Meson-induced Quarkonium Production

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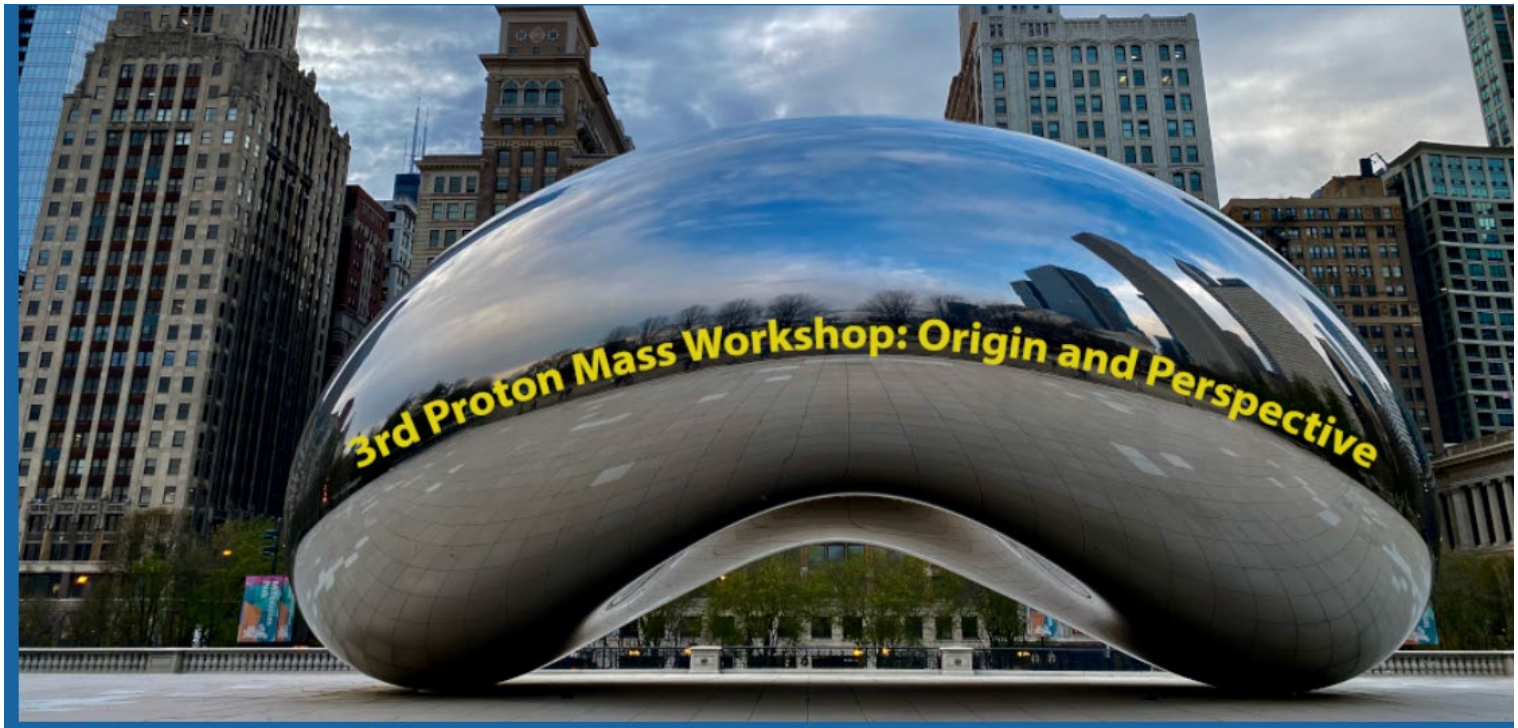


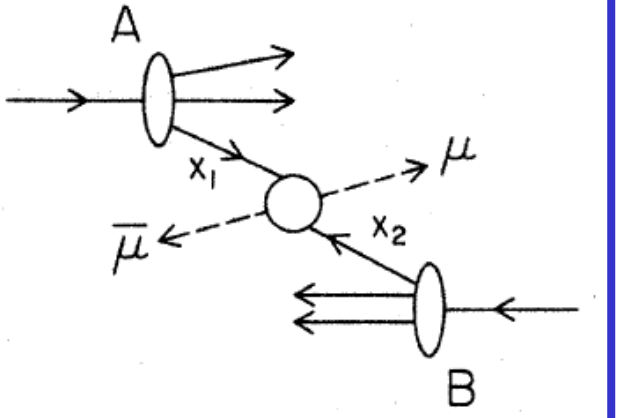
Meson-induced Quarkonium Production

- Why is it interesting?
  - Compared to proton, very little is known about partonic contents of pion and kaon
  - Mass decomposition for pion and kaon?
  - Gluon content in meson via J/Ψ production?
  - Exclusive production of J/Ψ with pion beam near threshold?

Meson partonic content from 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; J/Ψ production also measured
- Relatively large cross section due to $\bar{u}d$ contents in π^-

For a very long time, only four pion parton distribution functions were available

- First: OW-P (PRD 30, 943 (1984))
  - LO QCD
  - Drell-Yan data from E537 and NA3

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

For a very long time, only four pion parton distribution functions were available

- 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

- Fourth: SMRS (PR D45, 2349 (1992))
  - NA10 and E615 D-Y data
  - WA70 direct photon data

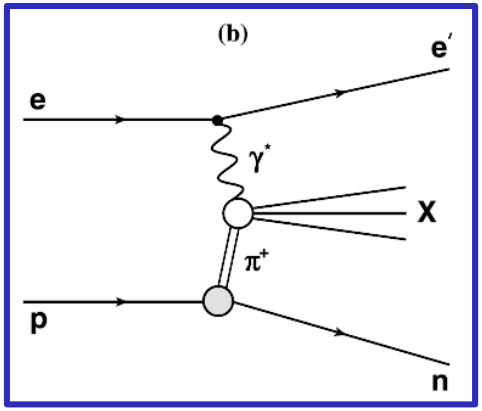
- Need new global fits to all existing data
- Need new experimental data with pion and kaon beams

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]

JAM Collaboration

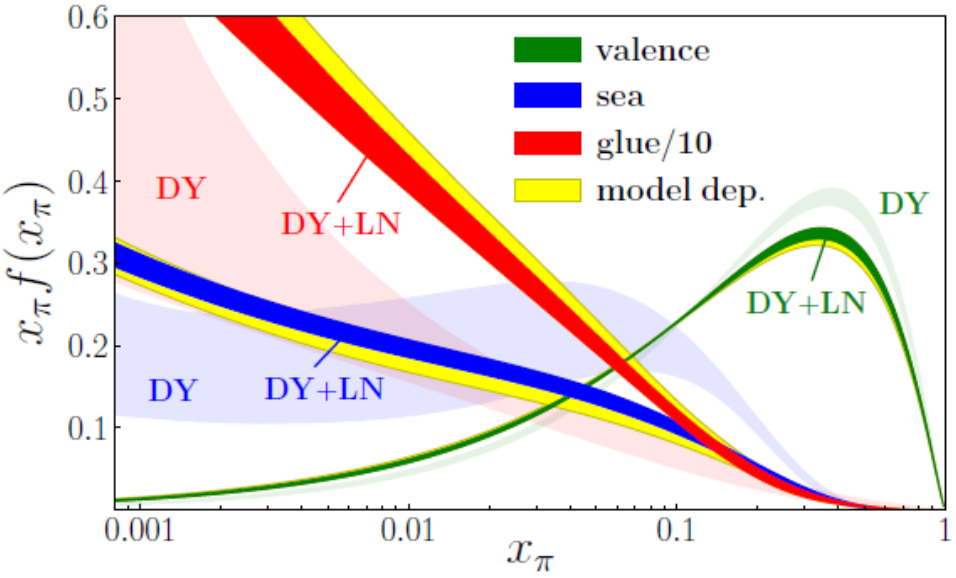
PRL 121, 152001 (2018)

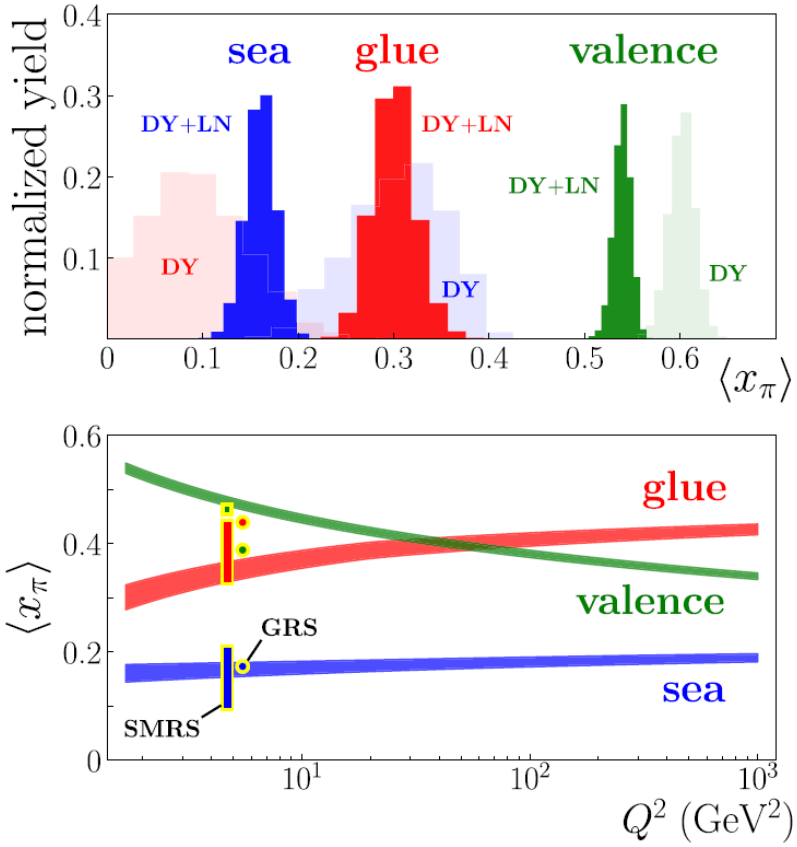


- Drell-Yan data from NA10 and E615
- Leading-neutron tagged DIS from HERA (H1 and ZEUS) provides information on the pion PDFs at small x
- Uncertainties of the pion PDFs are determined

Implications of the JAM results

PRL 121, 152001 (2018)





- The tagged-DIS data significantly reduce the uncertainty of the pion PDFs
- Further measurements of tagged-DIS can be pursued at JLab and EIC

PHYSICAL REVIEW D **102,** 014040 (2020)

Parton distribution functions of the charged pion within the xFitter framework

Ivan Novikov,[1,2,*] Hamed Abdolmaleki,[3] Daniel Britzger,[4] Amanda Cooper-Sarkar,[5] Francesco Giuli,[6] Alexander Glazov,[2,†] Aleksander Kusina,[7] Agnieszka Luszczak,[8] Fred Olness,[9] Pavel Starovoitov,[10] Mark Sutton,[11] and Oleksandr Zenaiev[12]

(xFitter Developers' team)

- Drell-Yan data from NA10 and E615
- Direct photon production data from WA70
- Uncertainties of the pion PDFs are determined
- Valence distribution is well determined, but not the sea and gluon distributions

A New Extraction of Pion Parton Distributions in the Statistical Model

Claude Bourrely[a], Franco Buccella[b], Jen-Chieh Peng[c]

Physics Letters B 813 (2021) 136021

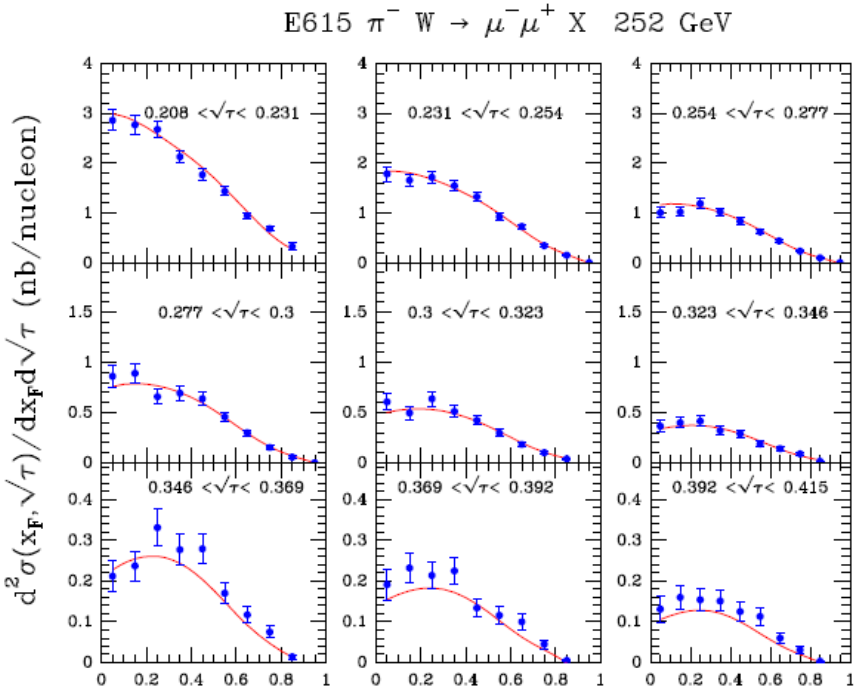
$$xU(x) = xD(x) = \frac{A_U X_U x^{b_U}}{\exp[(x - X_U)/\bar{x}] + 1} + \frac{\tilde{A}_U x^{\tilde{b}_U}}{\exp(x/\bar{x}) + 1} . \quad (7)$$

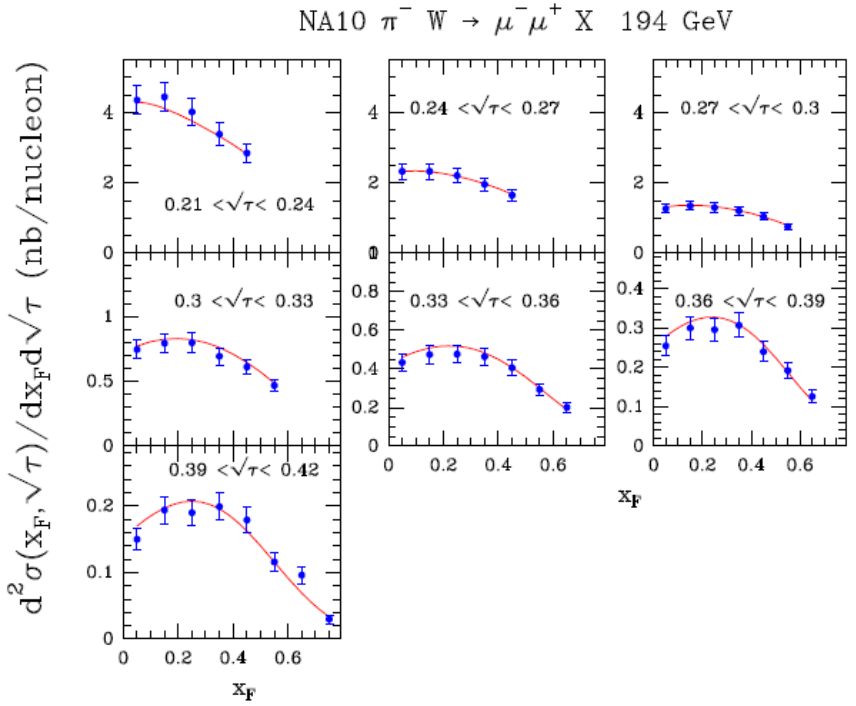
$$x\bar{U}(x) = x\bar{D}(x) = \frac{A_U (X_U)^{-1} x^{b_U}}{\exp[(x + X_U)/\bar{x}] + 1} + \frac{\tilde{A}_U x^{\tilde{b}_U}}{\exp(x/\bar{x}) + 1} . \quad (8)$$

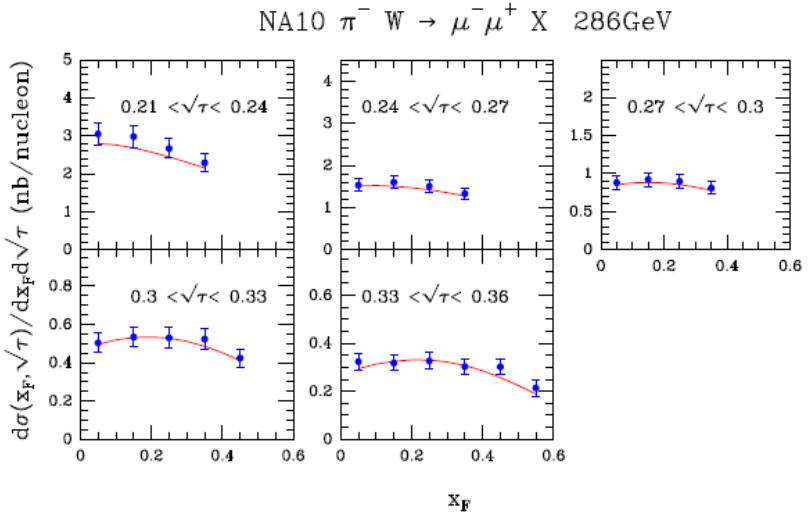
$$xS(x) = x\bar{S}(x) = \frac{\tilde{A}_U x^{\tilde{b}_U}}{2[\exp(x/\bar{x}) + 1]} . \quad (9)$$

$$xG(x) = \frac{A_G x^{b_G}}{\exp(x/\bar{x}) - 1} . \quad (10)$$

- The statistical model describes proton's PDF very well
- The antiquark's flavor structure is related to quark's flavor structure
- The antiquark's spin structure is related to quark's spin structure
- It is not clear if the statistical model also works for meson's PDFs

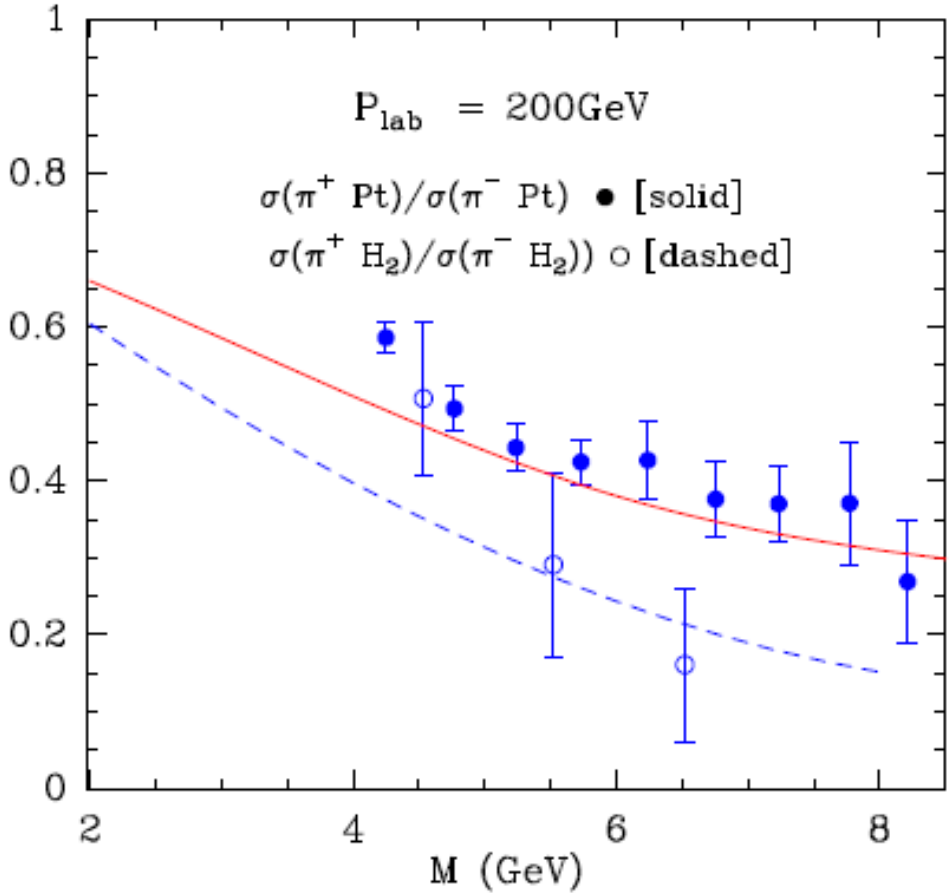






With only a few parameters for the pion PDFs, the Drell-Yan data are well described by the statistical model

Comparison with other Drell-Yan data



The statistical model can also describe well the $\sigma(\pi^+ + Pt) / \sigma(\pi^- + Pt)$ Drell-Yan data, which were not included in the fit.

Comparison between proton and pion PDFs in the statistical model

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

$A_U = 0.776 \pm 0.15$ $\quad$ $b_U = 0.500 \pm 0.02$

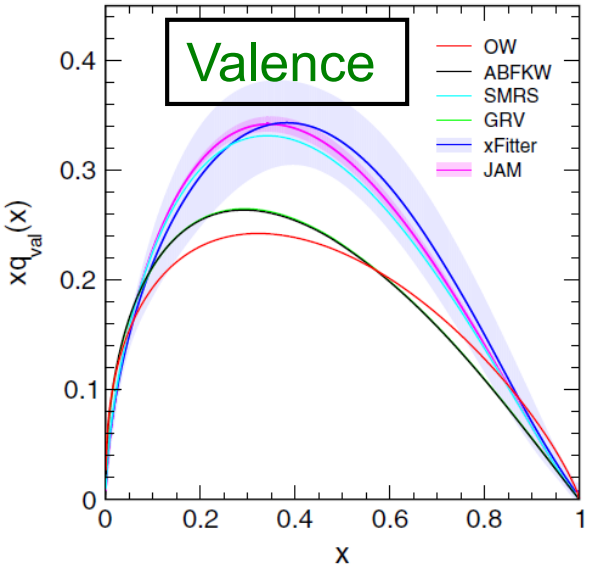
$X_U = 0.756 \pm 0.01$ $\quad$ $\bar{x} = 0.1063 \pm 0.004$

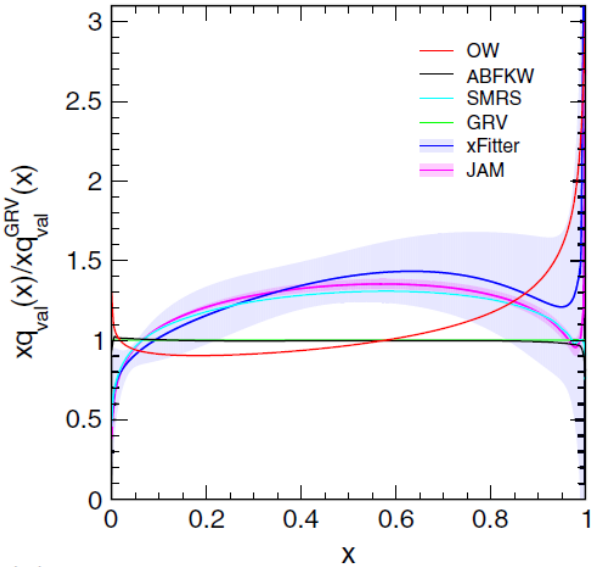
$\tilde{A}_U = 2.089 \pm 0.21$ $\quad$ $\tilde{b}_U = 0.4577 \pm 0.009$

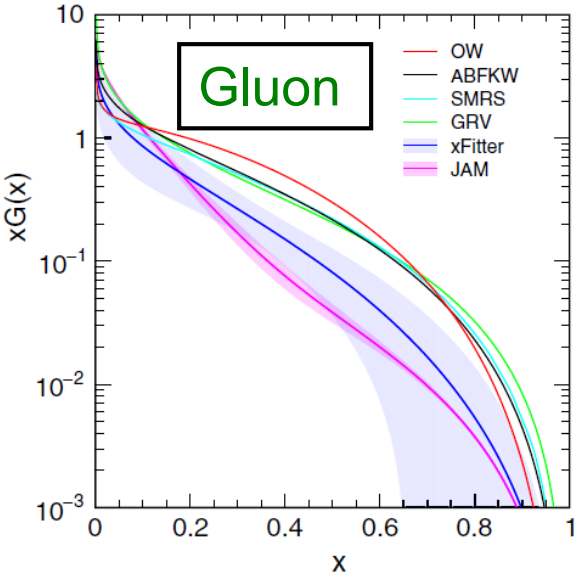
$A_G = 31.17 \pm 1.7$ $\quad$ $b_G = 1 + \tilde{b}_U$.

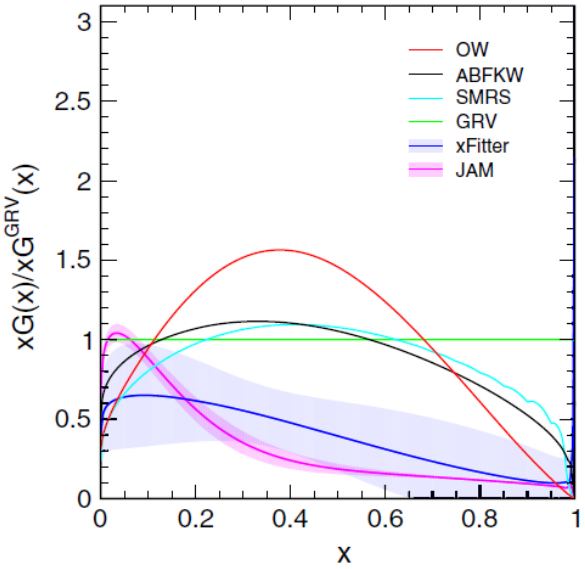
- The temperature, $\bar{x} = 0.106$, found for pion is very close to that obtained for proton, $\bar{x} = 0.090$, suggesting a common feature for the statistical model description of baryons and mesons
- The chemical potential of the valence quark for pion, $X_U = 0.756$, is significantly larger than for proton, $X_U = 0.39$

Valence and gluon distributions for various pion PDFs







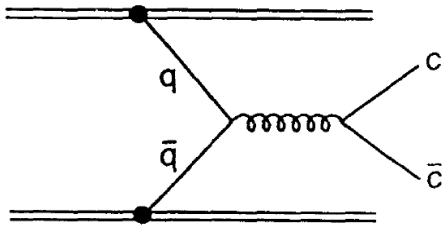


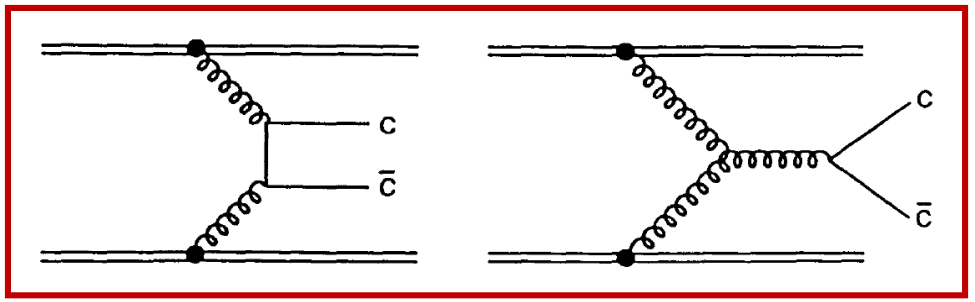
- Quite good agreements for valence quark PDFs
- Much larger variations for the gluon PDFs

Constraining gluon distribution of pion with pion-induced J/Ψ production

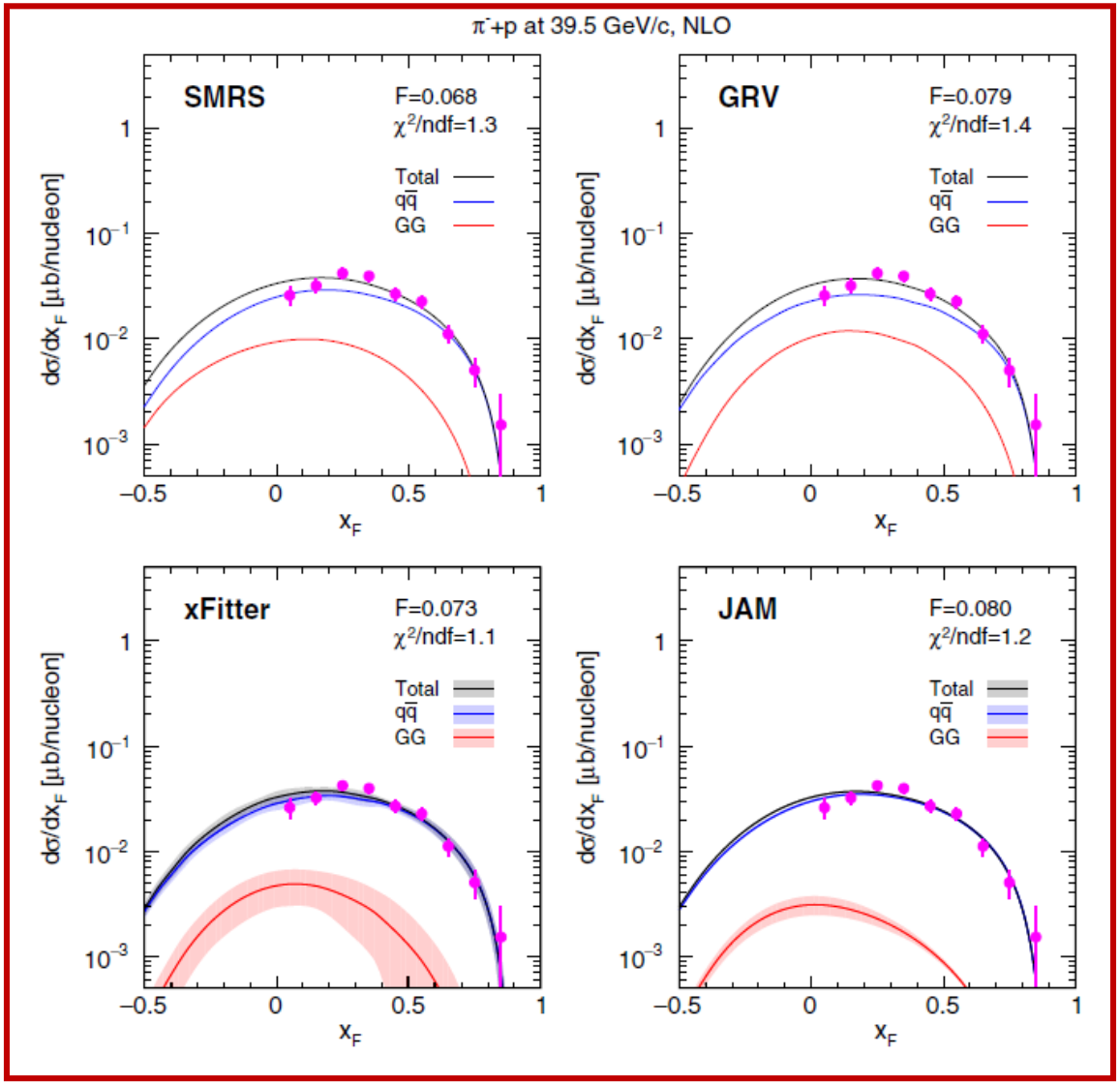
Chang, Platchkov, Sawada, JCP, PRD 102 (2020) 054024

- An attempt to compare existing pion PDFs in their abilities to describe existing pion-induced *J/Ψ* production data
- The existing data are sensitive to the gluon PDF in pion, which is poorly known and is of much theoretical interest



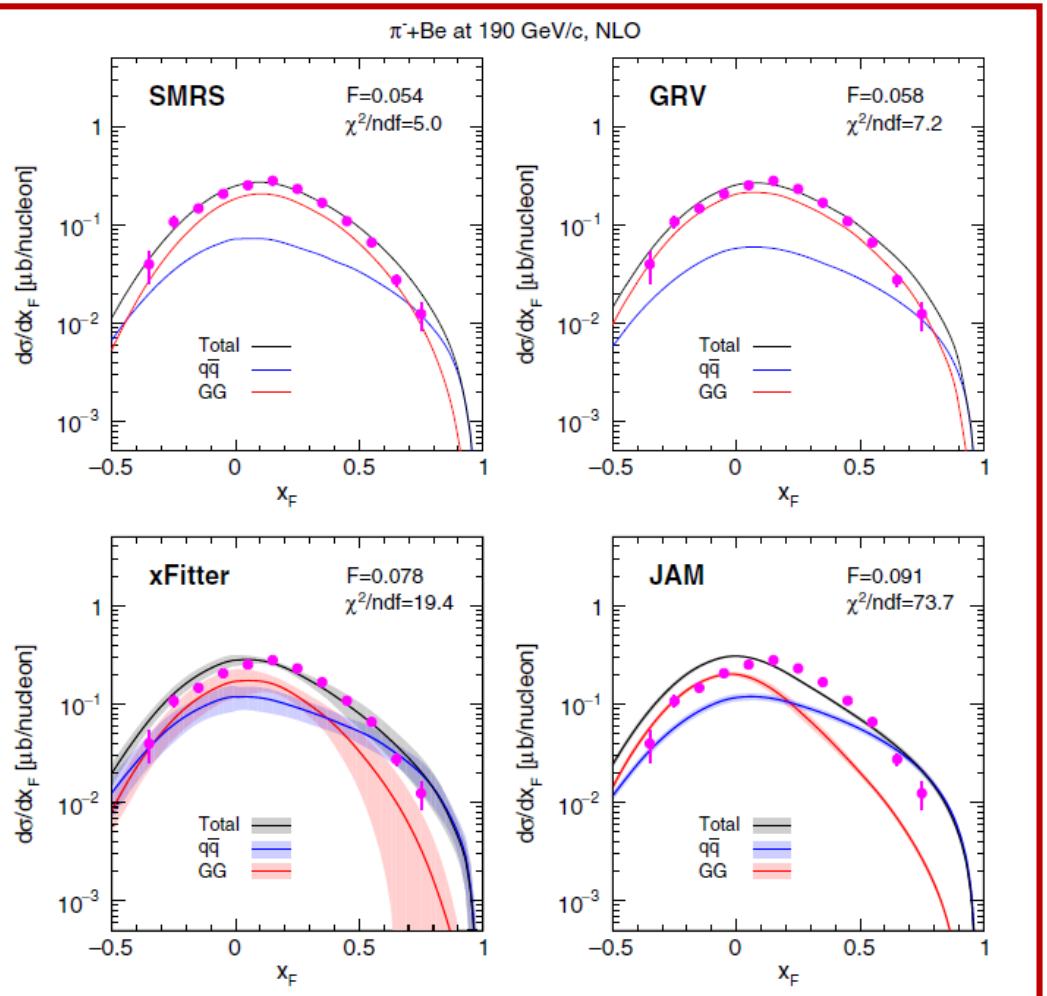


Comparison between data and calculations for different PDFs



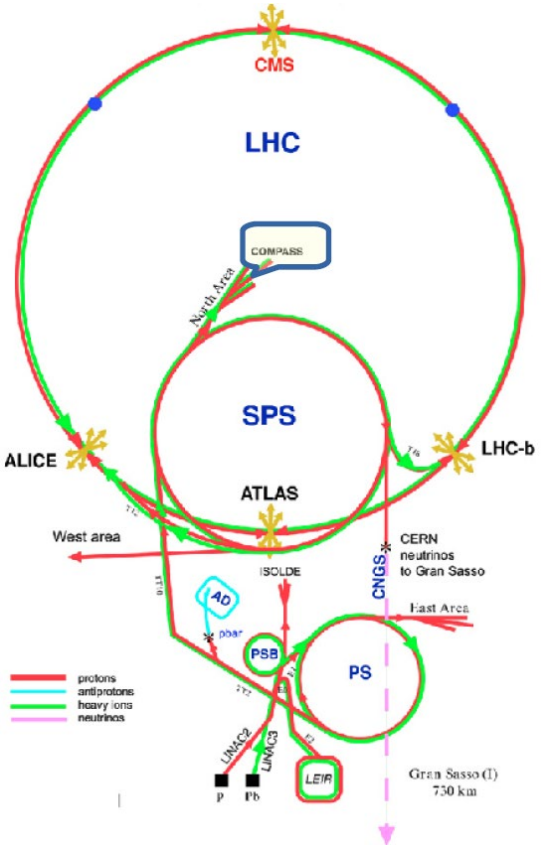
- At the lowest beam energy (39.5 GeV), $q\bar{q}$ annihilation dominates
- All PDFs are in good agreement with data, reflecting similar valence quark distributions

Comparison between data and calculations for different PDFs



- At the COMPASS beam energy (190 GeV), GG fusion dominates at $x_F \sim 0$ for all PDFs
- At forward x_F, $q\bar{q}$ annihilation dominates
- JAM and xFitter GG fusion contribution falls off rapidly at large x_F

COMPASS++/AMBER (Phase-I was just approved)



Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^{\pm}$	high-pressure H2	2022 1 year
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^{\pm}$	$NH_3^{\uparrow}$	2022 2 years
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^{\pm}$	C/W	2022 1-2 years

- Expect new Drell-Yan and J/Ψ production data with pion beam in the near future !

Exclusive Drell-Yan and J/Ψ production with pion beam

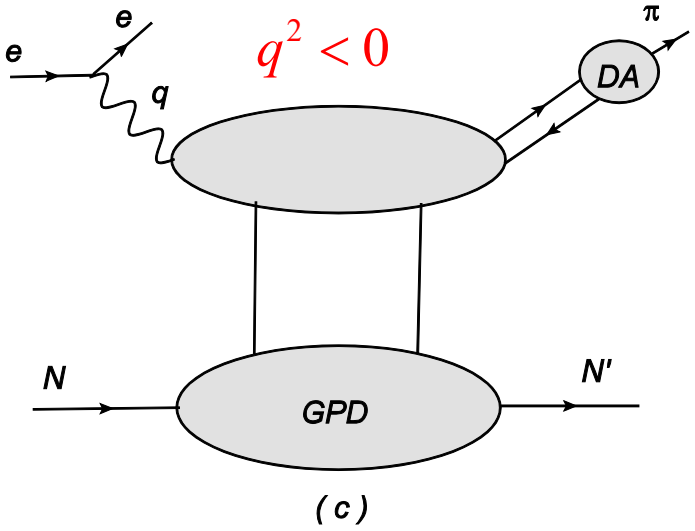
- Exclusive Drell-Yan with meson and antiproton beams are the time-like processes complementary to the deeply virtual meson production at JLab, HERMES and COMPASS
- Exclusive Drell-Yan with meson beam at J-PARC will also complement the program at FAIR using antiproton beam

Takahiro Sawada, Wen-Chen Chang, Shunzo Kumano, Jen-Chieh Peng, Shinya Sawada, Kazuhiro Tanaka, Phys. Rev. D93 (2016) 114034

DEMP versus exclusive Drell-Yan

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

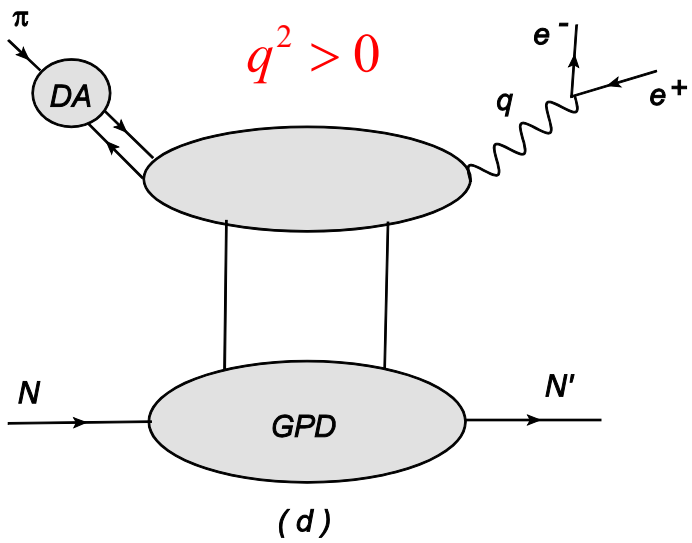
Deep Exclusive Meson Production



space-like photon

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

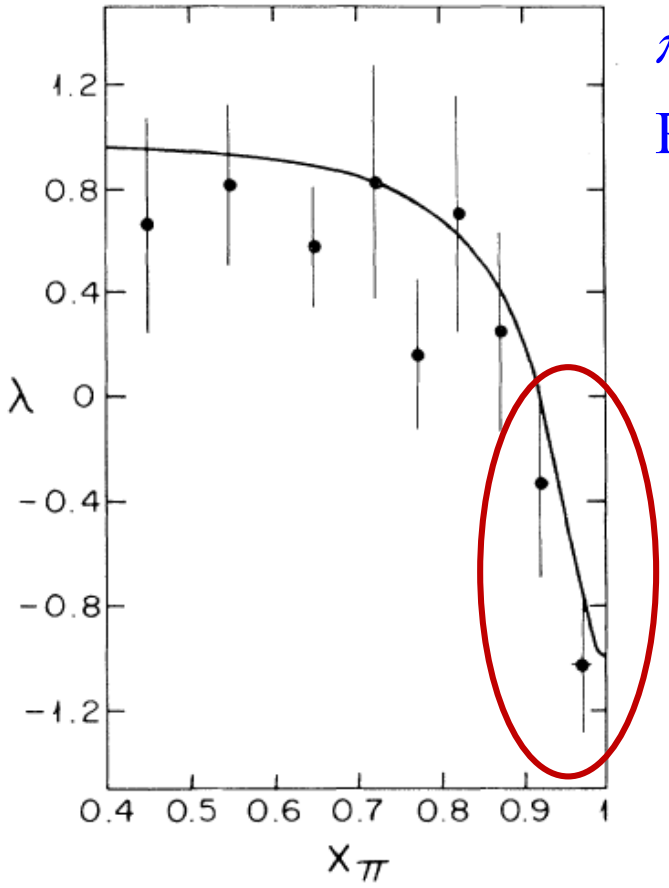
Exclusive Drell-Yan



time-like photon

Longitudinally polarized dilepton is expected

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



$\pi^- + W \to \mu^- + \mu^+ + X$ 80 GeV π^-

PRL 55 (1985) 2649

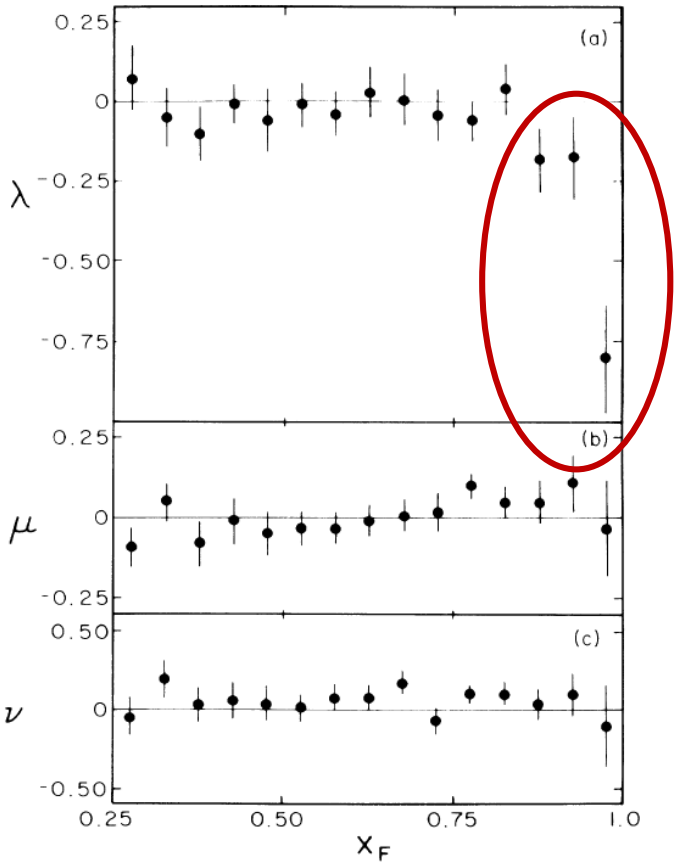
$$\frac{d\sigma}{d\Omega} \propto (1 + \lambda \cos^2\theta)$$

$\lambda = 1$: transversely polarized

$\lambda = -1$: longitudinally polarized

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

Evidence for longitudinally polarized dilepton in meson-induced J/Ψ at large x_F?



$\pi^- + W \to J/\Psi + X$ 252 GeV π^-

PRL 58 (1987) 2523

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

$\lambda = 1$: transversely polarized

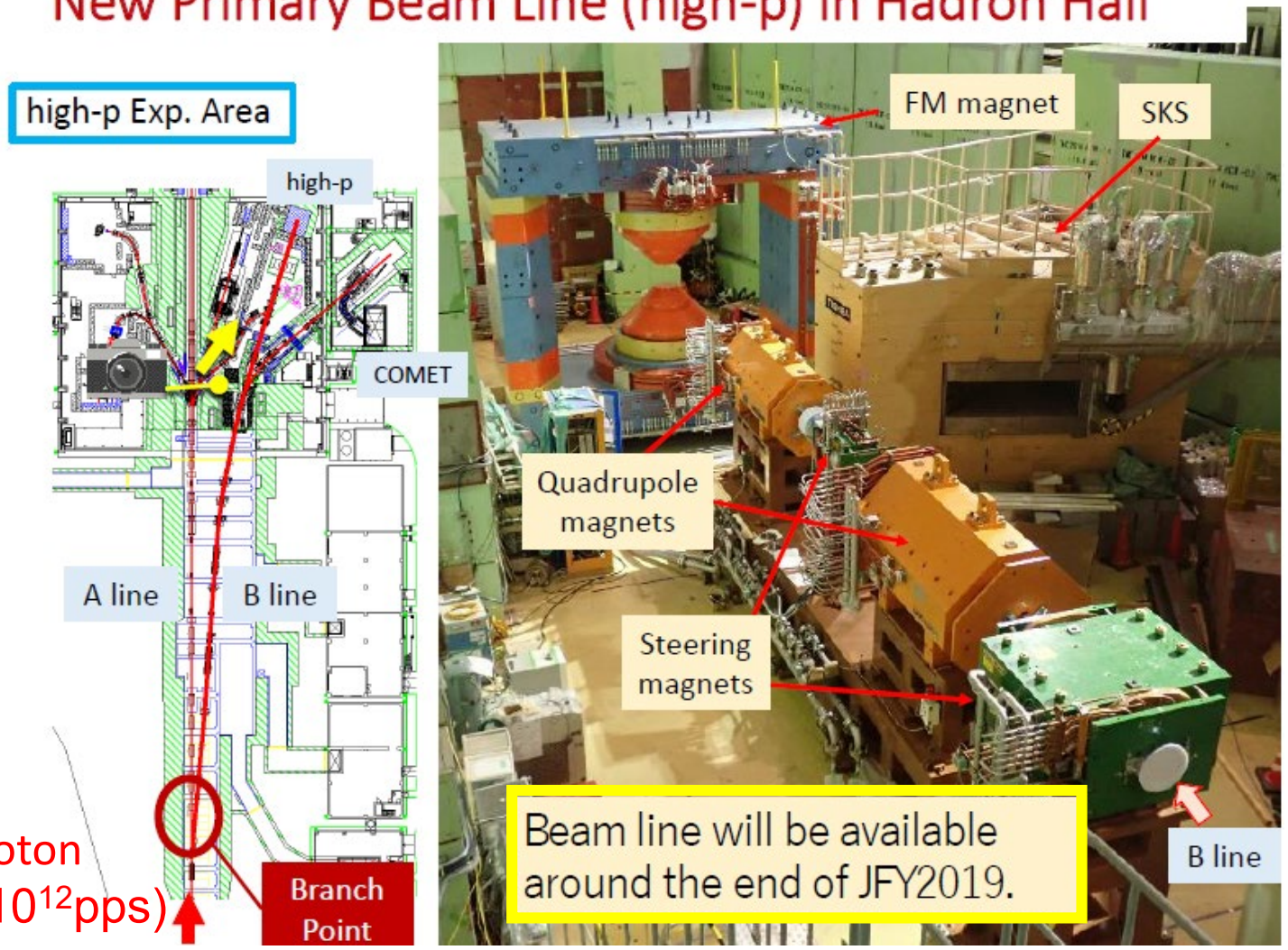
$\lambda = -1$: longitudinally polarized

As $x_F \to 1$, inclusive J/Ψ becomes exclusive J/Ψ!

J-PARC High-momentum Beam Line (can also provide secondary pion or kaon beam)

S. Sawada, Pacific Spin 2019

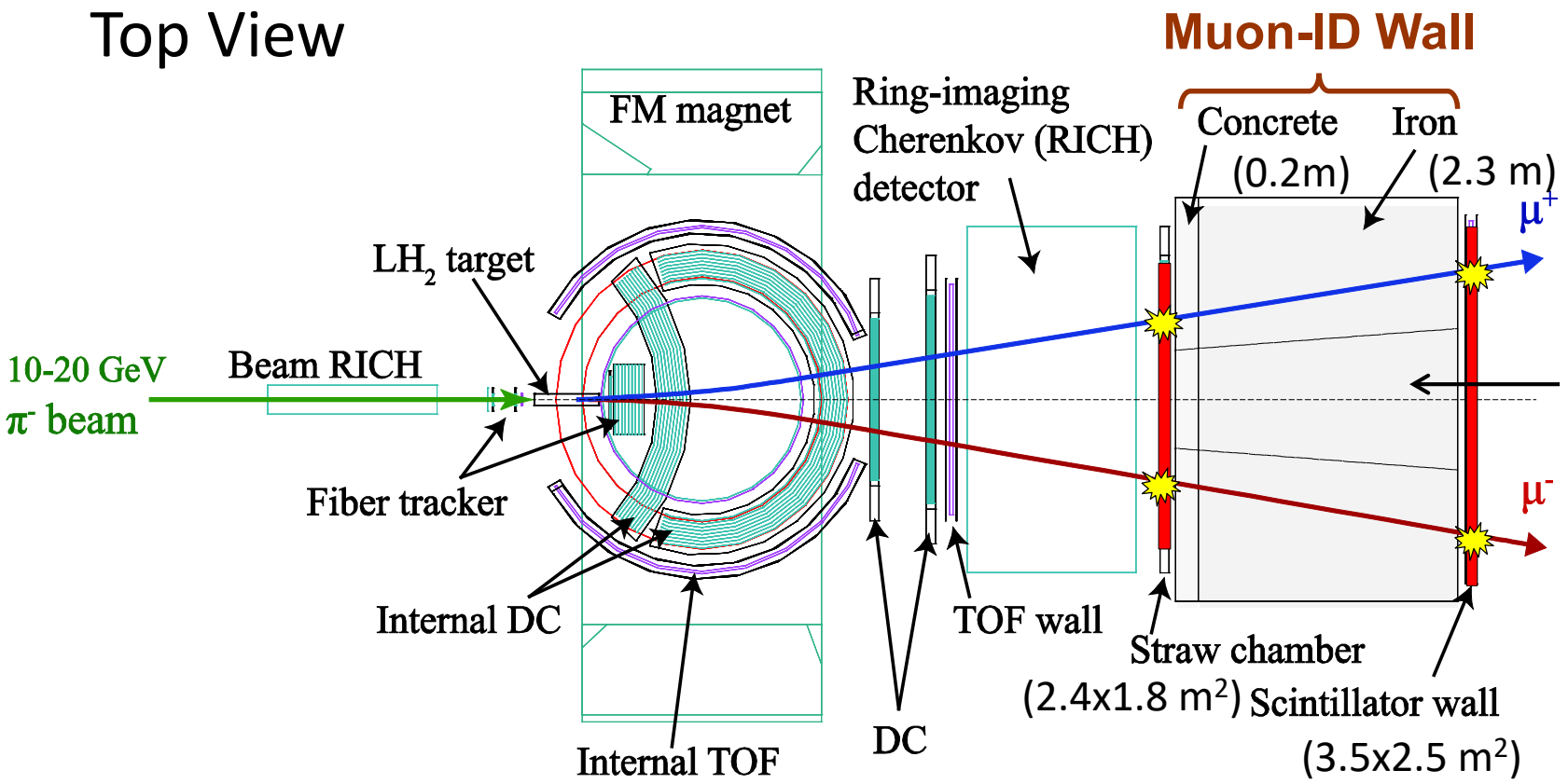
New Primary Beam Line (high-p) in Hadron Hall



30 GeV proton
(~10^{10} – 10^{12}pps)

Exclusive Drell-Yan and J/Ψ measurement in J-PARC E50 Spectrometer

Top View



Original Configuration
for Charmed Baryon Spectroscopy

Stage-1 approved by J-PARC PAC-18, August 12, 2014.

Extension part

Proposal is currently being prepared.

Summary and future prospect

- Meson parton distributions represent
  - ∗ New territory for theory and experiment
  - ∗ Unique opportunities at COMPASS, JLab, J-PARC, and EIC
- J/ψ production provides useful information on meson quark and gluon contents
  - ∗ Existing data should be included in the global fits for constraining the gluon distribution in pion and kaon
  - ∗ Analysis is underway to find possibly different gluon distributions in kaon and pion
- Exclusive J/ψ production with meson beam could provide information complementary to exclusive photo - J/ψ production