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Accessing pion's large-x gluon by fixed-target charmonium production

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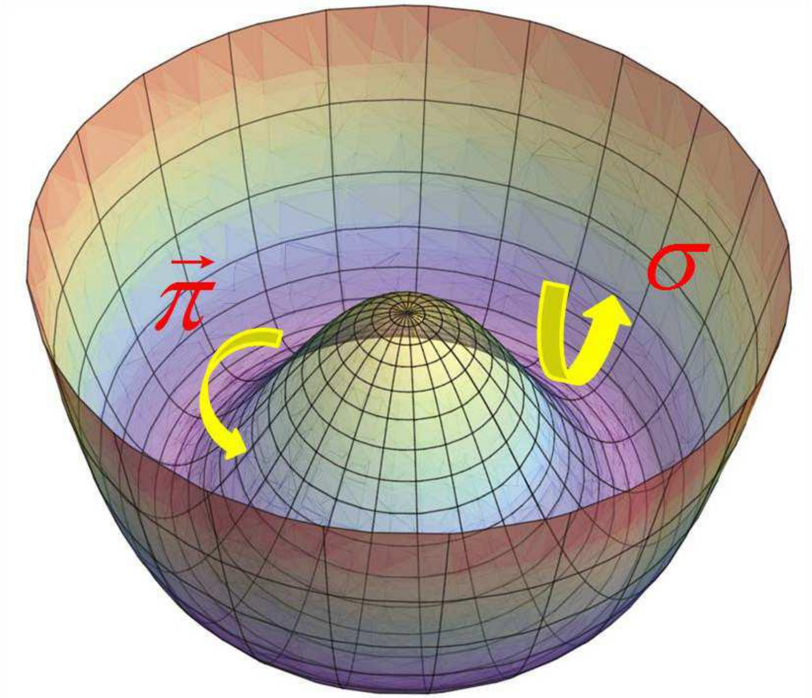
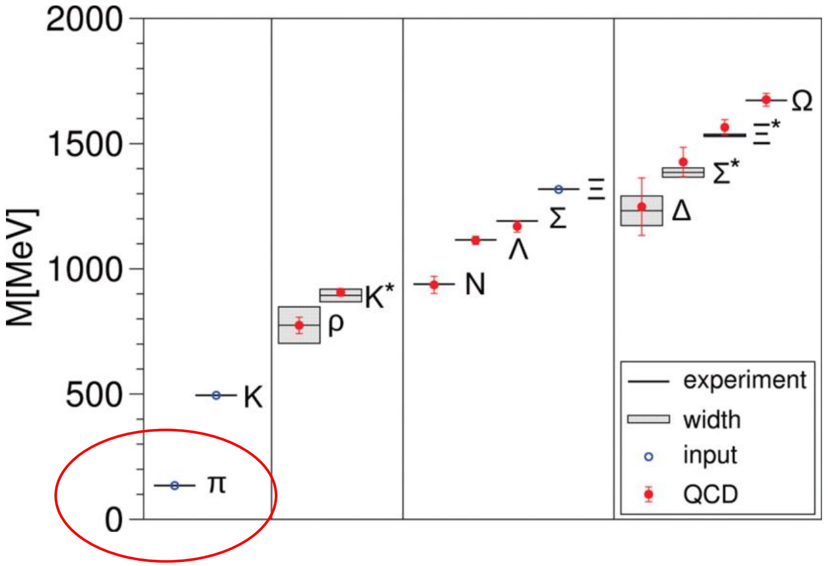
Pion

Nambu–Goldstone Boson of broken chiral symmetry of QCD



https://arxiv.org/pdf/1804.05664.pdf

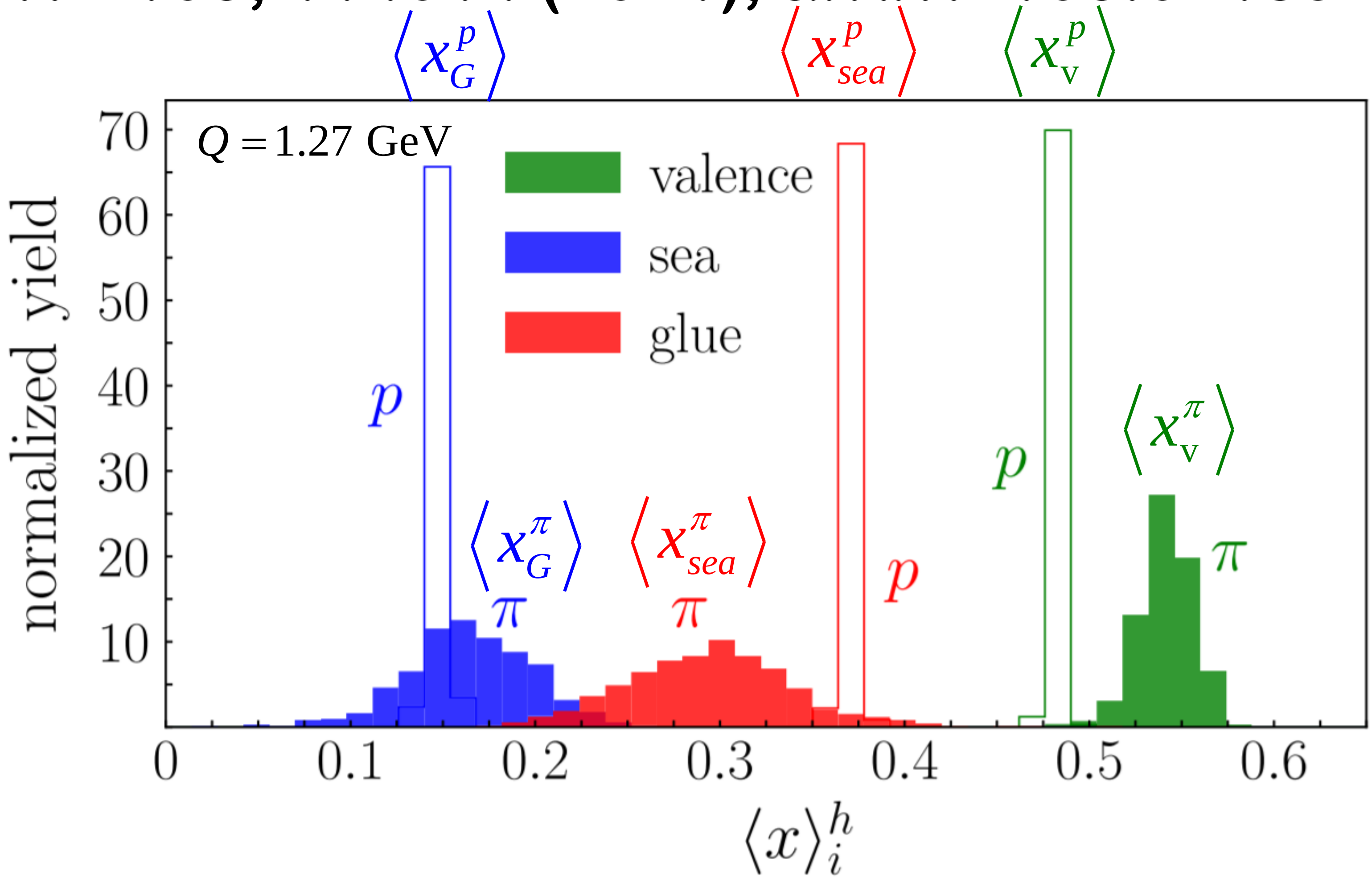
The lightest QCD bound state



http://arxiv.org/pdf/0906.3599v1.pdf

JAM21

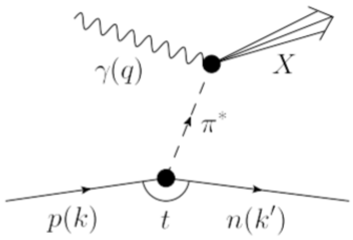
PRD 103, 114014 (2021); arXiv:2103.02159



Pion's PDFs are much less determined than proton's.

How to Access Pion

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

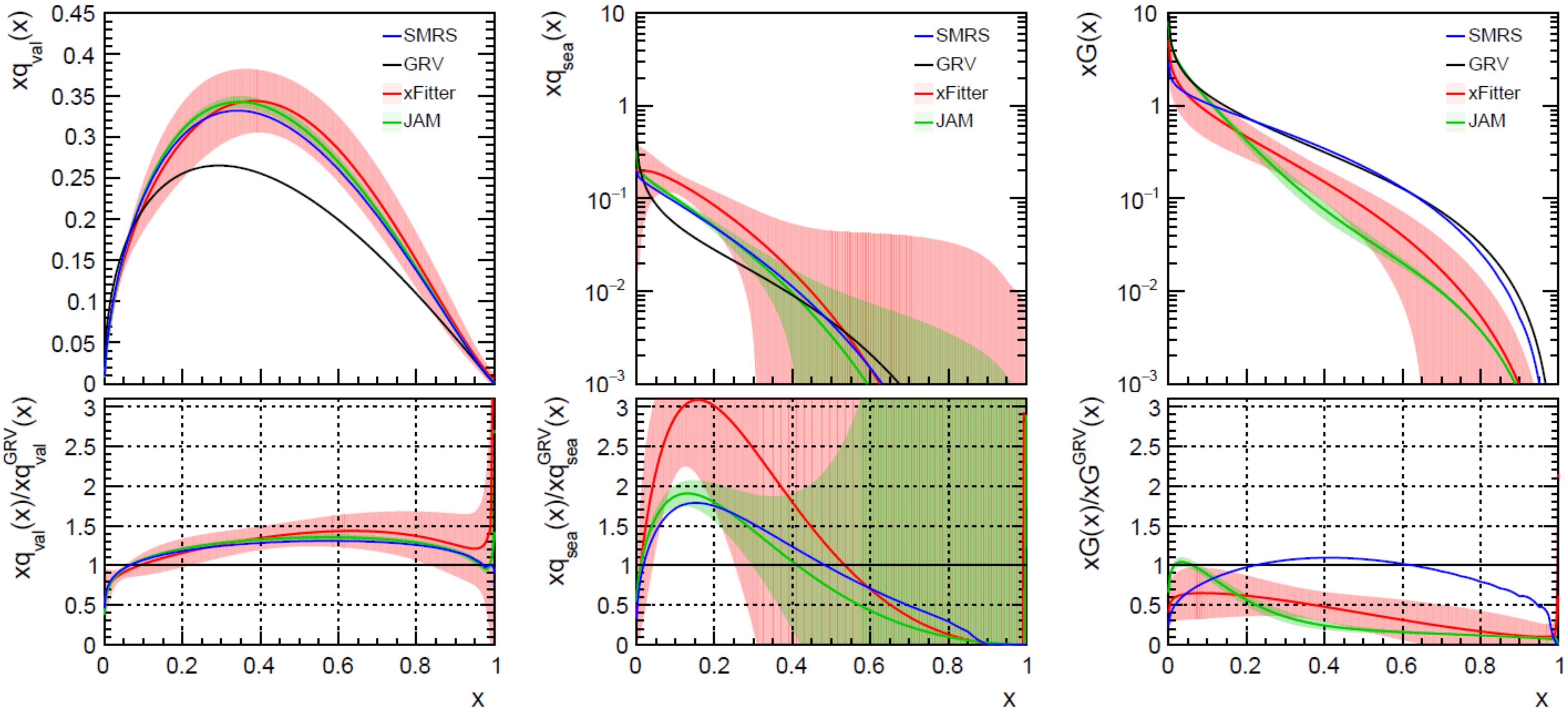


Pion PDFs (2021)

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	*				NPA 2019 PLB 2021
xFitter	*	*			PRD 2020
JAM21	*			*	PRD 2021 2108.05822

Pion PDFs

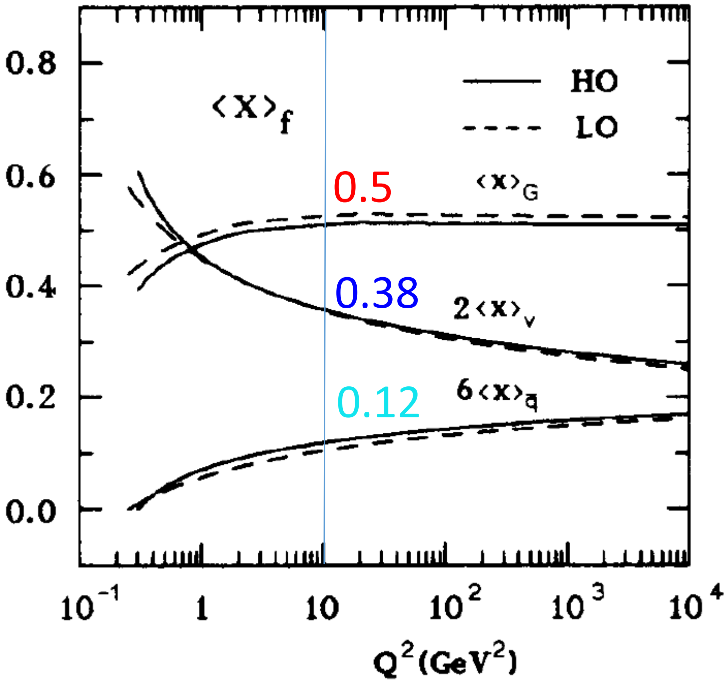
$$Q^2 = 9.6 \text{ GeV}^2$$



Large discrepancy of valence quark and gluon densities at x>0.1 is seen

GRV vs. JAM

GRV



JAM

data sets	$\mu^2 = 10$ GeV^2		
	$\langle x \rangle_v^\pi$	$\langle x \rangle_s^\pi$	$\langle x \rangle_g^\pi$
DY	0.49(1)	0.26(8)	0.25(8)
DY+LN	0.43(2)	0.17(3)	0.40(4)
DY+LN+DYp_T	**0.44(1)**	**0.19(2)**	**0.37(3)**

The hierarchy of <x> of valence quark and gluon is opposite in GRV and JAM.

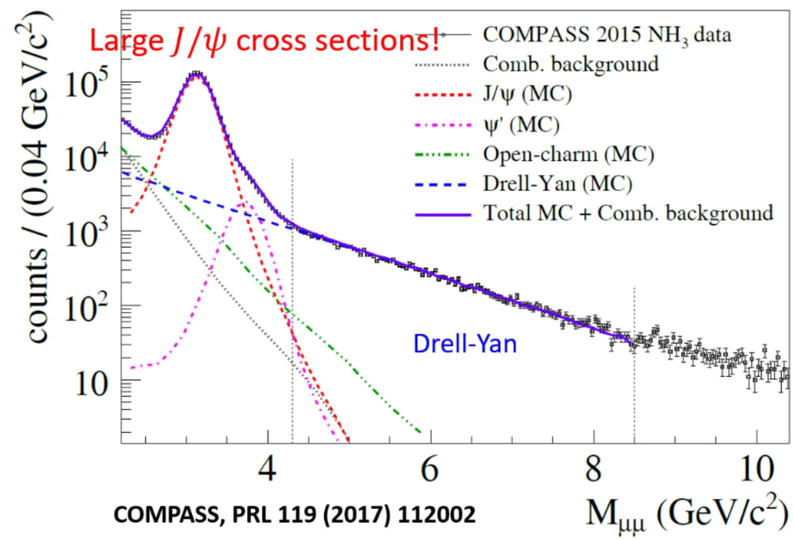
Lattice QCD [2109.10692]

$$Q^2 = 4.0 \text{ GeV}^2$$

	this work	[20]	JAM [44]	xFitter [45]
$\langle x \rangle_l^R$	$0.601(28)(_{-21})$	–	–	–
$\langle x \rangle_s^R$	$0.059(13)(_{-10})$	–	–	–
$\langle x \rangle_c^R$	$0.019(05)(_{-10})$	–	–	–
$\langle x \rangle_g^R$	$0.52(11)(^{+02})$	–	0.42(4)	0.25(13)
$\sum_f \langle x \rangle_f^R$	$0.68(05)(_{-03})$	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)	–	–	–

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

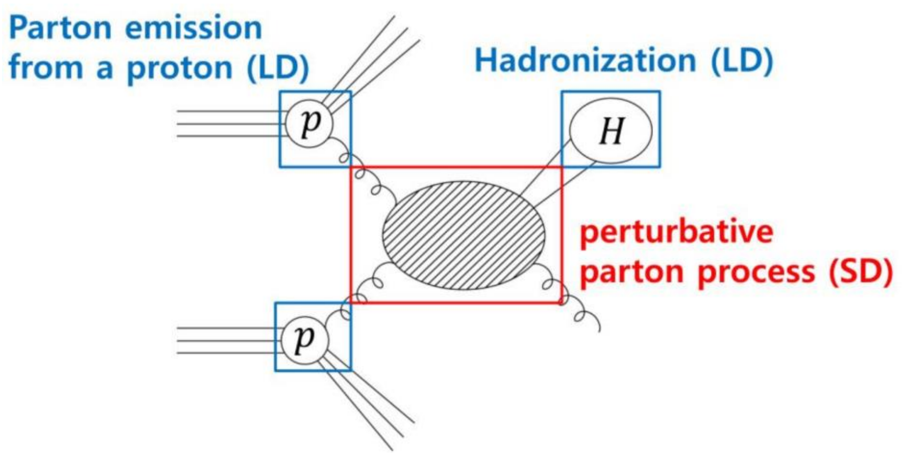
Paper	Reference	Year	Collab	E (GeV)	sqrt(s) (GeV)	Beam	Targets
Fermilab							
Branson	PRL 23, 1331	1977	Princ-Chicago	225	20.5	π-, π+, p	C, Sn
Anderson	PRL 42, 944	1979	E444	225	20.5	π-, π+, K+, p, ap	C, Cu, W
Abramov	Fermi 91-062-E	1991	E672/E706	530	31.5	π-	Be
Kartik	PRD 41, 1	1990	E672	530	31.5	π-	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



COMPASS, PRL 119 (2017) 112002

Model Dependence of $c\bar{c}$ pair Hadronizing

- **Color singlet model (CSM)**: only pairs with matched quantum number of the charmonium.
- **Color evaporation model (CEM)**: all pairs with mass less than $D\bar{D}$ threshold. One hadronization parameter for each type of charmonium.
- **Non-relativistic QCD model (NRQCD)**: all pairs of different color and spin sates fragmenting with different probabilities – long-distance matrix elements (LDMEs).



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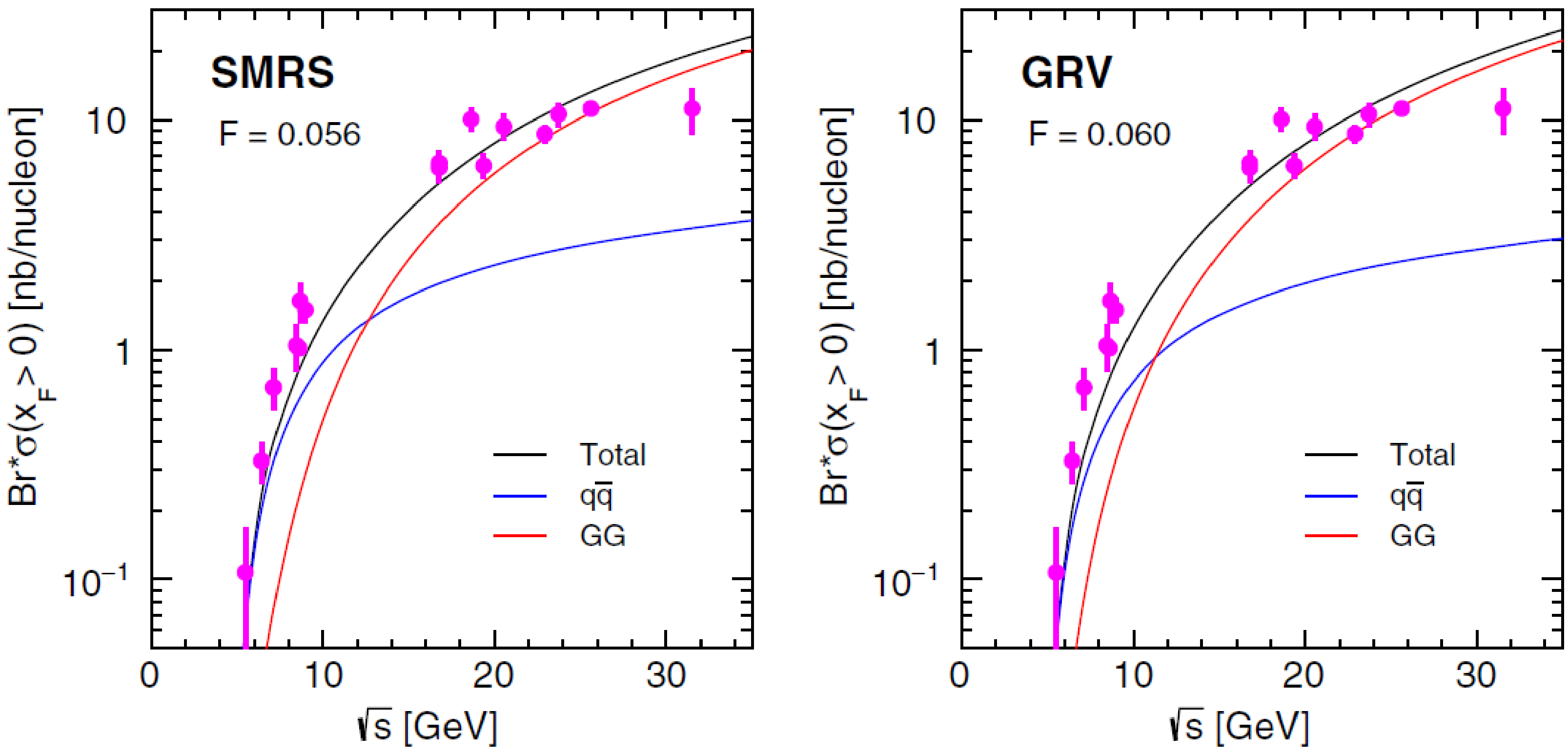
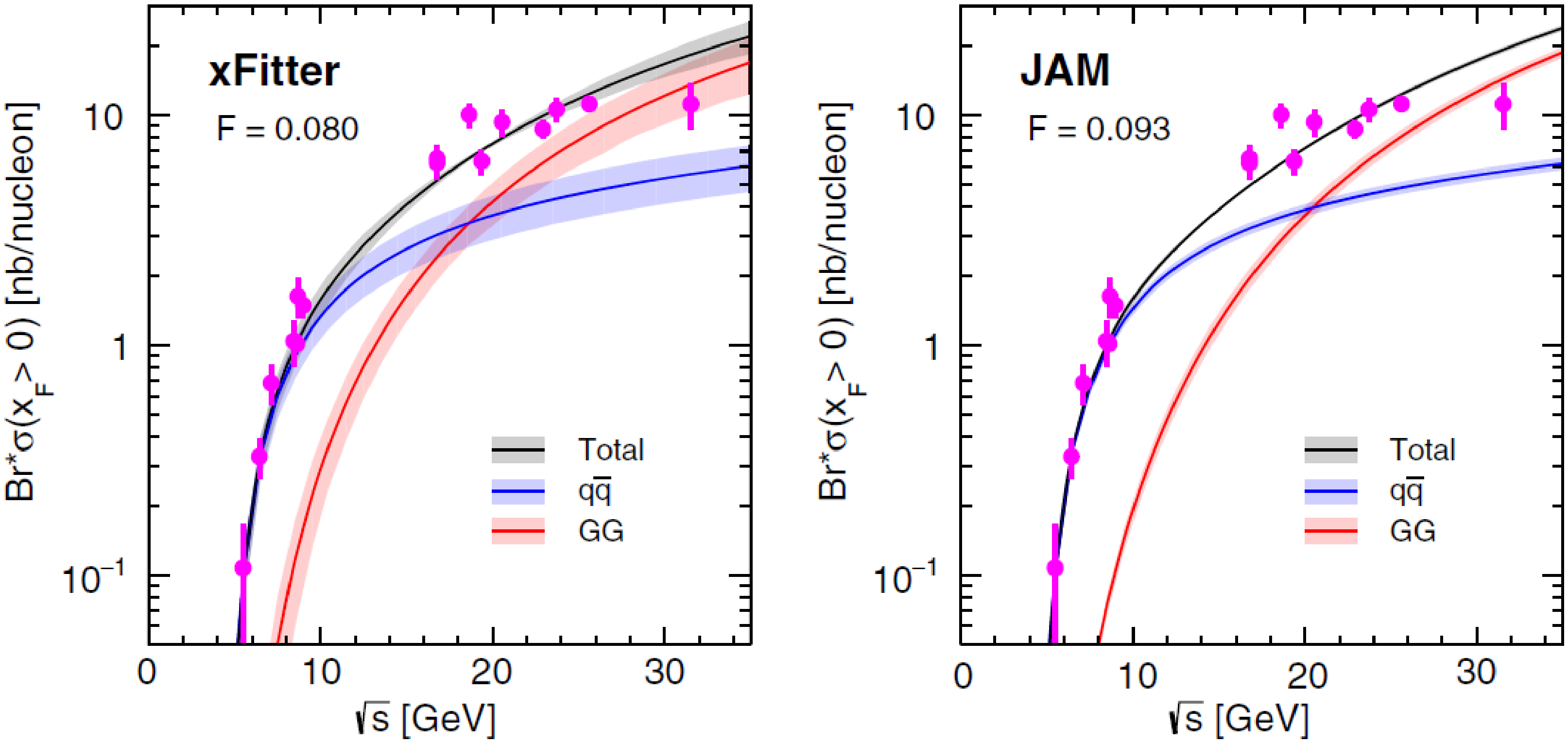
The gluon distributions of the pion obtained from various global fits exhibit large variations among them. Within the framework of the color evaporation model, we show that the existing pion-induced J/ψ

Data vs. NLO CEM
: Energy dependence



GG dominates at high energies, while $q\bar{q}$ is important near threshold.

Data vs. NLO CEM
: Energy dependence



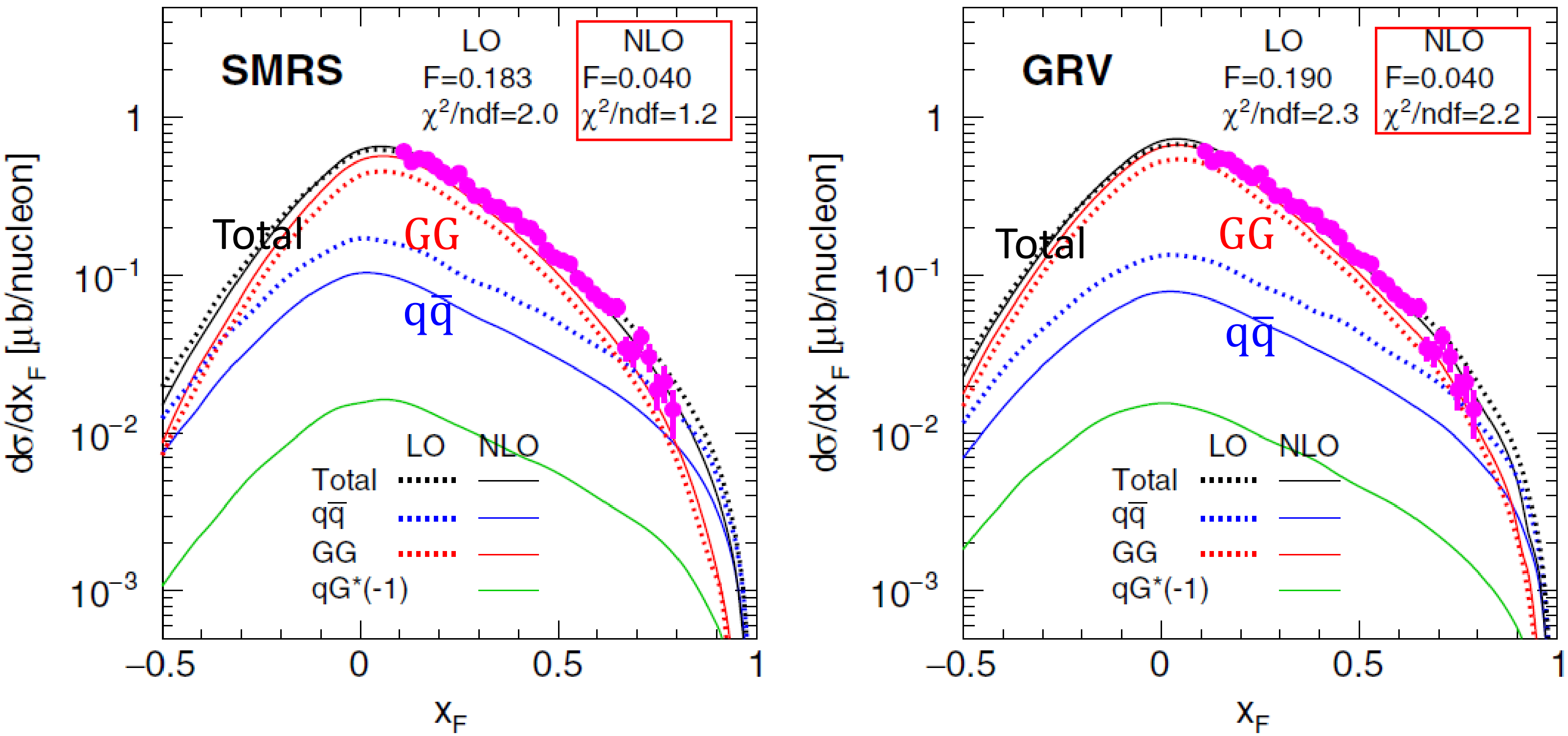
GG dominates at high energies, while $q\bar{q}$ is important near threshold.

Data vs. CEM LO/NLO

[$\pi^- + Be \rightarrow Jpsi + X$ at 515 GeV]

m_c=1.5 GeV, μ_F=2m_c, μ_R=m_c,
Hadronization parameter F determined by the fit.

Data from PRD 53, 4723 (1996)



The GG contribution dominates except at very forward or backward directions.
The weighting of GG contribution is enhanced in the NLO calculations.

Data vs. CEM LO/NLO

[$\pi^- + Be \to Jpsi + X$ at 515 GeV]

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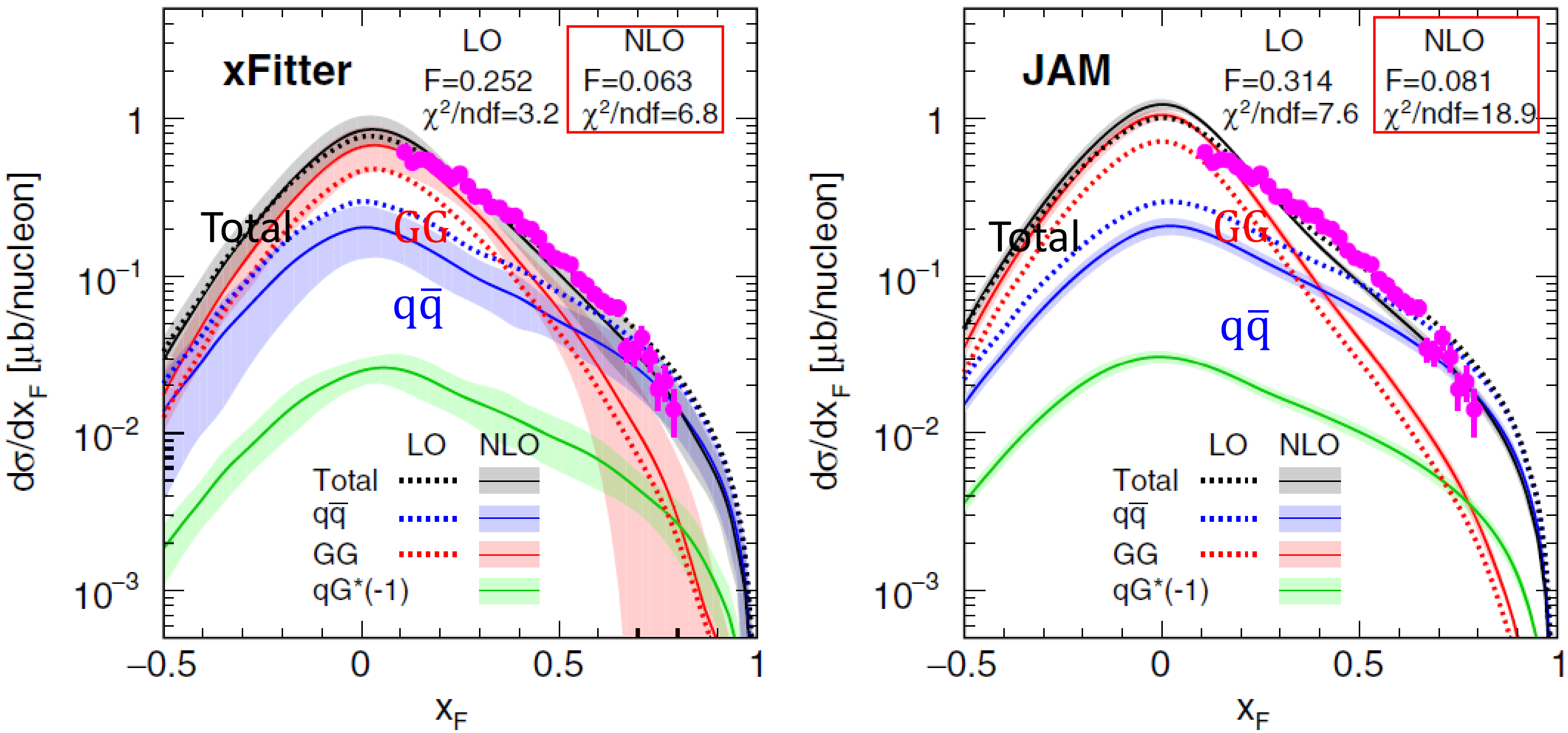


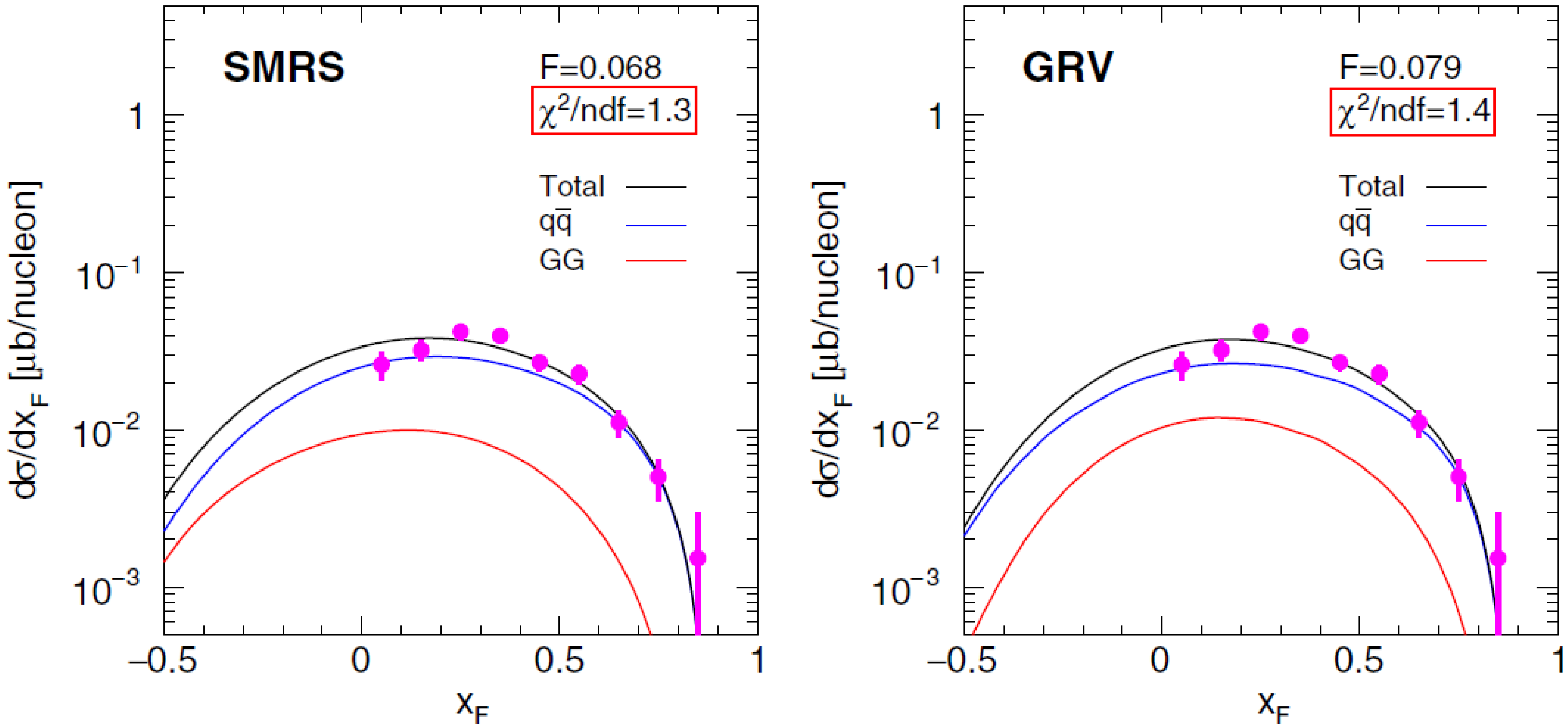
The GG contribution dominates except at very forward or backward directions.
The weighting of GG contribution is enhanced in the NLO calculations.

Data vs. NLO CEM

[$\pi^- + p \to Jpsi + X$ at 39.5 GeV]

m_c=1.5 GeV, μ_F=2m_c, μ_R=m_c,
Hadronization parameter F determined by the fit.

Data from PLB 98, 220 (1981)

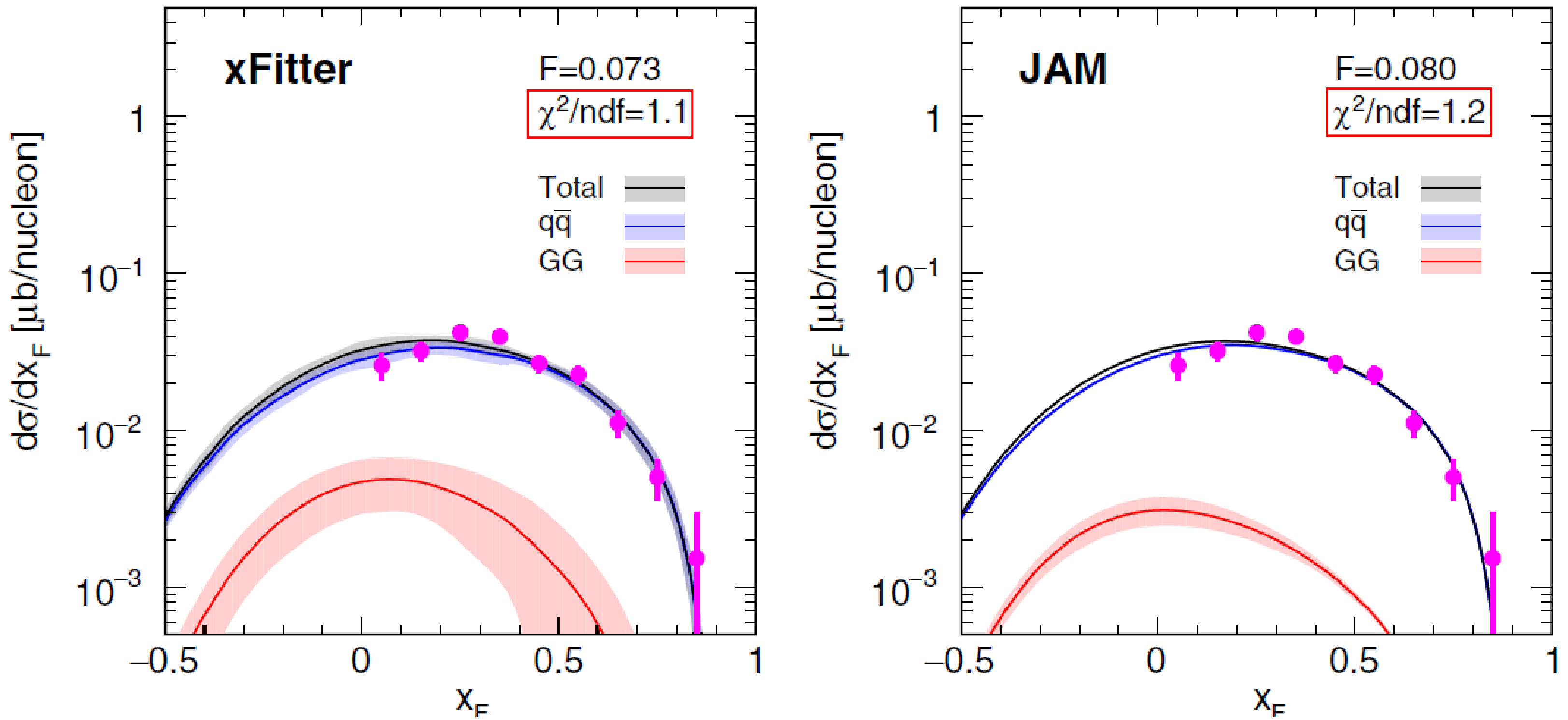


Calculations of all four PDFs describe the data well.

Data vs. NLO CEM

[$\pi^- + p \rightarrow Jpsi + X$ at 39.5 GeV]

Data from PLB 98, 220 (1981)



Calculations of all four PDFs describe the data well.

Data vs. CEM Calculations

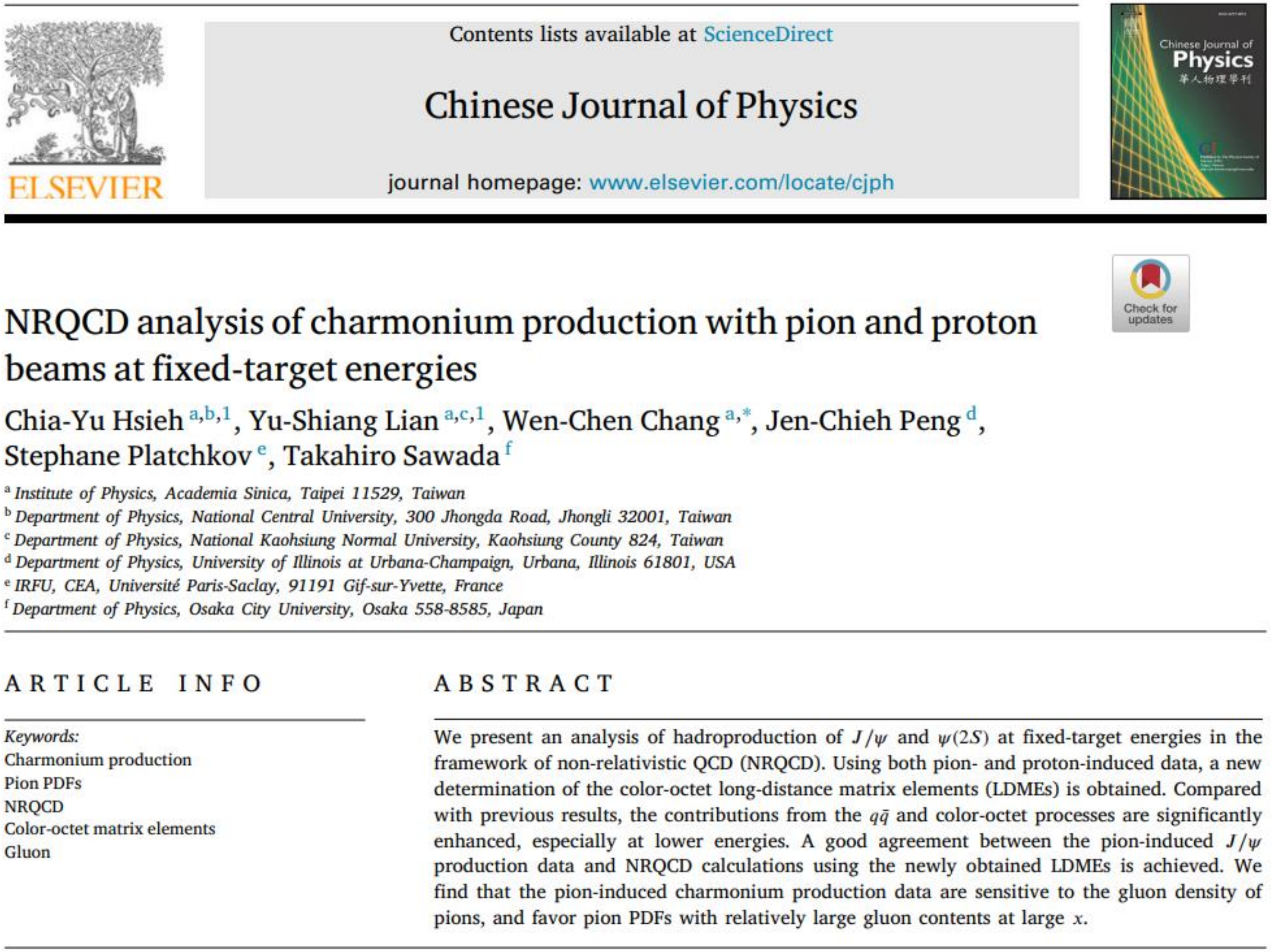
TABLE III. Results of F factor and χ^2/ndf value of the best fit of the NLO CEM calculations for SMRS, GRV, xFitter, and JAM pion PDFs to the data listed in Table II. The F^* factor and χ^2/ndf^* are the ones corresponding to the fit with inclusion of PDF uncertainties for xFitter and JAM.

Data	SMRS		GRV		xFitter				JAM			
Experiment (P_{beam})	F	χ^2/ndf	F	χ^2/ndf	F	F^*	χ^2/ndf	χ^2/ndf^*	F	F^*	χ^2/ndf	χ^2/ndf^*
E672, E706 (515)	0.040	1.2	0.040	2.2	0.063	0.063	6.8	4.7	0.081	0.081	18.9	18.5
E705 (300)	0.052	2.3	0.053	1.9	0.073	0.076	3.2	1.3	0.086	0.086	16.1	15.9
NA3 (280)	0.046	1.5	0.049	2.0	0.067	0.069	5.0	3.2	0.081	0.081	10.4	10.3
NA3 (200)	0.046	2.1	0.050	2.2	0.065	0.066	5.0	1.3	0.081	0.081	7.7	7.6
WA11 (190)	0.054	5.0	0.058	7.2	0.078	0.076	19.4	6.2	0.091	0.091	73.7	72.9
NA3 (150)	0.065	1.1	0.071	1.0	0.089	0.091	2.6	1.6	0.108	0.108	3.9	3.8
E537 (125)	0.044	1.5	0.049	1.5	0.065	0.065	3.1	1.4	0.083	0.083	3.5	3.5
WA39 (39.5)	0.068	1.3	0.079	1.4	0.073	0.072	1.1	0.8	0.080	0.080	1.2	1.2

- The hadronization F factor is stable across energy.
- High-energy J/ψ data have a large sensitivity to the large-x gluon density of pions.
- The valence-quark distributions plays a minor role if away from the threshold.
- **CEM NLO calculations favor SMRS and GRV PDFs whose gluon densities at x > 0.1 are higher, compared with xFitter and JAM PDFs.**

Are these observations model dependent?

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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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.

(LO) NRQCD Framework
PRD 54, 2005 (1996)

PHYSICAL REVIEW D VOLUME 54, NUMBER 3 1 AUGUST 1996

Hadroproduction of quarkonium in fixed-target experiments

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(Received 25 March 1996)

We analyze charmonium and bottomonium production at fixed-target experiments. We find that the inclusion of color octet production channels removes large discrepancies between experiment and the predictions of the color singlet model for the total production cross section. Furthermore, including octet contributions accounts for the observed direct to total J/ψ production ratio. As found earlier for photoproduction of quarkonia, a fit to fixed-target data requires smaller color octet matrix elements than those extracted from high-p_t production at the Fermilab Tevatron. We argue that this difference can be explained by systematic differences in the velocity expansion for collider and fixed-target predictions. While the color octet mechanism thus appears to be an essential part of a satisfactory description of fixed-target data, important discrepancies remain for the χ_{c1}/χ_{c2} production ratio and J/ψ (ψ') polarization. These discrepancies, as well as the differences between pion- and proton-induced collisions, emphasize the need for including higher twist effects in addition to the color octet mechanism. [S0556-2821(96)05515-4]

PACS number(s): 13.85.Ni, 13.88.+e, 14.40.Gx

Long-Distance Matrix Elements (LDMEs) PRD 54, 2005 (1996)

$\left\langle O_{1,8}^{H}\left[{}^{2S+1}L_J\right]\right\rangle$

H	$q\bar{q}$	GG	qG
$J/\psi,\ \psi(2S)$	$\langle \mathcal{O}_8^H[{}^3S_1]\rangle\ (\mathcal{O}(\alpha_s^2))$	Δ_8^H [a] $(\mathcal{O}(\alpha_s^2))$	
		$\langle \mathcal{O}_1^H[{}^3S_1]\rangle\ (\mathcal{O}(\alpha_s^3))$	
χ_{c0}	$\langle \mathcal{O}_8^H[{}^3S_1]\rangle\ (\mathcal{O}(\alpha_s^2))$	$\langle \mathcal{O}_1^H[{}^3P_0]\rangle\ (\mathcal{O}(\alpha_s^2))$	
χ_{c1}	$\langle \mathcal{O}_8^H[{}^3S_1]\rangle\ (\mathcal{O}(\alpha_s^2))$	$\langle \mathcal{O}_1^H[{}^3P_1]\rangle\ (\mathcal{O}(\alpha_s^3))$	$\langle \mathcal{O}_1^H[{}^3P_1]\rangle\ (\mathcal{O}(\alpha_s^3))$
χ_{c2}	$\langle \mathcal{O}_8^H[{}^3S_1]\rangle\ (\mathcal{O}(\alpha_s^2))$	$\langle \mathcal{O}_1^H[{}^3P_2]\rangle\ (\mathcal{O}(\alpha_s^2))$	

[a] $\Delta_8^H = \langle \mathcal{O}_8^H[{}^1S_0]\rangle + \frac{3}{m_c^2}\langle \mathcal{O}_8^H[{}^3P_0]\rangle + \frac{4}{5m_c^2}\langle \mathcal{O}_8^H[{}^3P_2]\rangle$.

Determined by fit of proton-induced data

H	$\langle \mathcal{O}_1^H[{}^3S_1]\rangle$	$\langle \mathcal{O}_1^H[{}^3P_0]\rangle/m_c{}^2$	$\langle \mathcal{O}_8^H[{}^3S_1]\rangle$	Δ_8^H
J/ψ	1.16		6.6×10^{-3}	3×10^{-2}
$\psi(2S)$	0.76		4.6×10^{-3}	5.2×10^{-3}
χ_{c0}		0.044	3.2×10^{-3}	

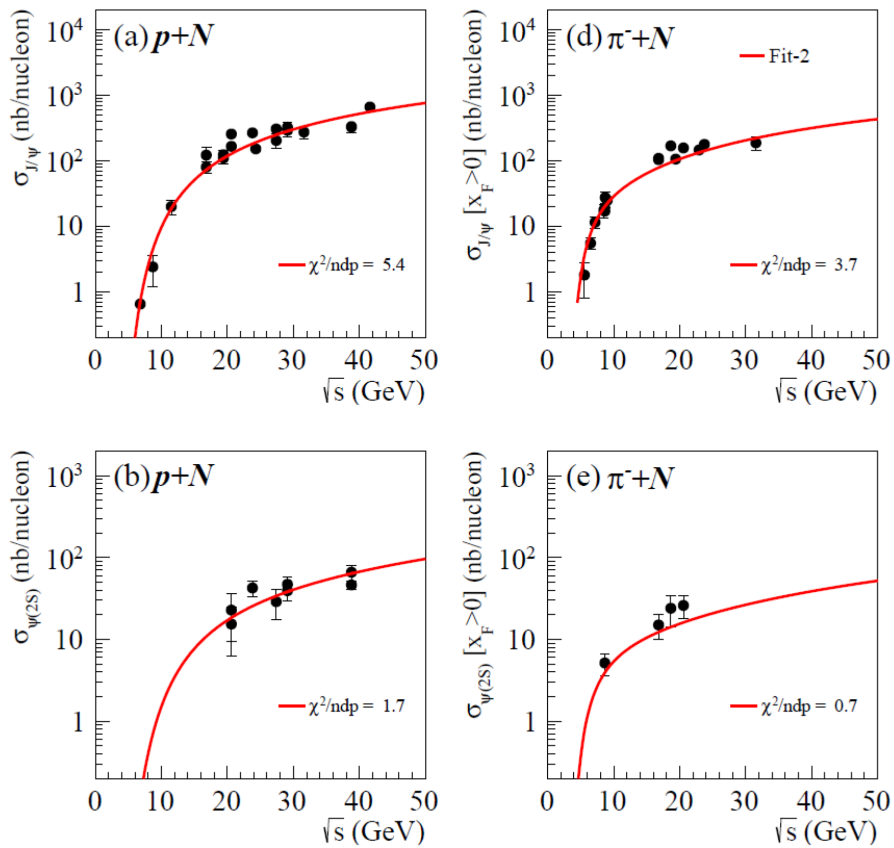
color-singlet (CS) LDMEs

color-octet (CO) LDMEs

$$\sigma_{J/\psi} = \sigma_{J/\psi}^{direct} + Br(\psi(2S)\to J/\psi X)\sigma_{\psi(2S)} + \sum_{J=0}^{2} Br(\chi_{cJ}\to J/\psi\gamma)\sigma_{\chi_{cJ}}$$

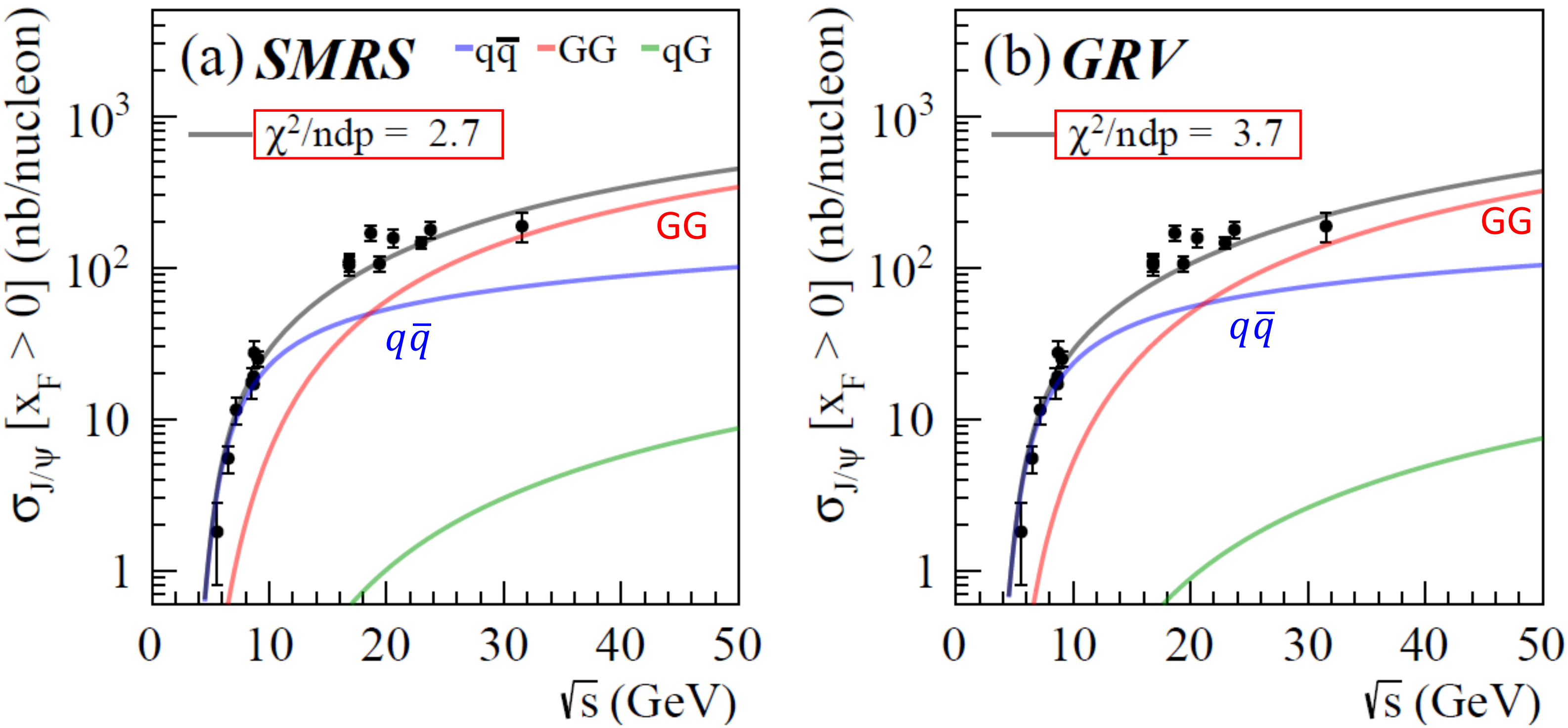
Jpsi and psi’: Data vs. NRQCD

Best-fitted CO [3S1] and [1S0] LDMEs by p+N Jpsi/psi’ and π^-+N Jpsi/psi’ data.

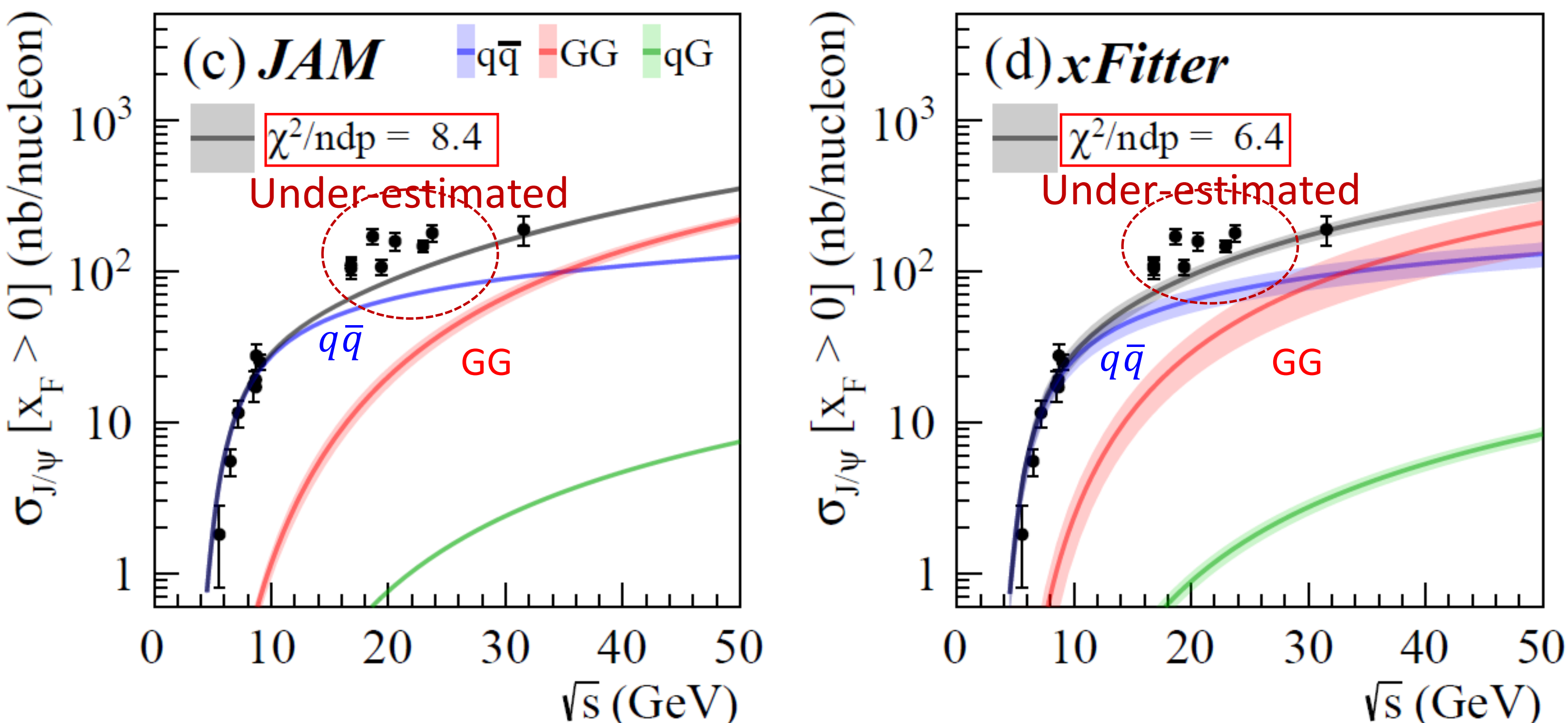


$\langle \mathcal{O}_8^{J/\psi}[^3S_1]\rangle$	6.6×10^{-3}	$(1.47 \pm 0.07) \times 10^{-1}$	$(9.5 \pm 0.4) \times 10^{-2}$
$\langle \mathcal{O}_8^{J/\psi}[^1S_0]\rangle^*$	3.75×10^{-3}	$(0 \pm 1) \times 10^{-4}$	$(2.2 \pm 0.3) \times 10^{-3}$
$\langle \mathcal{O}_8^{\psi(2S)}[^3S_1]\rangle$	4.6×10^{-3}	$(2.5 \pm 0.2) \times 10^{-2}$	$(2.6 \pm 0.2) \times 10^{-2}$
$\langle \mathcal{O}_8^{\psi(2S)}[^1S_0]\rangle^*$	6.5×10^{-4}	$(0 \pm 1) \times 10^{-4}$	$(5 \pm 8) \times 10^{-5}$

π^-+N→Jpsi+X: pion PDFs



π^-+N→Jpsi+X: pion PDFs

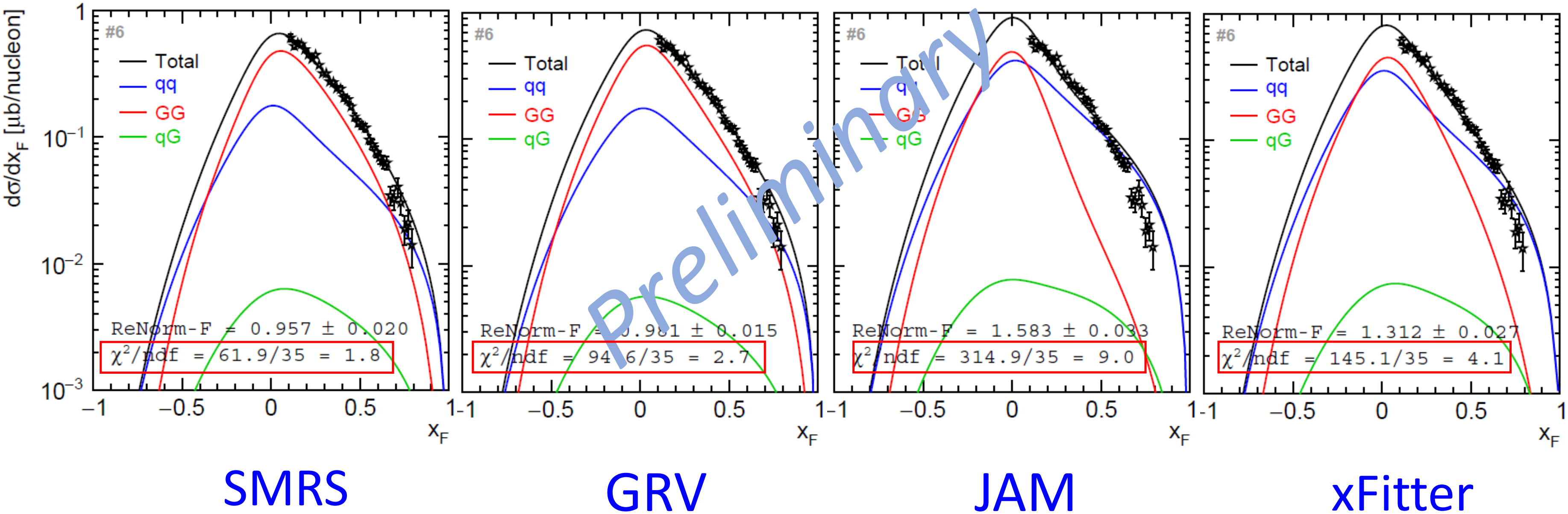


The dependence of best-fit LDMEs to the pion PDFs is mild.
The deficiency of JAM and xFitter in the GG contributions generates a relatively larger χ^2 in the description of total cross section data.

Data vs. NRQCD

[$\pi^- + Be \rightarrow Jpsi + X$ at 515 GeV]

Data from PRD 53, 4723 (1996)



SMRS & GRV provide a better description of data than JAM and xFitter.

Summary

- The pion PDFs were determined by the Drell-Yan, direct photon, J/psi and recently leading-neutron data. Nevertheless discrepancy of valence quark and gluon densities at x>0.1 is seen.
- Within CEM and NRQCD, the high-energy J/psi data are shown to be sensitive to the pion gluon distribution. The current data favor the SMRS and GRV pion PDFs, containing relatively stronger gluon strengths at large x.
- Despite the uncertainty of charmonium fragmentation, it is important to include J/psi data in new global analyses of pions, for better determining the gluons.