

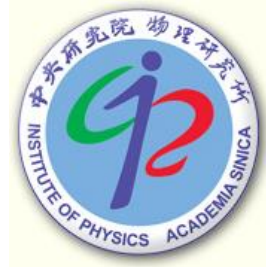
EIC-Asia Workshop on QCD and Hadron Structure
IoP, Academia Sinica, April 30, 2026

Pion and Kaon PDFs

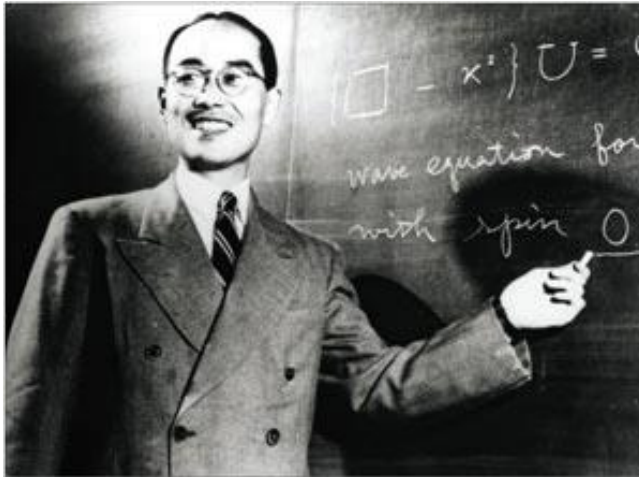
Wen-Chen Chang 章文箴

Institute of Physics, Academia Sinica, Taiwan

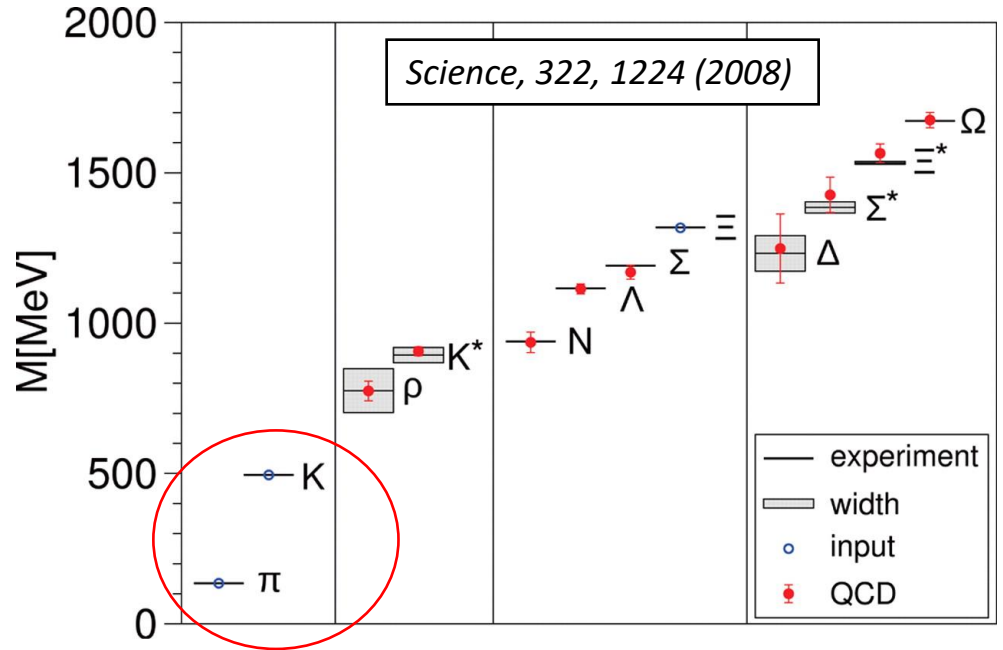
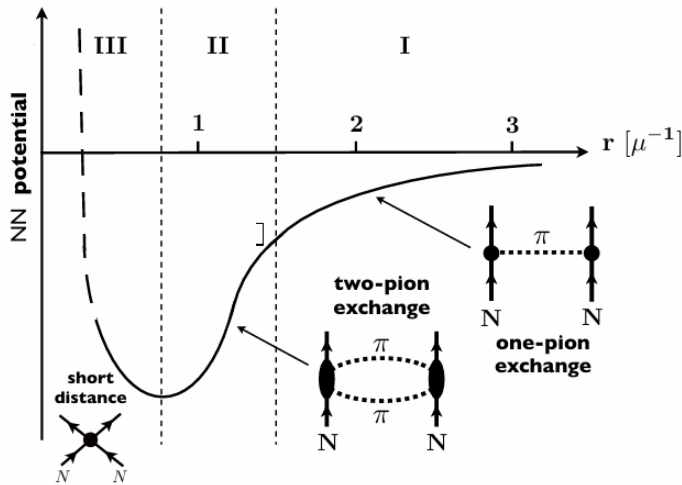
In collaboration with
Chia-Yu Hsieh, Yu-Shiang Lian, Jen-Chieh Peng,
Stephane Platchkov, Satyajit Puan, and Takahiro Sawada



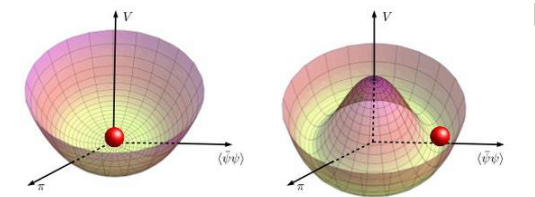
Pion/Kaon: Goldstone Bosons of Strong Interaction



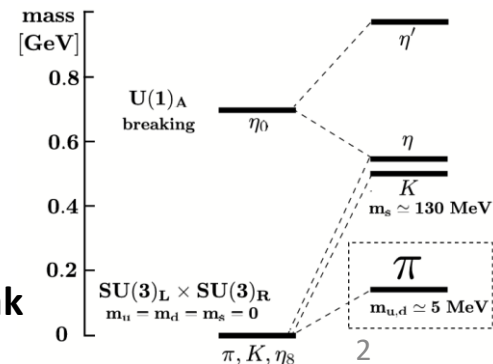
Hideki Yukawa, 1935



<https://arxiv.org/pdf/0704.1992>



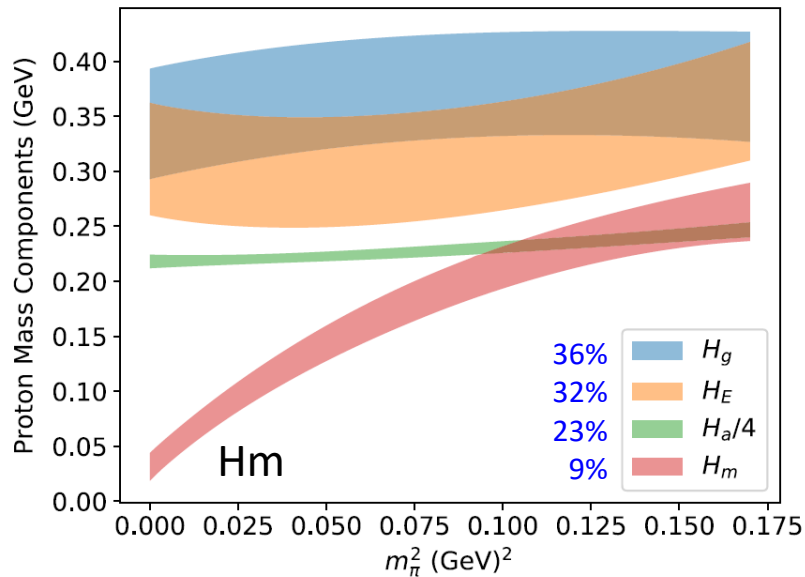
Spontaneous symmetry break



Mass Decomposition

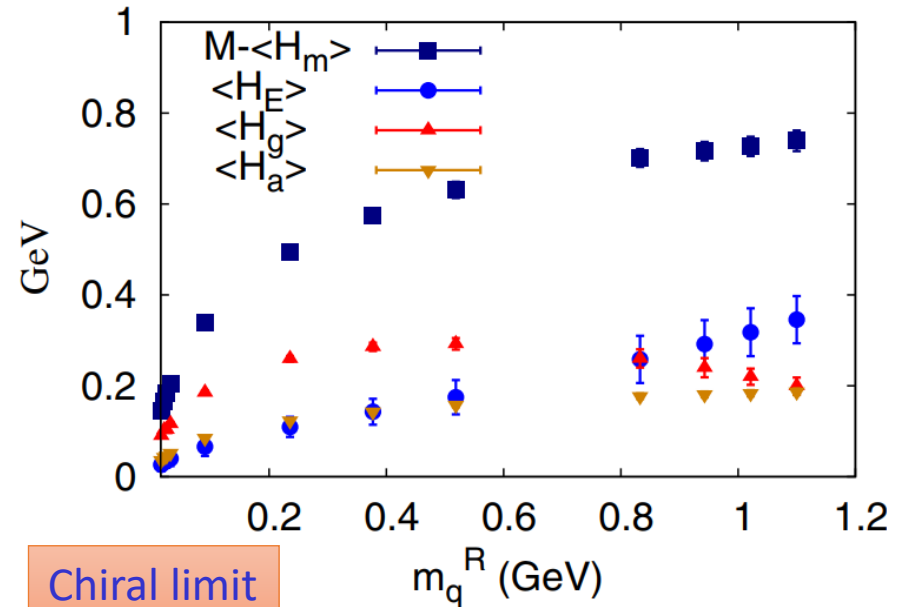
Proton

PRL 121, 212001 (2018)



Pion

PRD 91, 074516 (2015)



Quark energy

Trace Anomaly (gluon condensate)

$$M = -\langle T_{44} \rangle = \underbrace{\langle H_m \rangle}_{\text{Quark mass}} + \underbrace{\langle H_E \rangle}_{\text{Gluon energy}}(\mu) + \underbrace{\langle H_g \rangle}_{\text{Gluon energy}}(\mu) + \frac{1}{4} \langle H_a \rangle$$

Pion/Kaon PDFs

- **Drell-Yan:** $\pi, K^\pm p \rightarrow \mu^+ \mu^- X$ (LO: sensitive to valence quarks)

- LO: $q\bar{q} \rightarrow \mu^+ \mu^-$
- NLO: $q\bar{q} \rightarrow \mu^+ \mu^- G, qG \rightarrow \mu^+ \mu^- q$ (large p_T)
- NNLO: $q\bar{q}G \rightarrow \mu^+ \mu^- G, qG \rightarrow \mu^+ \mu^- qG, GG \rightarrow \mu^+ \mu^- q\bar{q}$

- **Direct photon:** $\pi, K^\pm p \rightarrow \gamma X$ (LO: sensitive to gluons)

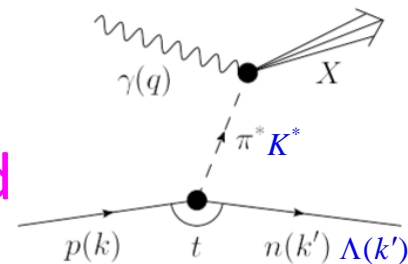
- LO: $q\bar{q} \rightarrow \gamma G, qG \rightarrow \gamma q$

- **Jpsi:** $\pi, K^\pm p \rightarrow J/\psi X$ (LO: sensitive to gluons)

- LO: $q\bar{q} \rightarrow c\bar{c} \rightarrow J/\psi X, GG \rightarrow c\bar{c} \rightarrow J/\psi X$

- NLO: $q\bar{q} \rightarrow c\bar{c}G \rightarrow J/\psi X, GG \rightarrow c\bar{c}G \rightarrow J/\psi X, qG \rightarrow c\bar{c}q \rightarrow J/\psi X$

- **Leading neutron (LN) electroproduction:**
Sullivan processes from a nucleon's pion cloud



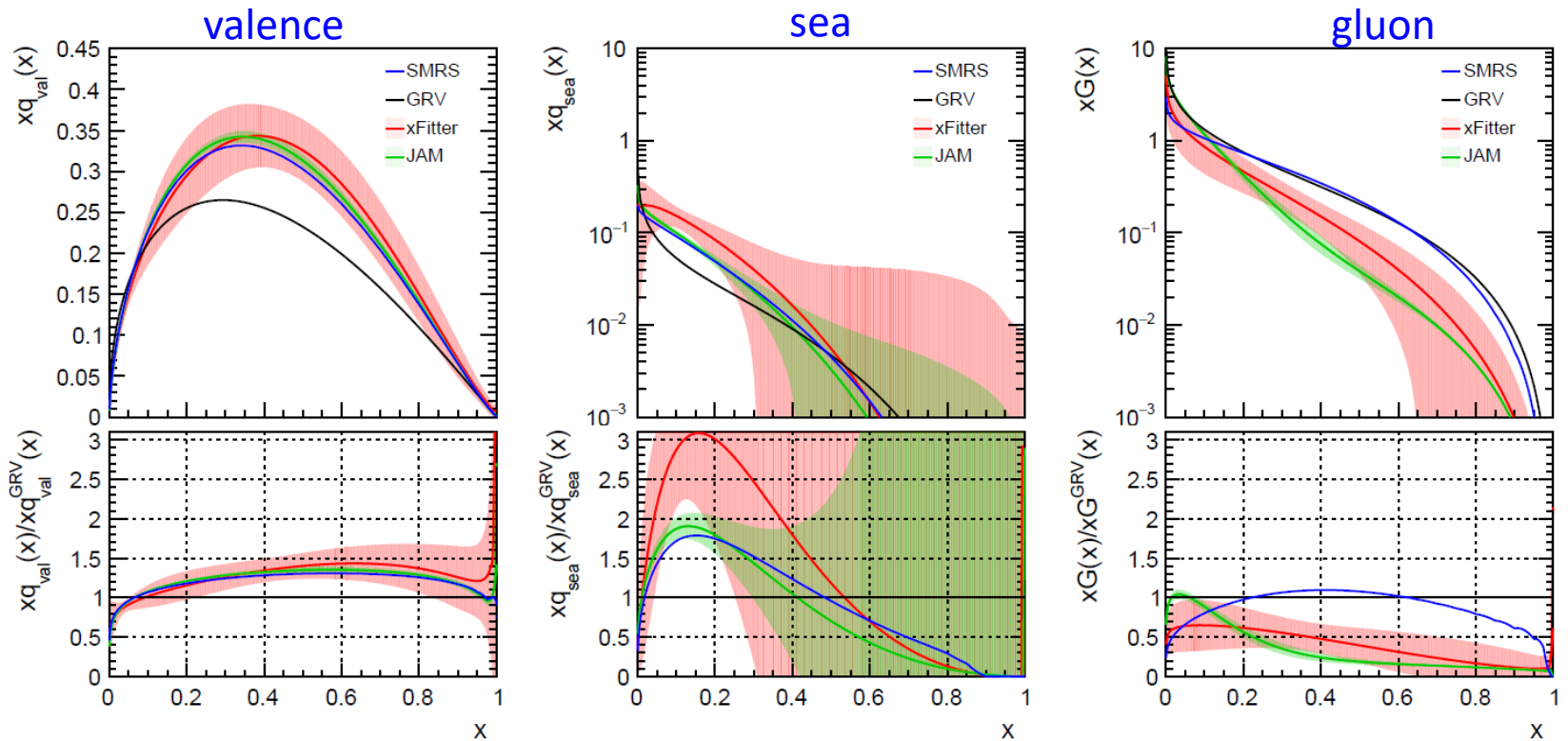
Pion PDFs (Global Analysis)

PDF	DY (xF, pT)	Direct γ	J/ψ	LN	Refs.
OW	*		*		PRD 1984
ABFKW	*	*			PLB 1989
SMRS	*	*			PRD 1992
GRV	*	*			ZPC 1992
GRS	*				EPJC 1999
JAM18	*			*	PRL 2018
BS, BBP	*				NPA 2019 PLB 2021
xFitter	*	*			PRD 2020
JAM21	*			*	PRD 2021 PRL 2021
Fanto	*	*		*	PRD 2024

Pion PDFs

$$Q^2 = 9.6 \text{ GeV}^2$$

PDF	$\int_0^1 x \bar{u}_{\text{val}}(x) dx$	$\int_0^1 x \bar{u}_{\text{sea}}(x) dx$	$\int_0^1 x G(x) dx$
OW	0.203	0.026	0.487
ABFKW	0.205	0.026	0.468
SMRS	0.245	0.026	0.394
GRV	0.199	0.020	0.513
JAM ^a	0.225 ± 0.003	0.028 ± 0.002	0.365 ± 0.016
xFitter ^a	0.228 ± 0.009	0.040 ± 0.020	0.291 ± 0.119



A large discrepancy of pion PDFs!

Theoretical Models of Pion/Kaon PDFs

- **Nambu–Jona-Lasinio (NJL) Model:** PRC 94, 035201 (2016); PRD 105, 034021, (2022)
- **Chiral Constituent Quark Model:** PRD 86, 074005 (2012); PRD 97, 074015 (2018); PRD 109, 054040 (2024)
- **Dyson-Schwinger Equations (DSE):** PRD 93, 074021 (2016); PRD 93, 054029 (2018); PRL 124, 042002 (2020); EPJC 80, 1064 (2020)
- **Light-front & Holographic QCD:** PRD 101, 034024 (2020); PRD 106, 034003 (2022); PRD 107, 114023 (2023)
- **Maximum Entropy Input:** PLB 800, 135066 (2020); EPJC 81, 302 (2021)
- **Instanton Model:** PRD 102, 014039 (2020)

Light-Front & DSE

[Z.F. Cui, ..., C. D. Roberts et al., [Eur. Phys. J. C \(2020\) 80:1064](#)]

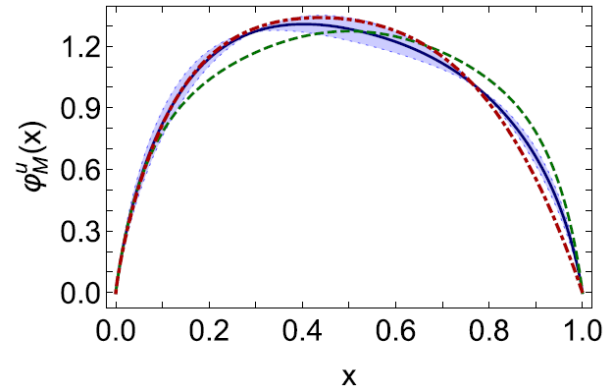
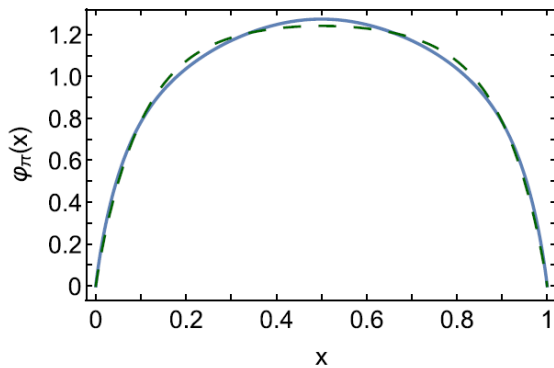
Modeling the distribution amplitude (valence quark distributions)

π

$$u^M(x, \zeta_H) \propto |\varphi_M^u(x, \zeta_H)|^2$$

Hadronic scale $\zeta_H = 0.331$ GeV

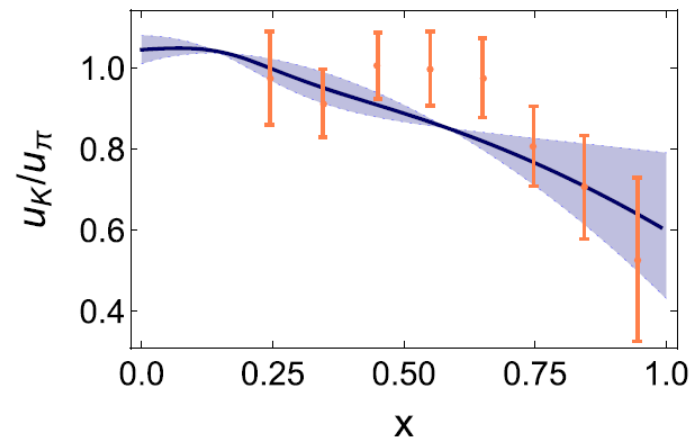
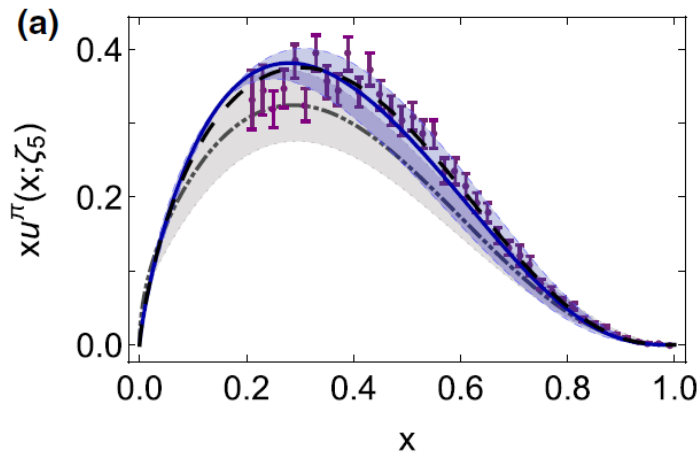
K



π

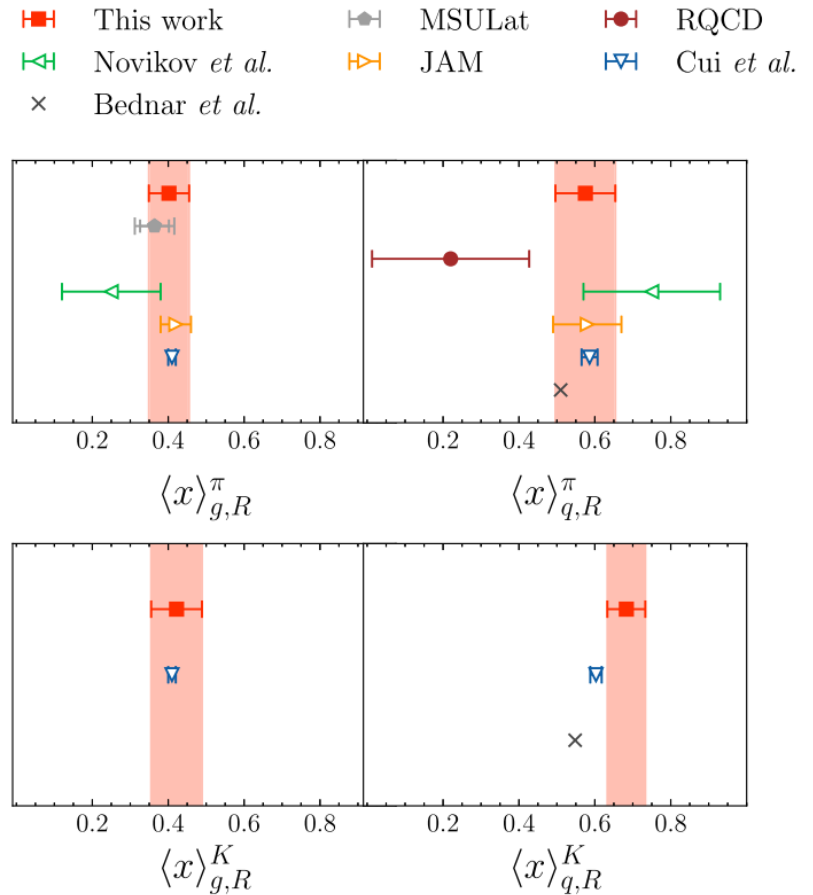
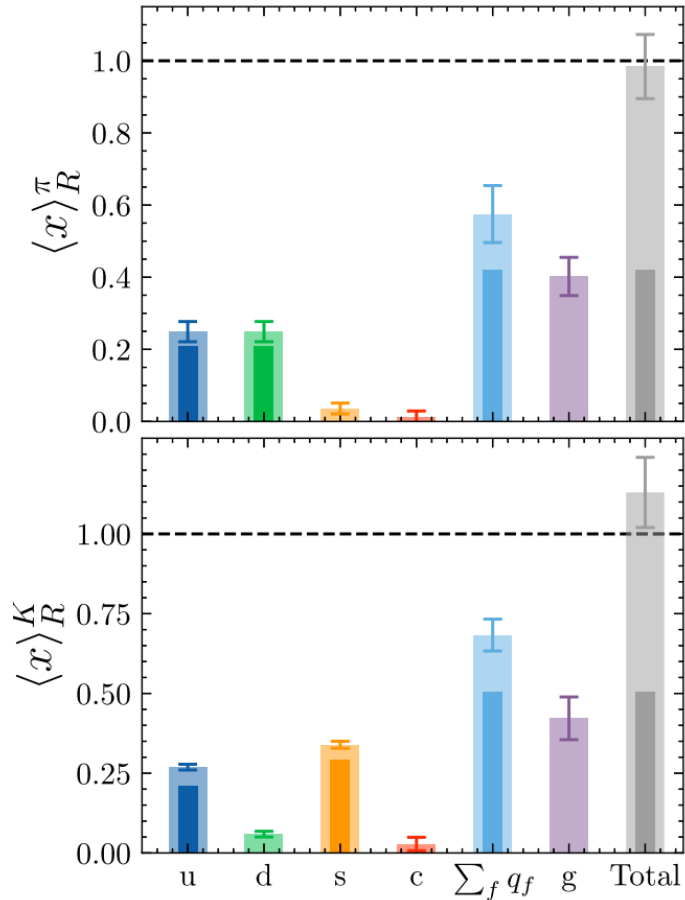
QCD evolution

K



Lattice QCD: Momentum Fractions

ETM Collaboration, [PRL 134, 131902 \(2025\)](#)



Lattice QCD: Momentum Fractions

ETM Collaboration, [PRL 134, 131902 \(2025\)](#)

	π	K	p (B -ensemble)
$\langle x \rangle_{u,R}$	0.249(28)	0.269(09)	0.354(30)
$\langle x \rangle_{d,R}$	0.249(28)	0.059(09)	0.188(19)
$\langle x \rangle_{s,R}$	0.036(15)	0.339(11)	0.052(12)
$\langle x \rangle_{c,R}$	0.013(16)	0.028(21)	0.019(09)
$\langle x \rangle_{q,R}$	0.402(53)	0.422(67)	0.427(92)
$\langle x \rangle_{q,R}$	0.575(79)	0.683(50)	0.618(60)
$\langle x \rangle_{u+d-2s,R}$	0.438(18)	-0.362(08)	...
$\langle x \rangle_{u+d+s-3c,R}$	0.521(51)	0.494(36)	...
$\langle x \rangle_{g,R} + \langle x \rangle_{q,R}$	0.984(89)	1.13(11)	1.04(11)

The gluon part is about the same for π , K and p !

Lattice QCD: Mellin Moments

ETM Collaboration, [PRD 104, 054504 \(2021\)](#)

$$\langle x^2 \rangle_{\pi^+}^u = 0.110(7)(12),$$

$$\langle x^2 \rangle_{K^+}^u = 0.096(2)(2),$$

$$\langle x^2 \rangle_{K^+}^s = 0.139(2)(1),$$

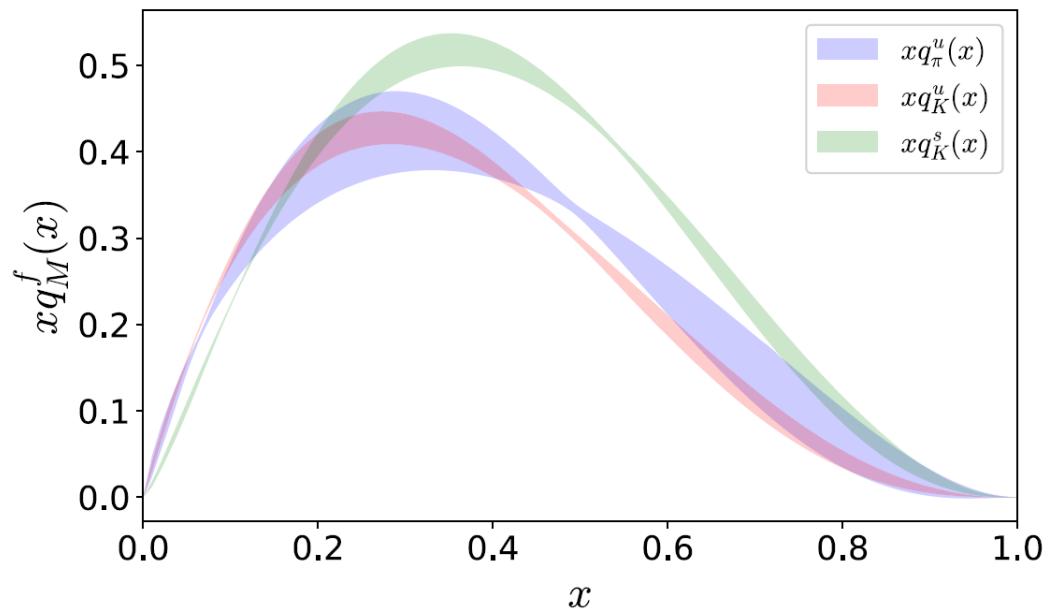
$$\langle x^3 \rangle_{\pi^+}^u = 0.024(18)(2),$$

$$\langle x^3 \rangle_{K^+}^u = 0.033(6)(1),$$

$$\langle x^3 \rangle_{K^+}^s = 0.073(5)(2),$$

$$\langle x^n \rangle = N \int_0^1 dx x^\alpha (1-x)^\beta (1+\gamma x).$$

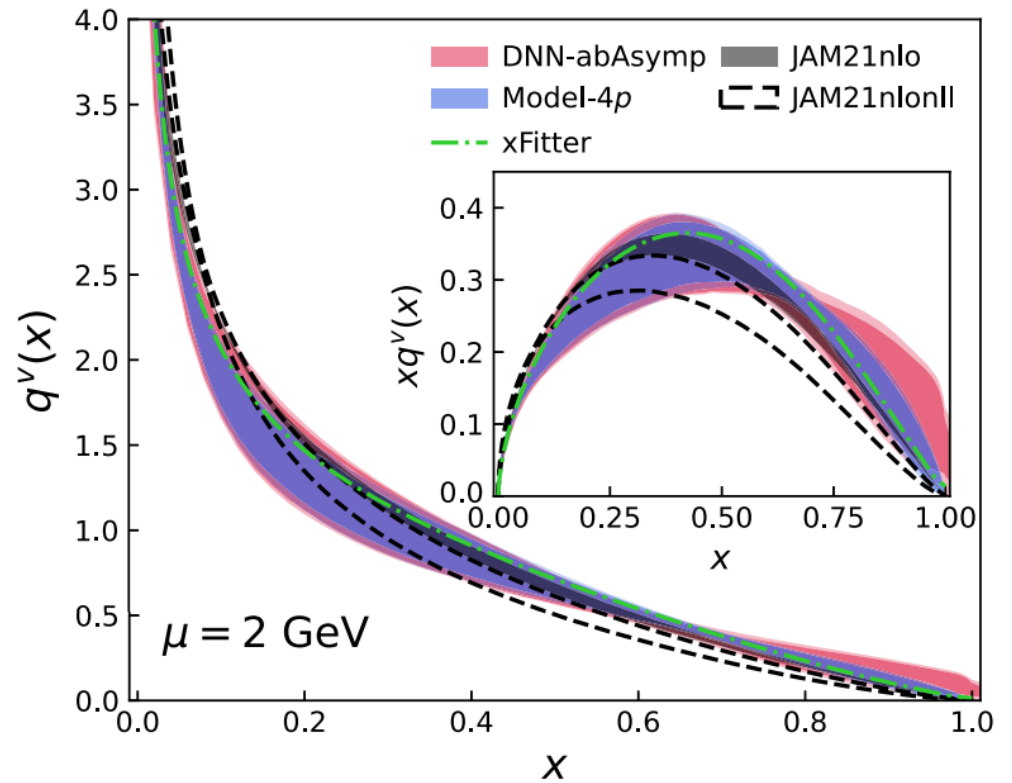
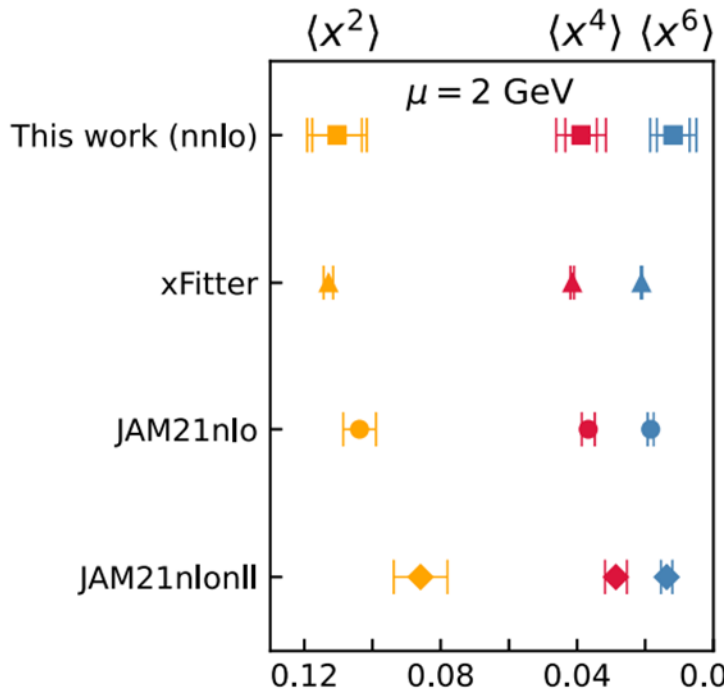
$$\langle x^n \rangle = \frac{(\prod_{i=1}^n (i+\alpha))(n+2+\alpha+\beta+(i+1+\alpha)\gamma)}{(\prod_{i=1}^n (i+2+\alpha+\beta))(2+\alpha+\beta+(1+\alpha)\gamma)}, \quad n > 0.$$



Reconstructed by the lattice data up to $\langle x^3 \rangle$.

Lattice QCD: Mellin Moments

Gao et al., PRD 106, 114510 (2022)



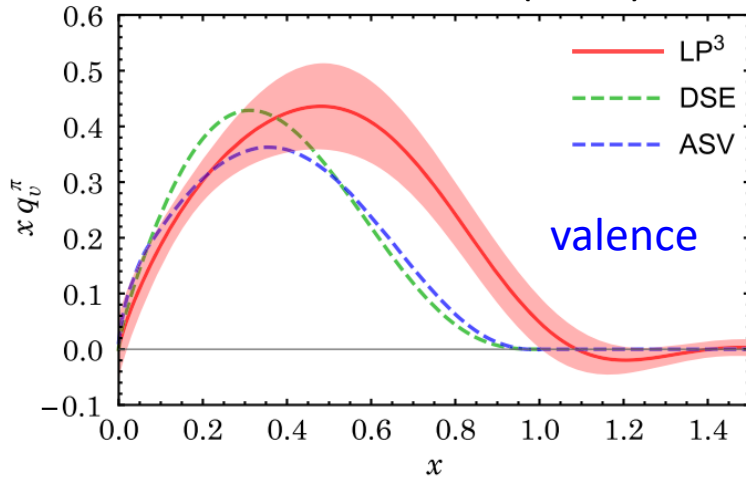
Reconstructed by the lattice data up to $\langle x^6 \rangle$.

Large Momentum Effective Theory (LaMET)

MSULat

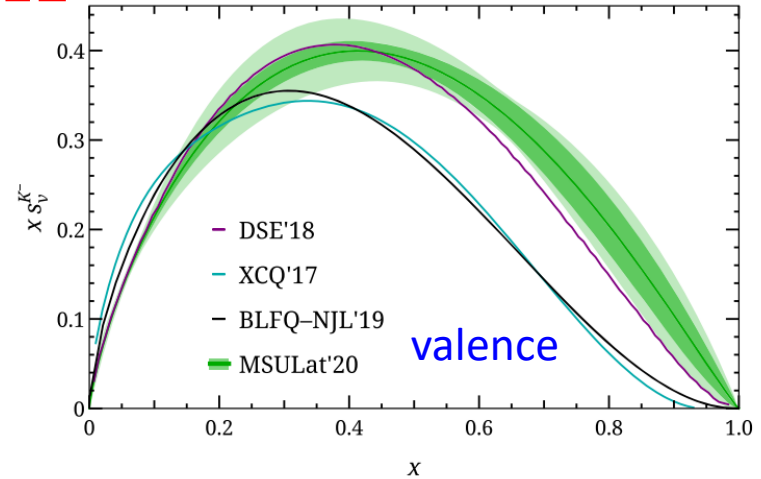
π

PRD 100, 034505 (2019)

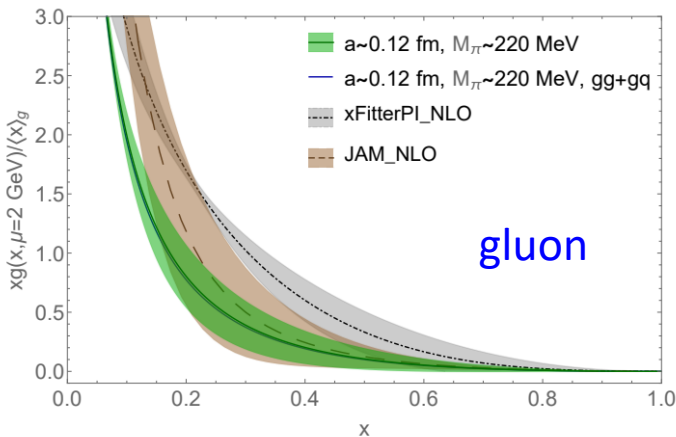


K

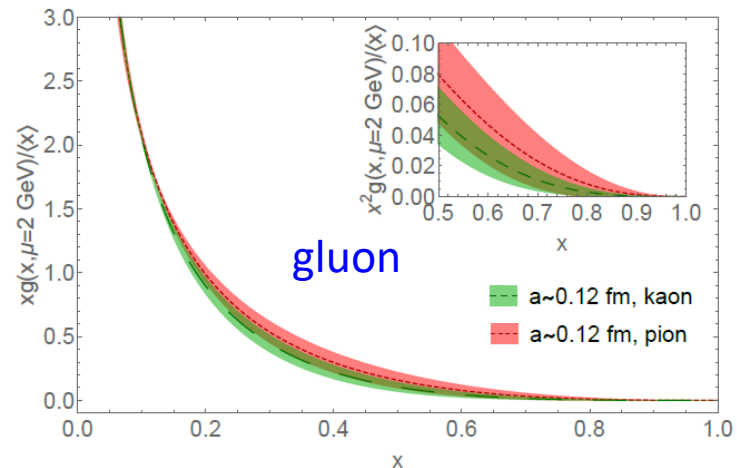
PRD 103, 014516 (2021)



PLB 823, 136778 (2021)



PRD 106, 094510 (2022)

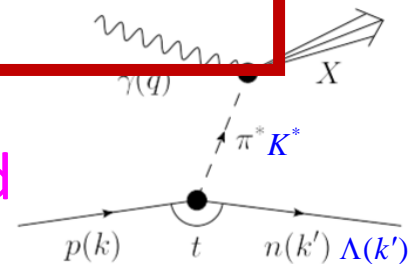


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- **Direct photon:** $\pi, K^\pm p \rightarrow \gamma X$ (LO: sensitive to gluons)
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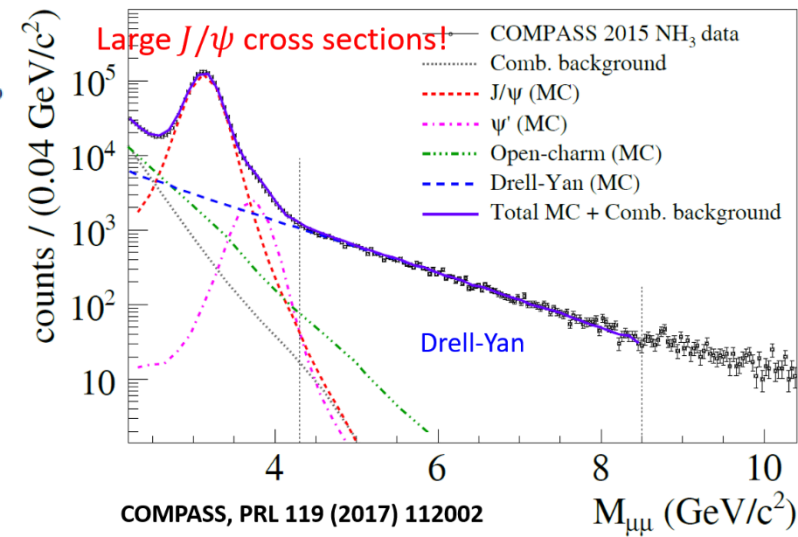
- **Jpsi:** $\pi, K^\pm p \rightarrow J/\psi X$ (LO: sensitive to gluons)
 - LO: $q\bar{q} \rightarrow c\bar{c} \rightarrow J/\psi X, GG \rightarrow c\bar{c} \rightarrow J/\psi X$
 - NLO: $q\bar{q} \rightarrow c\bar{c}G \rightarrow J/\psi X, GG \rightarrow c\bar{c}G \rightarrow J/\psi X, qG \rightarrow c\bar{c}q \rightarrow J/\psi X$

- **Leading neutron (LN) electroproduction:**
Sullivan processes from a nucleon's pion cloud



Pion-induced J/psi Production - Fixed-target Experiments

Paper	Reference	Year	Collab	E sqrt(s) (GeV) (GeV)		Beam	Targets
Fermilab							
Branson	PRL 23, 1331	1977	Princ-Chicago	225	20.5	π^- , π^+ , p	C, Sn
Anderson	PRL 42, 944	1979	E444	225	20.5	π^- , π^+ , K ⁺ , p, ap	C, Cu, W
Abramov	Fermi 91-062-E	1991	E672/E706	530	31.5	π^-	Be
Kartik	PRD 41, 1	1990	E672	530	31.5	π^-	C, AL, Cu, Pb
Katsanevas	PRL 60, 2121	1988	E537	125	15.3	π^- , ap	Be, Cu, W
Akerlof	PR D48, 5067	1993	E537	125	15.3	π^- , ap	Be, Cu, W
Antoniazzi	PRD 46, 4828	1992	E705	300	23.7	π^- , π^+	Li
Gribushin	PR D53, 4723	1995	E672/E706	515	31.1	π^-	Be
Koreshev	PRL 77, 4294	1996	E706/E672	515	31.1	π^-	Be
CERN							
Abolins	PLB 82, 145	1979	WA11/Goliath	150	16.8	π^-	Be
McEwen	PLB 121, 198	1983	WA11	190	18.9	π^-	Be
Badier	Z.Phys. C20, 101	1983	NA3	150	16.8	π^- , π^+ , K ⁻ , K ⁺ , p, ap	H, Pt
"	"	1983	NA3	200	19.4	π^- , π^+ , K ⁻ , K ⁺ , p, ap	H, Pt
"	"	1983	NA3	280	22.9	π^- , π^+ , K ⁻ , K ⁺ , p, ap	H, Pt
Corden	PLB 68, 96	1977	WA39	39.5	8.6	π^- , π^+ , K ⁻ , K ⁺ , p, ap	Cu
Corden	PLB 96, 411	1980	WA39	39.5	8.6	π^- , π^+ , K ⁻ , K ⁺ , p, ap	W
Corden	PLB 98, 220	1981	WA39	39.5	8.6	π^- , π^+ , K ⁻ , K ⁺ , p, ap	p
Corden	PLB 110, 415	1982	WA40	39.5	8.6	π^- , π^+ , K ⁻ , K ⁺ , p, ap	p, W
Alexandrov	NPB 557, 3	1999	Beatrice	350	25.6	π^-	Si, C, W



LO & NLO Diagrams of $c\bar{c}$ Production

LO

A. Petrelli et al./Nuclear Physics B 514 (1998) 245-309

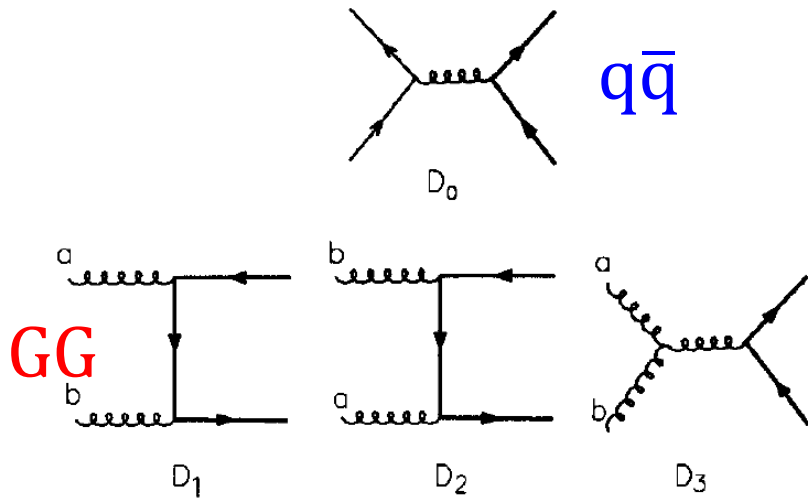


Fig. 2. Diagrams for the $q\bar{q}$ and gg Born amplitudes.

NLO

A. Petrelli et al./Nuclear Physics B 514 (1998) 245-309

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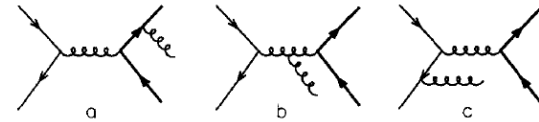


Fig. 8. Diagrams for the real corrections to the $q\bar{q}$ channels. Permutations of outgoing gluons and/or reversal of fermion lines are always implied.

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A. Petrelli et al./Nuclear Physics B 514 (1998) 245-309

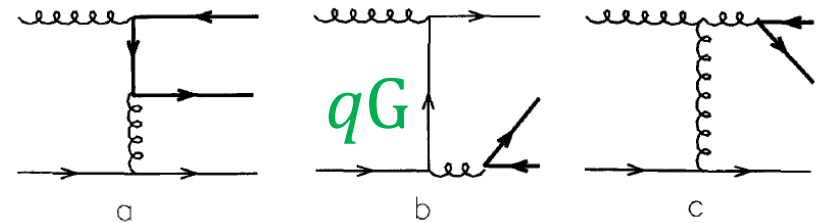
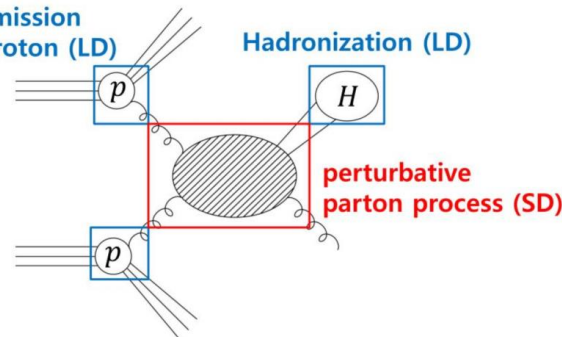


Fig. 7. Diagrams for the gg channels. Reversal of fermion lines is always implied.

Parton emission
from a proton (LD)

Hadronization (LD)



Color Evaporation Model (CEM)

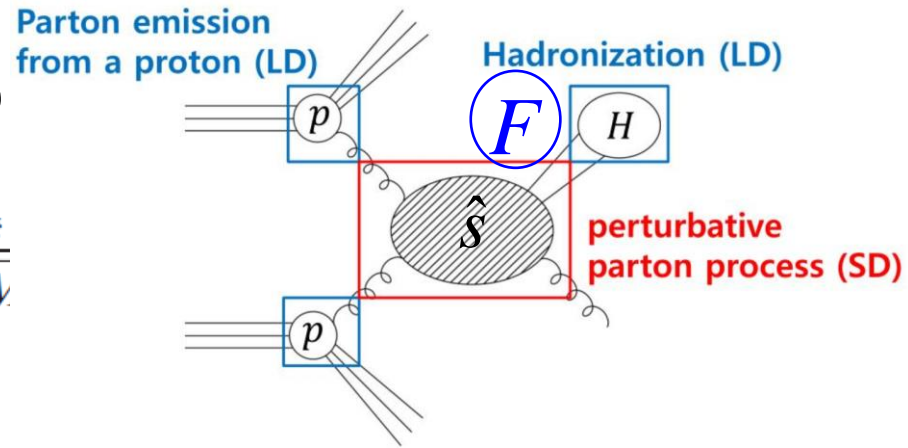
$$\sigma[AB \rightarrow J/\psi X]$$

$$= \langle F \rangle \sum_{i,j} \int_{2m_c}^{2m_D} d\hat{s} \int dx_1 dx_2 f_{i/A}(x_1, \mu_F) f_{j/B}(x_2, \mu_F)$$

$$\hat{\sigma}[ij \rightarrow c\bar{c}X](x_1 P_A, x_2 P_B, \mu_F, \mu_R) \delta(\hat{s} - x_1 x_2 s)$$

$$\begin{aligned} \left. \frac{d\sigma}{dx_F} \right|_{J/\psi} &= \langle F \rangle \sum_{i,j=q,\bar{q},G} \int_{2m_c}^{2m_D} dM_{c\bar{c}} \frac{2M_{c\bar{c}}}{s \sqrt{x_F^2 + 4M_{c\bar{c}}^2}} \\ &\times f_i^\pi(x_1, \mu_F) f_j^N(x_2, \mu_F) \\ &\times \hat{\sigma}[ij \rightarrow c\bar{c}X](x_1 P_\pi, x_2 P_N, \mu_F, \mu_R), \end{aligned}$$

$$x_F = 2p_L/\sqrt{s}, \quad x_{1,2} = \frac{\sqrt{x_F^2 + 4M_{c\bar{c}}^2}/s \pm x_F}{2},$$



LO/NLO calculations of $\hat{\sigma}[ij \rightarrow c\bar{c}X]$:

- P.Nason, S. Dawson and R.K. Ellis, Nucl. Phys. B303 (1988) 607
- M.L. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B405 (1993) 507

Non-relativistic QCD (NRQCD)

The "cascade" (factorization) approach of NRQCD

For **heavy** quarkonia
two distinguishable steps
are foreseen

1) short-distance
partonic process

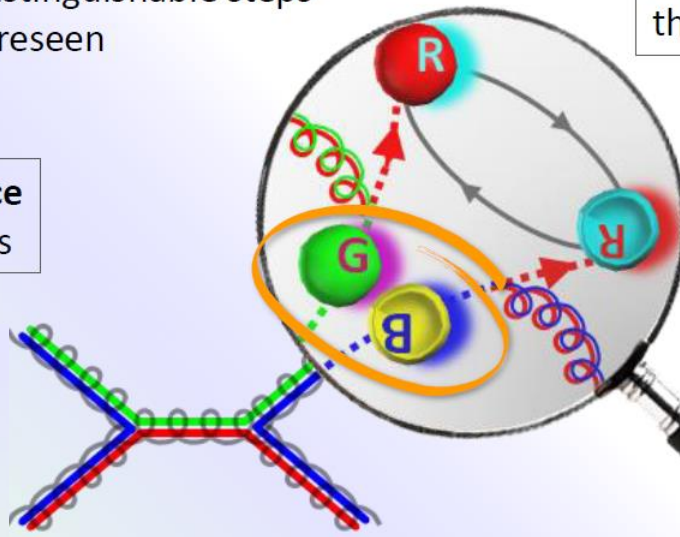
2) long-distance evolution to
the colour-neutral bound state

quantum numbers
change to final

$$\left\{ \begin{array}{l} \eta_c, \eta_b [^1S_0] \\ \psi, \Upsilon [^3S_1] \quad \chi_{c0}, \chi_{b0} [^3P_0] \\ \chi_{c1}, \chi_{b1} [^3P_1] \quad \chi_{c2}, \chi_{b2} [^3P_2] \end{array} \right.$$

produces *in general* a coloured $Q\bar{Q}$ pair
of any $^{2S+1}L_J$ quantum numbers

$$\begin{array}{l} 1S_0 \quad 1S_0 \quad 3S_1 \quad 3P_0 \quad 3P_2 \\ 1D_2 \quad 3P_2 \quad 3D_3 \quad 1P_1 \quad 3S_1 \\ 3P_1 \quad 3D_2 \quad 3D_1 \quad 3P_1 \end{array}$$



1) short-distance coefficients (SDCs):
 p_T -dependent partonic cross sections

2) long-distance matrix elements (LDMEs):
constant, fitted from data

$$\sigma(A + B \rightarrow Q + X) = \sum_{S, L, C} \mathcal{S}\{A + B \rightarrow (Q\bar{Q})_C [^{2S+1}L_J] + X\} \cdot \mathcal{A}\{(Q\bar{Q})_C [^{2S+1}L_J] \rightarrow Q\}$$

$Q\bar{Q}$ angular momentum
and colour configurations

https://agenda.infn.it/event/20446/contributions/124767/attachments/76906/99037/PietroFaccioli_Trieste2020.pdf

Color evaporation model (CEM)

Phys. Rev. D 102, 054024 (2020); arXiv: 2006.06947

PHYSICAL REVIEW D **102**, 054024 (2020)

Constraining gluon density of pions at large x by pion-induced J/ψ production

Wen-Chen Chang 


Institute of Physics, Academia Sinica, Taipei 11529, Taiwan

Jen-Chieh Peng

Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

Stephane Platchkov 

IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

Takahiro Sawada 

Department of Physics, Osaka City University, Osaka 558-8585, Japan



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The gluon distributions of the pion obtained from various global fits exhibit large variations among them. Within the framework of the color evaporation model, we show that the existing pion-induced J/ψ

Non-relativistic QCD model (NRQCD)

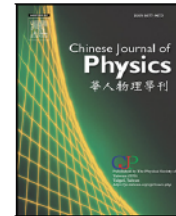
[Chin.J.Phys. 73 \(2021\) 13](#); [arXiv: 2103.11660](#)



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NRQCD analysis of charmonium production with pion and proton beams at fixed-target energies

Chia-Yu Hsieh ^{a,b,1}, Yu-Shiang Lian ^{a,c,1}, Wen-Chen Chang ^{a,*}, Jen-Chieh Peng ^d,
Stephane Platchkov ^e, Takahiro Sawada ^f

^a Institute of Physics, Academia Sinica, Taipei 11529, Taiwan

^b Department of Physics, National Central University, 300 Zhongda Road, Zhongli 32001, Taiwan

^c Department of Physics, National Kaohsiung Normal University, Kaohsiung County 824, Taiwan

^d Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

^e IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

^f Department of Physics, Osaka City University, Osaka 558-8585, Japan

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Gluon

ABSTRACT

We present an analysis of hadroproduction of J/ψ and $\psi(2S)$ at fixed-target energies in the framework of non-relativistic QCD (NRQCD). Using both pion- and proton-induced data, a new determination of the color-octet long-distance matrix elements (LDMEs) is obtained. Compared with previous results, the contributions from the $q\bar{q}$ and color-octet processes are significantly enhanced, especially at lower energies. A good agreement between the pion-induced J/ψ production data and NRQCD calculations using the newly obtained LDMEs is achieved. We find that the pion-induced charmonium production data are sensitive to the gluon density of pions, and favor pion PDFs with relatively large gluon contents at large x .

Non-relativistic QCD model (NRQCD)

[Phys. Rev. D 107, 056008 \(2023\)](#); [arXiv: 2209.04072](#)

PHYSICAL REVIEW D **107**, 056008 (2023)

Fixed-target charmonium production and pion parton distributions

Wen-Chen Chang¹, Jen-Chieh Peng², Stephane Platchkov³, and Takahiro Sawada⁴

¹*Institute of Physics, Academia Sinica, Taipei 11529, Taiwan*

²*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*

³*IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*

⁴*Nambu Yoichiro Institute of Theoretical and Experimental Physics, Osaka Metropolitan University, Osaka 558-8585, Japan*



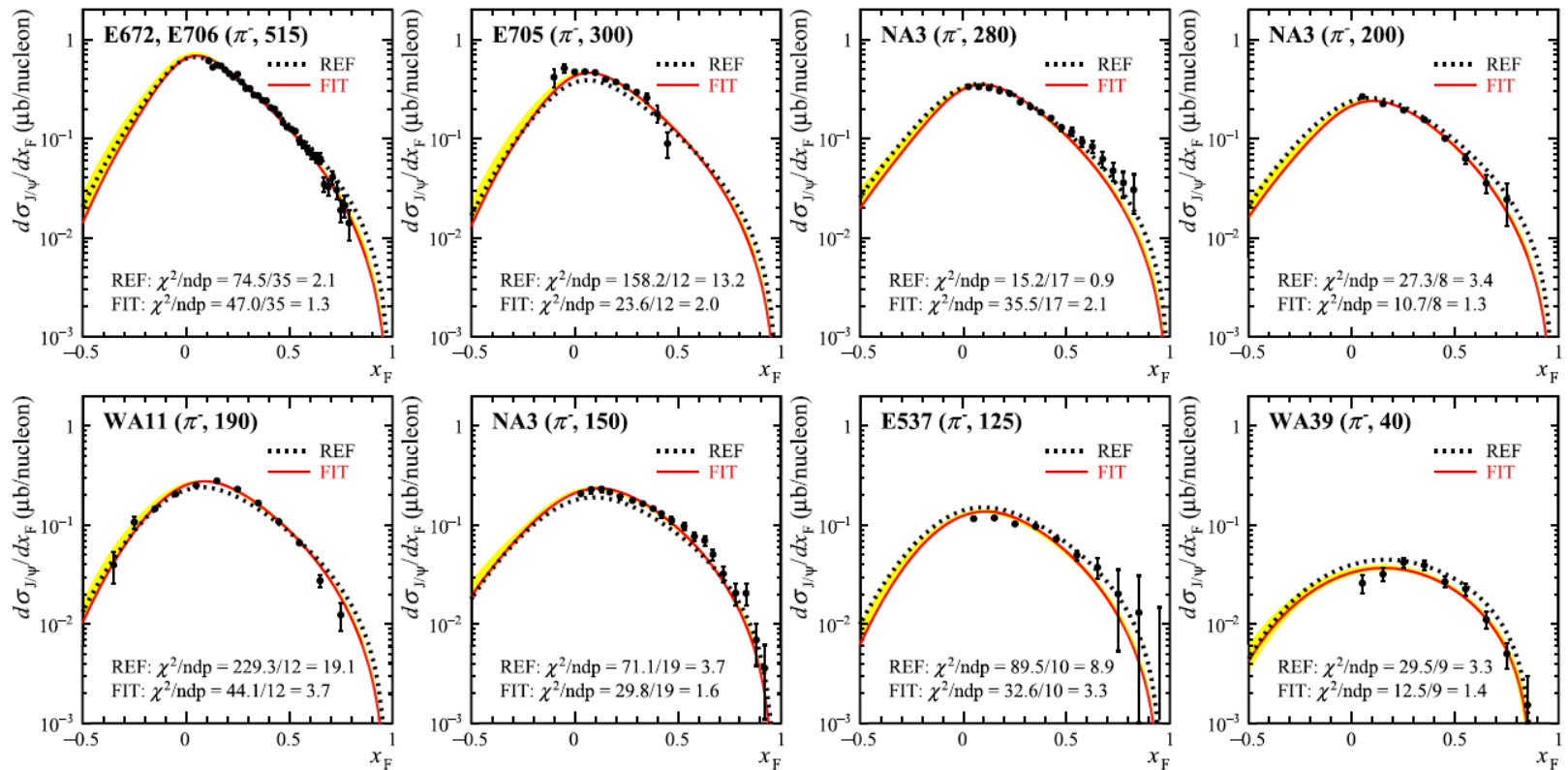
(Received 8 September 2022; accepted 31 January 2023; published 7 March 2023)

We investigate how charmonium hadroproduction at fixed-target energies can be used to constrain the gluon distribution in pions. Using nonrelativistic QCD (NRQCD) formulation, the J/ψ and $\psi(2S)$ cross sections as a function of longitudinal momentum fraction x_F from pions and protons colliding with light targets, as well as the $\psi(2S)$ to J/ψ cross section ratios, are included in the analysis. The color-octet long-distance matrix elements are found to have a pronounced dependence on the pion parton distribution functions (PDFs). This study shows that the x_F differential cross sections of pion-induced charmonium production impose strong constraints on the pion's quark and gluon PDFs. In particular, the pion PDFs with larger gluon densities provide a significantly better description of the data. It is also found that the production of the $\psi(2S)$ state is associated with a larger quark-antiquark contribution, compared with J/ψ .

Pion PDFs (Global Analysis)

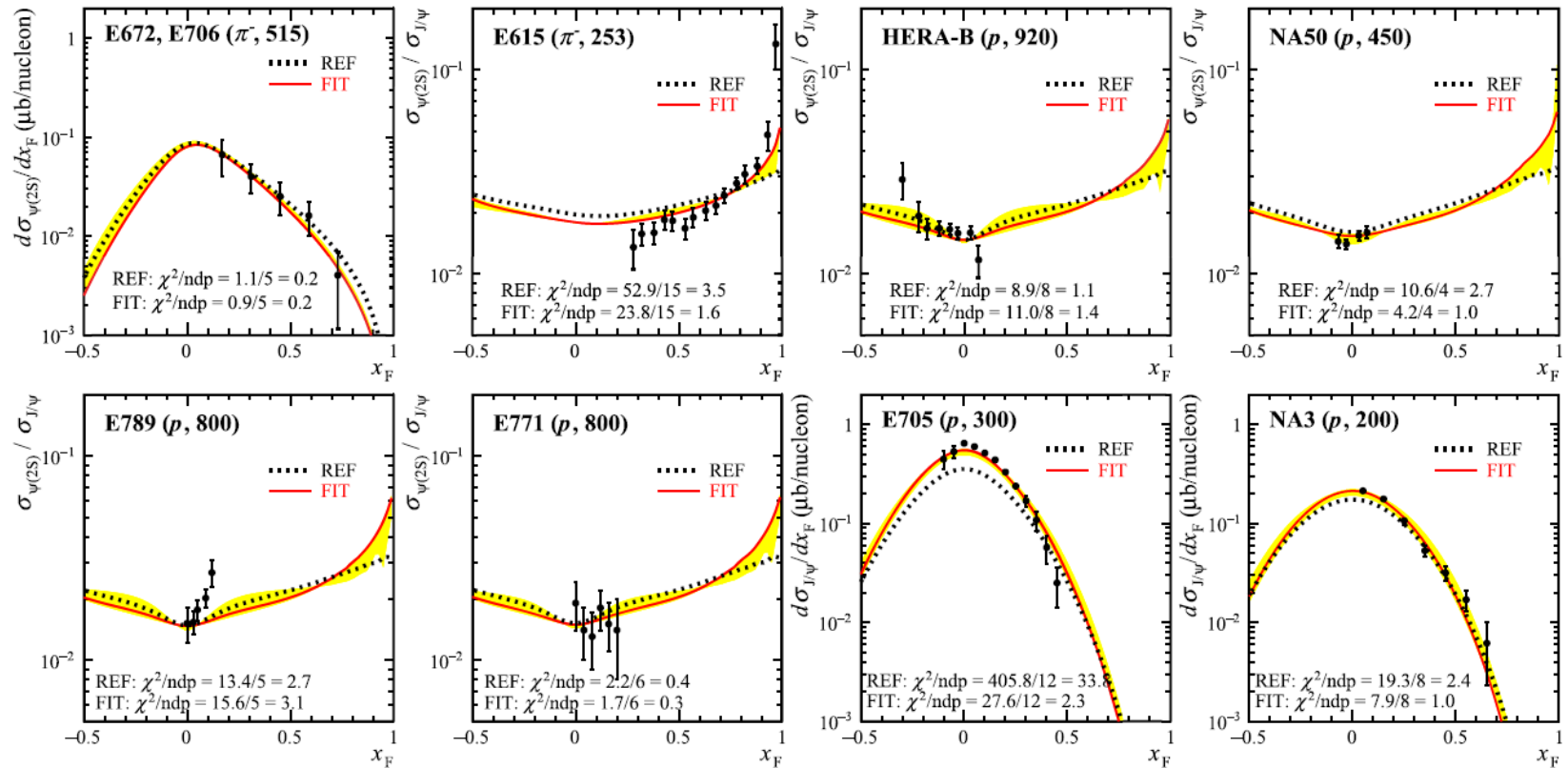
PDF	DY (xF, pT)	Direct γ	J/ψ	LN	Refs.
OW	*		*		PRD 1984
ABFKW	*	*			PLB 1989
SMRS	*	*			PRD 1992
GRV	*	*			ZPC 1992
GRS	*				EPJC 1999
JAM18	*			*	PRL 2018
BS, BBP	*				NPA 2019 PLB 2021
xFitter	*	*			PRD 2020
JAM21	*			*	PRD 2021 PRL 2021
Fanto	*	*		*	PRD 2024

Fixed-Target Charmonium Production



[Phys. Rev. D 107, 056008 \(2023\)](#)

Fixed-Target Charmonium Production

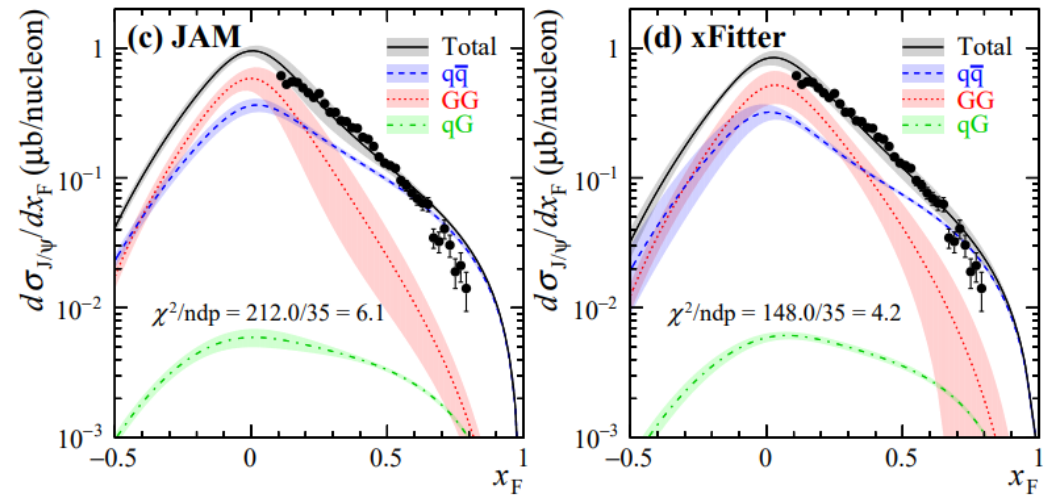
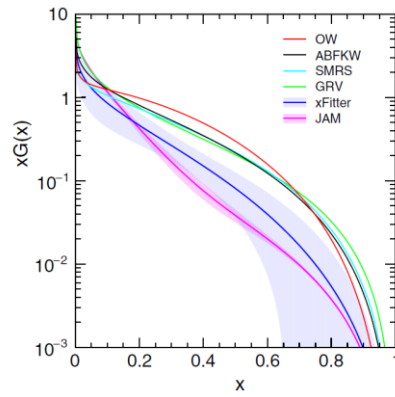
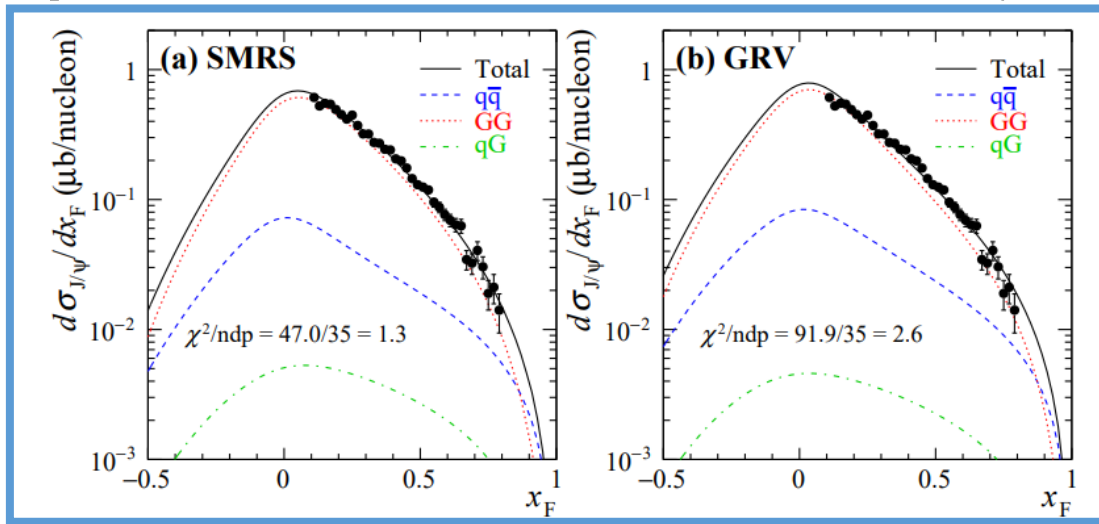


[Phys. Rev. D 107, 056008 \(2023\)](#)

Data vs. NRQCD

$[\pi^- + Be \rightarrow J\psi + X \text{ at } 515 \text{ GeV, PRD 53, 4723 (1996)}]$

$$x_F = 2p_L^{\gamma*} / \sqrt{s}$$

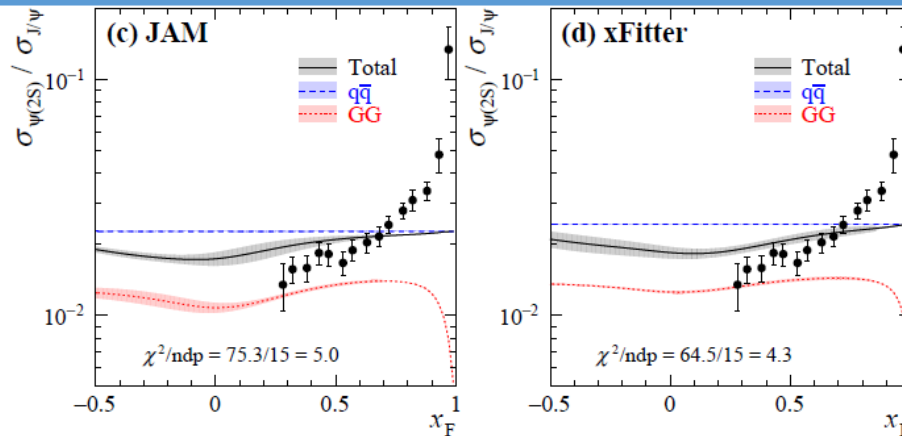
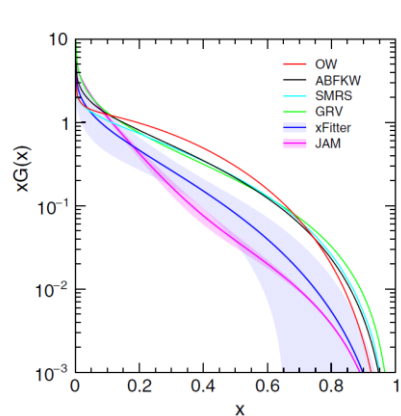
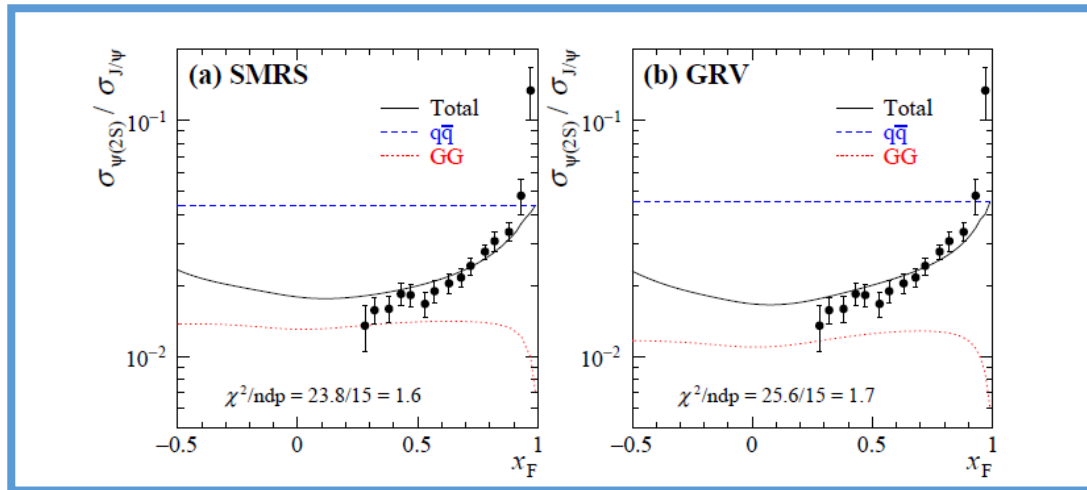


Data favor SMRS and GRV PDFs with larger gluon densities at $x > 0.1$.

Data vs. NRQCD

$[\pi^- + W \rightarrow J\psi/\psi' + X \text{ at } 252 \text{ GeV, PRD 44, 1909 (1991)}]$

$$x_F = 2p_L^{\gamma*} / \sqrt{s}$$



Data favor SMRS and GRV PDFs with larger gluon densities at $x > 0.1$.

Kaon PDFs

[PLB 855,138820, \(2024\); arXiv: 2402.02860](#)

Phys. Lett. B 855 (2024) 138820



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Letter

Constraining kaon PDFs from Drell-Yan and J/ψ production

Wen-Chen Chang ^{a,  ,*}, Jen-Chieh Peng ^{b,  ,c}, Stephane Platchkov ^{d, } , Takahiro Sawada ^{e, }



^a Institute of Physics, Academia Sinica, Taipei 11529, Taiwan

^b Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

^c Department of Physics, National Central University, Chung-Li, 32001, Taiwan

^d IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

^e Institute for Cosmic Ray Research, The University of Tokyo, Gifu 506-1205, Japan

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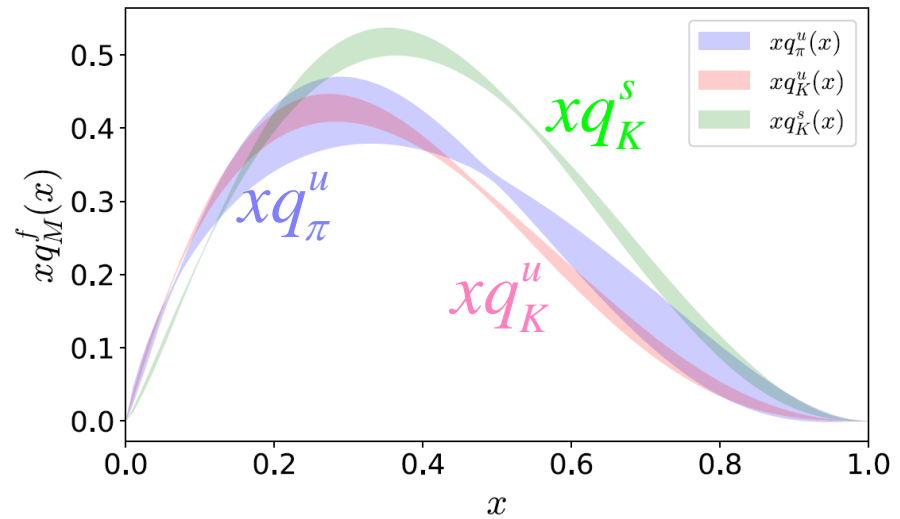
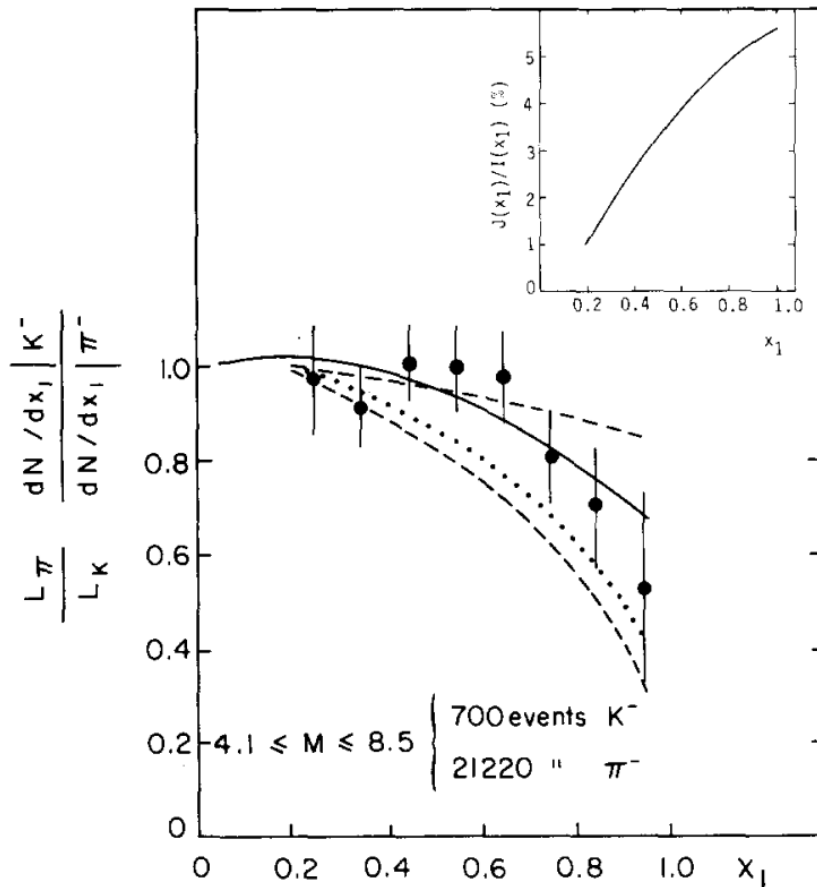
ABSTRACT

The kaon parton distribution functions (PDFs) are poorly known due to paucity of kaon-induced Drell-Yan data. Nevertheless, these Drell-Yan data suggest a softer valence u quark distribution of the kaon compared to that of the pion. We discuss the opportunity to constrain the kaon PDFs utilizing the existing kaon-induced J/ψ production data. We compare the K^-/π^- and K^+/π^+ cross-section ratio data with calculations based on two global-fit parametrizations and two recent theoretical predictions for the kaon and pion PDFs, and test the results with two quarkonium production models. The K^-/π^- cross-section ratio for J/ψ production provides independent evidence of different valence quark distributions in pion and kaon. The K^+/π^+ J/ψ data are found to be sensitive to the gluon distribution in kaon. We show that these J/ψ production data provide valuable constraints for evaluating the adequacy of currently available sets of kaon PDFs.

K/ π Drell-Yan Ratios

NA10: J. Badier et al., Phys. Lett. B 93, 354 (1980)

$$\frac{\sigma^{DY}(K^-)}{\sigma^{DY}(\pi^-)}(x_F) = \frac{\bar{u}^K(x_1)u^N(x_2)}{\bar{u}^\pi(x_1)u^N(x_2)} = \frac{\bar{u}^K}{\bar{u}^\pi}(x_1)$$

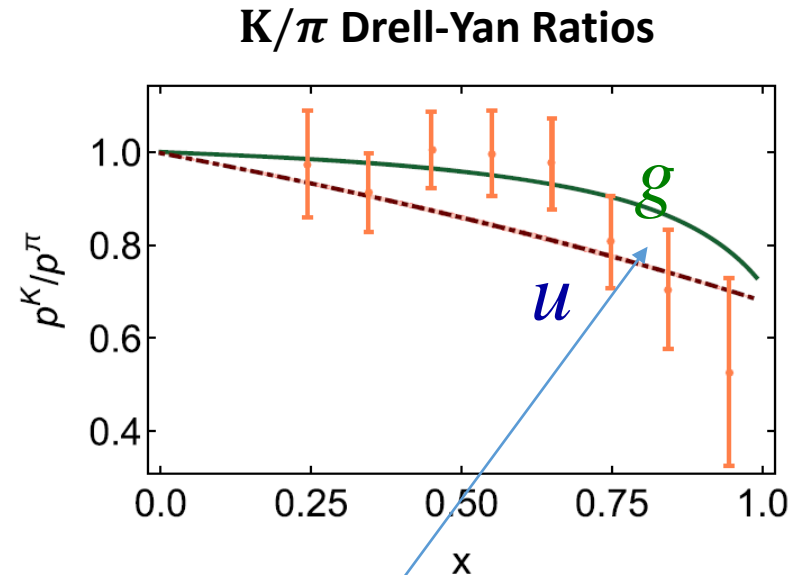
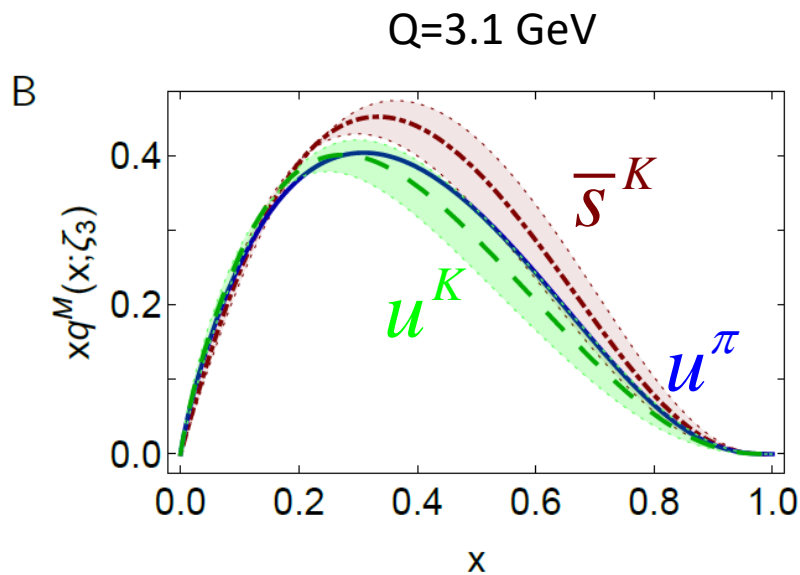


The \bar{u} distribution of kaon is softer than pion's.

Kaon PDFs: Dyson-Schwinger Equation (DSE)

[Eur. Phys. J. C \(2020\) 80:1064](#)

This paper contains comprehensive numerical information of determined kaon/pion PDFs.

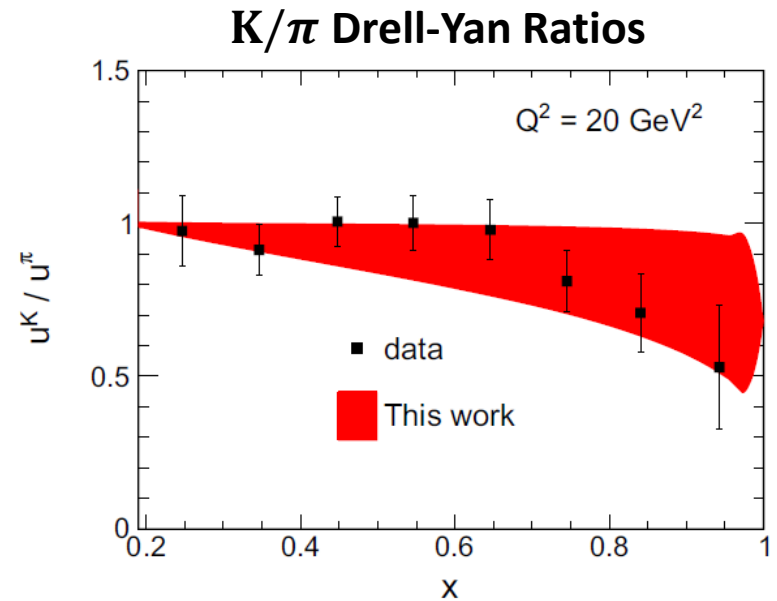
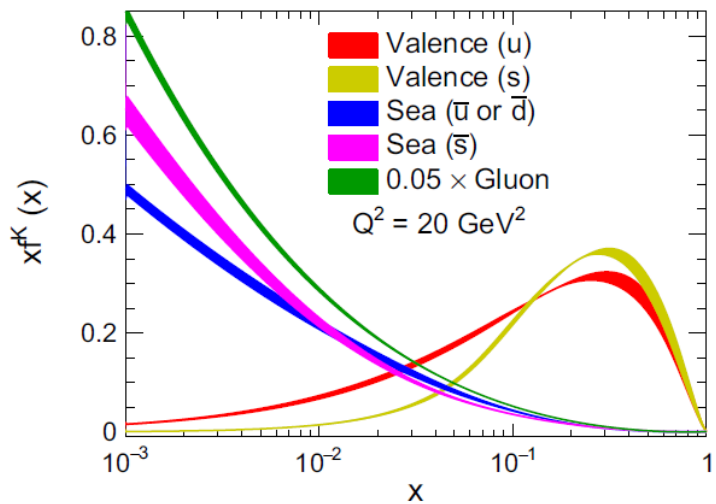
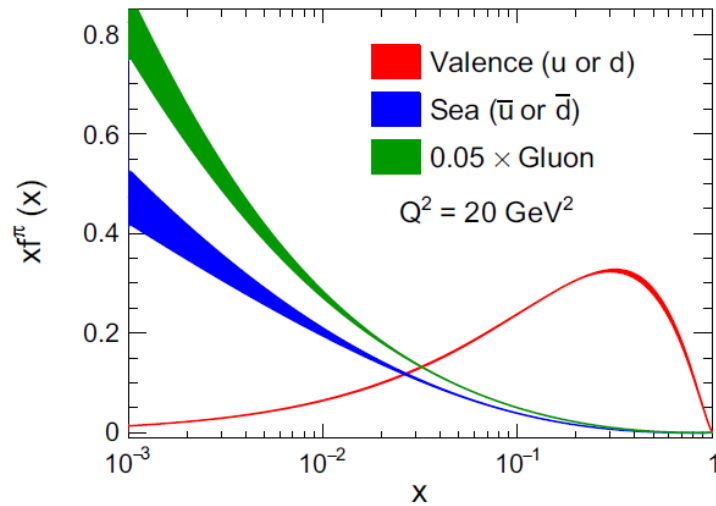


$$\langle x[2u^\pi(x; \zeta_3) + g^\pi(x; \zeta_3) + S^\pi(x; \zeta_3)] \rangle = 1.$$

A slightly smaller kaon gluon distribution at large x , compared to the pion.

Kaon PDFs: Maximum Entropy Input

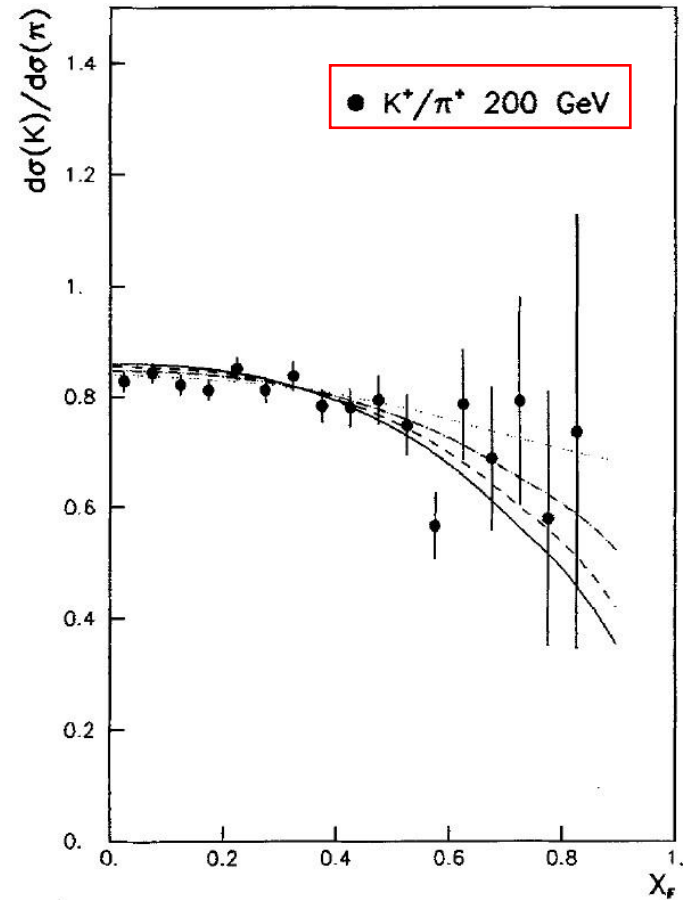
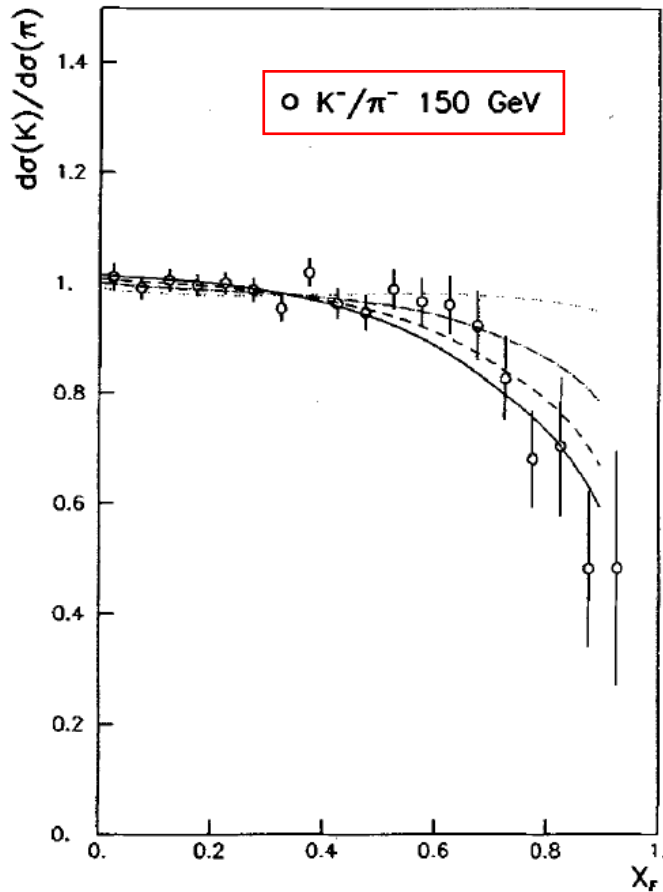
[Eur. Phys. J. C \(2021\) 81:302](#)



K/ π Jpsi Ratios

NA3: Z. Phys. C 20, 101 (1983)

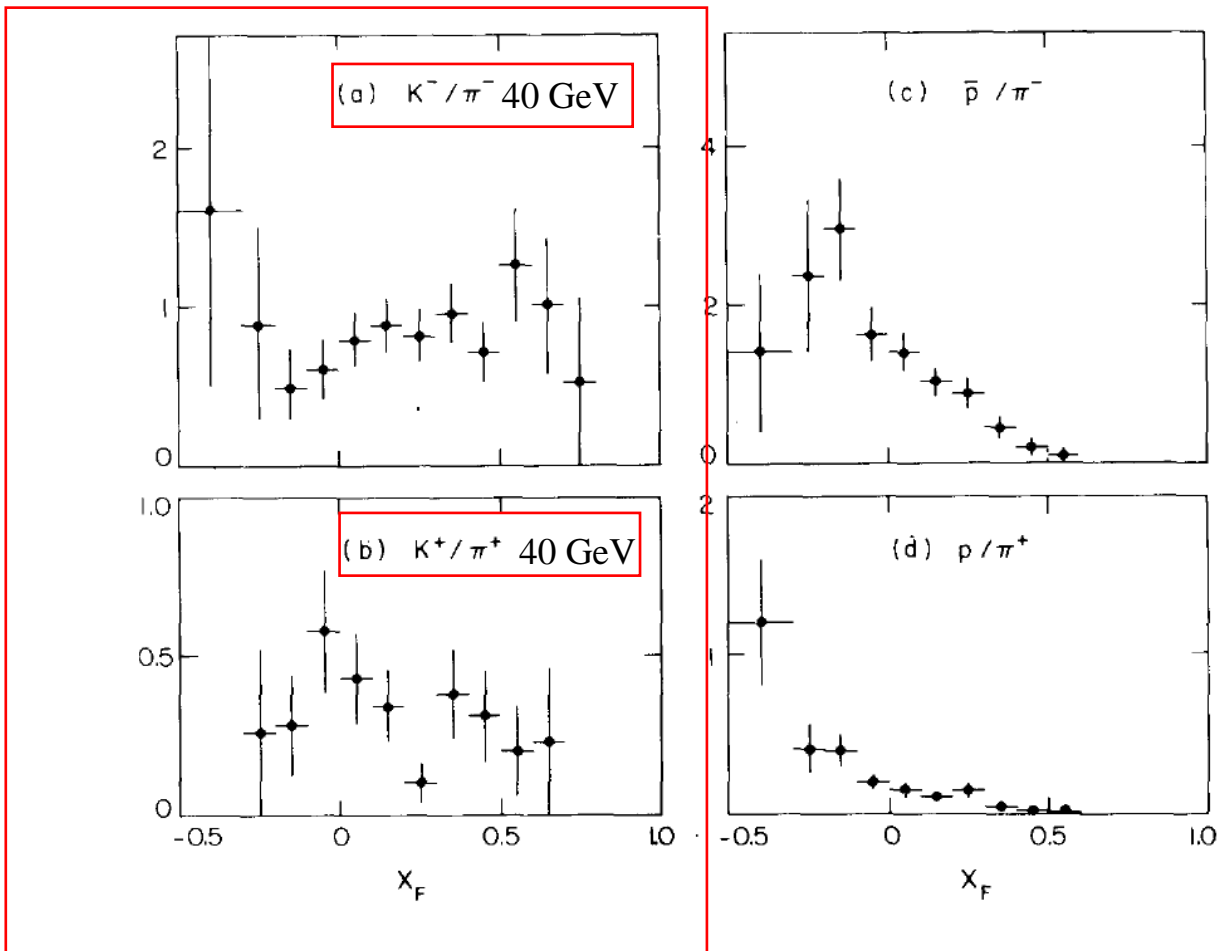
$$\frac{\sigma^{Jpsi}(K^-)}{\sigma^{Jpsi}(\pi^-)}(x_F) = \frac{\sigma(\bar{u}^K(x_1)u^N(x_2)) + \sigma(G^K(x_1)G^N(x_2))}{\sigma(\bar{u}^\pi(x_1)u^N(x_2)) + \sigma(G^\pi(x_1)G^N(x_2))} \quad \frac{\sigma^{Jpsi}(K^+)}{\sigma^{Jpsi}(\pi^+)}(x_F) = \frac{\sigma(u^K(x_1)\bar{u}^N(x_2)) + \sigma(\bar{s}^K(x_1)s^N(x_2)) + \sigma(G^K(x_1)G^N(x_2))}{\sigma(u^\pi(x_1)\bar{u}^N(x_2)) + \sigma(\bar{d}^\pi(x_1)d^N(x_2)) + \sigma(G^\pi(x_1)G^N(x_2))}$$



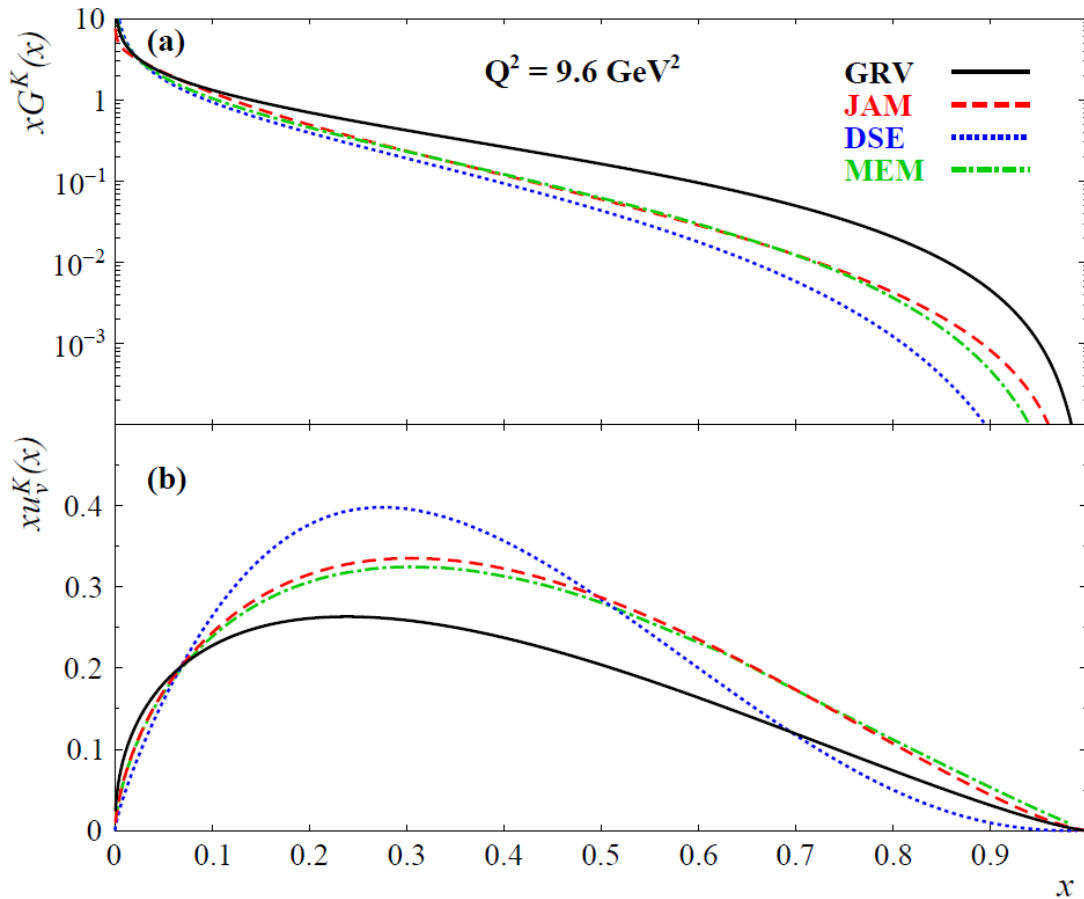
K/ π Jpsi Ratios

WA39: Phys. Lett. B 96, 411 (1980)

$$\frac{\sigma^{Jpsi}(K^-)}{\sigma^{Jpsi}(\pi^-)}(x_F) = \frac{\sigma(\bar{u}^K(x_1)u^N(x_2)) + \sigma(G^K(x_1)G^N(x_2))}{\sigma(\bar{u}^\pi(x_1)u^N(x_2)) + \sigma(G^\pi(x_1)G^N(x_2))} \quad \frac{\sigma^{Jpsi}(K^+)}{\sigma^{Jpsi}(\pi^+)}(x_F) = \frac{\sigma(u^K(x_1)\bar{u}^N(x_2)) + \sigma(\bar{s}^K(x_1)s^N(x_2)) + \sigma(G^K(x_1)G^N(x_2))}{\sigma(u^\pi(x_1)\bar{u}^N(x_2)) + \sigma(\bar{d}^\pi(x_1)d^N(x_2)) + \sigma(G^\pi(x_1)G^N(x_2))}$$



Kaon PDFs: GRV, JAM, DSE, MEM

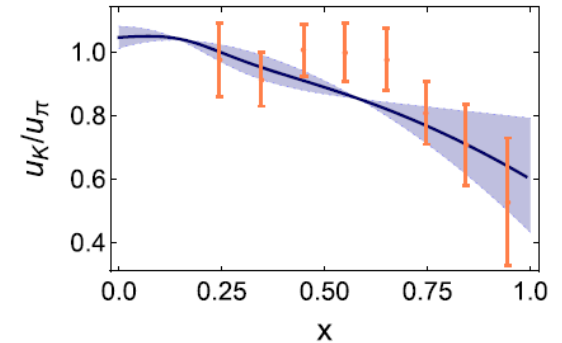


K (GRV, JAM): GRS ansatz

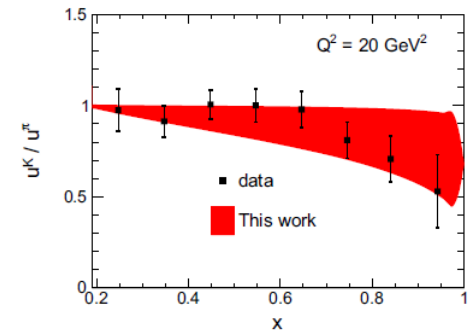
$$\bar{u}_v^K(x) = N_u \bar{u}_v^\pi(x) (1-x)^{0.17}$$

$$s_v^K(x) = 2\bar{u}_v^\pi(x) - \bar{u}_v^K(x)$$

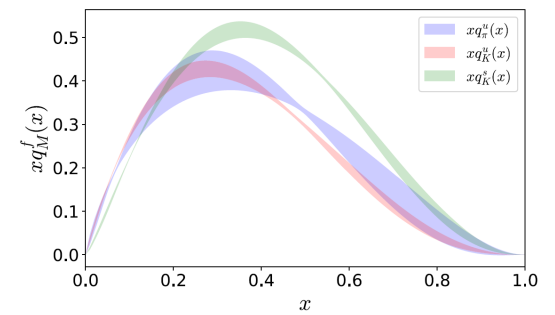
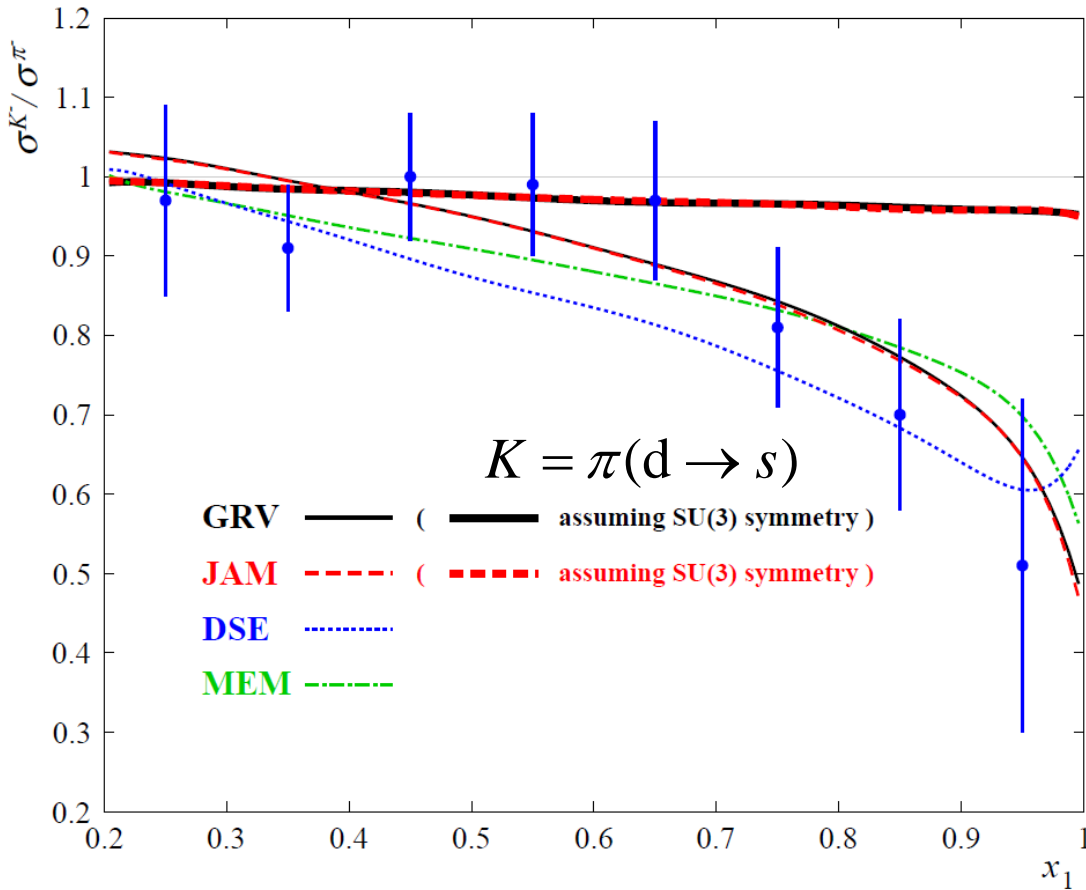
DSE: Eur. Phys. J. C (2020) 80:1064



MEM: Eur. Phys. J. C (2021) 81:302



K/ π Drell-Yan Ratios

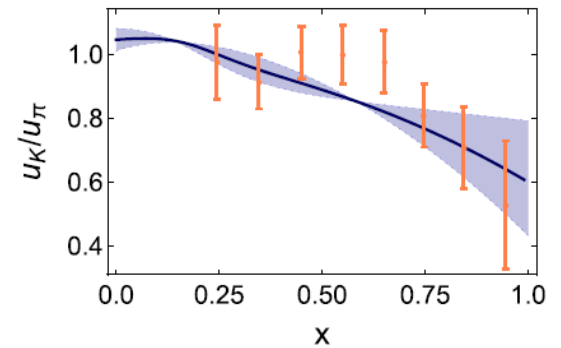


GRV, JAM: GRS ansatz

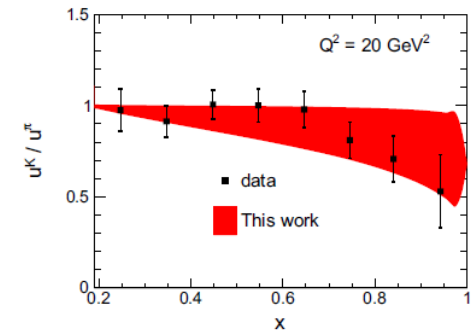
$$\bar{u}_v^K(x) = N_u \bar{u}_v^\pi(x) (1-x)^{0.17}$$

$$s_v^K(x) = 2\bar{u}_v^\pi(x) - \bar{u}_v^K(x)$$

DSE: Eur. Phys. J. C (2020) 80:1064

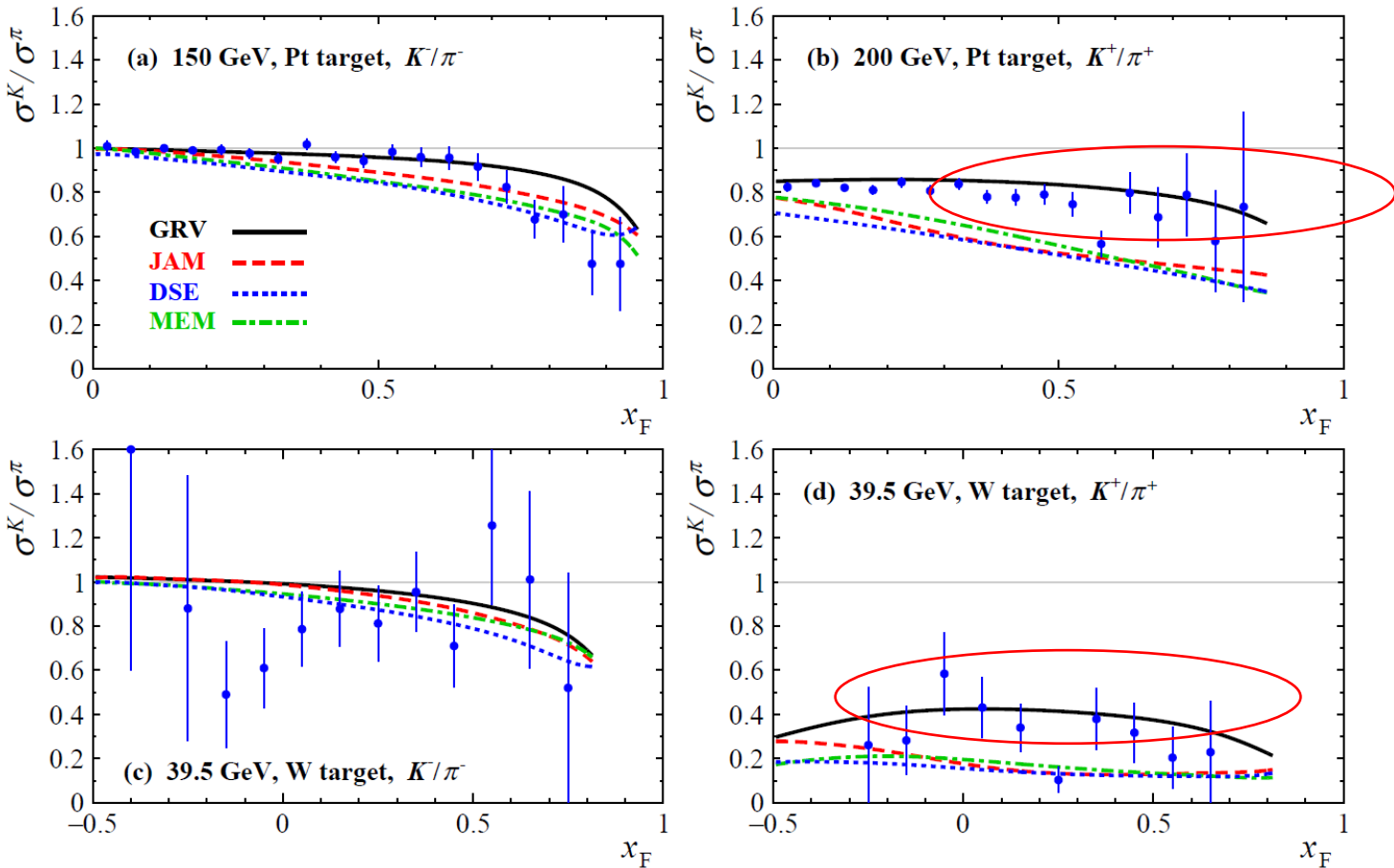


MEM: Eur. Phys. J. C (2021) 81:302



K/π Jpsi Ratios: CEM

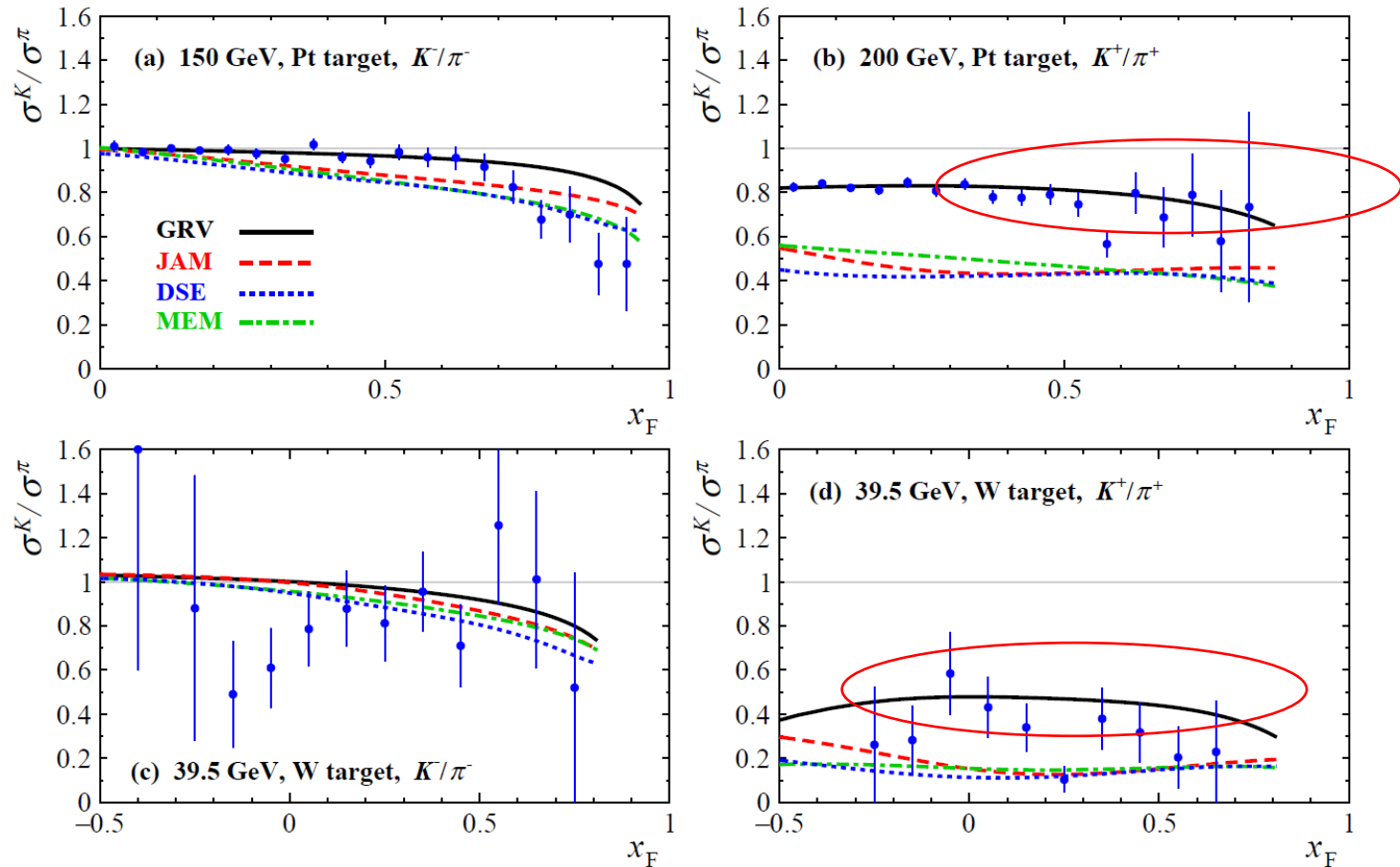
W.C. Chang et al., [PLB 855, 138820 \(2024\)](#); [arXiv: 2402.02860](#)



Data favor GRV PDFs with larger gluon densities at $x > 0.1$.

K/π Jpsi Ratios: NRQCD

W.C. Chang et al., [PLB 855, 138820 \(2024\)](#); [arXiv: 2402.02860](#)

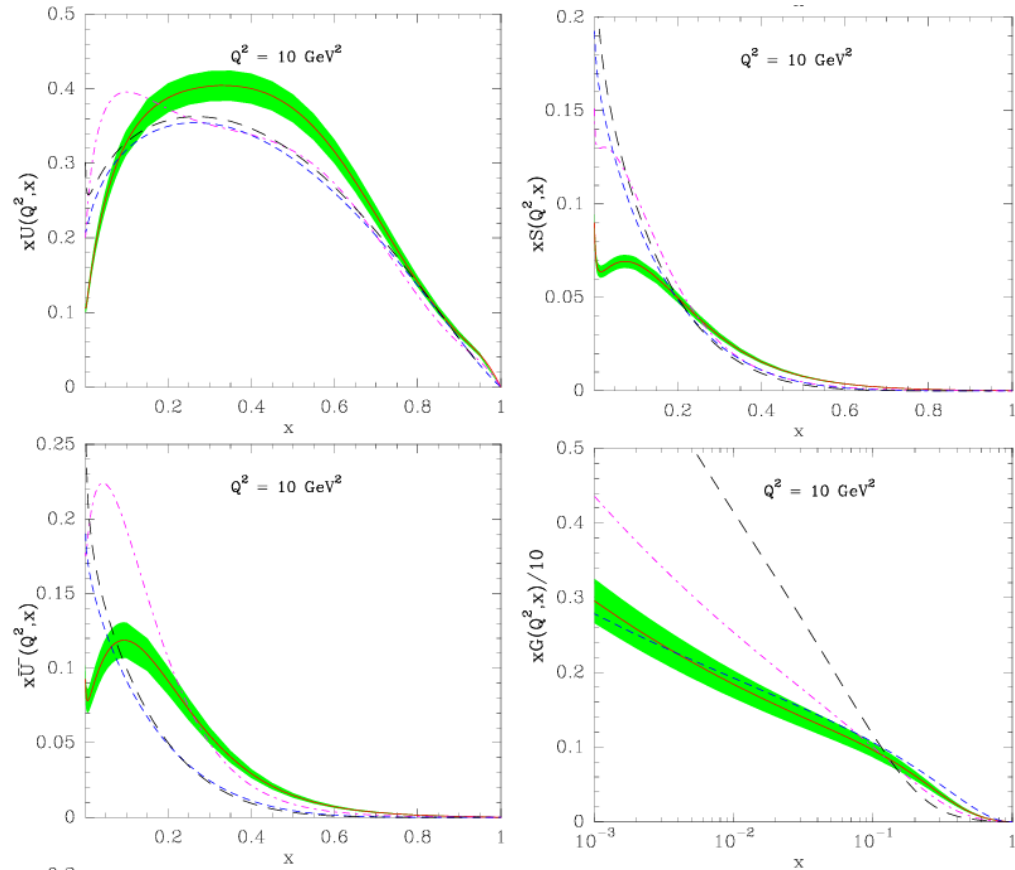
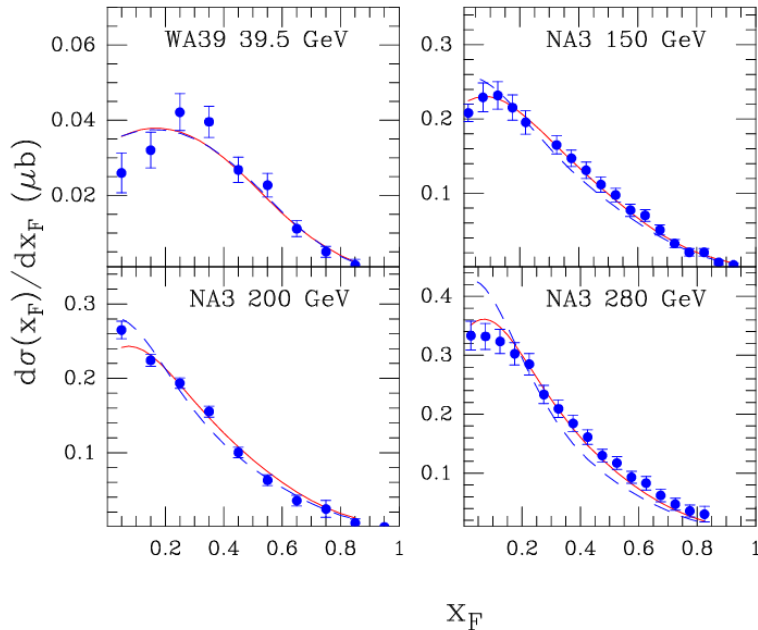


Data favor GRV PDFs with larger gluon densities at $x > 0.1$.

Pion PDFs with J/psi data: Statistic Model

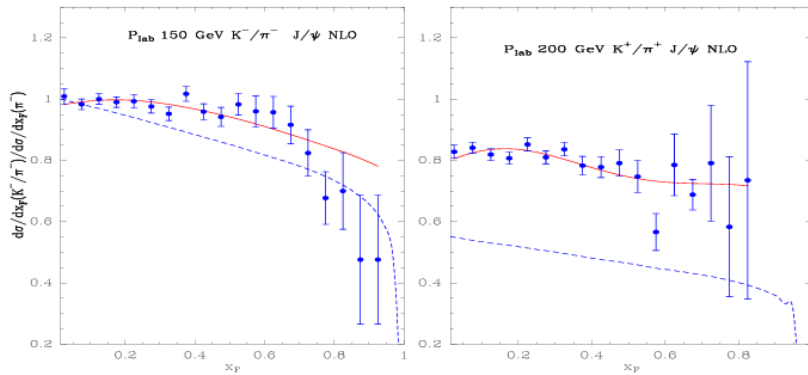
C. Bourrely, W.C. Chang, J.C. Peng, [PRD 105, 076018 \(2022\)](#), [arXiv:2202.12547](#)

WA39 and NA3 J/ ψ ($\pi^- H_2$)



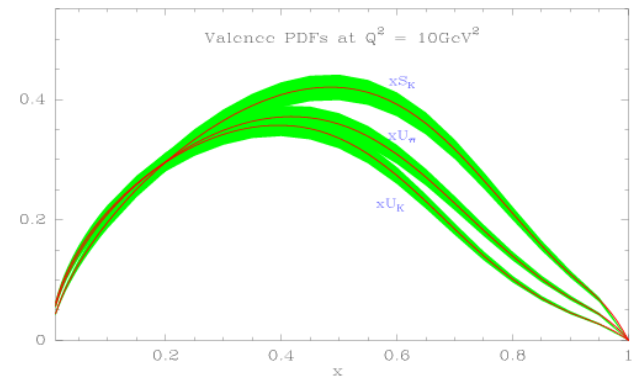
Kaon PDFs with J/psi data: Statistic Model

C. Bourrely, F. Buccella, W.C. Chang, J.C. Peng, [PLB 848, 138395 \(2024\)](#); [arXiv:2305.18117](#)

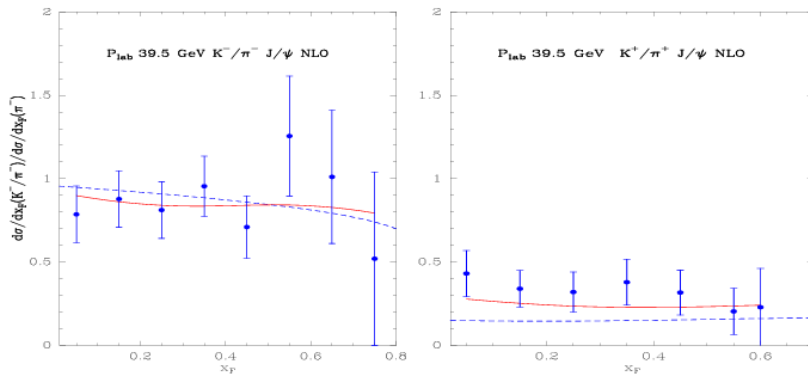


(a)

(b)

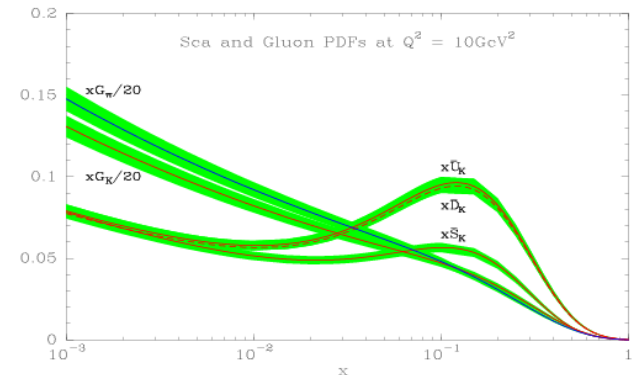


(a)



(c)

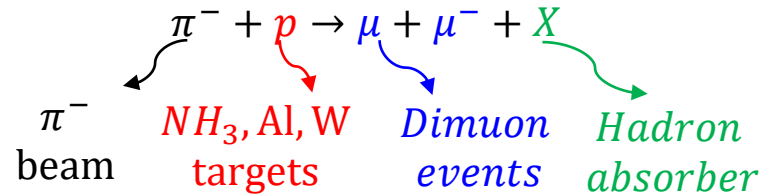
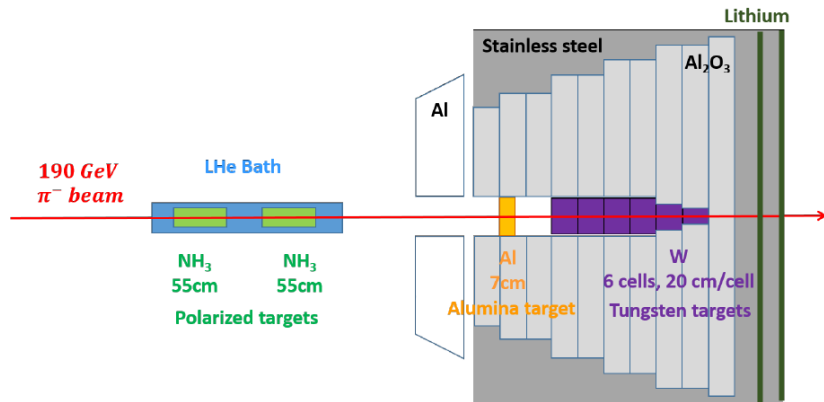
(d)



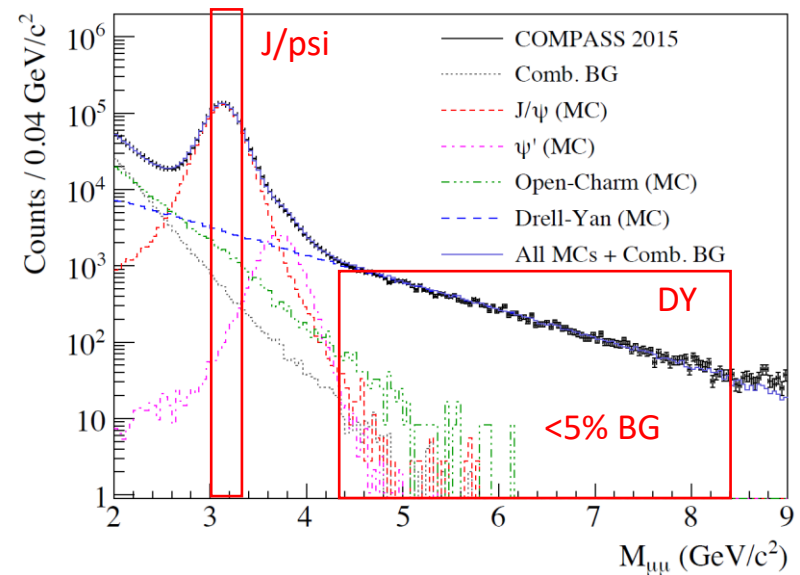
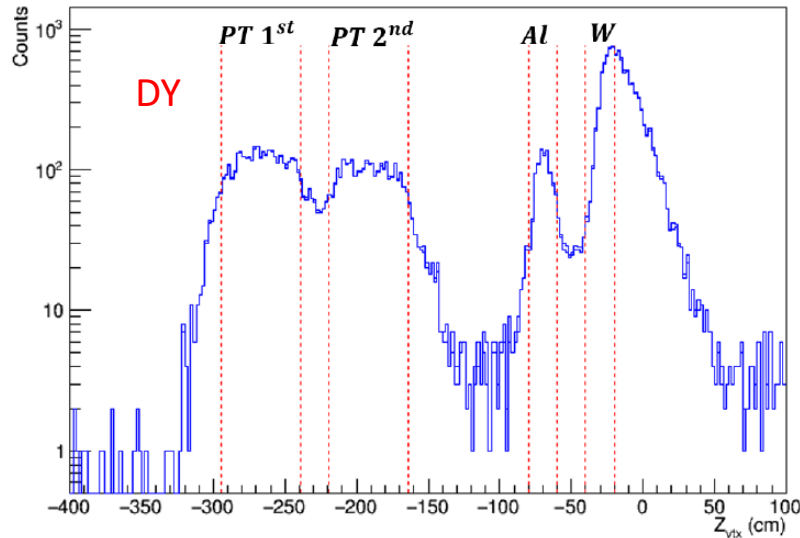
(b)

COMPASS at CERN

:190 GeV π^- -induced DY/Jpsi

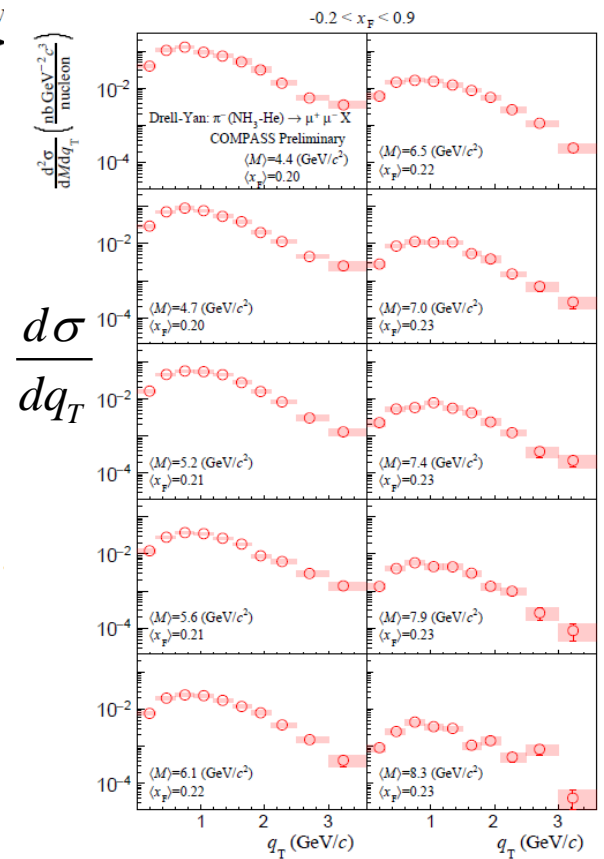
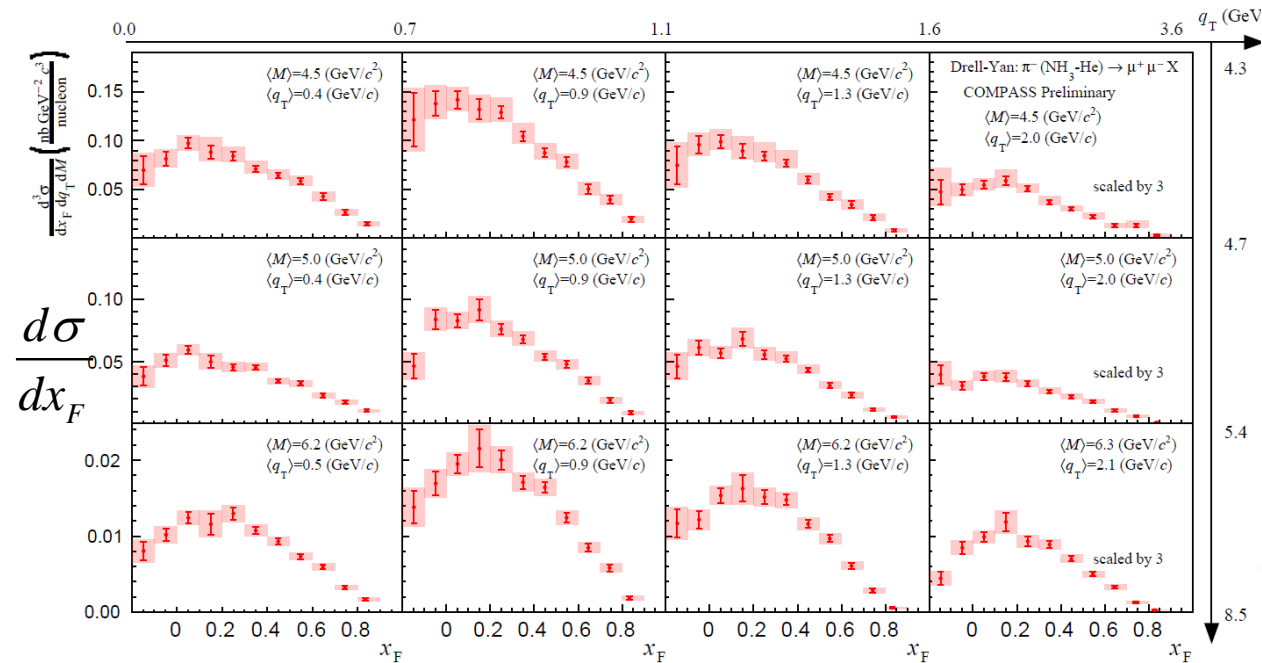


- **Beam** : 190 GeV π^-
- **Target** : Polarized ammonia targets(PT), Al, W



Outlook

COMPASS at CERN :190 GeV π^- -induced DY



Important information to construct
the unpolarized PDFs and TMDs of pions

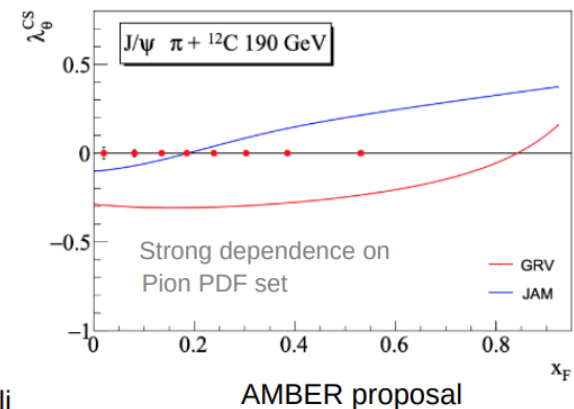
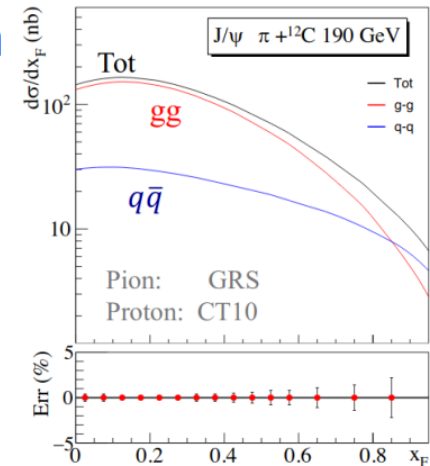
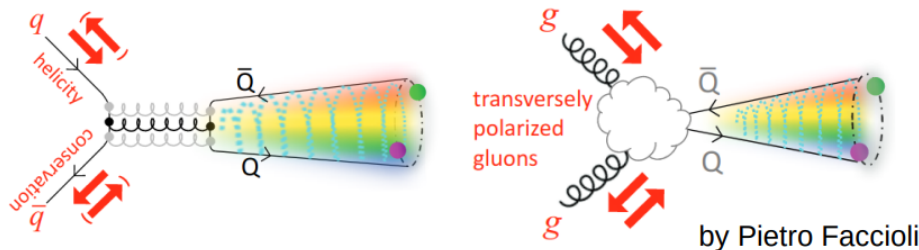
AMBER at CERN

$:\pi^\pm / K^\pm$ -induced DY/Jpsi



Phase-I: J/ψ & Gluon content in the pion

- **Large statistics** on J/ψ production at dimuon channel
- **Inclusive**: due to the hadron absorber, we cannot distinguish prompt production from the rest
- Expected significant **feed-down**: $\psi(2S)$, χ_{c1} , χ_{c2}
- In the **low-pT regime**
- Expected to have **dominant** contribution from $2 \rightarrow 1$ processes
- Use J/ψ polarization to distinguish production mechanism:



AMBER at CERN

: π^\pm / K^\pm -induced DY/Jpsi



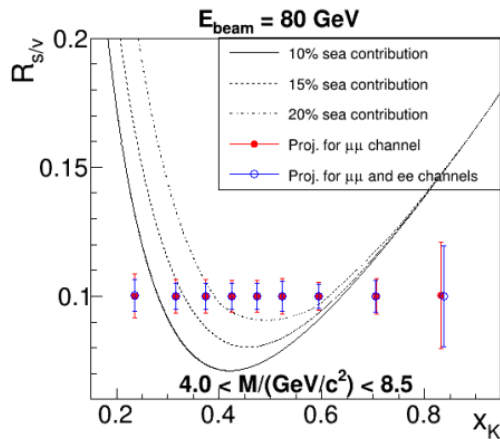
Phase-II: Kaon structure

Kaon structure: a window to the region of interference between the **Higgs mechanism** and the **EHM mechanism**

The only available experimental data:

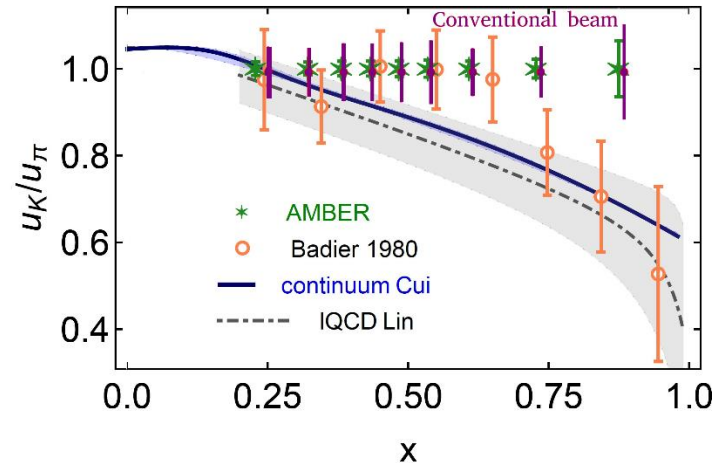
NA3 → 200 GeV K^- beam on 6 cm Pt target

↳ 700 kaon-induced Drell-Yan events



Kaon sea-valence separation using both charges kaon beams:

$$R_{s/v} = \frac{\sigma^{K^+C}}{\sigma^{K^-C} - \sigma^{K^+C}}$$



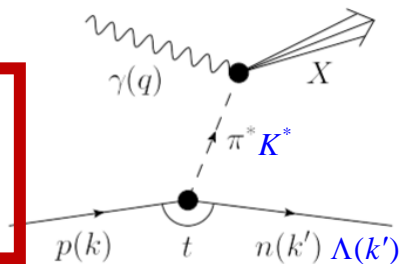
Assumed an RF-separated beam of 2×10^7 kaons/second.

16

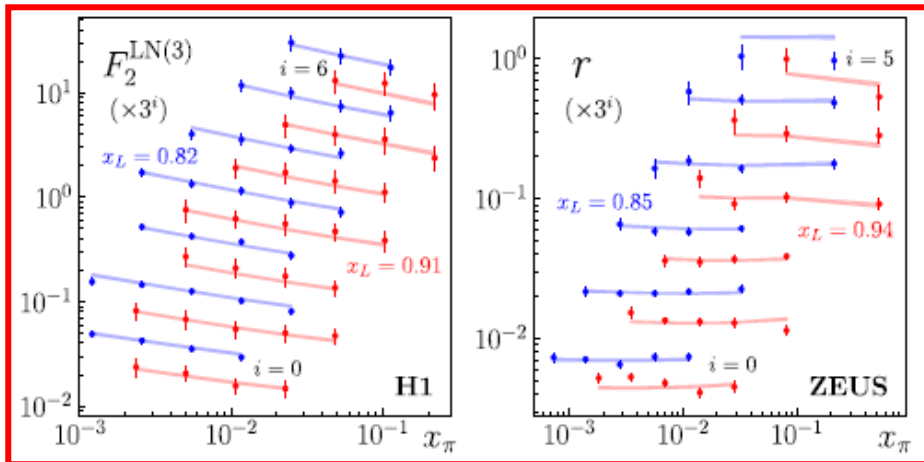
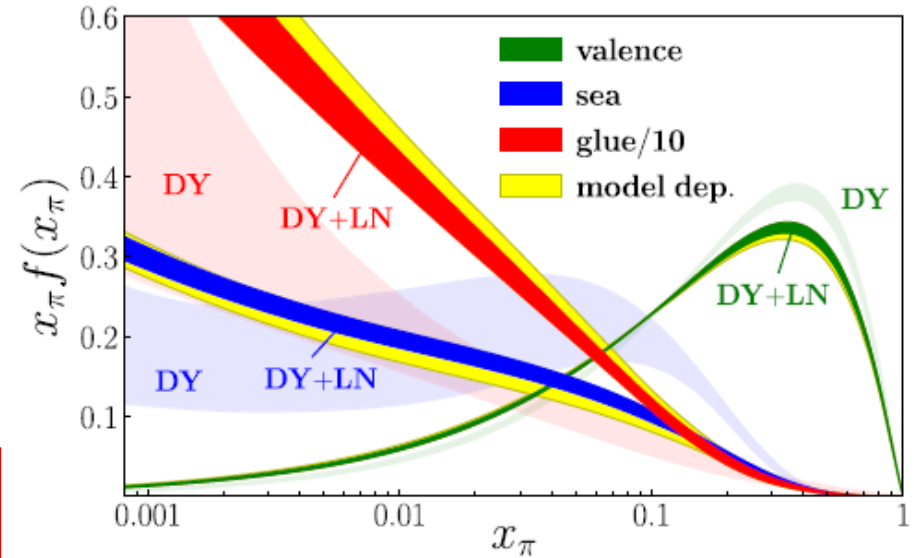
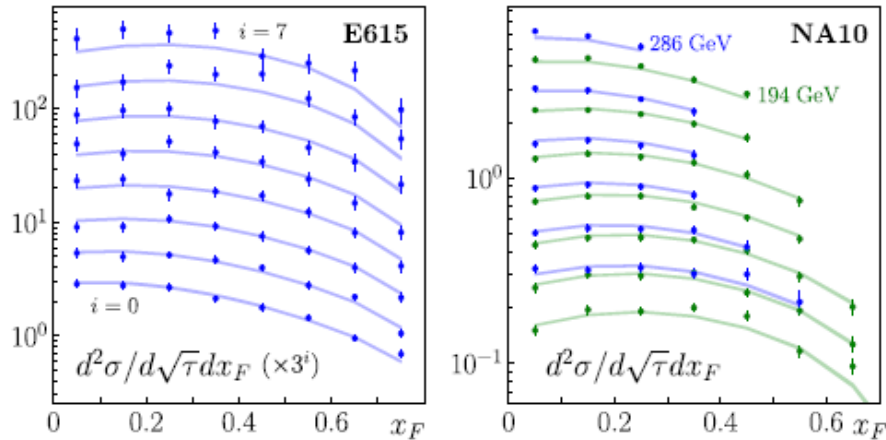
Pion/Kaon PDFs

- **Drell-Yan:** $\pi, K^\pm p \rightarrow \mu^+ \mu^- X$ (LO: sensitive to valence quarks)
 - LO: $q\bar{q} \rightarrow \mu^+ \mu^-$
 - NLO: $q\bar{q} \rightarrow \mu^+ \mu^- G, qG \rightarrow \mu^+ \mu^- q$ (large p_T)
 - NNLO: $q\bar{q}G \rightarrow \mu^+ \mu^- G, qG \rightarrow \mu^+ \mu^- qG, GG \rightarrow \mu^+ \mu^- q\bar{q}$
- **Direct photon:** $\pi, K^\pm p \rightarrow \gamma X$ (LO: sensitive to gluons)
 - LO: $q\bar{q} \rightarrow \gamma G, qG \rightarrow \gamma q$
- **Jpsi:** $\pi, K^\pm p \rightarrow J/\psi X$ (LO: sensitive to gluons)
 - LO: $q\bar{q} \rightarrow c\bar{c} \rightarrow J/\psi X, GG \rightarrow c\bar{c} \rightarrow J/\psi X$
 - NLO: $q\bar{q} \rightarrow c\bar{c}G \rightarrow J/\psi X, GG \rightarrow c\bar{c}G \rightarrow J/\psi X, qG \rightarrow c\bar{c}q \rightarrow J/\psi X$

- **Leading neutron (LN) electroproduction:**
Sullivan processes from a nucleon's pion cloud



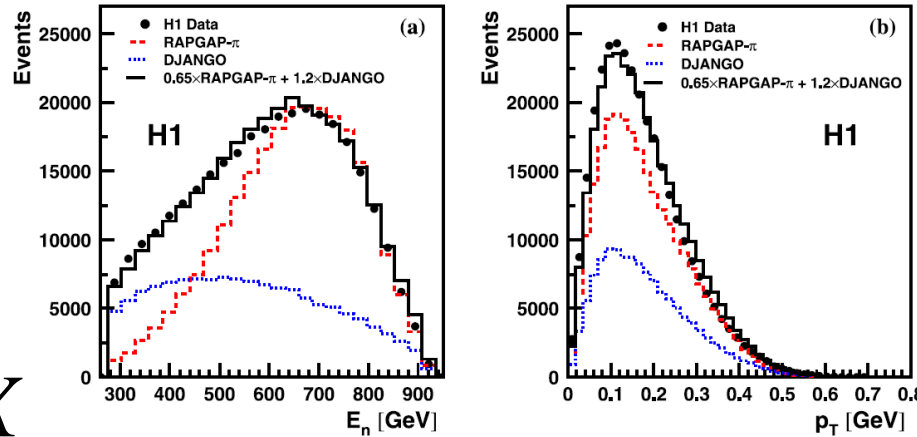
JAM18: Include leading neutron (LN) electroproduction from HERA [Barry et al., PRL 121, 152001 (2018)]



- Uncertainties are much reduced using DY+LN, as compared to DY alone.

Sullivan Process: H1 (DESY)

Fig. 3 The observed neutron energy (a) and transverse momentum (b) distributions in the kinematic range $6 < Q^2 < 100 \text{ GeV}^2$ and $1.5 \cdot 10^{-4} < x < 3 \cdot 10^{-2}$. The data are compared to the predictions of RAPGAP- π (dashed line) and DJANGO (dotted line) Monte Carlo simulations. Also shown is a weighted combination of those two simulations (full line), as described in Sect. 3.4

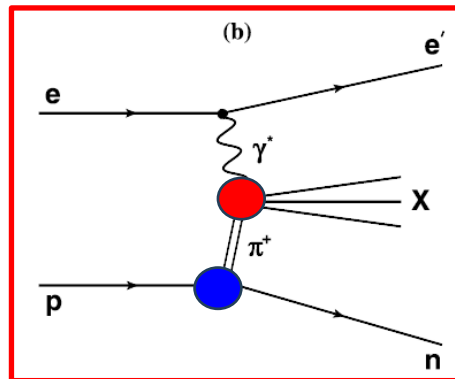
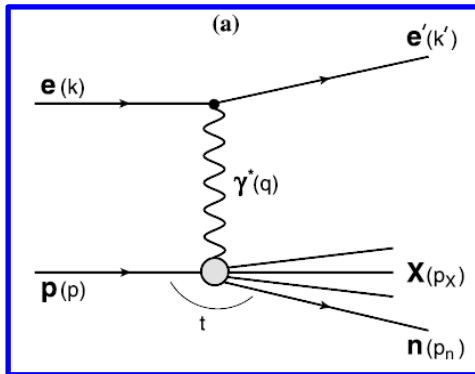


$$ep \rightarrow enX$$

DIS target fragmentation

One-pion exchange (Sullivan process)

$$x_L = \frac{E_n}{E_p}$$



$$F_2^{\text{LN}(3)}(x, Q^2, x_L) = 2f_{\pi N}(\bar{x}_L)F_2^\pi(x_\pi, Q^2).$$

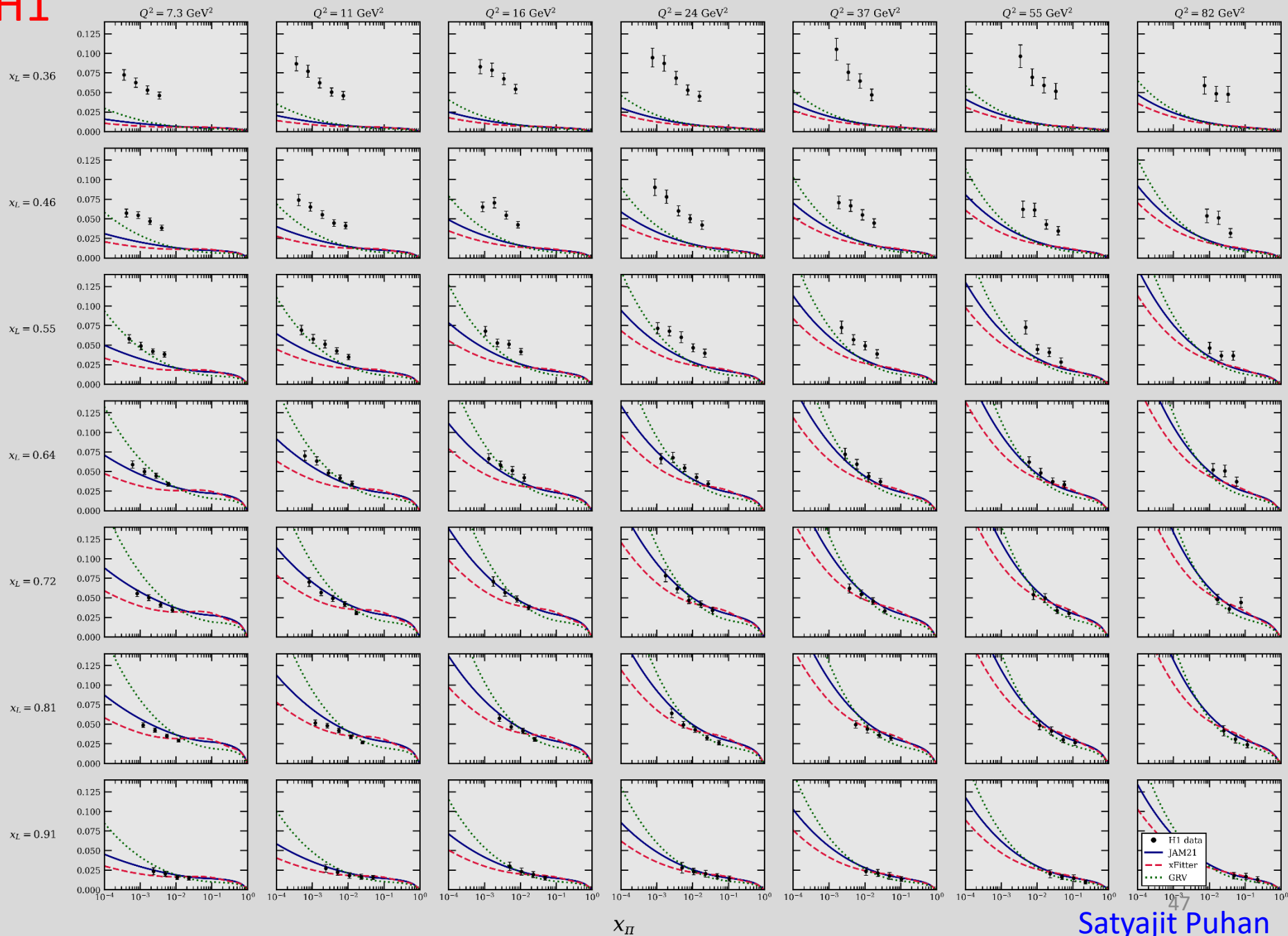
Splitting function $f_{\pi N}$

Pion structure function F_2^π

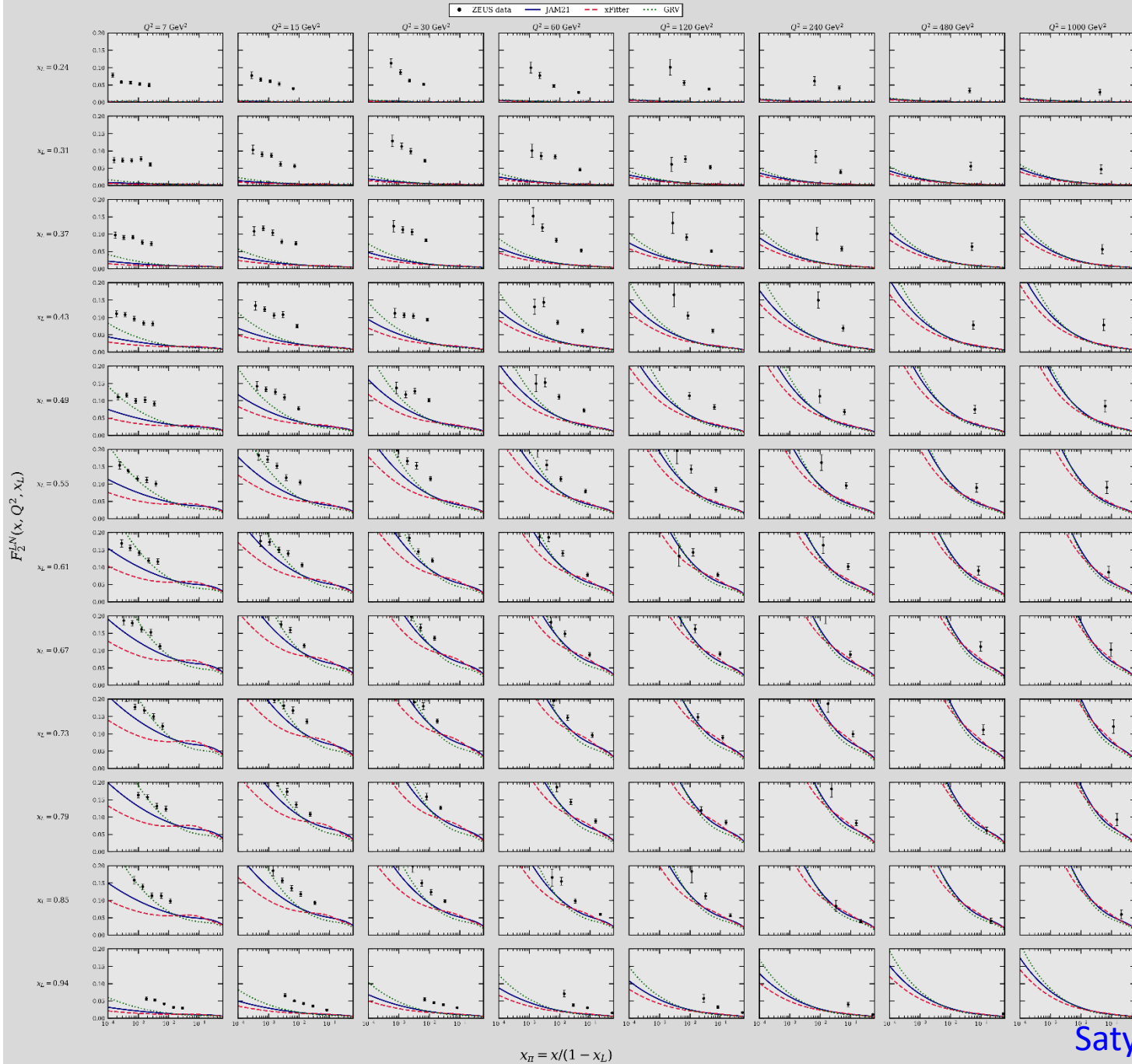
$$f_{\pi N}(\bar{x}_L) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2 \frac{\bar{x}_L [k_\perp^2 + \bar{x}_L^2 M^2]}{x_L^2 D_{\pi N}^2} |\mathcal{F}|^2,$$

HERA-ZEUS-H1 Data vs JAM21/xFitter/GRV Pion PDFs (NLO)

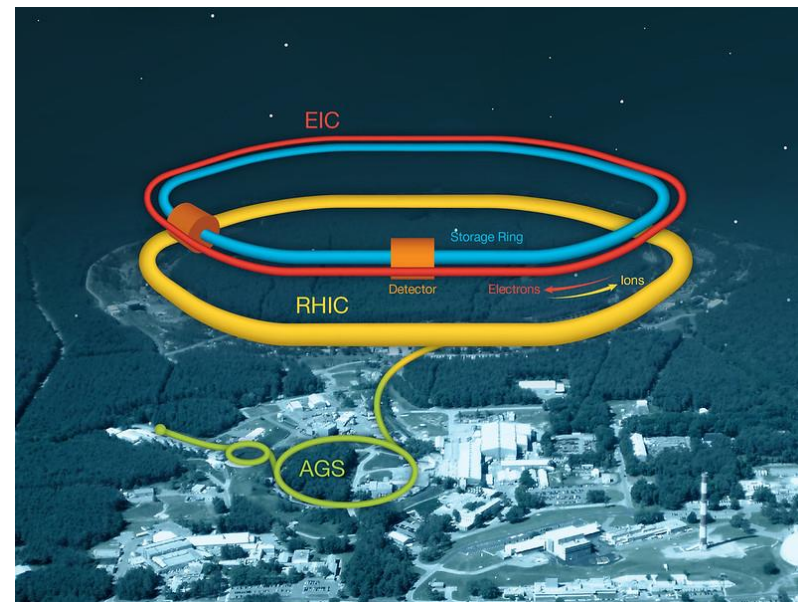
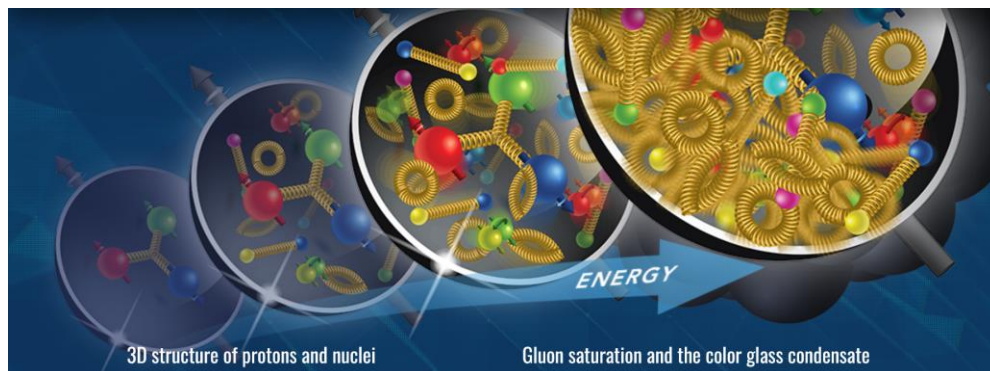
H1

 $F_2^{LN}(x, Q^2, x_L)$ 

ZEUS points transformed as $(x/\Delta x_L)F_2^N$



U.S. Electron-Ion Collider ePIC Collaboration



NTU



AS



NCU



NTHU

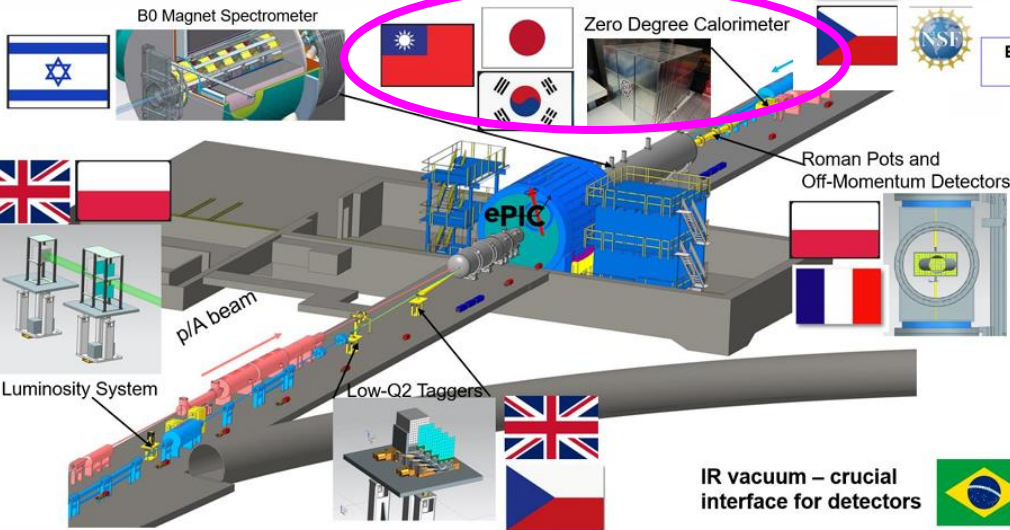
Physics Goals

- Precision 3D imaging of protons and nuclei
- Solving the proton spin puzzle
- Search for saturation
- Quark and gluon confinement
- Quarks and gluons in nuclei

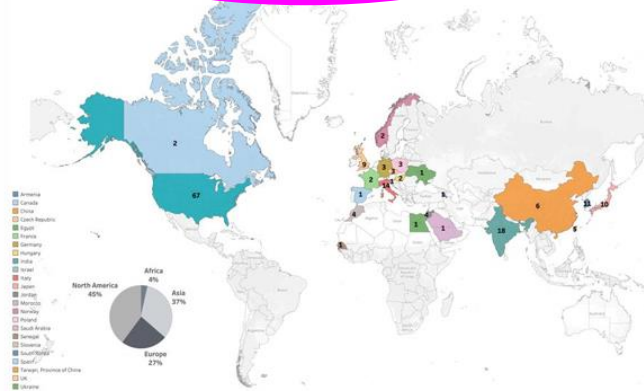
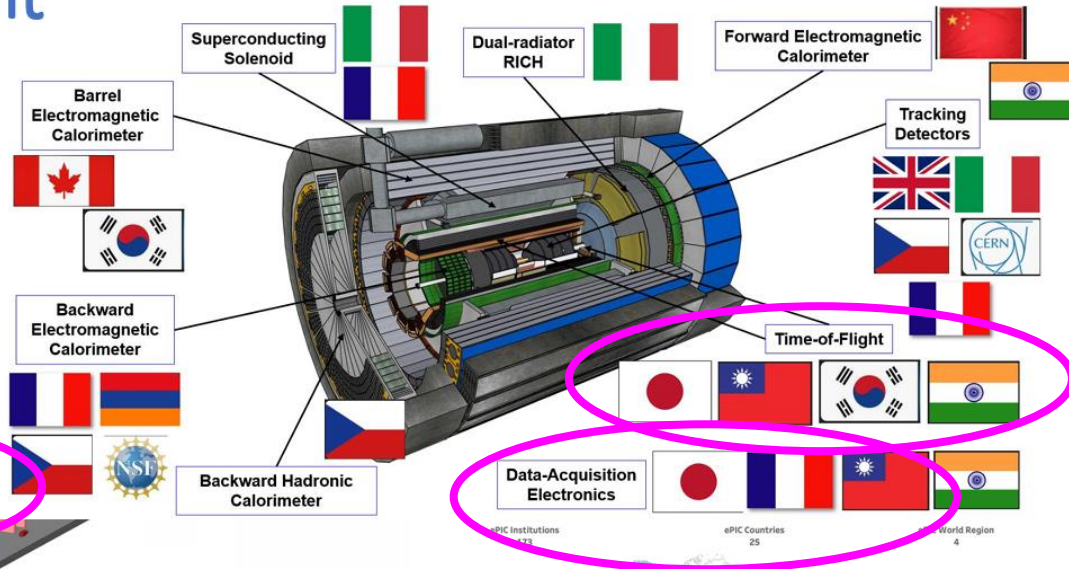
International engagement

- Large involvement from non-US institutions in ePIC central & far-forward/far-backward detectors
- Also contributions to EIC accelerator (magnets, cryomodules...)

Far-forward/far-backward detectors

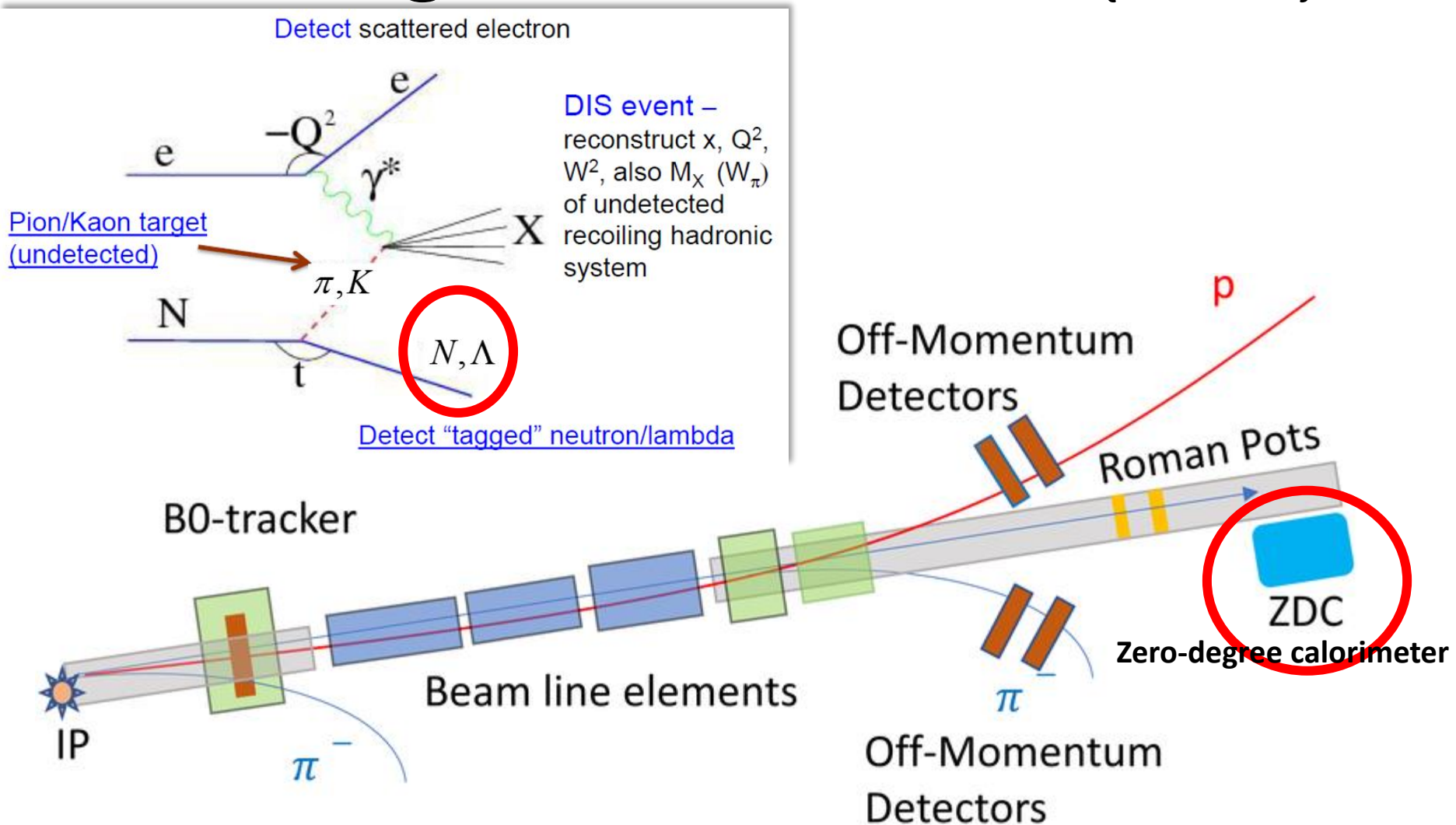


Central detector

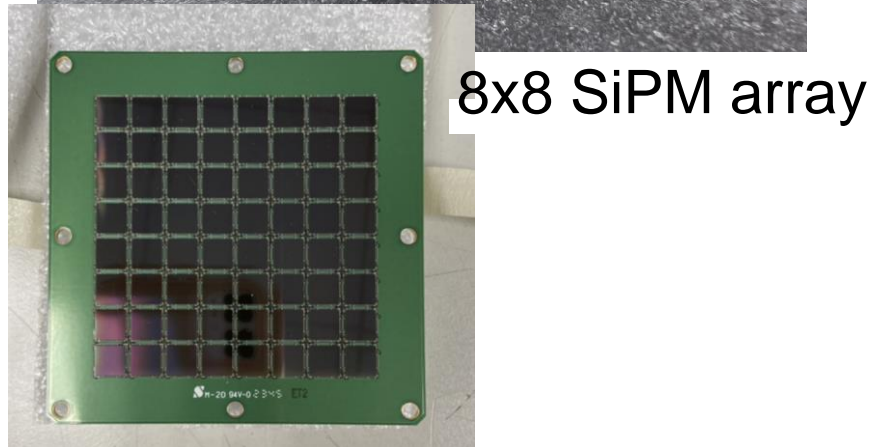
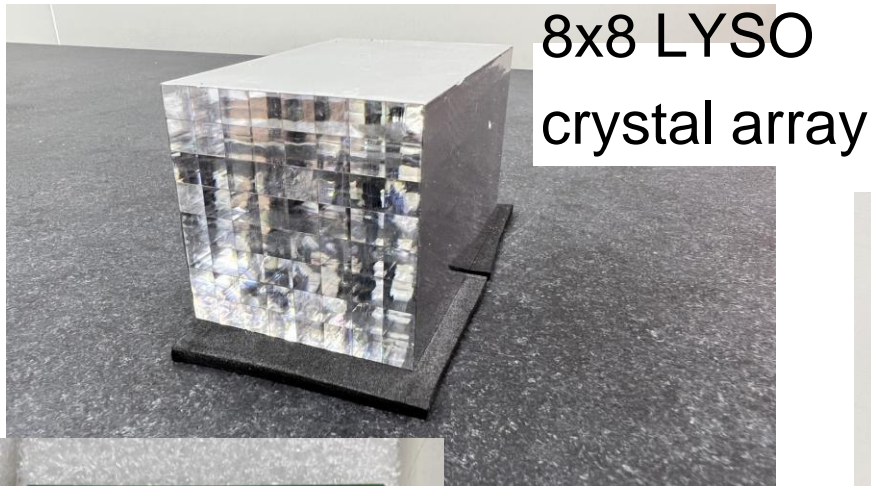


<https://indico.cern.ch/event/1479384/contributions/6594156/attachments/3134260/5560767/IS2025.pdf>

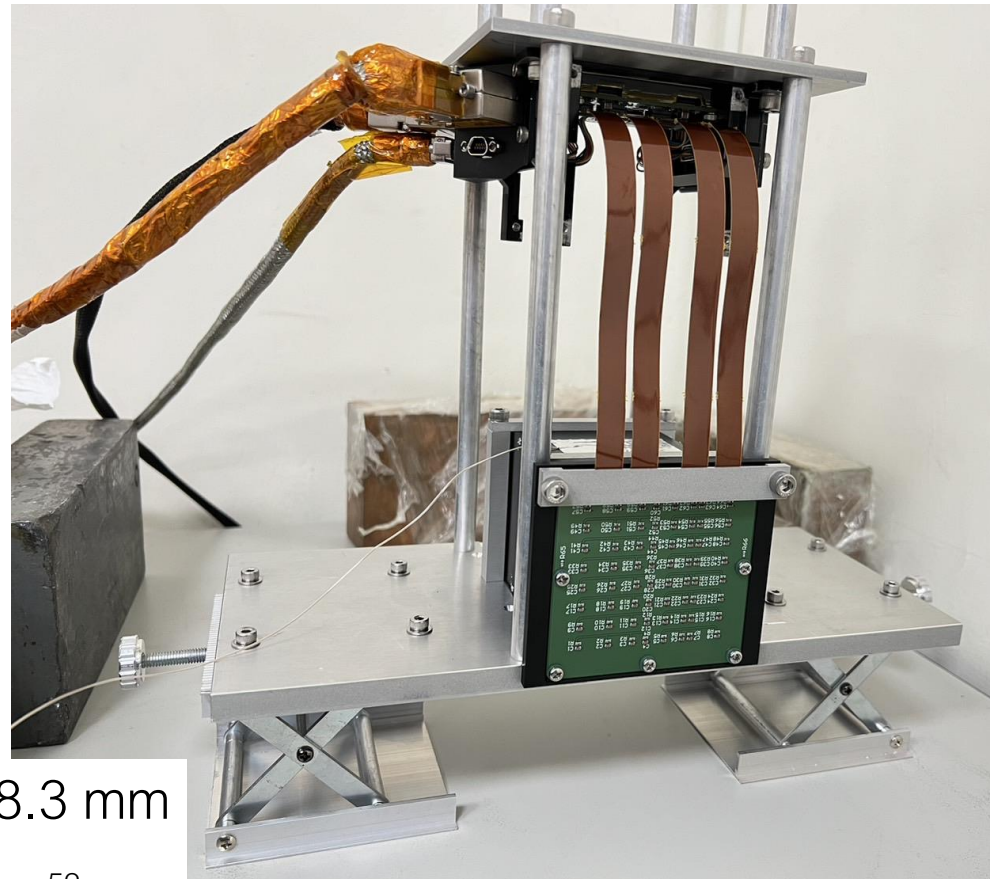
Far-Forward detectors: Zero-degree calorimeter (ZDC)



ZDC-ECAL Prototype: LYSO Crystals

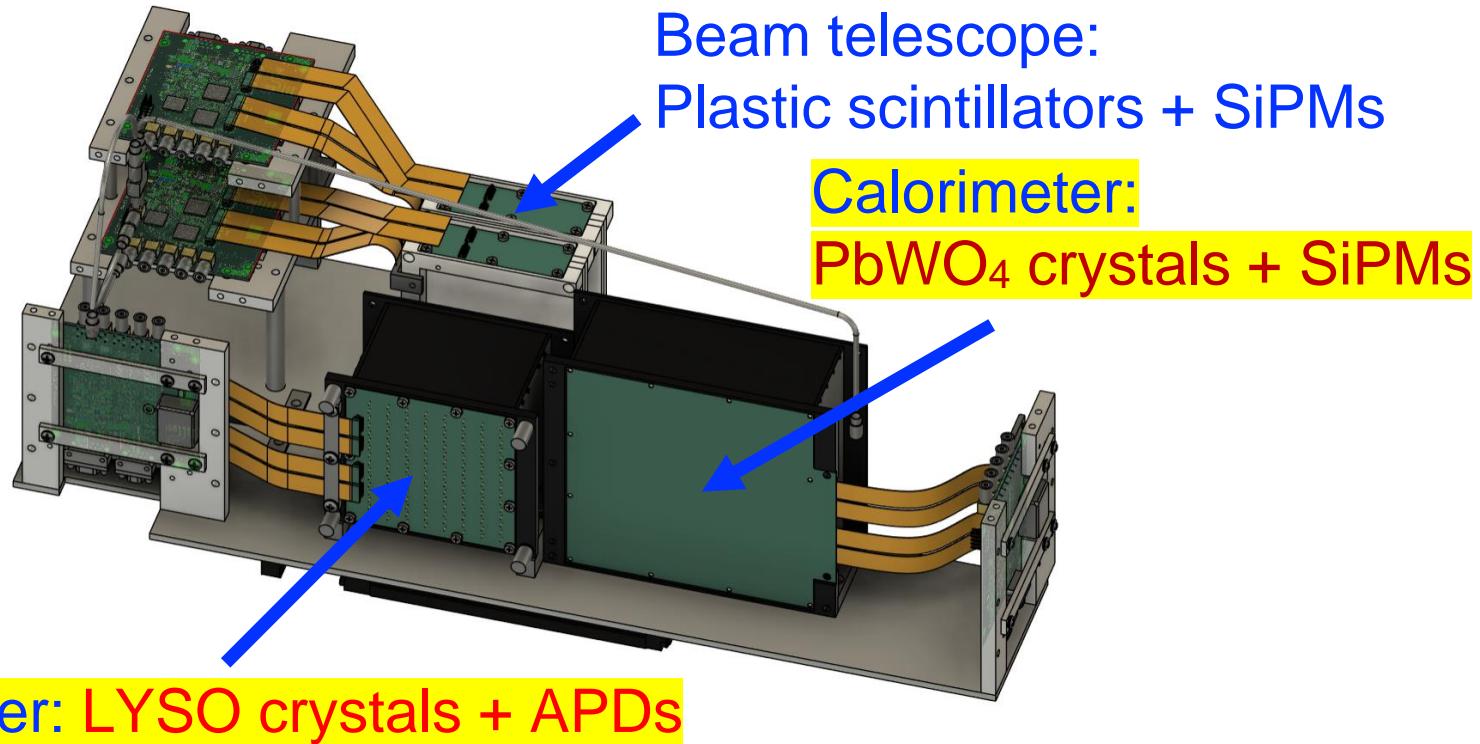


LYSO calorimeter prototype



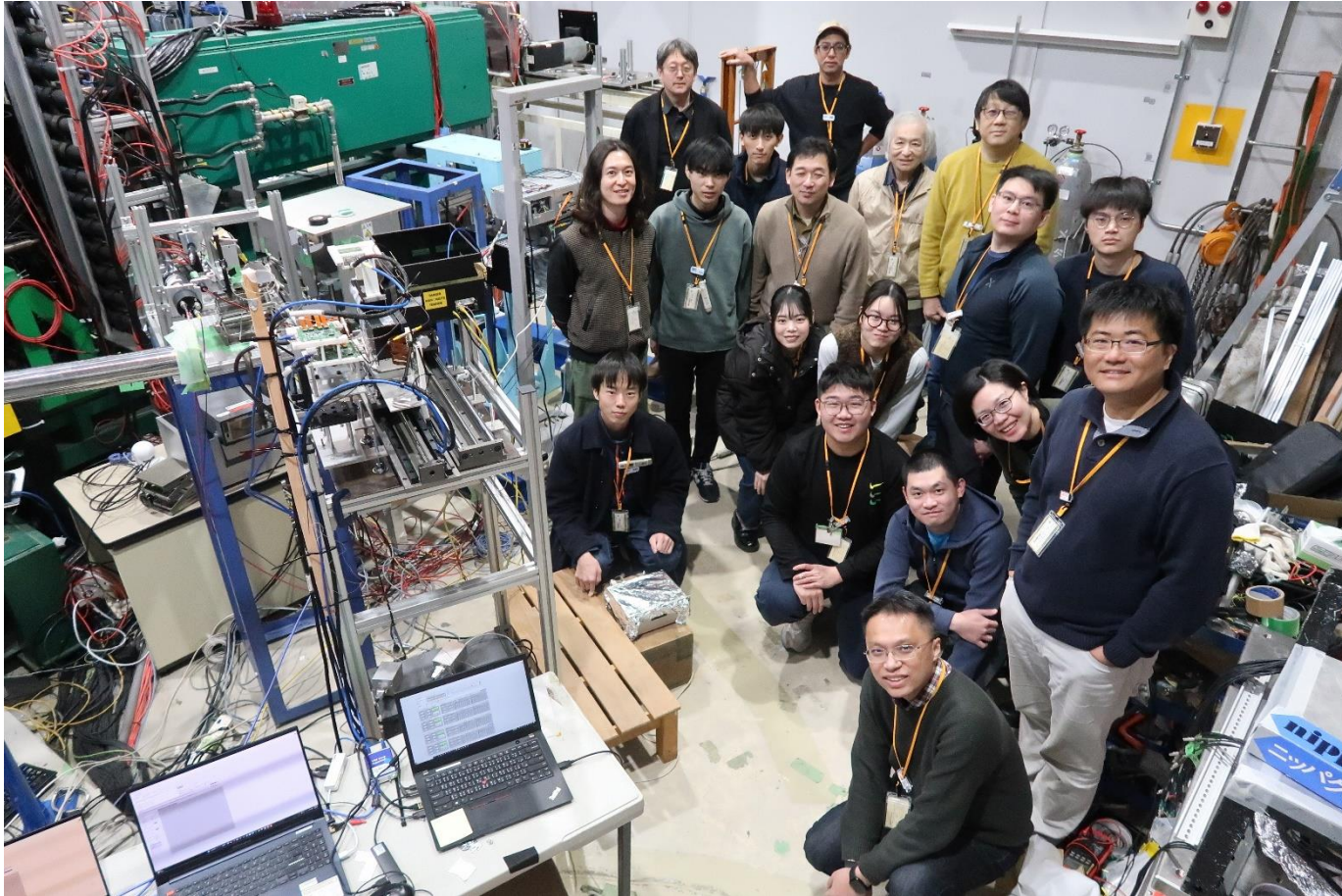
One crystal: 7.12 mm x 7.12 mm x 88.3 mm
8x8 array: 56.96 mm x 56.96 mm

2nd beam test @ RARIS



- Scheduled for February 2025
- Test two prototypes: LYSO+APD and PbWO₄+SiPM

Beam test @ Tohoku, Japan 2025/2 [Teams of Japan, Korea and Taiwan]



Summary

- Pion/kaon PDFs are poorly known. **DY process** is mostly sensitive to the **valence quarks**. Existing fixed-target **charmonium** data could provide valuable constraints on the **gluons**.
- Theoretical efforts are required to extract pion/kaon PDFs from **charmonium** production and **Sullivan process** reliably.
- **Outlook**
 - Coming COMPASS results of pion-induced **DY/Jpsi**
 - Future AMBER measurements of π^\pm/K^\pm -induced **DY/Jpsi**
 - Future measurements of **Sullivan** process in U.S. EIC.