Parton distribution functions of π and K from J/Ψ production and updates on plans at COMPASS and J-PARC

Jen-Chieh Peng

University of Illinois at Urbana-Champaign

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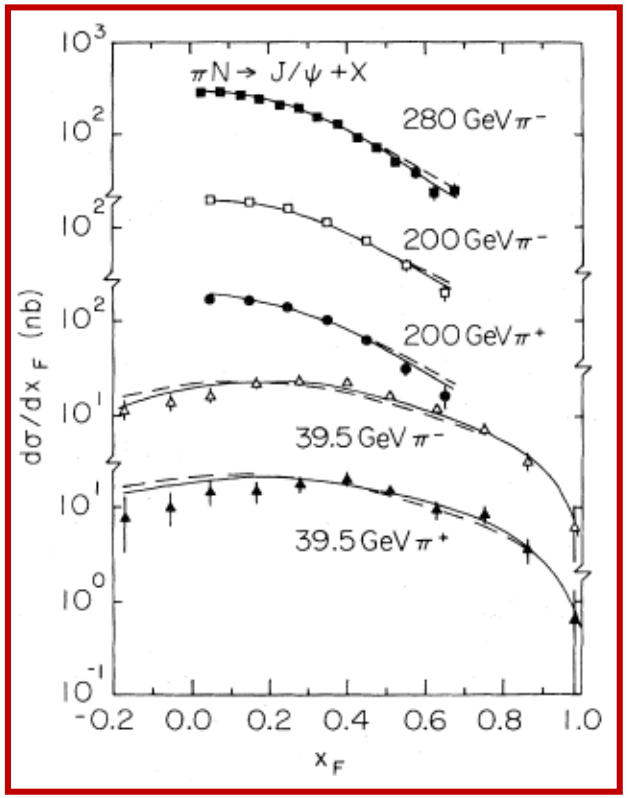
Catholic University, May 24-25, 2018

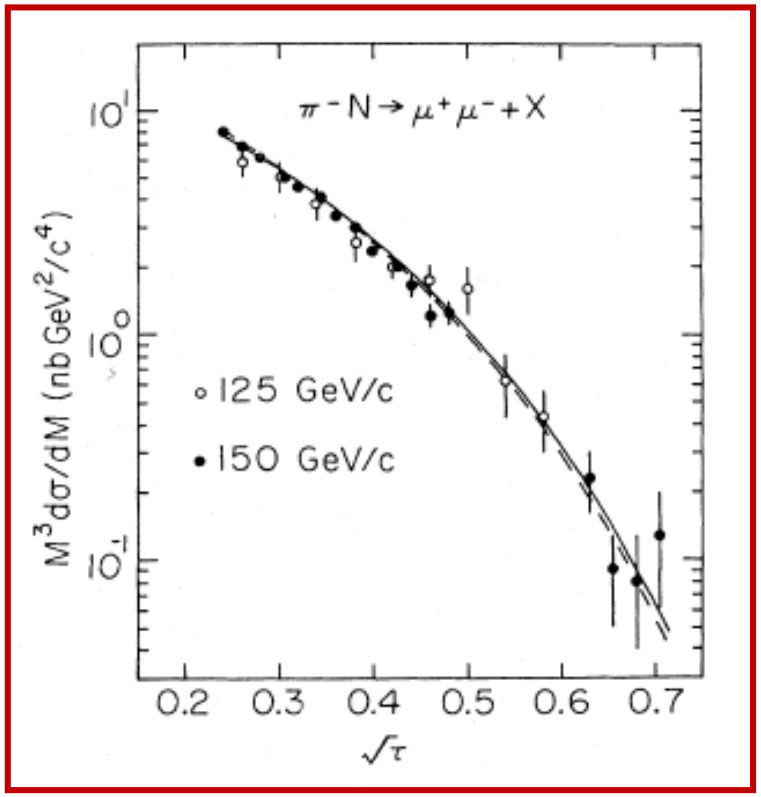
Outline

- Global fits for meson PDFs
- Pion PDFs from J/Ψ production
- Kaon PDFs from J/Ψ production
- Status and plans at COMPASS on meson PDFs
- Prospect of exclusive Drell-Yan and J/Ψ production at J-PARC

Four pion PDF sets available at LHAPDF library

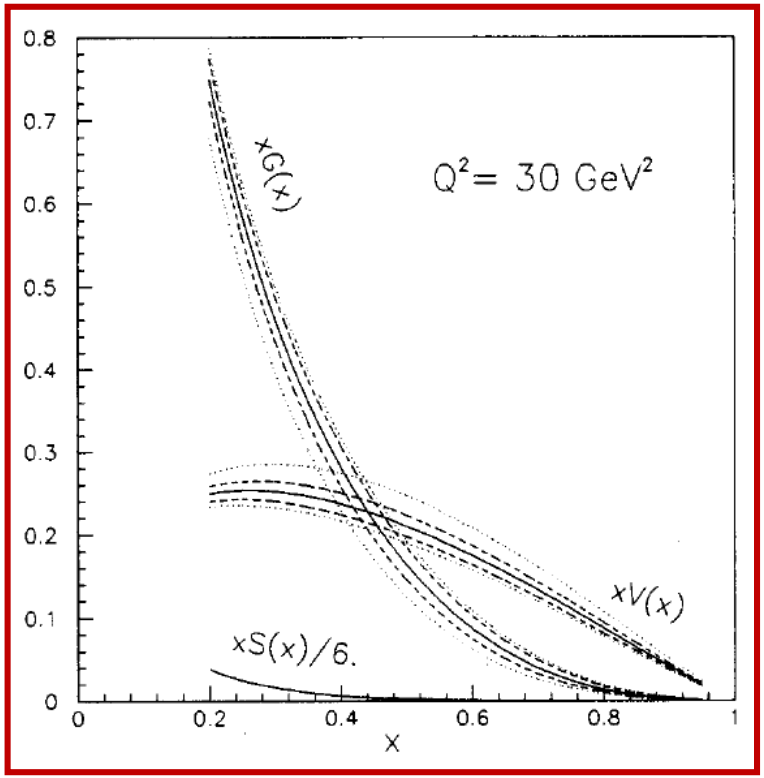
- First: OW-P (PRD 30, 943 (1984))
  - LO QCD
  - J/Ψ data from NA3 and WA39
  - D-Y data from E537 and NA3





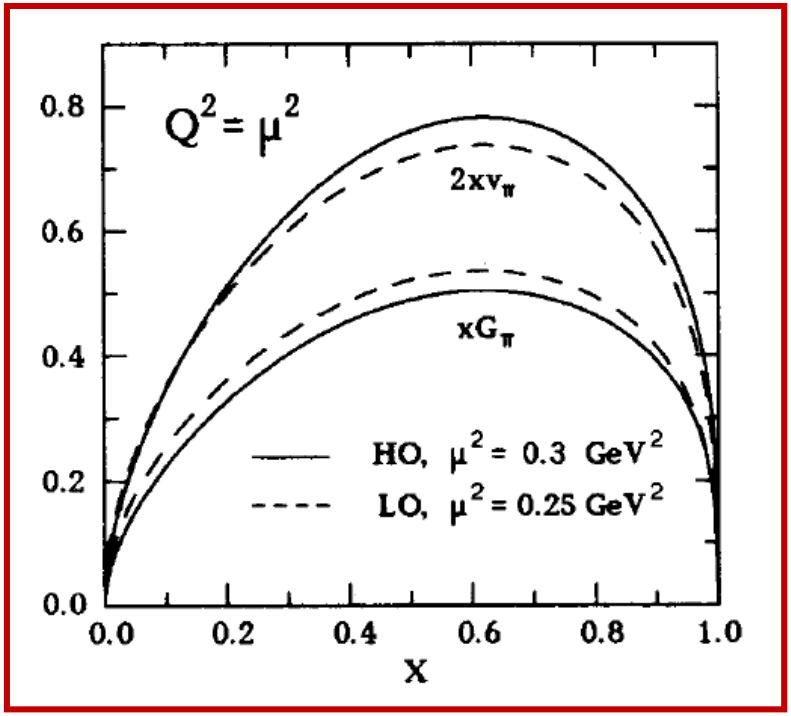
Four pion PDF sets available at LHAPDF library

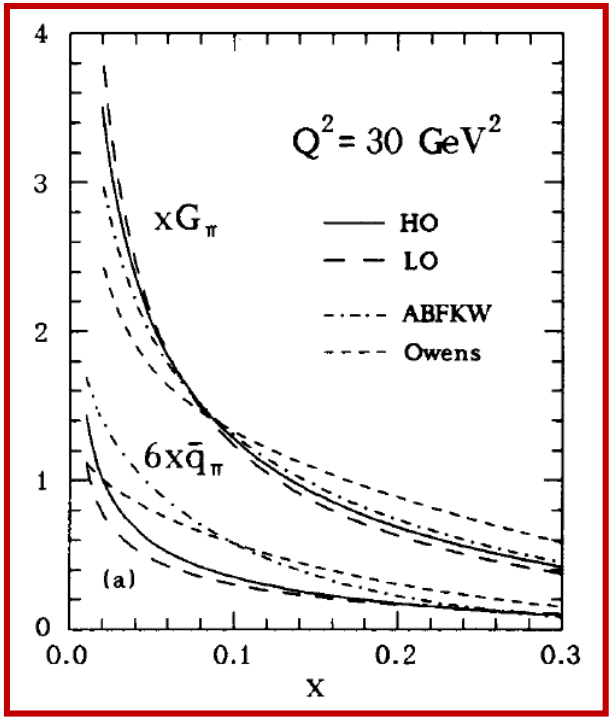
- Second: ABFKW-P (PL 233, 517 (1989))
  - NLO QCD
  - Direct photon data from WA70 and NA24
  - Sea-quark distribution from NA3



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

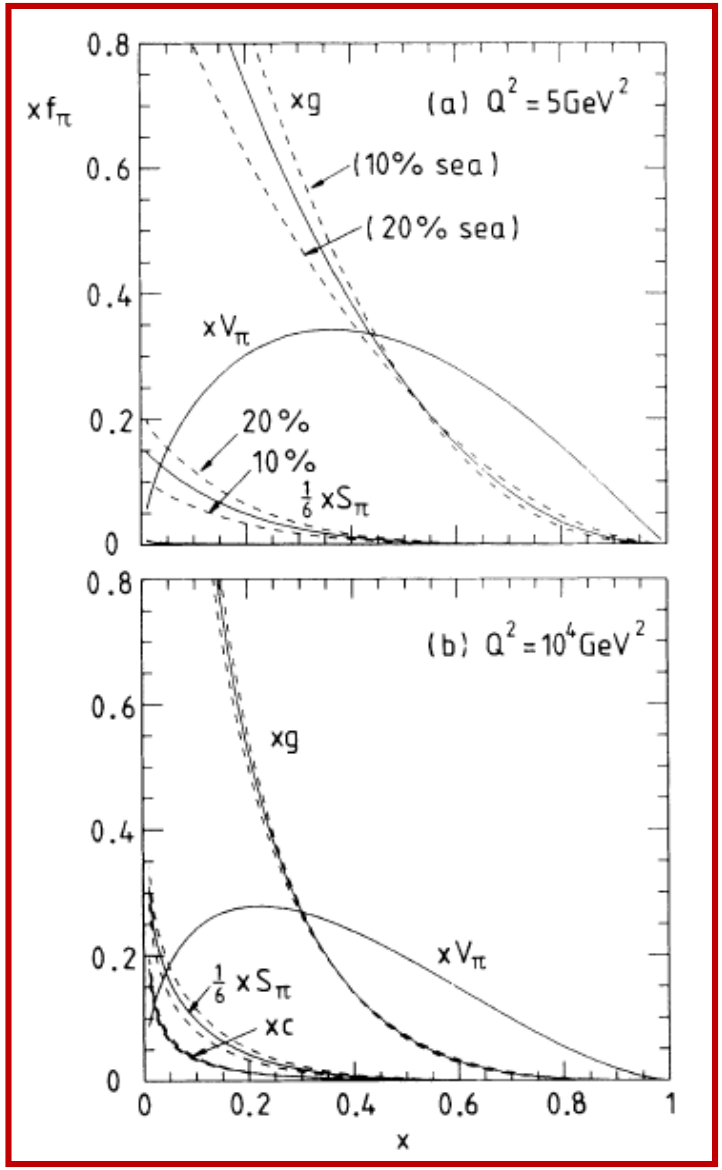




Four pion PDF sets available at LHAPDF library

- 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

Claude Bourrely

Aix Marseille Univ, Univ Toulon, CNRS, CPT, Marseille, France

Jacques Soffer

Physics Department, Temple University,
1835 N, 12th Street, Philadelphia, PA 19122-6082, USA

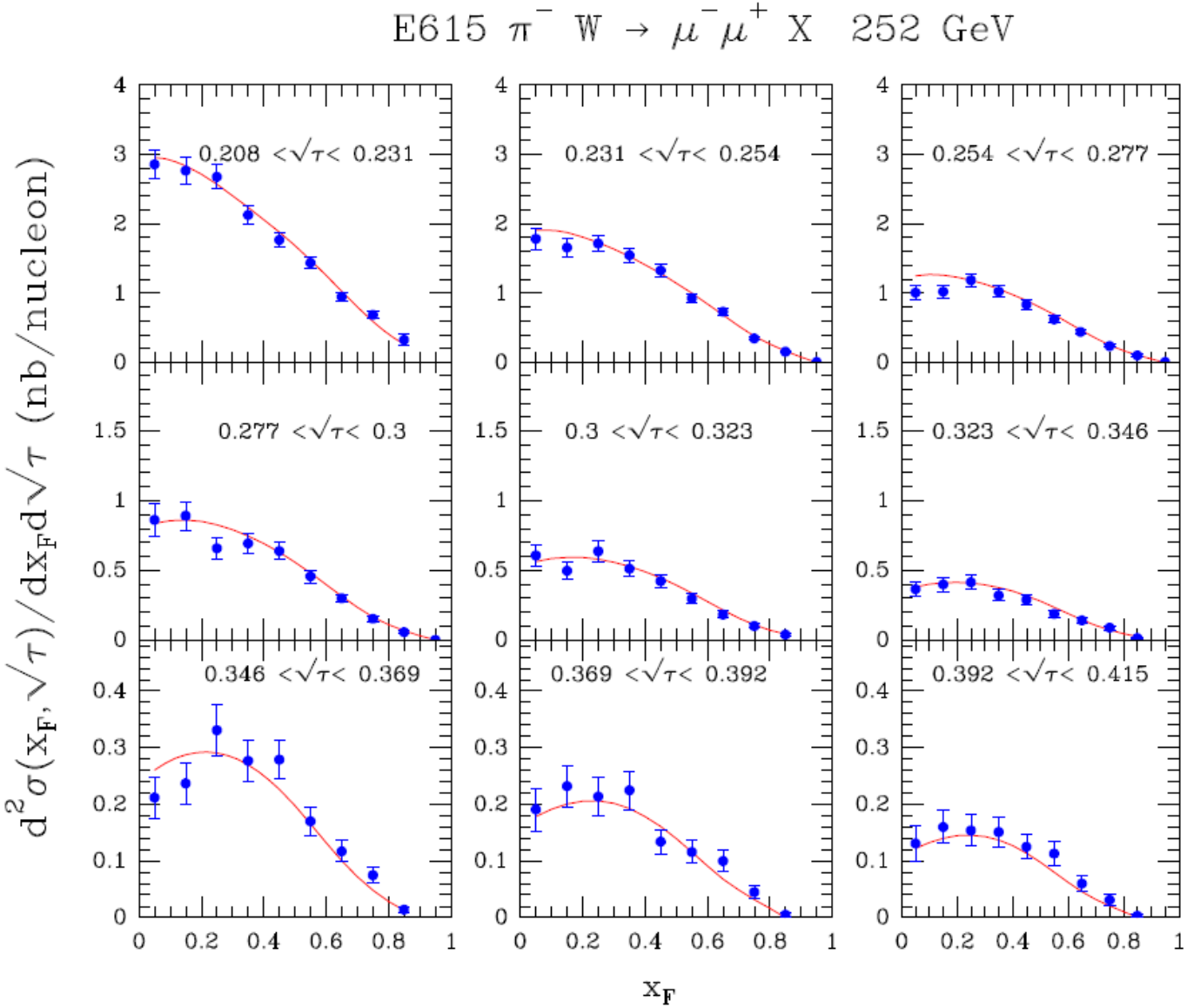
Abstract

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

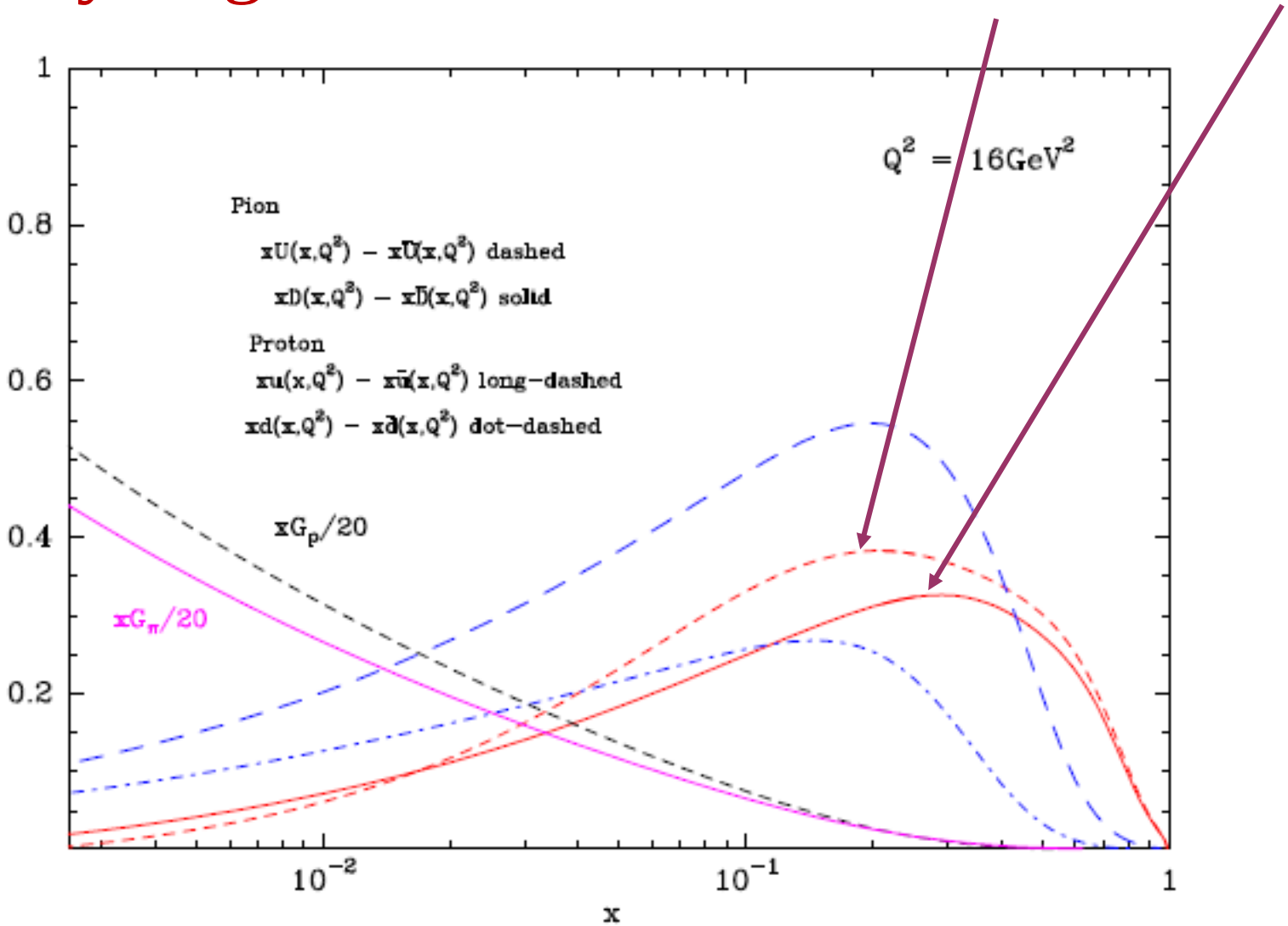
$$xQ^{\pm}(x) = \frac{A_Q X_Q^{\pm} x^{b_Q}}{\exp[(x - X_Q^{\pm})/\bar{x}] + 1}, \quad (2)$$

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

and four potentials

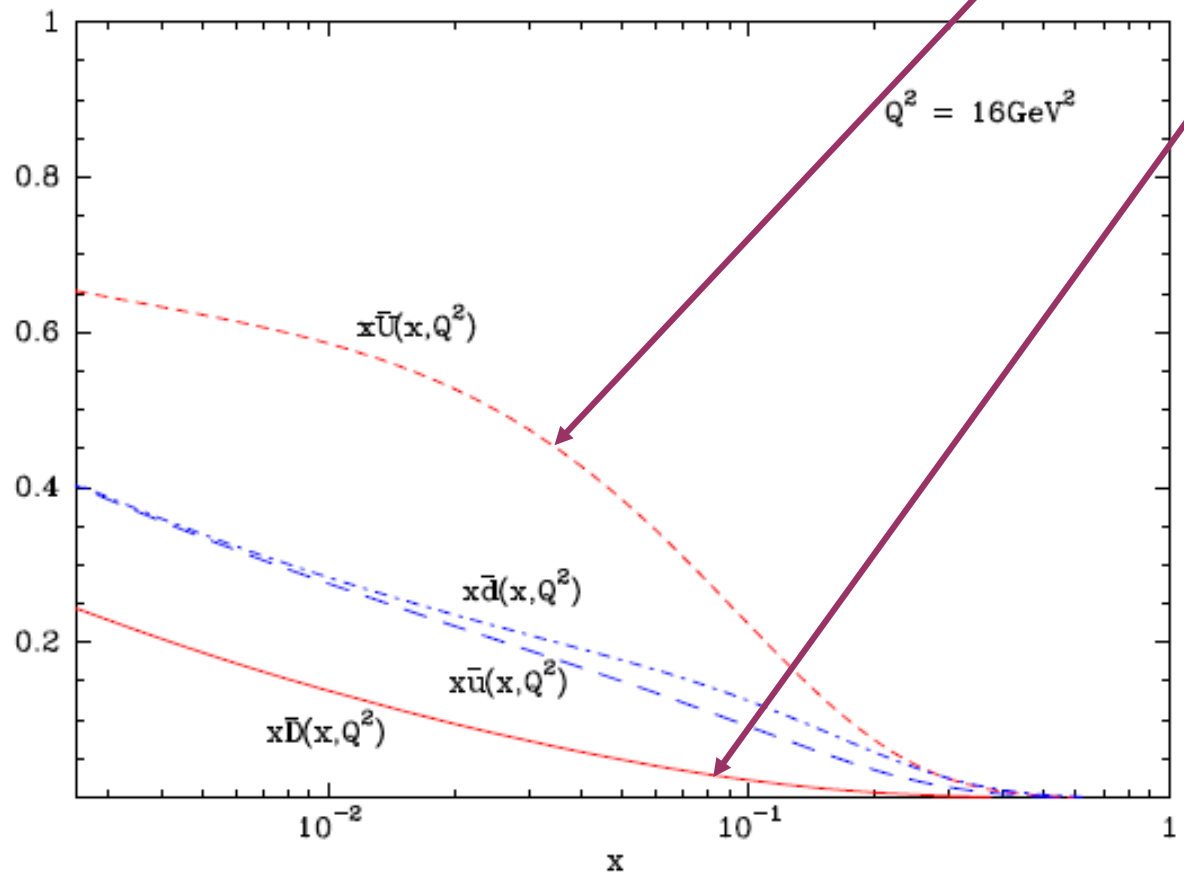
$$X_U^+ = 0.787 \pm 0.007, \; X_U^- = 0.185 \pm 0.030,$$
$$X_D^+ = 0.866 \pm 0.024, \; X_D^- = 0.718 \pm 0.044. \quad (13)$$

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

First Monte Carlo global QCD analysis of pion parton distributions

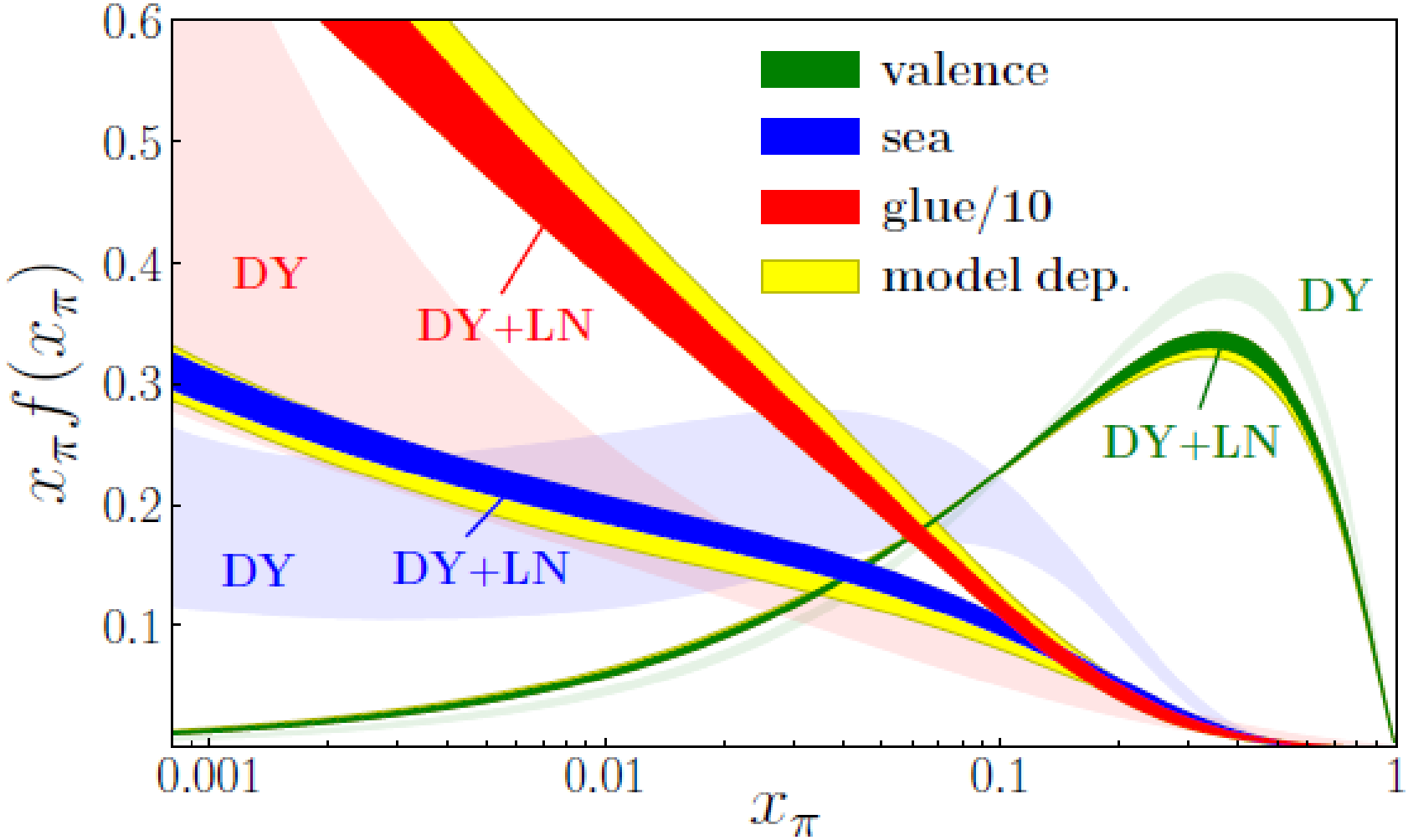
P. C. Barry,[1] N. Sato,[2] W. Melnitchouk,[3] and Chueng-Ryong Ji[1]

[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

arXiv: 1804.01965

- Drell-Yan data from NA10 and E615
- Leading-neutron tagged DIS from HERA (H1 and ZEUS)


valence
sea
glue/10
model dep.
DY
DY+LN
DY
DY+LN
DY
DY+LN
0.6
0.5
0.4
0.3
0.2
0.1
0.001
0.01
0.1
1
$x_\pi f(x_\pi)$
x_π

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!

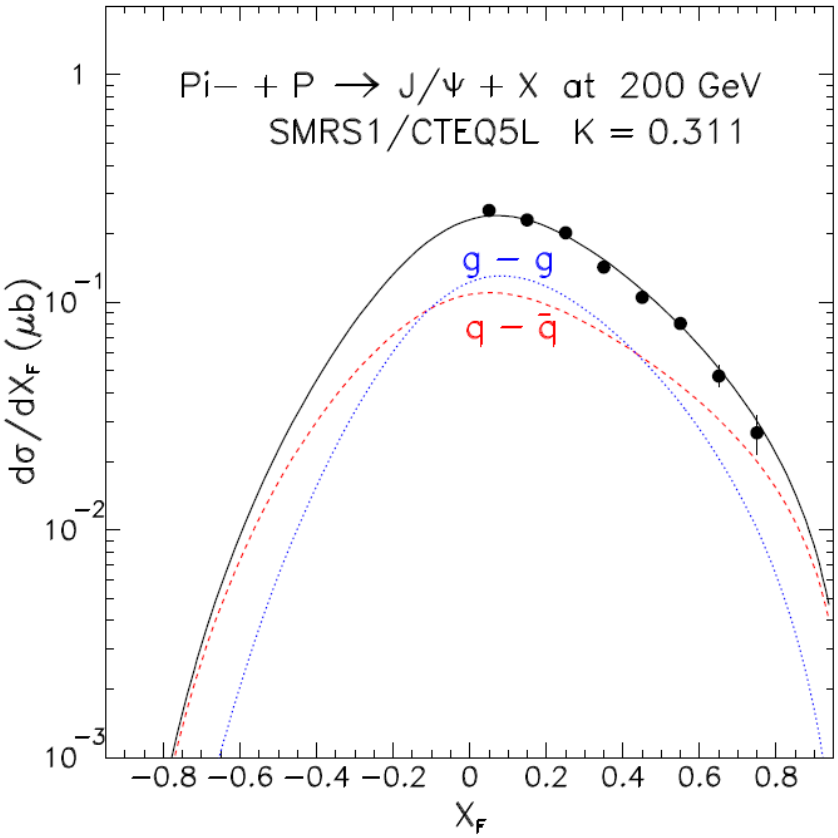
$\sigma_{J/\Psi}(\pi^- + p) - \sigma_{J/\Psi}(\pi^+ + p)$ is positive

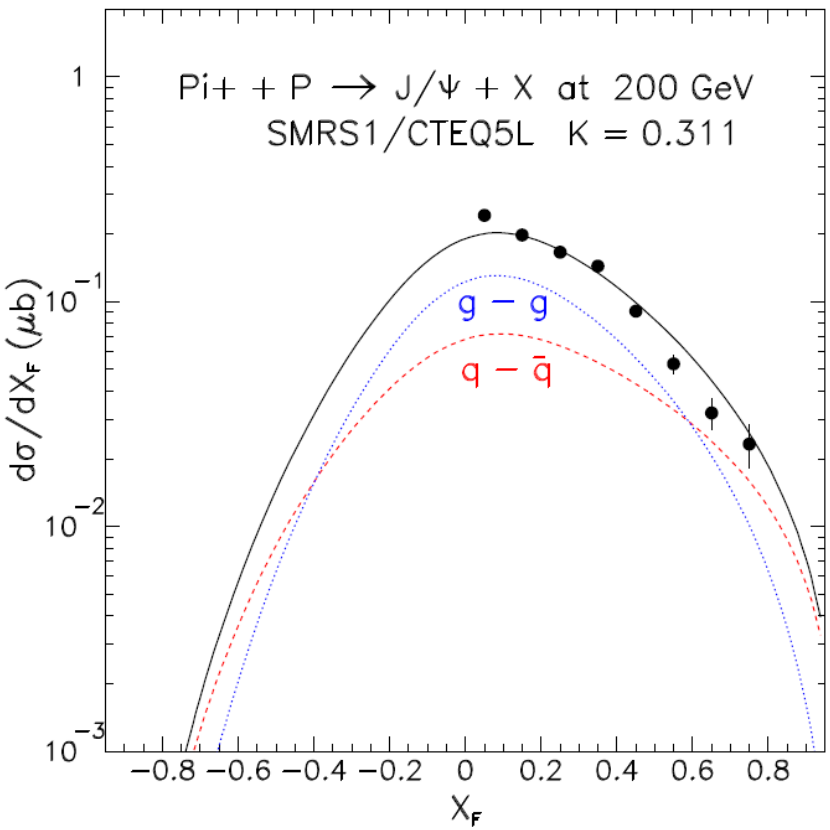
Directly proportional to $u_V(x_2) - d_V(x_2)$

Directly proportional to $V_\pi(x_1)$

Are there relevant data already?

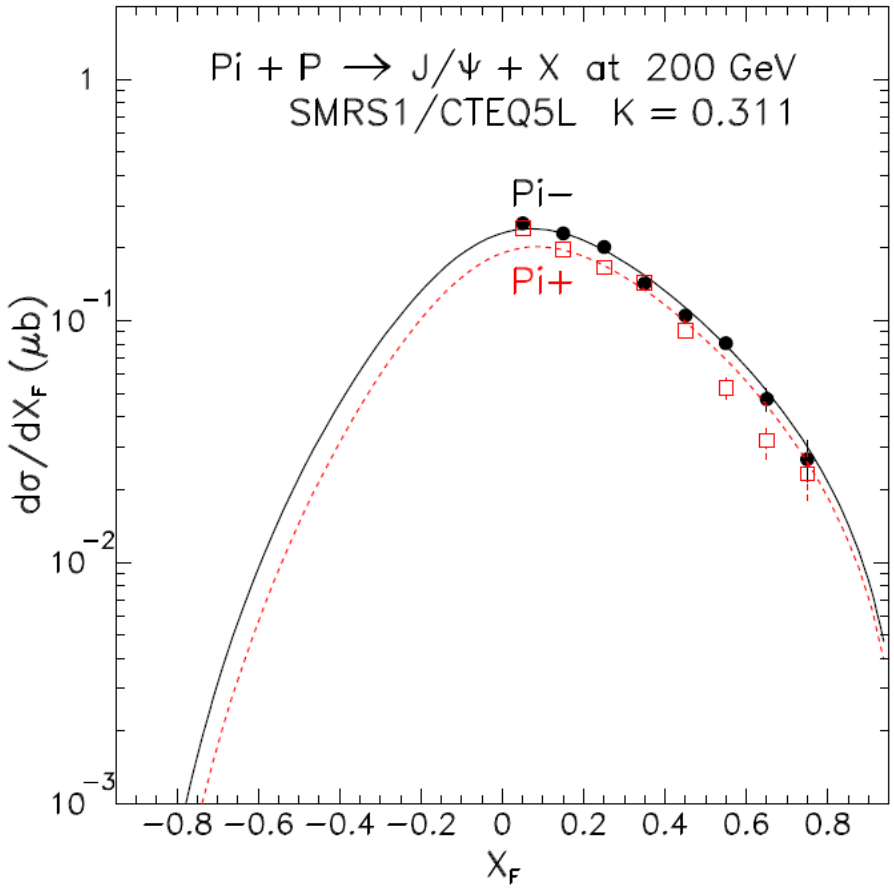
Data extracted from the NA3 paper and the Ph.D thesis of Charpentier





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 $u_V(x_2) - d_V(x_2)$

How to determine the valence quark distribution in kaon?

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

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

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

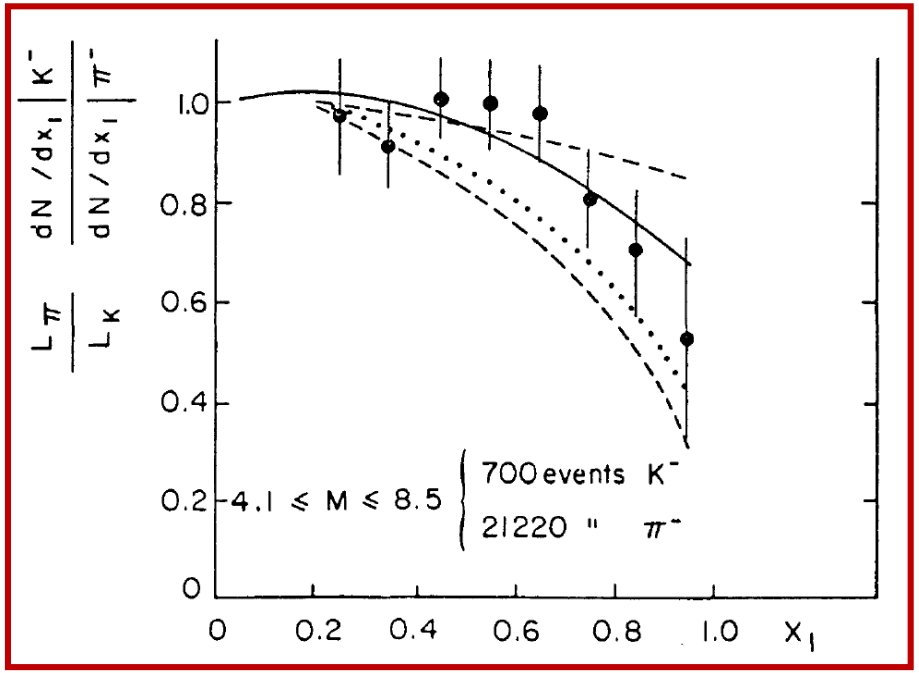
$$\sigma_{DY}(K^- + D) - \sigma_{DY}(K^+ + D) \propto 4V_K^u(x_1)V_N(x_2)$$

Only the valence-quark term remain!

$\sigma_{DY}(K^+ + D)$ 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



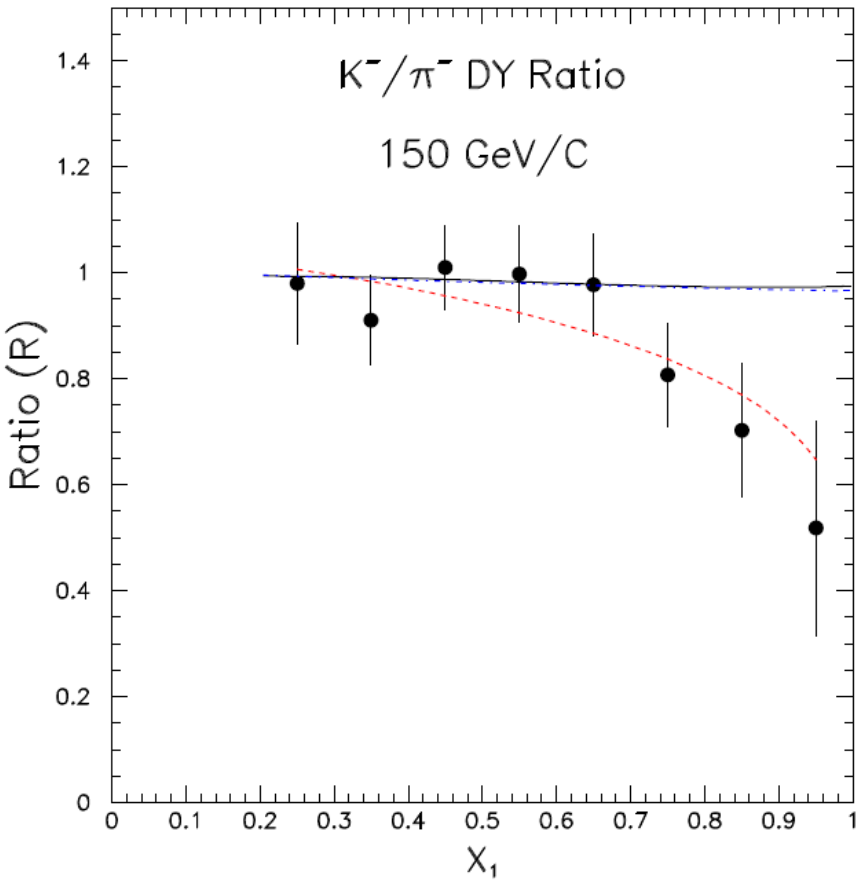
From NA3; 150 GeV, Pt target

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

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

$R \simeq (1-x)^{0.18\pm0.07} \Rightarrow$ 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

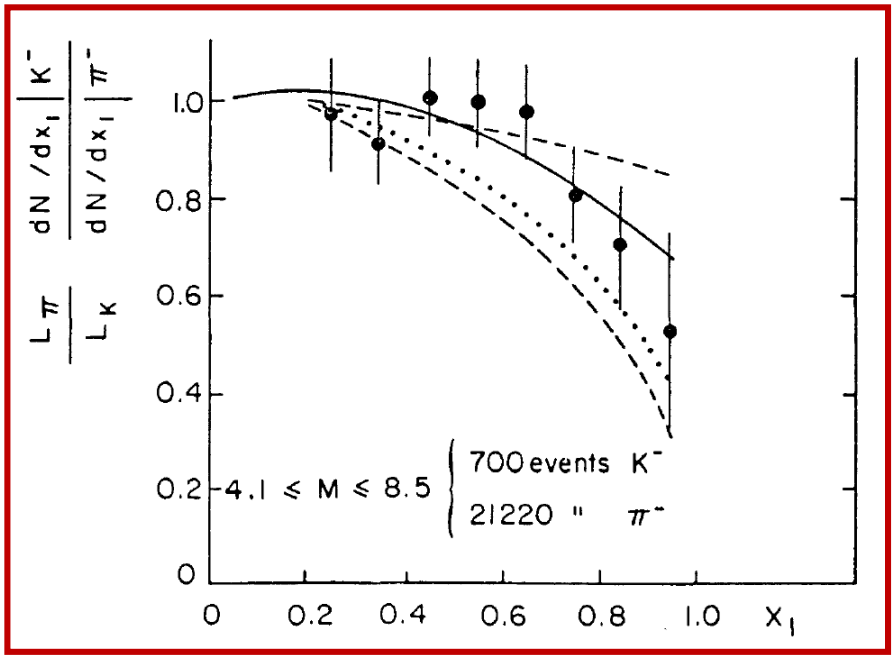
$$\bar{u}_K^V(x) = 1.061\,\bar{u}_\pi^V(x)(1-x)^{0.203}$$

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

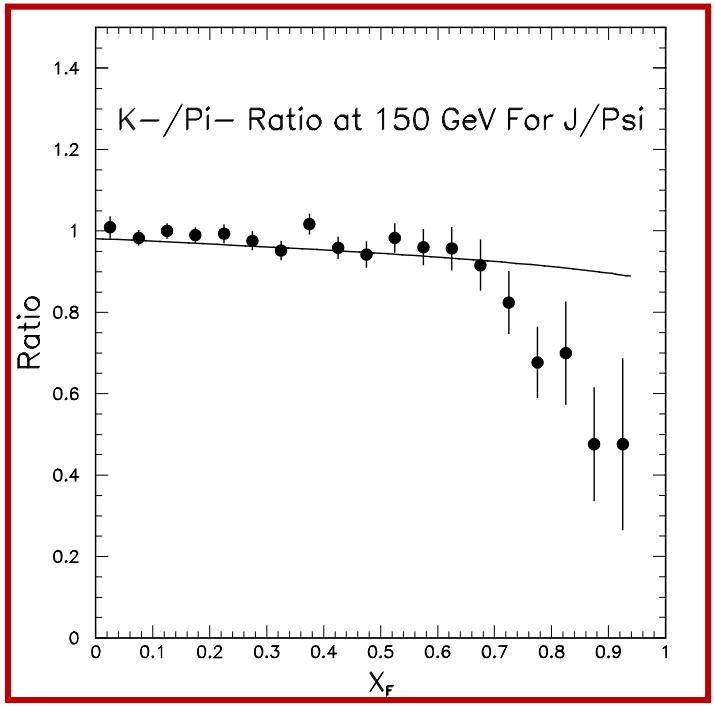
$(K^- + \mathrm{Pt}) / (\pi^- + \mathrm{Pt})$ ratios for J/Ψ production

From NA3; 150 GeV, Pt target

Ratios for D-Y



Ratios for J/Ψ

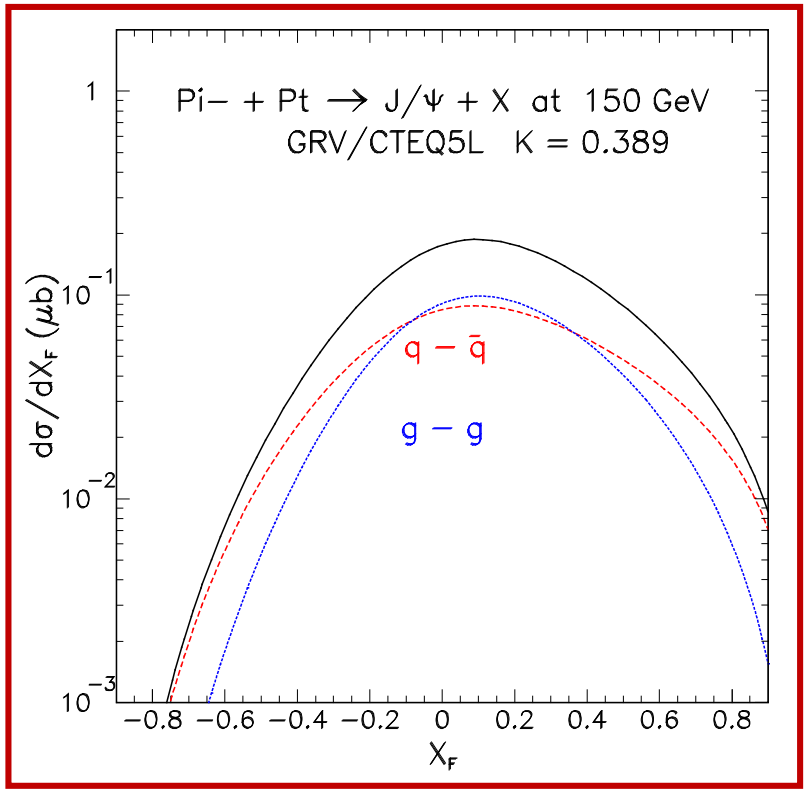


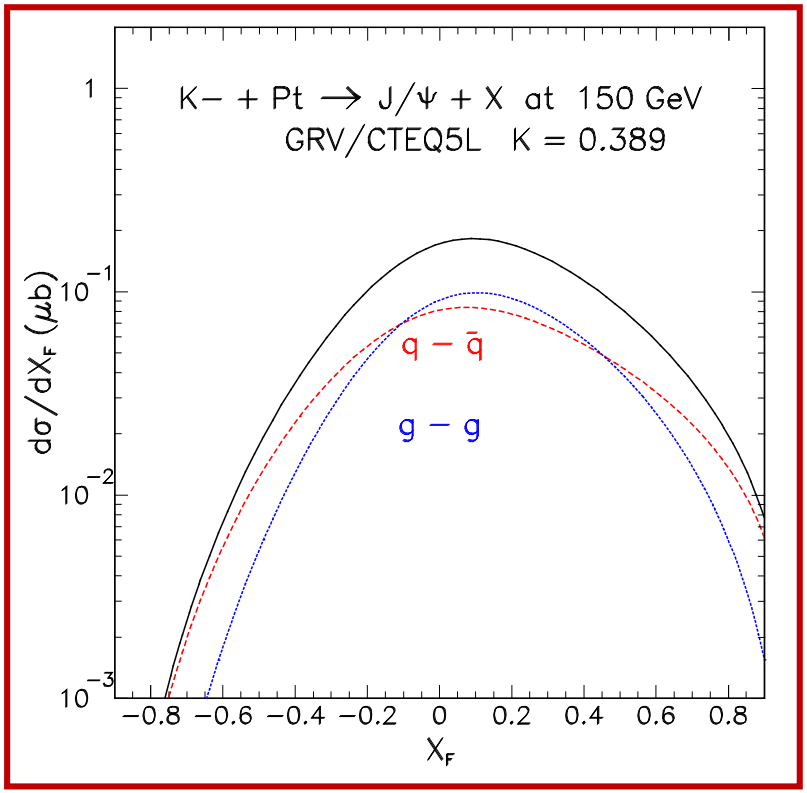
Similar behavior at large x_F for D-Y and J/Ψ production?

J/Ψ production in the Color Evaporation Model

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

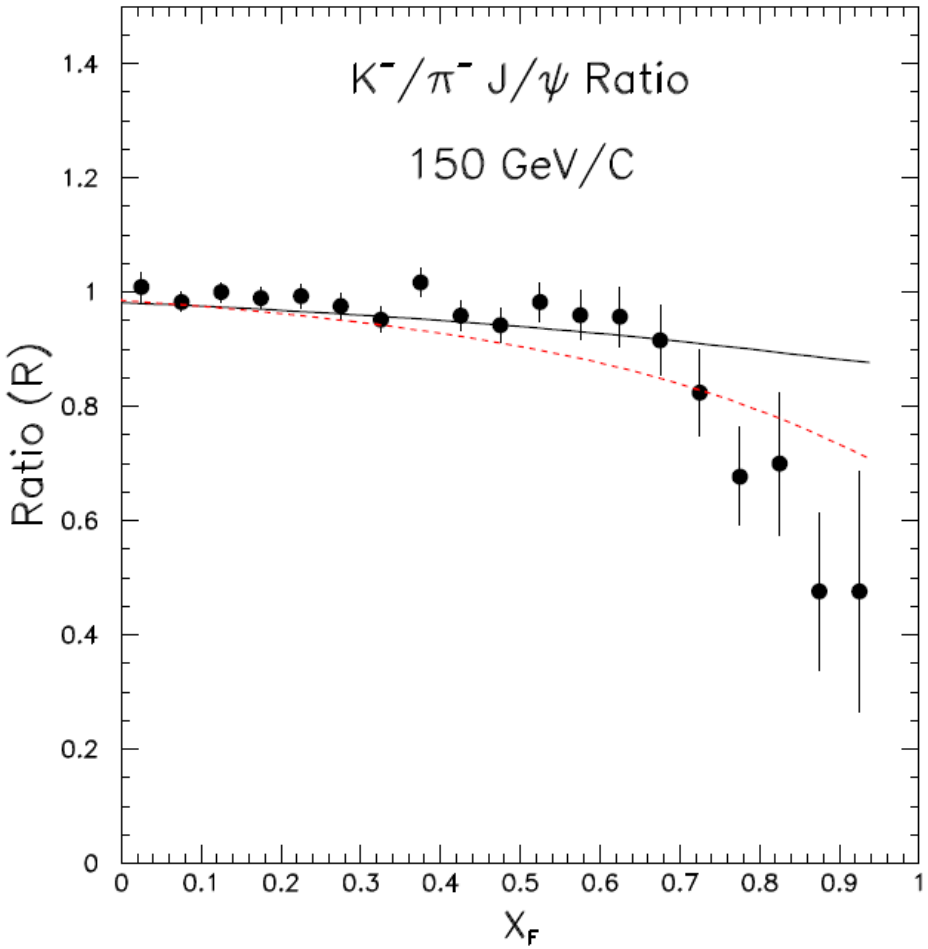
$$K^- + \mathrm{Pt} \rightarrow J/\Psi + x$$





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

Comparison between color-evaporation model calculation and data



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same PDF for π^- and K^- in LO

Red dashed curve:

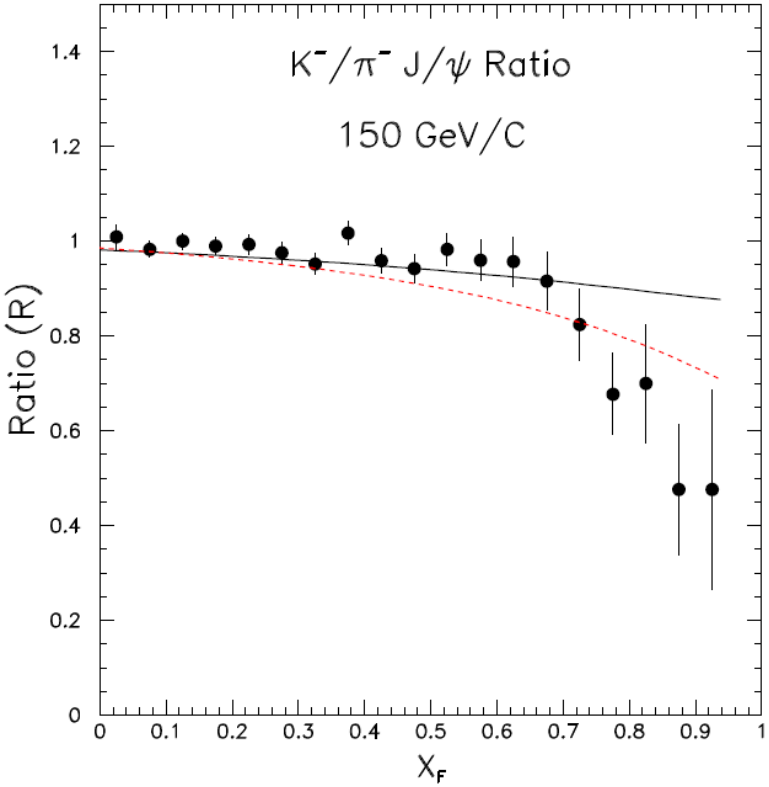
Modified K^- pdf

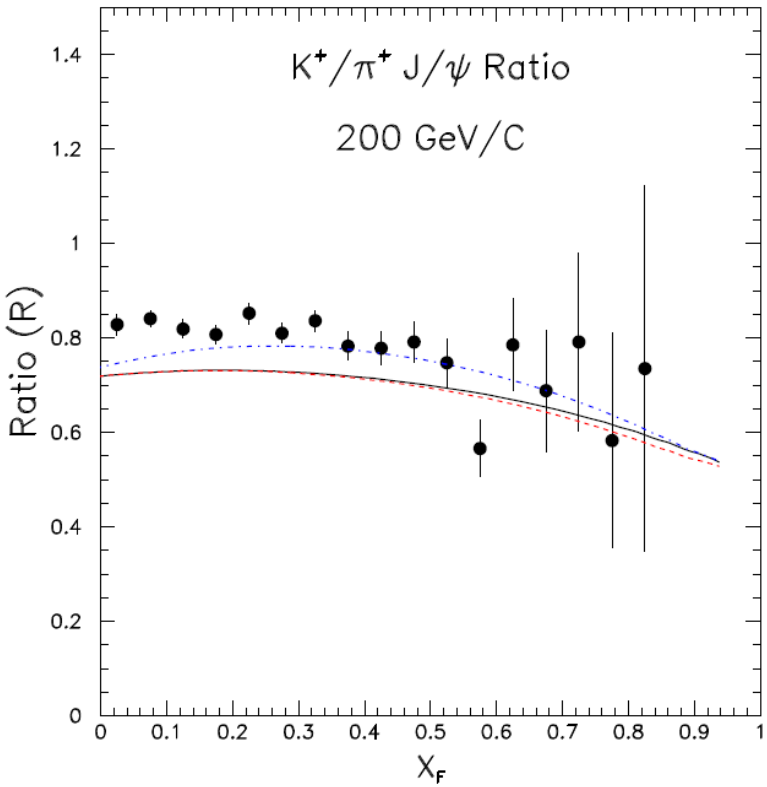
$$\bar{u}_K^V(x) = 1.061\,\bar{u}_\pi^V(x)(1-x)^{0.203}$$

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

See JCP, Chang, Platchkov, Sawada arXiv:1711.00839

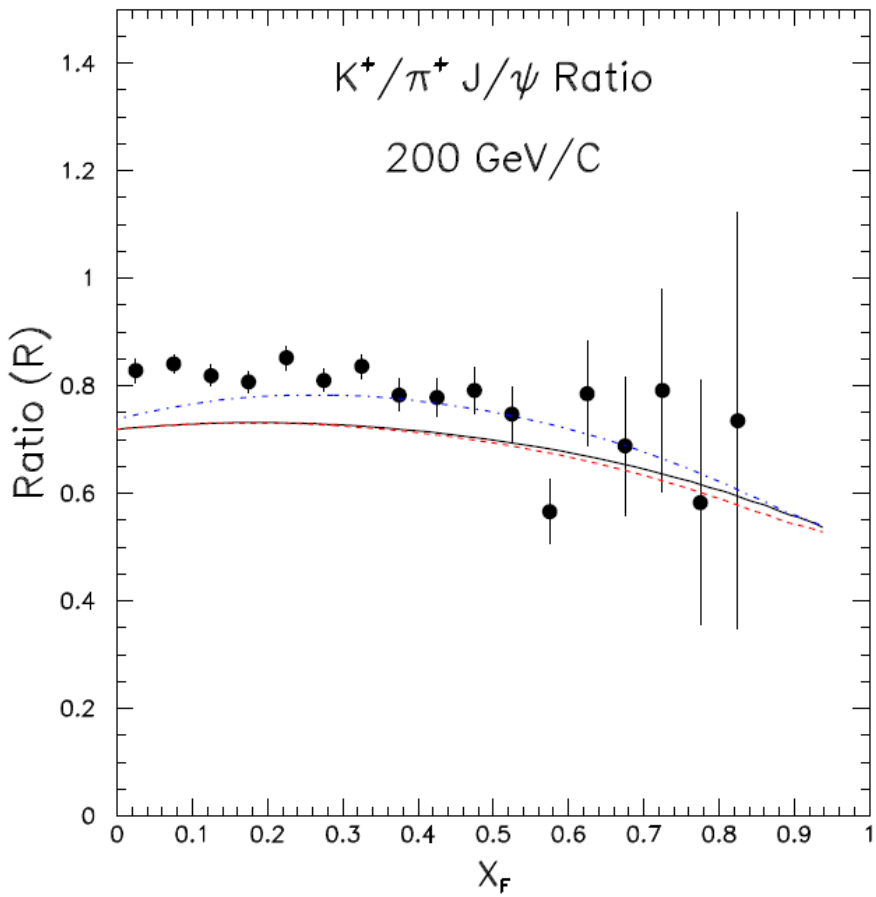
Comparison between K^- / π^- and K^+ / π^+ J / ψ production ratios





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

Comparison between color-evaporation model calculation and data



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Modified K^- pdf

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

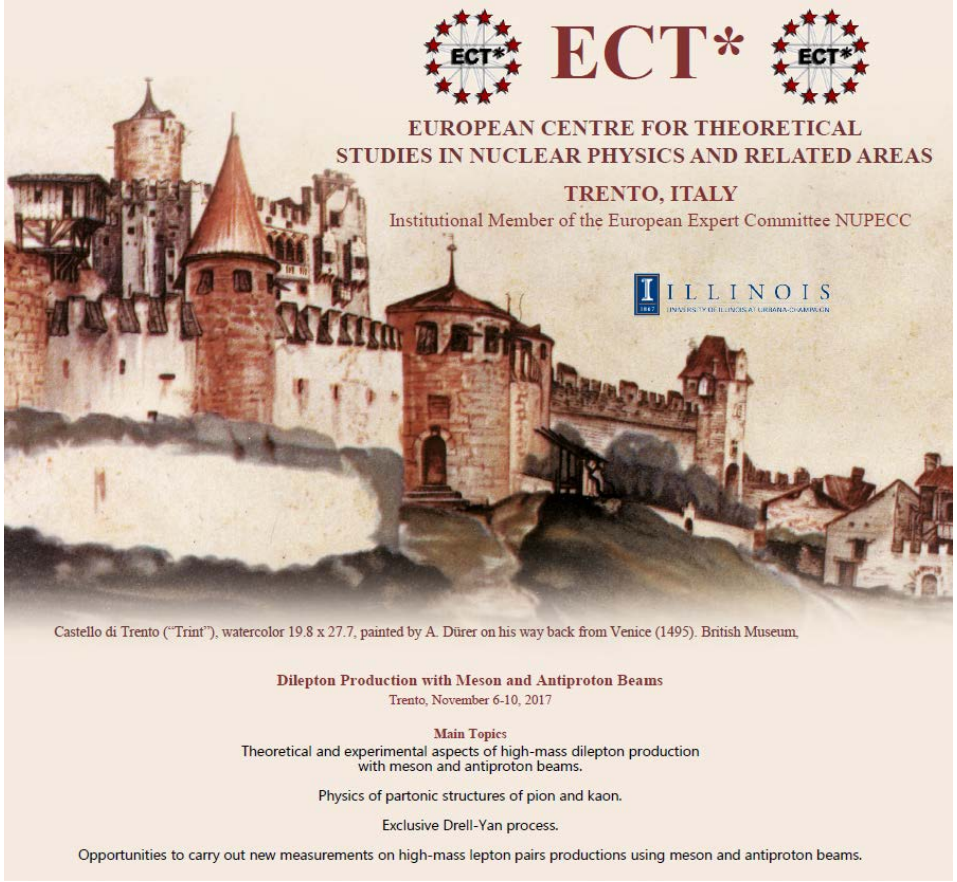
Blue dot-dashed curve:

increase gluon content in K^- by 10%

See JCP, Chang, Platchkov, Sawada arXiv:1711.00839

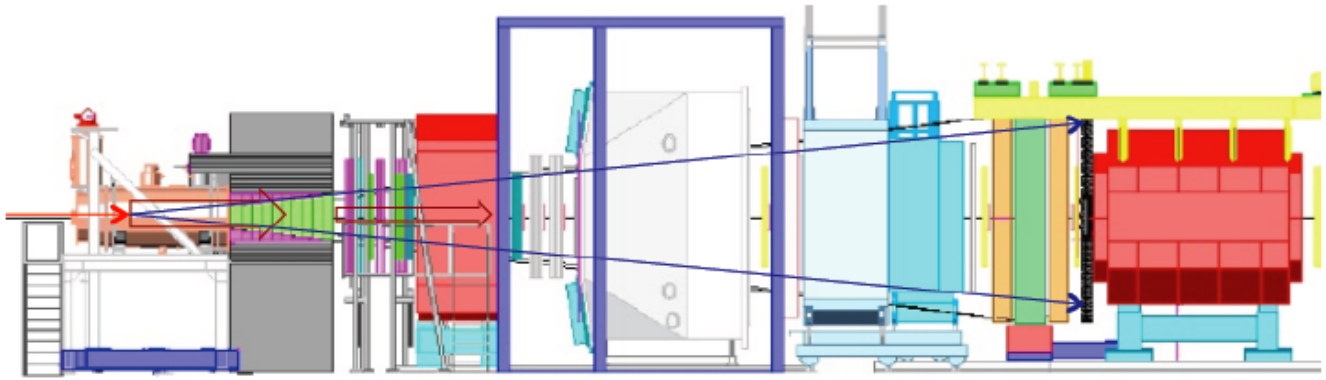
ECT* Workshop on “Dilepton Production with Meson and Antiproton Beams” November 6-10, 2017

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



Pion induced Drell-Yan – Present

COMPASS @ CERN



...

- π^- beam at 190 GeV
- Hadron beam intensity 7×10^7/second
- 110 cm NH_3 target + 7 cm Al target + 120 cm W target
- 240cm Absorber, 120 cm W beam plug
- dimuons geometrical acceptance $\approx$ 40%

COMPASS Coll.; Phys.Rev.Lett. **119** (2017) 112002; CERN-SPSC-2010-014

COMPASS results to come

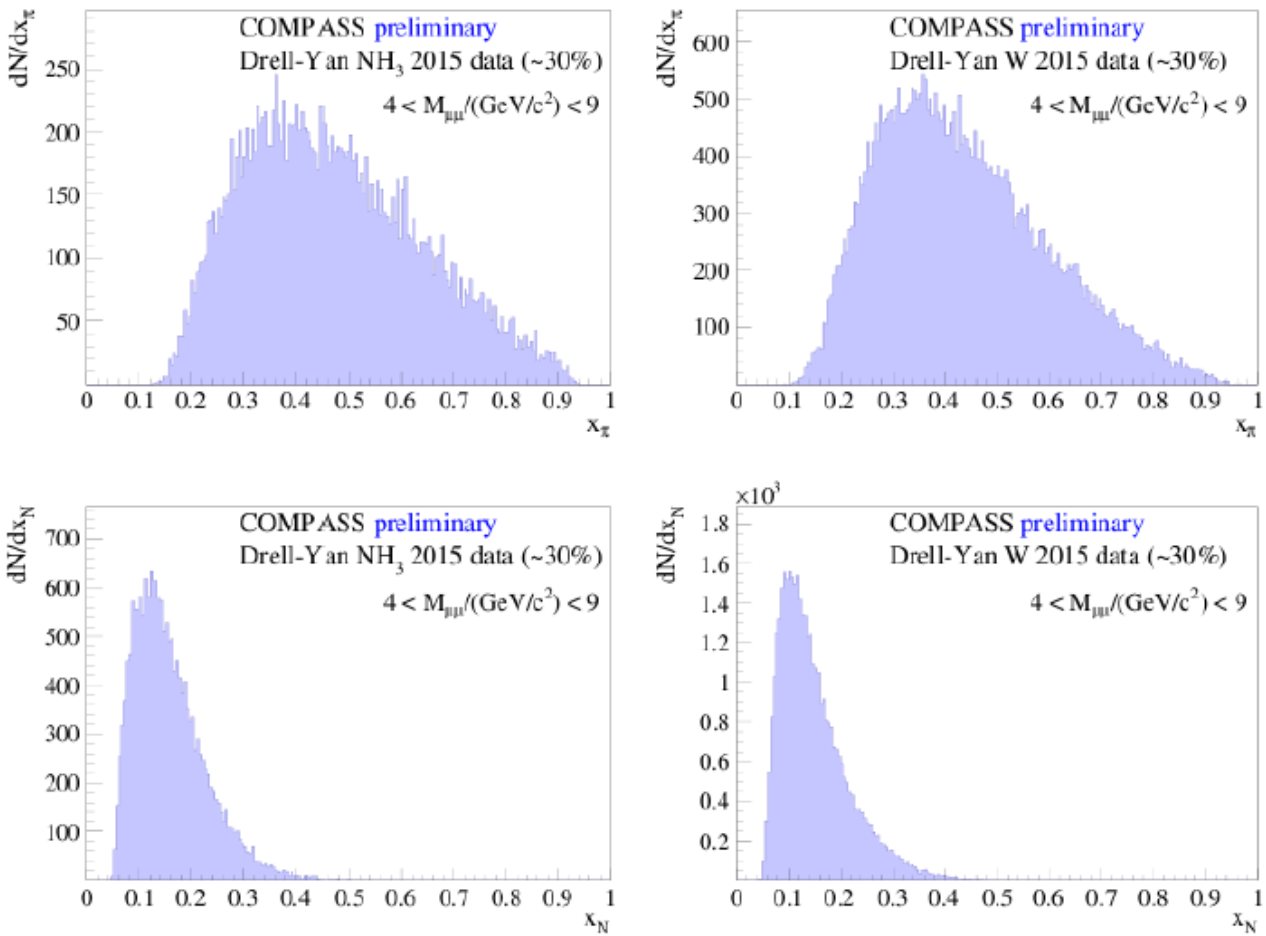
The Drell-Yan results from COMPASS are just starting to emerge. In the near future, expect:

- Unpolarized Drell-Yan angular distributions from π^- on NH_3
- Absolute Drell-Yan cross-sections of pion collisions on NH_3 and on W targets
- Nuclear effects from the ratio of Drell-Yan on W to NH_3

These results will allow to clarify already a number of open issues:

- Solve normalization issue between NA10 and E615 data
- Repeat the studies of nuclear effects from pion-induced Drell-Yan, as done by NA10
- Ultimately new global fits towards pion PDFs
- Global fits of nPDFs including new pion induced Drell-Yan data, as EPPS16

COMPASS coverage



35 000 DY events from NH_3

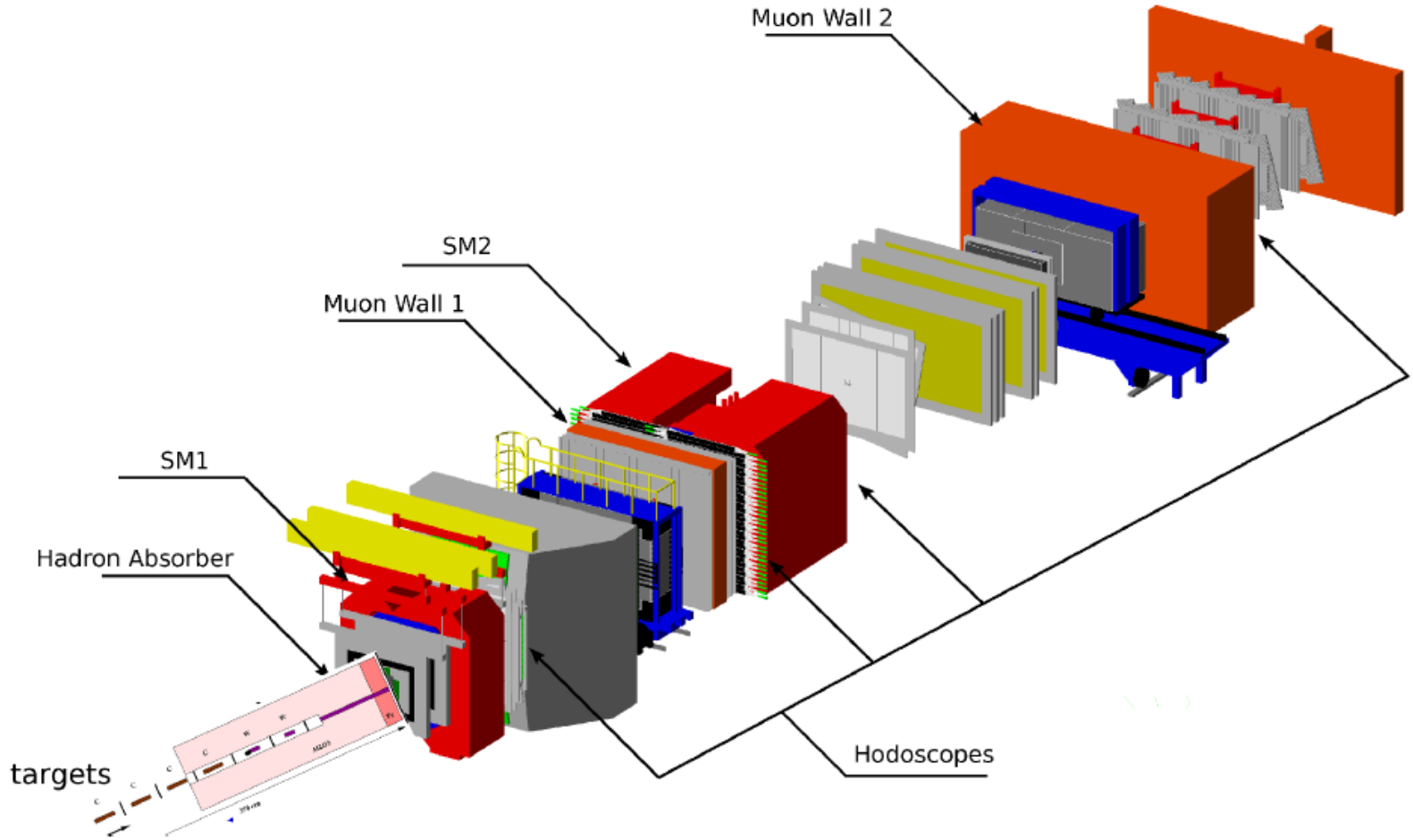
15 000 DY events from W

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

First step: addressing pion structure



COMPASS-like. Only target and absorber are modified.

Expected statistics

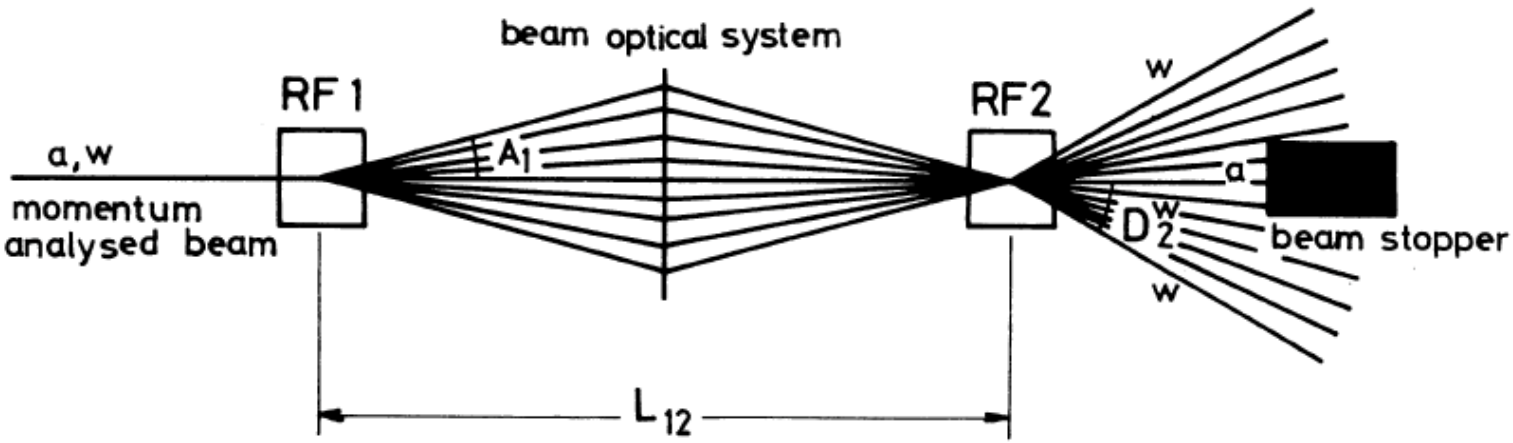
Experiment	Beam type (GeV)	Beam intensity (part/sec)	Target type	DY mass (GeV/c^2)	DY events
This exp	π^+ 190	1.7×10^7	100cm C	4.3 – 8.5	23000
				3.8 – 4.3	14000
				2.0 – 3.8	133000
This exp	π^- 190	6.8×10^7	100cm C	4.3 – 8.5	22000
				3.8 – 4.3	12000
				2.0 – 3.8	127000
This exp	π^+ 190	0.2×10^7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

- Consider 255 days with π^+ beam and 25 days with π^- beam
- Assumed efficiencies similar to those in COMPASS measurements, CEDAR efficiency 90%.
- positive hadron beam: 73% p; 24% π^+; 3% K^+
- negative hadron beam: 97% π^-; 2.5% K^-; $< 1\%$ $\bar{p}$
- DY in extended mass ranges: events weighted by their signal probability, as given by neural network / machine learning techniques (assumed efficiency of 80%)

RF-separated Beams

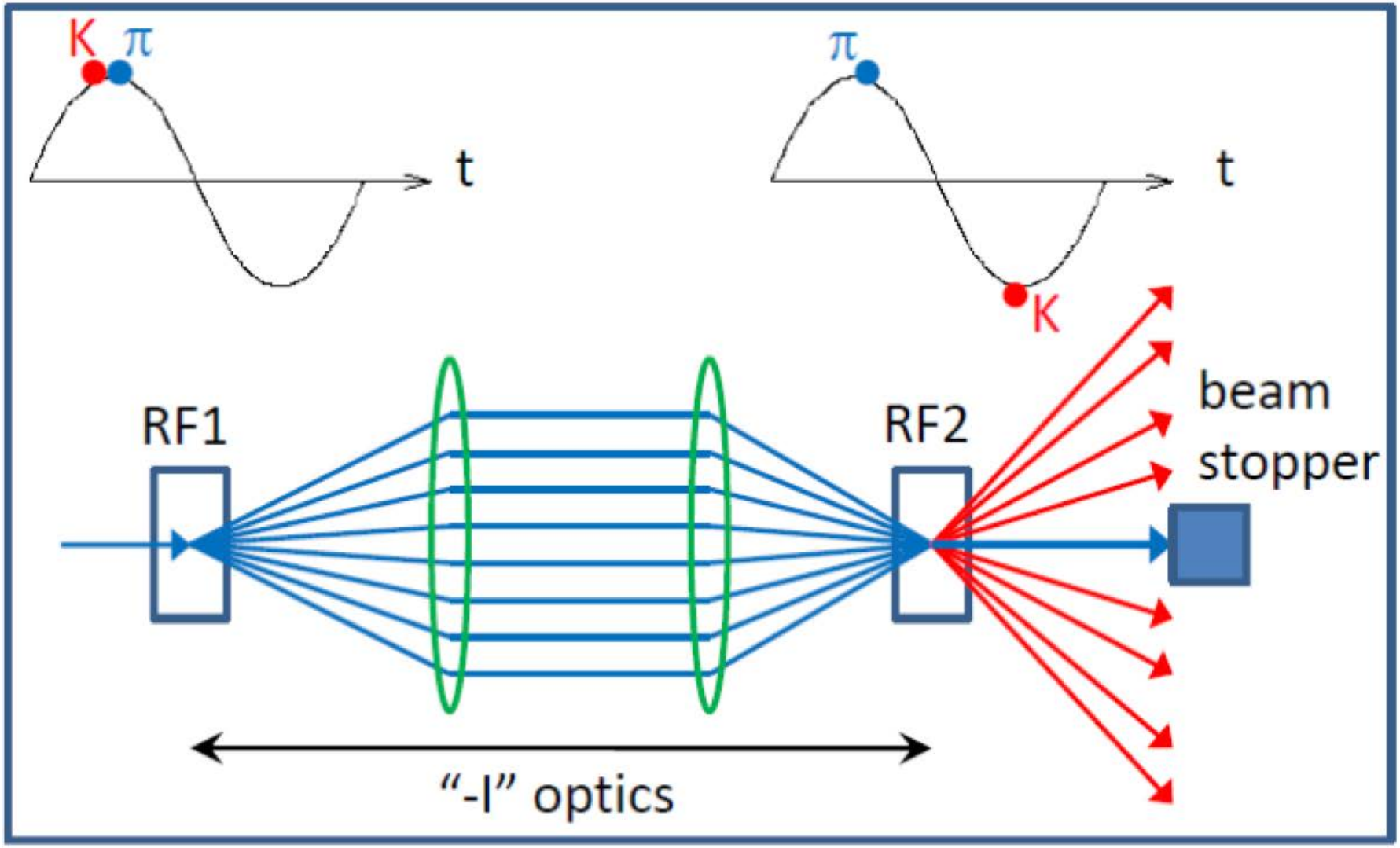
Note: Preliminary considerations, guided by initial studies for P326 and CKM studies by J.Doornbos/TRIUMF

Panofsky-Schnell-System with two cavities (CERN 68-29):



- Particle species have same momenta but different velocities
- Time-dependent transverse kick by RF cavities in dipole mode
- RF1 kick compensated or amplified by RF2
- Selection of particle species by selection of phase difference

  $\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$


K
π
t
π
t
K
RF1
RF2
beam
stopper
"-I" optics

Expected statistics

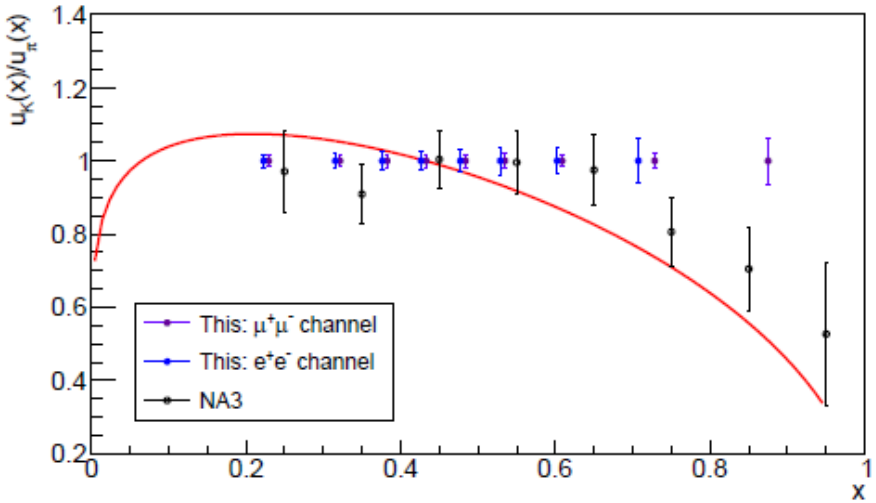
Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$	DY events e^+e^-
NA3	6cm Pt	K^-	1.6×10^6	150	4.1 – 8.5	700	0
This exp.	100cm C	K^-	2.1×10^7	80	4.0 – 8.5	25,000	13,700
				100		40,000	17,700
				120		54,000	20,700
		K^+	2.1×10^7	80	4.0 – 8.5	2,800	1,300
				100		5,200	2,000
				120		8,000	2,400
This exp.	100cm C	π^-	4.8×10^7	80	4.0 – 8.5	65,500	29,700
				100		95,500	36,000
				120		123,600	39,800

Assuming 140 days for each beam charge and realistic efficiencies.

This 1:1 time sharing is optimal for: good valence extraction, but still manage some sea-valence separation.

A time sharing 3:1 would be the best for optimal sea-valence separation.

Precision on valence kaon/pion ratio



• • 140 days of K^- beam of 100 GeV momentum

line: DSE prediction, following C. Chen et al., PRD 93 074021, 2016

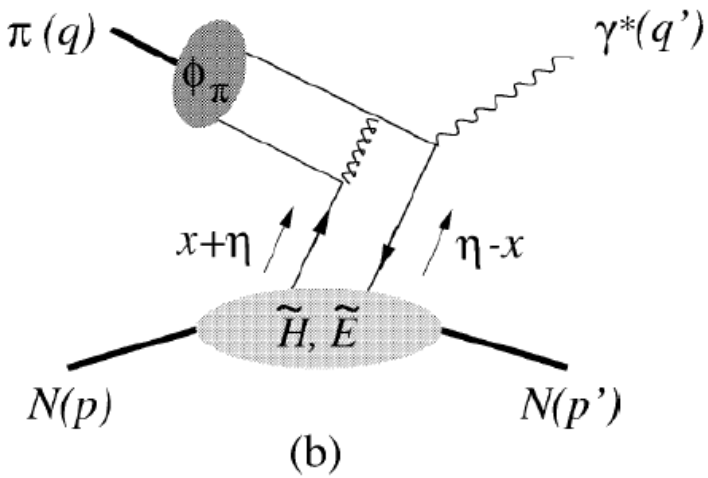
- Discriminating power between the existing kaon models

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

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

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

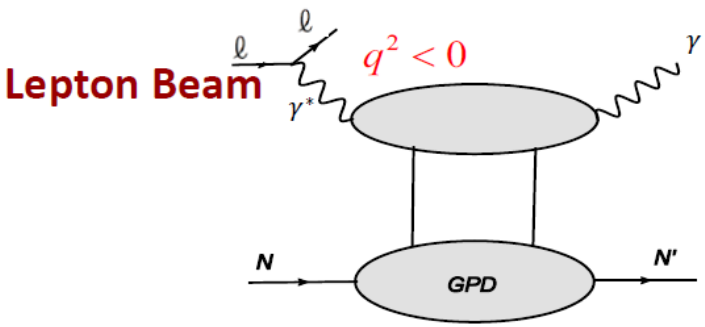
$$\tilde{\mathcal{H}}^{du}(\eta,t) = \frac{8\alpha_S}{3} \int_{-1}^{1} dz\, \frac{\phi_\pi(z)}{1-z^2} \int_{-1}^{1} dx \left[\frac{e_d}{-\eta-x-i\epsilon} - \frac{e_u}{-\eta+x-i\epsilon}\right] [\tilde{H}^d(x,\eta,t) - \tilde{H}^u(x,\eta,t)]$$

Extraction of **GPDs**

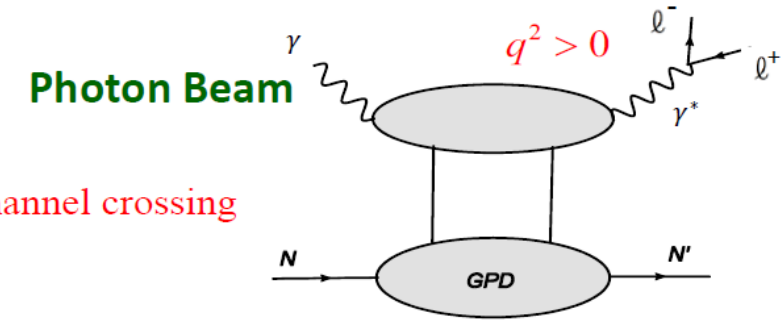
Space-like vs. Time-like Processes

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

Deeply Virtual Compton Scattering (DVCS)

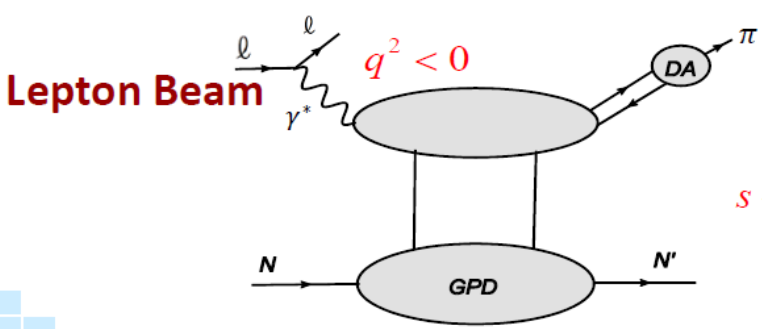


Time-like Compton Scattering (TCS)

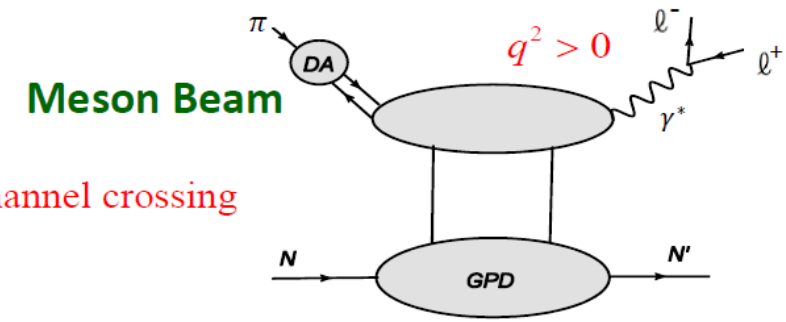


$s \leftrightarrow u$ channel crossing

Deeply Virtual Meson Production (DVMP)



Exclusive meson-induced DY

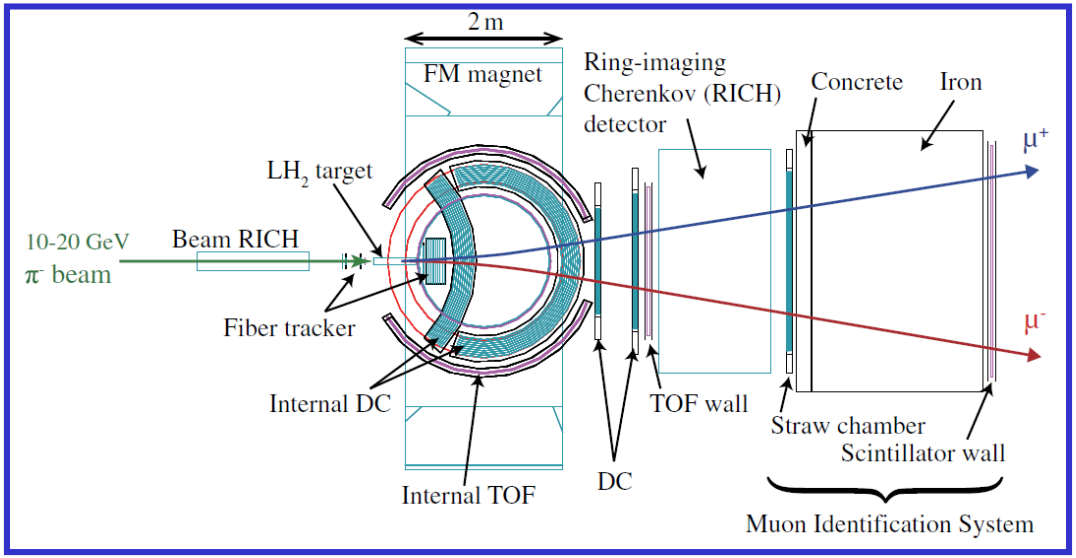


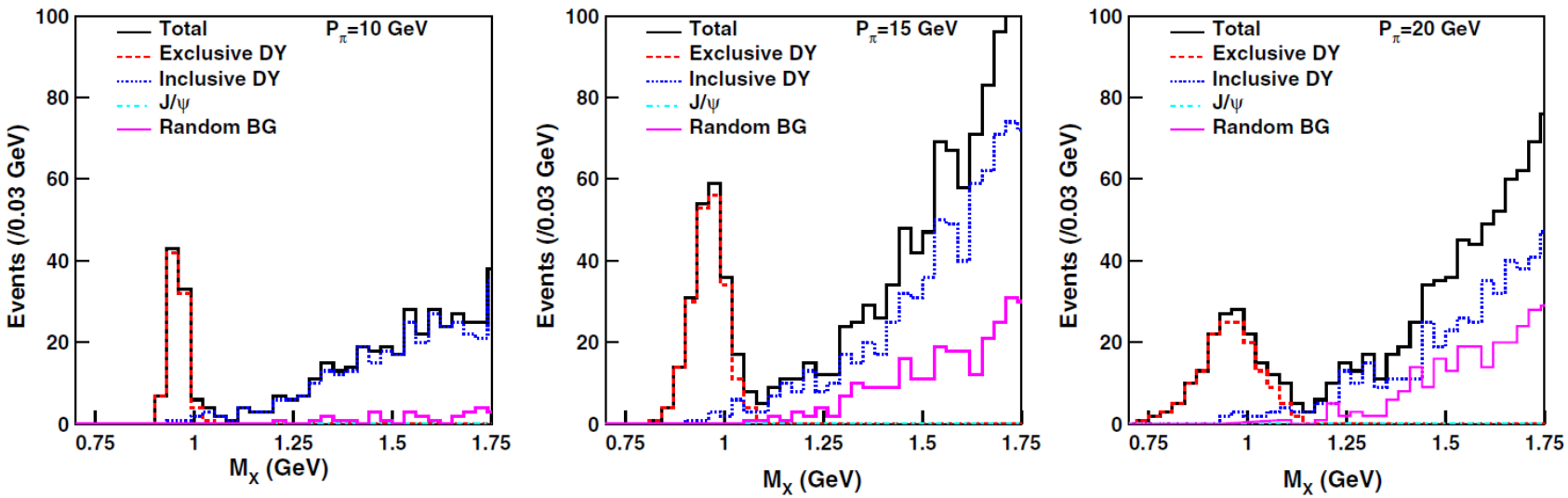
$s \leftrightarrow u$ channel crossing

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

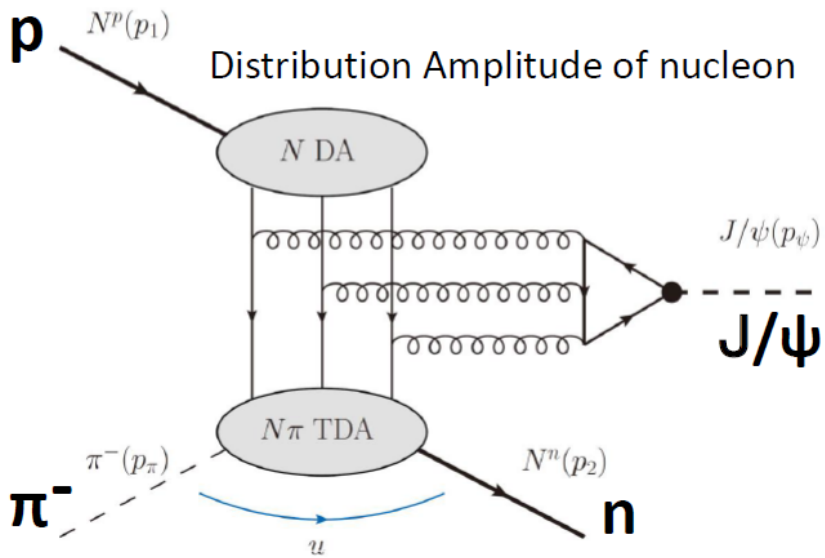
T. Sawada, W. C. Chang, et al.





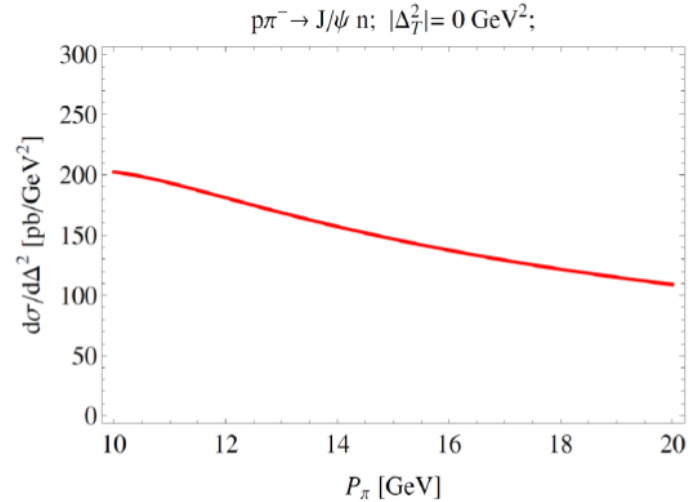
Pion-induced exclusive backward J/ψ production

B. Pire et.al
Phys. Rev. D 95, 034021 (2017)



Transition Distribution Amplitude
for pion → nucleon

Differential cross section at J-PARC energy

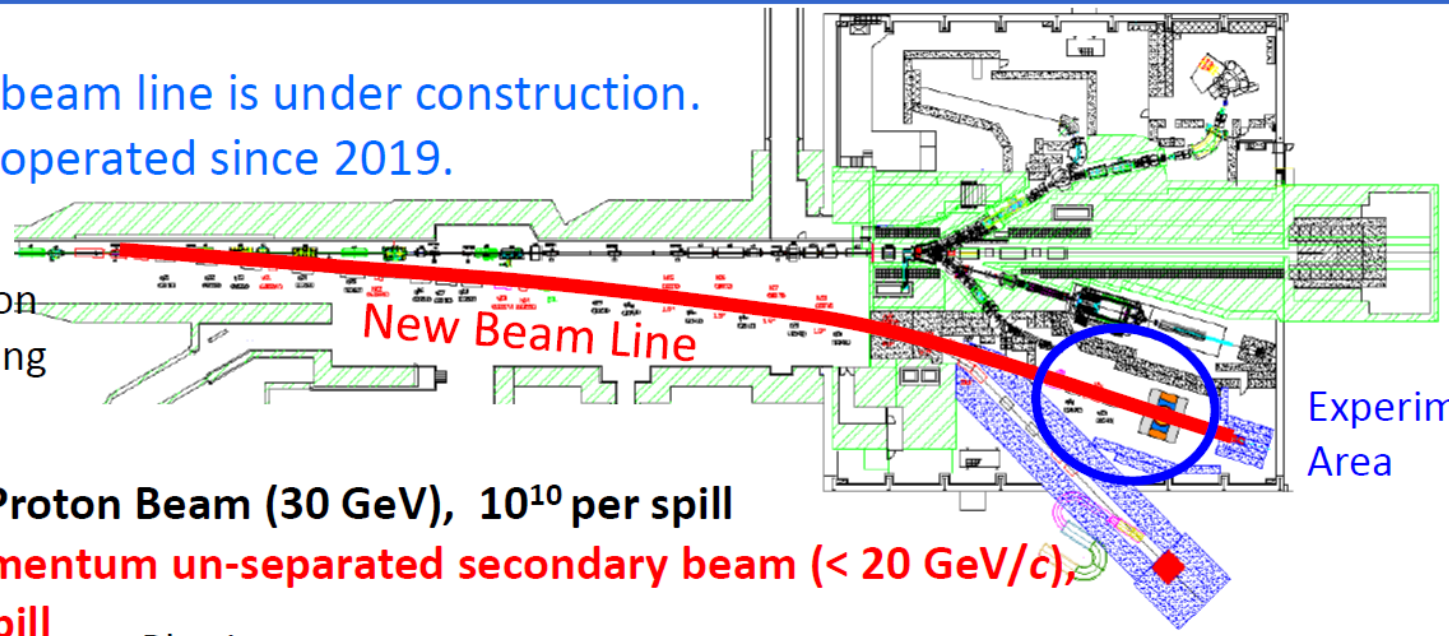


Momentum of Pion Beam (GeV)

might be observed in J-PARC ?

High Momentum Beam Line at J-PARC

The new beam line is under construction.
It will be operated since 2019.



30 GeV proton
from main-ring

Experimental
Area

- **Primary Proton Beam (30 GeV), 10^{10} per spill**
- **High Momentum un-separated secondary beam (< 20 GeV/*c*), 10^{8} per spill**

Physics:

Vector meson modification in the nuclear matter
Charmed Baryon spectroscopy
Nucleon Structure

Summary

- Meson and Kaon parton distributions
  - ∗ New territory for theory and experiment
  - ∗ Unique opportunities at COMPASS, JLab, J-PARC, and EIC
- 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