Meson Structure from Dilepton Production

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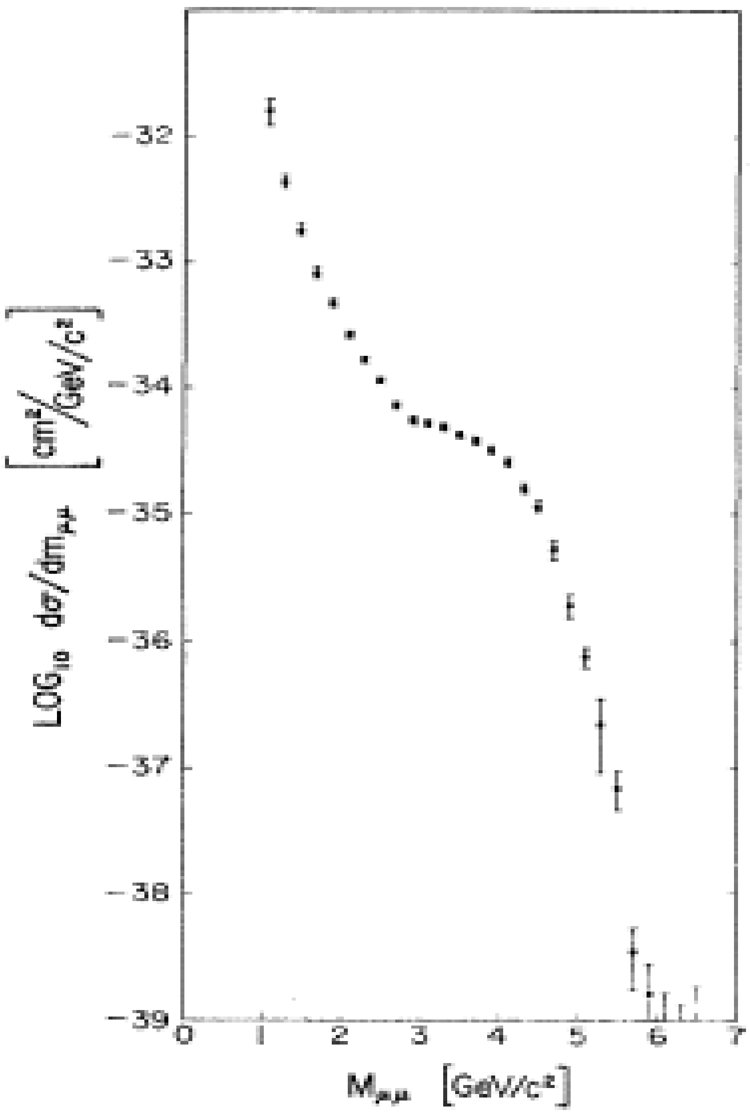
In collaboration with Wen-Chen Chang, Stephane Platchkov and Takahiro Sawada

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

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)

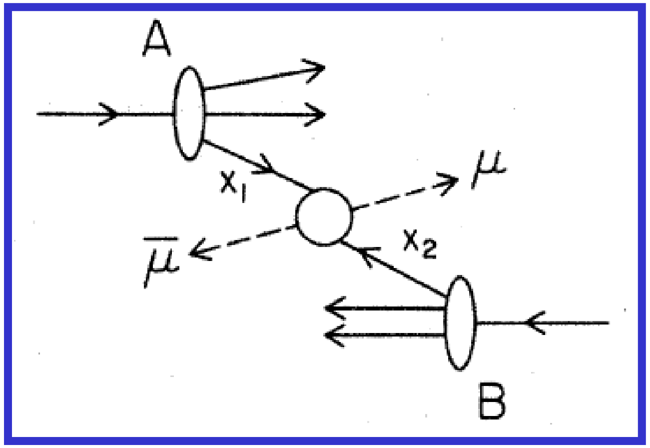
Missed the J/Ψ signal !

"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), $(\gamma\rho)$ 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. (In particular no rela-

List of Drell-Yan experiments with π^- beam

Exp	P (GeV)	targets	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

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	

Drell-Yan experiments with K^- beam

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

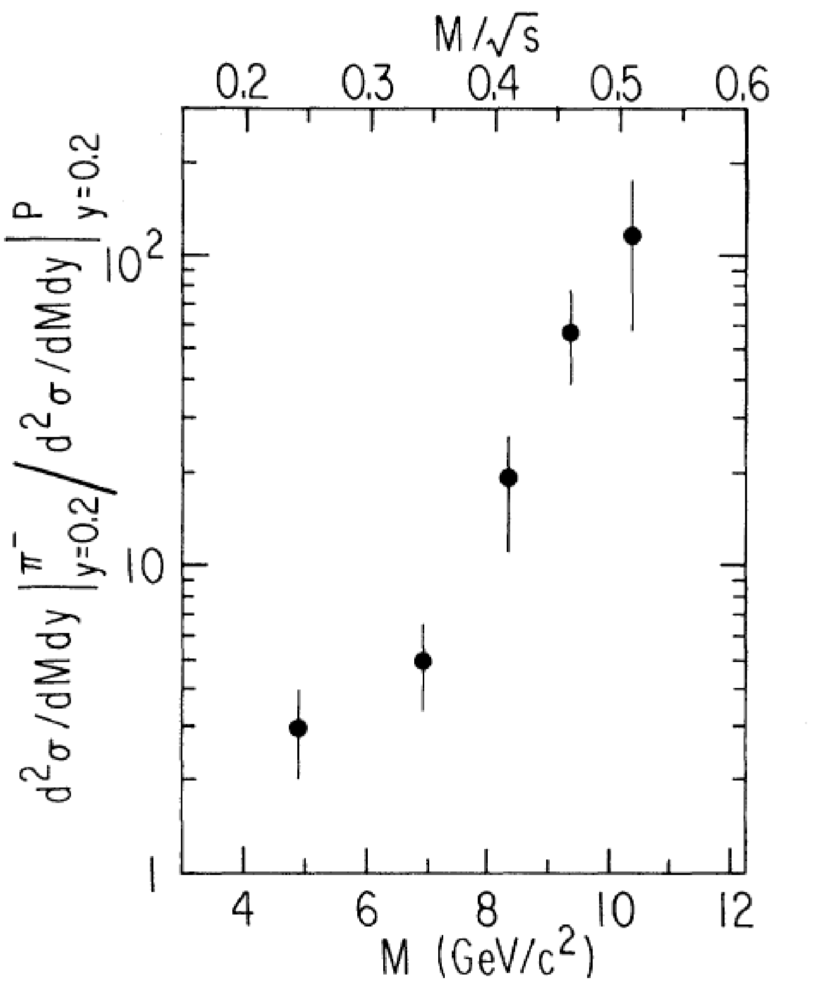
Drell-Yan experiments with K^+ beam

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



From E331/E444

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

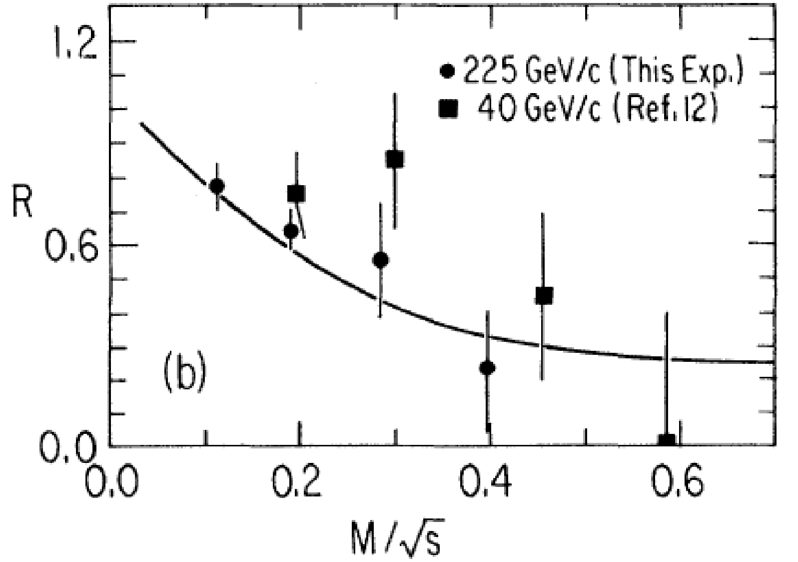
$$\simeq \frac{4\bar{u}_\pi(x_1)u_N(x_2) + d_\pi(x_1)\bar{d}_N(x_2)}{4u_p(x_1)\bar{u}_N(x_2) + d_p(x_1)\bar{d}_N(x_2)}$$

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

Rapid rise in R at large M reflects the valence/sea ratio:

$$\frac{u_N(x_2)}{\bar{u}_N(x_2)}$$

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



From E331/E444

Defining

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

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

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

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

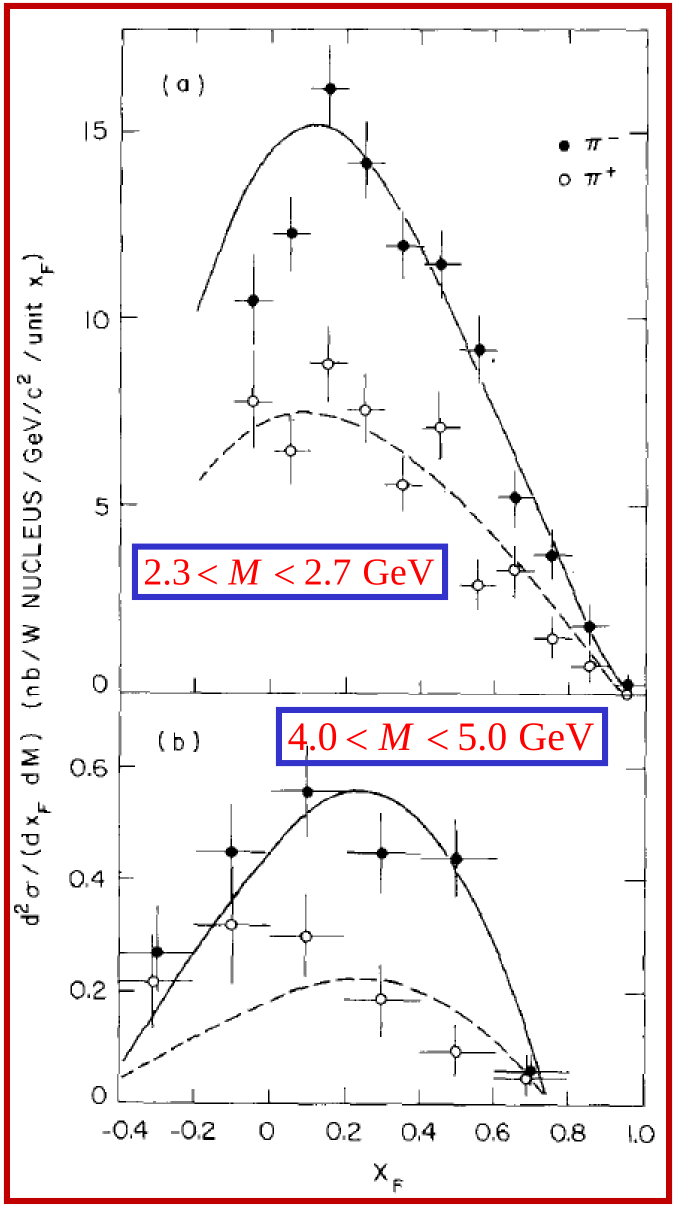
Considering only the u and d flavors:

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

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

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

$(\pi^- + W)$ versus $(\pi^+ + W)$ Drell-Yan cross sections

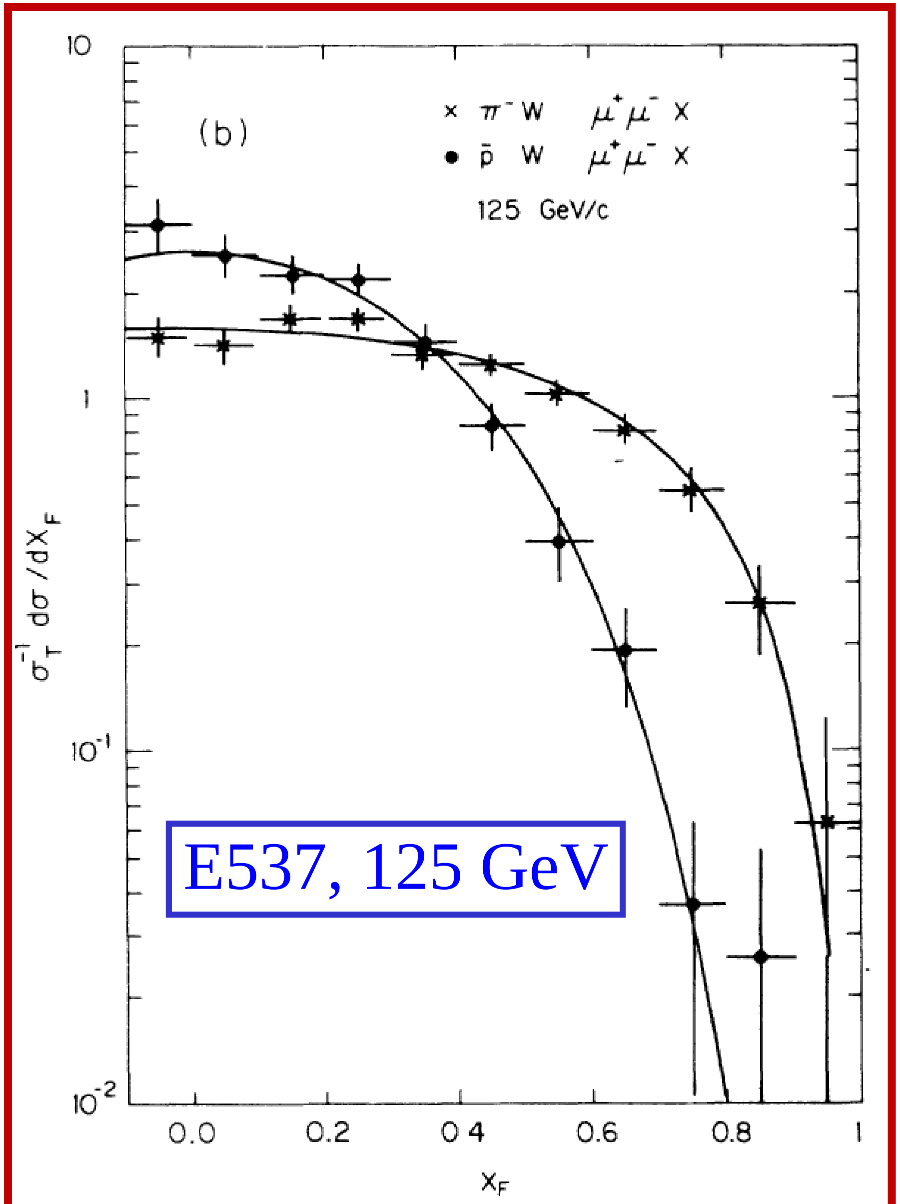


WA39, 40 GeV

$$\sigma(\pi^- + W) > \sigma(\pi^+ + W)$$

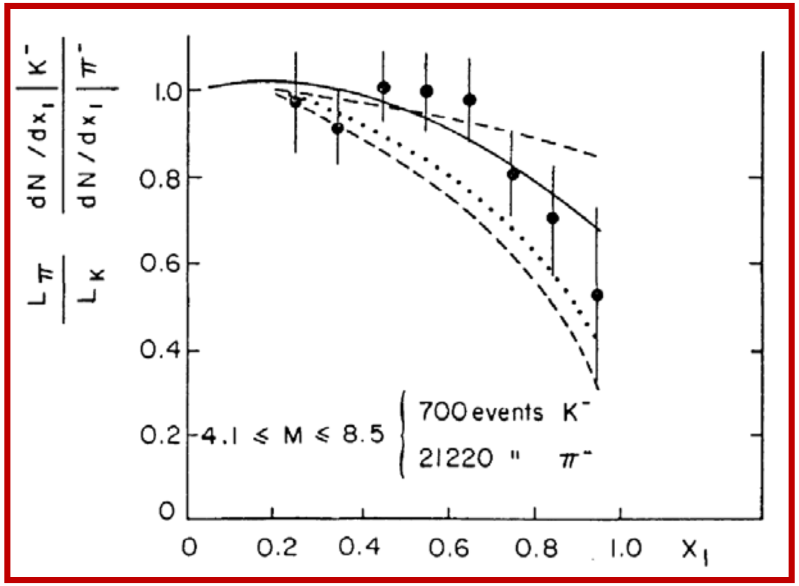
eV

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



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

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



From NA3; 150 GeV, Pt target

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

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

$$V^u_K(x) = \bar{u}^V_{K^-}(x); \quad V^s_K(x) = s^V_{K^-}(x)$$

$$S_K(x) = u_{K^-}(x) = \bar{d}_{K^-}(x) = s_{K^-}(x)$$

$$V_N(x) = [u^V_p(x) + d^V_p(x)]/2$$

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

Ignoring the sea-sea terms:

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

$$\simeq \frac{4V^u_K(x_1)V_N(x_2) + 4V^u_K(x_1)S_N(x_2) + V^s_K(x_1)s_p(x_2) + 5S_K(x_1)V_N(x_2)}{4V_\pi(x_1)V_N(x_2) + 5S_\pi(x_1)V_N(x_2) + 5V_\pi(x_1)S_N(x_2)} \simeq \frac{V^u_K(x_1)}{V_\pi(x_1)}$$

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

Difference of $(\pi^- + D)$ and $(\pi^+ + D)$ Drell-Yan cross sections

Defining

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

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

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

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

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

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

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

Only the valence-quark term remain!

- Only very low statistics data for $\sigma_{DY}(\pi^+ + D)$ are available!
- $\sigma_{DY}(\pi^+ + D)$ is more sensitive to pion's sea-quark content than $\sigma_{DY}(\pi^- + D)$!

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

Difference of $(K^- + D)$ and $(K^+ + D)$ Drell-Yan cross sections

$$V_K^u(x) = \bar{u}_{K^-}^V(x) = \bar{d}_{K^+}^V(x); \quad V_K^s(x) = s_{K^-}^V(x) = \bar{s}_{K^+}^V(x)$$

$$S_K(x) = u_{K^-}(x) = \bar{d}_{K^-}(x) = s_{K^-}(x) = d_{K^+}(x) = \bar{u}_{K^+}(x) = s_{K^+}(x)$$

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

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

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

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

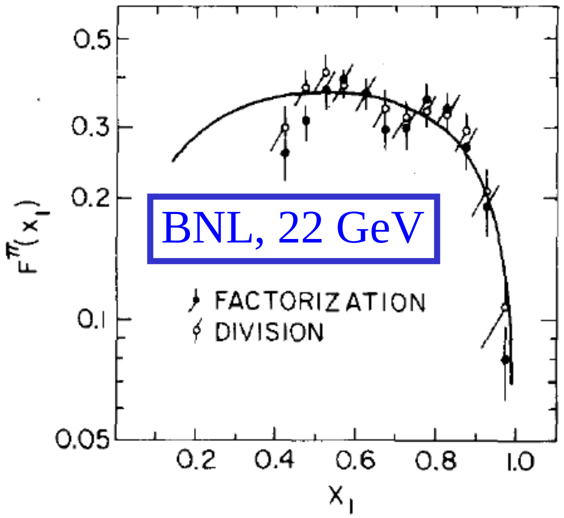
$$\sigma_{DY}(K^- + D) - \sigma_{DY}(K^+ + D) \propto 4V_K^u(x_1)V_N(x_2)$$

Only the valence-quark term remain!

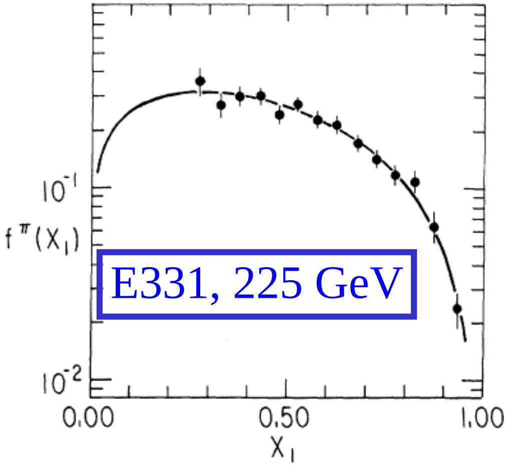
$\sigma_{DY}(K^+ + D)$ is more sensitive to kaon's sea-quark content than $\sigma_{DY}(K^- + D)$ (especially data at low x_1 and large x_2 (negative x_F) region!)

See Londergan al., PL B380 (1996) 393

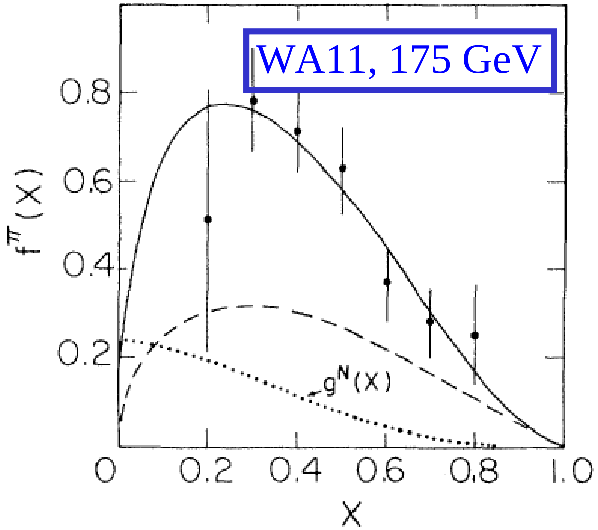
Attemps to extract the pion valence quark distribution



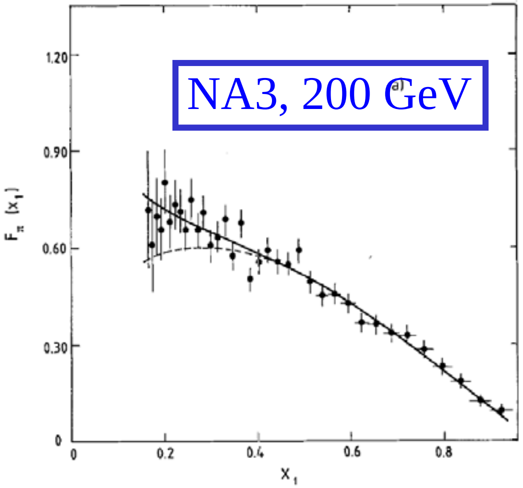
$$F^{\pi}(x) = 0.72x^{0.5}(1-x)^{0.46}$$



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

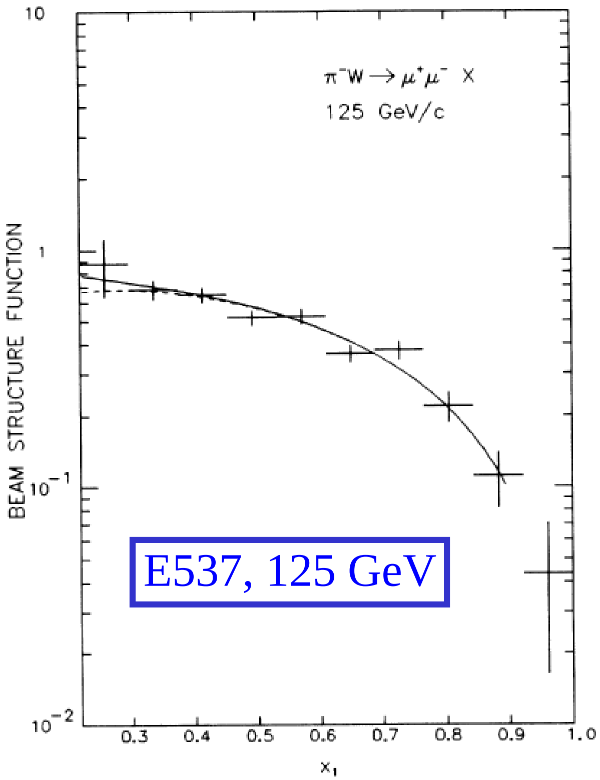


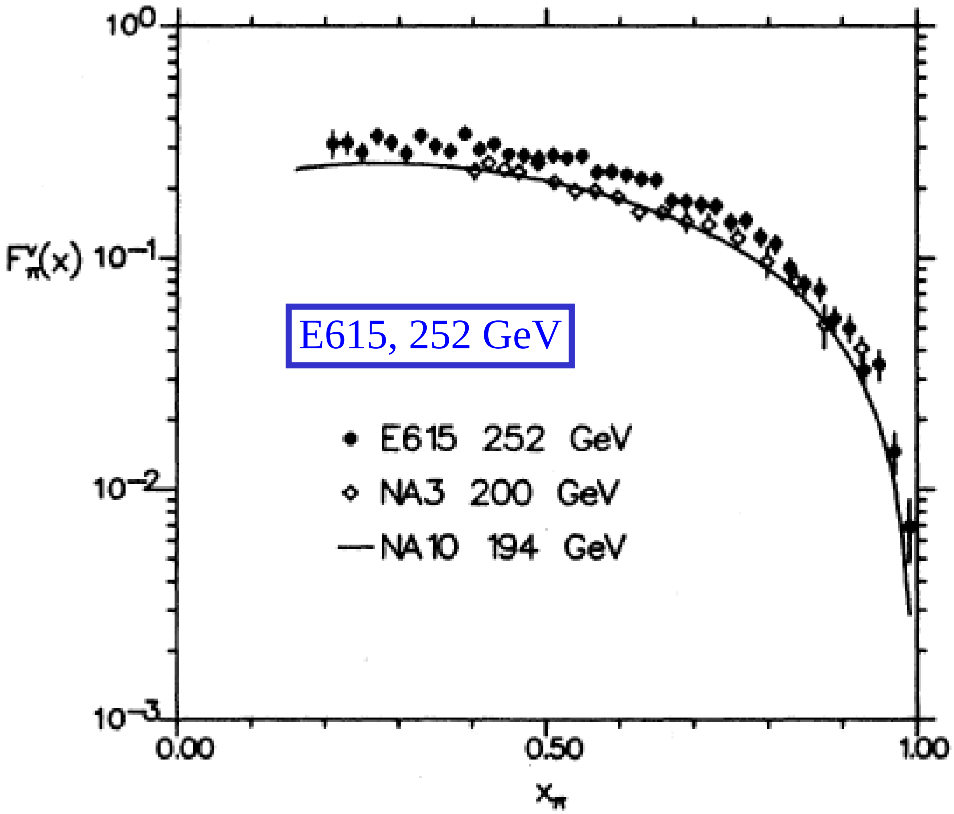
$$F^{\pi}(x) = 2.43x^{0.5}(1-x)^{1.57}$$



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

Attemps to extract the pion valence quark distribution





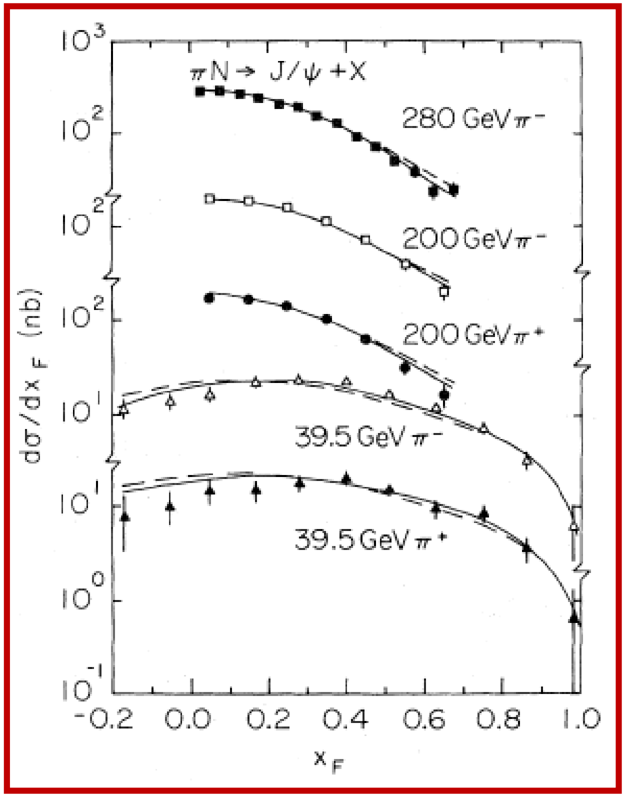
$$F^\pi(x) = Ax^{0.442}(1-x)^{1.248}$$

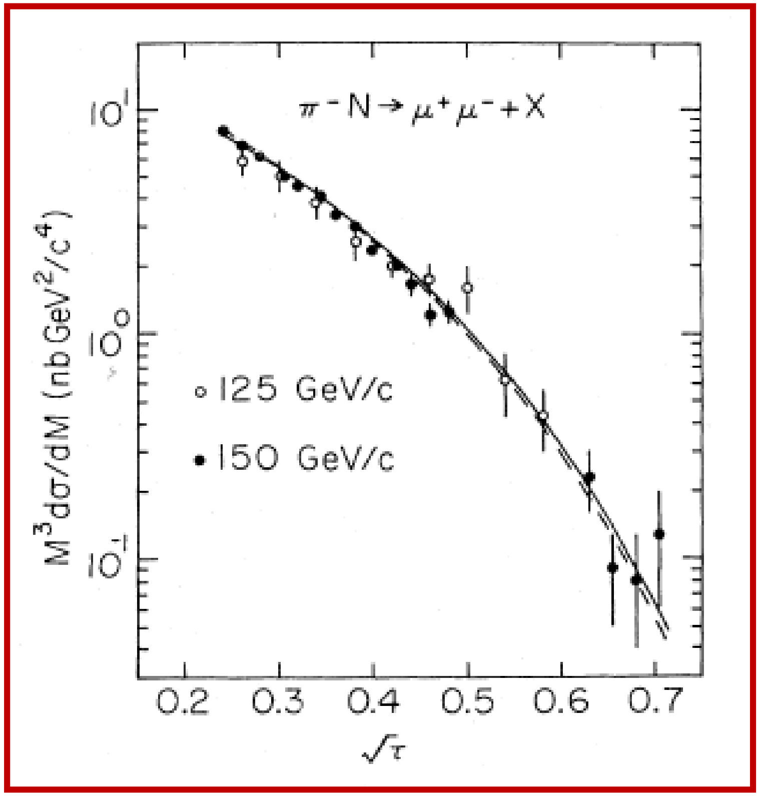
$$F^\pi(x) = Ax^{0.6}(1-x)^{1.26}$$

A global fit to all data is needed

Four pion PDF sets available at LHAPDF library

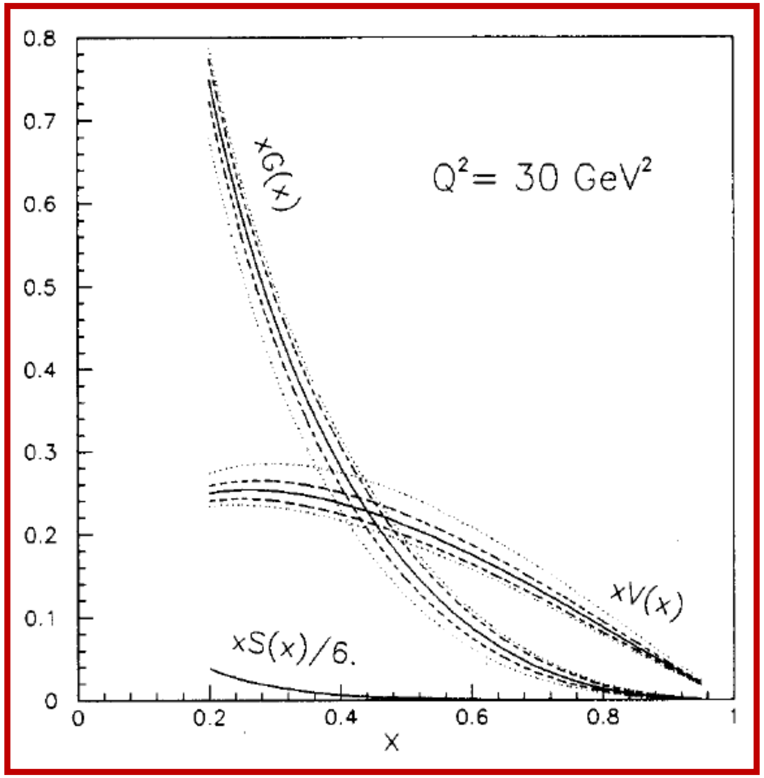
- OW-P (PRD 30, 943 (1984))
  - LO QCD
  - J/Psi data from NA3 and WA39; D-Y data from E537 and NA3





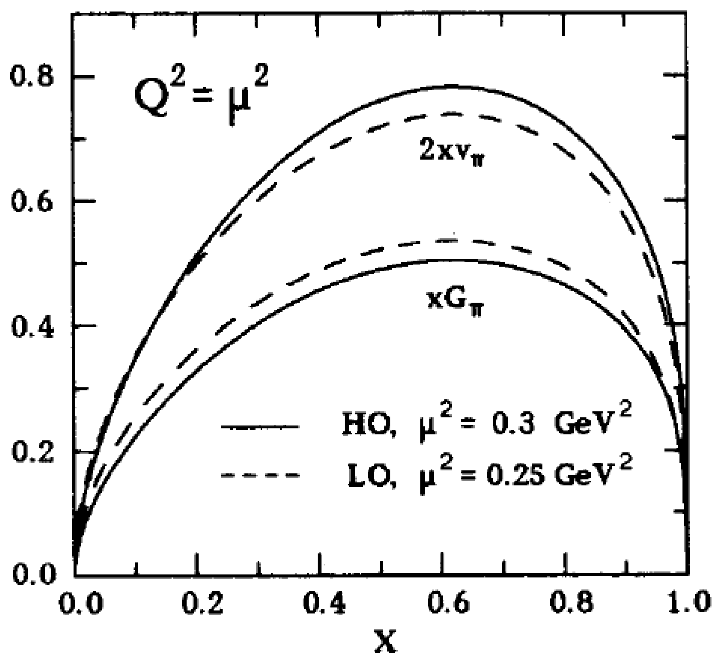
Four pion PDF sets available at LHAPDF library

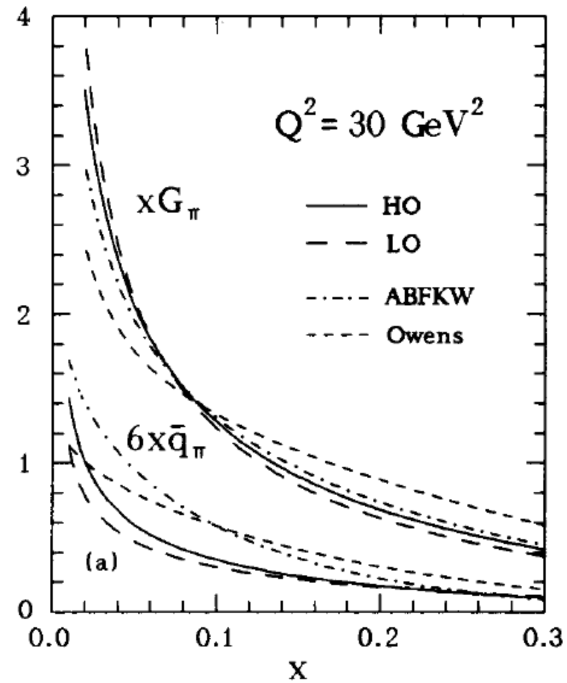
- ABFKW-P (PL 233, 517 (1989))
  - NLO QCD
  - Direct photon data from WA70 and NA24; Sea-quark distribution from NA3



Four pion PDF sets available at LHAPDF library

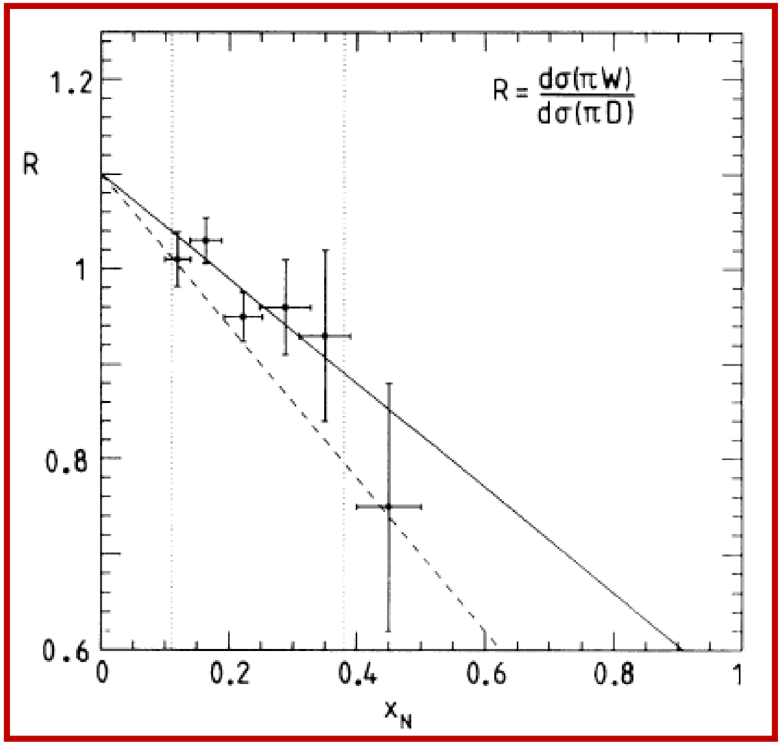
- GRV-P (Z. Phys. C53, 651 (1992))
  - LO and NLO QCD
  - Only valence and valence-like gluon at initial scale. Sea is entirely from QCD evolution

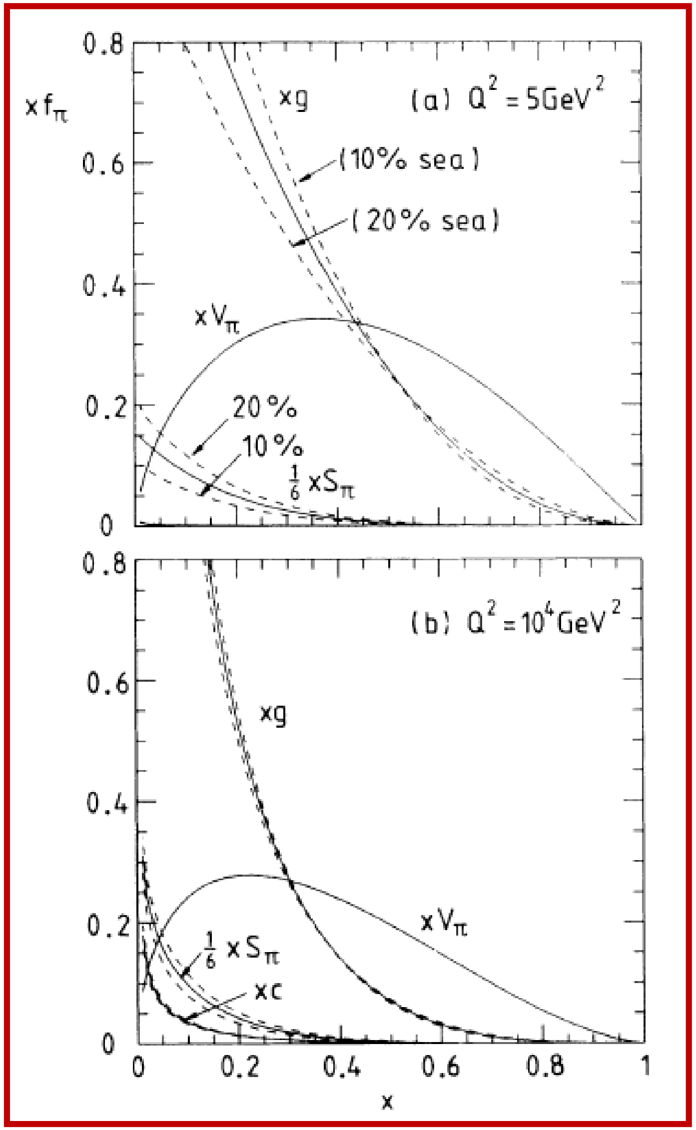




Four pion PDF sets available at LHAPDF library

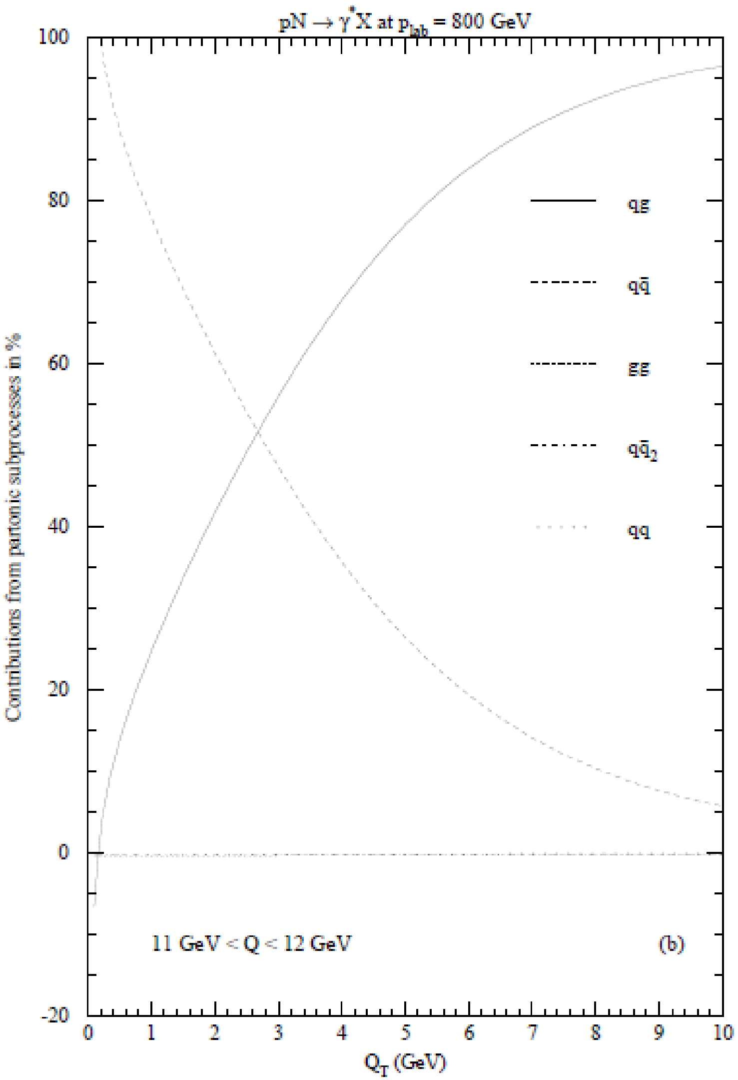
- SMRS-P (PR D45, 2349 (1992))
  - NLO QCD
  - NA10 and E615 D-Y data, WA70 direct photon data





Massive Lepton Pairs as a Prompt Photon Surrogate

Edmond L. Berger[a], Lionel E. Gordon[b,c], and Michael Klasen[a]



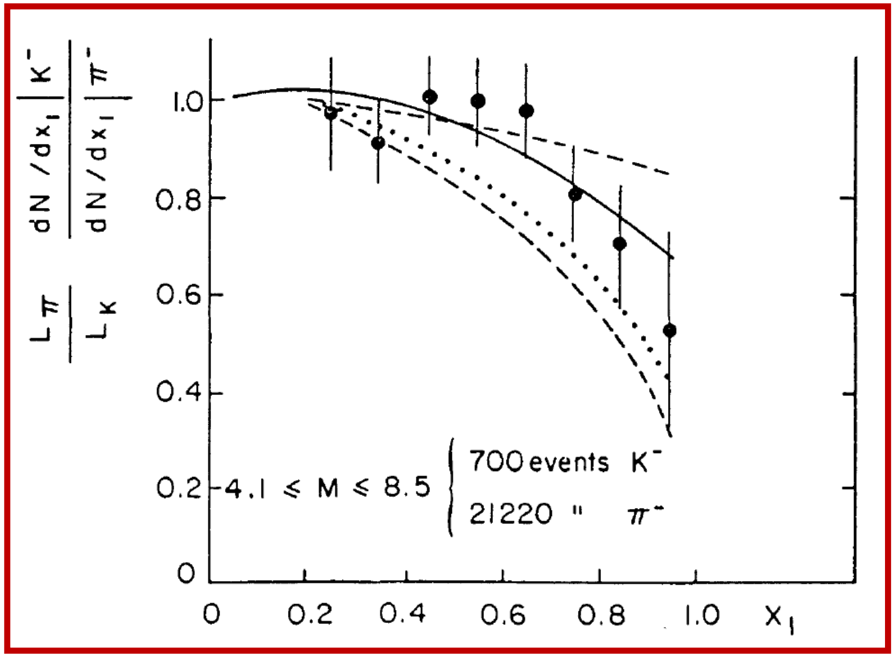
PR D58, 074012 (1998)

Dimuons at high p_T are dominated by quark-gluon process. They are senitive to pion's gluon distribution, just like direct-photon production

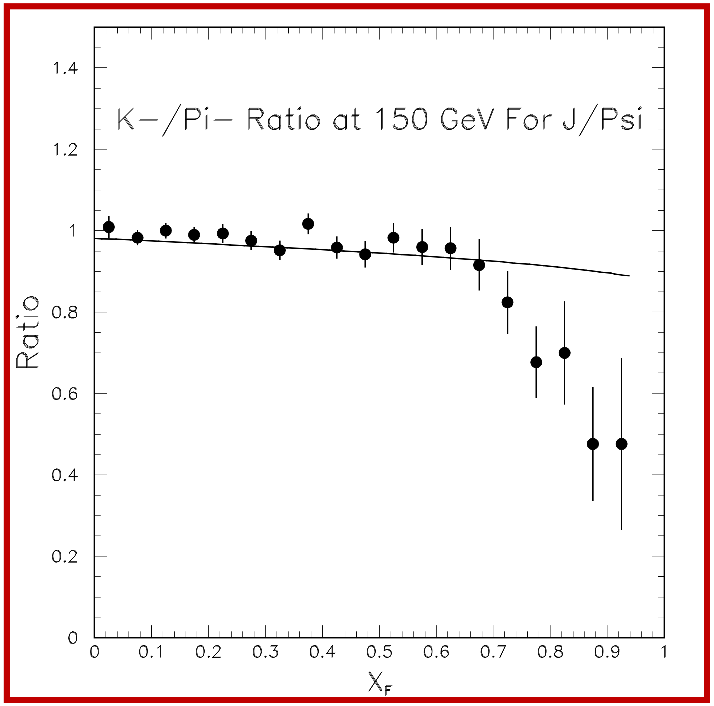
$(K^- + \mathrm{Pt}) / (\pi^- + \mathrm{Pt})$ ratios for J/Ψ production

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?

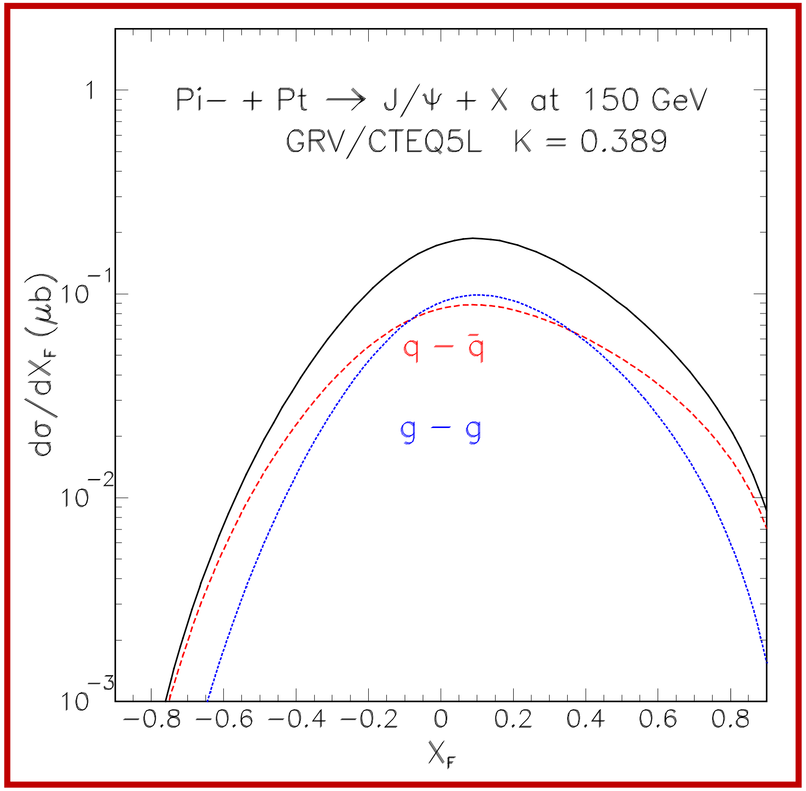
J/Ψ production in the Color Evaporation Model

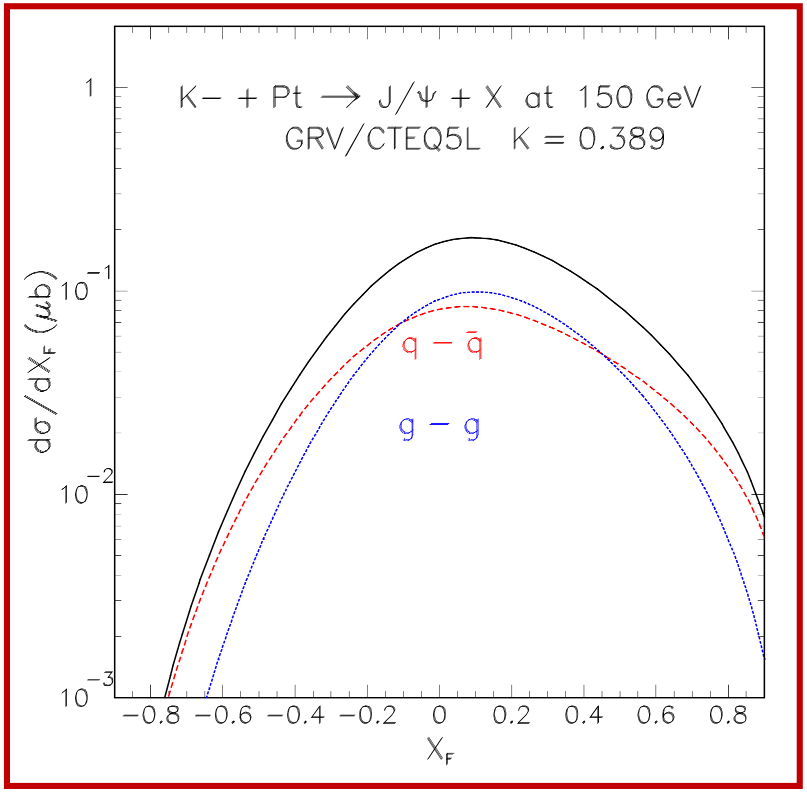
- Use GRV for pion and kaon PDF and CTEQ5L for proton PDF
- Use same normalization factor for pion and kaon beams
- Take into account the proton and neutron numbers in the platinum target
- Compare the calculation with NA3 data

J/Ψ production in the Color Evaporation Model

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

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



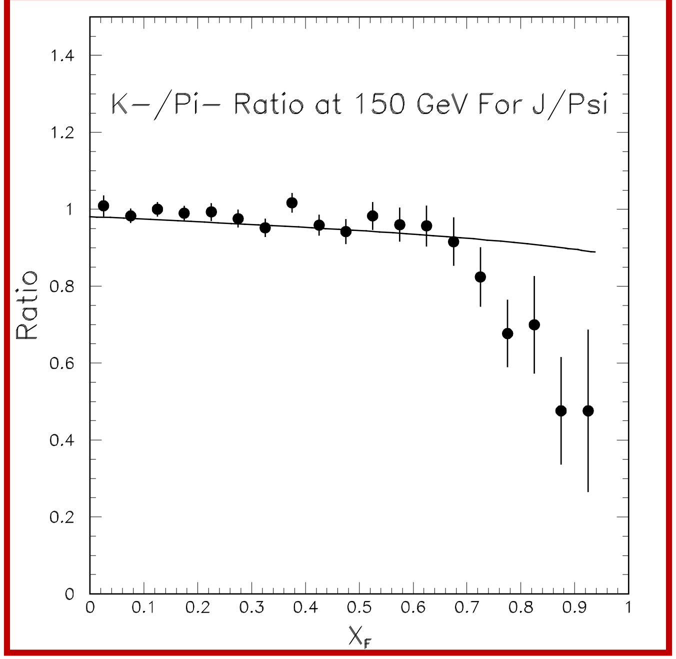


$q-\overline{q}$ annihilation is important at large x_F

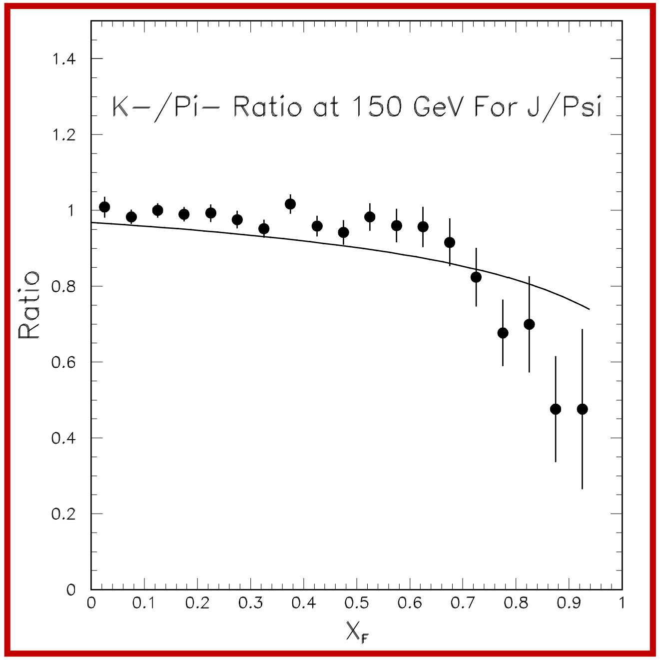
Comparison between data and calculations

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

same pdf for K^- and π^-



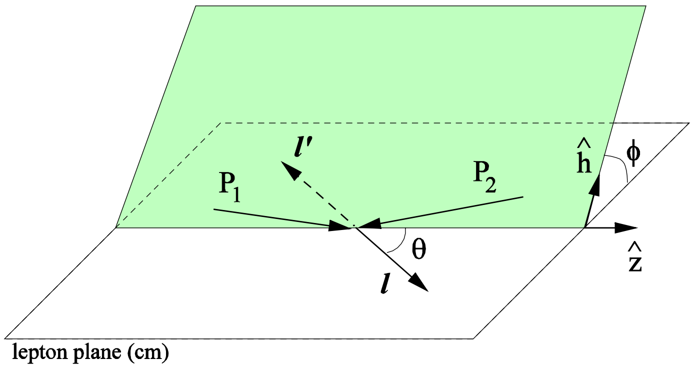
modified pdf for K^-



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

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

Drell-Yan decay angular distributions



$h_1 + h_2 \to \gamma^* + x \to l^+ + l^- + x \quad (q + \overline{q} \to \gamma^*)$

Θ and Φ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest-frame

Collins-Soper frame

A general expression for Drell-Yan decay angular distributions:

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right) = \left[\frac{3}{4\pi}\right]\left[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

"Naive" Drell-Yan (transversely polarized γ^*, no transverse momentum) $\to \lambda = 1,\ \mu = 0,\ \nu = 0$

In general : $\lambda \neq 1,\ \mu \neq 0,\ \nu \neq 0$

Decay angular distributions in pion-induced Drell-Yan

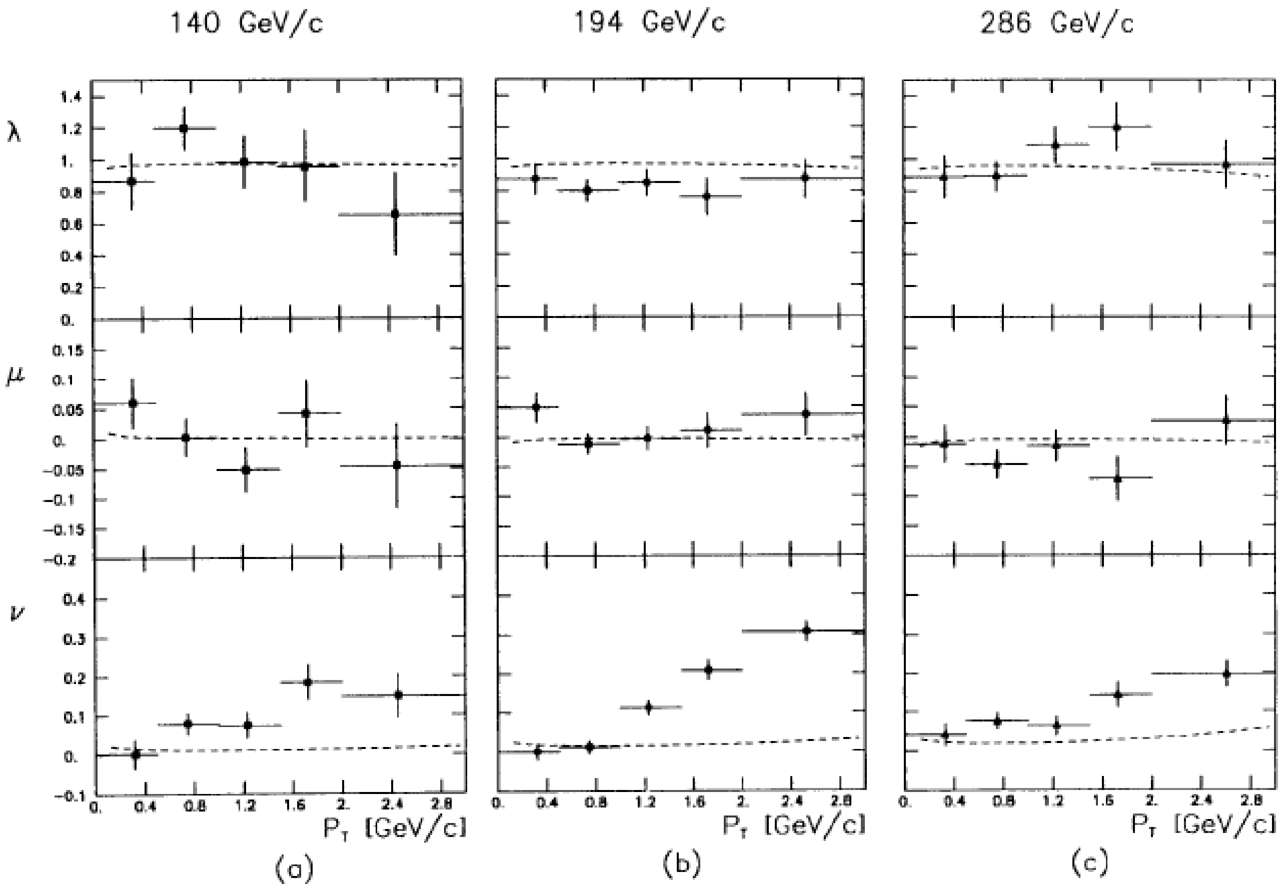


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. **a** 140 GeV/c; **b** 194 GeV/c; **c** 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

NA10 $\pi^- + W$

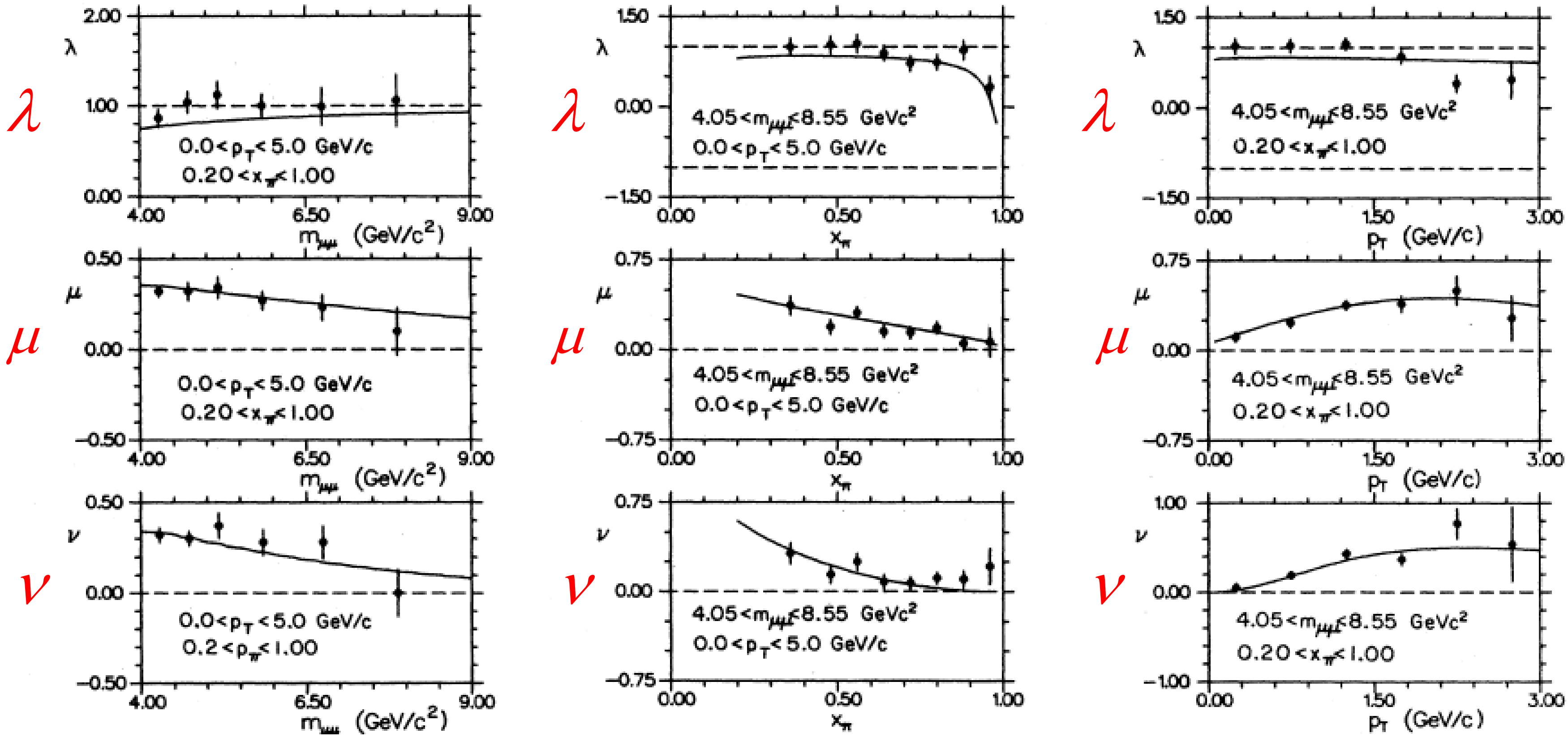
Z. Phys. 37 (1988) 545

Dashed curves are from pQCD calculations

$\nu \neq 0$ and ν increases with p_T

Decay angular distributions in pion-induced Drell-Yan

E615 Data 252 GeV $\pi^- + W$ Phys. Rev. D 39 (1989) 92

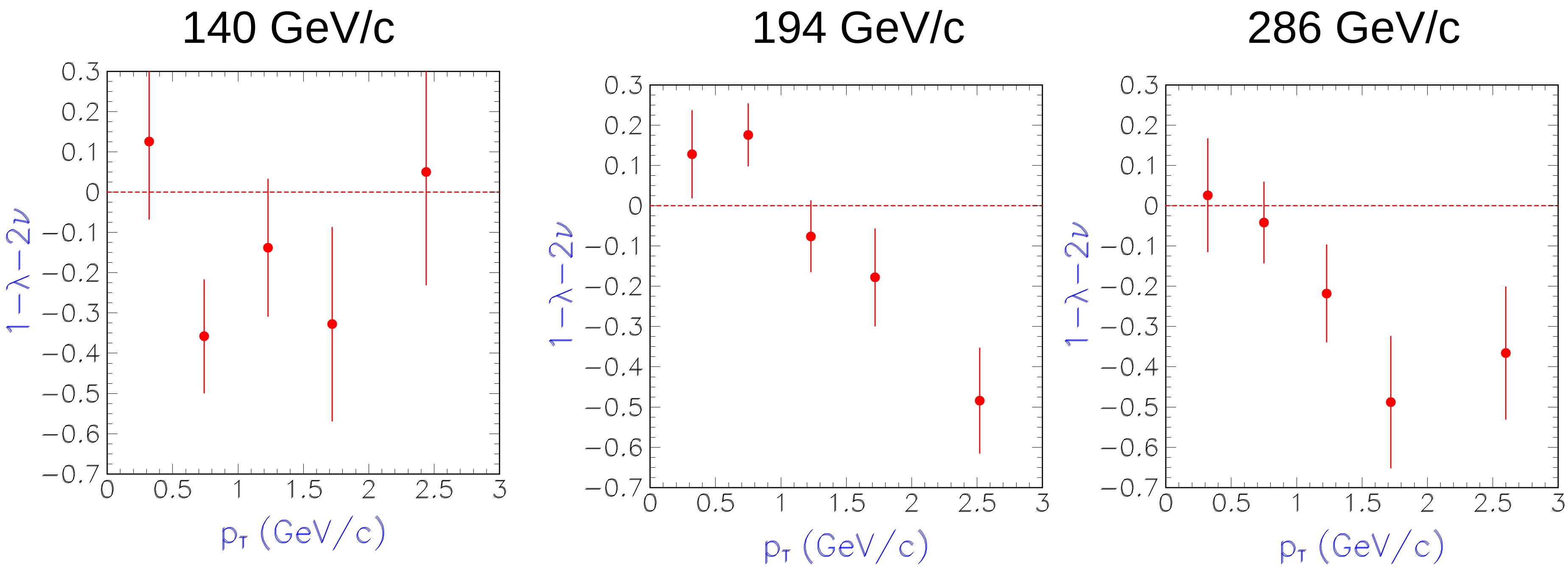


$m_{\mu\mu}$(GeV/c^2) x_π p_T(GeV/c)

$\lambda \neq 1,\ \mu \neq 0,\ \nu \neq 0$ and they vary with $m_{\mu\mu}$, p_T, and x_π

Decay angular distributions in pion-induced Drell-Yan

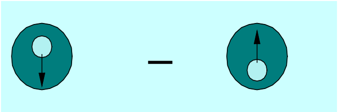
Is the Lam-Tung relation violated?



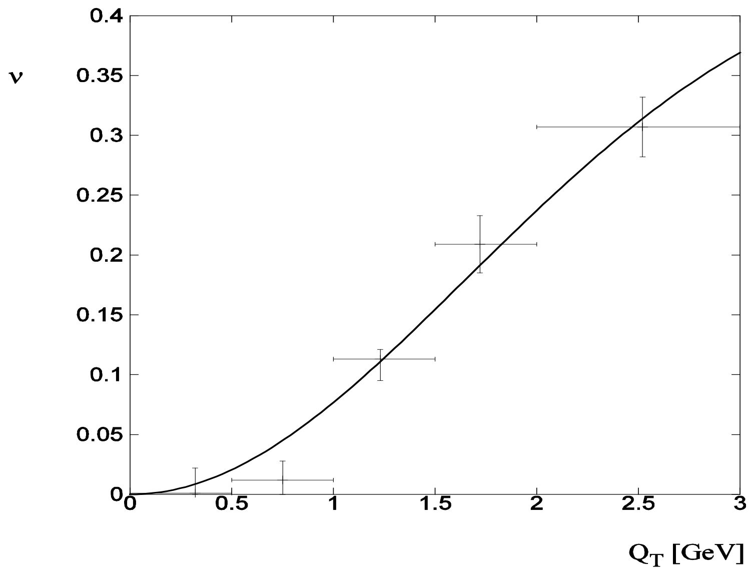
Data from NA10 (Z. Phys. 37 (1988) 545)

Violation of the Lam-Tung relation suggests interesting new origins (Brandenburg, Nachtmann, Mirkes, Brodsky, Khoze, Müller, Eskolar, Hoyer,Väntinnen, Vogt, etc.)

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 $\nu \propto \left(\frac{h_1^\perp}{f_1}\right)\left(\frac{\overline{h}_1^\perp}{\overline{f}_1}\right)$



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

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

Boer, PRD 60 (1999) 014012

κ_1=0.47, M_C=2.3 GeV

ν>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?

From TDIS to TSIDIS at EIC

TSIDIS (Tagged Semi-Inclusive DIS)

TSIDIS

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

underlying process:

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

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^+

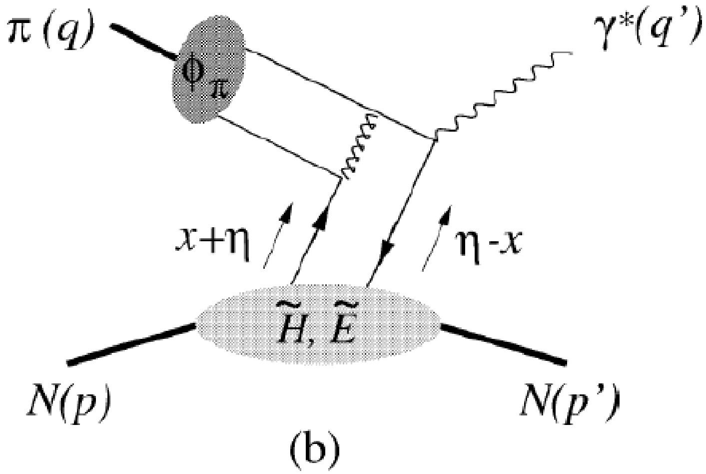
3) Pion B-M function is extracted from $\cos 2\phi$ modultion

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

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

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

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

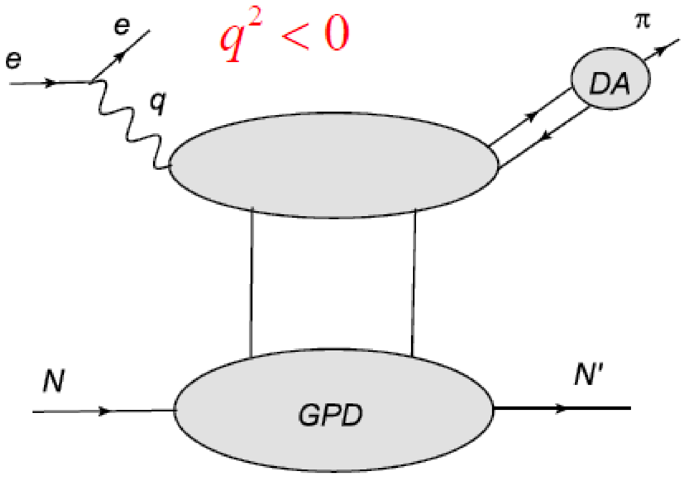
DEMP versus exclusive dilepton production

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

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

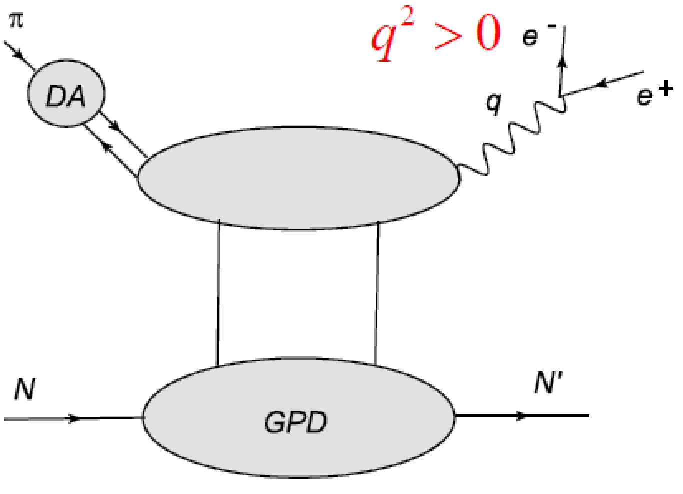
Deep Exclusive Meson Production

Exclusive Dilepton Production



(c)

space-like photon

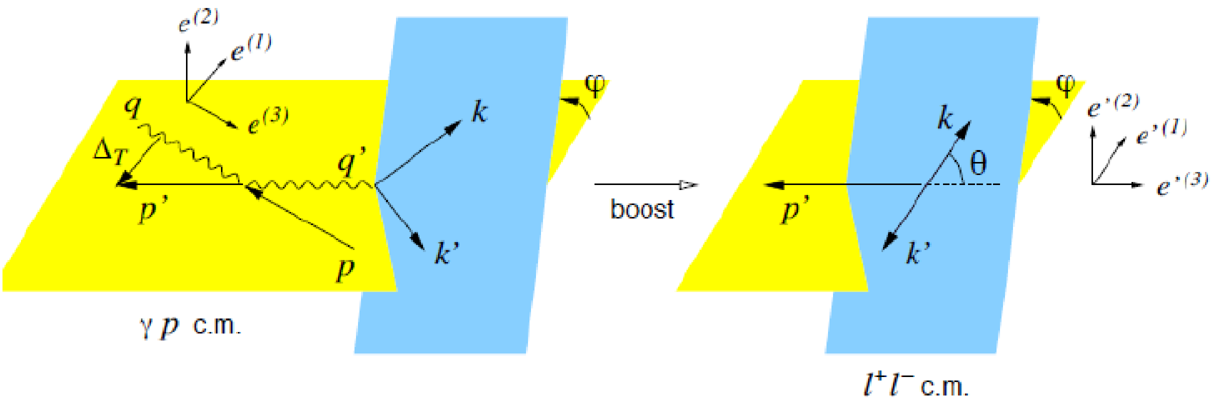


(d)

time-like photon

Longitudinally polarized dilepton is expected

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

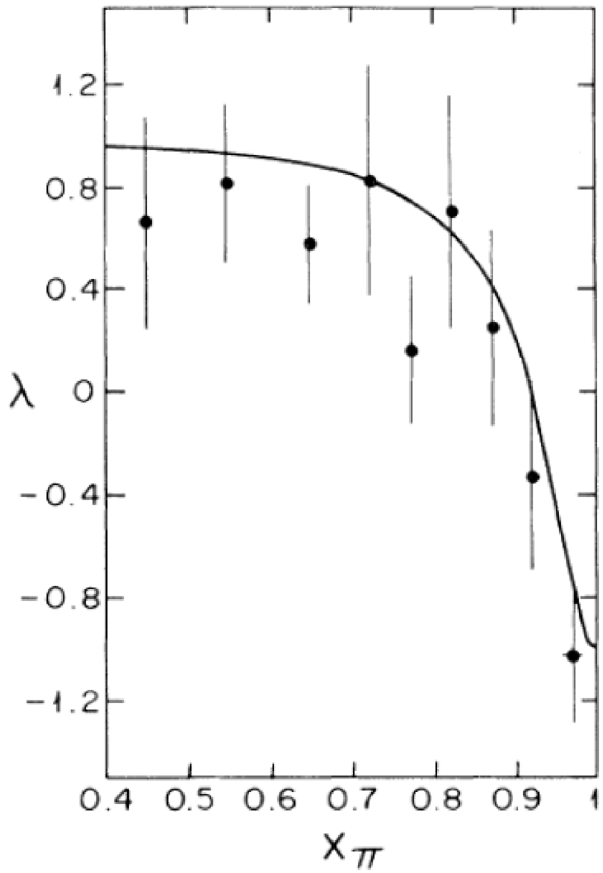


$$\frac{d\sigma}{dQ'^2\, dt\, d(\cos\theta)\, d\varphi} = \frac{\alpha_{em}}{256\,\pi^3} \frac{\tau^2}{Q'^6} \Sigma_{\lambda',\lambda} |M^{0\lambda',\lambda}|^2 \sin^2\theta$$

Crucial Test of the validity of the twist expansion

Transversely polarized dilepton for inclusive Drell-Yan

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



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

$\lambda = 1$: transversely polarized

$\lambda = -1$: longitudinally polarized

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

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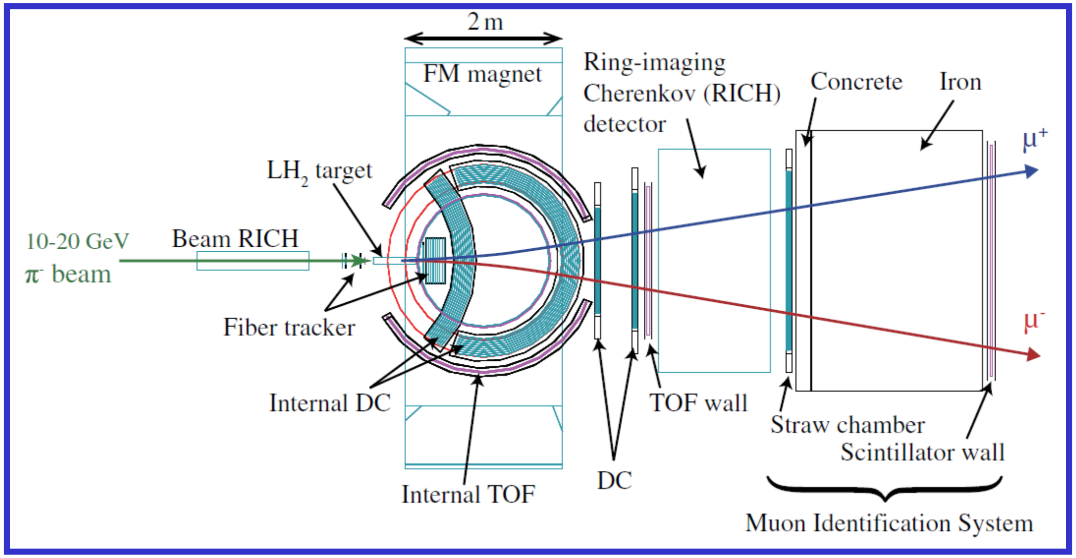
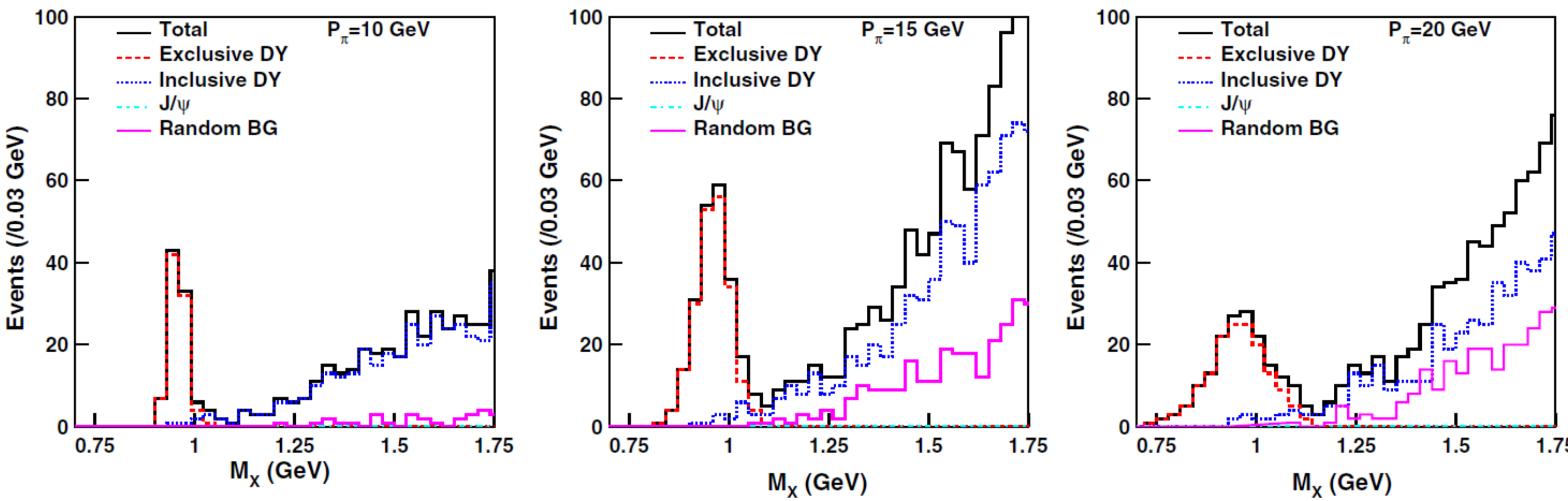
Accessing proton generalized parton distributions and pion distribution amplitudes with the exclusive pion-induced Drell-Yan process at J-PARC





Summary and future Prospect

- Pion valence-quark distribution
  - * Need more data on $\pi^- + D$ and $\pi^- + p$ (to minimize nuclear effects)
  - * Need more data on $\pi^+ + D$ (to isolate valence quark distribution from $\sigma(\pi^- + D) - \sigma(\pi^+ + D)$)
- Pion sea-quark distribution
  - * Need more data on $\pi^+ + D$ at negative x_F
- Pion gluon distribution
  - * Need low-mass high-p_T Drell-Yan data on $\pi^+ + D$ (where q-G process dominates)

Summary and future Prospect

- Kaon parton distributions
  - ∗ Need D-Y data on $K^- + D$ and $K^+ + D$ (see talk by Stephane Platchkov)
  - ∗ Need J/Ψ data on $K^- + D$ and $K^+ + D$ (to probe both the valence-quark and gluon distribution of kaon)
- Pion's Boer-Mulders function
  - ∗ Feasibility to measure TSIDIS at EIC?
  - ∗ 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