

2nd TIDC EIC Workshop

Pion and Kaon PDFs for EIC

Institute of Physics, Academia Sinica

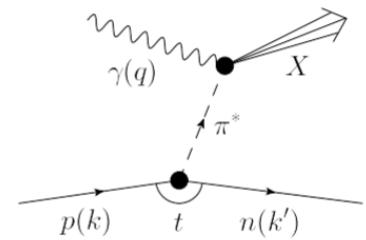
Wen-Chen Chang

January 3 , 2023

- Related data and recent studies of pion PDFs
- Related data and recent studies of kaon PDFs
- Future experimental programs related to the pion/kaon PDFs

Experimental Approaches

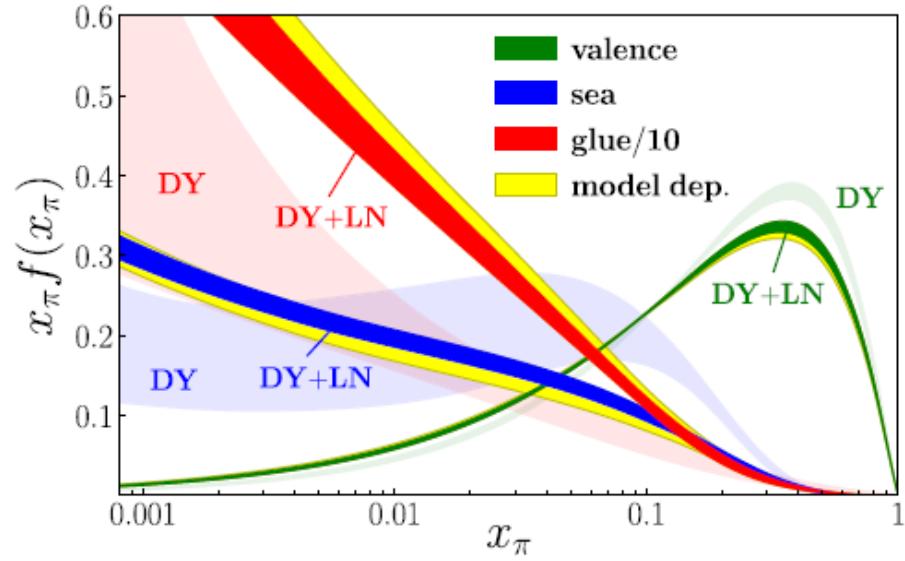
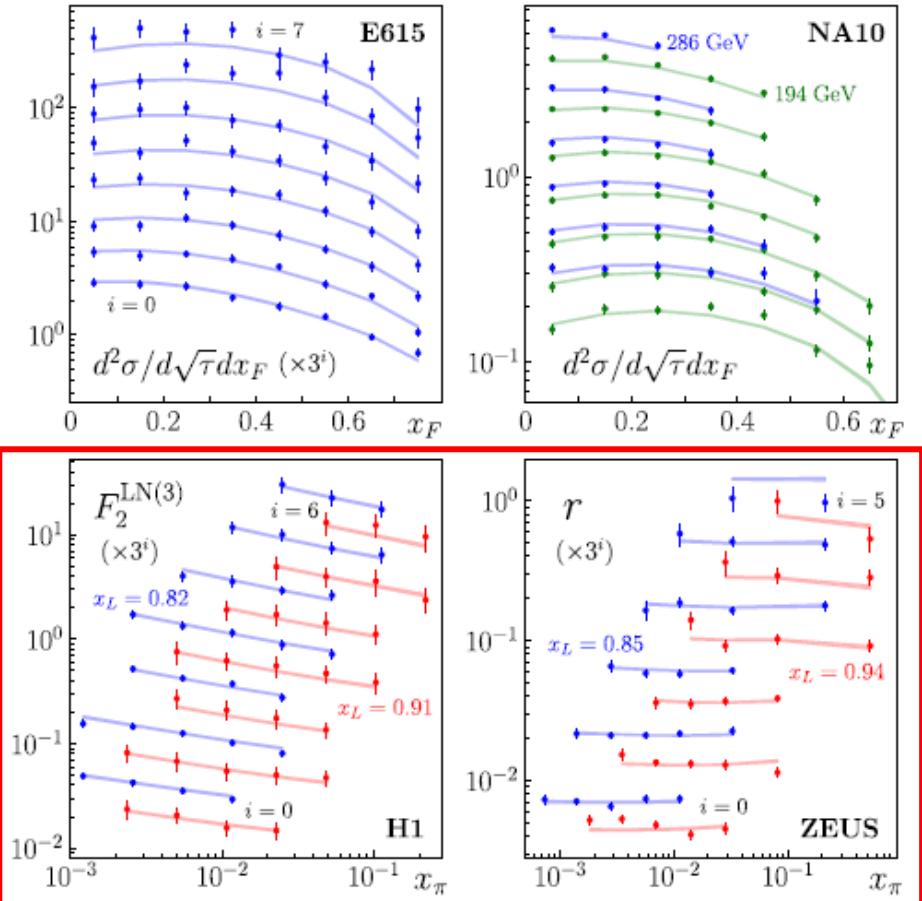
- Drell-Yan: $\pi^\pm p \rightarrow \mu^+ \mu^- X$ (LO: sensitive to valence quarks)
 - LO: $q\bar{q} \rightarrow \mu^+ \mu^-$
 - NLO: $q\bar{q} \rightarrow \mu^+ \mu^- G, qG \rightarrow \mu^+ \mu^- q$ (large p_T)
 - NNLO: $q\bar{q}G \rightarrow \mu^+ \mu^- G, qG \rightarrow \mu^+ \mu^- qG, GG \rightarrow \mu^+ \mu^- q\bar{q}$
- Direct photon: $\pi^\pm p \rightarrow \gamma X$ (LO: sensitive to gluons)
 - LO: $q\bar{q} \rightarrow \gamma G, qG \rightarrow \gamma q$
- Jpsi: $\pi^\pm p \rightarrow J/\psi X$ (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 (2021)

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

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.

JAM21: finite qT

[Cao et al., PRD 103, 114014 (2021)]

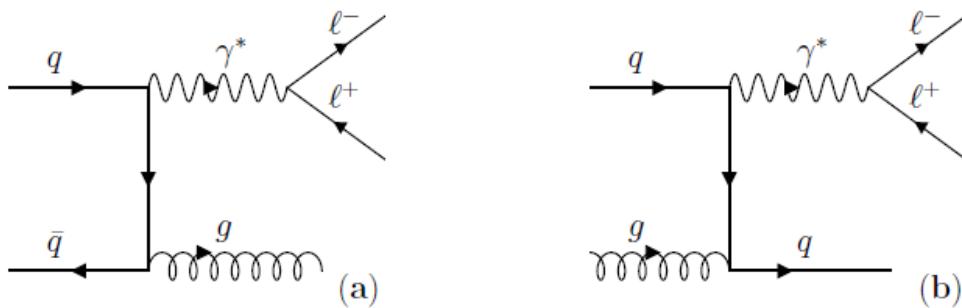
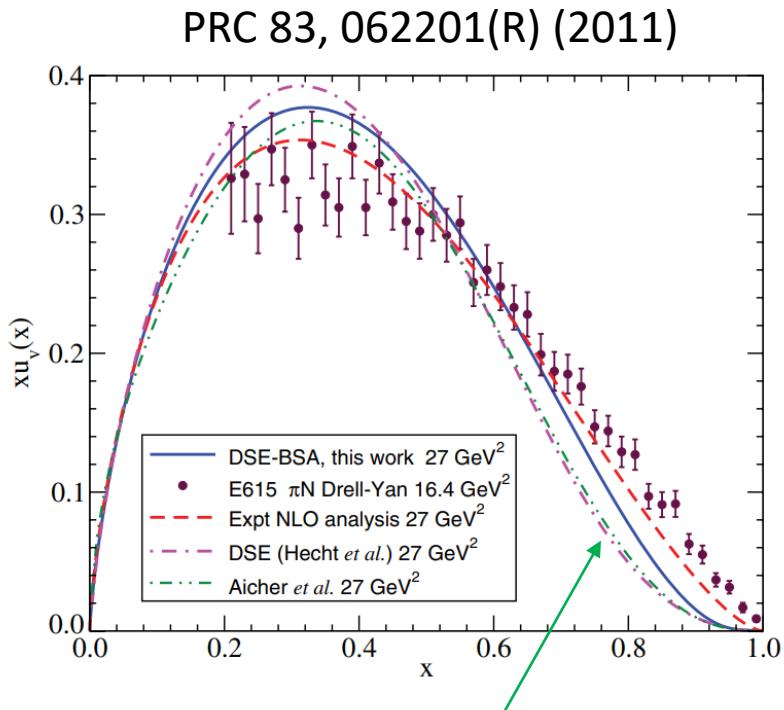


FIG. 1. Examples of LO diagrams for the large transverse momentum region in Drell-Yan lepton-pair production for the $q\bar{q}$ channel (a) and qg channel (b).

$H_{a,b}^{\text{DY}}$ starts at $\mathcal{O}(\alpha_s^0)$, and in our analysis we compute corrections up to $\mathcal{O}(\alpha_s)$. Our study is the first attempt to include both p_T -differential and p_T -integrated pion-nucleus Drell-Yan data [4, 5] on the same footing, taking advantage of the fact that the p_T -dependent cross sections provide access to a larger region of parton momentum fractions relative to the p_T -integrated case.

JAM21: Threshold Resummation

[Barry et al., PRL 127, 232001 (2021)]



With threshold resummation, $\beta_v^{\text{eff}} \sim 2$
(PRL 105 (2010) 252003)

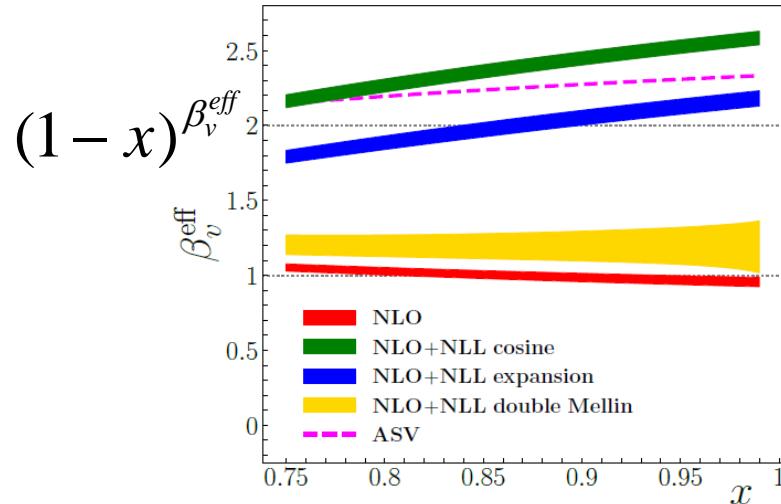


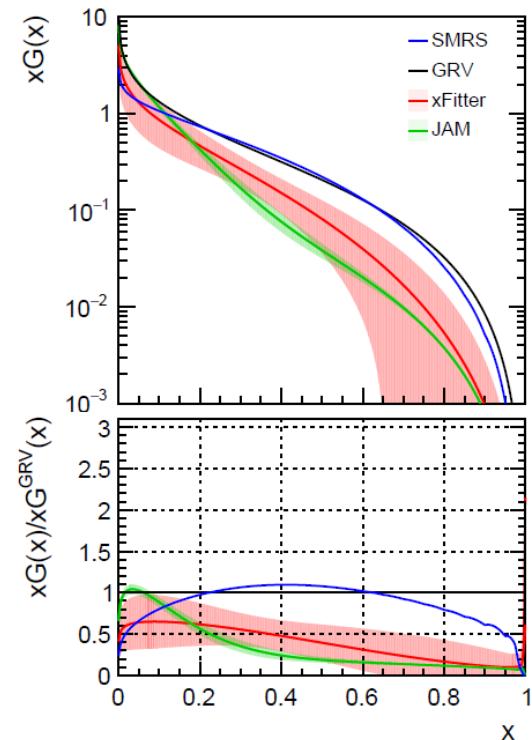
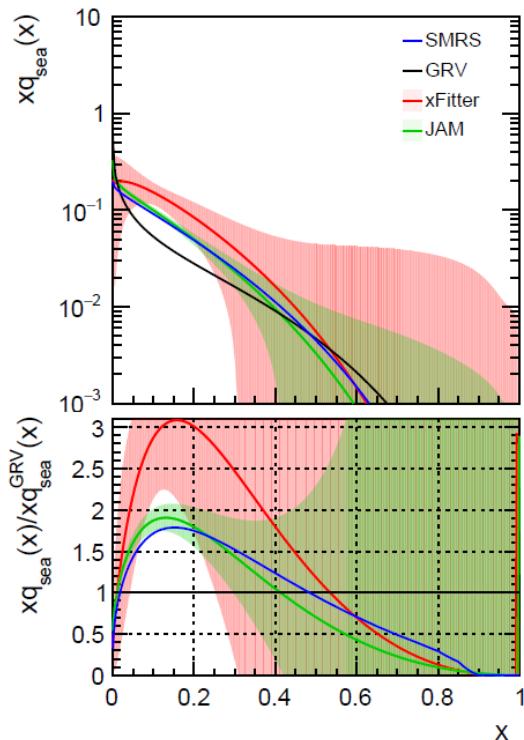
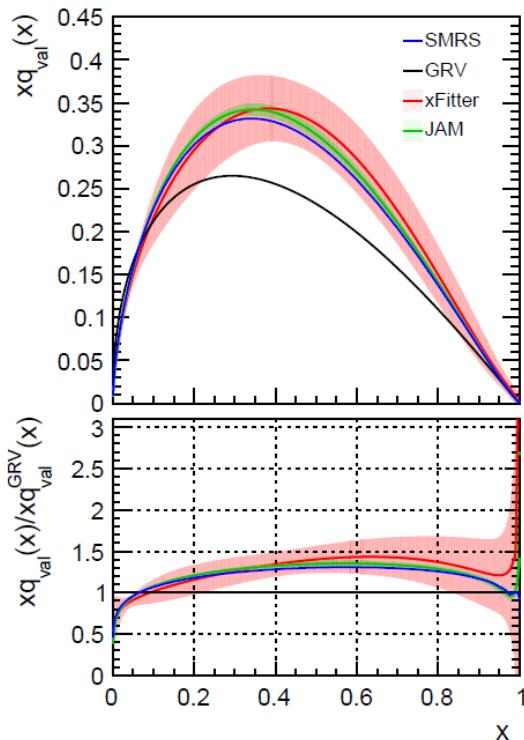
FIG. 3. Effective exponents β_v^{eff} for the various prescriptions versus x at the scale μ_0 , compared with the ASV extraction [33]. The values $\beta_v^{\text{eff}} = 1$ and 2 are shown for reference.

results in a wide variety of β_v^{eff} values, with the cosine and expansion methods yielding $\beta_v^{\text{eff}} > 2$, consistent with ASV [33], and as large as ≈ 2.6 . However, with the double Mellin method the effective exponent is much closer to the NLO case, with $\beta_v^{\text{eff}} \approx 1.2$ as $x \rightarrow 1$. This suggests that with currently available data and theoretical methods, we cannot distinguish between $\beta_v^{\text{eff}} \sim 1$ and ~ 2 asymptotic behaviors.

Large systematics of threshold resummation prescriptions!

Pion PDFs

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



The gluon distributions of SMRS and GRV are significantly larger than JAM and xFitter for $x > 0.1$.

LQCD: Pion Momentum Fractions

[Alexandrou et al., PRL 127, 252001 (2021)]

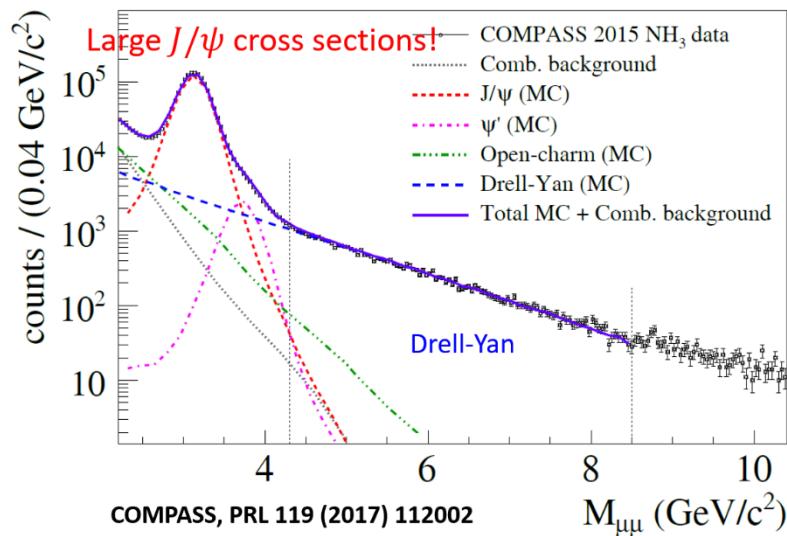
TABLE I. Compilation of results and comparison to literature.
All values are at 2 GeV in the $\overline{\text{MS}}$ scheme.

	RQCD	JAM	xFitter	
This work	[20]	[45]	[46]	
$\langle x \rangle_l^R$	0.601(28)($_{-21}^{+02}$)	...	...	...
$\langle x \rangle_s^R$	0.059(13)($_{-10}^{+02}$)	...	...	...
$\langle x \rangle_c^R$	0.019(05)($_{-10}^{+02}$)	...	...	...
$\langle x \rangle_g^R$	0.52(11)($_{-03}^{+02}$)	...	0.42(4)	0.25(13)
$\Sigma_f \langle x \rangle_f^R$	0.68(05)($_{-03}^{+02}$)	0.220(207)	0.58(9)	0.75(18)
$\langle x \rangle_{u+d-2s}^R$	0.48(01)	0.344(28)	...	...
$\langle x \rangle_{u+d+s-3c}^R$	0.60(03)	...	...	...

The gluon momentum fraction from LQCD is larger than those of JAM and xFitter.

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

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

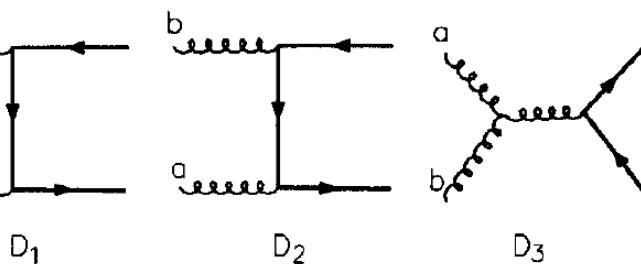
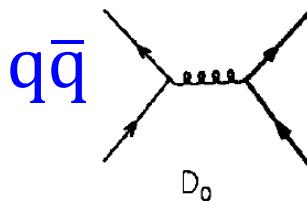


Fig. 2. Diagrams for the $q\bar{q}$ and g

NLO

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

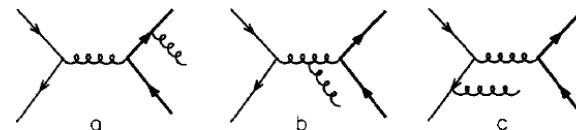
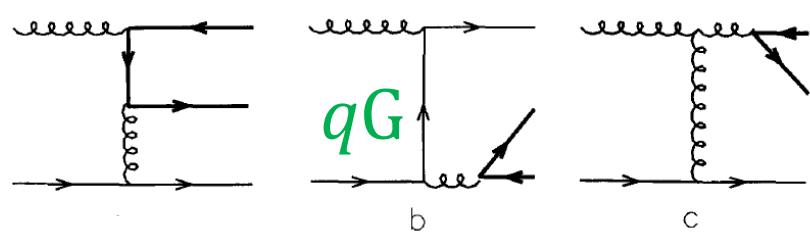


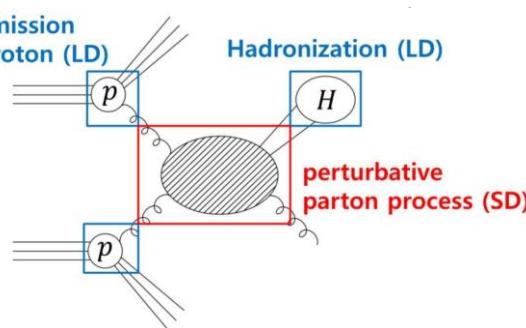
Fig. 8. Diagrams for the real corrections to the $q\bar{q}$ channels. Permutations of outgoing gluons and/or reversal of fermion lines are always implied.

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



the gq channels. Reversal of fermion lines is always implied.



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

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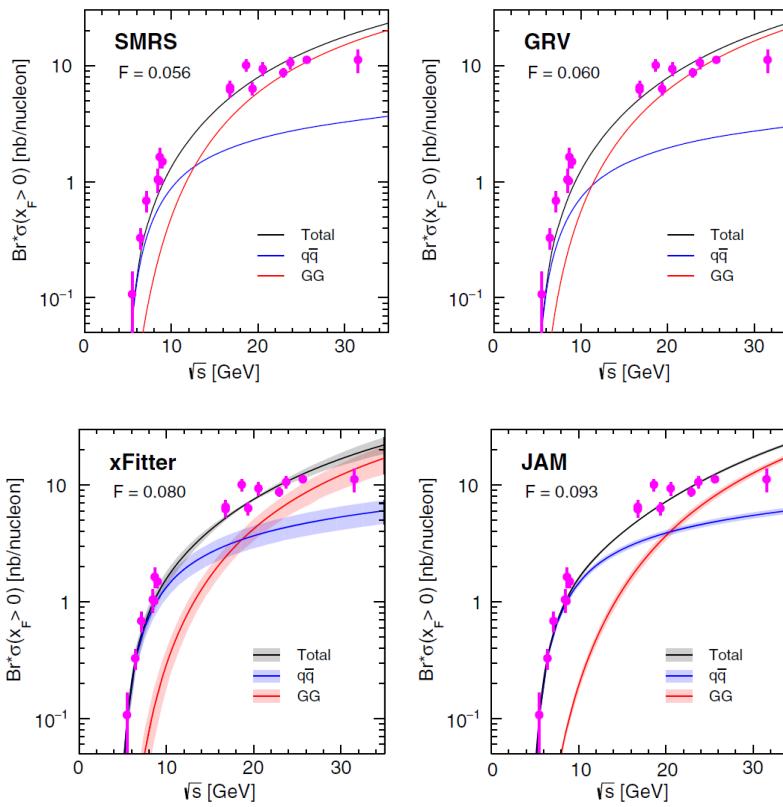
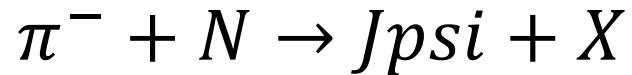
Department of Physics, Osaka City University, Osaka 558-8585, Japan



(Received 12 June 2020; accepted 8 September 2020; published 24 September 2020)

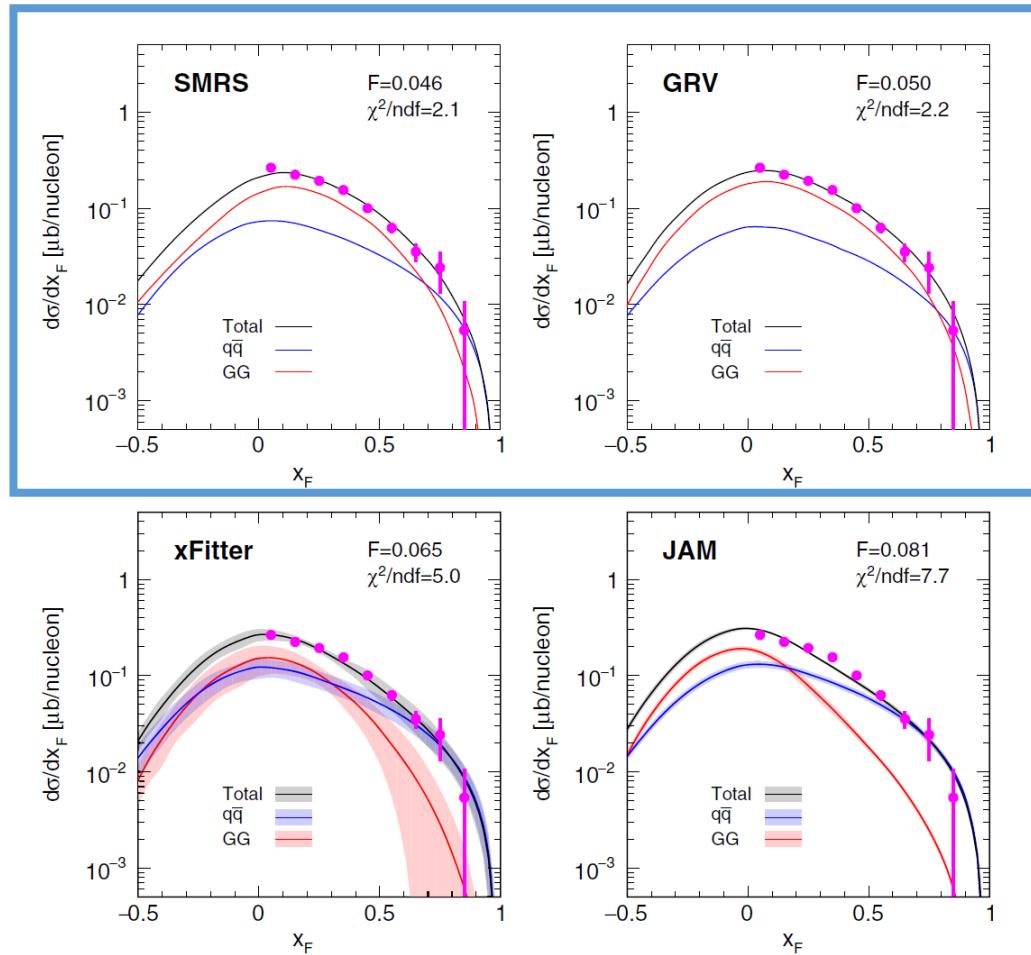
The gluon distributions of the pion obtained from various global fits exhibit large variations among them. Within the framework of the color evaporation model, we show that the existing pion-induced J/ψ

Data vs. CEM NLO: $\sigma(\sqrt{s})$



Data vs. CEM NLO

$\pi^- + Pt \rightarrow Jpsi + X$ at **200 GeV**, Z. Phys. C20,101(1983)]



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

Non-relativistic QCD model (NRQCD)

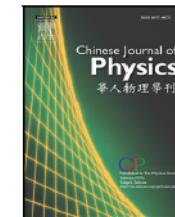
[Chin.J.Phys. 73 \(2021\) 13; arXiv: 2103.11660](#)



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



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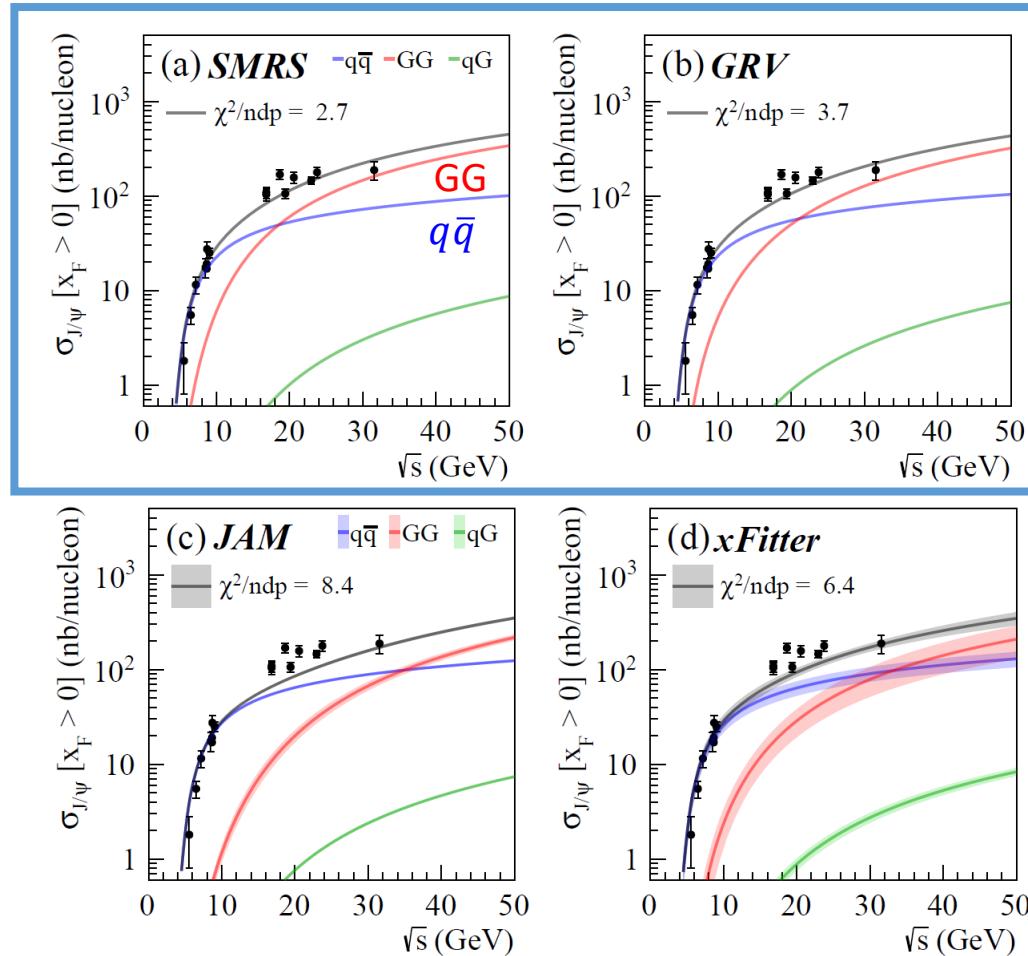
Color-octet matrix elements

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 .

$\pi^- + N \rightarrow J/\psi + X$: pion PDFs



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

Non-relativistic QCD model (NRQCD)

[arXiv: 2209.04072](https://arxiv.org/abs/2209.04072)

Fixed-target charmonium production and pion parton distributions

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Osaka Metropolitan University, Osaka 558-8585, Japan*

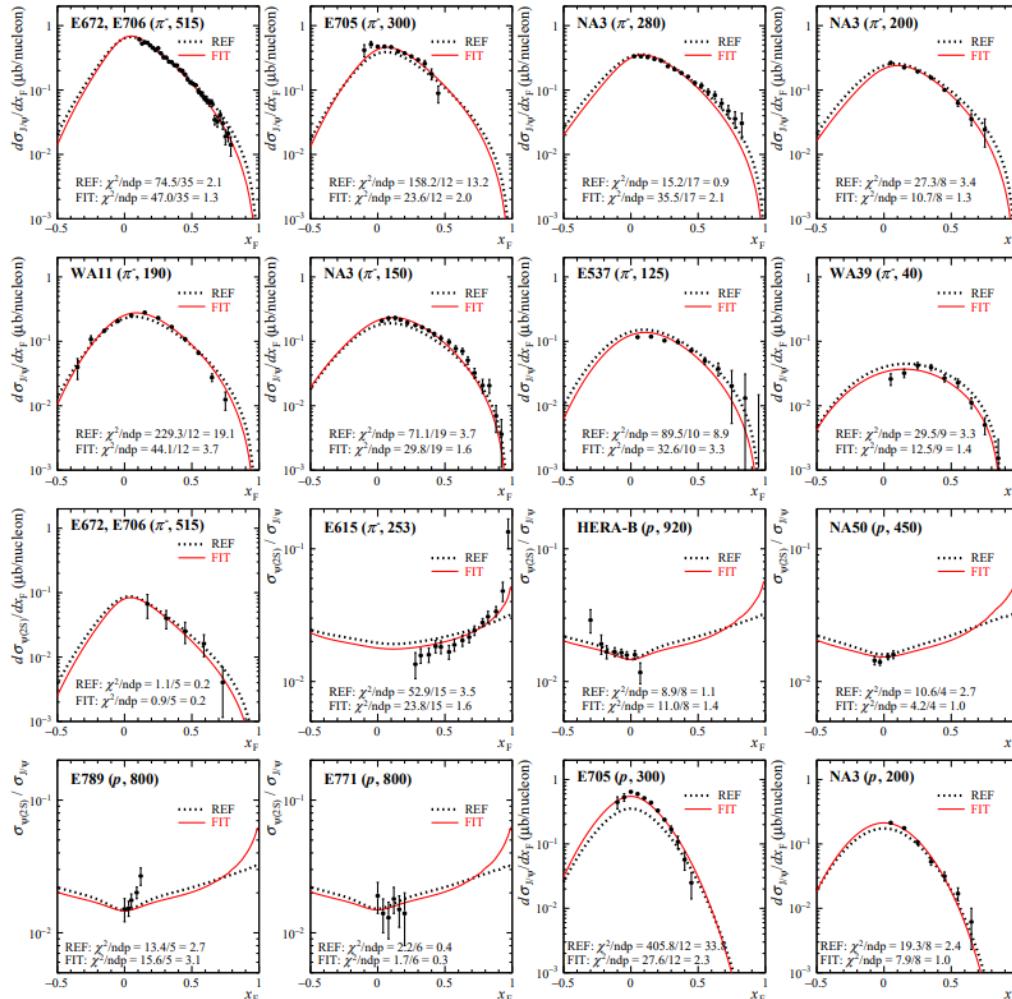
(Dated: September 12, 2022)

We investigate how charmonium hadroproduction at fixed-target energies can be used to constrain the gluon distribution in pion. Using non-relativistic 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 .

I. INTRODUCTION

production of the heavy quark pair is treated perturbatively, whereas its hadronization to a bound state is described in

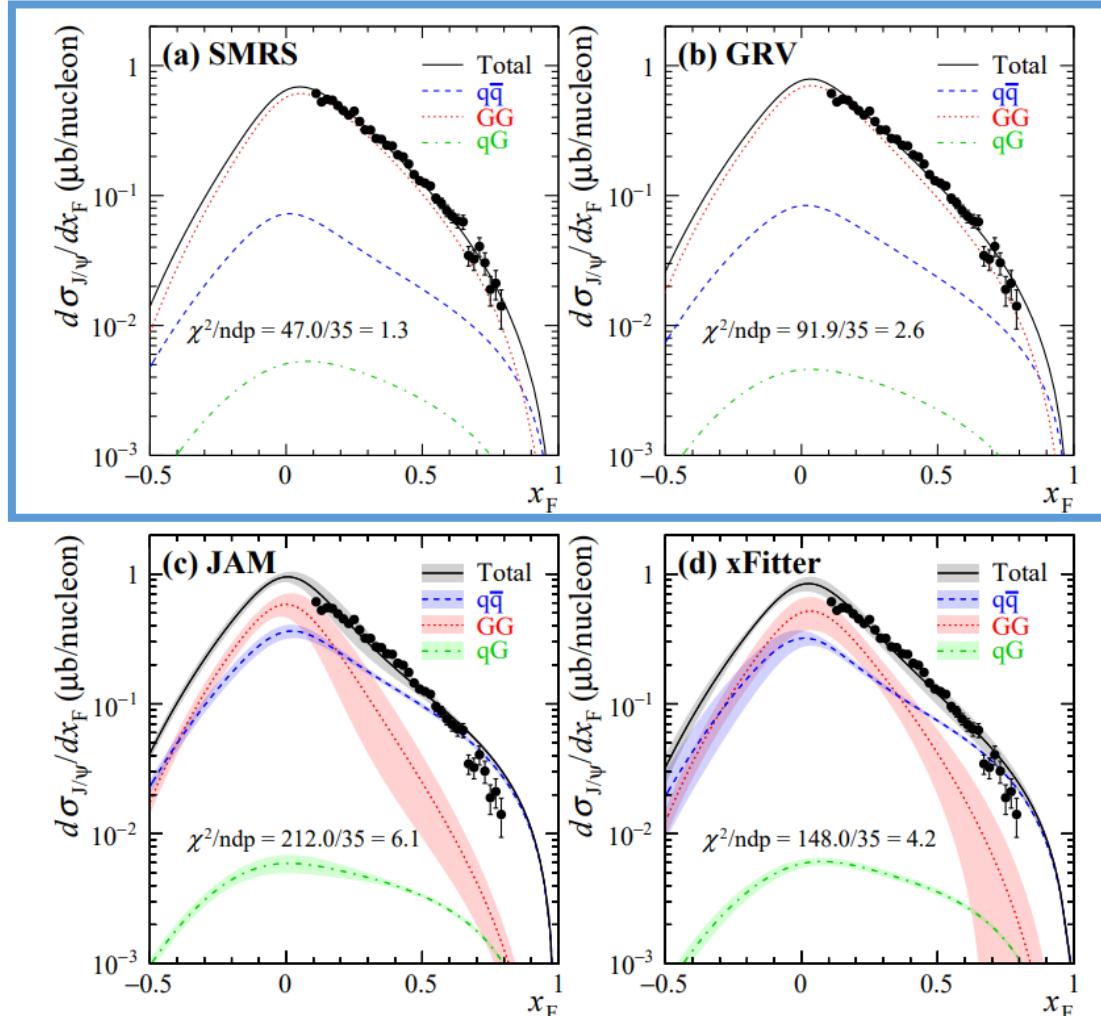
Data (J/ψ , ψ') vs. NRQCD



We can achieve a reasonable description of the charmonium data with the proton and pion beams by NRQCD calculations with similar LDMEs obtained in Chin. J. Phys. 73 (2021) 13.

Data vs. NRQCD

$[\pi^- + Pt \rightarrow J\psi + X$ at **200 GeV**, Z. Phys. C20,101(1983)]

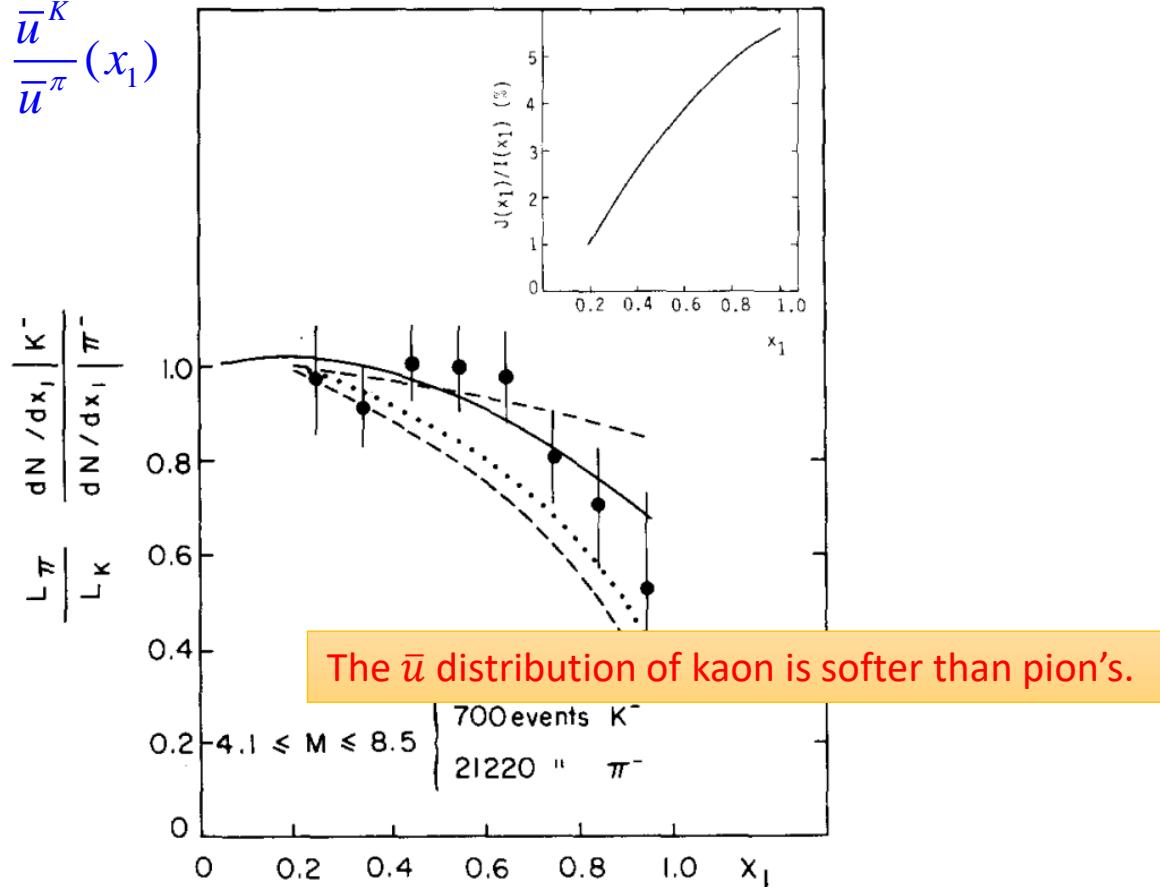


Data favor SMRS and GRV PDFs with larger gluon densities at $x > 0.1$.

Kaon/Pion Drell-Yan Ratios

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

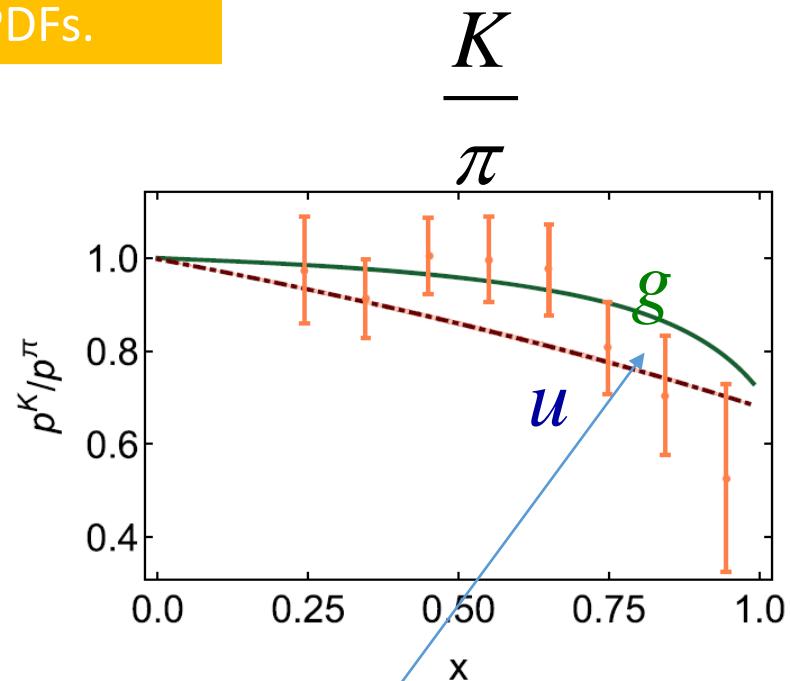
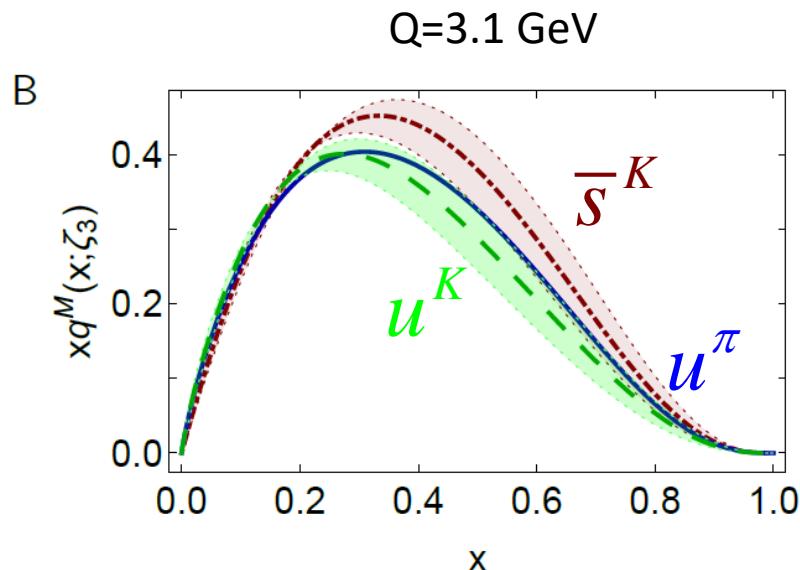
$$\frac{\sigma^{DY}(K^-)}{\sigma^{DY}(\pi^-)}(x_F) = \frac{\bar{u}^K(x_1)u^N(x_2)}{\bar{u}^\pi(x_1)u^N(x_2)} = \frac{\bar{u}^K}{\bar{u}^\pi}(x_1)$$



Kaon PDFs: Dyson-Schwinger Equation (DSE)

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

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



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

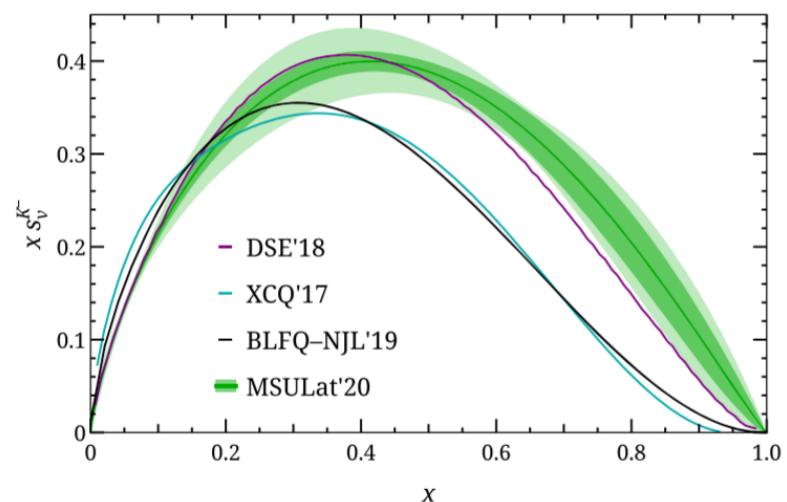
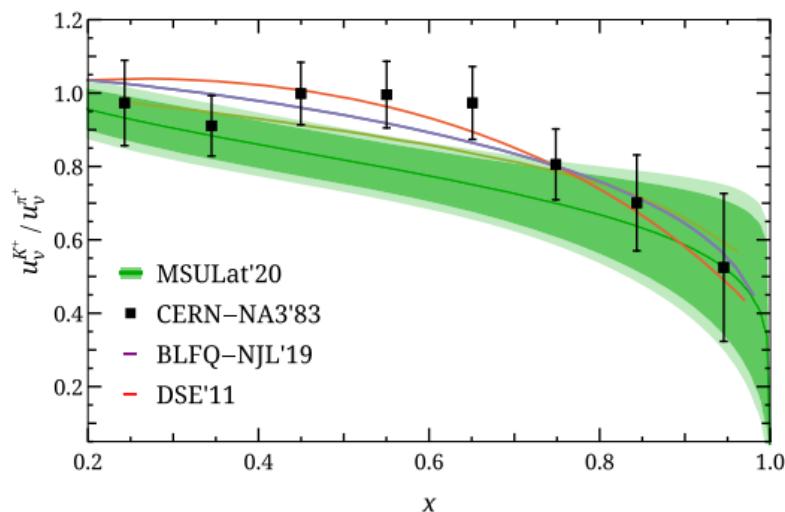
A slightly smaller kaon gluon distribution at large x,
compared to the pion.

Kaon PDFs: LQCD(quasi-PDF)

H.W. Lin et al., [PRD 103, 014516 \(2021\)](#)

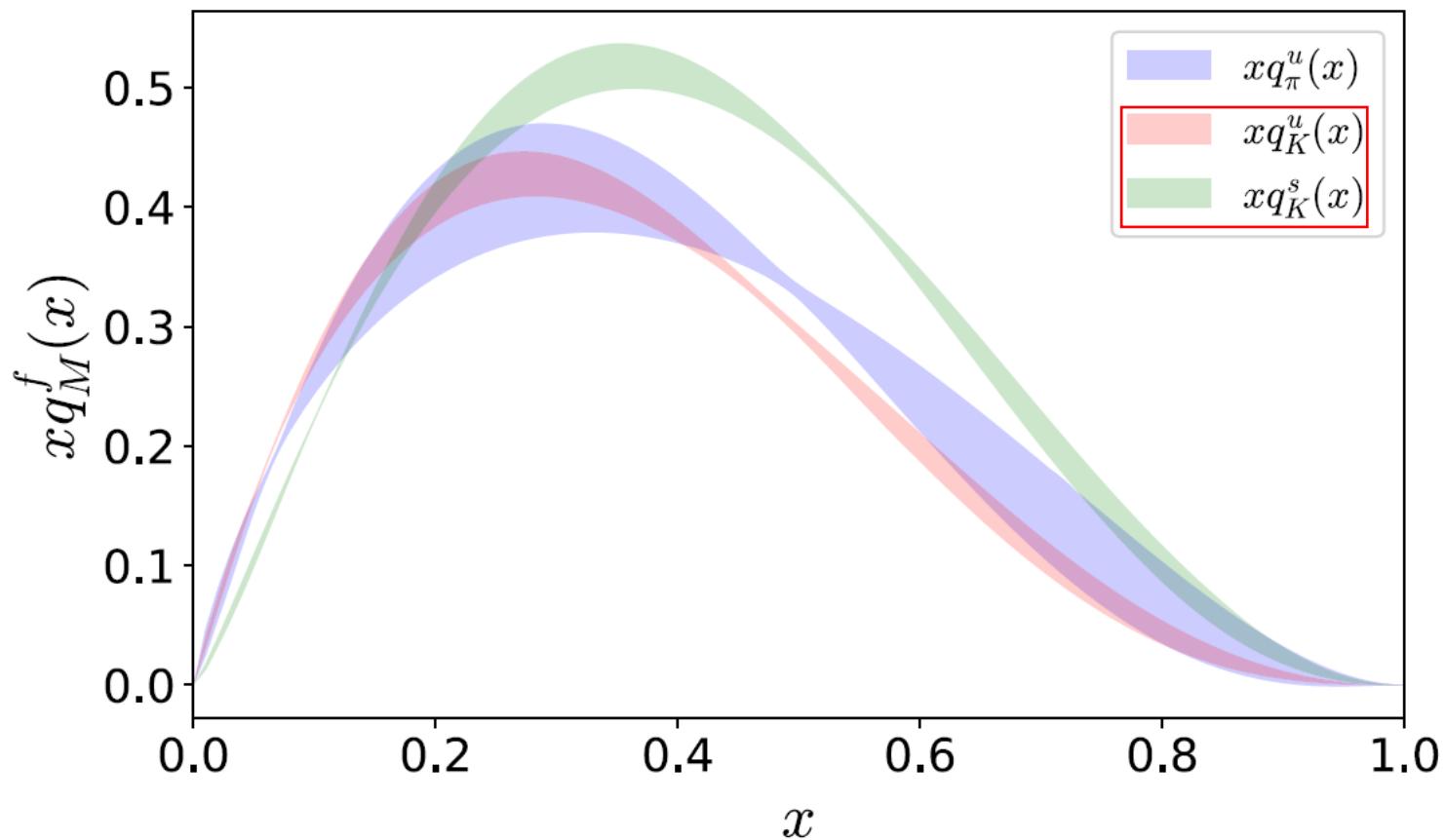
Valence (s)

$Q^2 = 27 \text{ GeV}^2$



Kaon PDFs: LQCD (Mellin moments)

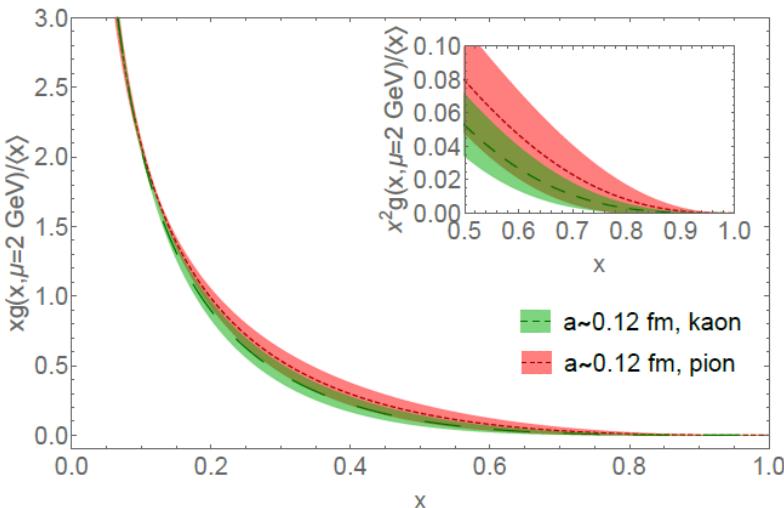
ETM Collaboration, [PRD 104, 054504 \(2021\)](#)



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

Kaon Gluon PDFs: LQCD(pseudo-PDF)

H.W. Lin et al., [PRD 106, 094510 \(2022\)](#)



one-sigma error for $x > 0.15$. On the right-hand side of Fig. 5, we compare the obtained kaon result at smaller lattice spacing with the pion results obtained from the same ensembles; we note the kaon gluon PDF is slightly smaller than the one obtained for the pion, similar to its corresponding quark valence PDF and DSE [88] results. We predict the kaon $\langle x^2 \rangle_g / \langle x \rangle_g$ and $\langle x^3 \rangle_g / \langle x \rangle_g$ to be 0.0779(94) and 0.0187(42), while in good agreement with corresponding results from DSE [88]: 0.075 and 0.015. On the pion $\langle x^2 \rangle_g / \langle x \rangle_g$, our 310-MeV results give .092(15) and 0.0250(75), while results from DSE [88], JAM [1, 2] andxFitter [3] are 0.076, 0.103, 0.158 and 0.015, 0.024, 0.048, respectively. Future study including finer lattice spacing and lighter pion mass will be important to refine this calculation and provide better predictions on this poorly known meson quantity.

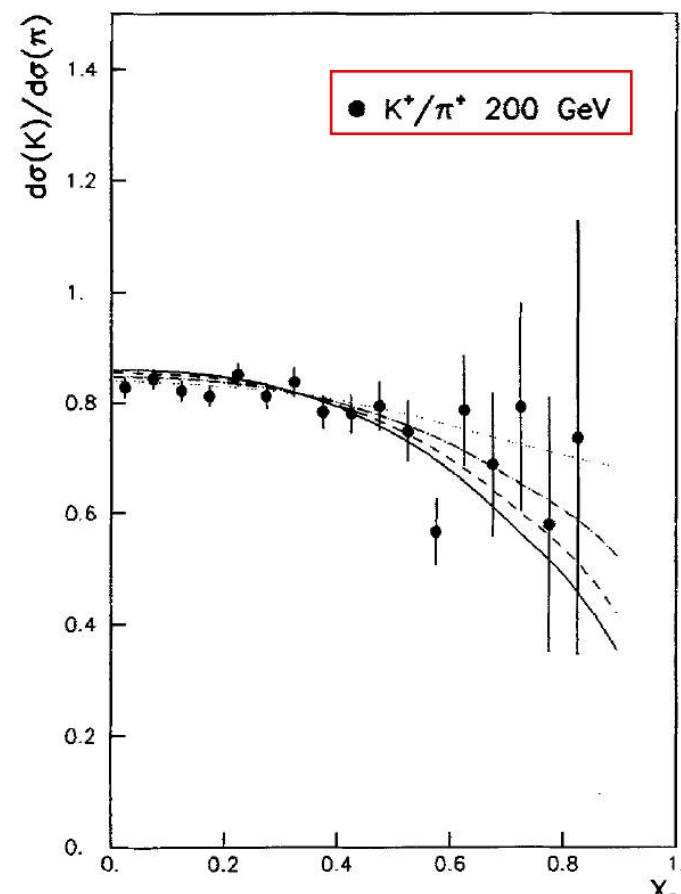
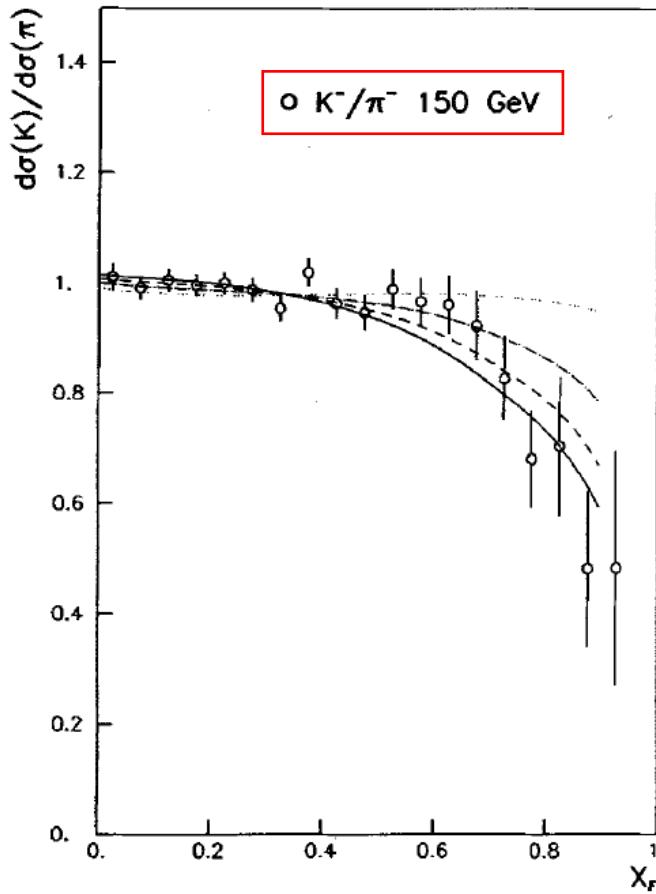
A slightly smaller kaon gluon distribution at large x , compared to the pion.

Kaon/Pion Jpsi Ratios

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

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

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

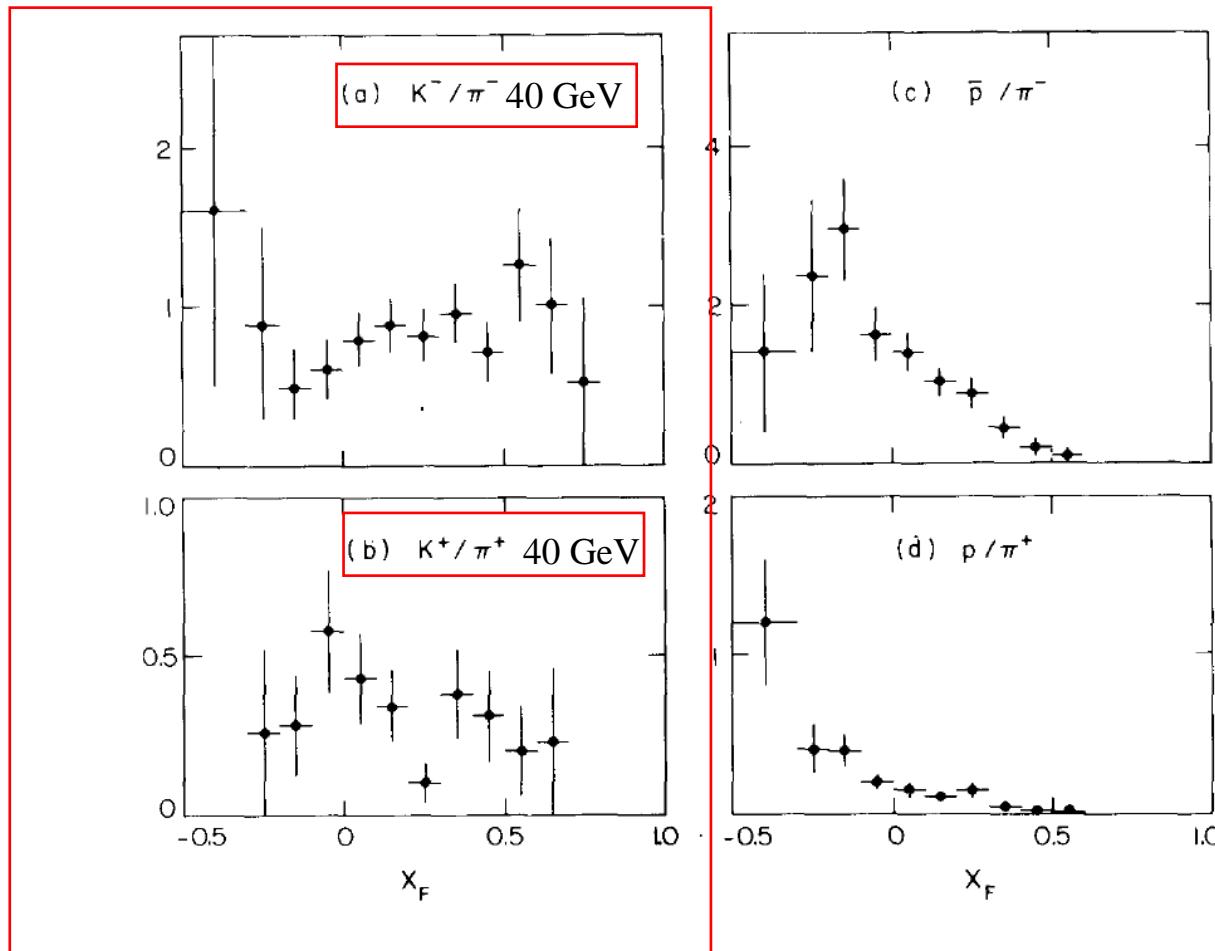


Kaon/Pion Jpsi Ratios

Phys. Lett. B 96, 411 (1980)

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

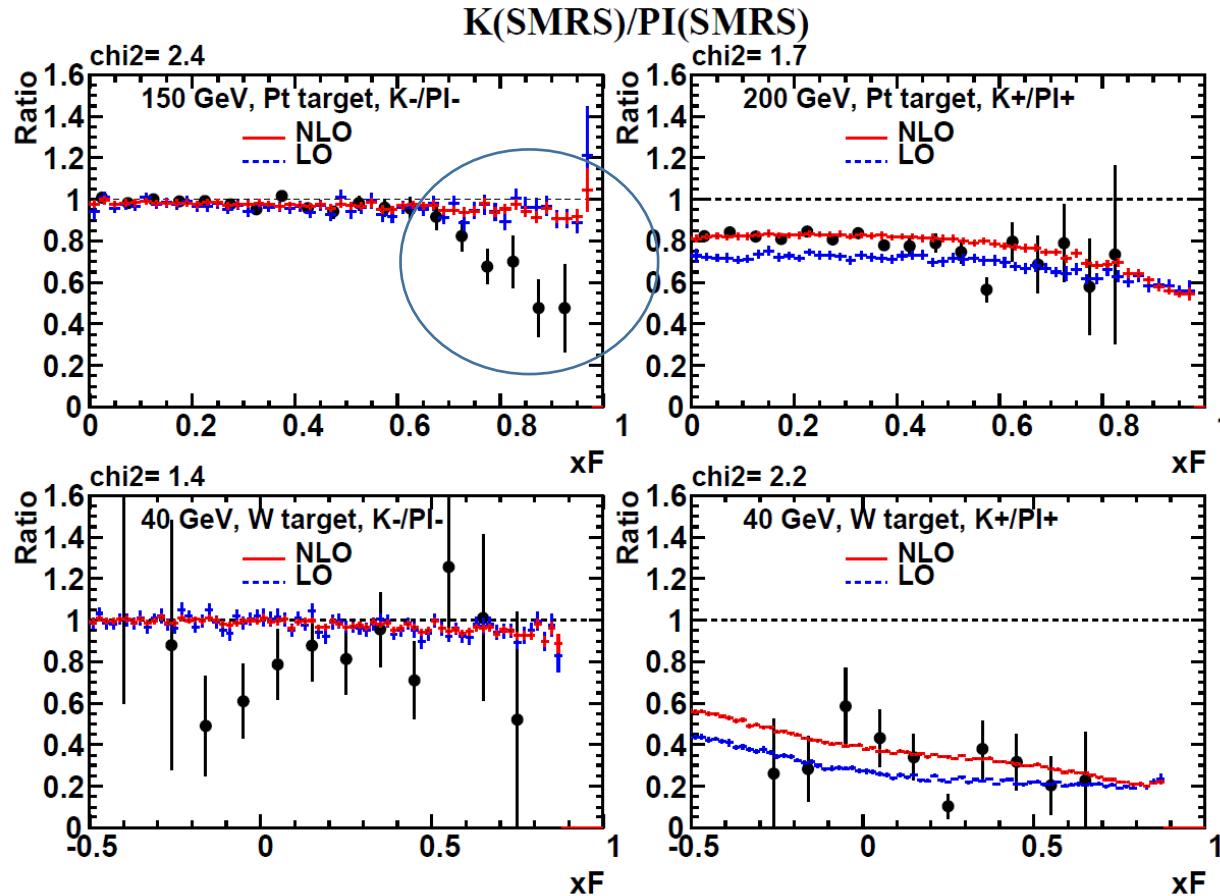
$$\frac{\sigma^{Jpsi}(K^+)}{\sigma^{Jpsi}(\pi^+)}(x_F) = \frac{\sigma(u^K(x_1)\bar{u}^N(x_2)) + \sigma(\bar{s}^K(x_1)s^N(x_2)) + \sigma(G^K(x_1)G^N(x_2))}{\sigma(u^\pi(x_1)\bar{u}^N(x_2)) + \sigma(\bar{d}^\pi(x_1)d^N(x_2)) + \sigma(G^\pi(x_1)G^N(x_2))}$$



CEM K/pi Ratios: SMRS

Kaon PDF: Pion PDF with $d \rightarrow s$

CEM NLO results agree with the data.



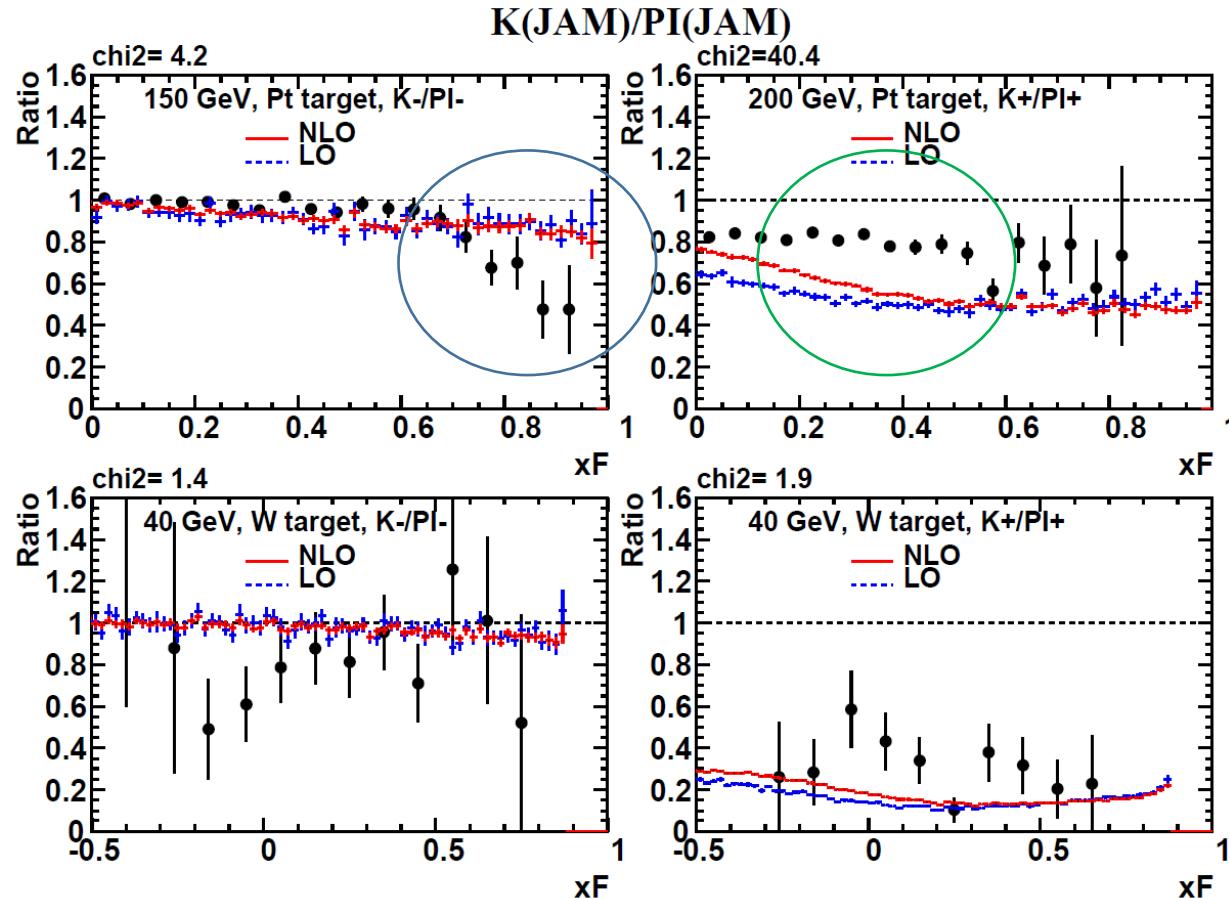
Color Evaporation Model (CEM)

W.C. Chang et al., Phys. Rev. D 102, 054024 (2020); arXiv: 2006.06947

CEM K/pi Ratios: JAM

Kaon PDF: Pion PDF with $d \rightarrow s$

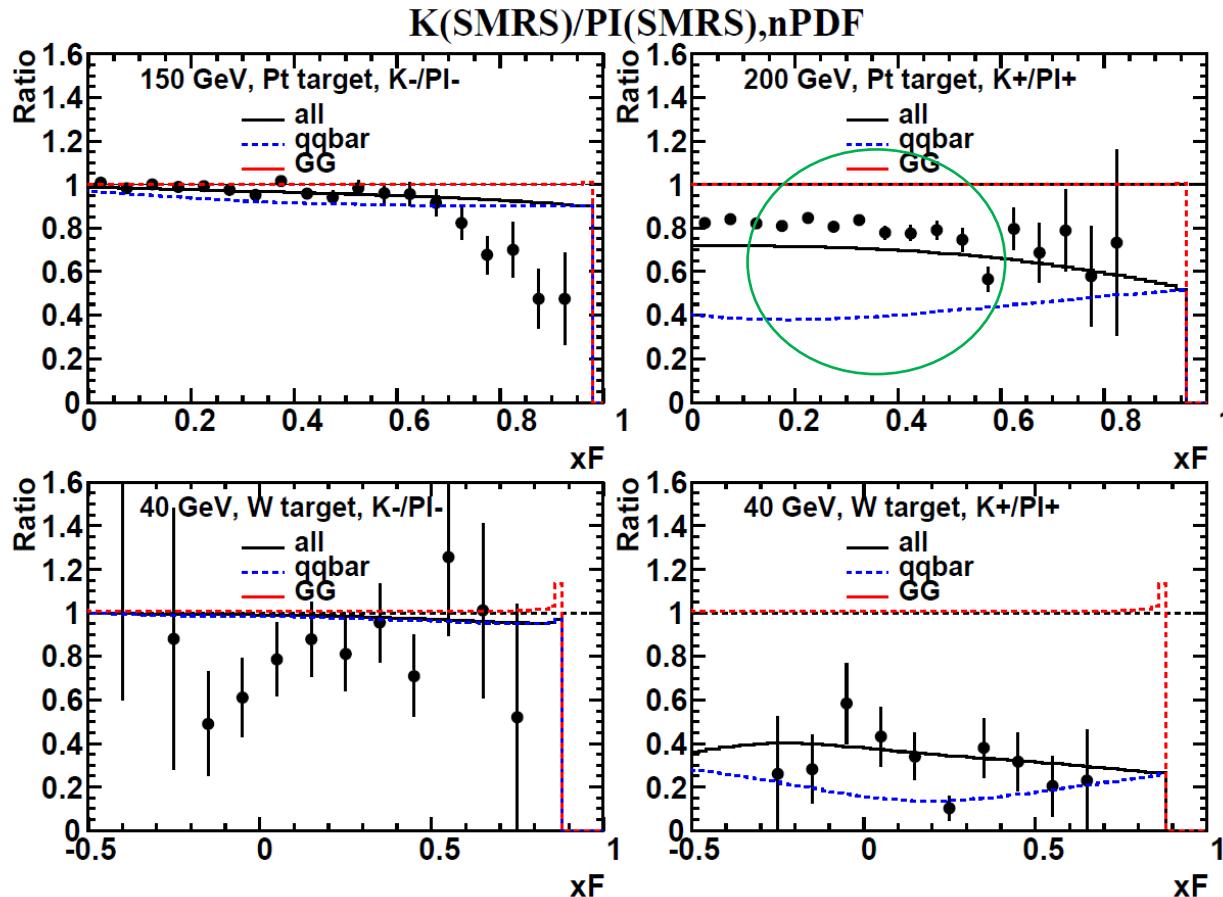
Data are under-estimated, due to weak gluon.



NRQCD K/pi Ratios: SMRS

Kaon PDF: Pion PDF with $d \rightarrow s$

Gluon strength in kaon is not large enough.



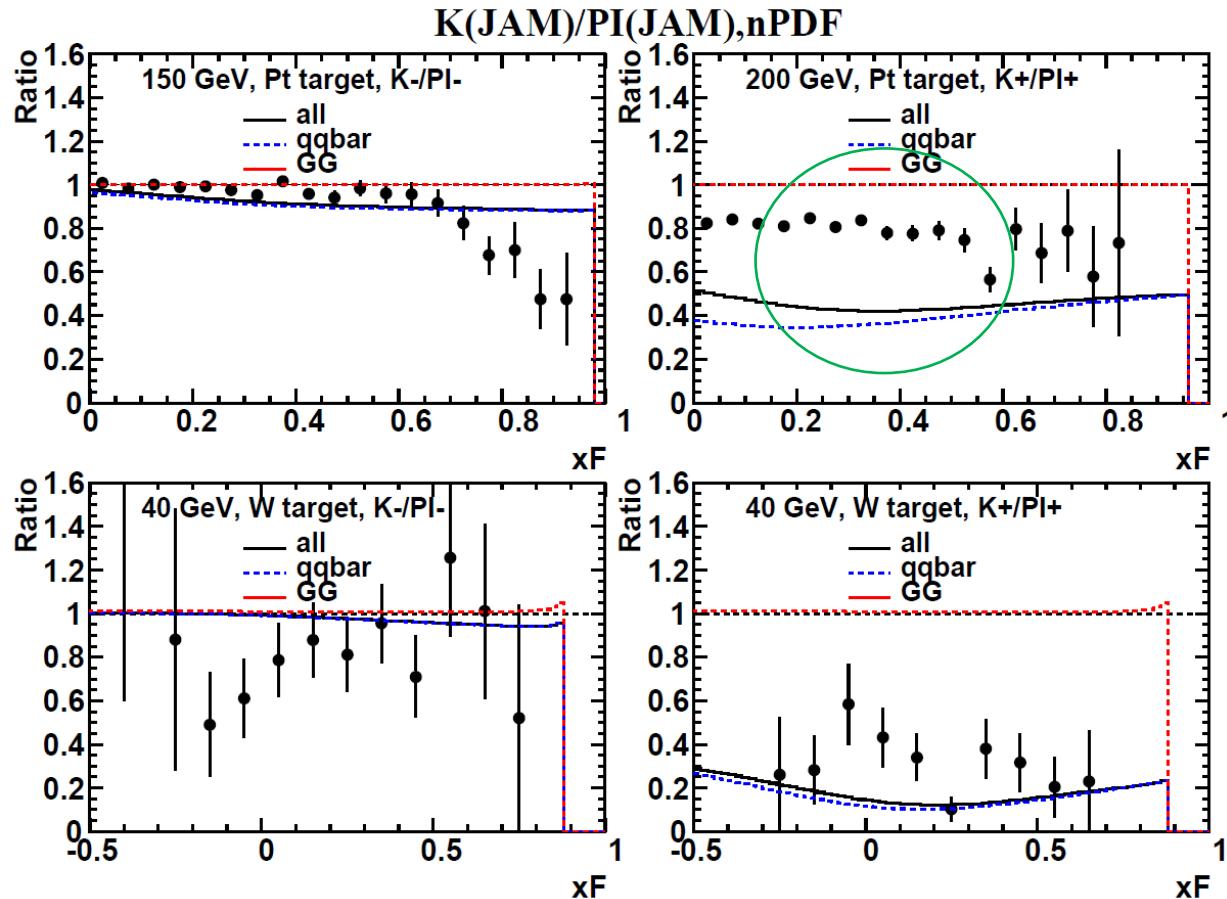
NRQCD

C.Y. Hsieh et al., Chinese Journal of Physics 73 (2021) 13

NRQCD K/pi Ratios: JAM

Kaon PDF: Pion PDF with d->s

Gluon strength in kaon is not large enough.



CERN: COMPASS++/AMBER

Year >2026

Unique opportunities with RF separated beam

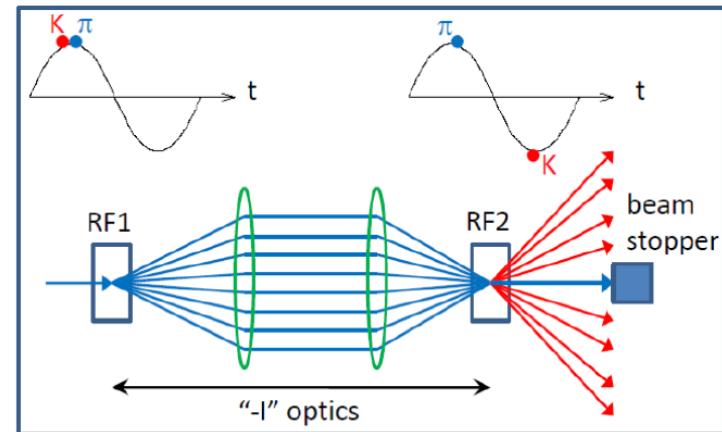
- Deflection with 2 cavities
- Relative phase = 0 → dump
- Deflection of wanted particle given by
$$\Delta\phi \approx \frac{\pi f L}{c} \frac{m_w^2 - m_u^2}{p^2}$$

To keep good separation:

L should increase as p^2 for a given $f \rightarrow$ limits the beam momentum

Initial expectations before further R&D:

~ 80 GeV Kaon beam
~ 110 GeV Anti-proton beam

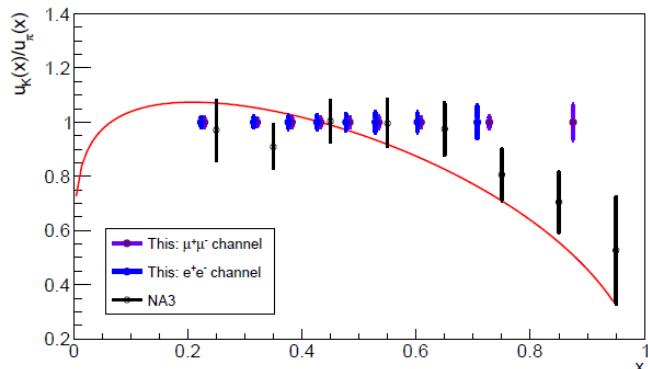


CERN: COMPASS++/AMBER

Year >2026

Projections for Kaon structure

140 days with $2 \times 10^7 \text{ s}^{-1}$ 100 GeV K^- beam:



Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+ \mu^-$
NA3	6 cm Pt	K^-		200	4.2 – 8.5	700
		K^-	2.1×10^7	80	4.0 – 8.5	25,000
				100	4.0 – 8.5	40,000
				120	4.0 – 8.5	54,000
This exp.	100 cm C					
		K^+	2.1×10^7	80	4.0 – 8.5	2,800
				100	4.0 – 8.5	5,200
				120	4.0 – 8.5	8,000
This exp.	100 cm C	π^-	4.8×10^7	80	4.0 – 8.5	65,500
				100	4.0 – 8.5	95,500
				120	4.0 – 8.5	123,600

π data taken simultaneously from beam impurity

Enlarge world data statistics by a factor 30

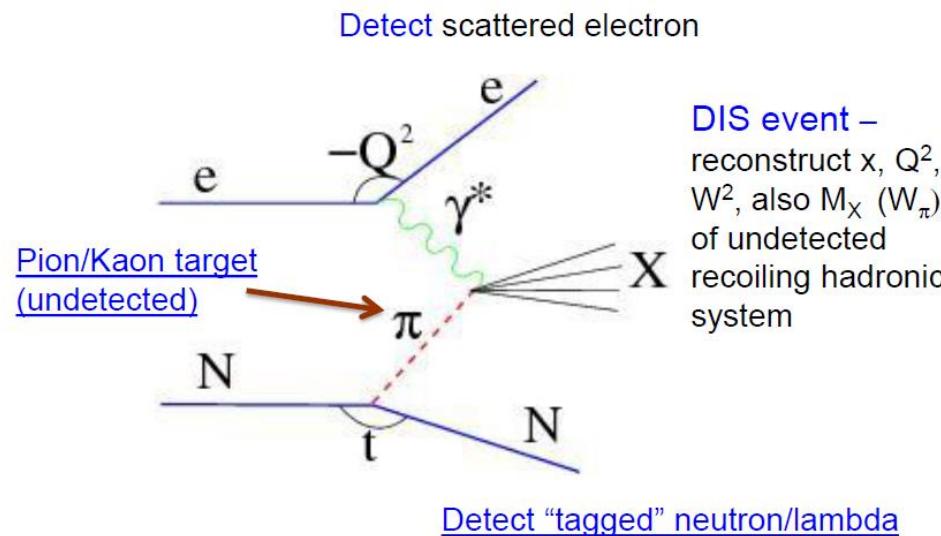
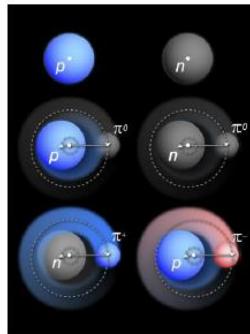
Determine u_K/u_π within a few percent

EIC: Tagged processes of DIS/Jpsi

Year >2030

Physics Objects for Pion/Kaon Structure Studies

- Sullivan process – scattering from nucleon-meson fluctuations



<https://indico.bnl.gov/event/8315/contributions/36990/attachments/28487/43882/CFNS-Pion-Kaon-Structure-Horn-nbk.pdf>

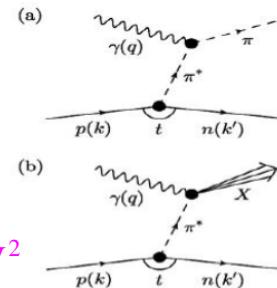
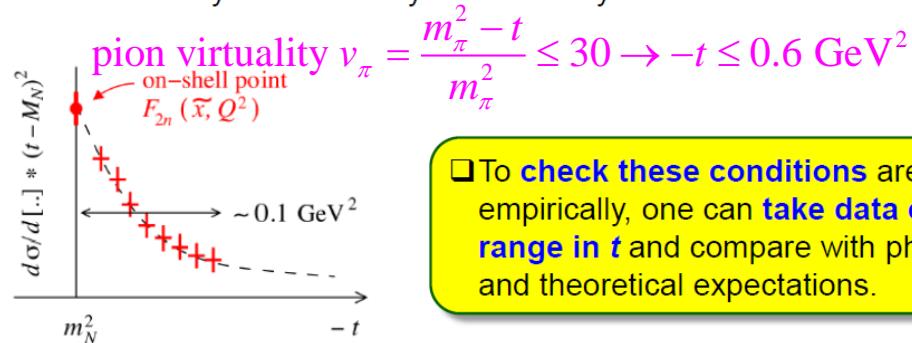
<https://arxiv.org/abs/1907.08218>

EIC: Sullivan Process

Year >2030

Pion and Kaon Sullivan Process

- The **Sullivan process** can provide reliable access to a **meson target** as t becomes space-like if the pole associated with the ground-state meson remains the dominant feature of the process and the structure of the related correlation evolves slowly and smoothly with virtuality.



To check these conditions are satisfied empirically, one can take data covering a range in t and compare with phenomenological and theoretical expectations.

- Recent **theoretical calculations** found that for $-t \leq 0.6 \text{ GeV}^2$, all changes in **pion structure are modest** so that a well-constrained experimental analysis should be reliable. Similar analysis for the kaon indicates that Sullivan processes can provide a valid kaon target for $-t \leq 0.9 \text{ GeV}^2$.

[S.-X. Qin, C. Chen, C. Mezrag and C. D. Roberts, Phys. Rev. C 97 (2018) 015203.]

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<https://indico.bnl.gov/event/8315/contributions/36990/attachments/28487/43882/CFNS-Pion-Kaon-Structure-Horn-nbk.pdf>

<https://arxiv.org/abs/1907.08218>

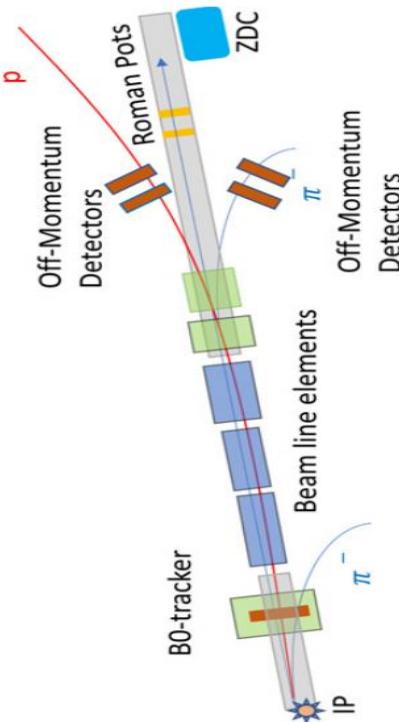
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EIC: Sullivan Process

Year >2030

Summary of Detector Requirements

Po-Ju Lin's talk



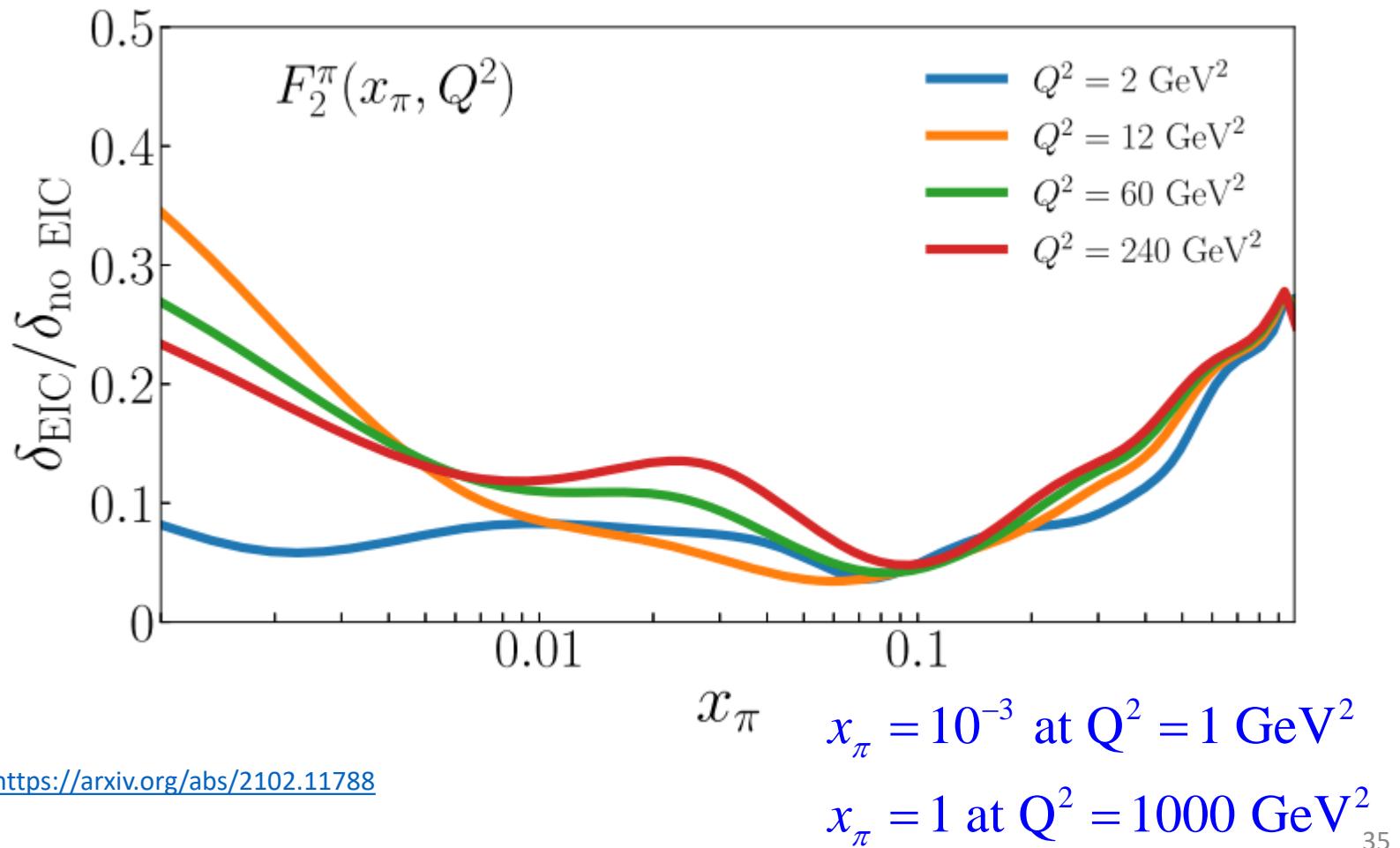
- For π -n:**
 - For all energies, the neutron detection efficiency is 100% with the planned ZDC
 - Lower energies (5 on 41, 5 on 100) require at least 60cm x 60cm to access wider range of energies
- For π -n and K^+/Λ :**
 - All energies need **good ZDC angular resolution** for the required -t resolution
 - High energies (10 on 100, 10 on 135, 18 on 275) require resolution of 1cm or better
- K^+/Λ benefits from low energies (5 on 41, 5 on 100) and also need:**
 - $\Lambda \rightarrow n + \pi^0$: additional high-res/granularity EMCal+tracking before ZDC – seems doable
 - $\Lambda \rightarrow p + \pi^-$: additional trackers in opposite direction on path to ZDC – more challenging
- Standard electron detection requirements
- Good hadron calorimetry for good x resolution at large x

<https://indico.bnl.gov/event/8315/contributions/36990/attachments/28487/43882/CFNS-Pion-Kaon-Structure-Horn-nbk.pdf>

<https://arxiv.org/abs/1907.08218> , <https://arxiv.org/abs/2102.11788>

EIC: Sullivan Process

Year >2030



Summary

- Light meson partonic structures are mostly determined by Drell-Yan process, supplemented by the other data of prompt-photon, charmonium production and the DIS Sullivan process.
- Lattice QCD makes significant progress in predicting the pion/kaon PDFs.
- Recent studies show that the large- x gluon strengths of modern xFitter and JAM pion PDFs seem too weak to describe both data sets of pion- and kaon-induced Jpsi production.
- Via the tagged-DIS, the EIC shall significantly improve our knowledge of pion/kaon PDFs. The far-forward detectors are essential for this measurement.