Exploring Meson and Nucleon Structure with Tagged Structure Functions

Thia Keppel
An experimental technique to probe the target regime in semi-inclusive deep inelastic scattering

- Nucleon valence structure at large $x$
- Probe the meson cloud of the nucleon
- Pion and kaon structure functions
- Diffractive scattering, structure of the Pomeron
- Fracture functions
- N-N interactions, short range correlations, EMC effect
- DVCS, remove $\sim$15% background from $(e,e'D)\gamma$, $(e,e'p)\gamma$, … – also neutron, pion DVCS!
- Lambda $\rightarrow p\pi^-$ decay to measure $p \rightarrow K^+\Lambda$ kaon cloud of the nucleon
- ……more!

Understand nucleon structure at a deeper level
Tagged Deep Inelastic Scattering: The Basic Experimental Approach

Describe with standard DIS variables $x_{Bj}$, $Q^2$, $W^2$, plus:

- $M_X = \text{mass of system } X$
- $t = \text{four-momentum transfer squared at the nucleon vertex}$
Example 1: BONUS at Jefferson Lab – use fixed target tagging to create an effective *free neutron* target

- Deuteron Target

- Measure DIS electron in coincidence with proton tag

- “Hard” scattering inelastic event (high Q, W)
  - Proton remains intact
  - Low momentum = barely off shell
  - Neutron target!
Why measure from a neutron target?...

- d/u PDFs at large x (extract from F2n/F2p structure function ratio)
- Access neutron resonances
- EMC and other nuclear effects in deuterium
- Pion and kaon structure functions
Large Uncertainties on Large x Valence pdfs

$g(x)$

$u(x)$

$d(x)$

$s(x)$

NNLO, $Q^2 = 100$ GeV$^2$
d/u at large x from F2n/F2p: Textbook Physics

Quark-Parton Model

\[
F_2^p(x) = x \hat{a}_q e^2 (q(x) + \overline{q}(x)) \gg x_c u(x) + \frac{1}{9} d(x)
\]

\[
F_2^n(x) \gg x_c d(x) + \frac{1}{9} u(x)
\]

(sea quark dominance, approaches 1)

u quark dominance, 
\(d/u \rightarrow 0\)

BUT……..
F2n/F2p (and, hence, d/u) is (was) actually unknown at large(st) x:

- Conflicting fundamental theory pictures
- Data inconclusive due to uncertainties in deuterium nuclear corrections

Review Articles:
N. Isgur, PRD 59 (1999),
S. Brodsky et al NP B441 (1995),
W. Melnitchouk and A. Thomas PL B377 (1996) 11,
The BONUS approach: TAG spectator proton at (very) low momentum and large angle

Target fragmentation negligible

Bound / free neutron structure $O \,(1\%)$

Final state interactions $O \,(5\%)$
Spectator Proton Tagging

• **Low momentum** spectator must escape target
  - Thin deuterium target
  - Low density detector media
  - Minimal insensitive material

• Large acceptance
  - Backward angles important
  - Symmetric about the target

• Detector sensitive to spectators, insensitive to background
  - Use solenoidal field to contain Moller electrons
BONUS in CLAS6 (e detector)

- BoNuS GEM-based rTPC (low momentum p detector)
- Solenoid Magnet (track curvature in rTPC)
Spectator Tagging - results

\[ p_n = (M_D - E_s, -\vec{p}_s); \quad \alpha_n = 2 - \alpha_s \]

\[ W^2 = M^2 + 2Mn - Q^2 \]

Inclusive data

\[ E = 4.223 \text{ GeV} \]

\[ \langle Q^2 \rangle = 1.19 (\text{GeV/c})^2 \]

\[ p_S = (E_s, \vec{p}_s); \quad \alpha_S = \frac{E_s - \vec{p}_s \cdot \vec{q}}{M_D / 2} \]

\[ x = \frac{Q^2}{2p_n m q_m} \approx \frac{Q^2}{2Mn(2 - \alpha_S)} \]

\[ W^*_2 = (p_n + q)^2 = p_n \mu p_\mu + 2((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}) - Q^2 \]

\[ \approx M^*_2 + 2M\nu(2 - \alpha_S) - Q^2 \]
Low momentum proton tagging achieved

- Likely not quite high enough $x$, $Q^2$
- Nonetheless powerful as input for (CJ) global PDF fits

Global PDF fits including the non-perturbative regime

Large-x treatment

<table>
<thead>
<tr>
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<th>JLab &amp; BONUS</th>
<th>HERMES</th>
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<th>Tevatron new W,Z</th>
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</table>

* NLO only  ** No jet data  ✗ see 1503.05221  ✗ see 1508.06621  ✗ no reconstructed W

Accardi, Melnitchouk, Owens, Sato, Keppel, Monaghan, friends See www.jlab.org/theory/cj/
- BONUS data well fit by CJ
- Effect of adding BONUS (also $W, \ell$ asymmetries from D0)
- **Substantial reduction in $d/u$ uncertainty at large $x$!**
- Can still improve…

www.jlab.org/theory/cj/index.html
Plans for 12 GeV

E12-06-113
“BONUS12” approved

- Data taking of 35 days on D2 and 5 days on H2 with \( L = 2 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1} \)
- Planned BoNuS detector DAQ and trigger upgrade
- DIS region with
  - \( Q^2 > 1 \text{ GeV}^2/c^2 \)
  - \( W^* > 2 \text{ GeV} \)
  - \( ps < 100 \text{ MeV}/c \)
  - \( \phi > 110^\circ \)
- Largest value for \( x^* = 0.80 \) (bin centered \( x^* = 0.76 \))
- Relaxed cut of \( W^* > 1.8 \text{ GeV} \) gives max. \( x^* = 0.83 \)
Why measure from a neutron target?....

- d/u PDFs at large x (extract from $F_{2n}/F_{2p}$ structure function ratio)
- Access neutron resonances
- EMC and other nuclear effects in deuterium
- Pion and kaon structure functions

S. Tkachenko et al., PRC 89 (2014) 045206, Addendum: PRC 90 (2014) 059901
Bloom-Gilman (Quark-Hadron) Duality

~1970 (BG, PRL. 25 1140) Remarkable observation that resonances:
(A) average to scaling curve; and (b) “slide” along it.

Plot vs. any variable that allows high Q, W data (scaling curve) to compare to low Q, W (resonance) data

• Since 2000: Vigorous experimental program at JLab and beyond
• Duality now tested and shown to hold above ~1 GeV2 above the Delta for:
  F2p, F1p, FLp
  F2d, F1d, FLd
  F2A – multiple nuclear targets
  g1p, g2p
  g1d
  g1n
  PVDIS
  Soon to be tested with neutrinos (MINERvA at FNAL)

Apparently a fundamental property of nucleon structure!

Not well understood at all — ideas???? (a talk in itself)

CERN Courier, December 2004
F2p, F1p, FLp

“For neutron targets, by contrast,….we anticipate systematic deviations from local duality.”

- **BONUS neutron data show duality still holding**
- Duality provides an experimental link for the transition from the non-perturbative to the perturbative regime
- But, how to understand????

I. Niculescu et al., PRC 91 (2015) no.5, 055206
Finally we have a complete understanding of the quark-hadron duality.

It is a 2-fold rotational symmetry!

Why measure from a neutron target?....

- d/u PDFs at large x (extract from F2n/F2p structure function ratio)
- Access neutron resonances
- EMC and other nuclear effects in deuterium
- Pion and kaon structure functions

BONUS Example

- BONUS neutron
- JLab, SLAC proton and deuteron
- Small or no effect

K.A. Griffioen et al., PRC 92 (2015) no.1, 015211
Why measure from a neutron target?....

- d/u PDFs at large x (extract from F2n/F2p structure function ratio)
- Access neutron resonances
- EMC and other nuclear effects in deuterium

Hopefully you’re convinced that we learned a lot here so far 😊

- What about pion and kaon structure functions?
Why are we interested in the pion?

- The pion is fundamental.
- The pion is the simplest hadron with only two valence quarks.
- The pion plays a key role in nucleon and nuclear structure
  - QCD’s Goldstone boson
  - Explains the long-range nucleon-nucleon interaction
  - A basic part of the standard model of nuclear physics
- “….any veracious description of the pion must properly account for its dual role as a quark-antiquark bound-state and the Nambu-Goldstone boson associated with dynamic chiral symmetry breaking. It is this dichotomy and its consequences that makes an experimental and theoretical elucidation of pion properties so essential to understanding the strong interaction.” Holt and Roberts, Rev. Mod. Phys. **82**, 2991 (2010)
- Many questions, for instance what is the origin of the d(bar) – u(bar) flavor asymmetry?
  - asymmetry in anti-quarks generated from pion valence distribution?
Example 2: TDIS at HERA – *proton* tag

- Tag leading baryon production
- $ep \rightarrow eXN$ via color singlet exchange

Detect forward proton

**Diffractive Scattering:**

- Large rapidity gap
- $xL = Ep/Ep_{beam} \sim 1$

Proton tagged data is well described by Regge theory inspired fits.

Gluons >> quarks in Pomeron?

$$F_2^{D(4)} = f_P(x_P, t)F_P(\beta, Q^2) + n_{IR} \cdot f_{IR}(x_P, t)F_{IR}(\beta, Q^2)$$

- Pomeron contribution
- Reggeon contribution

The Pomeron diverges as $1/(1-xL)$, the f-Reggeon is flat.
The leading neutron results are different.
- There is no elastic (diffractive) peak present.
- Pion \((1-x_L)\)
- The leading neutron rate is roughly a factor of two lower than the leading proton rate for \(x_L<1\).
- Proton isoscalar events include diffractive Pomeron
- Neutron events isovector only

One pion exchange is the dominant mechanism.
- Can extract pion structure function
Pion Structure Function Measurements

Knowledge of the pion structure function is very limited due to the lack of a pion target.

- Pionic Drell-Yan from nucleons in nuclei
- HERA TDIS data at low $x$

Theoretical calculations in the valence region tended to disagree with each other – and with the data

- NNLO refit of old D-Y data, including resummation of soft gluon contributions, agrees with DSE (Aicher, Schafer, Vogelsang, PRL 105 (2010) 252003)

Critical to test! See Craig’s talk!!
BONUS Detector Provides Basis for Potential HERA-type Experiments at JLab

Example: Sullivan process scattering from neutron-pion fluctuation

detect scattered electron –
*large acceptance a plus*

Incoming electron –
*high current a plus*

DIS event – reconstruct x, Q2, W2, also MX of undetected recoiling hadronic system

want *charged* pion target (undetected)

need fluctuating nucleon to be a neutron……

neutron in deuteron target

Detected protons need to be *low* momentum
- Tag target hadron
- Extrapolate to pole
- Barely off-shell neutron

detected spectator proton tags neutron target (BONUS experiment technique)

detecting two protons with common vertex in coincidence tags “pion” target!
Note: only need one p for hydrogen target
Extrapolation to the pole

Need range of low momentum protons

The ratio of off-shell to on-shell pion electromagnetic form factor


Pion’s valence-quark GPD in unified DSE framework: virtuality-independent form factor suggests virtuality-independent parton distribution function

Within ~5% at proposed kinematics
How to estimate rates?

- Use Sullivan process and pion cloud model

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

\[ f_{\pi N}(z) = c_i g_{\pi NN}^2 \int_0^\infty \frac{dk_{1\perp}^2}{1-z} \frac{G_{\pi N}^2}{z (M^2 - 8_{\pi N})^2} \left( \frac{k_{1\perp}^2 + z^2 M^2}{1-z} \right) \]

Pion expected to be dominant – also estimated \( r, D \)

Form factor \( G_{\pi N} \)
constrained by comparing the meson cloud contributions with data on inclusive \( pp \rightarrow nX \) scattering

Light-cone momentum distributions, \( f_{\pi N}(z) \)
and \( f_{\pi \Delta}(z) \), as a function of the meson light-cone momentum fraction

Important to note – kinematic limits:
- \( z \ll |k|/M \), where \( k \) is p 3-momentum = \(-p'\)
- \( 60 < |k| < 400 \text{ MeV/c} \) corresponds to \( z < \sim 0.2 \)
- Also, \( x < z \! \! \! \! '\)
- Low \( x \), high \( W \) at 11 GeV means \( Q^2 \sim 2 \text{ GeV}^2 \)

T. J. Hobbs et al, Few Body Syst. 56 (2015) no.6-9
Basis for rate estimations of physics signal

**Proton**

- Inclusive structure function $F_2(x)$

**Contribution to $F_2$ from pions via Sullivan process**

- Top:
  - For different tagged $p$ momenta ranges $\Delta k$: 60-100, 100-200, 200-300, 300-400 MeV
  - Neutron will be similar

**Bottom:**

- Neutron plot shows contributions from $r$, $D$
- Proton will be similar

Signal is orders of magnitude smaller than inclusive DIS – *need high luminosity*
Approved JLab Hall A TDIS Experiment

Hall A with Super Bigbite:
- High luminosity,
  50 mAmp, \( \mathcal{L} = 3 \times 10^{36}/\text{cm}^2\text{s} \)
- Large acceptance
  Super Bigbite \( \sim 70 \) msr, hadron spectrometer
- HCAL will be used in RTPC calibration

Need to…
- Add BONUS-type RTPC, requires solenoidal field
- Modify SBS for electron detection

Scattered electron detection in Super Bigbite Spectrometer (SBS) – construction to complete 2017
Projected TDIS Kinematics – *optimized for meson cloud*

High $W^2$
- High $M_x^2$
- DIS!

All data obtained *simultaneously* at one $E = 11$ GeV setting, only a target change – will run hydrogen and deuterium (neutron)

Low $t$, high $(1-z)$

$x$ range $\sim 0.1$

$1 < Q^2 < 2$ GeV$^2$
Projected Results I
- proton

\( F_2^{p}(x) \) is well-known inclusive DIS

\( F_2^{(pp)}(x) \) is total pion contribution to structure function

Colored lines are pion contribution for different bins in p\textsubscript{proton}

Data for 200 < p\textsubscript{proton} < 250 MeV/c are representative to show uncertainty
- will have multiple momentum bins

**Full** data set shown here
- all momentum bins in MeV/c

Error bars largest at highest x points – less statistics
- at fixed x, these are the lowest t values
F2n(x) is inclusive DIS – tagged by additional low momentum, backward angle $p$ as in BONUS

F2(pN)(x) is total pion contribution to structure function

Colored lines are expected total Delta and rho contribution for $250 < p_{\text{proton}} < 400$ MeV/c.

Data for pion contribution are representative to show uncertainty

Full data set shown here - all momentum bins in MeV/c

Do not show lowest momentum $<x> = 0.075$ data - run lower luminosity due to larger background
- Large x structure of the pion is of particular recent interest, verify resummed Drell-Yan results
- Q2 range will check evolution
- Large x, low Q complementary to HERA low x

Will also measure n, p (p-, p0) difference
- look for isospin dependence
- very different backgrounds
- Projected Results – Kaon Structure Function from TDIS at Jlab
  - Not approved yet – would possibly get “for free”
  - This is *just a first preliminary look*, en -> (eKL) -> epp-
  - Very difficult
  - Still simulating (K. Park), expect at least double the uncertainty

At high $x$, the shapes of valence $u$ quark distributions in pion, kaon and proton are different, and so are their asymptotic $x \to 1$ limits

- Some of this is due to the comparison of a two- versus three-quark system, and a meson with a heavier $s$ quark
- However, effects of gluons come in as well (again, see Craig’s talk)
Tagged DIS at the EIC

The technique is uniquely suited to colliders: there is no target material absorbing low-momentum nucleons, *and it can be used with polarized ion beams* (longitudinal and transverse).

- Full acceptance for spectators from longitudinally and transversely polarized light ion beams
- *Neutron* detection in a 25 mrad cone around 0°
- Secondary high dispersive ion focus ~40 m downstream of IP

The mEIC designs provide electron–nucleon squared center–of–mass energies in the range 250 – 2500 GeV² at luminosities up to 10³⁴ cm⁻² s⁻¹
EIC Needs Good Acceptance for TDIS-type Forward Physics!

Example: acceptance for $p'$ in $e + p \rightarrow e' + p' + X$

Acceptance in diffractive peak ($X_L > \sim .98$)
- ZEUS: $\sim 2\%$
- JLEIC: $\sim 100\%$ (also covers much higher $X_L$ than ZEUS)

Huge gain in acceptance for forward tagging to measure $E2n$
Projected Data Example: Neutron Structure at the EIC

See Spectator Tagging Project at https://www.jlab.org/theory/tag/

e + D → e' + p + X a la BONUS

$$\alpha_R \equiv 2(ER + pzR)/(ED + pzD)$$

residue = free neutron

TDIS measurements require coverage for [protons] with low momenta relative to beam momentum ($p_T < 200$ MeV, $p_T/p(\text{beam}) \sim 0.8 - 1.2$), and good momentum resolution ($\Delta p_T \sim 20$ MeV).

TDIS also requires that the intrinsic momentum spread in the ion beam be small to allow for accurate reconstruction.

(JL)EIC being designed for this purpose.
Counts assume roughly one year of running (26 weeks at 50% efficiency) with 5 GeV electrons and 50 GeV protons at luminosity of 10^34/s cm^2

Counts here still need to be multiplied with geometric detection efficiency ~ 20%.
TDIS opens a door to access effective (neutron, pion, kaon...?) targets
- **Critical, fundamental hadron structure measurements!**
- Nucleons, pions, kaons, are the basic building blocks of nuclear matter. *We should know their structure functions!*
- The distributions of quarks and gluons in pions, kaons, and nucleons will be different.. without data flavor decomposition impossible
- Is the origin of mass encoded in differences of gluons in pions, kaons, nucleons (at non-asymptotic Q2)?

TDIS opens a door to probe meson cloud of the nucleon
- **Direct measurement of nucleon-meson fluctuation component of DIS**

Very few experiments to date

Understand nucleon structure and QCD at a deeper level

**Thank You!!!**
Backups
Structure Function Measurements

Proton –
- Well understood
- $F_{2p}$ measured over 5 orders of magnitude in $x$, $Q^2$
- $F_{2p}$ measured by dozens of experiments at numerous laboratories and for decades
- FL measurements also exist
- Well described by DGLAP, global pdf fits

Neutron –
- One experiment
- Limited kinematics (low $Q$, high $x$)
- No FL data
- Deuteron Available

Pion –
- Two experiments
- Limited kinematics (low $x$, moderate $x$, scant $Q^2$ reach at same $x$)
- No FL data
Angular dependence

\[ Q_2 = 1.66 \text{ GeV}^2 \]
\[ W^* = 1.73 \text{ GeV} \]

- No significant deviations from PWIA (\( p_s < 100 \text{ MeV/c} \)), first 2 panels
- Possible \( \theta \) dependence at higher momenta
Beam Time Request

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<tr>
<th>x range</th>
<th>$\sigma_e$ in SBS (nb)</th>
<th>$F_2^\pi N/F_2$ (x 10^{-5})</th>
<th>TDIS $\pi N$ Rate (Hz)</th>
<th>Yield $H_2$ 10 days (k)</th>
<th>Yield $D_2$ 5 days (k)</th>
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Rate(DIS$\pi N$) = Rate(DIS)$\times$(F$2^\pi N$/F$2$)
Rate(TDIS$\pi N$) = Rate(DIS$\pi N$)$\times$ effRTPC$\times$ effSBS

$\text{effRTPC} = 0.4 \text{ and effSBS} = 0.9$

Luminosity = $3 \times 10^{36}/\text{cm}^2 \text{ s}$

All data (per target) obtained simultaneously

5 bins in x, each with 6 bins in momentum

1% statistical uncertainty on average

Highest x, lowest momentum point drives time request

neglected for deuterium

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<th>$\Delta k$ (MeV/c)</th>
<th>$\Delta T$ (MeV)</th>
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Low luminosity, HCAL quasi-elastic runs for calibration and background studies

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23 days

46
Dominant Sources of Systematic Uncertainty

- Accidental background subtraction 5%
  - Requested beam time to run 5 days at reduced luminosity to evaluate
- (Untagged) DIS electron cross section 3%
  - Target density, beam charge, spectrometer acceptance, detector and trigger efficiency, ....
  - SBS and RTPC stay at same kinematics, entire detector system serves as a luminosity monitor
  - Will correct inclusive electron to very well-known cross sections
- RTPC absolute efficiency 2%
  - Propose to run with HCAL quasi-elastic neutrons to calibrate at p<200 MeV/c
  - Stability of RTPC will be monitored with accidental elastic protons
- RTPC deadtime uncertainty ~ 1%
  - Requested beam time to run at lower luminosity, also during calibration
- RTPC momentum resolution (<)1%
  - Large momentum bins proposed
- RTPC angular acceptance ~ 1%
  - Survey and simulation, calibration via D(e,e’n)p,
- Beam position (<)1%
  - Precision BPMs, calibration of the position dependence

**TOTAL ESTIMATE 6.5%**
Fracture Functions Allow for Rigorous Description of TDIS
(conditional pdfs, ~diffractive pdfs)

(a) Inclusive DIS $eN \rightarrow e' + X$
(b) Parton distribution $f(x)$ describes the probability distribution of quarks with respect to their light-cone momentum fraction $x$ in the target
(c) Conditional cross section with an identified hadron in the target fragmentation region $eN \rightarrow e' + h$(target) + $X$
(d) Fracture function, or conditional parton distribution describes the probability to find a hadron $h$ in the target fragmentation region, with light-cone momentum fraction $1 - z$ and transverse momentum $p_T$, after removing a quark with light-cone momentum fraction $x$.

- Particular, conditional case of DIS
- Defined through factorization theorem, universal
- Factorization for FF in SIDIS has been proven at collinear and soft level
- Hard cross section same as inclusive
- DGLAP evolution same as PDFs
- Can be extracted from data

D. De Florian and R. Sassot, Phys. Rev. D56 (1997) 426
Fracture Functions – nucleon structure and dynamics

**different physical interpretations in different regions of x**

\[ p \rightarrow p \quad x \ll 1 \]

Pomeron exchange

\[ p \rightarrow n \text{ or } n \rightarrow p \quad x \sim 0.1 \]

charged pion exchange

\[ x > 0.3 \]

*hadronization of nucleon with “hole” in light cone wavefunction*

*Non-perturbative interactions: cSB fields in QCD vacuum, color confinement*
Measuring Fracture Functions

Definition
\[ f(x, z, p_T) = \] probability to find hadron in target fragmentation region…. 
("tag" the recoil proton) 
……after removing a quark with light cone momentum fraction x 
(standard DIS \( F_2(x) \))

Measure
 tagged DIS/untagged (inclusive) DIS
Understanding Target Region Important for Semi-Inclusive Physics at JLab

- Significant component of JLab 12 GeV program
  - Flavor decomposition, transverse momentum dependent pdfs, single spin asymmetries
  - Focus on current fragmentation region

At JLab energies the current and target fragmentation regions are not widely separated, hence a quantitative understanding of target fragmentation will be a prerequisite for the analysis of semi-inclusive DIS in the current fragmentation region.
Sign change of $\bar{d}(x) - \bar{u}(x)$ at $x \sim 0.25$? (or $\bar{d}(x) / \bar{u}(x) < 1$ at $x \sim 0.25$?)

Why is it interesting? (no models can explain it yet!)

Meson cloud model  

Chiral-quark soliton model  

Statistical model

From Alberg’s talk  

From Wakamatsu’s talk  

From Soffer’s talk

J-C Peng, Trento 2013 workshop
Think about both hydrogen and deuterium.

\[ p(e,e'p)X \text{ and } n(e,e'p)X \]

- Charged pion exchange has less background from Pomeron and Reggeon processes, \( r_0 \) production.
- The \( p+N \) cloud doubles \( p0N \) cloud in the proton.

\[
|p > \rightarrow \sqrt{1 - a - b}|p_0 >
\]

\[
+ \sqrt{a} \left( -\sqrt{\frac{1}{3}}|p_0\pi^0 > + \sqrt{\frac{2}{3}}|n_0\pi^+ > \right)
\]

\[
+ \sqrt{b} \left( -\sqrt{\frac{1}{2}}|\Delta^+_0\pi^- > - \sqrt{\frac{1}{3}}|\Delta^+\pi^0 > + \sqrt{\frac{1}{6}}|\Delta^0_0\pi^+ > \right)
\]

Regge approach: \( a=0.105, b=0.015 \)
\[ \text{Nikolaev et al.,PRD60(1999)014004} \]

Chiral approach: \( a=0.24, b=0.12 \)
\[ \text{Thomas, Melnitchouk & Steffens,PRL85(2000)2892} \]
Abundant Evidence for *Some* Mesonic Content of the Nucleon

On the Interaction Between Neutrons and Electrons*

E. Fermi and L. Marshall

Argonne National Laboratory and Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received September 2, 1947)

moment equal to \( \frac{e\hbar}{2\mu c} \), we are led to the estimate that the average number of mesotrons near a neutron is 0.2. Therefore, in calculating the nu-

Neutron Charge Density

Pion Form Factor

- Partially conserved axial current, chiral quark models, vector meson dominance models - substantial, successful theory development
- In contrast, scant experimental data – do not know magnitude of mesonic content
- How does mesonic content affect structure functions, parton distributions?
Models of the structure function

- SU(6)-symmetric wave function of the proton in the quark model (spin up):

\[
\left| p \right\rangle \propto \frac{1}{\sqrt{18}} |3u| |ud\rangle_{S=0} |u| \sqrt{2} |ud\rangle_{S=1} |\sqrt{2}d\rangle |uu\rangle_{S=1} |2d\rangle |uu\rangle_{S=1}
\]

- u and d quarks identical, N and D would be degenerate in mass.
- In this model: d/u = 1/2, F2n/F2p = 2/3.

- SU(6) symmetry is broken: N-D Mass Splitting
  - Mechanism produces mass splitting between S=1 and S=0 diquark spectator.
  - Symmetric states are raised, antisymmetric states are lowered (~300 MeV).
  - S=1 suppressed => d/u = 0, F2n/F2p = 1/4, for x -> 1

- pQCD: helicity conservation (q\right\rangle \propto p)
TDIS RTPC

- Luminosity of $3 \times 10^{36}$ Hz/cm²
  
  Higher current means Al target straw

- Need to preserve low $p$ tagging
  
  40 cm long target cell (1 atm H₂ at 77 K)

- Larger bore, higher field
  
  Increased drift region
  
  Improved momentum resolution
  
  Momentum up to 400 MeV/c

- Coordinate resolution of 1 mm
  
  1 mm x 21 mm in each U&V

  Angular resolution of 0.2 degrees
  
  24,000 readout pads

- Sensitive volume
  
  He-CH₄ (10%) – 0.15 atm & 77K

  Inner radius (track) of 5 cm

  Outer radius (track) of 15 cm

- Benefit from decade of active GEM development, for instance:

Das et al, Gas-gain study of standard CERN GEM and thick GEM in low-pressure He/CO₂ mixed gas
NIM A 625 (2011) 39

Buzulutskov A. etal, GEM operation in helium and neon at low temperatures
NIM A548 (2005) 487

"Advances in Cryogenic Avalanche Detectors" (review), JINST 7:C02025,2012

Adamova et al, The CERES/NA45 radial drift Time Projection Chamber, 0.34/0.64 mm resolution
NIM A 593 (2008) 203

Lener et al, Performance of a GEM-based Time Projection Chamber prototype for the AMADEUS experiment, 0.25 mm resolution
arXiv:1302.3054
Radial TPC in Field for Monte Carlo Simulations

Monte Carlo simulates electromagnetic interactions
- Moller scattering, secondaries ~10 MHz
- Photoproduction ~20 MHz
- Includes deuteron photodisintegration ~20 MHz
- Elastic scattering by far largest
direct calculation 170 MHz
5 MHz/cm² s - OK for GEMs
Developing the F2p case
hydrogen target, worst theoretical backgrounds

Calculation from B. Kopeliovich at JLab TDIS kinematics