Outcome of the June CFNS Workshop on π and *K* Structure at the EIC

Tanja Horn

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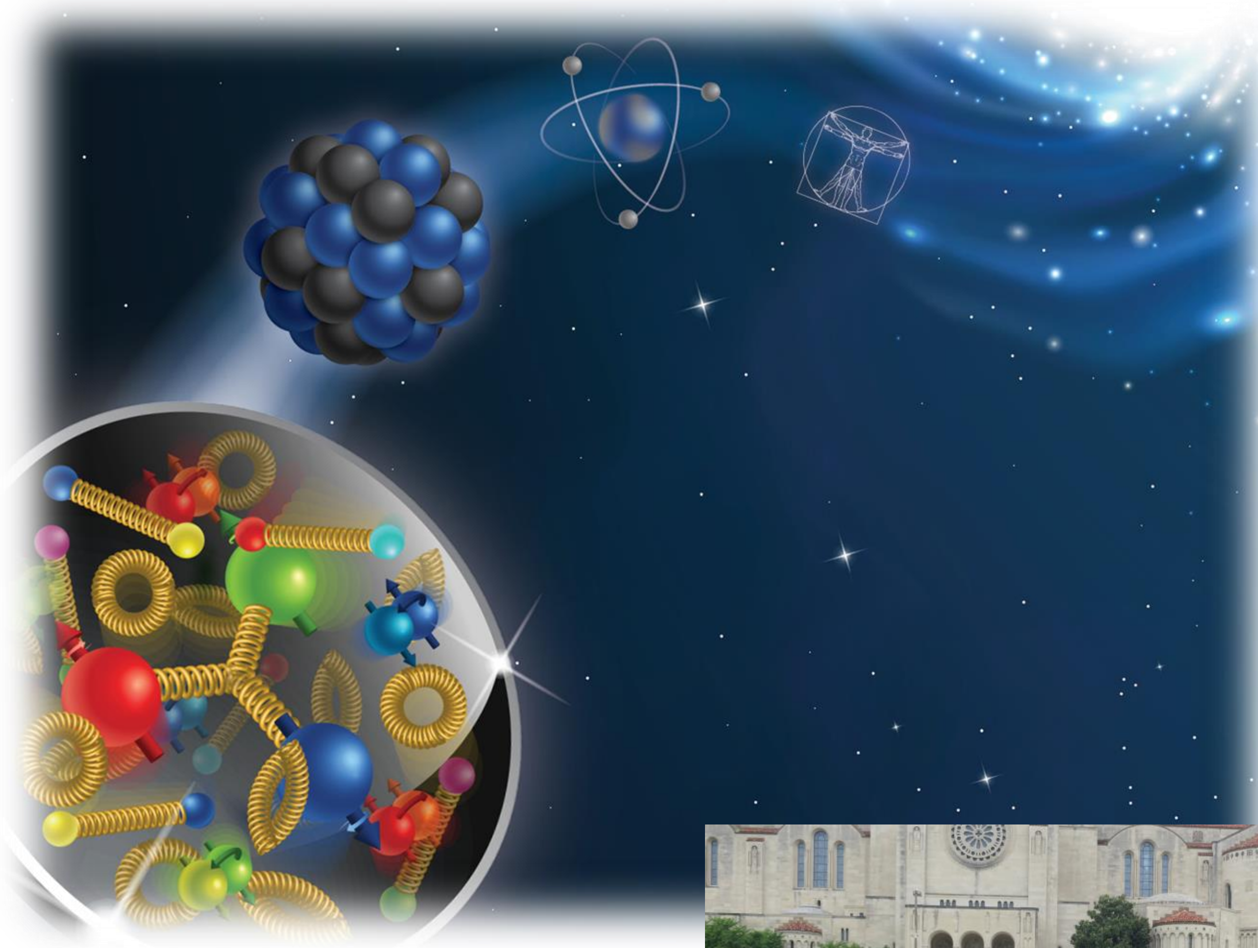
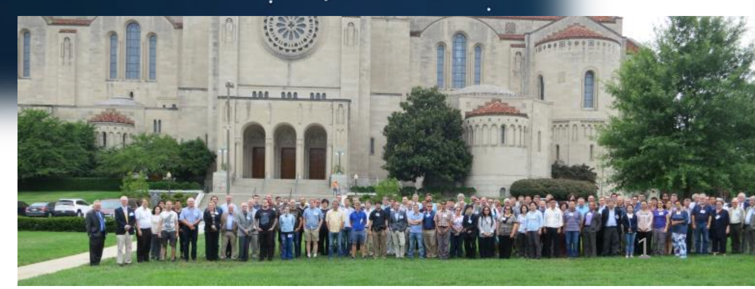
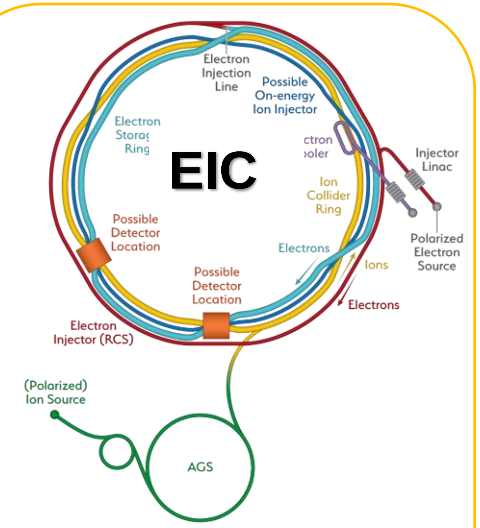




Introduction

- ❑ Studies of hadron structure, in 1D, via electromagnetic form factors and PDFs, and 3D, through TMDs and GPDs, are entering a new era of discovery.
  - ➢ first results from the 12 GeV upgrade of CEBAF at Jefferson Lab
  - ➢ announcement of an EIC to be sited at BNL
  - ➢ steady progress toward exascale computing
  - ➢ continuing development of global analysis frameworks
  - ➢ rapid progress in QCD theory

- ❑ All this demands a coordinated effort, aimed at exploiting these developments and ensuring they can be combined synergistically to deliver, at last, a complete picture of the structure of hadrons.



CD-0 was approved by DOE in December 2019

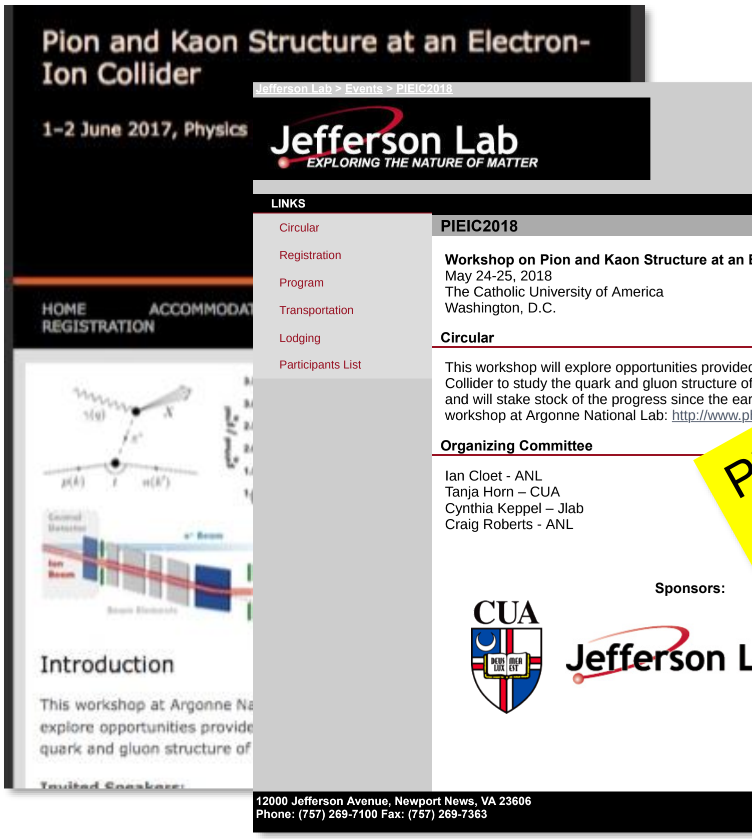
Site selection at BNL announced in January 2020

Hadron Structure: Key Experimental Efforts at the EIC

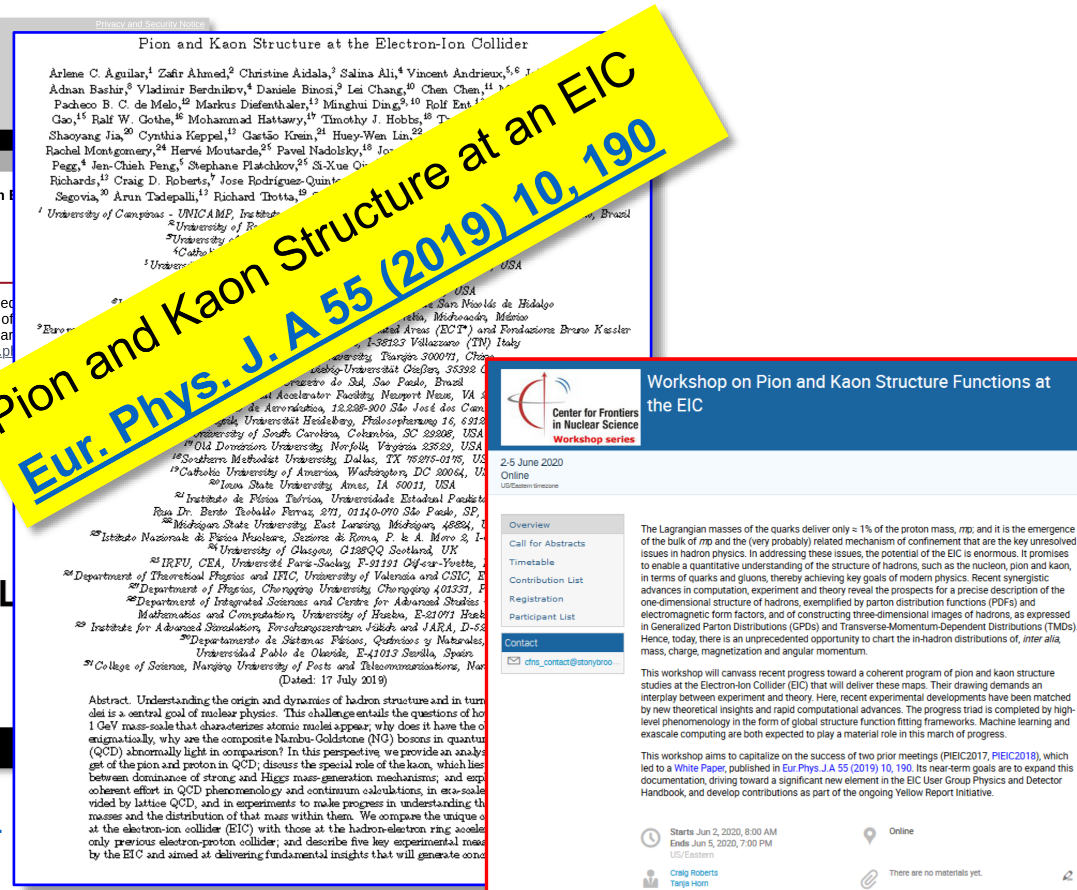
- Hadron masses in light quark systems
  - Pion and kaon parton distribution functions (PDFs) and generalized parton distributions (GPDs)
- Gluon (binding) energy in Nambu-Goldstone modes
  - Open charm production from pion and kaon
- Mass acquisition from Dynamical Chiral Symmetry Breaking (DCSB)
  - Pion and kaon form factors
- Strong vs. Higgs mass generating mechanisms
  - Valence quark distributions in pion and kaon at large momentum fraction x
- Timelike analog of mass acquisition
  - Fragmentation of a quark into pions or kaons

Context: π/K Structure at an EIC and Understanding Mass

- PIEIC Workshops hosted at ANL (2017) and CUA (2018)
- ECT* WS: Emergent Mass and its Consequences (2018)



PIEIC White Paper (2019)



- AMBER/CERN Workshop (2020)
- CFNS Workshop (2020)
- ECT*: Workshop on Mass in the Standard Model and Consequences of its Emergence (2021)

Context: Meson SF Yellow Report Working Group

Formed in 2019 in context of the EIC User Group Yellow Report Effort

- Meson SF WG: 22 members, 13 institutions, 7 countries
- BJ meetings every 2-3 weeks
- To join the Meson Structure Functions WG mailing list, contact T. Horn (hornt@cua.edu)
- Part of the EIC Diffractive Reactions & Tagging PWG

Meson SF Working group members:

John R. Arrington (ANL), Carlos Ayerbe, Daniele Binosi (ECT*), Lei Chang (Nankai U.), Rolf Ent (Jlab), Tobias Frederico (Instituto Tecnologico 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(Nanjng U.), Jorge Segovia (Universidad Pablo de Olavide), Arun Tadepalli (JLab), Richard Trotta (CUA), Rik Yoshida (ANL)

The Physics Working Group is divided in the following subgroups:

- **Inclusive Reactions:** to join this group and its mailing list, contact R. Fatemi
  - **Conveners:** Renee Fatemi (Kentucky), Nobuo Sato (JLab), Barak Schmookler (Stony Brook)
- **Semi-inclusive Reactions:** to join this group and its mailing list, contact R. Seidl
  - **Conveners:** Ralf Seidl (RIKEN), Justin Stevens (W&M), Alexey Vladimirov (Regensburg), Anselm Vossen (Duke), Bowen Xiao (CCNU, China)
- **Jets, Heavy Quarks:** to join this group and its mailing list, contact L. Mendez
  - **Conveners:** Leticia Mendez (ORNL), Brian Page (BNL), Frank Petriello (ANL & Northwestern U.), Ernst Sichtermann (LBL), Ivan Vitev (LANL)
- **Exclusive Reactions:** to join this group and its mailing list, contact S. Fazio
  - **Conveners:** Raphaël Dupré (Orsay), Salvatore Fazio (BNL), Tuomas Lappi (Jyvaskyla), Barbara Pasquini (Pavia), Daria Sokhan (Glasgow)
- **Diffractive Reactions & Tagging:** to join this group and its mailing list, contact W. Cosyn
  - **Conveners:** Wim Cosyn (Florida), Or Hen (MIT), Doug Higinbotham (JLab), Spencer Klein (LBNL), Anna Stasto (PSU)

Remote Workshop
2-5 June, 2020

Large (remote) interest:
- 139 participants registered
- Diverse mix from 75 institutions and 15 countries
- Attendance: ~100 participants/day

Center for Frontiers in Nuclear Science
Workshop series

Workshop on Pion and Kaon Structure Functions at the EIC

2-5 June 2020
Online
US/Eastern timezone

- Overview
- Call for Abstracts
- Timetable
- Contribution List
- Registration
- Participant List

Contact
cfns_contact@stonybroo...

The Lagrangian masses of the quarks deliver only ≈ 1% of the proton mass, *mp*; and it is the emergence of the bulk of *mp* 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.

Starts Jun 2, 2020, 8:00 AM
Ends Jun 5, 2020, 7:00 PM
US/Eastern

Online

Craig Roberts
Tanja Horn

There are no materials yet.

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

Workshop on Pion and Kaon Structure Functions at the EIC

Center for Frontiers in Nuclear Science Workshop series

Remote Workshop

2-5 June, 2020

- The main foci of the workshop were:
  - further expanding and strengthening the science case for π and K SF at the EIC
  - understanding the detector requirements and developing strategies to meet them.
  - Synergies and areas of complementary potential with other facilities

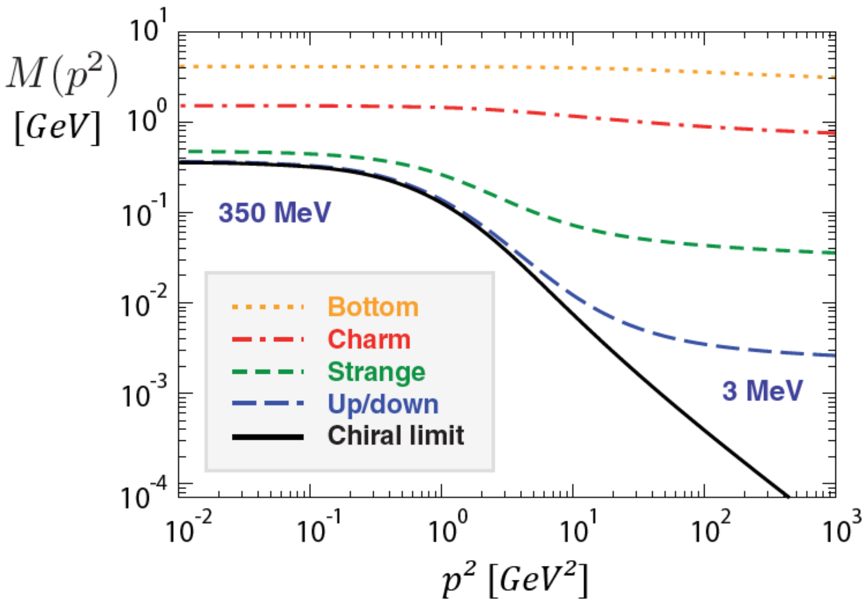
- The main topics included:
  - Setting the stage
  - Experiments and methods
  - Large-x PDFs and resummation
  - PDA and PDF connections
  - Toward 3D meson structure

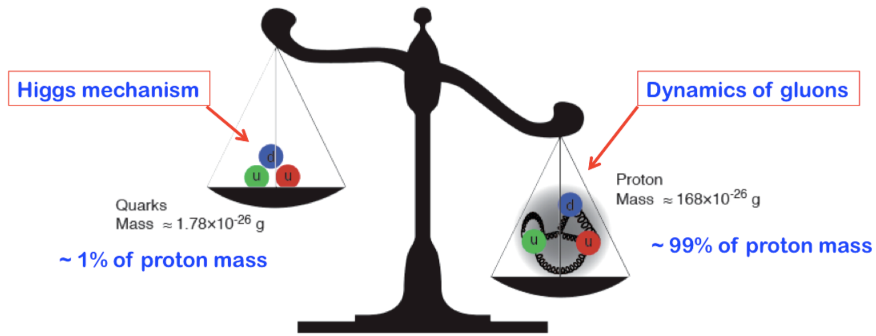
https://indico.bnl.gov/e/PIEIC2020

Setting the Stage

Pions and kaons – Nature's only known (pseudo-) Nambu-Goldstone modes – are fundamental to our existence. Yet, little is known about π and K structure

"Mass without mass!"





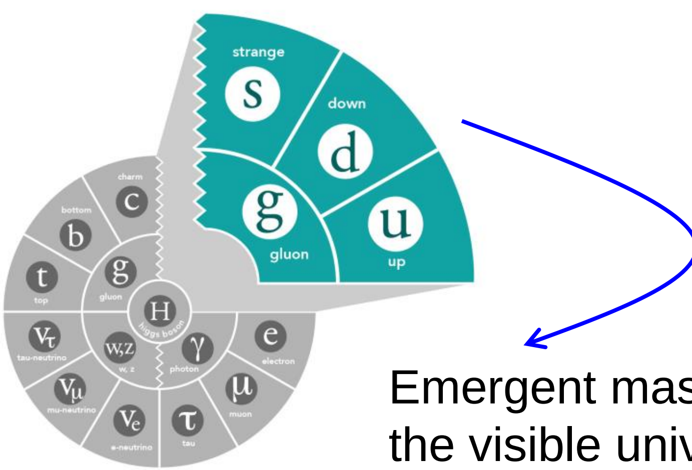
The light quarks acquire (most of) their masses as effect of the gluon cloud.

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



Emergent mass of the visible universe

Experiments and Methods

- EIC opens a window to map the quark and gluon distributions in pions and kaons at a similar level as for the proton when using only HERA data.
  - This could give crucial insights to the understanding of mass.

- EIC allows to explore the pion and kaon structure functions over a large QCD landscape in x and Q^2 to map the quark and gluon distributions, and give unique insight in the emergent-mass mechanism understanding and why the pion mass is so light.

Pion Structure Function Projections

To reach the large x region at a certain intermediate Q^2, the lowest possible energy is normally best

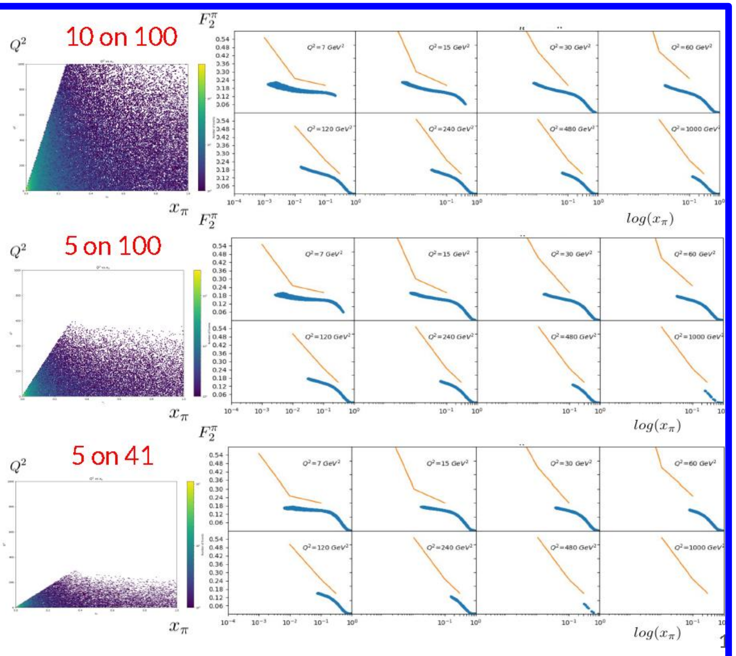
For high beam energies this area requires y to be low

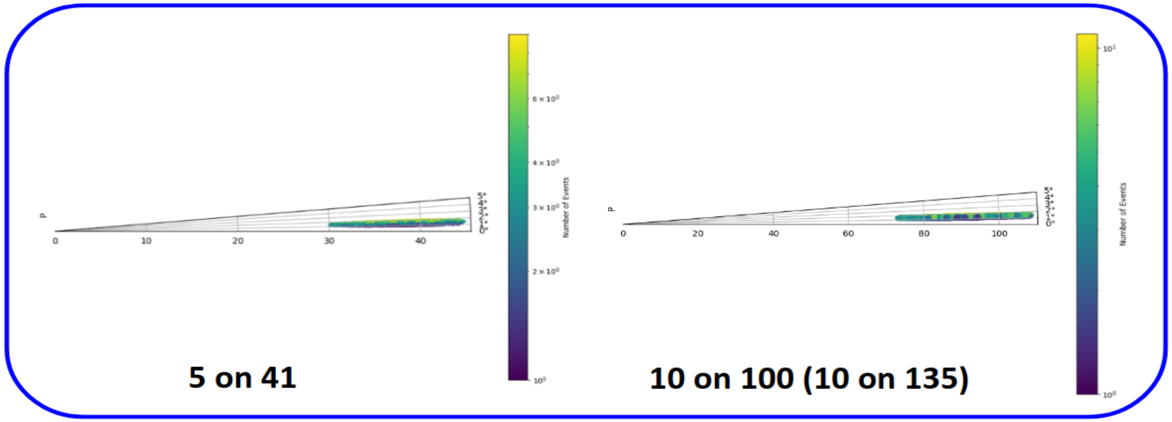
5 on 100 can access more acceptance at high-x, but lose acceptance to the low-x region

Even more for 5 on 41

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

Richard Trotta





Kinematics of the forward-going baryon

Experiments and Methods

- Lattice QCD calculations have advanced through the development and adoption of new theoretical ideas, algorithmic advances, and the march to the exascale era
  - x-dependent PDFs from Euclidean-space lattice, characterized through the computation of quasi-PDFs, pseudo-PDFs, and “lattice cross sections”.
  - key measures of hadron structure, such as the nucleon's axial-vector charge, with controlled uncertainties, directly at the physical light-quark masses
  - unpolarized and polarized x-dependent PDFs at the physical light-quark masses - methods are now being applied to the calculation of GPDs and TMDs.

Pion and Kaon Structure

Jianwei Qiu

- Pion decays, and there is no stable pion target
- Pion beam:
  - Talking advantage of time-dilation, $\pi + p \to \ell^+\ell^- + X$ 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

$$\frac{1}{2}\left[T^{\mu\nu}_{v5}(\xi,p) + T^{\mu\nu}_{5v}(\xi,p)\right] = \frac{\xi^4}{2}\langle h(p)|\left(\mathcal{J}^{\mu}_{v}(\xi/2)\,\mathcal{J}^{\nu}_{5}(-\xi/2) + \mathcal{J}^{\mu}_{5}(\xi/2)\,\mathcal{J}^{\nu}_{v}(-\xi/2)\right)|h(p)\rangle$$
$$\equiv \epsilon^{\mu\nu\alpha\beta}\,p_\alpha\xi_\beta\,\widetilde{T}_1(\omega,\xi^2) + (p^\mu\xi^\nu - \xi^\mu p^\nu)\,\widetilde{T}_2(\omega,\xi^2)$$

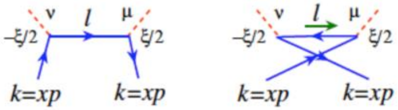
Vanishes under T

✧ Collinear factorization:

$$\widetilde{T}_i(\omega,\xi^2) = \sum_{f=q,\bar{q},g}\int_0^1 \frac{dx}{x}\, f(x,\mu^2)\, C_i^f(\omega,\xi^2;x,\mu^2) + \mathcal{O}\left[|\xi|/\mathrm{fm}\right]$$

✧ Lowest order coefficient functions:

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



$$T_1(\widetilde{x},\xi^2) \equiv \int \frac{d\omega}{2\pi} e^{-i\widetilde{x}\omega}\,\widetilde{T}_1(\omega,\xi^2)$$
$$= \frac{1}{\pi^2}\left(q(\widetilde{x},\mu^2) - \overline{q}(\widetilde{x},\mu^2)\right) \equiv \frac{1}{\pi^2} q_v(\widetilde{x},\mu^2)$$

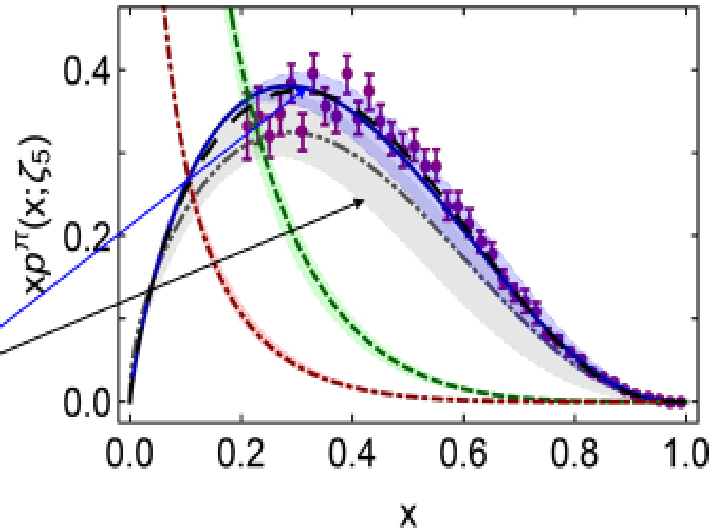
Sufian et al. PRD99 (2019) 074507

Experiments and Methods

π valence-quark distributions 20 Years of Evolution → 2019

$\beta^{contm}(\zeta_5) = 2.66(12)$
$\beta^{lattice}(\zeta_5) = 2.45(58)$

- Novel lattice-QCD algorithms beginning to yield results for pointwise behaviour of $u^\pi(x;\zeta)$
- Developments in continuum-QCD have enabled 1st parameter-free predictions of valence, glue and sea distributions within the pion
  - Reveal that $u^\pi(x;\zeta)$ is hardened by emergent mass
- Agreement between new continuum prediction for $u^\pi(x;\zeta)$ [Ding:2019lwe] and recent lattice-QCD result [Sufian:2019bol]
- Real strides being made toward understanding pion structure.
- Standard Model prediction is stronger than ever before
- *Now – after 30 years – new era dawning in which the ultimate experimental checks can be made*



Craig Roberts. pi & K structure - window onto EHM

Craig Roberts

Summary – Experiments and Methods

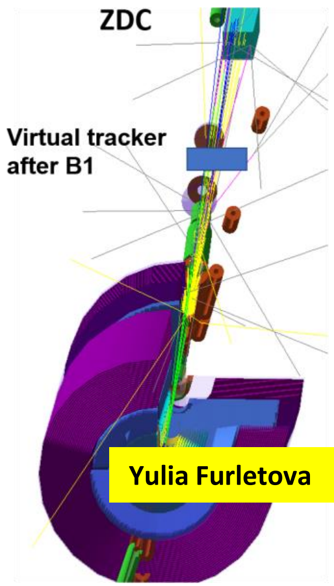
Discussion leader: Paul Reimer (ANL)

- ❑ Much progress with continuum and lattice calculations

Electron-Ion Collider

- ❑ 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

Summary of Detector Requirements



- ❑ **For π-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 π-n and K^+/Λ:**
  - ➢ 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^+/Λ benefits from low energies (5 on 41, 5 on 100) and also need:**
  - ➢ $\Lambda \to n + \pi^0$: additional high-res/granularity EMCal+tracking before ZDC – seems doable
  - ➢ $\Lambda \to p + \pi^-$: 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

- ❑ Each of these elements is crucial to our understanding of the structure of hadrons - understanding can only proceed through a combined campaign of experiment, theory and global fitting.

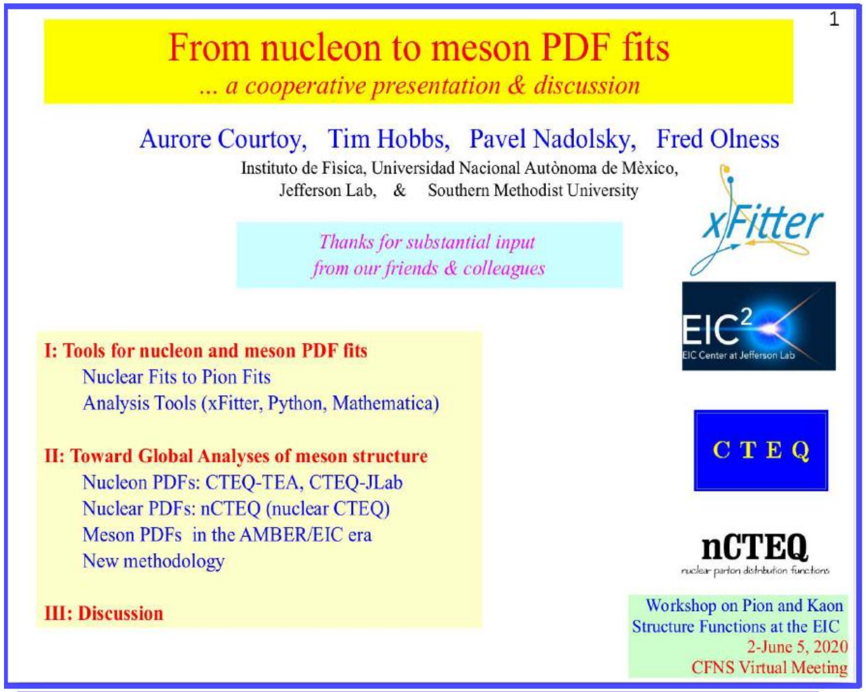
Large-x PDFs and Resummation

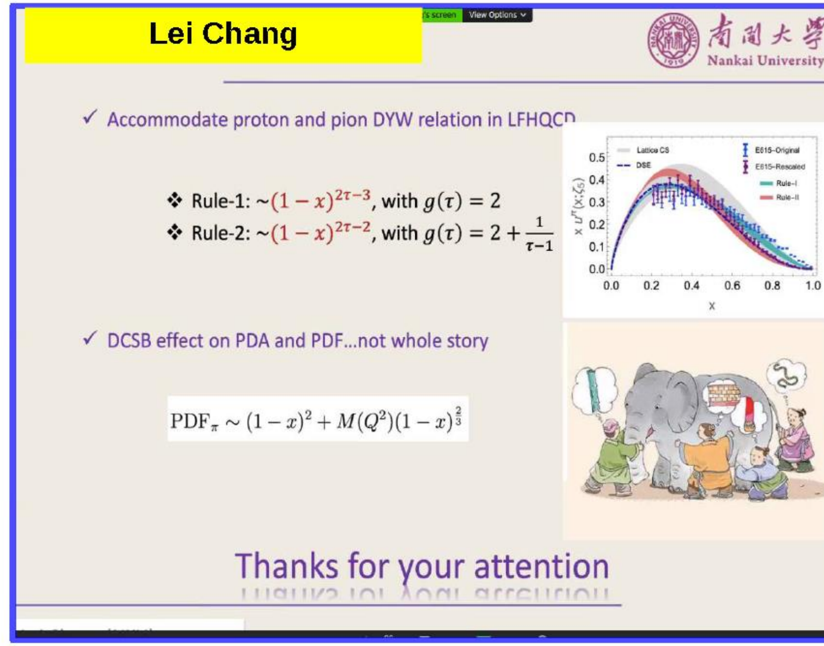
- The final element of a triad of progress is the increasing effort aimed at the development of global fitting frameworks, exemplified by the JAM collaboration at Jefferson Lab, the multi-institutional CTEQ collaboration, and the NNPDF effort in Europe, which are exploiting ideas of machine learning and neural networks.

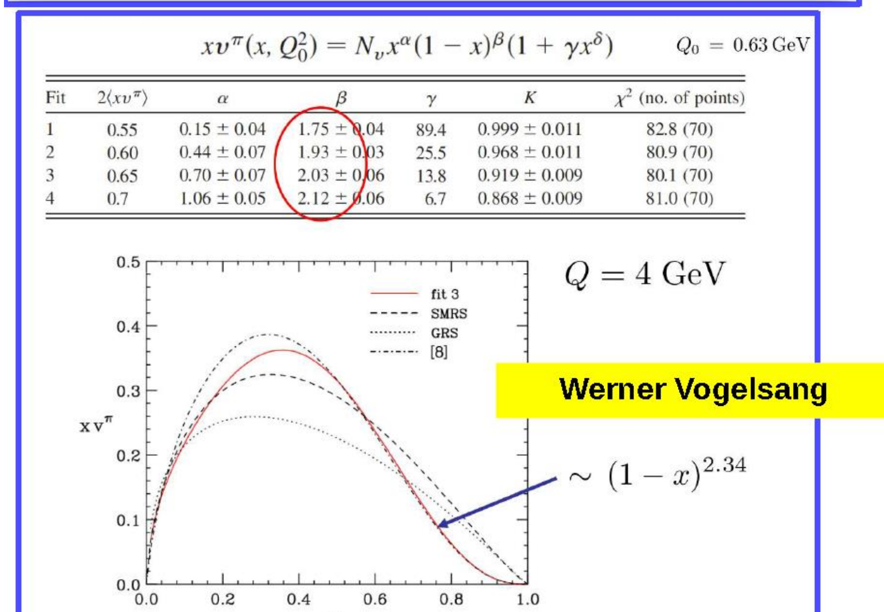
- The development of global fitting for the collinear PDFs is the culmination of nearly three decades of effort.

- Important questions still remain, and the development of such frameworks for TMDs and for GPDs is key to capitalizing on the theoretical and experimental advances in 3D imaging.

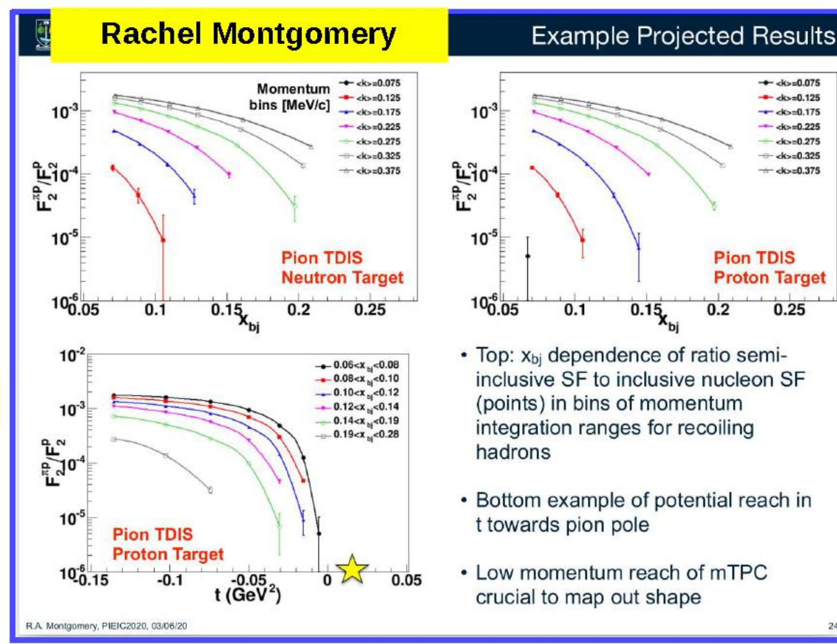
Overview – large-x PDFS







Fit	$2\langle xv^\pi\rangle$	α	β	γ	K	χ^2 (no. of points)
1	0.55	0.15 ± 0.04	1.75 ± 0.04	89.4	0.999 ± 0.011	82.8 (70)
2	0.60	0.44 ± 0.07	1.93 ± 0.03	25.5	0.968 ± 0.011	80.9 (70)
3	0.65	0.70 ± 0.07	2.03 ± 0.06	13.8	0.919 ± 0.009	80.1 (70)
4	0.7	1.06 ± 0.05	2.12 ± 0.06	6.7	0.868 ± 0.009	81.0 (70)



Overview – large-x PDFS

Minghui Ding

Summary and outlook

✤ Summary

- Using a continuum approach, presented a symmetry-preserving calculation of the pion's PDF.
  - A novel term $q^{\pi}_{BC}(x;\zeta_H)$ is necessary to keep $q^{\pi}(x;\zeta_H) = q^{\pi}(1-x;\zeta_H)$ and then $\langle x^1_{\pi}\rangle = 1/2$;
  - $\zeta_H = 0.30\,\text{GeV}$ 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 $\langle 2x\rangle^{\pi}_q = 0.48(3)$. Valence quark $q^{\pi}(x;\zeta_5)$ agrees with rescaled E615 data and lQCD prediction, large x behaviour $\beta(\zeta_5) = 2.66(12)$, and first moment $\langle 2x\rangle^{\pi}_q = 0.42(4)$.
  - Gluon and sea quark PDFs ζ_2, $\langle x\rangle^{\pi}_g = 0.41(2)$, $\langle x\rangle^{\pi}_{sea} = 0.11(2)$, ζ_5, $\langle x\rangle^{\pi}_g = 0.45(1)$, $\langle x\rangle^{\pi}_{sea} = 0.14(2)$.

✤ Outlook
- Kaon PDFs.
- Nucleon PDFs.

Thank you

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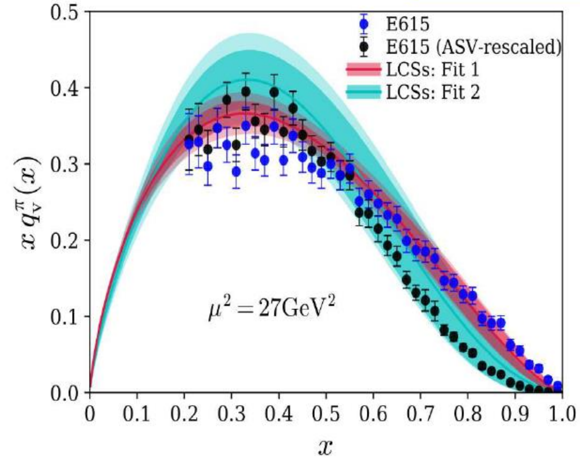
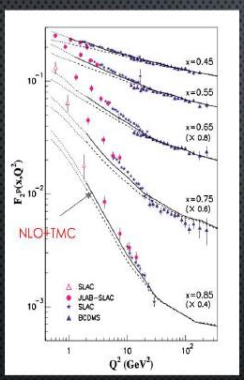
David Richards



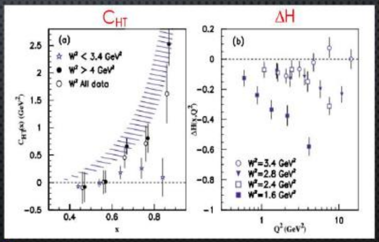
Slightly favors softer $[(1-x)^2]$ fit → *need for finer resolution in Ioffe time..*

Simonetta Liuti

First hint of W² dependent effects



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



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

Patrick Barry

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 3rd, 2020

Contact: pcbarry@ncsu.edu

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Summary – large-x PDFS

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

- ❑ Global PDF fit results with uncertainties have revealed the importance of new pion and kaon data.
- ❑ Recent efforts have re-emphasized the importance of including resummation in global analyses.
- ❑ Time to look at flexible functional forms
  - ➢ The current form: $x^a (1\text{-}x)^b$ is very restrictive

xFitter Pion PDFs

Experiment	Normalization uncertainty	χ^2/N_{points}
E615	15 %	206/140
NA10 (194 GeV)	6.4%	107/67
NA10 (286 GeV)	6.4%	95/73
WA70	32%	64/99

$$xv(x) = A_v x^{B_v}(1-x)^{C_v}(1+D_v x^{\alpha}),$$
$$xS(x) = A_S x^{B_S}(1-x)^{C_S}/\mathcal{B}(B_S+1, C_S+1),$$
$$xg(x) = A_g(C_g+1)(1-x)^{C_g},$$

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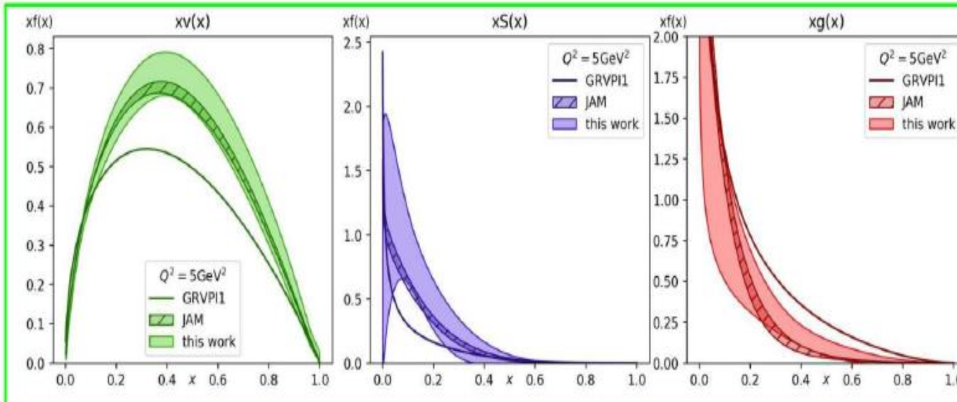
	$\langle xv\rangle$	$\langle xS\rangle$	$\langle xg\rangle$	Q^2 (GeV^2)
JAM [26]	0.54 ± 0.01	0.16 ± 0.02	0.30 ± 0.02	1.69
JAM (DY)	0.60 ± 0.01	0.30 ± 0.05	0.10 ± 0.05	1.69
this work	0.55 ± 0.06	0.26 ± 0.15	0.19 ± 0.16	1.69
Lattice-3 [16]	0.428 ± 0.030			4
SMRS [20]	0.40 ± 0.02			4
Han et al. [42]	0.428 ± 0.03			4
DSE [7]	0.52			4
this work	0.50 ± 0.05	0.25 ± 0.13	0.25 ± 0.13	4
JAM	0.48 ± 0.01	0.17 ± 0.01	0.35 ± 0.02	5
this work	0.49 ± 0.05	0.25 ± 0.12	0.26 ± 0.13	5
Lattice-1 [14]	0.558 ± 0.166			5.76
Lattice-2 [15]	0.48 ± 0.04			5.76
this work	0.48 ± 0.05	0.25 ± 0.12	0.27 ± 0.13	5.76
WRH [21]	0.434 ± 0.022			27
ChQM-1 [11]	0.428			27
ChQM-2 [13]	0.46			27
this work	0.42 ± 0.04	0.25 ± 0.10	0.32 ± 0.10	27
SMRS [20]	0.49 ± 0.02			49
this work	0.41 ± 0.04	0.25 ± 0.09	0.34 ± 0.09	49



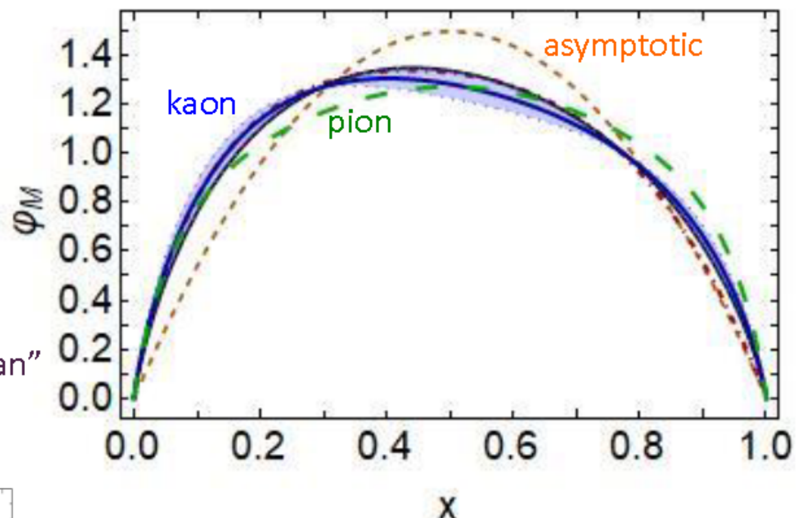
❑ To access the full power of quark PDFs, pion and kaon structure function data at large x, covering a wide range in Q^2, are needed.

Overview – PDA and PDF

Discussion leader: Craig Roberts (Nanjing U.)

Meson leading-twist DAs

- Continuum results exist & lQCD results arriving
- Common feature = broadening
- Origin = EHM
- NO differences between π & K if EHM is all there is
  - Differences arise from Higgs-modulation of EHM mechanism
  - "Contrasting π & K properties reveals Higgs wave on EHM ocean"



Pion and Kaon Distribution Amplitudes in the Continuum Limit

Rui Zhang,[1,2,*] Carson Honkala,[3] Huey-Wen Lin,[1,2,†] and Jiunn-Wei Chen[4,‡]

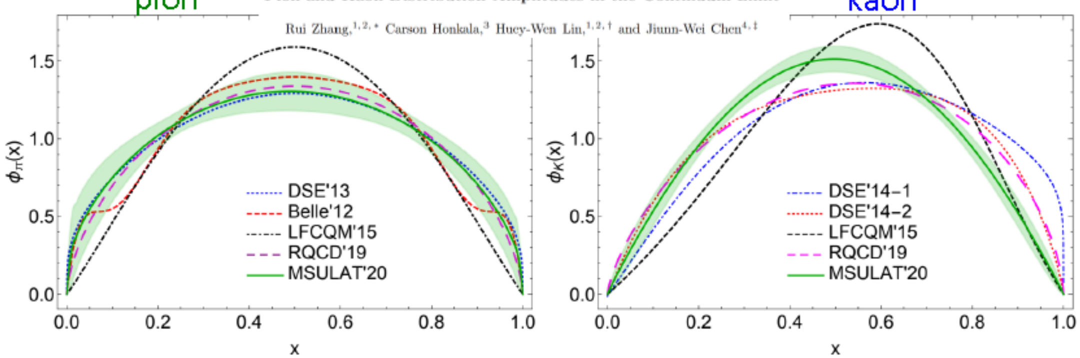


FIG. 10. Fit of the $P_z = 4\frac{2\pi}{L}$ pion (left) and kaon (right) data to the analytical form in Bjorken-x space, compared with previous calculations (with only central values shown). Although we do not impose the symmetric condition $m = n$, both results for the pion and kaon are symmetric around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

- 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.)

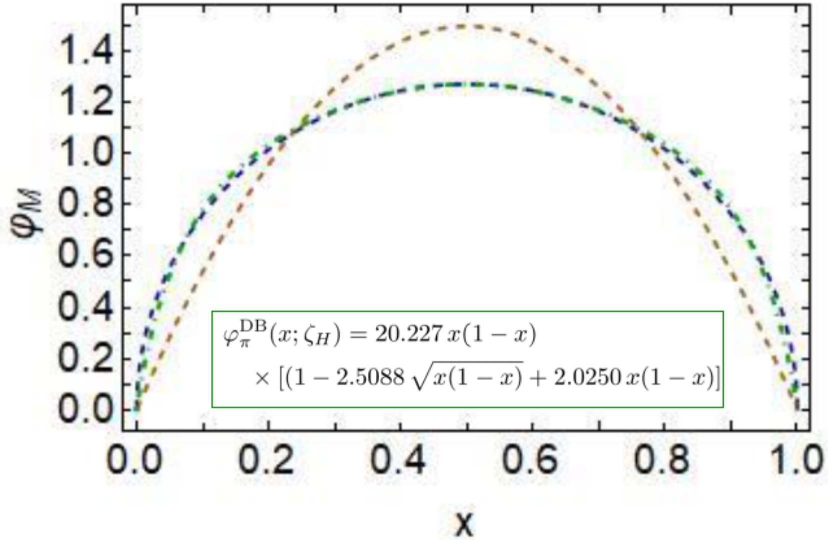
Meson leading-twist DAs and valence-quark DFs

- Broadening need not and should not disturb the DA's endpoint behaviour
- QCD: $\varphi(x) = x\,(1-x) f(x), f(x \simeq 0) = constant_1, f(x \simeq 1) = constant_2$
- 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"

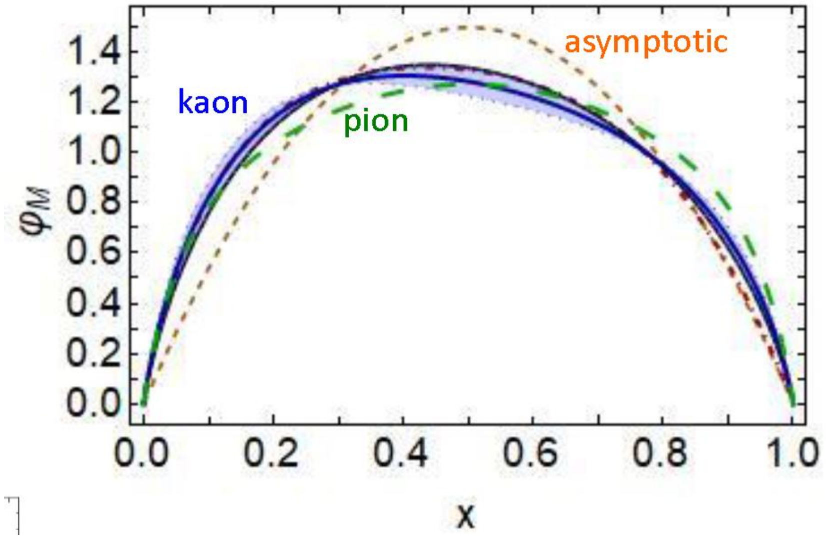


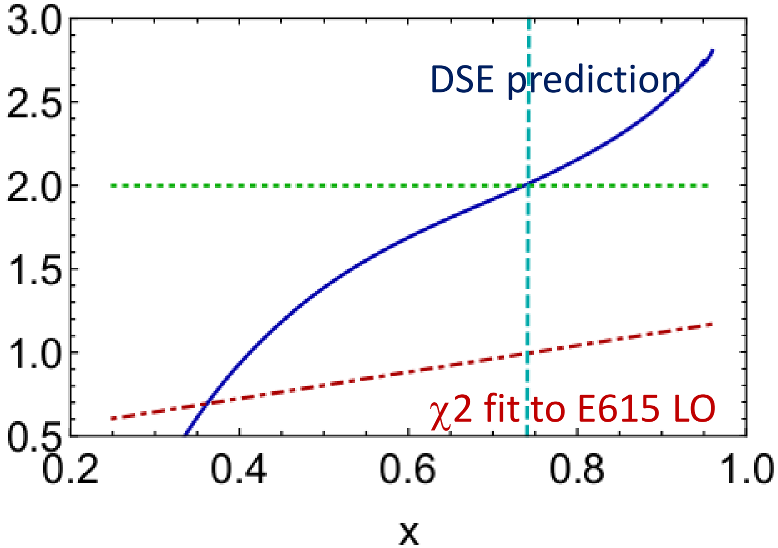
Summary – PDA and PDF

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:

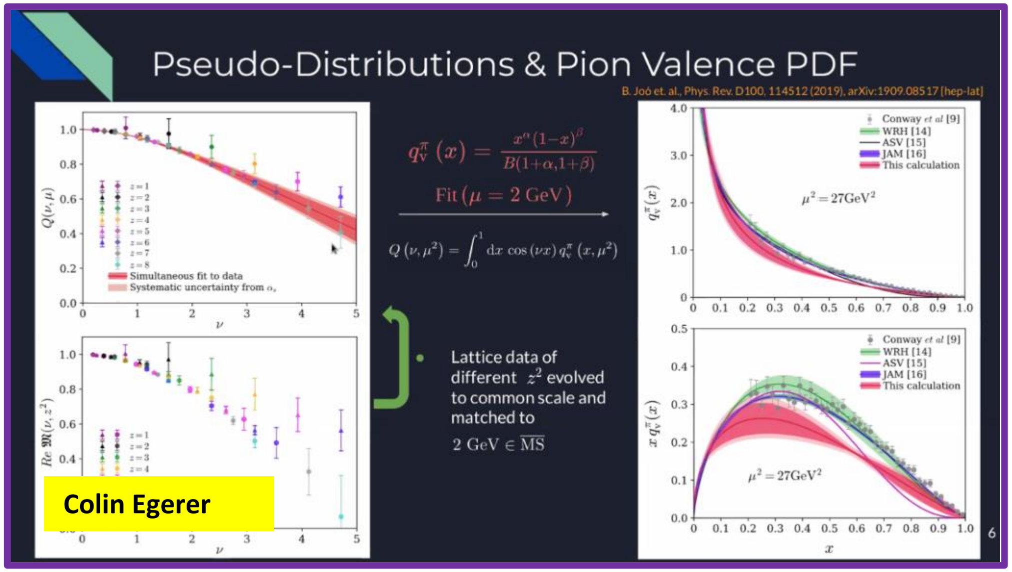
J=0 … $(1/k^2)^n \Leftrightarrow (1-x)^{2n}$

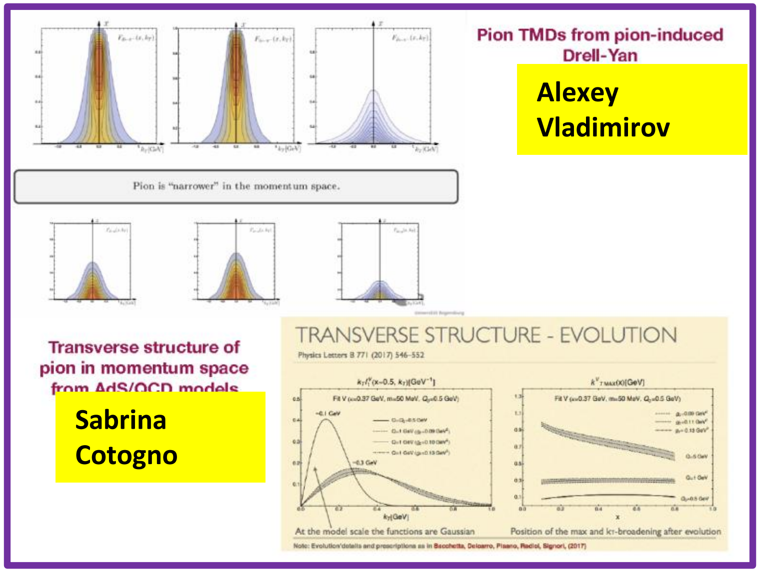


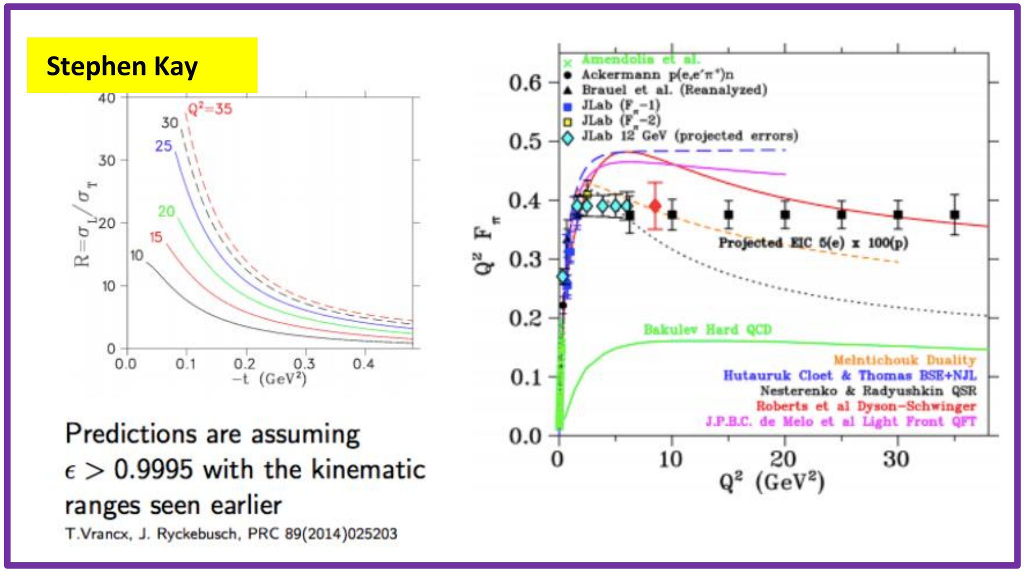


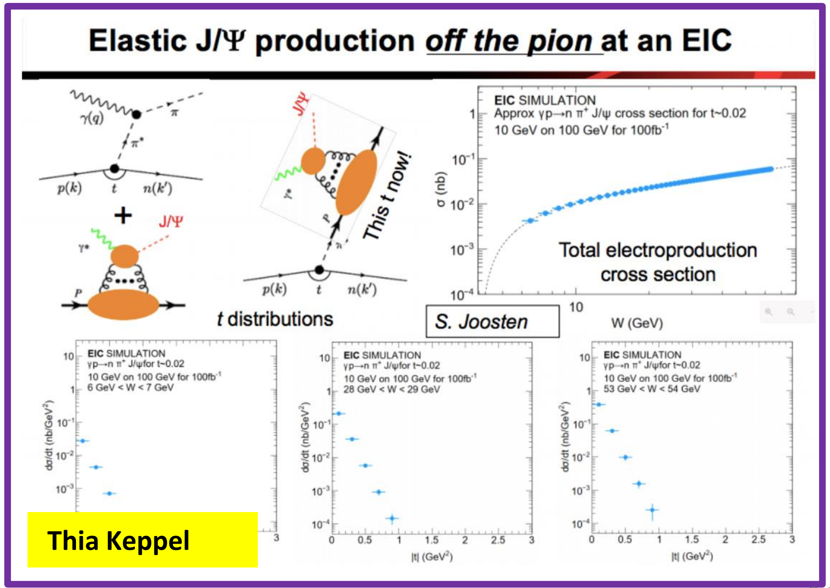
- ➢ Contemporary continuum theory indicates that this QCD prediction could be validated with precise data and sound extraction on the domain 0.6 < x < 0.8.

Overview – Towards 3D Meson Structure









Summary – Towards 3D Meson Structure

Discussion leader: Daria Sokhan (U. Glasgow)

- Ongoing theoretical studies are working to determine regions where it is theoretically safe to interpret measurements in terms of pion and kaon 3D structure functions, as well as to define domains that can be used to distinguish between different models and better understand backgrounds.

- On the experiment side, the development of EIC detector requirements is the focus of the Meson Structure Working Group (MSWG).
  - For pion GPD studies, one must show that the Sullivan process dominates, and that the forward-going baryon and its decay products can be detected - affects detector design, e.g. requirements on electron calorimetry.
  - For both pion and kaon structure function measurements, good ZDC angular resolution is required at all energies to achieve the required (-t) resolution. For kaon structure function measurements, additional high-resolution/high-granularity EM calorimetry and tracking are needed before the ZDC. Studies have shown that good hadron calorimetry for good z resolution at large x is needed.

- 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

- This was the 3rd workshop in a series that began in 2017 following conversations during the 2016 International Nuclear Physics Conference.
  - part of a wider effort that involves a worldwide community of scientists (experiment, phenomenology, theory) in joint activities at the world's leading accelerator facilities, and in organizing conferences and workshops at numerous international centers, e.g. Institute for Nonperturbative Physics (INP), Nanjing, China; Université Paris-Saclay, France; ECT*, Trento, Italy; CERN, Geneva, Switzerland; JLab, Newport News, USA; and CFNS, SUNY – Stony Brook, USA.

- These coordinated efforts aim to address the challenge of explaining the origin and distribution of the vast bulk of visible mass in the Universe.

- Progress and insights have been delivered by an amalgam of experiment, phenomenology, and theory; and the continued exploitation of existing synergies is essential in order to capitalize on the extraordinary opportunities promised by new generation facilities.

- Discussions are continuing as the experimental opportunities and capacities evolve.

- In the coming year, conferences and workshops are planned, e.g. at CERN, Saclay, ECT*, and INP.

Future Prospects and Community Identified Needs

- The case for pion and kaon structure function studies is strong.

- There is a pressing need for a program of experiments that extend the exploration of hadron structure to include the pion and kaon

- Progress with hadron structure studies requires development of a rigorous phenomenological framework capable of reliably connecting experimental measurement and theoretical predictions to the fundamental elements of the Standard Model

- All understanding gained and lessons learnt during four decades of PDF phenomenology must be incorporated into future analyses.
  - 1D PDFs: the issue of threshold (next-to-leading logarithm) resummation and its impact on the large-x behavior of extracted PDFs must be resolved;
  - 3D structure of hadrons: there is great need for clear statements of all challenges faced and discussion of feasible approaches to overcoming them

- There is an urgent need to develop all arms of phenomenology and theory as soon as possible because Science is entering a new era, with facilities being built that can definitively expose pion and kaon structure experimentally