Pion and Kaon PDFs from Drell-Yan and J/ψ Production

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COMAP-VIII Mini-Workshop

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Partonic structures of pion and kaon

Why is it interesting?

- Lightest $q\bar{q}$ bound states, and Goldstone bosons
- A simpler hadronic system than the nucleon
- Mass decomposition of pion and kaon
- Spin-0 π and K contrasting spin-1/2 nucleon
- Compared to nucleons, very little is known experimentally for the partonic structures of mesons

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 and SU(2) flavor symmetries)

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

For kaons, more PDFs are needed (breaking of SU(3) flavor symmetry)

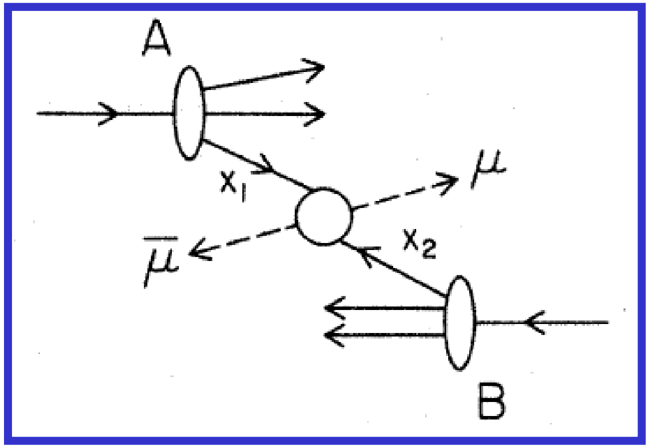
- $u^V_{K^+}(x) \neq \bar{s}^V_{K^+}(x)$ (analogous to $u^V_p(x) \neq d^V_p(x)$)
- $\bar{u}_{K^+}(x) \neq \bar{d}_{K^+}(x)$ (analogous to $\bar{u}_p(x) \neq \bar{d}_p(x)$)

Many interesting questions can be raised on the comparison between pion and kaon parton distributions

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)



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

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 $(e\nu)$.

(4) The full range of processes of the type (1) with incident p, $\bar{p}$, π, K, γ, etc., affords the interesting possibility of comparing their parton and antiparton structures.

List of 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. C53, 651 (1992)

- Fourth: SMRS (PR D45, 2349 (1992))

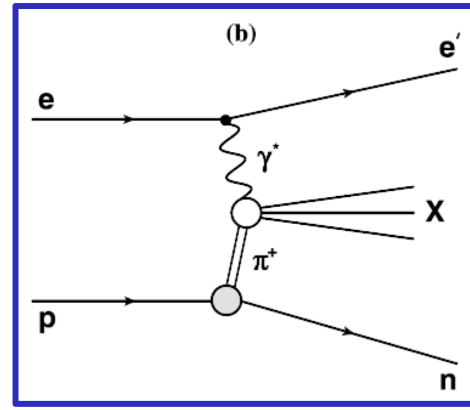
- Need new global fits to all existing data
- Need new experimental data with pion and kaon beams

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

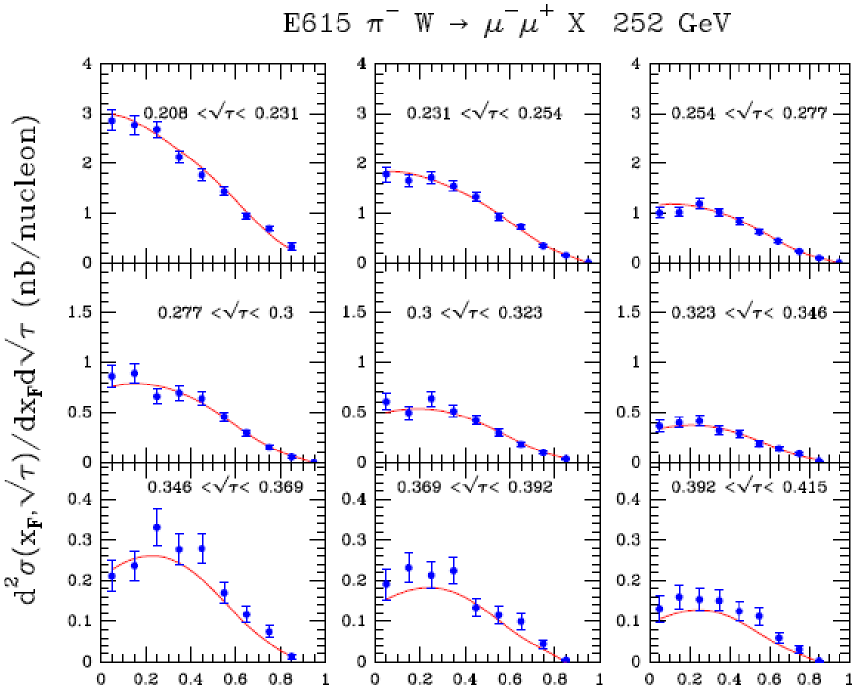
$$xU(x) = xD(x) = \frac{A_U X_U x^{b_U}}{\exp[(x - X_U)/\bar{x}] + 1} + \frac{\tilde{A}_U x^{\tilde{b}_U}}{\exp(x/\bar{x}) + 1} . \qquad (7)$$

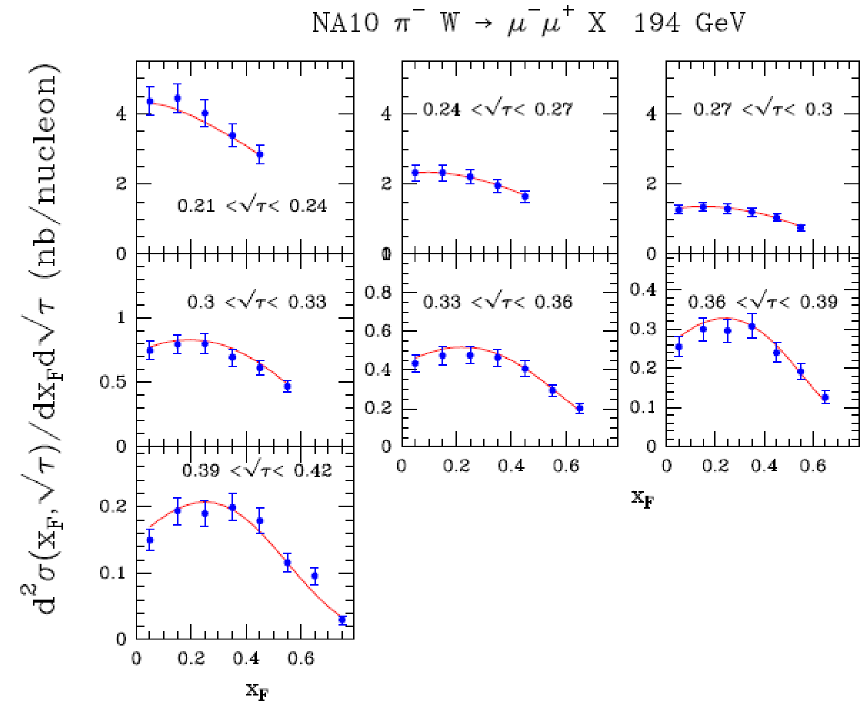
$$x\bar{U}(x) = x\bar{D}(x) = \frac{A_U (X_U)^{-1} x^{b_U}}{\exp[(x + X_U)/\bar{x}] + 1} + \frac{\tilde{A}_U x^{\tilde{b}_U}}{\exp(x/\bar{x}) + 1} . \qquad (8)$$

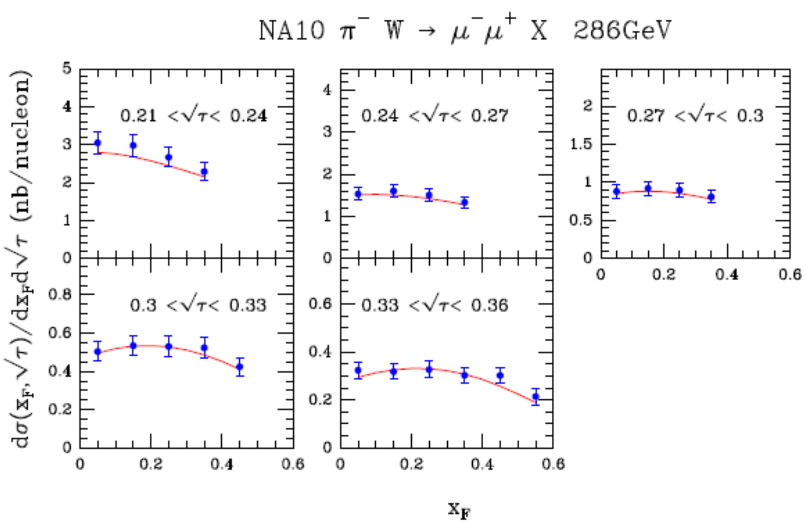
$$xS(x) = x\bar{S}(x) = \frac{\tilde{A}_U x^{\tilde{b}_U}}{2[\exp(x/\bar{x}) + 1]} . \qquad (9)$$

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

- 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

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

$$A_U = 0.776 \pm 0.15 \qquad b_U = 0.500 \pm 0.02$$

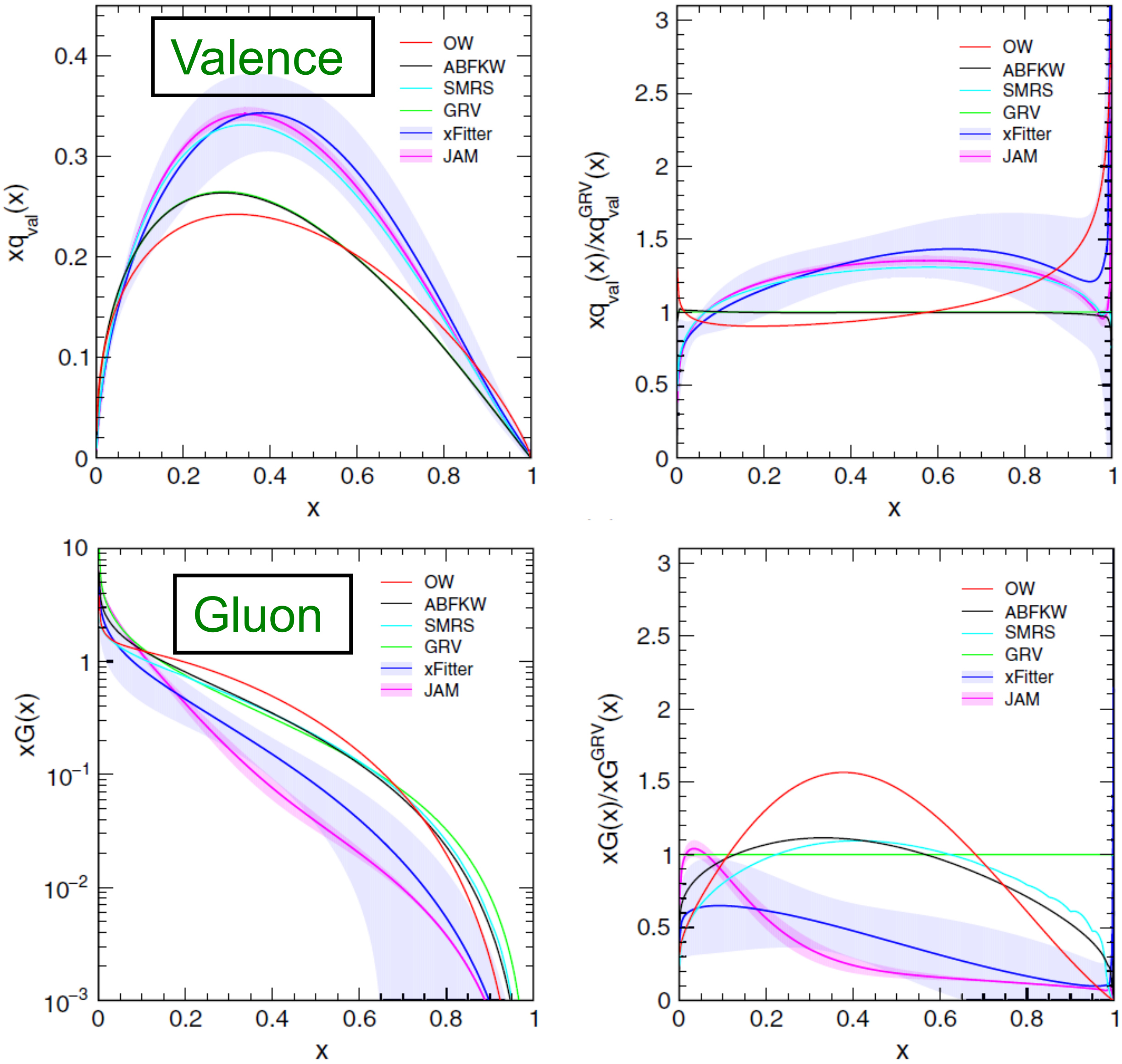
$$X_U = 0.756 \pm 0.01 \qquad \bar{x} = 0.1063 \pm 0.004$$

$$\tilde{A}_U = 2.089 \pm 0.21 \qquad \tilde{b}_U = 0.4577 \pm 0.009$$

$$A_G = 31.17 \pm 1.7 \qquad b_G = 1 + \tilde{b}_U \,.$$

- The temperature, $\overline{x} = 0.106$, found for pion is very close to that obtained for proton, $\overline{x} = 0.090$, 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

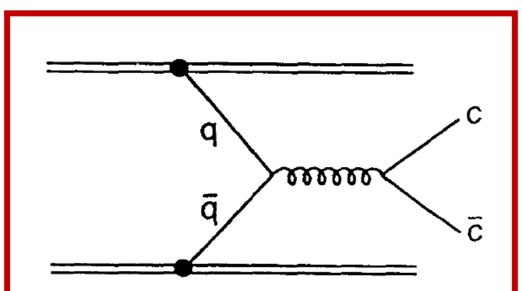


- Quite good agreements for valence quark PDFs
- Much larger variations for the gluon PDFs

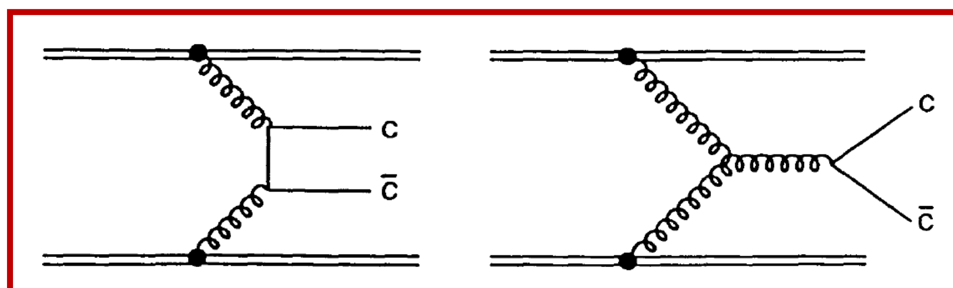
Constraining gluon distribution of pion with pion-induced J/Ψ production

- 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

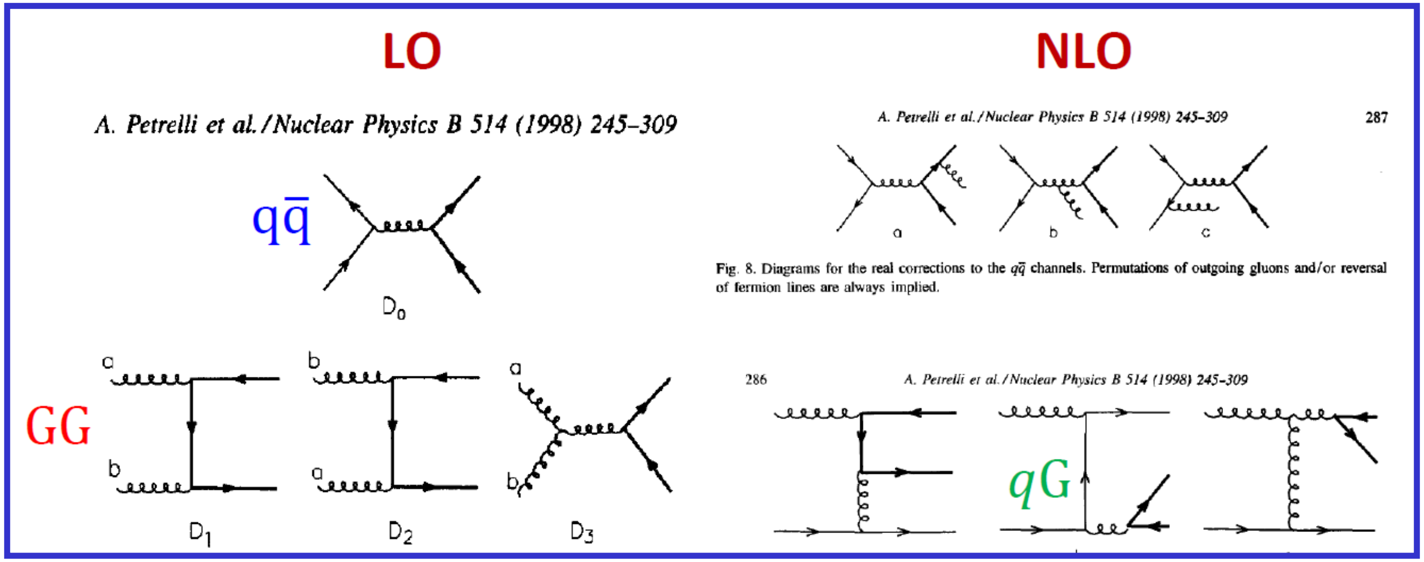
J/Ψ (q-qbar annihilation)



J/Ψ (gluon-gluon fusion)

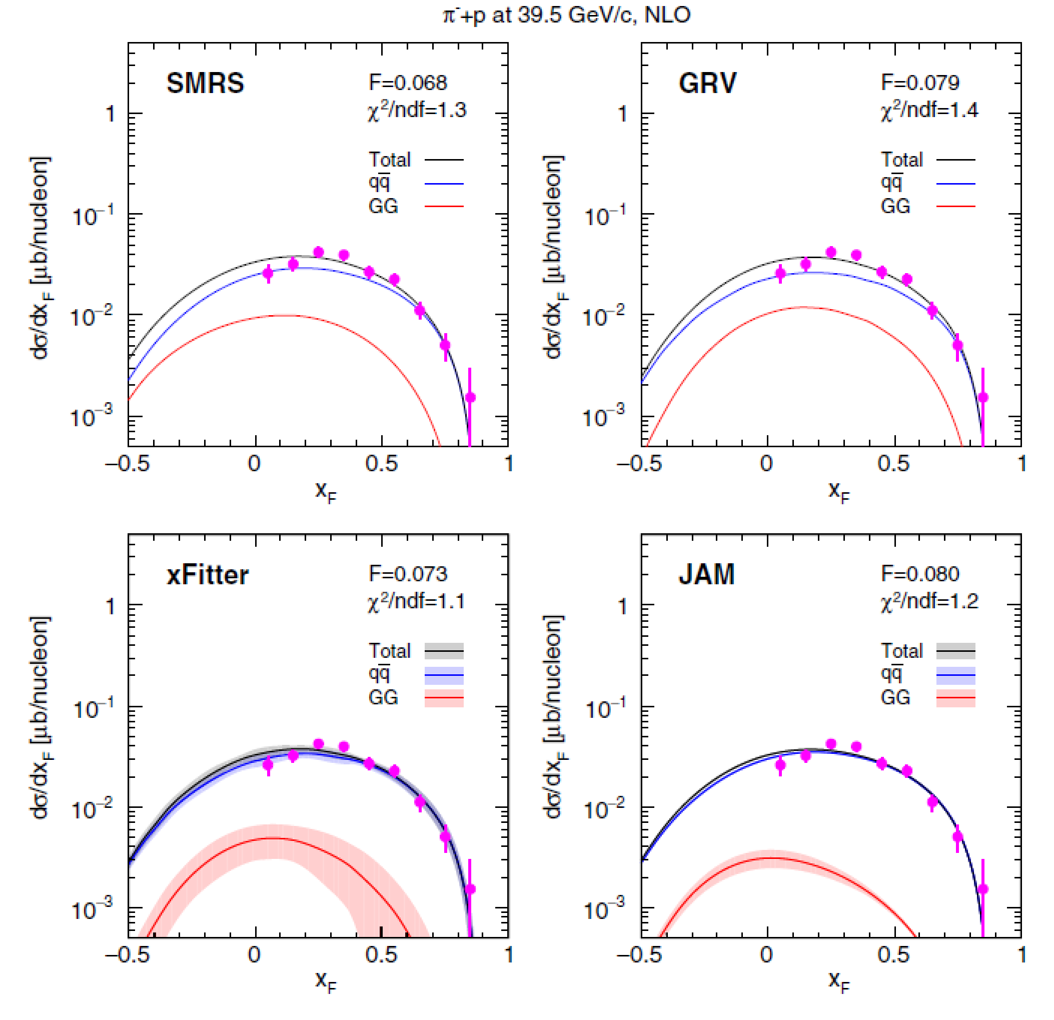


Different models for quarkonium production



- **Color evaporation model (CEM)**: all pairs with mass less than $D\bar{D}$ threshold. One hadronization parameter for each charmonium.
- **Non-relativistic QCD model (NRQCD)**: all pairs of different color and spin sates fragmenting with different probabilities – long-distance matrix elements (LDMEs).

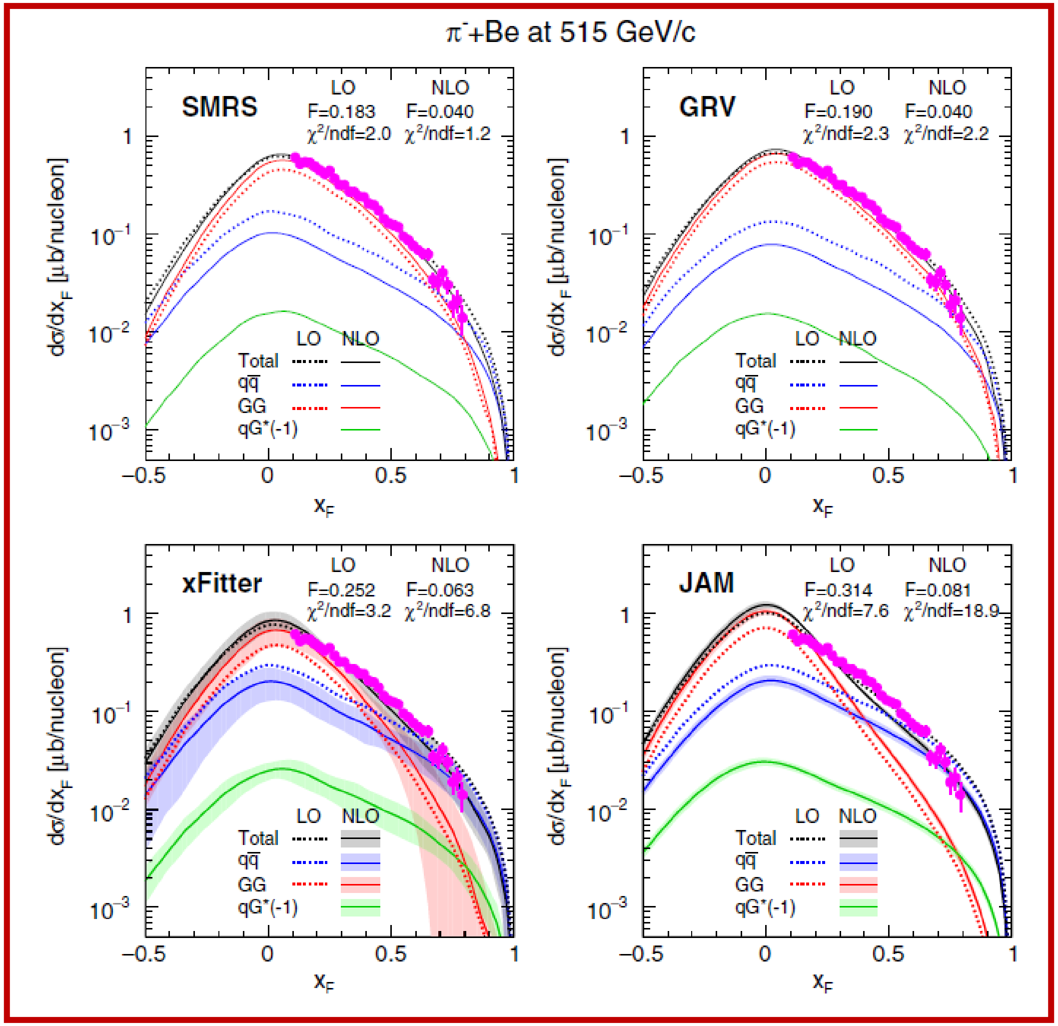
Comparison between data and NLO CEM calculations for different pion PDFs



- At the lowest beam energy (39.5 GeV), $q\bar{q}$ annihilation dominates
- All PDFs are in good agreement with data, reflecting similar valence quark distributions

Chang, Platchkov, Sawada, JCP, PRD 102 (2020) 054024

Comparison between data and calculations for different PDFs

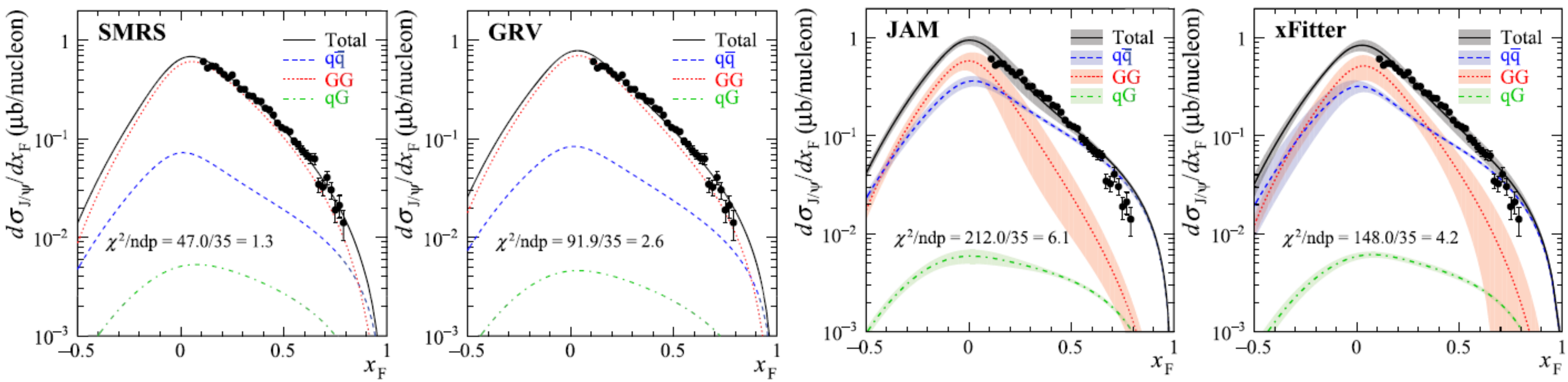


- At the highest available beam energy (515 GeV), GG fusion dominates at wider range of x_F for all PDFs
- JAM and xFitter GG fusion contribution falls off rapidly at large x_F

Chang, Platchkov, Sawada, JCP, PRD 102 (2020) 054024

Comparison between J/Ψ $d\sigma/dx_F$ data and NRQCD calculations for different pion PDFs

$\pi^- + Be$ at 515 GeV



Chang, JCP, Platchkov, Sawada, PRD 107, 056008 (2023)

- The SMRS and GRV give smaller χ^2 than JAM and xFitter
- It would be very important to include the J/Ψ data in the global fit to better constrain gluon distribution in mesons

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

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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 in the statistical model

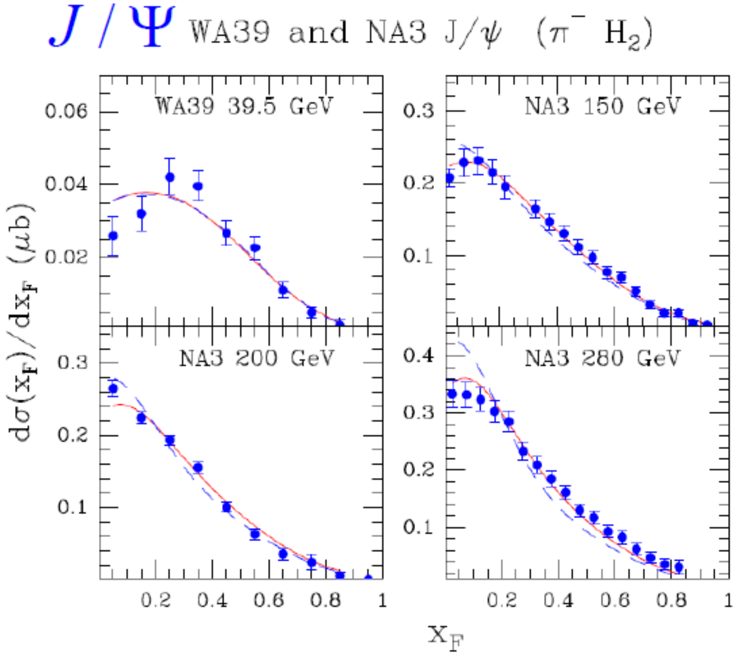
$$xU(x) = xD(x) = \frac{A_U X_U x^{b_U}}{\exp[(x - X_U)/\bar{x}] + 1} + \frac{\tilde{A}_U x^{\tilde{b}_U}}{\exp(x/\bar{x}) + 1}$$

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

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

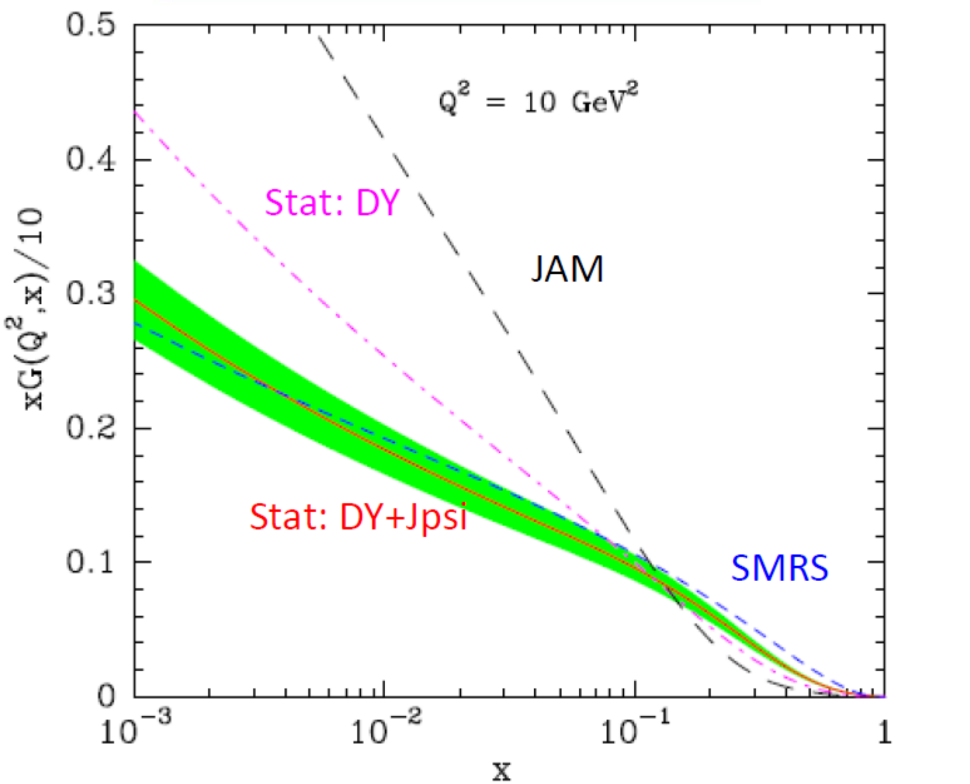
$$xG(x) = \frac{A_G x^{b_G}}{\exp(x/\bar{x}) - 1}, \qquad b_G = 1 + \tilde{b}_U$$

J/Ψ



NRQCD for J/Ψ Production

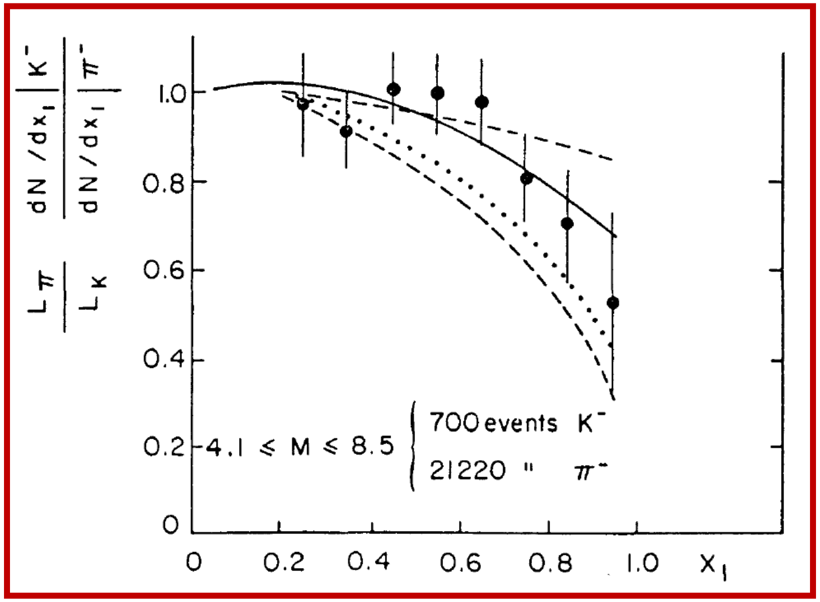
Phys.Rev.D 105 (2022) 076018



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

$$R = \frac{\sigma_{DY}(K^- + D)}{\sigma_{DY}(\pi^- + D)}$$

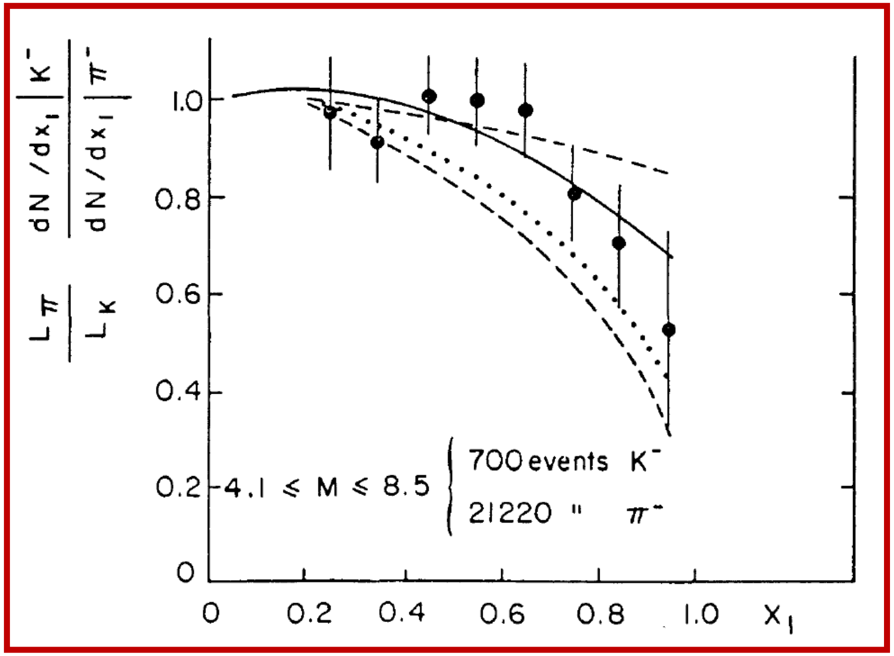
$$\simeq \frac{4V_K^u(x_1)V_N(x_2) + 4V_K^u(x_1)S_N(x_2) + V_K^s(x_1)s_p(x_2) + 5S_K(x_1)V_N(x_2)}{4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2)} \simeq \frac{V_K^u(x_1)}{V_\pi(x_1)}$$

$R \simeq (1-x)^{0.18\pm0.07} \Rightarrow$ softer u-valence in kaon than in pion

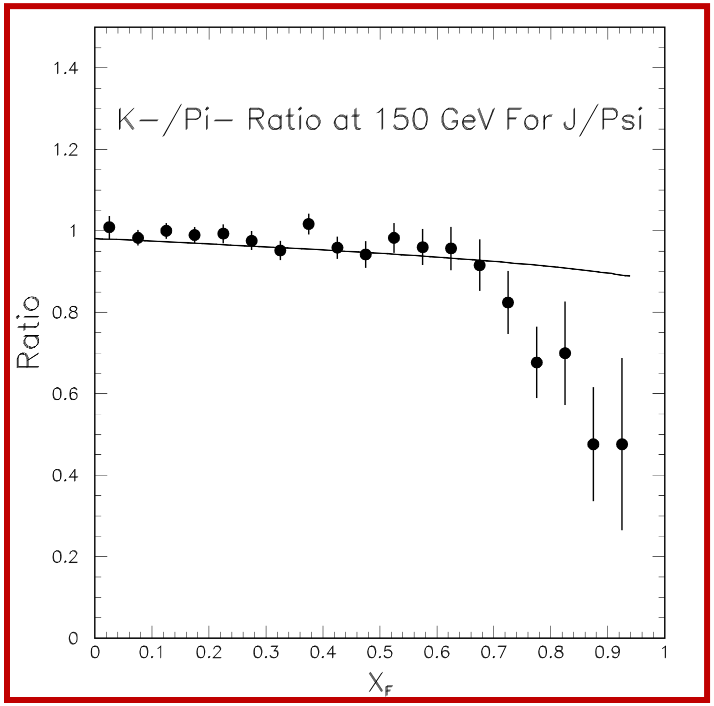
$(K^- + \mathrm{Pt}) / (\pi^- + \mathrm{Pt})$ ratios for J/Ψ production

From NA3; 150 GeV, Pt target

Ratios for D-Y



Ratios for J/Ψ



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

Pion PDFs

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

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

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

$$xG_\pi(x) = \frac{A_G x^{b_G}}{\exp(x/\bar{x}) - 1}, \quad b_G = 1 + \tilde{b}_U .$$

Kaon PDFs

$$xU_K(x) = \frac{A_{UK} X_{UK} x^{b_{UK}}}{\exp[(x - X_{UK})/\bar{x}] + 1} + \frac{\tilde{A}_{UK} x^{\tilde{b}_{UK}}}{\exp(x/\bar{x}) + 1};$$

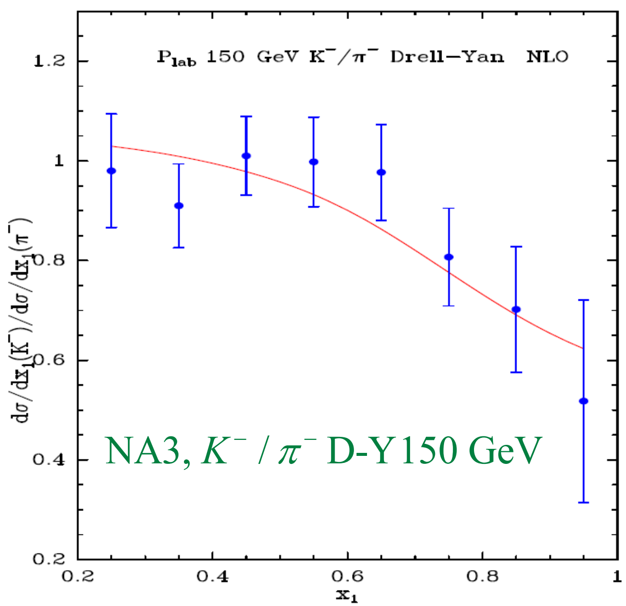
$$x\bar{U}_K(x) = \frac{A_{UK} (X_{UK})^{-1} x^{b_{UK}}}{\exp[(x + X_{UK})/\bar{x}] + 1} + \frac{\tilde{A}_{UK} x^{\tilde{b}_{UK}}}{\exp(x/\bar{x}) + 1};$$

$$xS_K(x) = \frac{A_{SK} X_{SK} x^{b_{SK}}}{\exp[(x - X_{SK})/\bar{x}] + 1} + \frac{\tilde{A}_{UK} x^{\tilde{b}_{UK}}}{2[\exp(x/\bar{x}) + 1]};$$

$$x\bar{S}_K(x) = \frac{A_{SK} (X_{SK})^{-1} x^{b_{SK}}}{\exp[(x + X_{SK})/\bar{x}] + 1} + \frac{\tilde{A}_{UK} x^{\tilde{b}_{UK}}}{2[\exp(x/\bar{x}) + 1]};$$

$$xD_K(x) = x\bar{D}_K(x) = \frac{\tilde{A}_{UK} x^{\tilde{b}_{UK}}}{(\exp(x/\bar{x}) + 1)};$$

$$xG_K(x) = \frac{A_{GK} x^{b_{GK}}}{\exp(x/\bar{x}) - 1}, \quad b_{GK} = 1 + \tilde{b}_{UK} .$$



The K^-/π^- D-Y data can be well described

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]

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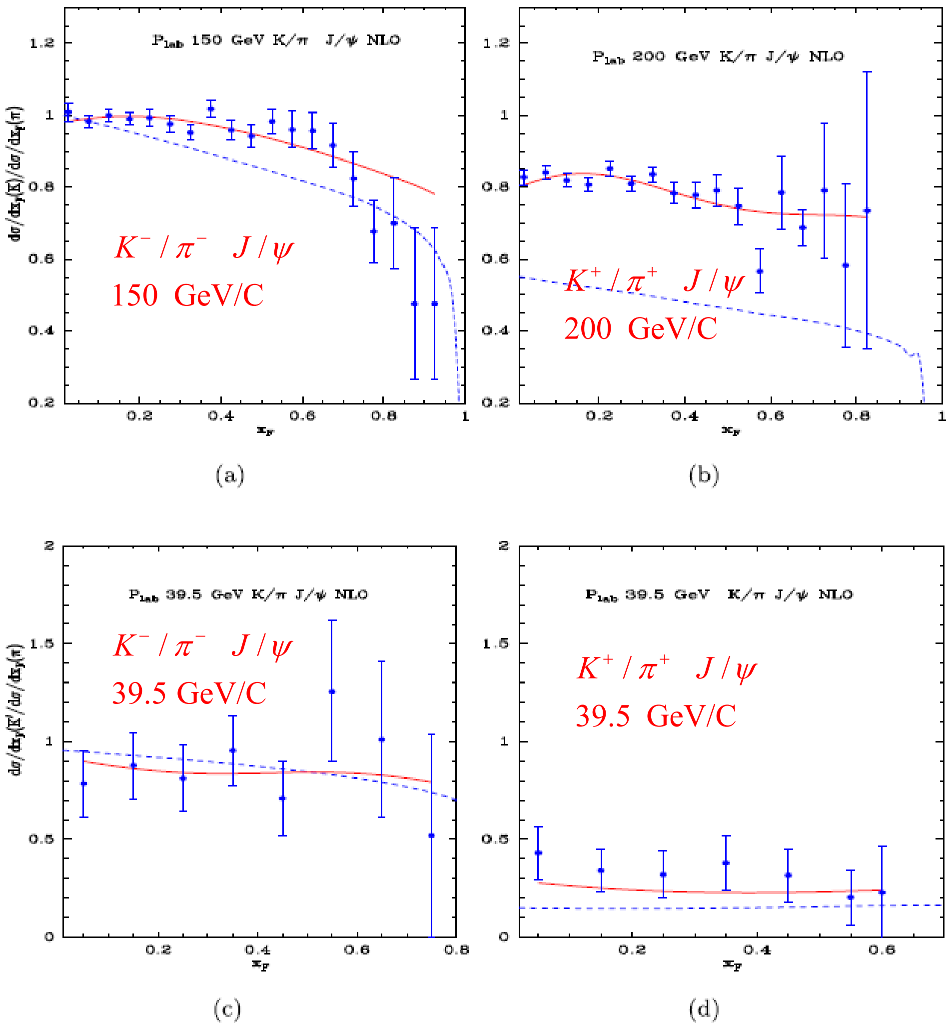

The K^-/π^- and K^+/π^+ J/Ψ data can also be well described by the statistical model (red curves)

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

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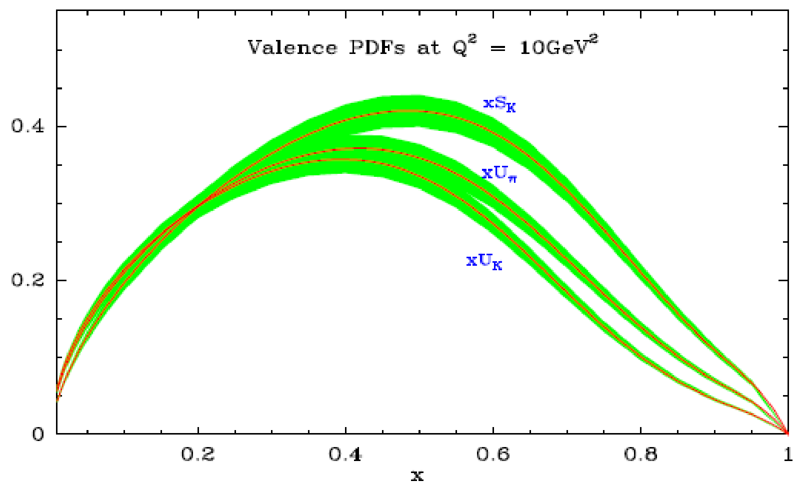
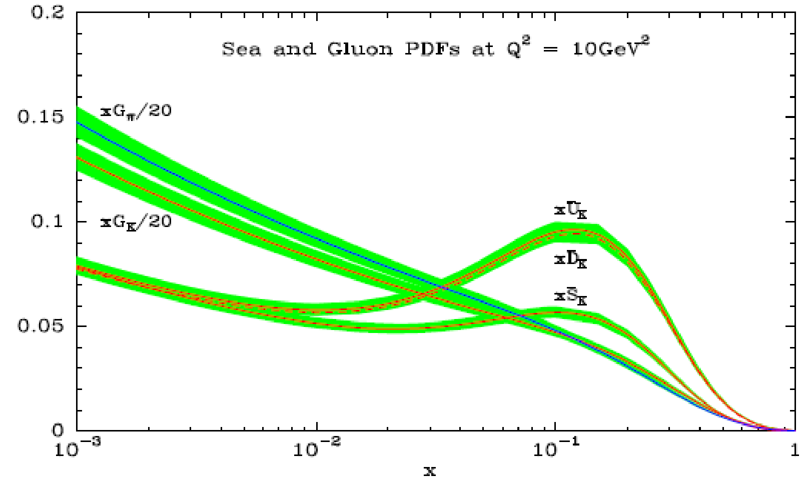
Phys. Lett. B 848 (2024) 138395

Comparison between the pion and kaon valence distributions

Comparison between the pion and kaon gluon distributions



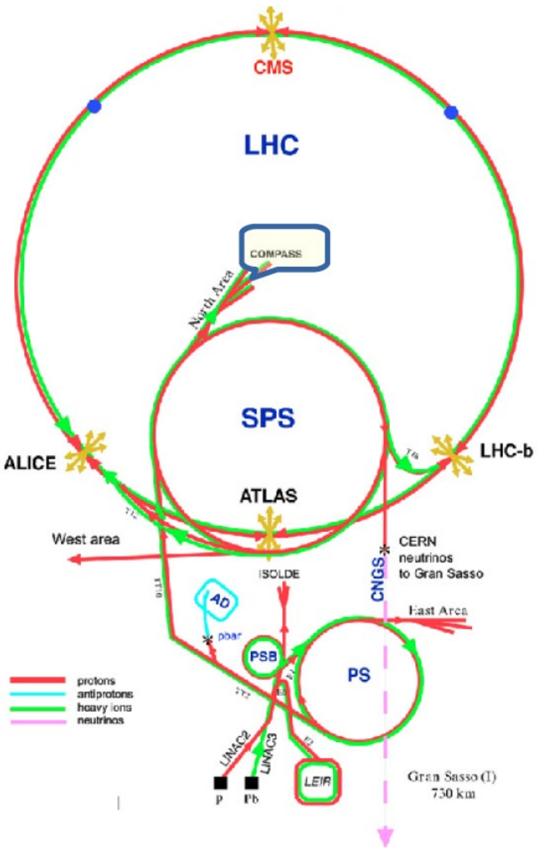


Momentum fractions of valence quarks, sea quarks, and gluons for π^- and K^- at the scale $Q^2 = 10$ GeV^2 obtained in the statistical model.

	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

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

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 !

Exclusive Drell-Yan and J/Ψ production with pion beam

- Exclusive Drell-Yan with meson and antiproton beams are the time-like processes complementary to the deeply virtual meson production at JLab, HERMES and COMPASS
- Exclusive Drell-Yan with meson beam at J-PARC will also complement the program at FAIR using antiproton beam

Takahiro Sawada, Wen-Chen Chang, Shunzo Kumano, Jen-Chieh Peng, Shinya Sawada, Kazuhiro Tanaka, Phys. Rev. D93 (2016) 114034

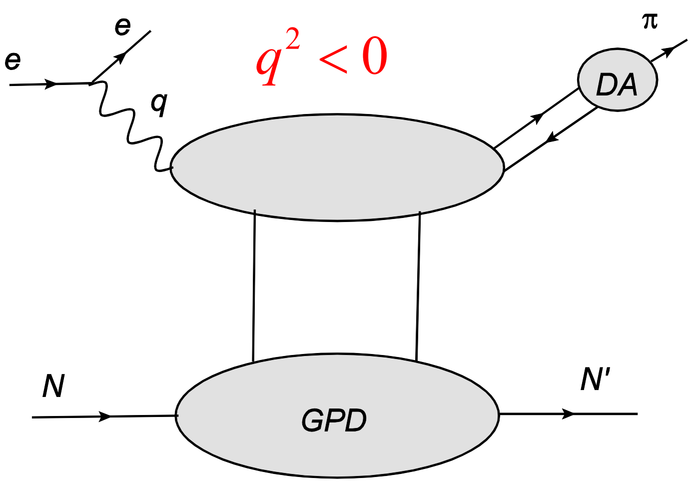
DEMP versus exclusive Drell-Yan

$$\gamma^* + N \rightarrow \pi + N'$$

$$\pi + N \rightarrow \gamma^* + N'$$

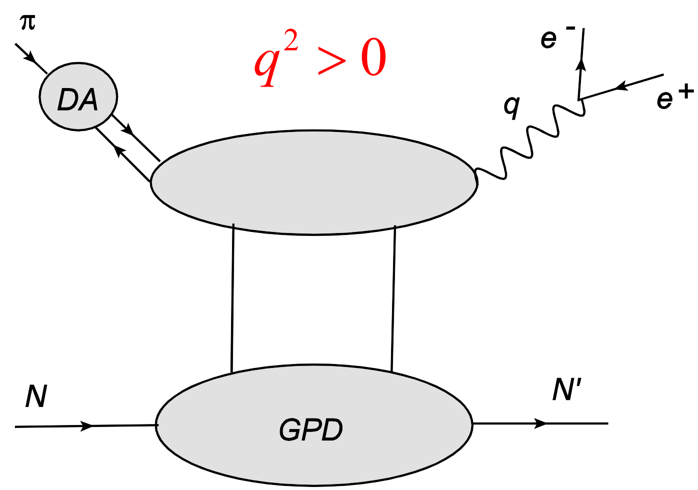
Deep Exclusive Meson Production

Exclusive Drell-Yan



(c)

space-like photon

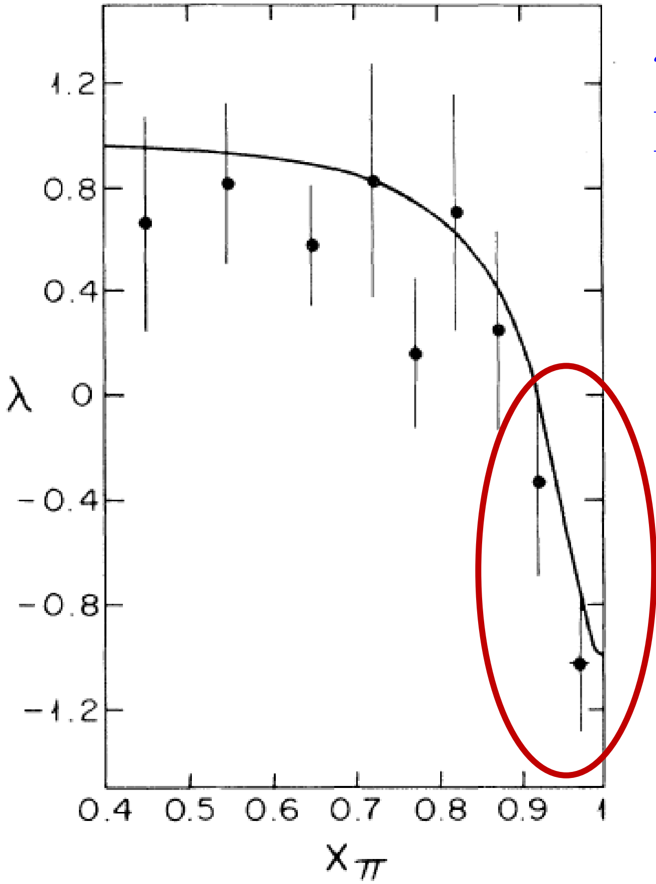


(d)

time-like photon

Longitudinally polarized dilepton is expected

Evidence for longitudinally polarized dilepton in meson-induced Drell-Yan at large *x*?



$\pi^- + W \to \mu^- + \mu^+ + X$ 80 GeV π^-

PRL 55 (1985) 2649

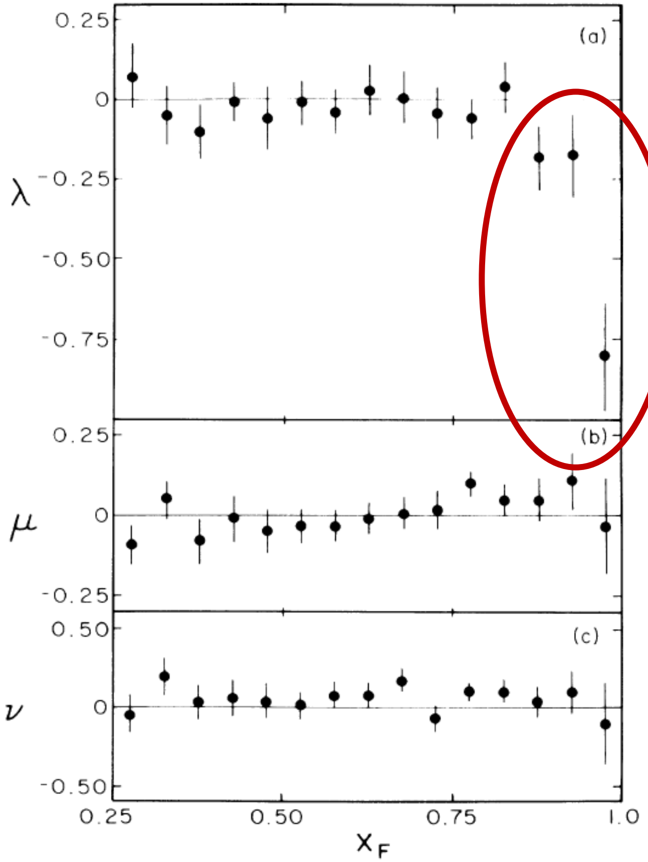
$$\frac{d\sigma}{d\Omega} \propto (1 + \lambda \cos^2\theta)$$

$\lambda = 1$: transversely polarized

$\lambda = -1$: longitudinally polarized

As $x_\pi \to 1$, inclusive Drell-Yan becomes exclusive Drell-Yan!

Evidence for longitudinally polarized dilepton in meson-induced J/Ψ at large x_F?



$\pi^- + W \to J/\Psi + X$ 252 GeV π^-

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$$\frac{d\sigma}{d\Omega} \propto (1 + \lambda \cos^2 \theta)$$

$\lambda = 1$: transversely polarized

$\lambda = -1$: longitudinally polarized

As $x_F \to 1$, inclusive J/Ψ becomes exclusive J/Ψ!

Summary

- Parton distributions of mesons represent
  - ∗ an interesting topic for theories and experiments
  - ∗ unique opportunities at COMPASS, AMBER, JLab, and EIC

- J/Ψ production provides useful information on the quark and gluon contents of mesons
  - ∗ Existing data should be included in the global fits for better constraining the gluon distributions in pion and kaon
  - ∗ First results on the extraction of meson PDFs in the framework of statistical model have been obtained using both the Drell-Yan and the J/Ψ data