Pion and Kaon PDFs from Di-lepton Production

Wen-Chen Chang

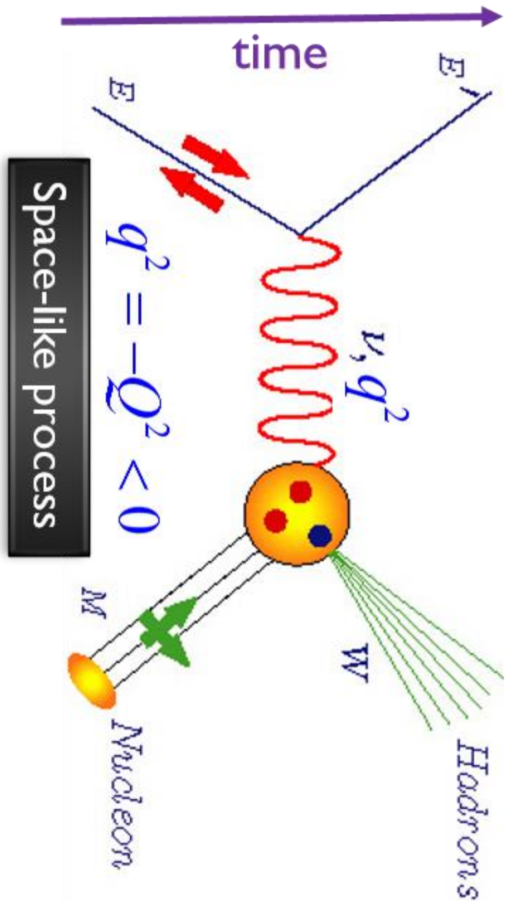
Institute of Physics, Academia Sinica

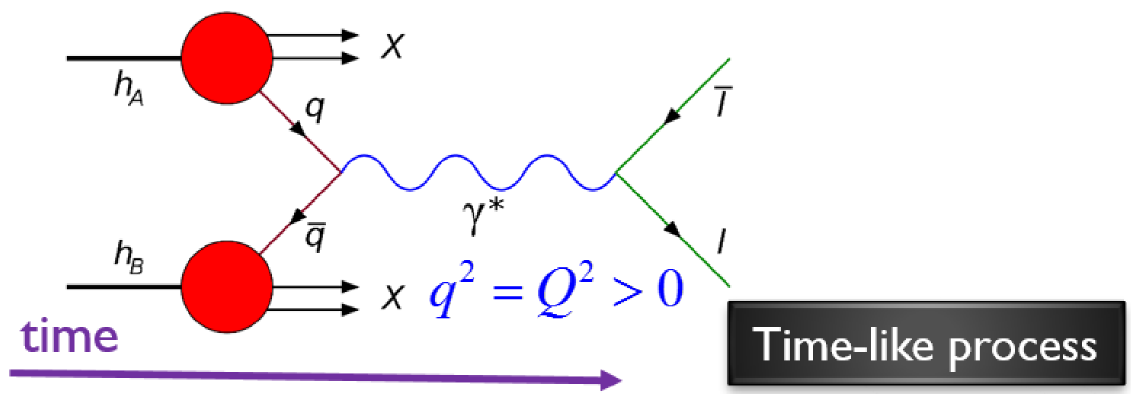
In collaboration with
Jen-Chieh Peng, Stephane Platchkov and Takahiro Sawada

Why are Pions and Kaons Important?

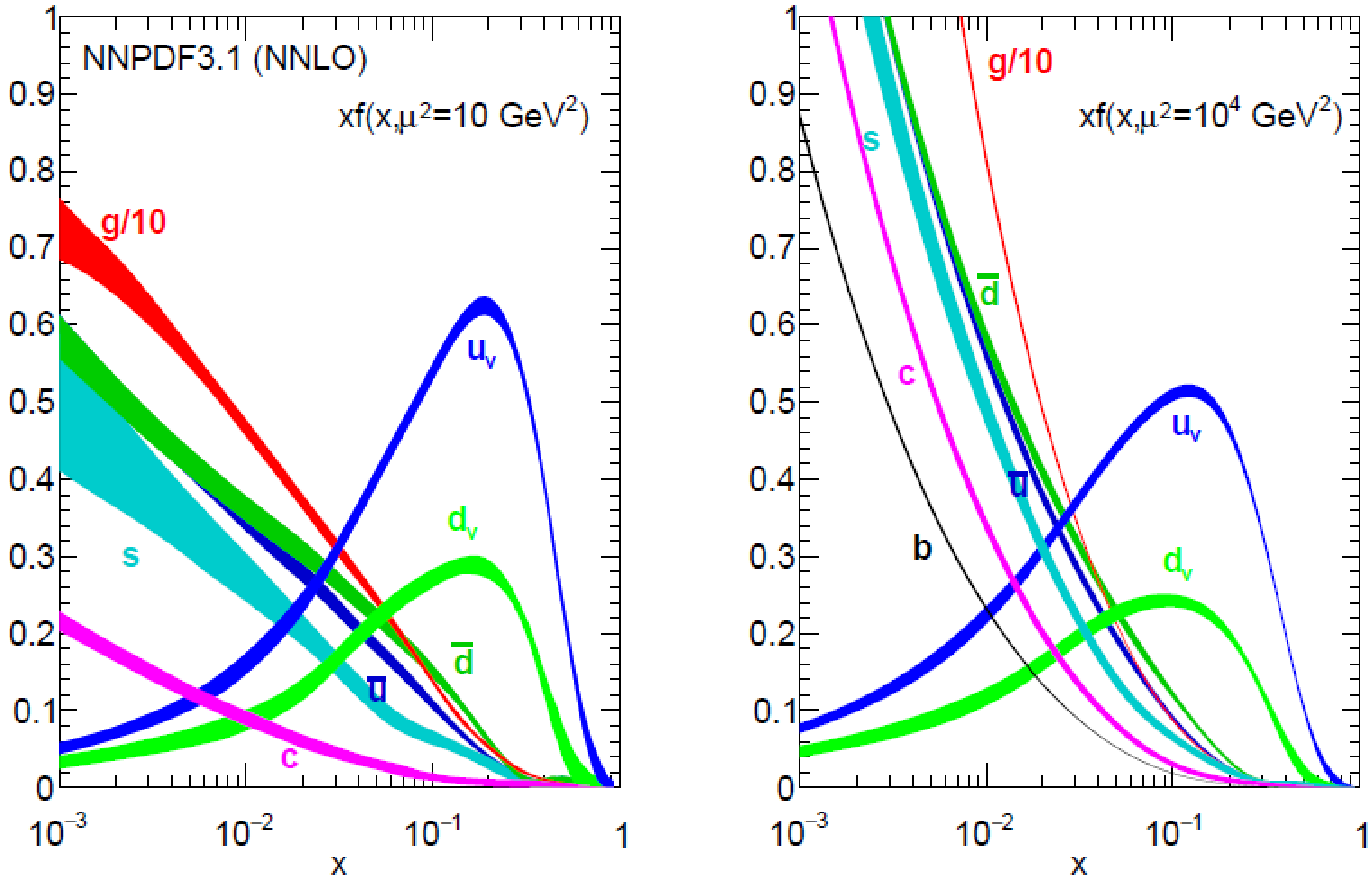
- Pions are the force carrier within the nucleus (Yukawa, 1935). Similarly kaons are responsible for the interaction between ΛN.
- Nambu-Goldstone bosons of spontaneous symmetry breaking of chiral symmetry $SU(3)_L * SU(3)_R$.
- Meson cloud picture of nucleons is important in understanding the flavor asymmetry of sea quarks of nucleons.
- …

Experimental Approach for Proton PDFs



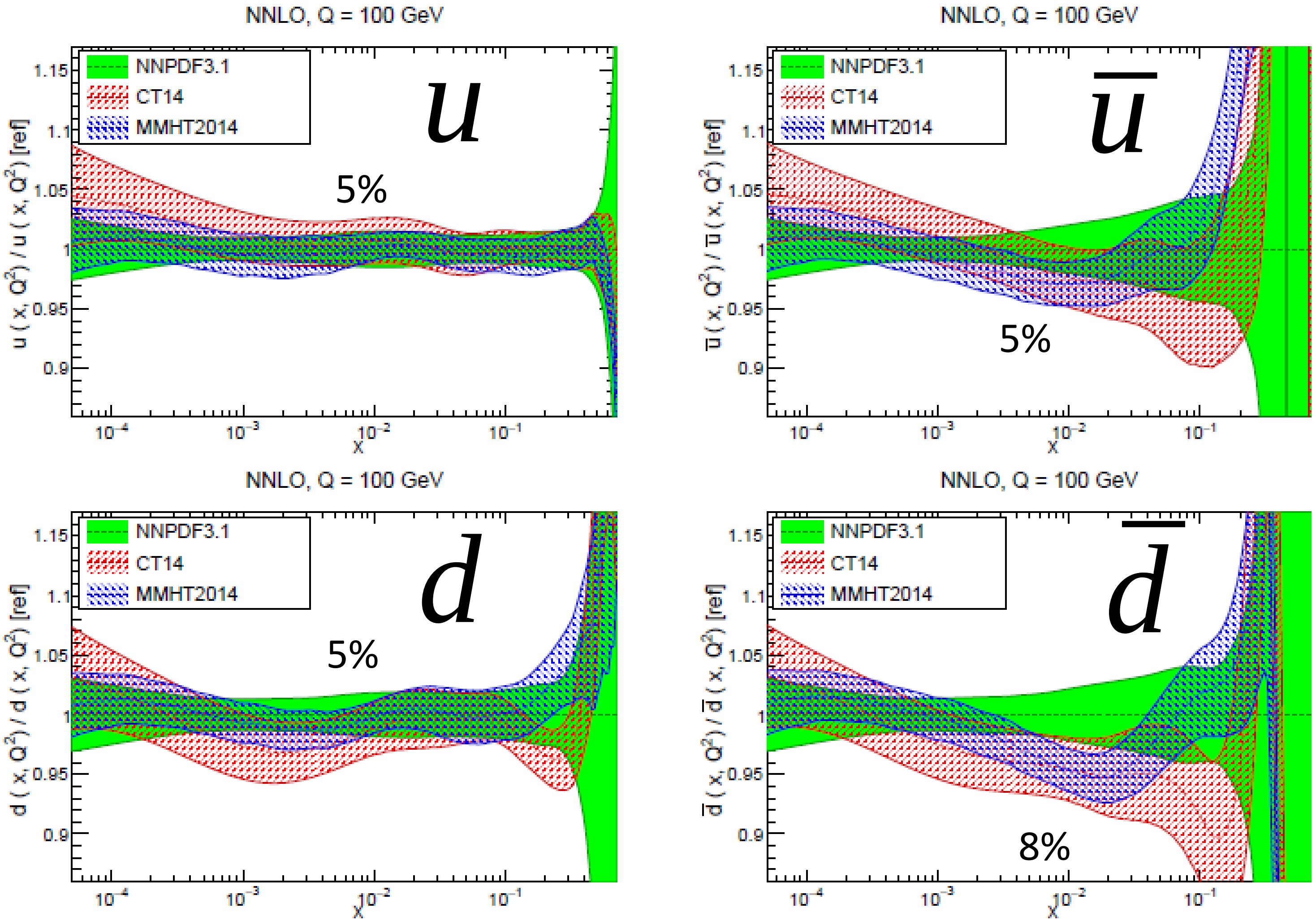


Proton PDF (NNPDF3.1)



1706.00428

Proton PDFs



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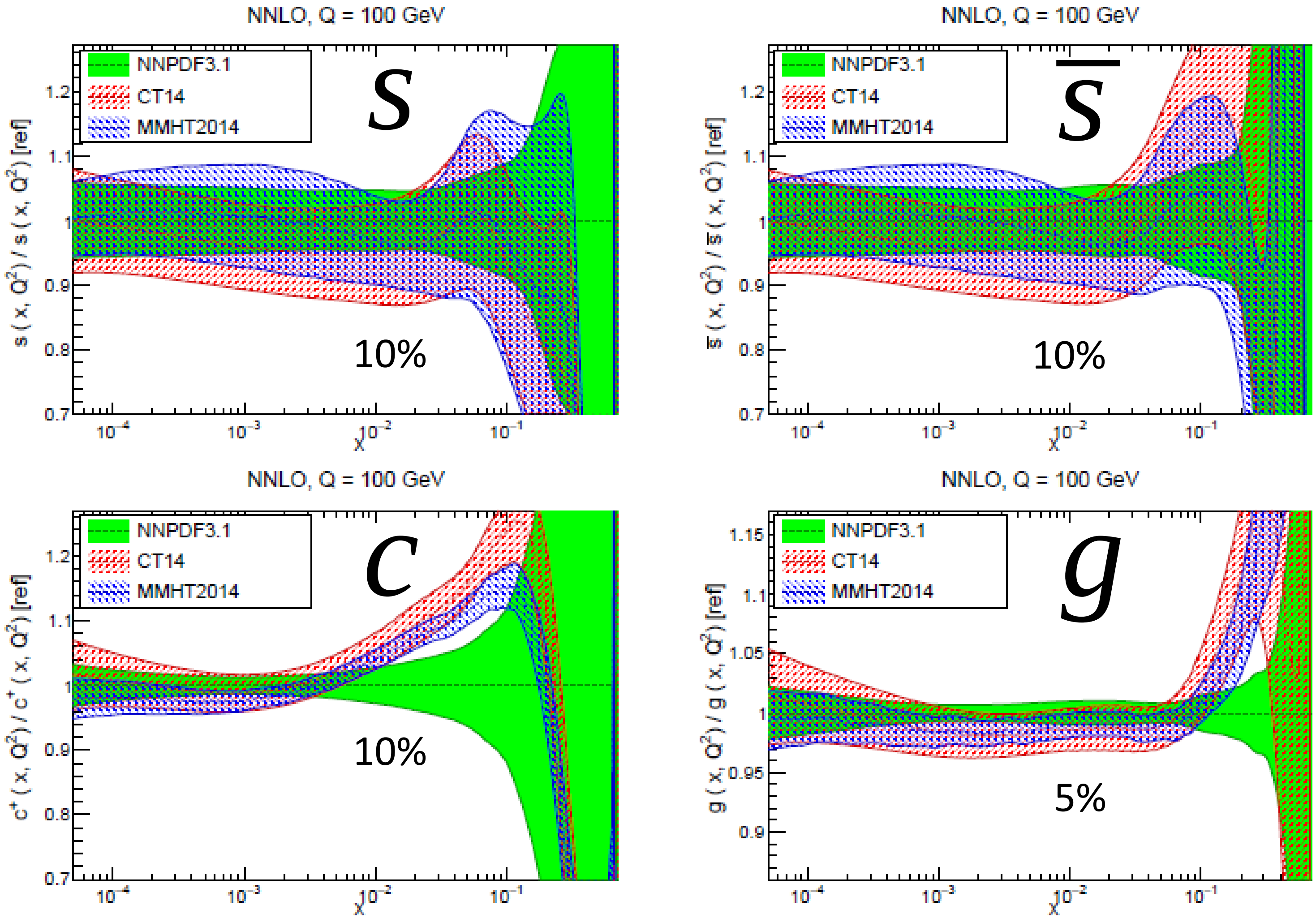
Proton PDFs



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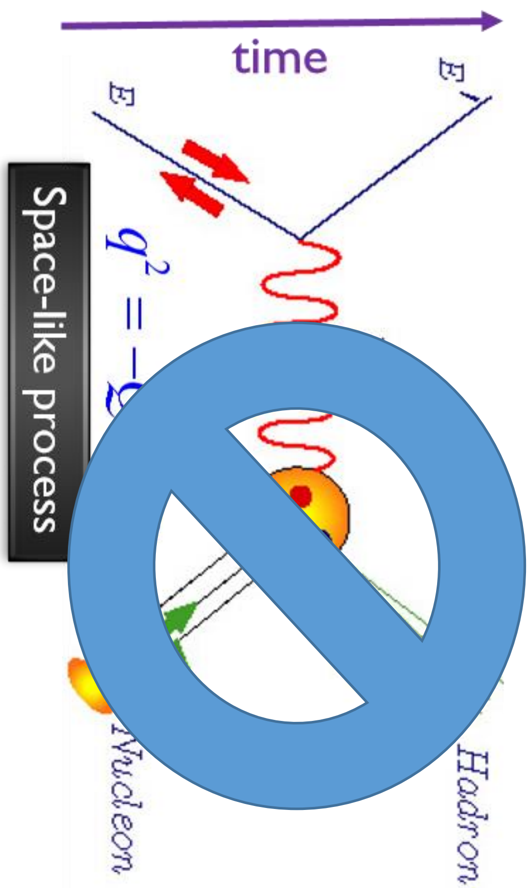
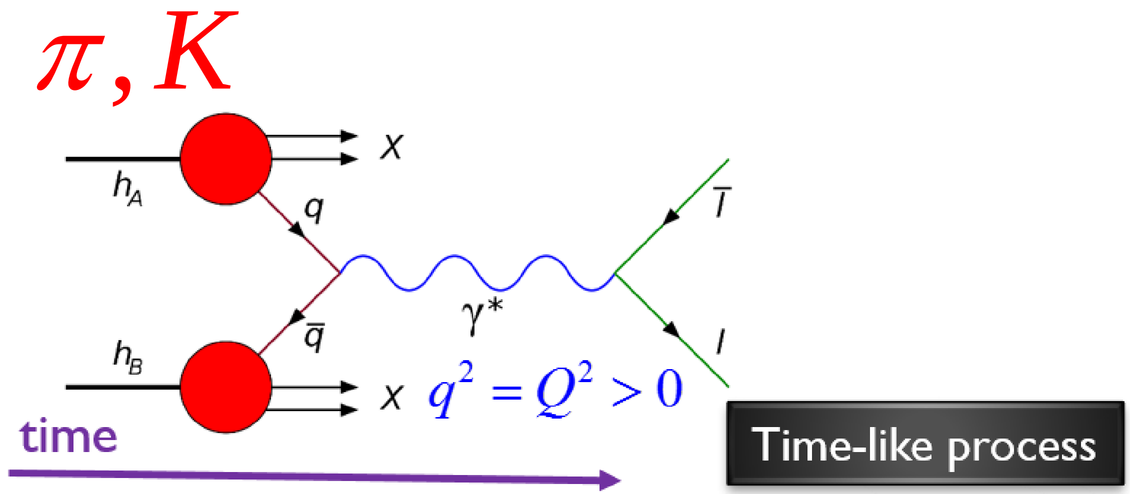
Experimental Approach for Pion and Kaon PDFs

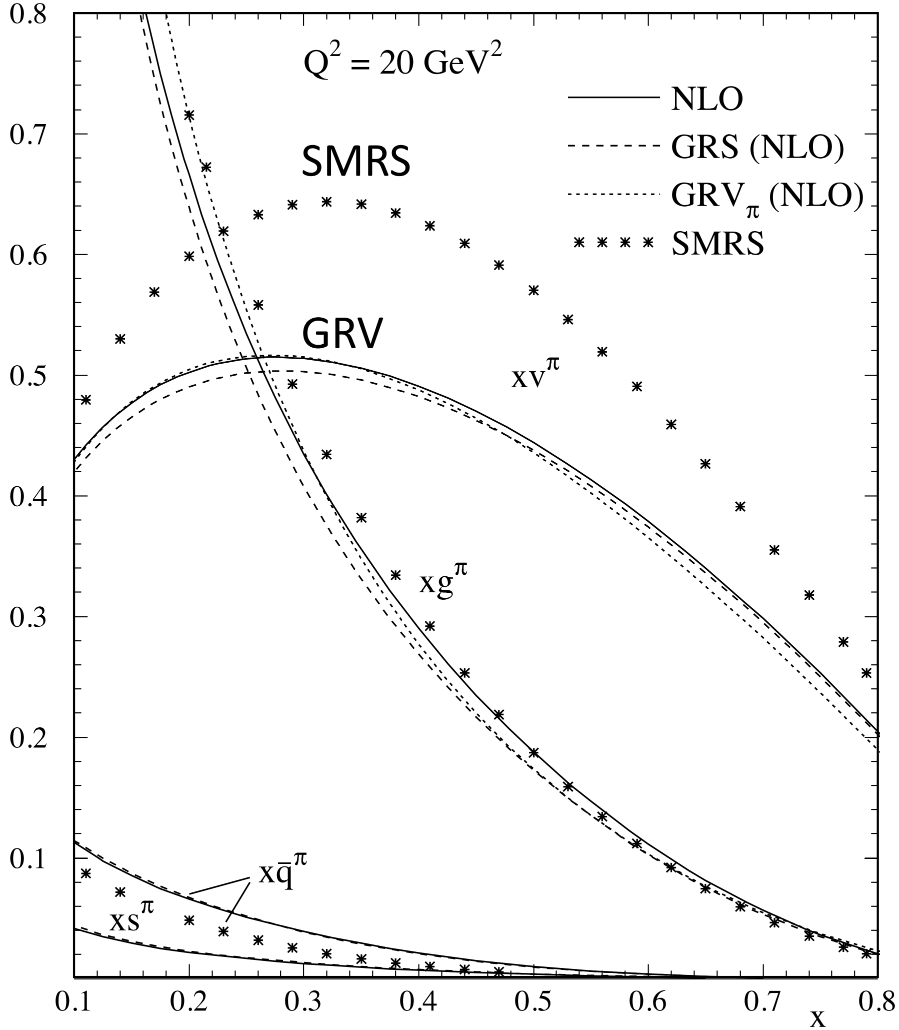




$$\bar{q}q \to \gamma^*$$
$$gq \to \gamma q$$
$$gg, \bar{q}q \to c\bar{c} \to J/\Psi$$

No rest targets of pions and kaons!

Pion PDFs (before 2018)



EPJC 10 (1999) 313

- No rest target of pions (kaons)! DIS approach is difficult.
- PDFs were mainly determined by Drell-Yan, single γ, J/psi data.
- **20% difference at x = 0.5 !**

List of Drell-Yan experiments with π^- beam

Exp	P (GeV)	targets	D-Y events
WA11	175	Be	500 (semi-exclusive)
WA39	40	W (H_2)	3839 (all beam, M > 2 GeV)
NA3	150, 200, 280	Pt (H_2)	21600, 4970, 20000 (535, 121, 741)
NA10	140, 194, 286	W (D_2)	~84400, ~150000, ~45900 (3200, --, 7800)
E331/E444	225	C, Cu, W	500
E326	225	W	
E615	80, 252	W	4060, ~50000

Almost more than 30 years old!

J.C. Peng, ANL pieic2017 workshop

List of Drell-Yan experiments with π^+ beam

Exp	P (GeV)	targets	D-Y events
WA39	40	W (H_2)	
NA3	200	Pt (H_2)	1750 (40)
E331/E444	225	C, Cu, W	

Drell-Yan experiments with K^- beam

Exp	P (GeV)	targets	D-Y events
WA39	40	W (H_2)	
NA3	150, 200	Pt	688, 90

Drell-Yan experiments with K^+ beam

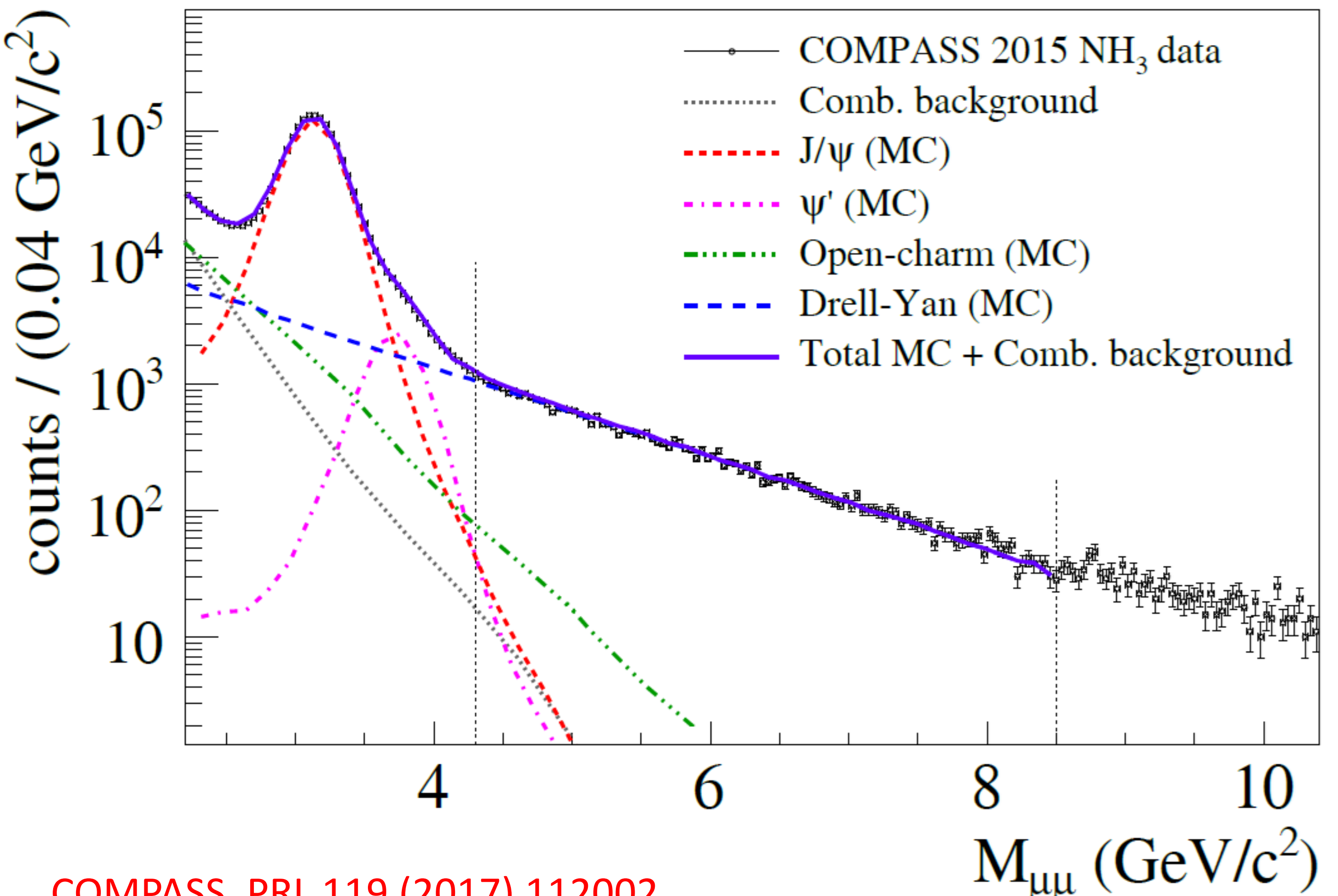
Exp	P (GeV)	targets	D-Y events
WA39	40	W (H_2)	
NA3	200	Pt	170

Drell-Yan experiments with $\bar{p}$ beam

Exp	P (GeV)	targets	D-Y events
WA39	40	W (H_2)	
NA3	150, 200	Pt	275, 32
E537	125	W, Cu, Be	380

J.C. Peng, ANL pieic2017 workshop

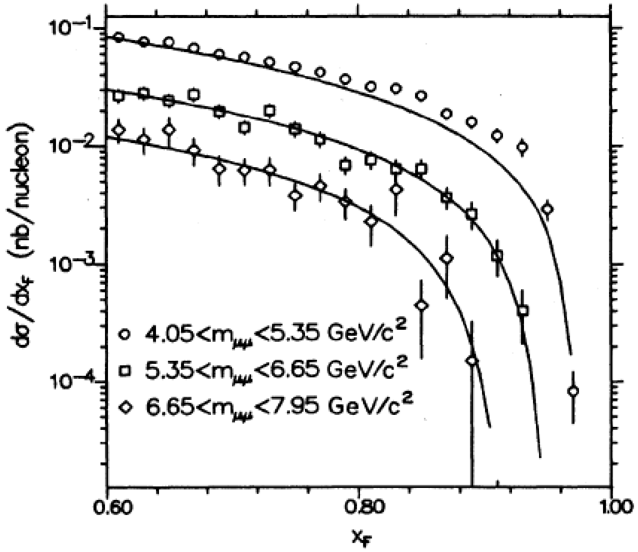
Dimuon Invariant-mass Spectrum (COMPASS Pion-Induced 2015 Run)



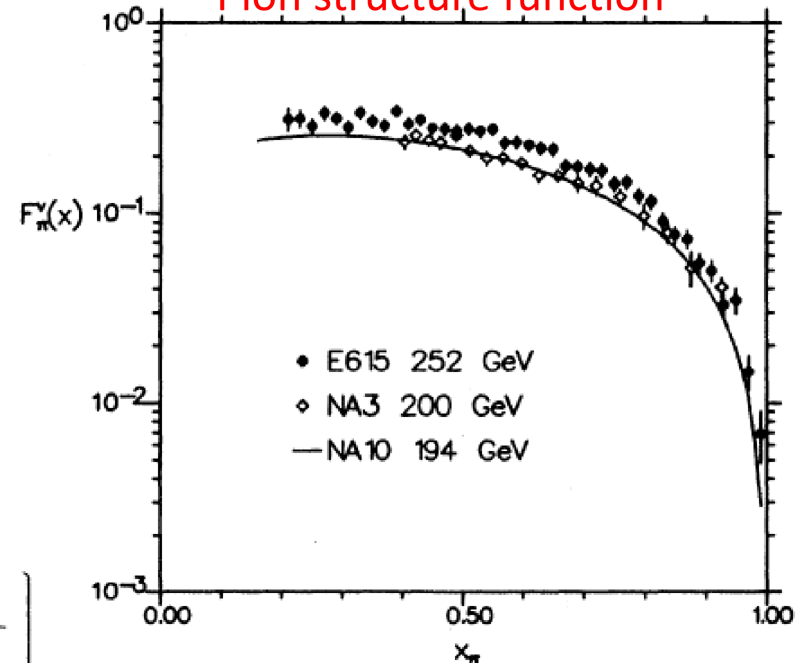
COMPASS, PRL 119 (2017) 112002

E615 $\sigma^{DY}(\pi^- + p \to \gamma^* X)$ [PRD 39, 92 (1989)]

Differential cross sections



Pion structure function



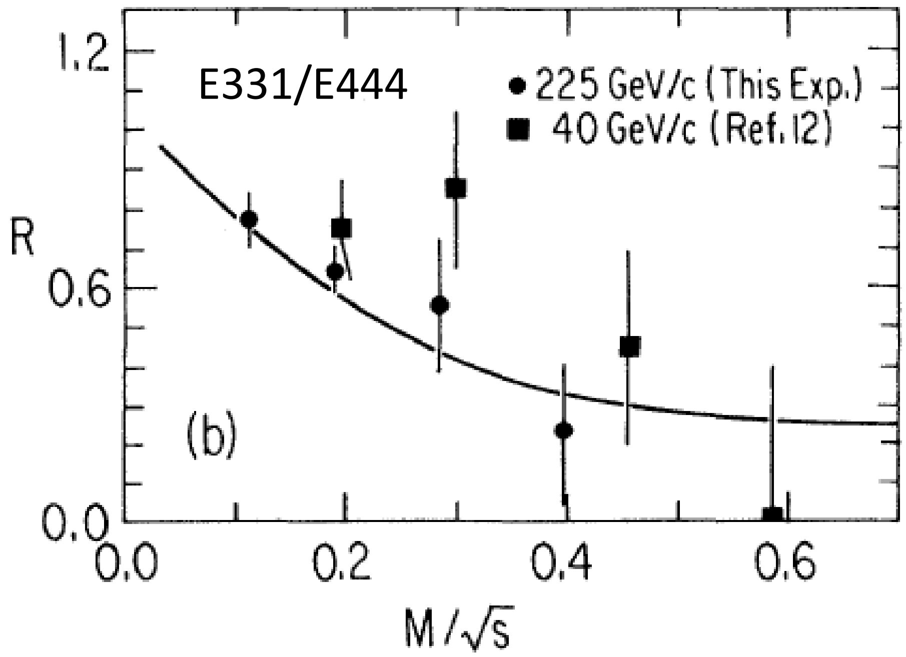
$$\frac{d^2\sigma}{dx_\pi dx_N} = \frac{4\pi\alpha^2}{9s}\left[\frac{F_\pi^v(x_\pi)G_N(x_N) + F_\pi^s(x_\pi)H_N(x_N)}{(x_\pi x_n)^2}\right]$$

where $x_\pi x_N = m_{\mu\mu}^2/s$ and

$$F_\pi^v(x_\pi) = x_\pi \bar{u}^v(x_\pi) = x_\pi d^v(x_\pi) \ ,$$

$$F_\pi^s(x_\pi) = x_\pi \bar{u}^s(x_\pi) = x_\pi u^s(x_\pi) = \cdots = x_\pi \bar{s}^s(x_\pi) \ ,$$

$\sigma^{DY}(\pi^+ C)/\sigma^{DY}(\pi^- C)$



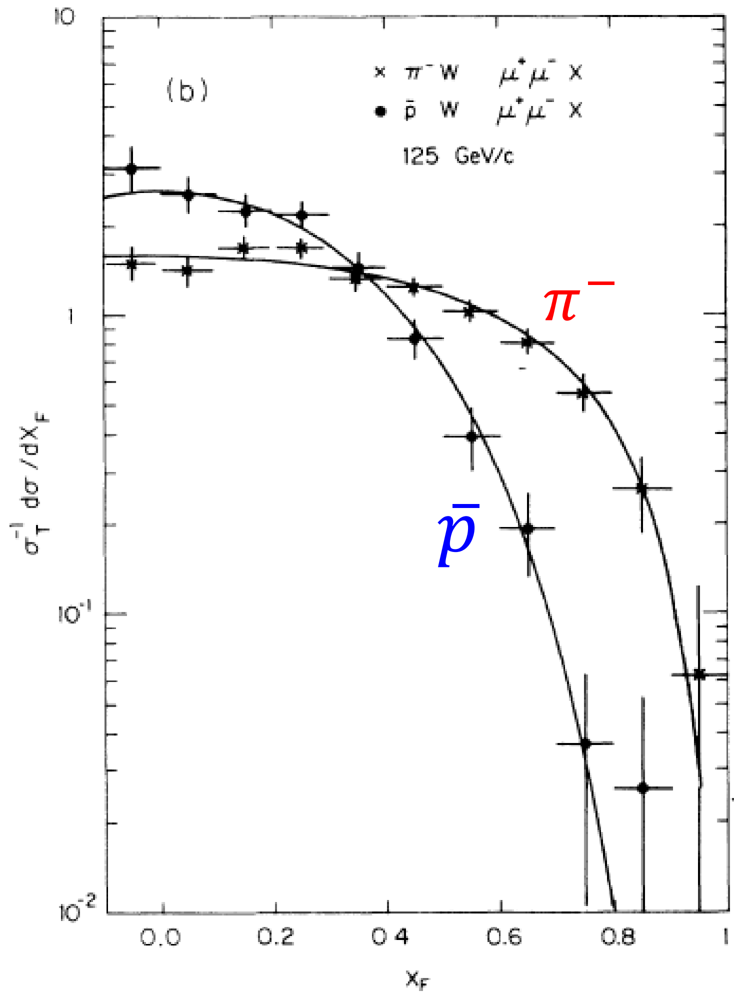
$$R = \frac{V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2) + 10S_\pi(x_1)S_N(x_2)}{4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2) + 10S_\pi(x_1)S_N(x_2)}$$

$$R = \frac{A+B}{4A+B} \Rightarrow \frac{1}{4} \le R \le 1$$

$\sigma^{DY}(\bar{p}W)\ vs.\ \sigma^{DY}(\pi^{-}W)$

E537, PRD 38 (1988) 1377

$$\sigma \propto V_{\bar{p},\pi}(x_1)V_N(x_2)$$

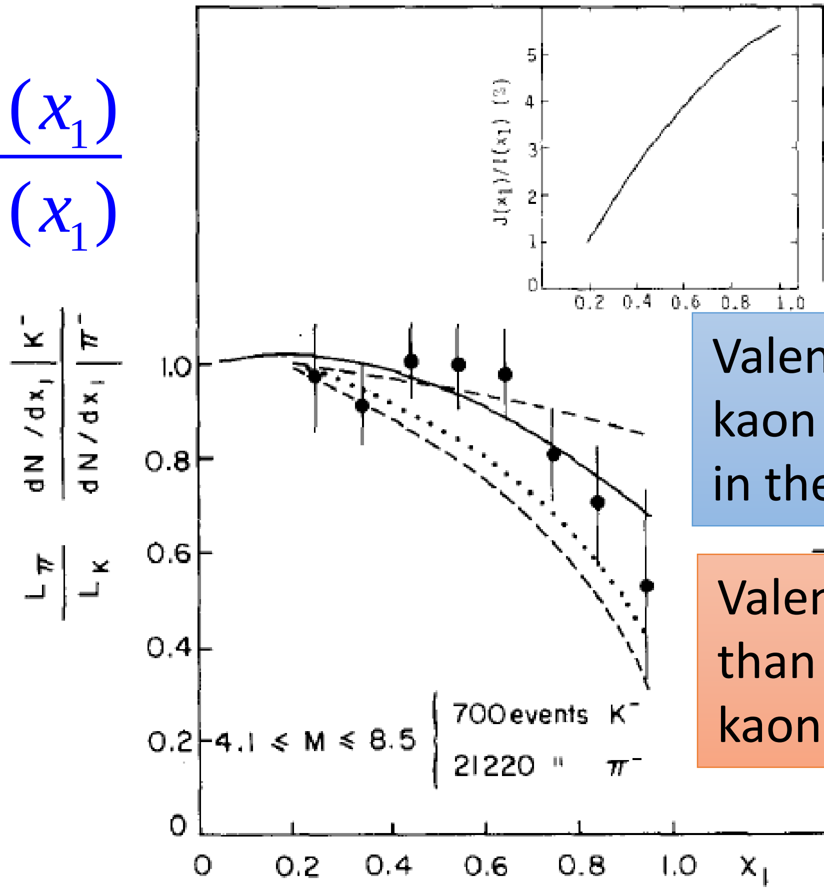


The valence quarks of pions are harder than those of protons.

$\sigma^{DY}(K^- Pt)/\sigma^{DY}(\pi^- Pt)$

NA3, PLB 93 (1980) 354

$$R = \frac{V_K^u(x_1)}{V_\pi^u(x_1)}$$



Valence $\bar{u}$-quarks in the kaon are softer than those in the pion.

Valence $\bar{u}$-quarks are softer than valence s-quarks in the kaon.

Accessing Valence and Sea Quarks of Pions and Kaons

$$\sigma^{DY}(\pi^- D) - \sigma^{DY}(\pi^+ D) = \frac{1}{3} q_\pi^v(x_1)[u_N^v(x_2) + d_N^v(x_2)]$$

$$4\sigma^{DY}(\pi^+ D) - \sigma^{DY}(\pi^- D)$$

$$= \frac{10}{3} \bar{q}_\pi^v(x_1) q_N^v(x_2) + \frac{5}{3} q_\pi^s(x_1)[u_N^v(x_2) + d_N^v(x_2)]$$

$$+ \frac{1}{3}(20 + 4\kappa) q_\pi^s(x_1) q_N^s$$

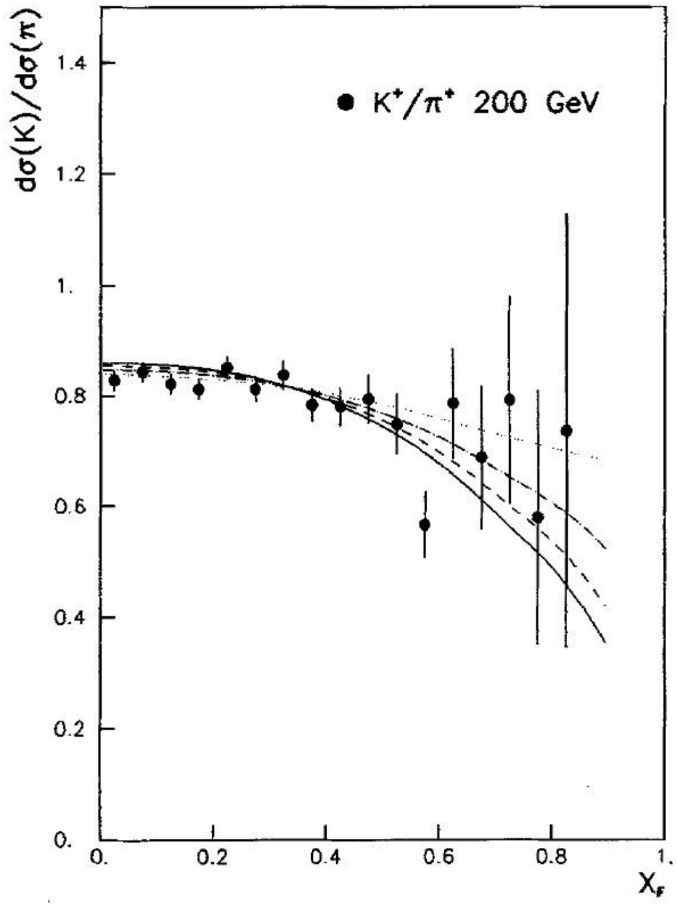
Londergan et al., PLB 361 (1995) 110

$$\sigma^{DY}(K^- D) - \sigma^{DY}(K^+ D) = \frac{8}{9} \bar{u}_K^v(x_1) q_N^v(x_2)$$

Londergan et al., PLB 380 (1996) 393

$\sigma^{J/\psi}(K^+D)/\sigma^{J/\psi}(\pi^+D)$

NA3, ZPC 20 (1983) 101



$$\pi^-(\bar{u}d,g)+p(uud,g)\propto \bar{u}_\pi u_p + g_\pi g_p$$

$$\pi^+(u\bar{d},g)+p(uud,g)\propto \bar{d}_\pi d_p + g_\pi g_p$$

$$K^-(\bar{u}s,g)+p(uud,g)\propto \bar{u}_K u_p + g_K g_p$$

$$K^+(u\bar{s},g)+p(uud,g)\propto g_K g_p$$

$$\frac{\sigma(K^+)}{\sigma(\pi^+)}=\frac{g_K g_p}{\bar{d}_\pi d_p + g_\pi g_p}$$

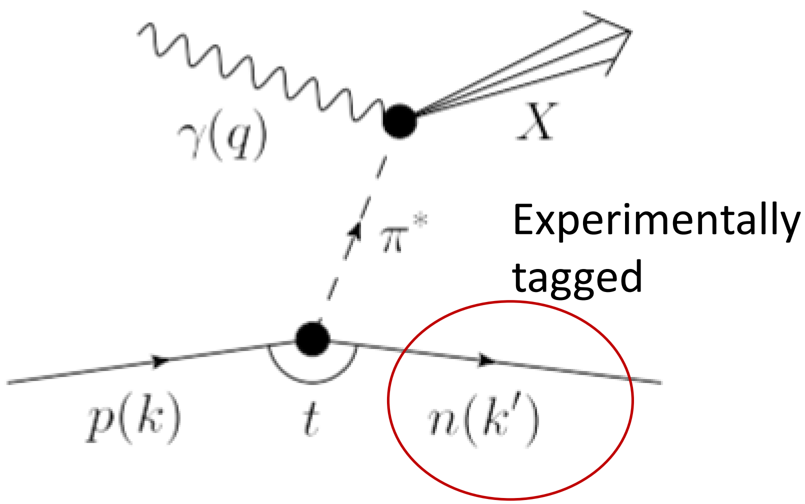
Assume $g_K g_p \approx g_\pi g_p$,

$$\frac{\sigma(K^+)}{\sigma(\pi^+)}=0.8 \text{ suggests } \frac{\bar{d}_\pi d_p}{g_{\pi,K} g_p}=\frac{1}{4}.$$

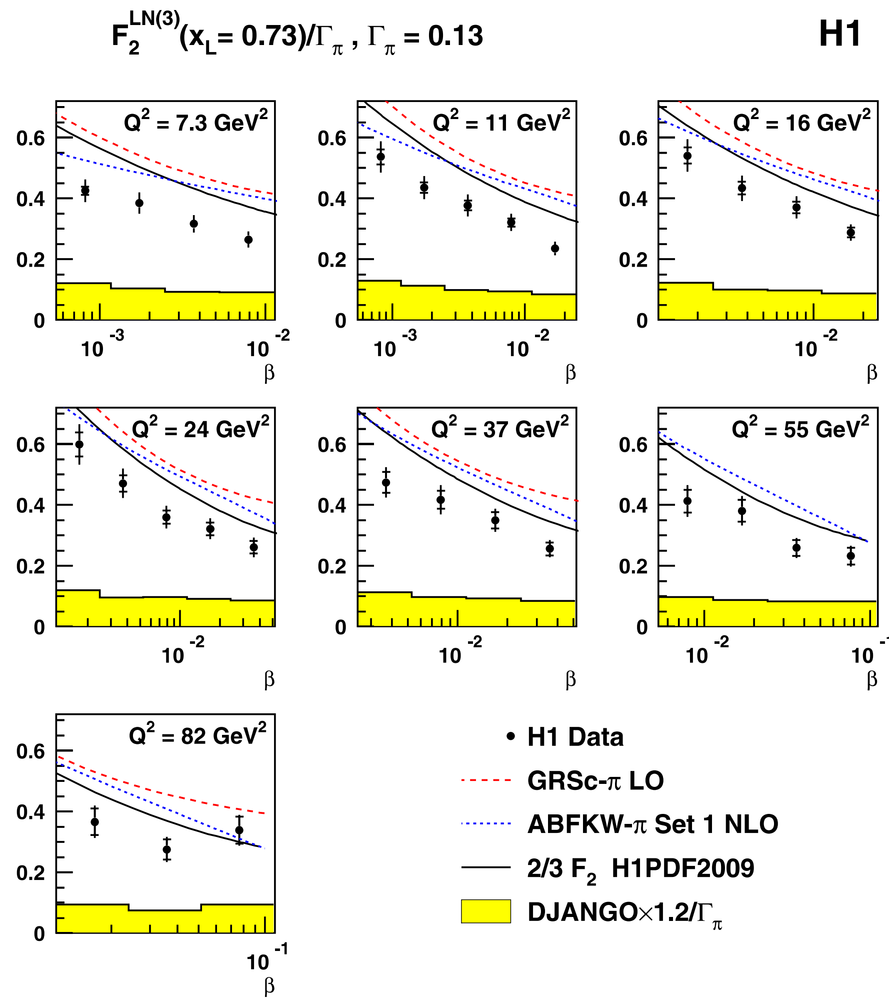
Pion PDFs in LHAPDF

- LHAPDF5:
  - OW-P LO: LO; D-Y and J/psi data [PRD 30, 943 (1984)]
  - ABFKW-P /NLO: NLO; D-Y and direct γ [PLB 233, 517 (1989)]
  - SMRS-P NLO: NLO; D-Y, J/psi and direct γ [PRD 45, 2349 (1992)]
  - GRV-P LO: LO; D-Y and direct γ [ZPC 53, 651 (1992)]
  - GRV-P NLO: NLO; D-Y and direct γ [ZPC 53, 651 (1992)]
- LHAPDF6:
  - GRVPI0: LO; D-Y and direct γ [ZPC 53, 651 (1992)]
  - GRVPI1: LO; D-Y and direct γ [ZPC 53, 651 (1992)]
  - JAM18 : NLO, D-Y and DIS-n-tagged [PRL 121, 152001 (2018)]

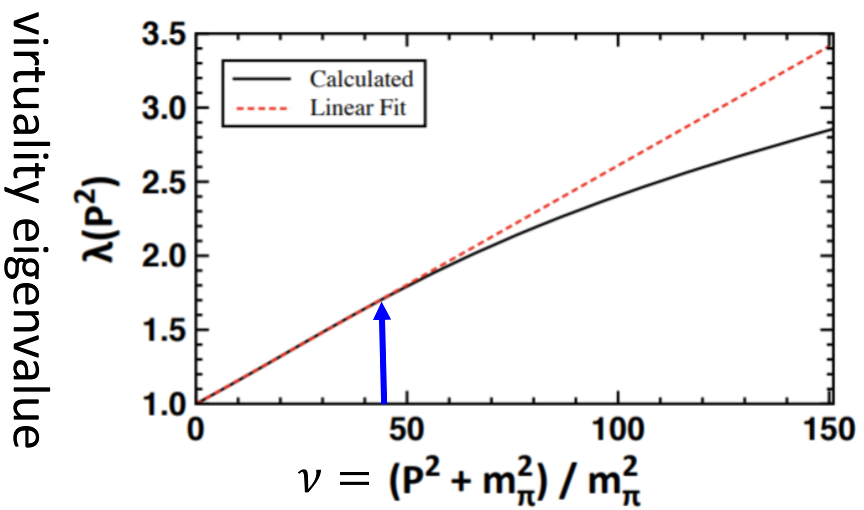
Leading neutron (LN) electroproduction from HERA

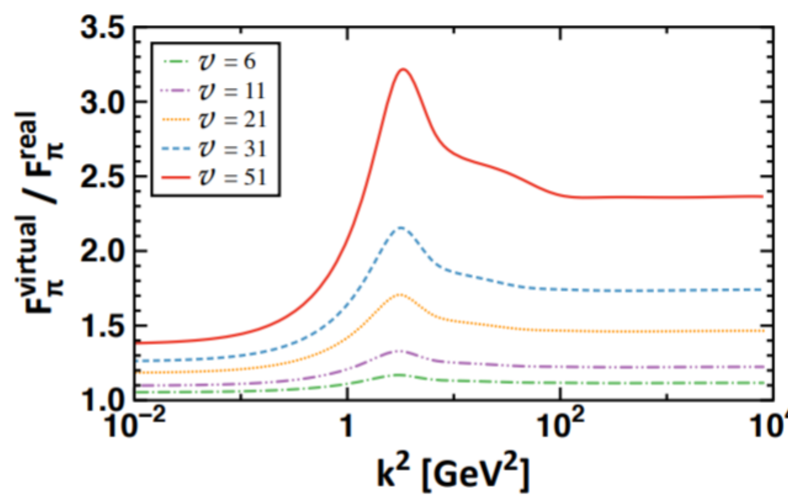


Sullivan processes
from a nucleon's pion cloud



Off-shell persistence of composite pions and kaons
S.X. Qin et al., PRC 97, 015203 (2018)





ν<45, pion pole dominates:
off-shell pion ≈ on-shell pion

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

JAM18: Include leading neutron (LN) electroproduction from HERA [Barry et al., PRL 121, 152001 (2018)]

PHYSICAL REVIEW LETTERS **121,** 152001 (2018)

Featured in Physics

First Monte Carlo Global QCD Analysis of Pion Parton Distributions

P. C. Barry,[1] N. Sato,[2] W. Melnitchouk,[3] and Chueng-Ryong Ji[1]

(Jefferson Lab Angular Momentum (JAM) Collaboration)

[1]*North Carolina State University, Raleigh, North Carolina 27607, USA*
[2]*University of Connecticut, Storrs, Connecticut 06269, USA*
[3]*Jefferson Lab, Newport News, Virginia 23606, USA*

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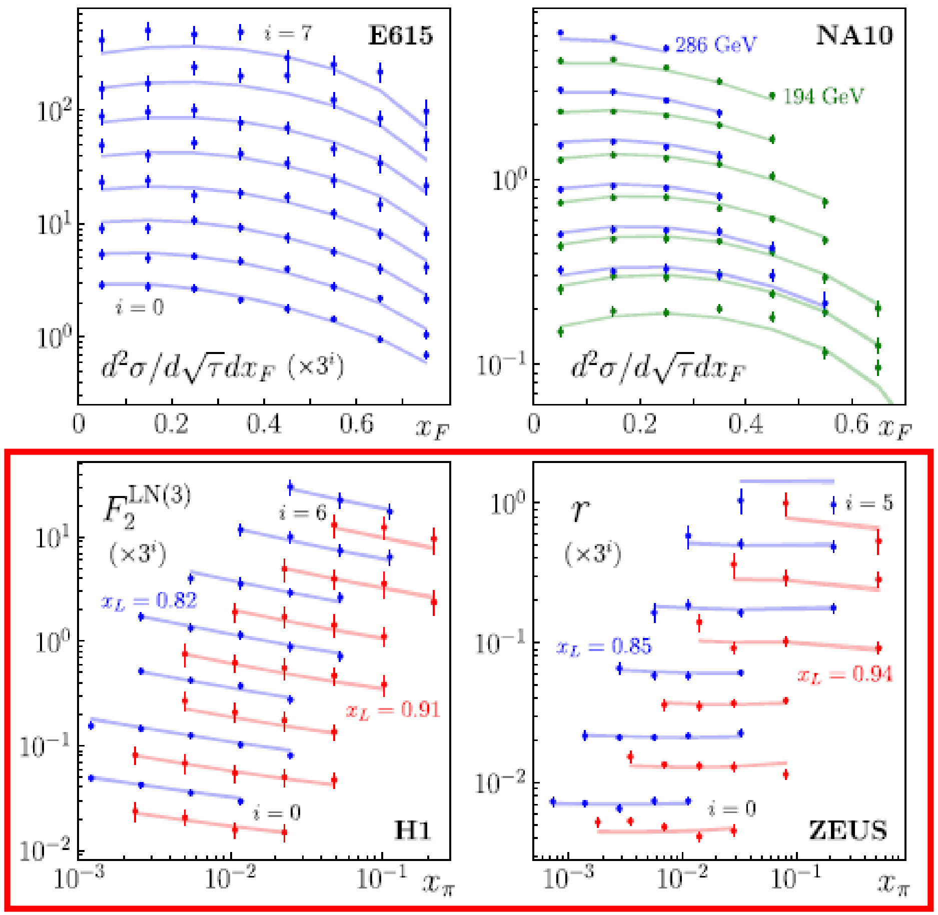
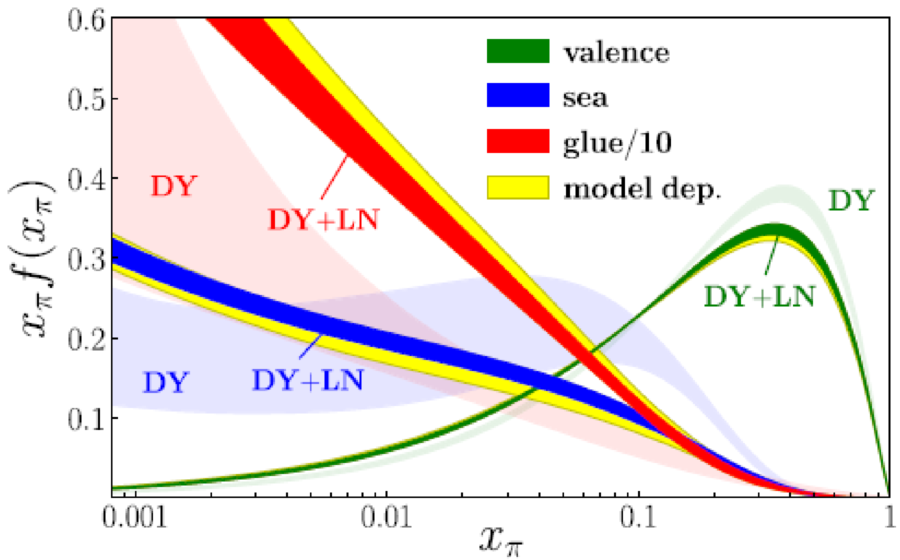
We perform the first global QCD analysis of parton distribution functions (PDFs) in the pion, combining πA Drell-Yan data with leading neutron electroproduction from HERA within a Monte Carlo approach based on nested sampling. Inclusion of the HERA data allows the pion PDFs to be determined down to much lower values of x, with relatively weak model dependence from uncertainties in the chiral splitting function. The combined analysis reveals that gluons carry a significantly higher pion momentum fraction, $\sim$30%, than that inferred from Drell-Yan data alone, with sea quarks carrying a somewhat smaller fraction, $\sim$15%, at the input scale. Within the same effective theory framework, the chiral splitting function and pion PDFs can be used to describe the $\bar{d} - \bar{u}$ asymmetry in the proton.

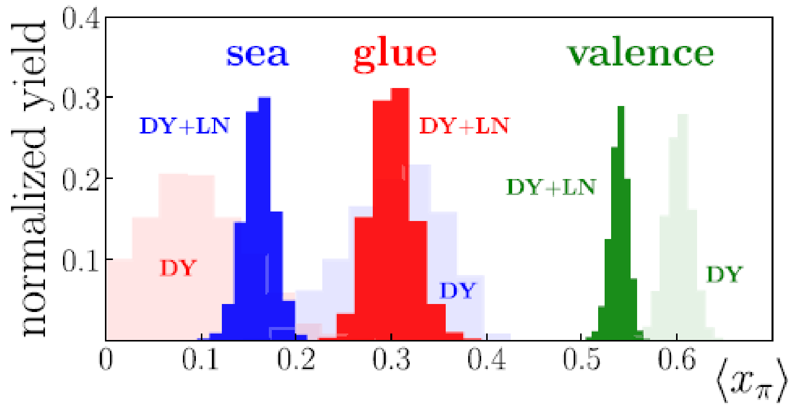
JAM18: Include leading neutron (LN) electroproduction from HERA [Barry et al., PRL 121, 152001 (2018)]

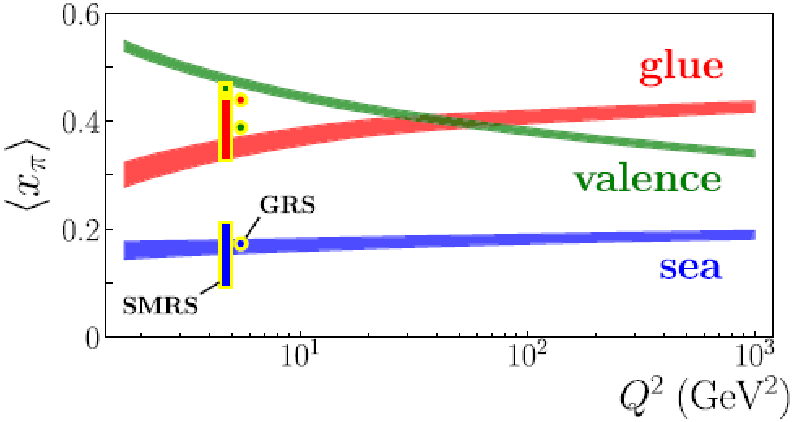




- Uncertainties are much reduced using DY+LN, as compared to DY alone.
- Large-x behavior: ~ $(1-x)^1$, instead of $(1-x)^2$ as expected by QCD or DSE.

JAM18: Include leading neutron (LN) electroproduction from HERA [Barry et al., PRL 121, 152001 (2018)]



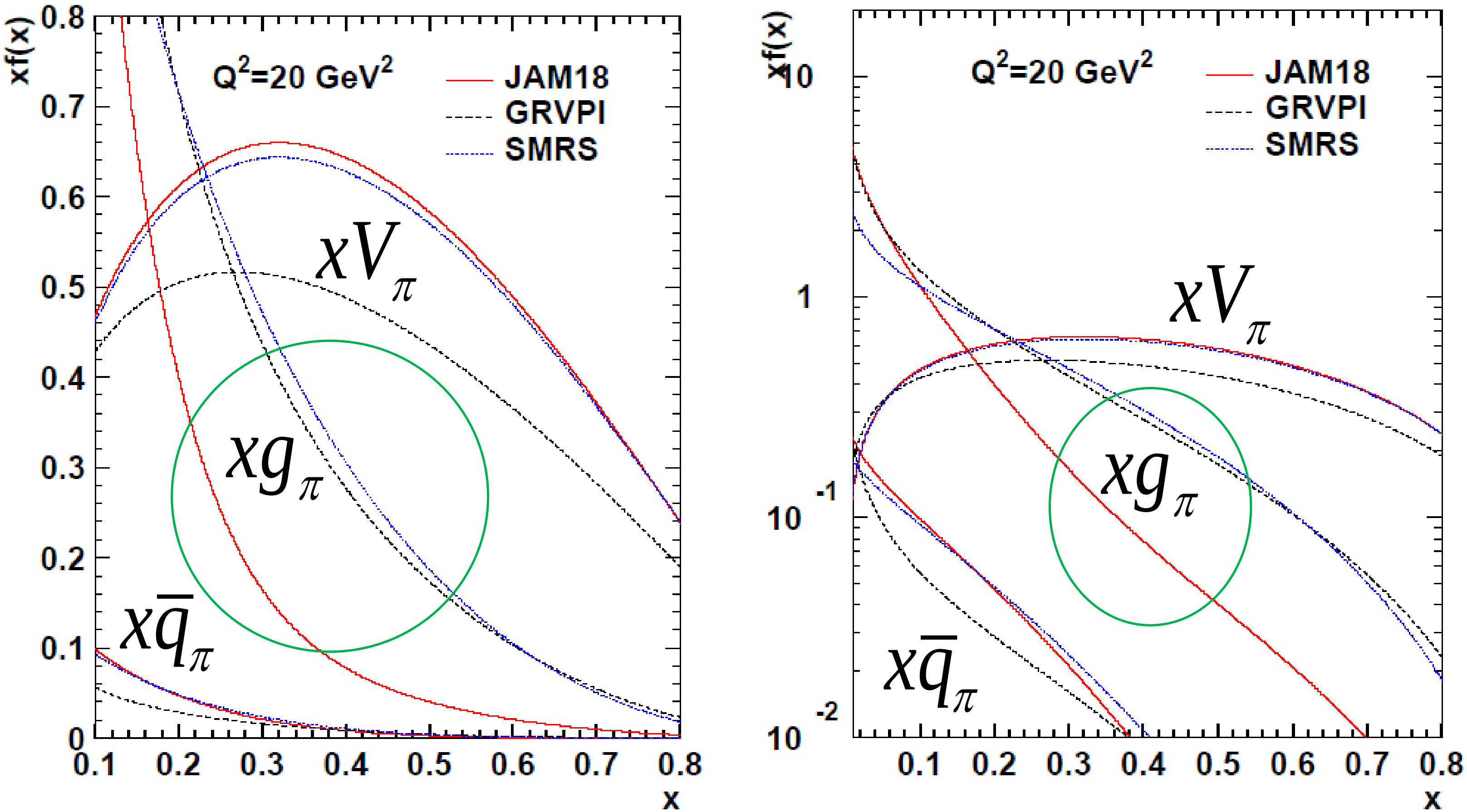


Q^2=5 GeV^2 Q^2=20 GeV^2

	$\langle xu^v \rangle$	$\langle xu^s \rangle$	$\langle xg \rangle$
JAM18	0.24, 0.21	0.027, 0.029	0.35, 0.39
GRVPI1 (GRS)	0.19, 0.17	0.018, 0.021	0.51, 0.52
SMRS1	0.23, 0.21	0.017, 0.020	0.51, 0.45
SMRS2	0.23, 0.21	0.025, 0.027	0.38, 0.41
SMRS3	0.23, 0.21	0.033, 0.034	0.34, 0.37

$\langle xf(x) \rangle$: JAM18 closer to SMRS3 (valence 48%, sea 17% and gluon 35%)

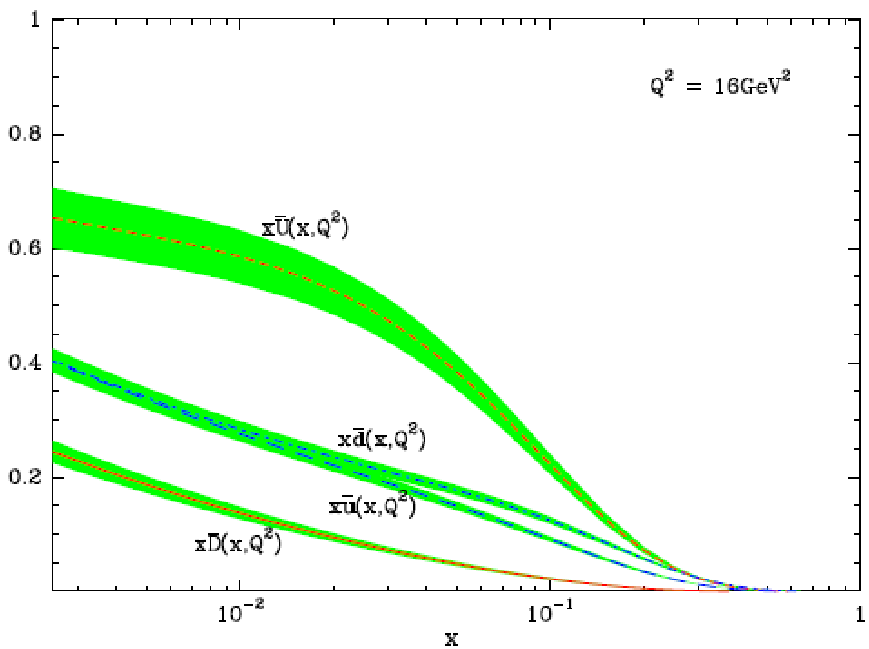
Pion PDFs (2018)

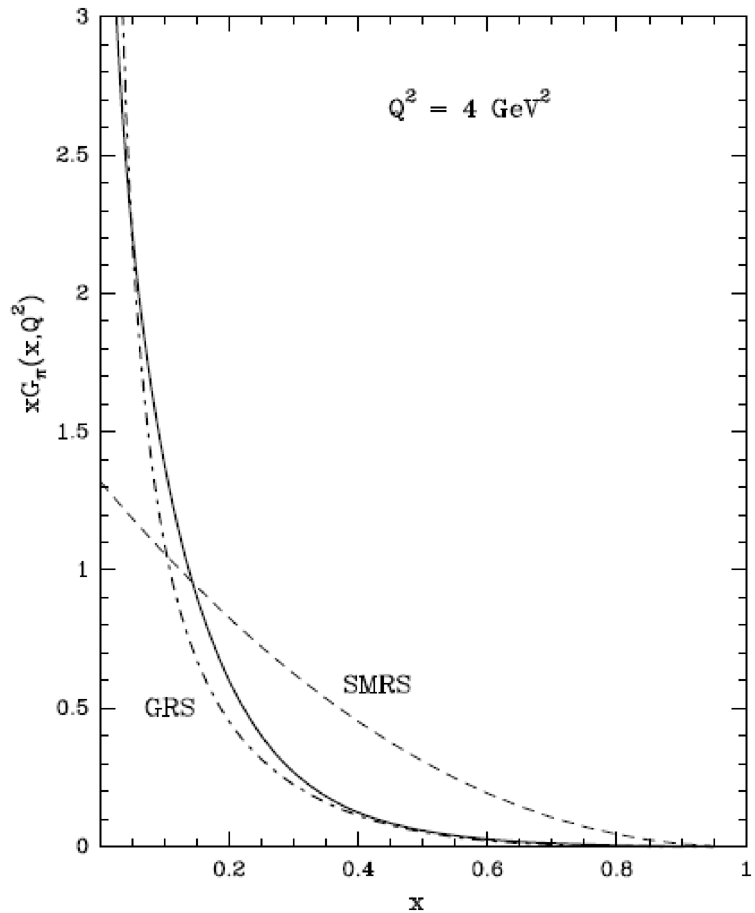


Gluon distribution of JAM18 is significantly reduced in the valence-x region.

Pion PDFs from Statistical approach

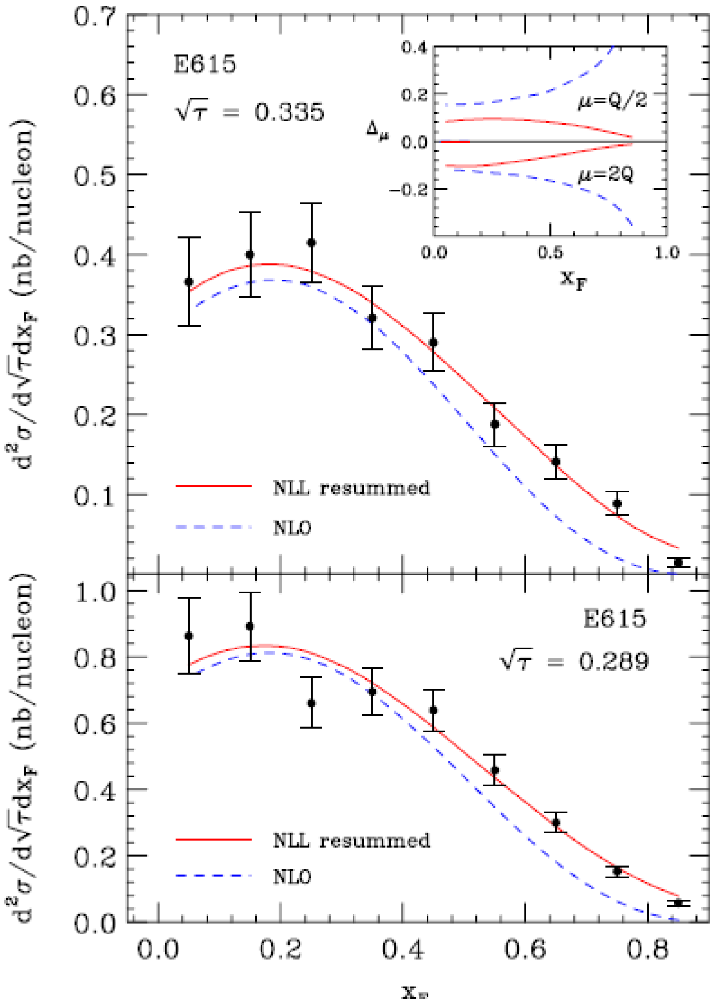
[Bourrely and Soffer, NPA 981, 118 (2019)]

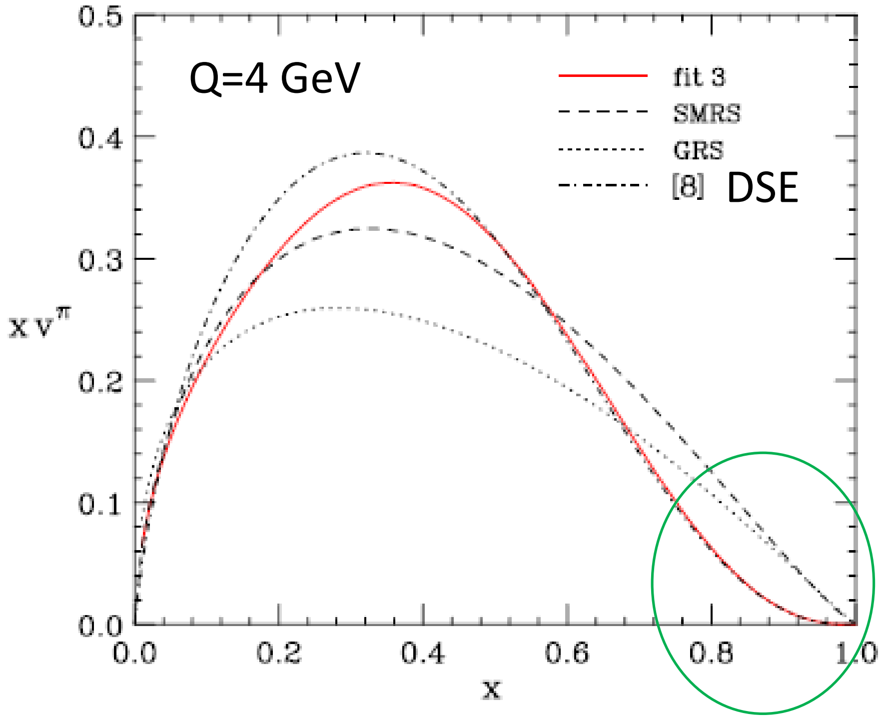




NLL Soft-Gluon Resummation at large-x

[Aicher, Schafer and Vogelsang, PRL 105, 252003 (2010)]

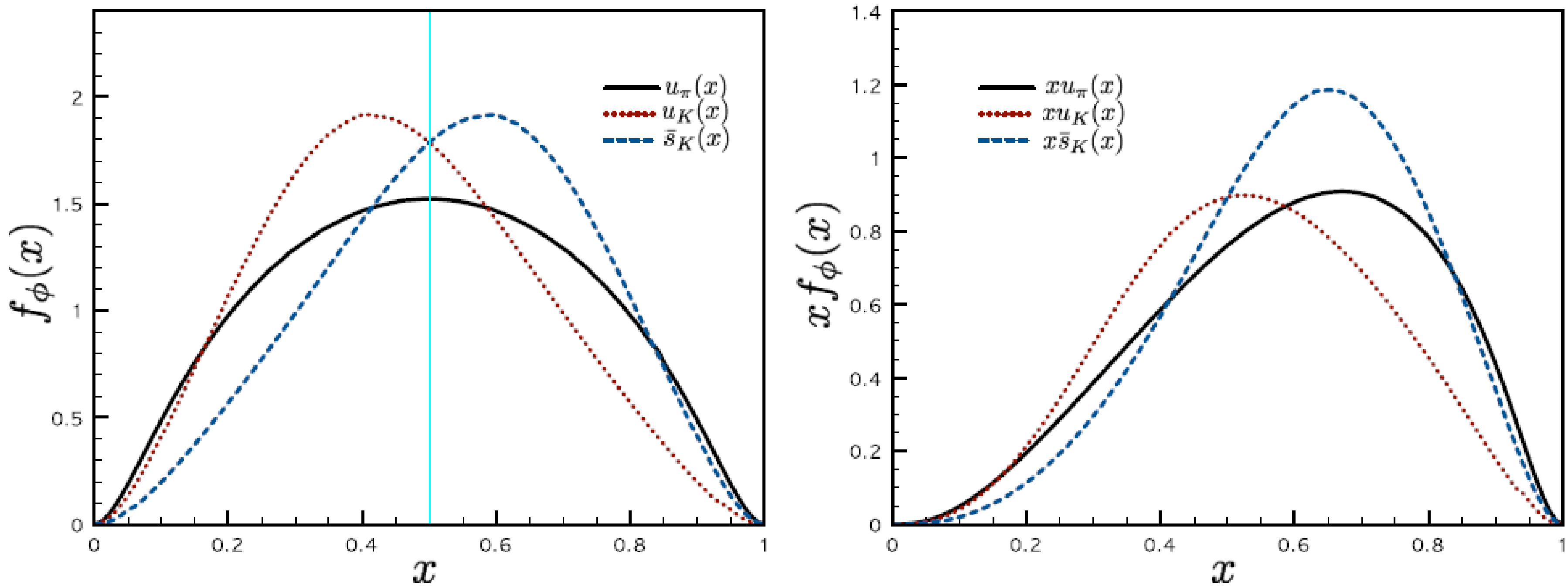




Softer valence quarks at large x.

Kaon PDFs from Gauge-Invariant Nonlocal Chiral Constituent Quark Model

[S. Nam, PRD 86, 074005 (2012)]

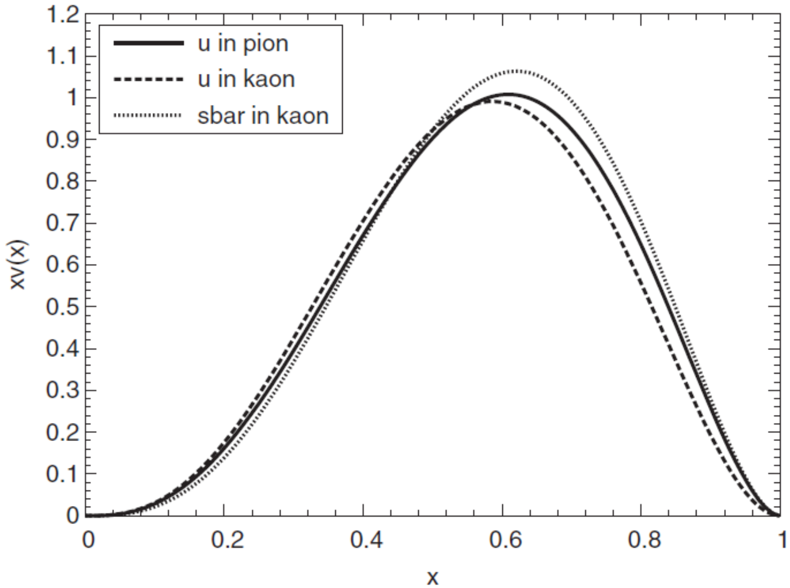


Large SU(3) symmetry-breaking effect.

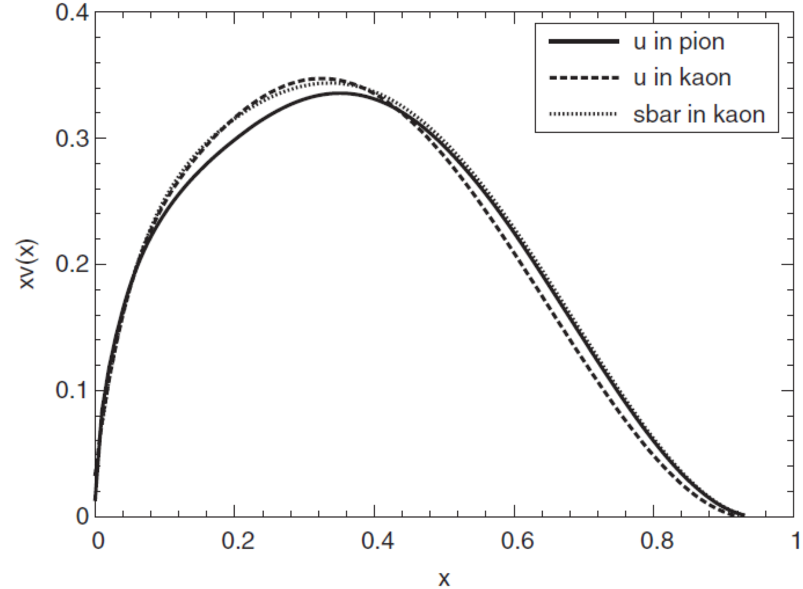
Kaon PDFs from Chiral Constituent Quark Model

[Watanabe, Sawada and Kao, PRD 97, 074015 (2018)]

$Q^2 = Q_0^2$



$Q^2 = 27\ GeV^2$

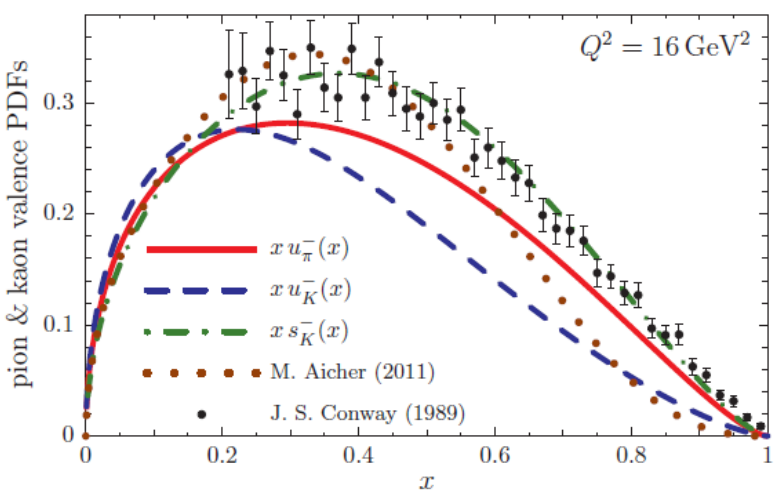


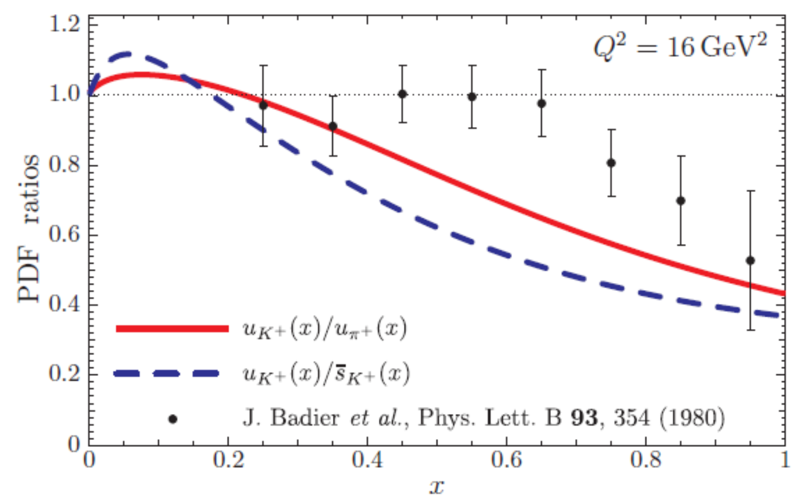
Very small SU(3) symmetry-breaking effect.

Pion and Kaon PDFs from NJL Model

[Hutauruk et al., PRC 94, 035201 (2016)]

$$R = \frac{V_K^u(x_1)}{V_\pi^u(x_1)}$$

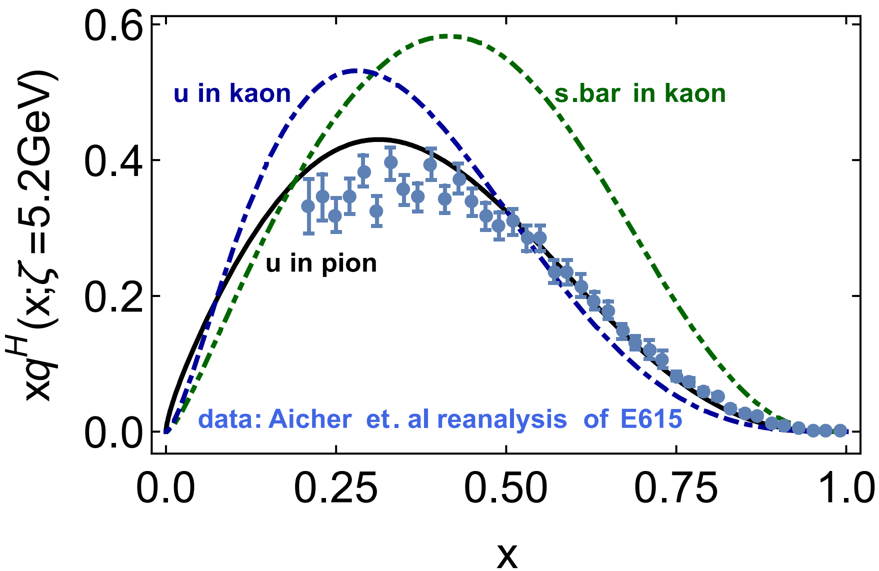


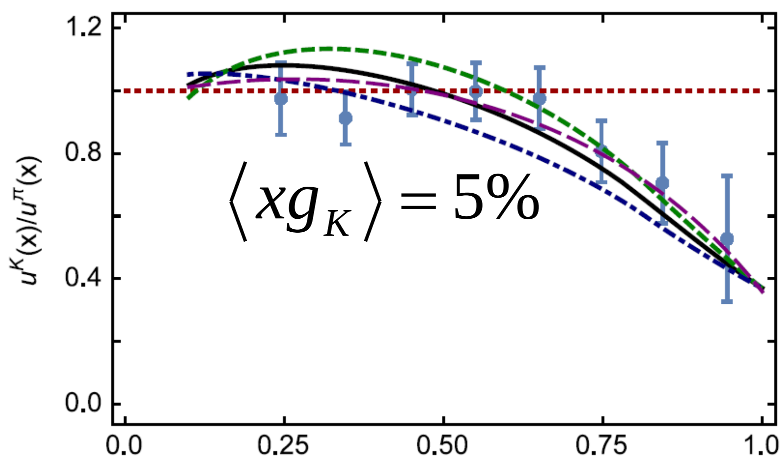


Large SU(3) symmetry-breaking effect.

Pion and Kaon PDFs from Dyson-Schwinger equations

[Chen et al., PRD 93, 074021 (2016)]



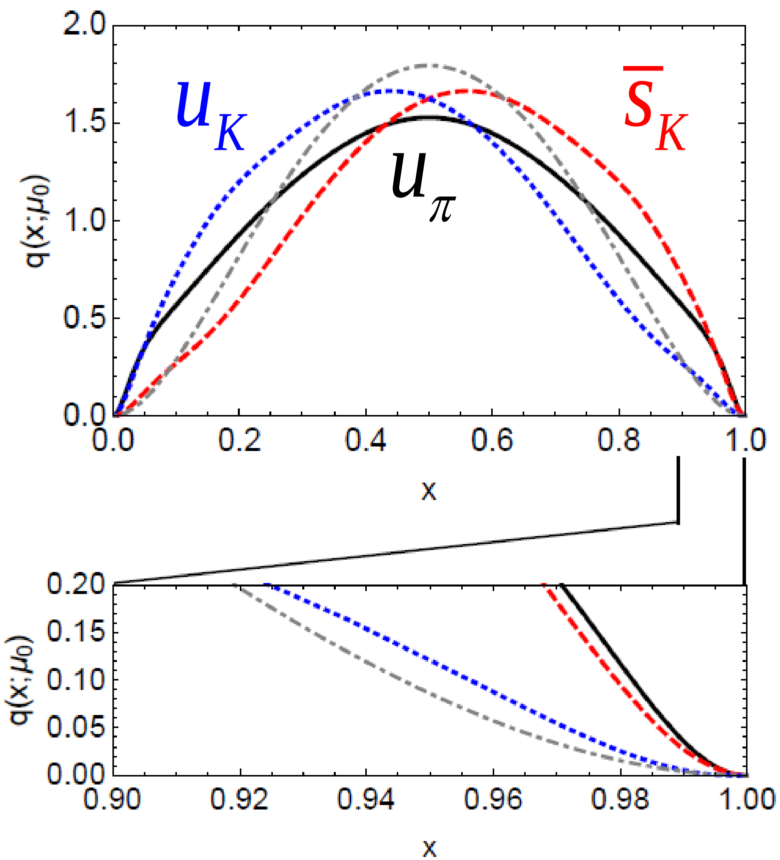


Large SU(3) symmetry-breaking effect.

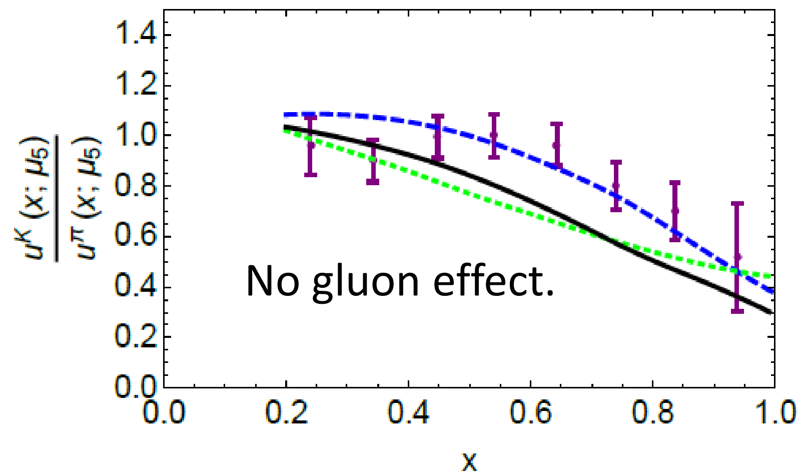
At Q=0.51 GeV, $\langle x g_K \rangle$= 5% but $\langle x g_\pi \rangle$= 35% . Gluons in kaons is softer in pions.

Pion and Kaon PDFs from Dyson-Schwinger equations

[Shi et al., Phys. Rev. D 93, 054029 (2018)]



Large SU(3) symmetry-breaking effect.



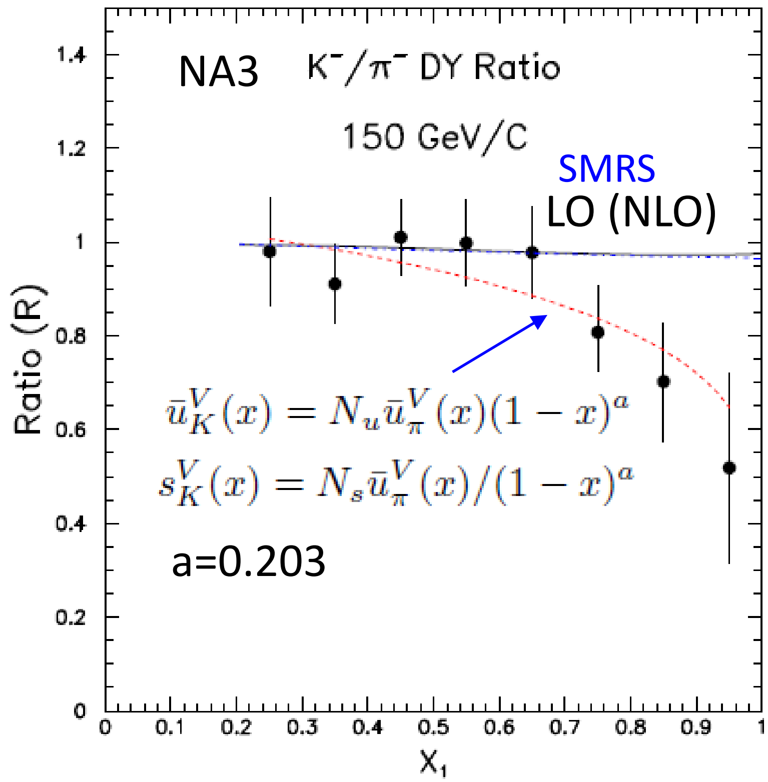
DSE: PRD 93, 074021 (2016)

NJL: PRC 94, 035201 (2016)

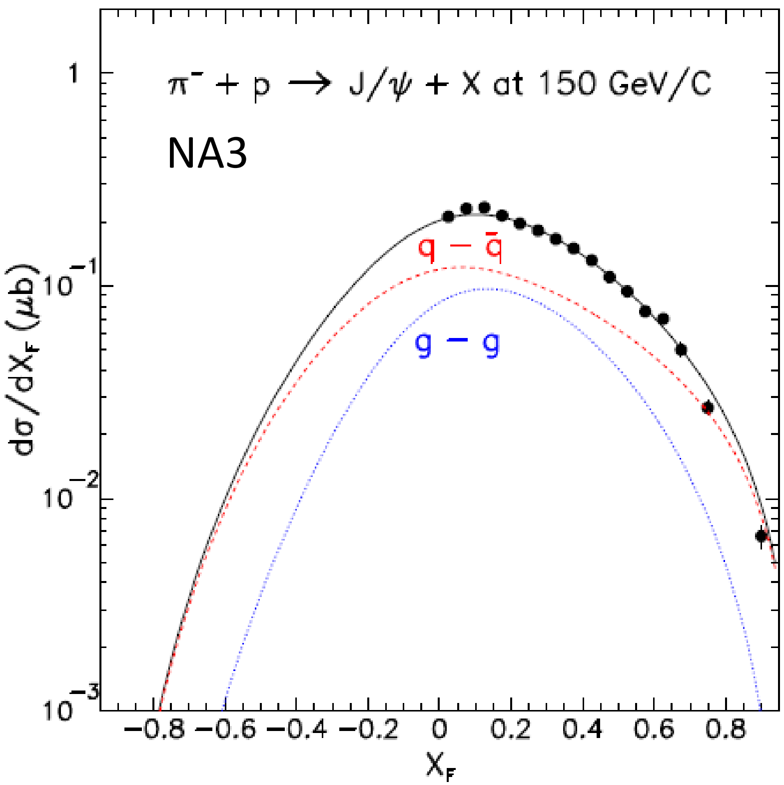
"Nevertheless in the DSE-BSE framework, a conclusive verification of this problem calls for a nonperturbative study on the pion and kaon bound state equations incorporating qqg component."

Phenomenology Study of NA3 Drell-Yan and J/psi Data

[Peng, Chang, Platchkov and Sawada, arXiv:1711.00839]



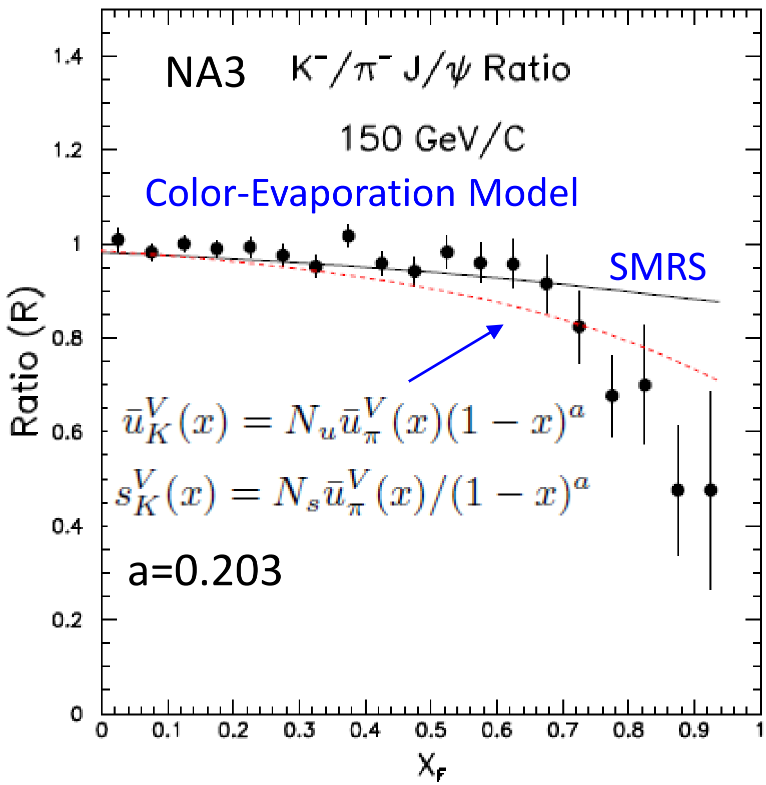
Color-Evaporation Model +SMRS



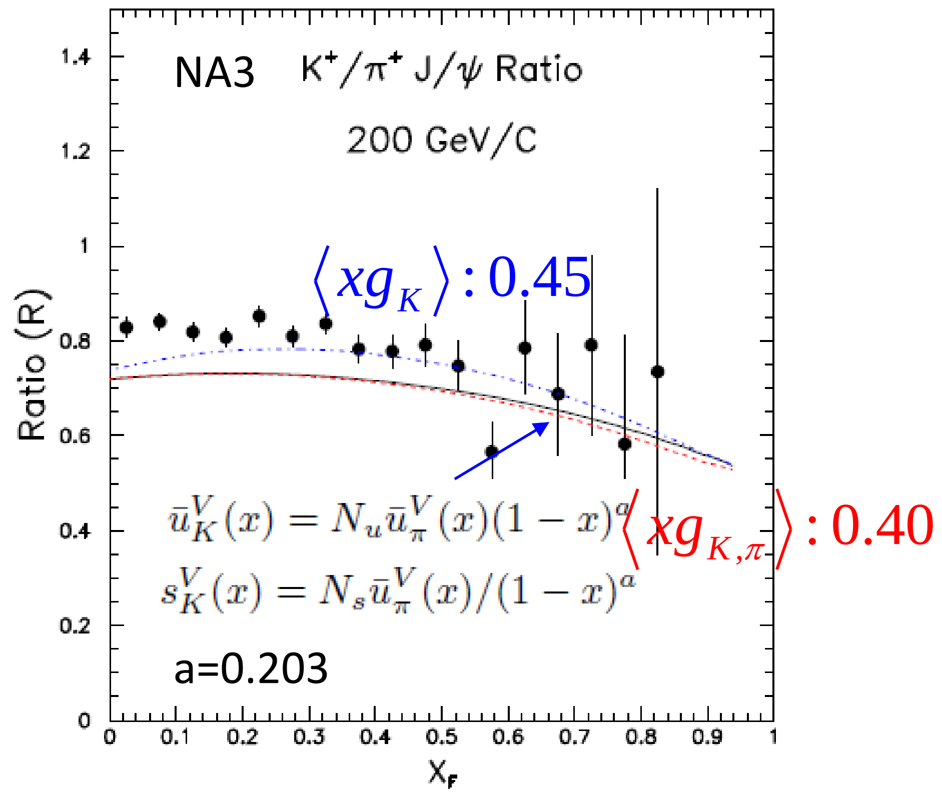
Color-Evaporation Model could describe the rapidity distributions well.

Phenomenology Study of NA3 Drell-Yan and J/psi Data

[Peng, Chang, Platchkov and Sawada, arXiv:1711.00839]



$$\frac{\langle x\bar{u}_K^V \rangle}{\langle x\bar{u}_\pi^V \rangle} < 1$$



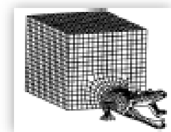
$$\frac{\langle xg_K \rangle}{\langle xg_\pi \rangle} > 1$$

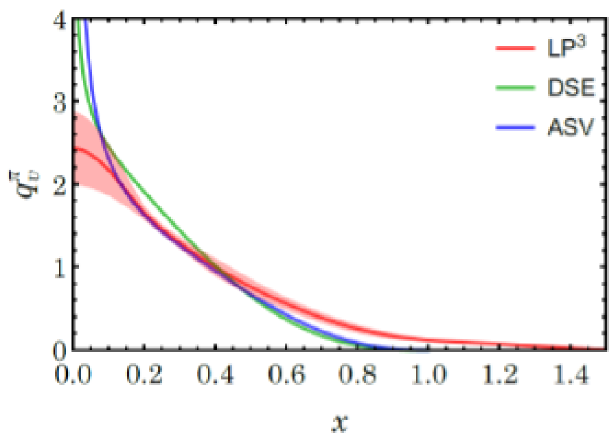
Pion PDFs from Lattice QCD
[J.W. Chen et al., 1804.01483]

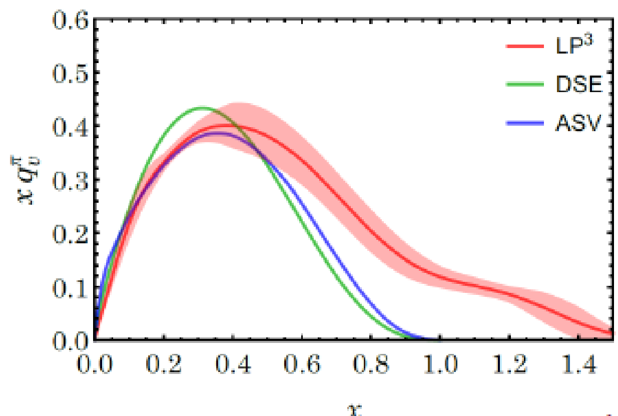
Pion PDF

- § Not trivial to calculate in reality either
- § The first lattice exploratory study
  - $M_\pi \approx 310$ MeV, $a \approx 0.12$ fm ($M_\pi L \approx 4.5$)

1804.01483 (LP³)







1602.01502 (DSE)
1009.2481(ASV)

- § Study of systematics needed
  - Lattice-spacing, finite-volume, larger P_z, ...

MICHIGAN STATE UNIVERSITY Huey-Wen Lin — PIEIC2018 33

[H.W. Lin, JLAB pieic2018 workshop]

New Measurements at CERN

Timelines (meson PDFs only)

- Present: (2015 and 2018) data – improved knowledge:
  - Pion valence PDF
  - Kaon/Pion u(x) ratio measurement: with an upgraded beam identification (CEDAR) in 2018

Compass

----------- Future options ------------

- Near future (No RF needed): 1 year $\pi+/\pi-$ run immediately after LS2
  - valence – sea separation of the pion PDFs
  - direct photon production : measurement of $g_\pi(x)$

New experiment

- RF separation: dedicated runs with an intense kaon beam
  - Kaon valence PDF
  - Kaon sea and/or valence strange distribution
  - Direct photon production : measurement of $g_K(x)$

New experiment

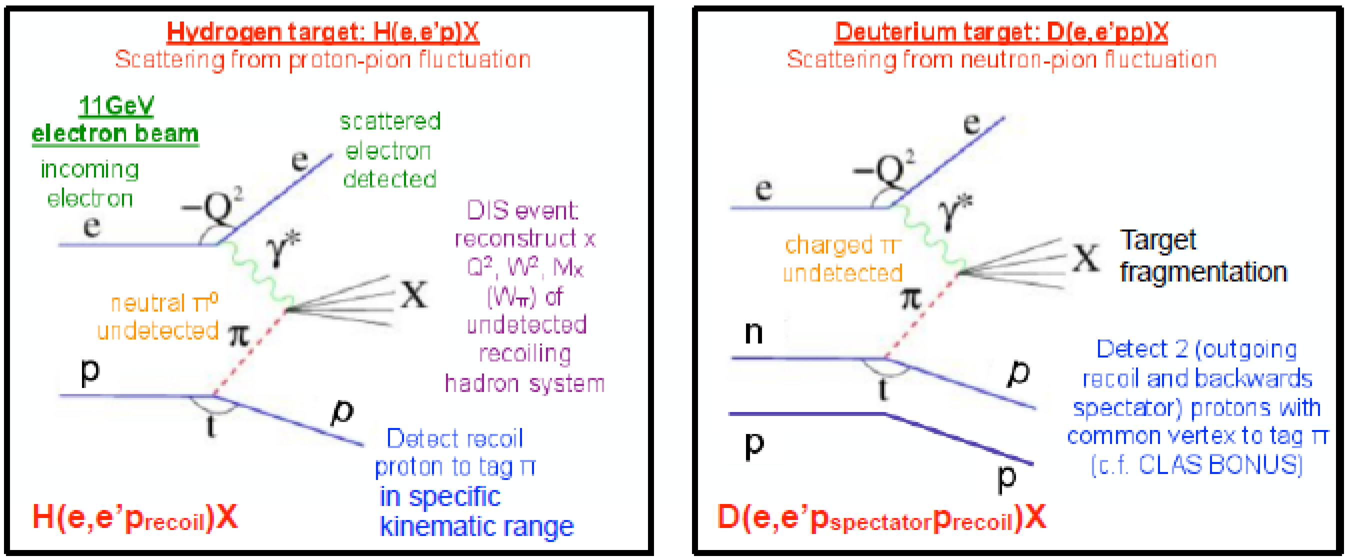
Letter of Intent writing has started. Ideas and contributions from people outside COMPASS more than appreciated

https://nqf-m2.web.cern.ch/

S. Platchkov, ANL pieic2017 workshop

New Measurements at JLAB

University of Glasgow — Pion TDIS Measurement in Hall A



- W^2 invariant mass squared, Q^2 virtuality exchanged photon, x Bjorken x
- t = 4-mom transfer squared at nucleon vertex = $k^2 = (p-p')^2$; p,p' initial,final proton momenta
- t must be small to extrapolate to pole ($|t| < 0.2(\mathrm{GeV/c})^2$)
- **The detected protons are low momentum (60MeV/c - 400MeV/c)**
- **Access to both neutral and charged meson clouds**

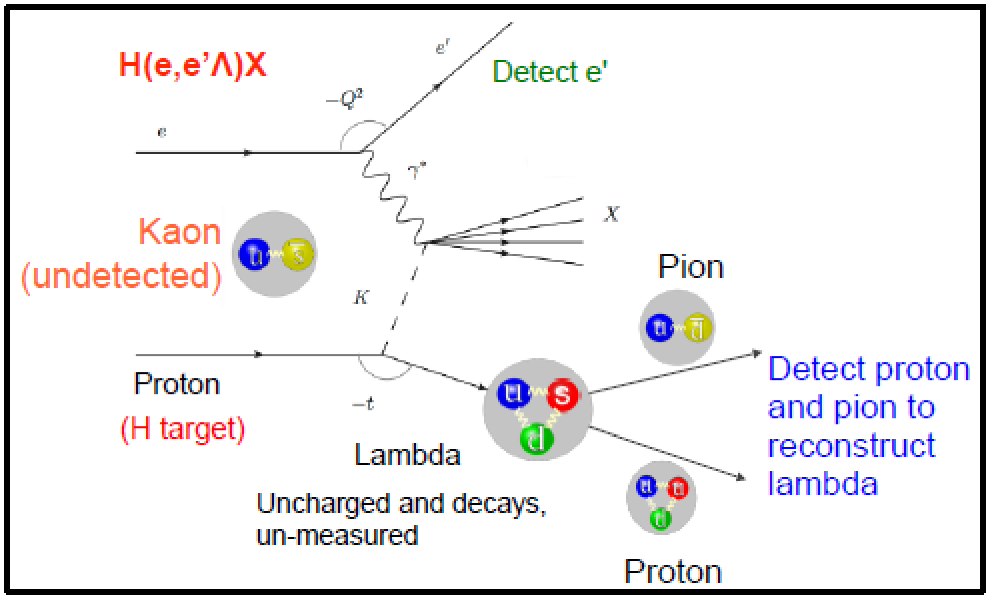
$8 < W^2 < 18$ GeV²
$1 < Q^2 < 3$ GeV²
$0.05 < x < 0.2$

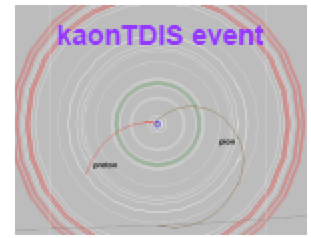
R.A. Montgomery, JLAB pieic2018 workshop

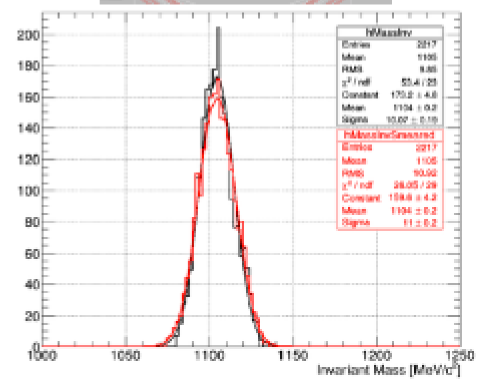
New Measurements at JLAB

University of Glasgow

Kaon TDIS Measurement in Hall A







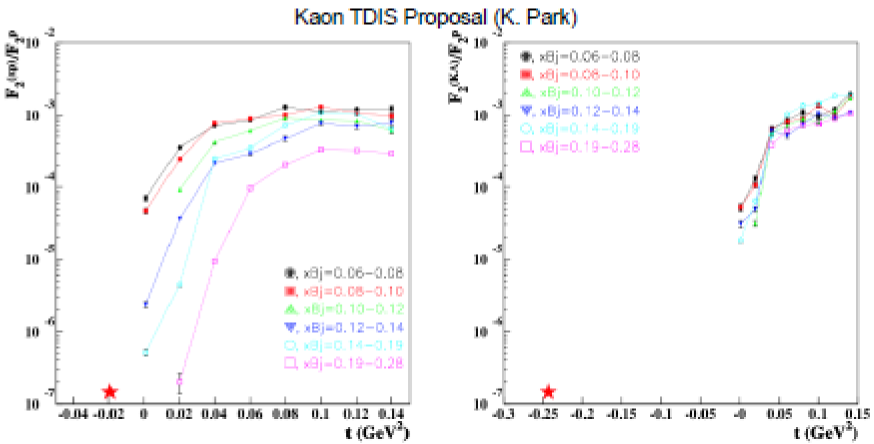
- Lambda reconstructed from pπ- invariant mass and track/vertex
- Proton and pion mostly emitted back to back, with angular and time correlation
- Protons, pions again low momentum in similar range as pion TDIS
- Kaon TDIS also background to pion TDIS (also e.g. $\Delta^0 \rightarrow p\pi^-$ and $\Sigma^0 \rightarrow \Lambda^0\gamma \rightarrow p\pi^-$ etc in pion exchange model) - would be useful to study
- Event generator written for kaon TDIS using chiral effective theory for strange quark asymmetry (arXiv:1610.03333 (2016)), splitting functions, all Feynman diagram contributions to s(bar) PDF in nucleon (K. Park, see proposal for details)

R.A. Montgomery, JLAB pieic2018 workshop

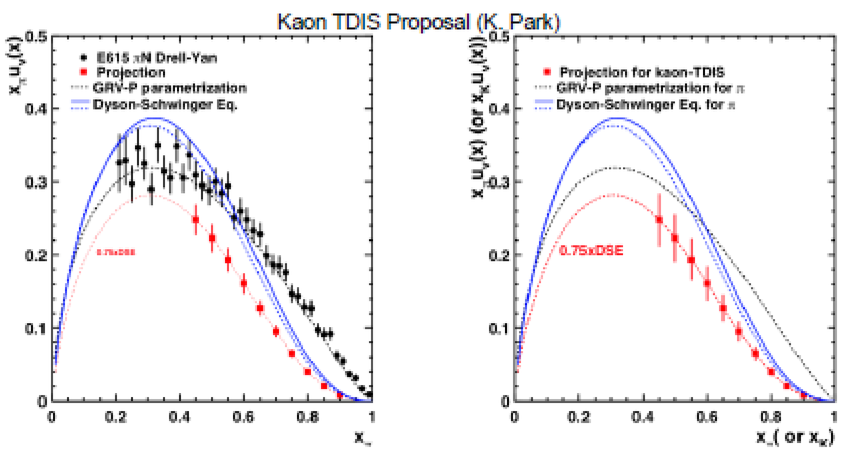
New Measurements at JLAB

University of Glasgow

Projected Results



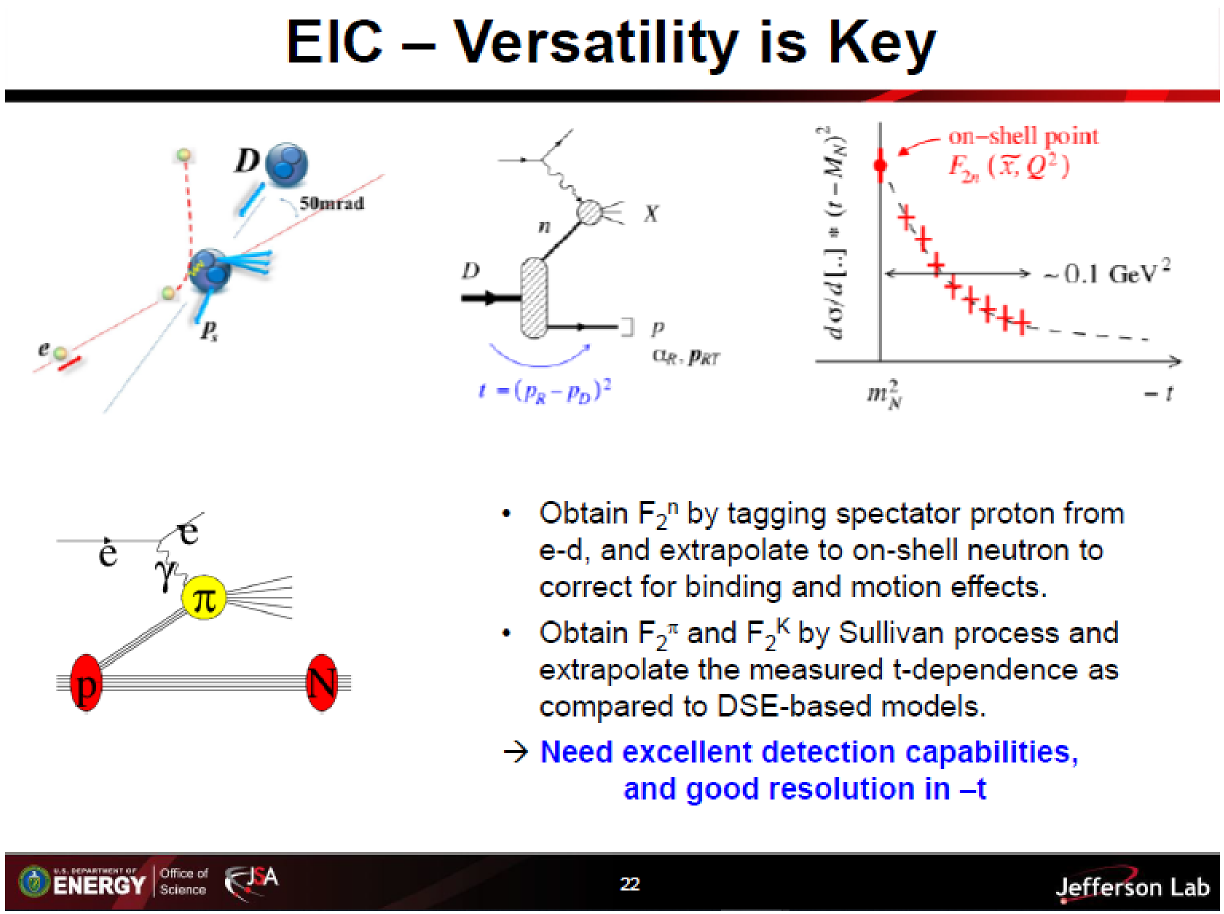
- t-dependence for different x_{Bj}
- $F_2^{(\pi p)}(t,\Delta x)/F_2^p$ for momentum 100 - 400MeV/c
- $F_2^{(K\Lambda)}(t,\Delta x)/F_2^p$ for momentum <100MeV/c
- Statistical errors included
- As low a momentum reach of mTPC as possible essential for extrapolation to obtain shape of curve



- Projected valence quark distribution as a function of $x_{\pi/K}$
- Results from Drell Yan E615
- GRV-P parameterisation and DSE for pion only
- 5% systematic uncertainty in pion flux assumed, total systematic uncertainty of 8.4% included

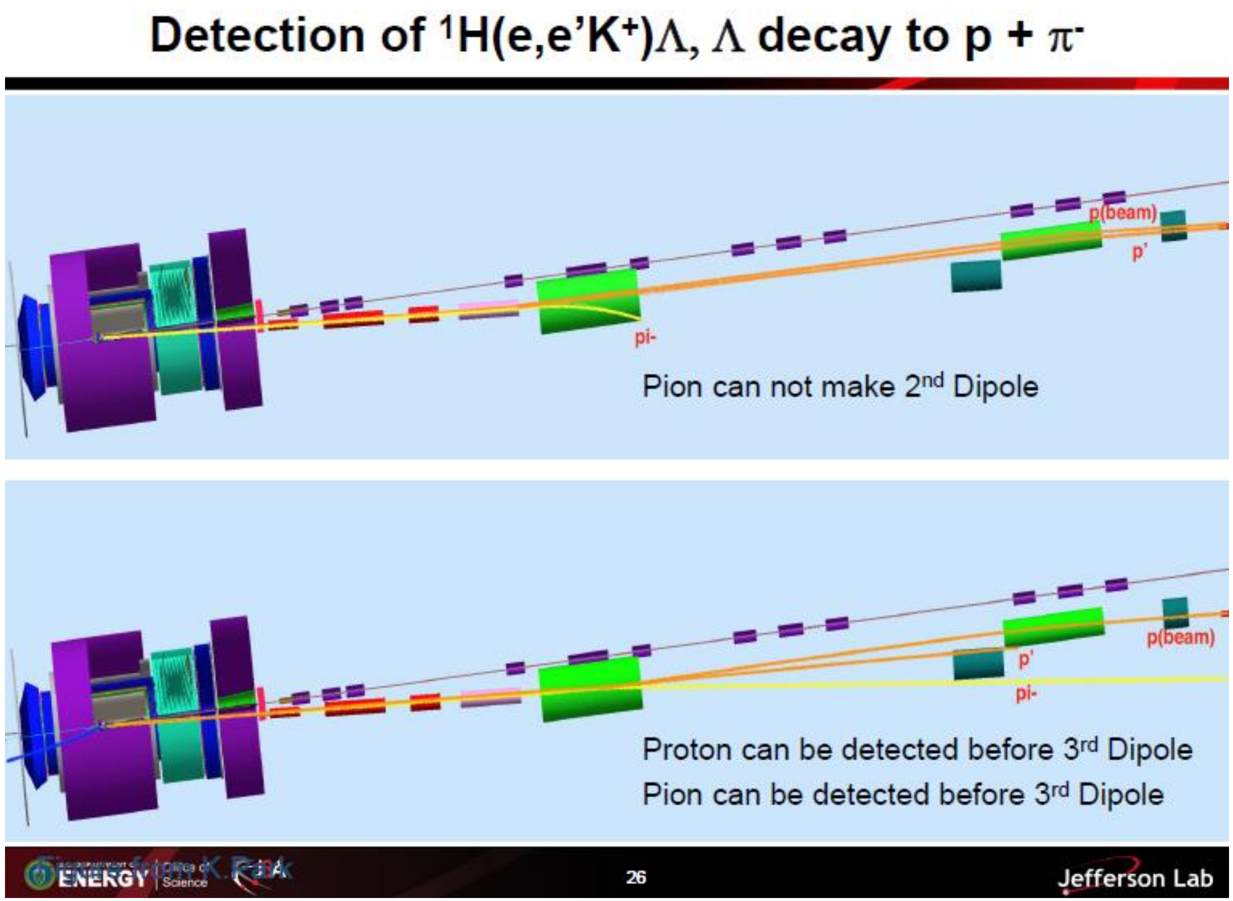
R.A. Montgomery, JLAB pieic2018 workshop

New Measurements at EIC, U.S.



[R. Ent, DIS 2018](#)

New Measurements at EIC, U.S.



[R. Ent, DIS 2018](#)

Summary

- Determination of pion and kaon PDFs is relatively preliminary and mainly through the dimuon production via Drell-Yan and J/psi.
- There is recent interesting progress in accessing pion and kaon PDFs by tagged-SIDIS process. New results of pion-induced Drell-Yan and J/psi production from COMPASS will be available soon.
- Continuing global analyses for pion PDFs with improved theoretical studies and new data sets are called for.
- The future RF-separated meson beams at CERN and TDIS in JLAB and U.S. EIC will constrain the meson PDFs at large-x and small-x regions further.