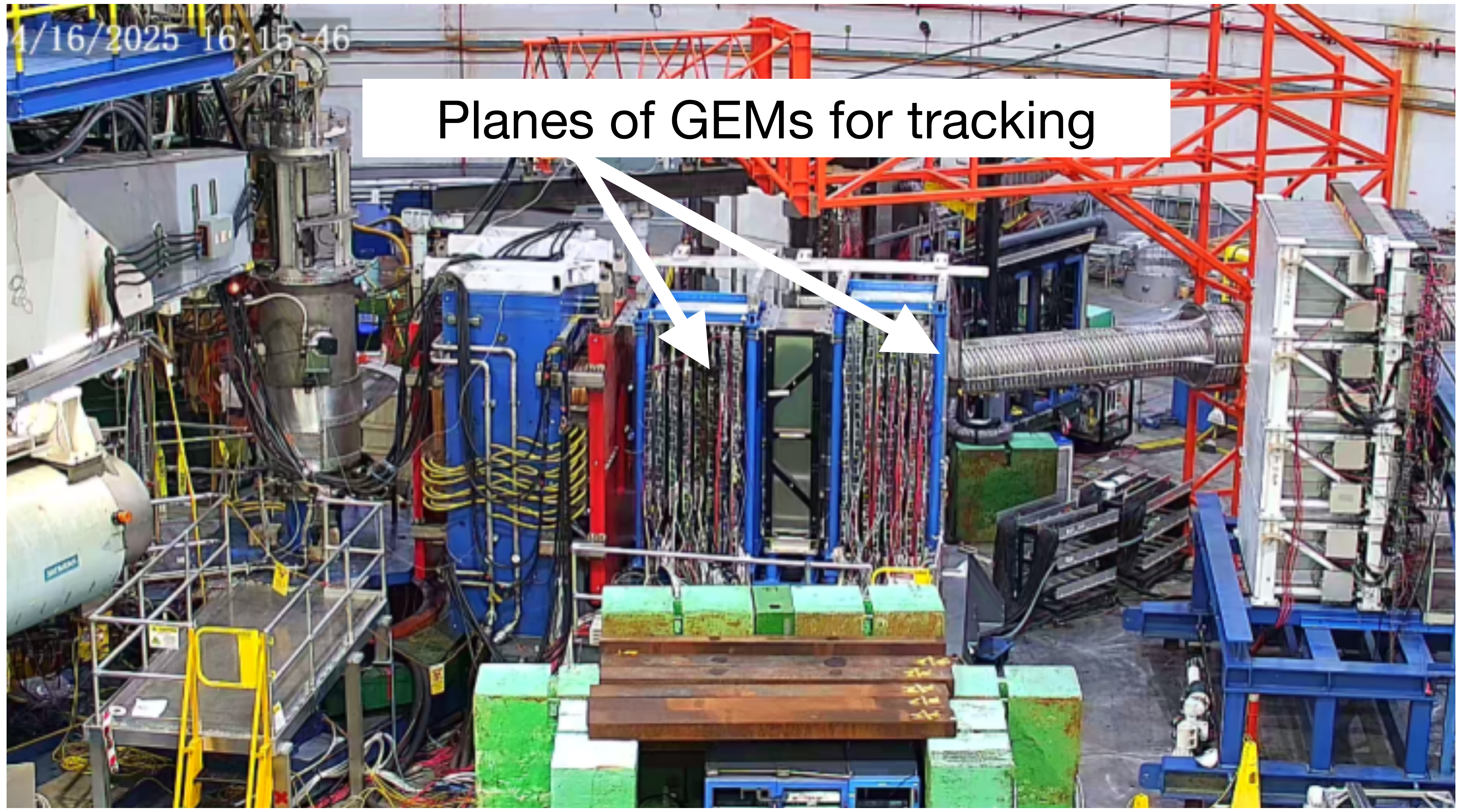
SBS Collaboration at JLab

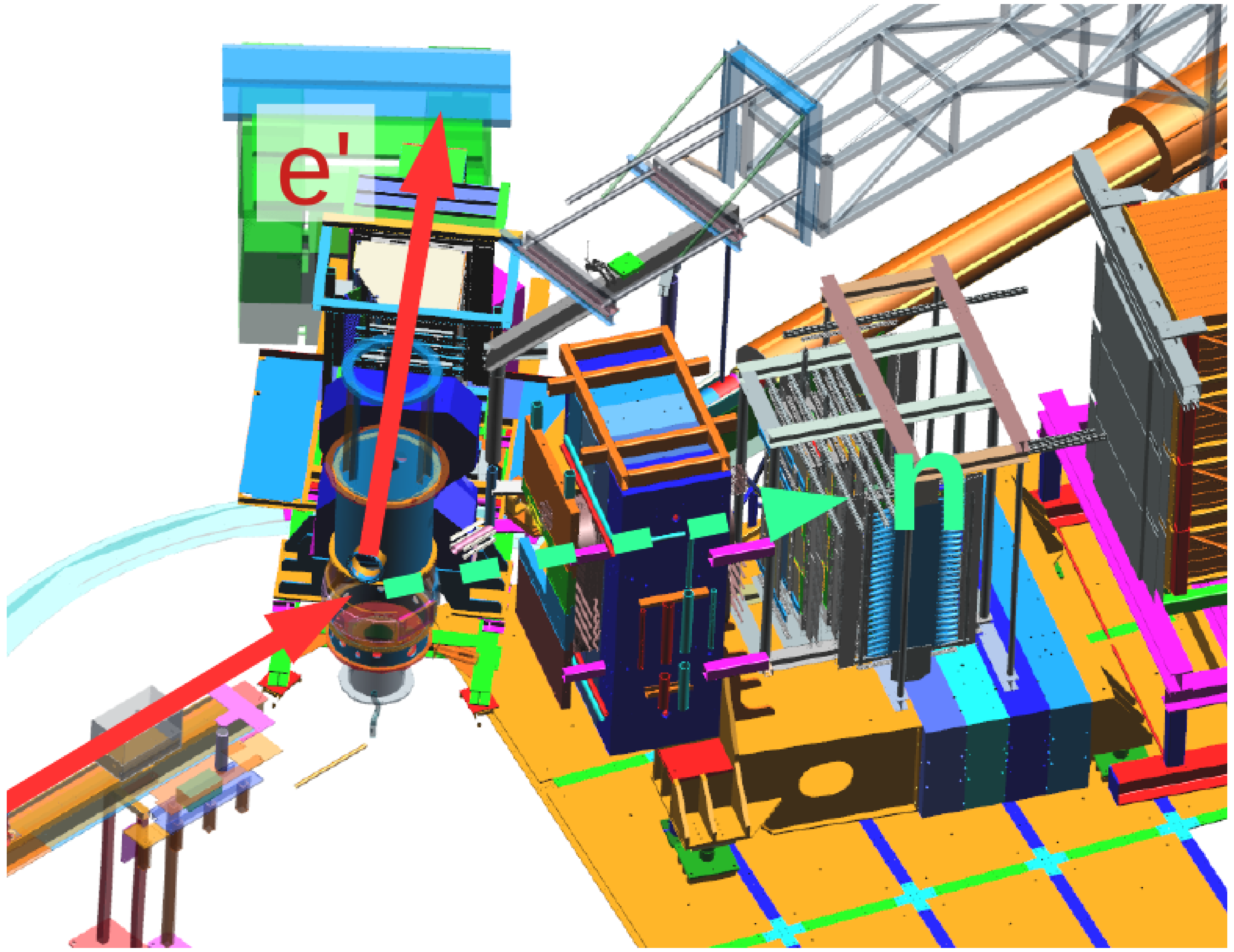
Suite of FF measurements at high Q^2

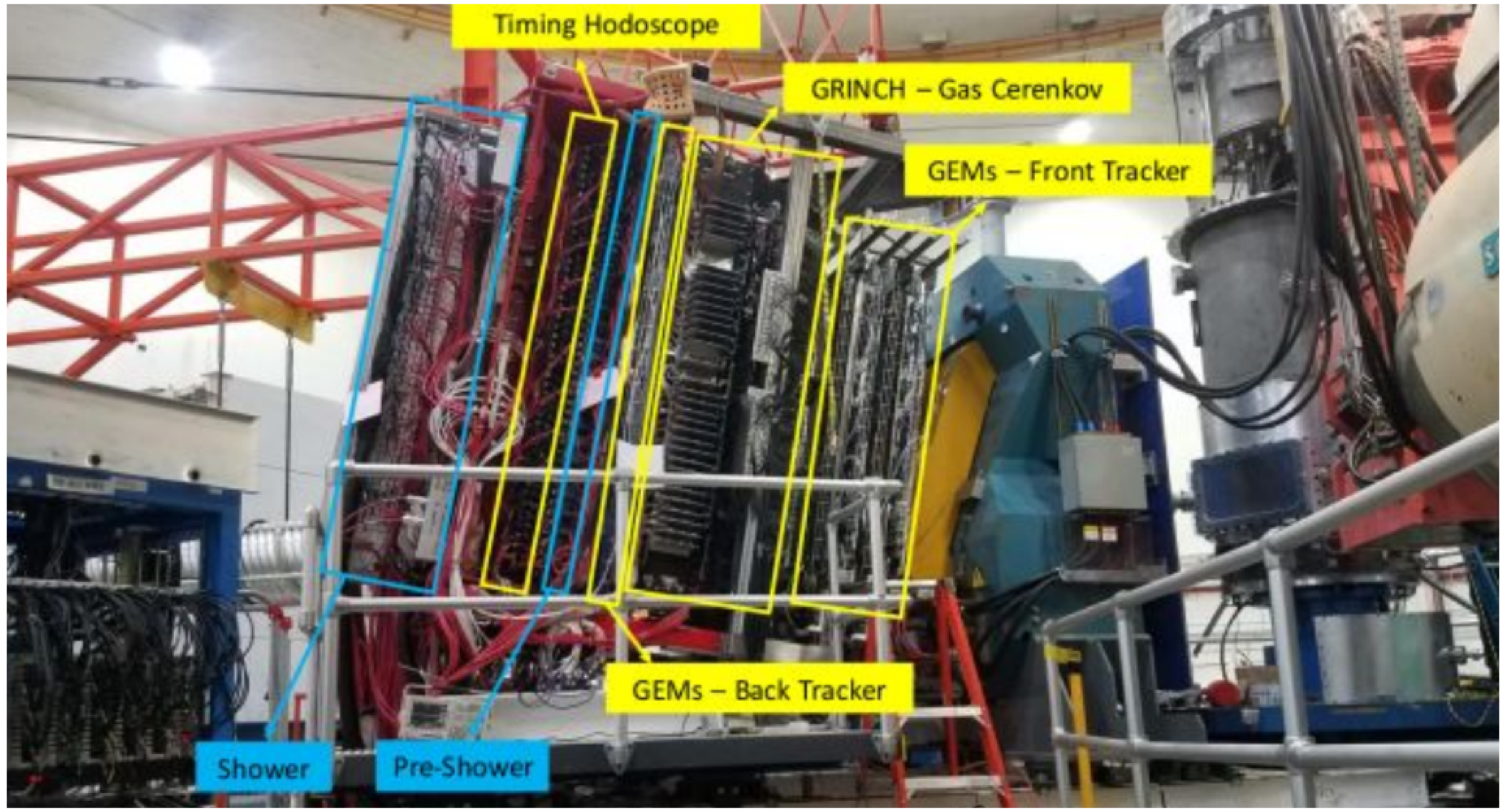
BigBite and Super Bigbite Spectrometers



Super Bigbite Spectrometer (SBS) Measurements





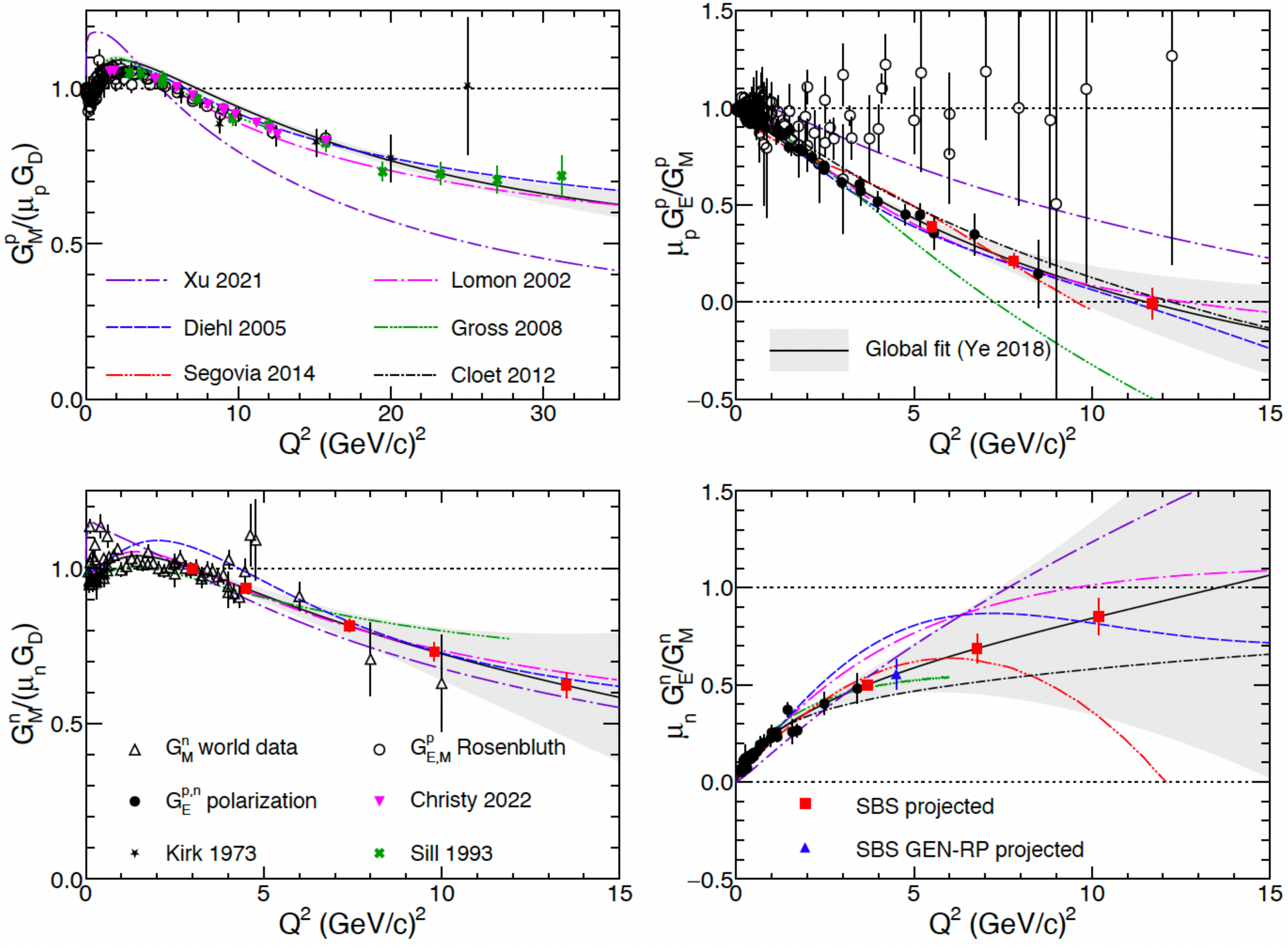


•Modular (tracking, calorimetry, timing, Cherenkov)
•High-rate detectors
•e.g. Gaseous electron multipliers (GEMs) for tracking

•University of Glasgow built a timing hodoscope time stamping electrons in BigBite arm and readout electronics

Super Bigbite Spectrometer (SBS) Measurements

A. Puckett, SBS Collaboration and Gross, F., et al., Eur. Phys. J. C 83, 1125 (2023)



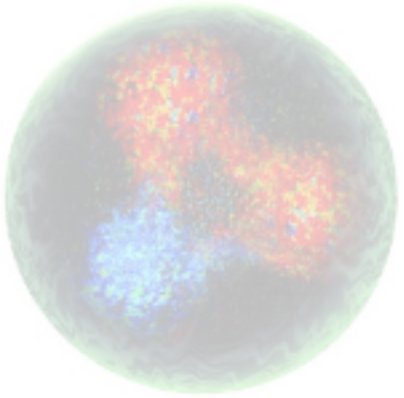
- Unprecedented extension to higher Q^2
- Improve statistical uncertainties at low Q^2
- Provide constraints for GPDs and hadron tomography
- Better discriminate between QCD models in transition region between perturbative and non-perturbative regimes
- Explore flavour separation and different quark contributions to nucleon structure
- (Including future strange quark measurements)

- Experiments started late 2020
- GMn, GEn(II), GEn-RP have completed data-taking, analysis underway
  - 3 PhD students at UoG so far
- GEp data-taking underway
- Stay tuned for future results

See slides from A. Cheyne (UoG) talk this morning for GEn-RP analysis

Hadron Tomography

Nucleon



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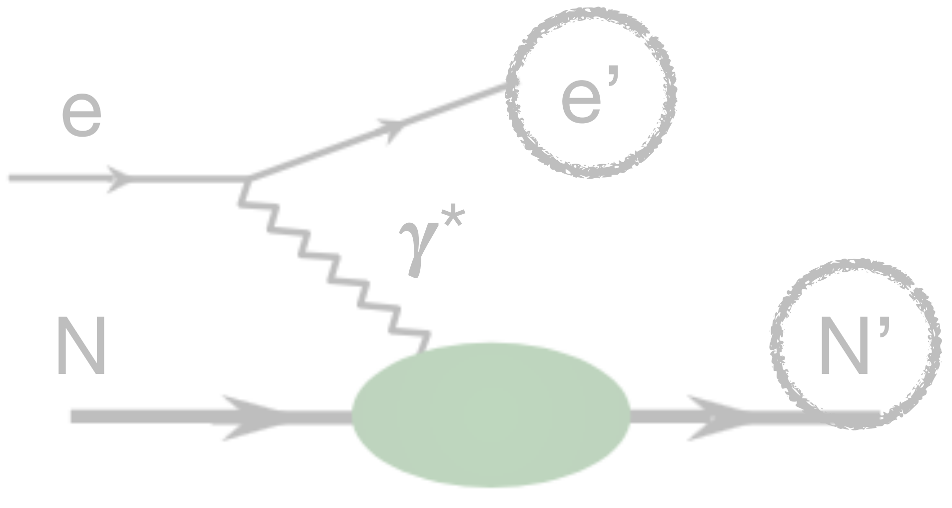
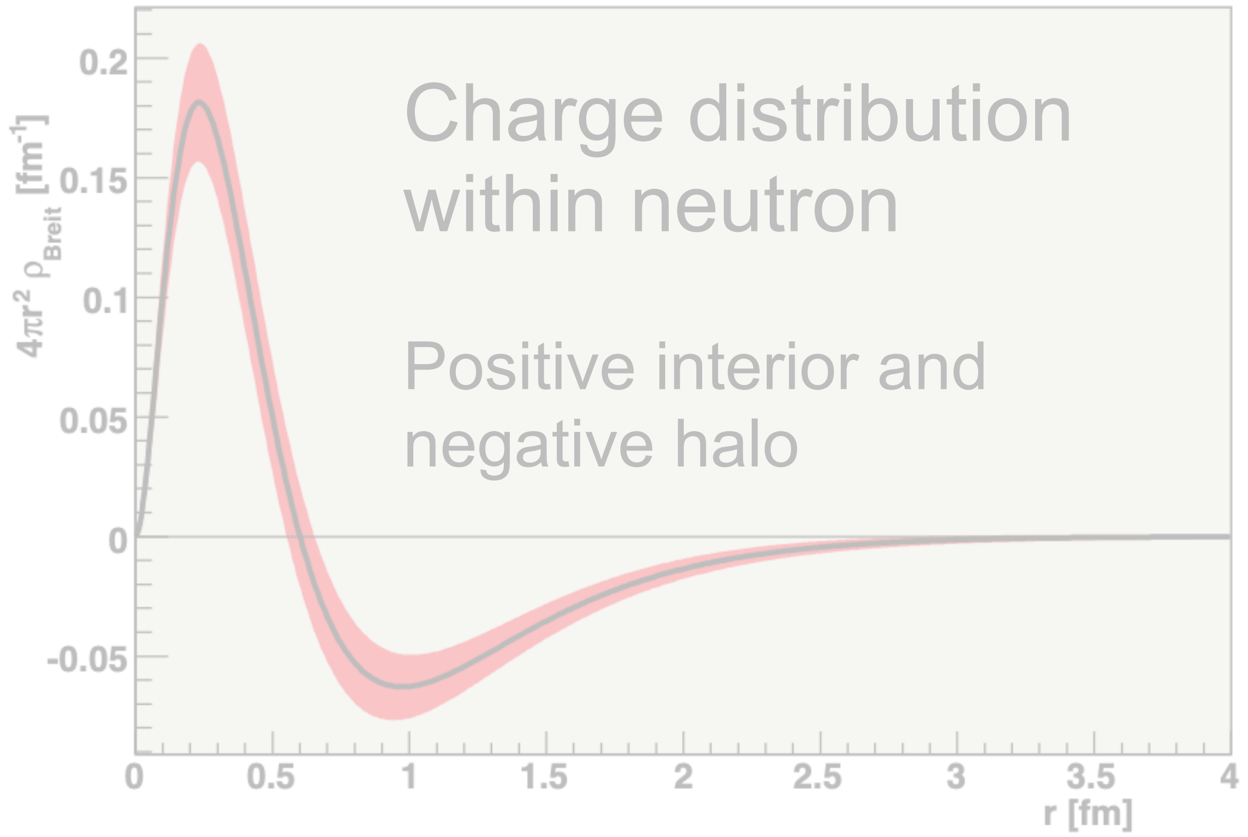


Exclusive Elastic scattering

DOE/NSF NSAC, arXiv:0809.3137v1



Transverse Momentum Dependent Distribution Functions (TMDs)

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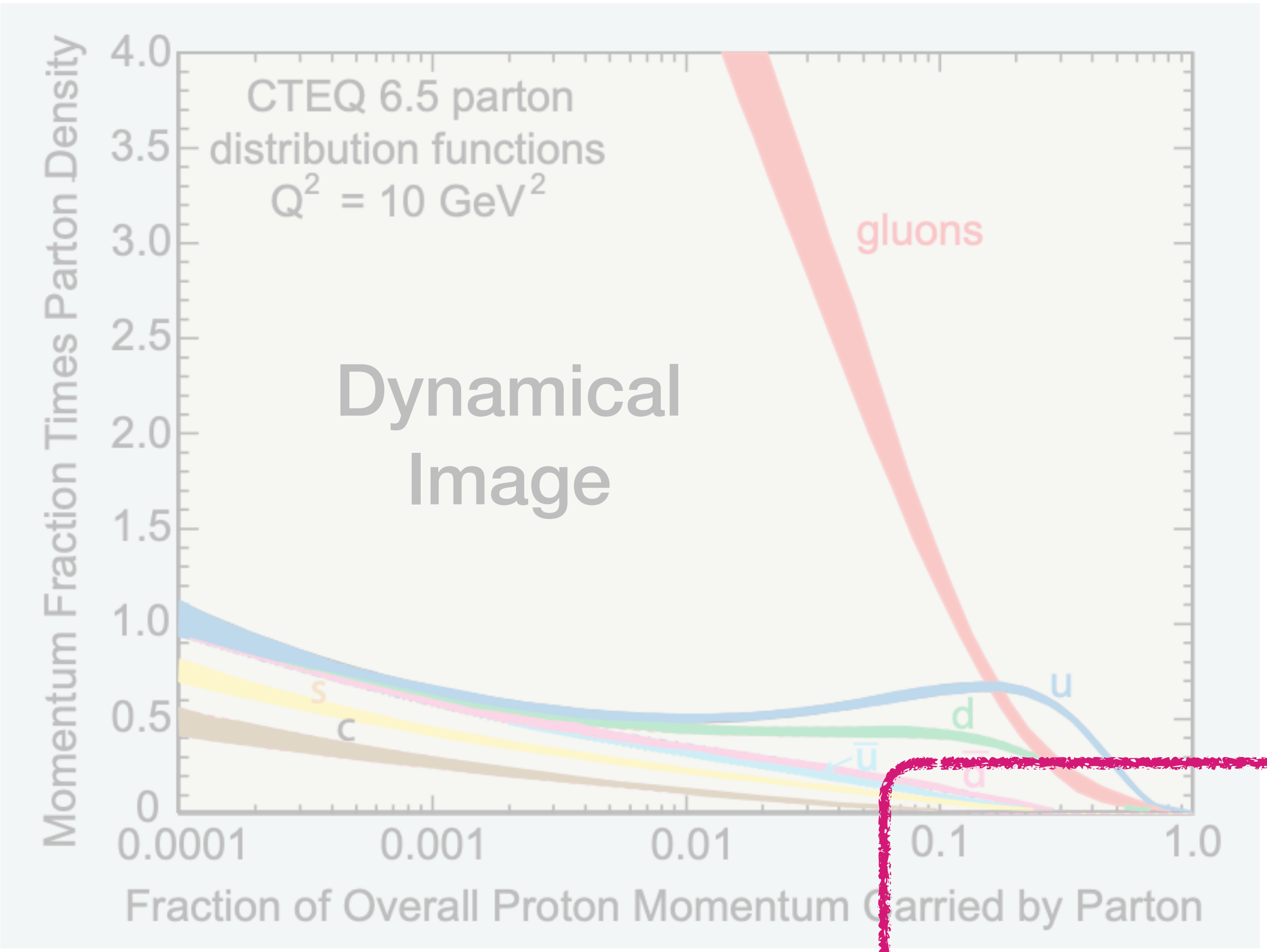
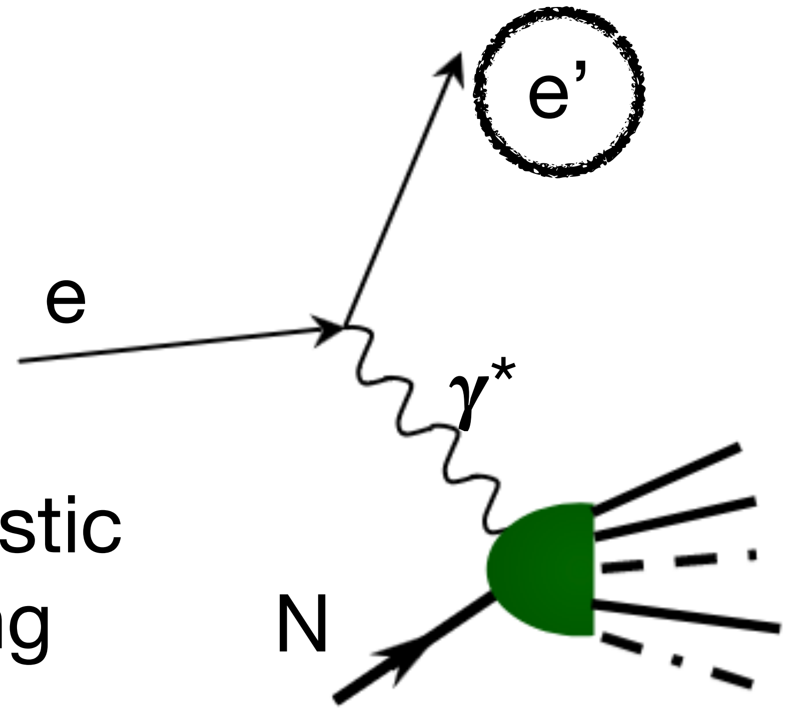


Inclusive structure example?

Deep Inelastic Scattering

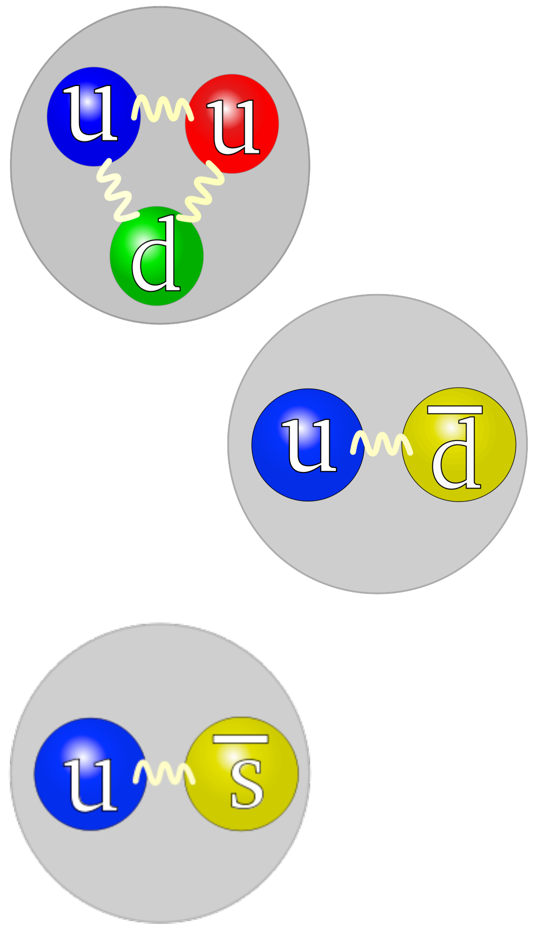


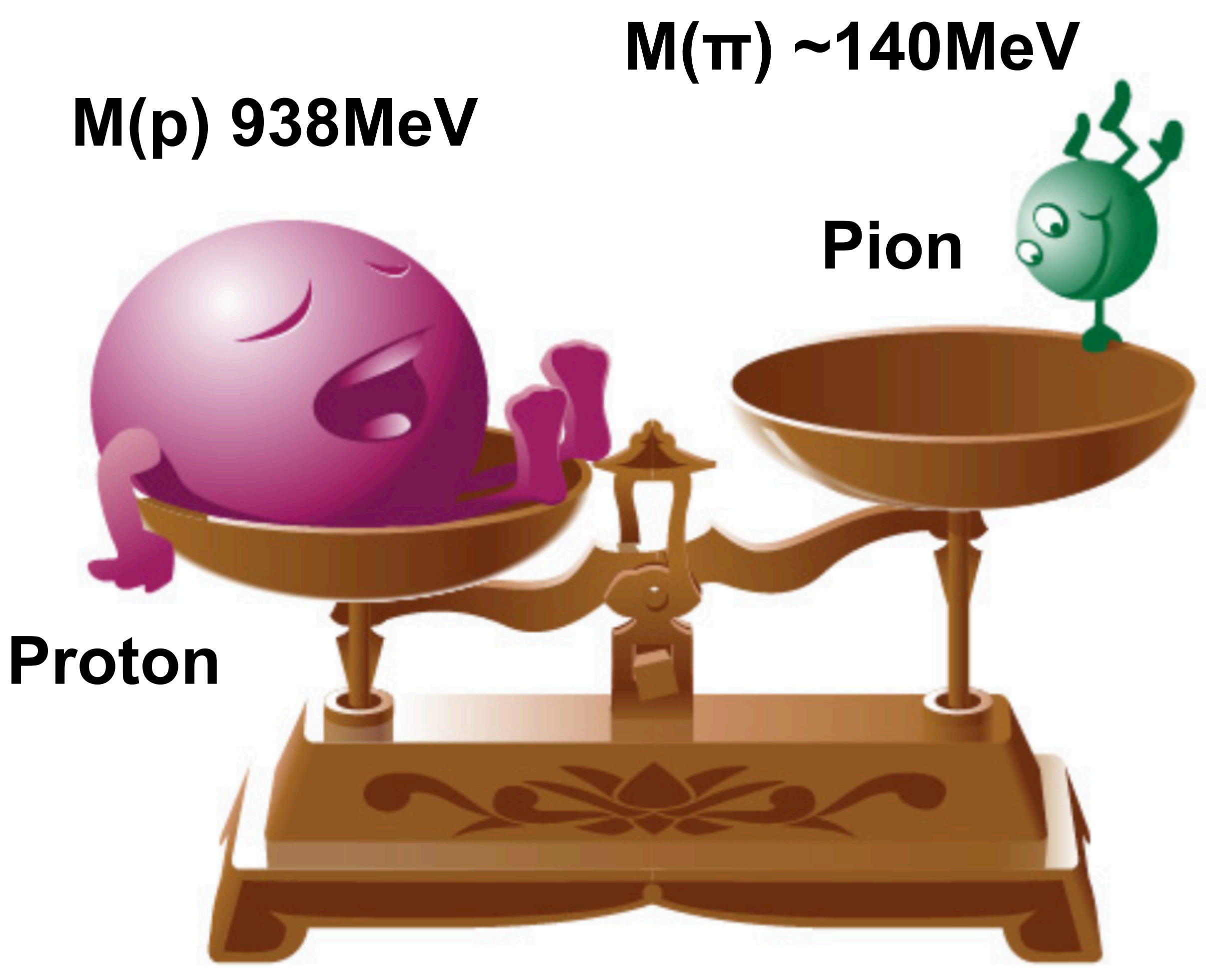
Inclusive Structure of Mesons

Proton

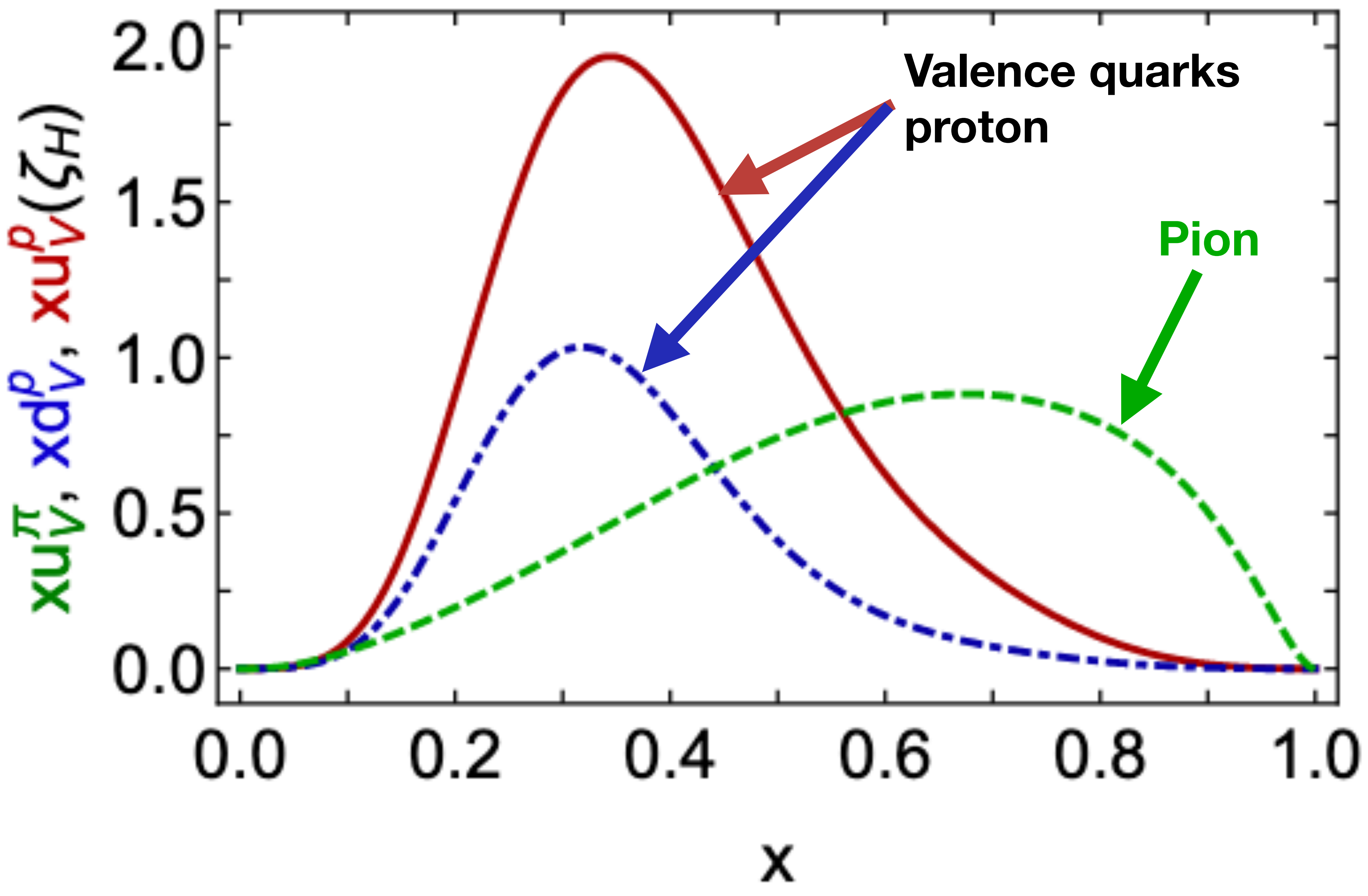
Pion

Kaon



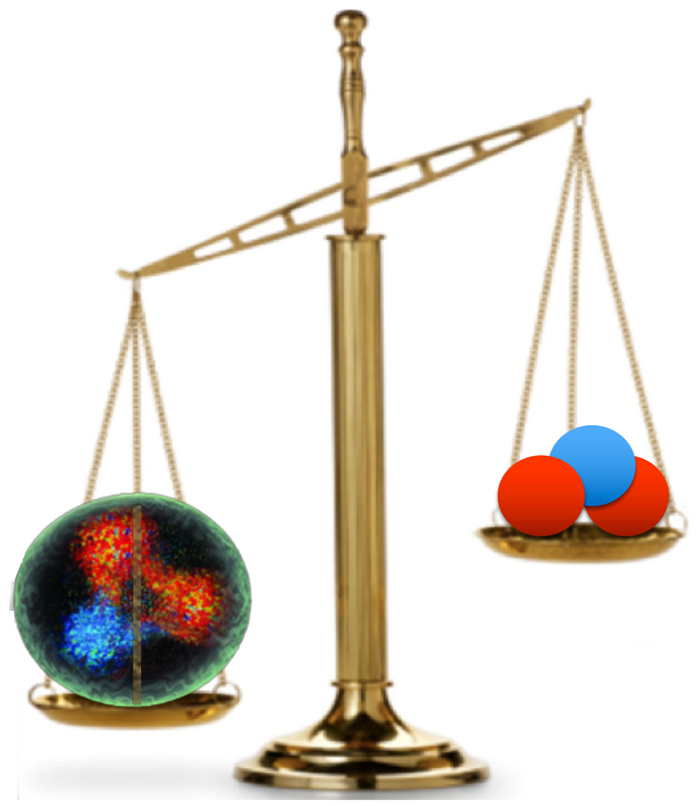


https://www.nobelprize.org/prizes/physics/2008/illustrated-information/



Continuum Schwinger function methods (DSE)

Ya Lu, Lei Chang, Khépani Raya, Craig Roberts, José Rodriguez-Quintero, 2203.00753 [hep-ph], Phys Lett B 830 (2022) 137130/1-7

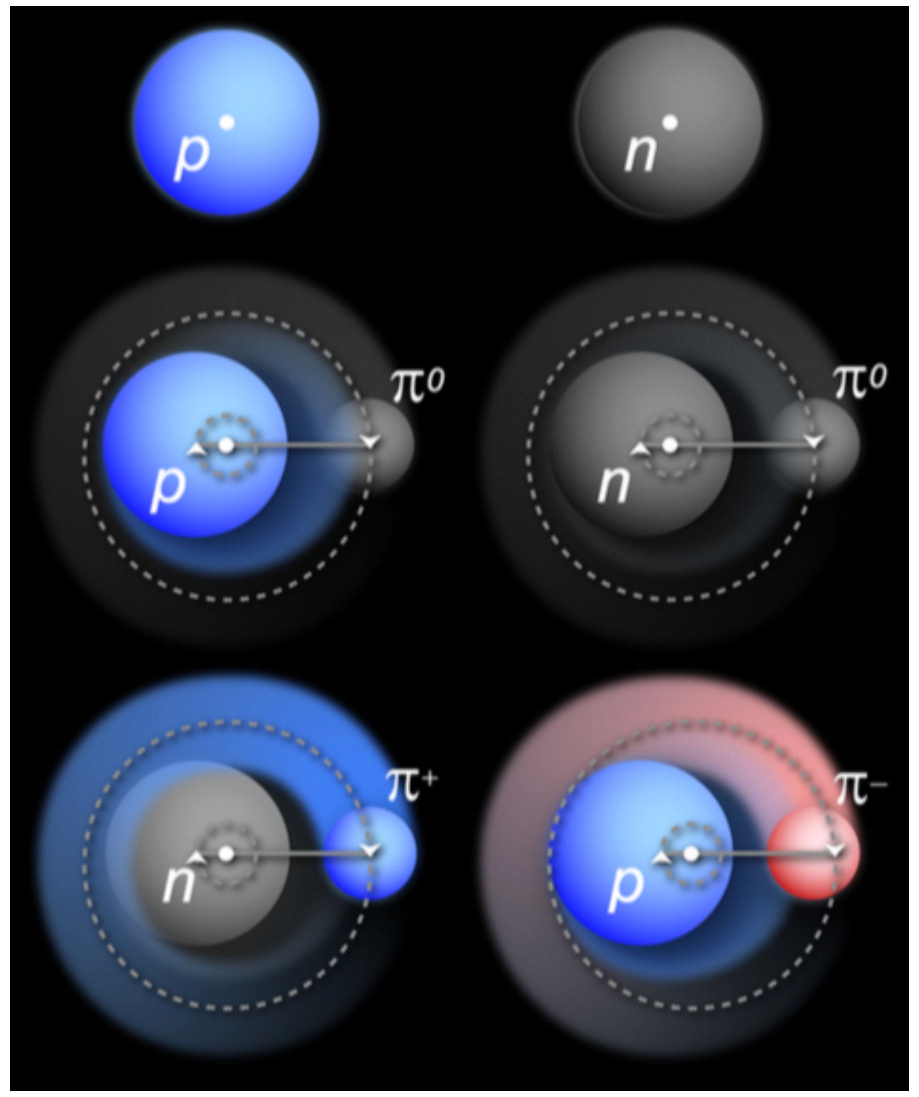


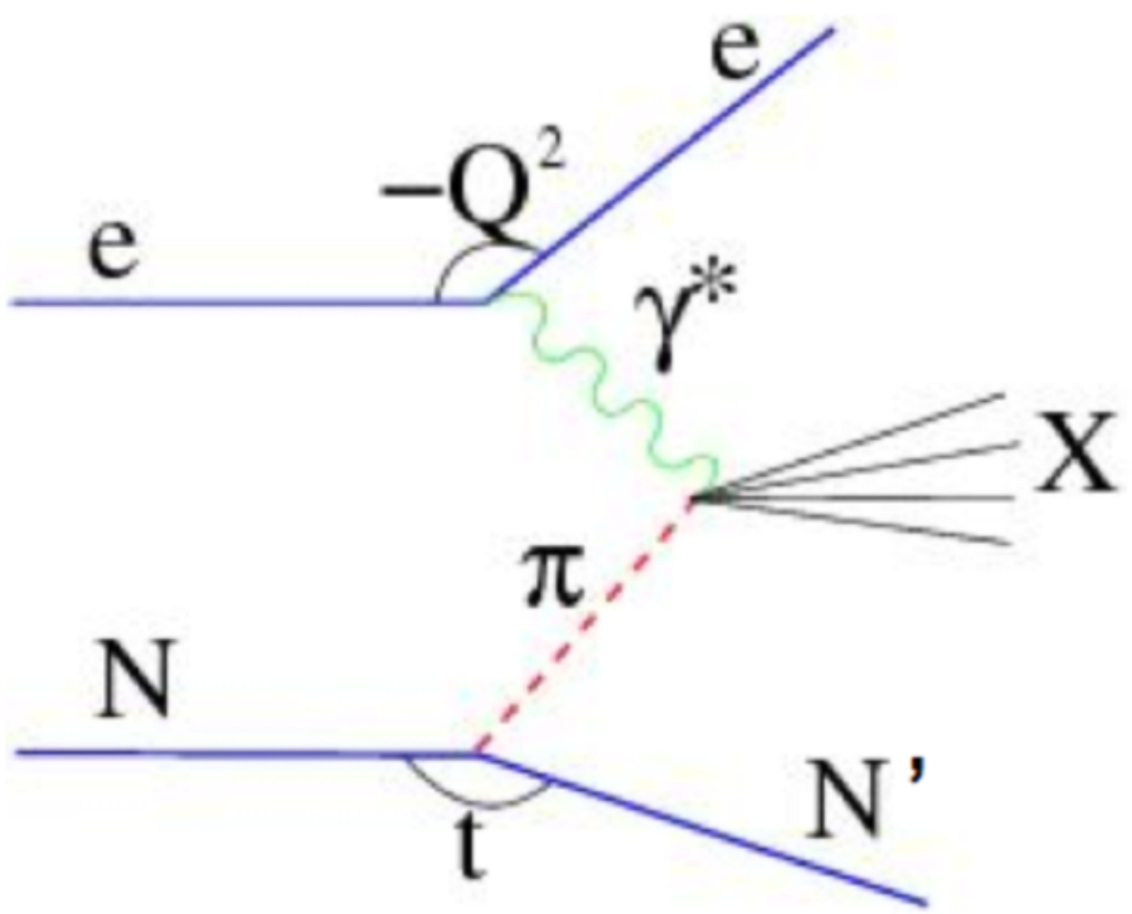
Hadron	Observed Mass (MeV)	Higgs Generated Mass (MeV)
Proton (uud)	~940	~10
Pion (ud̄)	~140	~7
Kaon (us̄)	~490	~100

- Very little known experimentally about internal structures of light mesons
- Substantial theoretical work - but we need data!

- Pions and kaons unexpectedly light
- Key for emergent hadronic mass (EHM) topics
- Gluon content in kaon expected to be different than pion
- Measuring distributions of light quarks versus strange quarks within pion/kaon yields experimental signatures of EHM
- Expect interesting implications for inclusive structure

Accessing Pions/Kaons at JLab - Sullivan Process



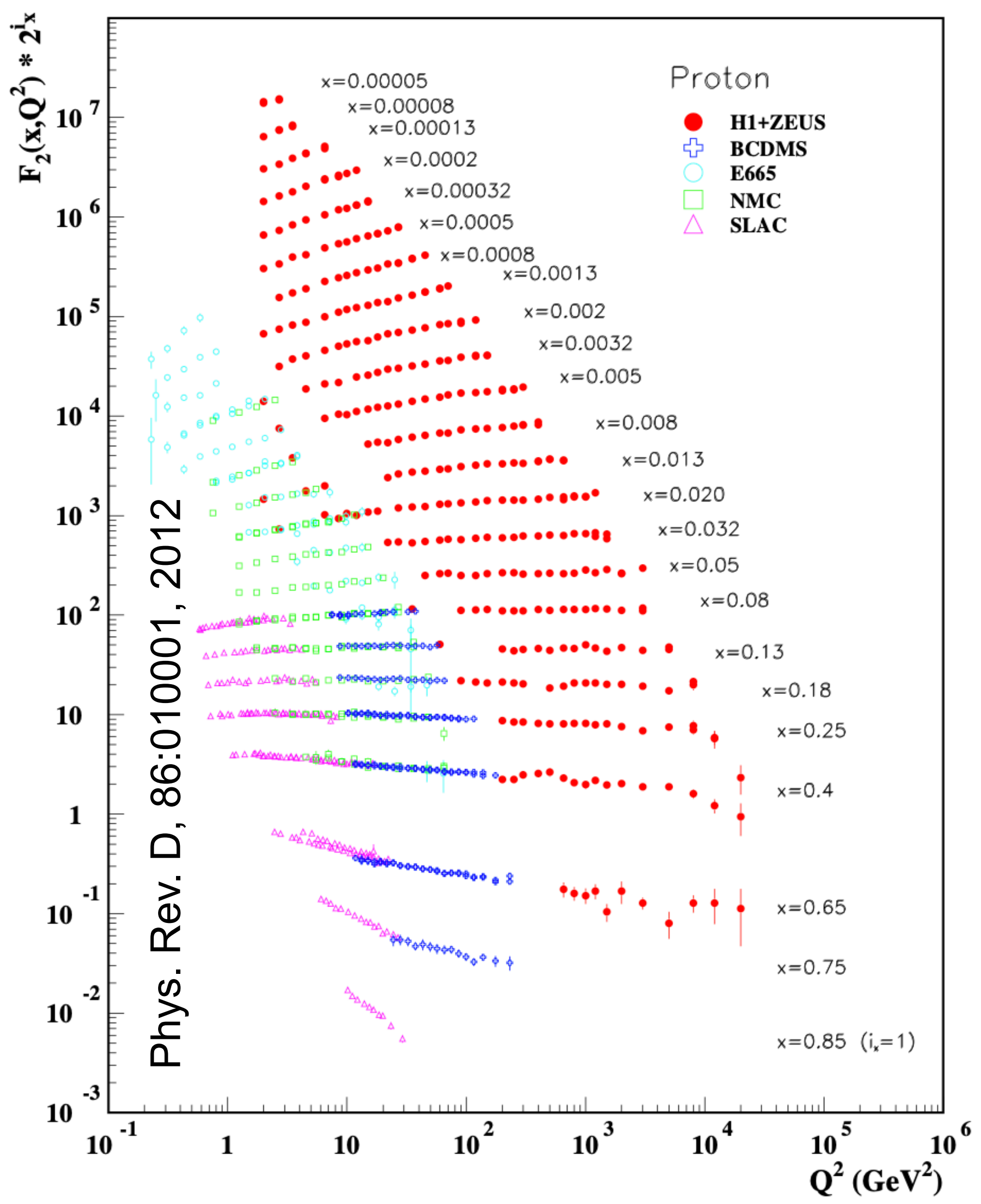


- DIS from virtual meson cloud of nucleon

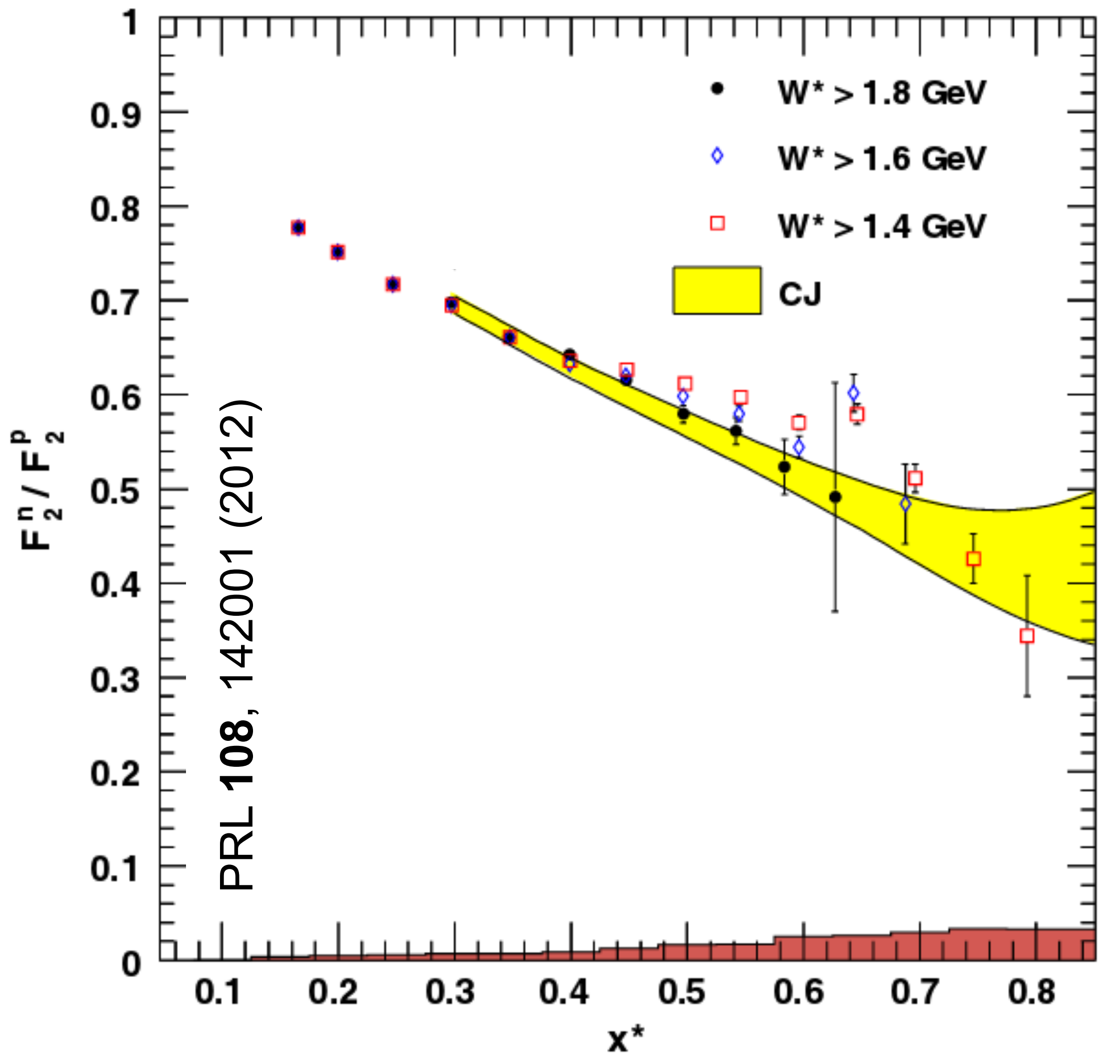
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2{}_0 \sin^4\frac{\theta}{2}}\cos^2\frac{\theta}{2}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

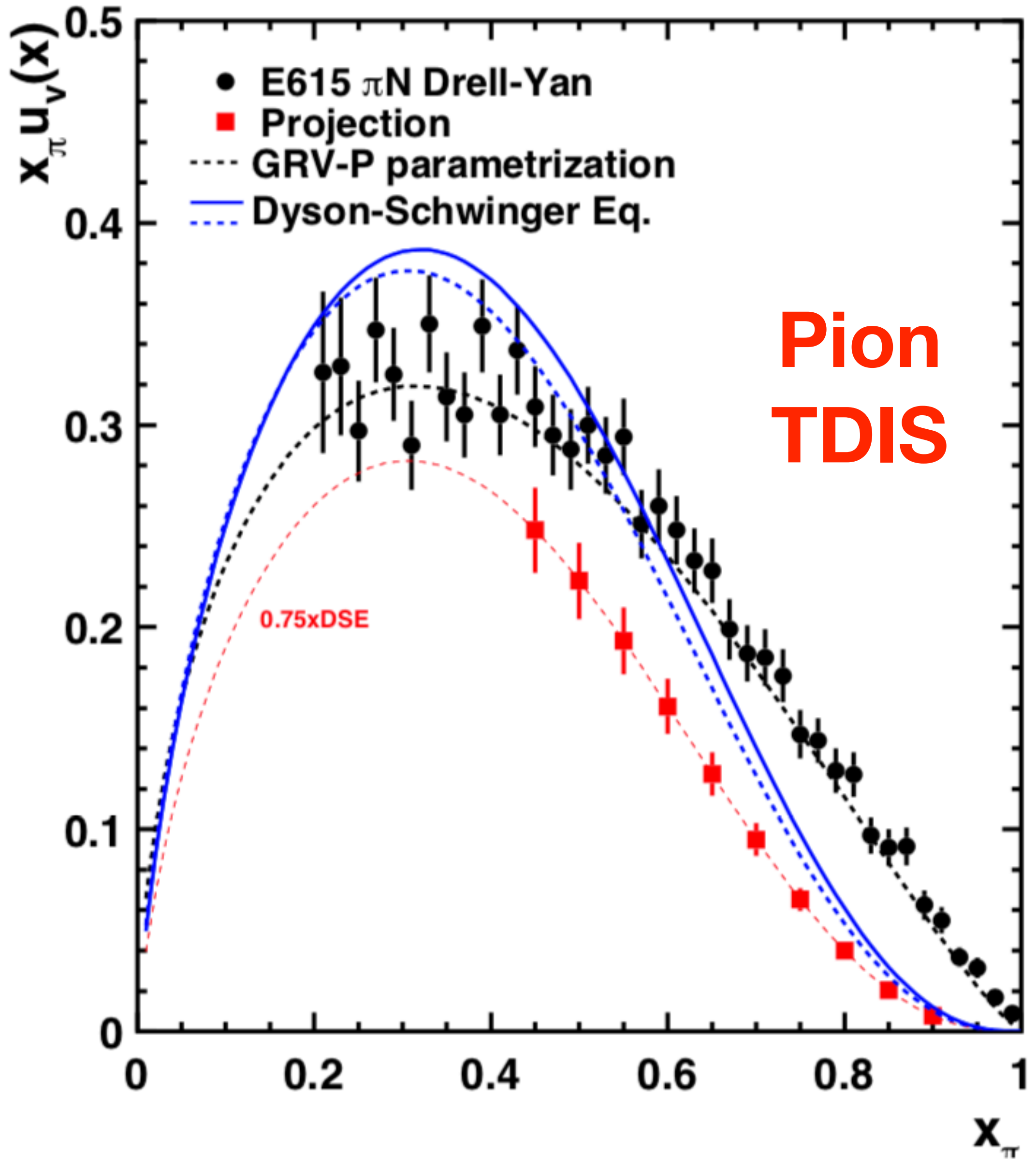
- Upcoming tagged deep inelastic scattering (TDIS) program
- Access F_2 structure functions for pions and kaons in valence region
- Sparse existing data for mesons (especially kaons)
- Vital input for PDFs

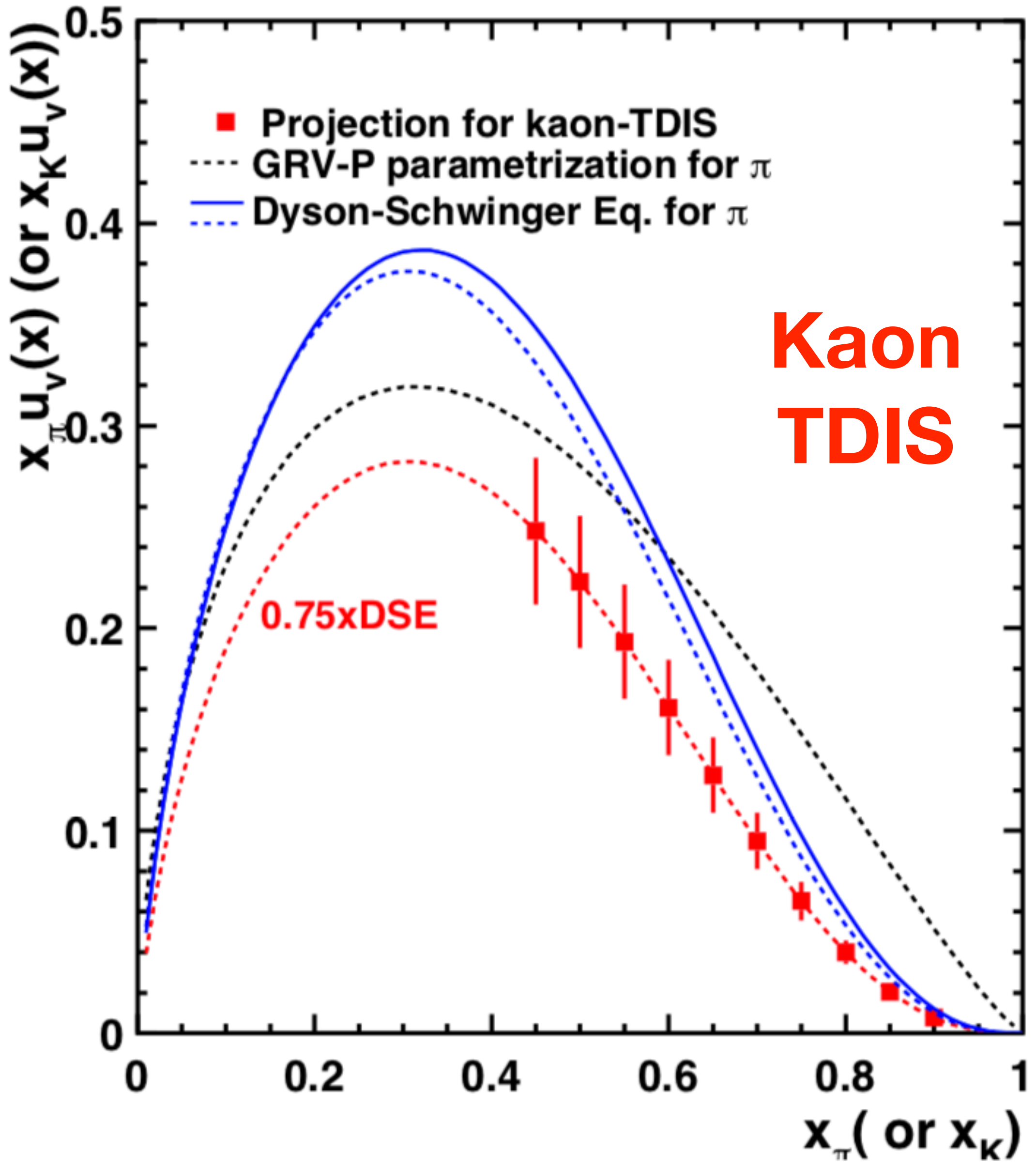
$F_2{}^p$



$F_2{}^n/F_2{}^p$

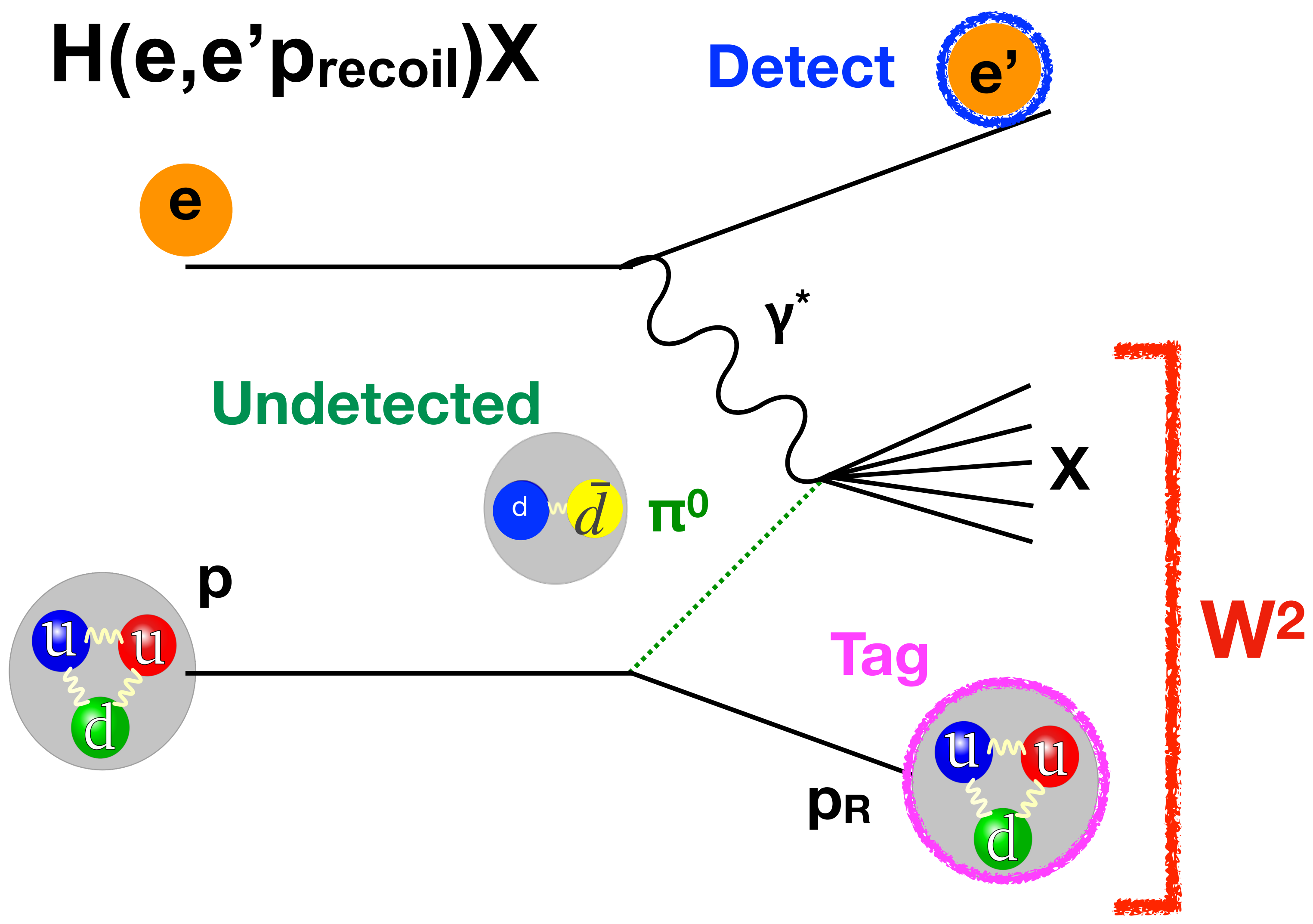


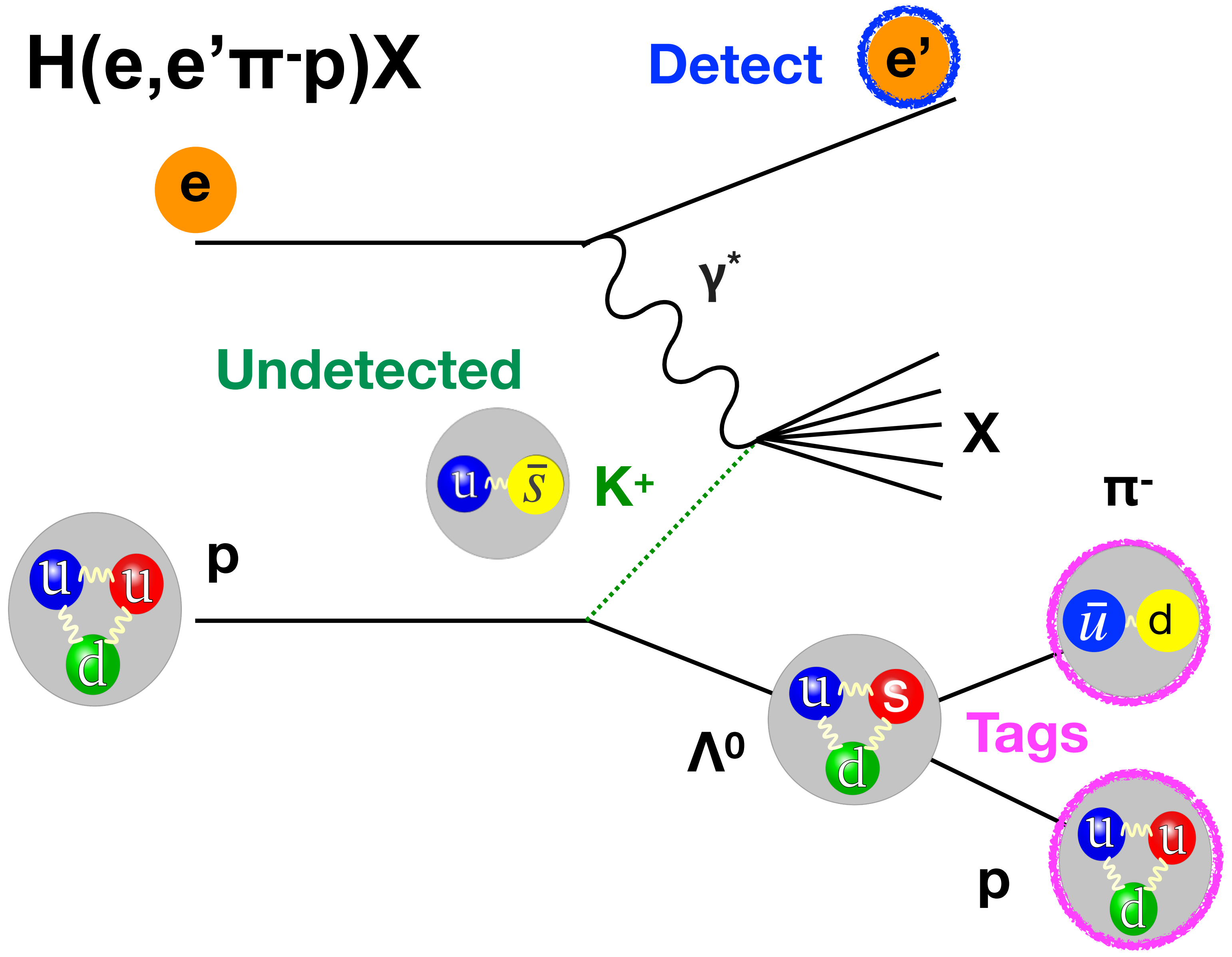




TDIS Measurements

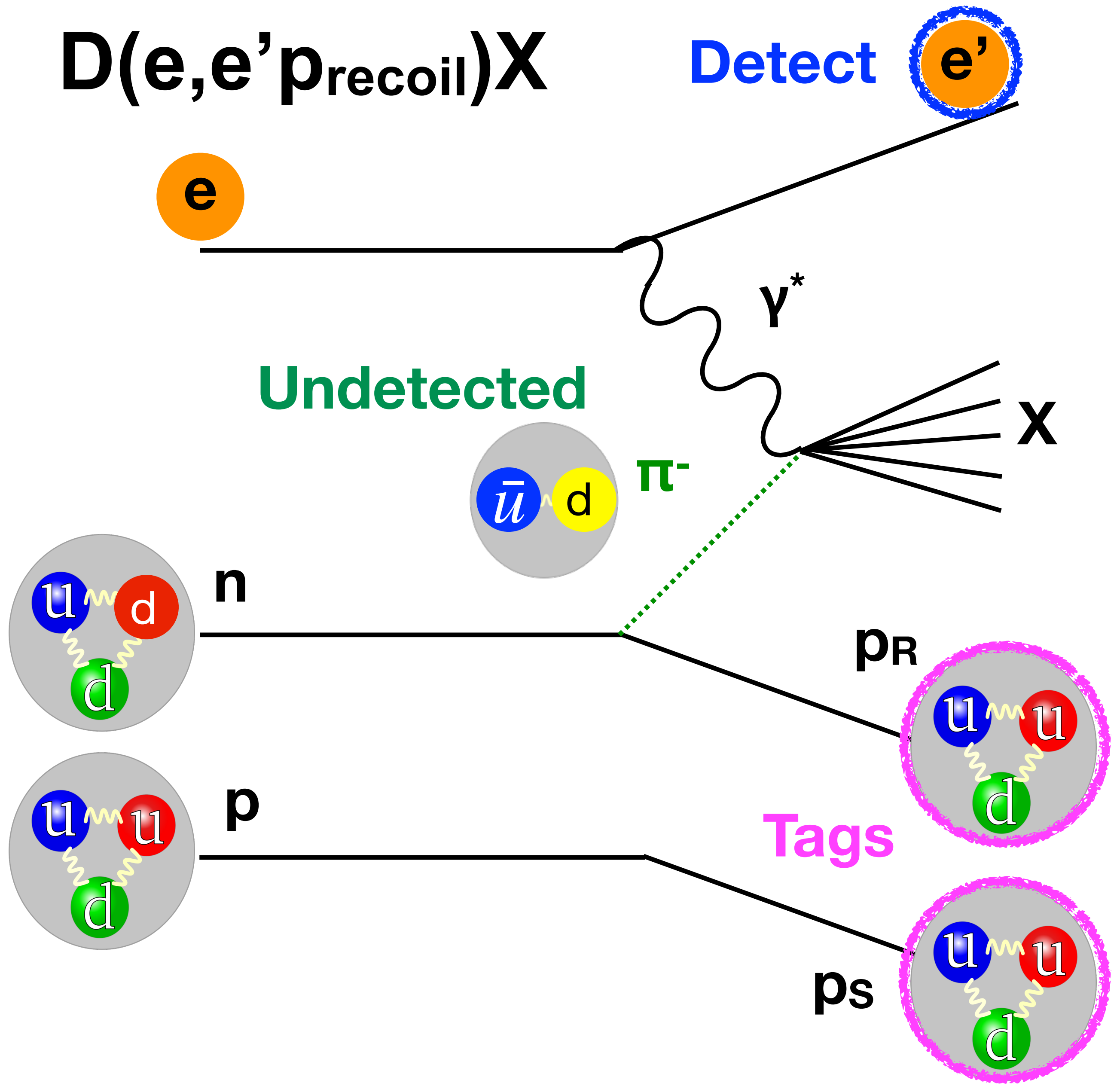
1st direct neutral pion measurement





Practically no data exists for kaon

Resolve QCD model tensions for charged pion



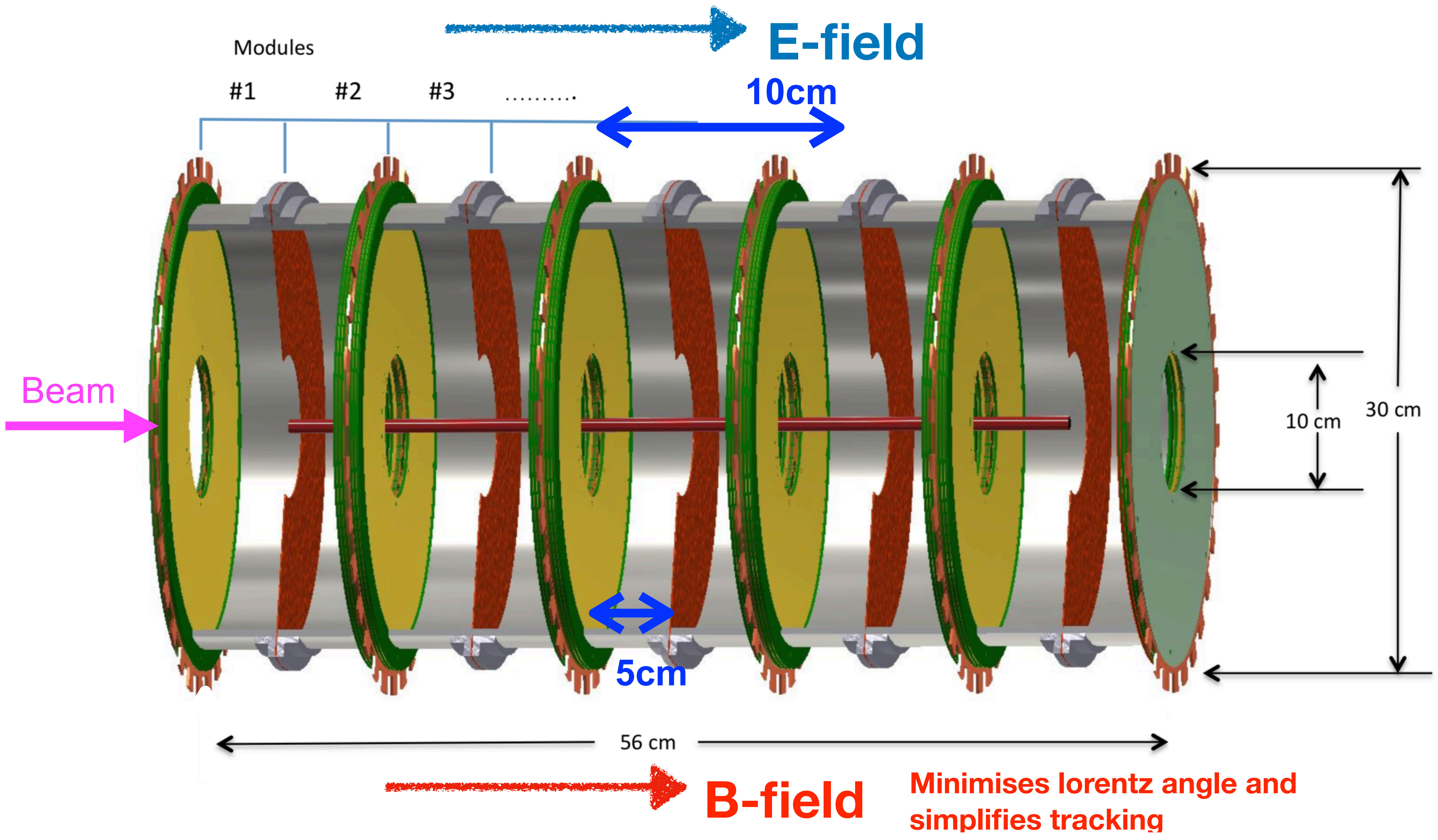
$8 < W^2 < 18$ GeV^2
$1 < Q^2 < 3$ GeV^2
$0.05 < x < 0.2$

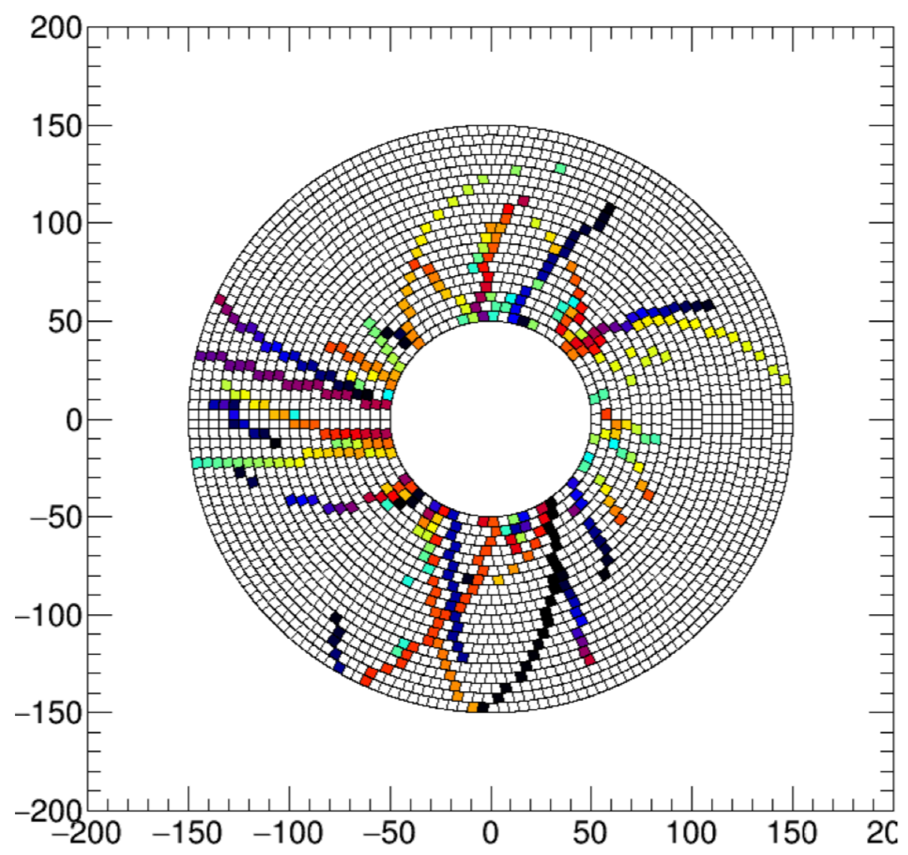
Reconstruct x, Q^2, W^2, and M_x of recoiling system for every event

- DIS with spectator tagging
- Access effective free targets not easily found in nature

- Cross - section is tiny → JLab unique facility for this
- SBS will detect scattered electrons
- Need a novel detector for the very low momentum recoiling hadrons (60 - 400 MeV/c)

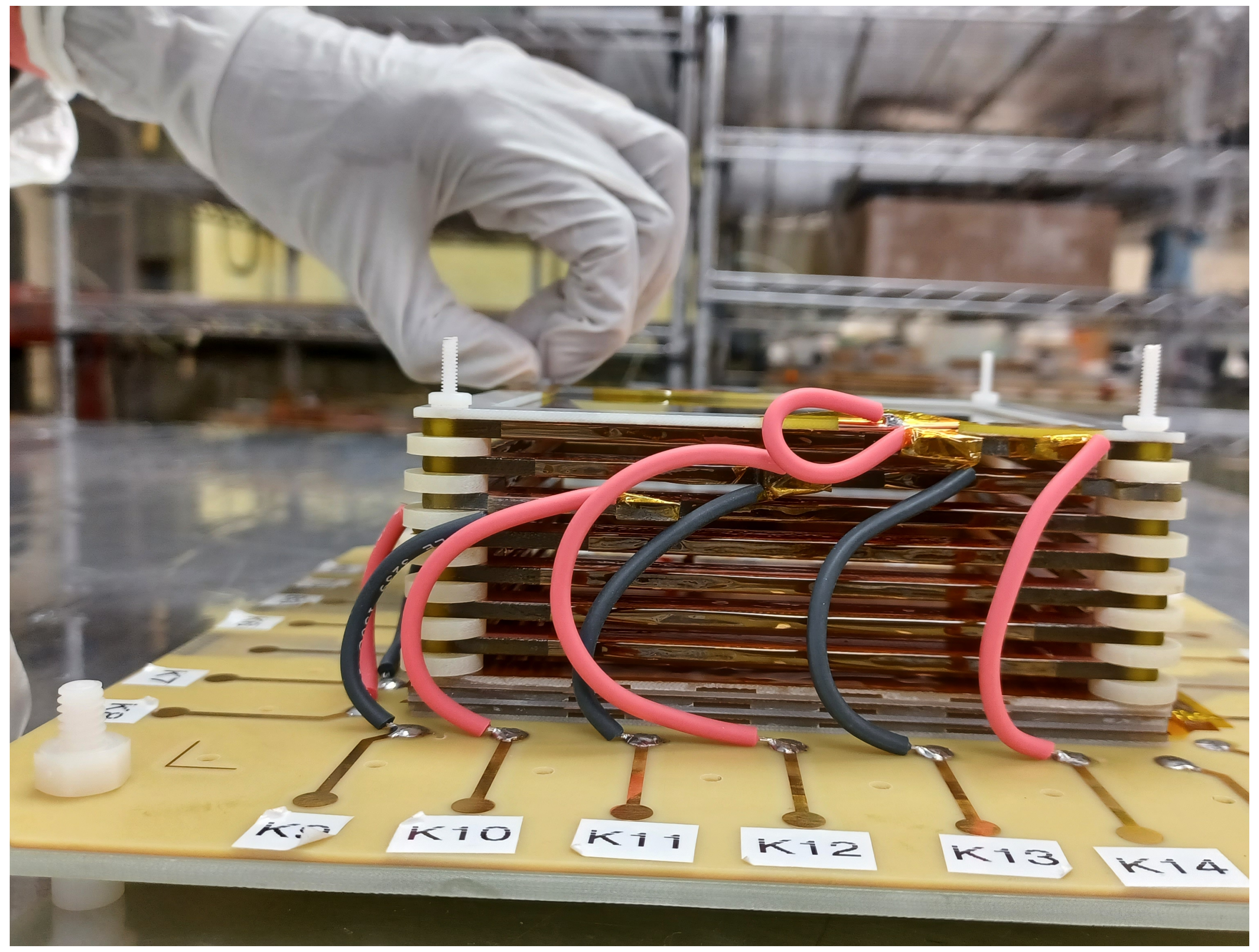
High Rate modular TPC

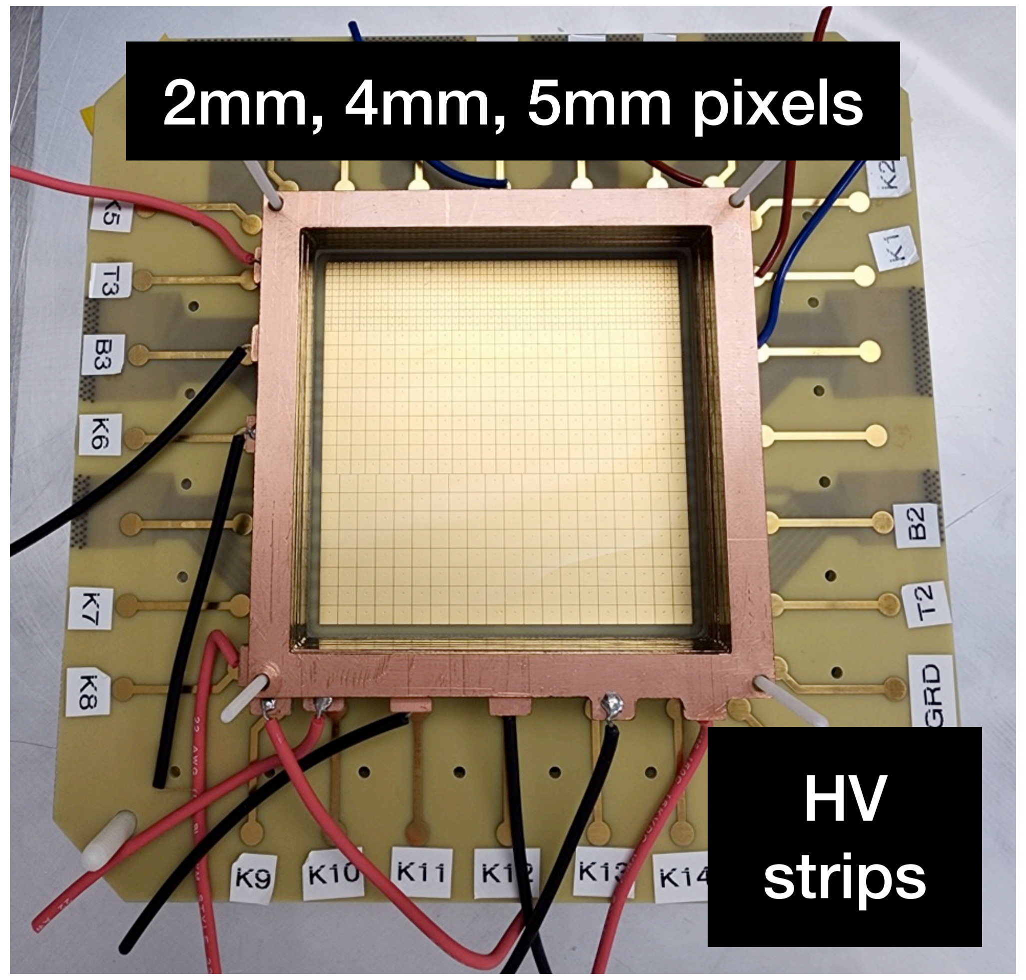


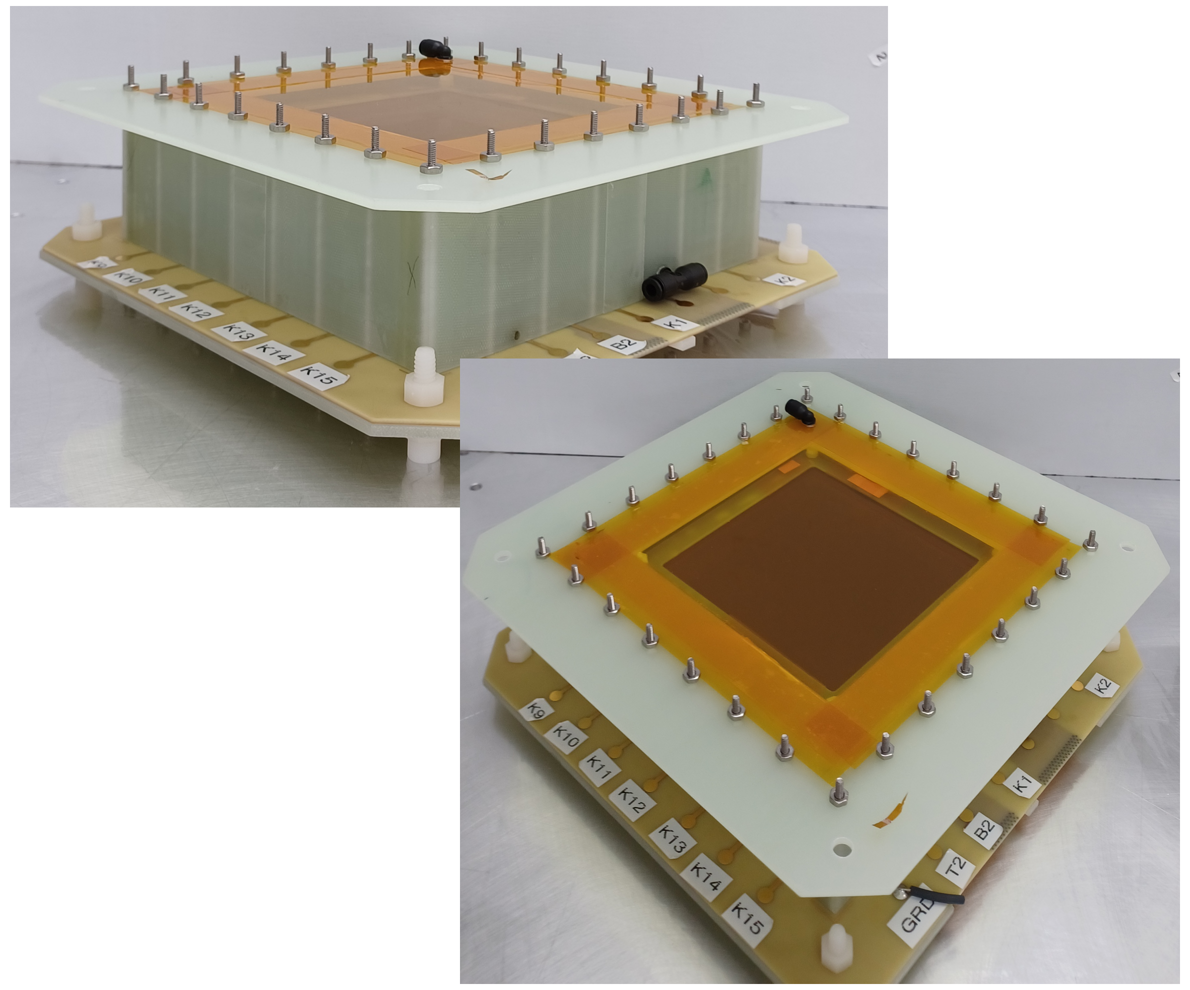


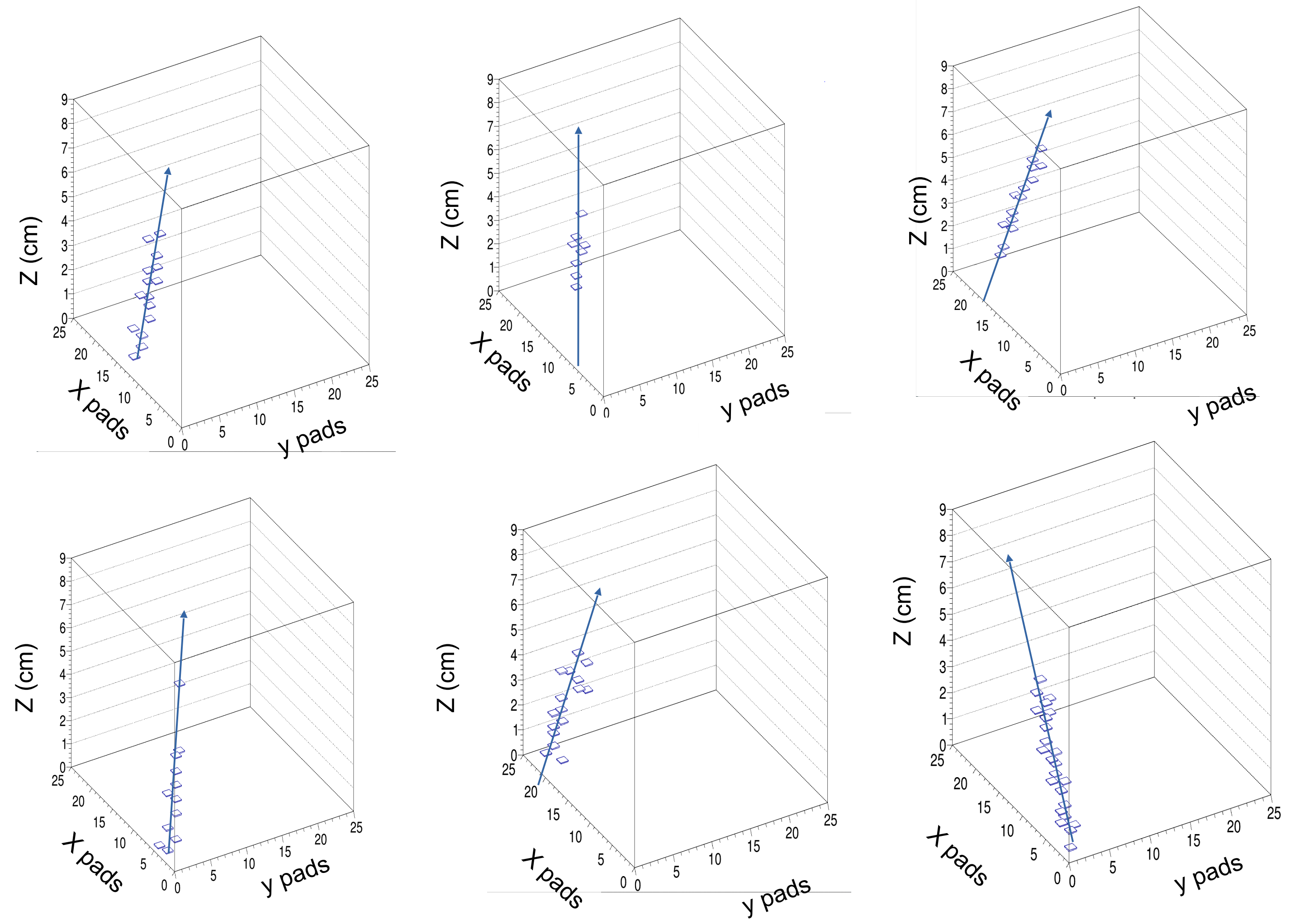
- Division into modules
  - reduced background rates
- GEM foil readout planes
- Segmented readout pads

- UVa constructed first prototype
  - (N. Liyanage, H. Nguyen)
- Testing on-going at JLab
- Next is cylindrical prototyping
- ML tracking in development (ACTS and GNN)



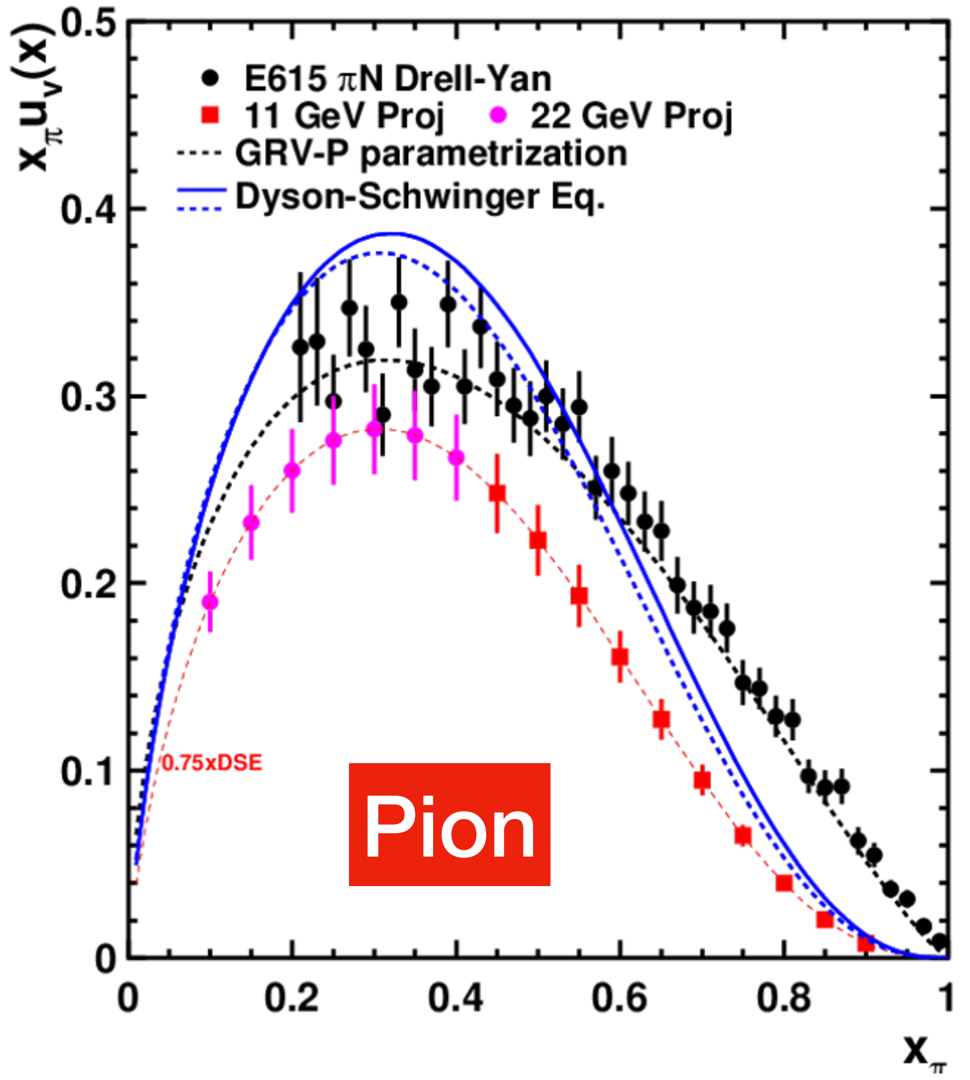


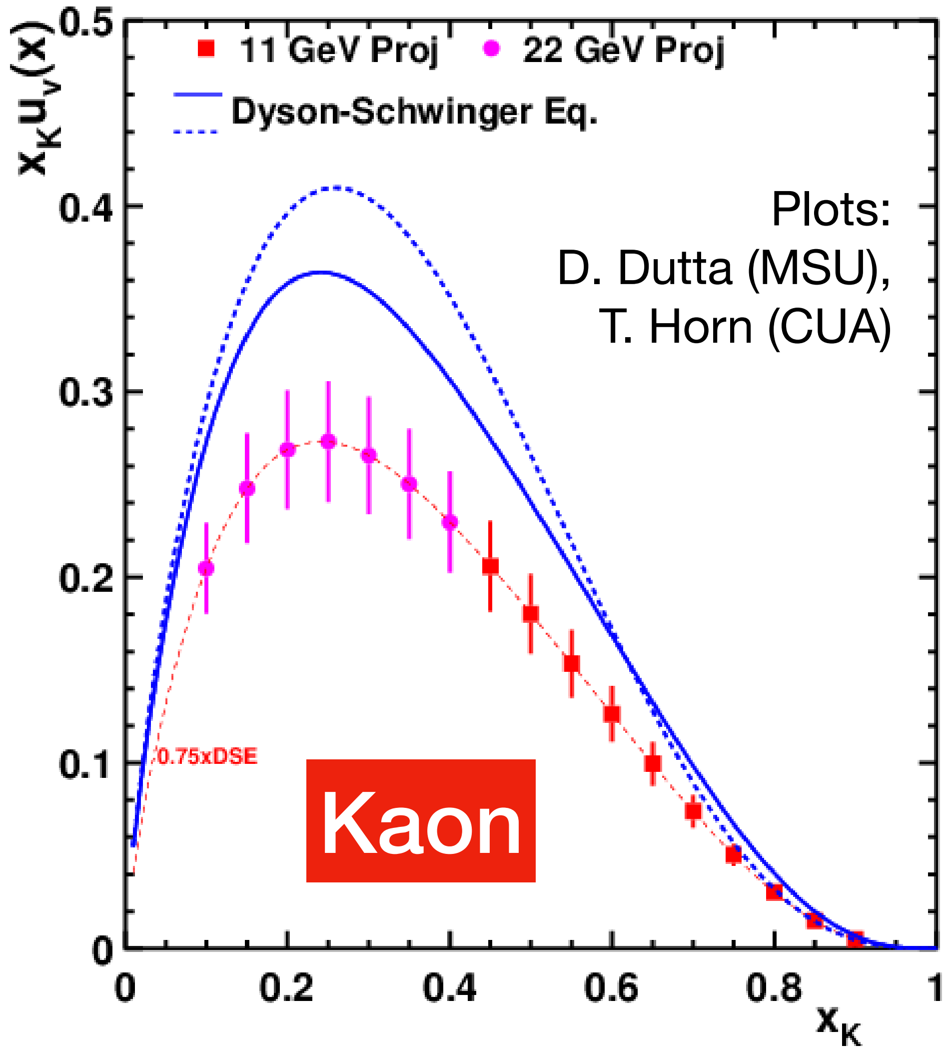




(S. Saha, E. Christy, JLab and A. Nadeeshani MSU)

Glimpse far into the Future

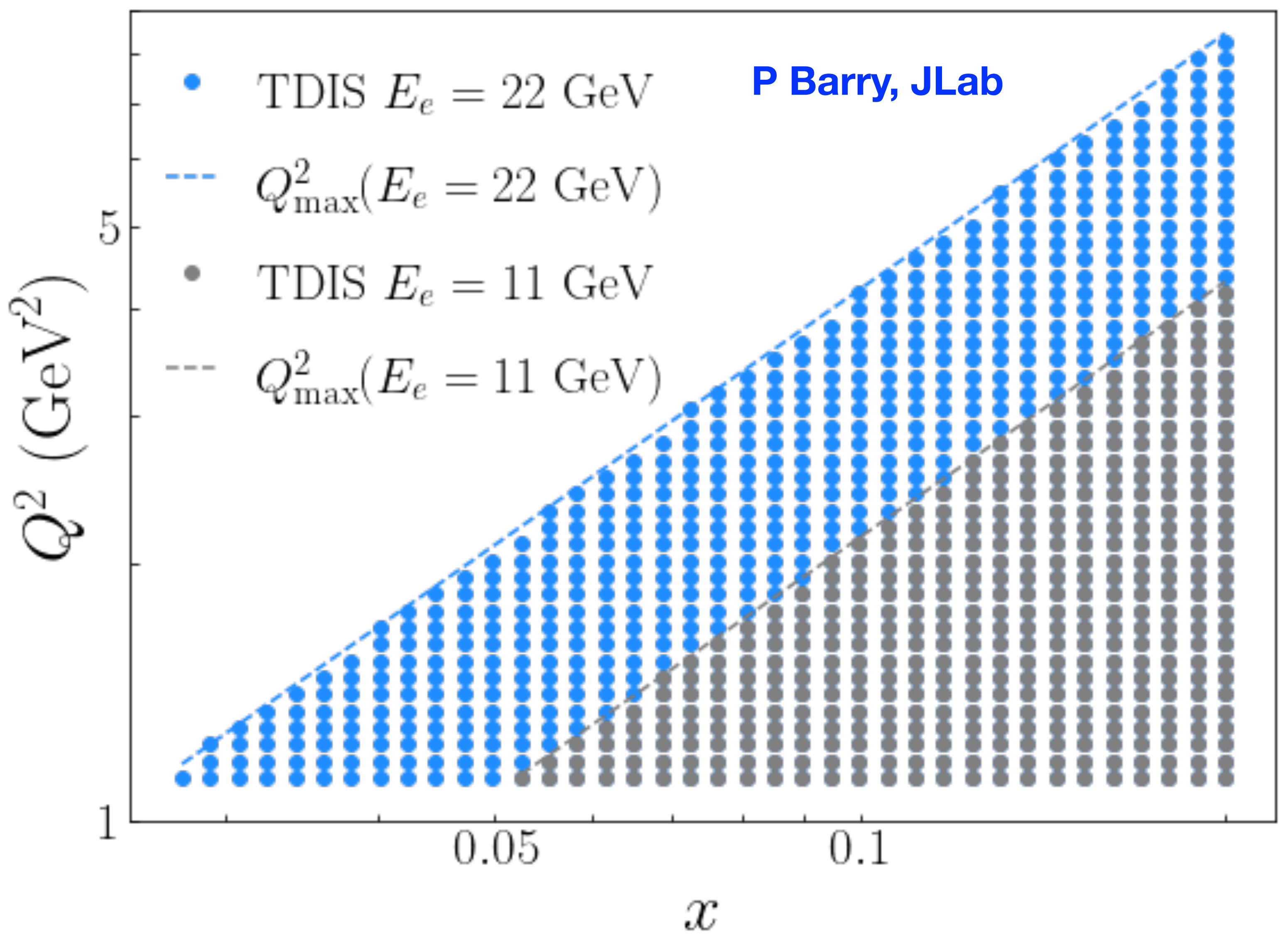


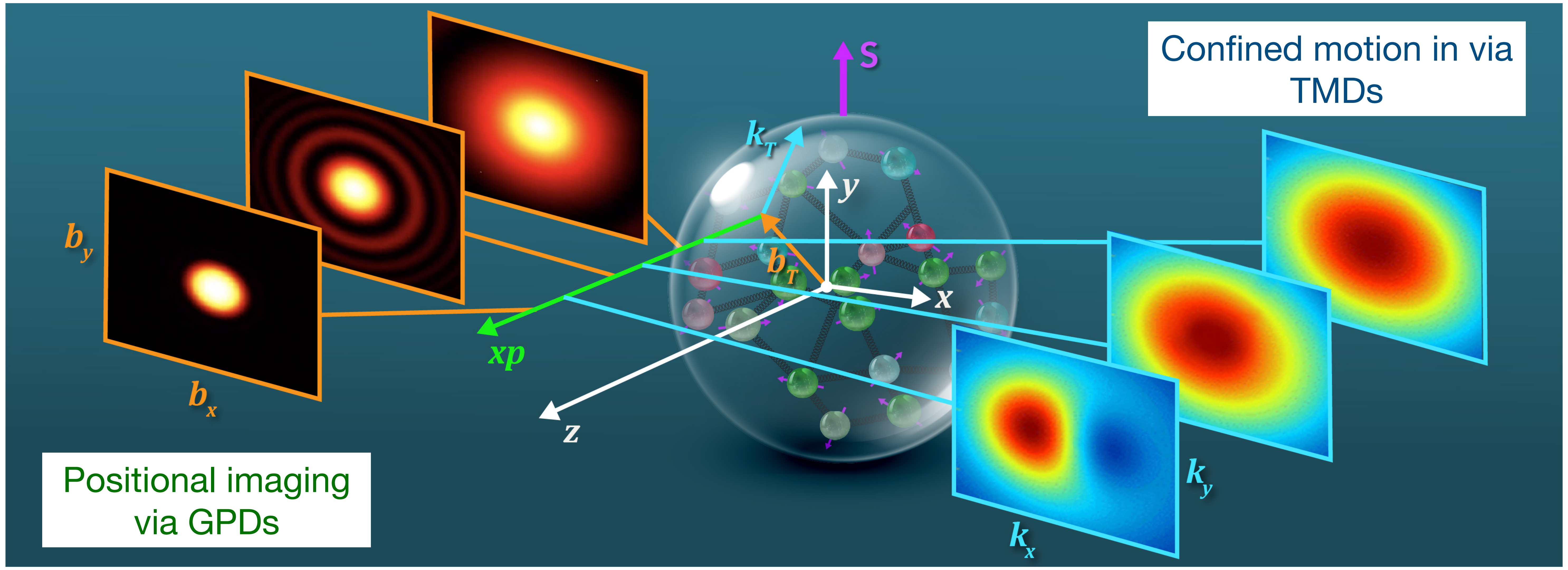


- Potential future staged upgrades to JLab are under investigation
- First would be a polarised positron beam upgrade
- Considerations are underway for a subsequent electron beam energy upgrade to 22GeV

- 22GeV expands kinematic phase space for TDIS, providing more data for PDF studies

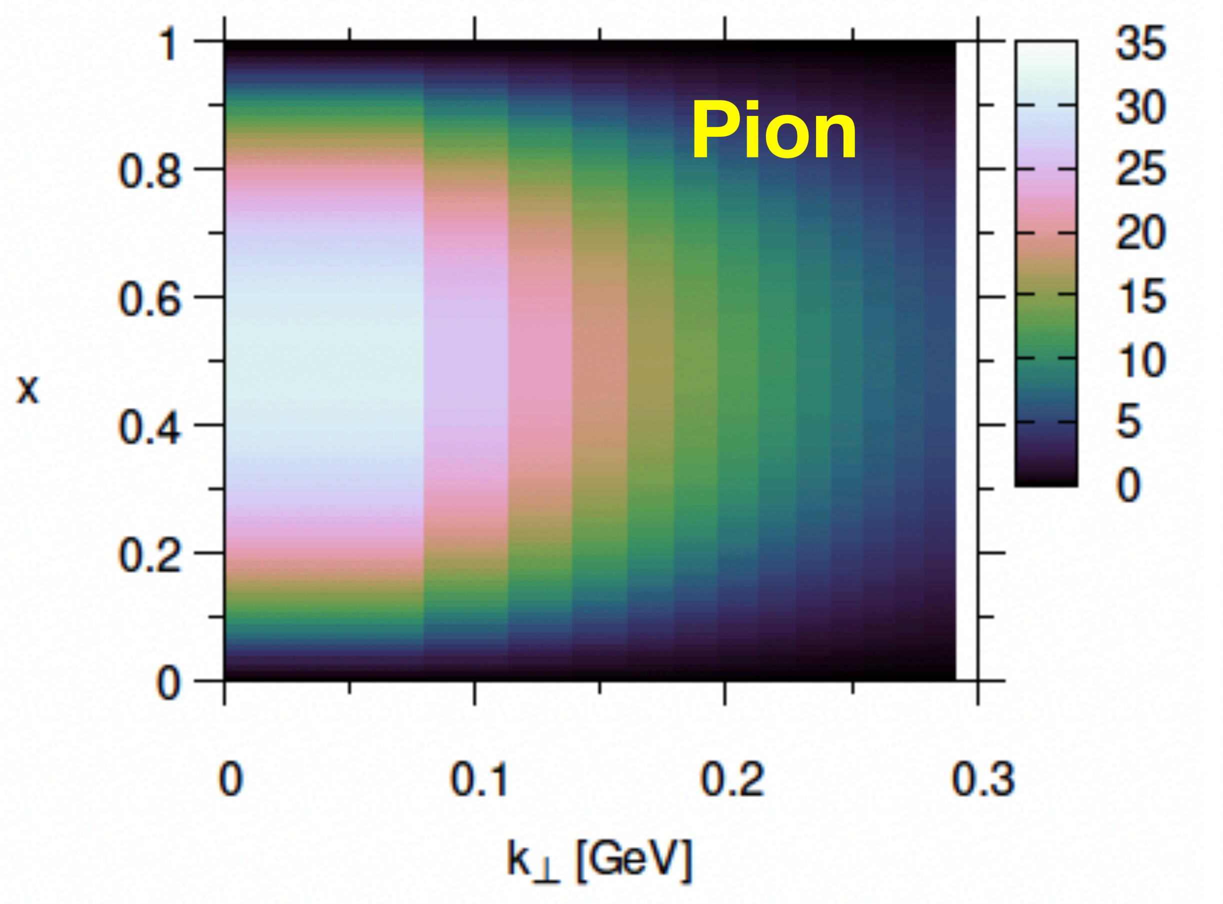
- 22GeV also unlocks a completely novel opportunity for meson tomography with TDIS

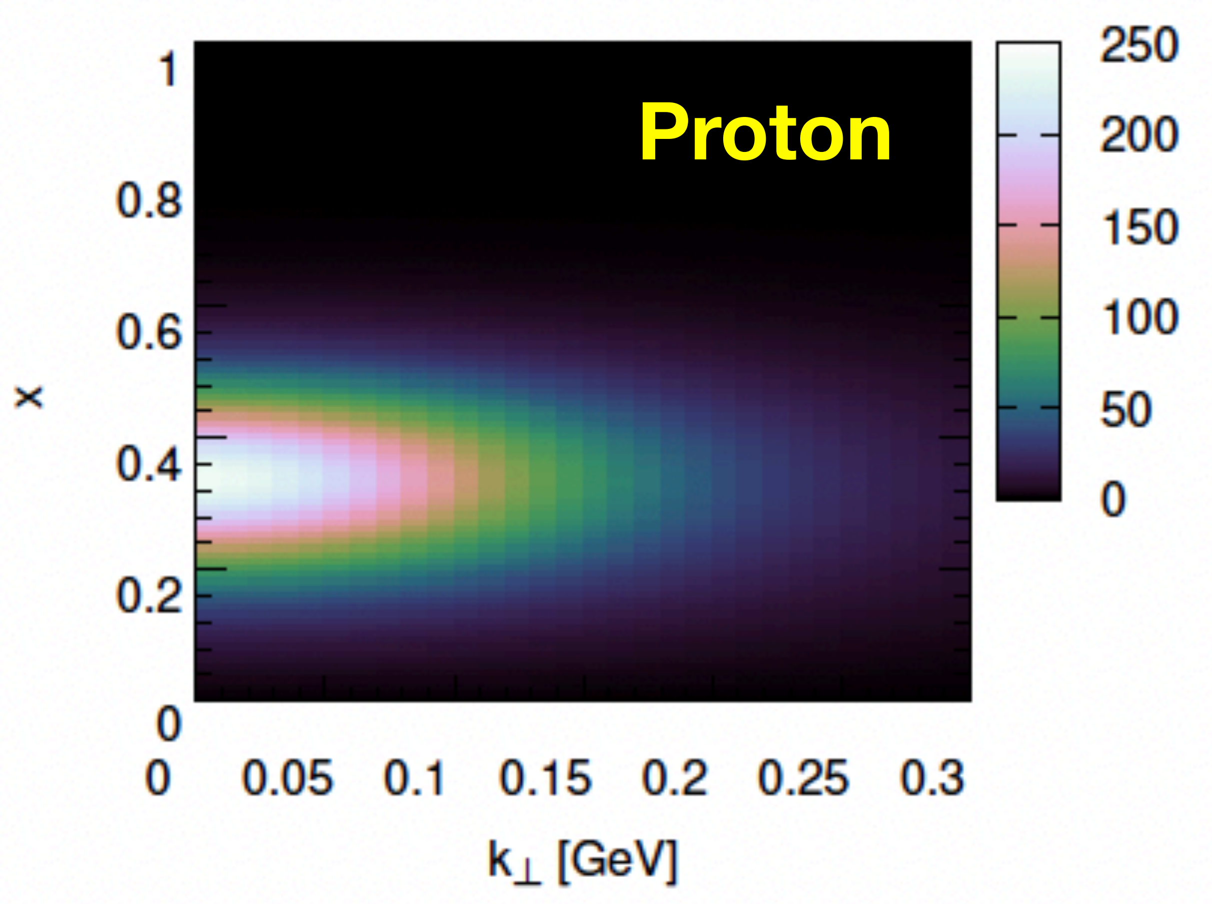




Glimpse into Future - Potential Energy Upgrade to 22GeV

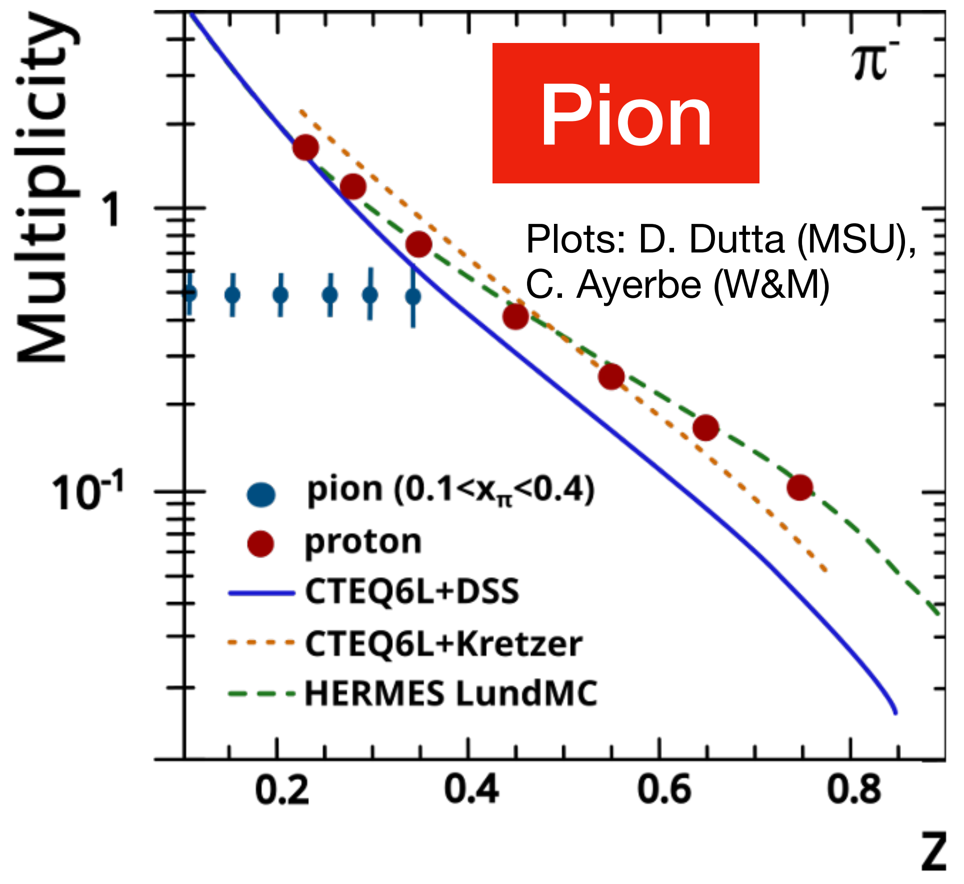
Unpolarised TMDs from T. Frederico and E. Ydrefors
PRD 105 (2022), L071505, PRD 104 (2021) 114012,
arXiv:2211.10959 [hep-ph]

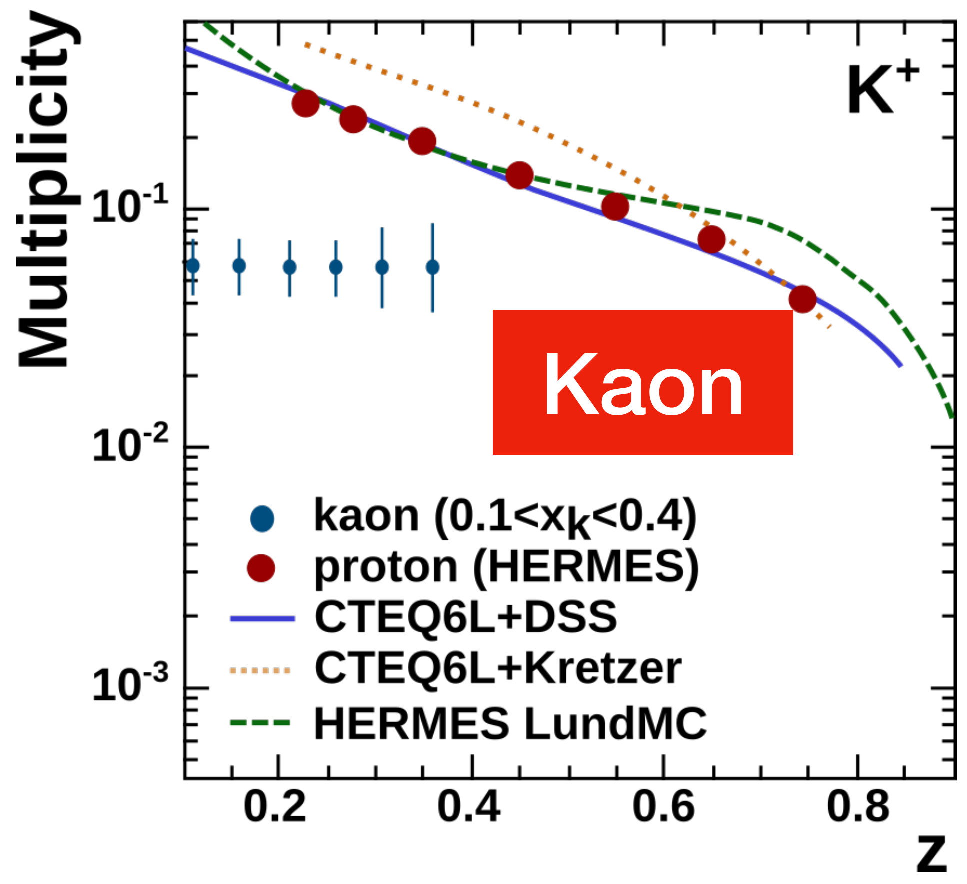


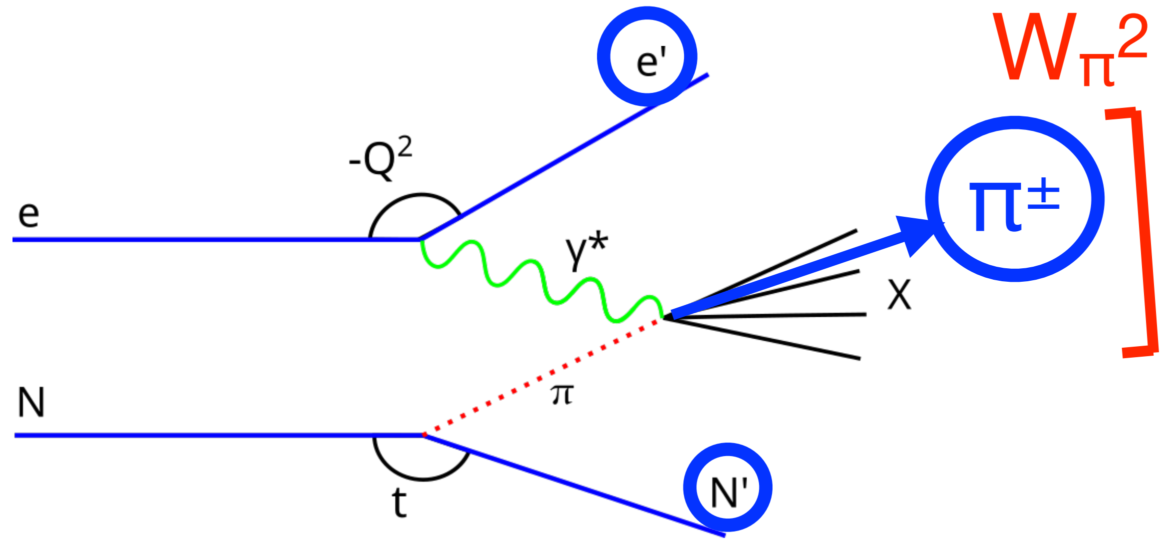


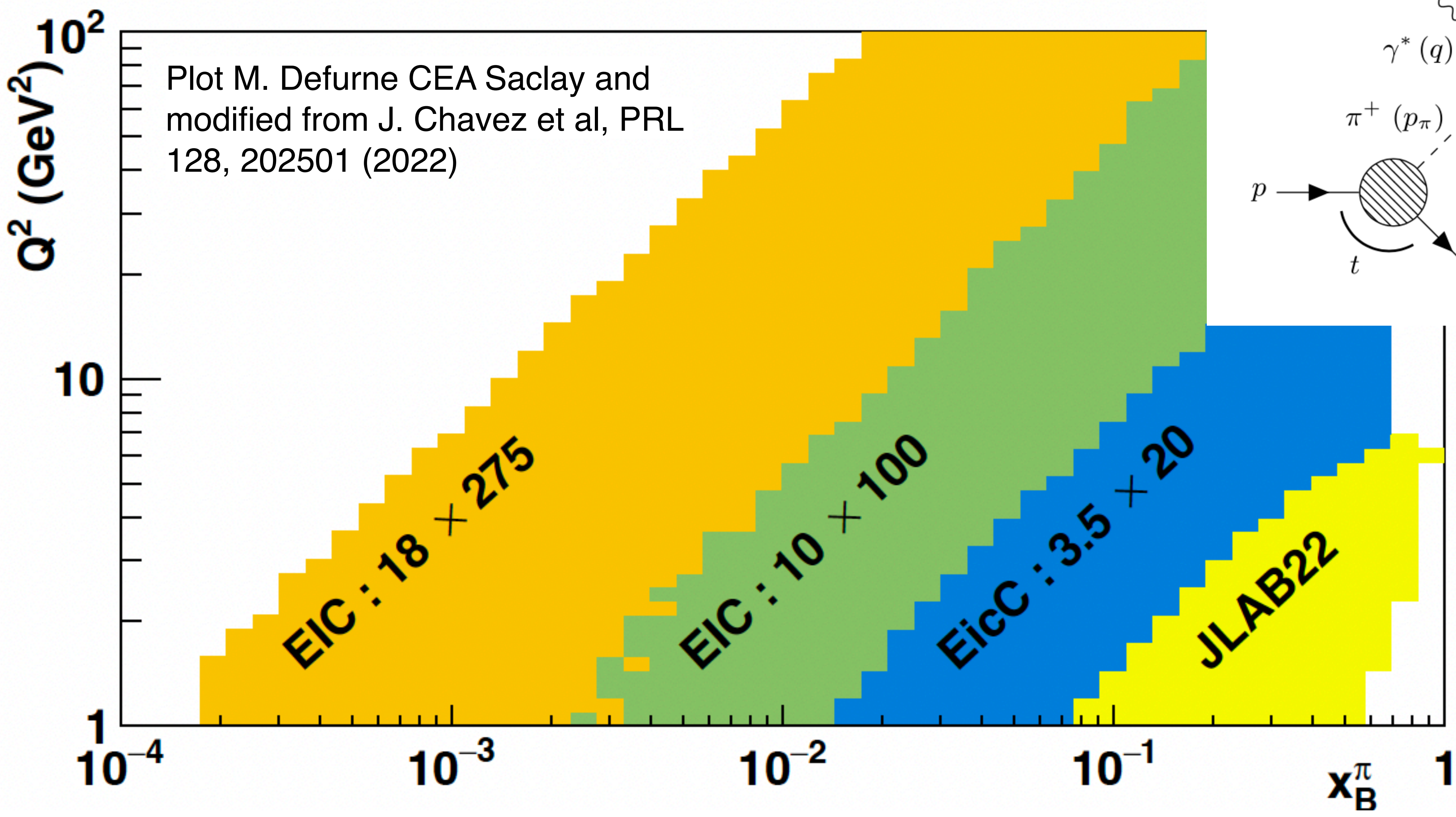
- Data with higher invariant mass available means SIDIS on virtual meson possible for first measurement of meson TMDs in valence region!
- Expect interesting differences between meson/nucleon TMDs
- 22GeV unlocks meson DVCS via Sullivan Process → GPDs and imaging of partons inside mesons
- Phase space for TDIS meson tomography program completely complimentary to future colliders
- Would require additional detectors for final states - under study

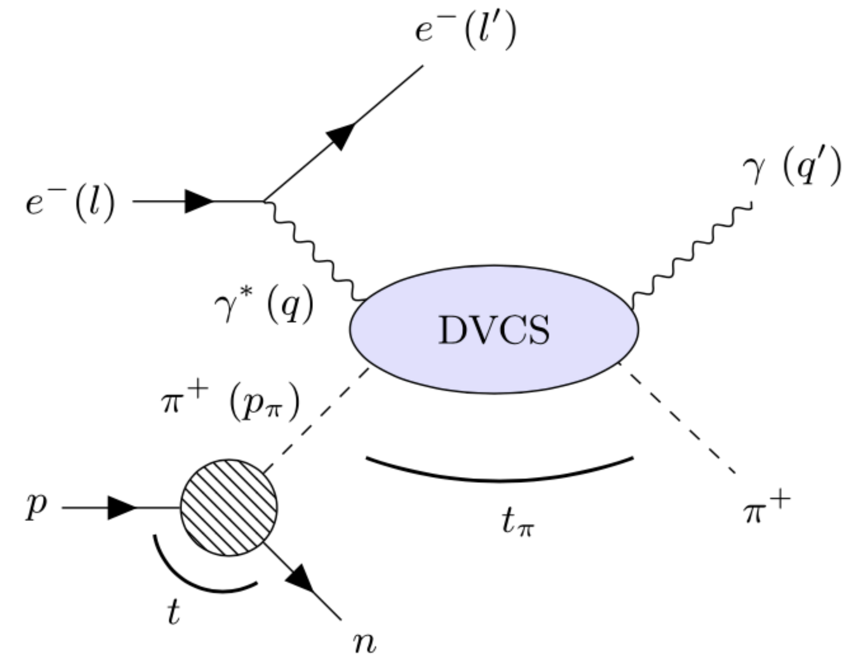
HERMES results from: A. Airapetian et al.
(HERMES Collaboration), Phys. Rev. D 87,
074029











Summary

JLab operates at the World's high-luminosity frontier in lepton scattering

Hadron structure topics at JLab are transforming our understanding of the nucleon and dynamics of QCD

On-going example activities include:

- Electromagnetic form factors of nucleon at high-Q^2
- Meson structure and emergent hadronic mass

Future upgrades at JLab, e.g. addition of SoLID, potential e^+ beam or potential energy upgrade, are unique opportunities and complimentary with future colliders

Also expect complimentary results from AMBER in near future

Thank you

And thank you to many colleagues for input to these slides
(JLab Hall A, SBS, and TDIS Collaborations, D. Hamilton (UoG))

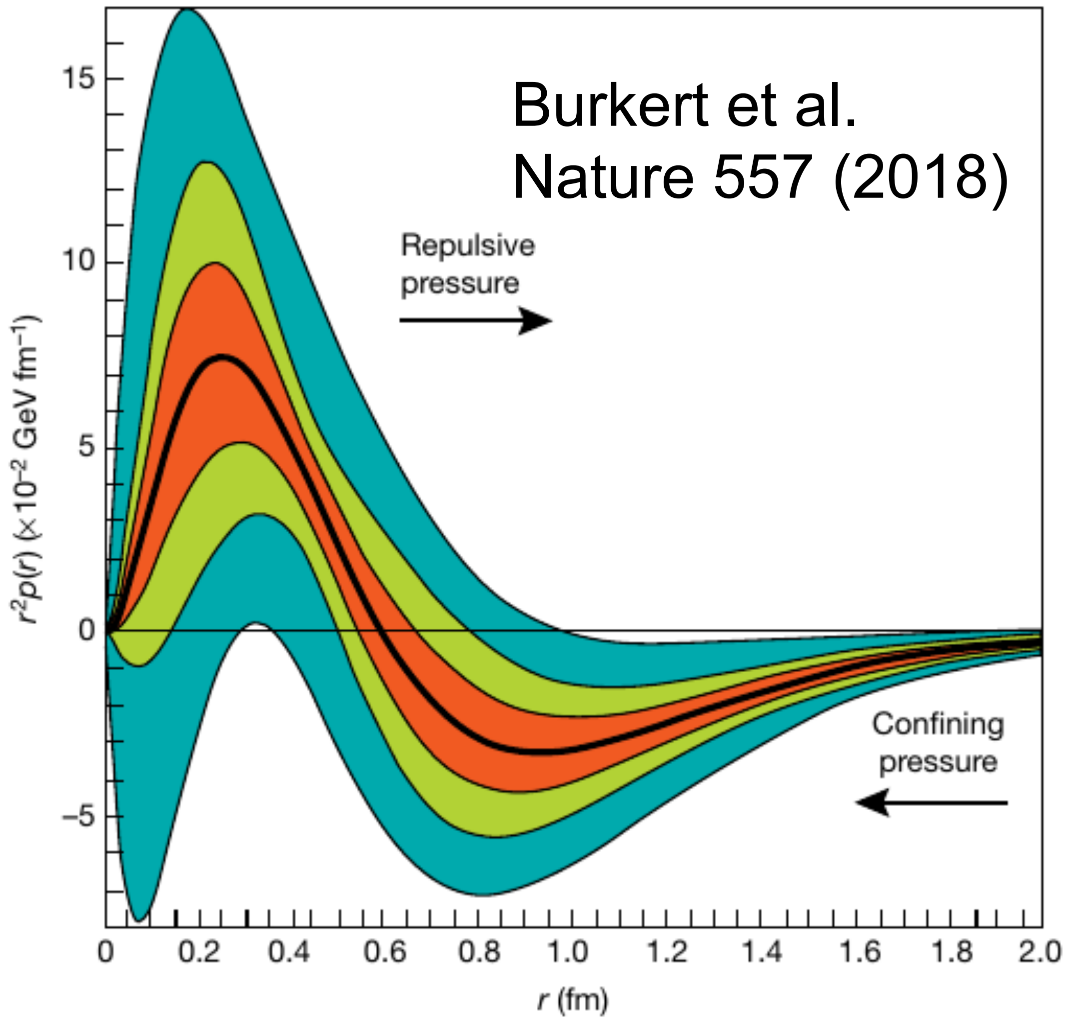
We only touched on a couple of examples …

- Vast hadron structure program at JLab
- e.g. recent highlights include novel insights into gravitational structure of nucleon

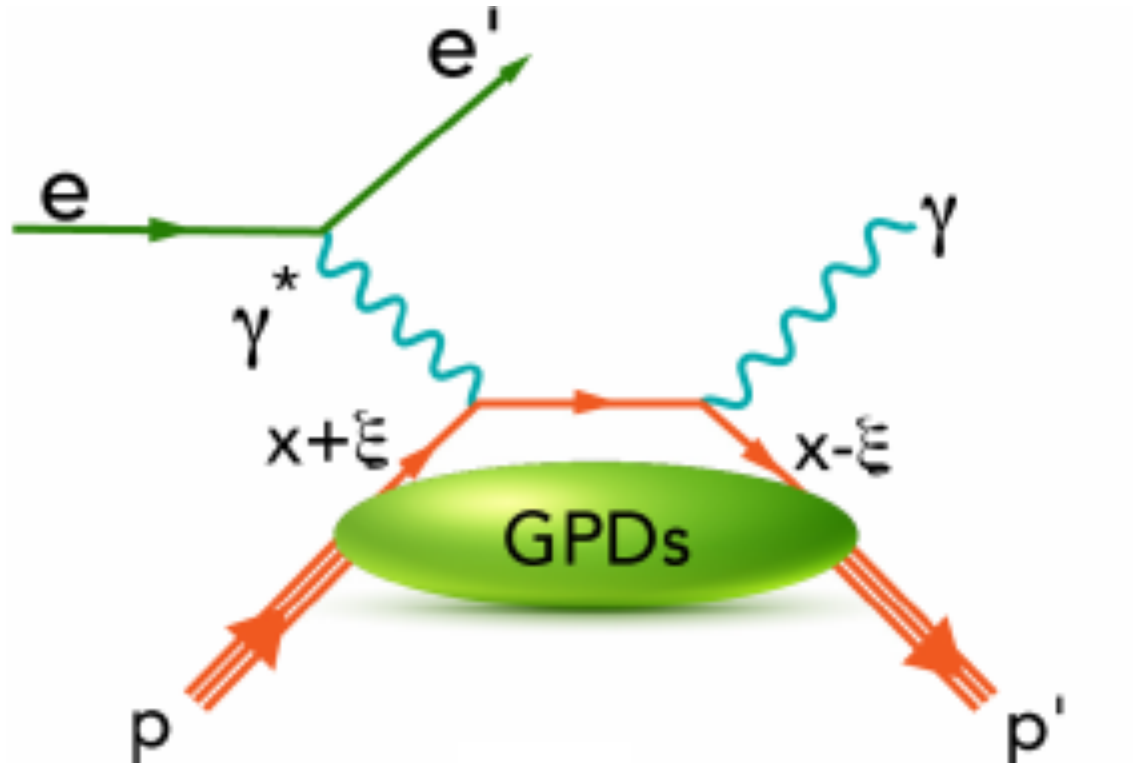
  - DVCS in Hall B yielded determination of nucleon's energy-momentum tensor via its gravitational form factor, allowing radial pressure and sheer forces on quarks to be extracted

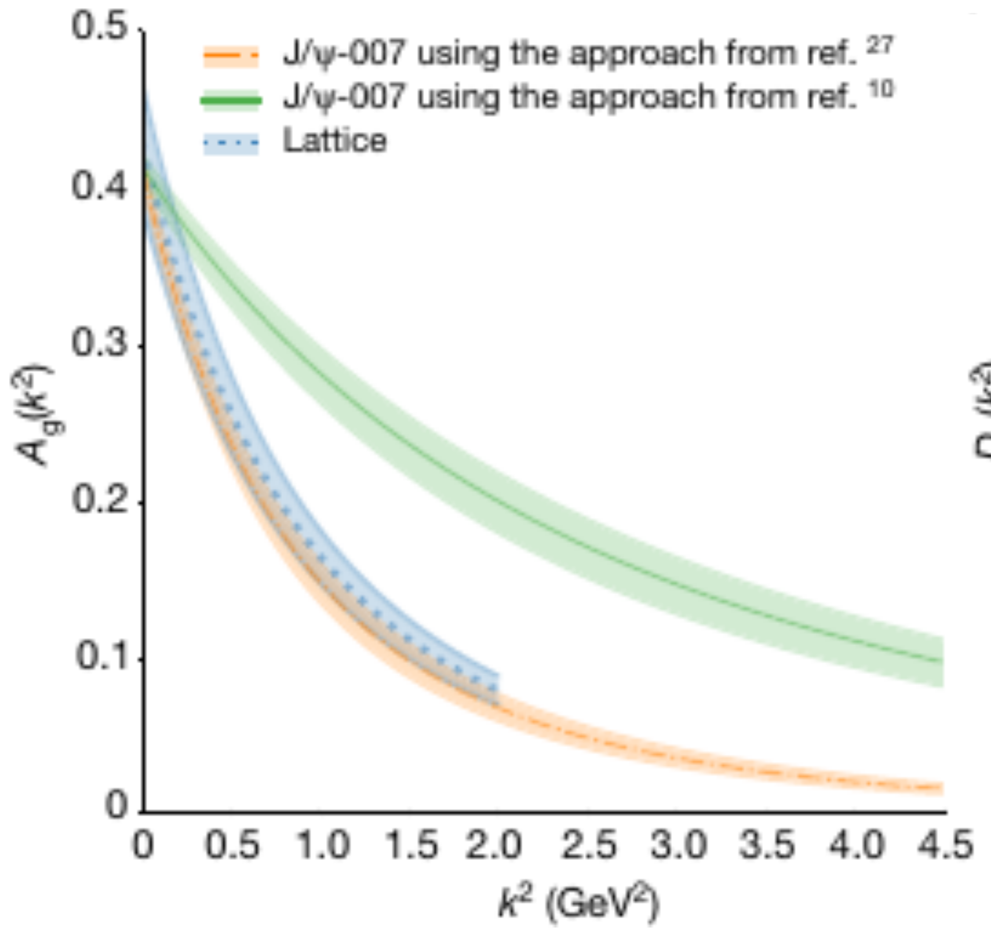
  - J/psi photo-production in Hall C provided access to gluon gravitational form factors, which hinting that the nucleon's mass radius is smaller than its charge radius

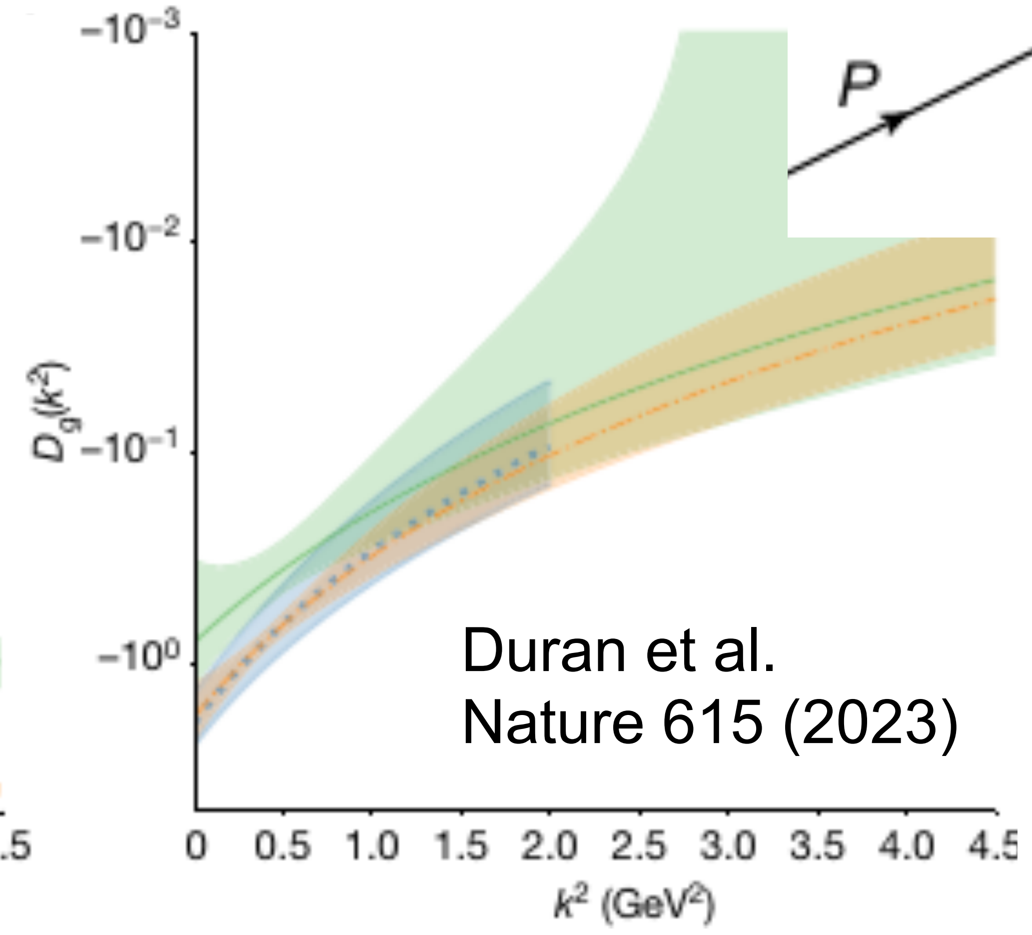
- *And much more…*



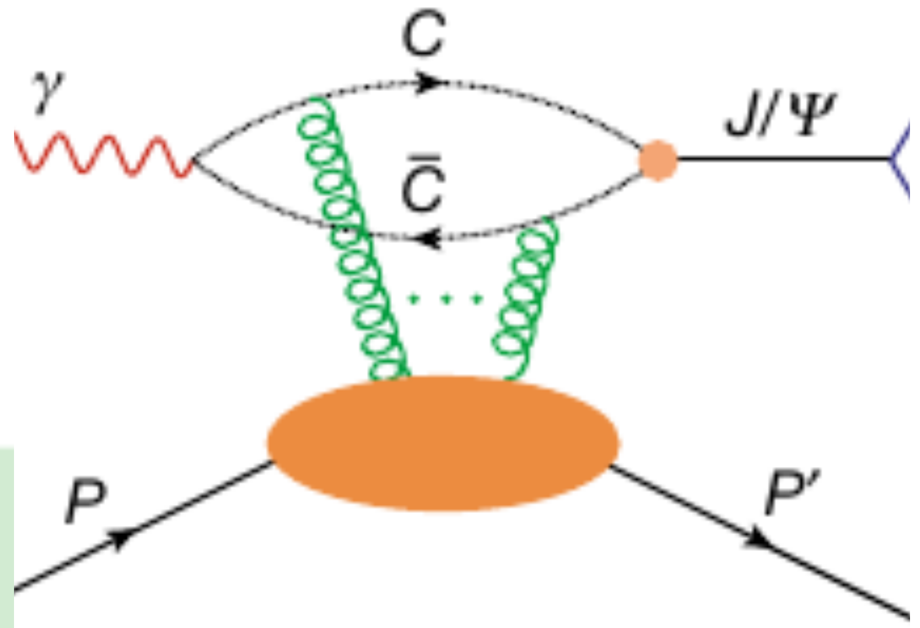
10^{35} Pa repulsive pressure at centre

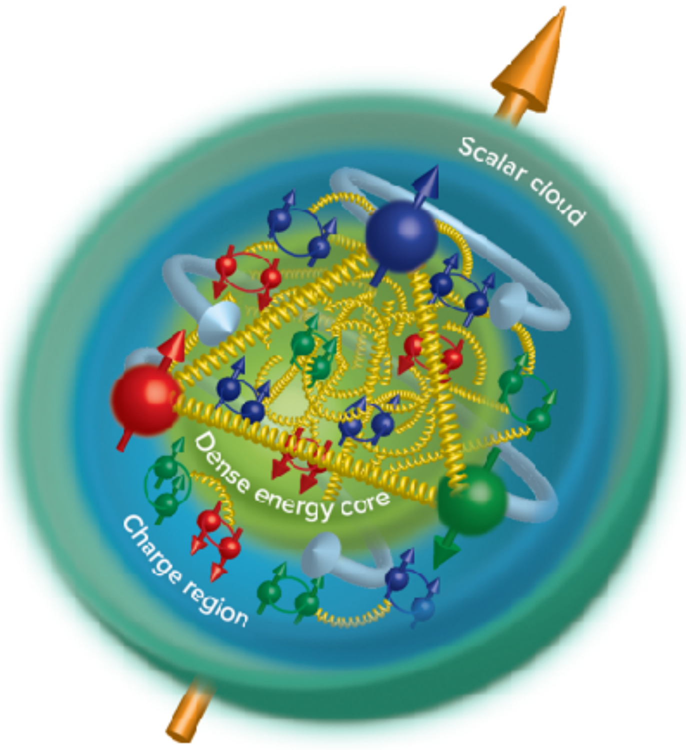






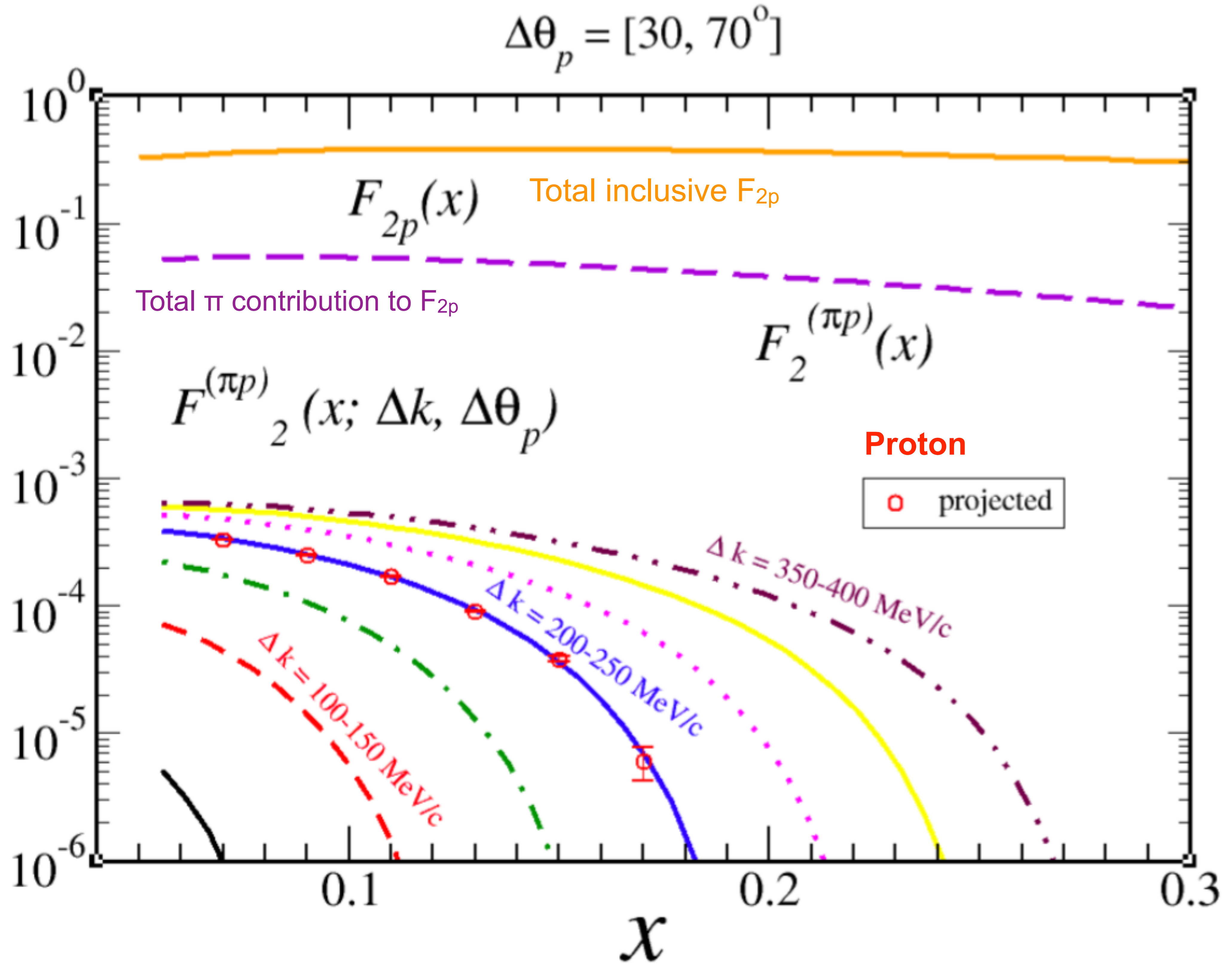
Duran et al.
Nature 615 (2023)

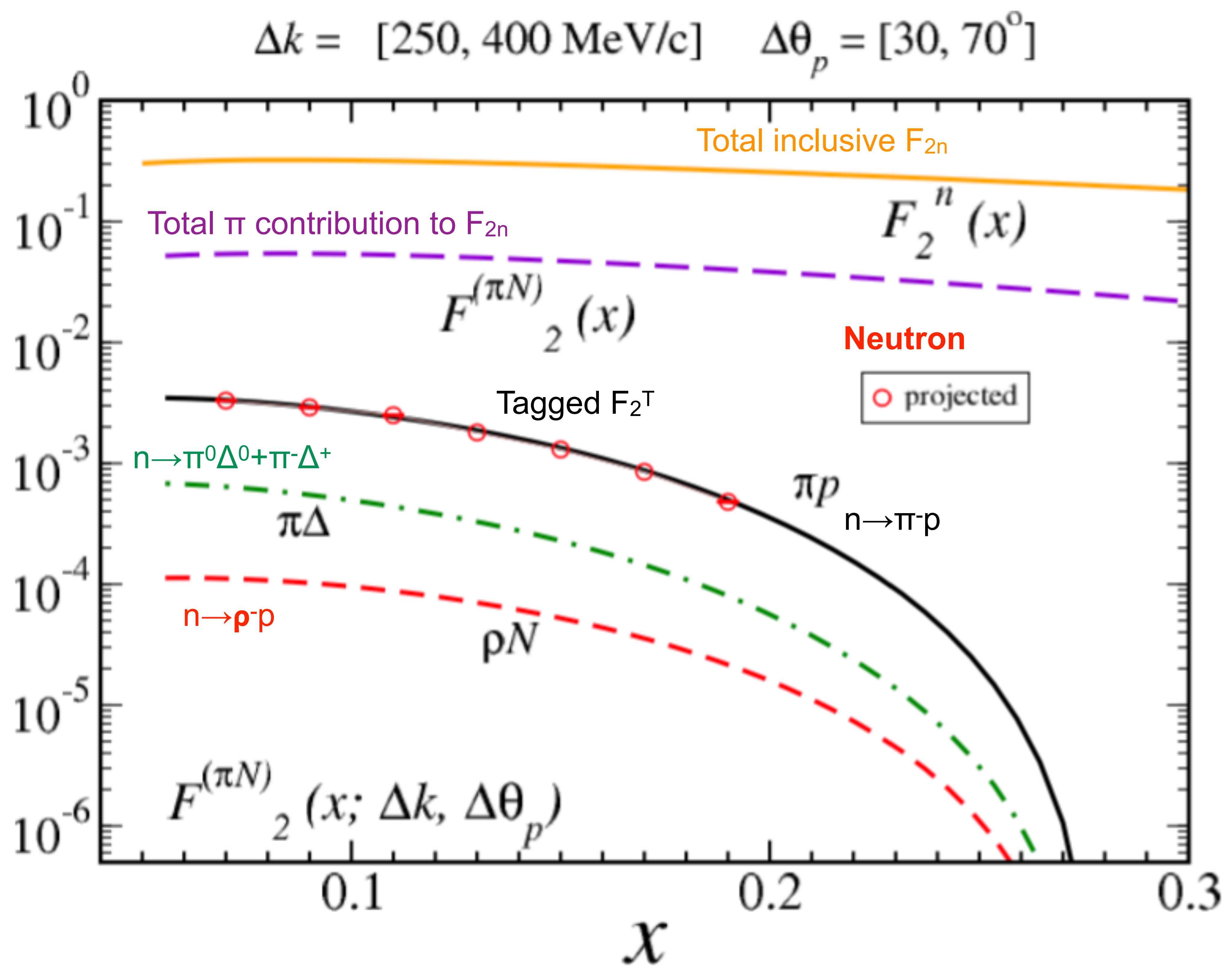




Gluonic Gravitational form Factors

Need High Luminosity





Predictions based on phenomenological pion cloud model

T.J. Hobbs, Few-Body Syst 56, 363 (2015)

$$R^T = \frac{d^4\sigma(ep \to e'Xp')}{dxdQ^2dzdt} \Big/ \frac{d^2\sigma(ep \to e'X)}{dxdQ^2} \Delta z \Delta t \sim \frac{F_2^T(x, Q^2, z, t)}{F_2^p(x, Q^2)} \Delta z \Delta t$$

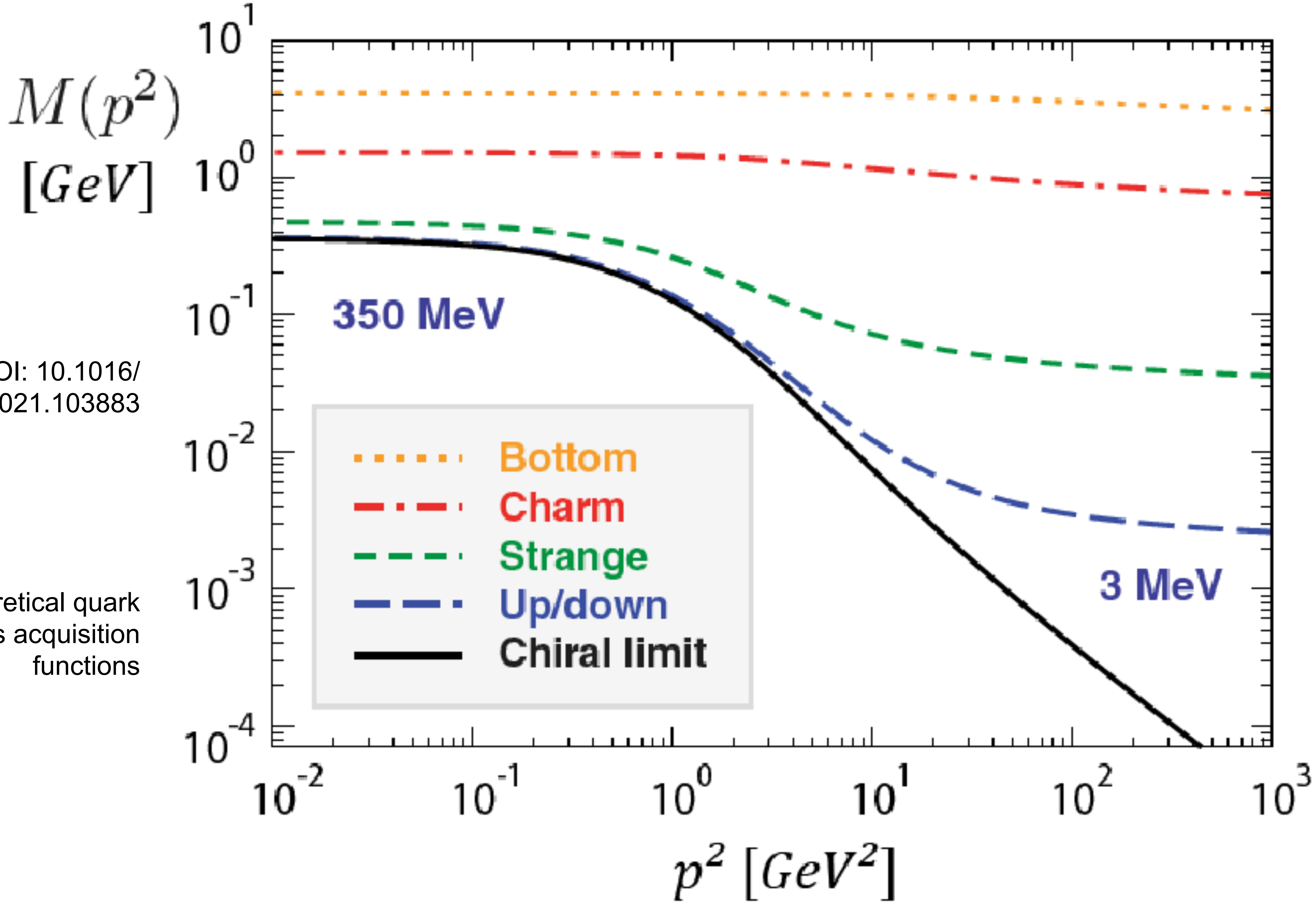
$$\boxed{F_2^T(x, Q^2, z, t) = \frac{R^T}{\Delta z \Delta t} F_2^p(x, Q^2)}$$

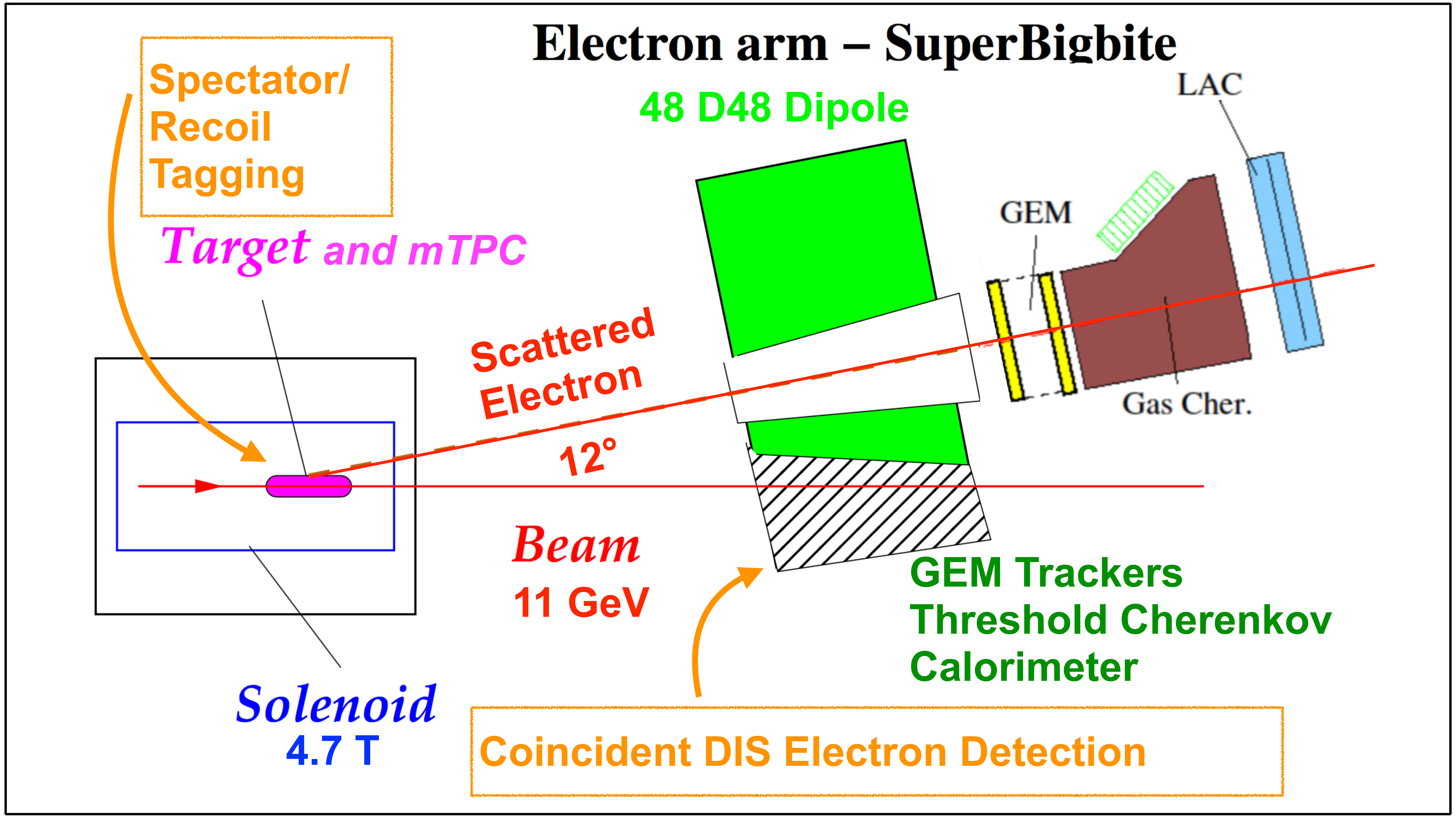
- Measure ratio of virtual meson tagged to total DIS cross-sections (reduce systematic uncertainties)
- Tagged signal orders of magnitude smaller than total inclusive DIS signal

Inclusive Structure of Mesons

DOI: 10.1016/
j.ppnp.2021.103883

Theoretical quark
mass acquisition
functions



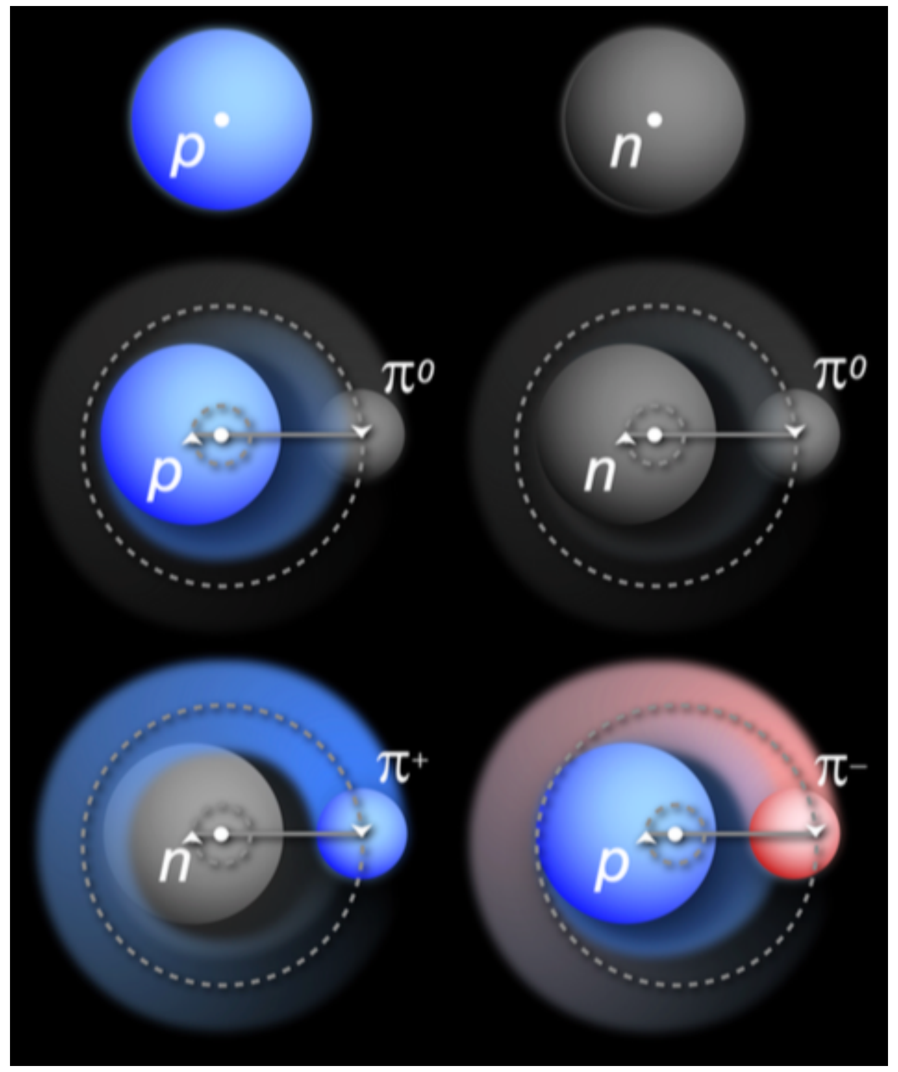


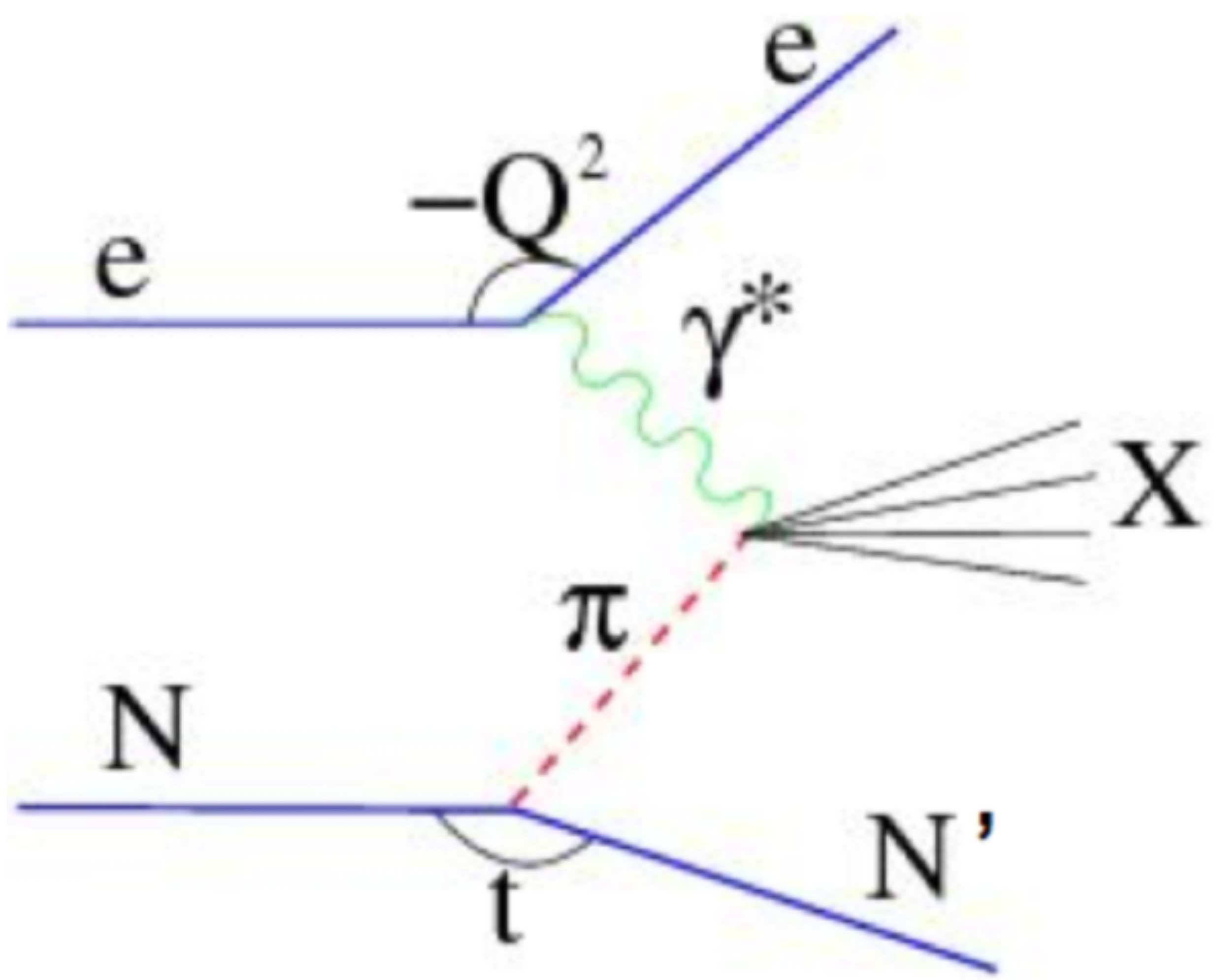
- SBS for e' detection
- Multiple Time Projection Chamber (mTPC) for recoil/ spectator tagging
- High luminosity (3 x 10^{36}Hz/ cm^2), so high rates
- (hundreds of MHz of background in mTPC region)…

Accessing Pions/Kaons

Sullivan Process

Hard scattering from virtual meson cloud of nucleon





Drell-Yan

Quark of pion (e.g.) annihilates with anti-quark of proton (e.g.), virtual photon decays into lepton pair