Meson Structure with Dilepton Production

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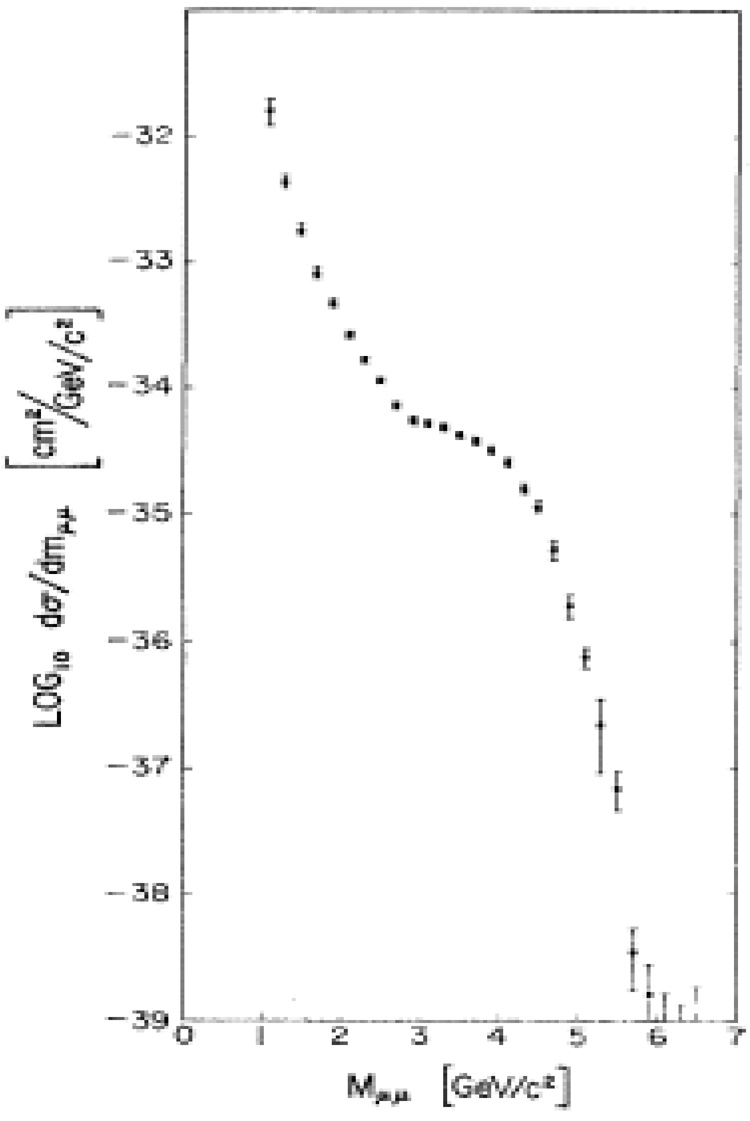
In collaboration with Wen-Chen Chang and Stephane Platchkov

Outline

- Overview of Drell-Yan experiments with meson beams
- What have we learned from these experiments
- What we would like to learn in the future
- Summary and outlook

First Dimuon Experiment



$p + U \rightarrow \mu^+ + \mu^- + X$ 29 GeV proton

Lederman et al. PRL 25 (1970) 1523

Experiment originally designed to search for neutral weak boson (Z^0)

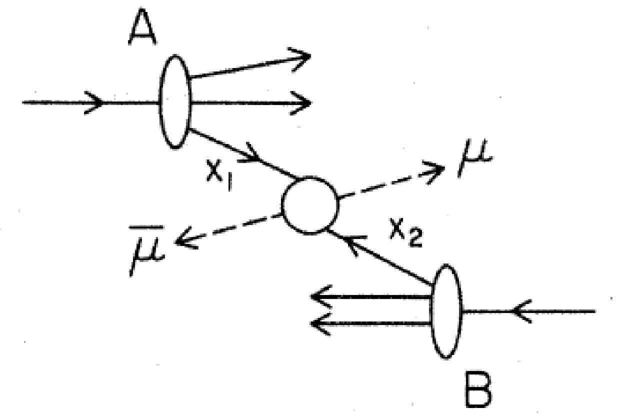
Missed the J/Ψ signal !

"Discovered" the Drell-Yan process

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
- 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

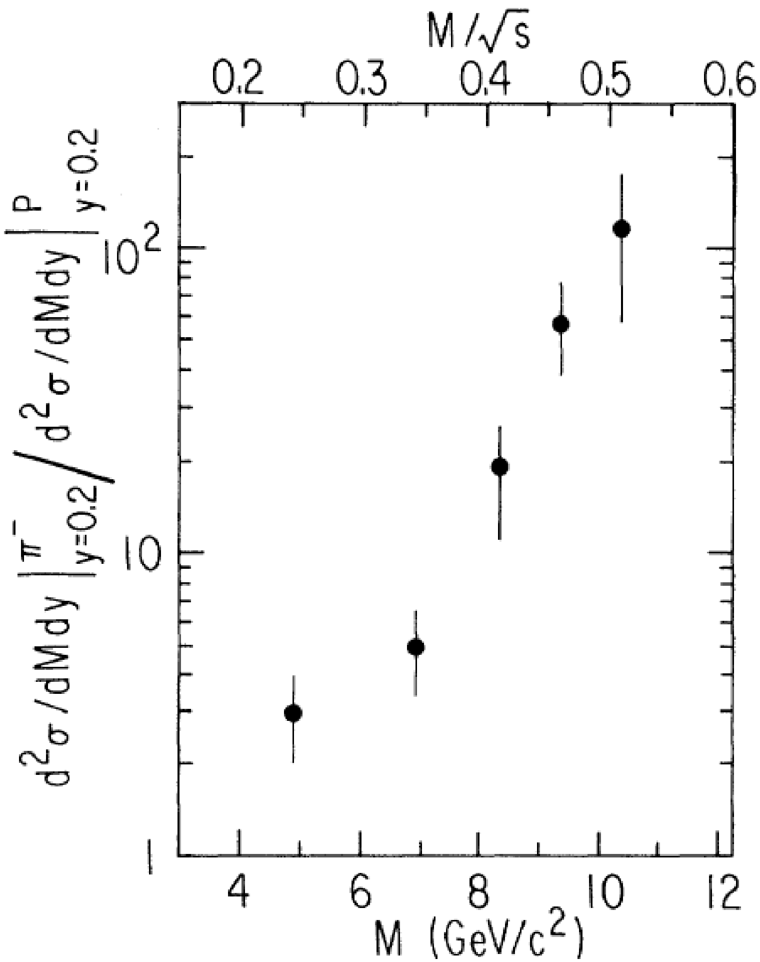
Drell-Yan experiments with K^+ beam

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

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



From E331/E444

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

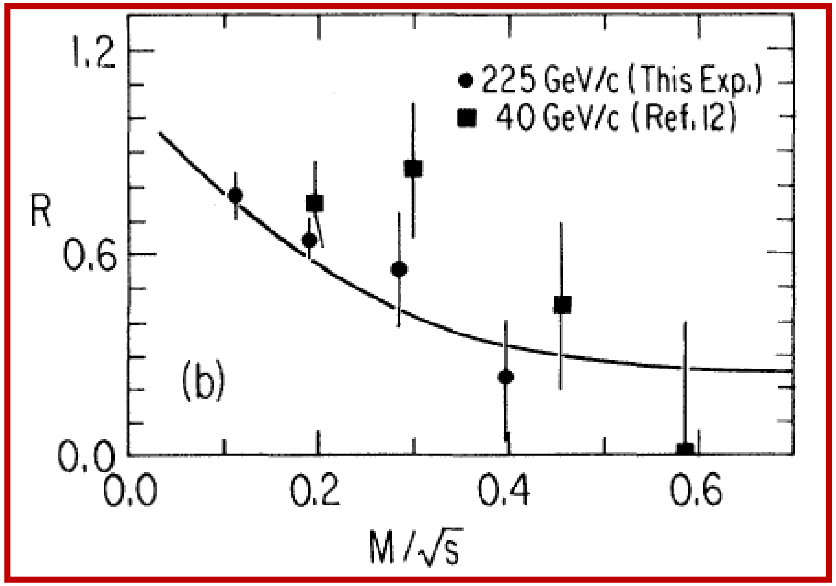
$$\simeq \frac{4\bar{u}_\pi(x_1)u_N(x_2) + d_\pi(x_1)\bar{d}_N(x_2)}{4u_p(x_1)\bar{u}_N(x_2) + d_p(x_1)\bar{d}_N(x_2)}$$

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

Black: valence Red: sea

Rapid rise in R at large M reflects the rise in valence/sea ratio as x increases: $\frac{u_N(x_2)}{\bar{u}_N(x_2)}$

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

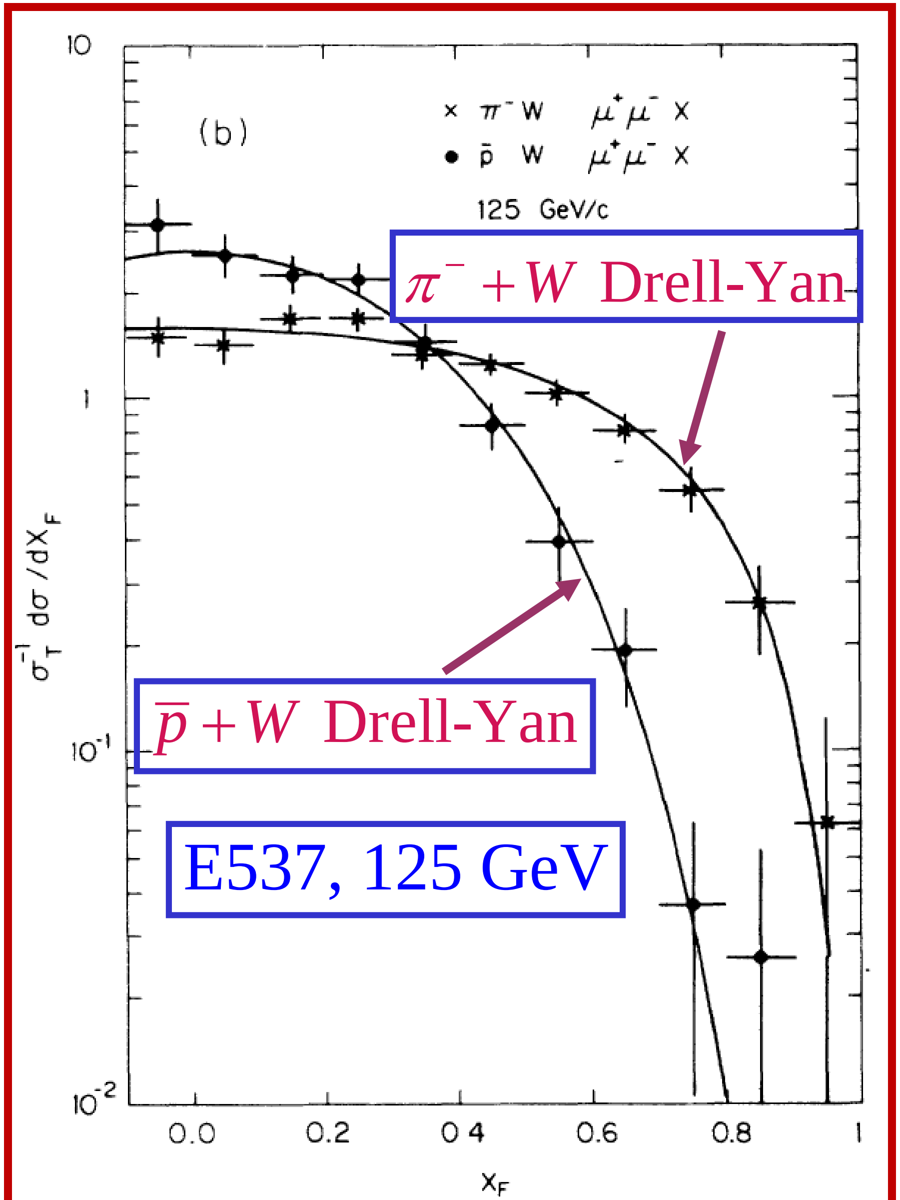
Black: Valence; Red: Sea

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

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

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

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



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

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!

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

How to determine the valence quark distribution in kaon?

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

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

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

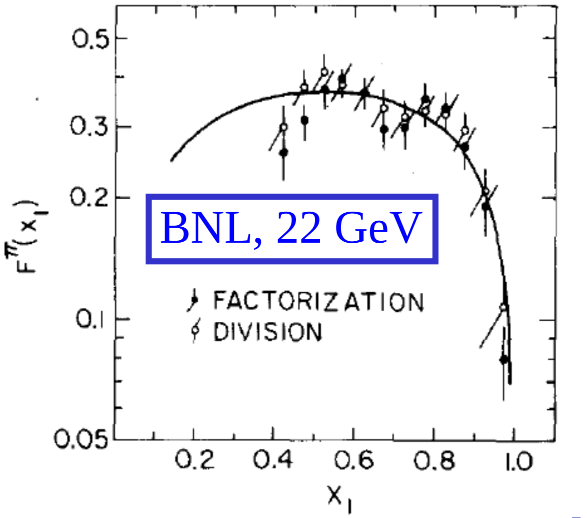
$$\sigma_{DY}(K^- + D) - \sigma_{DY}(K^+ + D) \propto 4V_K^u(x_1)V_N(x_2)$$

Only the valence-quark term remain!

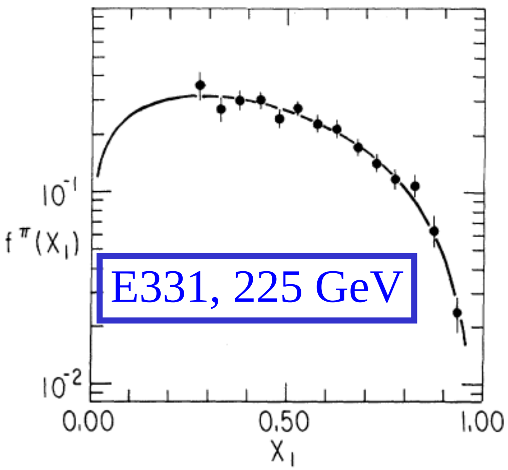
$\sigma_{DY}(K^+ + D)$ is more sensitive to kaon's sea-quark content than $\sigma_{DY}(K^- + D)$ (especially data at low x_1 and large x_2 (negative x_F) region!)

See Londergan al., PL B380 (1996) 393

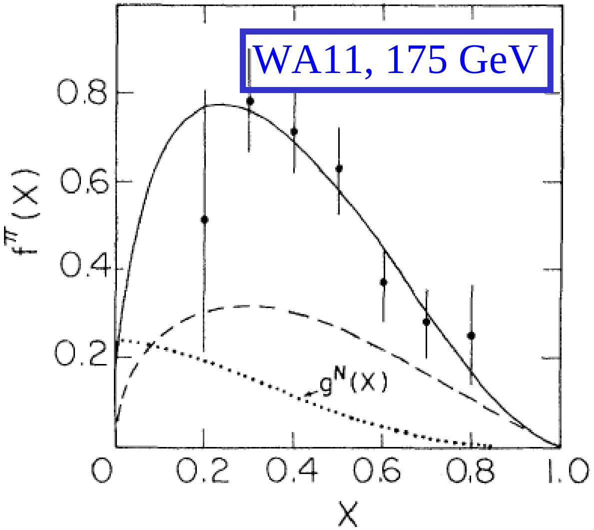
Attemps to extract the pion valence quark distribution



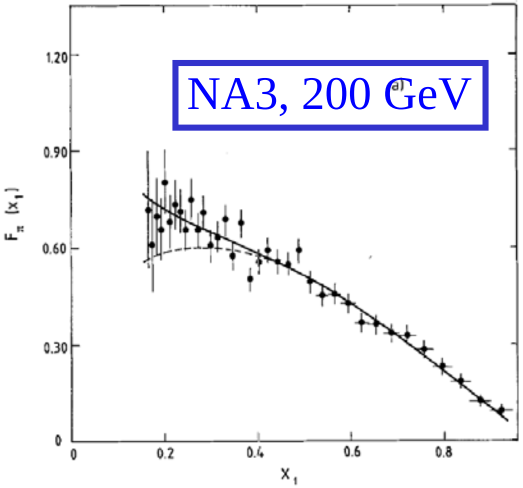
$$F^{\pi}(x) = 0.72x^{0.5}(1-x)^{0.46}$$



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

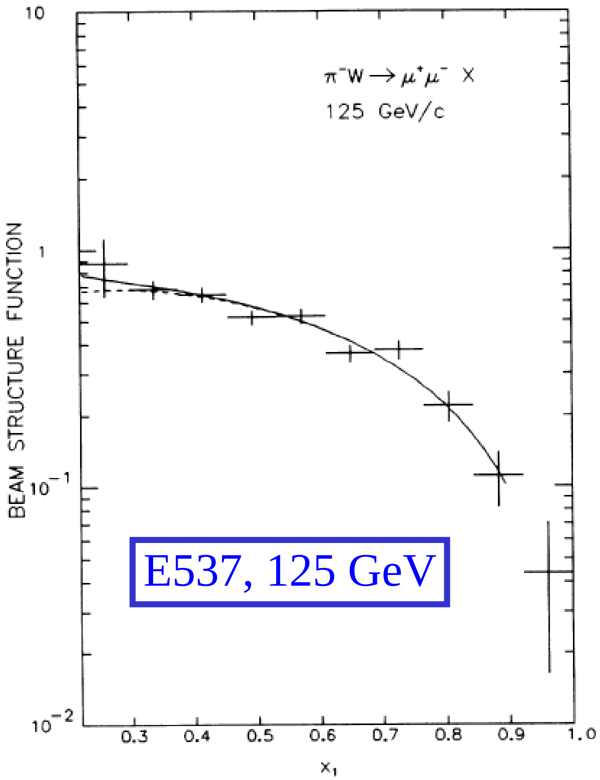


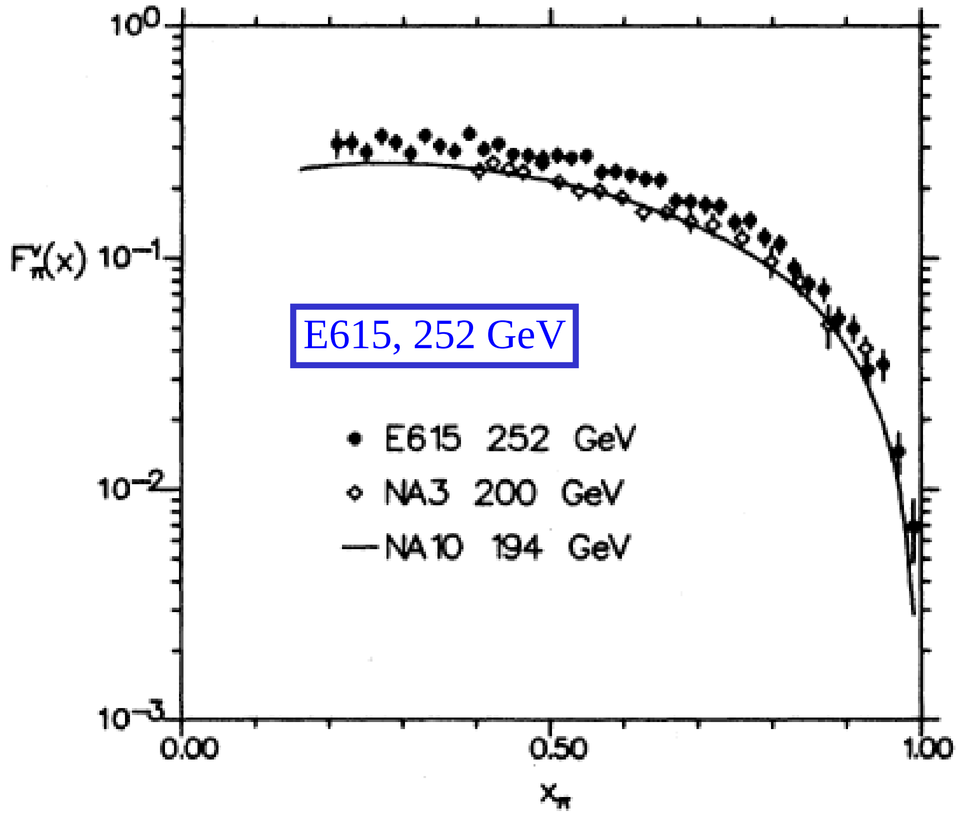
$$F^{\pi}(x) = 2.43x^{0.5}(1-x)^{1.57}$$



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

Attemps to extract the pion valence quark distribution





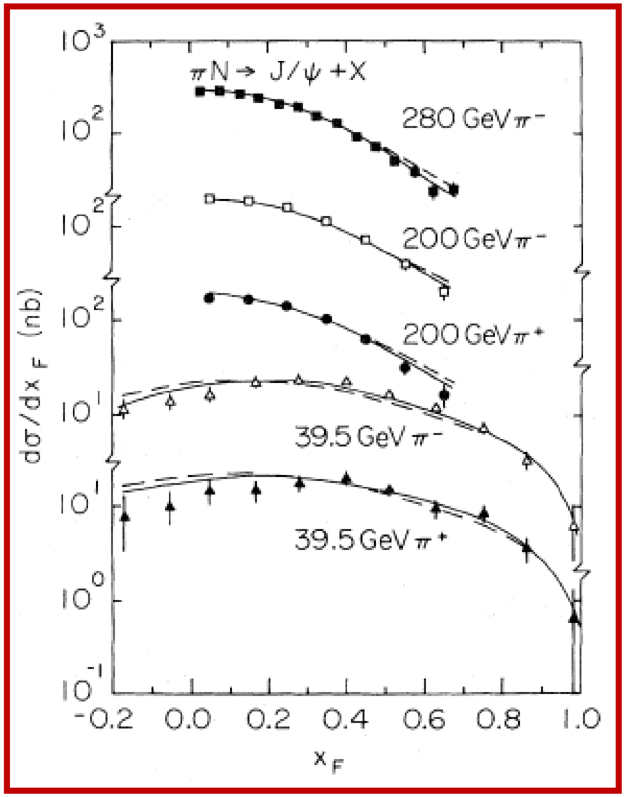
$$F^{\pi}(x) = Ax^{0.442}(1-x)^{1.248}$$

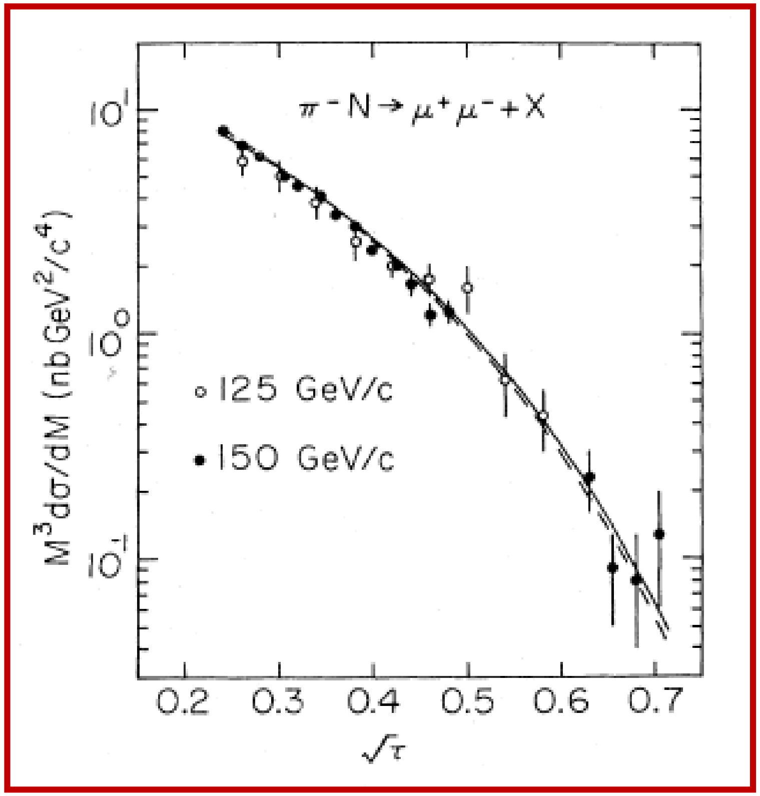
$$F^{\pi}(x) = Ax^{0.6}(1-x)^{1.26}$$

A global fit to all data is needed

Four pion PDF sets available at LHAPDF library

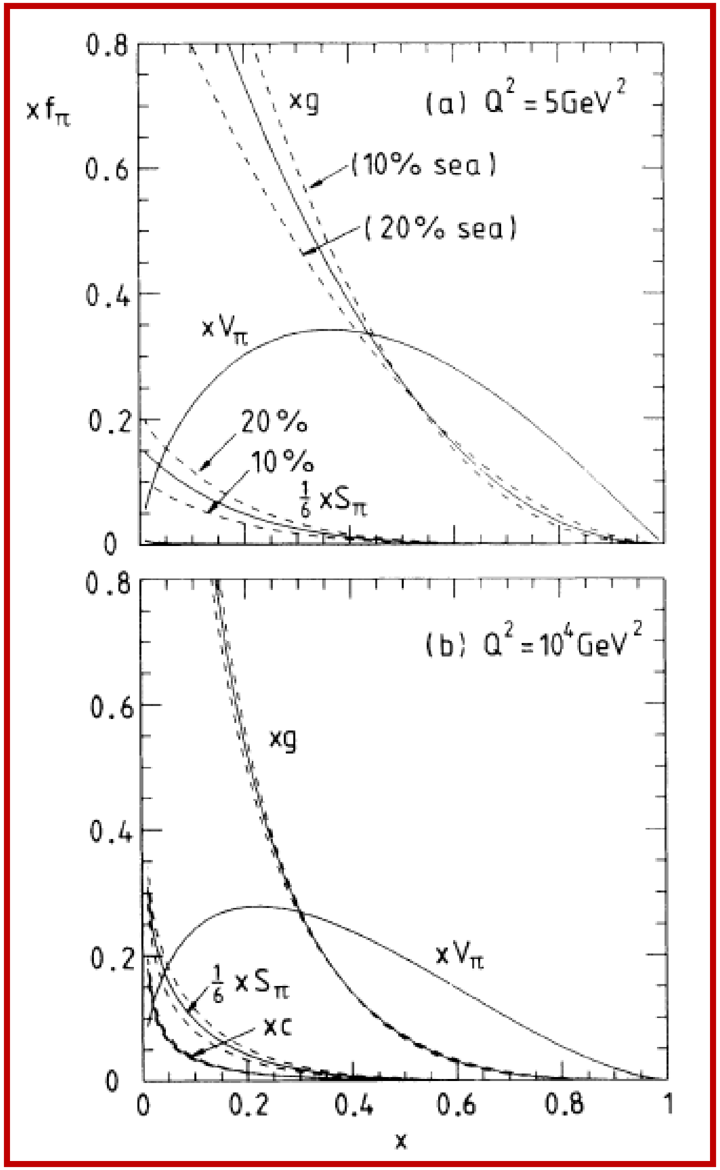
- OW-P (PRD 30, 943 (1984))
  - LO QCD
  - J/Ψ data from NA3 and WA39; D-Y data from E537 and NA3





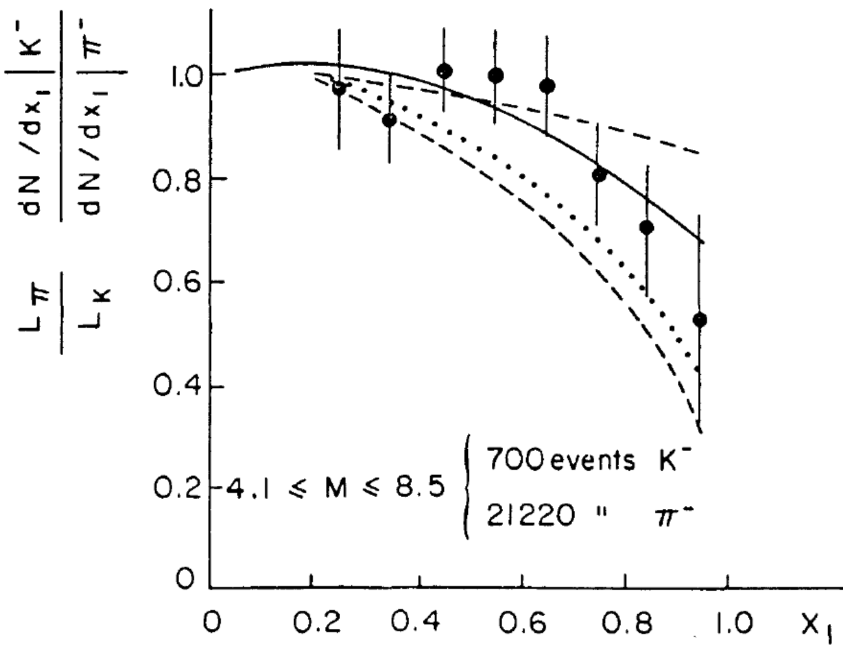
Four pion PDF sets available at LHAPDF library

- 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

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



From NA3; 150 GeV, Pt target

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

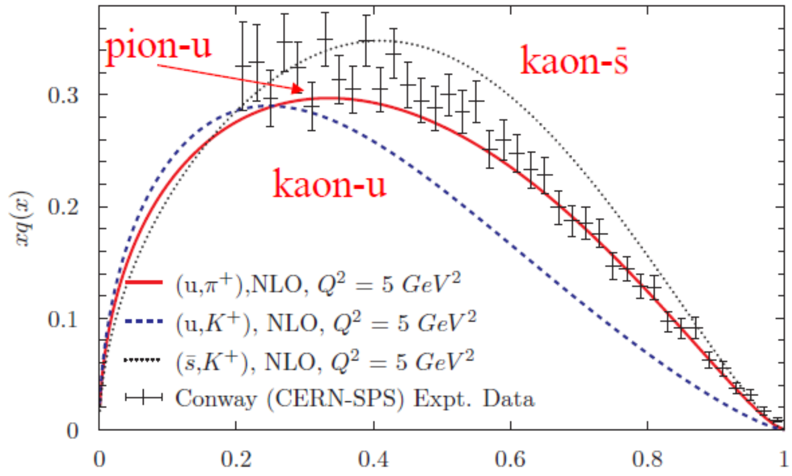
$$\simeq \frac{4V_K^u(x_1)V_N(x_2) + 4V_K^u(x_1)S_N(x_2) + V_K^s(x_1)s_p(x_2) + 5S_K(x_1)V_N(x_2)}{4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2)} \simeq \frac{V_K^u(x_1)}{V_\pi(x_1)}$$

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

Comparison between data and theory

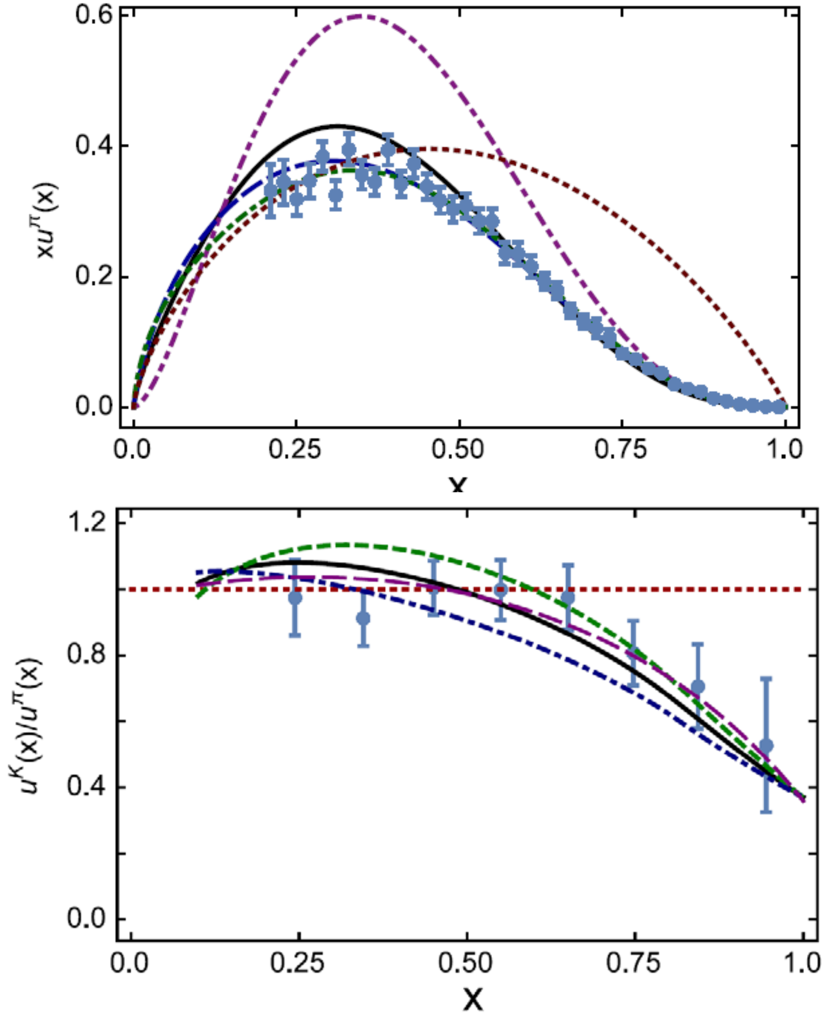
- Nambu-Jona-Lasinio model

Hauturuk, Cloët and Thomas, Phys. Rev. C 94, 035201 (2016).



- Dyson-Schwinger Equation

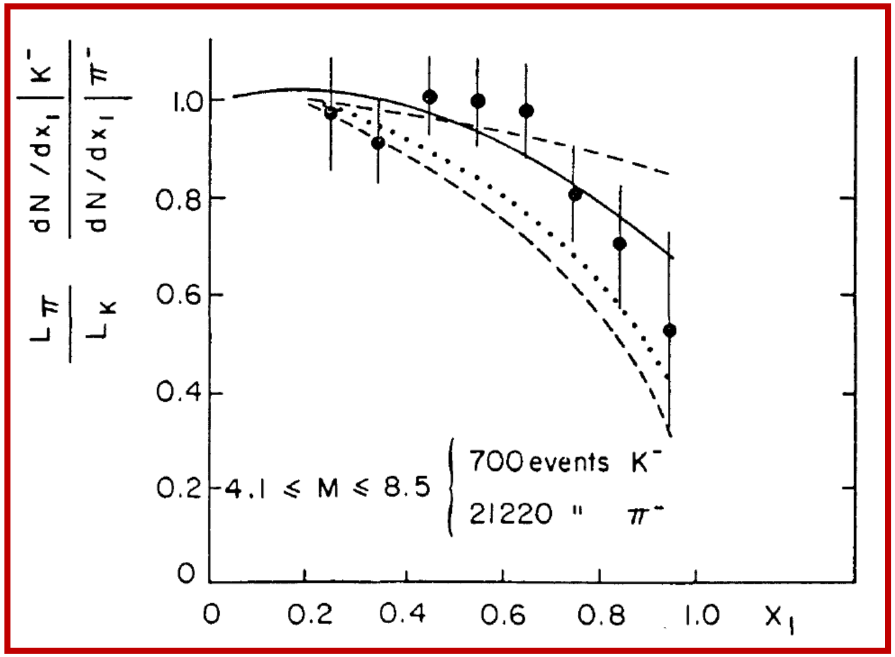
Chen chen et al., Phys. Rev. D 93, 074021 (2016).



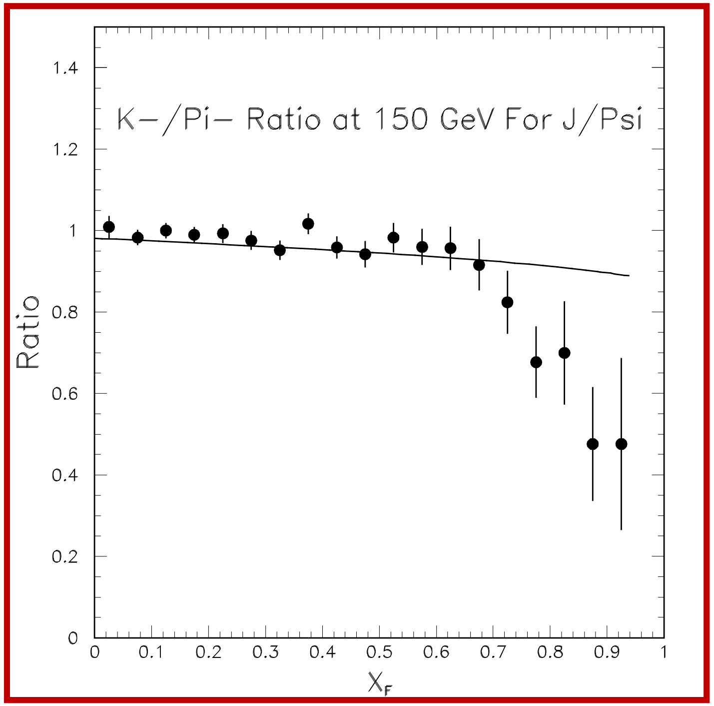
$(K^- + Pt) / (\pi^- + Pt)$ ratios for J/Ψ production

From NA3; 150 GeV, Pt target

Ratios for D-Y



Ratios for J/Ψ

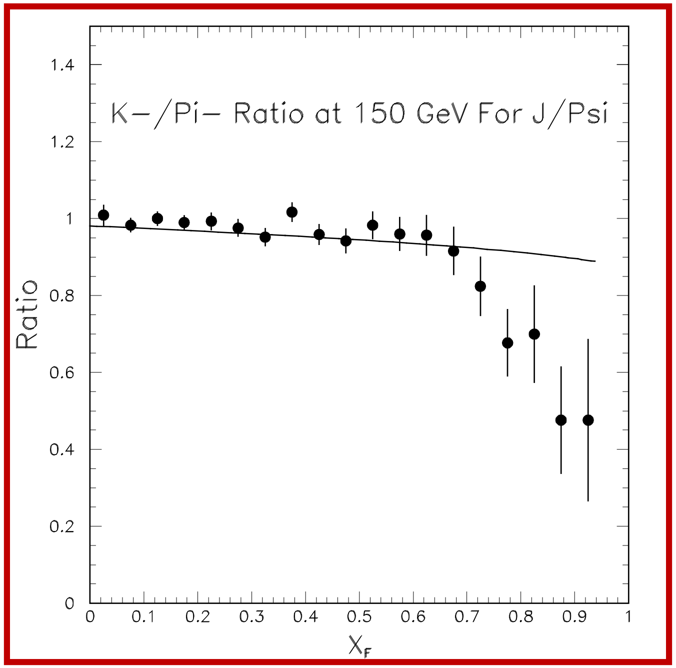


Similar behavior at large x_F for D-Y and J/Ψ production?

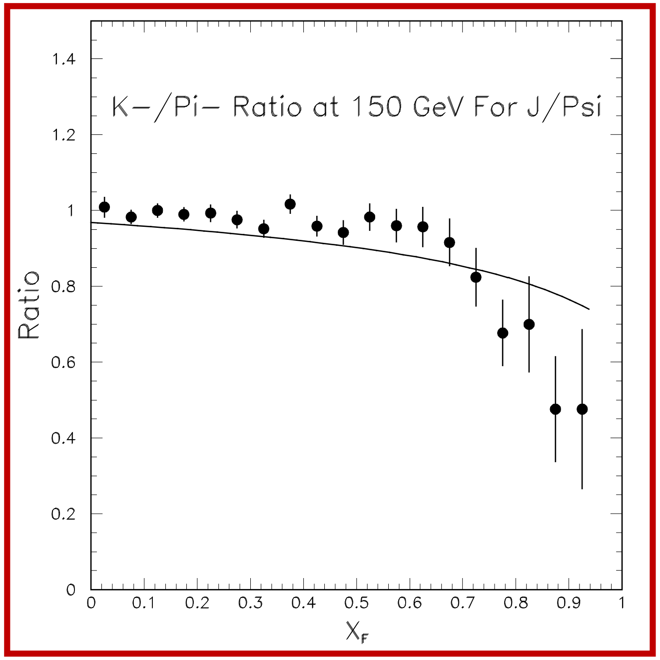
Comparison between data and CEM calculations

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

same pdf for K^- and π^-



modified pdf for K^-

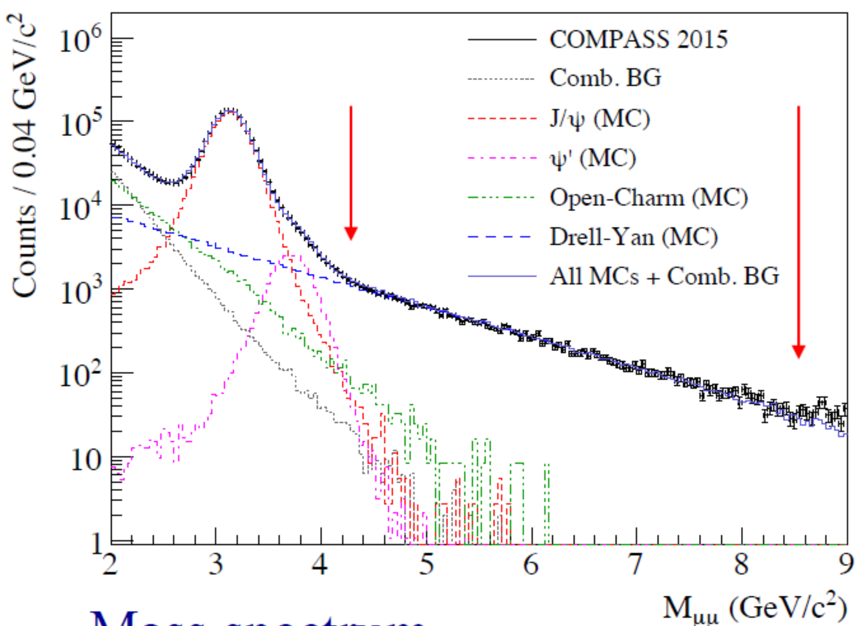


Modified kaon PDF has the ubar valence quark distribution multiplied by $(1-x)^{0.18}$ and the strange quark distribution divided by $(1-x)^{0.18}$

The K / π ratios of J/Ψ production at large x_F might indicate a softer $\bar{u}$ in K^- than in the pion, similar to the D-Y data?

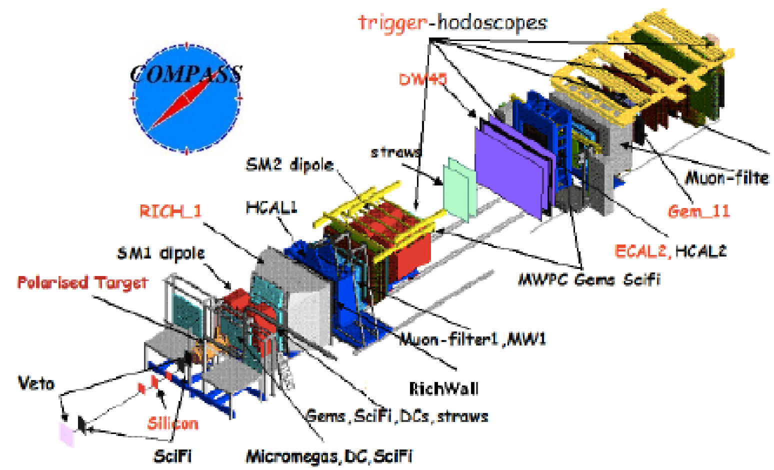
Dilepton data with meson beams at COMPASS

- Drell-Yan data from 2015: 4.3 – 8.5 GeV/c^2



Mass spectrum

190 GeV π^- beam



See talks of M. Perdekamp and W.C. Chang

- Prospect of RF-separated kaon and antiproton beams in the future

Three proton parton distributions describing transverse momentum and/or transverse spin

Three transverse quantities:

1) Nucleon transverse spin

$\vec{S}_{\perp}^{N}$

2) Quark transverse spin

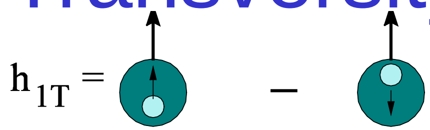
$\vec{s}_{\perp}^{q}$

3) Quark transverse momentum

$\vec{k}_{\perp}^{q}$

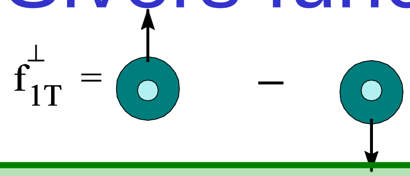
$\Rightarrow$ Three different correlations

1) Transversity



Correlation between $\vec{s}_{\perp}^{q}$ and $\vec{S}_{\perp}^{N}$

2) Sivers function



Correlation between $\vec{S}_{\perp}^{N}$ and $\vec{k}_{\perp}^{q}$

3) Boer-Mulders function

Correlation between $\vec{s}_{\perp}^{q}$ and $\vec{k}_{\perp}^{q}$

One pion parton distribution describing transverse momentum and transverse spin

Two transverse quantities:

1) Quark transverse spin

$$\vec{s}_\perp^{\,q}$$

2) Quark transverse momentum

$$\vec{k}_\perp^{\,q}$$

$\Rightarrow$ One correlation

1) Boer-Mulders function

$h_1^\perp$ =

Correlation between $\vec{s}_\perp^{\,q}$ and $\vec{k}_\perp^{\,q}$

It can be measured in Drell-Yan process

Boer-Mulders functions:

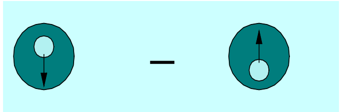
- Unpolarized Drell-Yan:

$$d\sigma_{DY} \propto h_1^{\perp}(x_q) h_1^{\perp}(x_{\bar{q}}) \cos(2\phi)$$

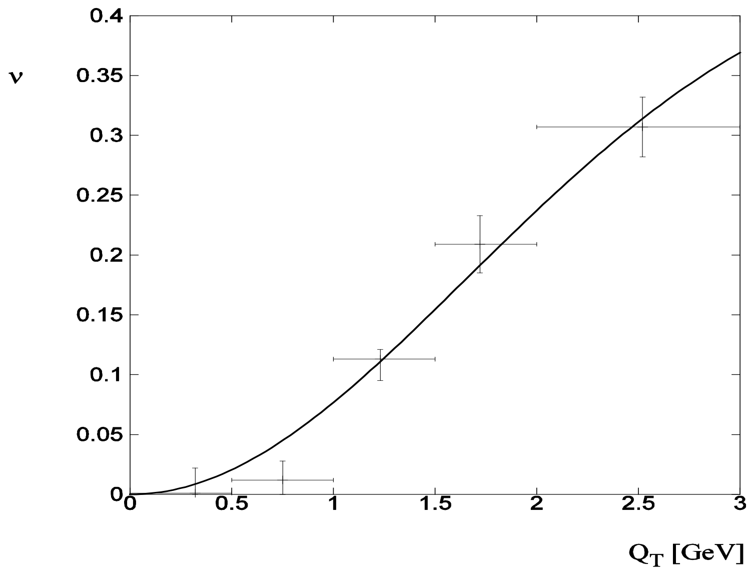
- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY (Boer-Mulders and Sivers functions)

Remains to be tested experimentally!

Boer-Mulders function $h_1^{\perp}$



- $h_1^{\perp}$ represents a correlation between quark's k_T and transverse spin in an unpolarized hadron (analogous to Collins function)
- $h_1^{\perp}$ is a time-reversal odd, chiral-odd TMD parton distribution
- $h_1^{\perp}$ can lead to an azimuthal dependence with $\nu \propto \left(\frac{h_1^{\perp}}{f_1}\right)\left(\frac{\bar{h}_1^{\perp}}{\bar{f}_1}\right)$



$$h_1^{\perp}(x, k_T^2) = \frac{\alpha_T}{\pi} c_H \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x)$$

$$\nu = 16\kappa_1 \frac{Q_T^2 M_C^2}{(Q_T^2 + 4M_C^2)^2}$$

Boer, PRD 60 (1999) 014012

$\kappa_1 = 0.47$, $M_C = 2.3$ GeV

$\nu > 0$ implies valence BM functions for pion and nucleon have same signs

Can one test the predicted sign-change from DIS to D-Y for pion's B-M function?

1) From NA10 pion Drell-Yan data, one deduces that the product of the pion valence quark B-M function and the proton valence quark B-M function is positive. Using *u*-quark dominance, we have:

$$h_{1,u}^{\perp,DY}(p) * h_{1,u}^{\perp,DY}(\pi) > 0$$

Therefore, either a) $h_{1,u}^{\perp,DY}(p) > 0;\ h_{1,u}^{\perp,DY}(\pi) > 0 \quad (sign - change)$

or b) $h_{1,u}^{\perp,DY}(p) < 0;\ h_{1,u}^{\perp,DY}(\pi) < 0 \quad (no\, sign - change)$

2) In polarized $\pi - p$ D-Y, the $\sin(\phi + \phi_S)$ modulation is sensitive to the sign of $h_{1,u}^{\perp,DY}(\pi)$ (being measured at COMPASS)

3) Need to measure the sign of pion's B-M function in DIS

HOW?

SIDIS on the meson cloud of proton at EIC

TSIDIS (Tagged Semi-Inclusive DIS)

TSIDIS

$$e^- + p \to e^{-\prime} + n + \pi^\pm + x$$

underlying process:

$$e^- + \pi^+ \to e^{-\prime} + \pi^\pm + x$$

1) An independent check of pion's PDF

2) Could allow valence-sea flavor separation

Detected π^- is most likely from $\bar{u}$ (or d) sea in π^+

Detected π^+ is most likely from valence u (or $\bar{d}$) in π^+

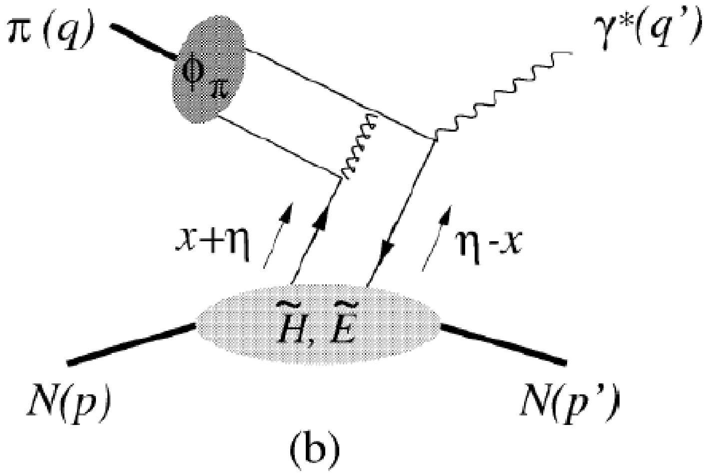
3) Pion B-M function is extracted from $\cos 2\phi$ modulation

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 ($\tilde{H}, \tilde{E}$)



Bjorken variable $\tau = \frac{Q'^2}{s-M^2}$

skewness $\eta = \frac{(p-p')^+}{(p+p')^+} = \frac{\tau}{2-\tau}$

$$\frac{d\sigma}{dQ'^2\, dt\, d(\cos\theta)\, d\varphi} = \frac{\alpha_{em}}{256\,\pi^3} \frac{\tau^2}{Q'^6} \sum_{\lambda',\lambda} |M^{0\lambda',\lambda}|^2 \sin^2\theta$$

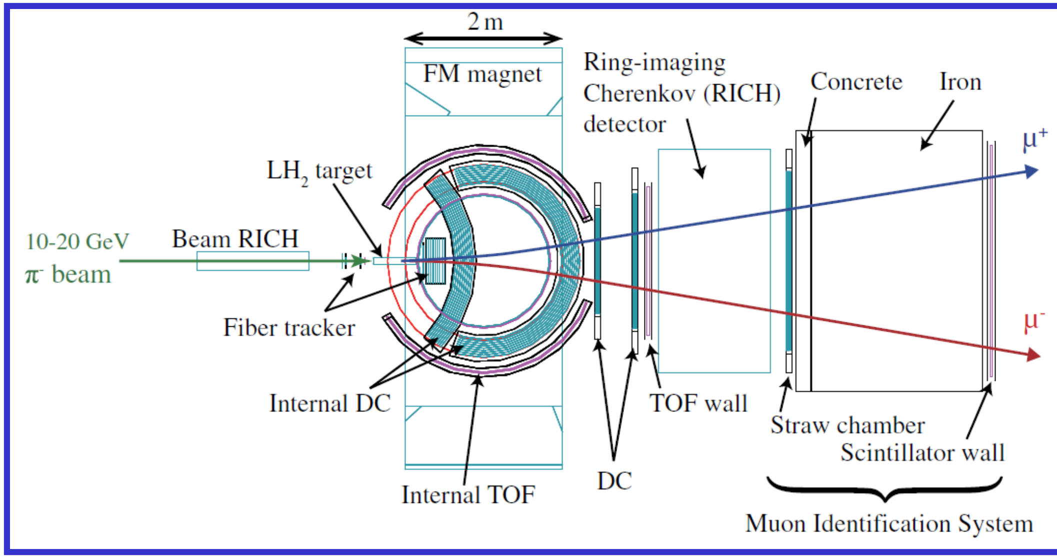
$$M^{0\lambda',\lambda}(\pi^- p \to \gamma^* n) = -ie\frac{4\pi}{3}\frac{f_\pi}{Q'}\frac{1}{(p+p')^+}\bar{u}(p',\lambda')\left[\gamma^+\gamma_5\, \tilde{\mathcal{H}}^{du}(\eta,t) + \gamma_5 \frac{(p'-p)^+}{2M}\, \tilde{\mathcal{E}}^{du}(\eta,t)\right] u(p,\lambda)$$

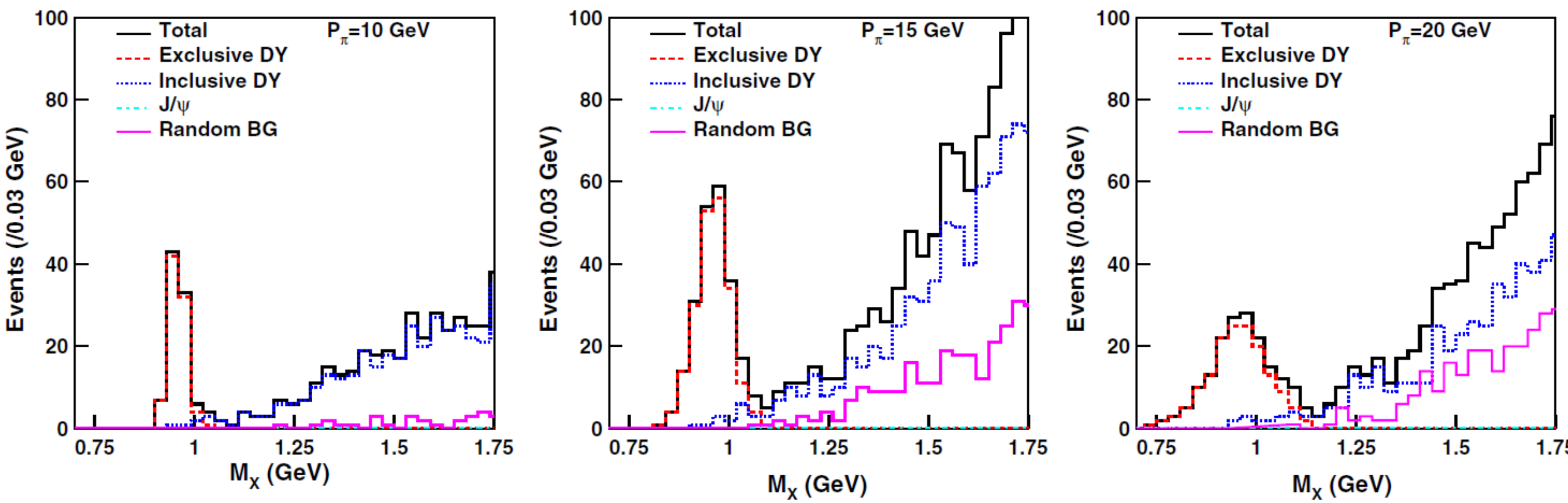
$$\tilde{\mathcal{H}}^{du}(\eta,t) = \frac{8\alpha_S}{3}\int_{-1}^{1} dz\, \frac{\phi_\pi(z)}{1-z^2}\int_{-1}^{1} dx\, \left[\frac{e_d}{-\eta-x-i\epsilon} - \frac{e_u}{-\eta+x-i\epsilon}\right]\left[\tilde{H}^d(x,\eta,t) - \tilde{H}^u(x,\eta,t)\right]$$

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

- Meson and Kaon parton distributions
  - * New territory for theory and experiment
  - * Unique opportunity at COMPASS
  - * Complementary to JLab/EIC tagged DIS programs
- Pion's TMD (Boer-Mulders function)
  - * Test sign-change prediction for pion B-M function
- Exclusive Drell-Yan with π^- and K^- beams
  - * Probe pion and kaon distribution amplitudes
  - * First measurement seems feasible at J-PARC