Extracting Parton Distributions of Pions and Kaons Using the Statistical Model

Jen-Chieh Peng

University of Illinois at Urbana-Champaign

and

National Central University

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Recent work on the partonic structure of pion and kaon

In collaboration with Claude Bourrely (Marseille), Franco Buccella (Rome), Wen-Chen Chang (Taipei), Stephane Platchkov (Saclay), and Takahiro Sawada (Tokyo)

8 publications:

Phys. Rev. D102, 054024 (2020)
Chin. J. Phys. 73, 13-23 (2021)
Phys. Lett. B813, 136021 (2021)
Phys. Rev. D105, 076018 (2022)
Phys. Rev. D107, 056008 (2023)
Phys. Lett. B848, 138395 (2024)
Phys. Lett. B855, 138820 (2024)
Phys. Lett. B866, 139582 (2025)

e-Print: 2503.00693 (2025)

Partonic structure of pion and kaon

Why is it interesting?

- Lightest $q\bar{q}$ bound states, and Goldstone bosons
- A simpler hadronic system than the nucleon
- Spin-0 π and K contrasting spin$-1/2$ nucleon
- Compared to nucleons, very little is known for the partonic structures of mesons
- Comparison between pion and kaon parton distributions
- Can be explored at JLab, AMBER, JPARC, and EIC

Partonic structures of pion and kaon

Spin-0 for π and K implies:

- No helicity distributions ($\Delta q(x) = 0,\ \Delta G(x) = 0$)
- No TMDs such as Transversity, Sivers, Prezelocity distributions (Boer-Mulders functions for π and K do exist)

Number of unpolarized partonic distributions is reduced from symmetry consideration (charge-conjugation (C) and Isospin (I) symmetries)

- $u^V_{\pi^+}(x) \overset{C}{=} \bar{u}^V_{\pi^-}(x) \overset{I}{=} \bar{d}^V_{\pi^+}(x) \overset{C}{=} d^V_{\pi^-}(x) \equiv V_\pi(x)$
- $\bar{u}_{\pi^+}(x) \overset{C}{=} u_{\pi^-}(x) \overset{I}{=} d_{\pi^+}(x) \overset{C}{=} \bar{d}_{\pi^-}(x) \equiv S_\pi(x)$

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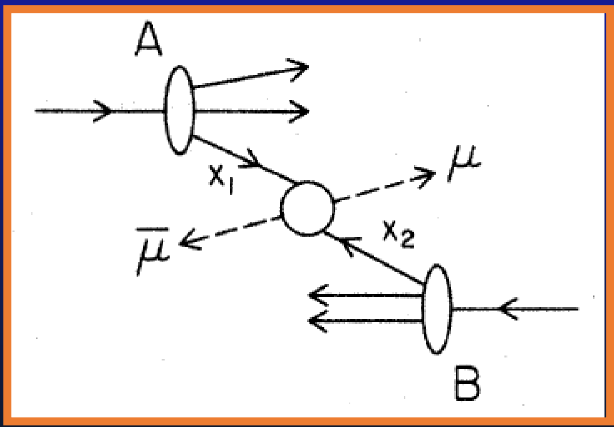
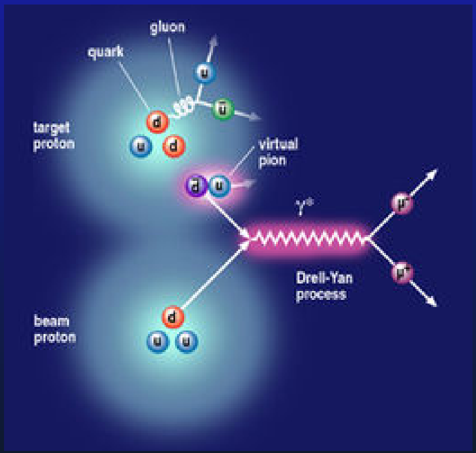
Meson partonic content from the Drell-Yan Process

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)



Cited over 1845 times



$$p + p \to (\mu^+ \mu^-) + \cdots . \qquad (1)$$

Our remarks apply equally to any colliding pair such as (pp), $(\bar{p}p)$, (πp), (γp) and to final leptons $(\mu^+ \mu^-)$, $(e\bar{e})$, $(\mu\nu)$, and $(e\nu)$.

Drell-Yan experiments with π^- beam

Experiments at CERN and Fermilab

Exp	P (GeV)	targets	Number of 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

- Relatively pure π^- beam; J/Ψ production also measured
- Relatively large cross section due to $\bar{u}d$ contents in π^-

For a very long time, only four pion parton distribution functions were available

- First: OW-P (PRD 30, 943 (1984))
- Second: ABFKW-P (PL 233, 517 (1989))
- Third: GRV-P (Z. Phys. C35, 651 (1992))
- Fourth: SMRS (PR D45, 2349 (1992))

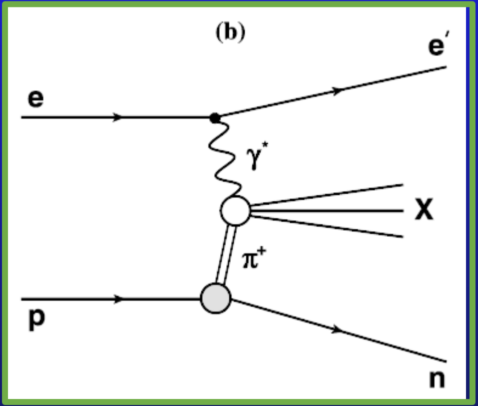
- Need new global fits to all existing data
- Need new experimental data with pion and kaon beams

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]

JAM Collaboration

PRL 121, 152001 (2018);
PRL 127, 232001 (2021)



- Drell-Yan data from NA10 and E615
- Leading-neutron tagged DIS from HERA provides information on the pion PDFs at small *x*
- The Q^2 evolution allows extraction of gluon distribution
- Uncertainties of the pion PDFs are determined

PHYSICAL REVIEW D **102**, 014040 (2020)

Parton distribution functions of the charged pion within the xFitter framework

Ivan Novikov,[1,2,*] Hamed Abdolmaleki,[3] Daniel Britzger,[4] Amanda Cooper-Sarkar,[5] Francesco Giuli,[6] Alexander Glazov,[2,†] Aleksander Kusina,[7] Agnieszka Luszczak,[8] Fred Olness,[9] Pavel Starovoitov,[10] Mark Sutton,[11] and Oleksandr Zenaiev[12]

(xFitter Developers' team)

- Drell-Yan data from NA10 and E615
- Direct photon production data from WA70
- Uncertainties of the pion PDFs are determined
- Valence distribution is well determined, but not the sea and gluon distributions

A New Extraction of Pion Parton Distributions in the Statistical Model

Claude Bourrely[a], Franco Buccella[b], Jen-Chieh Peng[c]

Physics Letters B 813 (2021) 136021

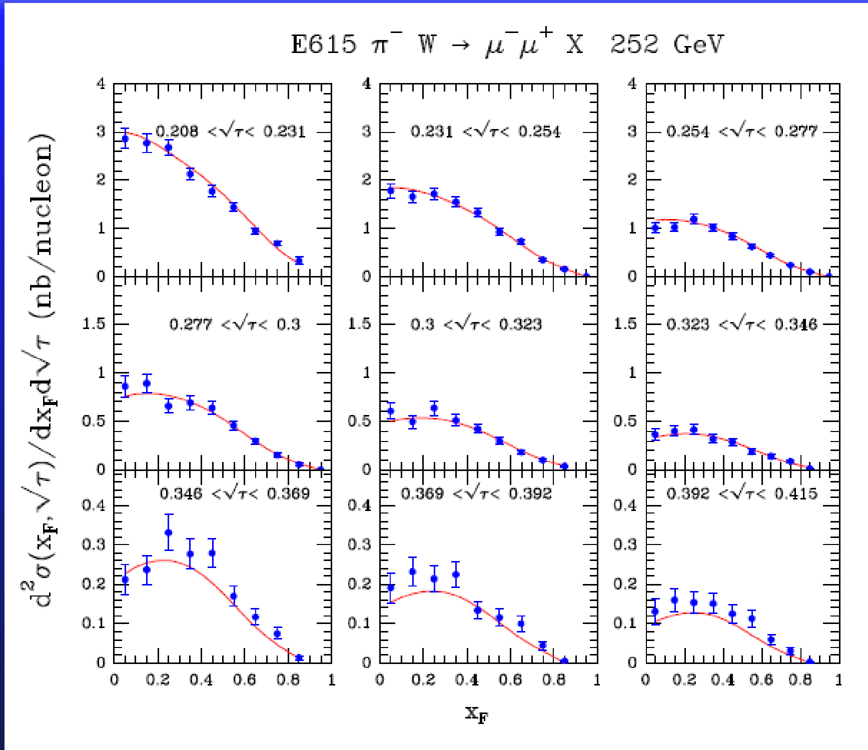
$$xU(x) = xD(x) = \frac{A_U X_U x^{b_U}}{\exp[(x - X_U)/\bar{x}] + 1} + \frac{\tilde{A}_U x^{\tilde{b}_U}}{\exp(x/\bar{x}) + 1} . \quad (7)$$

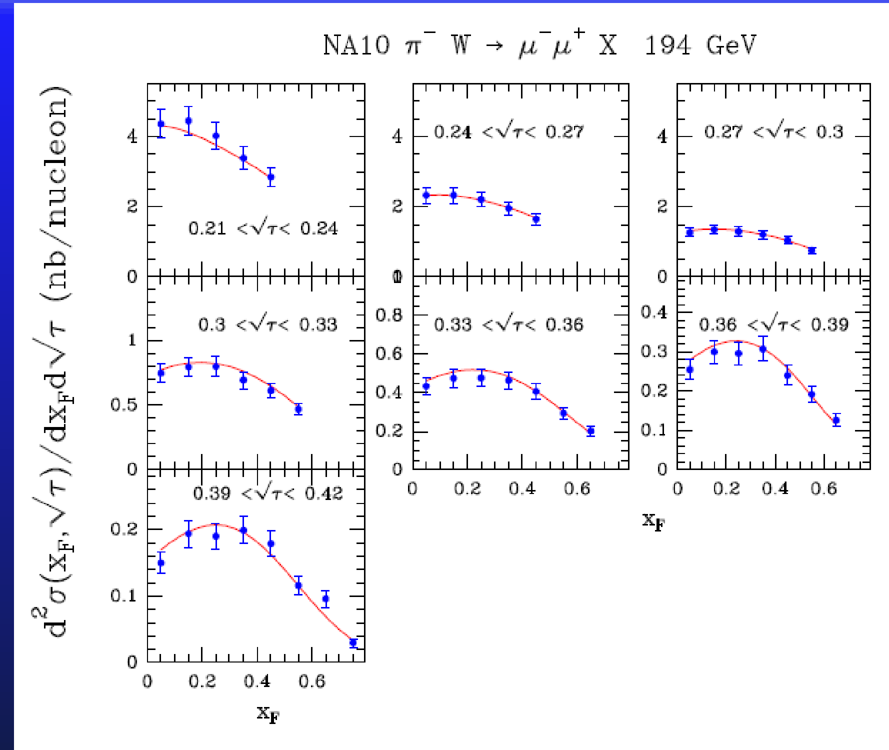
$$x\bar{U}(x) = x\bar{D}(x) = \frac{A_U (X_U)^{-1} x^{b_U}}{\exp[(x + X_U)/\bar{x}] + 1} + \frac{\tilde{A}_U x^{\tilde{b}_U}}{\exp(x/\bar{x}) + 1} . \quad (8)$$

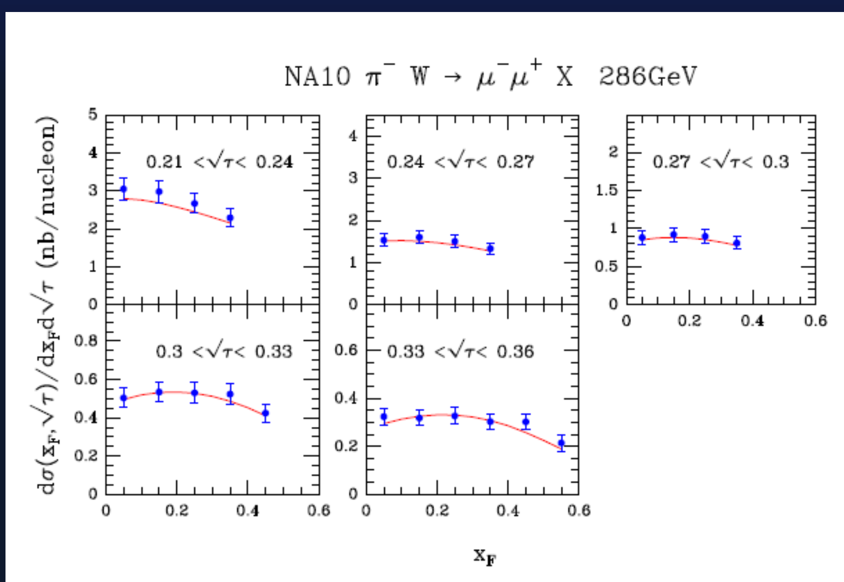
$$xS(x) = x\bar{S}(x) = \frac{\tilde{A}_U x^{\tilde{b}_U}}{2[\exp(x/\bar{x}) + 1]} . \quad (9)$$

$$xG(x) = \frac{A_G x^{b_G}}{\exp(x/\bar{x}) - 1} . \quad (10)$$

- The statistical model describes proton's PDF very well
- The antiquark's flavor structure is related to quark's flavor structure
- The antiquark's spin structure is related to quark's spin structure
- It is not clear if the statistical model also works for meson's PDFs







With only a few parameters for the pion PDFs, the Drell-Yan data are well described by the statistical model

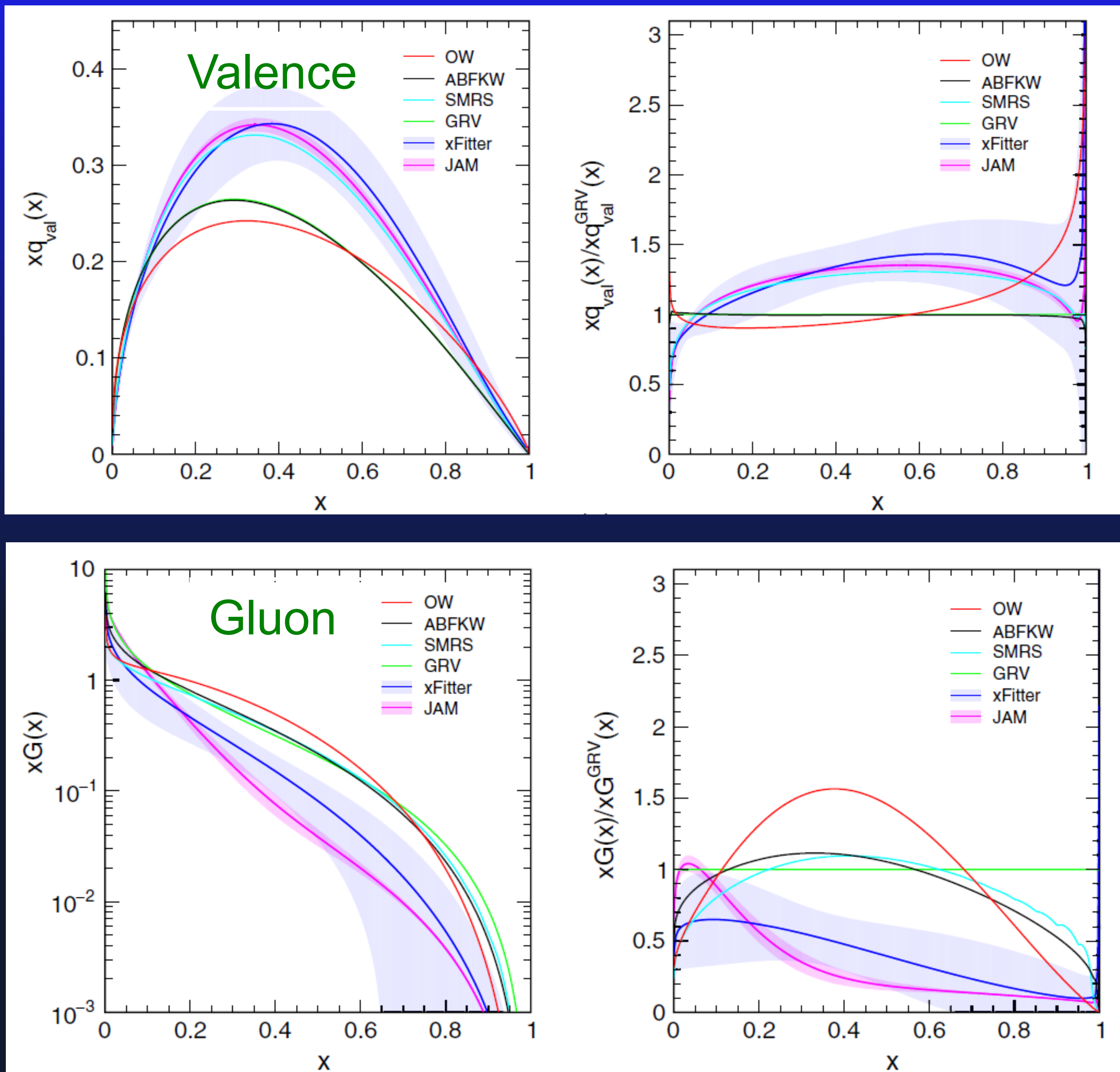
Comparison between proton and pion PDFs in the statistical model

$$xQ^{\pm}(x) = \frac{A_Q X_Q^{\pm} x^{b_Q}}{\exp[(x - X_Q^{\pm})/\bar{x}] + 1},$$

$A_U = 0.776 \pm 0.15$	$b_U = 0.500 \pm 0.02$
$X_U = 0.756 \pm 0.01$	$\bar{x} = 0.1063 \pm 0.004$
$\tilde{A}_U = 2.089 \pm 0.21$	$\tilde{b}_U = 0.4577 \pm 0.009$
$A_G = 31.17 \pm 1.7$	$b_G = 1 + \tilde{b}_U$.

- The temperature, $\bar{x} = 0.106$, found for pion is very close to that obtained for proton, $\bar{x} = 0.090$, suggesting a common feature for the statistical model description of baryons and mesons
- The chemical potential of the valence quark for pion, $X_U = 0.756$, is significantly larger than for proton, $X_U = 0.39$

Valence and gluon distributions for various pion PDFs

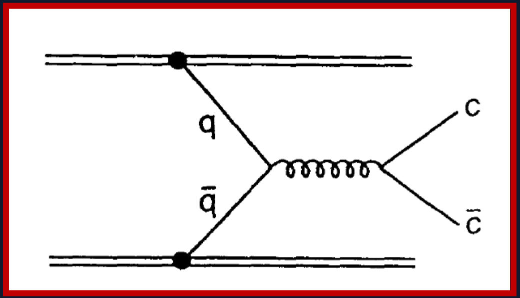


- Quite good agreements for valence quark PDFs
- Much larger variations for the gluon PDFs

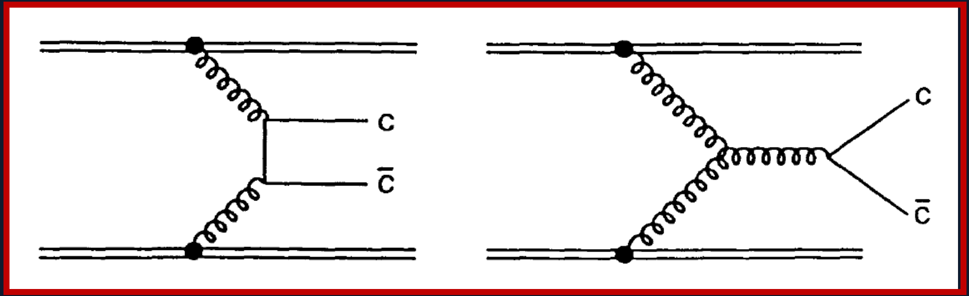
Constraining gluon distribution of pion with pion-induced J/Ψ production

- The Drell-Yan data are not sensitive to the gluon distributions in pion
- The J/Ψ production data are sensitive to the gluon PDF in pion, which is poorly known and is of much theoretical interest

J/Ψ (q-qbar annihilation)



J/Ψ (gluon-gluon fusion)



Pion PDFs using DY and J/Ψ data in the statistical model

PHYSICAL REVIEW D **105,** 076018 (2022)

Pion partonic distributions in a statistical model from pion-induced Drell-Yan and J/Ψ production data

Claude Bourrely,[1] Wen-Chen Chang,[2] and Jen-Chieh Peng[3]

[1]*Aix Marseille Univ, Université de Toulon, CNRS, CPT, Marseille, France*
[2]*Institute of Physics, Academia Sinica, Taipei 11529, Taiwan*
[3]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*

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We present a new analysis to extract pion parton distribution functions (PDFs) within the framework of the statistical model. Starting from the statistical model first developed for the spin-1/2 nucleon, we extend this model to describe the spin-0 pion. Based on a combined fit to both the pion-induced Drell-Yan data and the pion-induced J/Ψ production data, a new set of pion PDFs has been obtained. The inclusion of the J/Ψ production data in the combined fit has provided additional constraints for better determining the gluon distribution in the pion. We also compare the pion PDFs obtained in the statistical model with other existing pion PDFs.

Pion PDFs using DY and J/Ψ data

Phys.Rev.D 105 (2022) 076018 ; arXiv: 2202.12547

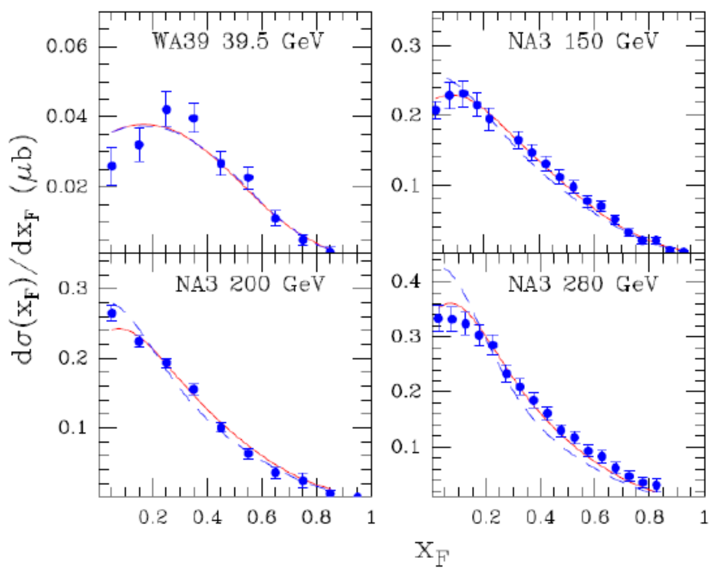
$$xU(x) = xD(x) = \frac{A_U X_U x^{b_U}}{\exp[(x - X_U)/\bar{x}] + 1} + \frac{\tilde{A}_U x^{\tilde{b}_U}}{\exp(x/\bar{x}) + 1}$$

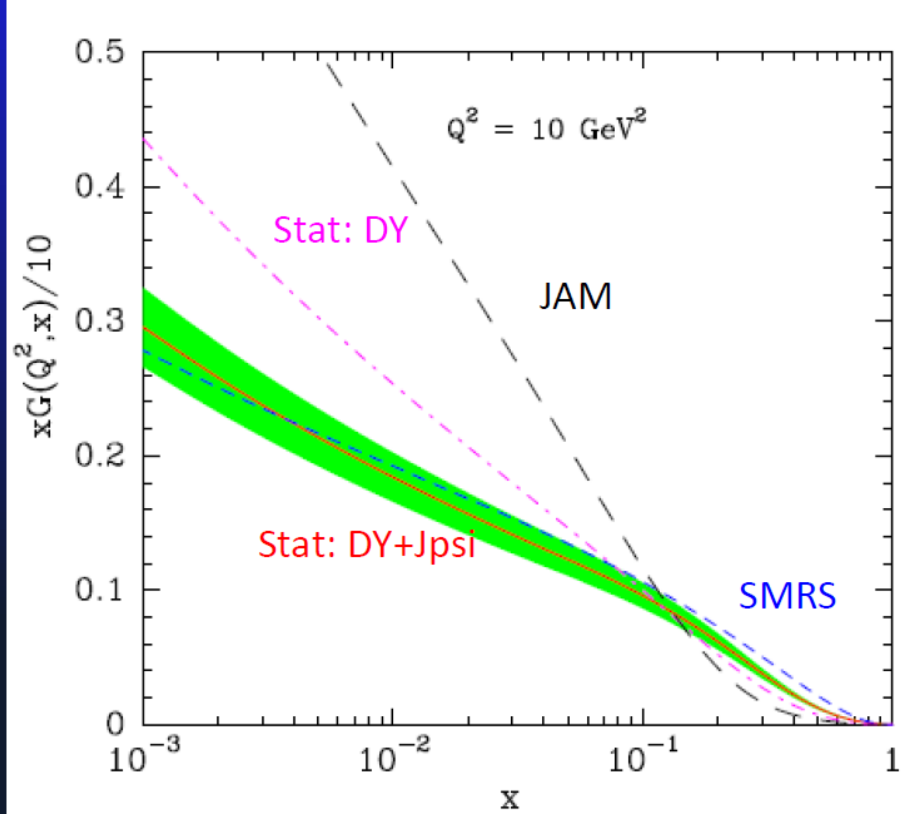
$$x\bar{U}(x) = x\bar{D}(x) = \frac{A_U (X_U)^{-1} x^{b_U}}{\exp[(x + X_U)/\bar{x}] + 1} + \frac{\tilde{A}_U x^{\tilde{b}_U}}{\exp(x/\bar{x}) + 1}$$

$$xS(x) = x\bar{S}(x) = \frac{\tilde{A}_U x^{\tilde{b}_U}}{2[\exp(x/\bar{x}) + 1]}$$

$$xG(x) = \frac{A_G x^{b_G}}{\exp(x/\bar{x}) - 1}, \qquad b_G = 1 + \tilde{b}_U$$

J/Ψ WA39 and NA3 J/ψ $(\pi^- H_2)$





NRQCD for J/Ψ Production

Inclusion of the J/Ψ data gives larger G(x) at x>0.1

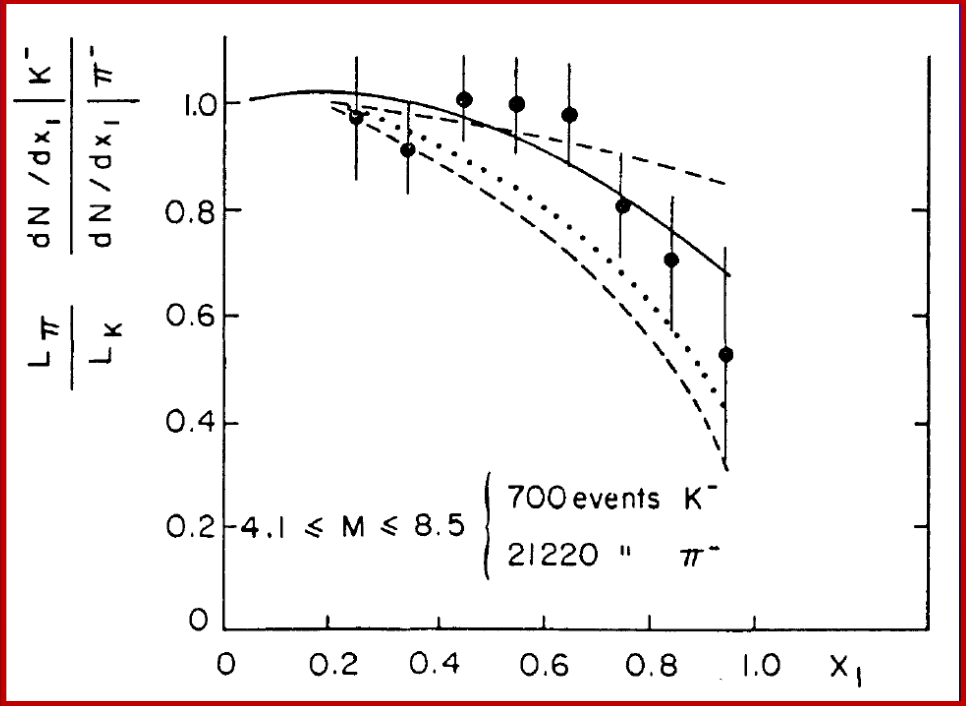
What do we know about the kaon PDF (very little!)

$\sigma(K^- + \mathrm{Pt}) / \sigma(\pi^- + \mathrm{Pt})$ Drell-Yan ratios

From NA3

150 GeV

Pt target



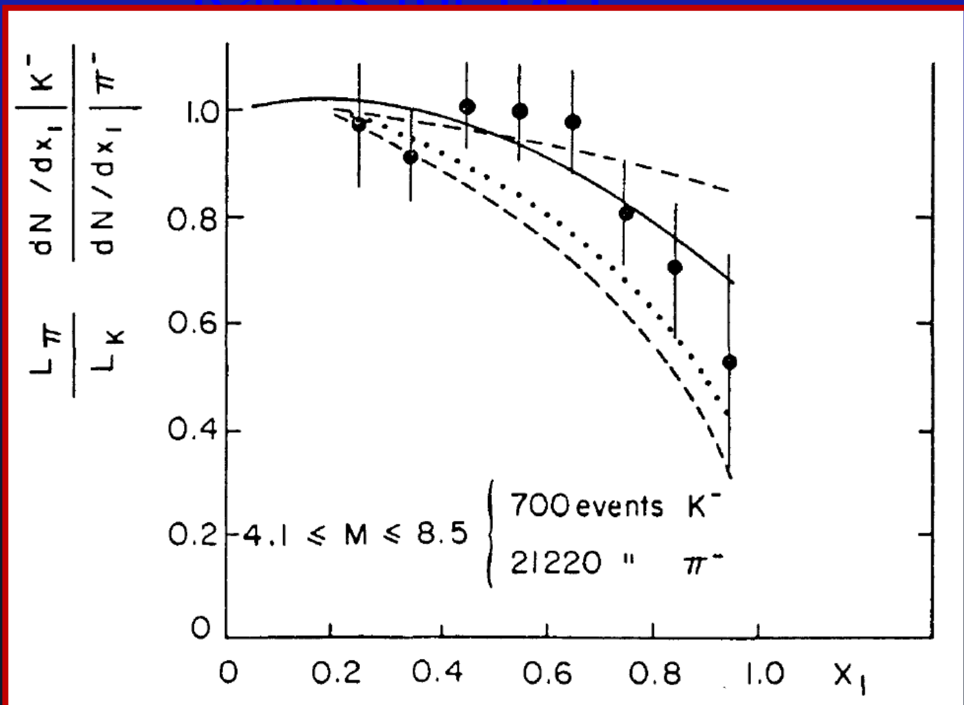
$$R = \frac{\sigma_{DY}(K^- + D)}{\sigma_{DY}(\pi^- + D)} \simeq \frac{V_K^u(x_1)}{V_\pi(x_1)}$$

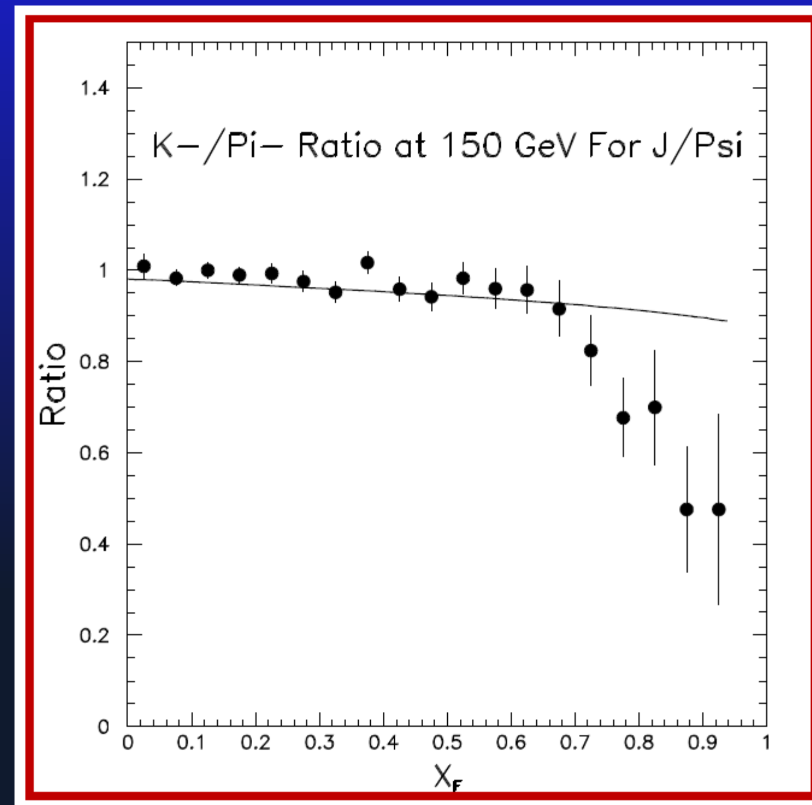
$R \simeq (1-x)^{0.18 \pm 0.07} \Rightarrow$ softer u-valence in kaon than in pion

$(K^- + \mathrm{Pt}) / (\pi^- + \mathrm{Pt})$ ratios for J/Ψ production

From NA3; 150 GeV, Pt target

Ratios for D-Y



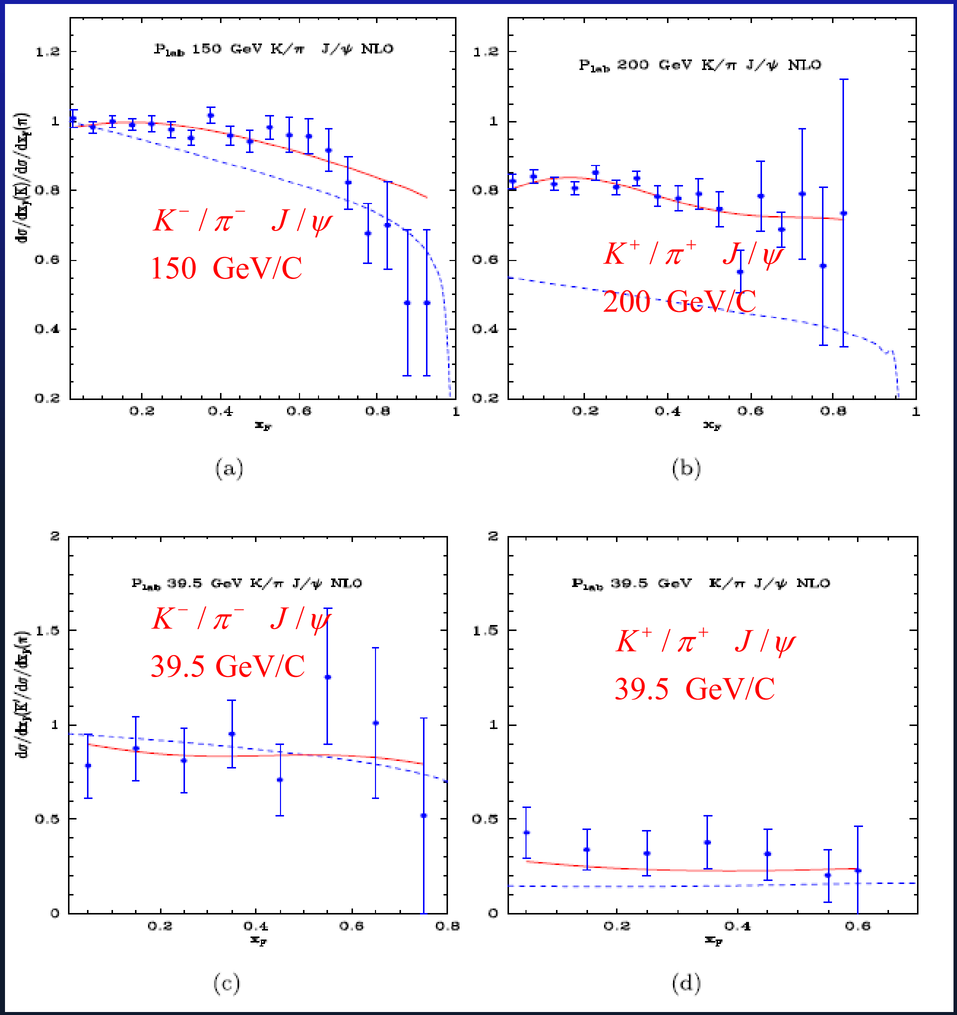


Similar behavior at large x_F for D-Y and J/Ψ production?

Extraction of kaon partonic distribution functions from Drell-Yan and J/ψ production data

Claude Bourrely [a,*], Franco Buccella [b], Wen-Chen Chang [c], Jen-Chieh Peng [d]

Phys. Lett. B 848 (2024) 138395



The K^-/π^- and K^+/π^+ J/Ψ data can also be well described by the statistical model (red curves)

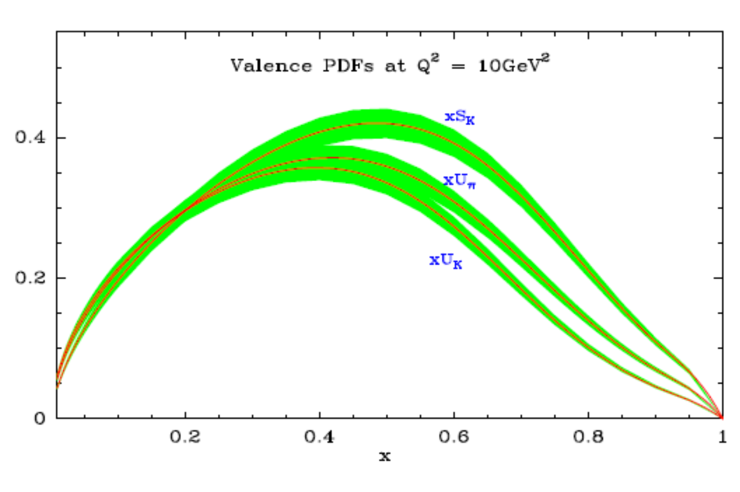
The dashed curves use the recent PDFs obtained in the "Maximum Entropy" approach

Extraction of kaon partonic distribution functions from Drell-Yan and J/ψ production data

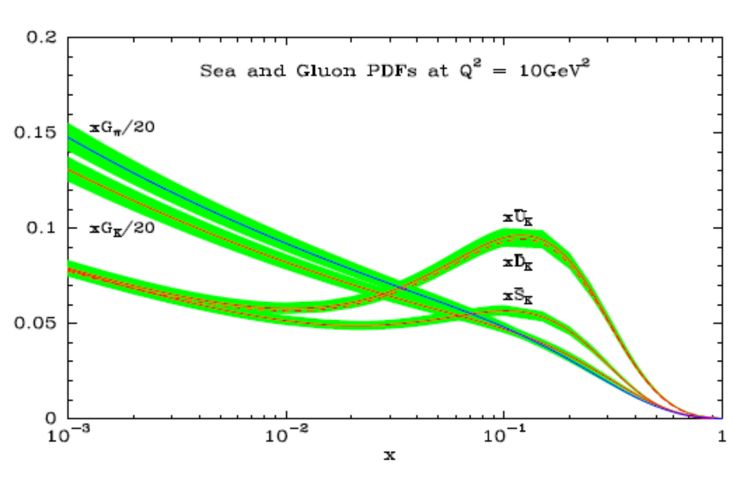
Claude Bourrely [a,*], Franco Buccella [b], Wen-Chen Chang [c], Jen-Chieh Peng [d]

Phys. Lett. B 848 (2024) 138395

Comparison between the pion and kaon valence distributions



Comparison between the pion and kaon gluon distributions



Momentum fractions of valence quarks, sea quarks, and gluons for π^- and K^- at the scale $Q^2 = 10$ GeV^2 obtained in the statistical model.

	u Valence	d Valence	s Valence	all Sea	Gluon
π^-	0.242 ± 0.004	0.242 ± 0.004	–	0.188 ± 0.004	0.326 ± 0.015
K^-	0.220 ± 0.002	–	0.276 ± 0.001	0.162 ± 0.006	0.331 ± 0.018

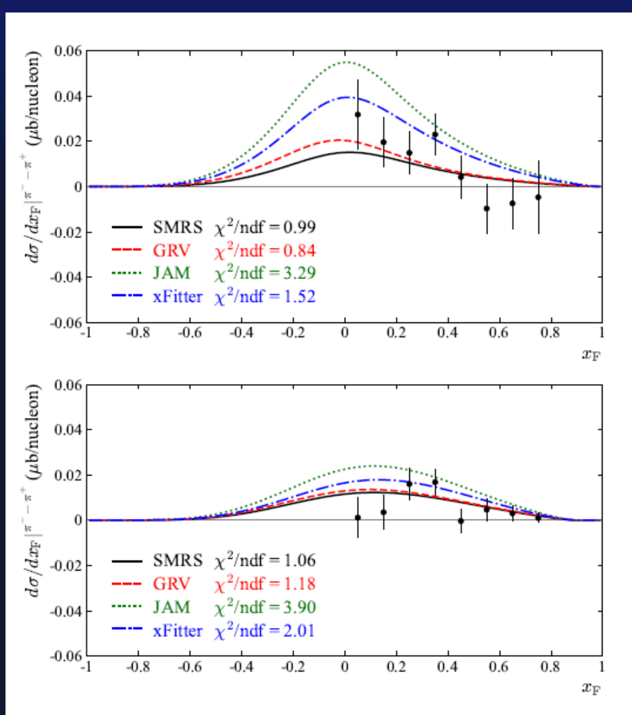
$$S_K > U_\pi > U_K; \;\; G_K \simeq G_\pi$$

Probing Pion Valence Quark Distribution with Beam-charge Asymmetry of Pion-induced J/ψ Production

Wen-Chen Chang[a,1], Marco Meyer-Conde[b,2], Jen-Chieh Peng[c,3], Stephane Platchkov[d,4], Takahiro Sawada[e,5]

Phys. Lett. B866 (2025) 139582

$$\begin{aligned} \sigma_{J/\psi}(\pi^- + p) \quad &- \quad \sigma_{J/\psi}(\pi^+ + p) \\ &\propto \quad V_\pi(x_1)[u_p^V(x_2) - d_p^V(x_2)]. \end{aligned}$$

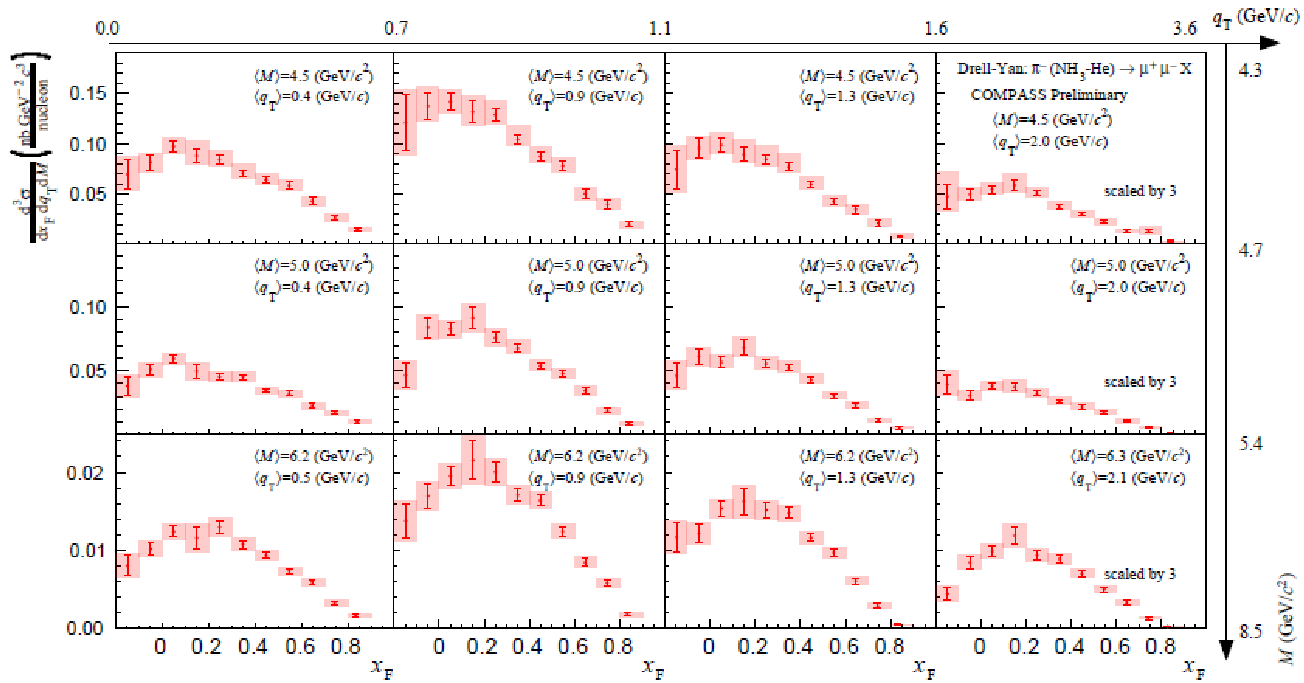


The beam-charge asymmetry of pion-induced J/Ψ data allow us to distinguish various pion PDFs

More Drell-Yan and J/ψ data are coming

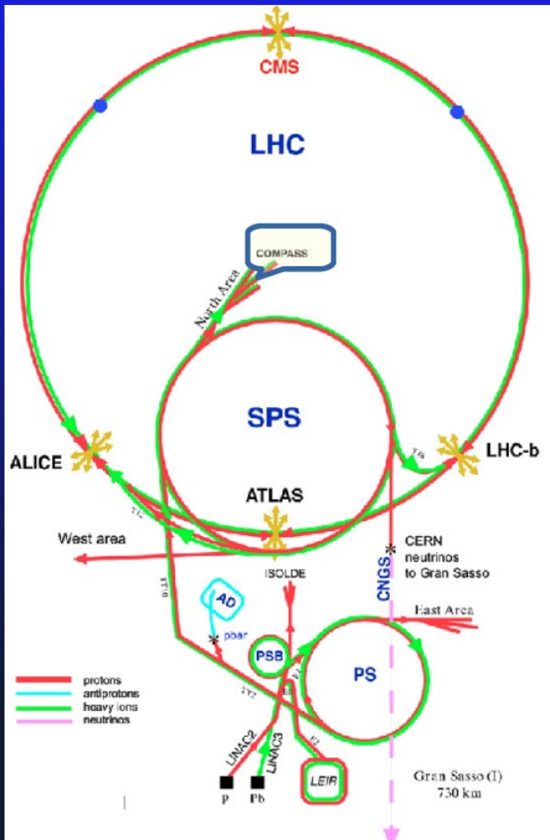
New pion-induced Drell-Yan data from COMPASS

3 dimensional Drell-Yan cross section on NH_3-He



- **First high statistics measurement with light material**
- Red line/shaded area: statistical / total (stat. and syst.) uncertainties
- Dominated by statistical uncertainty

AMBER (Phase-I was approved)



Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^{\uparrow}$	2022 2 years
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years

- Expect new Drell-Yan and J/Ψ production data with pion (kaon) beams in the near future !

Summary

- We have shown that meson-induced J/Ψ production data can probe the gluon distributions in pion and kaon
- We performed the first extraction of kaon quark and gluon distributions using the Drell-Yan and the J/Ψ production data
- We have extended the statistical model approach from nucleon PDFs to meson PDFs
- Parton distributions of mesons represent an interesting topic for theories and experiments
- Can be explored at AMBER, JLab, JPARC and EIC