Pion and Kaon Structure Functions at EIC

Collaboration with Ian Cloet, Thia Keppel, Wally Melnitchouk, Kijun Park, Paul Reimer, Craig Roberts, Nobuo Sato, Richard Trotta, Andres Vargas, Rik Yoshida

Thanks to: Roy Holt, Yulia Furletova, Elke Aschenauer and Steve Wood

Rolf Ent (JLab), Tanja Horn (CUA)

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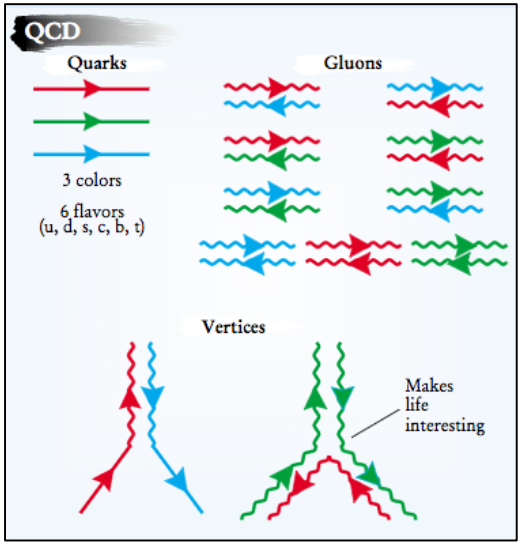
April 16-20, 2018

Outline

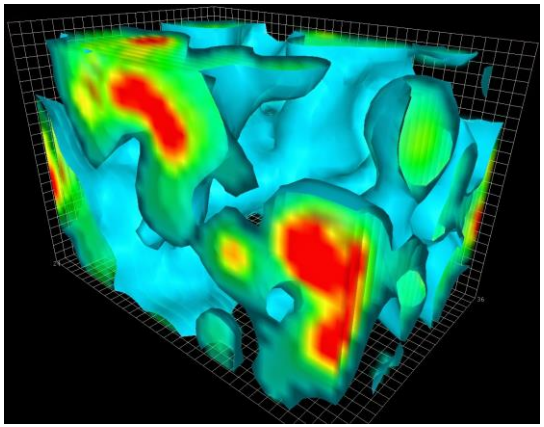
- The Emergence of Mass
- J/Ψ and Upsilon Threshold Production at an EIC
- Pion and Kaon PDFs – History
- Detection Capabilities at an EIC
- Off-Shellness
- First Check of Impact of EIC on Pion PDFs
- Disentangling the Flavor Dependence

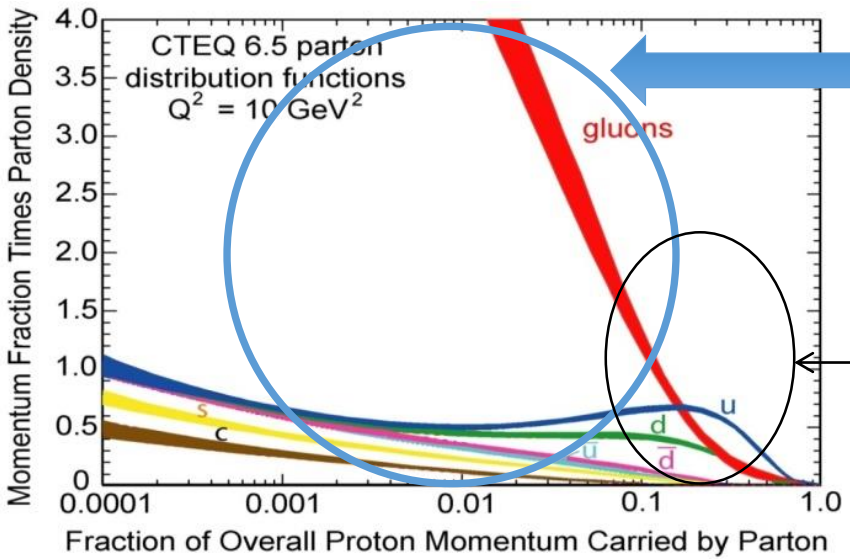
Cold Matter is Unique



Interactions and Structure are entangled because of gluon self-interaction.

Observed properties such as mass and spin emerge from this complex system.

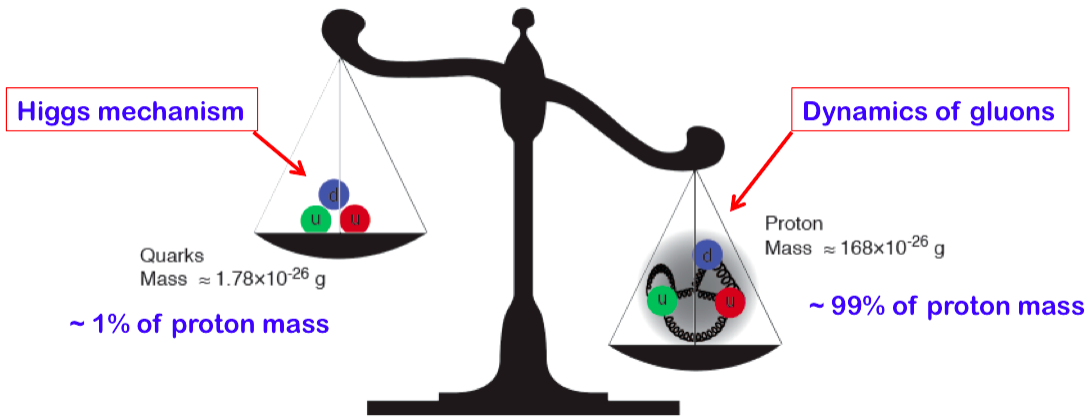


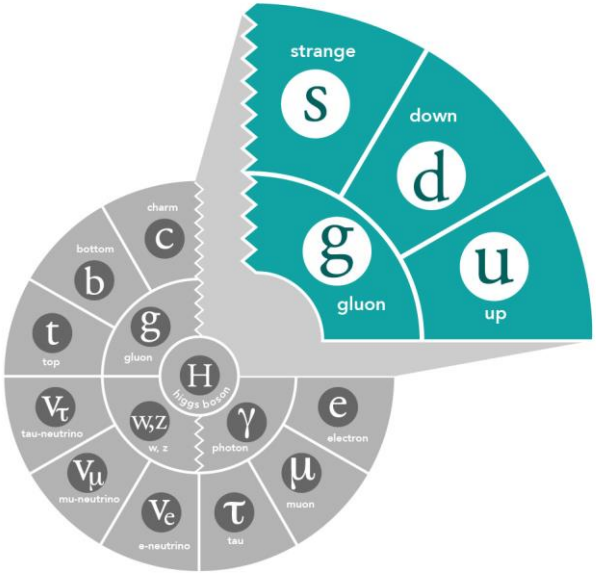


EIC needed to explore the gluon dominated region

JLAB 12 to explore the valence quark region

The Incomplete Nucleon: Mass Puzzle





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

- Proton mass:

$$M = \overbrace{E_q + E_g}^{\text{Relativistic motion}} + \overbrace{\chi_{m_q} + T_g}^{\text{Quantum fluctuation}}$$

Quark Energy — Gluon Energy — Quark Mass — Trace Anomaly

The Incomplete Nucleon: Mass Puzzle

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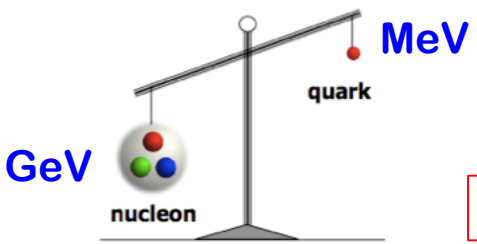


Relativistic motion

Quantum fluctuation

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

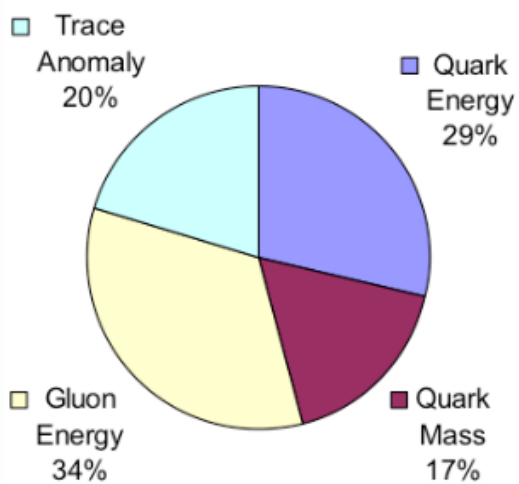
Quark Energy

Gluon Energy

Quark Mass

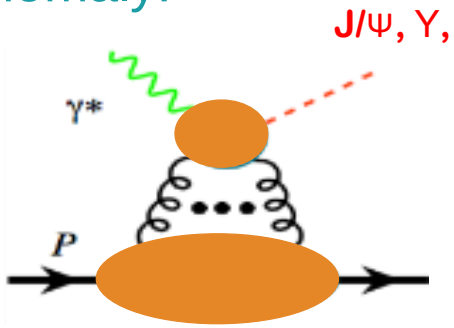
Trace Anomaly

- Preliminary Lattice QCD results:



- EIC projected measurements:
  - ✧ trace anomaly:

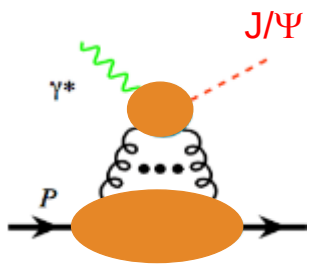
Upsilon production near the threshold



  - ✧ Quark-gluon energy: SIDIS

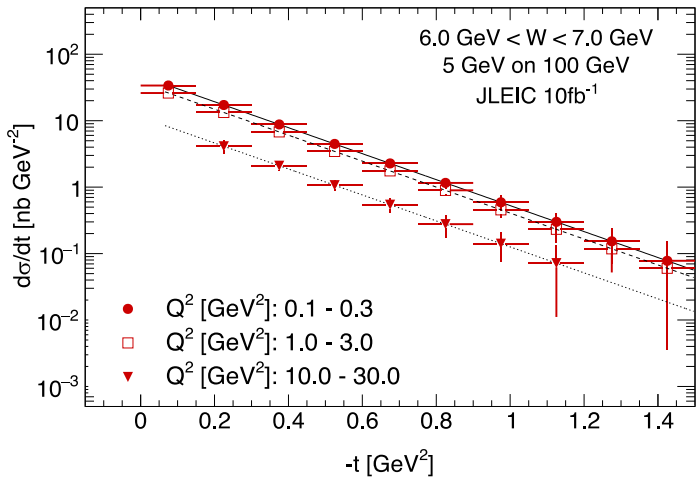
Elastic J/Ψ production near threshold at an EIC

At an EIC a study of the Q^2 dependence in the threshold region is possible

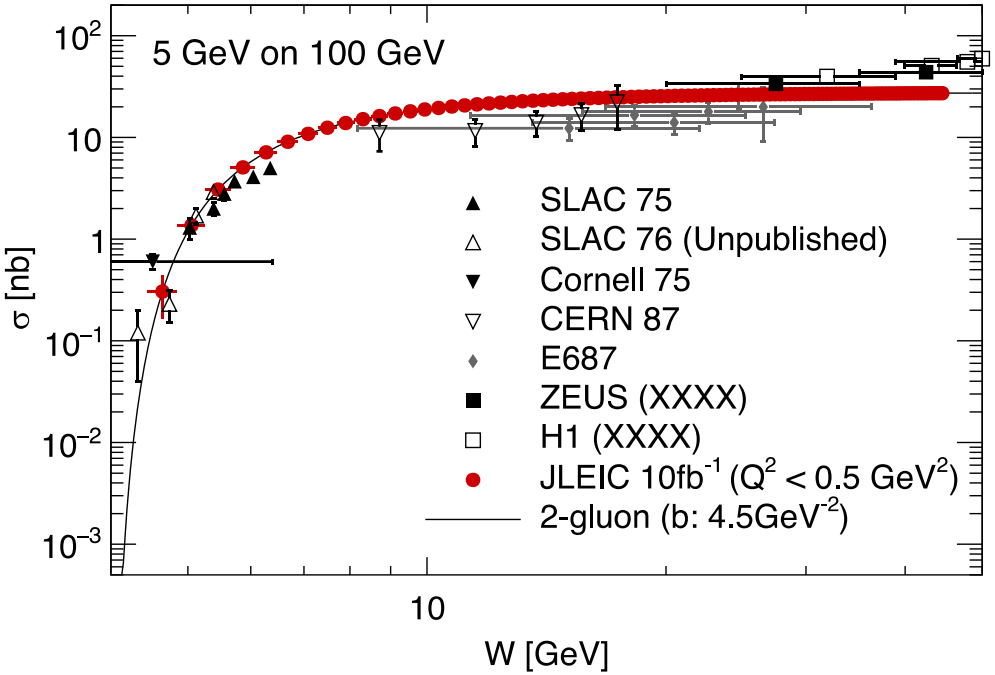


S. Joosten, Z-E. Meziani

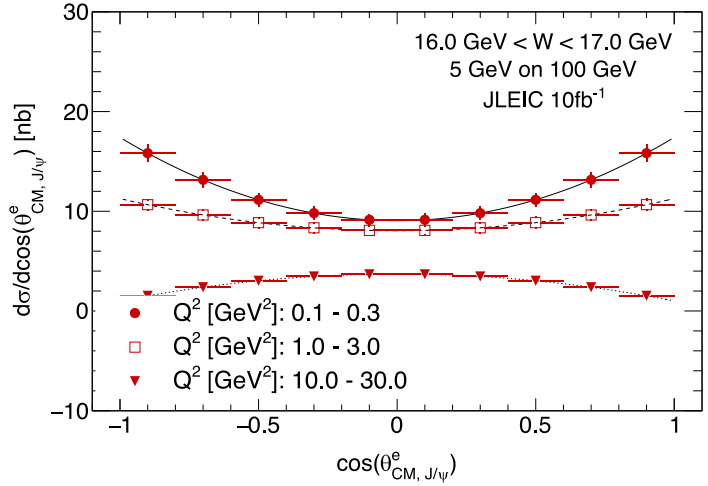
t distribution



Total electroproduction cross section

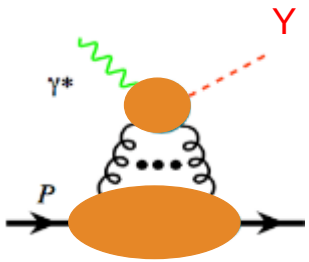


angular distribution of decay



Elastic Y production near threshold at an EIC

At an EIC a study of the Q^2 dependence in the threshold region is possible



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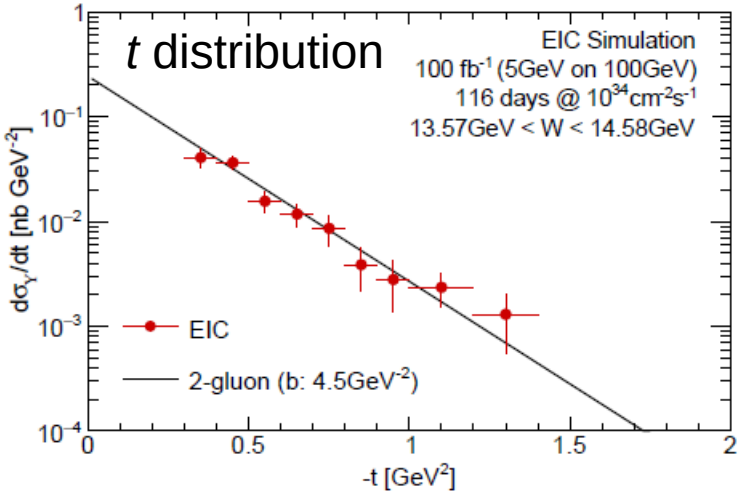
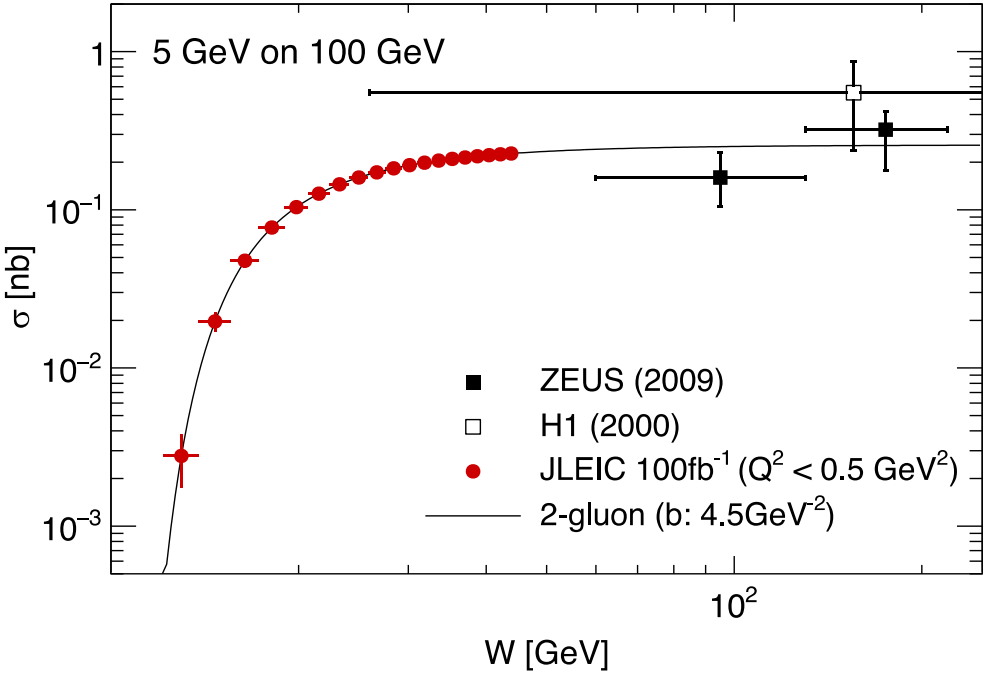
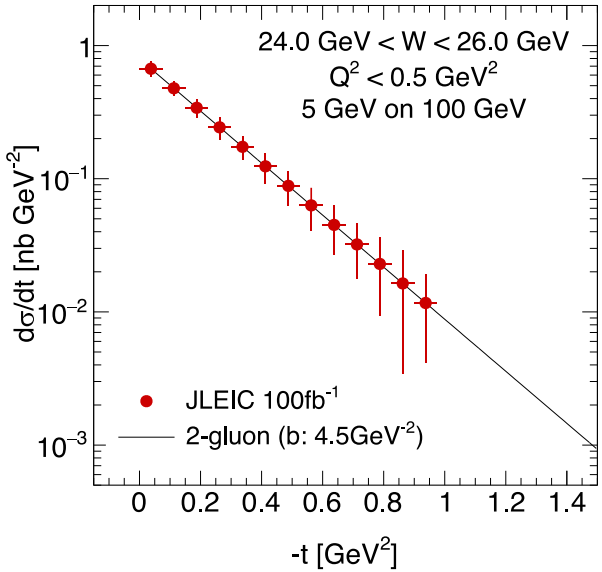
Low W → trace anomaly
Large W → Gluon GPDs

(see arXiv:1802.02616)







The Incomplete Nucleon: Mass Puzzle

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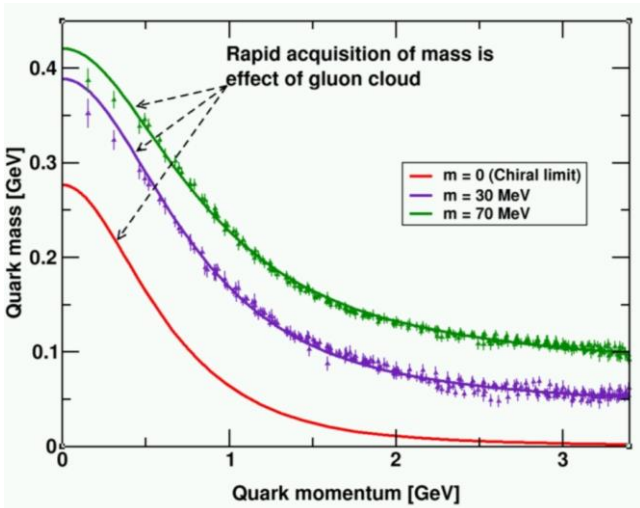
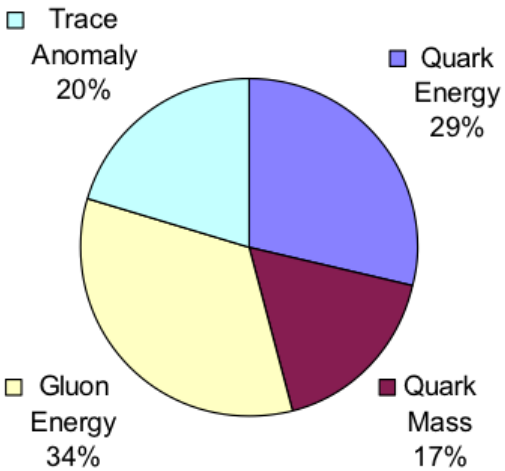


"Mass without mass!"

Bhagwat & Tandy/Roberts et al



Proton: Mass ~ 940 MeV

preliminary LQCD results on mass budget, or view as mass acquisition by DχSB

Kaon: Mass ~ 490 MeV

at a given scale, less gluons than in pion

Pion: Mass ~ 140 MeV

mass enigma – gluons vs Goldstone boson

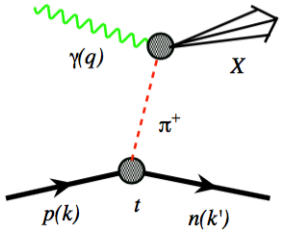
❑ EIC's expected contribution in:

✧ Quark-gluon energy:

$\propto$ *quark-gluon momentum fractions*

In nucleon with DIS and SIDIS

In pions and kaons with Sullivan process



Origin of mass of QCD's pseudoscalar Goldstone modes

- Exact statements from QCD in terms of current quark masses due to PCAC

  (Phys. Rep. 87 (1982) 77;
  Phys. Rev. C 56 (1997) 3369;
  Phys. Lett. B420 (1998) 267)

$$f_\pi m_\pi^2 = (m_u^\zeta + m_d^\zeta)\rho_\pi^\zeta$$
$$f_K m_K^2 = (m_u^\zeta + m_s^\zeta)\rho_K^\zeta$$

- Pseudoscalar masses are generated dynamically – If $\rho_\pi \neq 0$, $m_\pi^2 \sim \sqrt{m_q}$
  - The mass of bound states increases as $\sqrt{m}$ with the mass of the constituents
  - In contrast, in quantum mechanical models, *e.g.*, constituent quark models, the mass of bound states rises linearly with the mass of the constituents
  - *E.g.*, with constituent quarks Q: in the nucleon $m_Q \sim \frac{1}{3} m_N \sim 310$ MeV, in the pion $m_Q \sim \frac{1}{2} m_\pi \sim 70$ MeV, in the kaon (with one s quark) $m_Q \sim 200$ MeV – **This is not real**.
  - In both DSE and LQCD, the mass function of quarks is the same, regardless what hadron the quarks reside in – **This is real**. It is the Dynamical Chiral Symmetry Breaking (DχSB) that makes the pion and kaon masses light.

- Assume DχSB similar for light particles: If $f_\pi = f_K \approx 0.1$ & $\rho_\pi = \rho_K \approx (0.5\ \text{GeV})^2$ @ scale $\zeta = 2$ GeV
  - $m_\pi^2 = 2.5 \times (m_u^\zeta + m_d^\zeta)$; $m_K^2 = 2.5 \times (m_u^\zeta + m_s^\zeta)$
  - Experimental evidence: mass splitting between the current s and d quark masses

$$m_K^2 - m_\pi^2 = (m_s^\zeta - m_d^\zeta)\frac{\rho^\zeta}{f} = 0.225\,\text{GeV}^2 = (0.474\,\text{GeV})^2 \qquad m_s^\zeta = 0.095\,\text{GeV},\ m_d^\zeta = 0.005\,\text{GeV}$$

In good agreement with experimental values

The role of gluons in pions

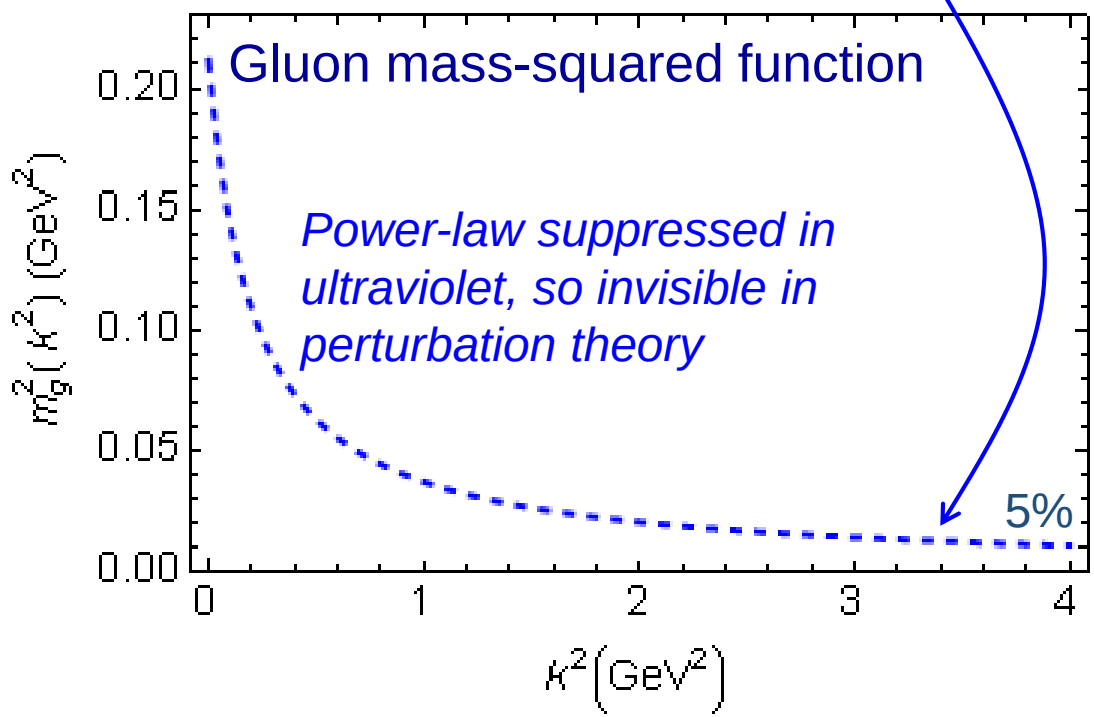
Pion mass is enigma – cannibalistic gluons vs massless Goldstone bosons

$$f_\pi E_\pi(p^2) = B(p^2)$$

$$m_g^2(k^2) = \frac{\mu_g^4}{\mu_g^2 + k^2}$$

Adapted from Craig Roberts:

- The most fundamental expression of Goldstone's Theorem and DCSB in the SM
- Pion exists if, and only if, mass is dynamically generated
- This is why $m_\pi = 0$ in the absence of a Higgs mechanism



What is the impact of this for gluon parton distributions in pions vs nucleons?
One would anticipate a different mass budget for the pion and the proton

Why should you be interested in pions and kaons?

1) The pion, or a meson cloud, explains light-quark asymmetry in the nucleon sea
2) Pions are the Yukawa particles of the nuclear force – but no evidence for excess of nuclear pions or anti-quarks
3) Kaon exchange is similarly related to the ΛN interaction – correlated with the Equation of State and astrophysical observations
4) Mass is enigma – cannibalistic gluons vs massless Goldstone bosons

Why should you be interested in pions and kaons?

Protons, neutrons, pions and kaons are the main building blocks of nuclear matter

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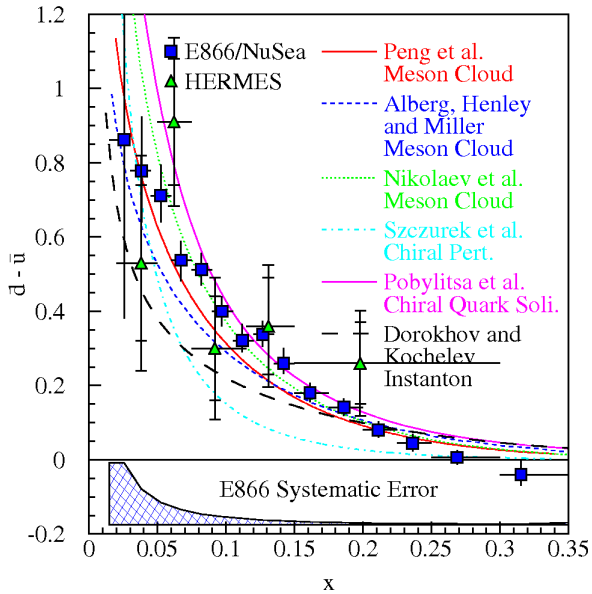
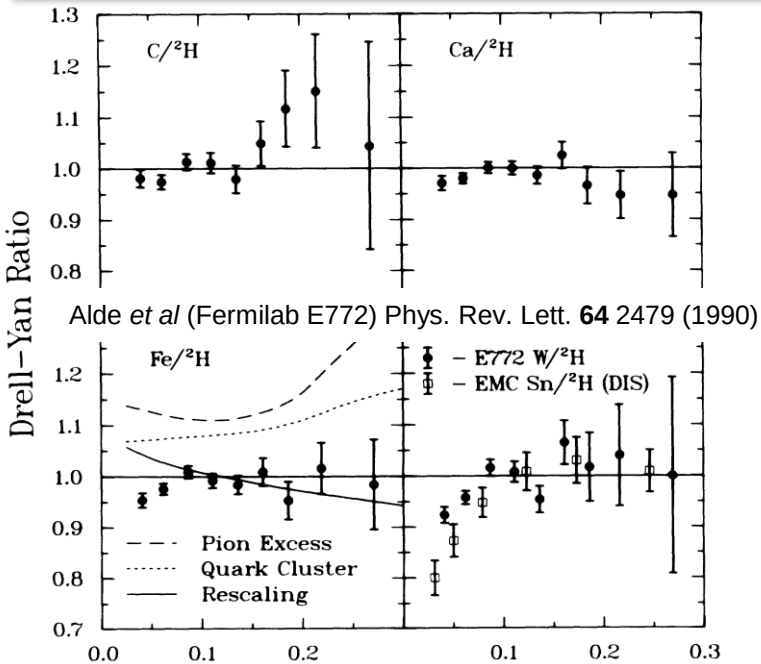
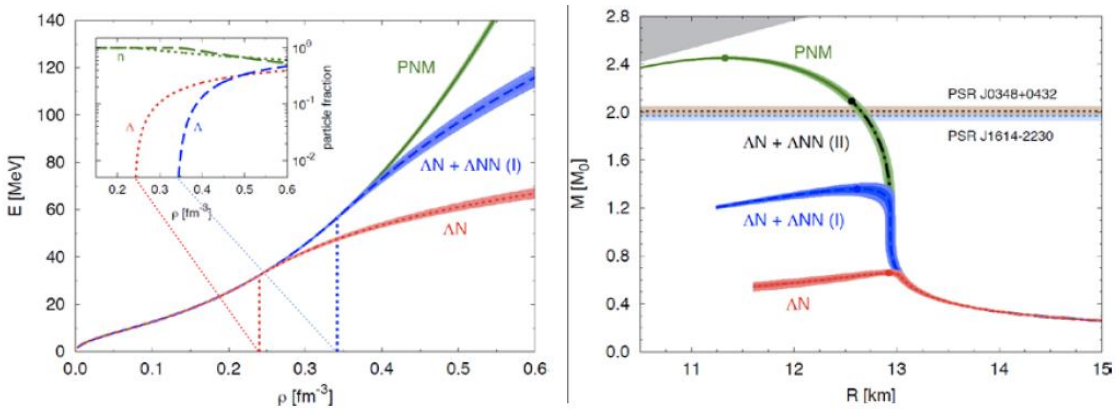




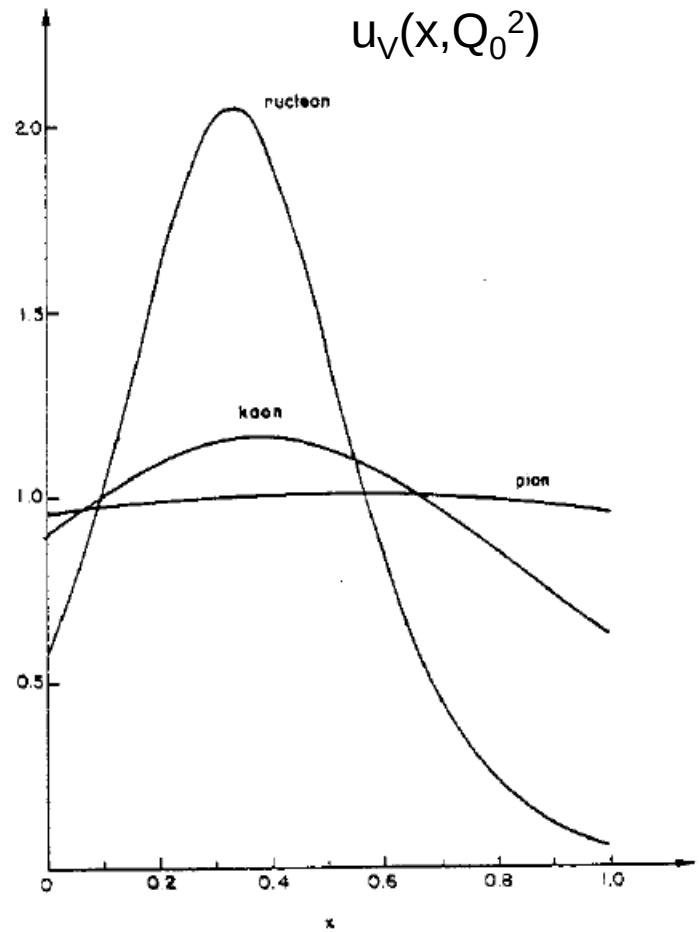
Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

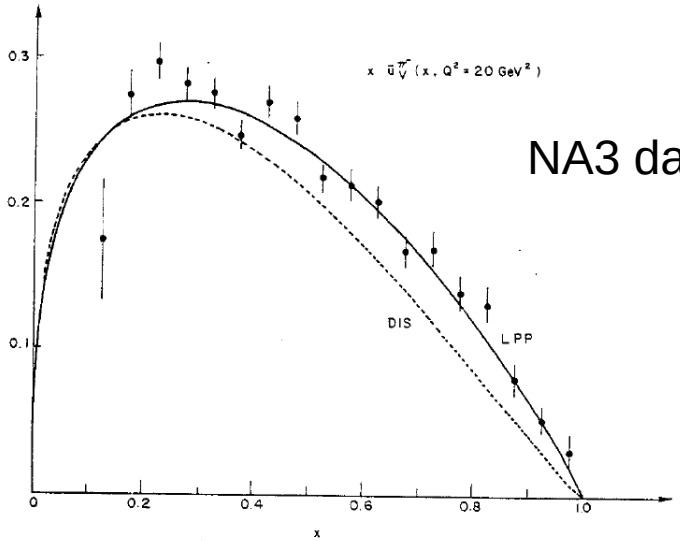


At some level an old story…

A model for nucleon, pion and kaon structure functions
F. Martin, CERN-TH 2845 (1980)

$u_V(x,Q_0^2)$

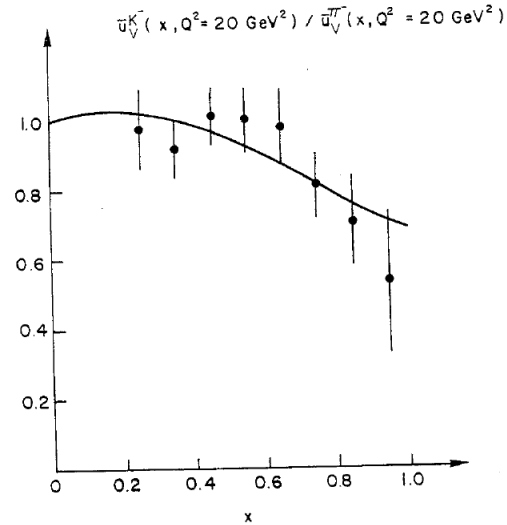




NA3 data

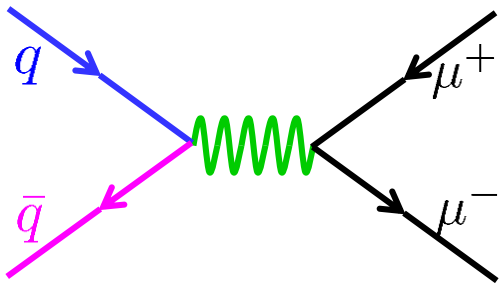
Predictions based on non-relativistic model with valence quarks only →

1) pion/kaon differs from proton: 2q vs. 3q system
2) kaon differs from pion as it owns one heavy quark



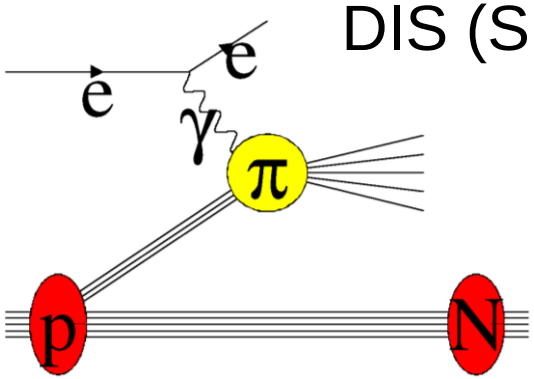
World Data on pion structure function F_2^π

Pion Drell-Yan

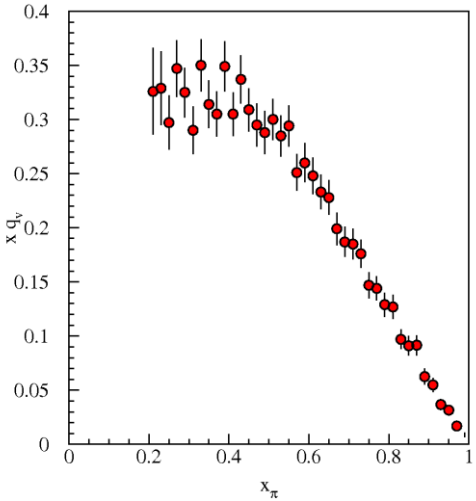


Data much more limited…

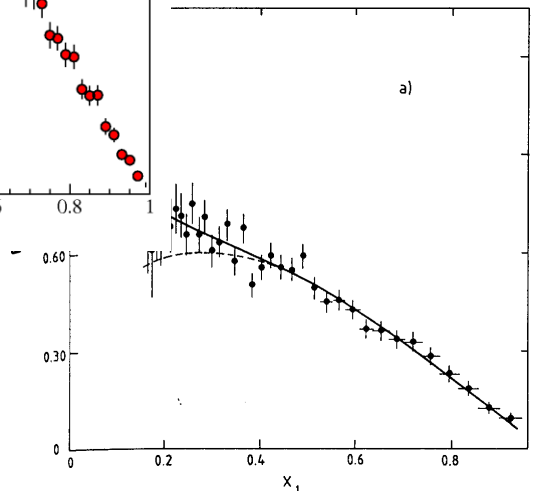
DIS (Sullivan Process)

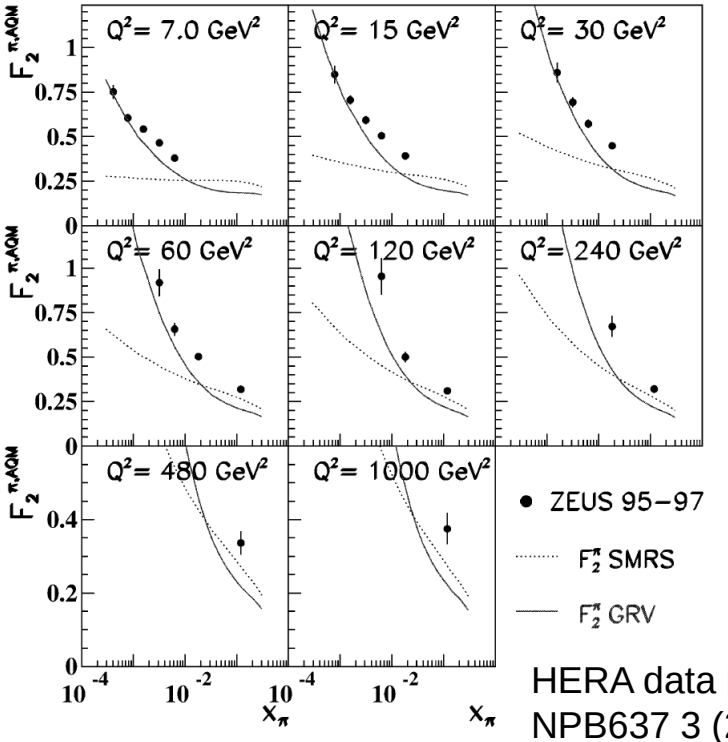


FNAL E615



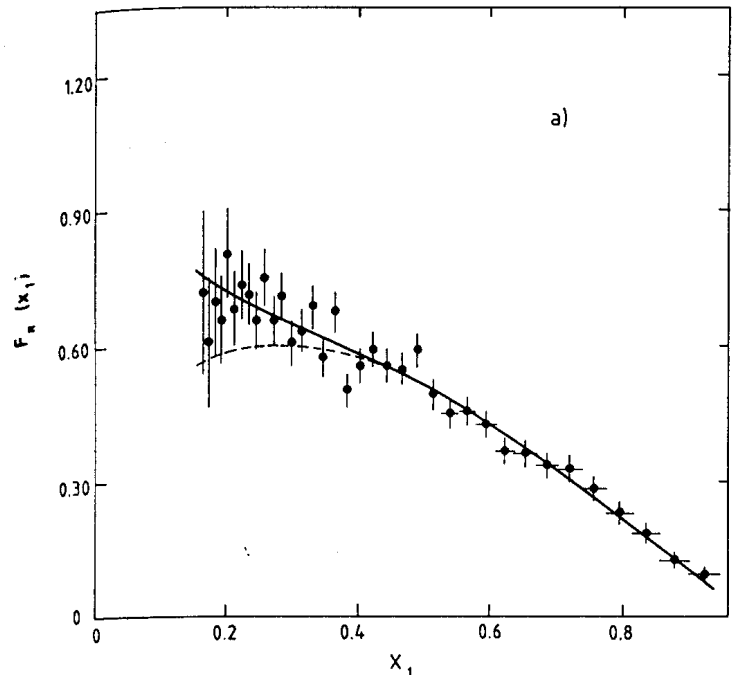
CERN NA3



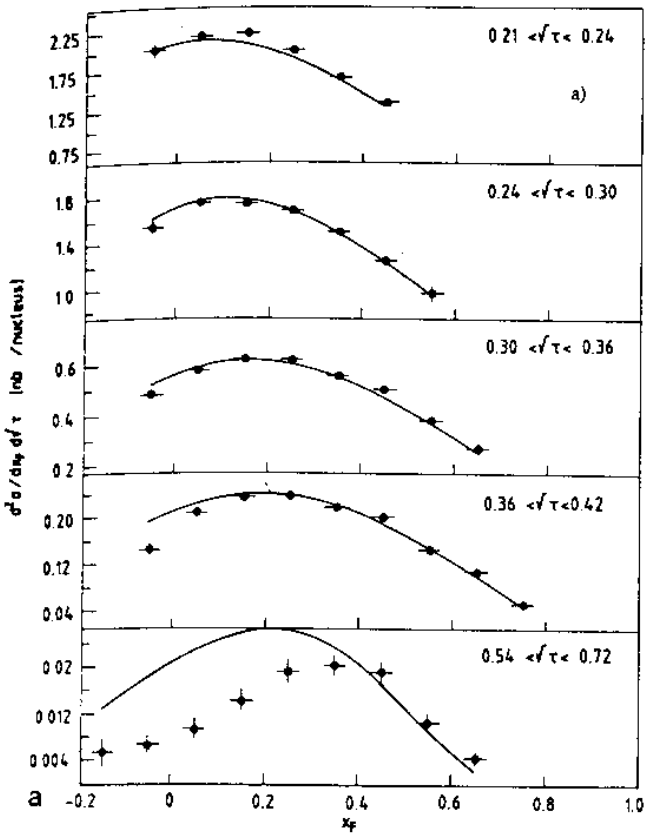


HERA data [ZEUS, NPB637 3 (2002)]

Pion Drell-Yan Data: CERN NA3 ($\pi^{+/-}$) NA10 (π^-)



NA3 200 GeV π^- data (also have 150 and 180 GeV π^- and 200 GeV π^+ data). *Can determine pion sea*!



NA10 194 GeV π^- data

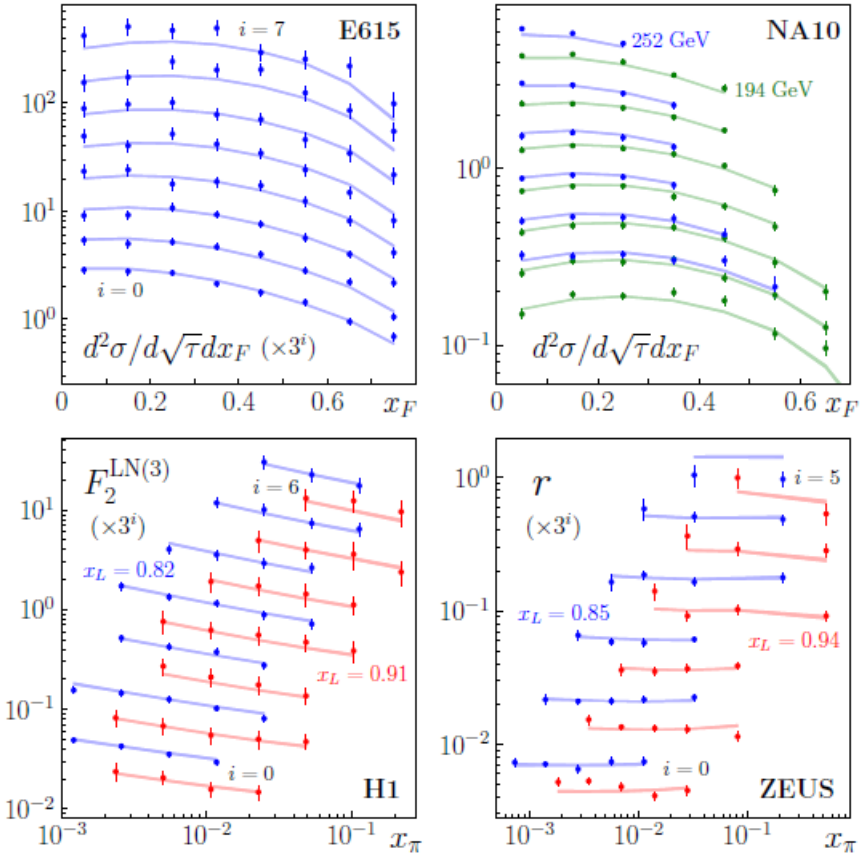
$$Q_\pi^{\text{sea}} \equiv \int_0^1 x q_\pi^{\text{sea}}(x) dx = 0.01$$

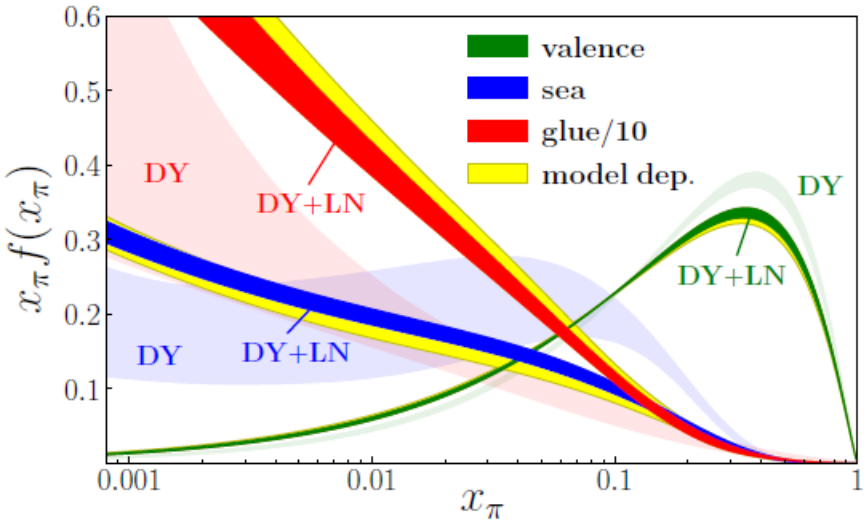
quark sea in pion is small – few %

First Monte Carlo global analysis of pion pdfs

arXiv:1804.01965v1 Barry, Sato, Melnitchouk and Ji

From combined Leading-Neutron and Drell-Yan analysis

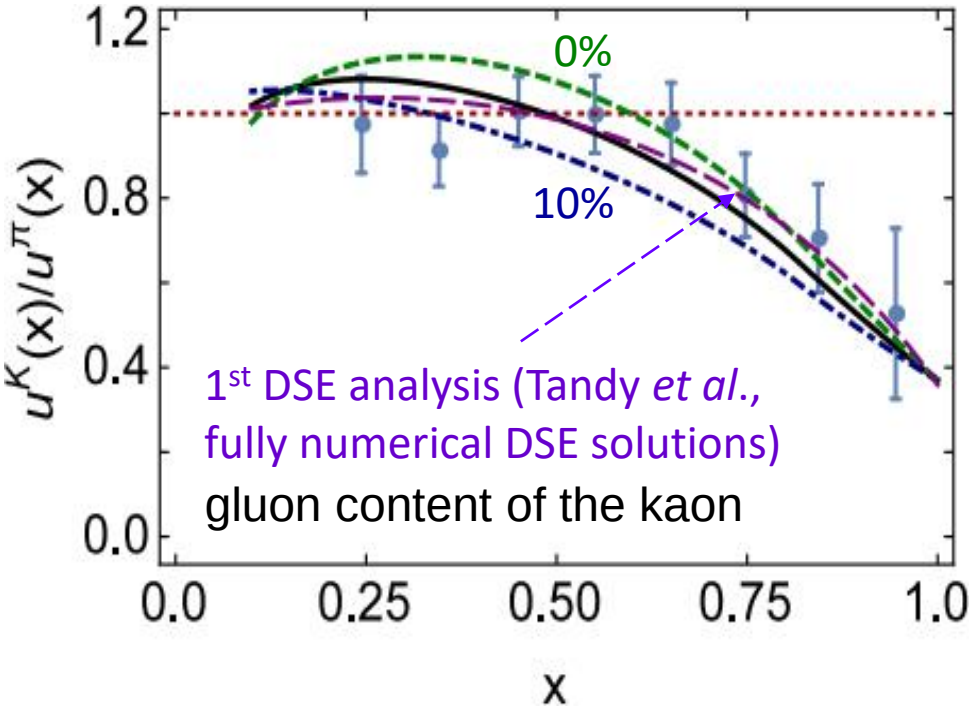




Kaon structure functions – gluon pdfs

Based on Lattice QCD calculations and DSE calculations:

- Valence quarks carry some 52% of the pion's momentum at the light front, at the scale used for Lattice QCD calculations, or ~65% at the perturbative hadronic scale
- At the same scale, valence-quarks carry ⅔ of the kaon's light-front momentum, or roughly 95% at the perturbative hadronic scale



Thus, at a given scale, there is far **less glue in the kaon than in the pion**:

- ❑ heavier quarks radiate less readily than lighter quarks
- ❑ heavier quarks radiate softer gluons than do lighter quarks
- ❑ Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- ❑ Momentum conservation communicates these effects to the kaon's u-quark.

quark and gluon pdfs in pions and kaons

- At low x to moderate x, both the quark sea and the gluons are very interesting.
  - Are the sea in pions and kaons the same in magnitude and shape?
  - Is the origin of mass encoded in differences of gluons in pions, kaons and protons, or do they in the end all become universal?

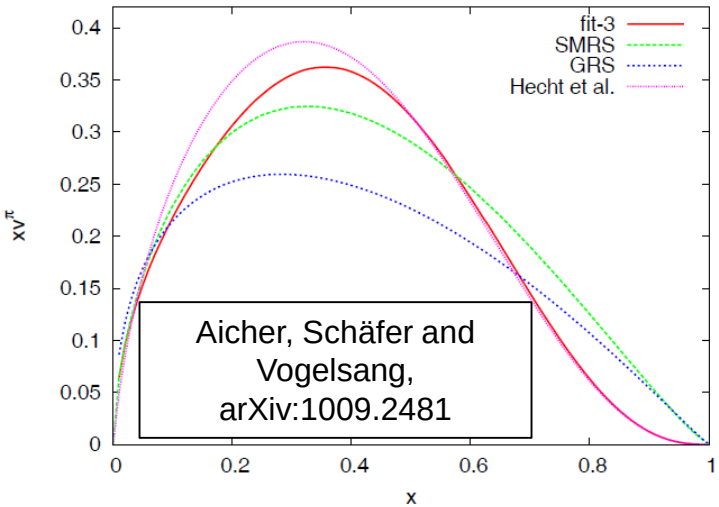
- At moderate x, compare pionic Drell-Yan to DIS from the pion cloud,
  - test of the assumptions used in the extraction of the structure function (and similar assumptions in the pion and kaon form factors).

- At high x, the shapes of valence u quark distributions in pion, kaon and proton are different, and so are their asymptotic x → 1 limits.
  - Some of these effects are due to the comparison of a two- versus three-quark system, and a meson with a heavier s quark embedded versus a lighter quark.
  - However, also effects of gluons come in. To measure this would be fantastic.
  - At high x, a long-standing issue has been the shape of the pion structure function as given by Drell-Yan data versus QCD expectations. However, this may be a solved case based on gluon resummation, and this may be confirmed with 12-GeV Jefferson Lab data. Nonetheless, soft gluon resummation is a sizable effect for Drell Yan, but expected to be a small effect for DIS, so additional data are welcome.

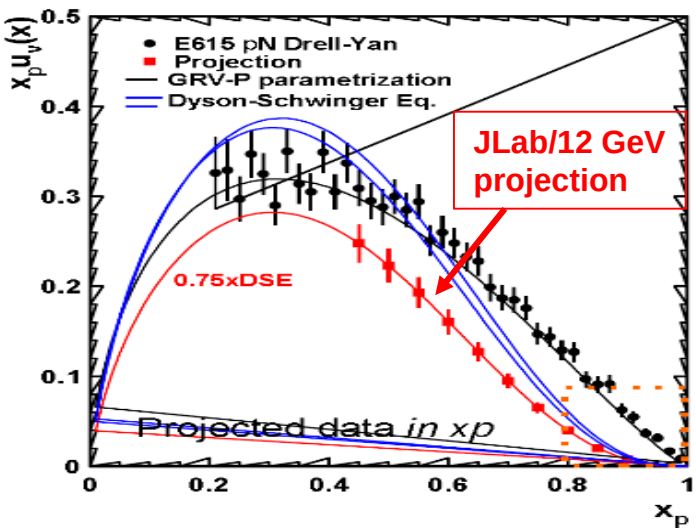
The issue at large-x: solved by resummation?

- Large x_{Bj} structure of the pion is interesting and relevant
  - Pion cloud & antiquark flavor asymmetry
  - Nuclear Binding
  - Simple QCD state & Goldstone Boson
- Even with NLO fit and modern parton distributions, pion did not agree with pQCD and Dyson-Schwinger

Pion SF: $(1-x)^{-1}$ or $(1-x)^{-2}$ dependence at large x?



- **Soft Gluon Resummation saves the day!**
  - JLab 12 GeV experiment can check at high-x
  - Resummation effects less prominent at DIS → EIC's role here may be more consistency checks of assumptions made in extraction

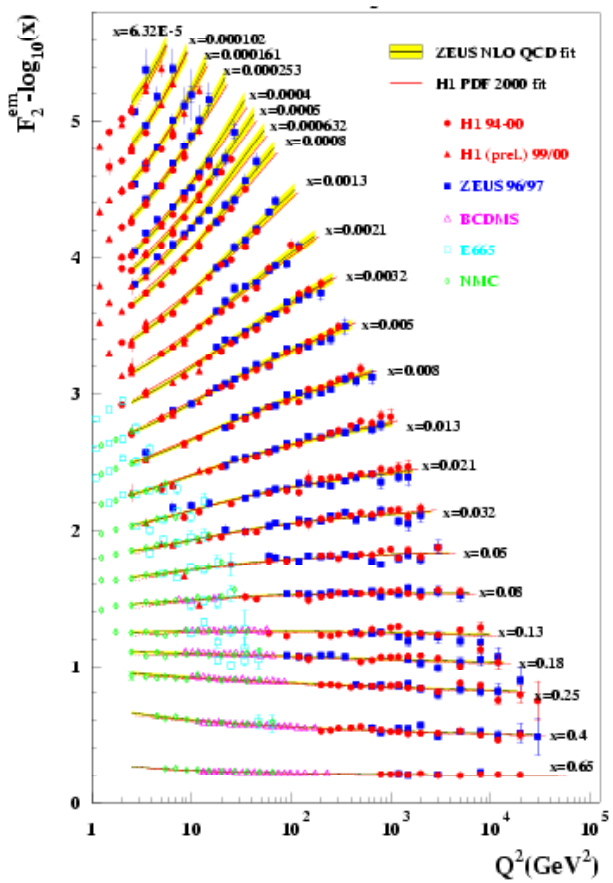


- Additional Bethe-Salpeter predictions to check in π/K Drell-Yan ratio

Landscape for p, π, K structure function after EIC

Proton: much existing from HERA
EIC will add:

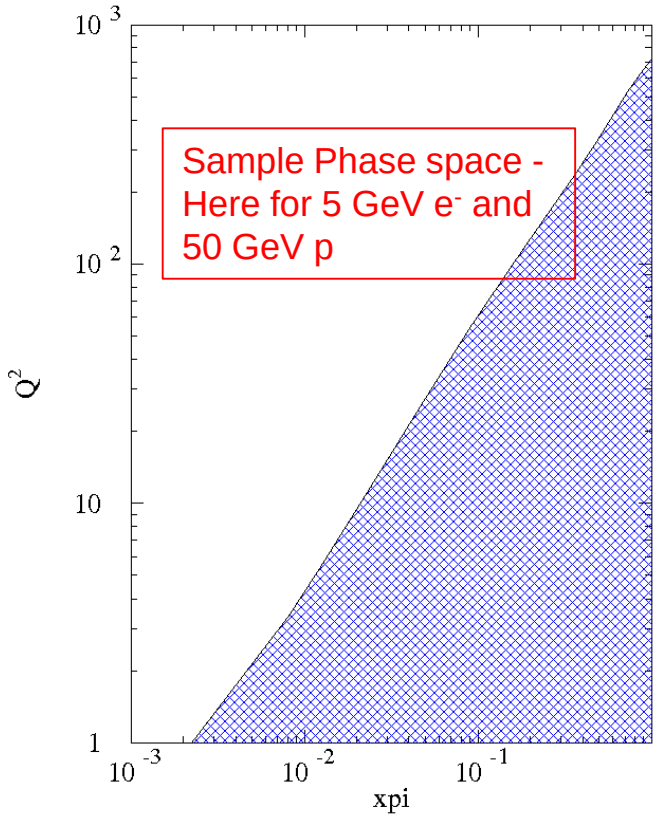
- Better constraints at large-x
- Precise F_2^n neutron SF data



Pion and kaon: only limited data from:

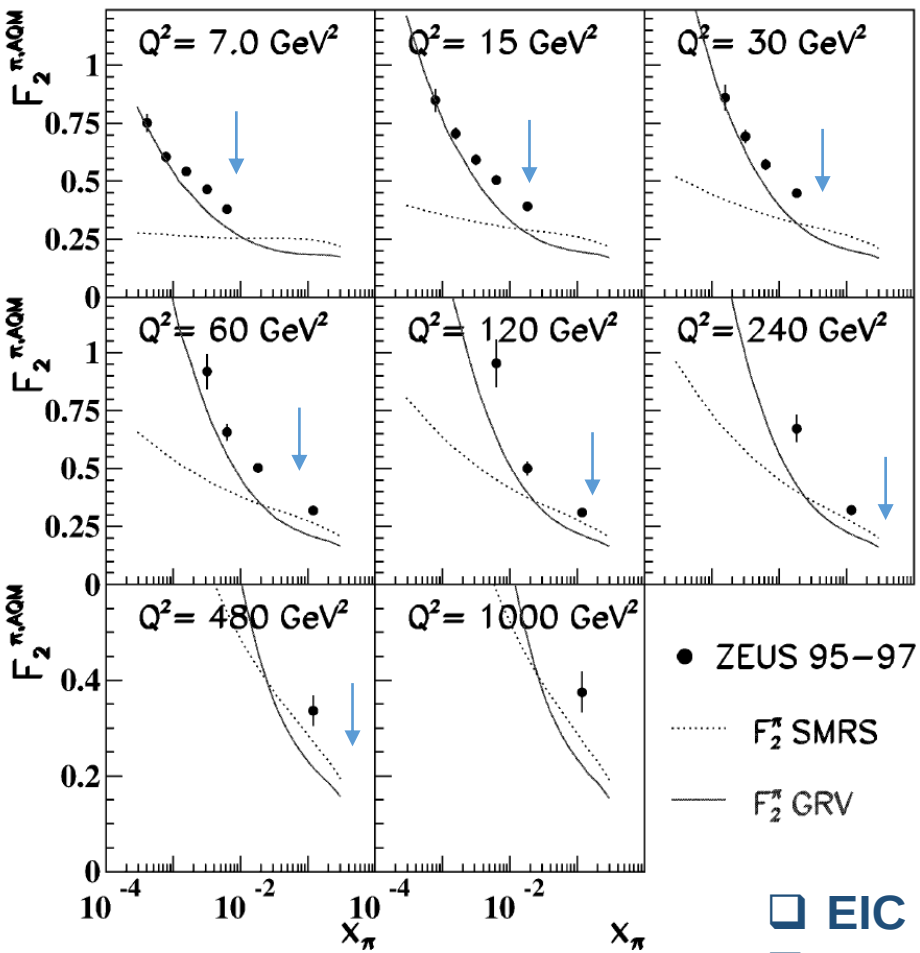
- Pion and kaon Drell-Yan experiments
- Some pion SF data from HERA

EIC will add large (x,Q^2) landscape for both pion and kaon!



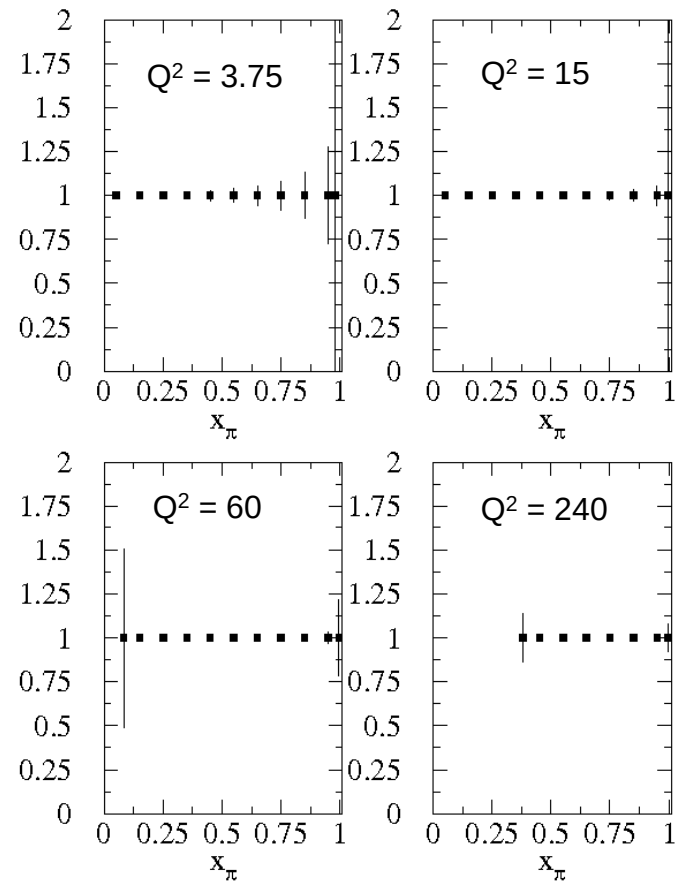
World Data on pion structure function F_2^π

HERA



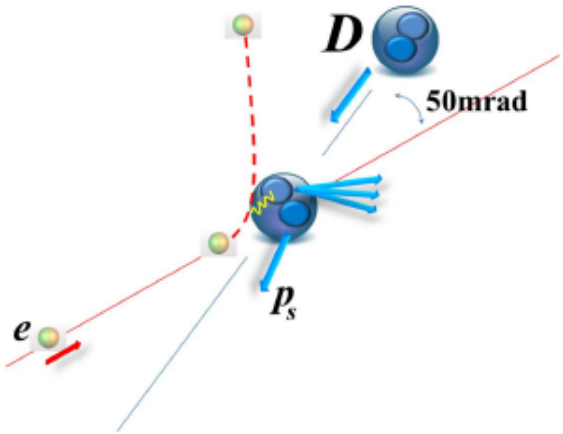
EIC

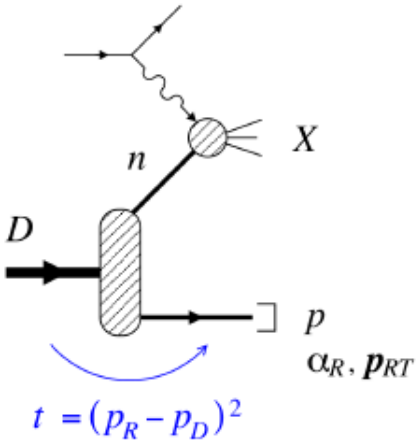
Here example for 5 GeV e⁻ and 50 GeV p

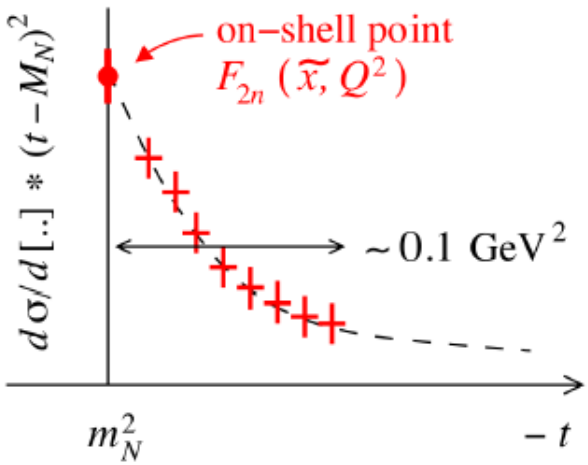


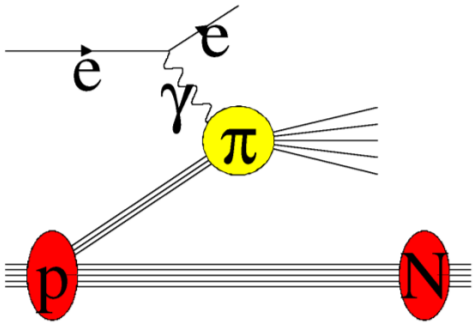
- ❑ **EIC kinematic reach down to a few $x=10^{-3}$**
- ❑ **Lowest x constrained by HERA**

EIC – Versatility is Key







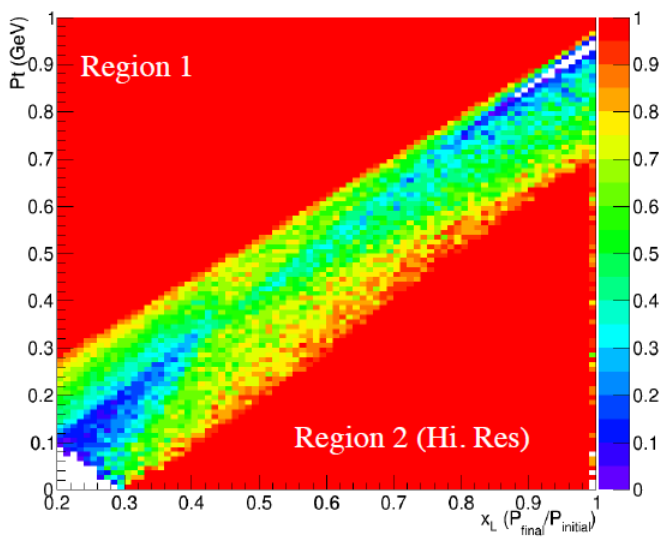


- Obtain F_2^n by tagging spectator proton from e-d, and extrapolate to on-shell neutron to correct for binding and motion effects.
- Obtain F_2^π and F_2^K by Sullivan process and extrapolate the measured t-dependence as compared to DSE-based models.

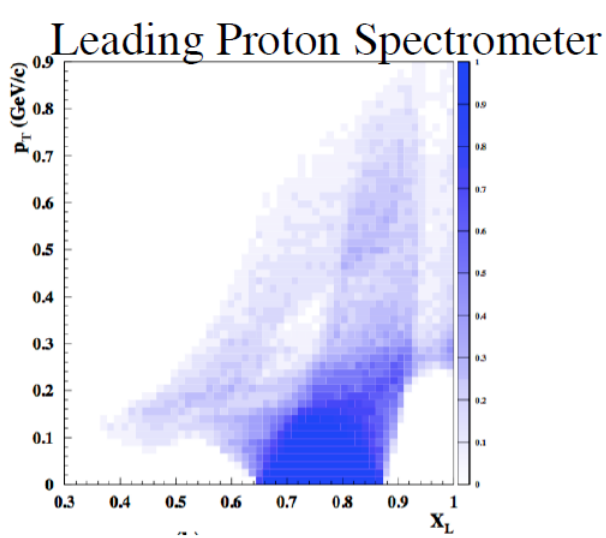
→ **Need excellent detection capabilities, and good resolution in –t**

Full Acceptance for Forward Physics!

Example: acceptance for p' in e + p → e' + p' + X



Zhiwen Zhao (Duke)

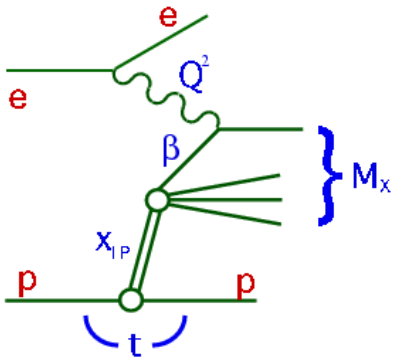


Acceptance in diffractive peak (X_L>~.98)

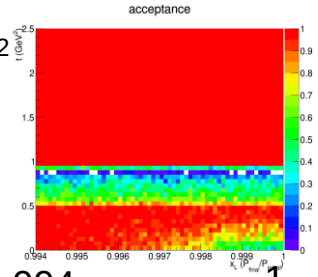
ZEUS: ~2%

JLEIC: ~100% (also covers much higher X_L than ZEUS)

Diffraction



t, GeV^2



Huge gain in acceptance for diffractive physics and forward tagging to measure F_2^n!!!

Towards Kaon Structure Functions

- To determine projected kaon structure function data from pion structure function projections, we scaled the pion to the kaon case with the *coupling constants*

*S. Goloskokov and P. Kroll, Eur.Phys.J. A**47** (2011) 112:*

$g_{\pi NN}$=13.1 $g_{Kp\Lambda}$=-13.3 $g_{Kp\Sigma 0}$=-3.5

(these values can vary depending on what model one uses, so sometimes a range is used, *e.g.*, 13.1-13.5 for $g_{\pi NN}$)

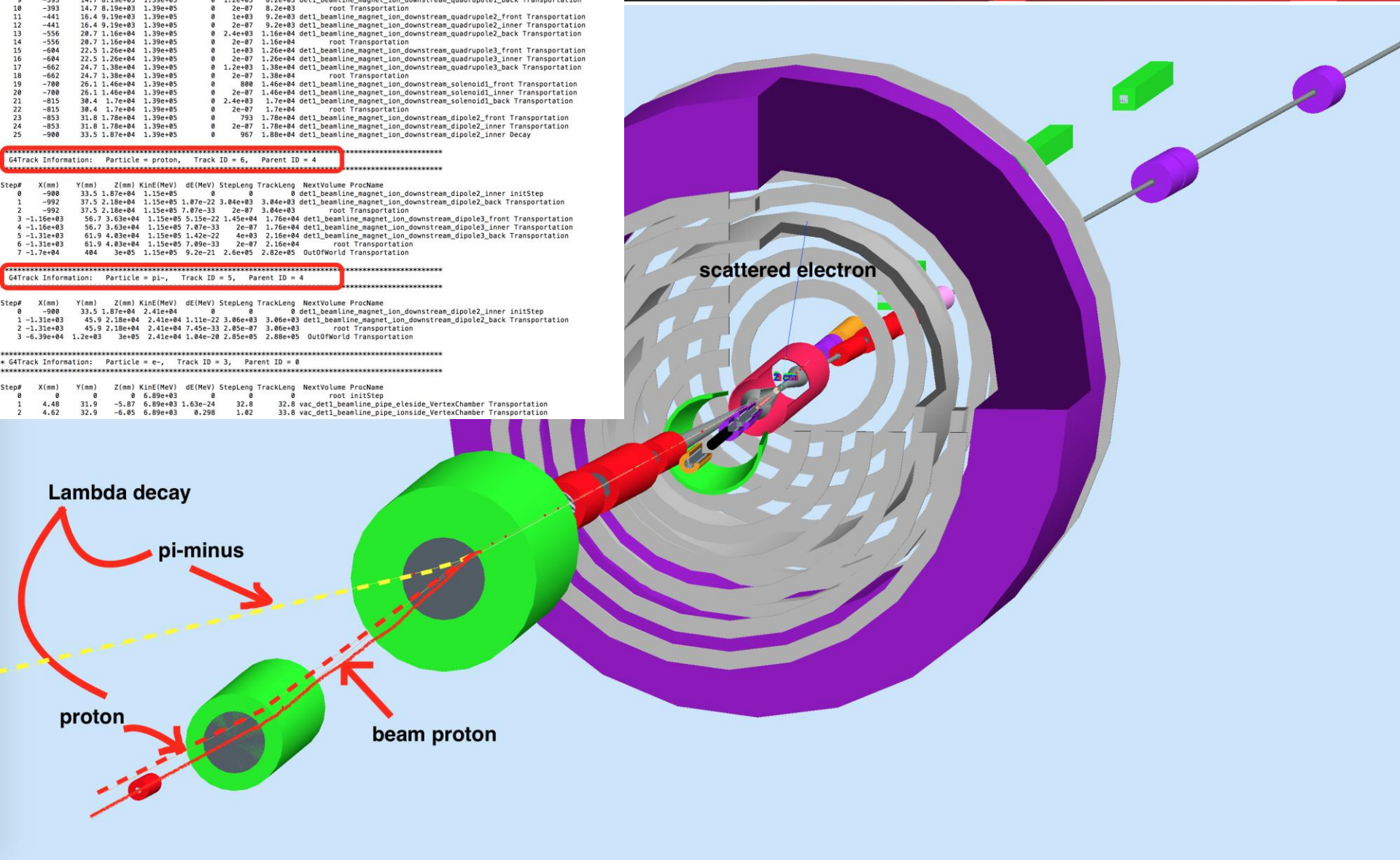
- Good geometric detection efficiencies for n, Λ, Σ detection at low -t

Process	**Forward Particle**	**Geometric Detection Efficiency (at small –t)**
$^1H(e,e'\pi^+)n$	N	> 20%
$^1H(e,e'K^+)\Lambda$	Λ	50%
$^1H(e,e'K^+)\Sigma$	Σ	17%

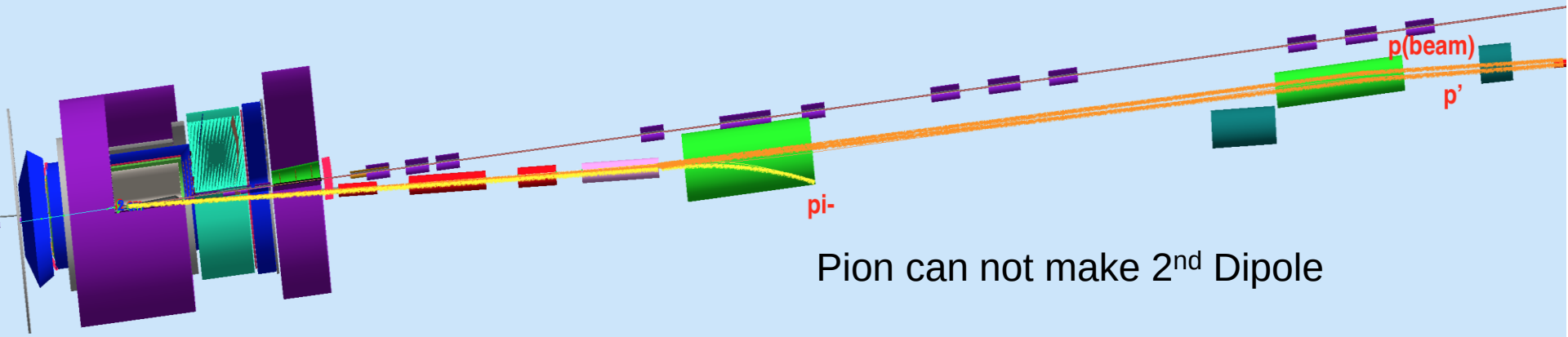
- Folding this together: kaon projected structure function data will be roughly of similar quality as the projected pion structure function data for the small-t geometric forward particle detection acceptances at JLEIC.

Plug event into GEMC: 5x100 GeV2, e/p beams

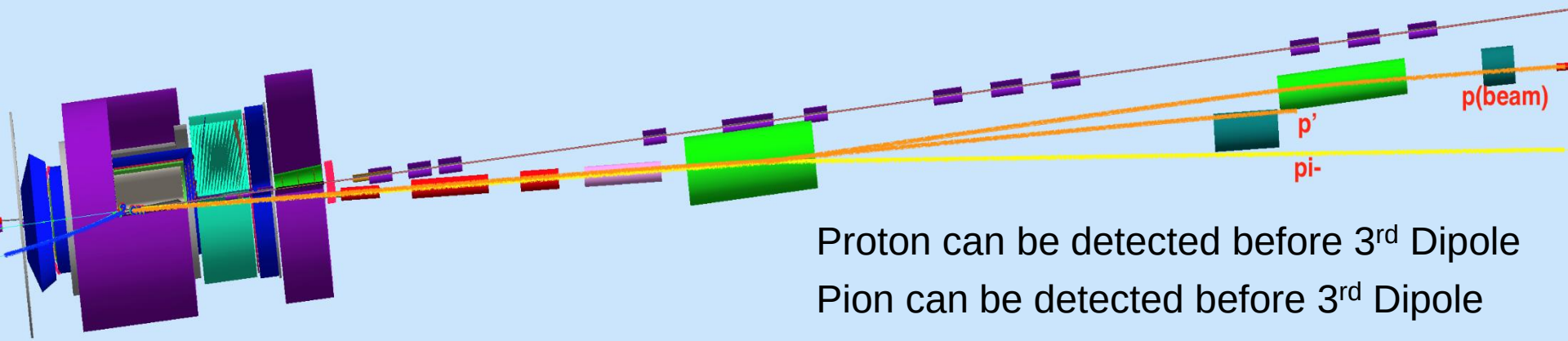
```
*******************************************************************************
G4Track Information:   Particle = lambda,   Track ID = 4,   Parent ID = 0
*******************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0        0        0        0  1.39e+05        0        0         0        root initStep
    1      -98     3.65 2.04e+03  1.39e+05        0 2.04e+03  2.04e+03 vac_det1_beamline_pipe_ionside_IonExtranceAperture Transportation
    2    -98.1     3.66 2.04e+03  1.39e+05        0        2  2.05e+03        root Transportation
    3     -240     8.94 4.99e+03  1.39e+05        0 2.95e+03     5e+03 det1_beamline_magnet_ion_downstream_dipole1_front Transportation
    4     -240     8.94 4.99e+03  1.39e+05        0    2e-07     5e+03 det1_beamline_magnet_ion_downstream_dipole1_inner Transportation
    5     -312     11.6 6.49e+03  1.39e+05        0  1.5e+03   6.5e+03 det1_beamline_magnet_ion_downstream_dipole1_back Transportation
    6     -312     11.6 6.49e+03  1.39e+05        0    2e-07   6.5e+03        root Transportation
    7     -336     12.5 6.99e+03  1.39e+05        0      500     7e+03 det1_beamline_magnet_ion_downstream_quadrupole1_front Transportation
    8     -336     12.5 6.99e+03  1.39e+05        0    2e-07     7e+03 det1_beamline_magnet_ion_downstream_quadrupole1_inner Transportation
    9     -393     14.7 8.19e+03  1.39e+05        0  1.2e+03   8.2e+03 det1_beamline_magnet_ion_downstream_quadrupole1_back Transportation
   10     -393     14.7 8.19e+03  1.39e+05        0    2e-07   8.2e+03        root Transportation
   11     -441     16.4 9.19e+03  1.39e+05        0    1e+03   9.2e+03 det1_beamline_magnet_ion_downstream_quadrupole2_front Transportation
   12     -441     16.4 9.19e+03  1.39e+05        0    2e-07   9.2e+03 det1_beamline_magnet_ion_downstream_quadrupole2_inner Transportation
   13     -556     20.7 1.16e+04  1.39e+05        0  2.4e+03  1.16e+04 det1_beamline_magnet_ion_downstream_quadrupole2_back Transportation
   14     -556     20.7 1.16e+04  1.39e+05        0    2e-07  1.16e+04        root Transportation
   15     -604     22.5 1.26e+04  1.39e+05        0    1e+03  1.26e+04 det1_beamline_magnet_ion_downstream_quadrupole3_front Transportation
   16     -604     22.5 1.26e+04  1.39e+05        0    2e-07  1.26e+04 det1_beamline_magnet_ion_downstream_quadrupole3_inner Transportation
   17     -662     24.7 1.38e+04  1.39e+05        0  1.2e+03  1.38e+04 det1_beamline_magnet_ion_downstream_quadrupole3_back Transportation
   18     -662     24.7 1.38e+04  1.39e+05        0    2e-07  1.38e+04        root Transportation
   19     -700     26.1 1.46e+04  1.39e+05        0      800  1.46e+04 det1_beamline_magnet_ion_downstream_solenoid1_front Transportation
   20     -700     26.1 1.46e+04  1.39e+05        0    2e-07  1.46e+04 det1_beamline_magnet_ion_downstream_solenoid1_inner Transportation
   21     -815     30.4  1.7e+04  1.39e+05        0  2.4e+03   1.7e+04 det1_beamline_magnet_ion_downstream_solenoid1_back Transportation
   22     -815     30.4  1.7e+04  1.39e+05        0    2e-07   1.7e+04        root Transportation
   23     -853     31.8 1.78e+04  1.39e+05        0      793  1.78e+04 det1_beamline_magnet_ion_downstream_dipole2_front Transportation
   24     -853     31.8 1.78e+04  1.39e+05        0    2e-07  1.78e+04 det1_beamline_magnet_ion_downstream_dipole2_inner Transportation
   25     -900     33.5 1.87e+04  1.39e+05        0      967  1.88e+04 det1_beamline_magnet_ion_downstream_dipole2_inner Decay

*******************************************************************************
G4Track Information:   Particle = proton,   Track ID = 6,   Parent ID = 4
*******************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0     -900     33.5 1.87e+04  1.15e+05        0        0         0 det1_beamline_magnet_ion_downstream_dipole2_inner initStep
    1     -992     37.5 2.18e+04  1.15e+05 1.07e-22 3.04e+03  3.04e+03 det1_beamline_magnet_ion_downstream_dipole2_back Transportation
    2     -992     37.5 2.18e+04  1.15e+05 7.07e-33    2e-07  3.04e+03        root Transportation
    3 -1.16e+03     56.7 3.63e+04  1.15e+05 5.15e-22 1.45e+04  1.76e+04 det1_beamline_magnet_ion_downstream_dipole3_front Transportation
    4 -1.16e+03     56.7 3.63e+04  1.15e+05 7.07e-33    2e-07  1.76e+04 det1_beamline_magnet_ion_downstream_dipole3_inner Transportation
    5 -1.31e+03     61.9 4.03e+04  1.15e+05 1.42e-22    4e+03  2.16e+04 det1_beamline_magnet_ion_downstream_dipole3_back Transportation
    6 -1.31e+03     61.9 4.03e+04  1.15e+05 7.09e-33    2e-07  2.16e+04       root Transportation
    7 -1.7e+04      404    3e+05  1.15e+05  9.2e-21  2.6e+05  2.82e+05  OutOfWorld Transportation

*******************************************************************************
G4Track Information:   Particle = pi-,   Track ID = 5,   Parent ID = 4
*******************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0     -900     33.5 1.87e+04  2.41e+04        0        0         0 det1_beamline_magnet_ion_downstream_dipole2_inner initStep
    1 -1.31e+03     45.9 2.18e+04  2.41e+04 1.11e-22 3.06e+03  3.06e+03 det1_beamline_magnet_ion_downstream_dipole2_back Transportation
    2 -1.31e+03     45.9 2.18e+04  2.41e+04 7.45e-33 2.05e-07  3.06e+03        root Transportation
    3 -6.39e+04  1.2e+03    3e+05  2.41e+04 1.04e-20 2.85e+05  2.88e+05  OutOfWorld Transportation

*******************************************************************************
* G4Track Information:   Particle = e-,   Track ID = 3,   Parent ID = 0
*******************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0        0        0        0  6.89e+03        0        0         0        root initStep
    1     4.48     31.9    -5.87  6.89e+03 1.63e-24     32.8      32.8 vac_det1_beamline_pipe_eleside_VertexChamber Transportation
    2     4.62     32.9    -6.05  6.89e+03    0.298     1.02      33.8 vac_det1_beamline_pipe_ionside_VertexChamber Transportation
```



Detection of $^{1}H(e,e'K^{+})\Lambda$, Λ decay to p + π^{-}



Pion can not make 2nd Dipole



Proton can be detected before 3rd Dipole

Pion can be detected before 3rd Dipole

Slide from K. Park

Sullivan process off-shellness corrections

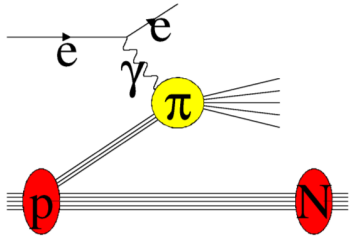
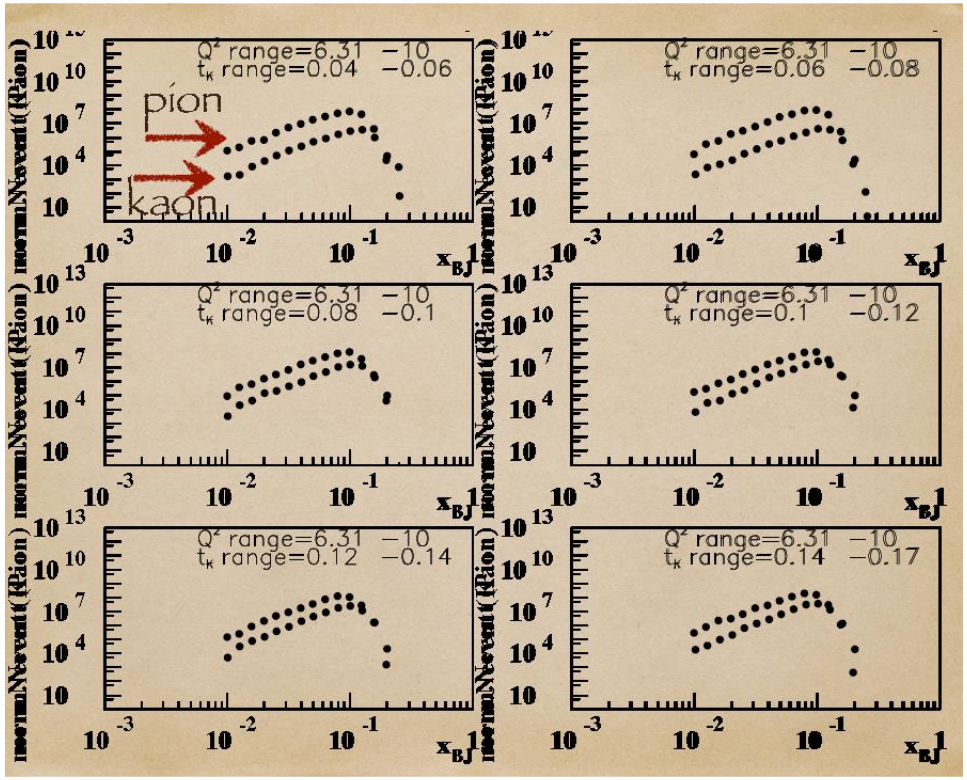


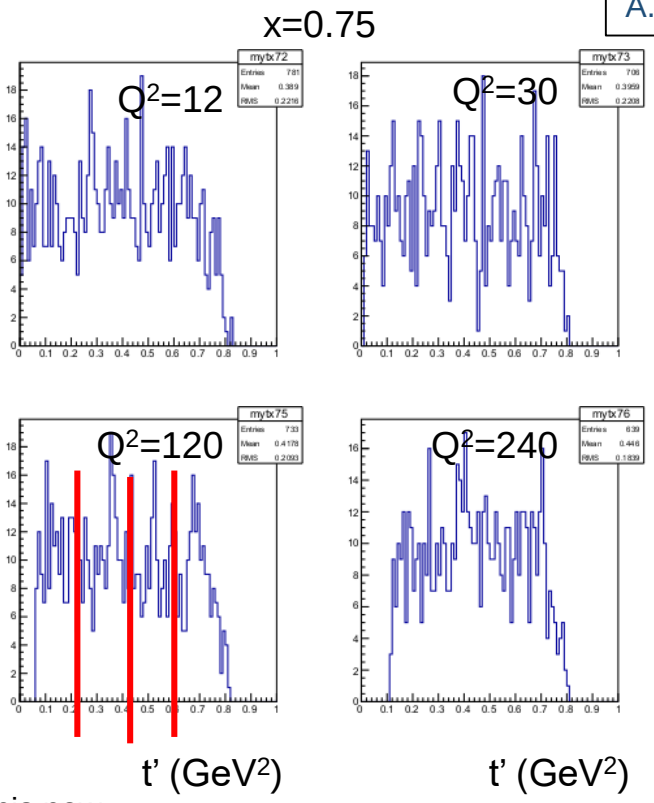
Figure from K. Park

- ❑ Like nuclear binding corrections (neutron in deuterium)
- ❑ Bin in t to determine the off-shellness correction
- ❑ Compare with Pionic/kaonic D-Y

EIC kinematic reach down to x=0.01 or a bit below

T. Horn,
R. Trotta,
A. Vargas

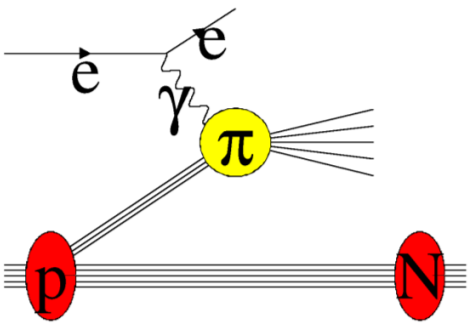




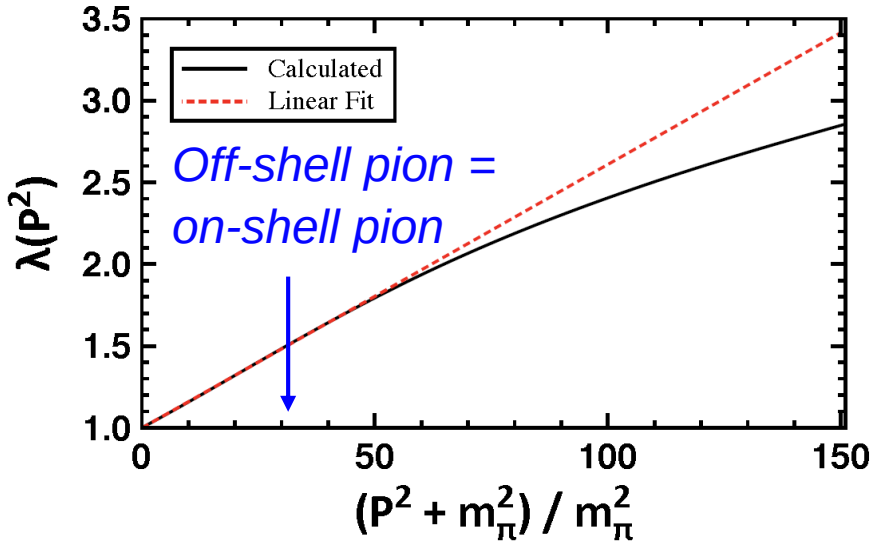
These are from initial trials and preliminary – we are redoing this now

Off-shellness considerations

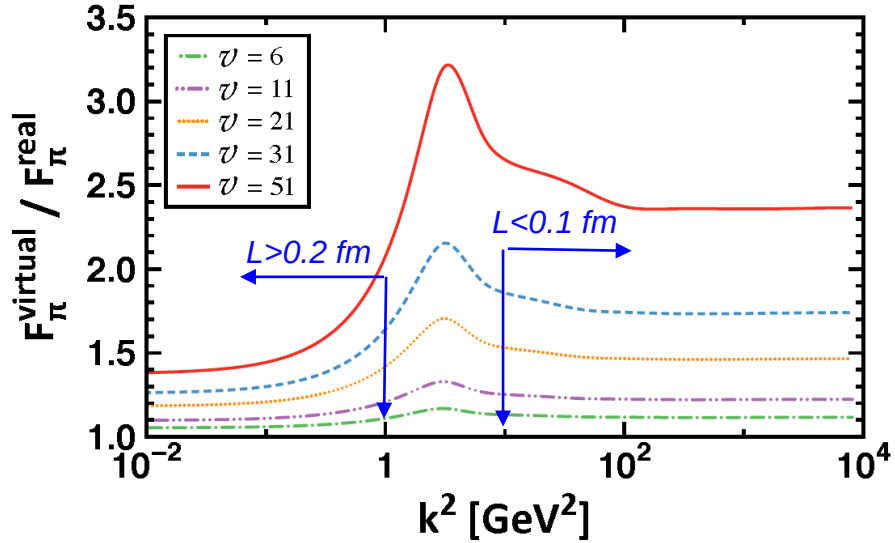
S-X Qin, C.Chen, C. Mezrag, C.D. Roberts, arXiv:1702.06100 (2017)



In the Sullivan process, the mesons in the nucleon cloud are virtual (off-shell) particles



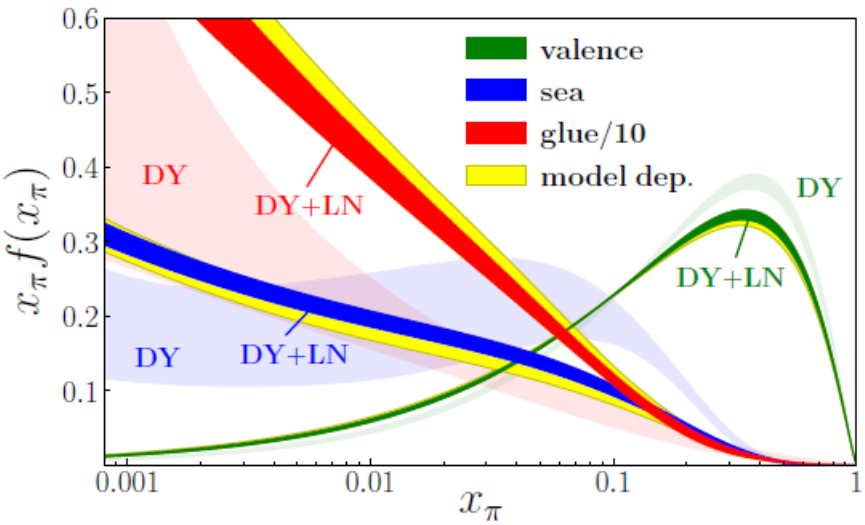
- Recent calculations estimate the effect in the BSE/DSE framework – as long as $\lambda(\nu)$ is linear in ν the meson pole dominates
  - Within the linearity domain, alterations of the meson internal structure can be analyzed through the amplitude ratio
- *Off-shell meson = On-shell meson* for t<0.6 GeV^2 (ν =31) for pions and t<0.9 GeV^2(ν_s~3) for kaons



This means that pion and kaon structure functions can be accessed through the Sullivan process

Web-based Self-Serve Pion PDF

From combined Leading-Neutron and Drell-Yan analysis



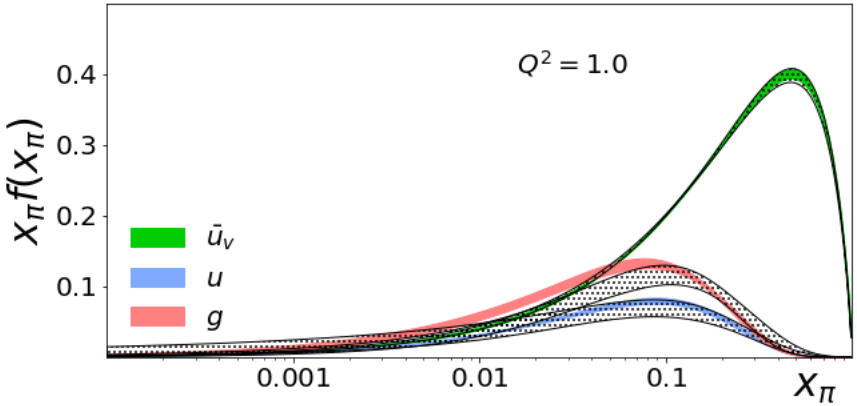
Web-based self-server performs a combined Leading-Neutron, Drell-Yan and new data analysis

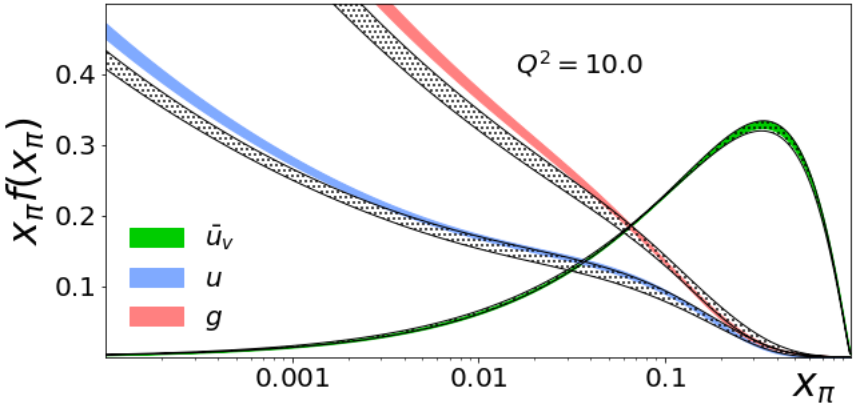
N. Sato

Github: https://github.com/JeffersonLab/jamfitter

Jupyter notebook: https://jupyter.jlab.org/

Present Projections

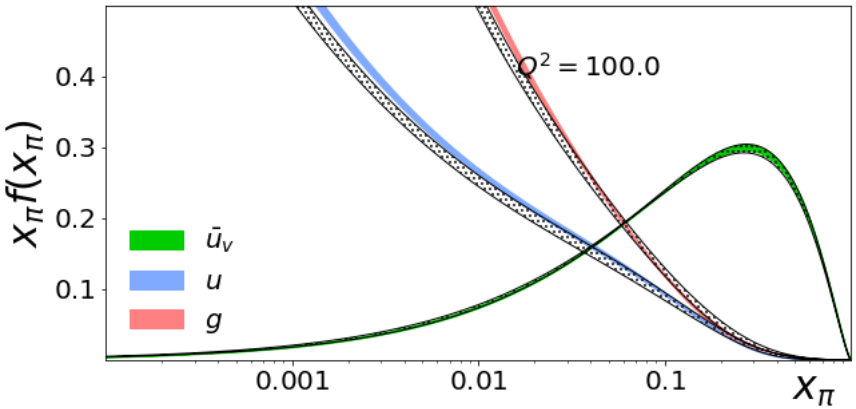




Work ongoing:

- Why did the curves shift?
- The pion D-Y data, even if not many, already do constrain the curves surprisingly well – due to the various sum rules?
- Curves to improve with the EIC projections, especially for kaon as will have similar-quality data.

Precision gluon constraints of pion and kaon pdfs are possible.

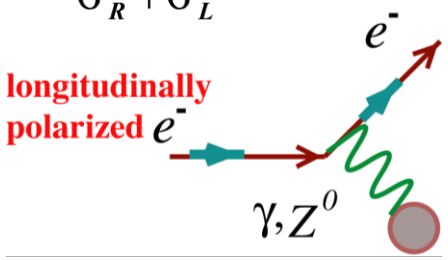


T. Horn

Disentangling the Flavor-Dependence

1) Using the Neutral-Current Parity-violating asymmetry A_{PV}

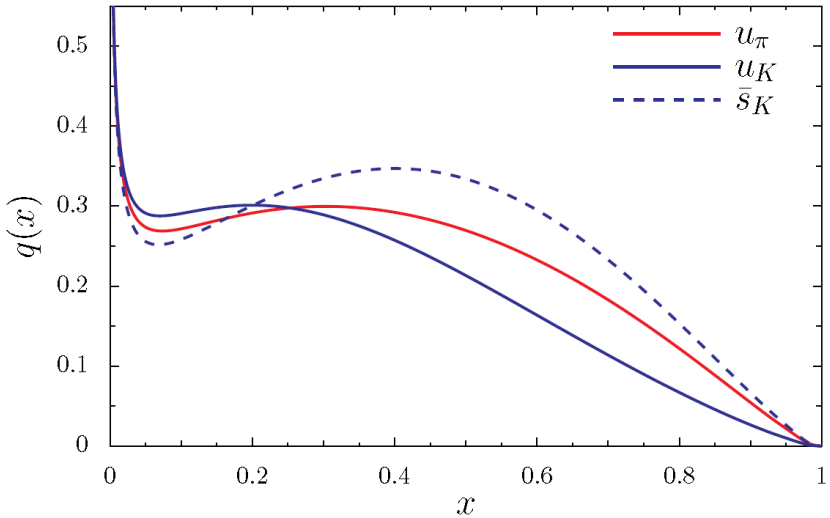
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



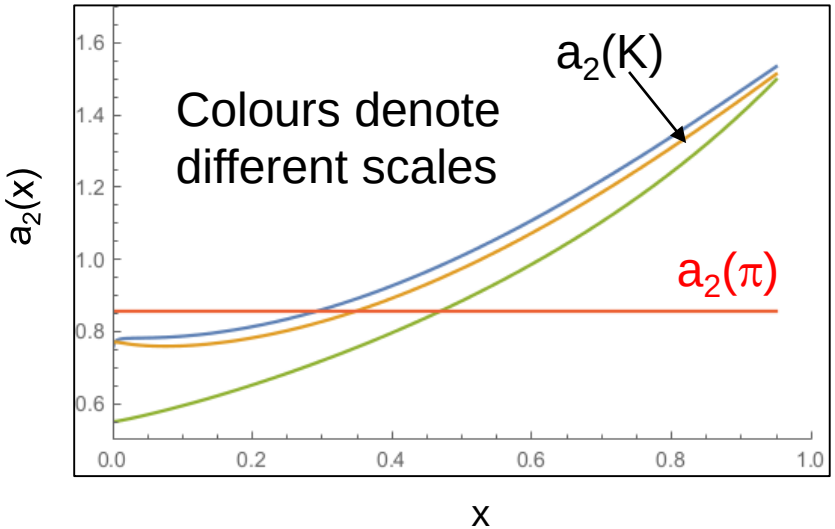
$$a_{2\pi}(x) = \frac{2\sum_q e_q g_V^q (q+\bar{q})}{\sum_q e_q^2 (q+\bar{q})} \simeq \frac{6\,u_\pi^+ + 3\,d_\pi^+}{4\,u_\pi^+ + d_\pi^+} - 4\sin^2\theta_W$$

$$a_{2K}(x) = \frac{2\sum_q e_q g_V^q (q+\bar{q})}{\sum_q e_q^2 (q+\bar{q})} \simeq \frac{6\,u_K^+ + 3\,s_K^+}{4\,u_K^+ + s_K^+} - 4\sin^2\theta_W$$

Figure from I. Cloet



Calculation by C.D. Roberts et al.



DSE-based parton distributions in pion and kaon

a_2 picks up different behavior of u and sbar. Flavor decomposition in kaon possible?

Pion and Kaon Structure at EIC Workshops

https://www.jlab.org/conferences/pieic18/index.html

PIEIC2018

Workshop on Pion and Kaon Structure at an Electron - Ion Collider
May 24-25, 2018
The Catholic University of America
Washington, D.C.
Circular
This workshop will explore opportunities provided by the Electron - Ion Collider to study the quark and gluon structure of the pion and kaon. It follows and will stake stock of the progress **since the earlier June 1-2, 2017 workshop at Argonne National Lab**: http://www.phy.anl.gov/theory/pieic2017

Organizing Committee
Ian Cloet - ANL
Tanja Horn – CUA
Cynthia Keppel – JLab
Craig Roberts - ANL

Summary

- Nucleons and the lightest mesons - pions and 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.
- Is the origin of mass encoded in differences of gluons in pions, kaons and nucleons (at non-asymptotic Q^2)?
- Some effects may be trivial – the heavier-mass quark in the kaon “robs” more of the momentum, and the structure functions of pions, kaons and protons at large-x should be different, but confirming these would provide textbook material.
- Utilizing electroweak processes, be it through parity-violating processes or neutral vs charged-current interactions, some flavor dependence appears achievable.

Active research ongoing - more at the upcoming meeting at CUA:
PIEIC2018 https://www.jlab.org/conferences/pieic18/index.html

BACKUP

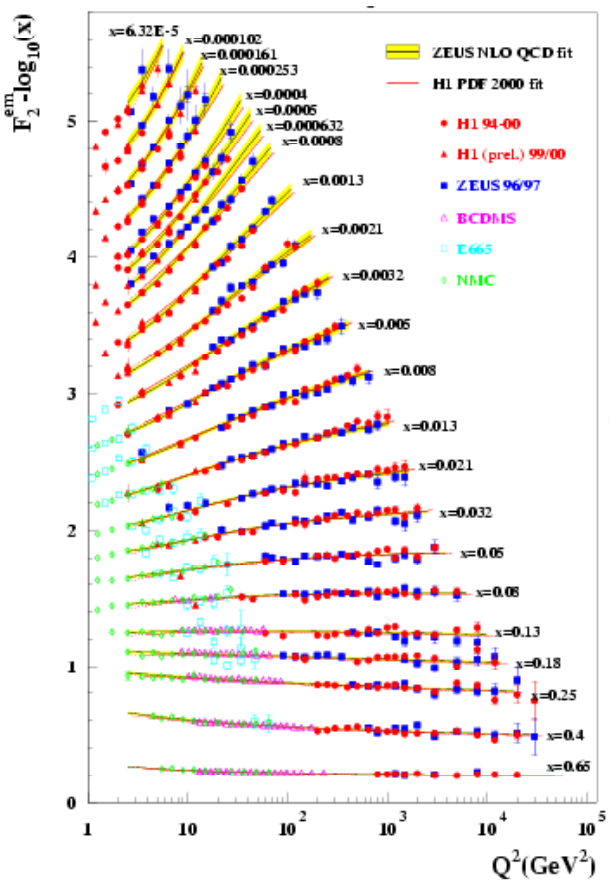
Pion and Kaon Structure Functions at EIC

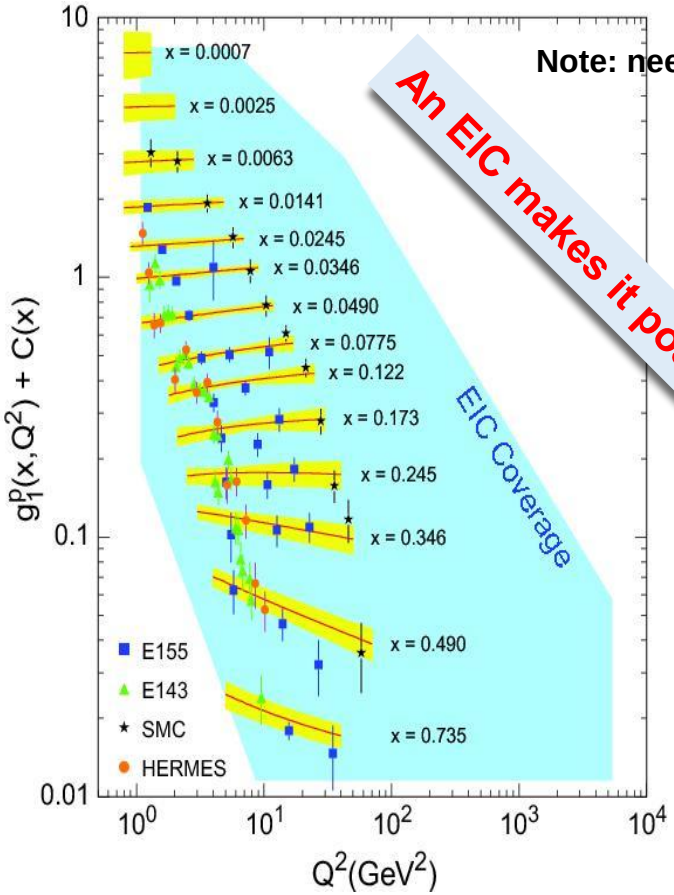
Pions and kaons are, along with protons and neutrons, the main building blocks of nuclear matter. The distribution of the fundamental constituents, the quarks and gluons, is expected to be different in pions, kaons, and nucleons. However, experimental data are sparse. As a result, there has been persistent doubt about the behavior of the pion's valence quark structure function at large Bjorken-x and virtually nothing is known about the contribution of gluons. The Electron-Ion Collider with an acceptance optimized for forward physics could provide access to structure functions over a larger kinematic region. This would allow for measurements testing if the origin of mass is encoded in the differences of gluons in pions, kaons, and nucleons, and measurements that could serve as a test of assumptions used in the extraction of structure functions. Measurements at an EIC would also allow to explore the effect of gluons at high x. In this talk we will discuss the prospects of such measurements.

World Data on F_2^p World Data on g_1^p World Data on h_1^p

Similar for F_2^n

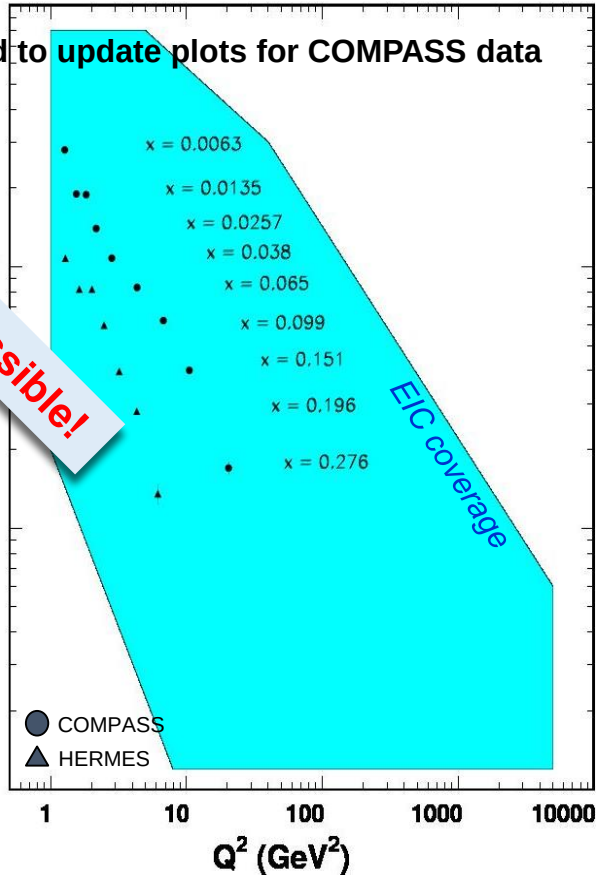
Similar for g_2^p, g_2^n (and b_1^d) $F_{UT}^{\sin(\phi_h+\phi_s)}(x,Q^2) + C(x) \propto h_1$





An EIC makes it possible!

Note: need to update plots for COMPASS data



momentum

spin

transverse spin ~ angular momentum

Calculable Limits for Parton Distributions

Calculable limits for ratios of PDFs at x = 1, same as predictive power of x → 1 limits for spin-averaged and spin-dependent proton structure functions (asymmetries)

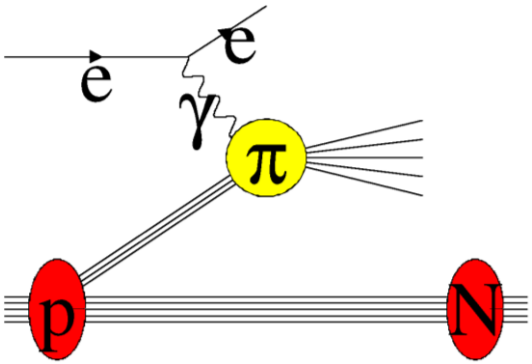
$$\left.\frac{u_V^K(x)}{u_V^\pi(x)}\right|_{x\to 1} = 0.37\,, \qquad \left.\frac{u_V^\pi(x)}{\bar{s}_V^K(x)}\right|_{x\to 1} = 0.29$$

On the other hand, inexorable growth in both pions' and kaons' gluon and sea-quark content at asymptotic Q^2 should only be driven by pQCD splitting mechanisms. Hence, also calculable limits for ratios of PDFs at x = 0, *e.g.*,

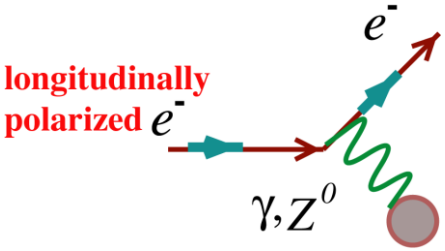
$$\lim_{x\to 0} \frac{u^K(x;\zeta)}{u^\pi(x;\zeta)} \xrightarrow{\Lambda_{\rm QCD}/\zeta \simeq 0} 1$$

The inexorable growth in both pions' and kaons' gluon content at asymptotic Q^2 brings connection to gluon saturation.

Electroweak Pion and Kaon Structure Functions



- The Sullivan Process will be sensitive to u and dbar for the pion, and likewise u and sbar for the kaon.
- Logarithmic scaling violations may give insight on the role of gluon pdfs
- Could we make further progress towards a flavor decomposition?



1) Using the Neutral-Current Parity-violating asymmetry A_{PV}

2) Determine xF_3 through neutral/charged-current interactions

$$F_2^{\gamma} = \sum_q e_q^2\, x\,(q+\bar{q})$$

In the parton model:

$$F_2^{\gamma Z} = 2\sum_q e_q\, g_V^q\, x\,(q+\bar{q})$$

Use different couplings/weights

$$x\,F_3^{\gamma Z} = 2\sum_q e_q\, g_A^q\, x\,(q-\bar{q})$$

Use isovector response

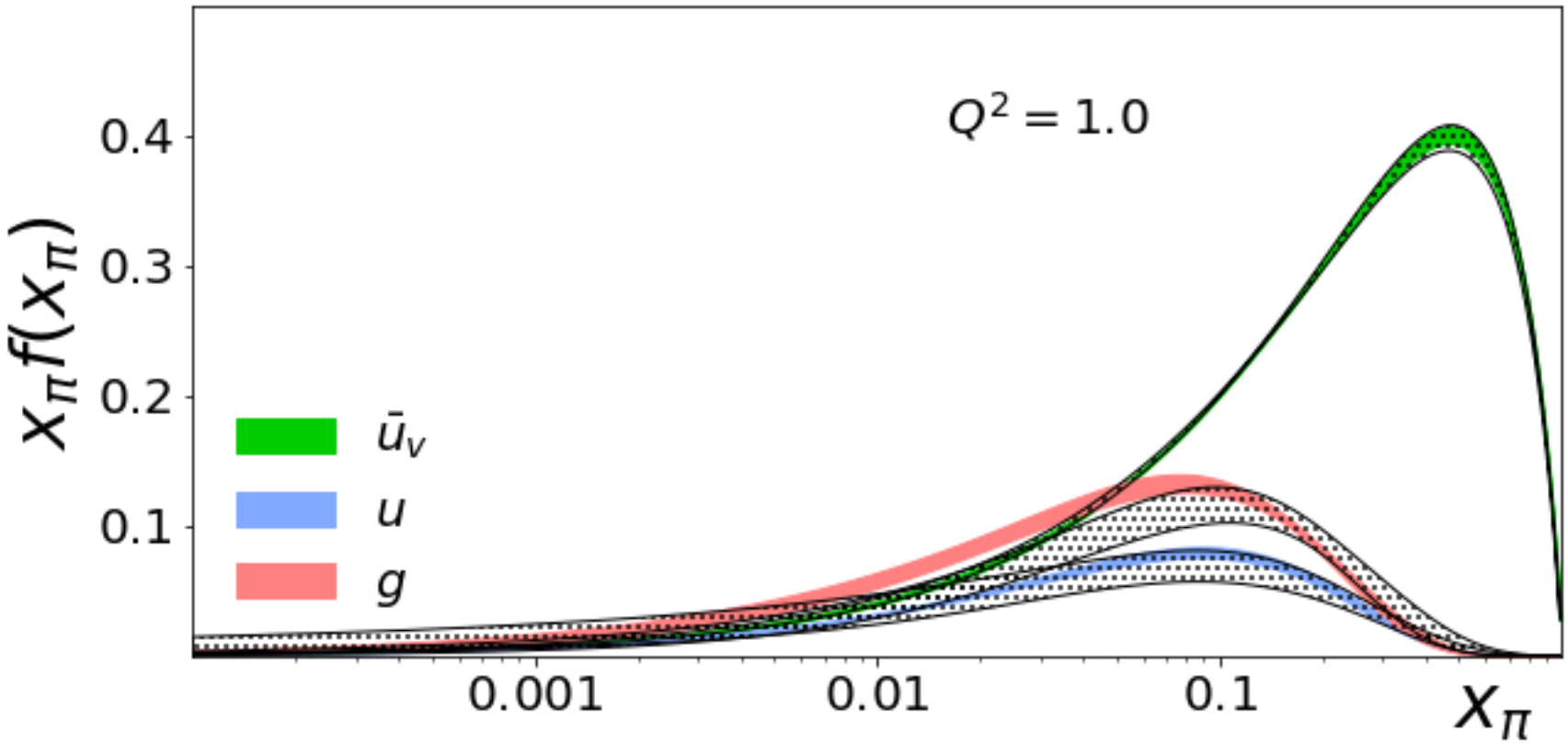
$$F_2^{W^+} = 2\,x\,(\bar{u}+d+s+\bar{c}) \quad F_3^{W^+} = 2\,(-\bar{u}+d+s-\bar{c}) \quad F_2^{W^-} = 2\,x\,(u+\bar{d}+\bar{s}+c) \quad F_3^{W^-} = 2\,(u-\bar{d}-\bar{s}+c)$$

3) Or charged-current through comparison of electron versus positron interactions

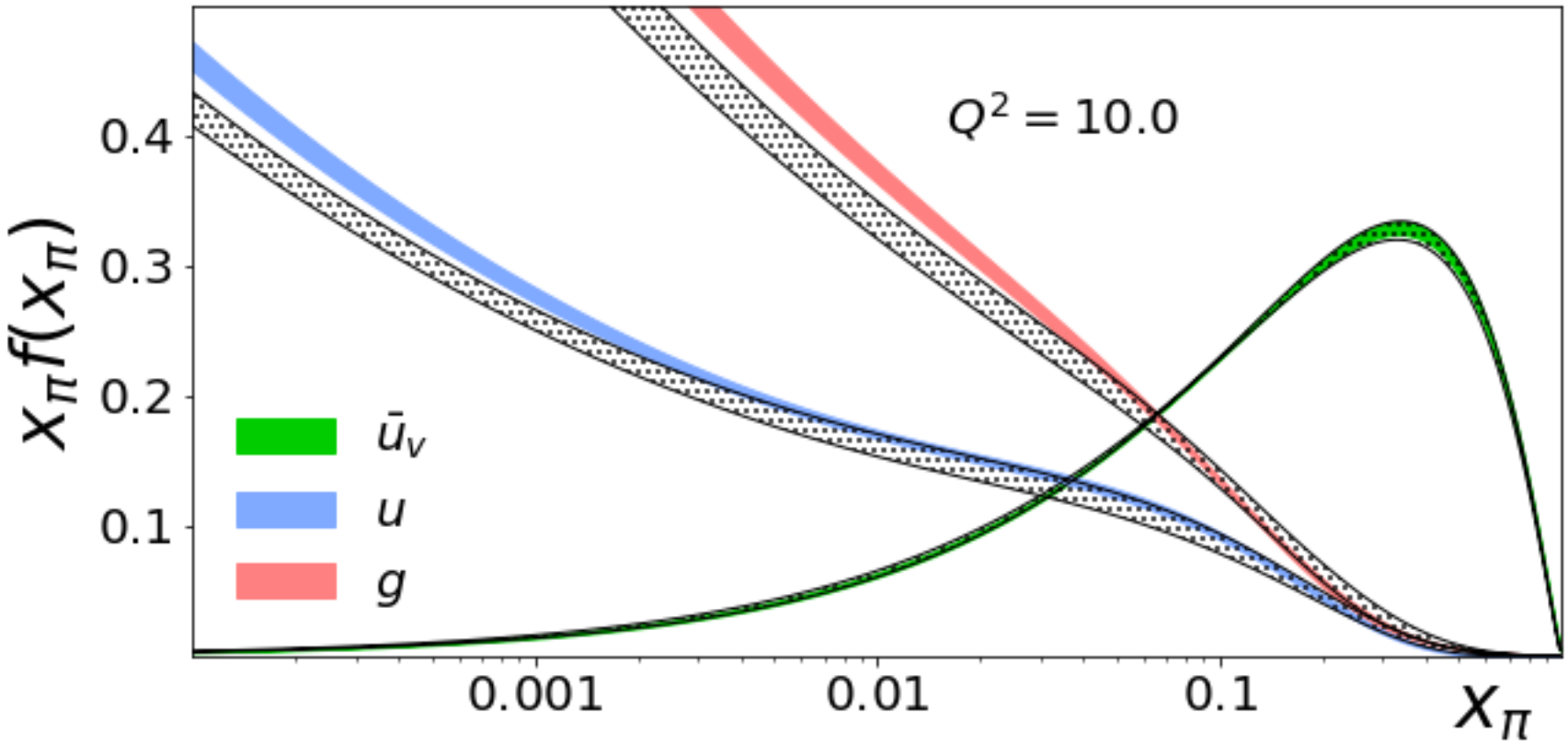
$$A = \frac{\sigma_R^{CC,e^+} \pm \sigma_L^{CC,e^-}}{\sigma_R^{NC} + \sigma_L^{NC}}$$

$$A = \frac{G_F^2\, Q^4}{32\,\pi^2\,\alpha_e^2}\left[\frac{F_2^{W^+} \pm F_2^{W^-}}{F_2^{\gamma}} - \frac{1-(1-y)^2}{1+(1-y)^2}\,\frac{xF_3^{W^+} \mp xF_3^{W^-}}{F_2^{\gamma}}\right]$$

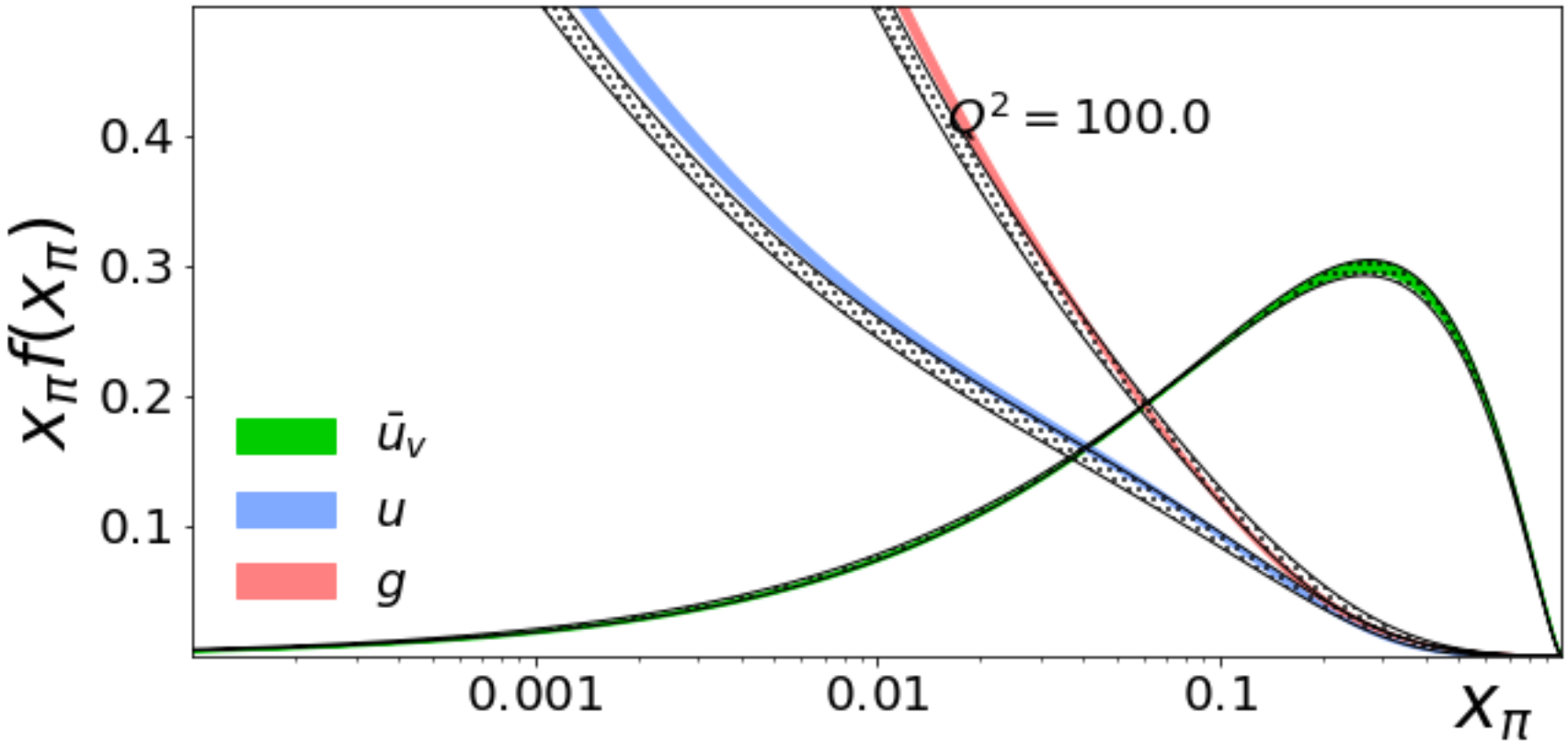
Present Projections



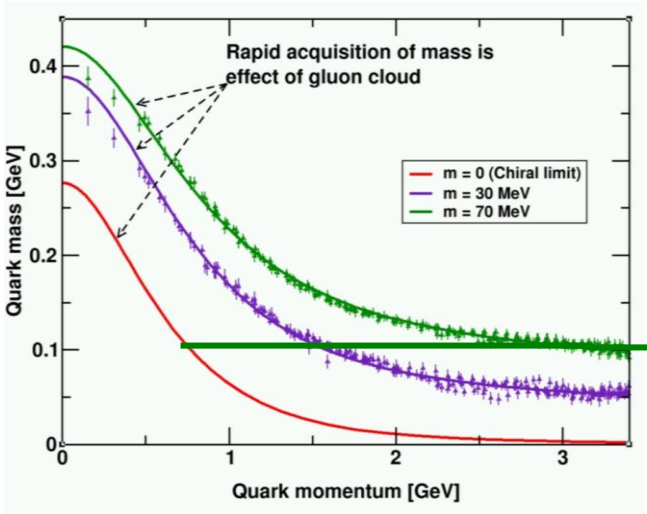
Present Projections

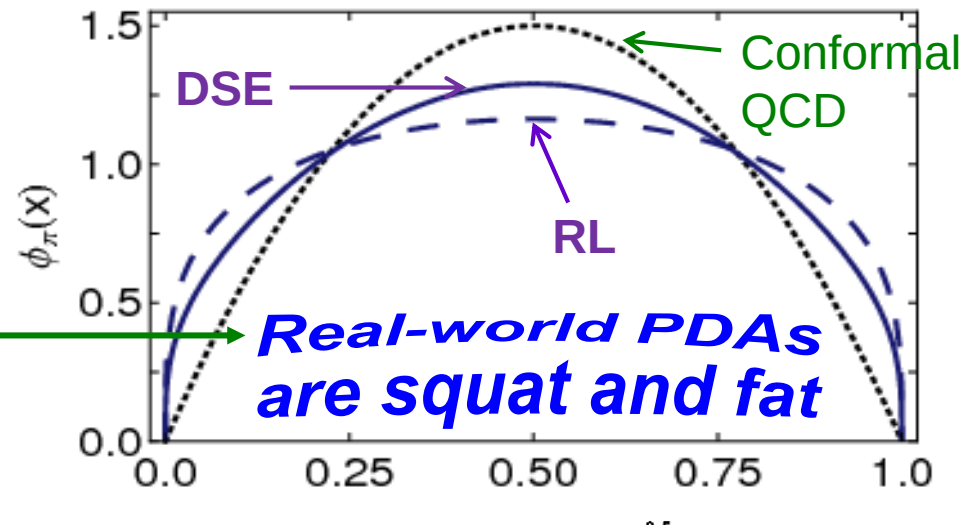


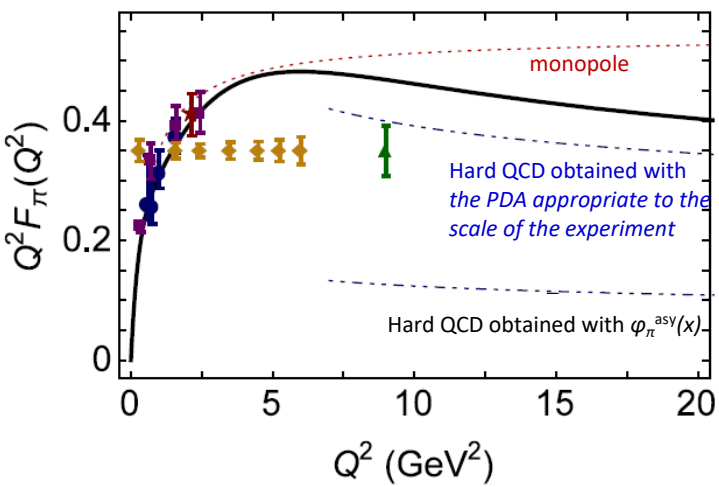
Present Projections



Pion Form Factor and Structure Function





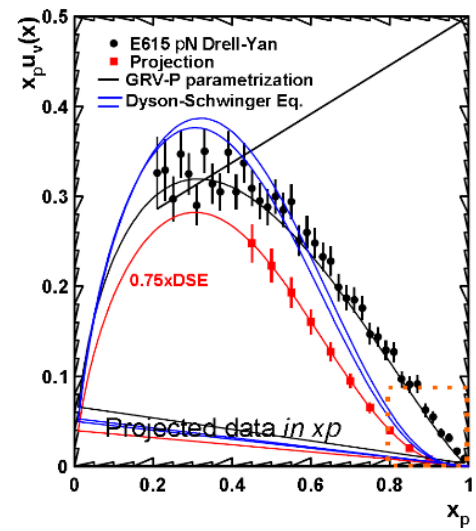


Pion FF – first quantitative access to hard scattering scaling regime?

Implications if so: two longstanding puzzles could be solved

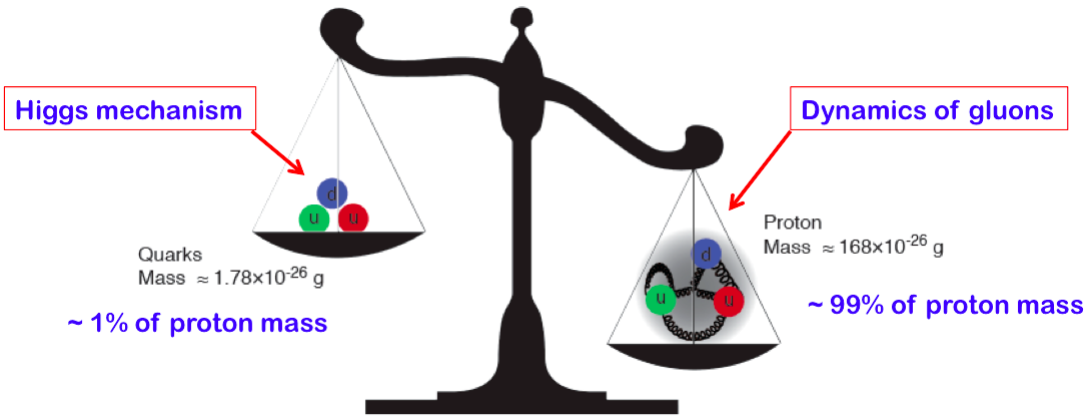
1. Magnitude of pion form factor in hard scaling regime
2. Power of pion parton behavior at large x

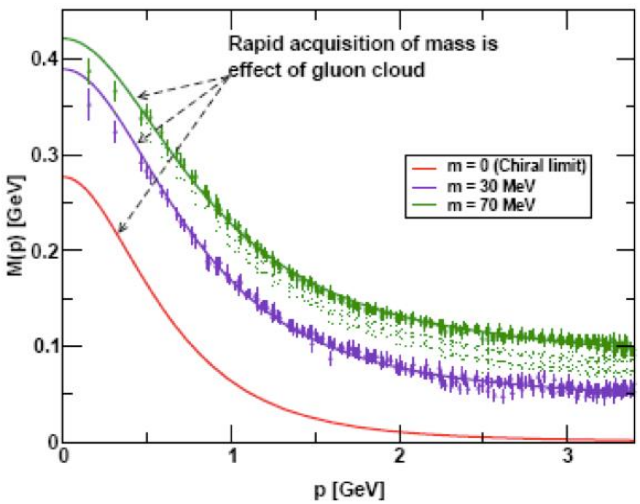
Also implications for nucleon and N form factor interpretation (not shown here).*



Pion SF – $(1-x)^{-1}$ or $(1-x)^{-2}$ dependence at large x?

The Incomplete Nucleon: Mass Puzzle





"Mass without mass!"

Bhagwat & Tandy/Roberts et al

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

- **Proton mass:**

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

Relativistic motion: E_q, E_g

Quantum fluctuation: χ_{m_q}, T_g

Quark Energy: E_q

Gluon Energy: E_g

Quark Mass: χ_{m_q}

Trace Anomaly: T_g