Parton distribution functions of π and K from Drell-Yan and J/Ψ production

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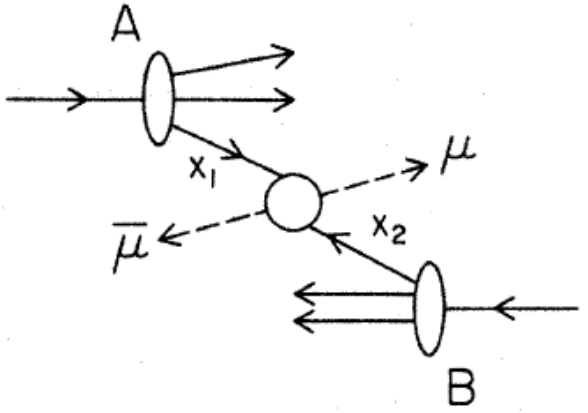
Outline

- Overview of experiments probing the meson parton distributions (Drell-Yan, J/Ψ production, direct photon production) with meson beams
- Status and Plans at COMPASS on meson PDFs
- Prospect for measuring exclusive Drell-Yan reaction at J-PARC

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)



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

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 $(e\nu)$.

(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^-

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	

- Require beam particle identification to reject large proton content
- Smaller DY cross section due to $\bar{d}u$ contents in π^+
- Very few DY data with π^+ beam

Drell-Yan experiments with K^- beam

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

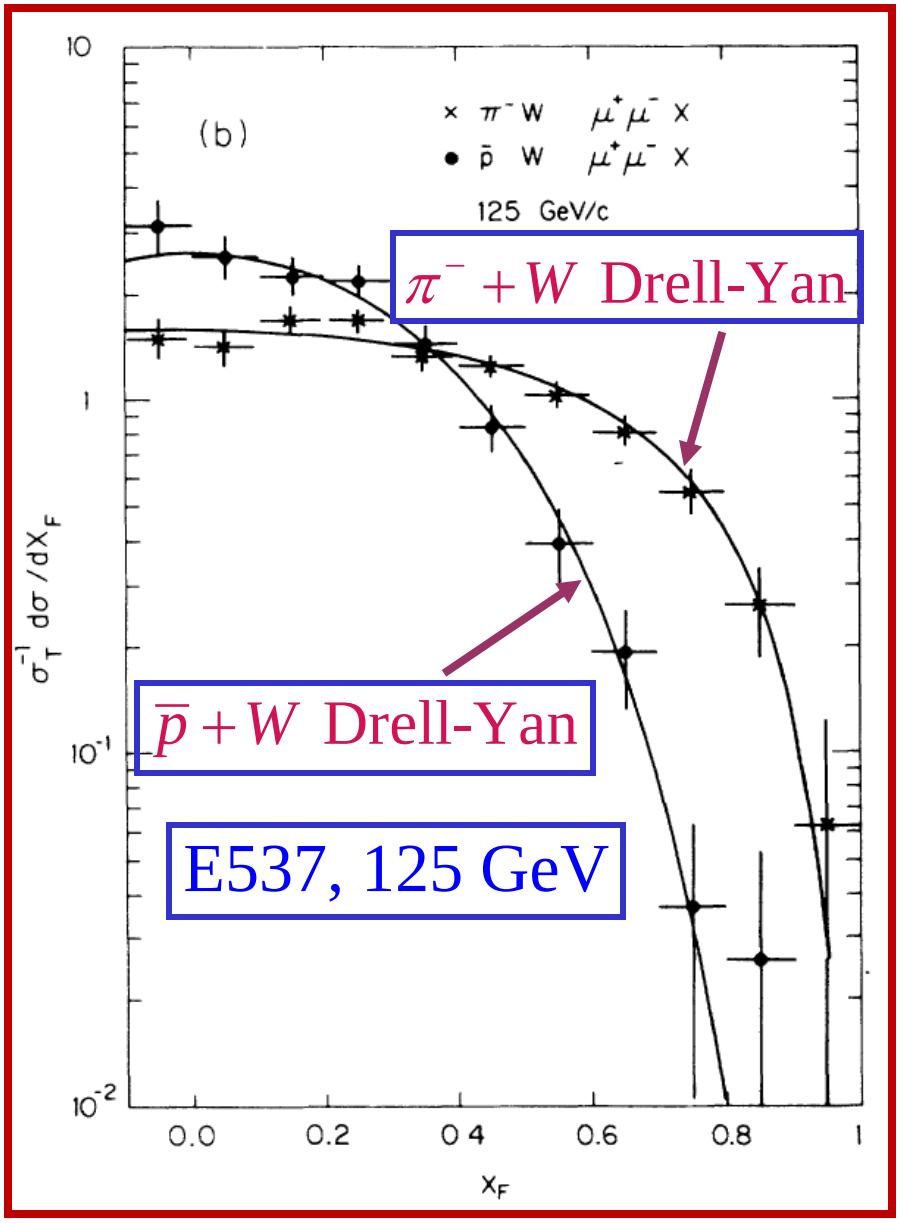
Drell-Yan experiments with K^+ beam

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

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

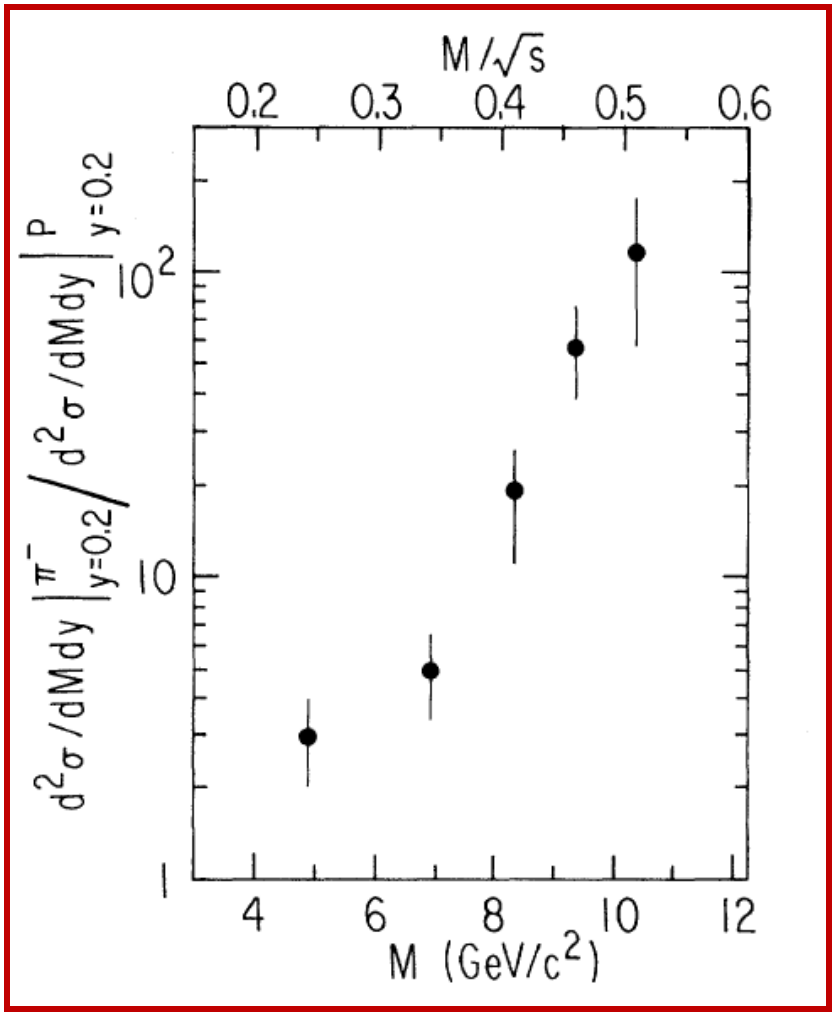
Exp	P (GeV)	targets	D-Y events
WA39	40	W (H_2)	
NA3	150, 200	Pt	275, 32
E537	125	W, Cu, Be	380

$(\pi^- + W)$ versus $(\bar{p} + W)$ Drell-Yan cross sections



Valence quark *x*-distribution in pion is broader than that in antiproton (proton)

Ratio of $(\pi^- + A)/(p + A)$ Drell-Yan cross sections



From E331/E444

$$R = \frac{(d^2\sigma_{DY}/dMdy)^{\pi+N}}{(d^2\sigma_{DY}/dMdy)^{p+N}}$$

$$\simeq \frac{4\bar{u}_\pi(x_1)u_N(x_2) + d_\pi(x_1)\bar{d}_N(x_2)}{4u_p(x_1)\bar{u}_N(x_2) + d_p(x_1)\bar{d}_N(x_2)}$$

$$\simeq \left(\frac{\bar{u}_\pi(x_1)}{u_p(x_1)}\right)\left(\frac{u_N(x_2)}{\bar{u}_N(x_2)}\right)$$

Black: valence Red: sea

Rapid rise in R at large M

reflects the rise in valence/sea

ratio as x increases: $\frac{u_N(x_2)}{\bar{u}_N(x_2)}$

How to determine the valence quark distribution in pion?

Compare $(\pi^- + D)$ with $(\pi^+ + D)$ Drell-Yan cross sections

$$\sigma_{DY}(\pi^- + D) \propto 4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2) + 10S_\pi(x_1)S_N(x_2)$$

$$\sigma_{DY}(\pi^+ + D) \propto V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2) + 10S_\pi(x_1)S_N(x_2)$$

$$\sigma_{DY}(\pi^- + D) - \sigma_{DY}(\pi^+ + D) \propto 3\, V_\pi(x_1)V_N(x_2)$$

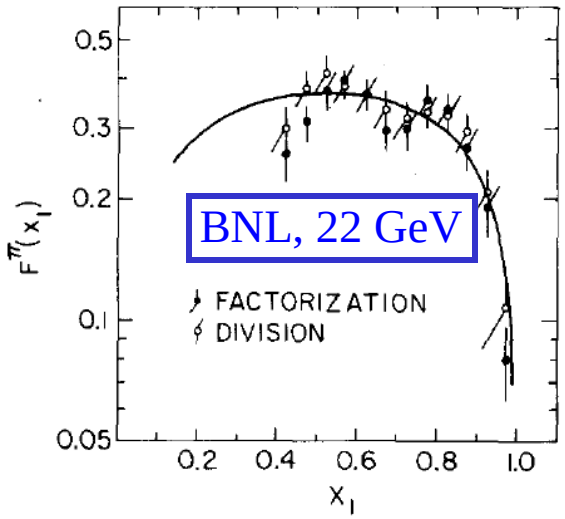
Only the valence-quark term remain!

Only very low statistics data for $\sigma_{DY}(\pi^+ + D)$ are available!

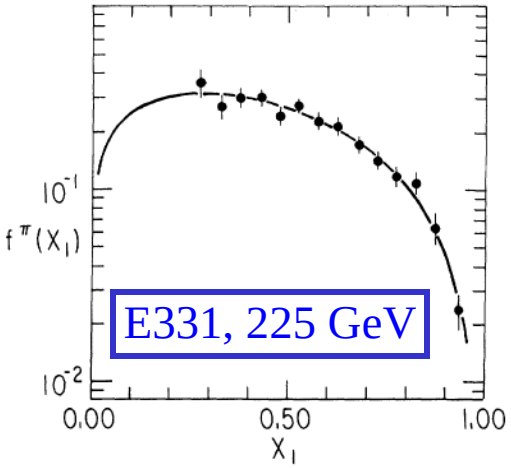
Hence only $\sigma_{DY}(\pi^- + A)$ data are utilized

See Londergan et al., PL B361 (1995) 110

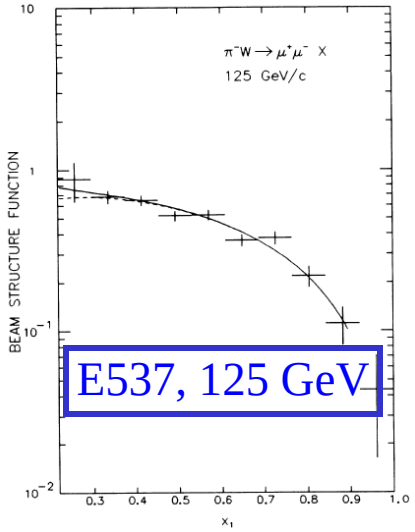
Attemps to extract the pion valence quark distribution



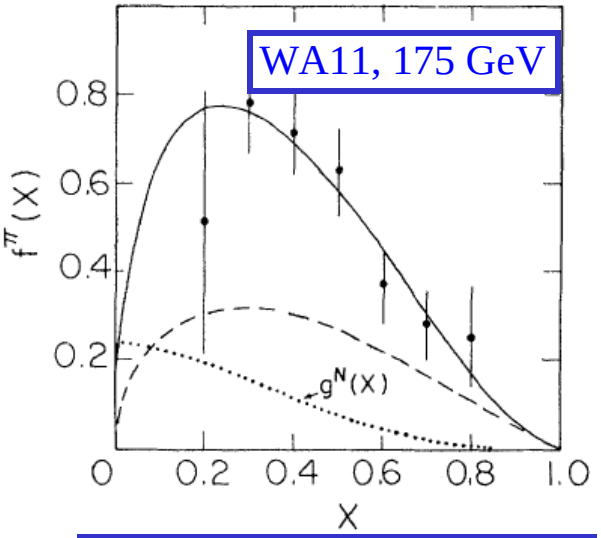
$F^{\pi}(x) = 0.72x^{0.5}(1-x)^{0.46}$



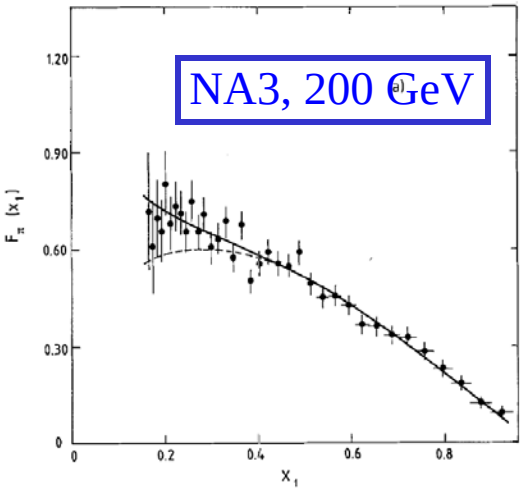
$F^{\pi}(x) = 0.90x^{0.5}(1-x)^{1.27}$



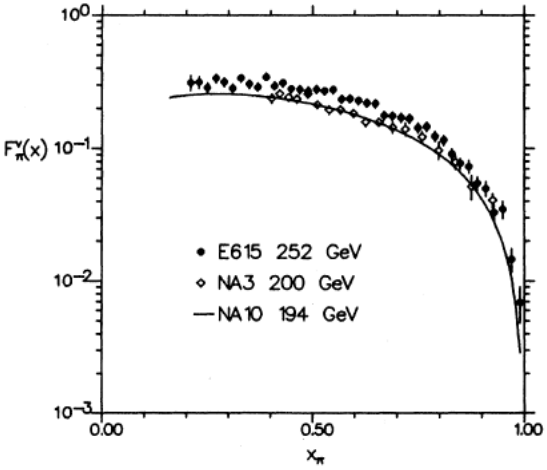
$F^{\pi}(x) = Ax^{0.442}(1-x)^{1.248}$



$F^{\pi}(x) = 2.43x^{0.5}(1-x)^{1.57}$



$F^{\pi}(x) = Ax^{0.45}(1-x)^{1.17}$



$F^{\pi}(x) = Ax^{0.6}(1-x)^{1.26}$

How to determine the sea quark distribution in pion?

Compare $(\pi^- + D)$ with $(\pi^+ + D)$ Drell-Yan cross sections

$$\sigma_{DY}(\pi^- + D) \propto 4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2) + 10S_\pi(x_1)S_N(x_2)$$

$$\sigma_{DY}(\pi^+ + D) \propto V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2) + 10S_\pi(x_1)S_N(x_2)$$

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

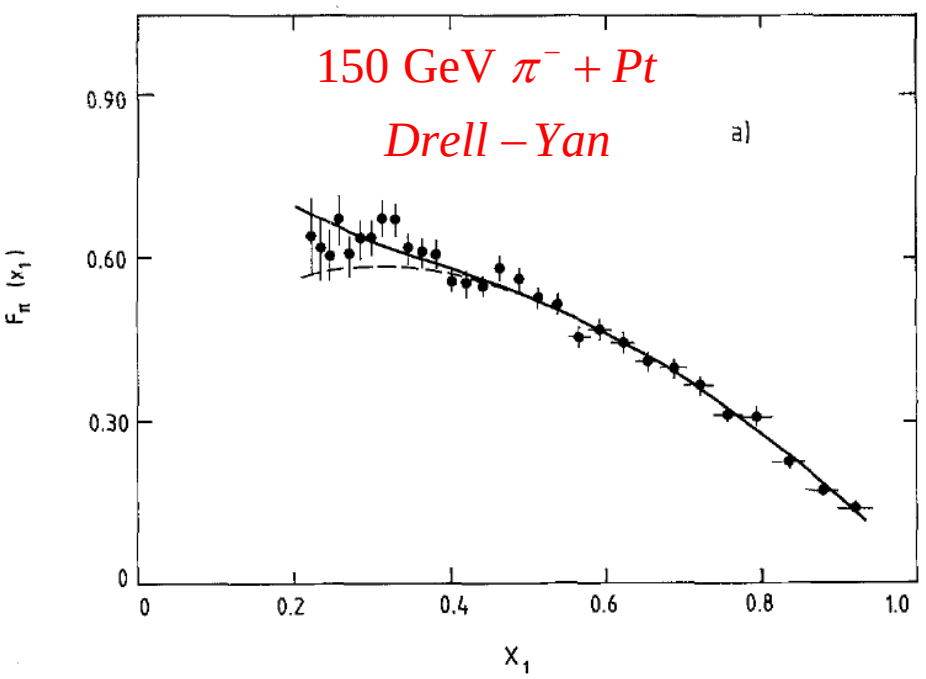
$$\propto 15S_\pi(x_1)V_N(x_2) + 15V_\pi(x_1)S_N(x_2) + 30S_\pi(x_1)S_N(x_2)$$

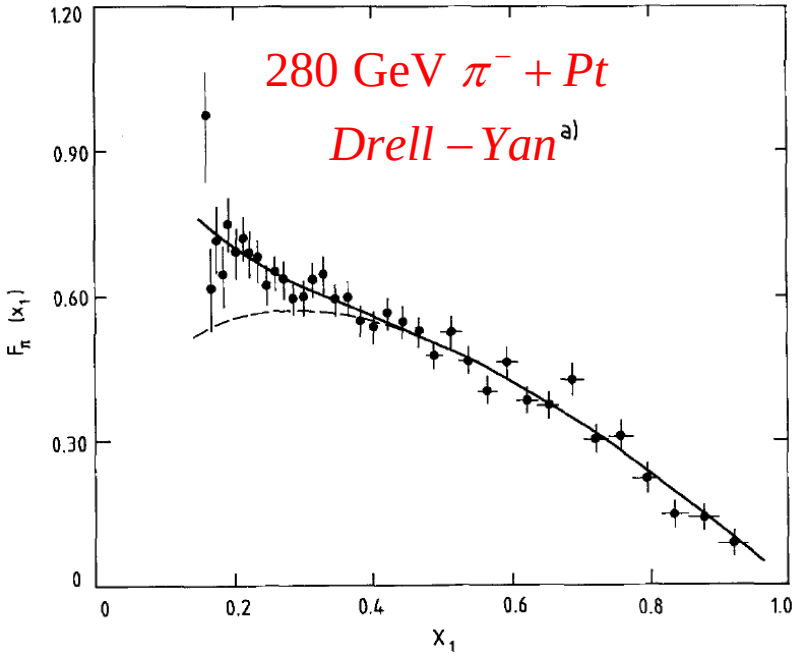
$S_\pi(x_1)$ can be extracted

Only very low statistics data for $\sigma_{DY}(\pi^+ + D)$ are available!

Hence only $\sigma_{DY}(\pi + A)$ data are utilized

Determine the sea quark distribution of pion in NA3





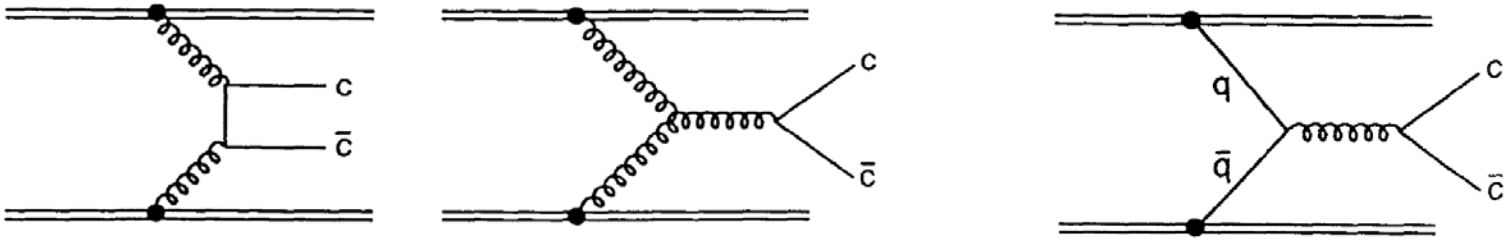
Dashed curve: without the pion sea contribution

Solid curve: including the pion sea contribution

How to determine the gluon distribution in pion?

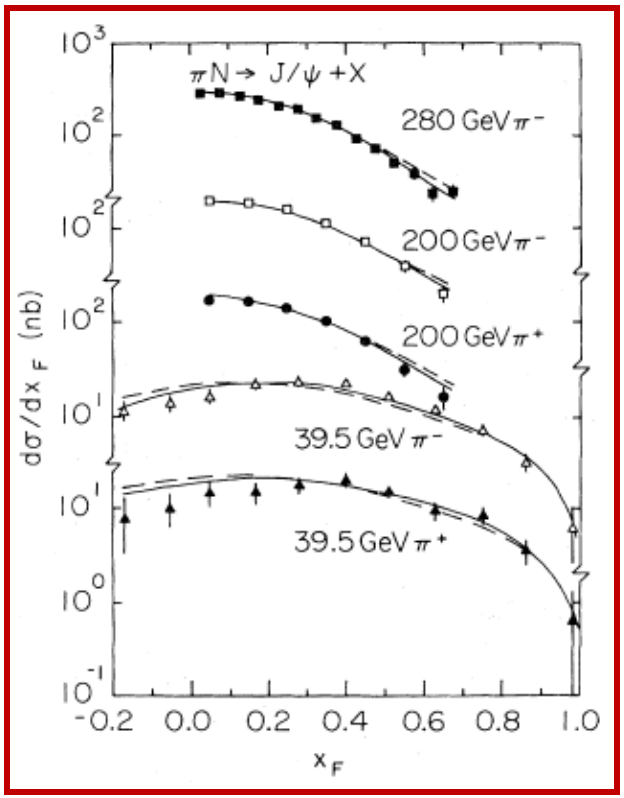
- J/Ψ production with pion beam
- Direct photon production with pion beam
- Charm production with pion beam
- Q^2-evolution of pion PDFs

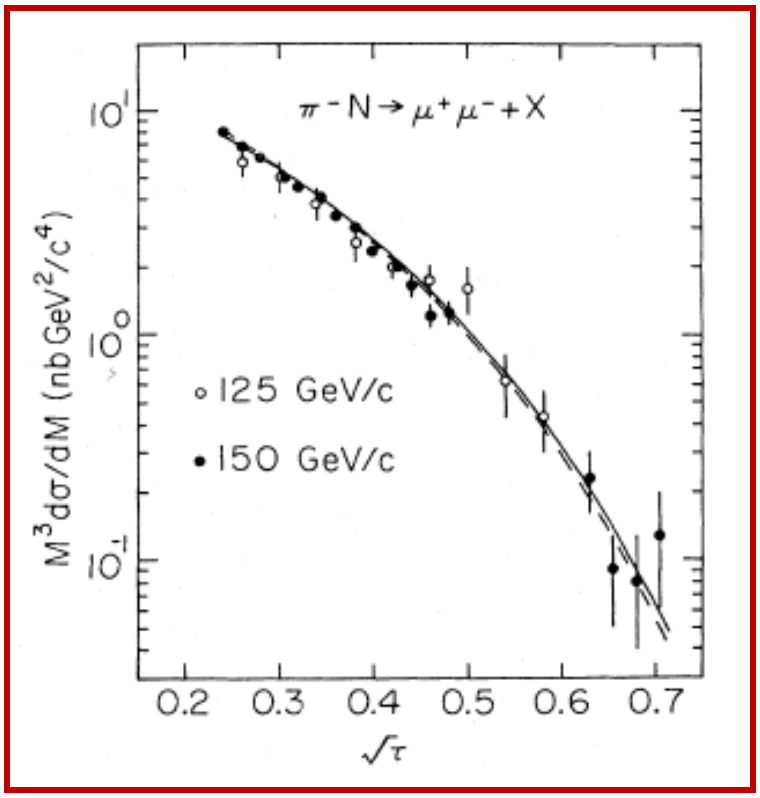
Diagrams for charm and J/Ψ production



Four pion PDF sets available at LHAPDF library

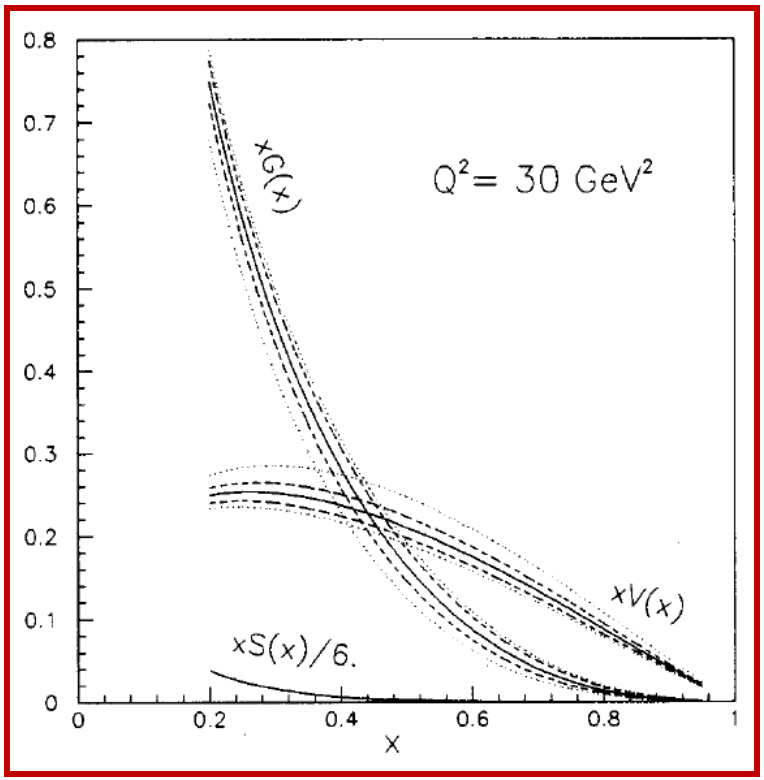
- First: OW-P (PRD 30, 943 (1984))
  - LO QCD
  - J/Ψ data from NA3 and WA39
  - D-Y data from E537 and NA3





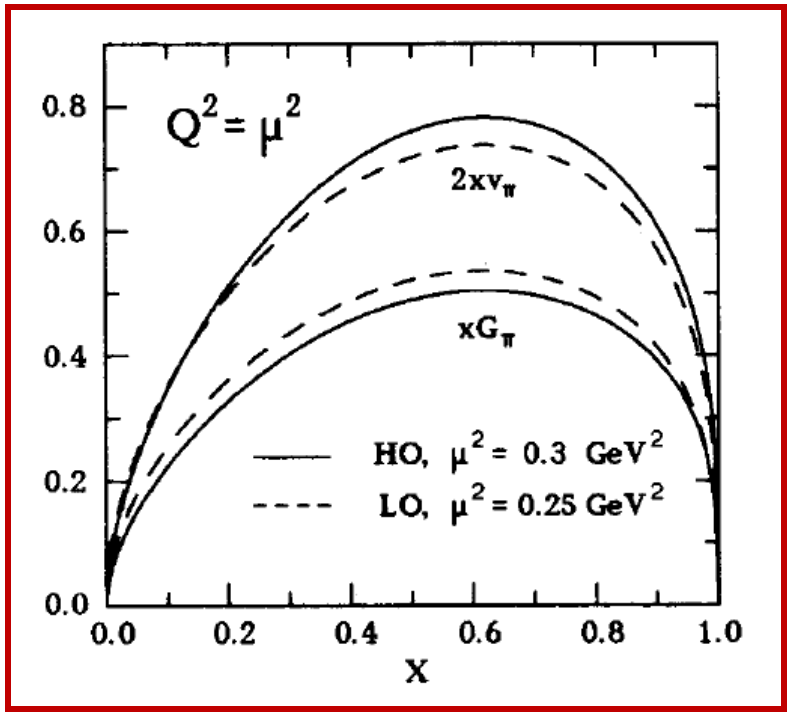
Four pion PDF sets available at LHAPDF library

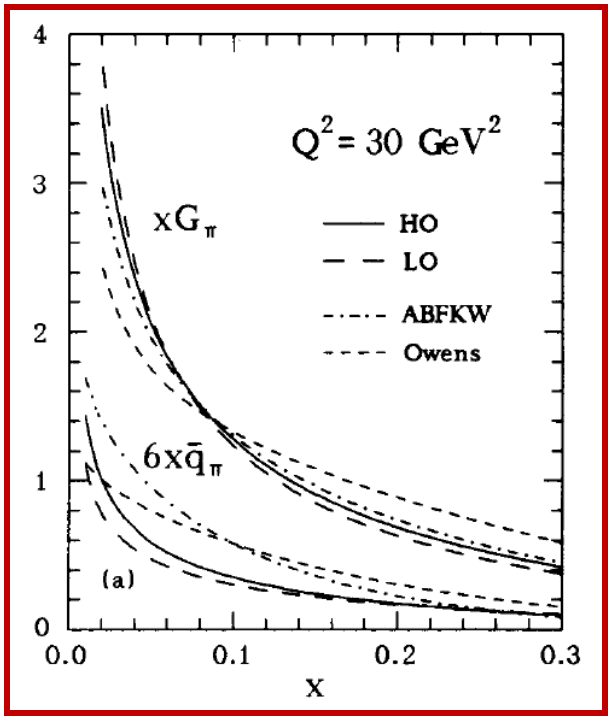
- Second: ABFKW-P (PL 233, 517 (1989))
  - NLO QCD
  - Direct photon data from WA70 and NA24
  - Sea-quark distribution from NA3



Four pion PDF sets available at LHAPDF library

- Third: GRV-P (Z. Phys. C53, 651 (1992))
  - Only valence and valence-like gluon at initial scale. Sea is entirely from QCD evolution
  - Valence distribution from fit to direct photon data

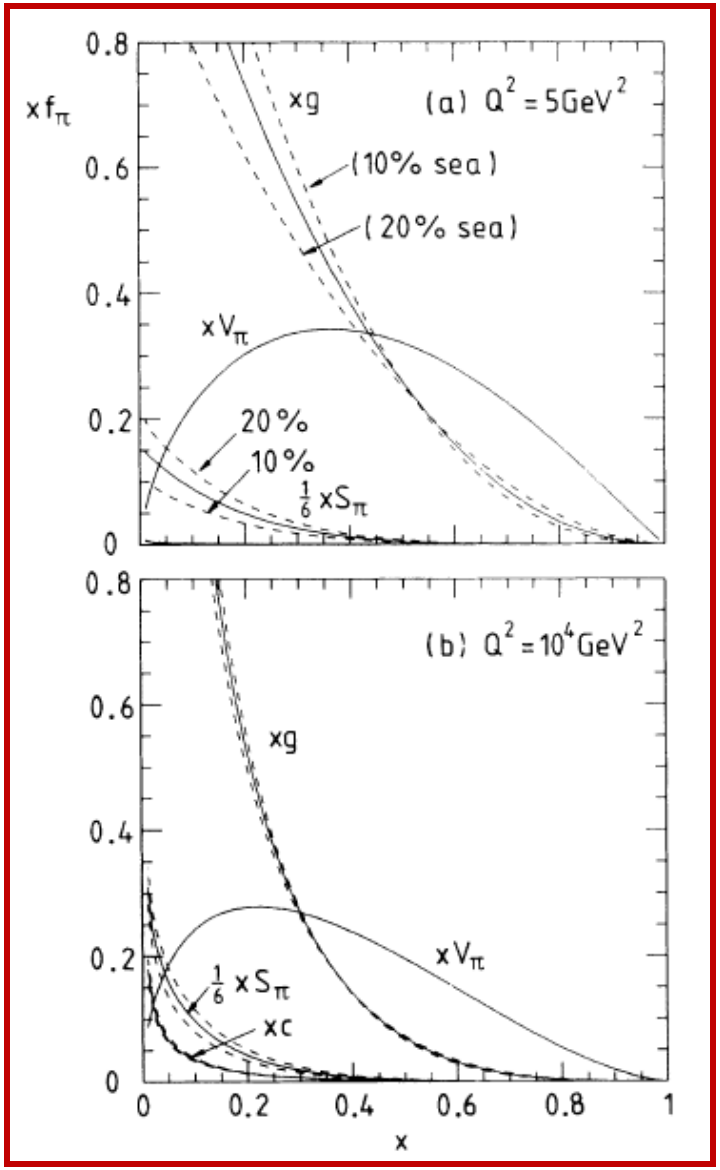




Four pion PDF sets available at LHAPDF library

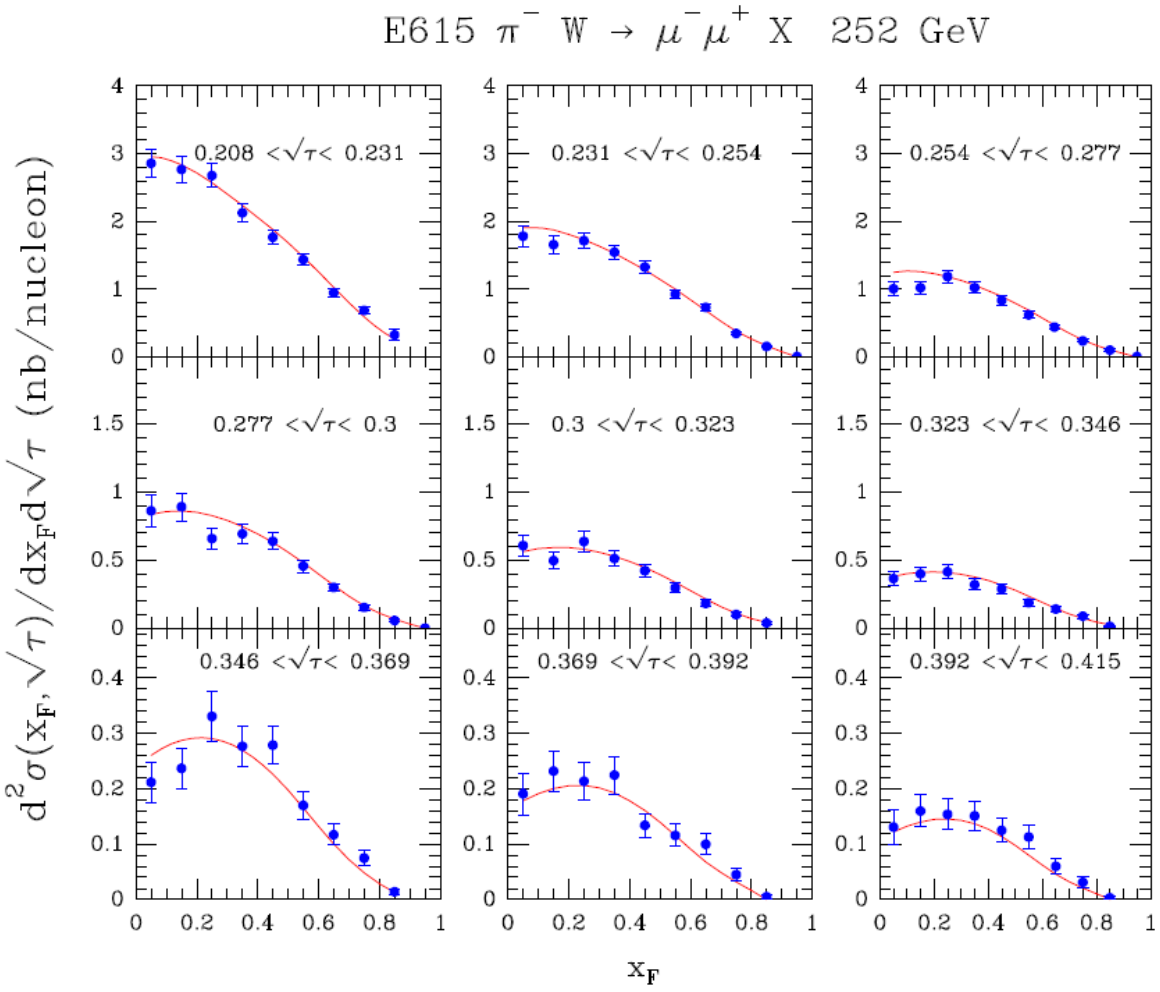
- Fourth: SMRS (PR D45, 2349 (1992))
  - NLO QCD
  - NA10 and E615 D-Y data
  - WA70 direct photon data

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



Recent extraction of pion PDF using a statistical model

Bourrely and Soffer (NP A981 (2019) 118)



Definitions of the pion PDFs

$$U = u_{\pi^+} = \bar{u}_{\pi^-}, D = \bar{d}_{\pi^+} = d_{\pi^-}, \bar{U} = \bar{u}_{\pi^+} = u_{\pi^-}, \bar{D} = d_{\pi^+} = \bar{d}_{\pi^-}. \quad (1)$$

This paper assumes that U and D can be different;

$\bar{U}$ and $\bar{D}$ can also be different

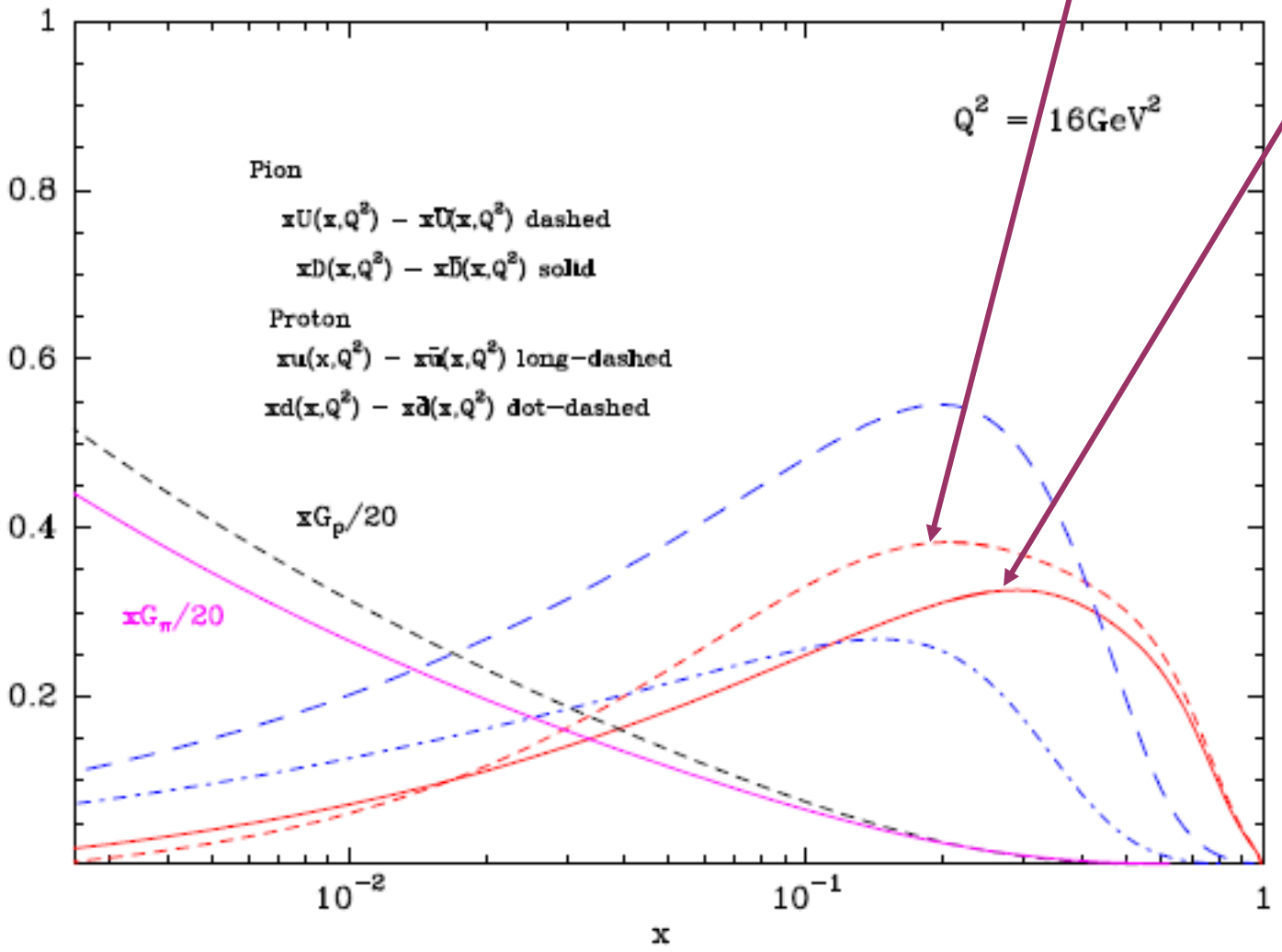
$$xQ^{\pm}(x) = \frac{A_Q X_Q^{\pm} x^{b_Q}}{\exp[(x - X_Q^{\pm})/\bar{x}] + 1}, \quad (2)$$

$$A_U = 0.537 \pm 0.100, \; A_D = 0.346 \pm 0.050,$$
$$b_U = 0.048 \pm 0.001, \; b_D = 0.466 \pm 0.014, \quad (12)$$

and four potentials

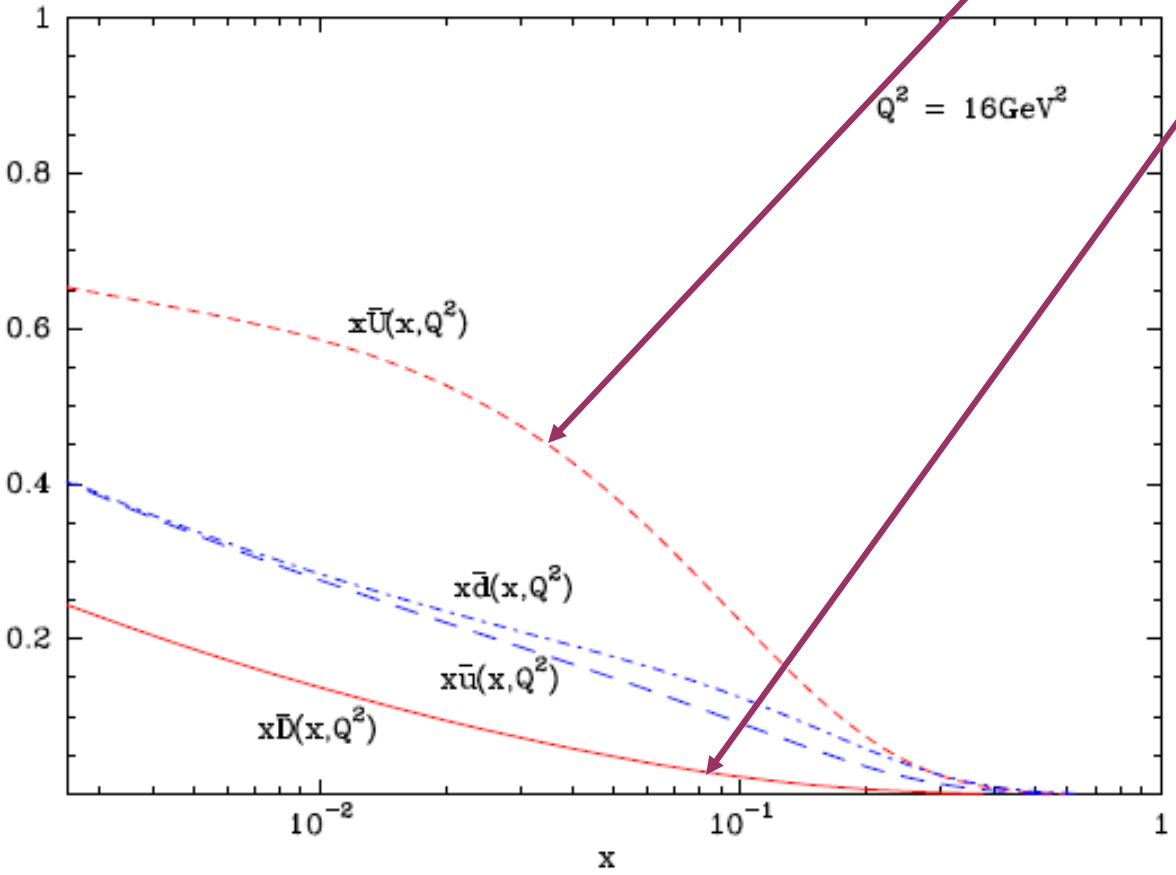
$$X_U^+ = 0.787 \pm 0.007, \; X_U^- = 0.185 \pm 0.030,$$
$$X_D^+ = 0.866 \pm 0.024, \; X_D^- = 0.718 \pm 0.044. \quad (13)$$

Very large difference between Uv and Dv



Data allow a large charge-symmetry breaking at a partonic level

Even larger difference between $\bar{U}$ and $\bar{D}$



More studies and data are needed to check this surprising and interesting result

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]

[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*

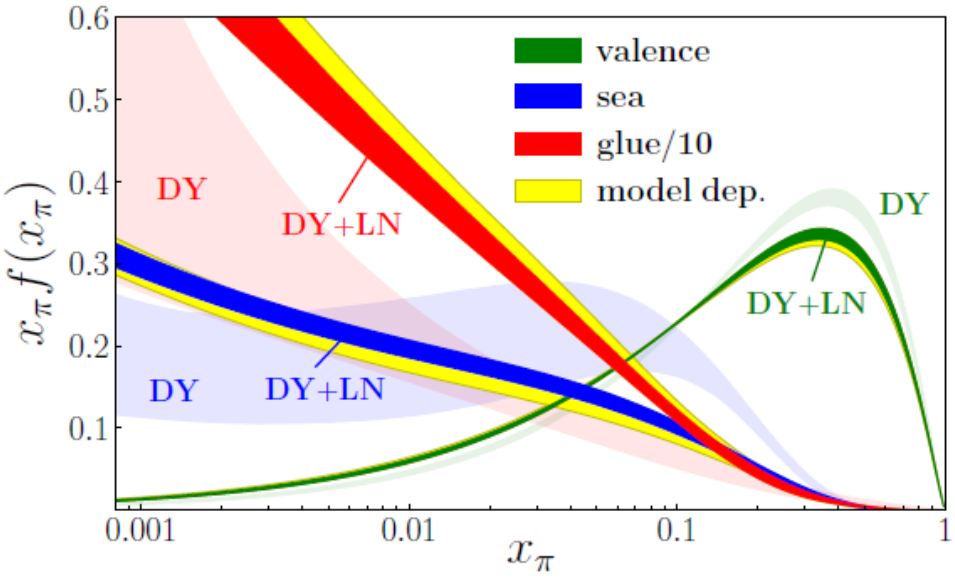
Jefferson Lab Angular Momentum (JAM) Collaboration

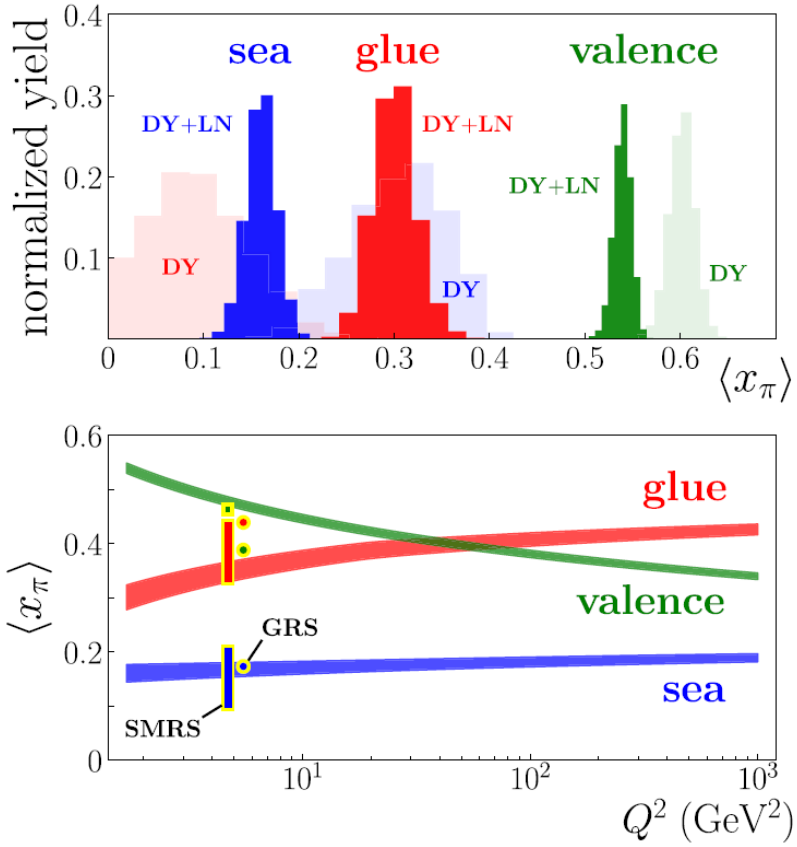
PRL 121, 152001 (2018)

- Drell-Yan data from NA10 and E615
- Leading-neutron tagged DIS from HERA (H1 and ZEUS) provides information on the pion PDFs at small x
- Uncertainties of the pion PDFs are determined

Implications of the JAM results

PRL 121, 152001 (2018)





- The tagged-DIS data significantly reduce the uncertainty of the pion PDFs
- Further measurements of tagfed-DIS can be pursued at 12 GeV and EIC

Can one extract meson PDFs from J/Ψ production?

Difference between $(\pi^- + p)$ and $(\pi^+ + p)$ J/Ψ cross sections

$$\sigma_{J/\Psi}(\pi^- + p) \propto V_\pi(x_1)[u(x_2) + \bar{d}(x_2)] + S_\pi(x_1)[u(x_2) + d(x_2) + \bar{u}(x_2) + \bar{d}(x_2)]$$

$$\sigma_{J/\Psi}(\pi^+ + p) \propto V_\pi(x_1)[d(x_2) + \bar{u}(x_2)] + S_\pi(x_1)[u(x_2) + d(x_2) + \bar{u}(x_2) + \bar{d}(x_2)]$$

$$\sigma_{J/\Psi}(\pi^- + p) - \sigma_{J/\Psi}(\pi^+ + p) \propto V_\pi(x_1)[u_V(x_2) - d_V(x_2)]$$

Only the valence-quark term remains!

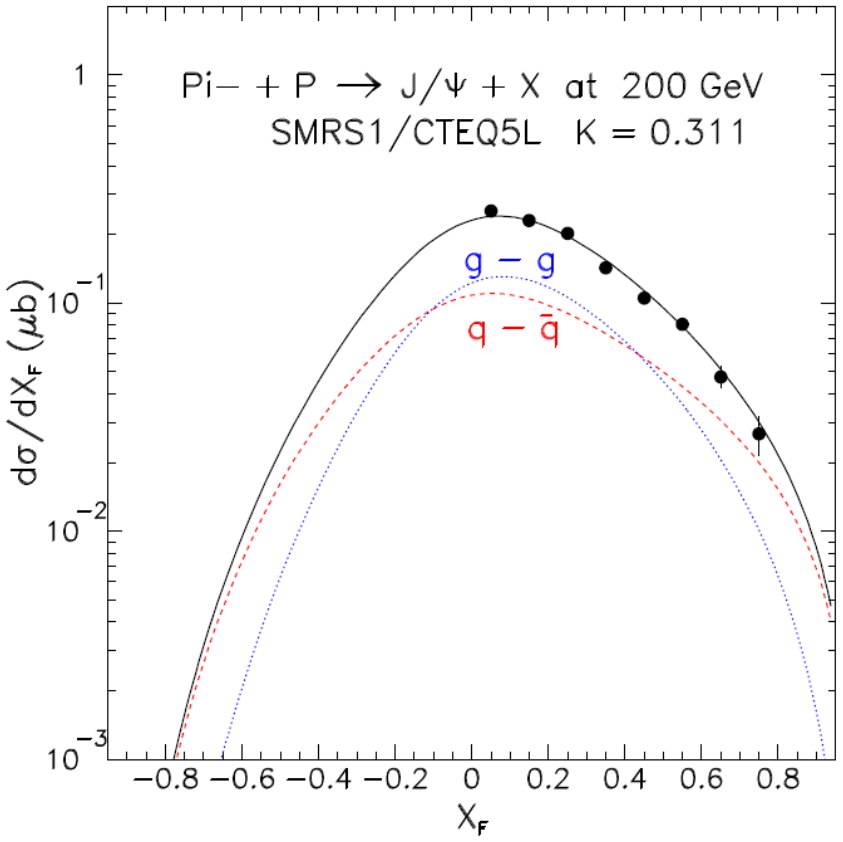
$\sigma_{J/\Psi}(\pi^- + p) - \sigma_{J/\Psi}(\pi^+ + p)$ is positive

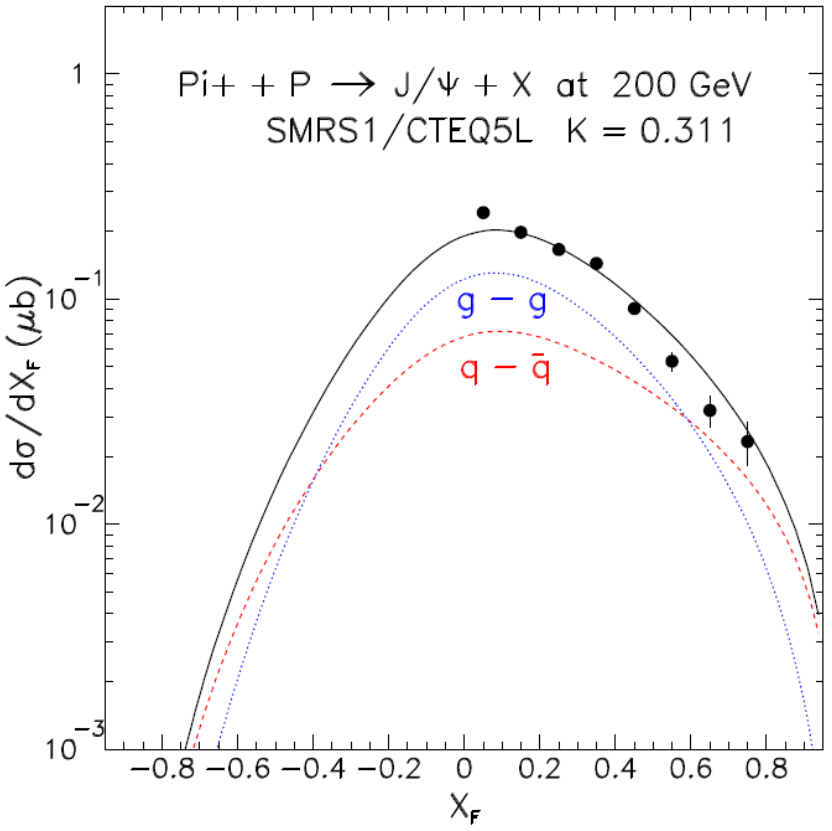
Directly proportional to $u_V(x_2) - d_V(x_2)$

Directly proportional to $V_\pi(x_1)$

Are there relevant data already?

Data from the NA3 paper and Ph.D thesis

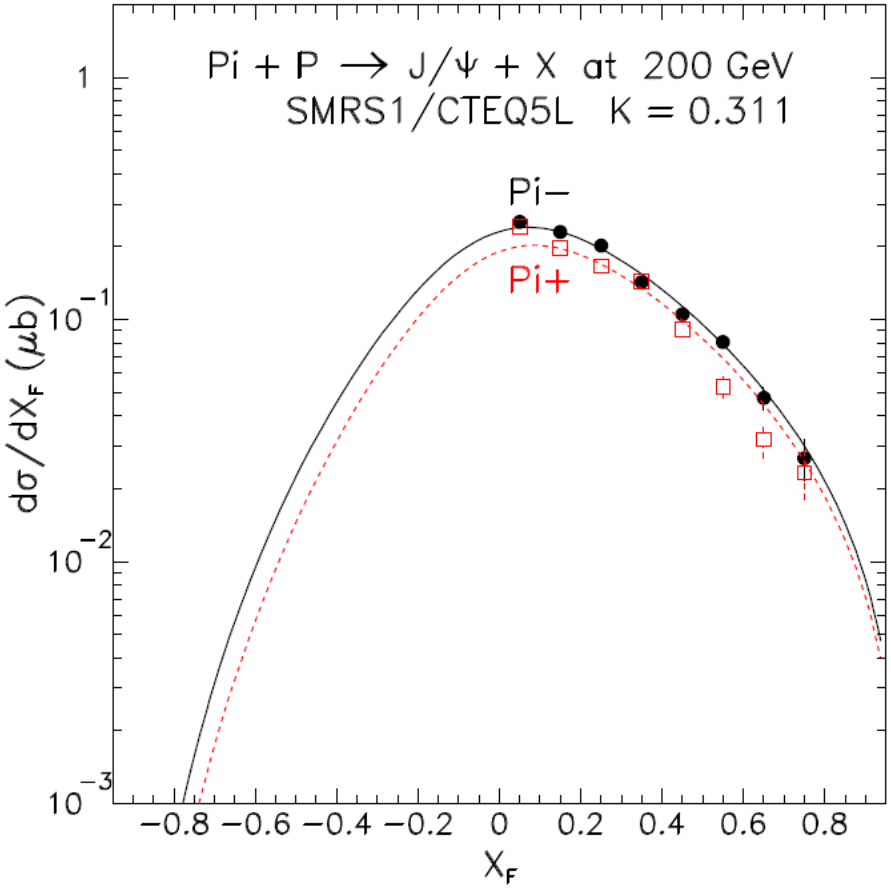




Calculations using Color Evaporation Model

$g-g$ fusion is the same for both, but $q-\bar{q}$ annihilation is larger for $\pi^- + p$ than for $\pi^- + p$

Comparison between the NA3 data and CEM calculations based on current pion and nucleon PDFs



$$\sigma_{J/\Psi}(\pi^- + p) - \sigma_{J/\Psi}(\pi^+ + p) \propto V_\pi(x_1)[u_V(x_2) - d_V(x_2)]$$

Sensitive to $V_\pi(x_1)$ and $u_V(x_2) - d_V(x_2)$

How to determine the valence quark distribution in kaon?

Compare $(K^- + D)$ with $(K^+ + D)$ Drell-Yan cross sections

$$\sigma_{DY}(K^- + D) \propto 4V_K^u(x_1)V_N(x_2) + 4V_K^u(x_1)S_N(x_2) + V_K^s(x_1)\bar{s}_N(x_2)$$
$$+ 5S_K(x_1)V_N(x_2) + 10S_K(x_1)S_N(x_2) + 2S_K(x_1)\bar{s}_N(x_2)$$

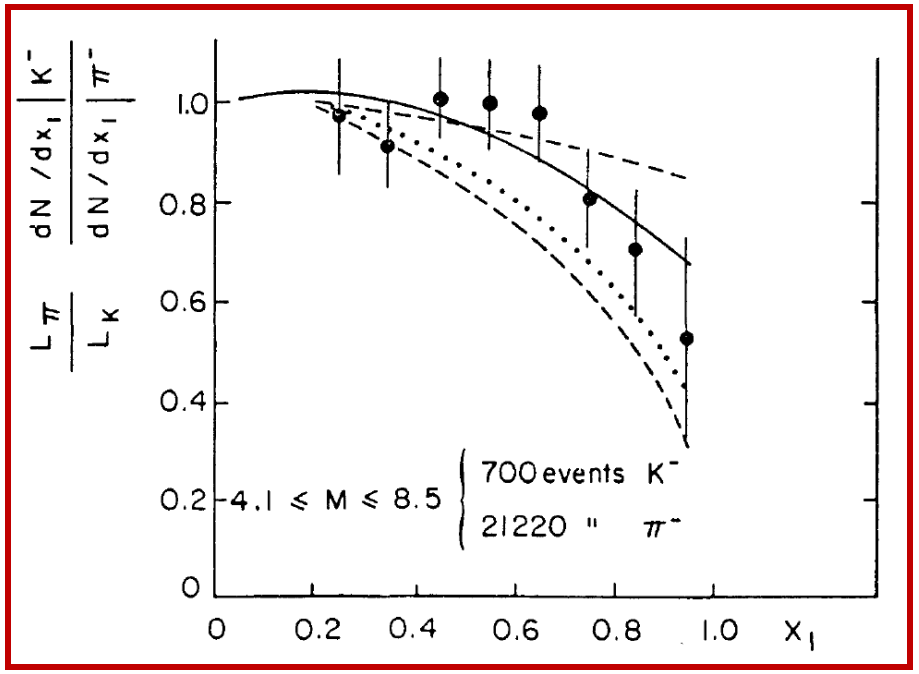
$$\sigma_{DY}(K^+ + D) \propto 4V_K^u(x_1)S_N(x_2) + V_K^s(x_1)\bar{s}_N(x_2)$$
$$+ 5S_K(x_1)V_N(x_2) + 10S_K(x_1)S_N(x_2) + 2S_K(x_1)\bar{s}_N(x_2)$$

$$\sigma_{DY}(K^- + D) - \sigma_{DY}(K^+ + D) \propto 4V_K^u(x_1)V_N(x_2)$$

Only the valence-quark term remain!

See Londergan et al., PL B380 (1996) 393

Kaon PDF from $(K^- + Pt)/(\pi^- + Pt)$ Drell-Yan ratios



From NA3; 150 GeV, Pt target

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

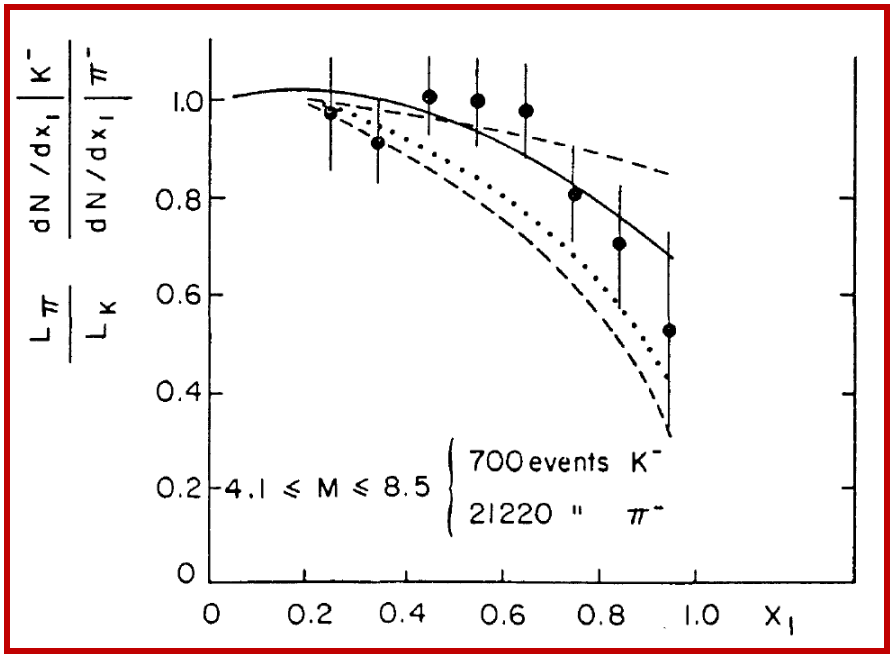
$$\simeq \frac{4V_K^u(x_1)V_N(x_2) + 4V_K^u(x_1)S_N(x_2) + V_K^s(x_1)s_p(x_2) + 5S_K(x_1)V_N(x_2)}{4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2)} \simeq \frac{V_K^u(x_1)}{V_\pi(x_1)}$$

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

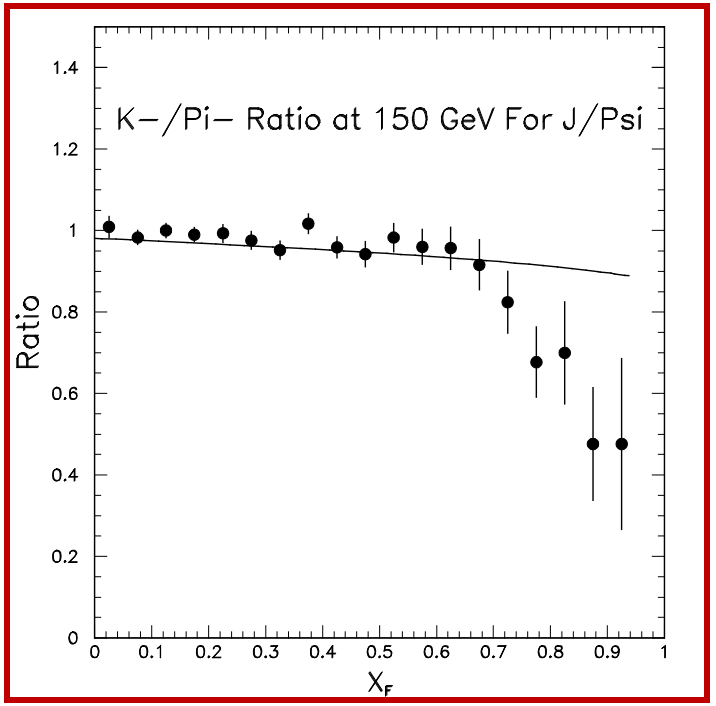
$(K^- + \mathrm{Pt}) / (\pi^- + \mathrm{Pt})$ ratios for J/Ψ production

From NA3; 150 GeV, Pt target

Ratios for D-Y



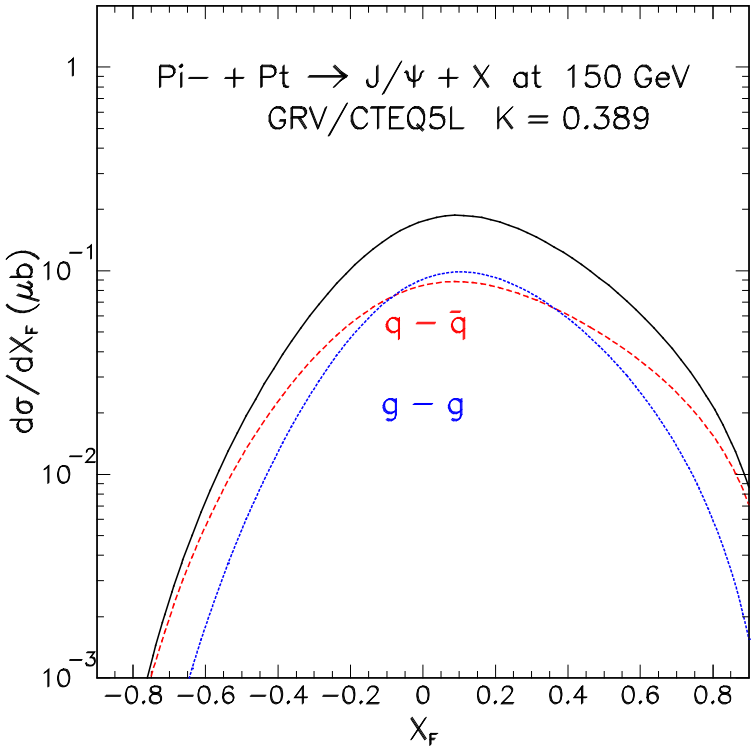
Ratios for J/Ψ



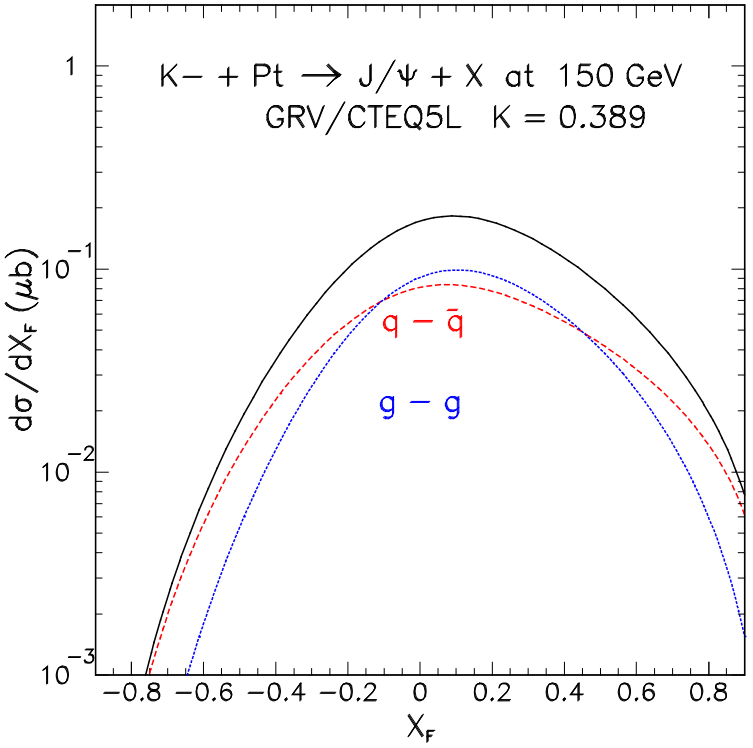
Similar behavior at large x_F for D-Y and J/Ψ production?

J/Ψ production in the Color Evaporation Model

$\pi^- + \mathrm{Pt} \rightarrow J/\Psi + x$

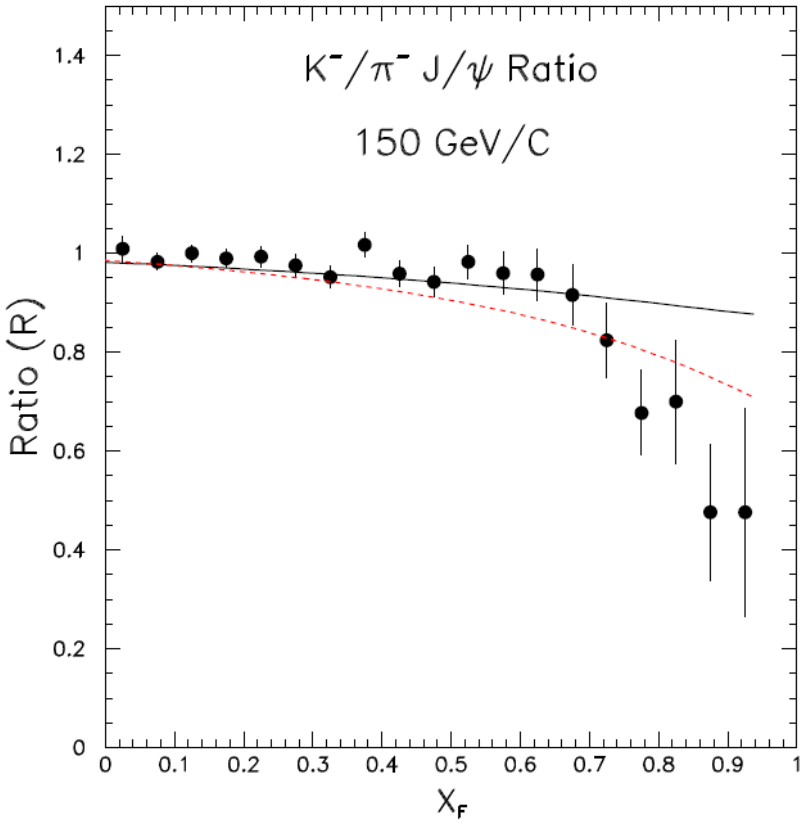


$K^- + \mathrm{Pt} \rightarrow J/\Psi + x$



$q - \bar{q}$ annihilation is important at large x_F

Comparison between color-evaporation model calculation and data



Black solid curve:

same PDF for π^- and K^- in LO

Red dashed curve:

Modified K^- pdf

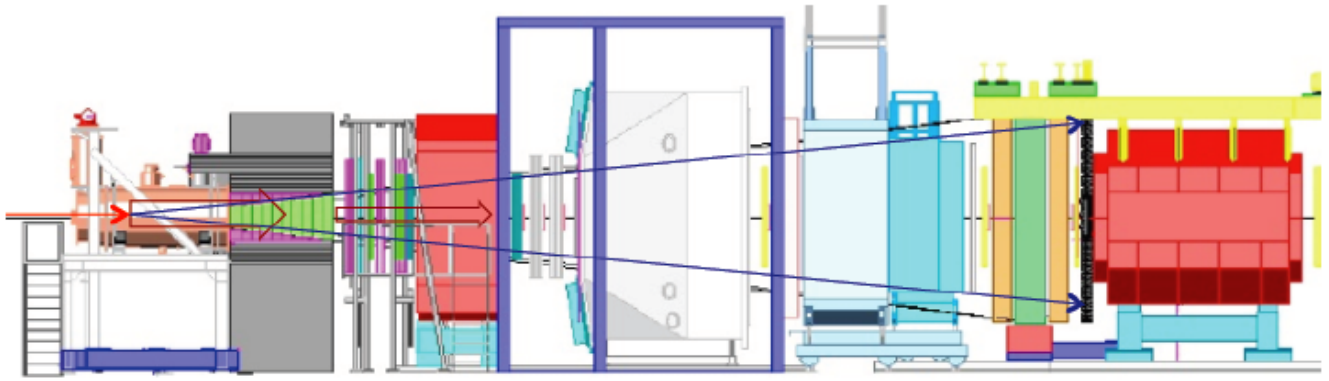
$$\bar{u}_K^V(x) = 1.061\,\bar{u}_\pi^V(x)(1-x)^{0.203}$$

$$s_K^V(x) = 0.937\,\bar{u}_\pi^V(x)(1-x)^{-0.203}$$

JCP, Chang, Platchkov, Sawada: 1711.00839

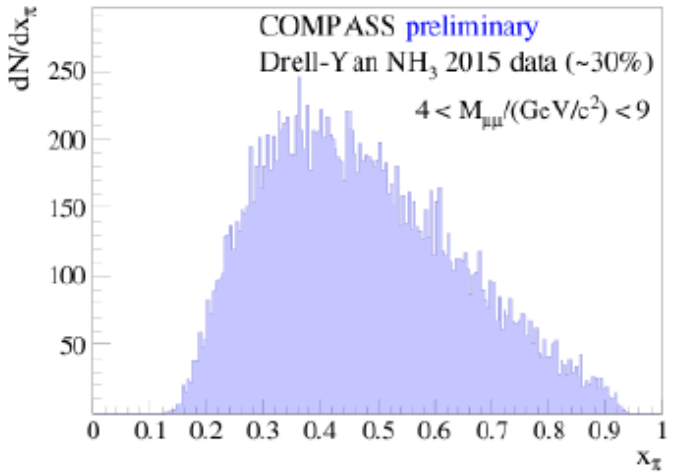
The J/Ψ data also suggest a softer u-valence in kaon than in pion

New $\pi^- + A$ Drell-Yan data collected at COMPASS

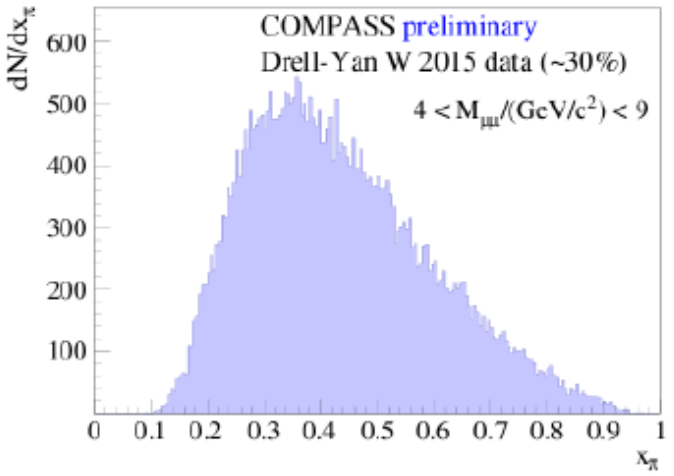


190 GeV π^- beam on NH_3 and W targets

covering the kinematic range $0.15 < x_\pi < 0.9$



~70,000 DY events from NH_3



~30,000 DY events from W target

Plan for new Drell-Yan measurments with π^+ and π^- beams at COMPASS

(using solid carbon and W targets)

Beam type (GeV)	Beam intensity (part/sec)	Target type	DY mass (GeV/c^2)	DY events
π^+ 190	1.7×10^7	100cm C	4.3 – 8.5	23000
			3.8 – 4.3	14000
			2.0 – 3.8	133000
π^- 190	6.8×10^7	100cm C	4.3 – 8.5	22000
			3.8 – 4.3	12000
			2.0 – 3.8	127000
π^+ 190	0.2×10^7	24cm W	4.3 – 8.5	7000
			3.8 – 4.3	4000
			2.0 – 3.8	40000
π^- 190	1.0×10^7	24cm W	4.3 – 8.5	6000
			3.8 – 4.3	3000
			2.0 – 3.8	39000

- This would represent a major increase for DY data with π^+ beam
- Intense kaon beams with RF-separator are also been actively considered

Exclusive dilepton production in πN interaction

$$\pi^- p \to \gamma^* n \to \mu^+ \mu^- n$$

E. Berger, M. Diehl, B. Pire, Phys. Lett. B523 (2001) 265

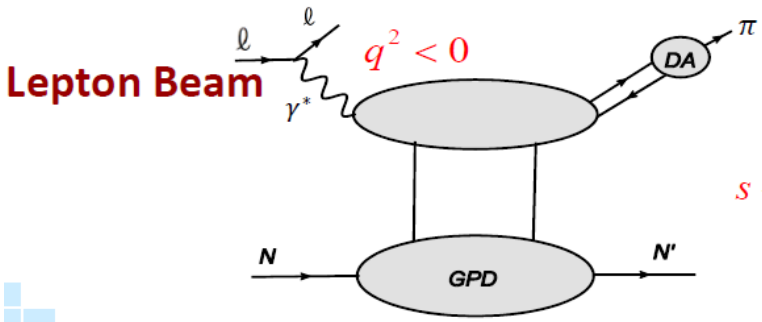
Probe pion distribution amplitude (ϕ_π) and nucleon GPD ($\tilde{H}, \tilde{E}$)

Extraction of **GPDs**

Space-like vs. **Time-like** Processes

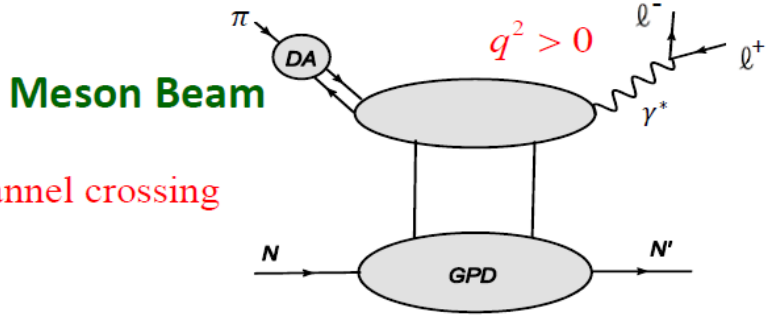
Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Meson Production (DVMP)



$s \leftrightarrow u$ channel crossing

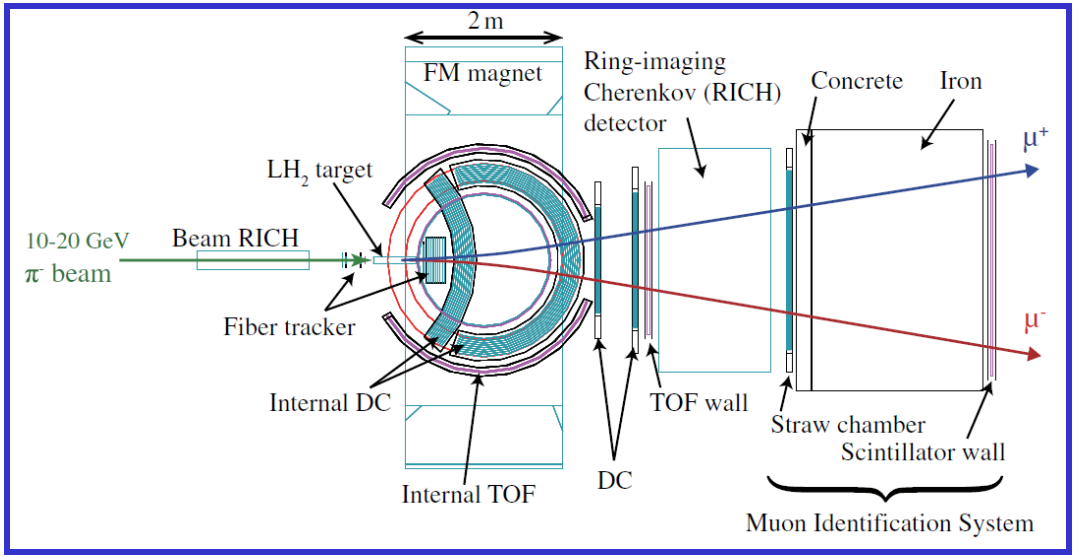
Exclusive meson-induced DY

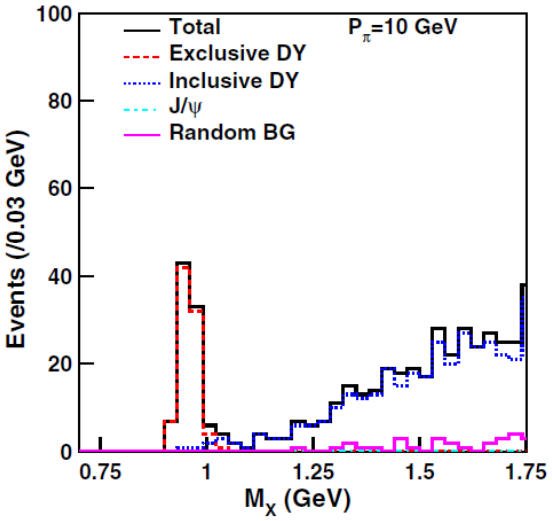


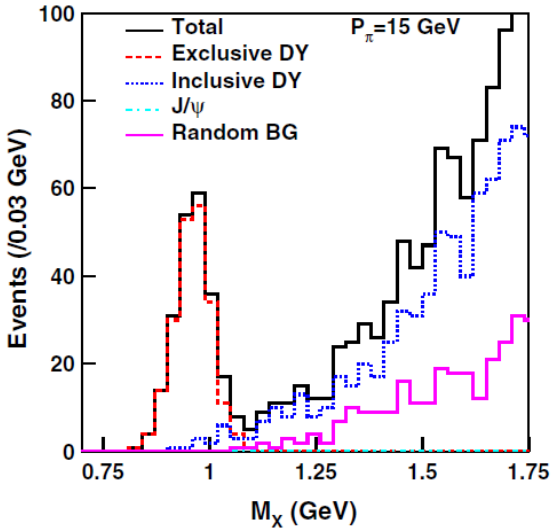
PHYSICAL REVIEW D **93,** 114034 (2016)

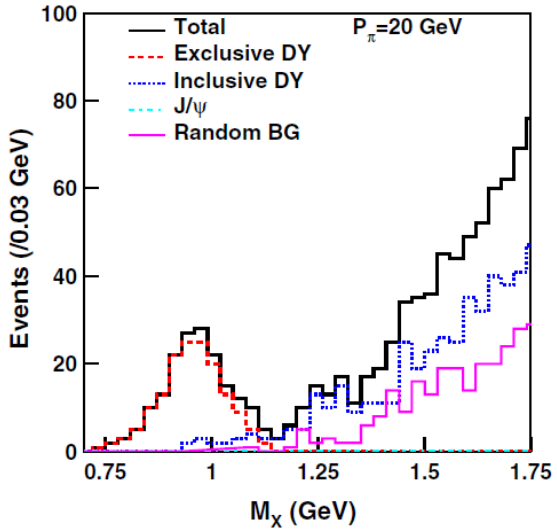
Accessing proton generalized parton distributions and pion distribution amplitudes with the exclusive pion-induced Drell-Yan process at J-PARC

T. Sawada, W. C. Chang, et al.









Summary

- Pion and Kaon parton distributions
  - New territory for theory and experiment
  - Unique opportunities at COMPASS, JLab, J-PARC, and EIC
- J/ψ production provides useful information on kaon quark and gluon contents
  - Existing data suggests different valence distribution in kaon and pion
  - Existing data suggests different gluon distribution in kaon and pion
- Exclusive DY and exculsive J/ψ production with meson beams to probe meson distribution amplitudes and nucleon GPD