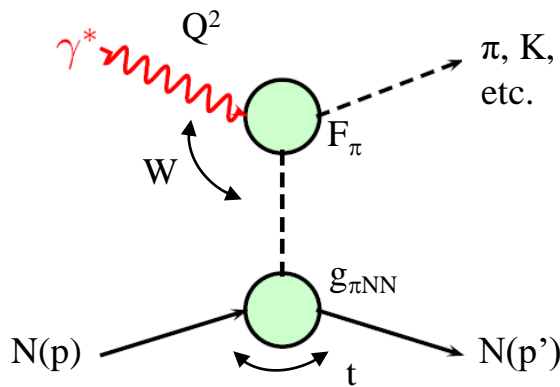


# EIC Meson Structure Functions

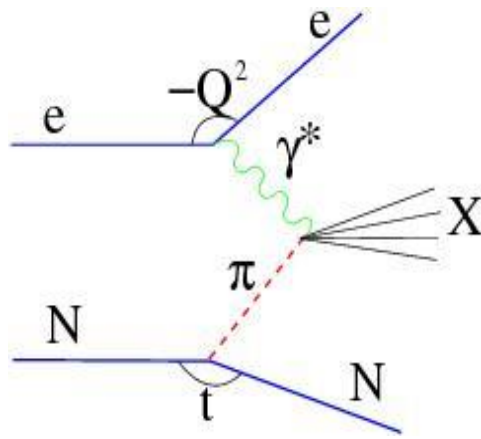
## Working Group Update



Tanja Horn

### For the Meson SF Working Group:

John R. Arrington (ANL), Carlos Ayerbe, Daniele Binosi (ECT\*), Lei Chang (Nankai U.), Rolf Ent (Jlab), Tobias Frederico (Instituto Tecnológico de Aeronautica), Timothy Hobbs (SMU), Tanja Horn (CUA), Garth Huber (U. Regina), Stephen Kay (U. Regina), Cynthia Keppel (Jlab), Bill Lee (W&M), Huey-Wen Lin (MSU), Rachel Montgomery (U. Glasgow), Ian L. Pegg (CUA), Paul Reimer (ANL), David Richards (Jlab), Craig Roberts (Nanjing U.), Jorge Segovia (Universidad Pablo de Olavide), Arun Tadepalli (JLab), Richard Trotta (CUA), Rik Yoshida (ANL)



2-5 June 2020

Online

US/Eastern timezone

## Remote Workshop 2-5 June, 2020

### Overview

Call for Abstracts

Timetable

Contribution List

Registration

Participant List

### Contact

✉ [cfns\\_contact@stonybrook...](mailto:cfns_contact@stonybrook.edu)

The Lagrangian masses of the quarks deliver only  $\approx 1\%$  of the proton mass,  $m_p$ ; and it is the emergence of the bulk of  $m_p$  and the (very probably) related mechanism of confinement that are the key unresolved issues in hadron physics. In addressing these issues, the potential of the EIC is enormous. It promises to enable a quantitative understanding of the structure of hadrons, such as the nucleon, pion and kaon, in terms of quarks and gluons, thereby achieving key goals of modern physics. Recent synergistic advances in computation, experiment and theory reveal the prospects for a precise description of the one-dimensional structure of hadrons, exemplified by parton distribution functions (PDFs) and electromagnetic form factors, and of constructing three-dimensional images of hadrons, as expressed in Generalized Parton Distributions (GPDs) and Transverse-Momentum-Dependent Distributions (TMDs). Hence, today, there is an unprecedented opportunity to chart the in-hadron distributions of, *inter alia*, mass, charge, magnetization and angular momentum.

This workshop will canvass recent progress toward a coherent program of pion and kaon structure studies at the Electron-Ion Collider (EIC) that will deliver these maps. Their drawing demands an interplay between experiment and theory. Here, recent experimental developments have been matched by new theoretical insights and rapid computational advances. The progress triad is completed by high-level phenomenology in the form of global structure function fitting frameworks. Machine learning and exascale computing are both expected to play a material role in this march of progress.

This workshop aims to capitalize on the success of two prior meetings (PIEIC2017, [PIEIC2018](#)), which led to a [White Paper](#), published in [Eur.Phys.J.A 55 \(2019\) 10, 190](#). Its near-term goals are to expand this documentation, driving toward a significant new element in the EIC User Group Physics and Detector Handbook, and develop contributions as part of the ongoing Yellow Report Initiative.

Large (remote)  
interest:

- 138 participants registered
- Attendance:  $\sim 100/\text{day}$



Starts Jun 2, 2020, 8:00 AM

Ends Jun 5, 2020, 7:00 PM

US/Eastern



Online



Craig Roberts

Tanja Horn

<https://indico.bnl.gov/e/PIEIC2020>

# Meson SF Workshop

- ❑ Two morning sessions from 8am to 1pm (ET) each day
  - 4 days, 8 talks each day
- ❑ Each day included a discussion session at the end of the “day”
- ❑ Themes of each day:
  - Setting the Stage
  - Experiments and methods
  - Large-x PDFs and resummation
  - PDF and PDA
  - Towards 3D Meson Structure

<https://indico.bnl.gov/e/PIEIC2020>

TUESDAY, 2 JUNE

8:00 AM → 9:55 AM


**Tuesday morning 1: Setting the stage**

Convener: Rolf Ent (Jefferson Lab)

8:00 AM

**Welcome and Introduction**

Speaker: Abhay Deshpande (Stony Brook University)

 00 Welcome-Pi-K-St...

8:15 AM

**Emergence of Pion and Kaon Structure – Introduction**

Speaker: Craig Roberts (Nanjing University)


 2006EHMEIC.pdf

 2006EHMEIC.pptx

8:40 AM

**Pion and Kaon Structure at an EIC – White Paper**

Speaker: Tanja Horn (Cath)


 CFNS-Pion-Kaon-Str...

 CFNS-Pion-Kaon-Str...

9:05 AM

**Pion and Kaon Structure with AMBER @ CERN**


Speaker: Oleg Denisov (INFN Torino)

 Oleg CFNS.pdf

9:30 AM

**Pion, Kaon and Proton Mass Understanding**

Speaker: Jianwei Qiu (Jefferson Lab)

 Qiu-PionKaon.pdf

9:55 AM → 10:15 AM **Break**

10:15 AM → 1:10 PM


**Tuesday morning 2: Setting the stage – Sullivan and Dreil-Yan methods**

Convener: Tanja Horn (Cath)

10:15 AM

**EIC detector, Simulations, Experimental Possibilities**


Speaker: Yulia Furlitova (Jefferson Lab)

 MesonStructure\_EI...

10:40 AM

**Pion and Kaon structure functions at EIC**


Speaker: Richard Trotta (The Catholic University of America)

 mesonSF\_CFNS.pdf

11:05 AM

**Pion/kaon structure study using Dreil-Yan pair production**

Speaker: Vincent Andrieux (UIUC)

 Andrieux\_EIC20200...

11:30 AM

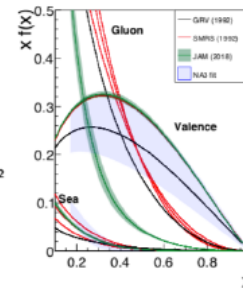
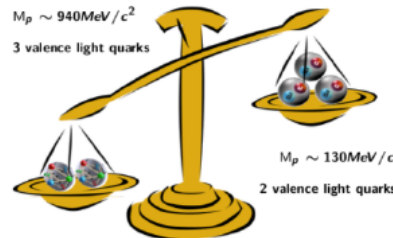
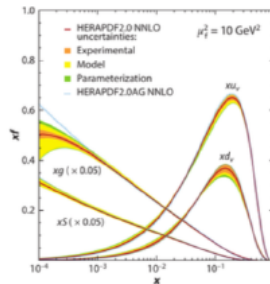
**Discussion on complementarity of experiments and theoretical methods**

Speaker: Paul E Reimer (Argonne National Laboratory)

# Pions and Kaons are fundamental

## Motivation

How to explain the origin of the mass of composite hadrons?

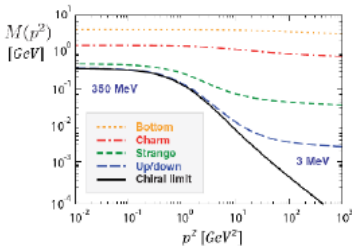


## The incomplete Hadron: Mass Puzzle

"Mass without mass!"

nucleon and the pion PDFs  
understand the hadrons mass budget.  
study their structure!

remote Jun-2020

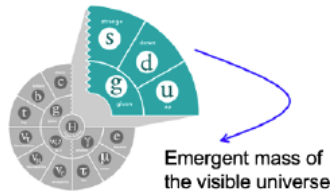


The light quarks acquire (most of) their masses as effect of the gluon cloud.  
The strange quark is at the boundary - both emergent-mass and Higgs-mass generation mechanisms are important.

**Proton: Mass ~ 940 MeV**  
preliminary LQCD results on mass budget,  
or view as mass acquisition by DCSB

**Kaon: Mass ~ 490 MeV**  
at a given scale, less gluons than in pion

**Pion: Mass ~ 140 MeV**  
mass enigma - gluons vs Goldstone boson



→ also see talks by Craig Roberts, Jianwei Qiu, ...

4

## Proton Mass

ates the mass of visible world:



**Higgs mechanism is not enough!!!**

**"Mass without mass!"**

□ How does QCD generate the nucleon mass?

"... 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. ..."

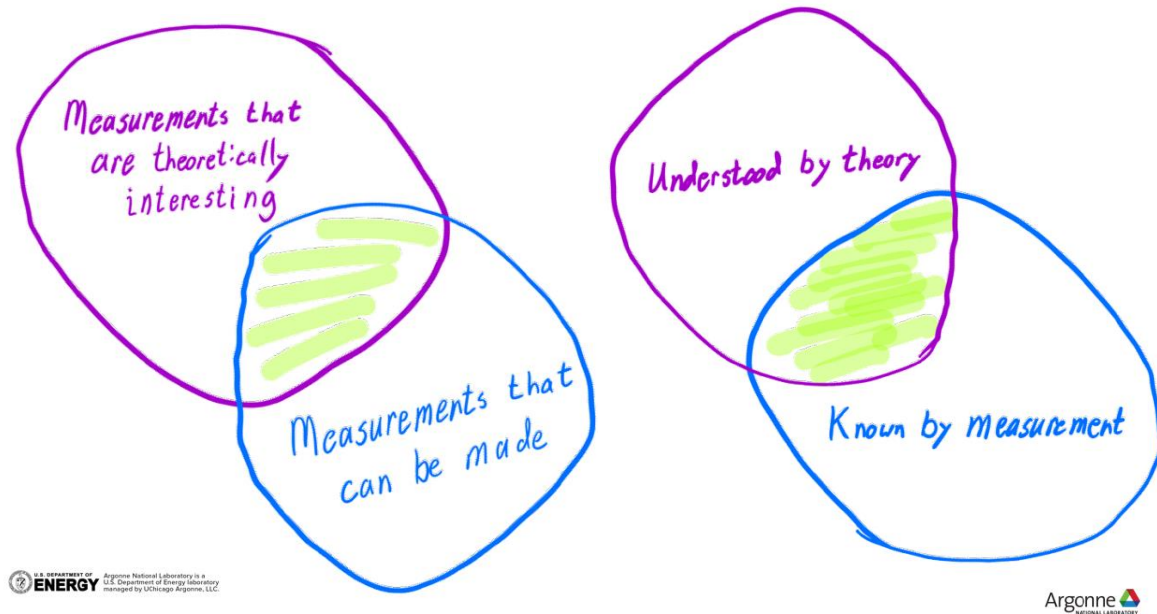
REACHING FOR THE HORIZON

The 2015 Long Range Plan for Nuclear Science

How to quantify and verify this, theoretically and experimentally?

# Complementarity of Experiments and Theoretical Models

Discussion leader: Paul Reimer (ANL)



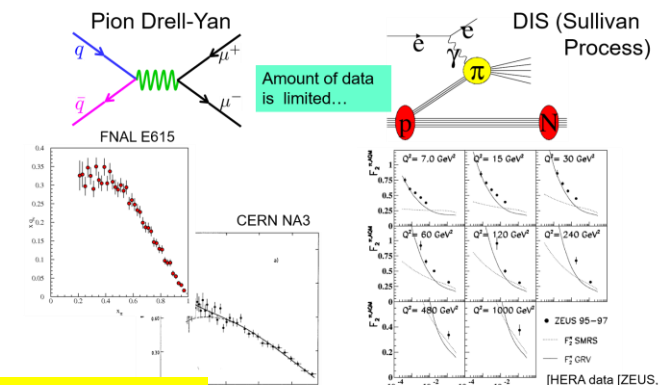
## Status: pion and kaon structure functions

### Pion

- Pointwise behaviour of pion's valence-quark distribution function: agreement between predictions from IQCD and symmetry-preserving QCD-consistent continuum analyses
- Amongst existing phenomenological studies of pion structure functions, only one employs a next-to-leading-order analysis that includes threshold resummation. This study is unique in producing a valence-quark DF that is consistent with large- $x$  QCD and matches continuum and lattice prediction
- General disagreement between phenomenological results and theory predictions for the pion's valence-quark DF feeds into uncertainty about pion's glue and sea distributions
- Resolution of these conflicts must await
  - Improved phenomenological analyses that include threshold resummation
  - New data that constrains the pion's glue and sea distributions.

Craig Roberts

## World Data on pion structure function $F_2^\pi$



Tanja Horn

ov, Vincent Andrieux, Richard Trotta, Rachel Montgomery, ...



# Overview – Experiments and Methods

Discussion leader: Paul Reimer (ANL)

## EHM COMPASS++/AMBER (PION INDUCED DY) (VINCENT)

PHASE-1

Pion structure in pion induced DY  
Expected accuracy as compared to NA3

- $\Sigma_{DY} = \sigma^{\pi^+ C} - \sigma^{\pi^- C}$ ; only valence-valence
- $\Sigma_{DY} = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$ ; no valence-valence
- Collect at least a factor 10 more statistics than presently available
- Minimize nuclear effects on target side
  - Projection for 2 x 140 days of Drell-Yan data taking
  - $\pi^+$  to  $\pi^-$  10:1 time sharing
  - 100 GeV beams on Carbon target (1.9A<sub>u</sub>)
  - Improvement of shielding to double the intensity is under investigation

Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (particles)	DY mass (GeV/c <sup>2</sup> )	DY events
NA3	30 cm W	252	$\pi^+$	$17.6 \times 10^7$	4.38 - 8.58	5000
			$\pi^-$	$18.6 \times 10^7$		30000
NA3	30 cm H <sub>2</sub>	208	$\pi^+$	$2.0 \times 10^7$	-1 - 8.5	40
			$\pi^-$	$3.0 \times 10^7$		121
NA10	6 cm Pt	308	$\pi^+$	$2.0 \times 10^7$	-2.3 - 8.5	1767
			$\pi^-$	$3.0 \times 10^7$		4961
	120 cm D <sub>2</sub>	284	$\pi^+$	$65 \times 10^7$	-2.3 - 8.5	7800
			$\pi^-$	$4.35 \times 10^7$		1200
COMPASS 2015	12 cm W	194	$\pi^+$	$65 \times 10^7$	-2.3 - 8.5	96600
			$\pi^-$	$4.07 \times 10^7$		155000
COMPASS 2016	140 cm NH <sub>2</sub>	190	$\pi^+$	$7.0 \times 10^7$	-2.3 - 8.5	35000
			$\pi^-$	$4.0 \times 10^7$		52000
This exp.	100 cm C	100	$\pi^+$	$1.7 \times 10^7$	-2.3 - 8.5	11700
			$\pi^-$	$6.8 \times 10^7$		11900
	100 cm C	100	$\pi^+$	$6.8 \times 10^7$	-2.3 - 8.5	67000
			$\pi^-$	$1.0 \times 10^7$		91100
	12 cm W	190	$\pi^+$	$0.4 \times 10^7$	-2.3 - 8.5	1100
			$\pi^-$	$1.8 \times 10^7$		14100
			$\pi^+$		-2.3 - 8.5	22100

Isoscalar target + Both positive and negative beams + High statistics

## Pion Structure Function Projections

### Electron-Ion Collider

possible energy is normally best

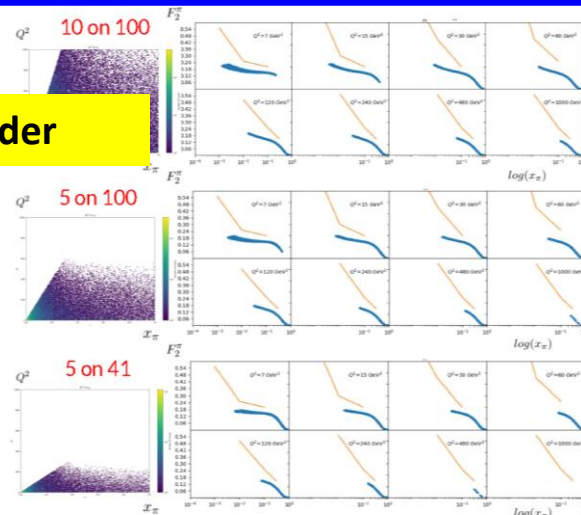
For high beam energies this area requires y to be low

5 on 100 can access more acceptance at high-x, but lose acceptance to the low-x region

Even more for 5 on 41

- There are some advantages for lower proton energy for K-Λ detection

Richard Trotta



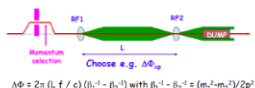
Oleg Denisov

## COMPASS++/AMBER (kaon induced DY) (Vincent)

Extremely important to compare the gluon content of kaon and pion (emergent mass)

- First ever DY measurements that could lead to kaon PDFs
- Achievable statistics depends on beam energy and on kaon beam purity. Assuming  $I = 7 \times 10^7$  s<sup>-1</sup> with 30% kaons:
  - 40 kevents (K<sup>+</sup>) and 5 kevents (K<sup>+</sup>) @ 100 GeV
  - 25 kevents (K<sup>-</sup>) and 3 kevents (K<sup>+</sup>) @ 80 GeV

Projected statistical errors after 140 days of running, compared to NA3 stat. errors



Experiment	Target type	Beam type	Beam intensity (particles)	Beam energy (GeV)	DY mass (GeV/c <sup>2</sup> )	DY events
NA3	6 cm Pt	K <sup>-</sup>	$2.1 \times 10^7$	200	4.2 - 8.5	700
		K <sup>+</sup>	$2.1 \times 10^7$	200	4.2 - 8.5	12,000
		K <sup>+</sup>	$2.1 \times 10^7$	200	4.2 - 8.5	18,000
		K <sup>+</sup>	$2.1 \times 10^7$	200	4.2 - 8.5	25,000
		K <sup>+</sup>	$2.1 \times 10^7$	200	4.2 - 8.5	40,000
		K <sup>+</sup>	$2.1 \times 10^7$	200	4.2 - 8.5	54,000
This exp.	100 cm C	K <sup>-</sup>	$2.1 \times 10^7$	60	4.0 - 8.5	1,000
		K <sup>+</sup>	$2.1 \times 10^7$	60	4.0 - 8.5	1,800
		K <sup>+</sup>	$2.1 \times 10^7$	60	4.0 - 8.5	2,800
		K <sup>+</sup>	$2.1 \times 10^7$	60	4.0 - 8.5	5,200
		K <sup>+</sup>	$2.1 \times 10^7$	60	4.0 - 8.5	8,000
This exp.	100 cm C	$\pi^-$	$4.8 \times 10^7$	60	4.0 - 8.5	31,000
		$\pi^-$	$4.8 \times 10^7$	60	4.0 - 8.5	50,800
		$\pi^-$	$4.8 \times 10^7$	60	4.0 - 8.5	65,500
		$\pi^-$	$4.8 \times 10^7$	60	4.0 - 8.5	95,500
		$\pi^-$	$4.8 \times 10^7$	60	4.0 - 8.5	123,600

Oleg Denisov

## Pion and Kaon Structure

□ Pion decays, and there is no stable pion target

□ Pion beam:

Talking advantage of time-dilation,  $\pi + p \rightarrow \ell^+ \ell^- + X$  Drell-Yan process

Precision of pion structure depends on our knowledge of proton structure

□ Lattice QCD:

– using a vector-axial-vector correlation as an example

$$\frac{1}{2} [T_{\pi\pi}^{\mu\nu}(\xi, p) + T_{\pi\pi}^{\mu\nu}(\xi, p)] = \frac{\xi^4}{2} \langle h(p) | (\mathcal{J}_\pi^\mu(\xi/2) \mathcal{J}_\pi^\nu(-\xi/2) + \mathcal{J}_\pi^\mu(-\xi/2) \mathcal{J}_\pi^\nu(\xi/2)) | h(p) \rangle$$

$$\equiv \epsilon^{\mu\nu\alpha\beta} p_\alpha \xi_\beta \tilde{T}_1(\omega, \xi^2) + (p^\mu \xi^\nu - \xi^\mu p^\nu) \tilde{T}_2(\omega, \xi^2)$$

♦ Collinear factorization:

$$\tilde{T}_i(\omega, \xi^2) = \sum_{f=q,g} \int_0^1 \frac{dx}{x} f(x, \mu^2) C_i^f(\omega, \xi^2; x, \mu^2) + \mathcal{O}(|\xi|/\text{fm})$$

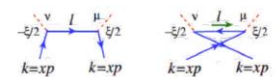
♦ Lowest order coefficient functions:

$$C_1^{q(0)}(\omega, \xi^2; x) = \frac{1}{\pi^2} x (e^{i\omega x} + e^{-i\omega x})$$

$$T_1(\tilde{x}, \xi^2) \equiv \int \frac{d\omega}{2\pi} e^{-i\omega \tilde{x}} \tilde{T}_1(\omega, \xi^2)$$

$$= \frac{1}{(n\tilde{x})^{15}} \pi \tilde{x}^2 \tilde{x}^2 = \frac{1}{(n\tilde{x})^2} \tilde{x}^2$$

Vanishes under T



Jianwei Qiu

ENERGY

Suffolk University

# Summary – Experiments and Methods

Discussion leader: Paul Reimer (ANL)

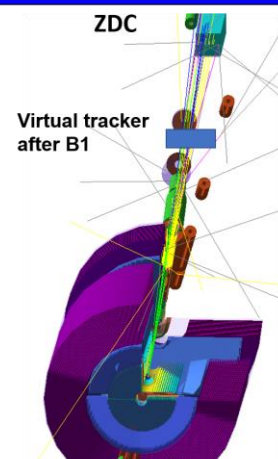
❑ Much progress with continuum and lattice calculations

❑ Many exciting opportunities at existing and future facilities:

- JLab 12 GeV – TDIS, valence PDF, exploratory kaon measurements
- AMBER@CERN – DY pion and kaon, plus prompt photons, sea quarks
- EIC – pion and kaon SF over large range in  $x$  and  $Q^2$ , gluon content
- EicC – pion and kaon SF

## Electron-Ion Collider

### Summary of Detector Requirements



Yulia Furlanova

#### ❑ For $\pi$ -n:

- For all energies, the neutron detection efficiency is 100% with the planned ZDC
- Lower energies (5 on 41, 5 on 100) require at least 60cm x 60cm to access wider range of energies

#### ❑ For $\pi$ -n and $K^*/\Lambda$ :

- All energies need good ZDC angular resolution for the required  $-t$  resolution
- High energies (10 on 100, 10 on 135, 18 on 275) require resolution of 1cm or better

#### ❑ $K^*/\Lambda$ benefits from low energies (5 on 41, 5 on 100) and also need:

- $\Lambda \rightarrow n + \pi^0$  : additional high-res/granularity EMCal+tracking before ZDC – seems doable
- $\Lambda \rightarrow p + \pi^-$  : additional trackers in opposite direction on path to ZDC – more challenging

#### ❑ Standard electron detection requirements

- ❑ Good hadron calorimetry for good  $x$  resolution at large  $x$

❑ To better define complementarity of experiments need input from theory on what is interesting to measure, e.g. for valence, sea, gluon content

# Overview – large-x PDFs

Discussion leaders: Tim Hobbs, Pavel Nadolsky, Fred Olness (SMU)

## From nucleon to meson PDF fits

... a cooperative presentation & discussion

Aurore Courtoy, Tim Hobbs, Pavel Nadolsky, Fred Olness

Instituto de Física, Universidad Nacional Autónoma de México,  
Jefferson Lab, & Southern Methodist University

Thanks for substantial input  
from our friends & colleagues



Workshop on Pion and Kaon  
Structure Functions at the EIC  
2-June 5, 2020  
CFNS Virtual Meeting

### I: Tools for nucleon and meson PDF fits

Nuclear Fits to Pion Fits  
Analysis Tools (xFitter, Python, Mathematica)

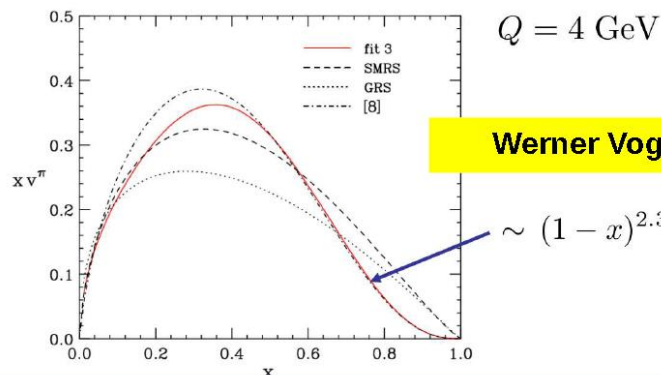
### II: Toward Global Analyses of meson structure

Nucleon PDFs: CTEQ-TEA, CTEQ-JLab  
Nuclear PDFs: nCTEQ (nuclear CTEQ)  
Meson PDFs in the AMBER/EIC era  
New methodology

### III: Discussion

$$xv^\pi(x, Q_0^2) = N_v x^\alpha (1-x)^\beta (1 + \gamma x^\delta) \quad Q_0 = 0.63 \text{ GeV}$$

Fit	$2\langle x v^\pi \rangle$	$\alpha$	$\beta$	$\gamma$	$K$	$\chi^2$ (no. of points)
1	0.55	$0.15 \pm 0.04$	$1.75 \pm 0.04$	89.4	$0.999 \pm 0.011$	82.8 (70)
2	0.60	$0.44 \pm 0.07$	$1.93 \pm 0.03$	25.5	$0.968 \pm 0.011$	80.9 (70)
3	0.65	$0.70 \pm 0.07$	$2.03 \pm 0.06$	13.8	$0.919 \pm 0.009$	80.1 (70)
4	0.7	$1.06 \pm 0.05$	$2.12 \pm 0.06$	6.7	$0.868 \pm 0.009$	81.0 (70)

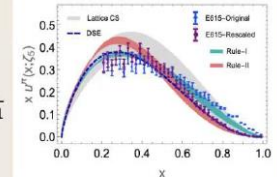


Werner Vogelsang

## Lei Chang

✓ Accommodate proton and pion DYW relation in LFHQCD

- ✦ Rule-1:  $\sim (1-x)^{2\tau-3}$ , with  $g(\tau) = 2$
- ✦ Rule-2:  $\sim (1-x)^{2\tau-2}$ , with  $g(\tau) = 2 + \frac{1}{\tau-1}$



✓ DCSB effect on PDA and PDF...not whole story

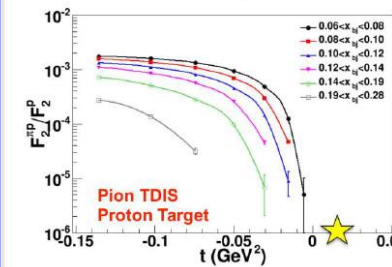
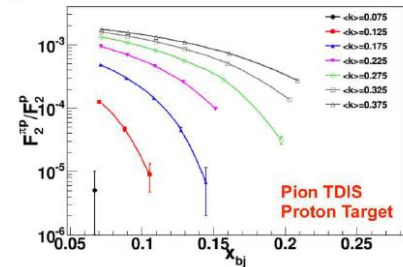
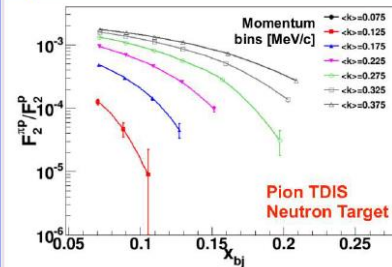
$$\text{PDF}_\pi \sim (1-x)^2 + M(Q^2)(1-x)^{\frac{2}{3}}$$



Thanks for your attention

## Rachel Montgomery

### Example Projected Results



- Top:  $x_{bj}$  dependence of ratio semi-inclusive SF to inclusive nucleon SF (points) in bins of momentum integration ranges for recoiling hadrons
- Bottom example of potential reach in  $t$  towards pion pole
- Low momentum reach of mTPC crucial to map out shape



# Overview – large-x PDFs

Discussion leaders: Tim Hobbs, Pavel Nadolsky, Fred Olness (SMU)

## Summary and outlook

Minghui Ding

### Summary

- Using a **continuum approach**, presented a symmetry-preserving calculation of the **pion's PDF**.
  - A novel term  $q_{BC}^\pi(x; \zeta_H)$  is necessary to keep  $q^\pi(x; \zeta_H) = q^\pi(1-x; \zeta_H)$  and then  $\langle x \rangle_\pi^1 = 1/2$ ;
  - $\zeta_H = 0.30 \text{ GeV}$  is the hadronic scale, and is determined by connecting the one-loop running coupling with QCD's **process-independent effective charge**.
  - $q^\pi(x; \zeta_H)$  is a **broad function** and is a consequence of **dynamical chiral symmetry breaking**.
  - Valence quark  $q^\pi(x; \zeta_2)$  large x behaviour  $\beta(\zeta_2) = 2.38(9)$ , and first moment  $\langle 2x \rangle_q^\pi = 0.48(3)$ . Valence quark  $q^\pi(x; \zeta_3)$  agrees with rescaled E615 data and IQCD prediction, large x behaviour  $\beta(\zeta_3) = 2.66(12)$ , and first moment  $\langle 2x \rangle_q^\pi = 0.42(4)$ .
  - Gluon and sea quark PDFs  $\zeta_2, \langle x \rangle_g^\pi = 0.41(2), \langle x \rangle_{sea}^\pi = 0.11(2), \zeta_3, \langle x \rangle_g^\pi = 0.45(1), \langle x \rangle_{sea}^\pi = 0.14(2)$ .

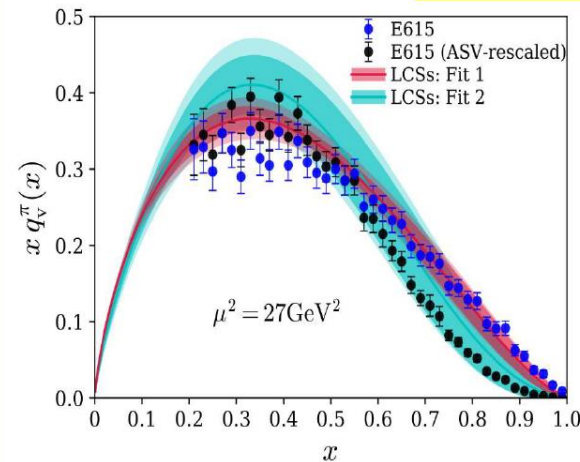
### Outlook

- Kaon PDFs.
- Nucleon PDFs.

Thank you

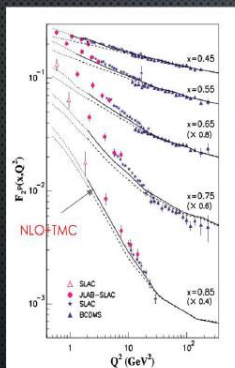
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David Richards

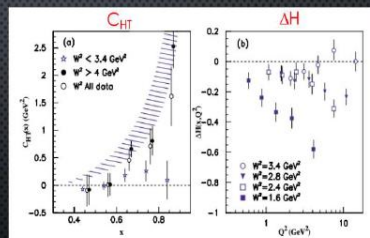


Slightly favors softer  $[(1-x)^2]$  fit  $\rightarrow$  need for finer resolution in Ioffe time..

First hint of  $W^2$  dependent effects



$$\frac{F_2^{\text{exp}}}{F_2^{\text{QCD+TMC}}} = 1 + \frac{C_{\text{HT}}(x)}{Q^2} + \Delta H(x, Q^2).$$



Simonetta Liuti

S. Liuti, R. Ent, C.E. Keppel, and I. Niculescu,  
Phys. Rev. Lett. **89**, 162001 (2002)

Jefferson Lab Angular  
Momentum Collaboration

NC STATE  
UNIVERSITY

## JAM Pion PDF Analysis Including Resummation

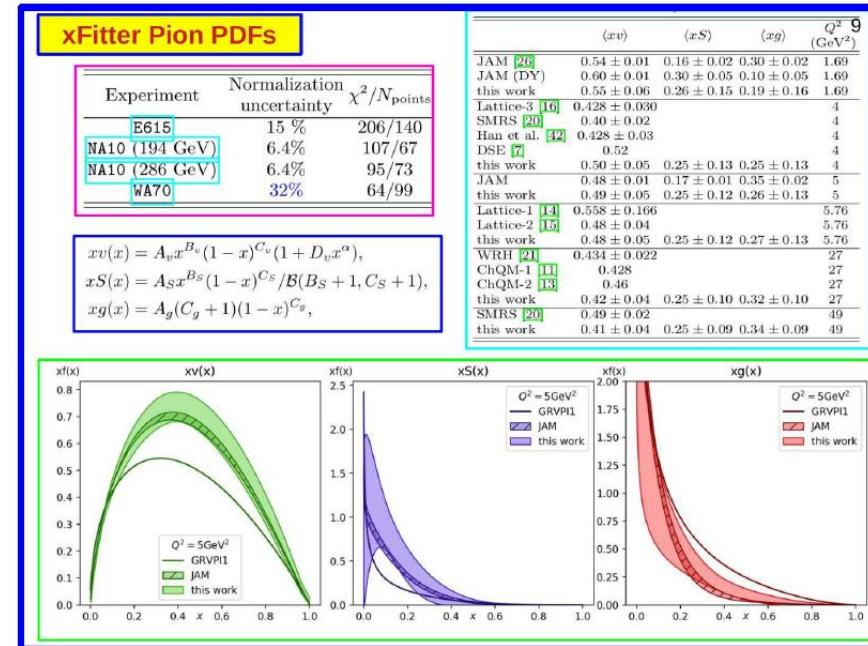
Patrick Barry, Nobuo Sato, Wally Melnitchouk, and C.-R. Ji  
Workshop on Pion and Kaon Structure Functions at the EIC  
Wednesday, June 3<sup>rd</sup>, 2020  
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Patrick Barry

# Summary – large-x PDFs

Discussion leaders: Tim Hobbs, Pavel Nadolsky, Fred Olness (SMU)

- ❑ Global fit results with uncertainties show that clearly not there yet – very sparse data
- ❑ Resummation is important to include in global fits
- ❑ Time to look at flexible functional forms
  - The current form:  $x^a (1-x)^b$  is very restrictive
- ❑ For full power of quark PDFs: need for pion and kaon SF data in the large x region, for large range of  $Q^2$
- ❑ Action item for Meson SF WG: pion structure function with estimate of uncertainties by varying PDFs – for EIC projections



# Overview – PDA and PDF

Discussion leader: Craig Roberts (Nanjing U.)

## Meson leading-twist DAs

- Continuum results exist & IQCD results arriving
- Common feature = broadening
- Origin = EHM
- NO differences between  $\pi$  & K if EHM is all there is
  - Differences arise from Higgs-modulation of EHM mechanism
  - “Contrasting  $\pi$  & K properties reveals Higgs wave on EHM ocean”

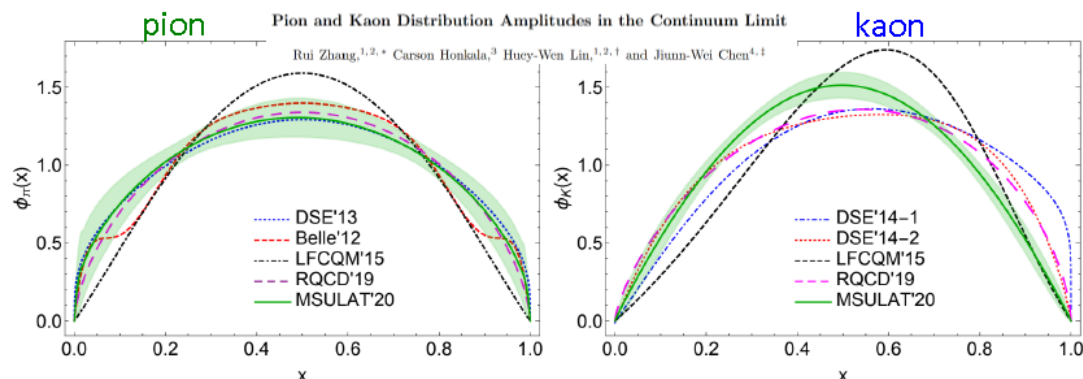
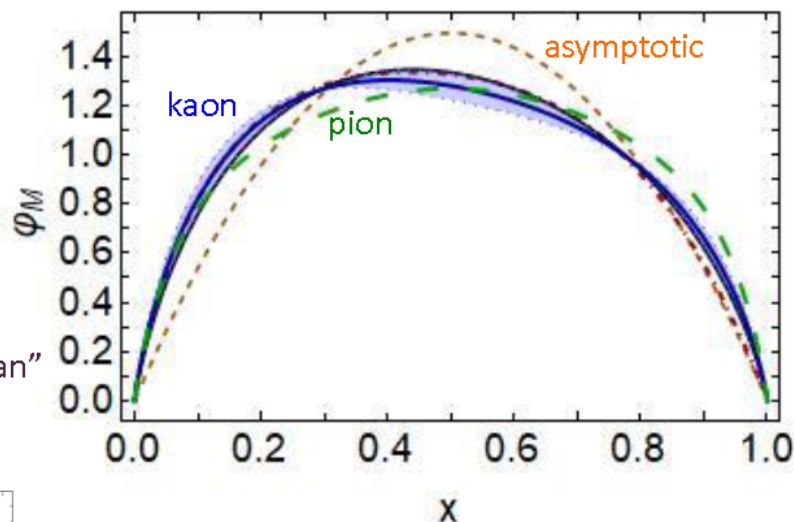


FIG. 10. Fit of the  $P_z = 4\frac{2\pi}{L}$  pion (left) and kaon (right) data to the analytical form in Bjorken- $x$  space, compared with previous calculations (with only central values shown). Although we do not impose the symmetric condition  $m = n$ , both results for the pion and kaon are symmetric around  $x = 1/2$  within error.

Craig Roberts,  $\pi$  & K structure - window onto EHM



- Kaon DA vs pion DA
  - almost as broad
  - peak shifted to  $x=0.4(5)$
  - $\langle \xi^2 \rangle = 0.24(1)$ ,  $\langle \xi \rangle = 0.035(5)$
- ERBL evolution logarithmic
- Broadening & skewing persist to very large resolving scales – beyond LHC

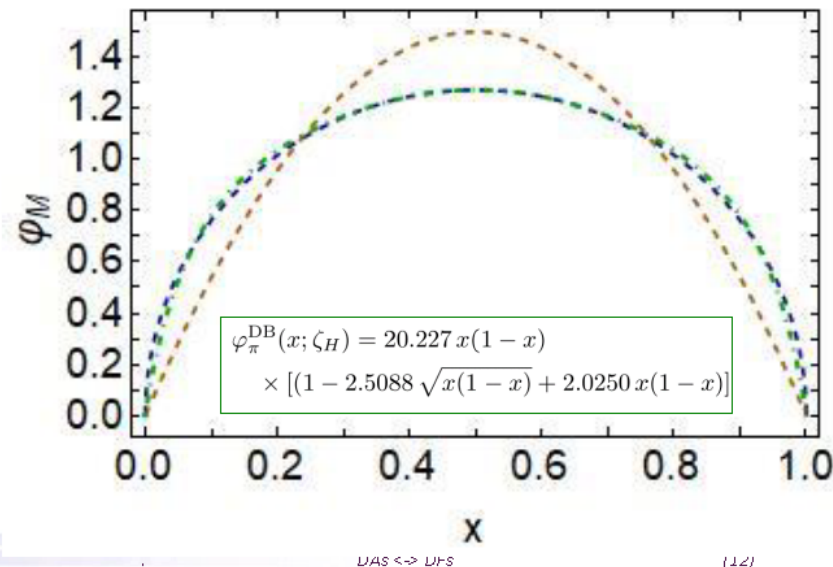


# Overview – PDA and PDF

Discussion leader: Craig Roberts (Nanjing U.)

## Meson leading-twist DAs and valence-quark DFs

- Broadening need not and should not disturb the DA's endpoint behaviour
- QCD:  $\varphi(x) = x(1-x)f(x)$ ,  $f(x \simeq 0) = \text{constant}_1$ ,  $f(x \simeq 1) = \text{constant}_2$
- Many models that express EHM-induced broadening violate this constraint
- Typically not a problem, unless endpoint behaviour is taken too seriously
- Example AdS/QCD:  $\varphi(x) = \frac{8}{\pi} \sqrt{x(1-x)}$
- Practically identical to the continuum prediction that preserves QCD constraint:
  - blue dashed vs green dot-dashed
  - However, AdS/QCD practitioners use DA to argue for  $x \simeq 1 \Rightarrow q^\pi(x; \zeta_H) \propto (1-x)^1$
  - Endpoint behaviour taken “too seriously”



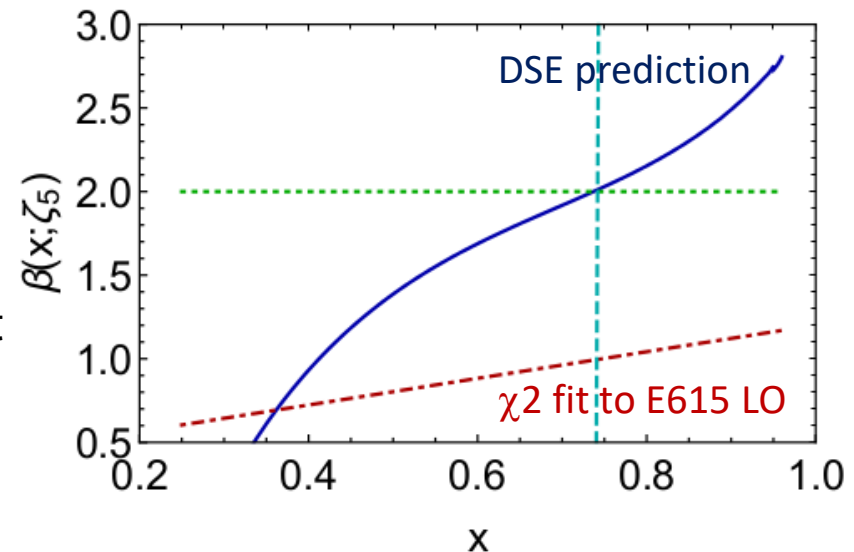
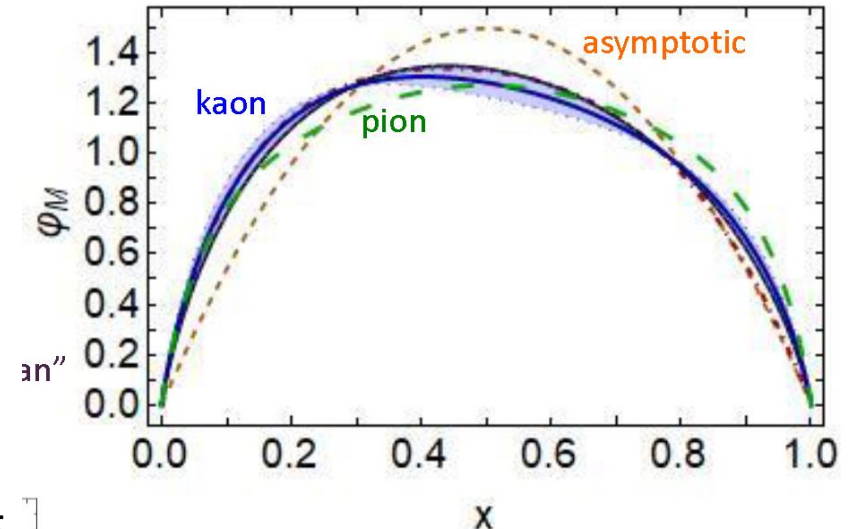
# Summary – PDA and PDF

Discussion leader: Craig Roberts  
(Nanjing U.)

- ❑ LFWF is the unifying object
  - EHM in every hadron LFWF
  - Experiments sensitive to differences in LFWF are sensitive to EHM
- ❑ Examples are PDA and PDF
  - Scaling in parton model- QCD gluon corrections give scaling violations, pion FF
- ❑ Broadening of DA – DF
  - Manifestation of EHM
  - Higgs violations (strange quark)
- ❑ Pion valence DF - all internally consistent calculations preserve:

$$J=0 \dots (1/k^2)^n \Leftrightarrow (1-x)^{2n}$$

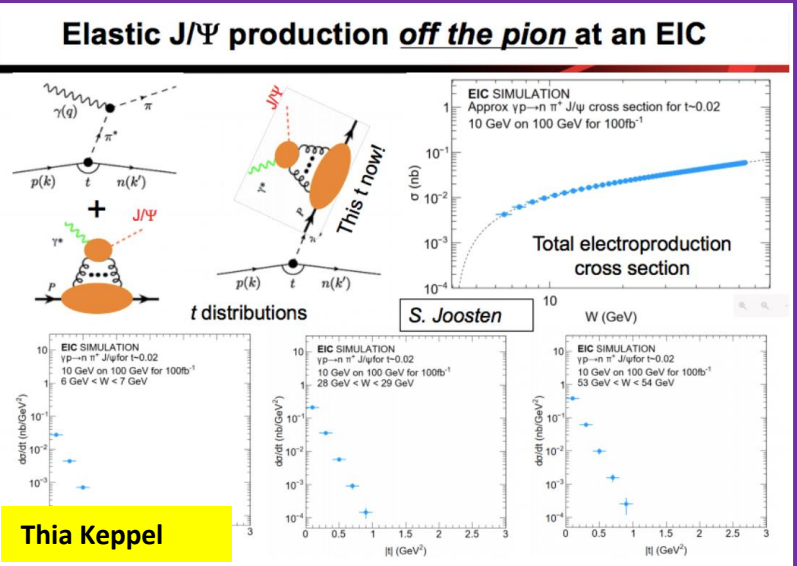
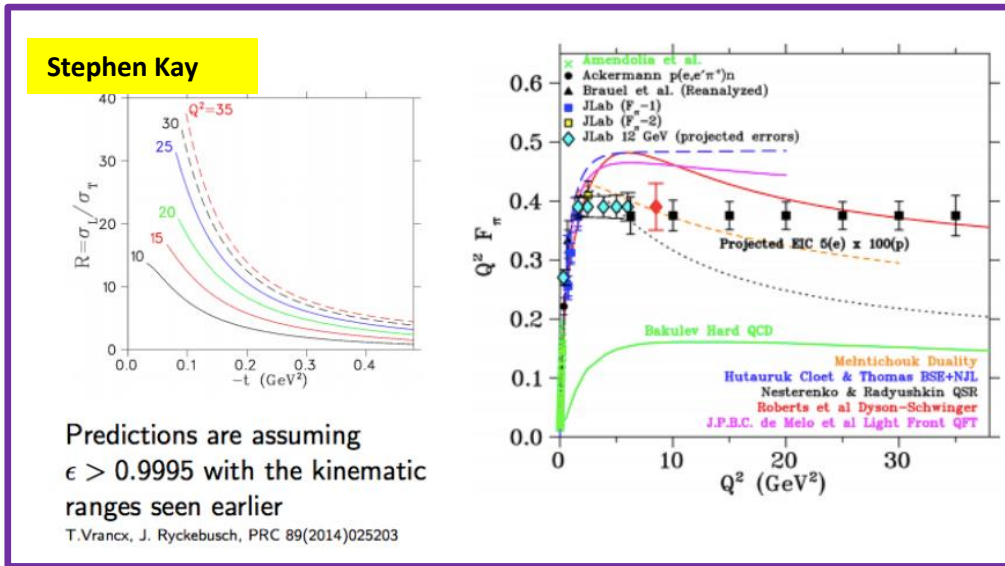
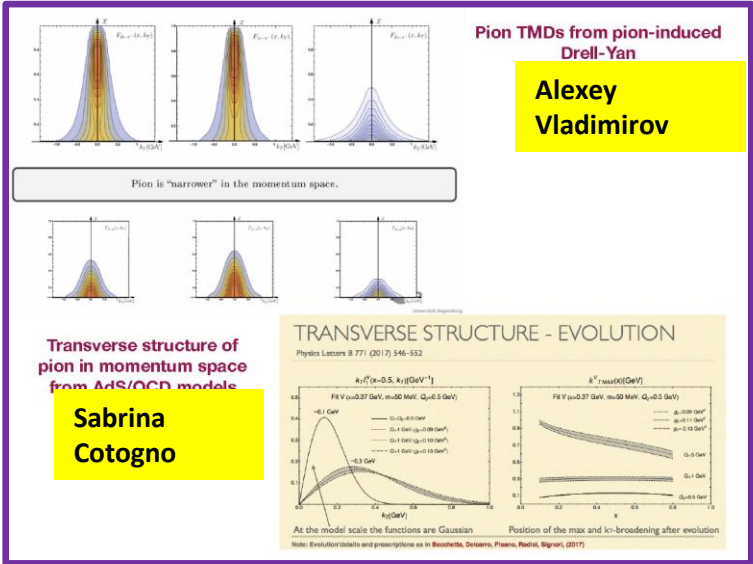
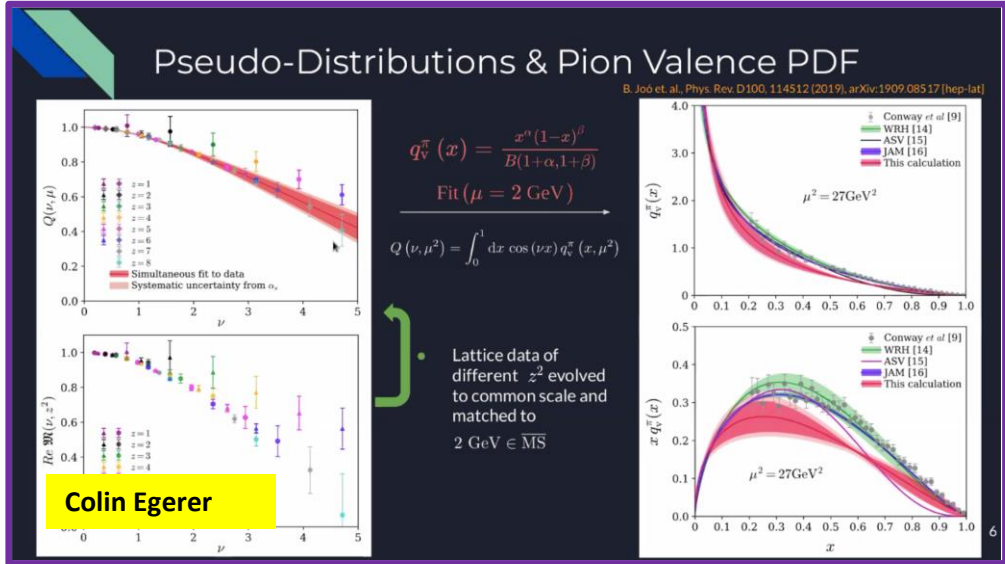
- Experimental test: precise data and sound extraction in region  $0.6 < x < 0.8$  sufficient to test QCD prediction





# Overview – Towards 3D Meson Structure

Discussion leader: Daria Sokhan (U. Glasgow)



# Summary – Towards 3D Meson Structure

Discussion leader: Daria Sokhan (U. Glasgow)

## ❑ Theoretical studies status

- Define regions where it is safe to extract pion and kaon SFs
- Better understand backgrounds, e.g. disentangle diffractive from other processes
- Region of interest to distinguish between different models

## ❑ Experimental status

- Detector development of requirements ongoing in meson SF WG
- For pion GPD need to show that Sullivan process dominates – impact on detectors, e.g. electron calorimetry to do pion DVCS

## ❑ Interesting prospects for pion TMDs

- ❑ Theory can make predictions for 3D structure, but much work needed on phenomenological connection between data and calculation

# Global Summary from the Meson SF WS

- ❑ Case for pion and kaon is strong
  - They are fundamental to our existence
  - They have almost never been explored
- ❑ Path from experiment to QCD via phenomenological analysis must be made very rigorous – a challenging task
- ❑ Fold in knowledge gained over the last ~3 decades on PDFs
  - ❑ Pion valence DF - all internally consistent calculations preserve:  $J=0 \dots (1/k^2)^n \Leftrightarrow (1-x)^{2n}$
  - ❑ Current fit form is very restrictive - time to look at flexible functional forms
- ❑ To better define complementarity of experiments need input from theory on what is interesting to measure, e.g. for valence, sea, gluon content

**The time is now to start the work because we are building facilities that can explore pion and kaon structure experimentally**

# Action Items Meson WG - Experiment

- ❑ Continue development of projections and detector requirements
  - Detector development of requirements
  - For pion GPD need to show that Sullivan process dominates – impact on detectors, e.g. electron calorimetry to do pion DVCS
- ❑ Pion structure function with estimate of uncertainties by varying PDFs – for EIC projections

**Next Meson SF Meeting: Monday 22 June at 4pm (ET)**

**To join the Meson WG: email one of the Conveners or Tanja Horn (hornt@cua)**





# Status: pion and kaon structure functions

## Pion

- Pointwise behaviour of pion's valence-quark distribution function: agreement between predictions from LQCD and symmetry-preserving QCD-consistent continuum analyses
- Amongst existing phenomenological studies of pion structure functions, only one employs a next-to-leading-order analysis that includes threshold resummation. This study is unique in producing a valence-quark DF that is consistent with large- $x$  QCD and matches continuum and lattice prediction
- General disagreement between phenomenological results and theory predictions for the pion's valence-quark DF feeds into uncertainty about pion's glue and sea distributions
- Resolution of these conflicts must await
  - Improved phenomenological analyses that include threshold resummation
  - New data that constrains the pion's glue and sea distributions.



# Status: pion and kaon structure functions

## Kaon

- Very little empirical information available on K DFs  $\Rightarrow$  no recent phenom. inferences.
  - Valence-quark distributions: results from models and a single, recent IQCD study
  - Kaon's glue and sea distributions: no results
- Hence, symmetry-preserving continuum QCD predictions sketched here for entire array of kaon DFs currently stand alone.
- One piece of available experimental information:  $u_K(x)/u_\pi(x)$ 
  - Continuum prediction for ratio is consistent with the data.
  - But, given the large errors, this ratio is very forgiving of even large differences between various calculations of the individual DFs used to produce the ratio.
    - Modern, precise data is critical if this ratio is to be used as a path to understanding the Standard Model's Nambu-Goldstone modes;
    - Results for  $u_\pi(x;\zeta_5)$ ,  $u_K(x;\zeta_5)$  separately would be better.



## Final remarks

1. A theoretical model cannot be falsified empirically if its uncertainty is unknown.
2. Multiple functional forms of PDFs adequately describe the global set of experimental data.
3. The  $x$  –dependence of the best-fit PDF depends on the PDF definition (e.g.,  $\overline{MS}$  factorization scheme), order of  $\alpha_s$ , treatment of power-suppressed corrections, and other factors. Comparison to the pheno PDF requires proper conversion into the definition adopted by the pheno PDF.
4. Threshold resummation may modify both the shapes and normalizations of some pion DY cross sections. The resummed  $W$  term dominant at  $Q^2/\hat{s} \rightarrow 1$  must be matched to the fixed-order (FO) cross section at  $Q^2/\hat{s} < 1$ . The resulting PDFs may depend on the resummed nonperturbative contributions at large Mellin moments  $N$  and the matching procedure.
5. Determination of sea quark and gluon PDFs in the pion generally benefits from the extended reach in  $Q$  in DIS and other processes.

# Overview – PDA and PDF

## PDAs & PDFs

- Relationship between leading-twist PDAs and valence-quark PDFs, expressed via a meson's light-front wave function (LFWF):

$$\varphi(x) \sim \int d^2 k_{\perp} \psi(x, k_{\perp}^2),$$

$$q(x) \sim \int d^2 k_{\perp} |\psi(x, k_{\perp}^2)|^2$$

- Given that factorization of LFWF is a good approximation for integrated quantities, then at the hadronic scale,  $\zeta_H$ :

$$q_{\pi,K}(x; \zeta_H) \propto \varphi_{\pi,K}^q(x; \zeta_H)^2$$

Proportionality constant is fixed by baryon number conservation

- Owing to parton splitting effects, this identity is not valid on  $\zeta > \zeta_H$ .

(Think about DGLAP and ERBL regions for a GPD.)

- Nevertheless, evolution equations are known; so the connection is not lost, it just metamorphoses.



# Overview – PDA and PDF

## Meson valence-quark DFs

- Owing to these relations
$$\varphi(x) \sim \int d^2 k_{\perp} \psi(x, k_{\perp}^2),$$
$$q(x) \sim \int d^2 k_{\perp} |\psi(x, k_{\perp}^2)|^2$$
- Broadening of DAs feeds into broadening of DFs
- Necessary consequence of EHM
- Moreover, any Higgs-boson related modulations of EHM in the DA will also be expressed in the DF
- Pion – Kaon comparisons great place to study interference between the Standard Model's two mass-generating mechanisms