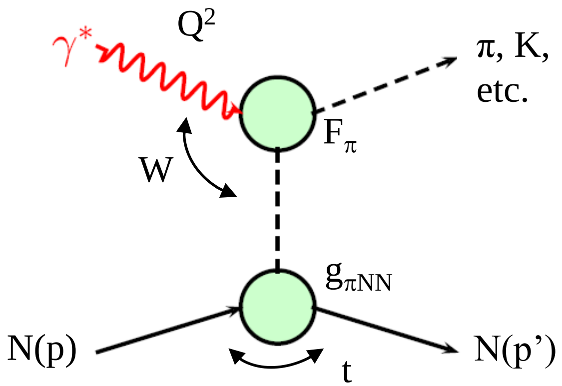
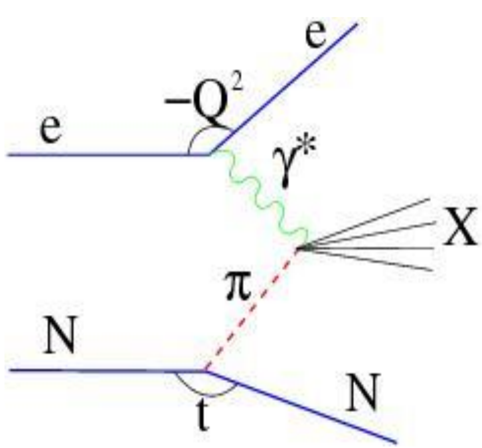
EIC Meson Structure Functions Working Group Update





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 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)

18 June 2020

Workshop on Pion and Kaon Structure Functions at the EIC

Center for Frontiers in Nuclear Science
Workshop series

2-5 June 2020
Online
US/Eastern timezone

Remote Workshop 2-5 June, 2020

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.

Large (remote) interest:
- 138 participants registered
- Attendance: ~100/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)

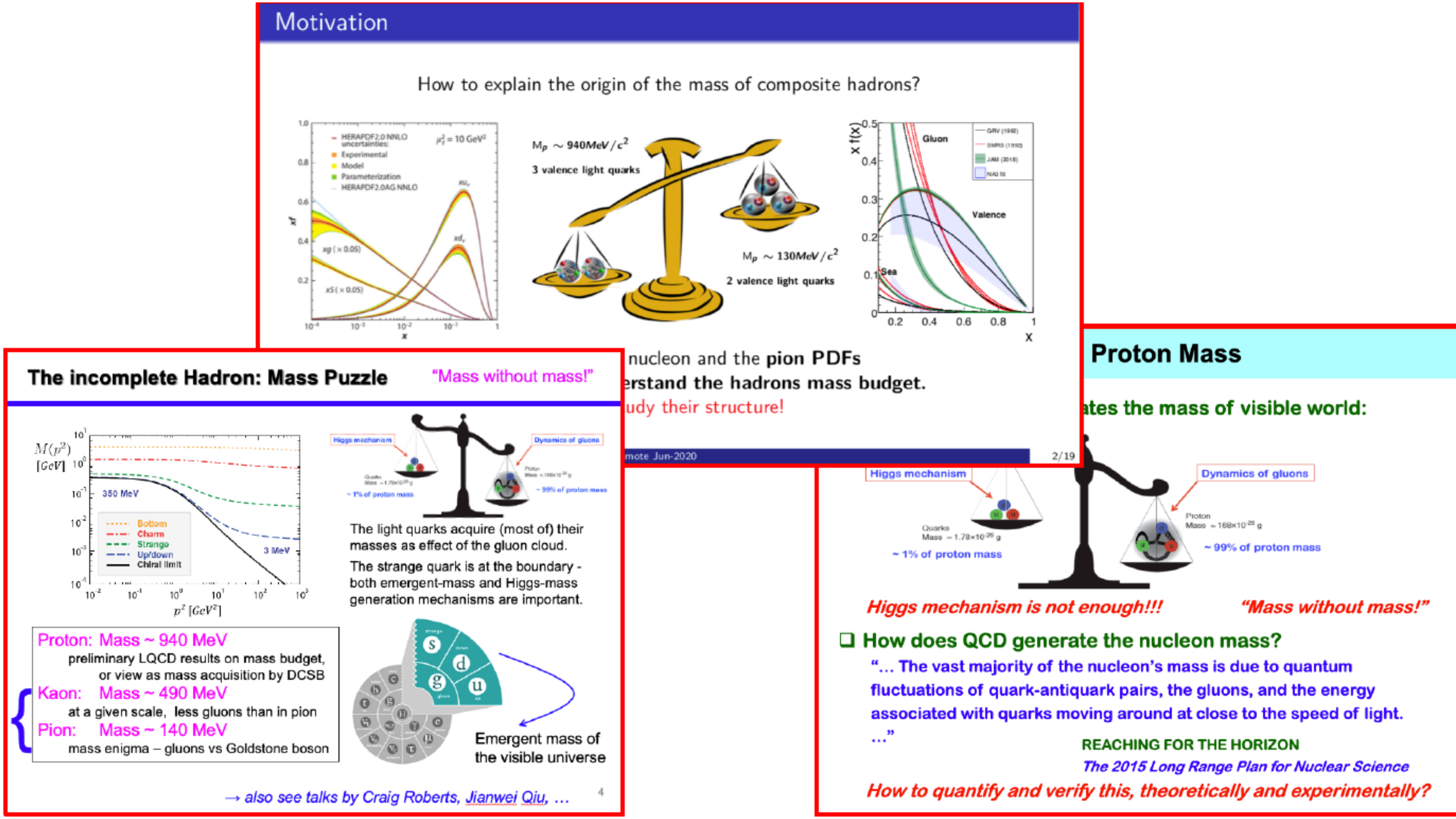
- **8:00 AM** Welcome and Introduction
  Speaker: Abhay Deshpande (Stony Brook University)
  00 Welcome-Pi-K-St...
- **8:15 AM** Emergence of Pion and Kaon Structure – Introduction
  Speaker: Craig Roberts (Nanjing University)
  2006EHMEIC.pdf 2006EHMEIC.pptx
- **8:40 AM** Pion and Kaon Structure at 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 Drell-Yan methods
Convener: Tanja Horn (Cath)

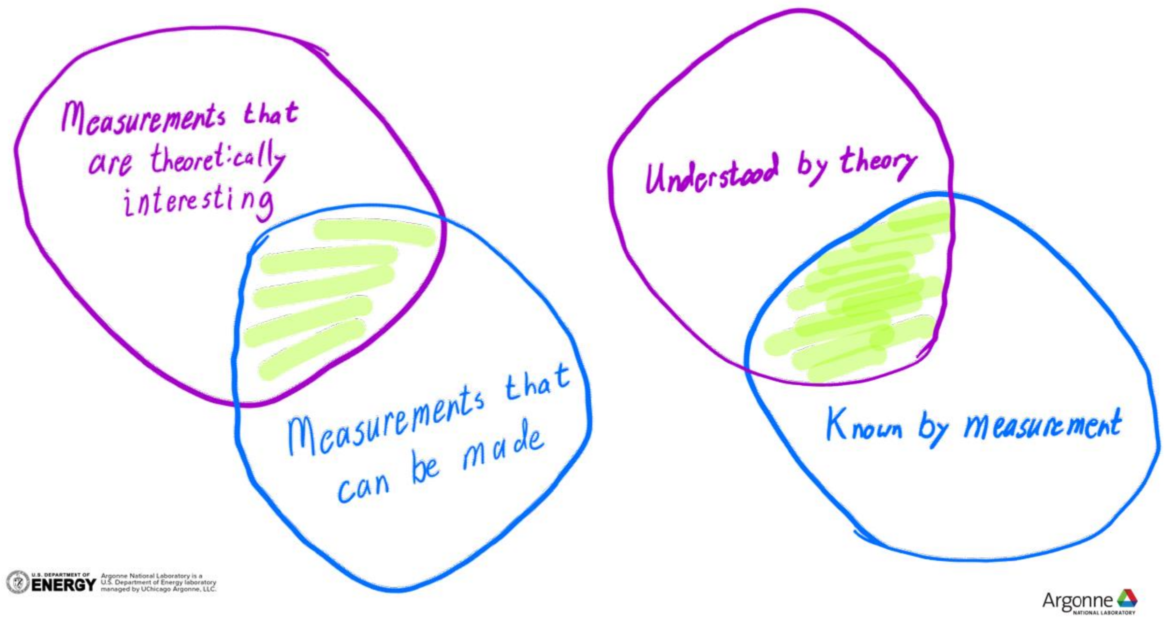
- **10:15 AM** EIC detector, Simulations, Experimental Possibilities
  Speaker: Yulia Furletova (Jefferson Lab)
  MesonStructure_EI...
- **10:40 AM** Pion and Kaon structure functions at EIC
  Speaker: Richard Trotta (The Catholic University of America)
  mesonSF_CFNS.pdf
- **11:05 AM** Pion/kaon structure study using Drell-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



Complementarity of Experiments and Theoretical Models

Discussion leader: Paul Reimer (ANL)



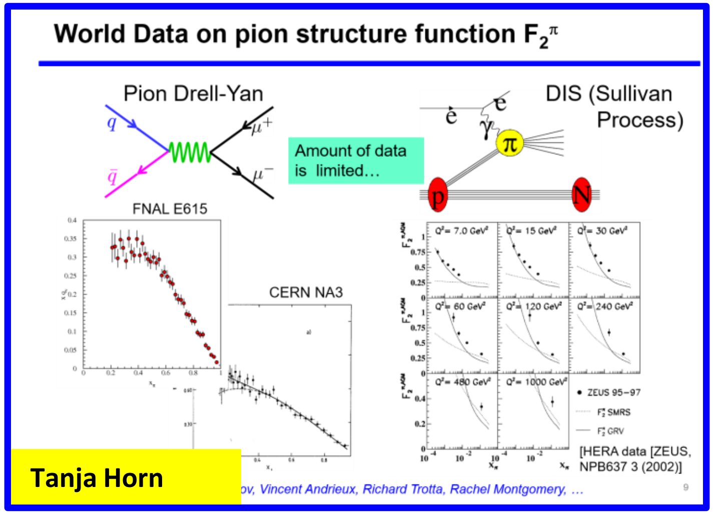
Status: pion and kaon structure functions

Pion

- Pointwise behaviour of pion's valence-quark distribution function: agreement between predictions from 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.

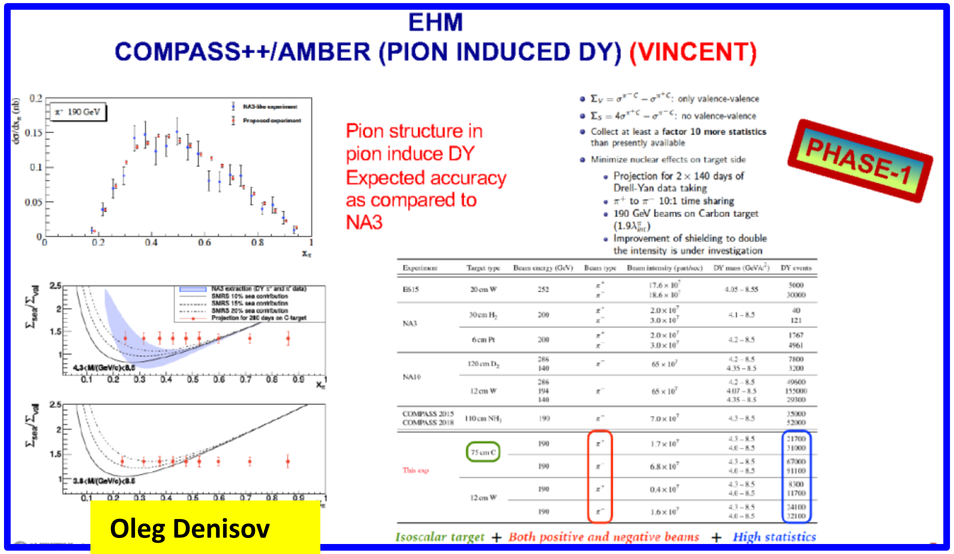
Craig Roberts

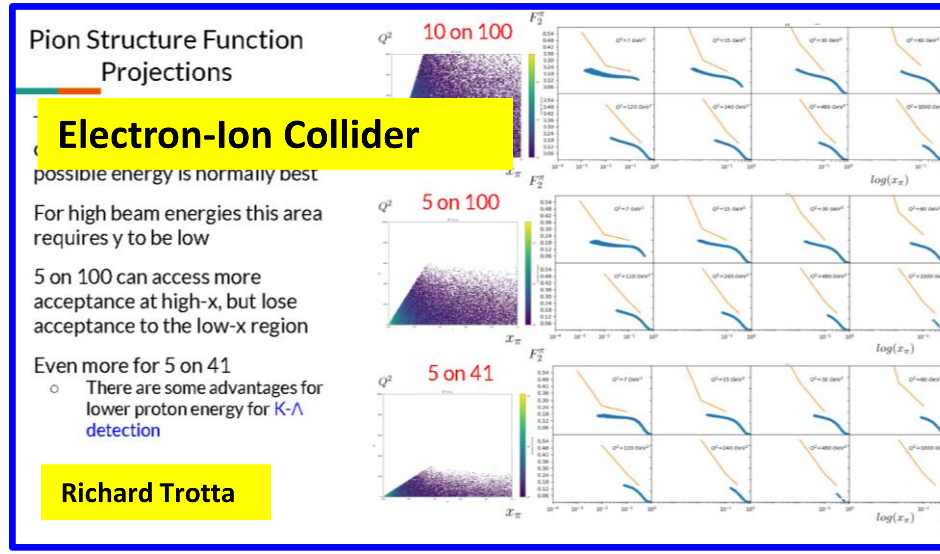
Pion and Kaon Structure Functions at the EIC 35 (43)

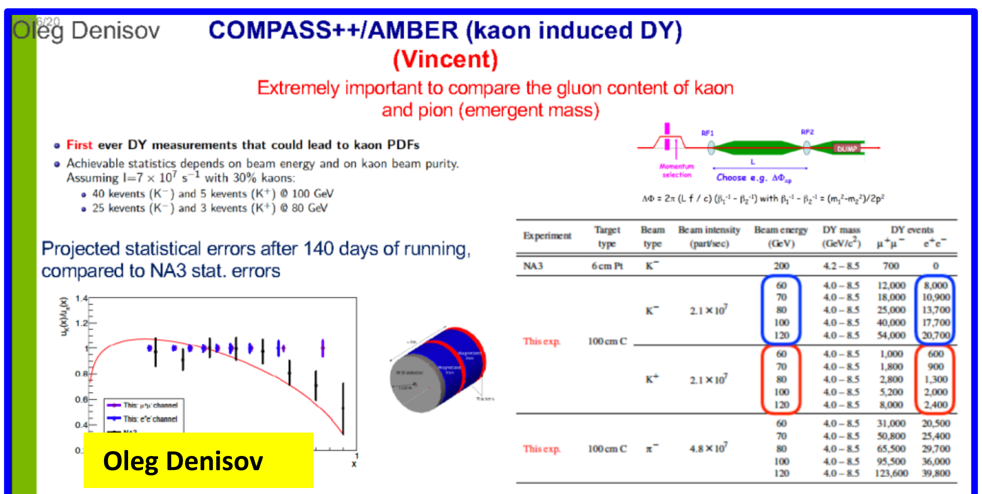


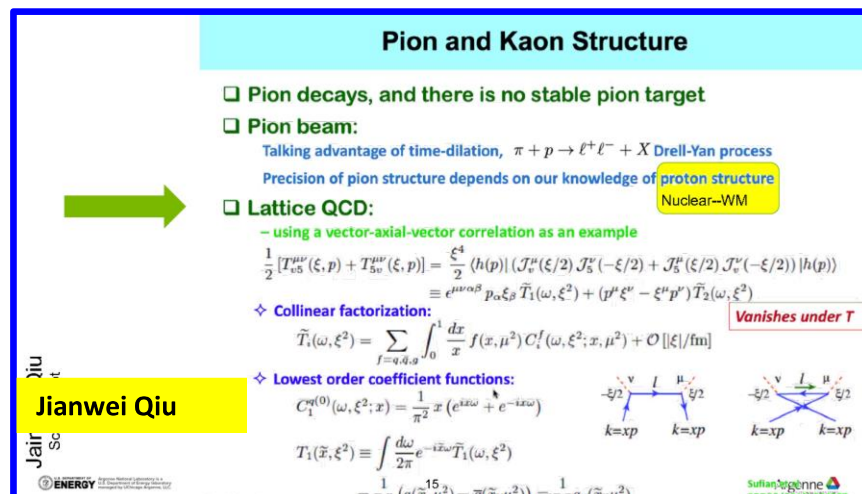
Overview – Experiments and Methods

Discussion leader: Paul Reimer (ANL)









Summary – Experiments and Methods

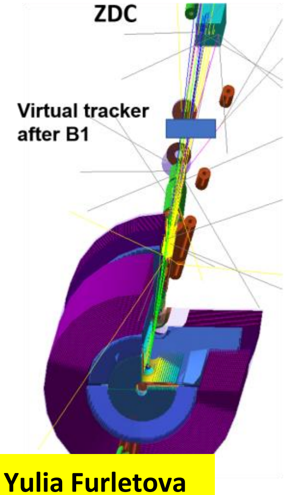
Discussion leader: Paul Reimer (ANL)

- ❑ 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 Q2, gluon content
  - ➢ EicC – pion and kaon SF

Electron-Ion Collider

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:**
  - ➢ $\Lambda \rightarrow n + \pi^0$: 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)

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From nucleon to meson PDF fits

... a cooperative presentation & discussion

Aurore Courtoy, Tim Hobbs, Pavel Nadolsky, Fred Olness

Instituto de Fìsica, Universidad Nacional Autònoma de Mèxico, Jefferson Lab, & Southern Methodist University

Thanks for substantial input from our friends & colleagues

xFitter

EIC² EIC Center at Jefferson Lab

CTEQ

nCTEQ nuclear parton distribution functions

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

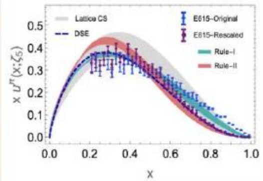
Workshop on Pion and Kaon Structure Functions at the EIC
2-June 5, 2020
CFNS Virtual Meeting

Lei Chang

Nankai University

✓ 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

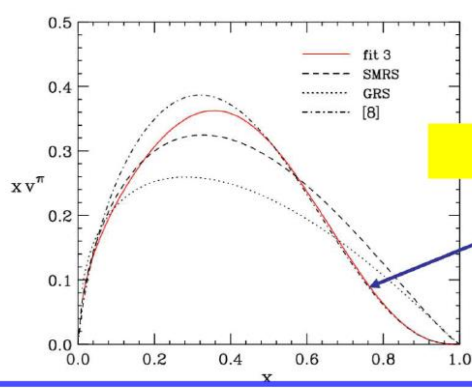
$$\mathrm{PDF}_\pi \sim (1-x)^2 + M(Q^2)(1-x)^{\frac{2}{3}}$$

Thanks for your attention

Werner Vogelsang

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

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)

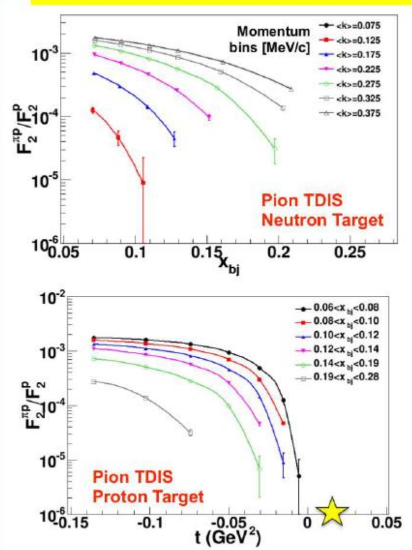


$Q = 4$ GeV

$\sim (1-x)^{2.34}$

Rachel Montgomery

Example Projected Results

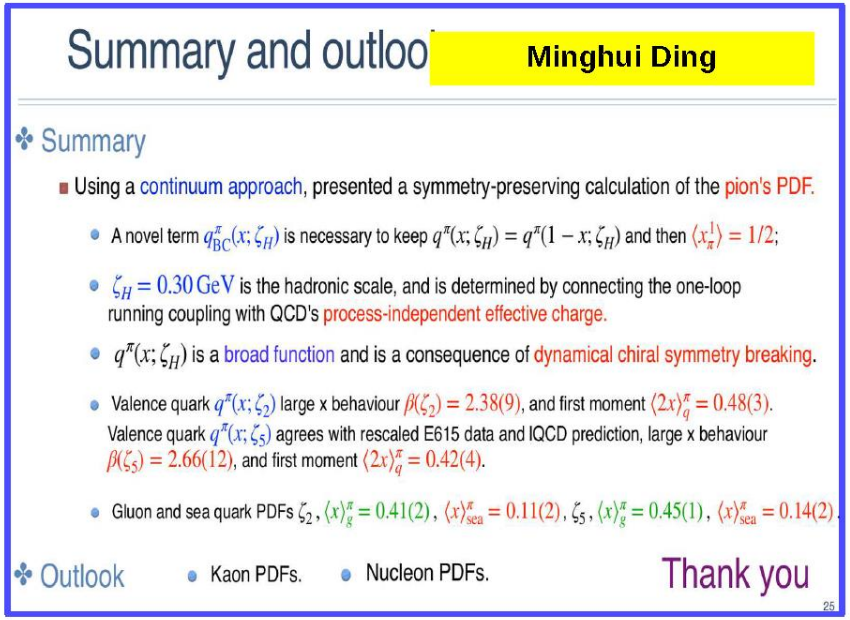


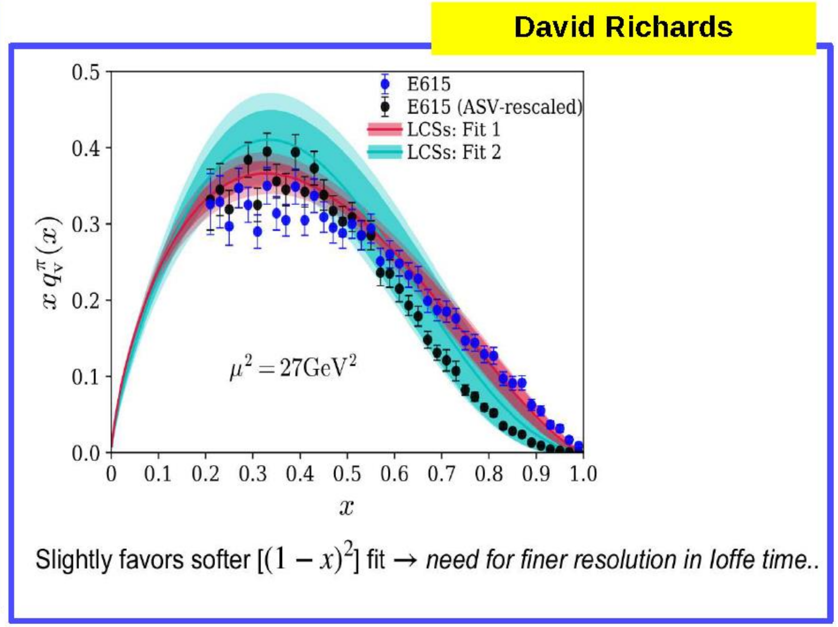
- Top: x_{bj} dependence of ratio semi-inclusive SF to inclusive nucleon SF (points) in bins of momentum integration ranges for recoiling hadrons
- Bottom example of potential reach in t towards pion pole
- Low momentum reach of mTPC crucial to map out shape

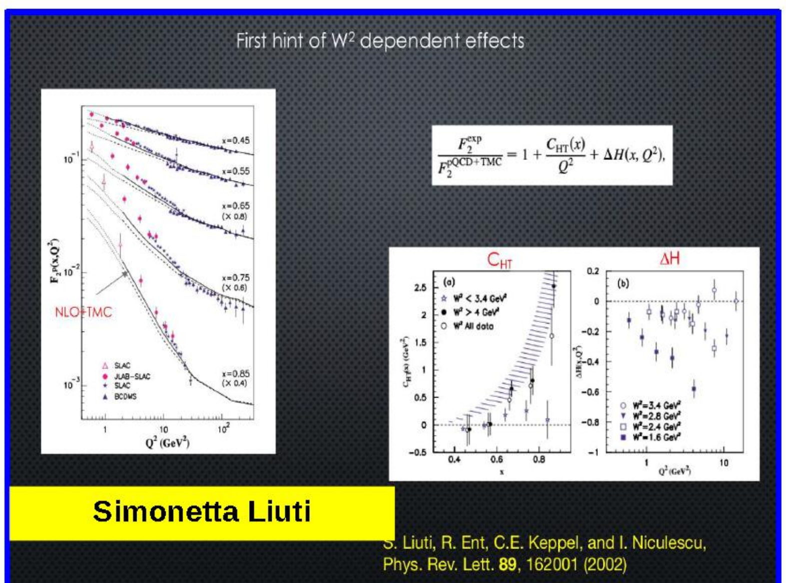
R.A. Montgomery, PIEIC2020, 03/06/20 24

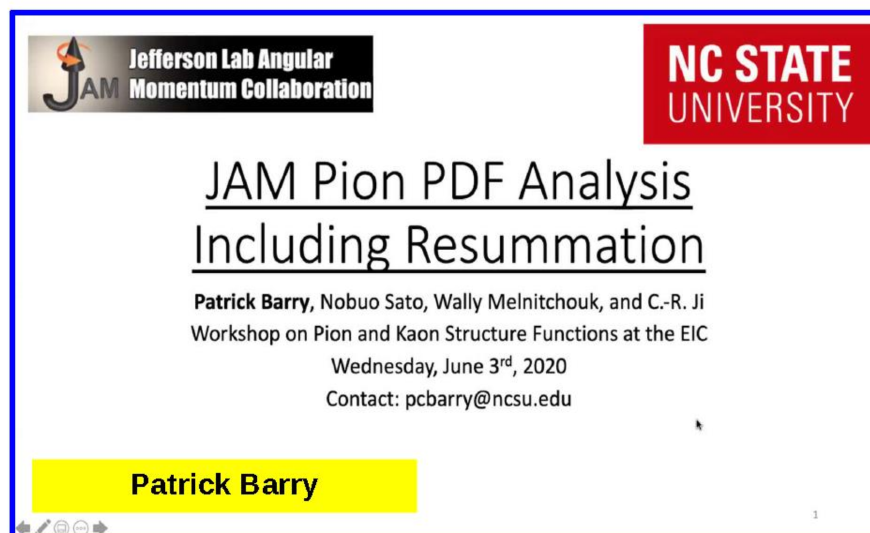
Overview – large-x PDFS

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









Summary – large-x PDFS

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

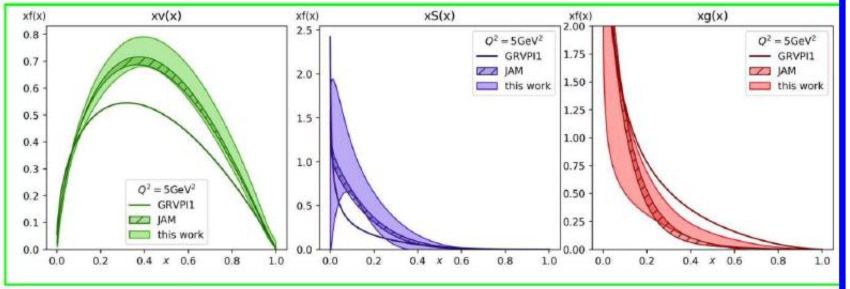
- ❑ Global fit results with uncertainties show that clearly not there yet – very sparse data
- ❑ Resummation is important to include in global fits
- ❑ Time to look at flexible functional forms
  - ➢ The current form: $x^a (1-x)^b$ is very restrictive

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

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

	$\langle xv \rangle$	$\langle xS \rangle$	$\langle xg \rangle$	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



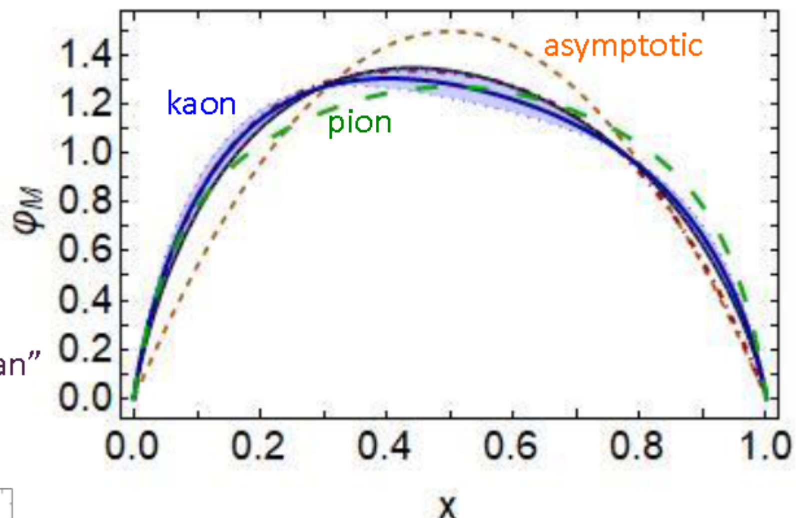
- ❑ For full power of quark PDFs: need for pion and kaon SF data in the large x region, for large range of Q^2
- ❑ Action item for Meson SF WG: pion structure function with estimate of uncertainties by varying PDFs – for EIC projections

Overview – PDA and PDF

Discussion leader: Craig Roberts (Nanjing U.)

Meson leading-twist DAs

- Continuum results exist & 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”



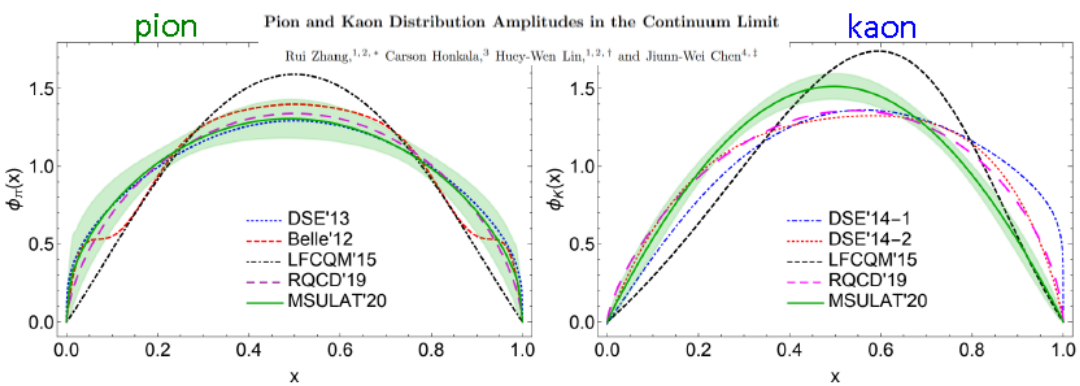


FIG. 10. Fit of the $P_z = 4\frac{2\pi}{L}$ pion (left) and kaon (right) data to the analytical form in Bjorken-x space, compared with previous calculations (with only central values shown). Although we do not impose the symmetric condition $m = n$, both results for the pion and kaon are symmetric around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

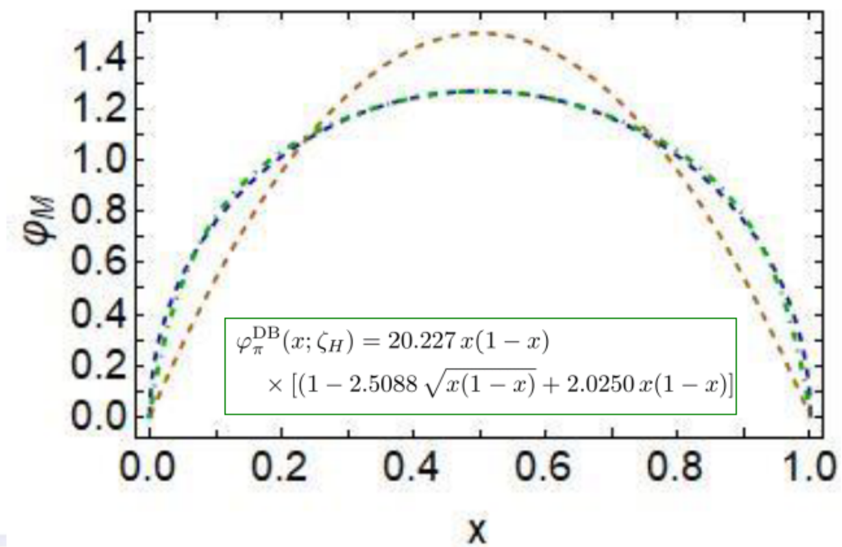
Discussion leader: Craig Roberts (Nanjing U.)

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 $x \simeq 1 \Rightarrow q^{\pi}(x;\zeta_{\rm H}) \propto (1-x)^1$
  - Endpoint behaviour taken "too seriously"

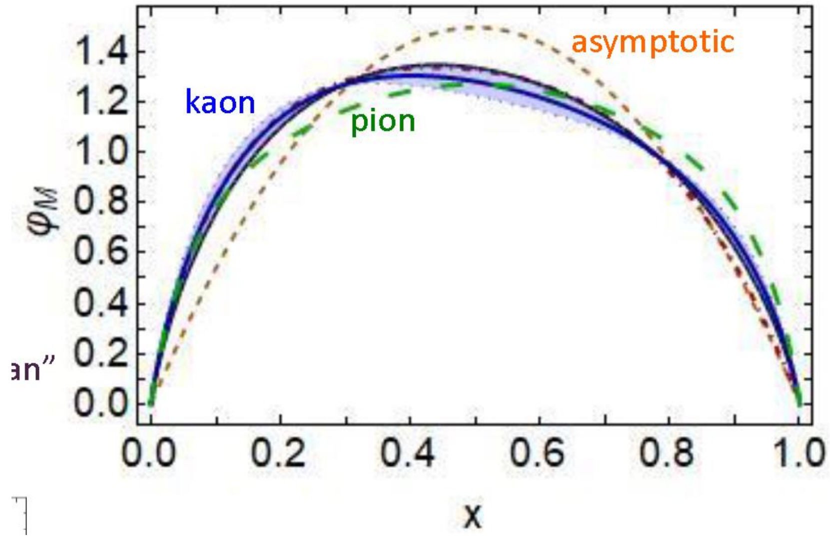


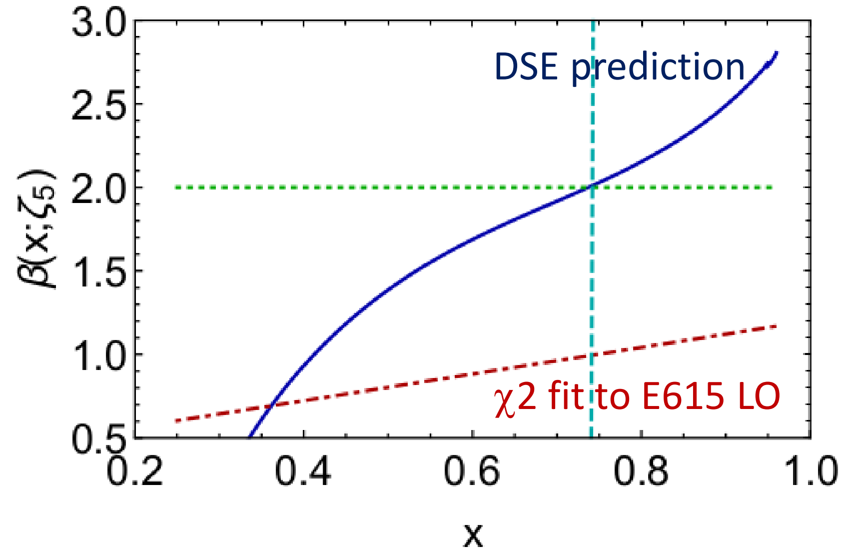
Summary – PDA and PDF

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:

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

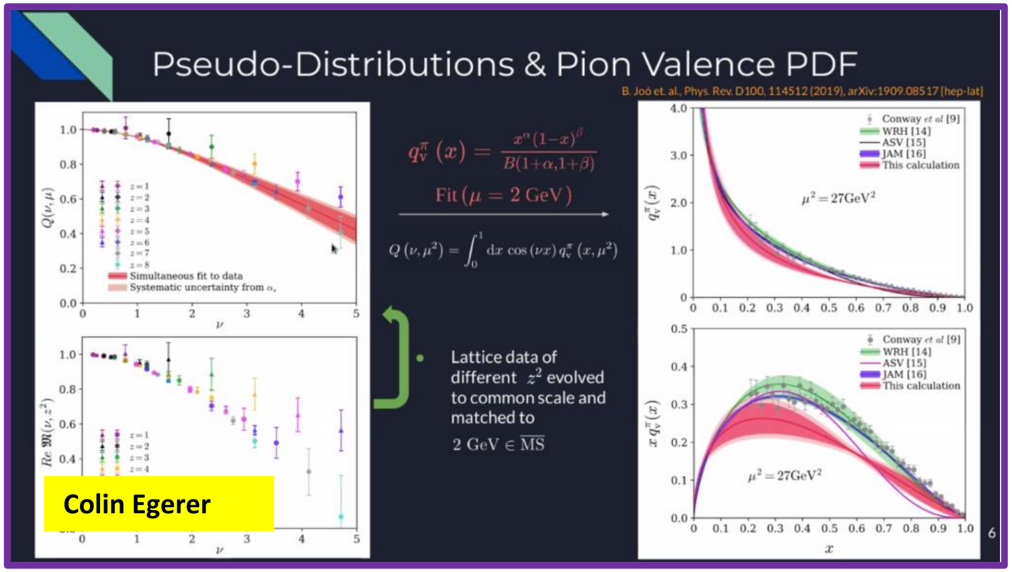


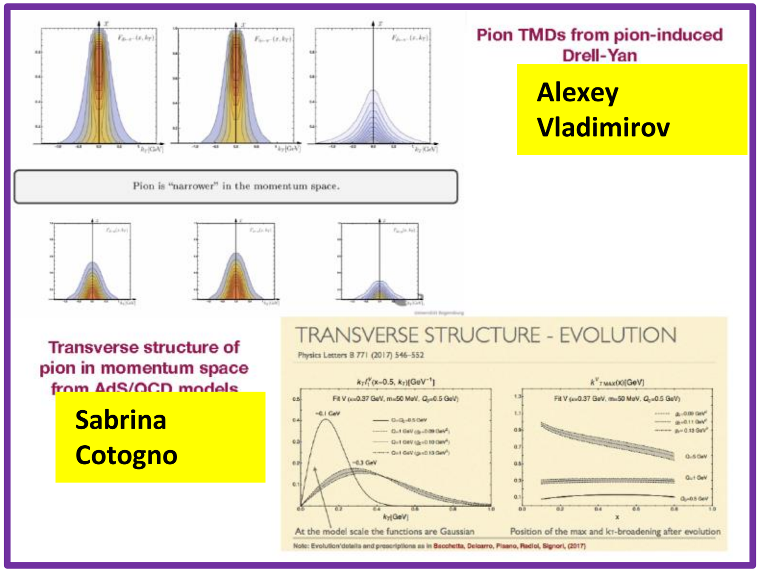


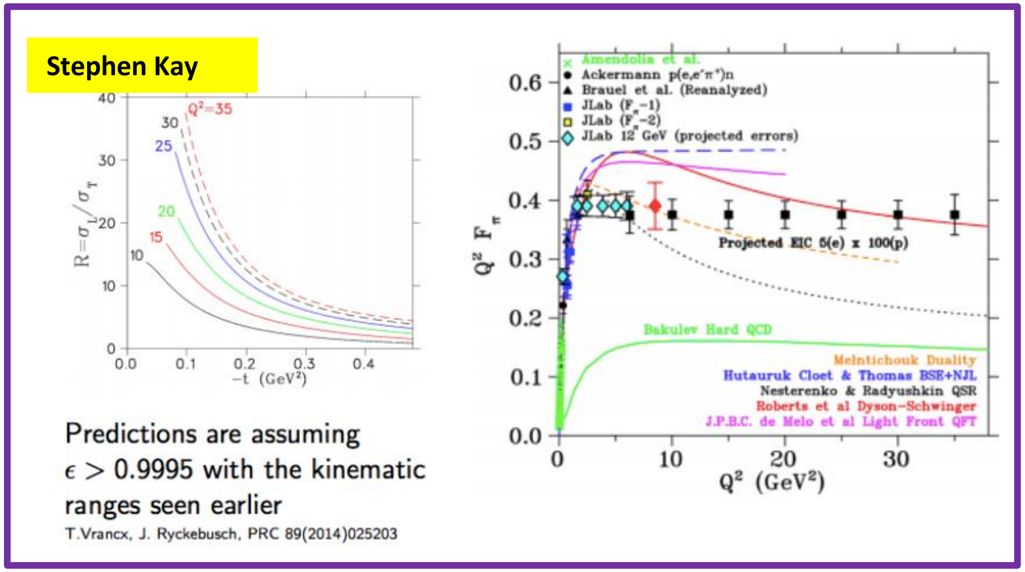
- ➢ Experimental test: precise data and sound extraction in region 0.6 < x < 0.8 sufficient to test QCD prediction

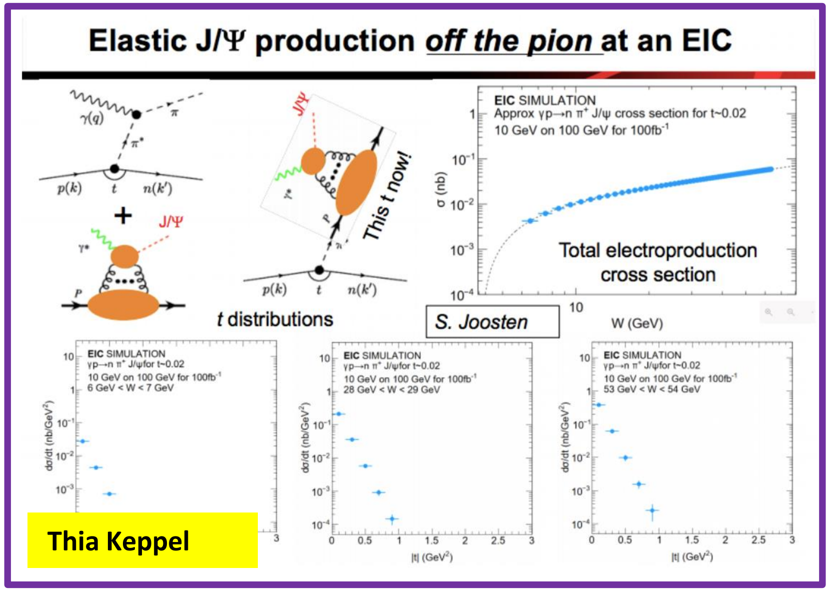
Overview – Towards 3D Meson Structure

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 ... $(1/k^2)^n \Leftrightarrow (1-x)^{2n}$
  - 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

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- 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 ⇒ no recent phenom. inferences.
  - Valence-quark distributions: results from models and a single, recent lQCD 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 α_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 $Q^2/\hat{s} \to 1$ must be matched to the fixed-order (FO) cross section at $Q^2/\hat{s} < 1$. The resulting PDFs may depend on the resummed nonpertubative 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):

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

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

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

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

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