Parton distribution functions of the pion and the kaon: What do we know and what more we can learn with modern facilities

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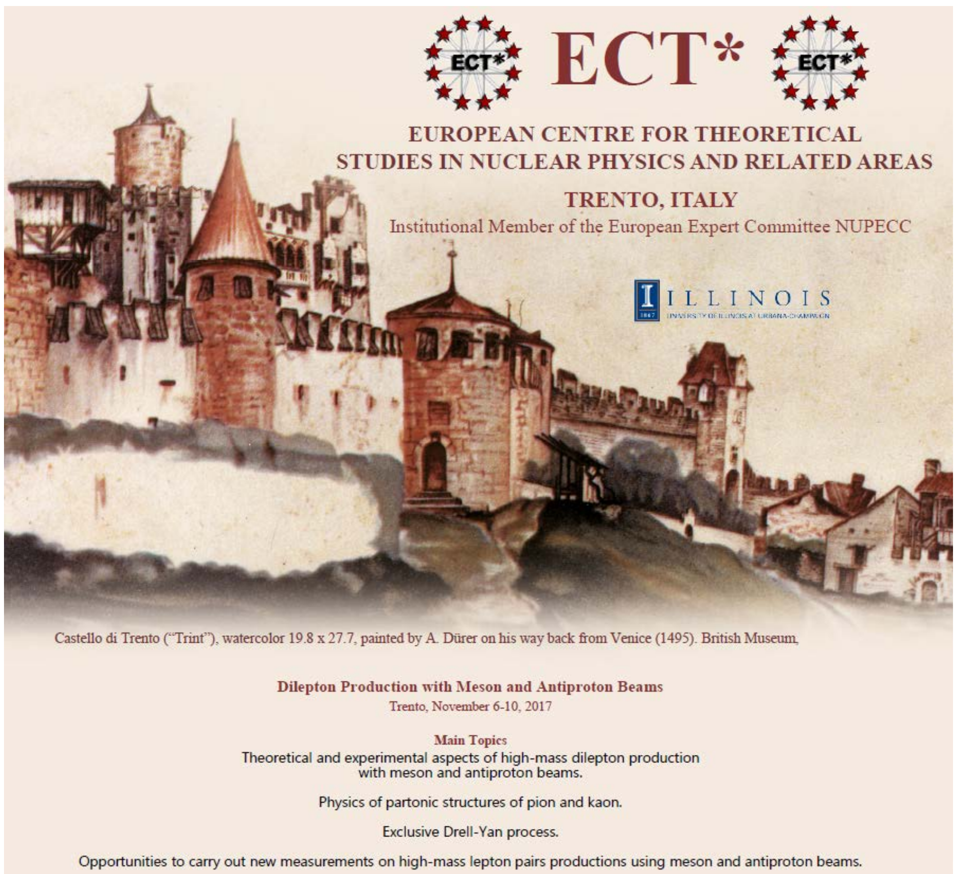
Based on talks presented at the recent ECT* Workshop

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

Wen-Chen Chang, Stephane Platchkov, Oleg Teryaev and Jen-Chieh Peng



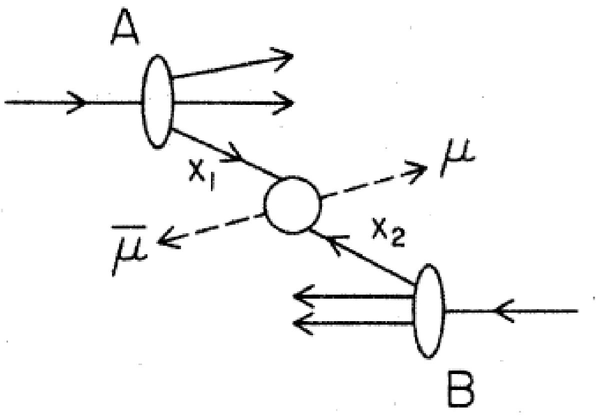
Outline

- Overview of experiments probing the meson parton distributions (Drell-Yan, J/Ψ production) with meson beams
- What have we learned from these experiments?
- What we would like to learn in the future

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)



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

Our remarks apply equally to any colliding pair such as (pp), $(\bar{p}p)$, (πp), $(\gamma\rho)$ 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

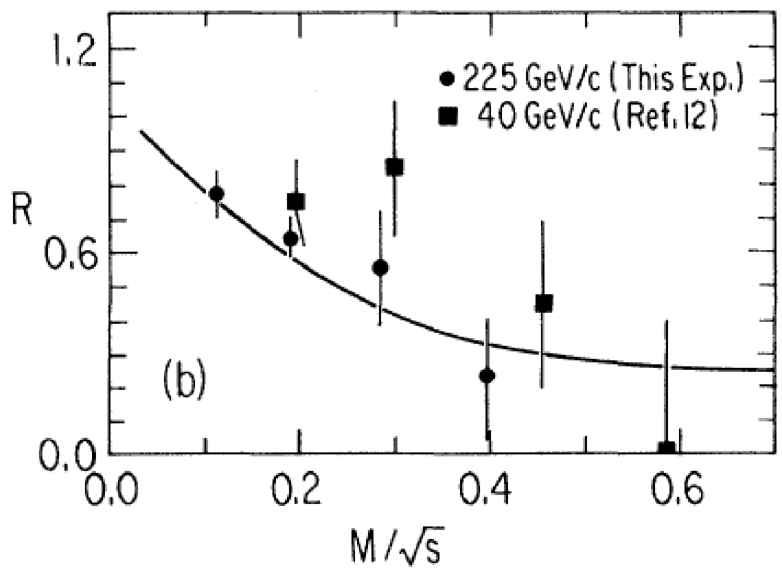
Drell-Yan experiments with K^+ beam

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

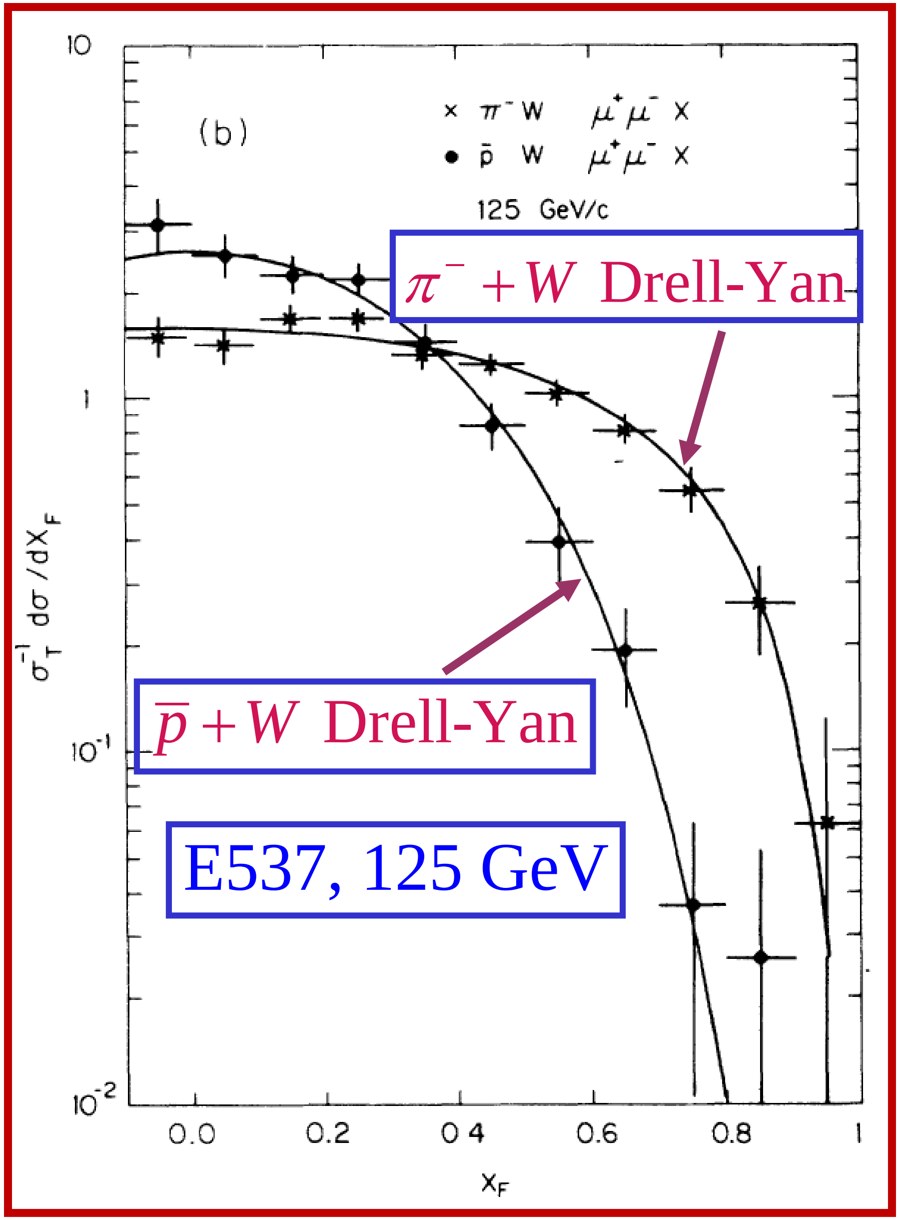
Black: Valence; Red: Sea

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

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

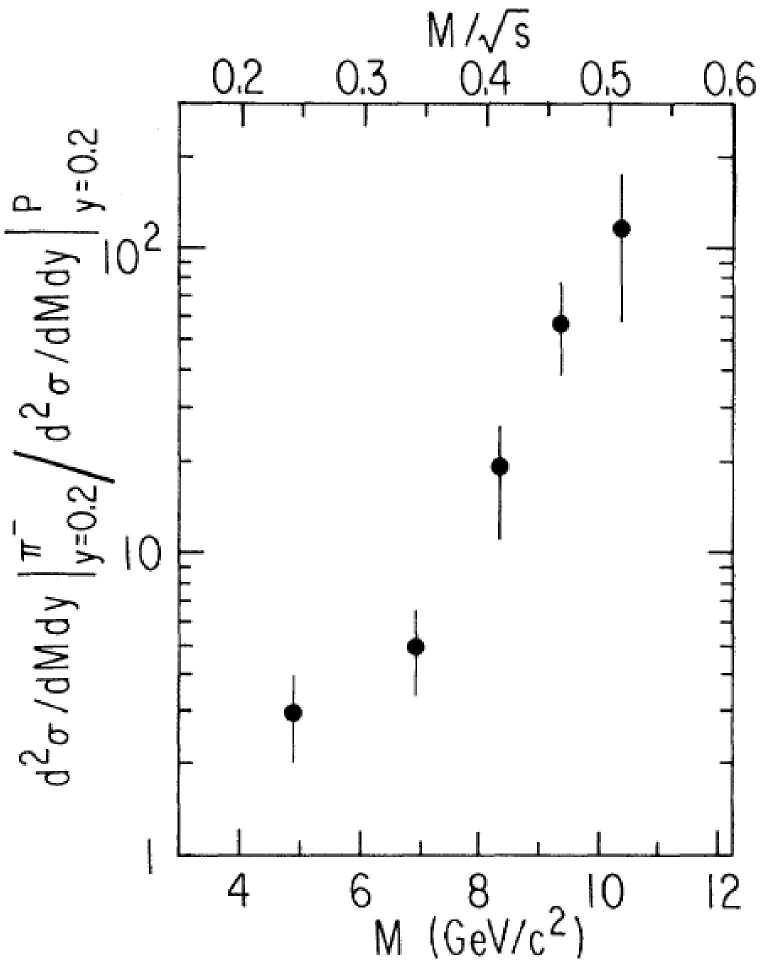
$$1/4 \le R \le 1$$

$(\pi^- + W)$ 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

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

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

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

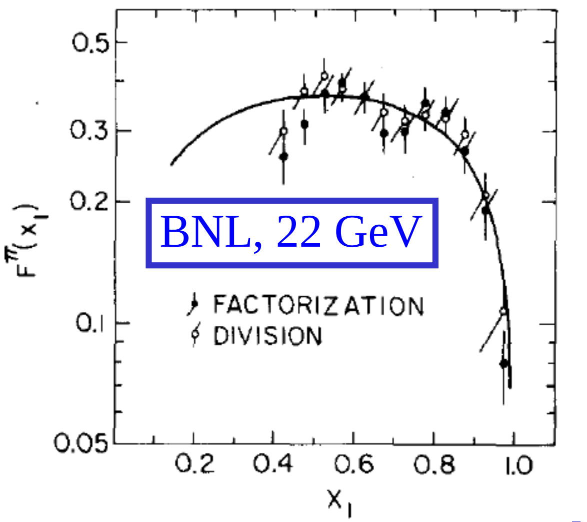
Only the valence-quark term remain!

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

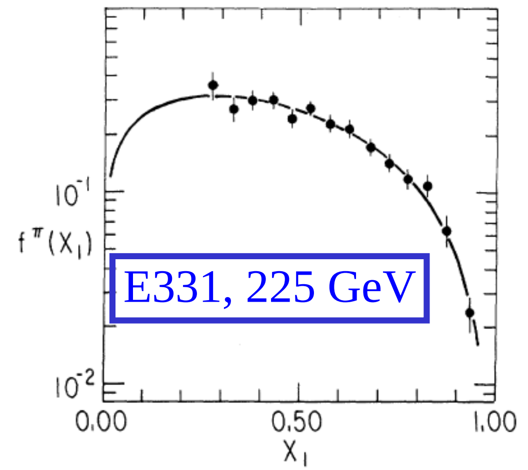
Hence only $\sigma_{DY}(\pi^- + A)$ data are utilized

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

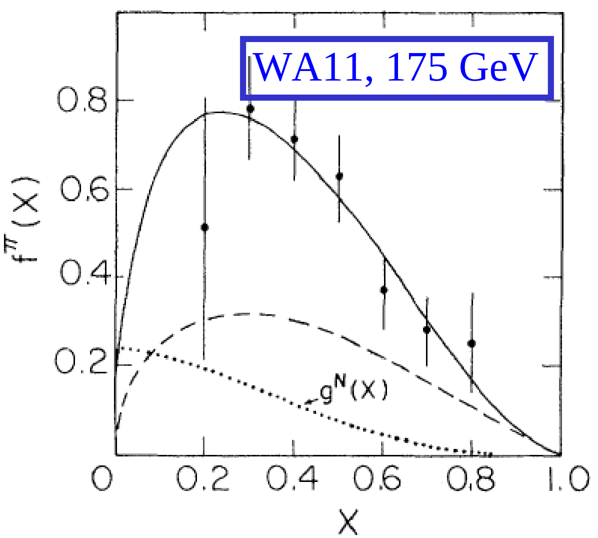
Attemps to extract the pion valence quark distribution



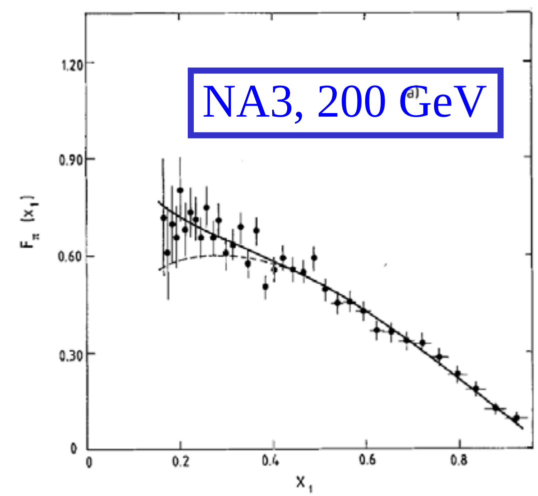
$$F^{\pi}(x) = 0.72x^{0.5}(1-x)^{0.46}$$



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

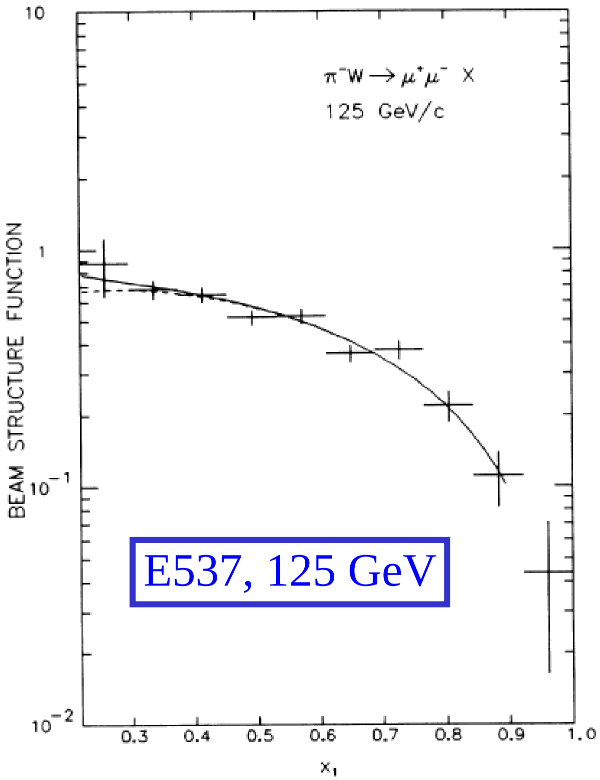


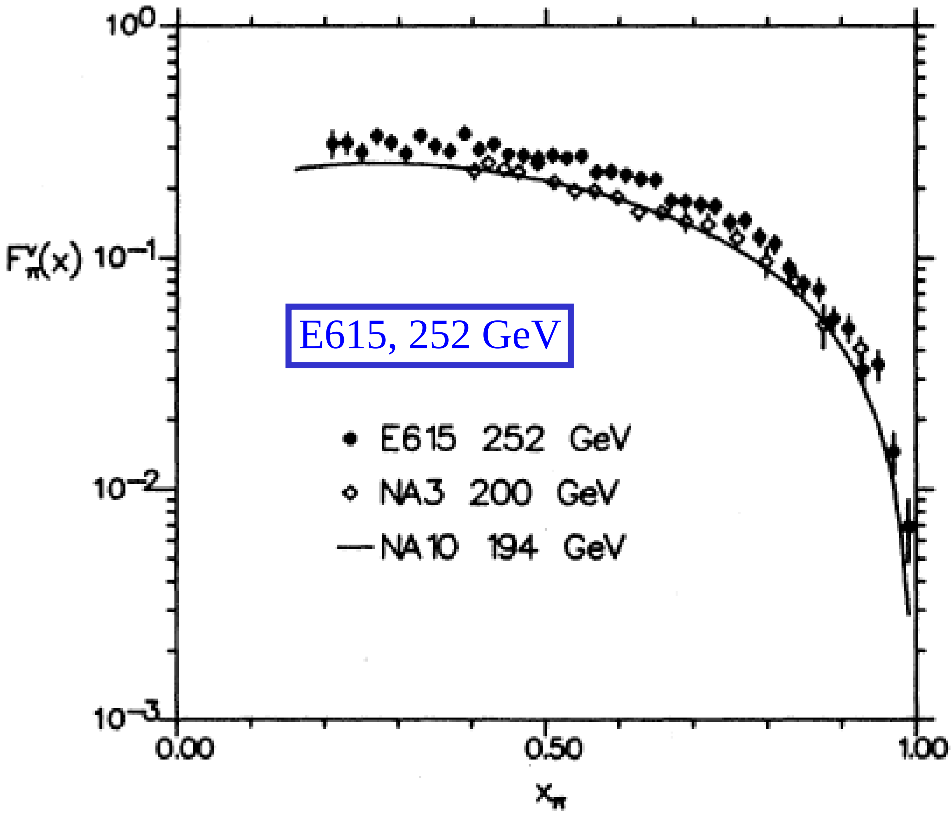
$$F^{\pi}(x) = 2.43x^{0.5}(1-x)^{1.57}$$



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

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

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

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

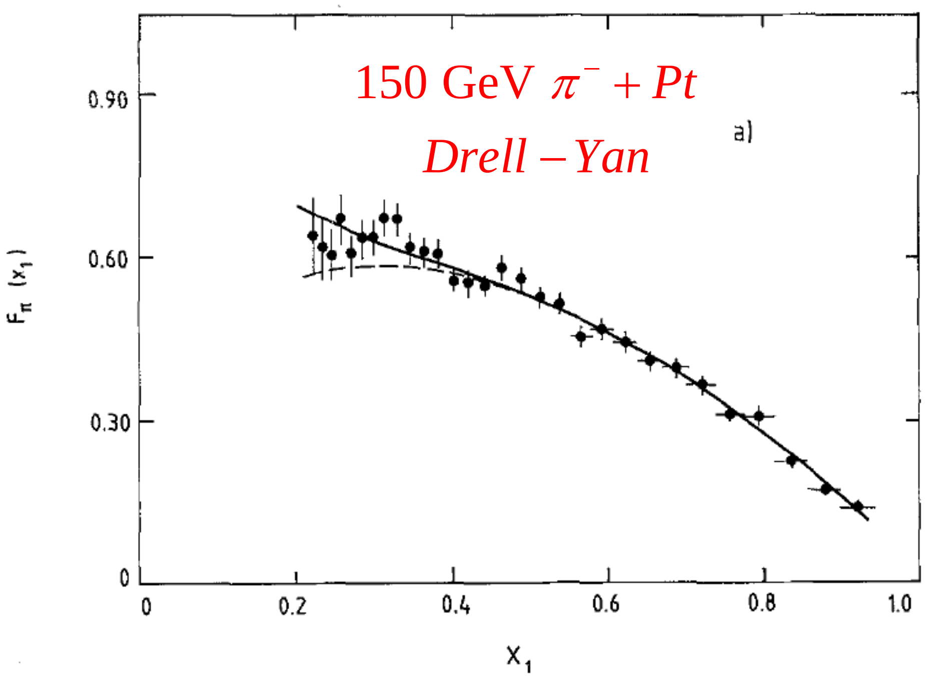
$$4\sigma_{DY}(\pi^+ + D) - \sigma_{DY}(\pi^- + D) \propto 15S_\pi(x_1)V_N(x_2) + 15V_\pi(x_1)S_N(x_2) + 30S_\pi(x_1)S_N(x_2)$$

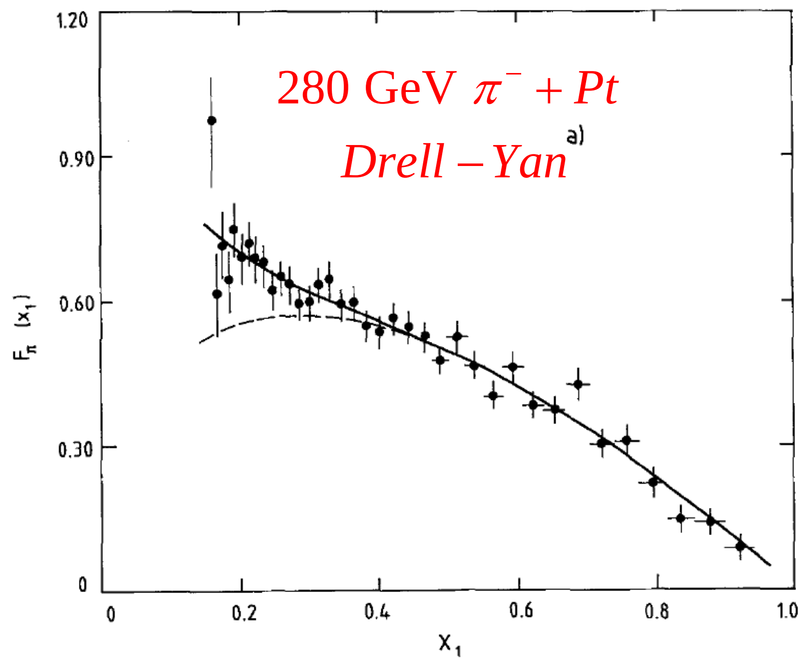
$S_\pi(x_1)$ can be extracted (better sensitivity for $S_\pi(x_1)$ at negative x_F; $x_1 < x_2$)

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





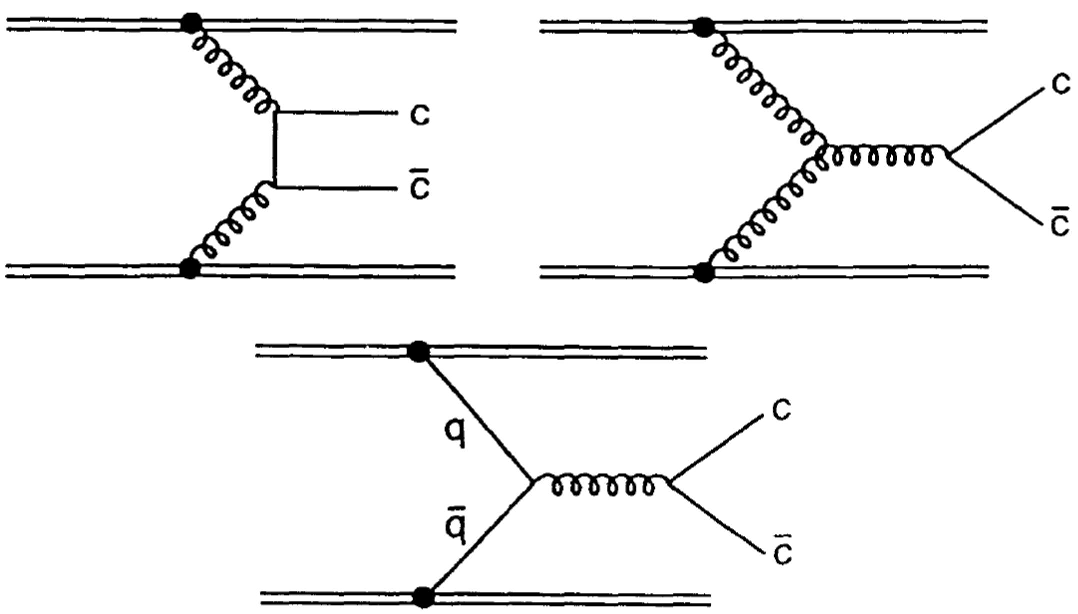
Dashed curve: without the pion sea contribution

Solid curve: including the pion sea contribution

New DY data with π^+ beam is crucial for probing pion's sea

How to determine the gluon distribution in pion?

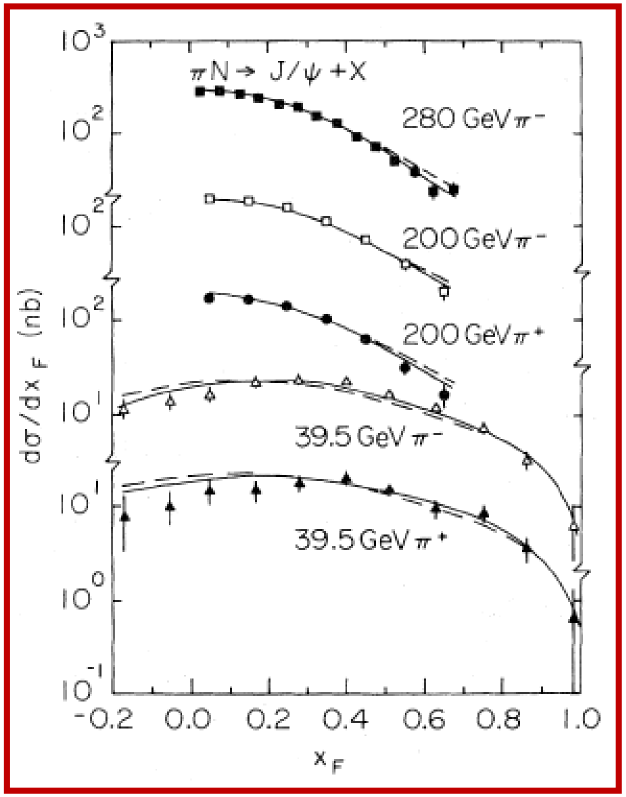
- J/Ψ production with pion beam
- Direct photon production with pion beam
- Charm production with pion beam

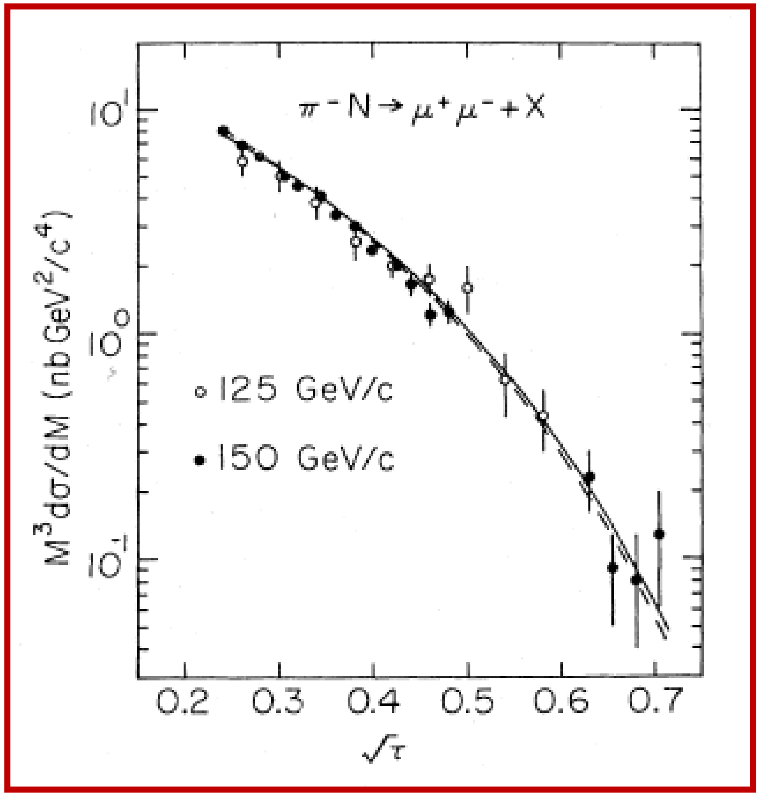


See Alexei Guskov's talk at ECT*

Four pion PDF sets available at LHAPDF library

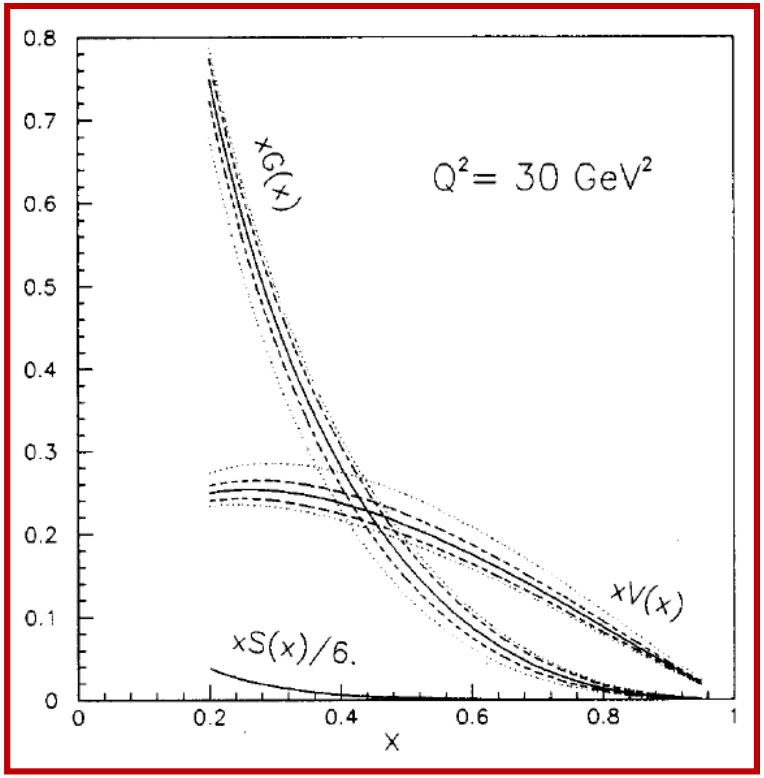
- First: OW-P (PRD 30, 943 (1984))
  - LO QCD
  - J/Ψ data from NA3 and WA39
  - D-Y data from E537 and NA3





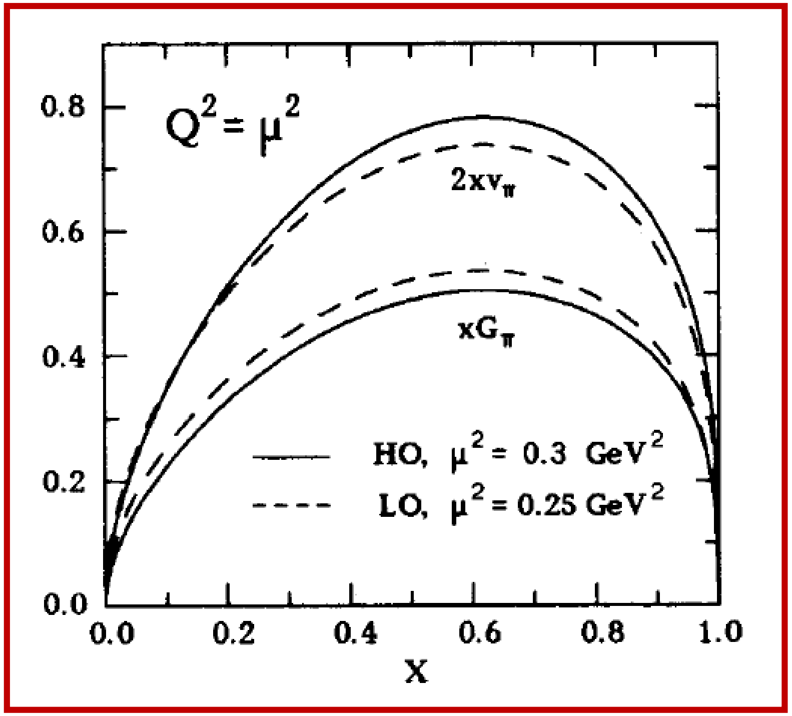
Four pion PDF sets available at LHAPDF library

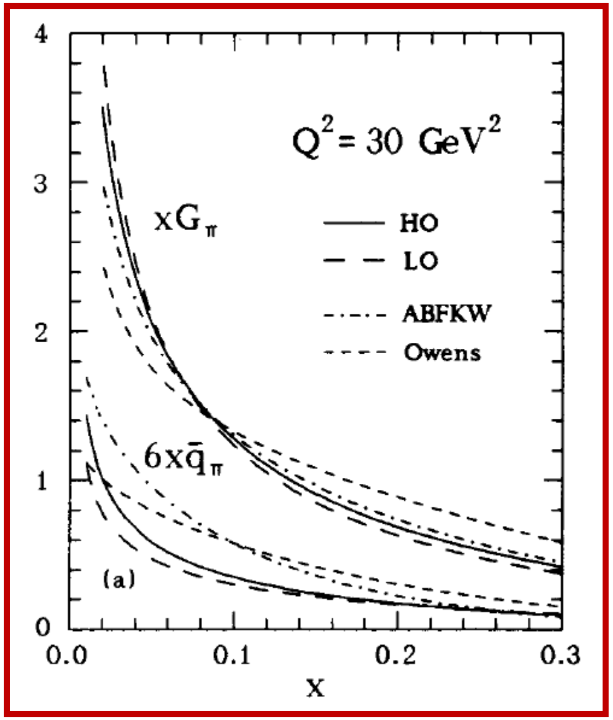
- Second: ABFKW-P (PL 233, 517 (1989))
  - NLO QCD
  - Direct photon data from WA70 and NA24
  - Sea-quark distribution from NA3



Four pion PDF sets available at LHAPDF library

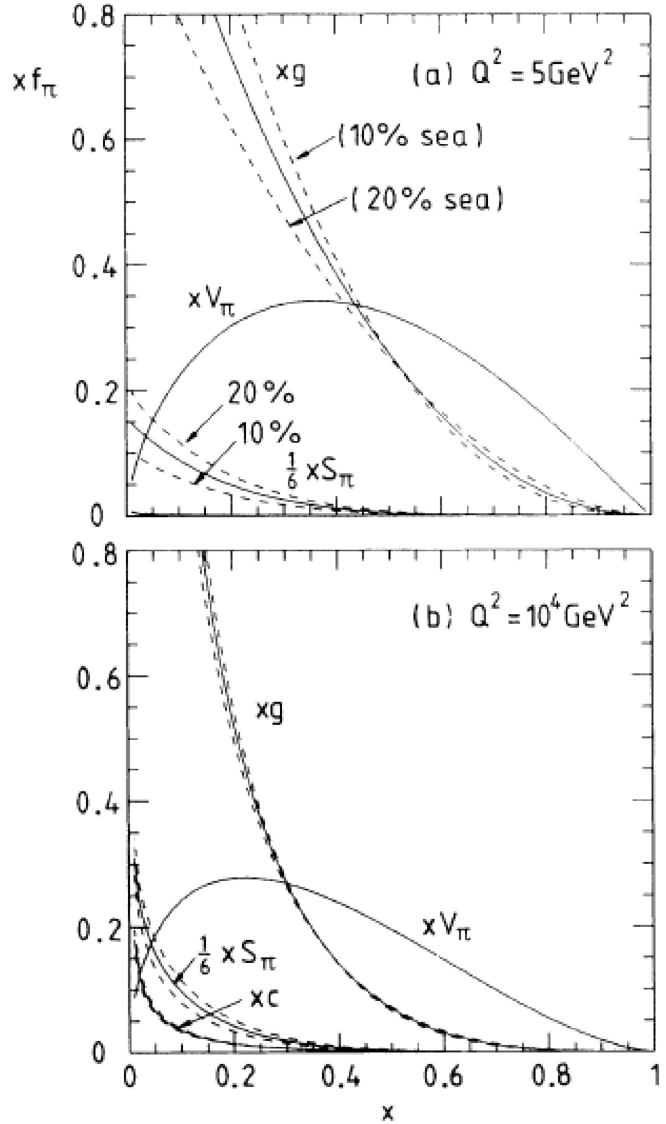
- Third: GRV-P (Z. Phys. C53, 651 (1992))
  - Only valence and valence-like gluon at initial scale. Sea is entirely from QCD evolution
  - Valence distribution from fit to direct photon data





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, 1802.03153

Statistical approach of pion parton distributions from Drell-Yan process

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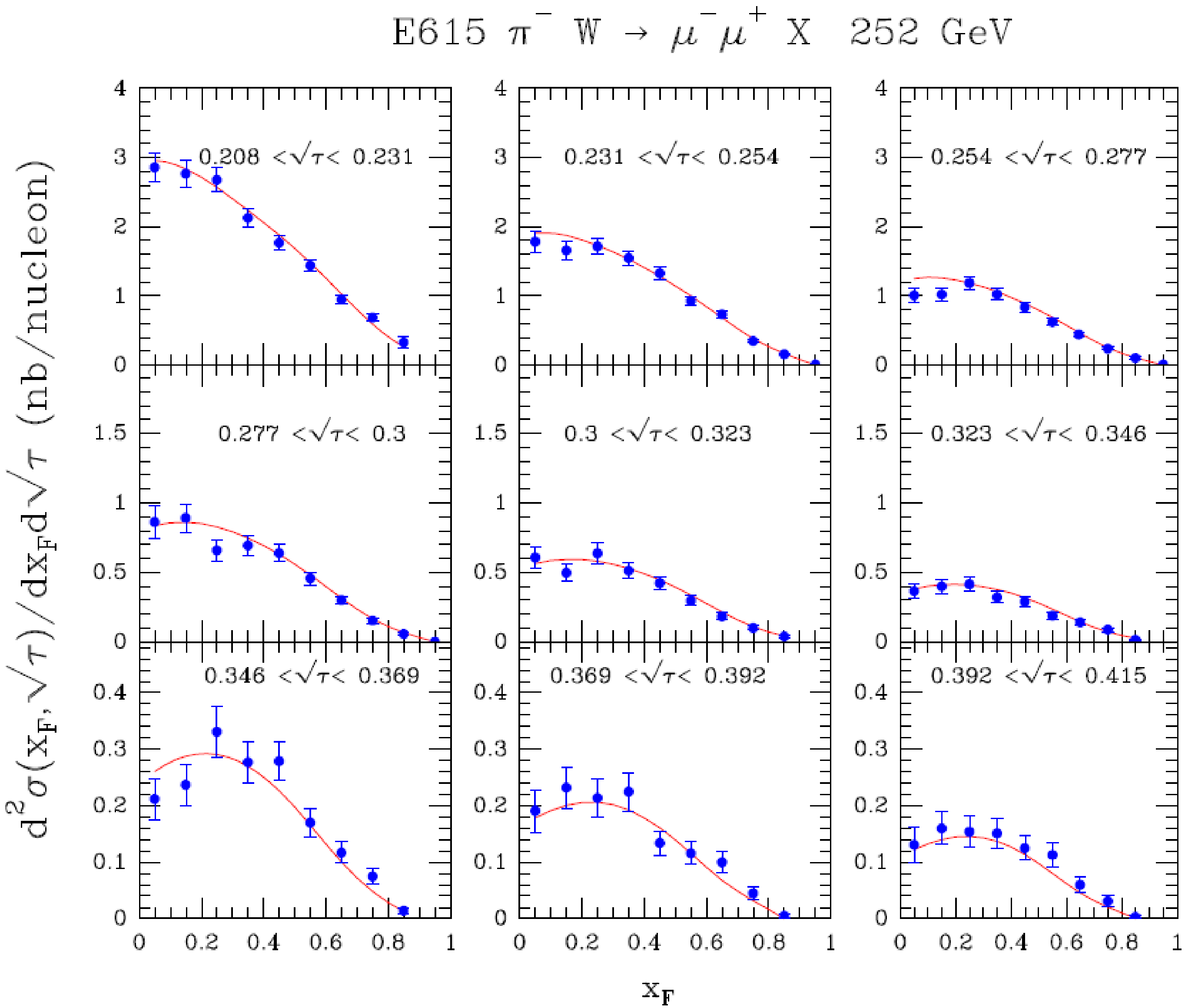
Abstract

The quantum statistical approach proposed more than one decade ago was used to determine the parton distributions for the proton by considering a large set of accurate Deep Inelastic Scattering experimental results. We propose to extend this work to extract the parton distributions for the pion by using data on lepton pair production from various experiments. This global next-to-leading order QCD analysis leads to a good description of several Drell-Yan $\pi^- W$ data. The resulting parton distributions are compared with earlier determinations. We will also discuss the difference between nucleon and pion structure in the same approach.

Key words: Drell-Yan process, Statistical distributions

Excellent fits to the data in NLO

Bourrely and Soffer, 1802.03153



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

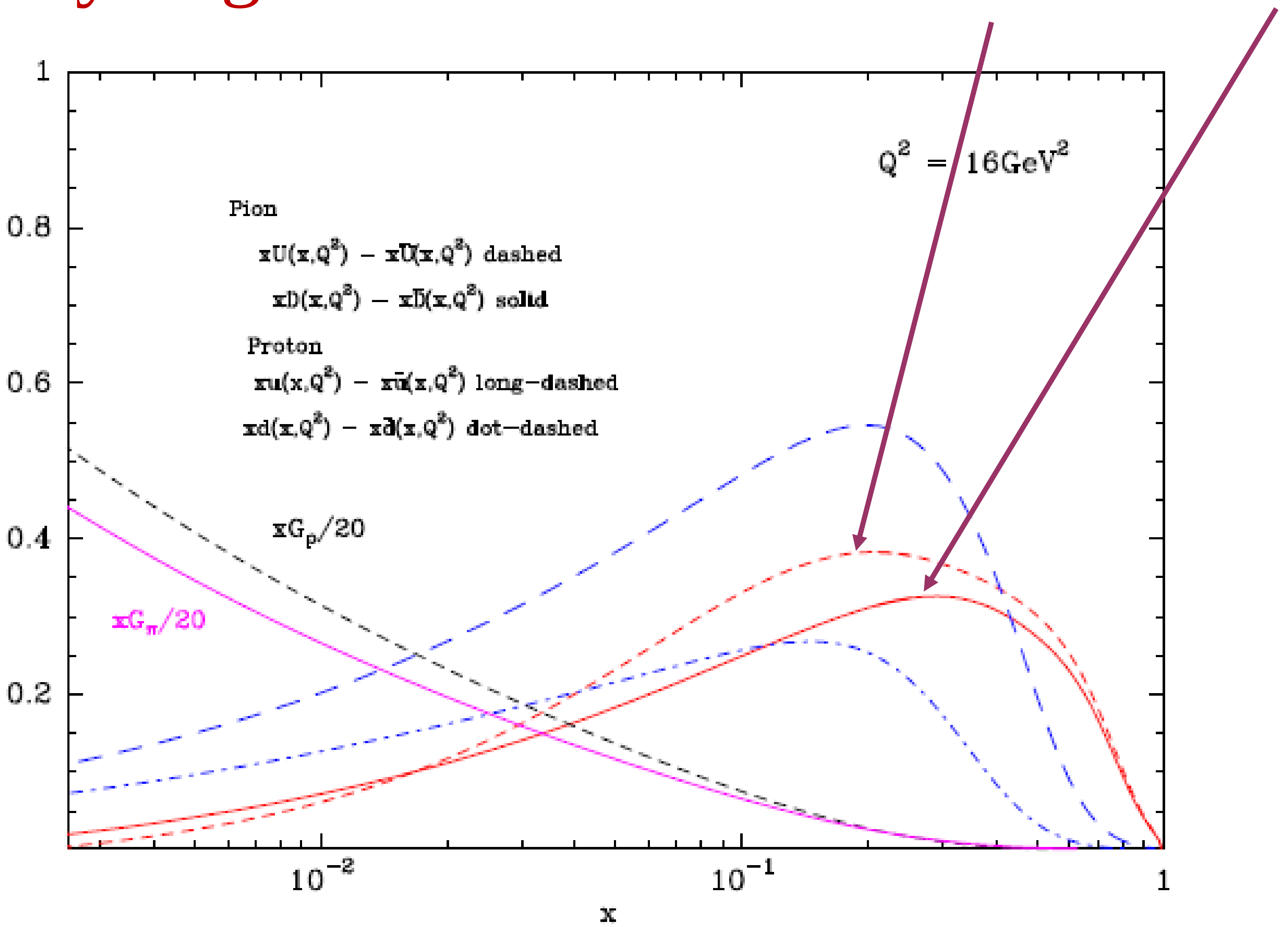
$$xQ^{\pm}(x) = \frac{A_Q X_Q^{\pm} x^{b_Q}}{\exp[(x - X_Q^{\pm})/\bar{x}] + 1}, \quad (2)$$

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

and four potentials

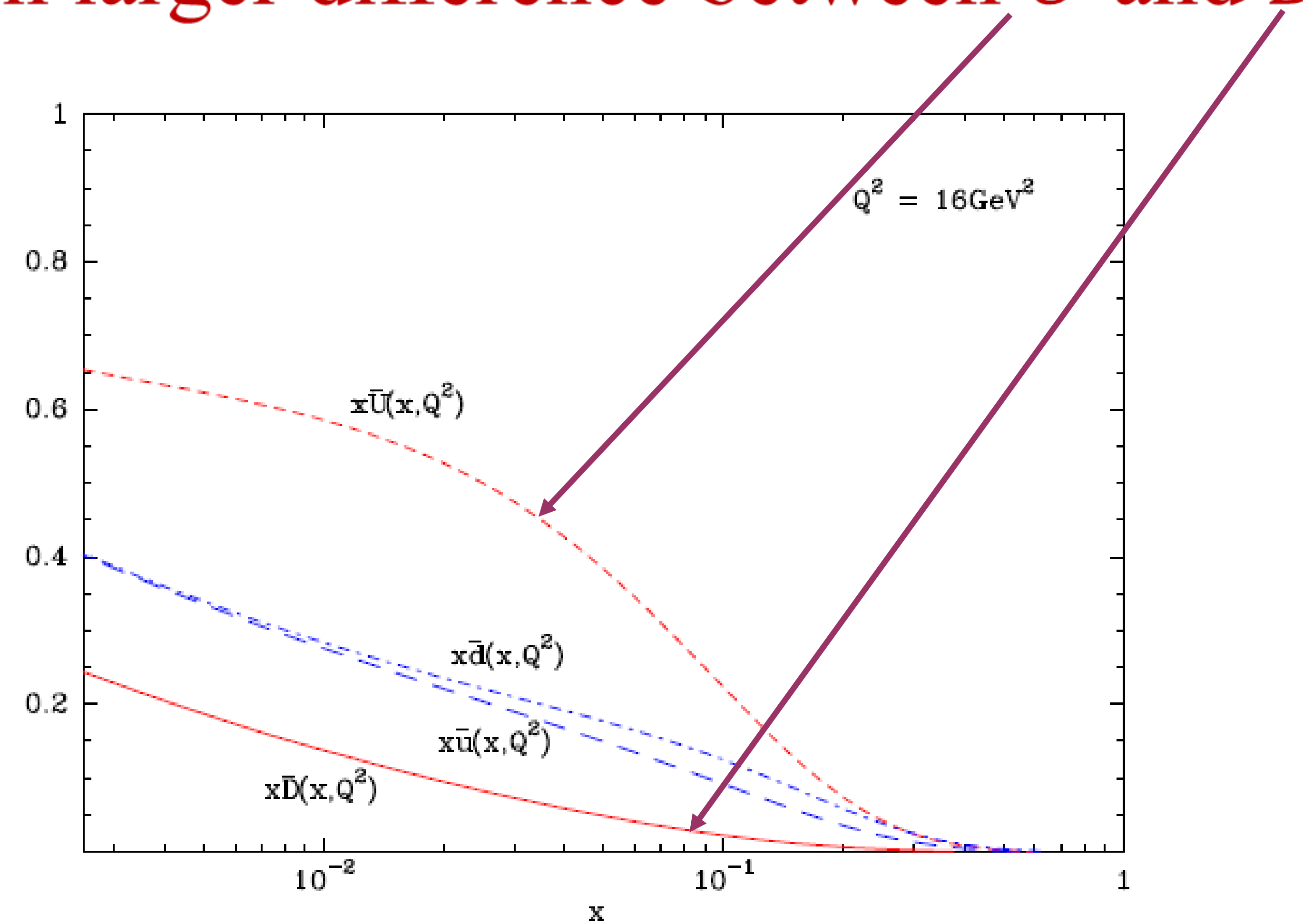
$$X_U^+ = 0.787 \pm 0.007,\ X_U^- = 0.185 \pm 0.030,$$
$$X_D^+ = 0.866 \pm 0.024,\ X_D^- = 0.718 \pm 0.044. \quad (13)$$

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

How to determine the valence quark distribution in kaon?

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

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

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

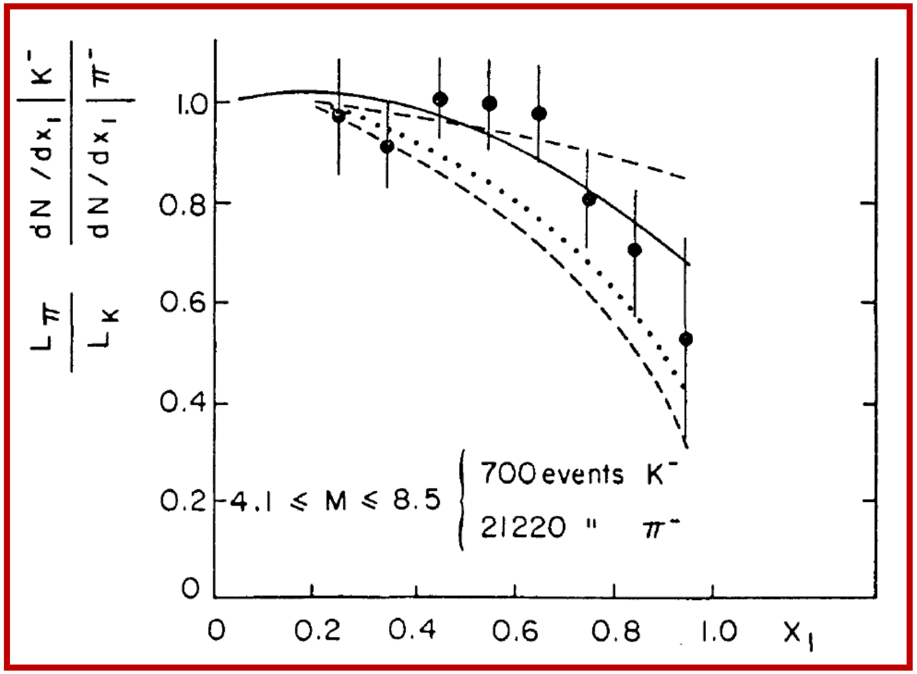
$$\sigma_{DY}(K^- + D) - \sigma_{DY}(K^+ + D) \propto 4V_K^u(x_1)V_N(x_2)$$

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



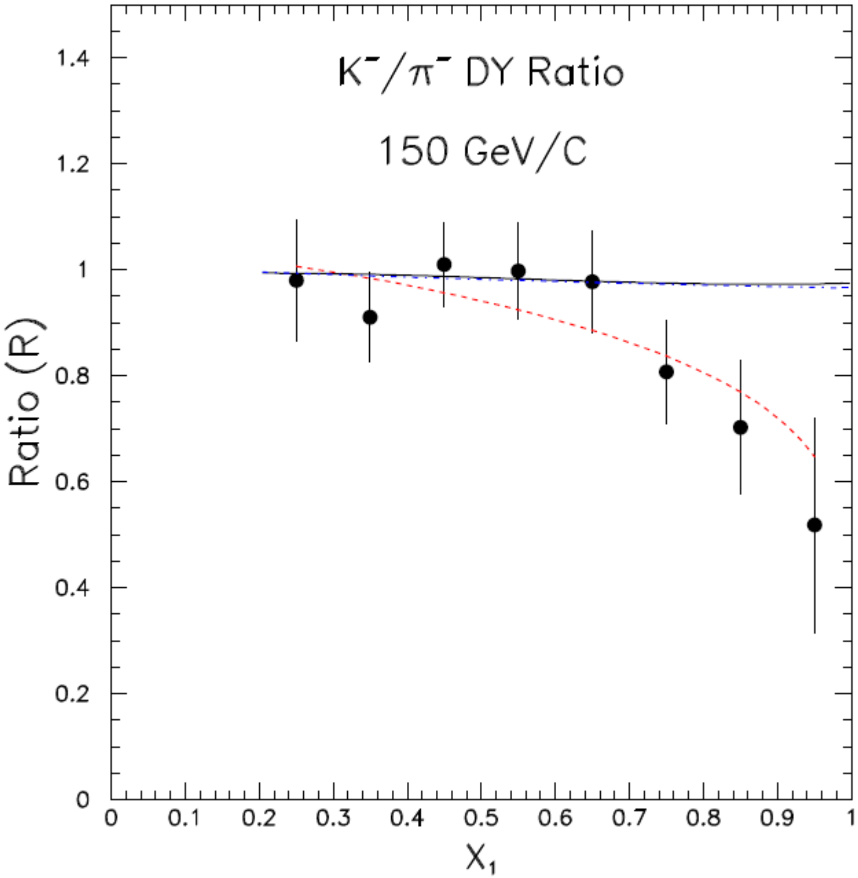
From NA3; 150 GeV, Pt target

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

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

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

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



See JCP, Chang, Platchkov, Sawada arXiv:1711.00839

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:

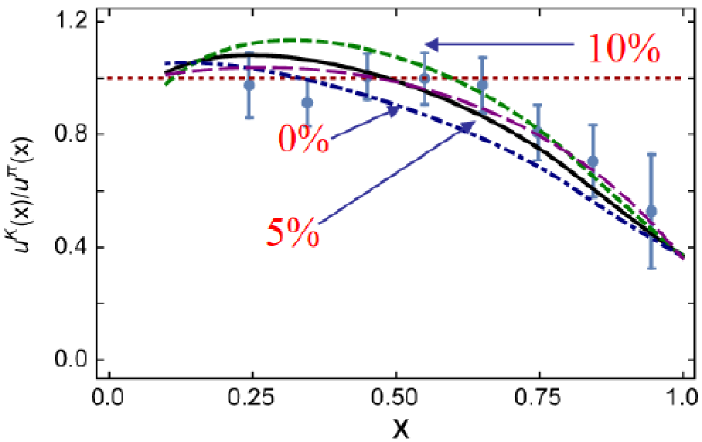
Modified K^- pdf

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

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

Interesting observation

C. Chen *et al.*, PRD 93 074021, 2016



Algebraic framework with DSE

- Determined dressed-quark at hadronic scale
- Kaon's momemtum fraction carried by gluon at hadronic scale: 1 parameter
- Fit to NA3 data

→ At hadronic scale gluons carry only 5% of the momentum of the kaon *vs* ∼30% in the pion

- Scarce data on *u*-valence
- No measurements on gluons
- No measurements on sea quarks

How to improve the situation?

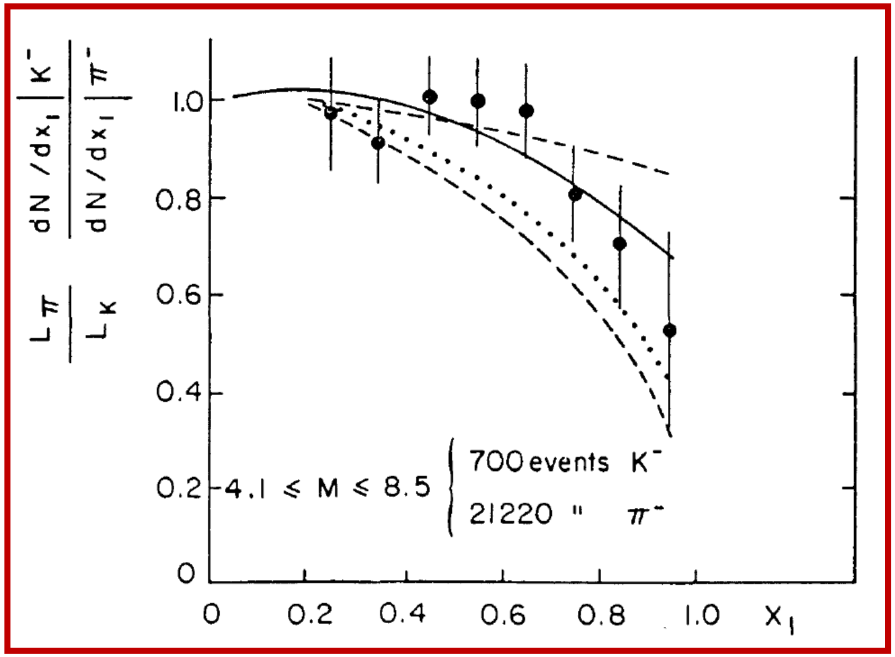
Vincent Andrieux's talk at ECT*

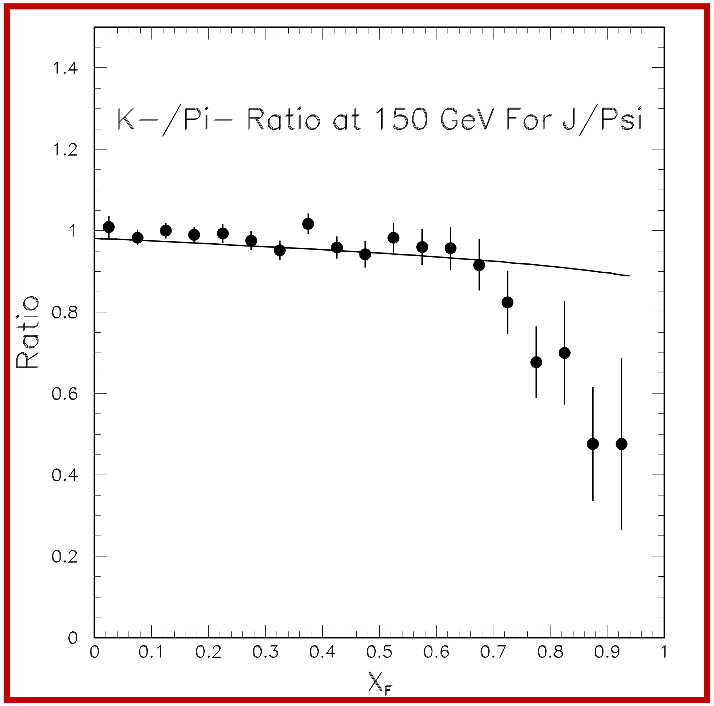
$(K^- + \mathrm{Pt})/(\pi^- + \mathrm{Pt})$ ratios for J/Ψ production

From NA3; 150 GeV, Pt target

Ratios for D-Y

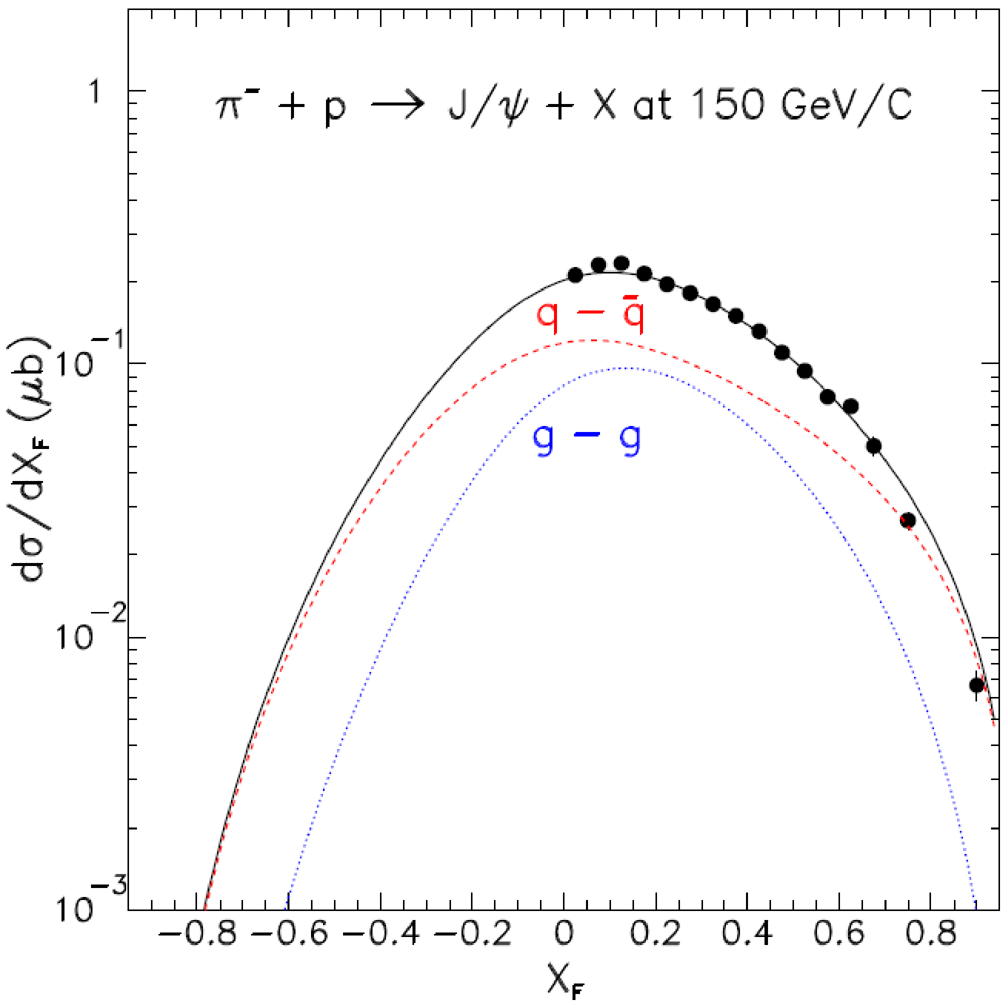
Ratios for J/Ψ





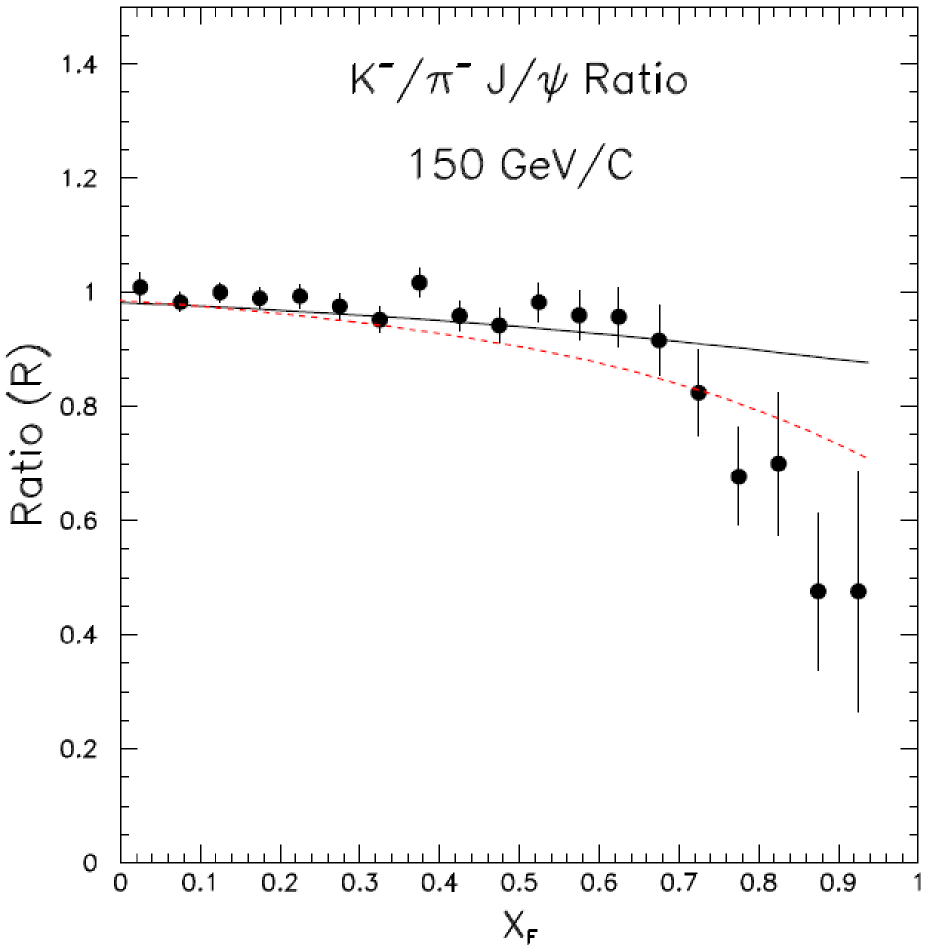
Similar behavior at large x_F for D-Y and J/Ψ production?

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:

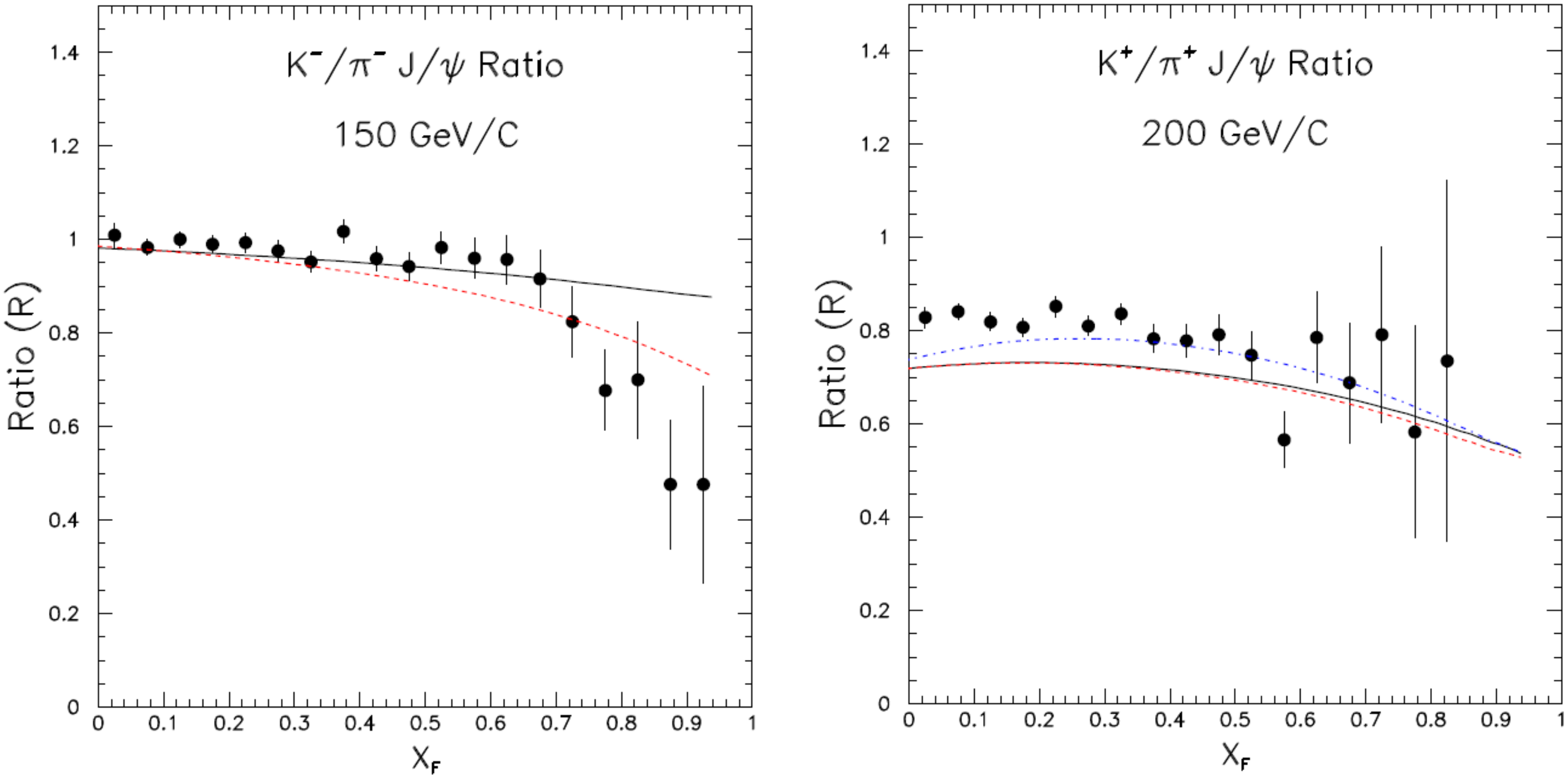
Modified K^- pdf

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

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

See JCP, Chang, Platchkov, Sawada arXiv:1711.00839

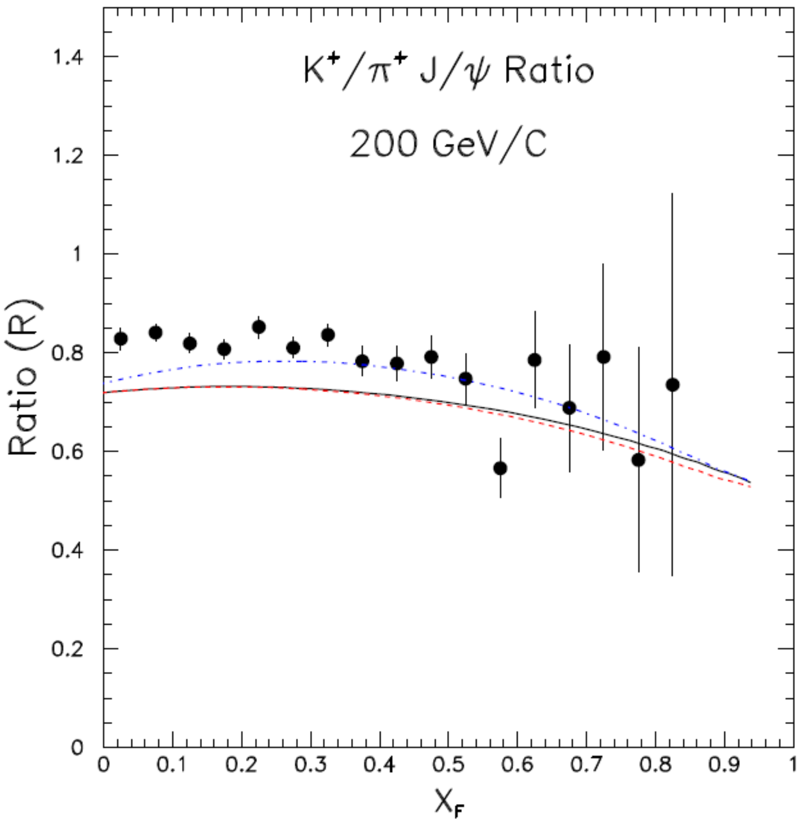
Comparison between K^- / π^- and K^+ / π^+ J/ψ production ratios



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

$q - \bar{q}$ annihilation is less important for K^+ than for K^-

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

Would be very insteresting to measure K^+/π^+ D-Y ratios

Another example of J/Ψ production as a useful tool meson PDF

(JCP, Chang, Platchkov, Sawada)

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

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

Define

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

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

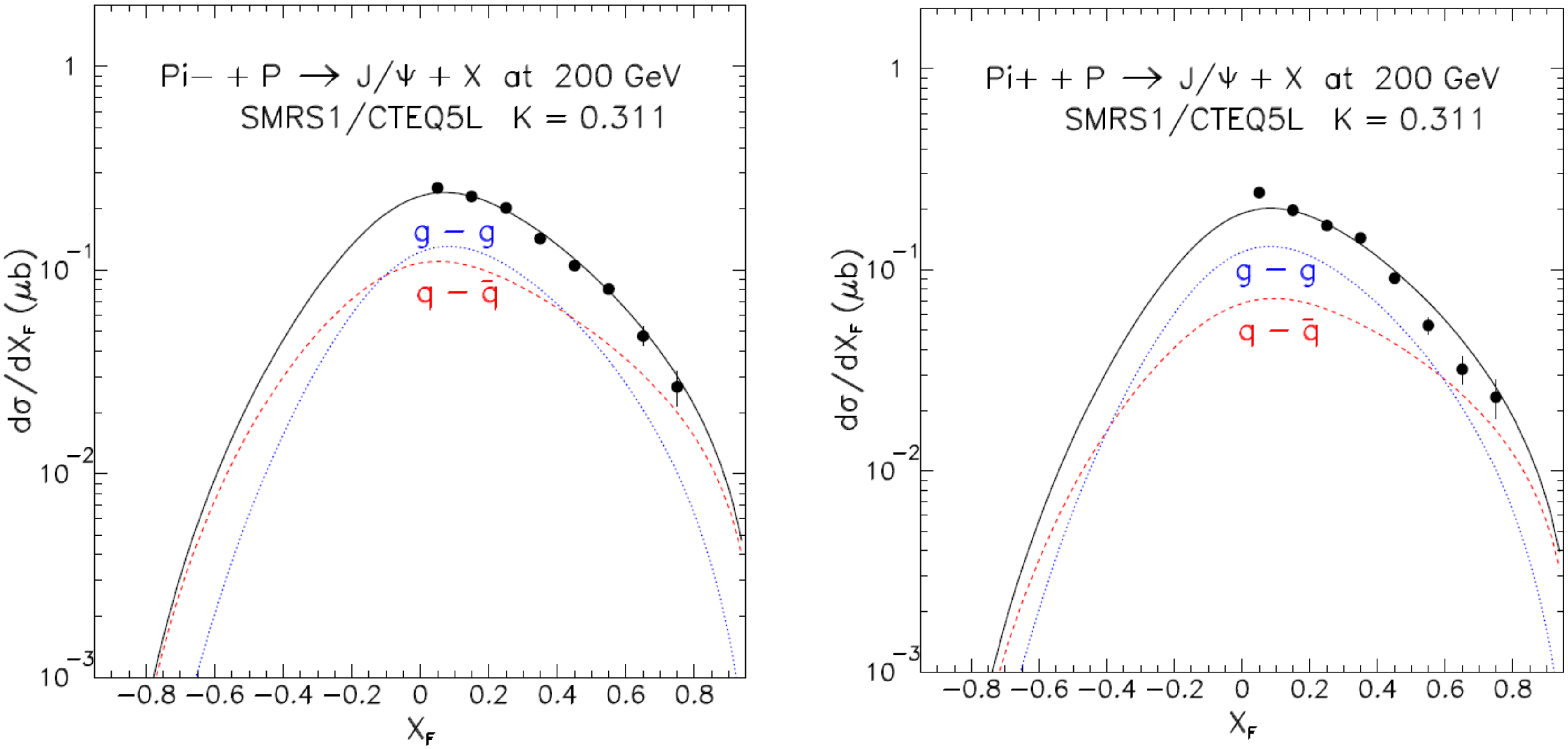
$$\sigma_{J/\Psi}(\pi^- + p) - \sigma_{J/\Psi}(\pi^+ + p) \propto V_\pi(x_1)[u_V(x_2) - d_V(x_2)] > 0$$

Only the valence-quark term remains!

Directly proportional to $V_\pi(x_1)$

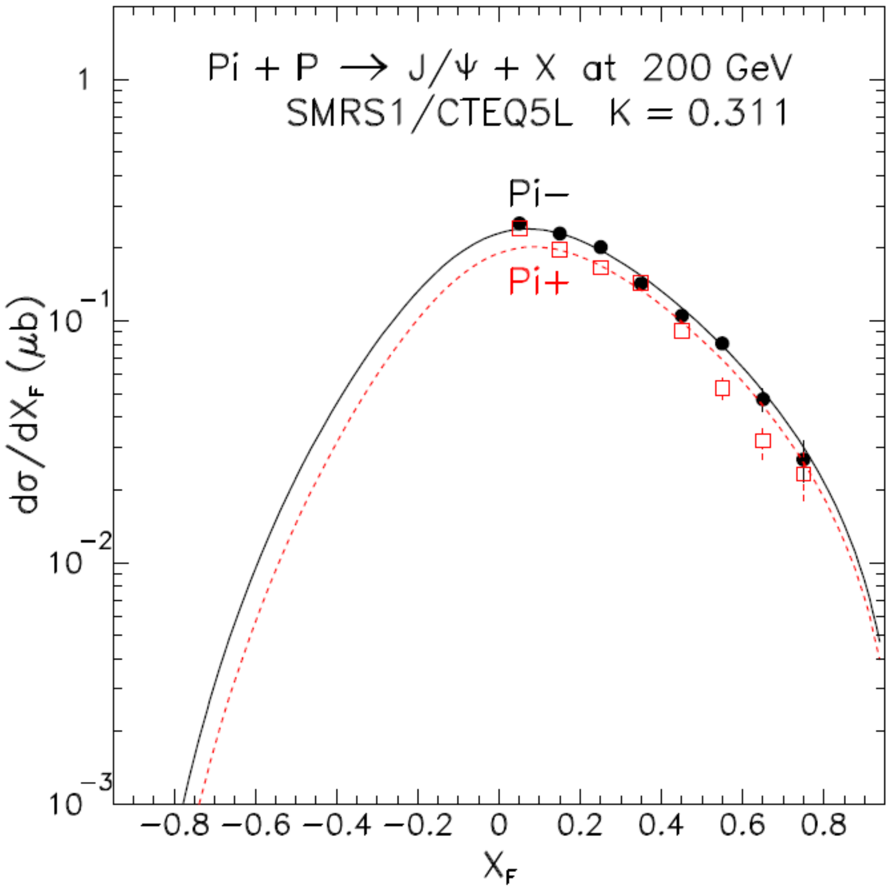
Are there relevant data already?

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 $u_V(x_2) - d_V(x_2)$

New DY experiment with $\pi^{\pm}$ beams

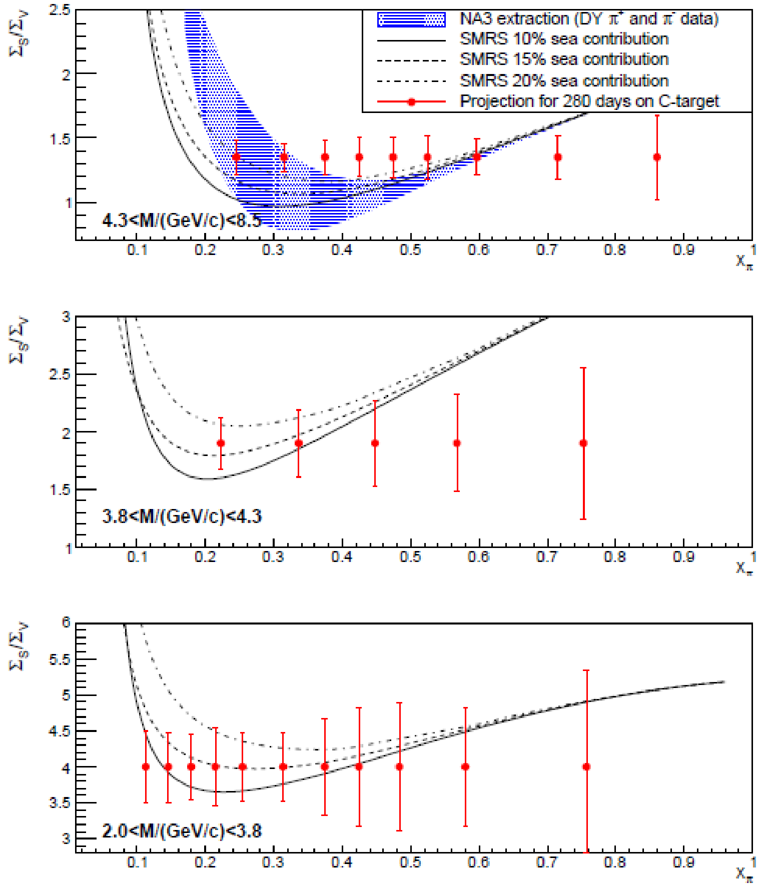
...And while we analyse these COMPASS data, we plan the next Drell-Yan challenge: a new experiment for meson structure studies

- High intensity pion beams of high energy: π^{+} and π^{-} at 190 GeV
- Optimal time sharing (wrt DY process) between the 2 beam polarities
- Light isoscalar target: carbon (4 cells); and heavy target: tungsten (2 cells)
- Large acceptance spectrometer – as COMPASS
- A fully charge-symmetric dimuon trigger system
- CEDARs system standing high intensity beams
- Multidimensional analysis techniques

Catarina Quintans' talk at ECT*

New DY experiment: pion sea to valence ratio

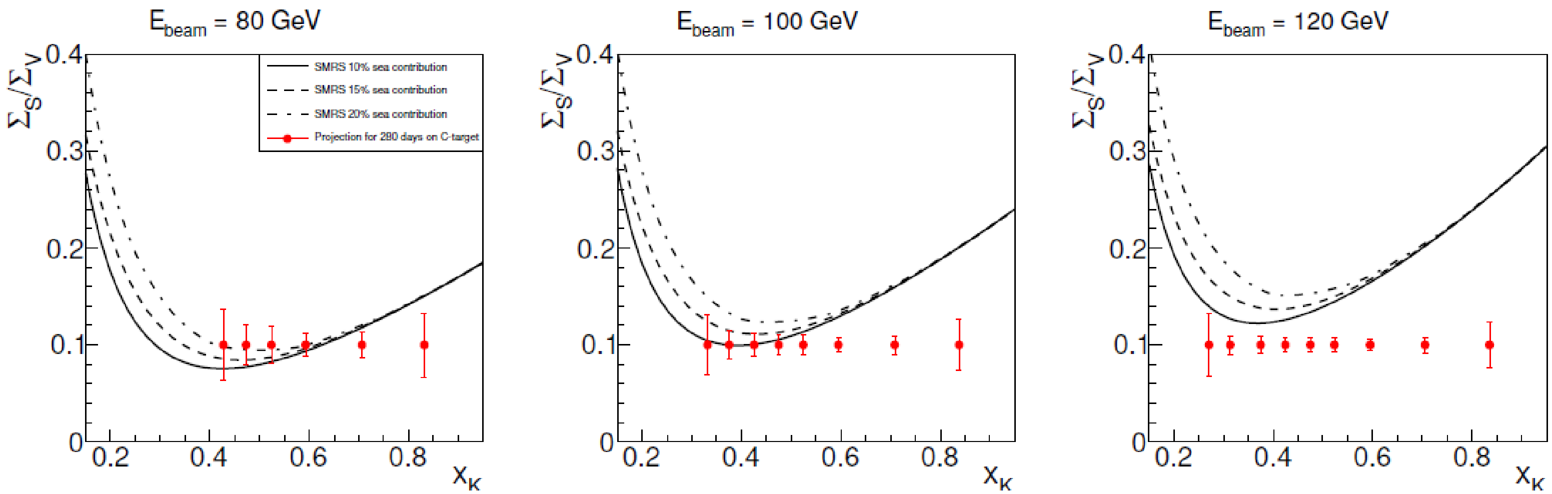
Expected accuracy compared to NA3 result



- Collect at least a factor 10 more statistics than presently available
- Minimize nuclear effects on target side
  - Projection for 2 years of Drell-Yan data taking
  - π^+ to π^- 10:1 time sharing
  - 190 GeV beams on Carbon target $(1.9\lambda^{\pi}_{int})$

Catarina Quintans' talk at ECT*

Initial results: Projections for valence/sea separation for Kaons



- **First measurement of sea in kaons**
- ∼15% statistical uncertainty at 120 GeV
- Effect expected to be sizeable J.T. Londergan *et al.*, PLB 380 (1996)
- Using SMRS-like 10% to 20% sea contributions: ∼ 30% variation
- Also sensitivity to valence strangeness

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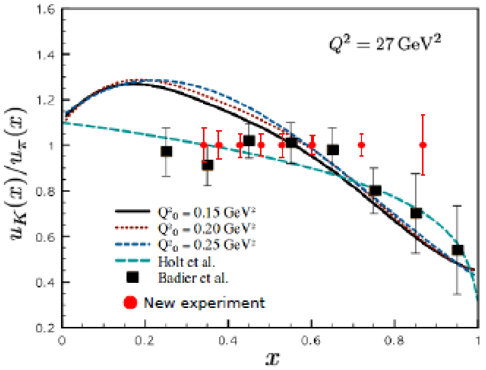
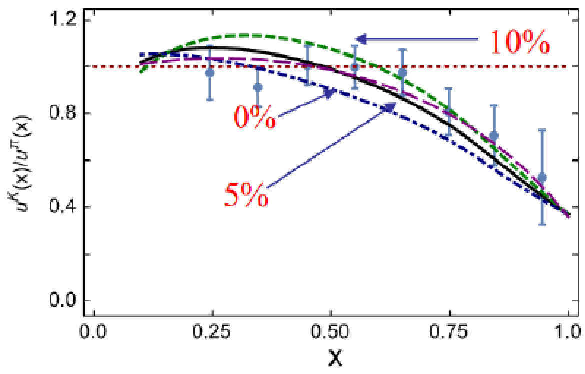
Initial results: Projections for Kaon structure

S-i. Nam PRD 86, 074005, 2012



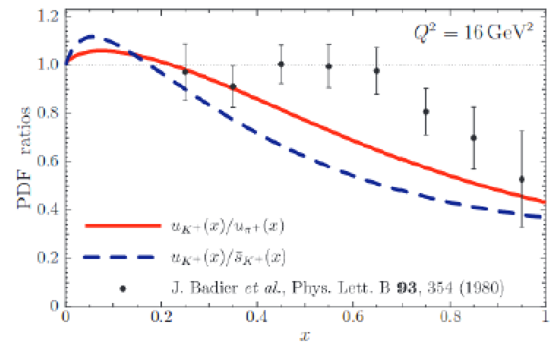
Gauge-invariant nonlocal chiral-quark model

C. Chen *et al.*, PRD 93 074021, 2016



Algebraic framework DSE

Hauturuk *et al.*, PRC94, 035201 (2016)



BSE for Nambu-Jonas-Lasinio model

- More data points and more precise compared to NA3
- It will constrain models

Conservative estimate: Room for improvement (apparatus, intensity, mass range, . . .)

Promising

Vincent Andrieux’s talk at ECT*

Summary

- Meson parton distributions (Valence, Sea, Gluon) represent
  - * an interesting and only marginally explored area in hadron physics
  - * a unique opportunity for COMPASS ("textbook" physics)
  - * a close connection to COMPASS physics and JLab/EIC programs
- Drell-Yan, J/ψ production can be well measured with meson beams at COMPASS
- Other interesting topics not included in this talk include
  - * Boer-Mulders functions in pion and kaon
  - * Test of the Gibov-Lipatov reciprocity, connecting meson PDF at large x and meson fragmentation function at large z
  - * Sea-quark flavor asymmetry in kaons (analog of $\bar{d}/\bar{u}$ in nucleon)
  - * Exclusive D-Y or exclusive J/Ψ production with meson beams to probe meson distribution amplitudes