Exploring Meson and Nucleon Structure

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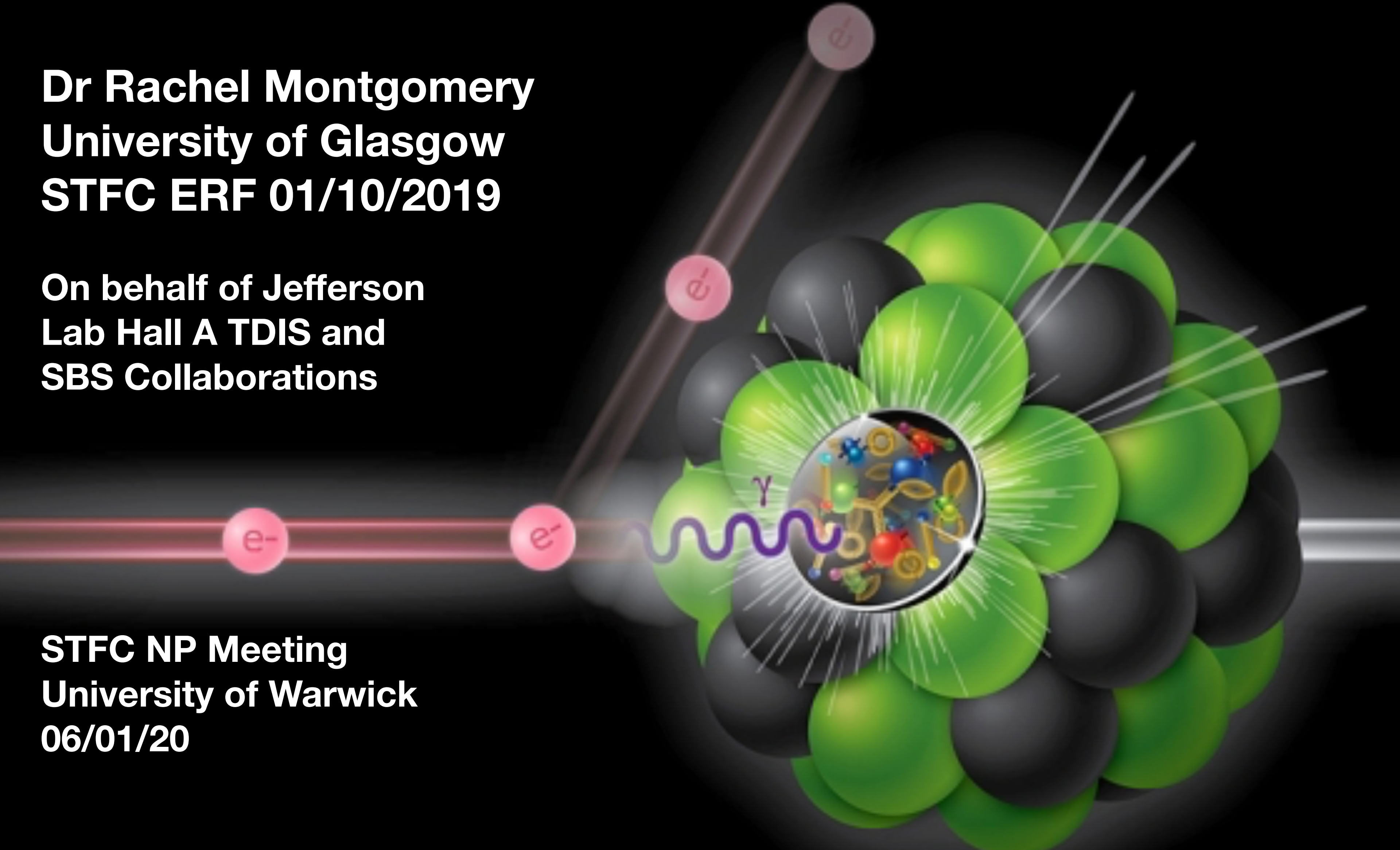
University of Glasgow
STFC ERF 01/10/2019

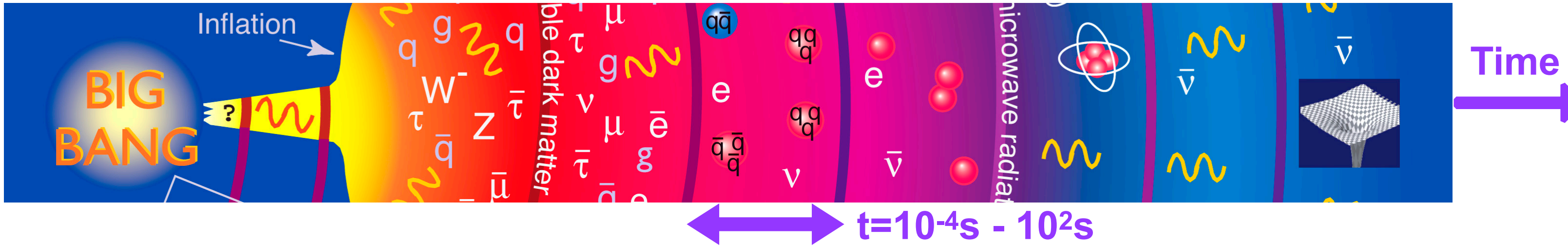
On behalf of Jefferson Lab Hall A TDIS and SBS Collaborations

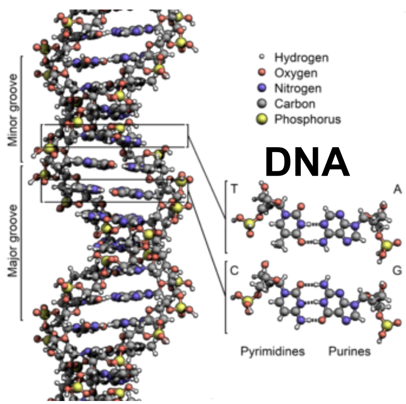


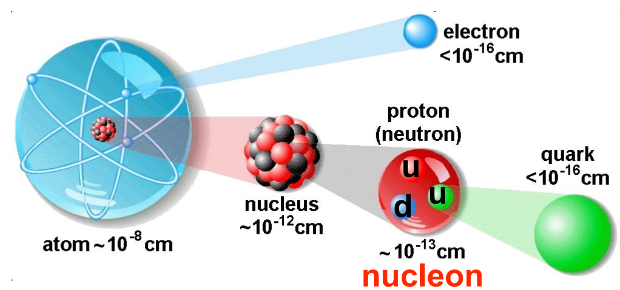
STFC NP Meeting
University of Warwick
06/01/20

Hadron Physics Challenges

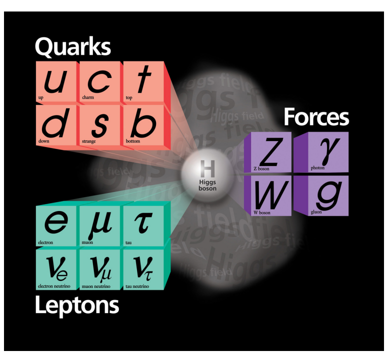
How did hadrons emerge?

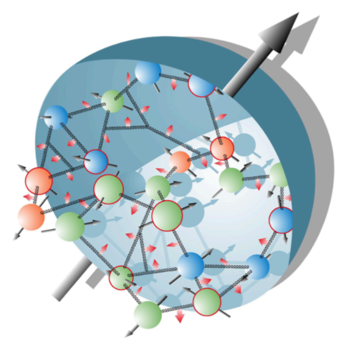






What is internal structure/dynamics of hadrons in terms of constituent partons

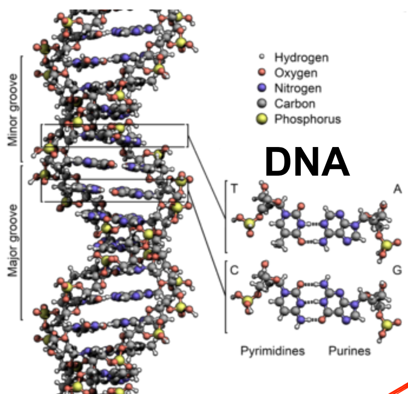




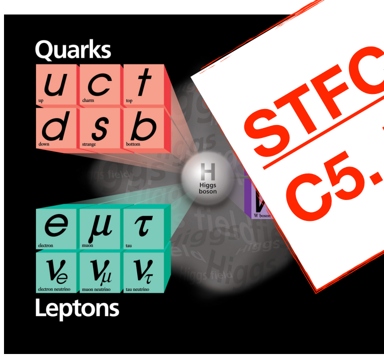
How are hadrons bound together?

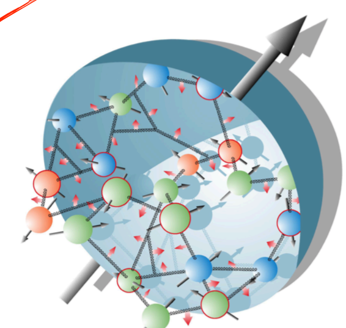
Hadron Physics Challenges

How did hadrons emerge?



hat is internal structure/dynamics of hadrons in terms of constituent partons

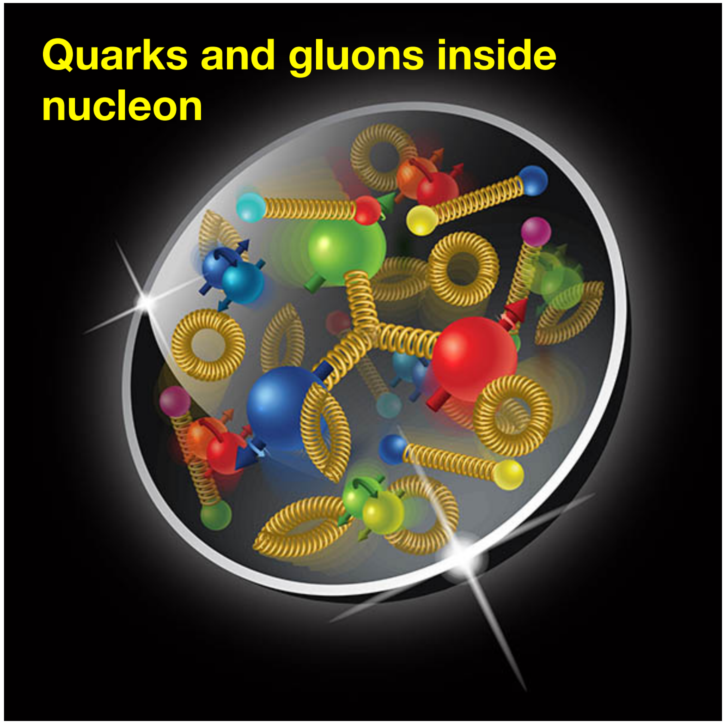


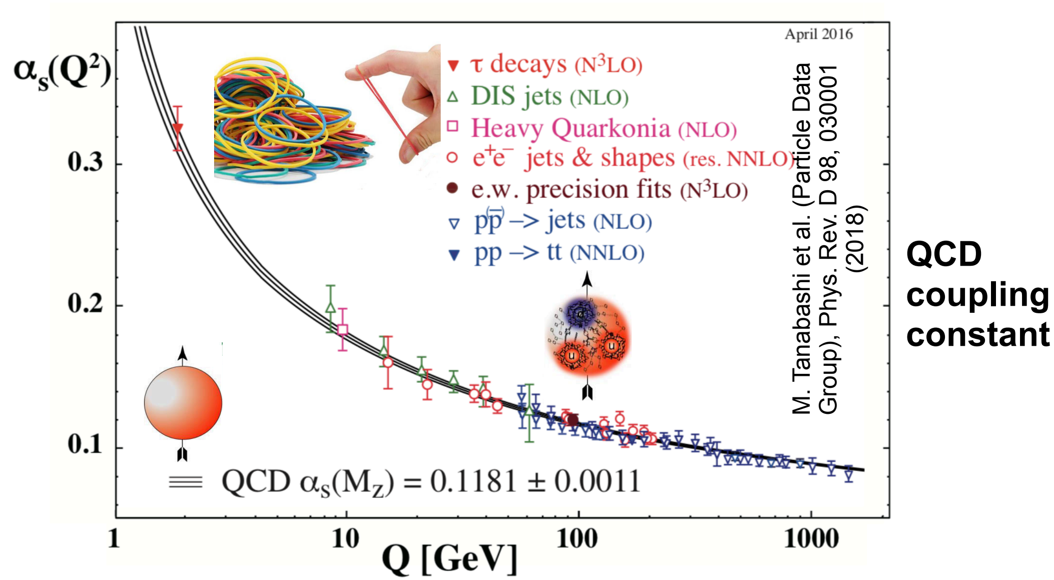


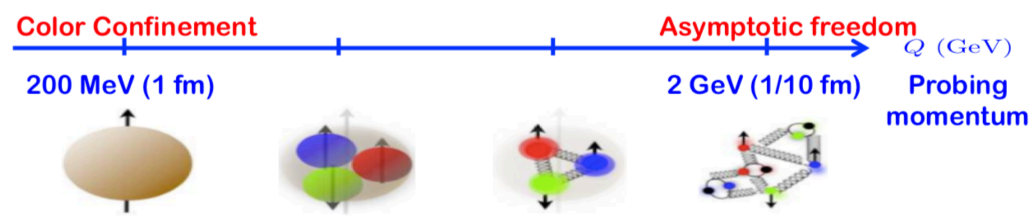
How are hadrons bound together?

STFC Science Challenges: C5. How do quarks and gluons form hadrons?

Quantum Chromodynamics



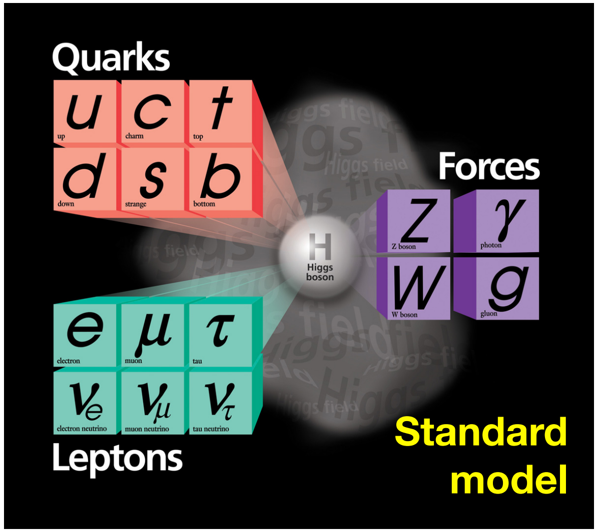




- Short distances: asymptotic freedom; understood through perturbation theory, tested 1% level
- Long distances (hadronic scale): confinement - no free quarks observed

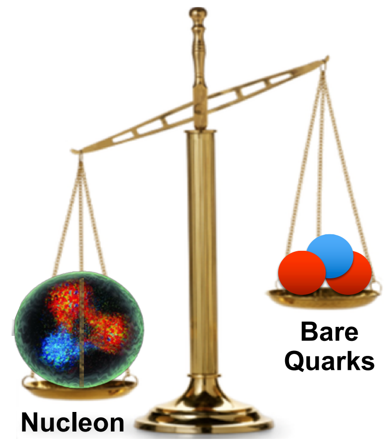
- Crucial to understanding observed properties of matter e.g. mass/spin

Nucleon Mass



Dynamics of gluons/ quarks

~99% nucleon mass



Higgs Mechanism

~1% nucleon mass

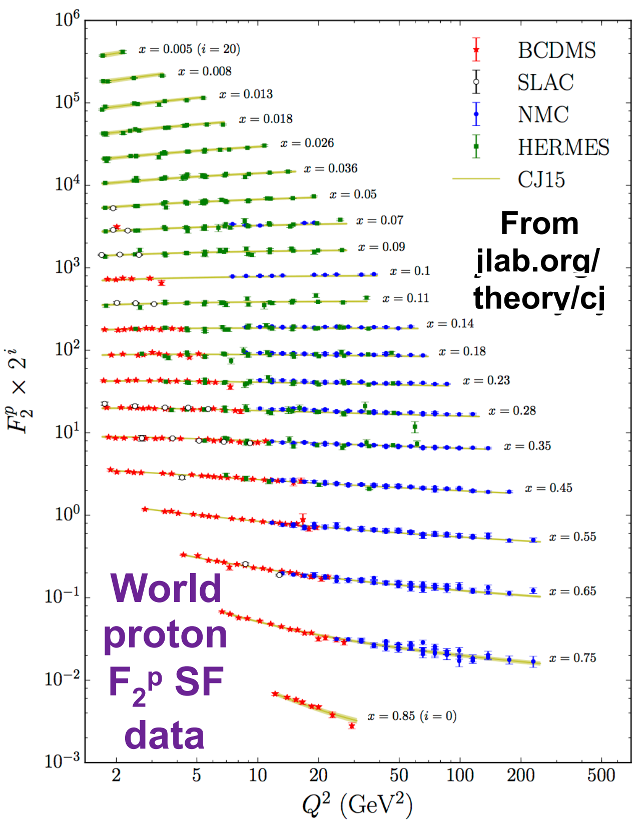
<u>Proton mass:</u>
M(up)
+M(up)
+M(down)
~10MeV
≠ 938MeV

- D. Gross Nobel Lecture 2004: “It is sometimes claimed that the origin of mass is the Higgs mechanism that is responsible for the breaking of the electroweak symmetry that unbroken would forbid quark masses. This is incorrect. 99%, of the proton mass is due to the kinetic energy and potential energy the massless gluons and the essentially massless quarks, confined within the proton.”

- Extracting distributions of quarks and gluons within hadrons
  - key insights to mass enigma for matter

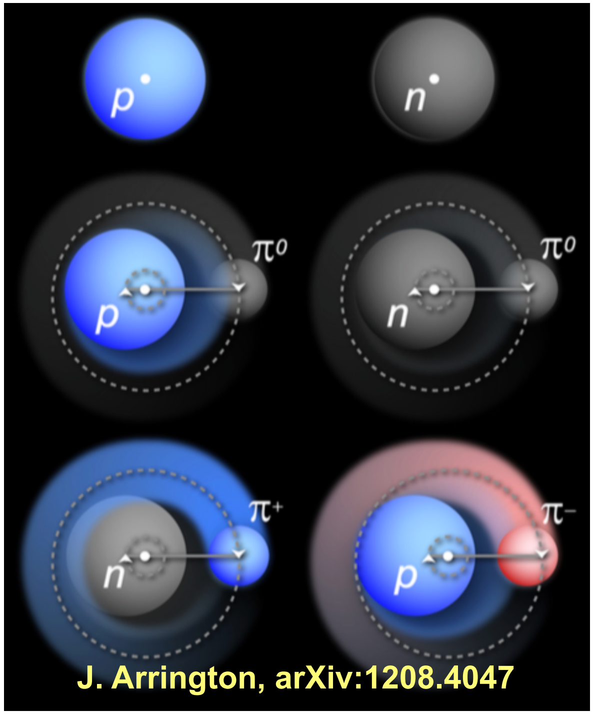
ERF Research Motivation - Light Meson Structure

- Detect observable hadrons
- → quark/gluon distributions
- e.g. structure functions (SF), parton distribution functions (PDF)
- Internal snapshots
- Physical input for phenomenological models

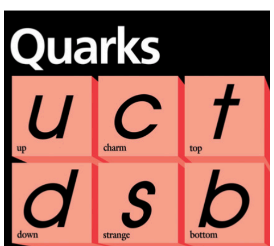


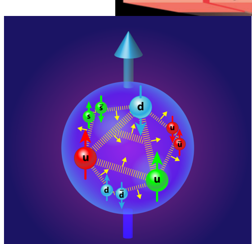
- Proton structure known with high precision
- Neutron fairly well known
- Structure data on light mesons pion/kaon **extremely** sparse
  - ERF
- Wider impact:
  - testing QCD theory (e.g. lattice QCD, chiral effective field theory)
  - EOS for nuclear matter involving strangeness (e.g. neutron stars)

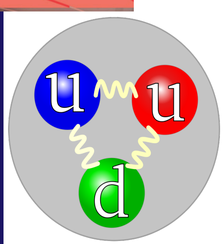
ERF Motivation - Light Meson Structure



J. Arrington, arXiv:1208.4047





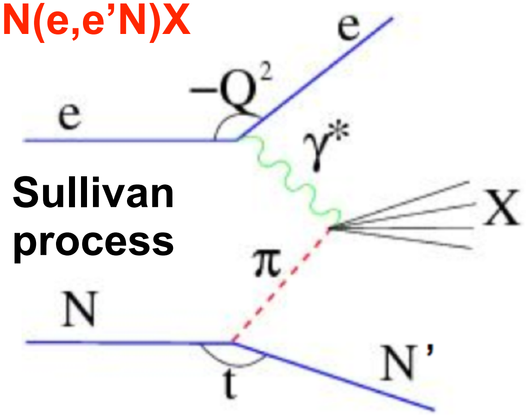


- Experimental evidence for mesonic content of nucleon
  - Fermi, Marshal (1927) **“nucleon exists ~20% time in virtual meson-nucleon state”**
- Nucleon’s pion content key in nucleon/nuclear structure
  - long range nucleon-nucleon interaction; simplest QCD state; dynamical chiral symmetry breaking; nucleon/nuclear PDFs…
- Kaon content also important:
  - access sea/glue, strangeness, combine with valence quark info for complete picture

- Substantial theoretical work
- **Experimental data sparse (lack stable targets)**
  - Magnitude mesonic content unknown
  - How does mesonic content affect internal nucleon dynamics?

Upcoming TDIS Experiment

N(e,e'N)X



- Tagged deep inelastic scattering (TDIS)
- Scattering from virtual meson cloud
- Tag nucleon's mesonic content directly

- Semi-inclusive deep inelastic scattering
- Novel probe of partonic structure
- Effective targets not found in nature

- DIS cross-section accesses sub-structure via SF

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

- Pion and kaon F_2 SF
- Independent pion measurements in valence regime for charged/neutral pion
- World-first extraction for kaon

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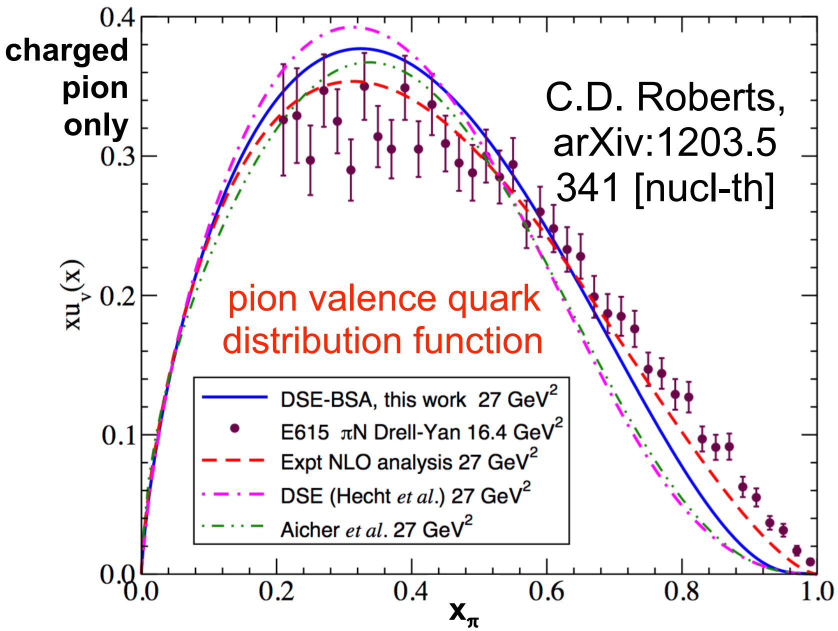
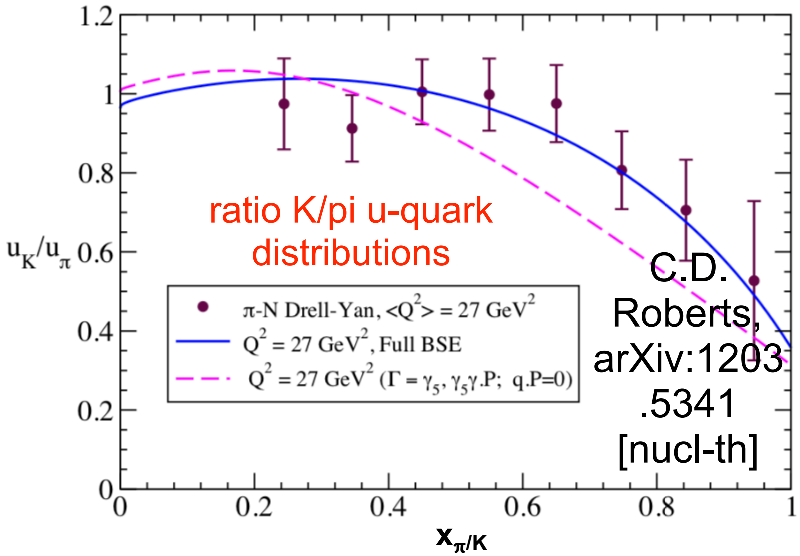
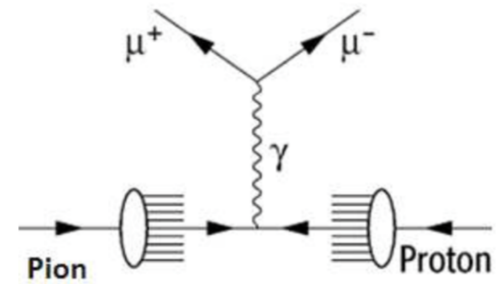
Previous Data for Pion/Kaon Structure





Overlapping Kinematics - Drell Yan

- CERN, Fermilab
- e.g. FNAL E615 $\pi^- + N \rightarrow \mu^+ + \mu^- + X$
- Data sparse
- Kaon practically non-existent
- Models disagree at high x

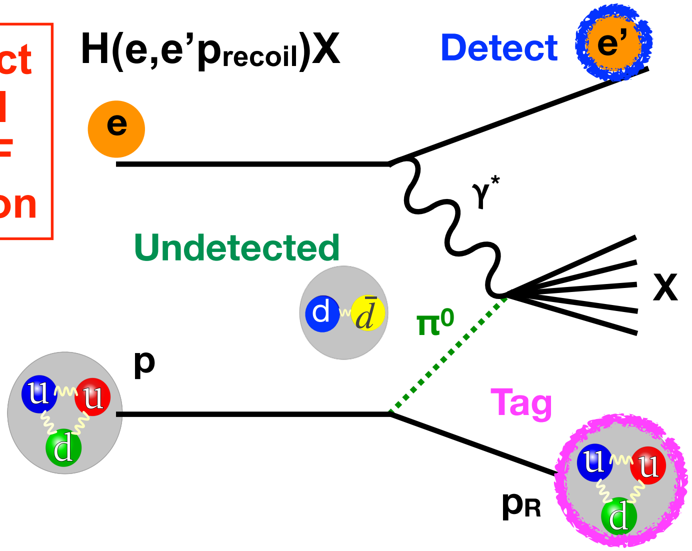


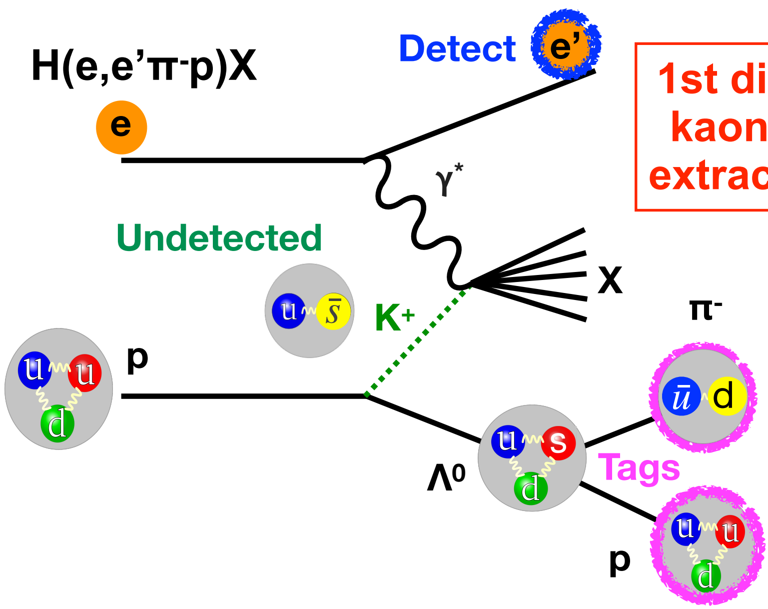
TDIS

- Independent cross-check
- Resolve tensions/improve accuracy for global PDF fits (N. Sato et al. arXiv: 1804.01965 (2018))
- More data, esp. kaon/neutral pions

TDIS Measurements

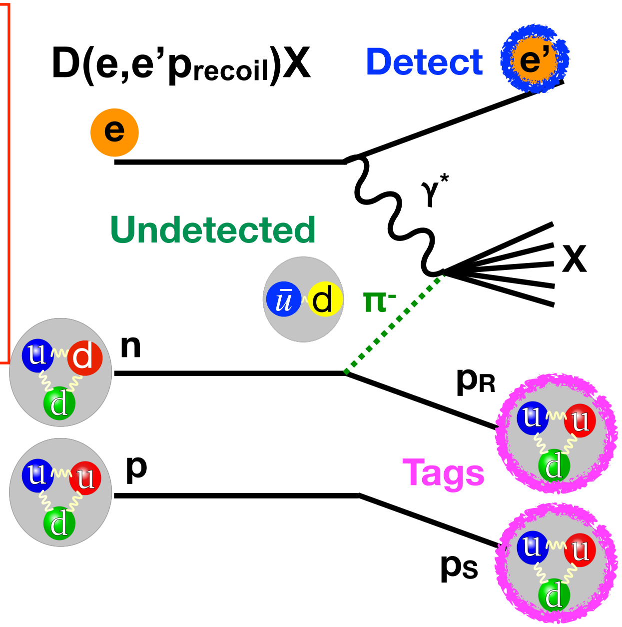
1st direct neutral pion SF extraction





1st direct kaon SF extraction

Resolve QCD model tensions for charged pion



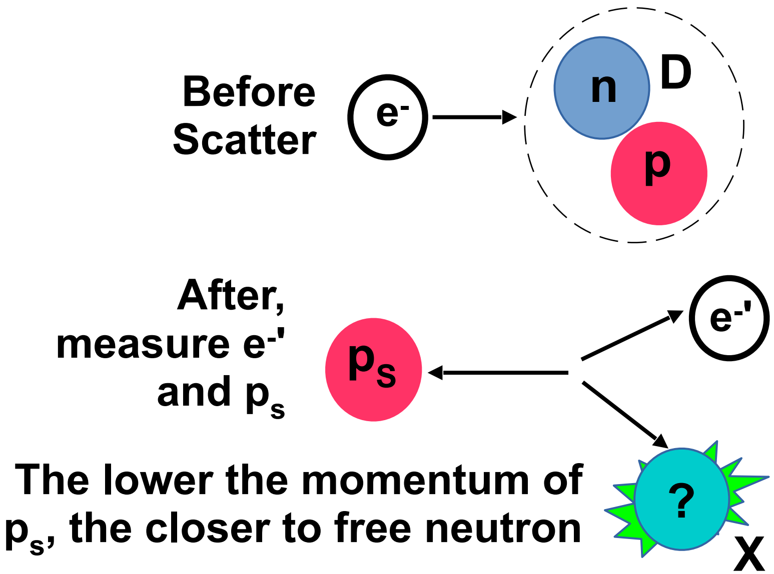
$8 < W^2 < 18$ GeV^2
$1 < Q^2 < 3$ GeV^2
$0.05 < x < 0.2$

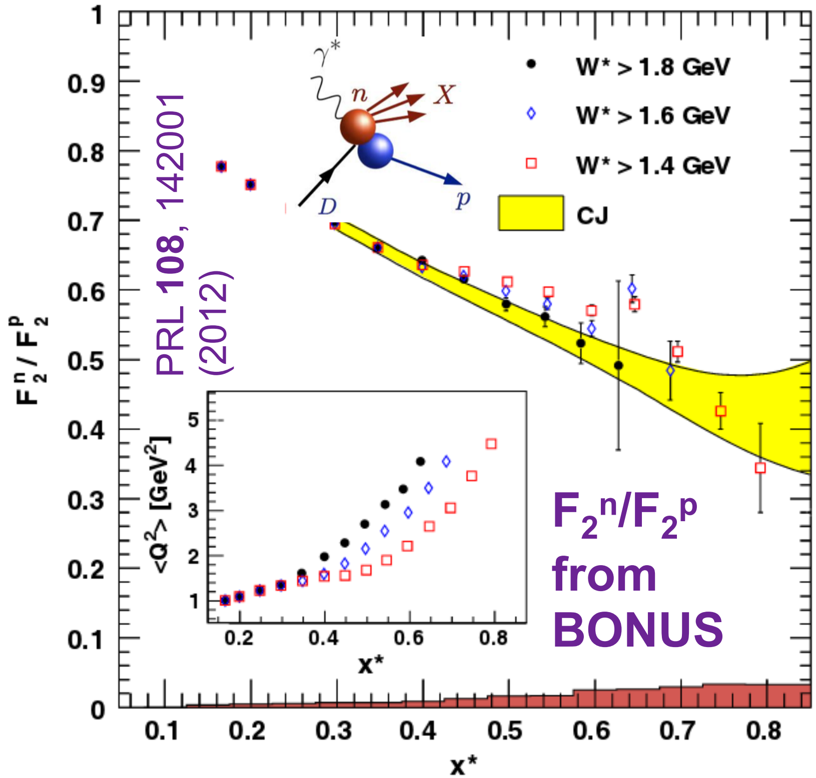
- Novel detector essential for tagging very low momentum recoiling hadrons (60 - 400 MeV/c)
- Key aim of ERF

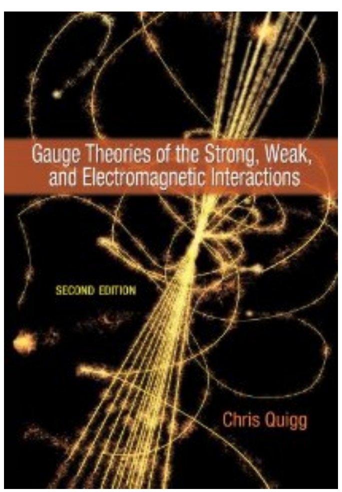
Aside - Spectator Tagging for Neutron Structure

$eD \rightarrow ep_S X$

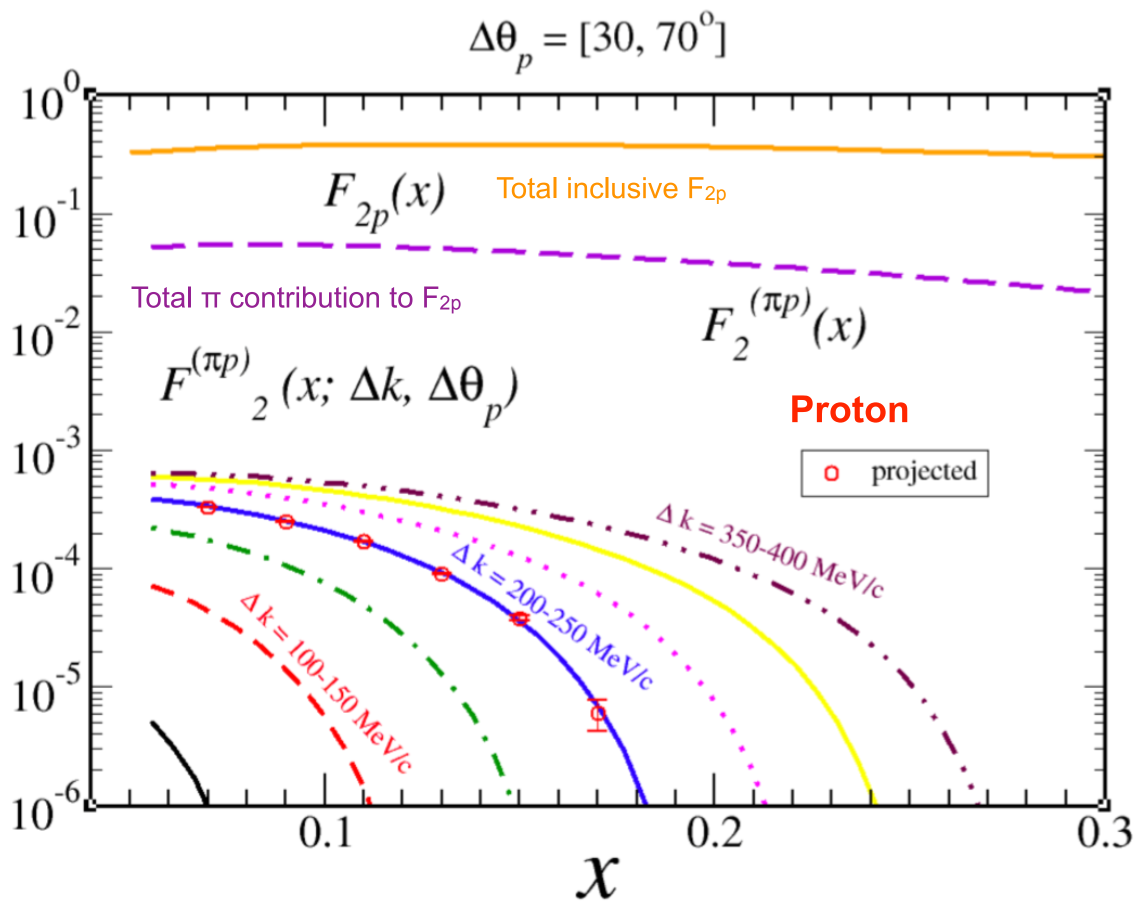
Effective free neutron target







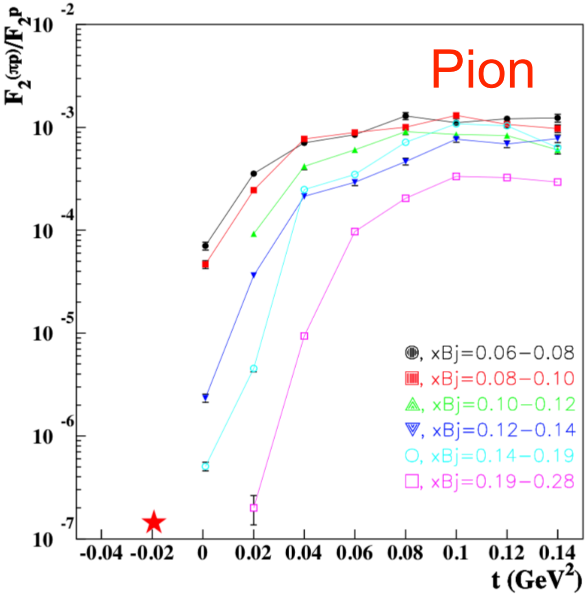
- BONUS at JLab
- Neutron SF (F_2^n) in valence regime
- Input global PDF fits (https://www.jlab.org/theory/cj/)
- Textbook physics
- Radial time projection chamber for low momentum p_S at angles >90

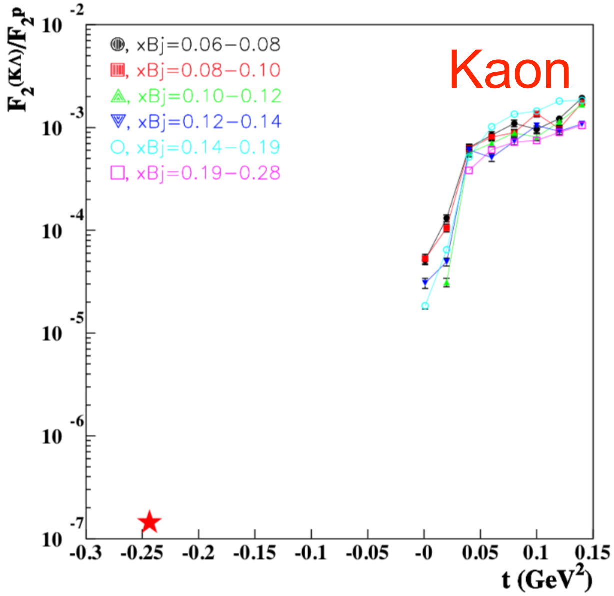


(T. J. Hobbs, Few Body Syst. 56 (2015) no.6-9)

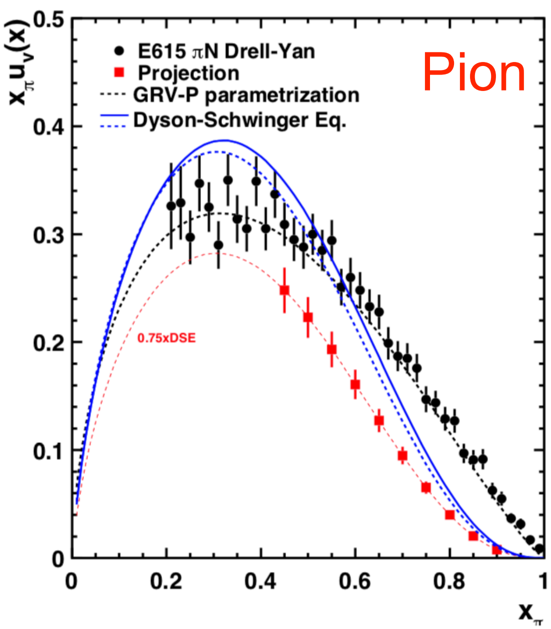
- Predictions based on phenomenological pion cloud model
- Tagged signal orders of magnitude smaller than DIS → **high luminosity**

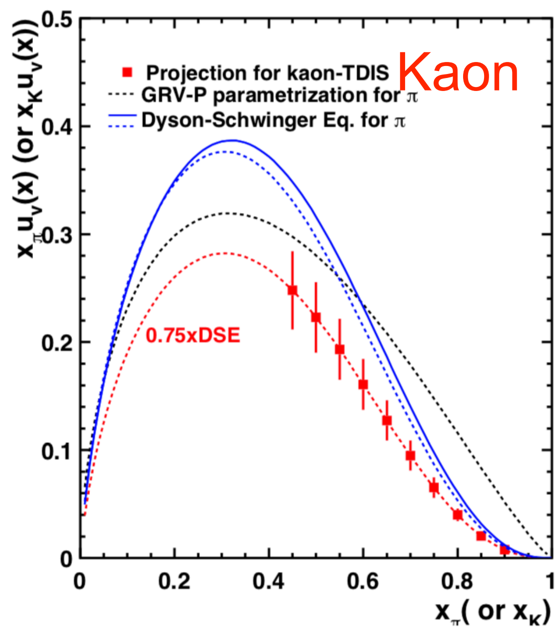
TDIS Projected Results





- Kinematical mapping
- Low momentum reach of tagging detector to obtain shape of curve





- Projected valence quark distributions
- Projections based on theory (T.J. Hobbs, Few Body Syst. 56 (2015) no.6-9; J.R. McKenney et al., Phys. Rev. D93 (2016), 05011)

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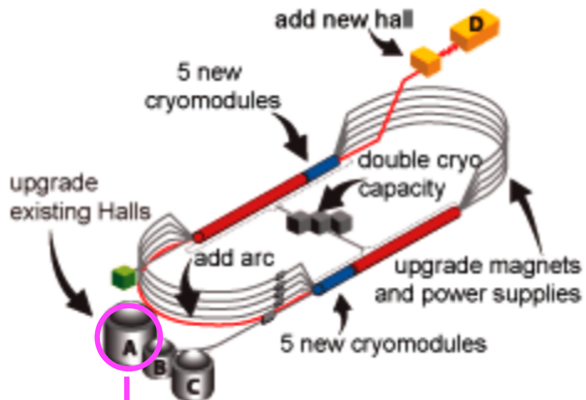
TDIS Experiment

- Jefferson Lab, Va, USA
- Shutdown 2012, electron beam 6GeV → 12GeV (now in 12GeV era!)
- Upgraded facility → pioneering DIS techniques



<u>6GeV Era:</u>

- High-resolution spectrometer pair
- Solid angle ~6msr
- σ_p/p: ~1×10^{-4}

<u>12GeV era:</u>

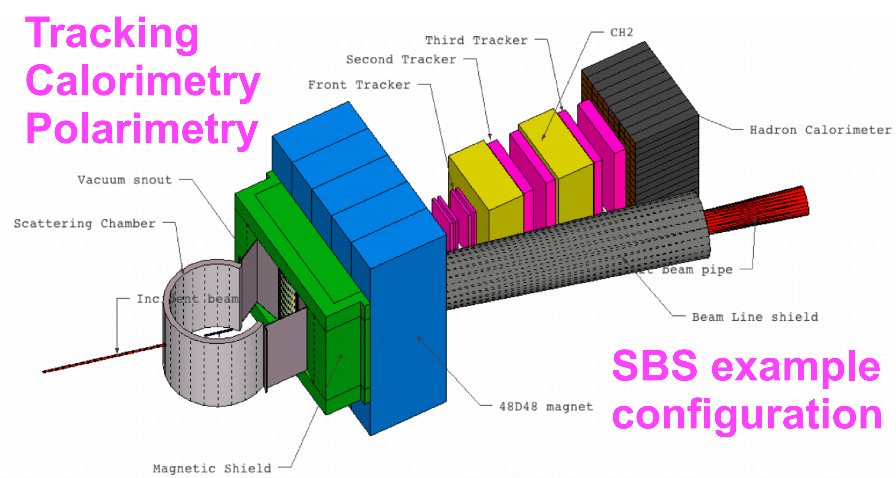
» New open geometry spectrometers…

TDIS Experiment

<u>Super BibBite Spectrometer</u>

- Open-geometry magnet
- Highly modular; segmented

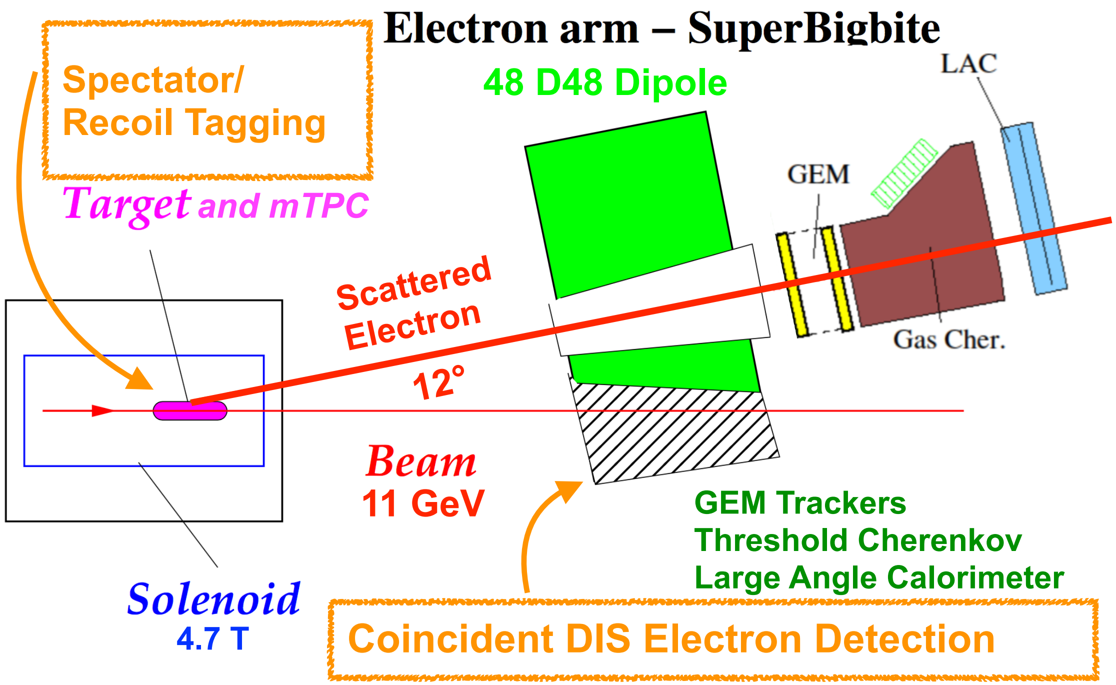
- Higher luminosities (~$8x10^{38}$Hz/cm^2)
- Increased acceptance (~70msr)
- σ_p/p: ~$1x10^{-3}$p[GeV/c]
- **Measure rapidly decreasing cross sections at higher Q^2 (>10GeV^2)**



- Multiple configurations
- Suite of nucleon structure experiments
- Nucleon form factors at large Q^2

- Major part of recent STFC Jefferson Lab Upgrade Project

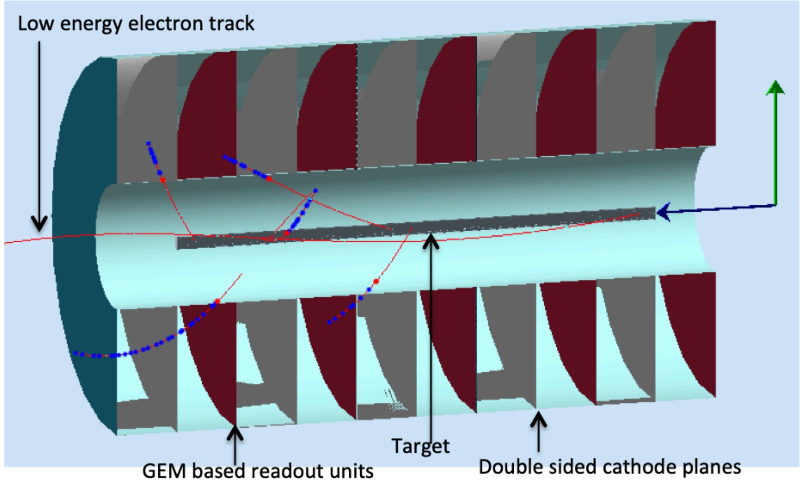
TDIS Experimental SetUp

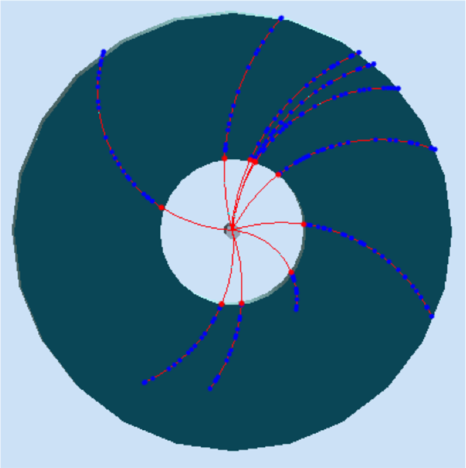


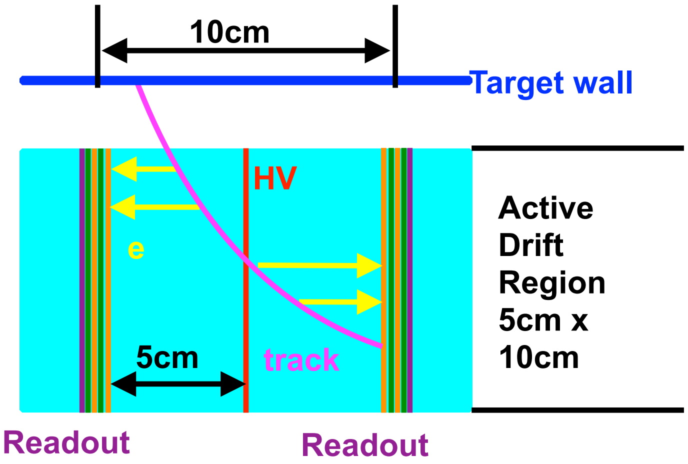
- 11GeV e^- beam, 50μA, high luminosity $3x10^{36}cm^{-2}s^{-1}$
- High density H/D target, 40cm length
- SBS for coincident e^-
- Multiple Time Projection Chamber (mTPC) for tagging
- Diameter 30cm, length 50cm
- Extremely challenging
  - 700MHz background (overlapping kinematics)
  - Significantly higher rates than previous similar sized TPCs
  - Very low momentum reach required (dE/dx, acceptance challenging)

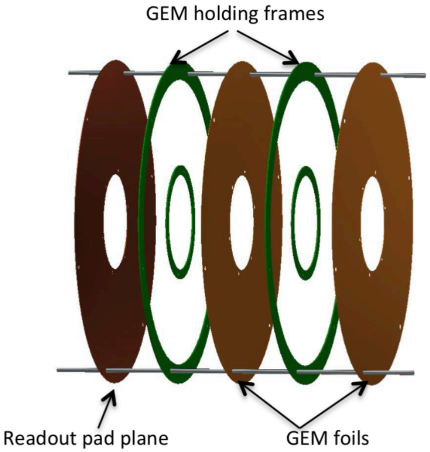
mTPC Design

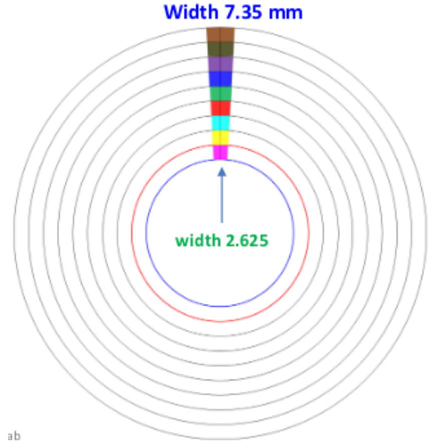
- Significant simulation work performed and on-going - major ERF activity
- Segmented mTPC/readout planes advantageous for rates and drift times
- ~70MHz/chamber and <1MHz/readout pad









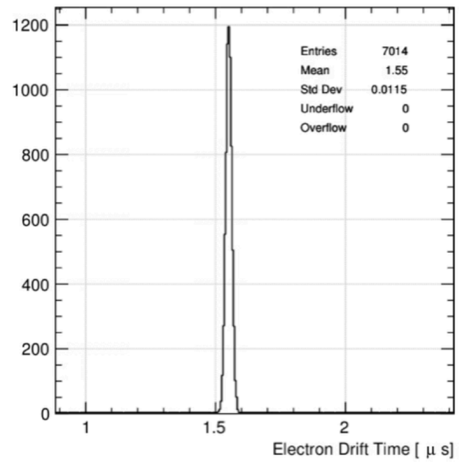


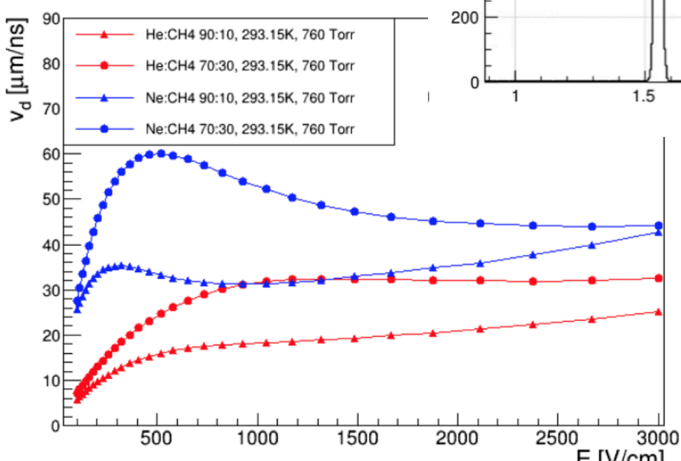
Double layer GEM/segmented pad readout

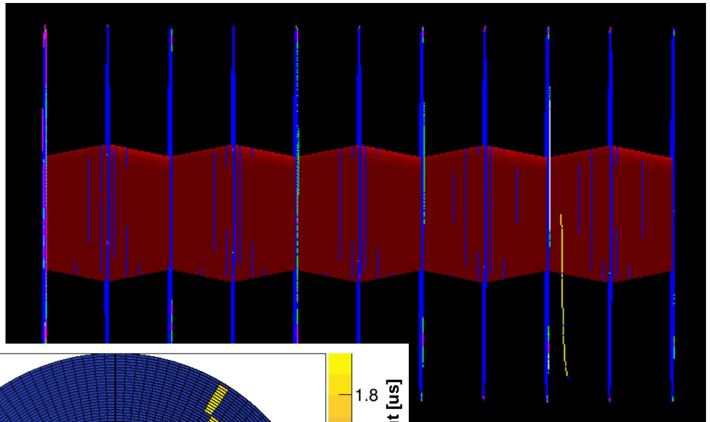
mTPC Current Status

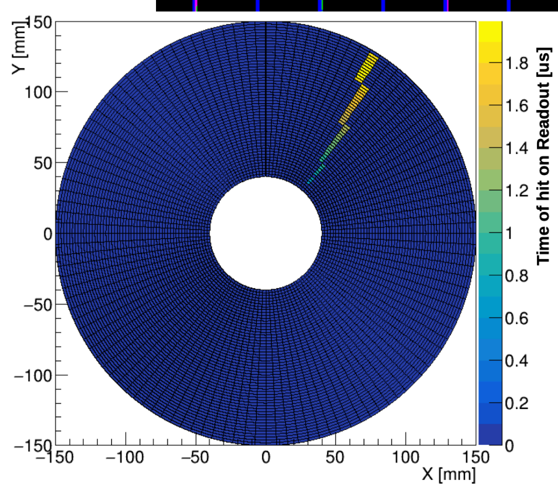
- Simulation work on mTPC final design
- Plan prototype chamber constructed by summer 2020 (UVa)
  - beam tests, simulation tuning, fine design tuning
- Readout electronics currently undergoing tests (JLab)
  - continuous readout; SAMPA chip from University of Sao Paolo (ALICE TPC upgrade)

Example drift charge studies in Magboltz, Garfield++









Example Geant4 mTPC studies

ERF Plans

- Simulations: mTPC design, overall TDIS experiment apparatus/ optimisation; trigger…
- Test prototype sectors: fine tune models/design
- Commission final mTPC: deliverable of extremely cutting edge device
- Track reconstruction software
- As co-spokesperson for both pion and kaon TDIS measurements take leading role in experimental campaign, data collection, result/outcome generation (pion/kaon SF extractions)
- Feasibility studies for longer term spectator tagging program, e.g. Electron Ion Collider
- University of Glasgow have committed £100k to this program, which will mostly be used to fund a PhD student

Summary

- JLab upgrade - unique opportunity to explore light meson structure

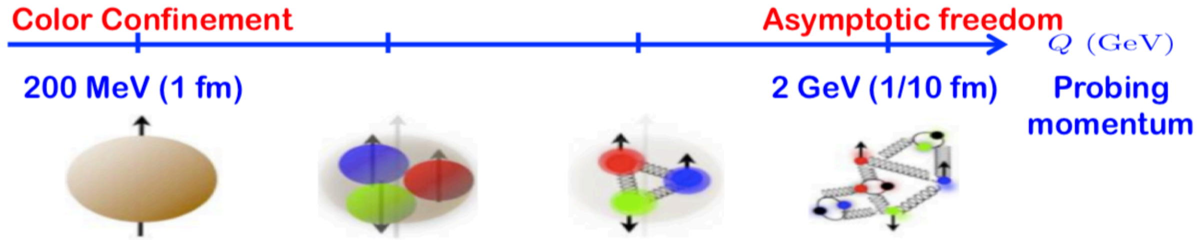
- TDIS
  - direct access to nucleon's meson content
  - novel probe of pion/kaon structure
  - substantial theoretical work, data sparse → world firsts

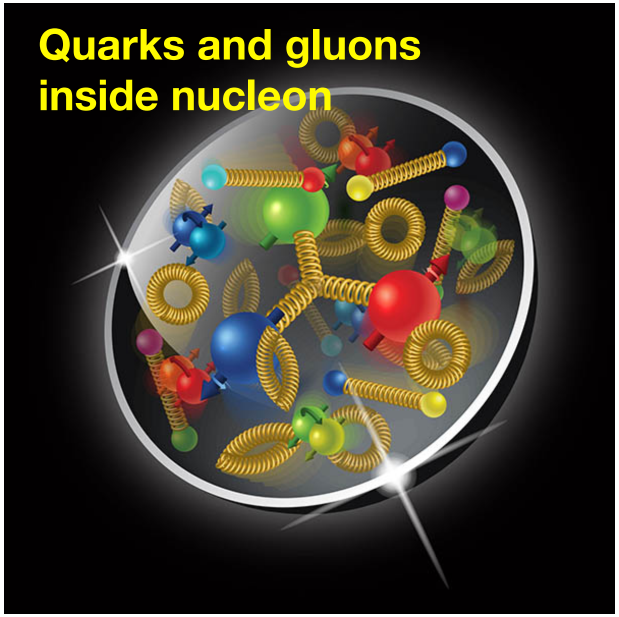
- ERF research will deliver
  - cutting edge instrumentation
  - pioneering experimental techniques
  - high impact physics (anticipated by global community)

- Path to the future
  - Gateway to spectator tagging at upcoming Electron Ion Collider
  - e.g. Pion and Kaon Structure at an Electron Ion Collider, C Roberts et al., arXiv:1907.08218v1 [nucl-ex], submitted Eur. Phys. J A

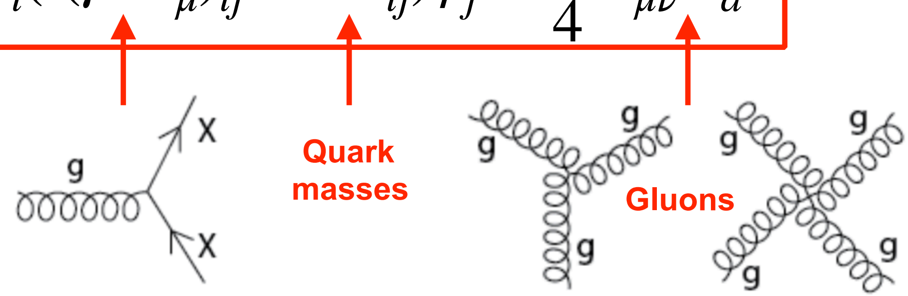
BACK UP

Quantum Chromodynamics





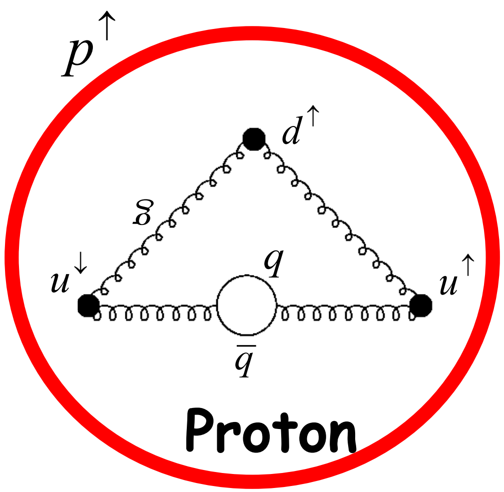
$$\mathscr{L}_{QCD} = \bar{\psi}_i (i(\gamma^\mu D_\mu)_{ij} - m\delta_{ij})\psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$



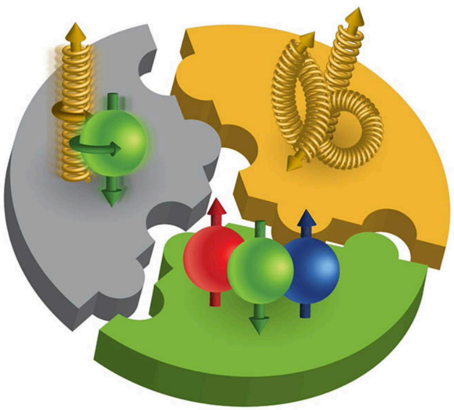
- Short distances: asymptotic freedom; understood through perturbation theory, tested 1% level
- Long distances (hadronic scale): confinement - no free quarks observed

- Crucial to understanding observed properties of matter e.g. mass/spin

Nucleon Spin



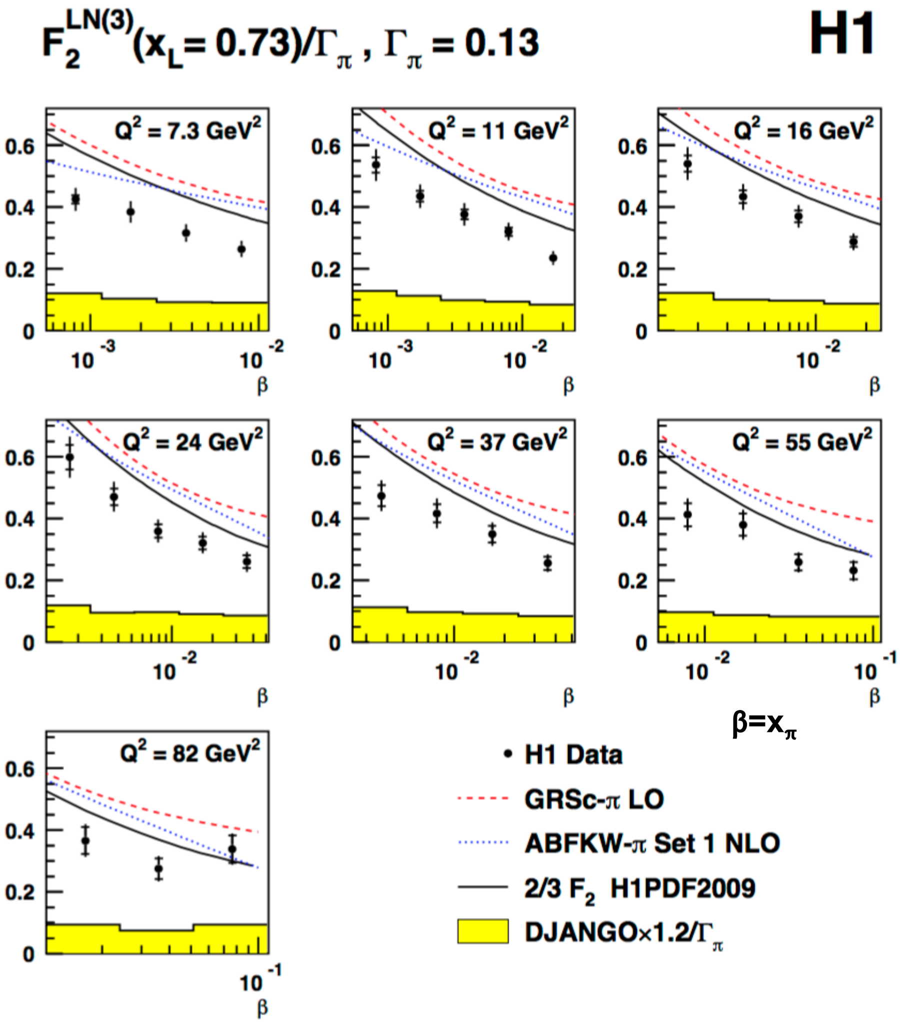
- e.g. “Proton Spin Crisis”
- Proton spin +1/2: expect 2 quarks +1/2 and one -1/2
- Data from muon-nucleon scattering 1980’s
  - 12% ± 16% proton’s spin carried by quarks
- Remainder: gluon spin and orbital angular momentum of quarks and gluons
- Still under experimental confirmation



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_Z$$

Quark Spin (~30%) — Gluon Spin (~40%) — Orbital Angular Momentum

- ‣ Extracting distributions of quarks and gluons within hadrons
  - ‣ understanding spin important check of QCD

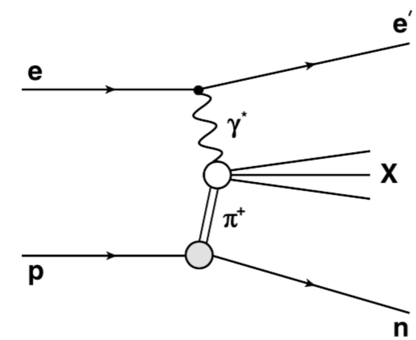


Eur. Phys. J. C (2010) 68: 381-399

HERA Tagged DIS

- Collider experiment
- Meson cloud virtual pion target
- ep → eXN
- Charged pion SF extracted

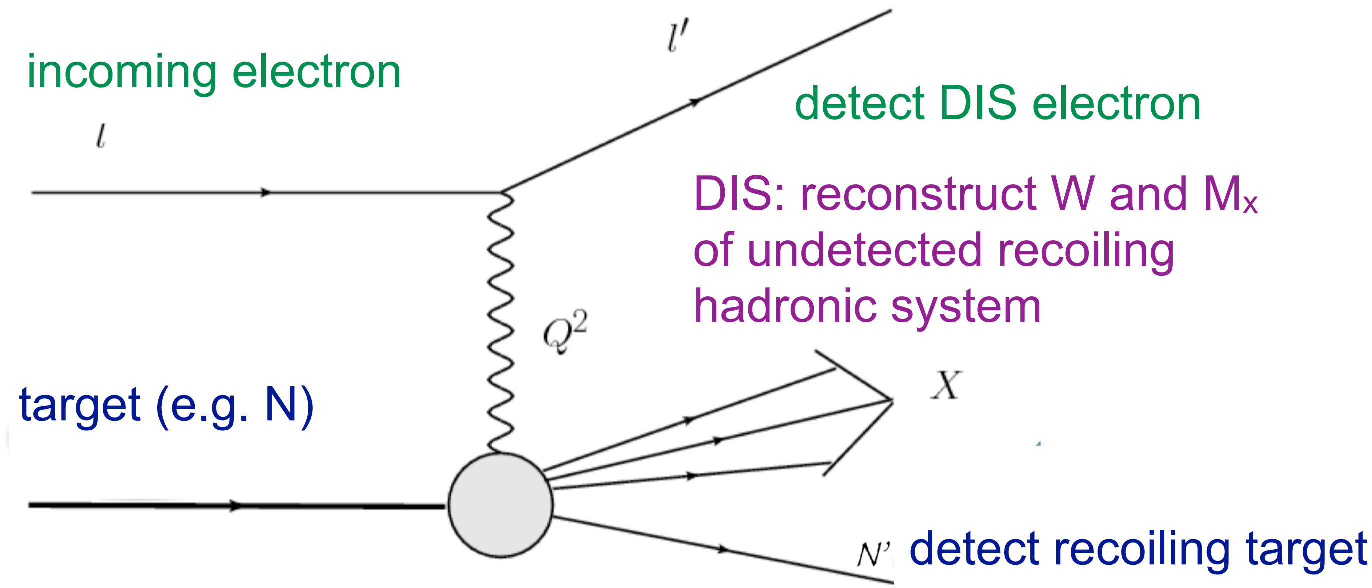
Diffractive scattering, forward detectors, different kinematics



TDIS

- Completely different kinematics
- Valence regime (not sea region)
- Evolution between kinematics

Basic Experimental Approach



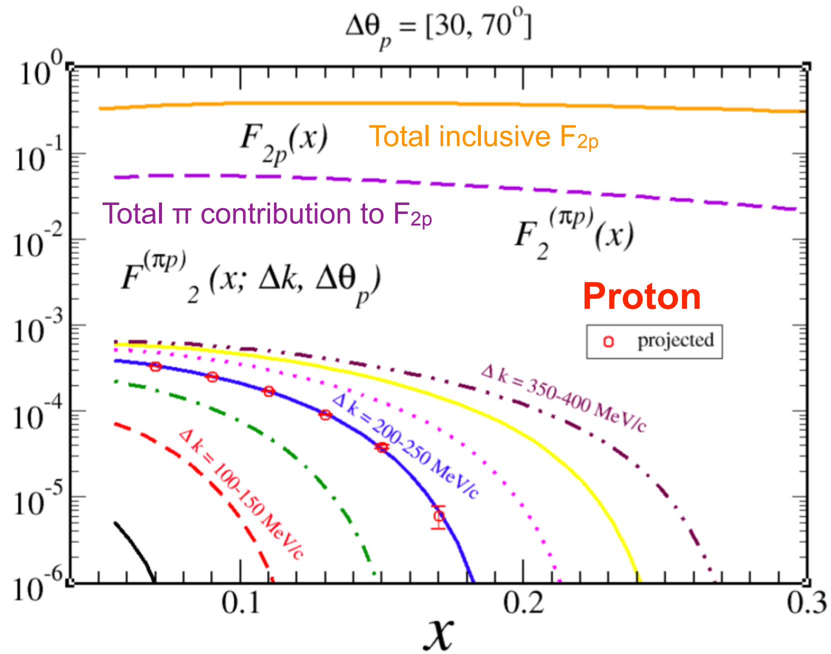
DIS variables: x_{Bj}, Q^2, W^2, M_x,
t (four-mom transfer squared at nucleon vertex)

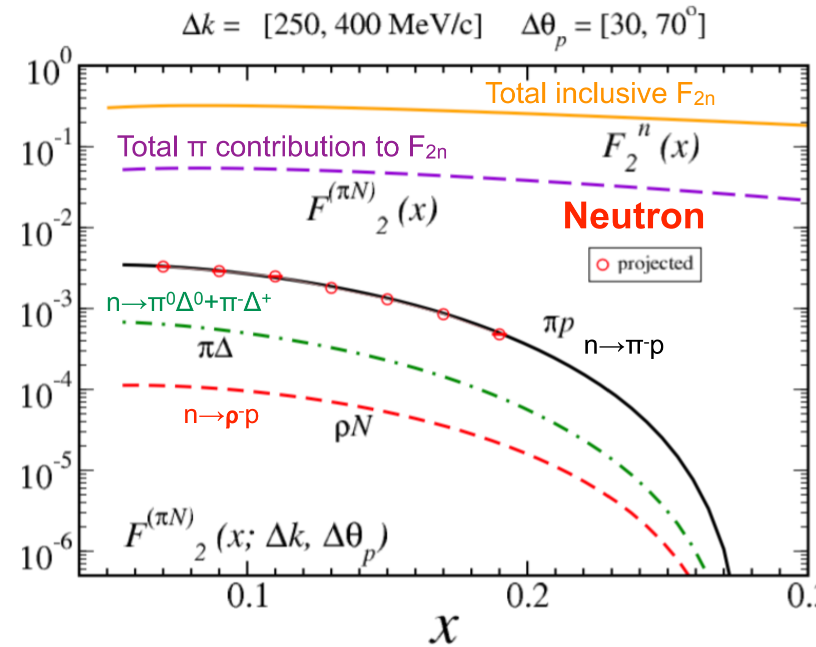
- Spectator tagging - fixed target nucleon fragmentation experiments
- Inclusive DIS cross-section accesses partonic sub-structure

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E_0^2 \sin^4\frac{\theta}{2}} \cos^2\frac{\theta}{2}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

- F1, F2 structure functions (SF)
- SF ➔ parton distribution functions (PDF) (momentum distributions)

TDIS Measurements





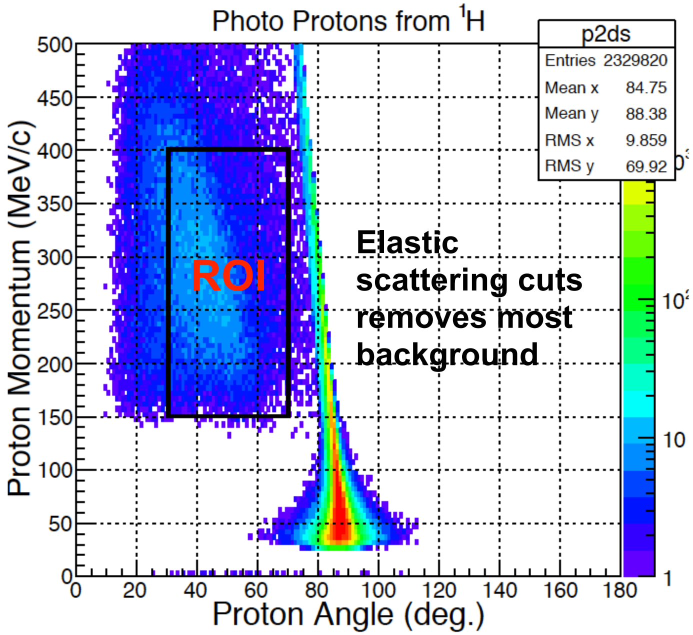
(T. J. Hobbs, Few Body Syst. 56 (2015) no.6-9)

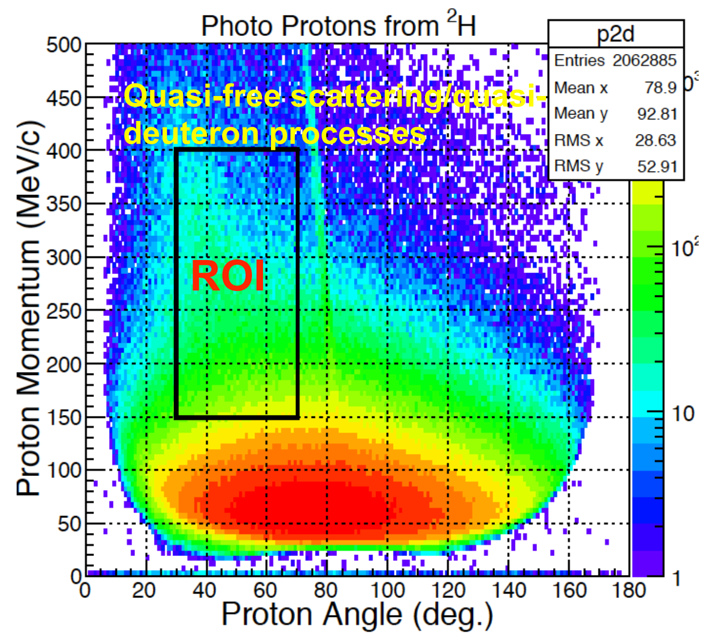
- Phenomenological pion cloud model
- Tagged signal orders of magnitude smaller than DIS → high luminosity
- Extraction of tagged SF: ratio of tagged to DIS cross-sections
- Reduces systematic uncertainties

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

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

TDIS Background Simulations





Target	θ_p (deg.)	$70 < p_p < 250$ (MHz)	$p_p > 250$ (MHz)	$150 < p_p < 400$ (MHz)
^{1}H	30 - 70	2.3	7.4	6.3
^{2}H	30 - 70	357	20.1	64
^{2}H	100 - 140	204	3.1	–
^{27}Al	30 - 70	0.37	0.0	0.05
^{27}Al	100 - 140	0.10	0.0	–

- Background rates very high
  - Protons from photo-nuclear/disintegration processes
- True recoils/spectators separated from accidentals using time/position vertex reconstruction

Phenomenological Pion Cloud Model and Pion TDIS

- Theoretical work used to study expected rates, required beam time, projected results etc based on a phenomenological pion cloud model
  - T.J. Hobbs, Phenomenological implications o the Nucleon's Meson Cloud, Few-Body Syst 56, 363 (2015)
  - H. Holtmann et al., Nucl. Phys. A 596, 631 (1996)
  - W. Melnitchouk, A.W. Thomas, Z. Phys. A 353, 311 (1995)

- Contribution to inclusive F_2 structure function of nucleon from scattering off virtual pion emitted by nucleon:

$$F_2^{(\pi N)}(x) = \int_x^1 dz\, f_{\pi N}(z)\, F_{2\pi}\left(\frac{x}{z}\right)$$

(z = k+/p+, light cone momentum fraction of initial nucleon carried by pion)

- Unintegrated distribution function (light-cone momentum distribution of π in nucleon):

$$f_{\pi N}(z) = \frac{1}{M^2}\int_0^\infty dk_\perp^2\, f_{\pi N}(z, k_\perp^2)$$

$k_\perp$ = transverse momentum of pion

- Semi-inclusive tagged structure function is un-integrated product:

$$F_2^{(\pi N)}(x, z, k_\perp) = f_{\pi N}(z, k_\perp)\, F_{2\pi}\left(\frac{x}{z}\right)$$

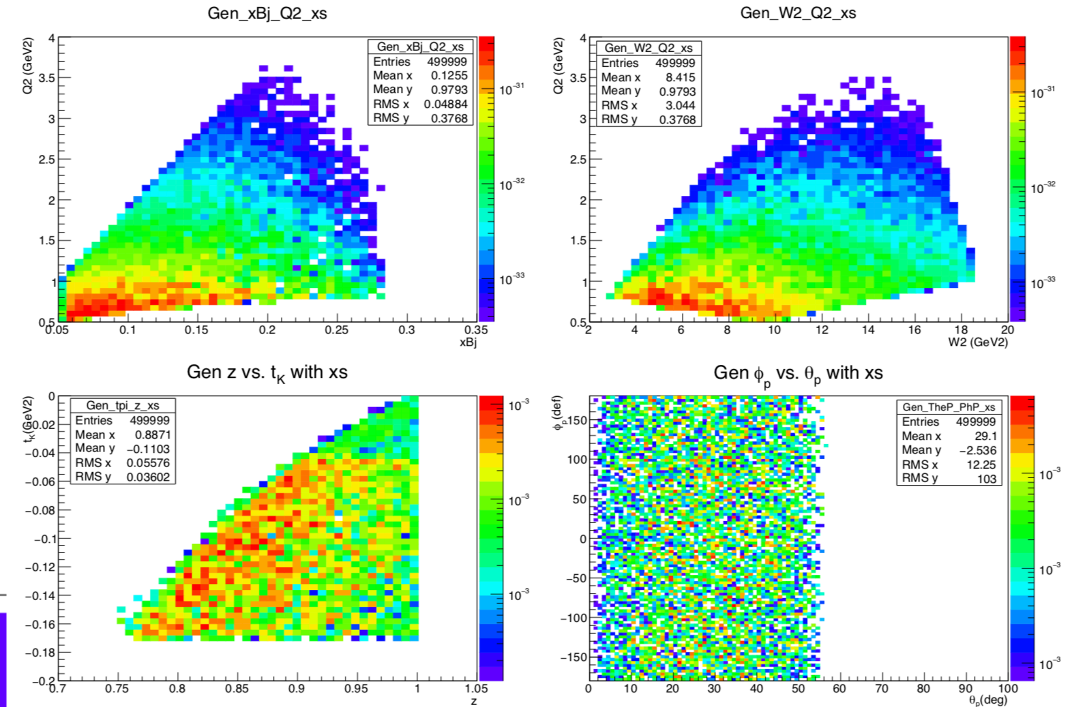
Pion "flux" Pion SF

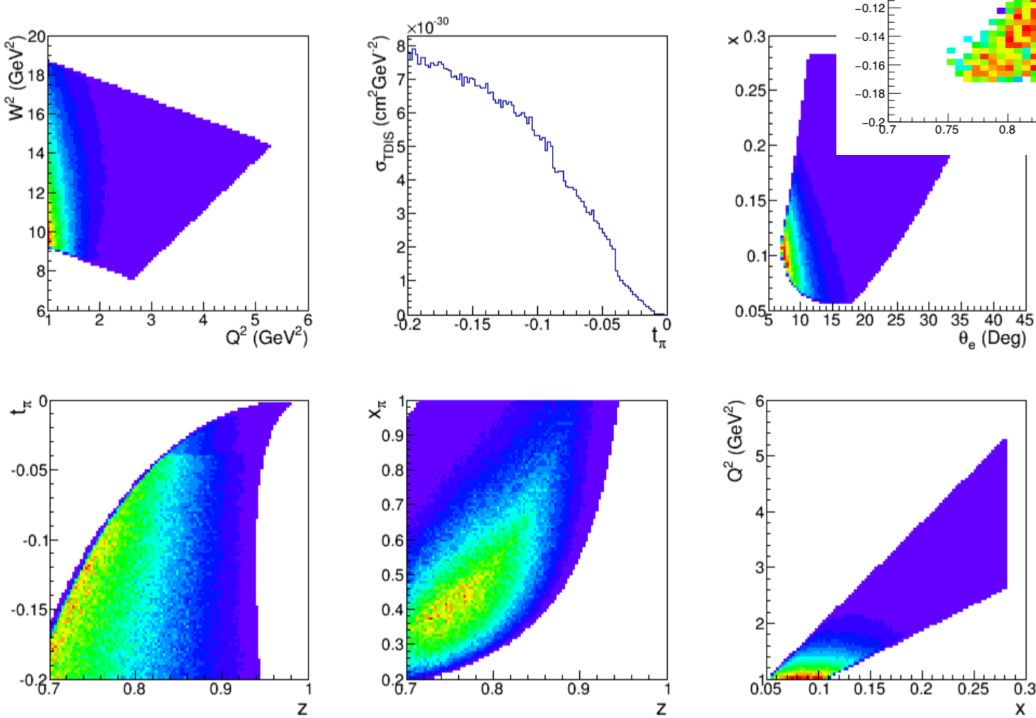
  - Seek to measure low-momentum region (pseudo scalar production dominates)
  - Interested in $z \lesssim 0.2$; $x<z \rightarrow$ defines maximum x, Q^2 (beam energy 11GeV)

TDIS Kinematic Reach in JLab's Hall A

- Event generators written for both pion and kaon TDIS processes to study simulations and kinematic reaches

- Right, kaon TDIS weighted by cross-section





- Left, pion TDIS weighted by cross-section (H target)

- x-range up to ~0.1
- After x-range optimised Q^2 reach fixed by limitation of 11GeV beam
- High W^2, M_x^2 indicates DIS regime
- **Similar reach for both pion/kaon TDIS**