Pion and Kaon Structure at 12 GeV JLab and EIC

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Thanks to: Yulia Furletova, Elke Aschenauer and Steve Wood

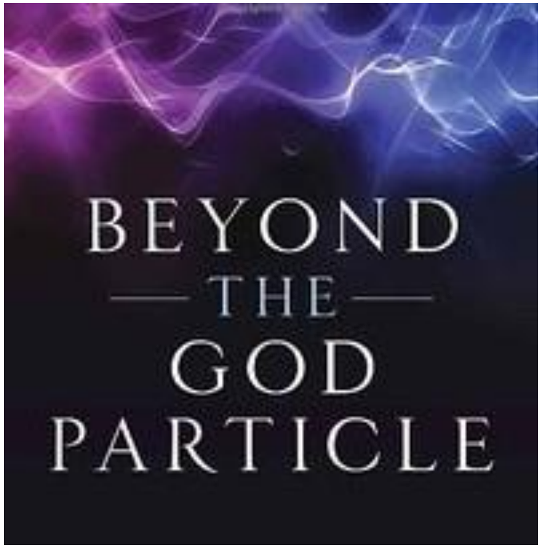
INT 17-3: Spatial and Momentum Tomography
of Hadrons and Nuclei

28 August - 29 September 2017,
INT - University of Washington

Emergence of Mass in the Standard Model

- ❑ LHC has NOT found the “God Particle” because the Higgs boson is NOT the origin of mass
  - Higgs-boson only produces a little bit of mass
  - Higgs-generated mass-scales explain neither the proton’s mass nor the pion’s (*near*-)masslessness

Slide adapted from Craig Roberts (EICUGM 2017)



- ➢ Proton is massive, *i.e*. the mass-scale for strong interactions is vastly different to that of electromagnetism
- ➢ Pion is unnaturally light (but not massless), despite being a strongly interacting composite object built from a valence-quark and valence antiquark
- ➢ Kaon is also light (but not massless), heavier than the pion constituted of a light valence quark and a heavier strange antiquark

- ❑ The strong interaction sector of the Standard Model, *i.e*. QCD, is the key to understanding the origin, existence and properties of (almost) all known matter

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 $\rho_p \neq 0$, $m_\pi^2 \sim \sqrt{m_q}$
  - The mass of bound states increases as √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.*, in models 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 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 $f_\pi = f_K \approx 0.1$, $\rho_\pi = \rho_K \approx (0.5\ \mathrm{GeV})^2$ @ 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

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

In good agreement with experimental values

The Role of Gluons in Pions

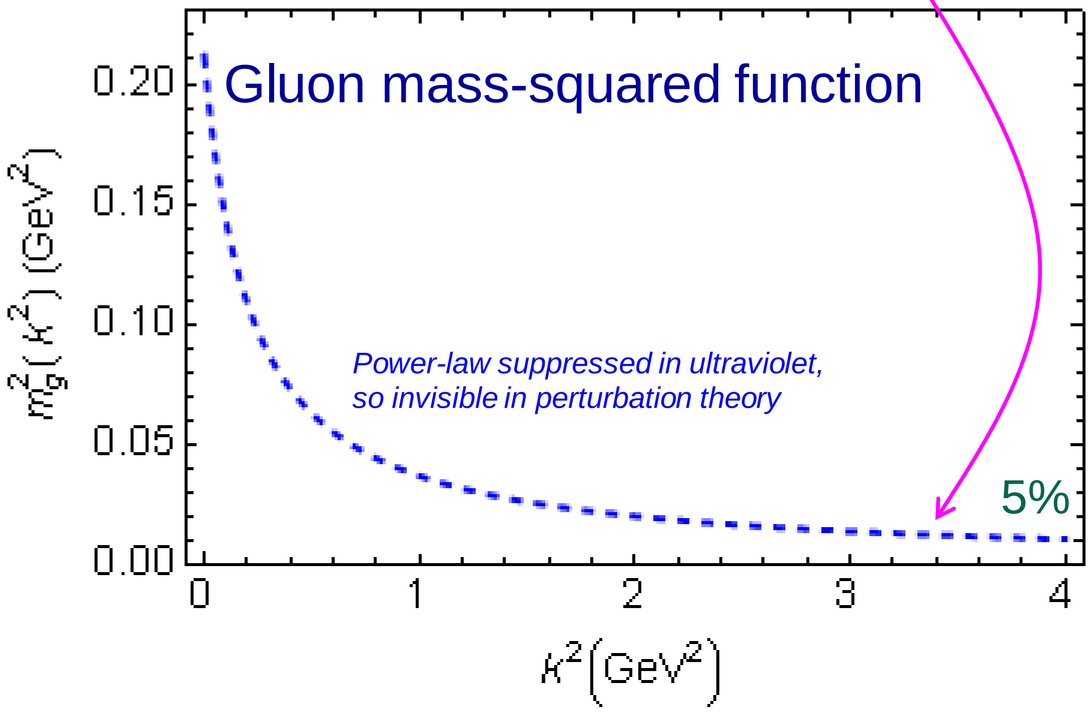
Pion mass is enigma – cannibalistic gluons vs massless Goldstone bosons

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

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

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



Power-law suppressed in ultraviolet, so invisible in perturbation theory

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?

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

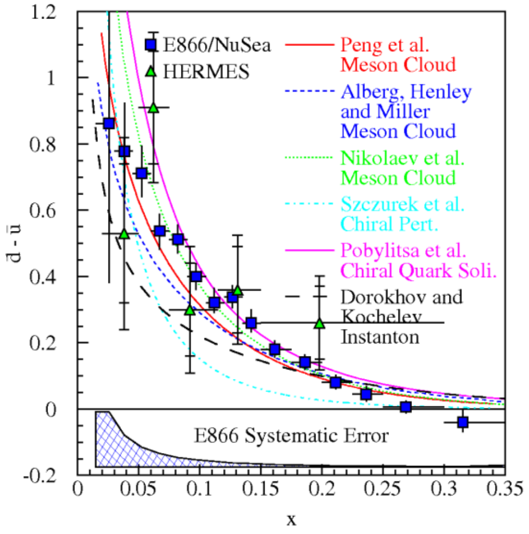
- ➢ **We should understand their structure (also mass)**

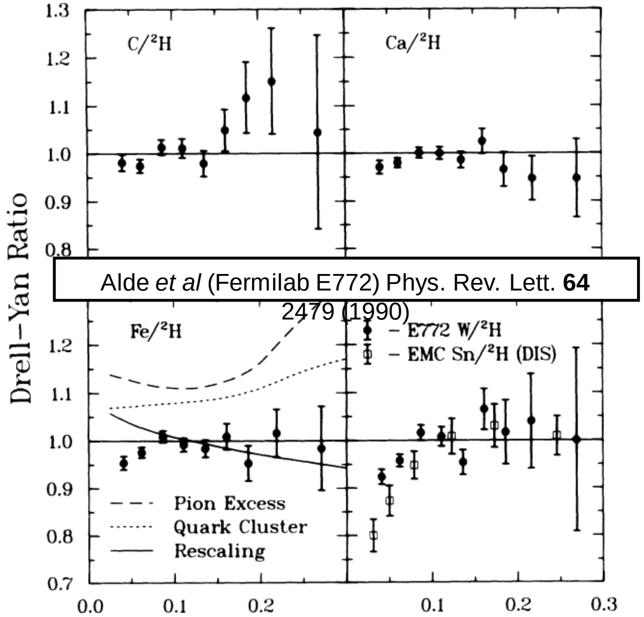
1) The pion, or a meson cloud, explains light-quark asymmetry in the nucleon sea

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

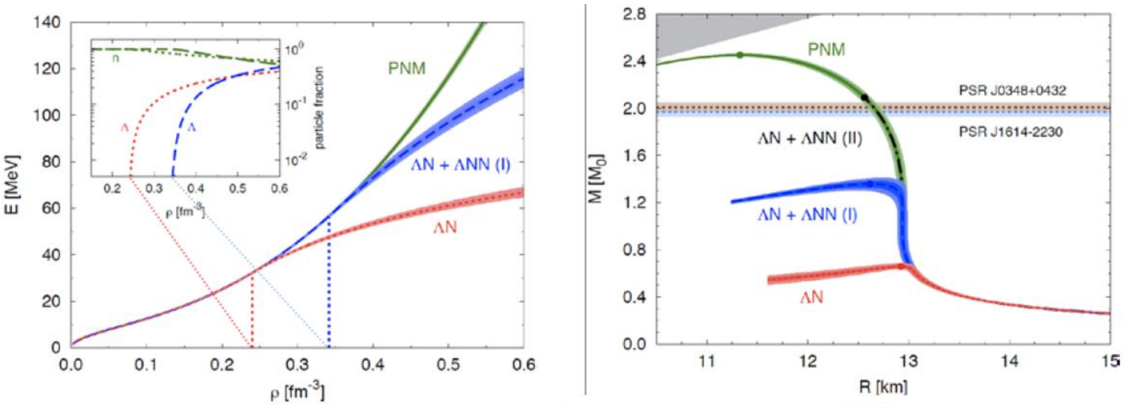
4) Mass is enigma – cannibalistic gluons vs massless Goldstone bosons





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

Equations of state and neutron star mass-radius relations

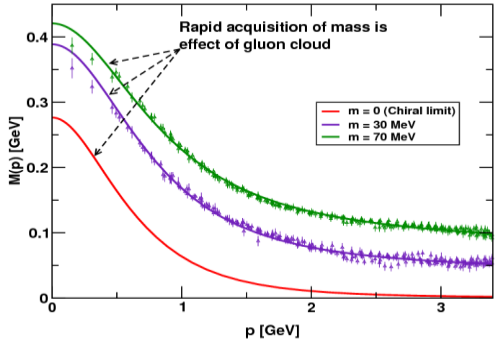


Observing Mass (1) : Pion and Kaon Form Factors

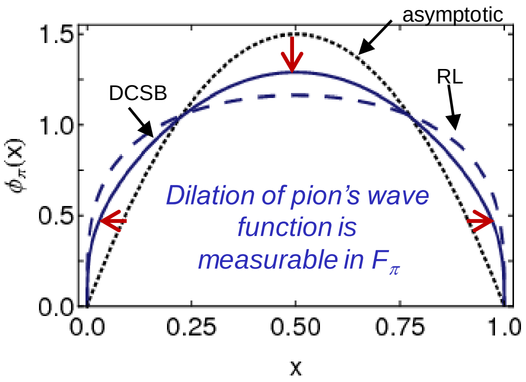
Form factors are essential for our understanding of internal hadron structure and the dynamics that bind the most basic elements of nuclear physics

- ☐ ***Pion and kaon form factors*** are of special interest in hadron structure studies
  - ➢ The *pion* is the lightest QCD quark system and also has a central role in our understanding of the dynamic generation of mass - *kaon* is the next simplest system containing strangeness

Clearest test case for studies of the transition from non-perturbative to perturbative regions



- ☐ Recent advances and future prospects in experiments
  - ➢ Dramatically improved precision in F_π measurements
  - ➢ 12 GeV JLab: F_π and exclusive meson studies up to highest possible Q^2 and possible F_{K+} extractions
- ☐ Form factor data drive renewed activity on theory side
  - ➢ Distribution amplitudes – signatures of dynamical chiral symmetry breaking



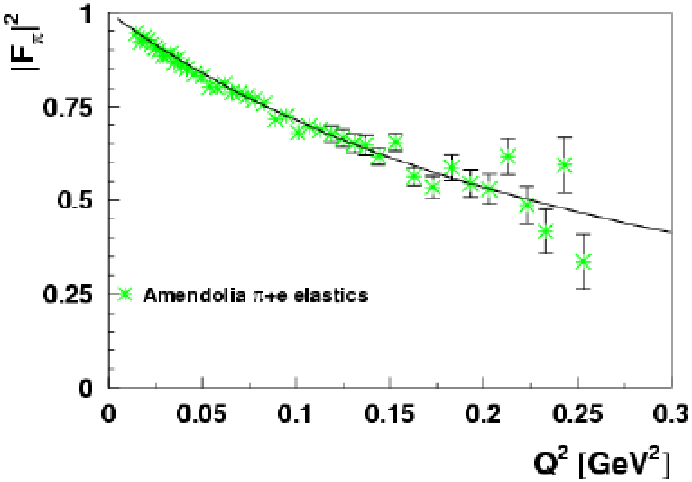
Dilation of pion's wave function is measurable in F_π

12 GeV JLab data up to Q^2=5-10 GeV^2 - calculations anticipate that hard QCD's signatures will be quantitatively revealed for pions and kaons

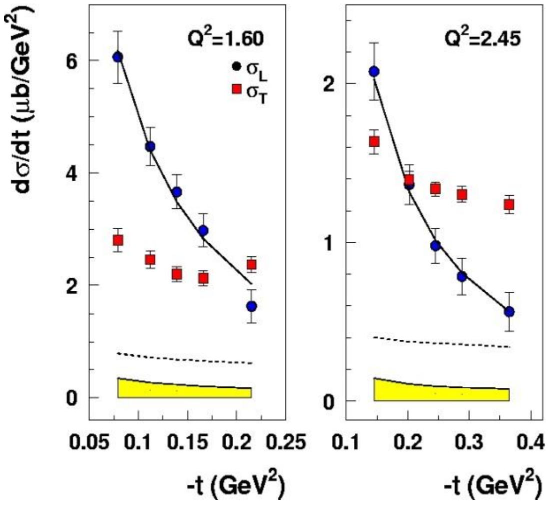
Measurement of π^+ Form Factor

- At low Q^2, $F_{\pi+}$ can be measured directly via high energy elastic π^+ scattering from atomic electrons
  - CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2

    *[Amendolia et al, NPB **277**,168 (1986)]*
  - These data used to constrain the pion charge radius: $r_\pi = 0.657 \pm 0.012$ fm



- At larger Q^2, $F_{\pi+}$ must be measured indirectly using the "pion cloud" of the proton in exclusive pion electroproduction: $p(e,e'\pi^+)n$ – ***L/T separations***



*[Horn et al., PRL **97**, (2006) 192001]*

- *Select pion pole process:* at small –*t* pole process dominates the longitudinal cross section, σ_L

  *[L. Favart, M. Guidal, T. Horn, P. Kroll, Eur. Phys. J A **52** (2016) no.6, 158]*

- *Isolate σ_L* - in the Born term model, F_π^2 appears as

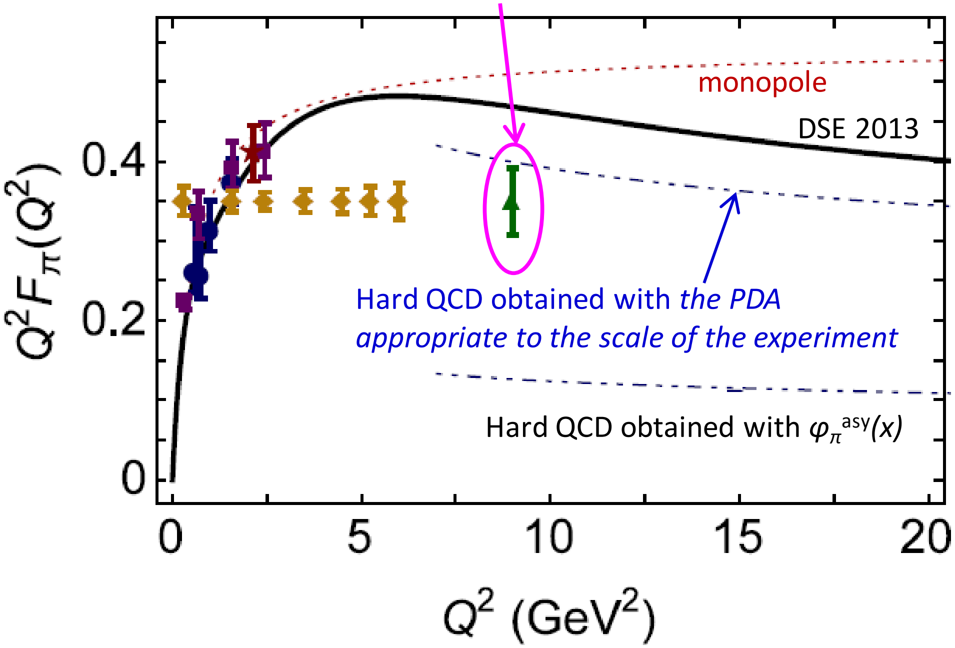
$$\frac{d\sigma_L}{dt} \propto \frac{-t}{(t-m_\pi^2)}\, g_{\pi NN}^2(t)\, Q^2 F_\pi^2(Q^2,t)$$

[In practice one uses a more sophisticated model]

JLab 12 GeV: F_π Measurements

For F_π 2017 status see Week 1 talk

E12-07-105: Q^2=8.5 GeV^2 and t_{min}~0.5 GeV^2



- ❑ JLab 12 GeV and HMS+SHMS in Hall C allow for:
  - ➢ Measurements of σ_L up to Q^2=8-9 GeV^2
  - ➢ Reliable F_π extractions from existing data to the highest possible Q^2
  - ➢ Validation of F_π extraction at highest Q^2

Projected precision using $R=\sigma_L/\sigma_T$ from VR model and assumes pole dominance – uncertainties are very sensitive to that value

JLab 12 GeV experiments have the potential to access the hard scattering scaling regime quantitatively for the first time – may also provide info on log corrections.

- ➢ These results would also have implications for nucleon structure interpretation

JLab12: Kaon Electroproduction and Form Factor

For F_K 2017 status see Week 1 talk

- ❑ **E12-09-011**: primary goal L/T separated kaon cross sections to investigate hard-soft factorization and non-pole contributions

*E12-**09**-011spokespersons: T. Horn, G. Huber, P. Markowitz*

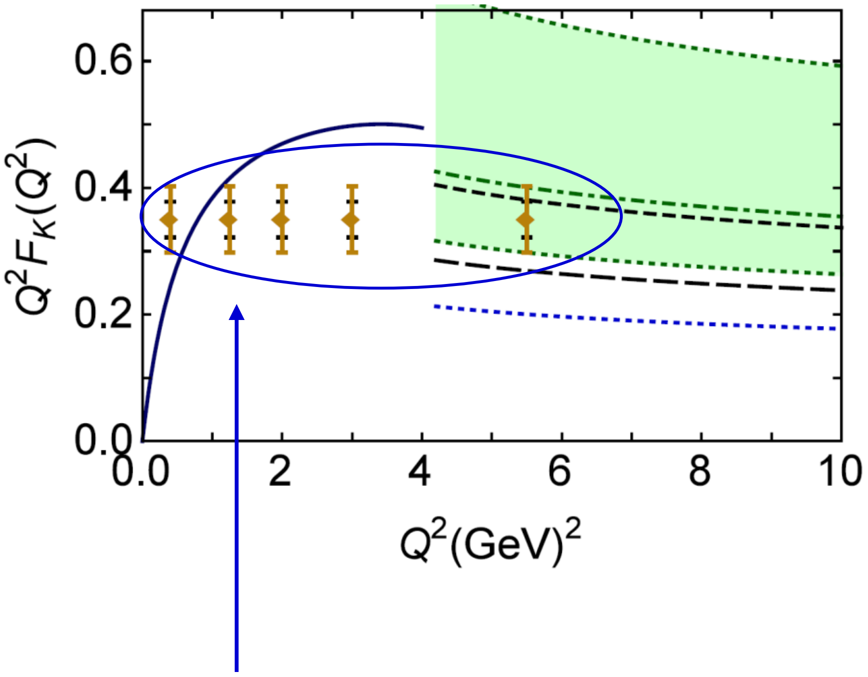
- ➢ **scheduled to run in 2018/19**

- ❑ Possible K^+ form factor extraction to highest possible Q^2 achievable at JLab

- ➢ Extraction like in the pion case by studying the model dependence at small t

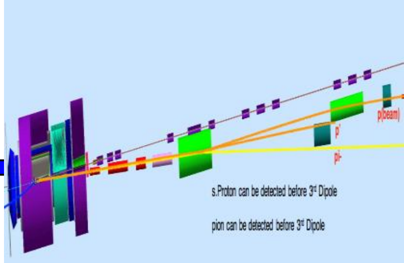
- ➢ Comparative extractions of F_π at small and larger t show only modest model dependence
  - ○ larger t data lie at a similar distance from pole as kaon data

[T. Horn, C.D. Roberts, J. Phys. G**43** (2016) no.7, 073001]

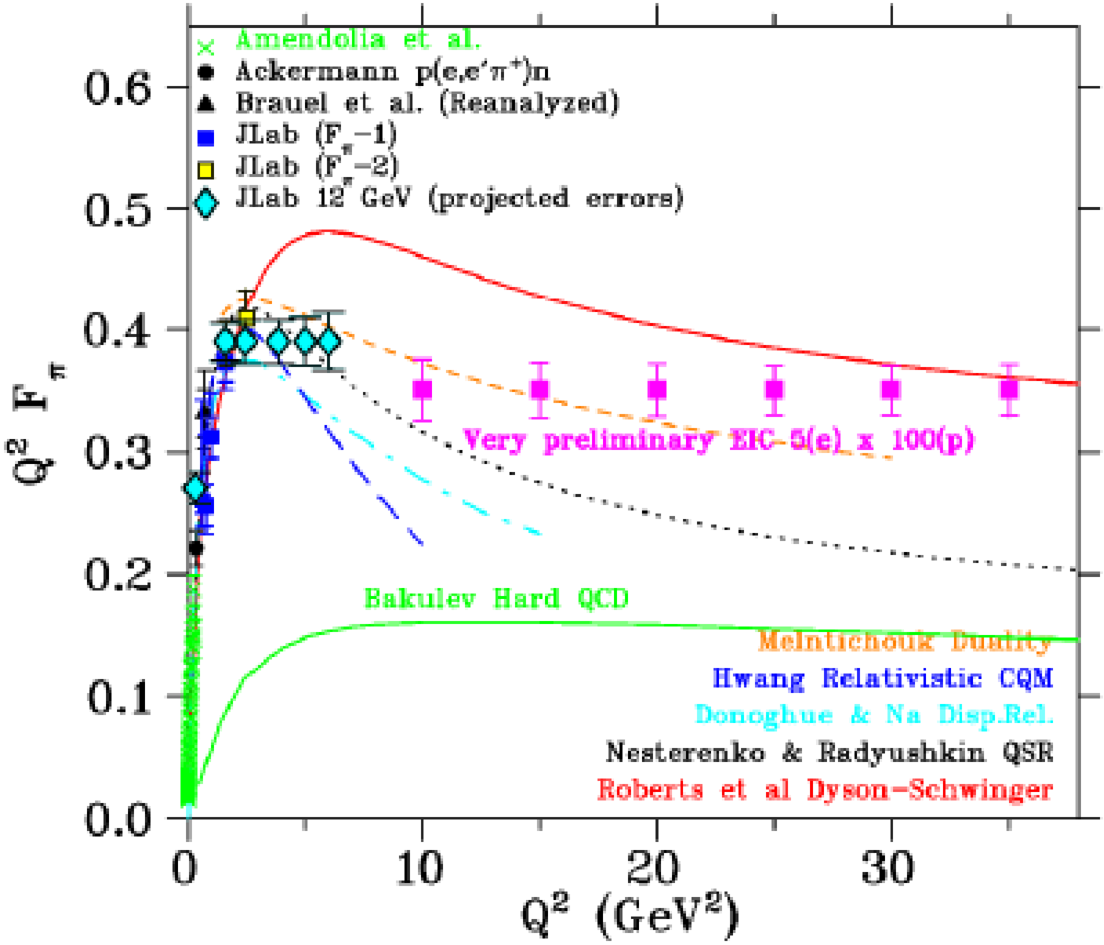


Possible extractions from 2018/19 run

EIC: Pion and Kaon Form Factors



1. VR model shows strong dominance of σ_L at small –t at large Q^2.
2. Assume σ_L dominance
3. Measure the π^-/π^+ ratio to verify – it will be diluted (smaller than unity) if σ_T is not small, or if non-pole backgrounds are large



- ☐ 5 GeV(e^-) x 100 GeV(p)
- ☐ Integrated luminosity: L=20 fb^{-1}/yr
- ☐ Identification of exclusive $p(e,e'\pi^+)n$ events
- ☐ 10% exp. syst. unc.
- ☐ $R=\sigma_L/\sigma_T$ from VR model, and π pole dominance at small t confirmed in ^2H π^-/π^+ ratios
- ☐ 100% syst. unc. in model subtraction to isolate σ_L

Adapted from Garth Huber slides (PIEIC2017)

Observing Mass (2): Pion and Kaon PDFs

*[From: T. Horn, C.D. Roberts, J. Phys. G**43** (2016) no.7, 073001]*

- ☐ Experimental data on π & K PDFs obtained in mesonic Drell-Yan scattering from nucleons in heavy nuclei; but not much and it's old: 1980-1989

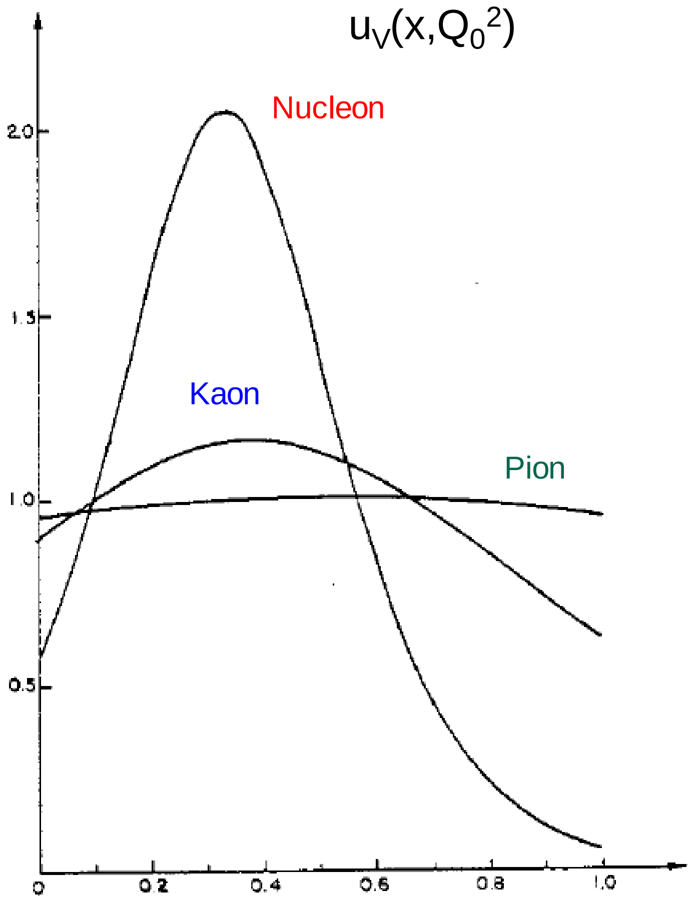
- ☐ Newer data would be welcome:
  - persistent doubts about the Bjorken-$x \simeq 1$ behavior of the pion's valence-quark PDF
  - single modest-quality measurement of $u^K(x)/u^\pi(x)$ cannot be considered definitive.

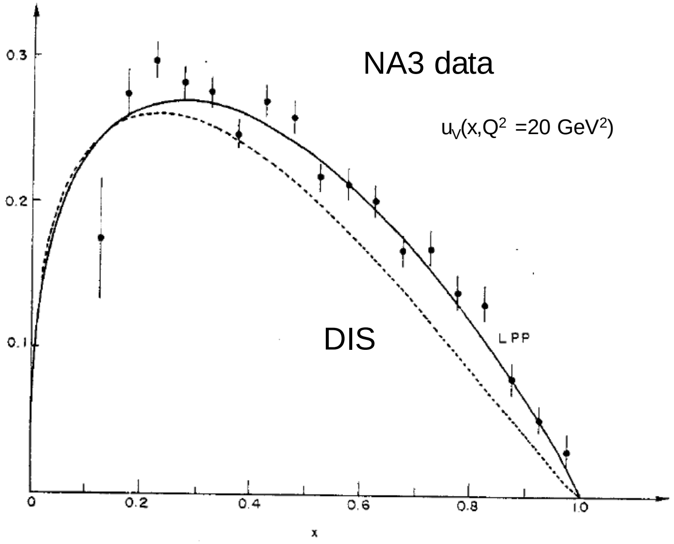
- ☐ Approved experiment, using tagged DIS at *JLab 12 GeV*, should contribute to a resolution of pion question; and a similar technique might serve for the kaon.

- ☐ Future:
  - ➢ new mesonic Drell-Yan measurements at modern facilities (*possible at COMPASS – see S. Platchkov talk at PIEIC2017*) could yield valuable information on π and K PDFs, as could two-jet experiments at the large hadron collider;
  - ➢ ***EIC would be capable of providing access to π and K PDFs through measurements of forward nucleon structure functions.***

At some level an old story…

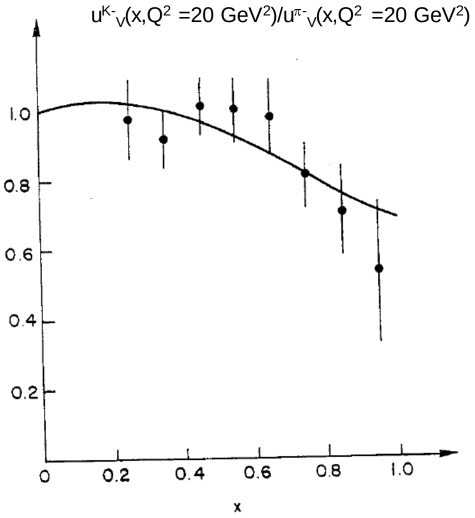
A model for nucleon, pion and kaon structure functions
F. Martin, CERN-TH 2845 (1980)





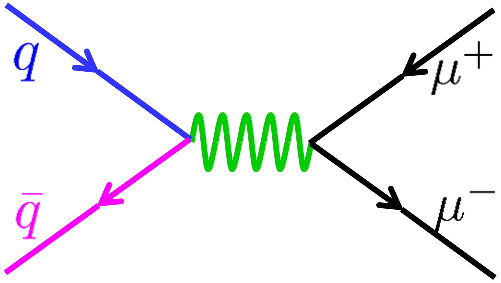
Predictions based on non-relativistic model with valence quarks only

- pion/kaon differs from proton: 2- vs. 3- quark system
- kaon differs from pion owing to one heavy quark



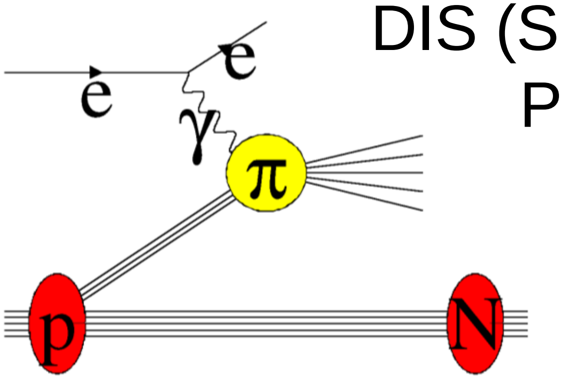
World Data on pion structure function F_2^{π}

Pion Drell-Yan



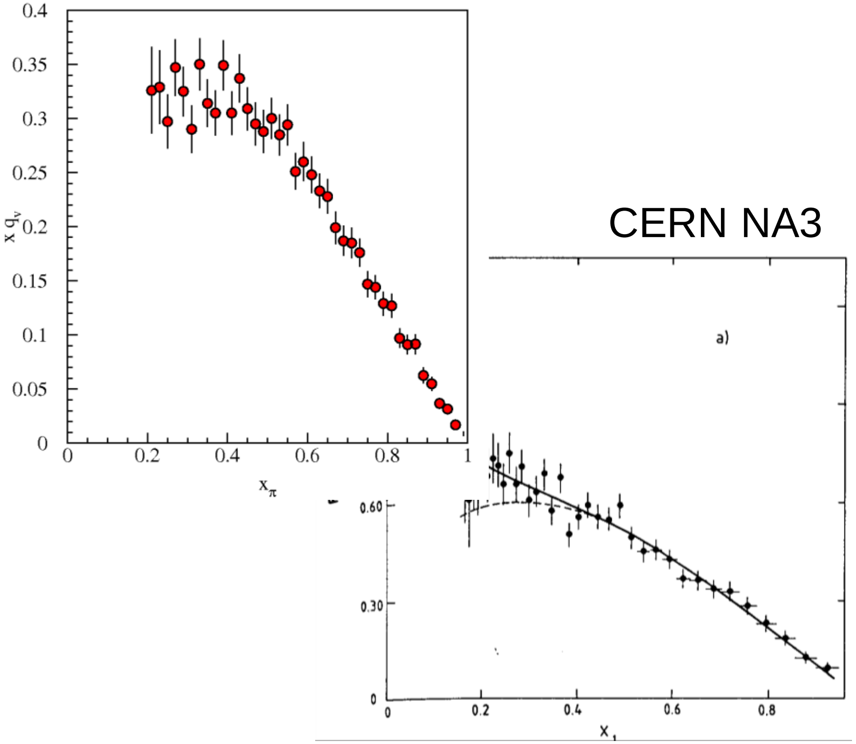
Data much more limited than nucleon…

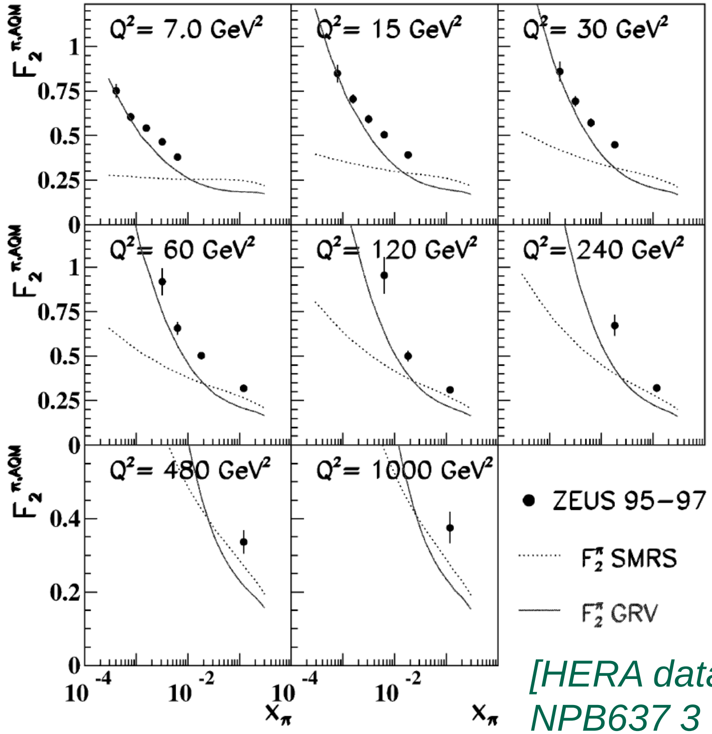
DIS (Sullivan Process)



FNAL E615

CERN NA3





[HERA data [ZEUS, NPB637 3 (2002)]

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.*,

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

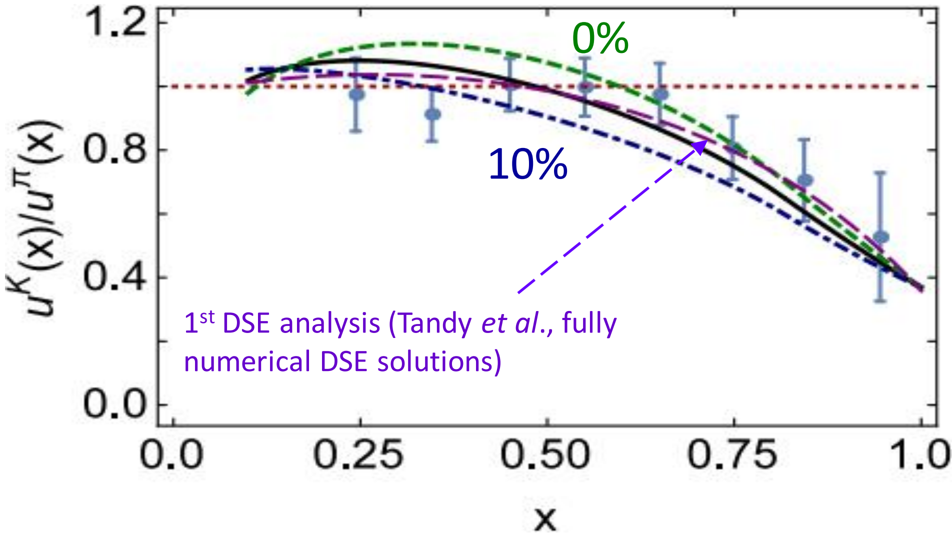
The inexorable growth in both pions' and kaons' gluon content at asymptotic Q^2 provides connection to gluon saturation.

Gluon Content in Kaon and Pion

Based on Lattice QCD calculations and DSE calculations:

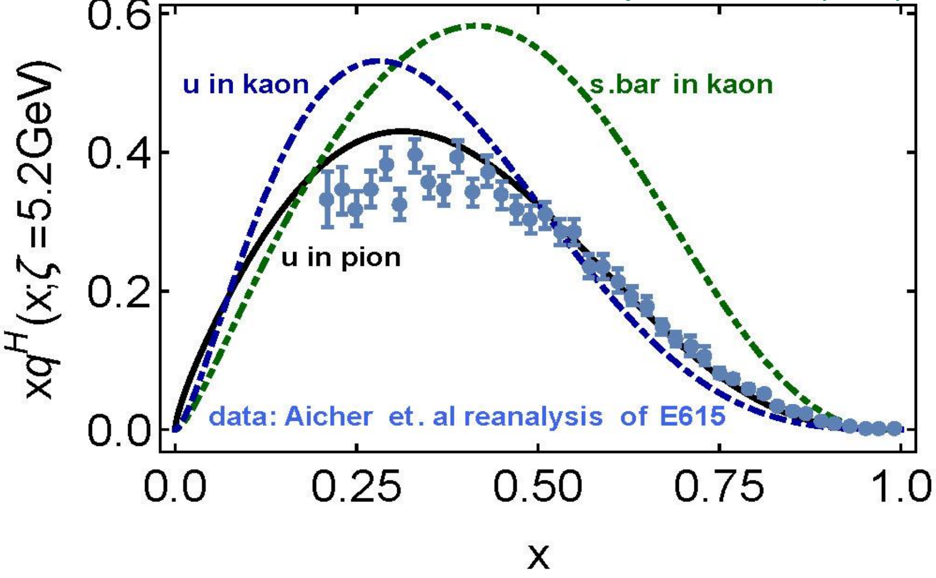
- Valence quarks carry 2/3 of the kaon’s momentum at the light front, at the scale used for Lattice QCD calculations, or roughly 95% at the perturbative hadronic scale
- At the same scale, valence-quarks carry 52% of the pion’s light-front momentum, or roughly 65% at the perturbative hadronic scale

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



1st DSE analysis (Tandy *et al.*, fully numerical DSE solutions)

C. Chen et al., Phys. Rev. D**93** (2016), 1



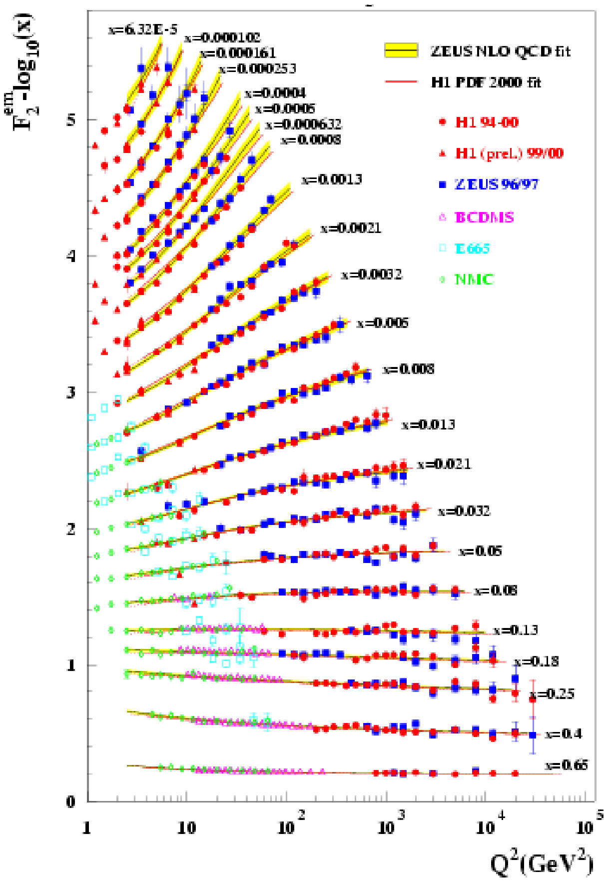
Quarks and Gluons in Pions and Kaons

- ❑ **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, effects of gluons come in as well. To measure these differences would be fantastic.

Landscape for p, π, K structure function after EIC

Proton: much existing from HERA

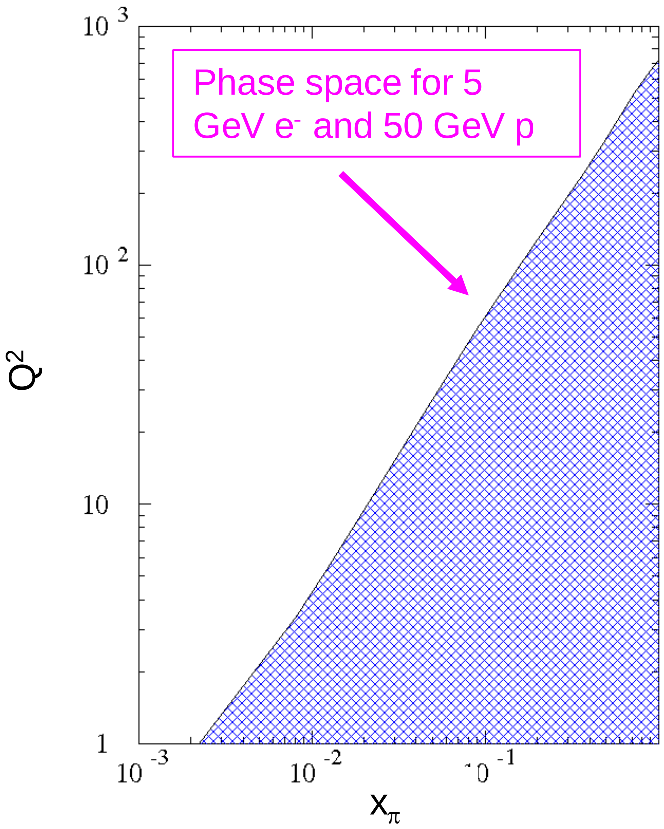
EIC will add:
- Better constraints at large-x
- Precise F_2^n neutron SF data



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!

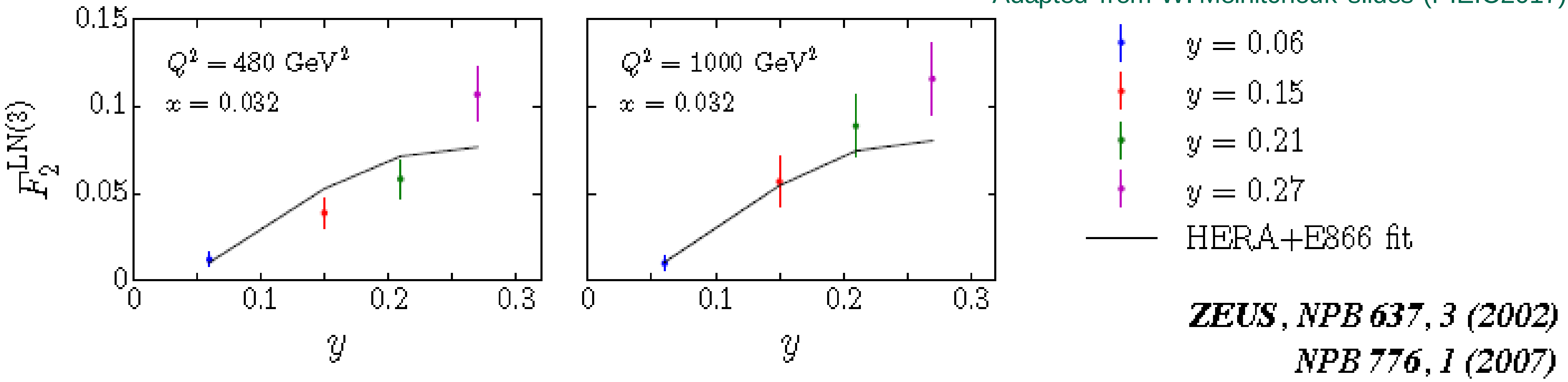
R. Trotta, A. Vargas, TH



Phase space for 5 GeV e^- and 50 GeV p

Combined Fit to HERA LN and E866 DY Data

Adapted from W. Melnitchouk slides (PIEIC2017)

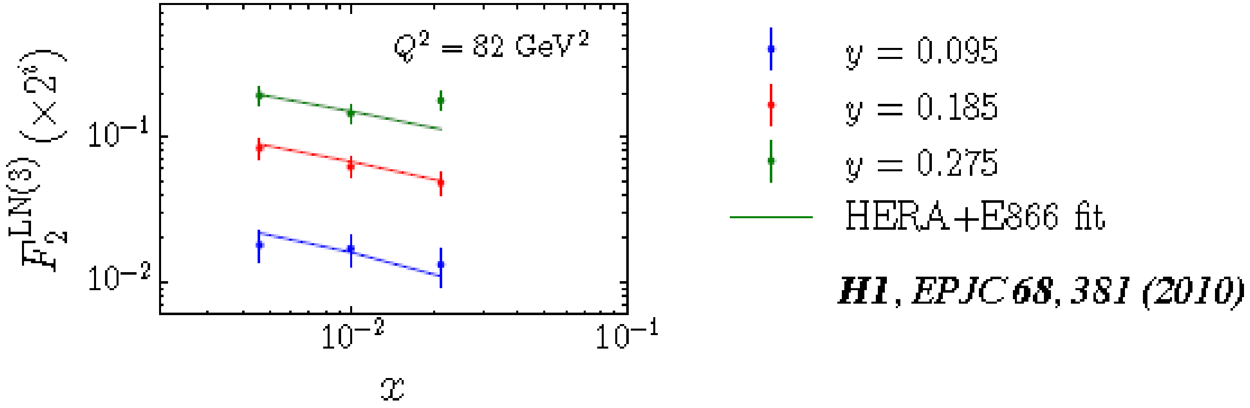


***ZEUS*, *NPB 637*, 3 (2002)**

***NPB 776*, 1 (2007)**

- ☐ Quality of fit depends on y-range fitted – to reduce model dependence fit up to y_{cut}=0.3 to which data can be described in term of π exchange

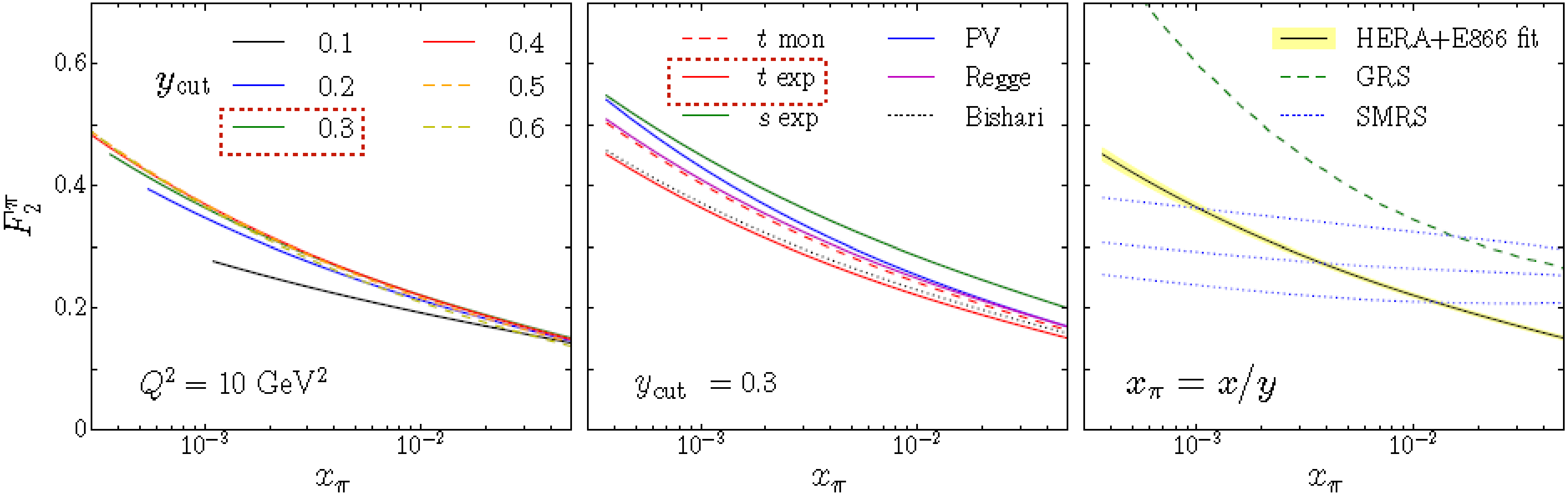
χ^2/dof=1.27 for 202 (187+15) points



***H1*, *EPJC 68*, 381 (2010)**

- ☐ Best fits for largest number of points by t-dependent exponential (and t-monopole) regulators

Extracted Pion Structure Function



$$F_2^\pi = N\, x_\pi^a \left(1 - x_\pi\right)^b, \quad a = a_0 + a_1 \eta$$

$$\eta \sim \log\left(\log Q^2\right)$$

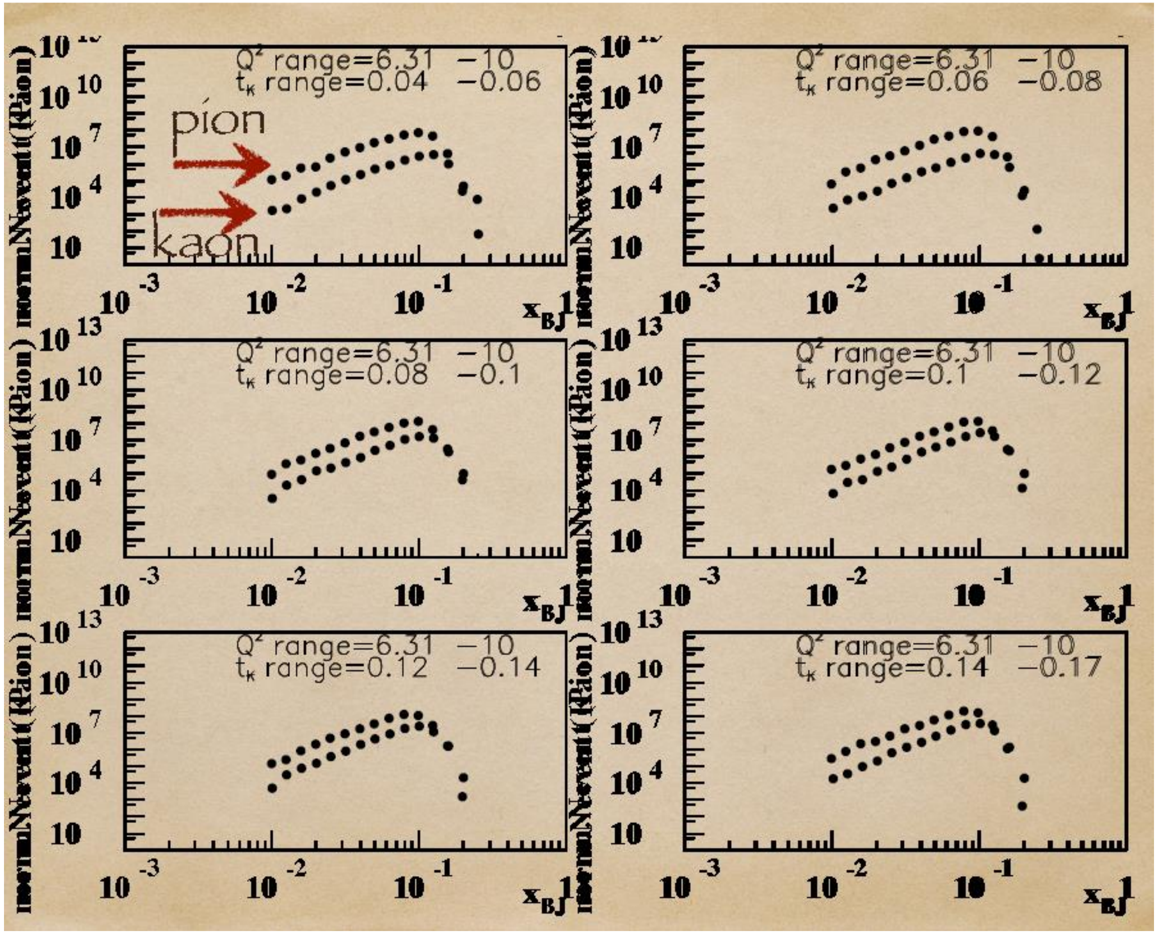
- Stable values of F_2^π at 4×10^{-4} ~< x_π ~<0.03 from combined fit

- Shape similar to GRS fit to πN Drell-Yan data (for x_π >~0.2) but smaller magnitude

Adapted from W. Melnitchouk slides (PIEIC2017)

Pion/kaon SF – EIC Kinematic Reach

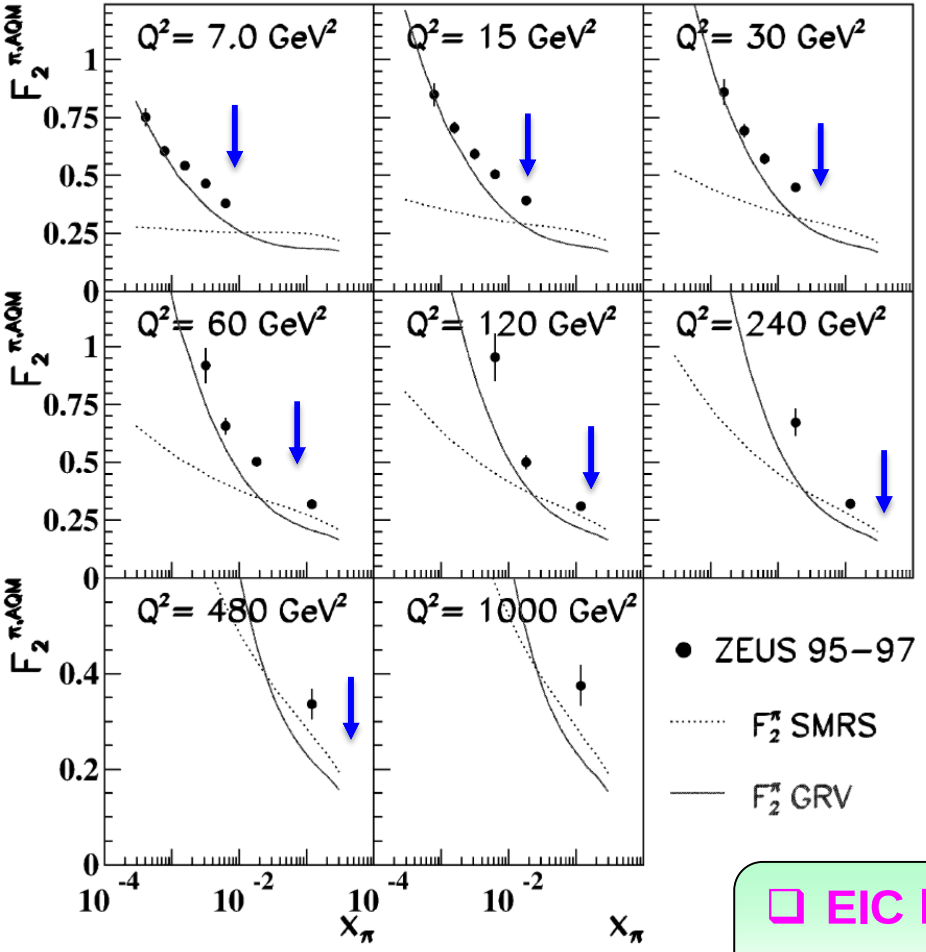
Figure from K. Park



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

World Data on Pion Structure Function F_2^{π}

HERA



EIC

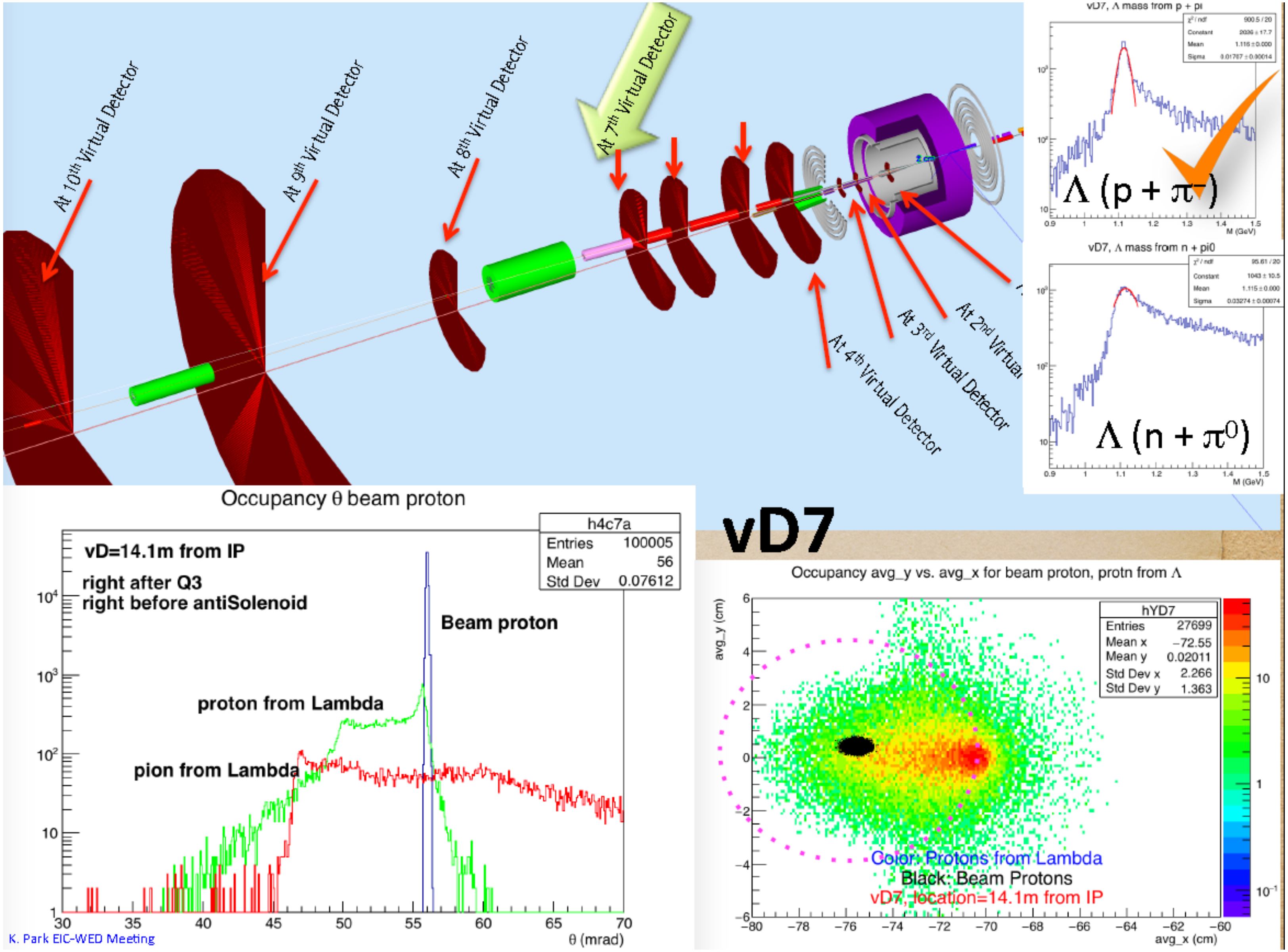
↓ roughly x_{min} for EIC projections

For 5 GeV e^- and 50 GeV p
@ luminosity 10^{34} $s^{-1}cm^{-2}$

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

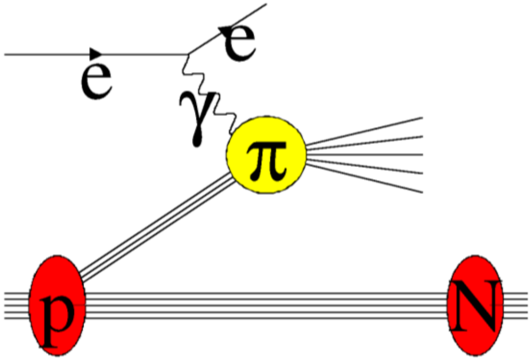
Detector Acceptance Simulation Example

Figures from K. Park



K. Park EIC-WED Meeting

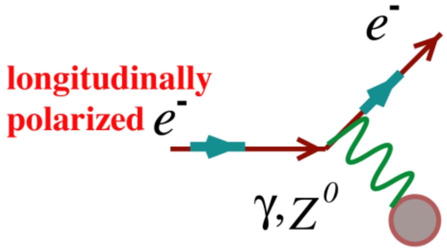
Electroweak Pion and Kaon Structure Functions



- 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 flavour decomposition?

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

2) Determine xF_3 through neutral/charged-current interactions



In the parton model:

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

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

Use different couplings/weights

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

Use isovector response

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

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

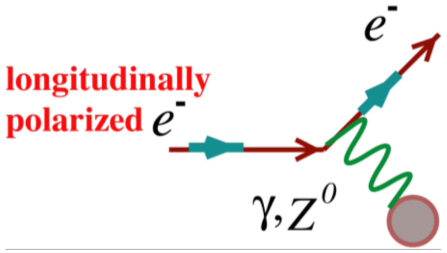
$$A = \frac{\sigma_R^{CC,e^+} \pm \sigma_L^{CC,e^-}}{\sigma_R^{NC}+\sigma_L^{NC}}$$

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

Disentangling the Flavour-Dependence (I)

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

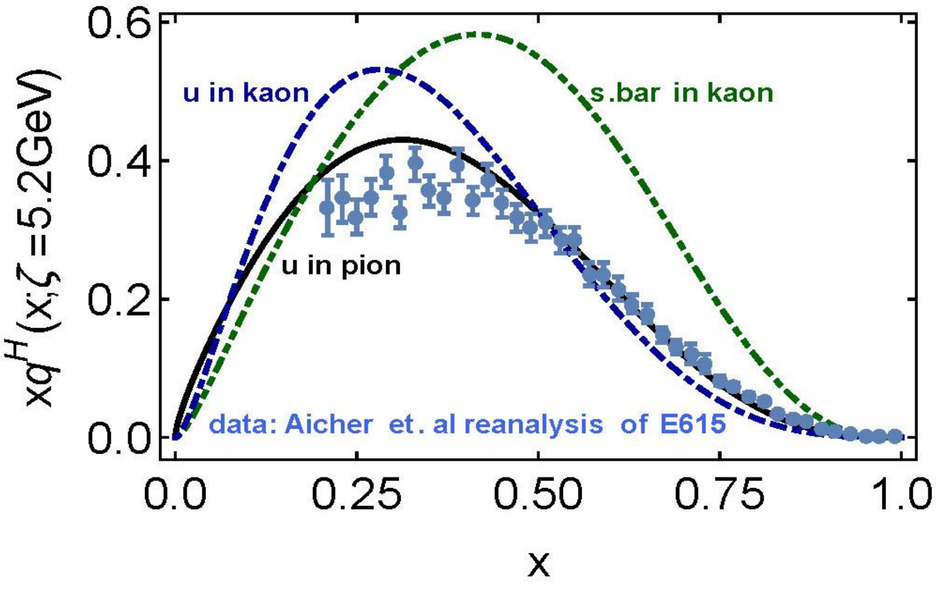
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



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

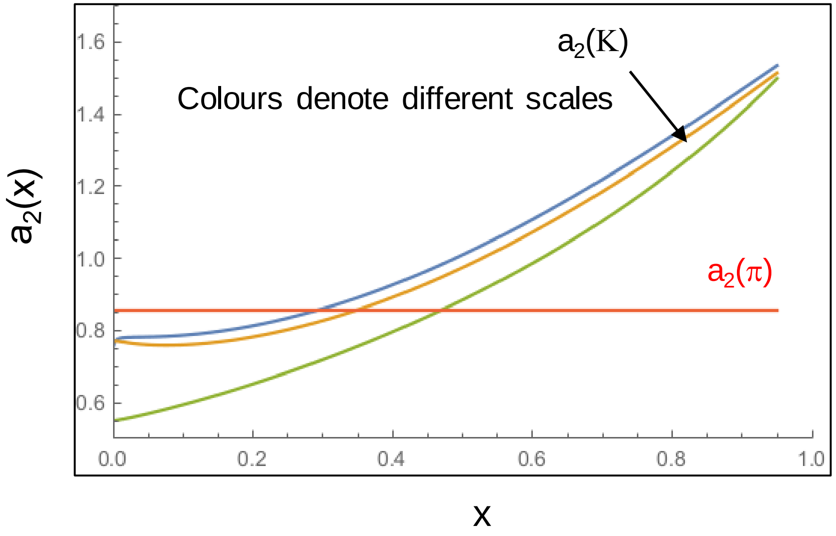
$$a_{2K}(x) = \frac{2\sum_q e_q\, g_V^q\, (q+\bar{q})}{\sum_q e_q^2\, (q+\bar{q})} \simeq \frac{6\,u_K^+ + 3\,s_K^+}{4\,u_K^+ + s_K^+} - 4\sin^2\theta_W.$$

C. Chen et al., Phys. Rev. D**93** (2016), 11



DSE-based parton distributions
in pion and kaon

Calculation by C.D. Roberts et al.



a_2 picks up different behaviour of u and sbar.
Flavour decomposition in kaon possible?

Disentangling the Flavour-Dependence (II)

3) Electroweak pion/kaon SF through comparison of electron versus positron interactions

NC, 10 GeV(e^+) x 100 GeV(p)

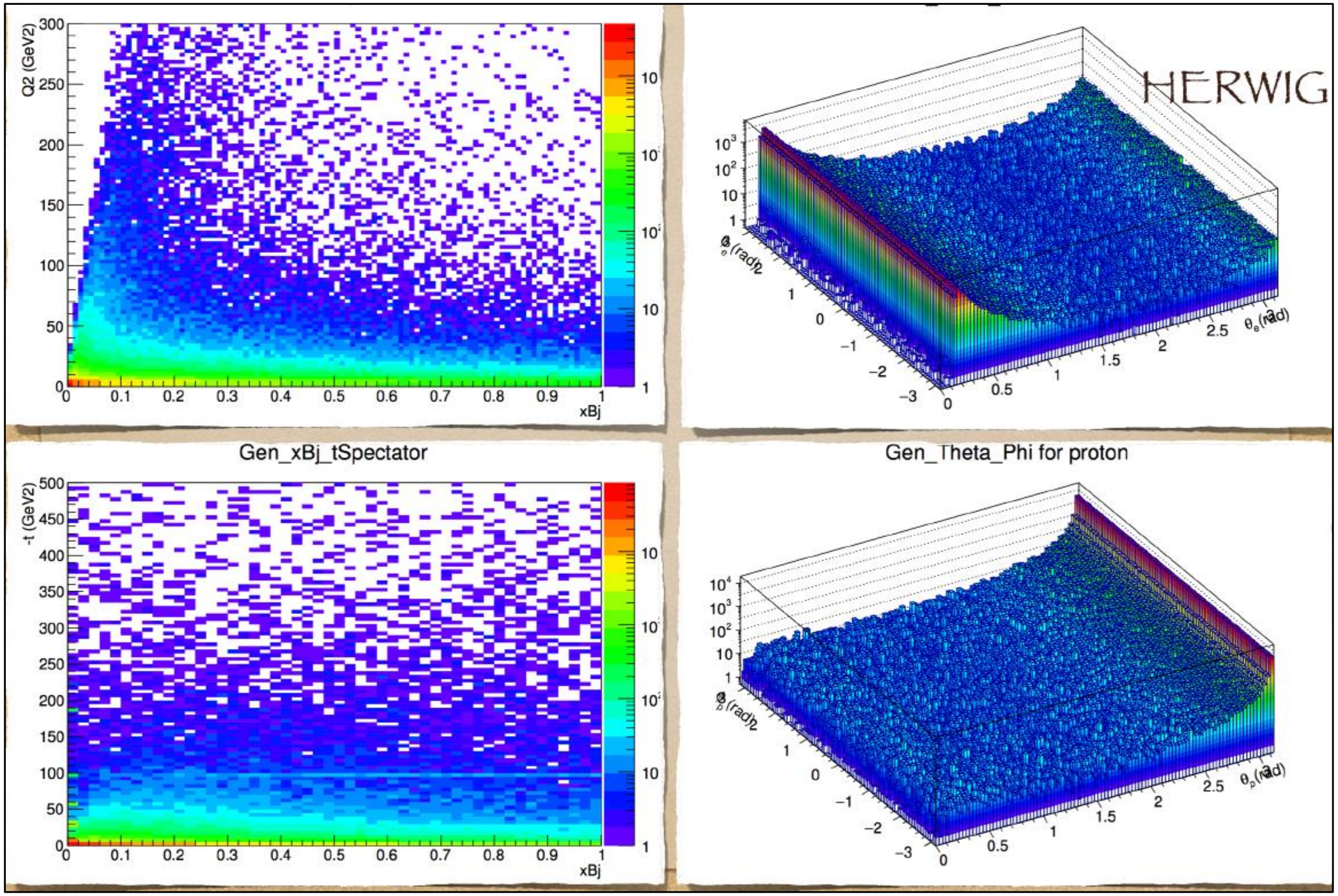


Figure from K. Park

Summary

- ❑ Nucleons and the lightest mesons - pions and kaons, are the basic building blocks of nuclear matter. We should know their form factors and structure functions.

- ❑ Pion and kaon form factor measurements guide our understanding of the dynamics that bind valence quarks into massive mesons.

- ❑ 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)?

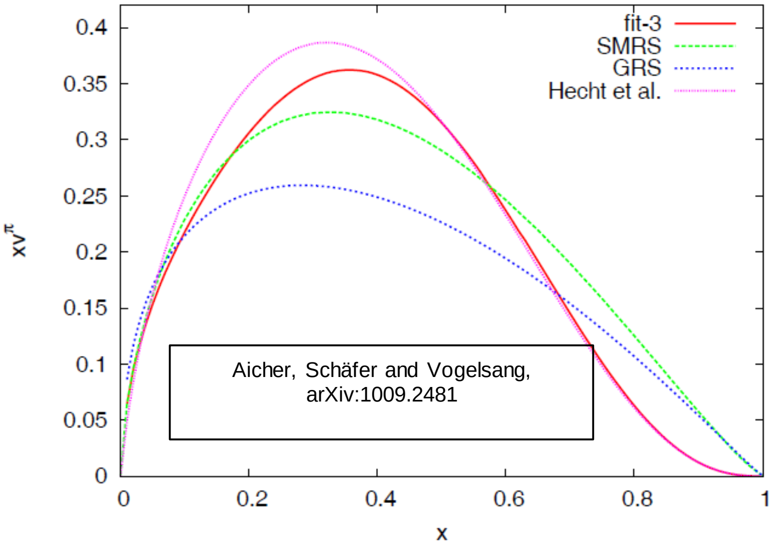
- ❑ Some effects may be trivial – the heavier-mass quark in the kaon “robs” more of the momentum, and the structure functions of pions, kaons and protons at large-x should be different, but confirming these would provide textbook material.

- ❑ Using electroweak processes, e.g., through parity-violating probes or neutral vs. charged-current interactions, disentangling flavour dependence seems achievable

JLab 12 GeV: resolve the issue at large-x

- ❑ Large x_{Bj} structure of the pion is interesting and relevant
  - ➢ Pion cloud & antiquark flavor asymmetry
  - ➢ Nuclear Binding
  - ➢ Simple QCD state & Goldstone Boson

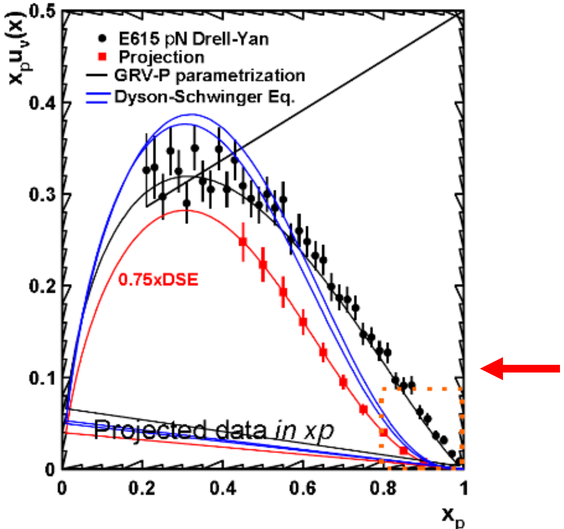
- ❑ Even with NLO fit and modern parton distributions, pion $(1-x)$ did not agree with pQCD and Dyson-Schwinger $(1-x)^2$



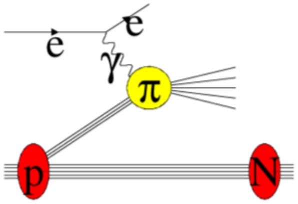
Aicher, Schäfer and Vogelsang, arXiv:1009.2481

- ❑ Soft Gluon Resummation saves the day!

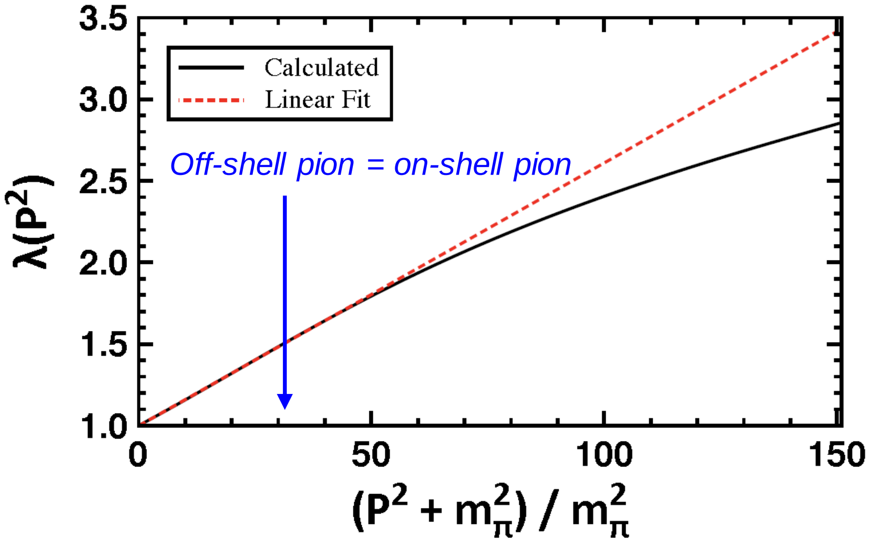
- ❑ JLab 12 GeV TDIS experiment can check at high-x



Off-shellness considerations



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

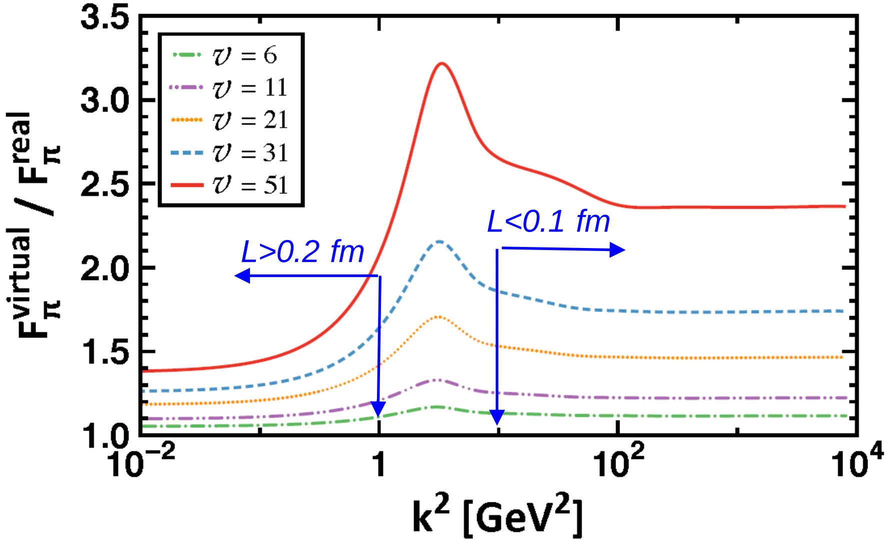


Off-shell pion = on-shell pion

- ☐ 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

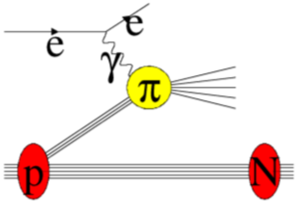


L>0.2 fm

L<0.1 fm

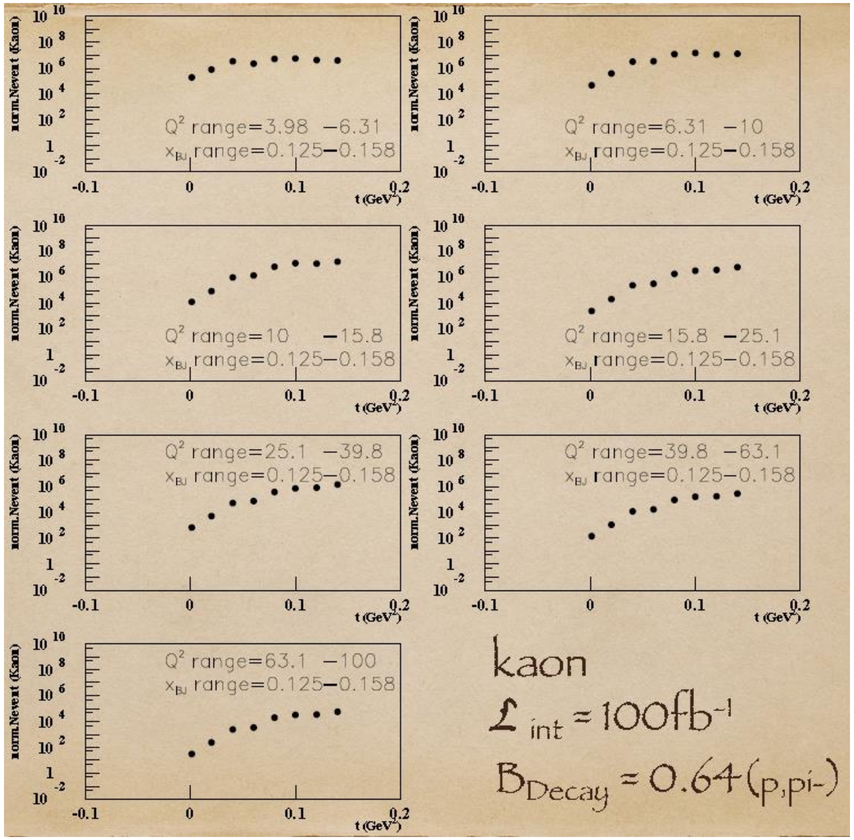
This means that pion and kaon structure functions can be accessed through the Sullivan process

Sullivan process off-shellness corrections



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

Figure from K. Park



x=0.75

R. Trotta, A. Vargas, TH