Meson Structure with Dilepton Production

Jen-Chieh Peng

University of Illinois at Urbana-Champaign

ECT* Workshop “Dilepton Production with Meson and Antiproton Beams”
Trento, November 6-10, 2017

In collaboration with Wen-Chen Chang, Stephane Platchkov, and Takahiro Sawada

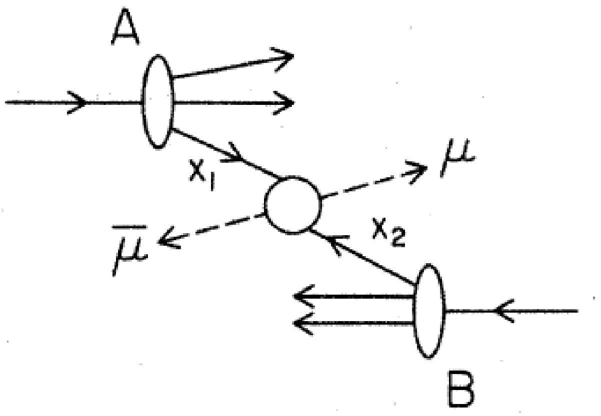
Outline

- Overview of dilepton production (Drell-Yan and J/Ψ) experiments with meson beams
- What have we learned from these experiments?
- What we would like to learn in the future from dilepton experiments
- Summary and outlook

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)



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

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

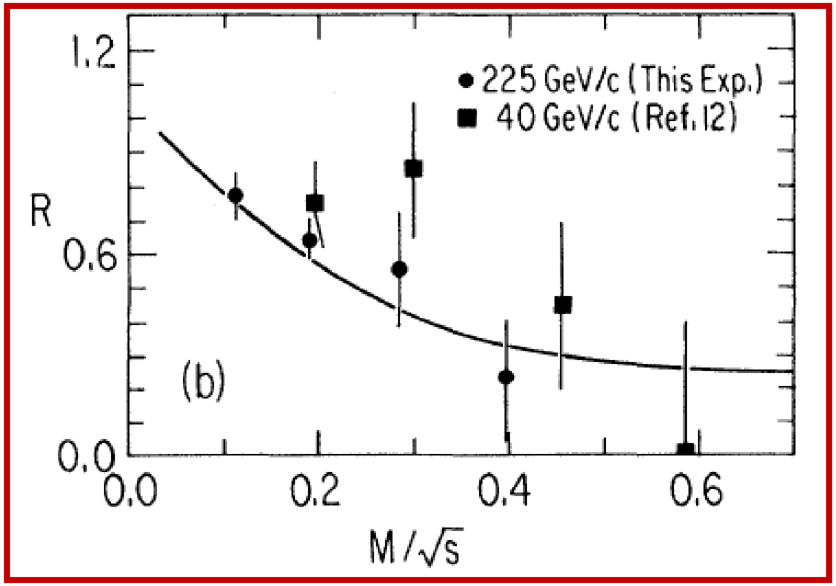
Drell-Yan experiments with K^+ beam

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

Ratios of $(\pi^+ + C)/(\pi^- + C)$ Drell-Yan cross sections



From E331/E444

Defining

$$V_\pi(x) = u^V_{\pi^+}(x) = \bar{d}^V_{\pi^+}(x) = d^V_{\pi^-}(x) = \bar{u}^V_{\pi^-}(x)$$

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

$$V_N(x) = [u_p(x) + d_p(x)]/2$$

$$S_N(x) = [\bar{u}_p(x) + \bar{d}_p(x)]/2$$

Considering only the u and d flavors

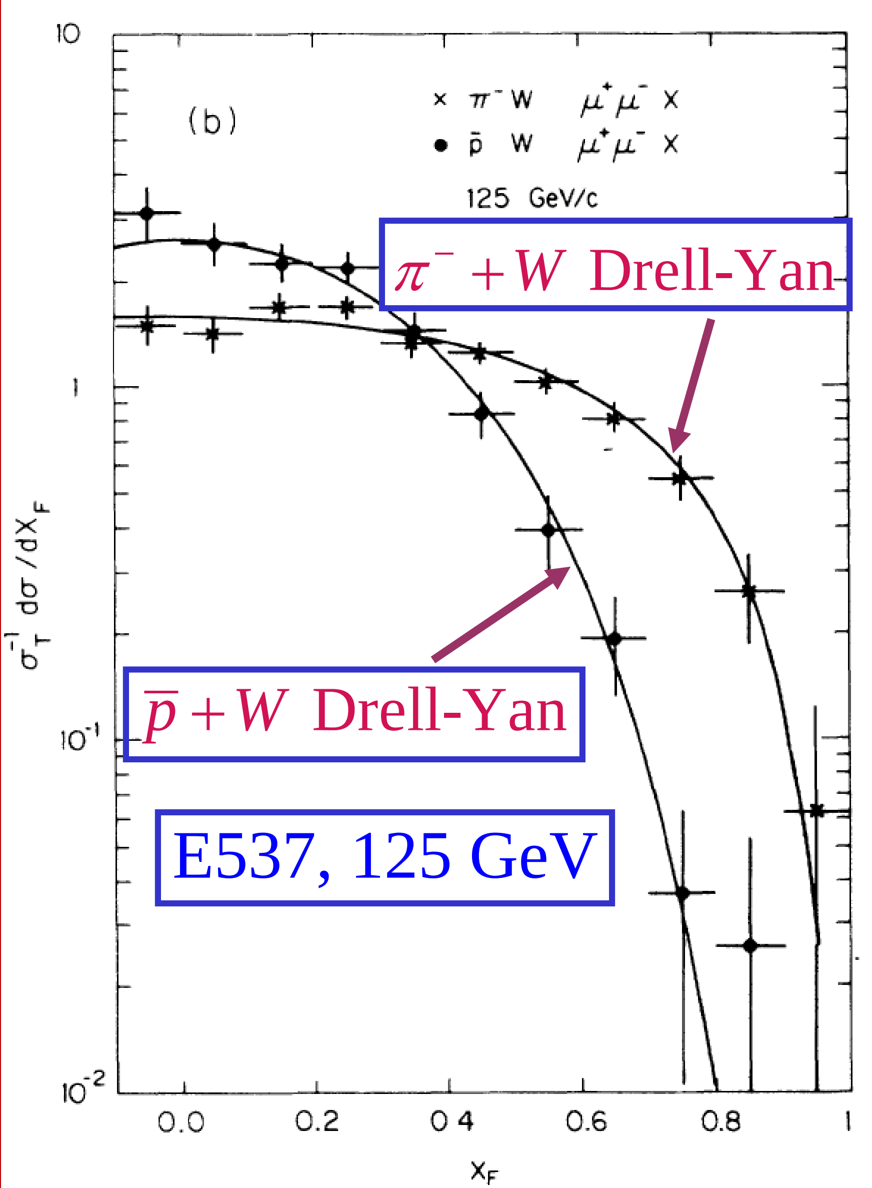
Black: Valence; Red: Sea

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

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

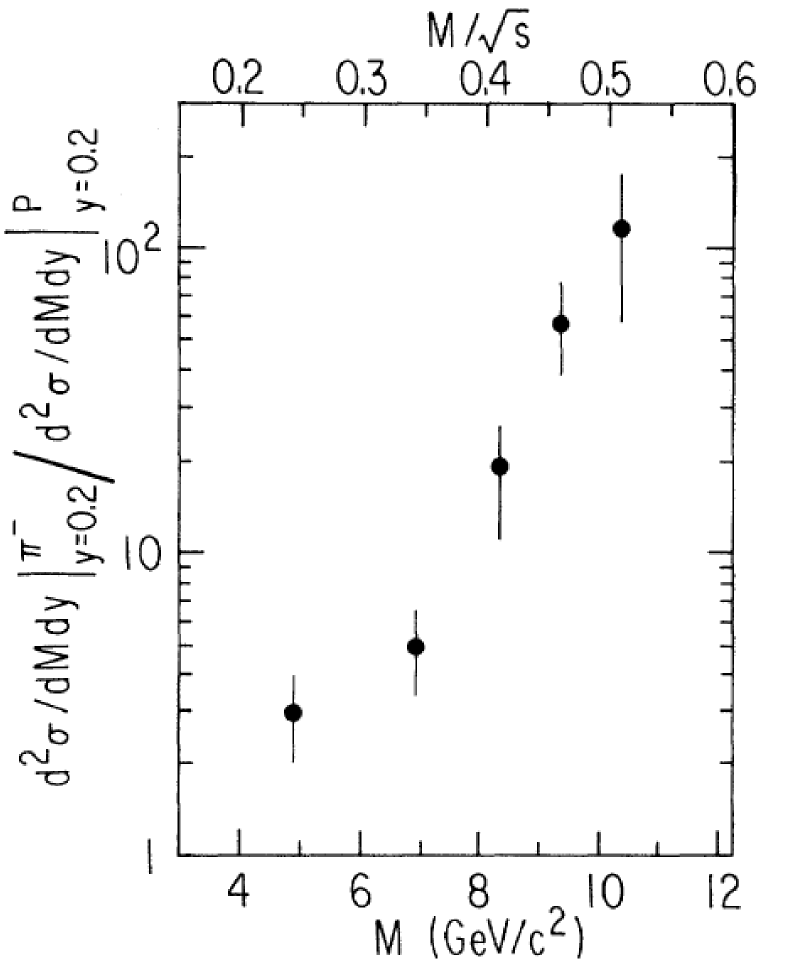
$$1/4 \le R \le 1$$

$(\pi^- + W)$ 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

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

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

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

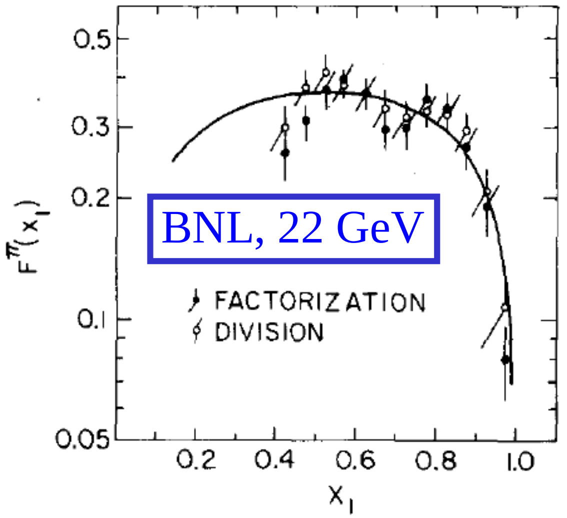
Only the valence-quark term remain!

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

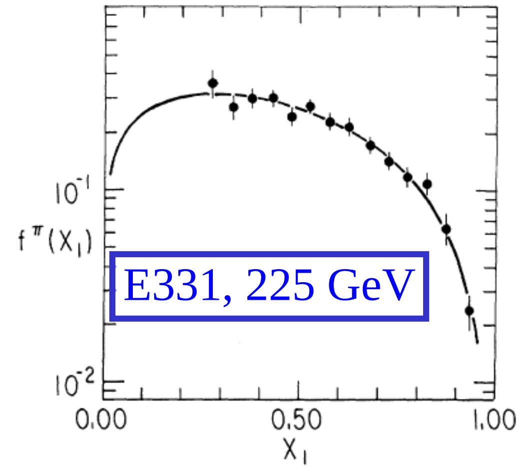
Hence only $\sigma_{DY}(\pi^- + A)$ data are utilized

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

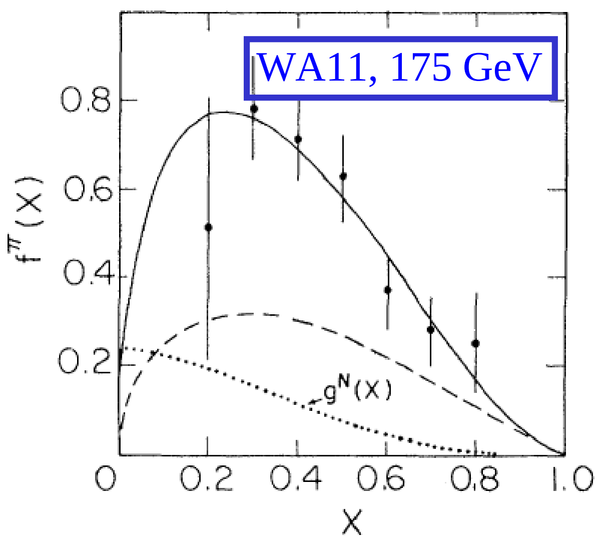
Attemps to extract the pion valence quark distribution



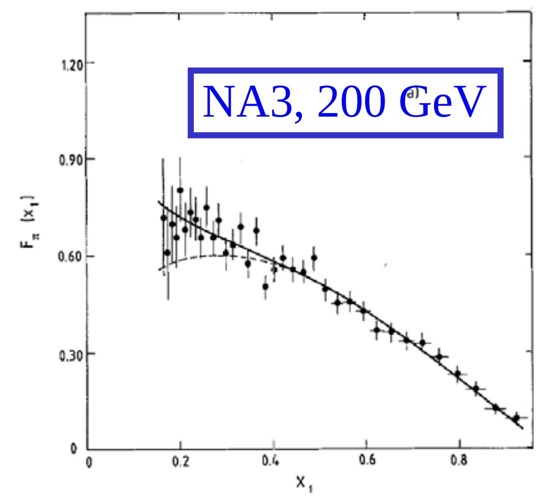
$$F^{\pi}(x) = 0.72x^{0.5}(1-x)^{0.46}$$



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

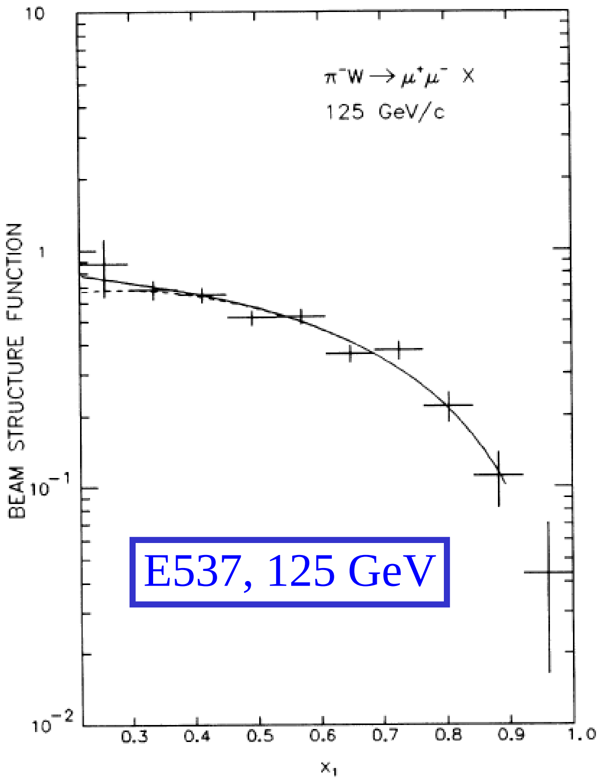


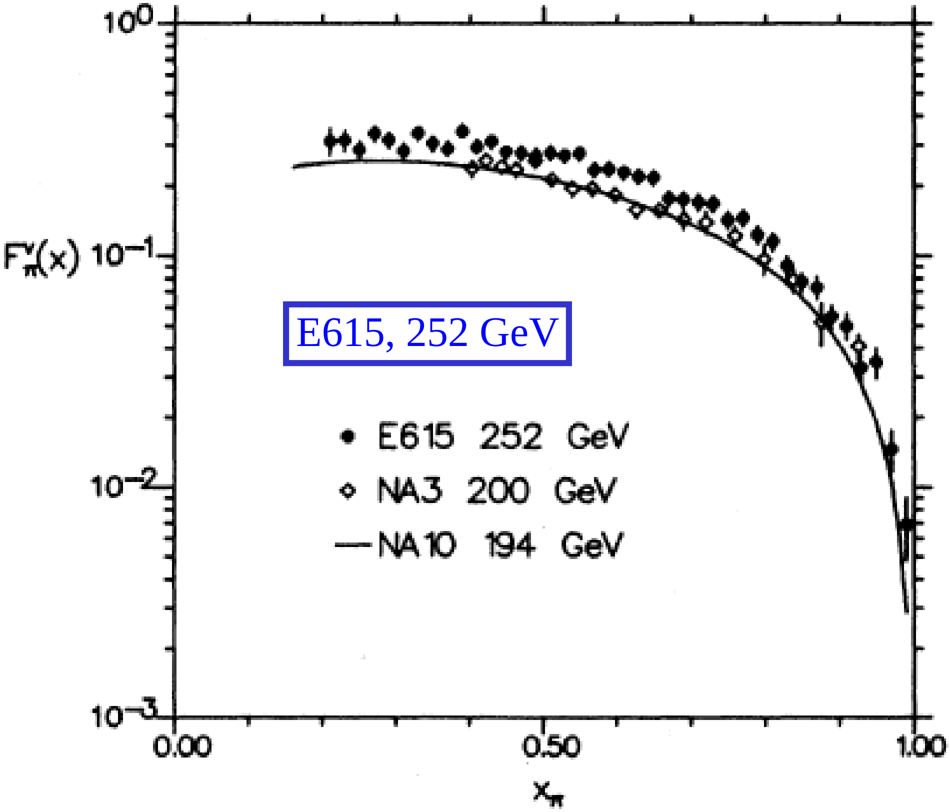
$$F^{\pi}(x) = 2.43x^{0.5}(1-x)^{1.57}$$



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

Attemps to extract the pion valence quark distribution





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

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

A global fit to all data is needed

How to determine the sea quark distribution in pion?

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

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

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

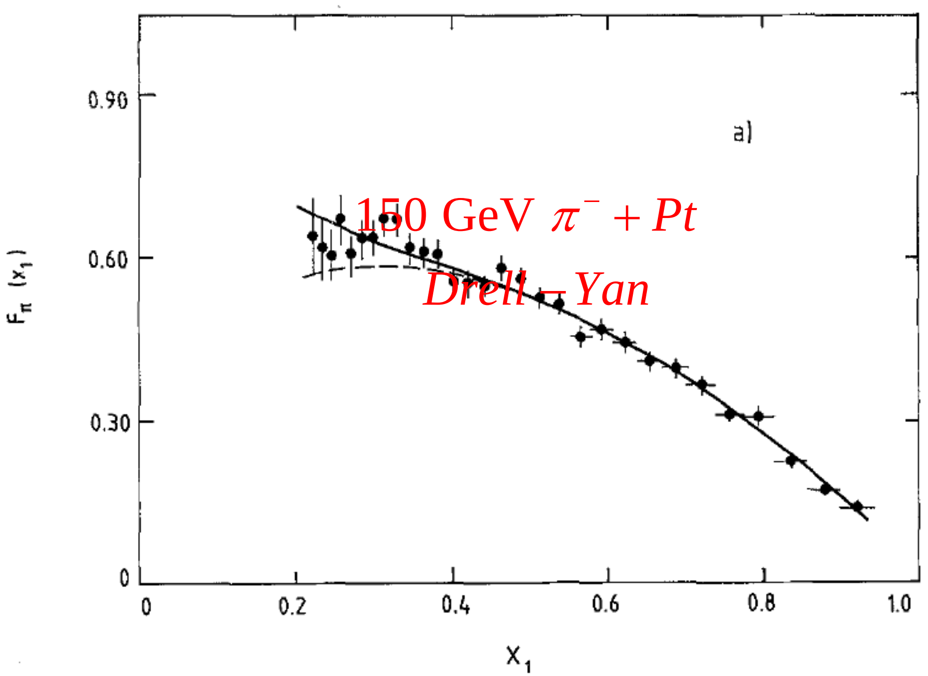
$$4\sigma_{DY}(\pi^+ + D) - \sigma_{DY}(\pi^- + D) \propto 15S_\pi(x_1)V_N(x_2) + 15V_\pi(x_1)S_N(x_2) + 30S_\pi(x_1)S_N(x_2)$$

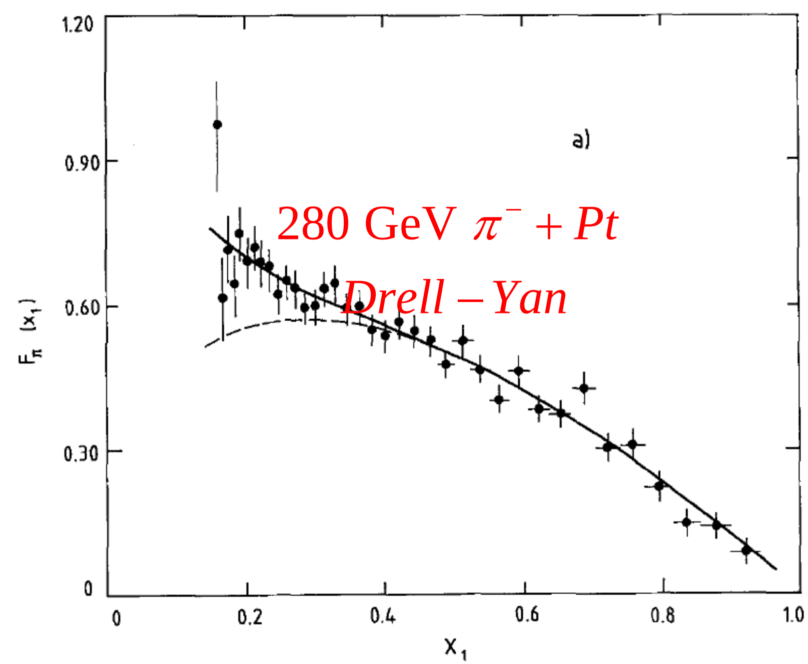
$S_\pi(x_1)$ can be extracted

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



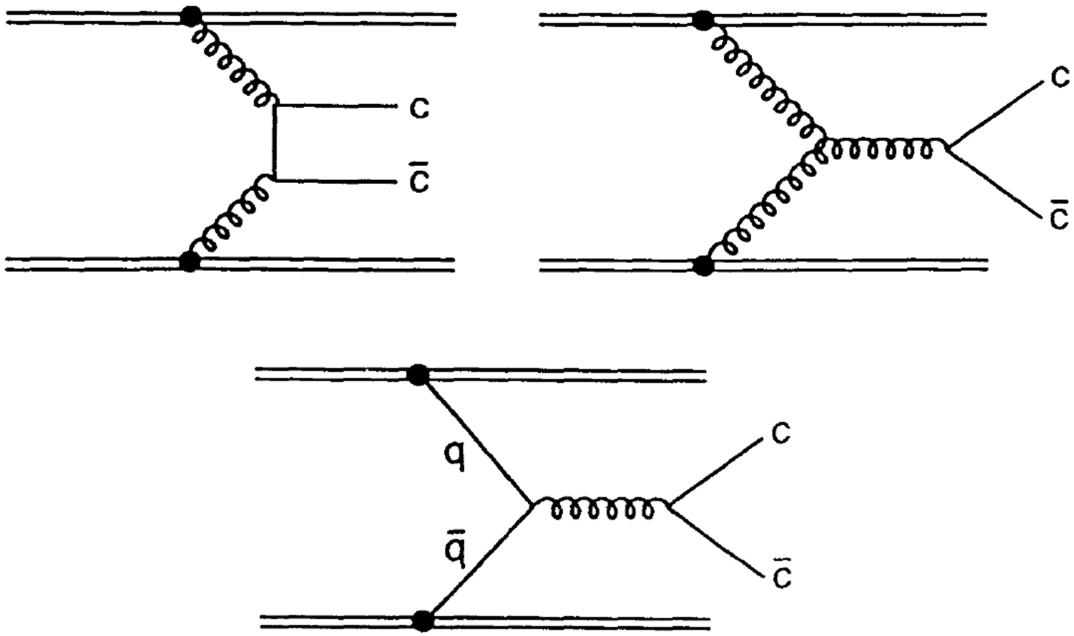


Dashed curve: without the pion sea contribution

Solid curve: including the pion sea contribution

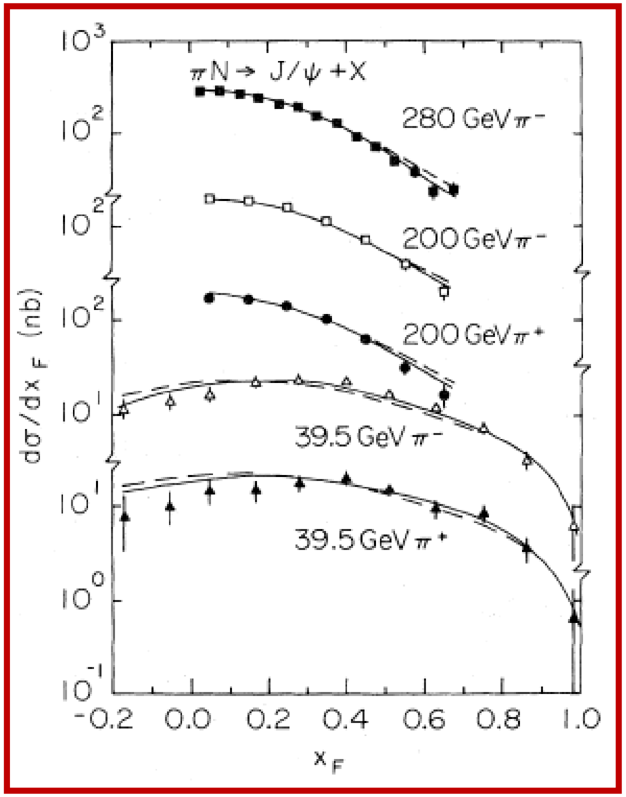
How to determine the gluon distribution in pion?

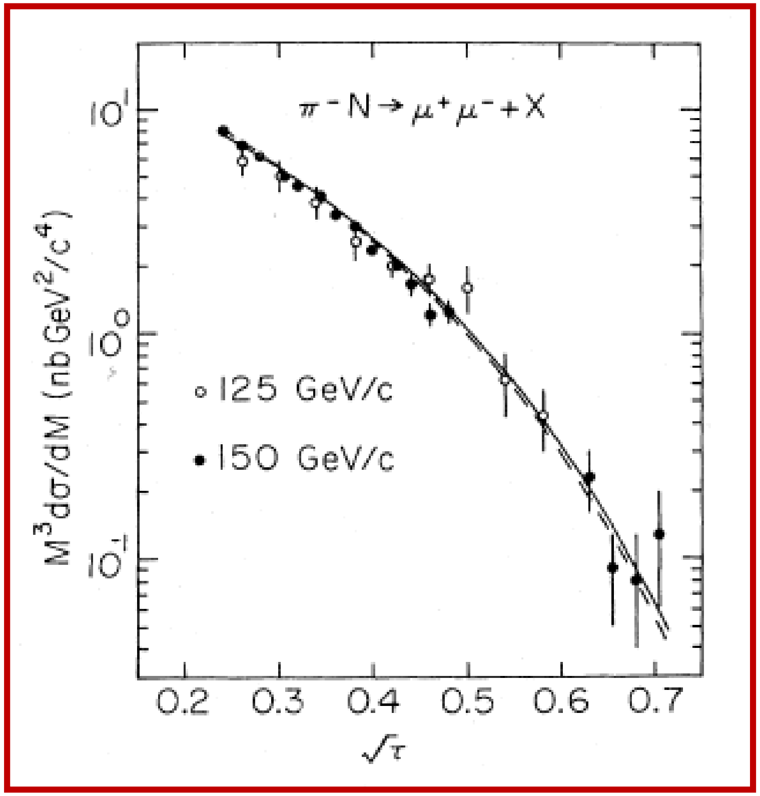
- J/Ψ production with pion beam
- Direct photon production with pion beam
- Charm production with pion beam



Four pion PDF sets available at LHAPDF library

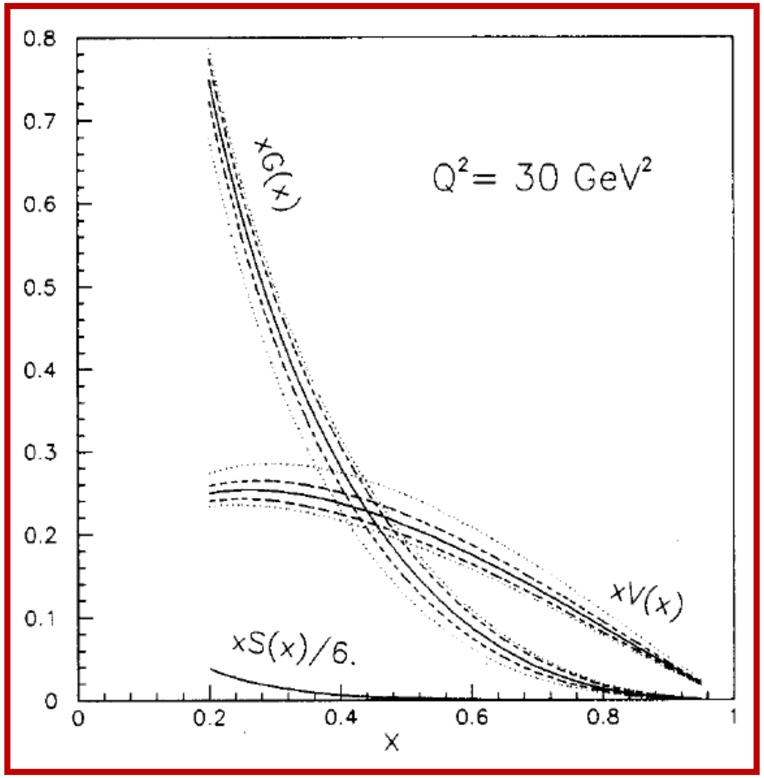
- OW-P (PRD 30, 943 (1984))
  - LO QCD
  - J/Ψ data from NA3 and WA39; D-Y data from E537 and NA3





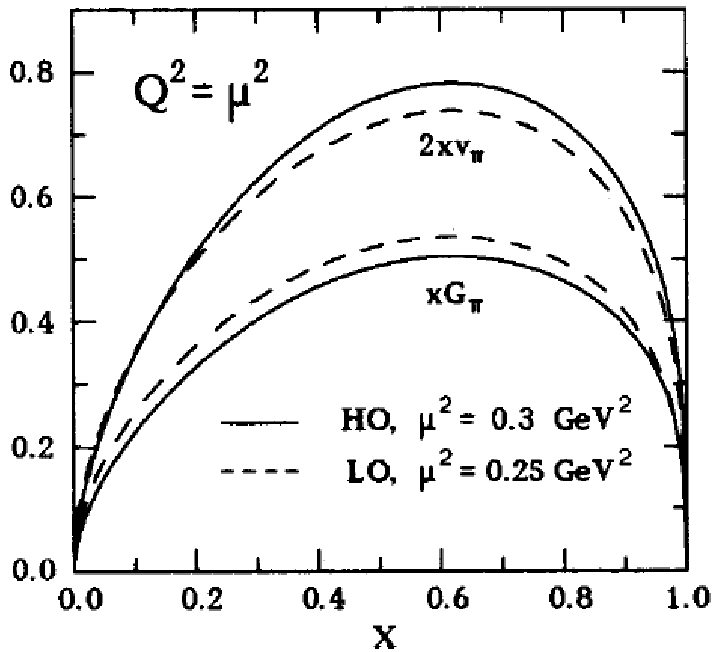
Four pion PDF sets available at LHAPDF library

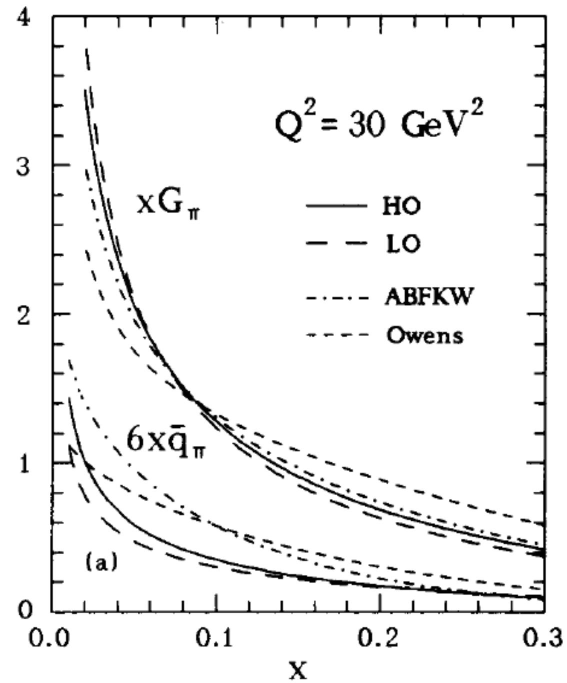
- ABFKW-P (PL 233, 517 (1989))
  - NLO QCD
  - Direct photon data from WA70 and NA24; Sea-quark distribution from NA3



Four pion PDF sets available at LHAPDF library

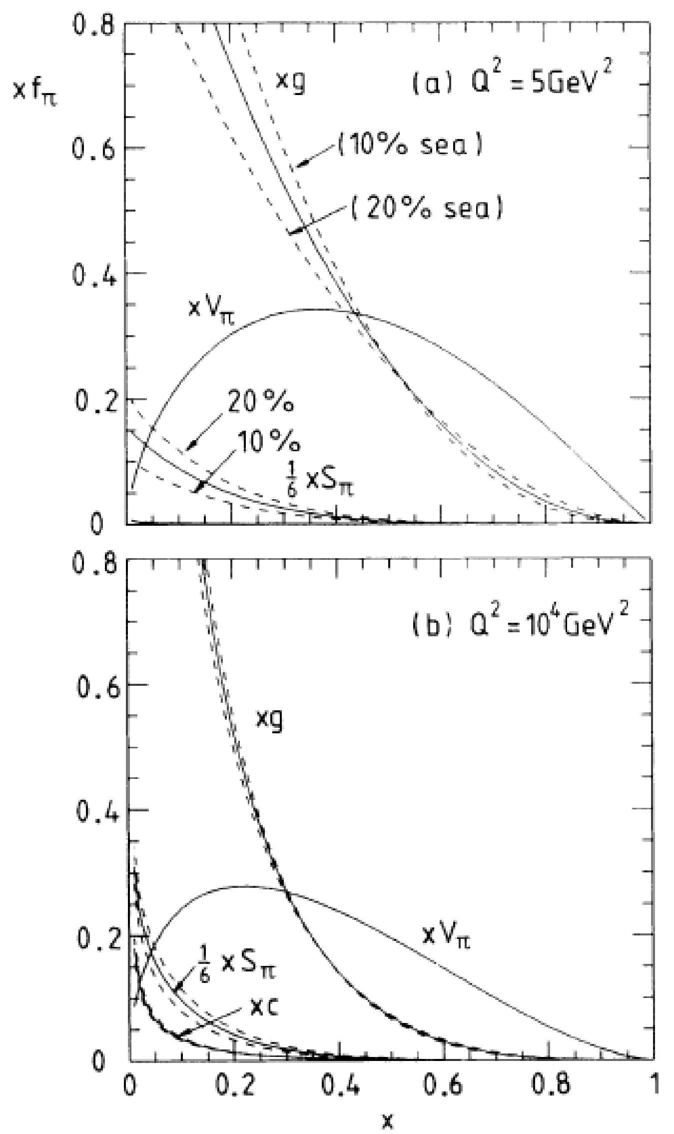
- GRV-P (Z. Phys. C53, 651 (1992))
  - LO and NLO QCD
  - Only valence and valence-like gluon at initial scale. Sea is entirely from QCD evolution





Four pion PDF sets available at LHAPDF library

- 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

How to determine the valence quark distribution in kaon?

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

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

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

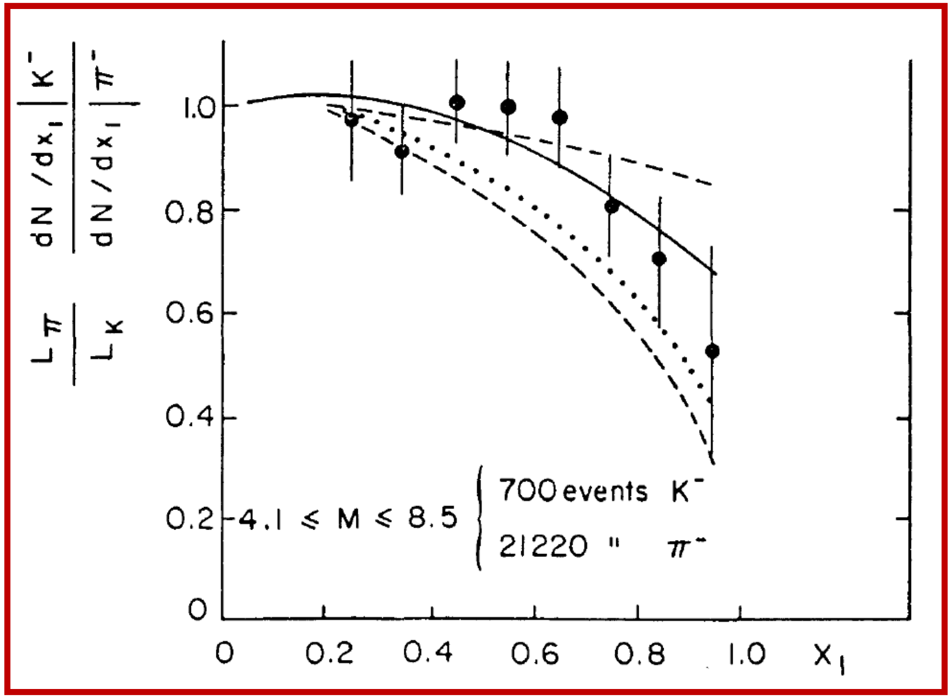
$$\sigma_{DY}(K^- + D) - \sigma_{DY}(K^+ + D) \propto 4V_K^u(x_1)V_N(x_2)$$

Only the valence-quark term remain!

$\sigma_{DY}(K^+ + D)$ is more sensitive to kaon's sea-quark content than $\sigma_{DY}(K^- + D)$ (especially data at low x_1 and large x_2 (negative x_F) region!)

See Londergan al., PL B380 (1996) 393

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



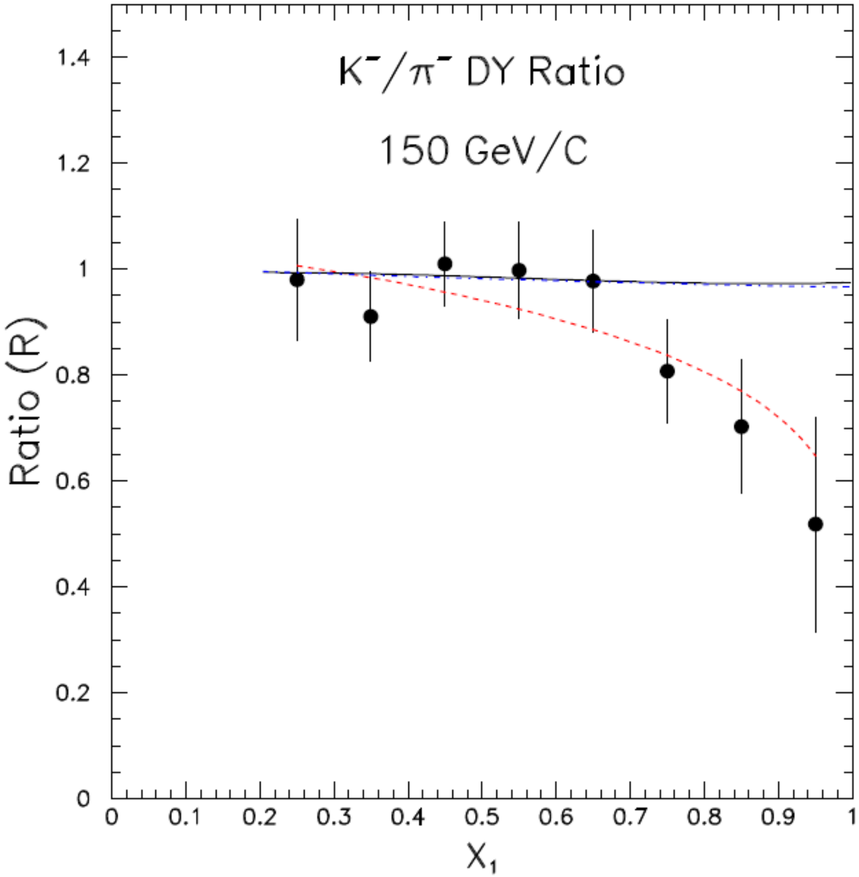
From NA3; 150 GeV, Pt target

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

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

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

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



Black solid curve:

same PDF for π^- and K^- in LO

Blue dot-dashed curve:

same PDF for π^- and K^- in NLO

Red dashed curve:

Modified K^- pdf

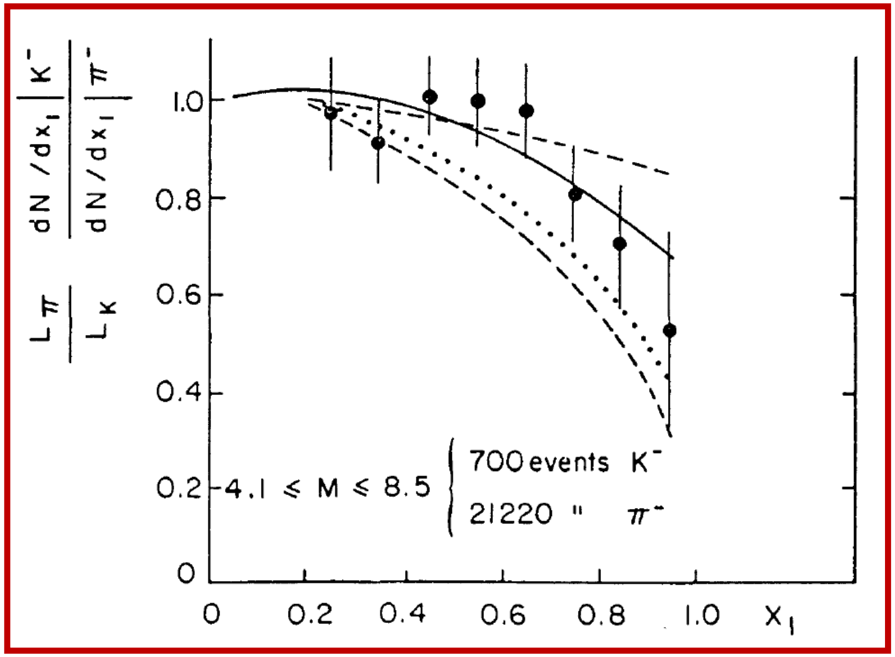
$$\bar{u}_K^V(x) = 1.061\bar{u}_\pi^V(x)(1-x)^{0.203}$$

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

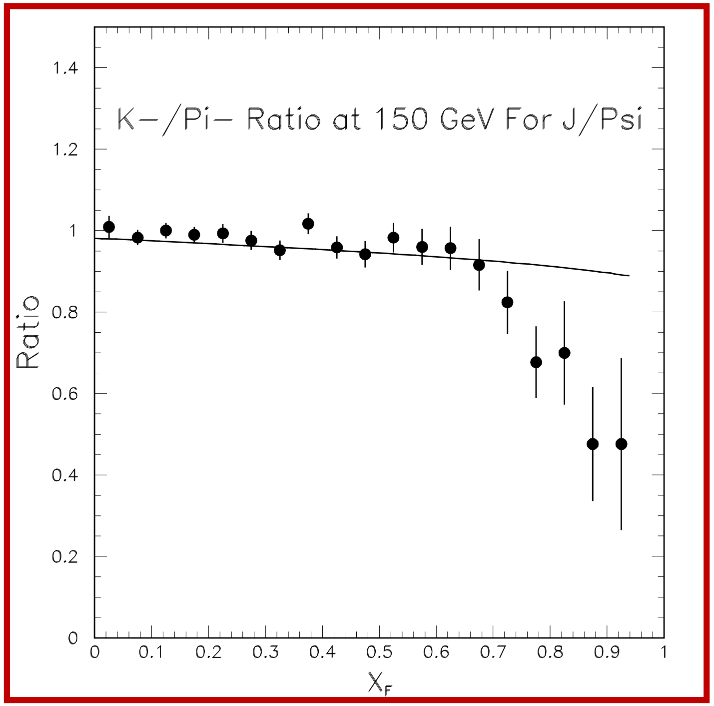
$(K^- + \mathrm{Pt}) / (\pi^- + \mathrm{Pt})$ ratios for J/Ψ production

From NA3; 150 GeV, Pt target

Ratios for D-Y

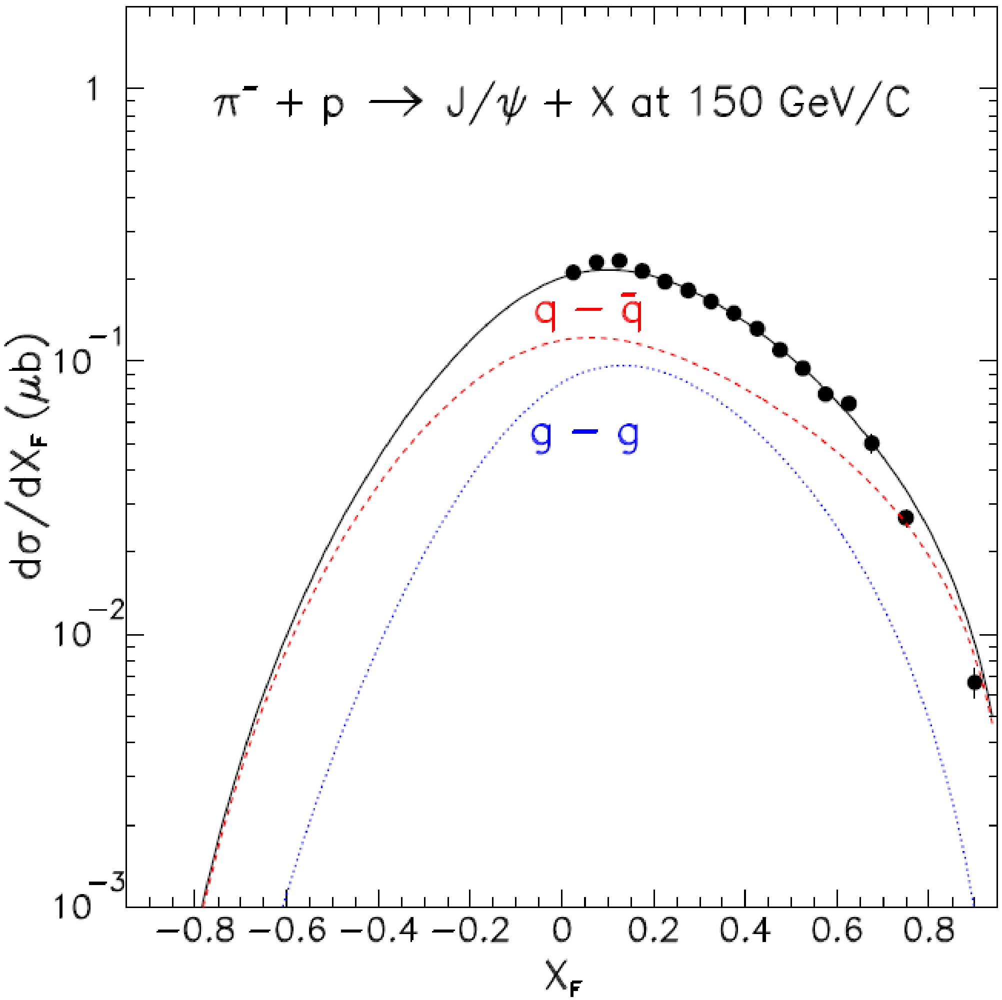


Ratios for J/Ψ



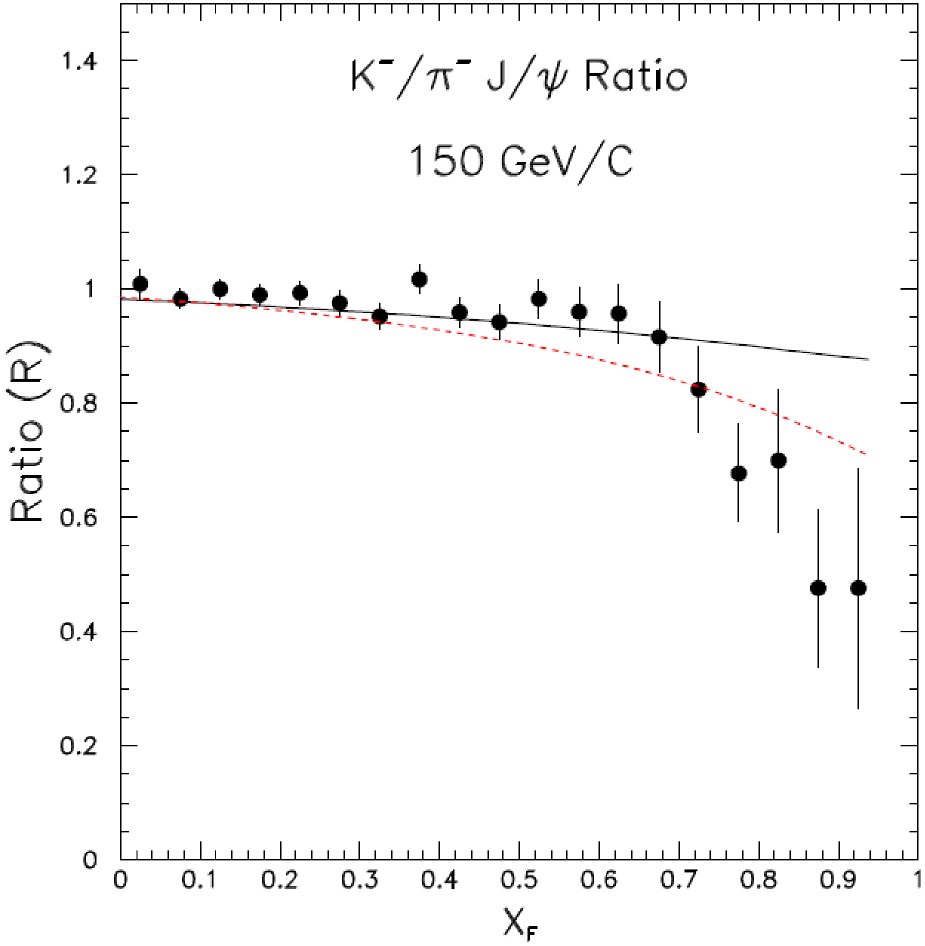
Similar behavior at large x_F for D-Y and J/Ψ production?

Comparison between color-evaporation model calculation and data



The $q\bar{q}$ annihilation is more importance than gg fusion

Comparison between color-evaporation model calculation and data



Black solid curve:

same PDF for π^- and K^- in LO

Red dashed curve:

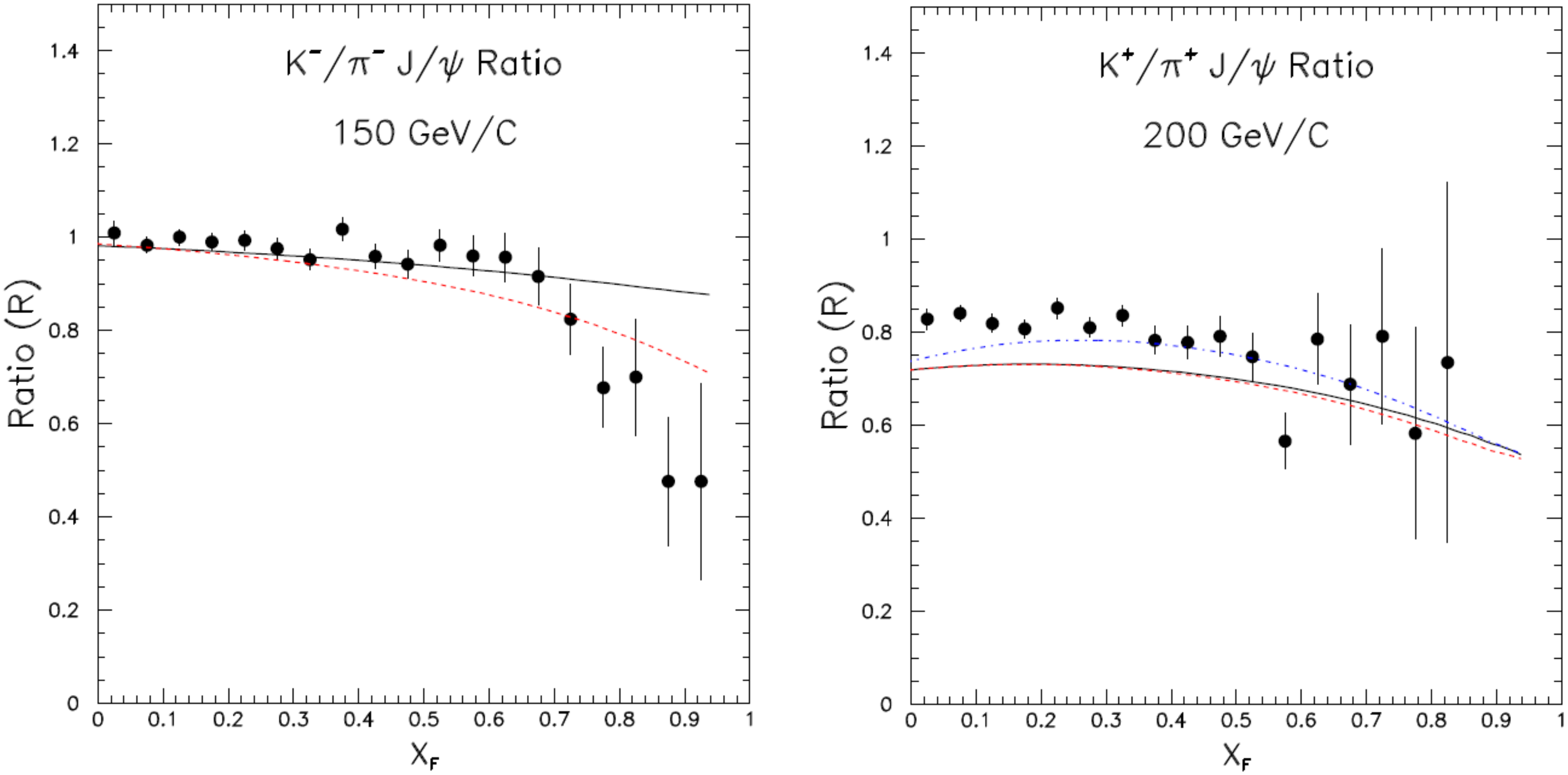
Modified K^- pdf

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

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

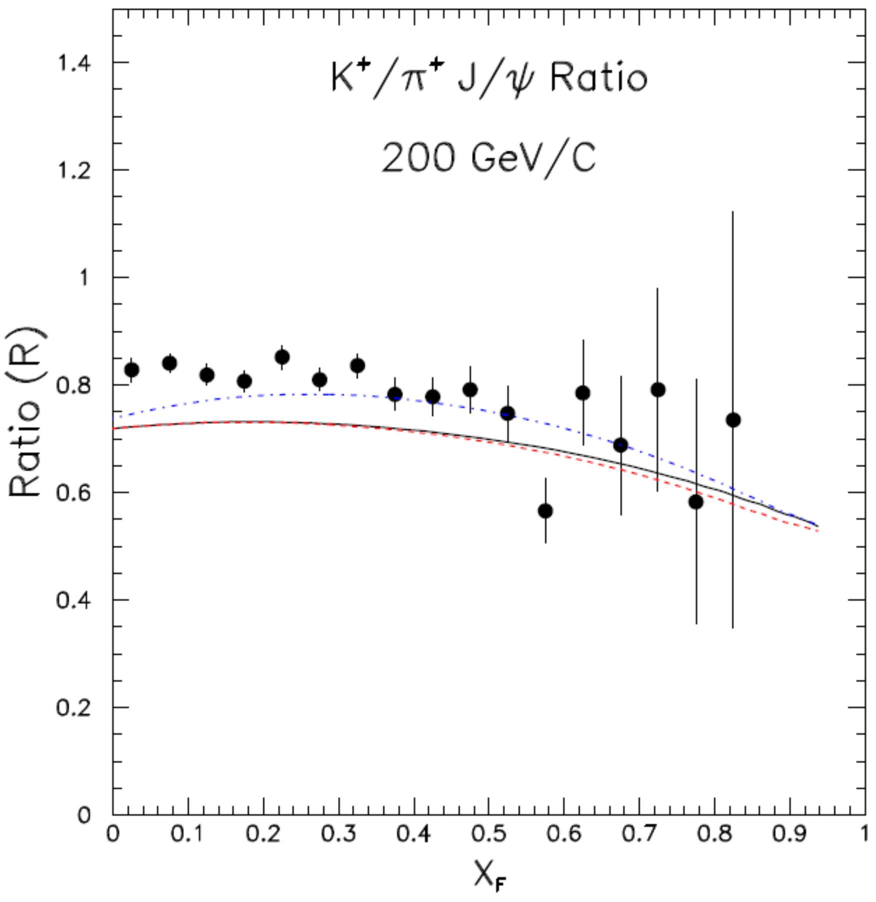
See JCP, Chang, Platchkov, Sawada arXiv:1711.00839

Comparison between K^- / π^- and K^+ / π^+ J / ψ production ratios



Why are ratios at large x_F so different between K^-/π^- and K^+/π^+?

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

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

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

Blue dot-dashed curve:

increase gluon content in K^- by 10%

See JCP, Chang, Platchkov, Sawada arXiv:1711.00839

Difference between $(\pi^- + p)$ and $(\pi^+ + p)$ Drell-Yan cross sections

Define

$$V_\pi(x) = u^V_{\pi^+}(x) = \bar{d}^V_{\pi^+}(x) = d^V_{\pi^-}(x) = \bar{u}^V_{\pi^-}(x)$$

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

$$\sigma_{DY}(\pi^- + p) \propto V_\pi(x_1)[4u(x_2) + \bar{d}(x_2)] + S_\pi(x_1)[4u(x_2) + d(x_2) + 4\bar{u}(x_2) + \bar{d}(x_2)]$$

$$\sigma_{DY}(\pi^+ + p) \propto V_\pi(x_1)[d(x_2) + 4\bar{u}(x_2)] + S_\pi(x_1)[4u(x_2) + d(x_2) + 4\bar{u}(x_2) + \bar{d}(x_2)]$$

$$\sigma_{DY}(\pi^- + p) - \sigma_{DY}(\pi^+ + p) \propto V_\pi(x_1)[4u_V(x_2) - d_V(x_2)]$$

Only the valence-quark term remains!

However, $4u_V(x_2) >> d_V(x_2)$, difficult to measure $u_V(x_2) - d_V(x_2)$

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

Define

$$V_\pi(x) = u^V_{\pi^+}(x) = \bar{d}^V_{\pi^+}(x) = d^V_{\pi^-}(x) = \bar{u}^V_{\pi^-}(x)$$

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

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

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

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

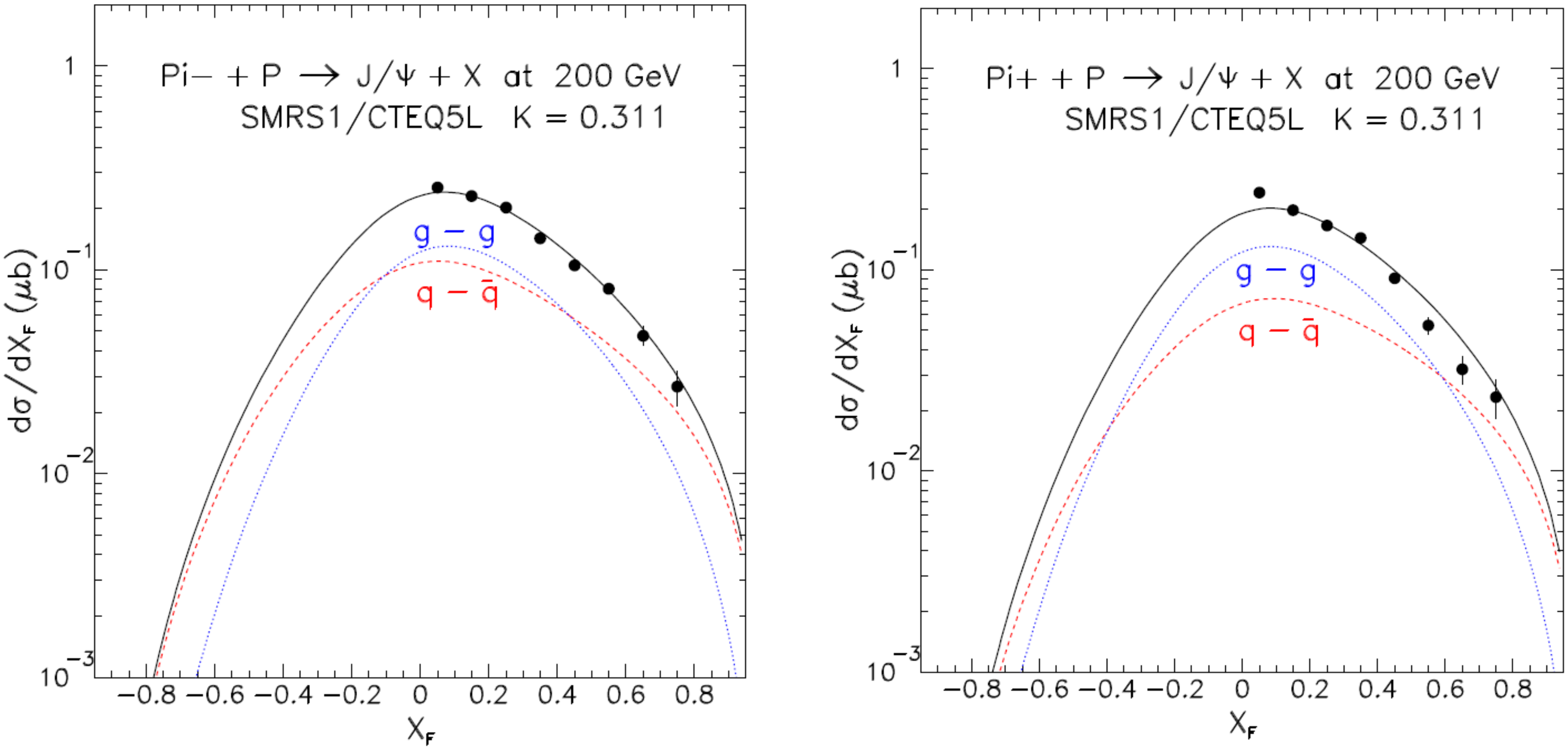
Only the valence-quark term remains!

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

Easier to measure $u_V(x_2) - d_V(x_2)$ than Drell-Yan!

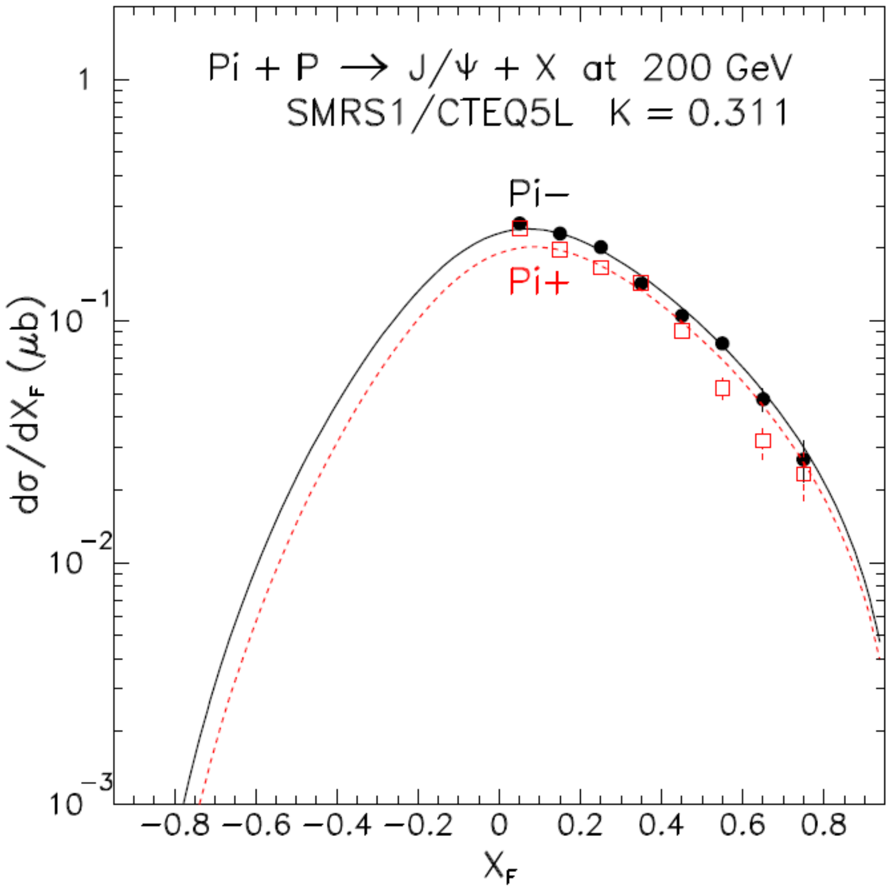
Are there relevant data from NA3 already?

Data extracted from the NA3 paper and the Ph.D thesis of Charpentier



g-g fusion is the same for both, but q-qbar annihilation is larger for pi- beam

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 $u_V(x_2) - d_V(x_2)$

Summary

- Meson and Kaon parton distributions
  - * New territory for theory and experiment
  - * Unique opportunity at COMPASS
  - * Complementary to JLab/EIC tagged DIS programs
- J/ψ 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
  - * Further studies on the production models are needed