Constraining pion PDFs with J/psi production

Wen-Chen Chang

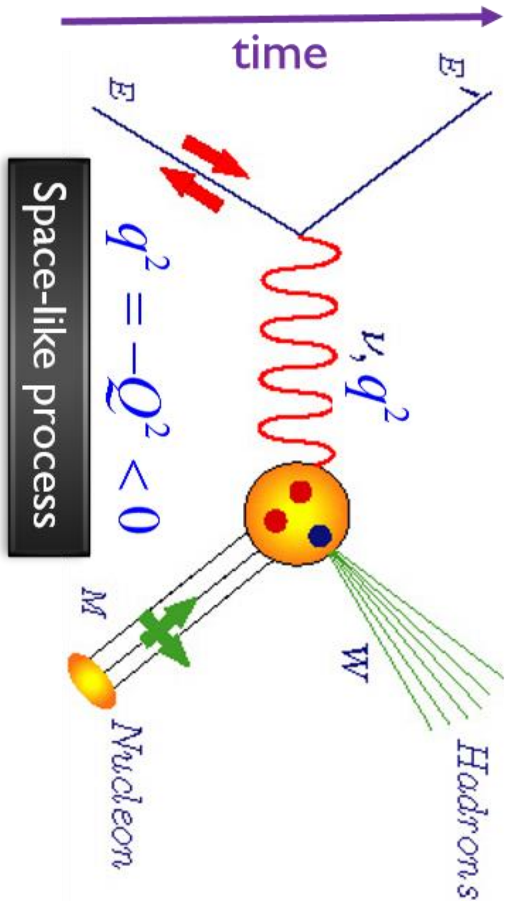
Institute of Physics, Academia Sinica, Taiwan

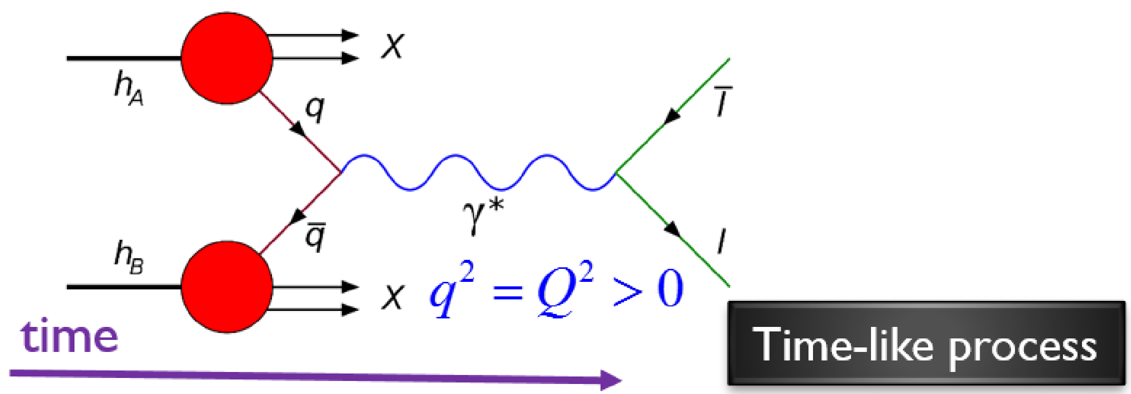
In collaboration with
Jen-Chieh Peng, Stephane Platchkov and Takahiro Sawada

Why are Pions Important?

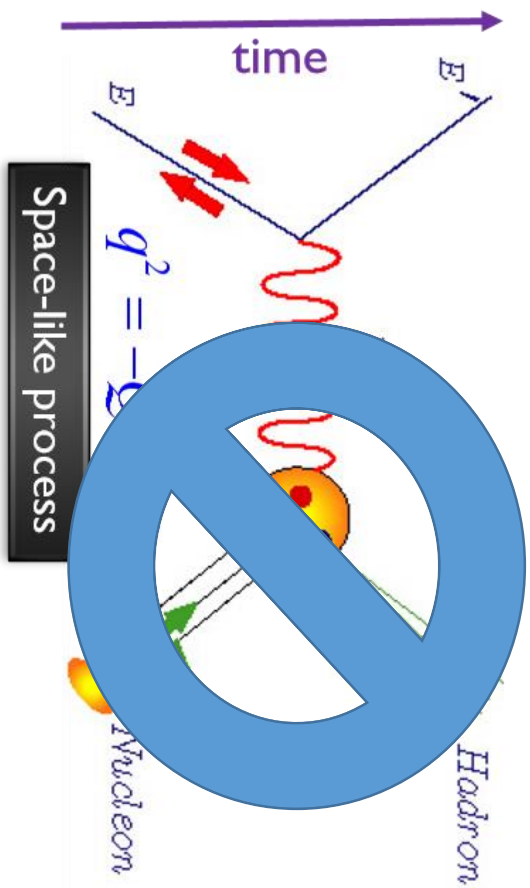
- Pions are the force carrier within the nucleus (Yukawa, 1935).
- Nambu-Goldstone bosons of spontaneous symmetry breaking of chiral symmetry $SU(3)_L * SU(3)_R$. The lightest QCD bound state.
- Pion cloud picture of nucleons is important in understanding the flavor asymmetry of sea quarks of nucleons.
- …

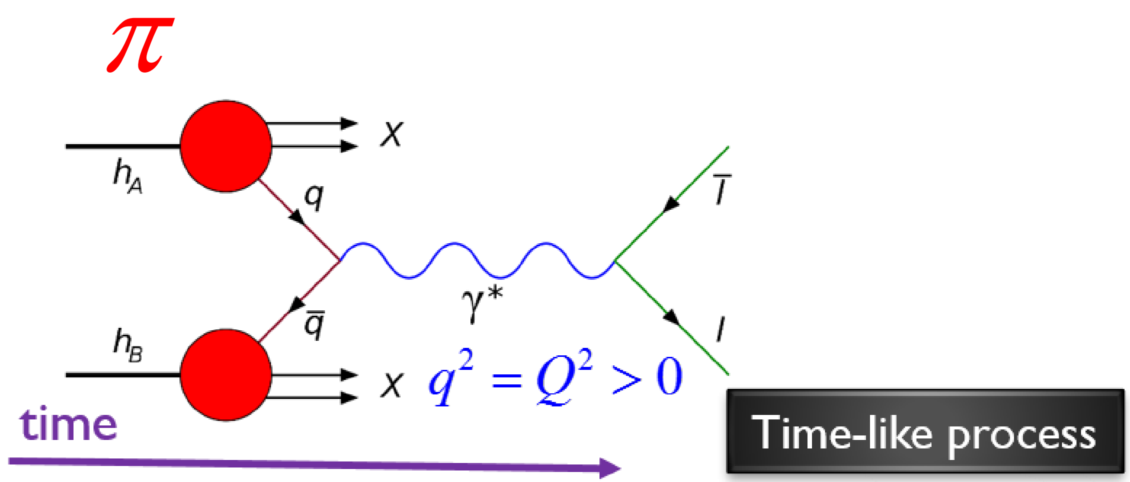
Experimental Approach for Proton PDFs





Experimental Approach for Pion PDFs





$$\bar{q}q \rightarrow \gamma^*$$
$$gq \rightarrow \gamma q$$
$$gg, \bar{q}q \rightarrow c\bar{c} \rightarrow J/\Psi$$

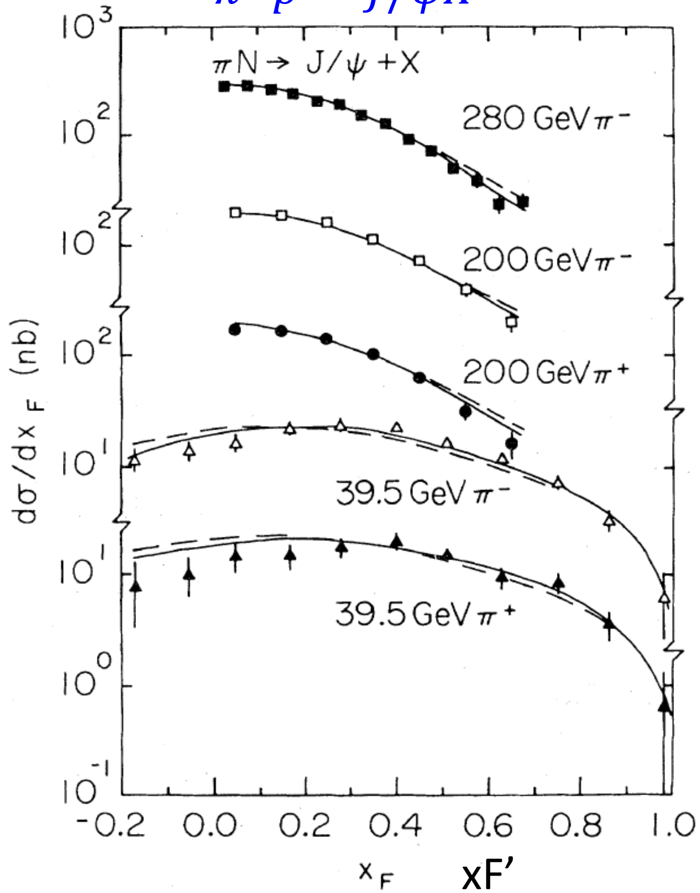
No rest targets of pions!

Pion-induced Reactions

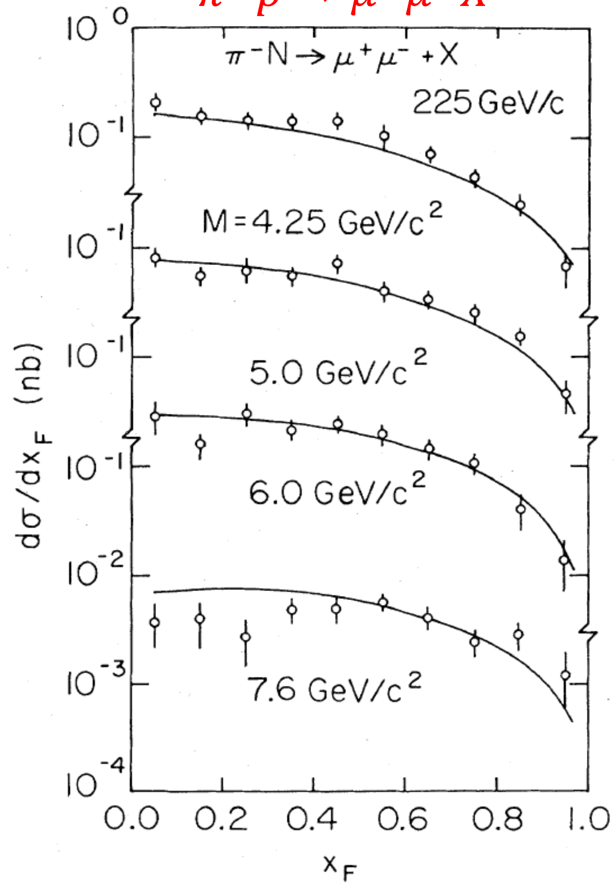
- Drell-Yan: $\pi^{\pm}p \rightarrow \mu^{+}\mu^{-}X$ (sensitive to valence quarks)
  [Marcia Quaresma's talk]
  - LO: $q\bar{q} \rightarrow \mu^{+}\mu^{-}$
  - NLO: $q\bar{q} \rightarrow \mu^{+}\mu^{-}G,\, qG \rightarrow \mu^{+}\mu^{-}q$
  - NNLO: $q\bar{q}G \rightarrow \mu^{+}\mu^{-}G,\, qG \rightarrow \mu^{+}\mu^{-}qG,\, GG \rightarrow \mu^{+}\mu^{-}q\bar{q}$
- Direct photon: $\pi^{\pm}p \rightarrow \gamma X$ (sensitive to gluons)
  [Alexey Guskov's talk]
  - LO: $q\bar{q} \rightarrow \gamma G,\, qG \rightarrow \gamma q$
- Jpsi: $\pi^{\pm}p \rightarrow J/\psi X$ (sensitive to gluons)
  [Stephane Platchkov's talk]
  - LO: $q\bar{q} \rightarrow c\bar{c} \rightarrow J/\psi X,\, GG \rightarrow c\bar{c} \rightarrow J/\psi X$
  - NLO: $q\bar{q} \rightarrow c\bar{c}G \rightarrow J/\psi X,\, GG \rightarrow c\bar{c}G \rightarrow J/\psi X,\, qG \rightarrow c\bar{c}q \rightarrow J/\psi X$

OW pion PDF
[J.F. Owens, PRD 30, 943 (1984)]

$\pi^{\pm}p \to J/\psi X$



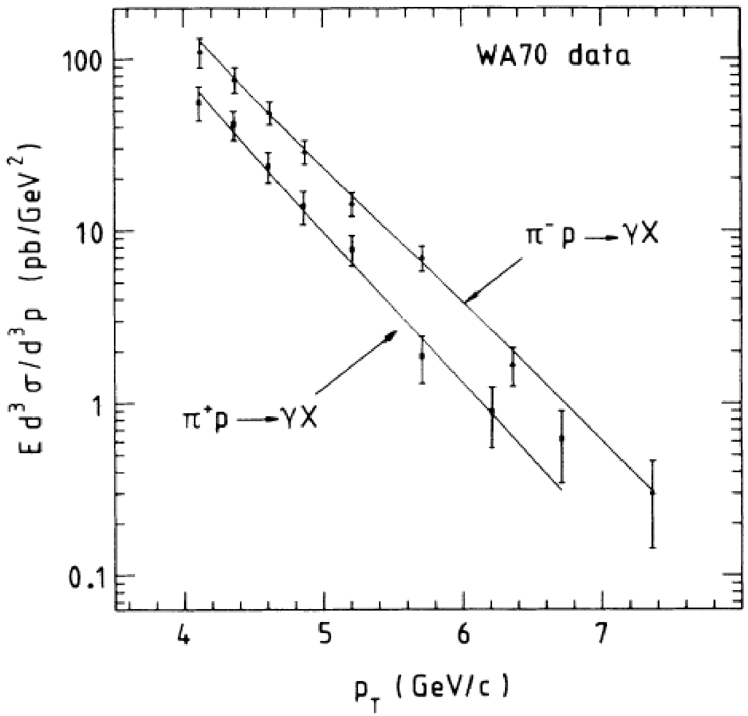
$\pi^{\pm}p \to \mu^{+}\mu^{-}X$



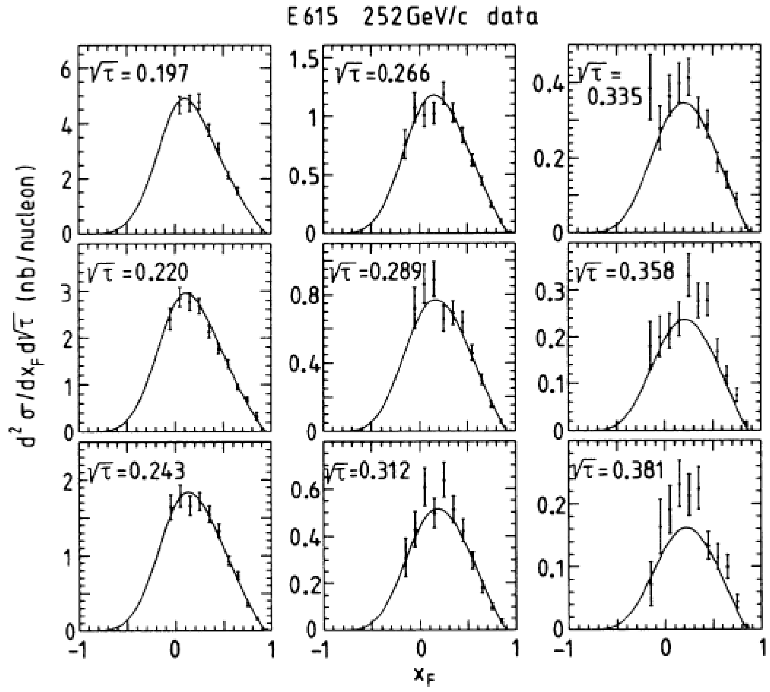
Fits to data of J/psi and DY production.

SMRS
[Sutton et al., PRD 45, 2349 (1992)]

$\pi^{\pm}p \rightarrow \gamma X$



$\pi^{\pm}p \rightarrow \mu^+\mu^- X$



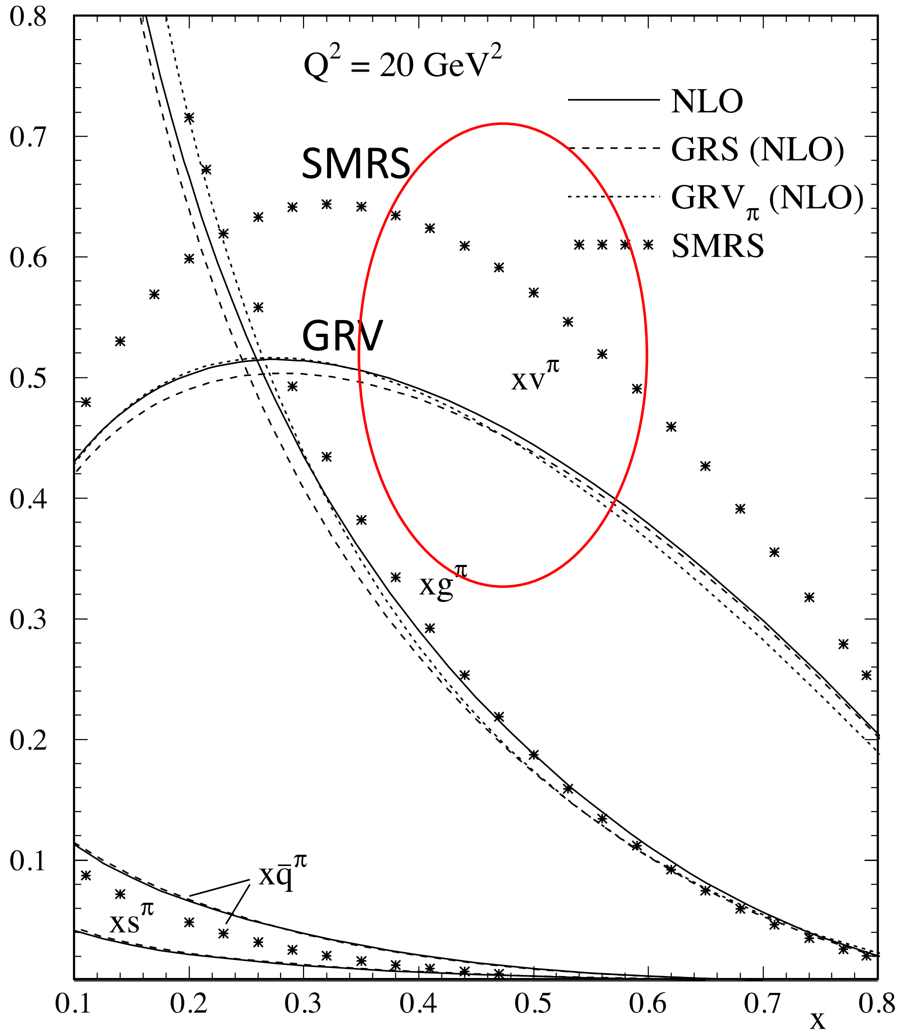
Fits to data of direct-γ and DY production.

Pion PDFs (before 2018)

PDF	DY	Direct γ	J/ψ	LN	Refs.
OW	*		*		PRD 1984
ABFKW	*	*			PLB 1989
SMRS	*	*			PRD 1992
GRV	*	*			ZPC 1992
GRS	*				EPJC 1999

- Valence quarks are well constrained by Drell-Yan data.
- Sea and gluons are constrained by the number of valence quarks and the momentum sum rule.
- Direct photon and J/psi data help to better constrain the gluons and thus sea quarks.
- GRS: relating sea quarks and gluons by a constituent quark model.

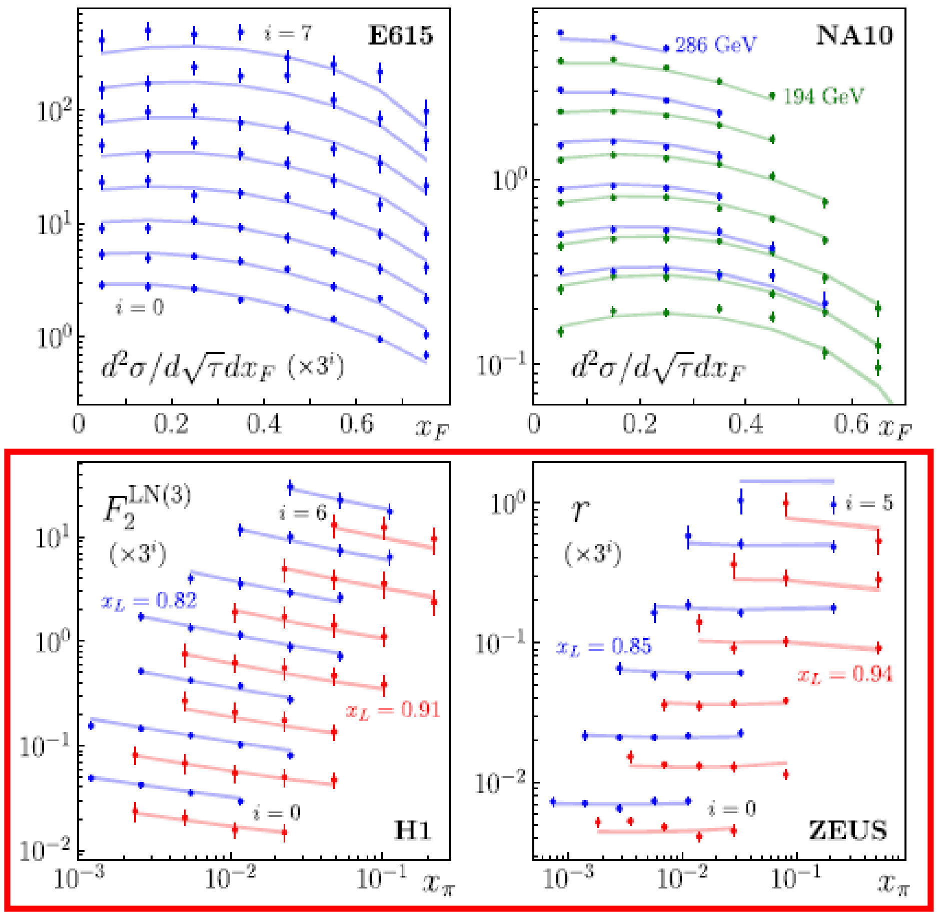
Pion PDFs (before 2018)

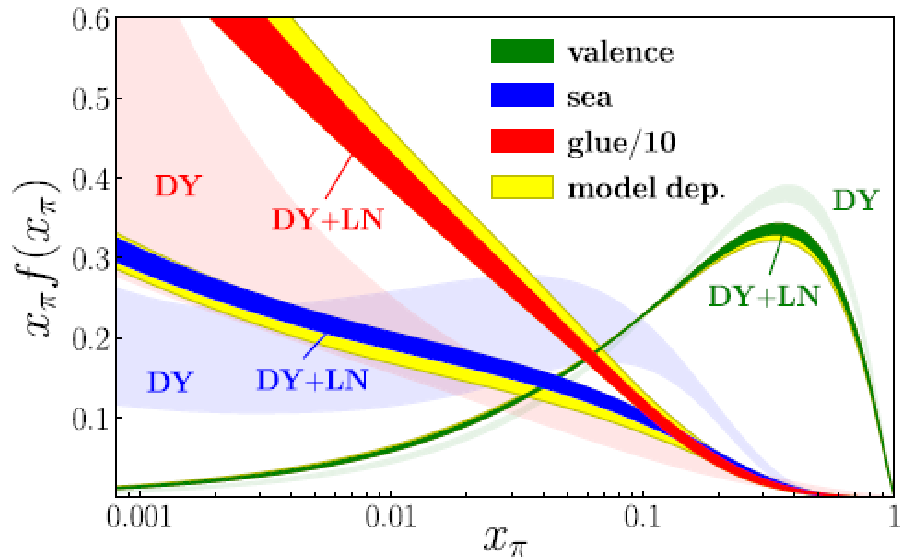


EPJC 10 (1999) 313

- PDFs were mainly determined by Drell-Yan, single γ, J/psi data.
- **20% difference of valence quarks at x = 0.5 !**

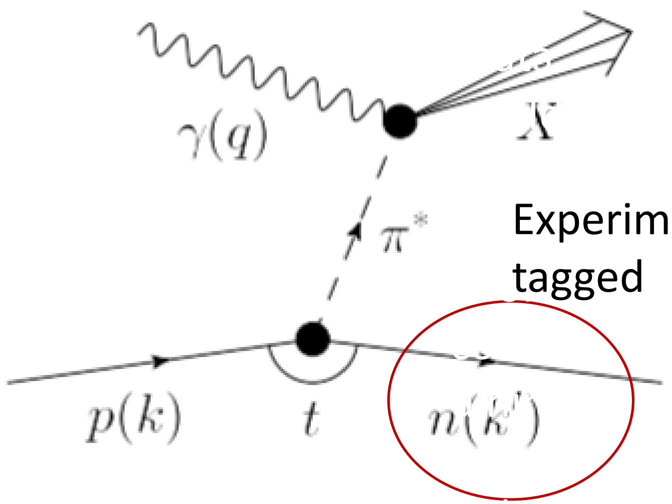
JAM18: Include leading neutron (LN) electroproduction from HERA [Barry et al., PRL 121, 152001 (2018)]





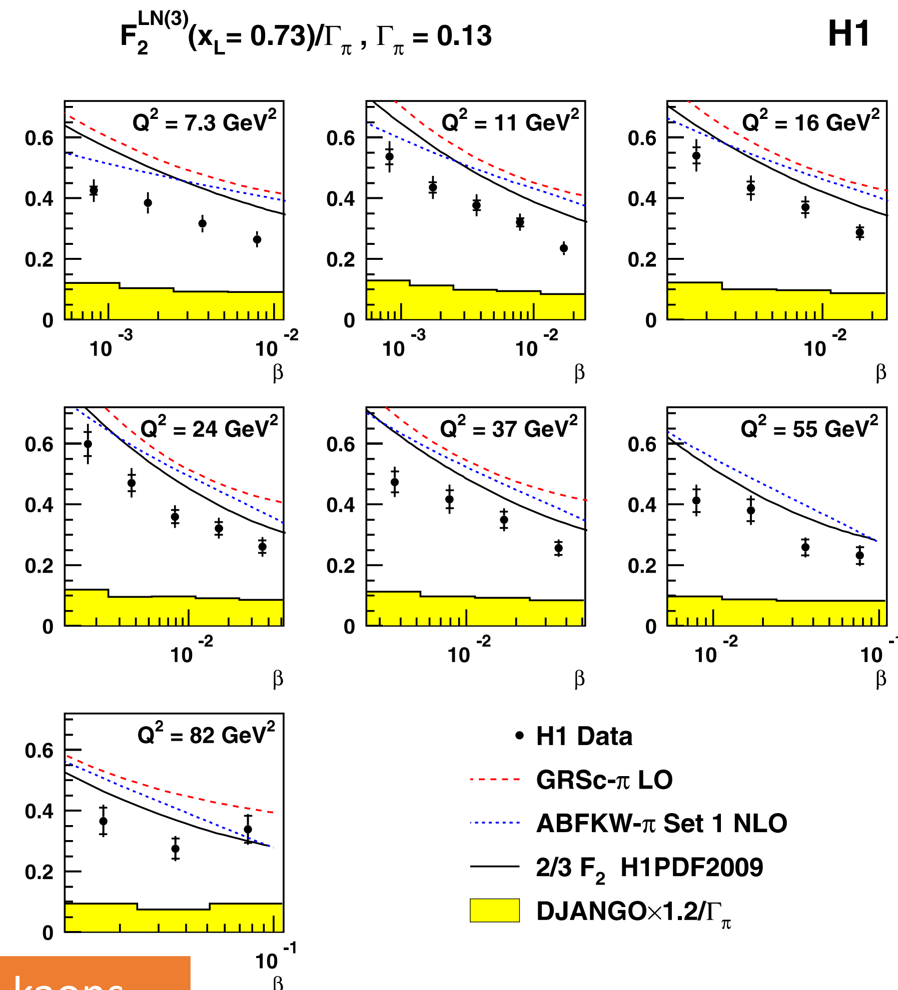
- Uncertainties are much reduced using DY+LN, as compared to DY alone.

Leading neutron (LN) electroproduction from HERA



Experimentally tagged

Sullivan processes from a nucleon's pion cloud



Off-shell persistence of composite pions and kaons
S.X. Qin et al., PRC 97, 015203 (2018)

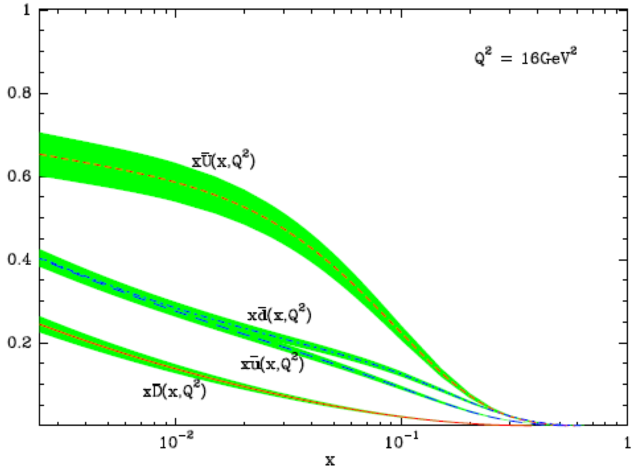
Statistical approach
[Bourrely and Soffer, NPA 981, 118 (2019)]

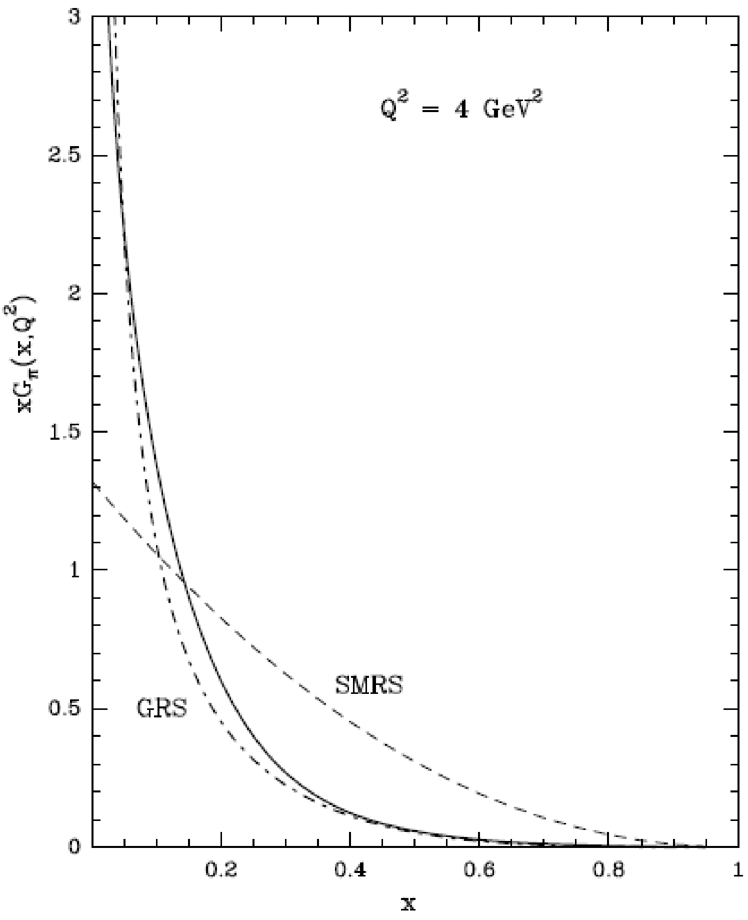
$$xQ^{\pm}(x) = \frac{A_Q X_Q^{\pm} x^{b_Q}}{\exp[(x - X_Q^{\pm})/\bar{x}] + 1}$$

$$x\bar{Q}^{\pm}(x) = \frac{\bar{A}(X_Q^{\mp})^{-1} x^{\bar{b}}}{\exp[(x + X_Q^{\mp})/\bar{x}] + 1}$$

$$xG_{\pi}(x) = A_G x^{b_G} / (\exp(x/\bar{x}) - 1)$$

$\bar{x}$=0.09: a universal temperature





xFitter:
[Novikov et al., arXiv:2002.02902]

Experiment	Normalization uncertainty	Normalization factor	χ^2/N_{points}
E615	15 %	1.160 ± 0.020	206/140
NA10 (194 GeV)	6.4%	0.997 ± 0.014	107/67
NA10 (286 GeV)	6.4%	0.927 ± 0.013	95/73
WA70	32%	0.737 ± 0.012	64/99

Figure 3 shows the obtained pion PDFs in comparison to a recent analysis by JAM [26], and to GRVPI1 [22] — the only set available in the LHAPDF6 [39] library. The new valence distribution presented here is in good agreement with JAM, and both disagree with the early GRV analysis. The relatively difficult to determine sea and gluon distributions are different in all three PDF sets, however, this new PDF and the JAM determination agree within the larger uncertainties of our fit.

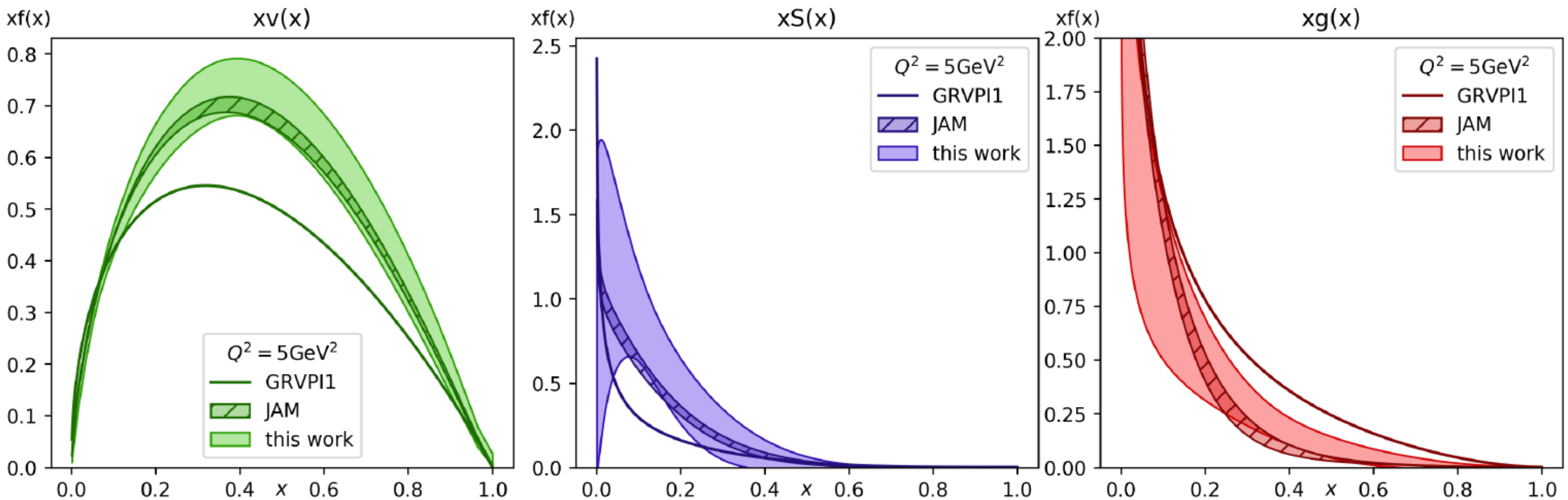


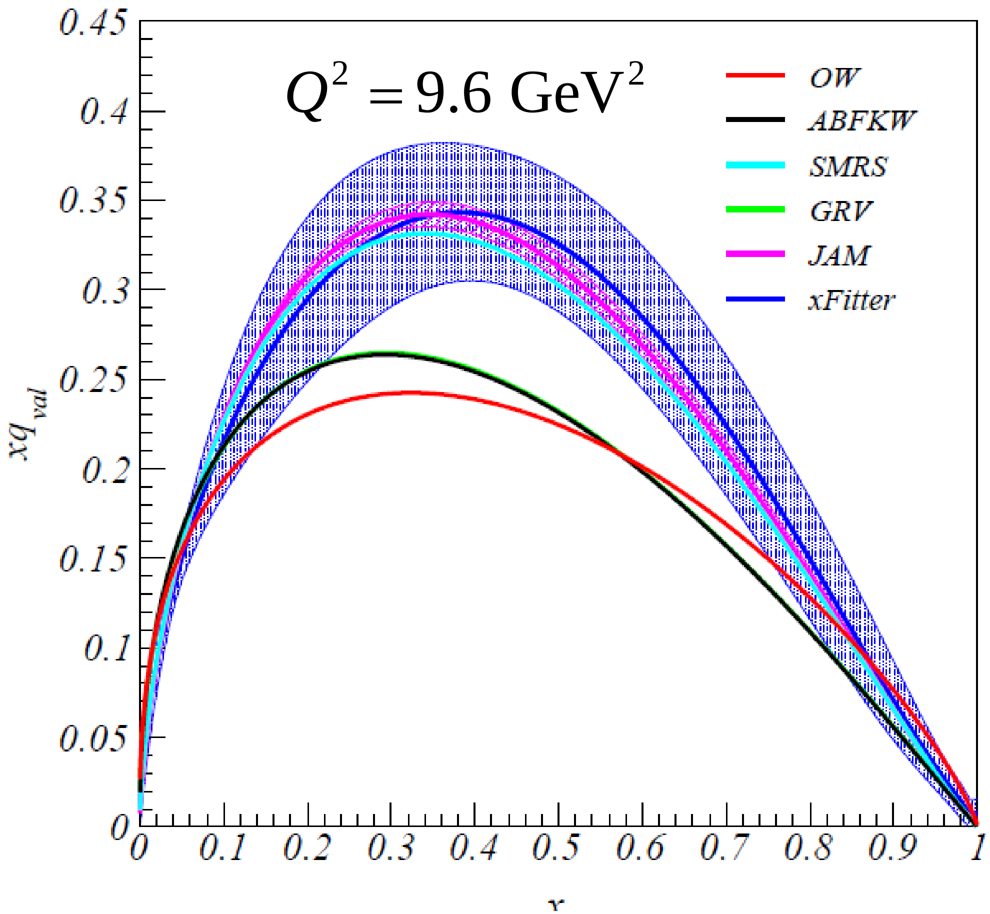
FIG. 3. Comparison between the pion PDFs obtained in this work, a recent determination by the JAM collaboration [26], and the GRVPI1 pion PDF set [22].

xFitter is consistent with JAM but disagrees with GRV.

Pion PDFs (2020)

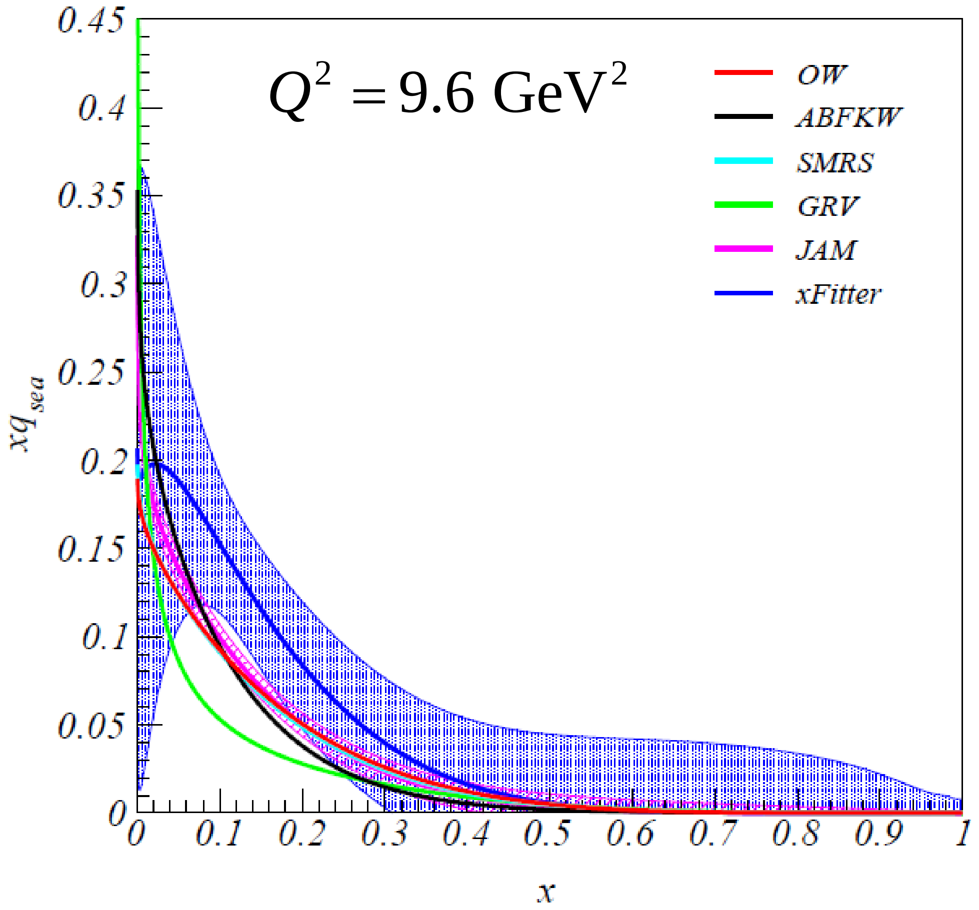
PDF	DY	Direct γ	J/ψ	LN	Refs.
OW	*		*		PRD 1984
ABFKW	*	*			PLB 1989
SMRS	*	*			PRD 1992
GRV	*	*			ZPC 1992
GRS	*				EPJC 1999
JAM	*			*	PRL 2018
BS	*				NPA 2019
xFitter	*	*			2002.02902

Pion PDFs: Valence Quarks

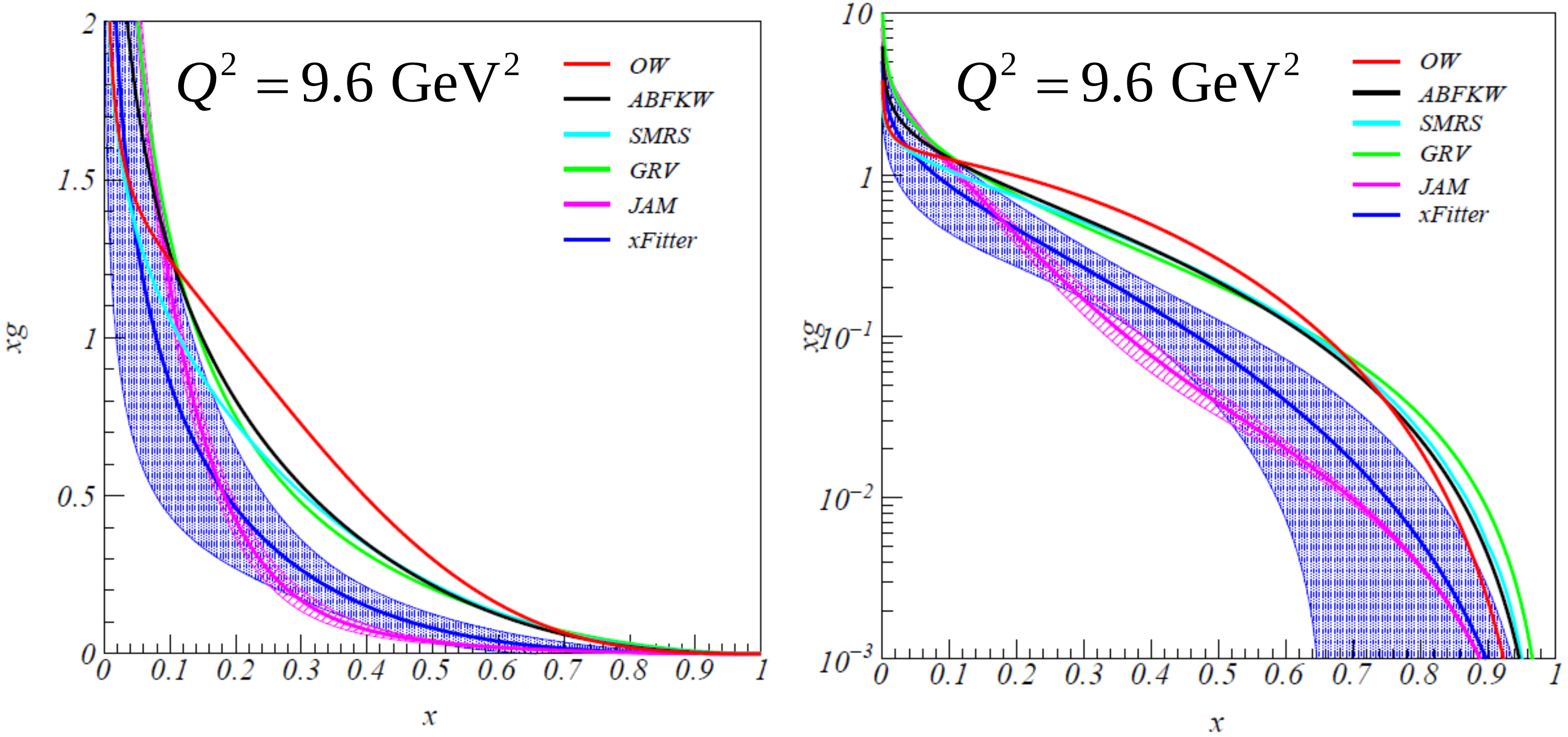


At x>0.1, qv(x) of OW, ABFKW and GRV are significantly lower than others'.

Pion PDFs: Sea Quarks

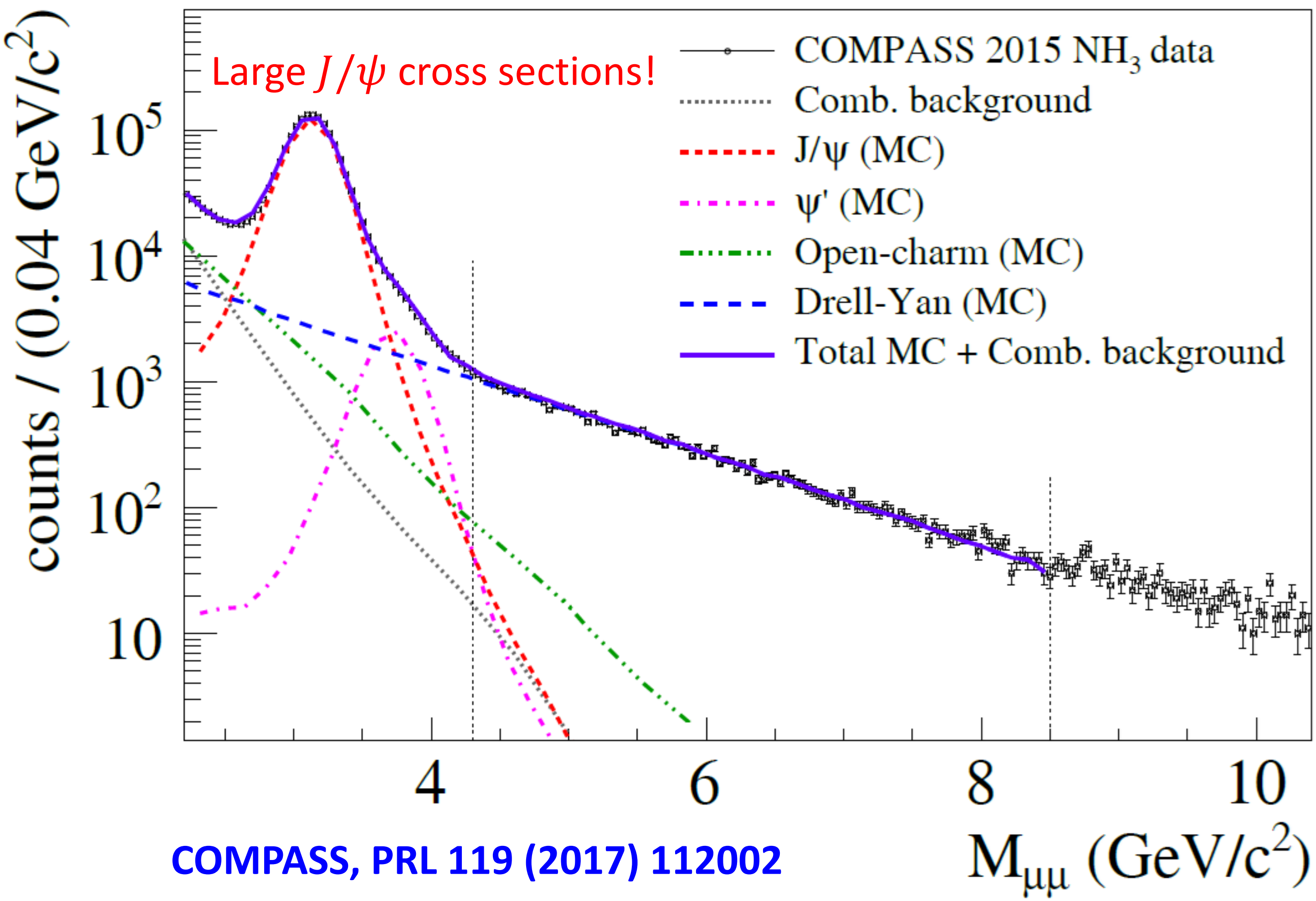


Pion PDFs: Gluons



At x>0.1, G(x) of JAM and xFitter are significantly lower than others'.

Dimuon Invariant-mass Spectrum (COMPASS Pion-Induced 2015 Run)



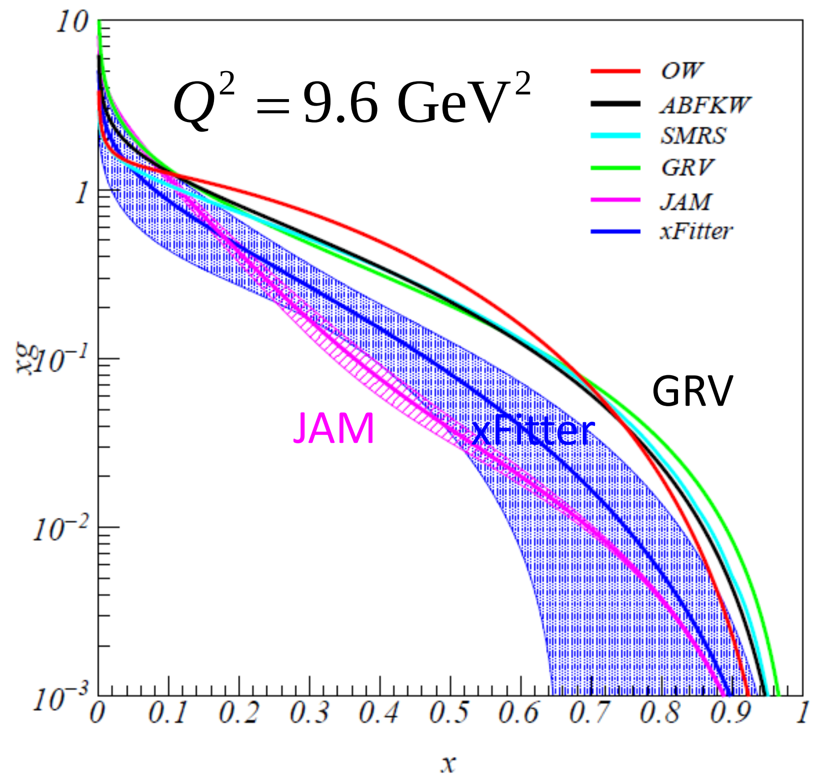
COMPASS, PRL 119 (2017) 112002

Pion-induced J/psi Data from 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

Goals of This Work

- Color evaporation model calculations of J/psi production: LO/NLO
- Three pion PDFs: GRV, xFitter and JAM with different gluon strength at large-x.
- To see how well the pion-induced $\sigma_{J/psi}(x_F)$ over a wide range of beam energy – [40, 515] GeV, can be described.



Model Dependence of $c\bar{c}$ pairs Fragmentation

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

Calculations of A+B→J/ψ+X in Color Evaporation Model

$$\frac{d\sigma_{J/\psi}}{d^3P_{J/\psi}} = F\int_{2m_c}^{2m_D} \frac{d\sigma_{c\bar{c}}(M_{c\bar{c}},P_{c\bar{c}})}{dM_{c\bar{c}}\,d^3P_{c\bar{c}}}dM_{c\bar{c}};\; P_{J/\psi} = P_{c\bar{c}}$$

$$d\sigma_{c\bar{c}}(M_{c\bar{c}},P_{c\bar{c}})[AB\to c\bar{c}X]$$

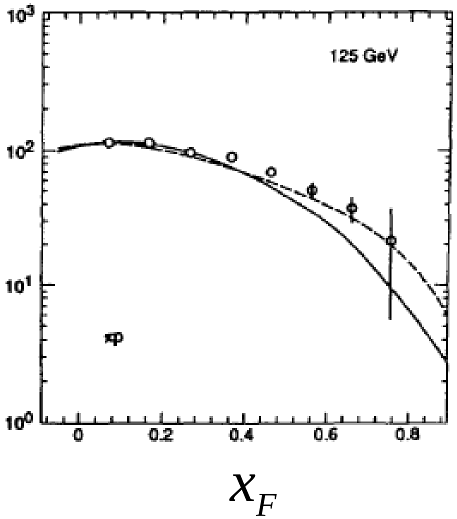
$$=\sum_{i,j}\int f_{i/A}(x_1,\mu_F)f_{j/B}(x_2,\mu_F)d\hat{\sigma}_{c\bar{c}}(x_1P_A,x_2P_B,\mu_F,\mu_R)[ij\to c\bar{c}X]dx_1dx_2$$

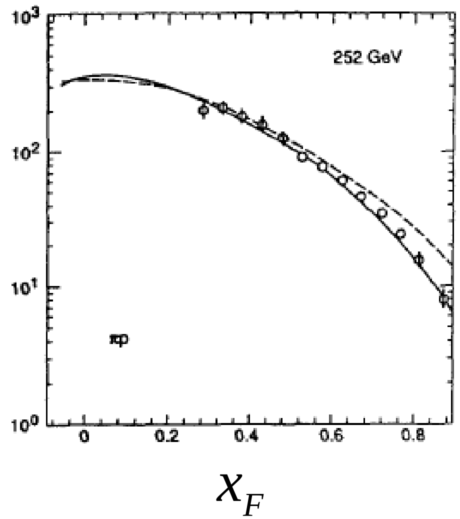
LO/NLO calculations of $d\hat{\sigma}_{c\bar{c}}[ij\to c\bar{c}X]$:

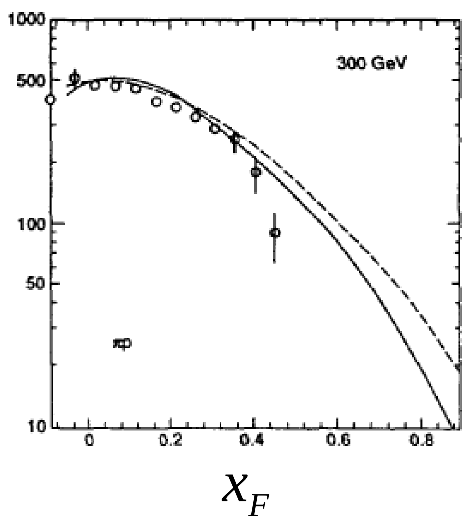
- P.Nason, S. Dawson and R.K. Ellis, Nucl. Phys. B303 (1988) 607
- M.L. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B405 (1993) 507

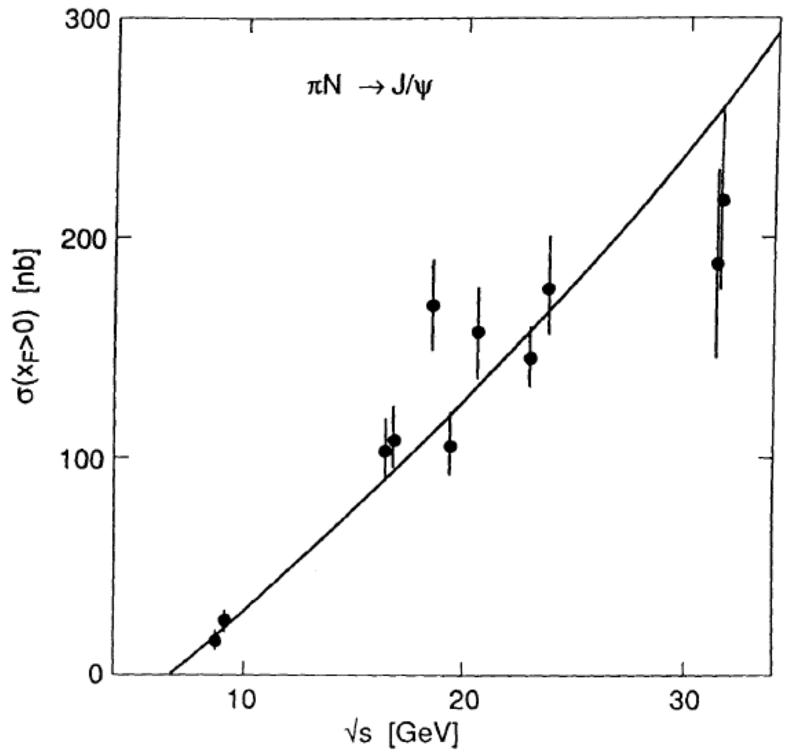
Data vs. CEM NLO

[Gavai et al., IJMPA 10, 3043 (1995)]





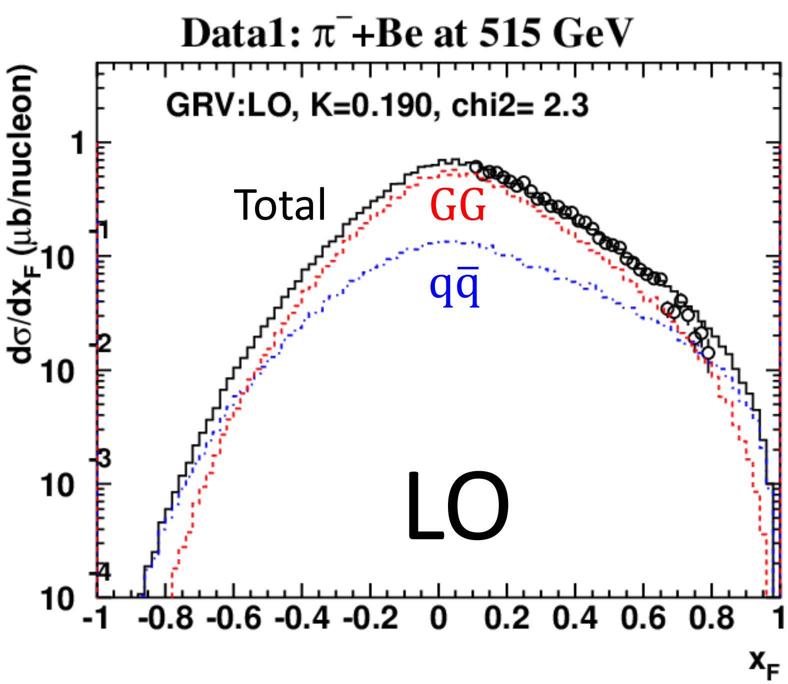


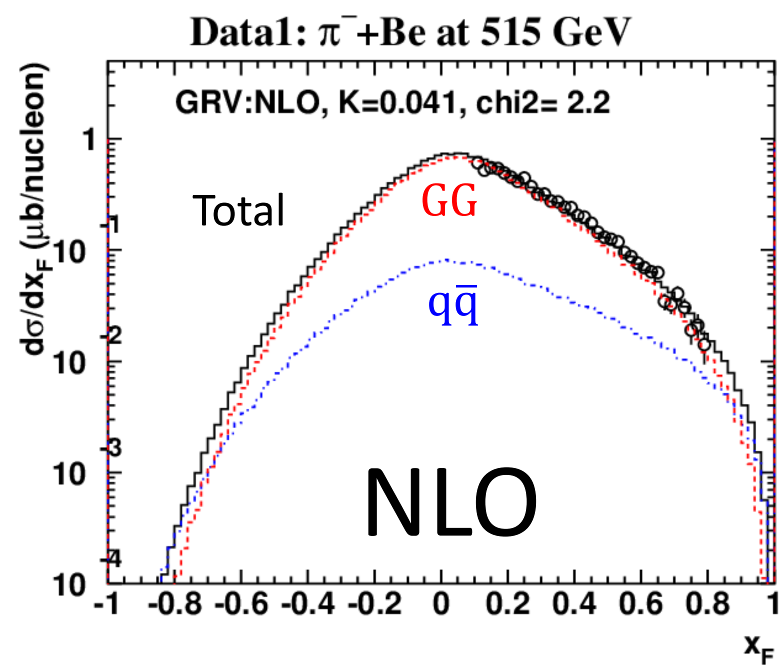


Data vs. CEM LO/NLO

[Pi- + Be →Jpsi + X at 515 GeV, PRD 53, 4723 (1996)]

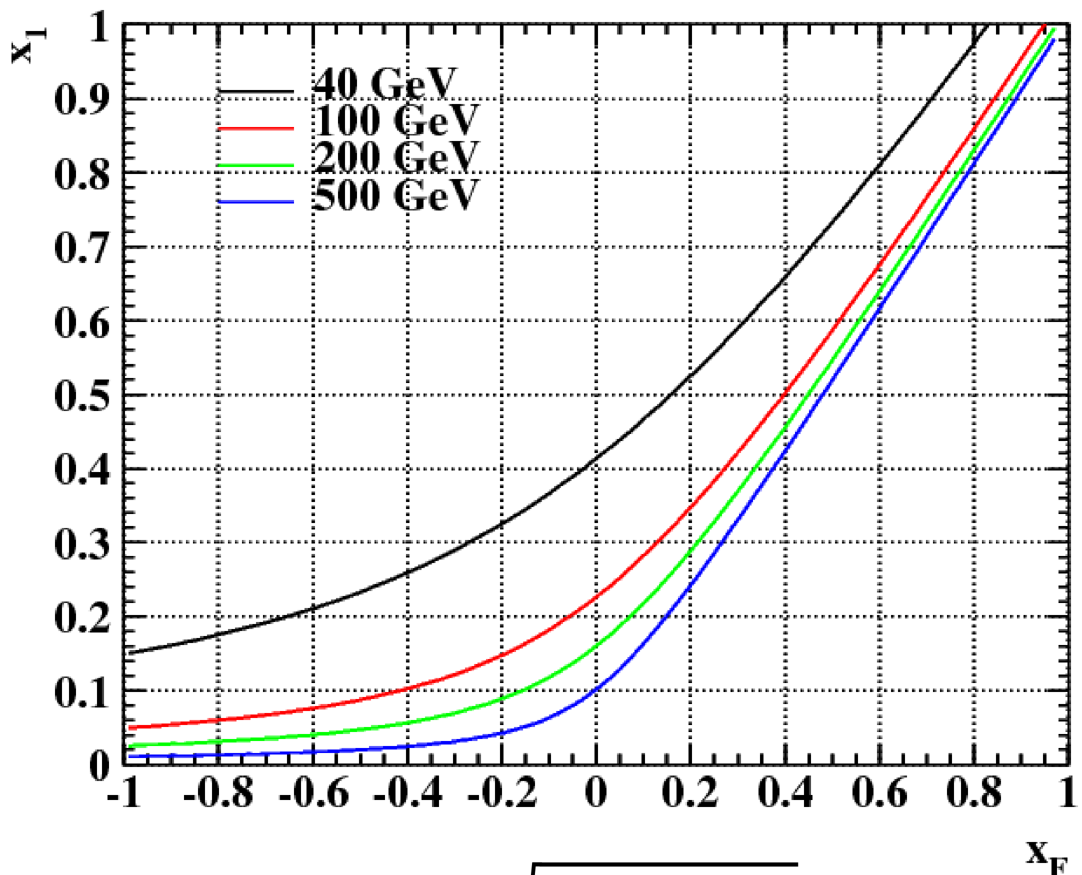
m_c=1.5 GeV, μ_F=2m_c, μ_R=m_c, F determined by the fit.





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

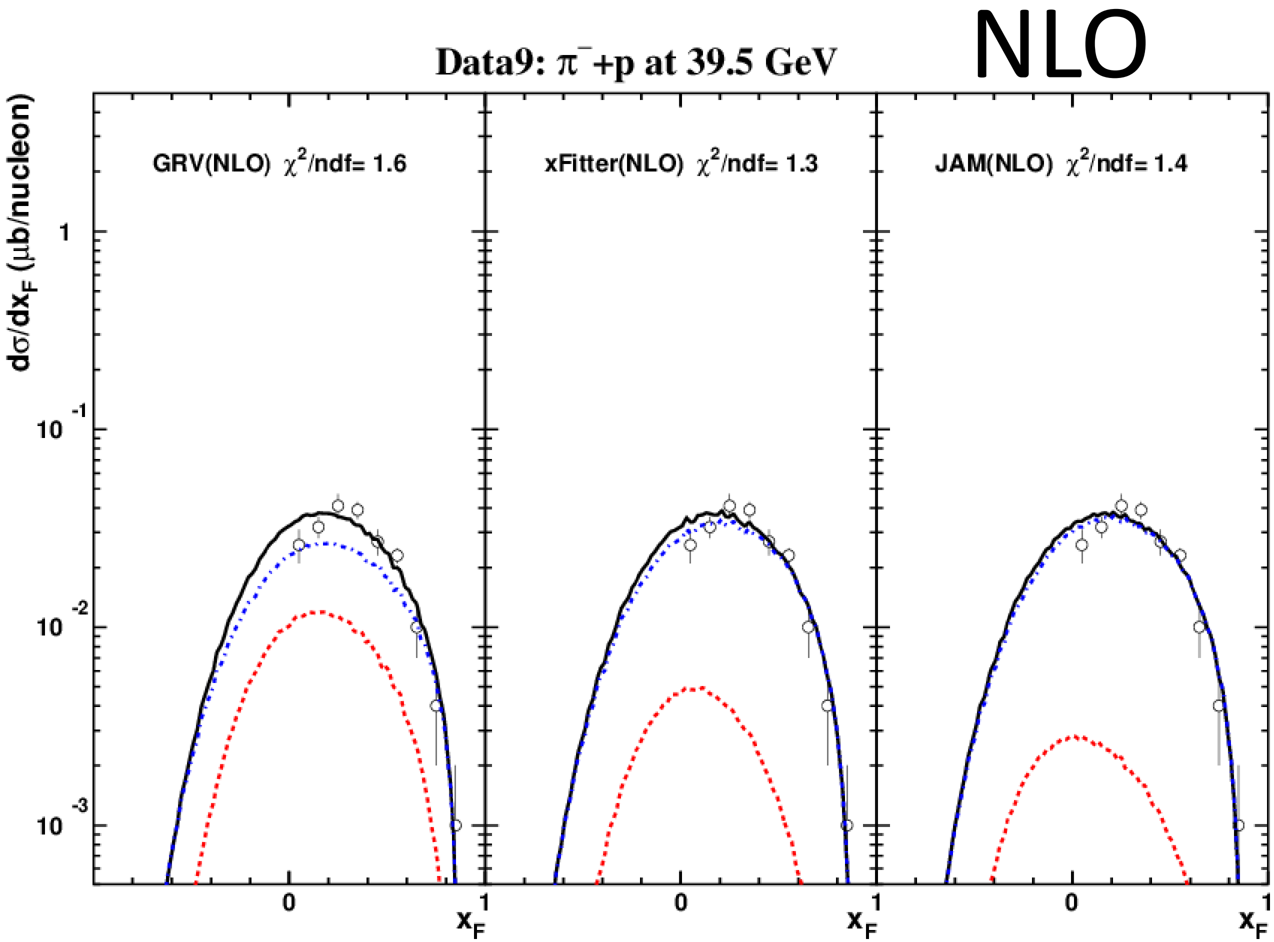
Sensitivity of $\sigma_{J/\psi}(x_F)$ to the $q_v(x_1)$ and $G(x_1)$ of Pions



- $x_1 = 0.5 * (\sqrt{{x_F}^2 + \frac{4Q^2}{s}} + x_F)$

Data vs. CEM NLO

[Pi+ + p→Jpsi + X at 39.5 GeV, PLB 98, 220 (1981)]

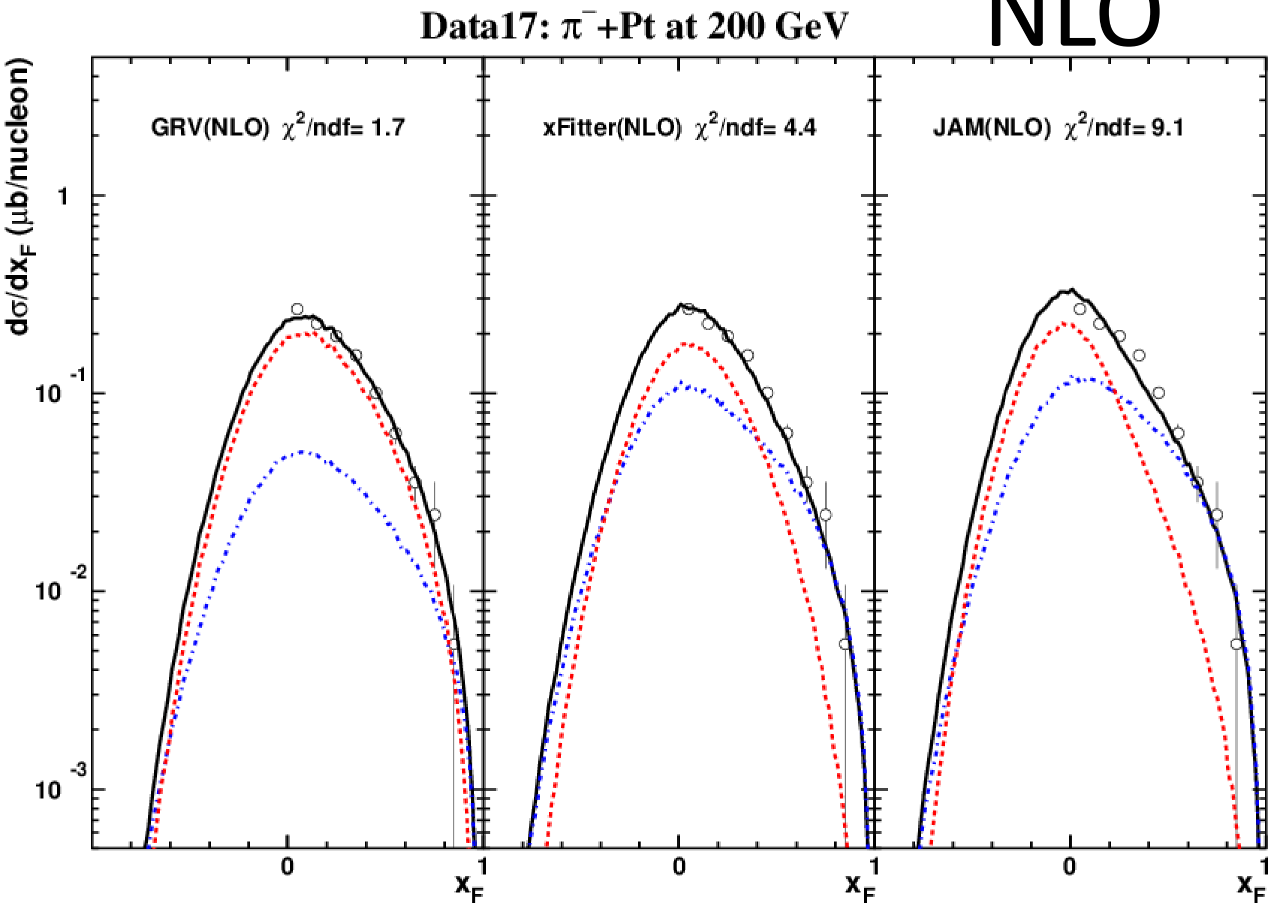


- Calculations of all three PDFs describe the data well.

Data vs. CEM NLO

[Pi- + Pt →Jpsi + X at 200 GeV, Z. Phys. C20,101(1983)]

NLO

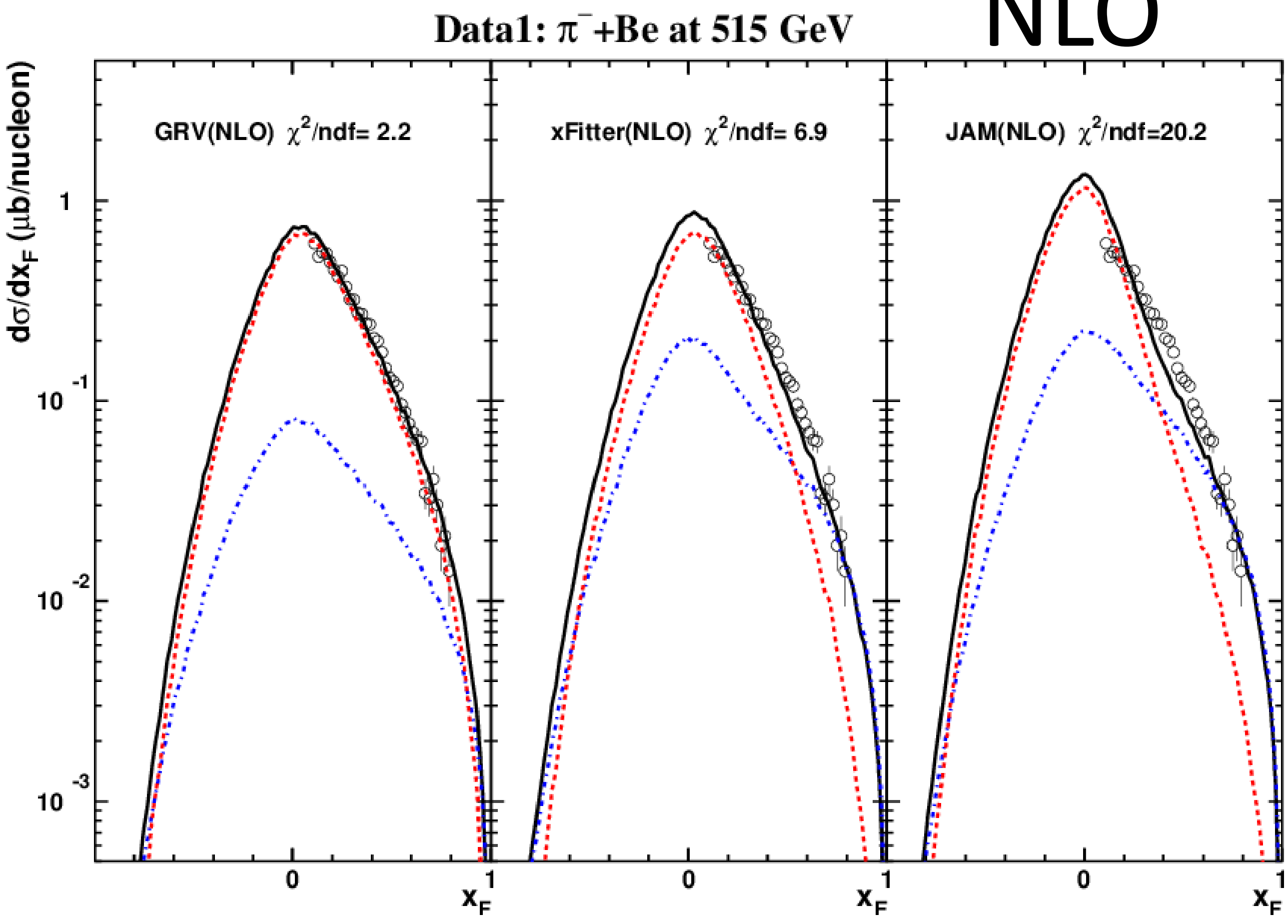


- To well describe the data for xF>0.2, an appropriate weighting of GG and $q\bar{q}$ contributions is necessary.
- The agreement of CEM calculations and data is in the sequence of GRV, xFitter and JAM.

Data vs. CEM NLO

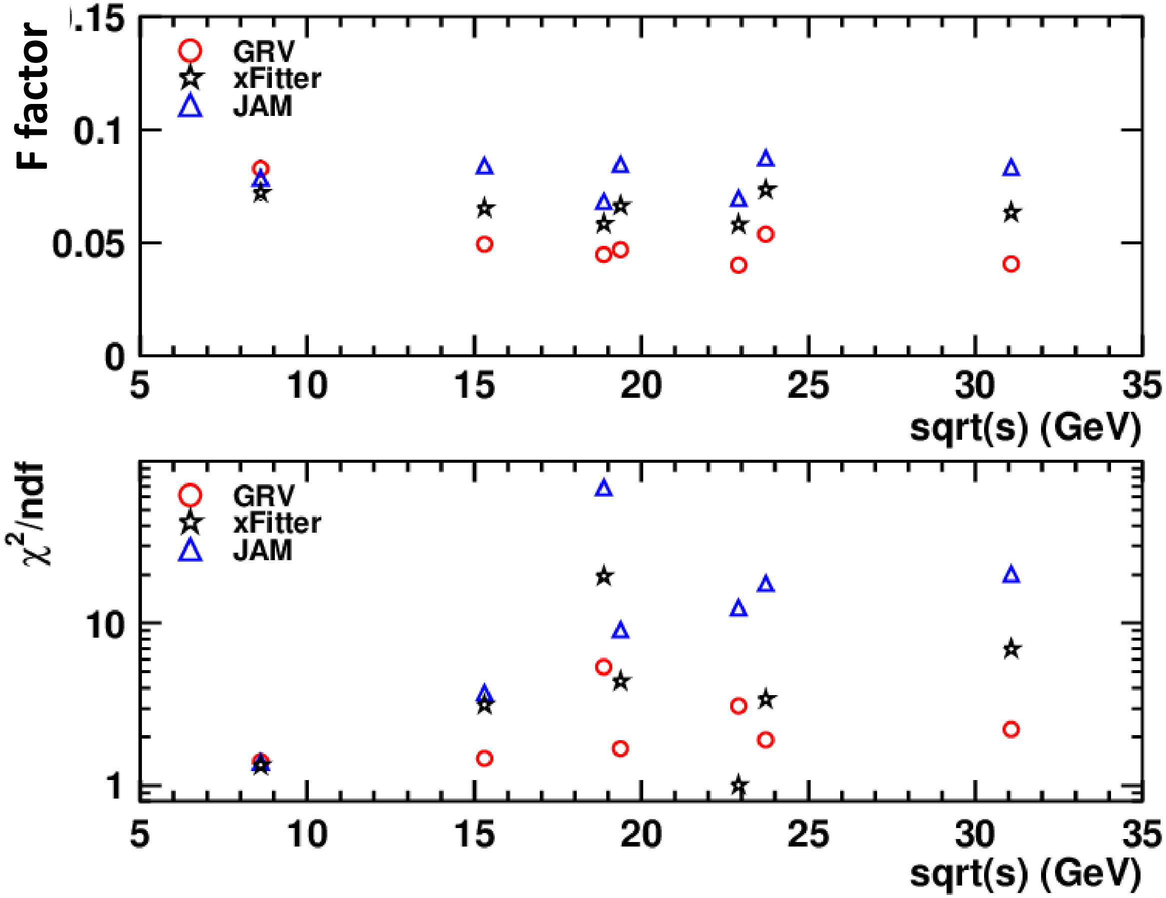
[Pi- + Be →Jpsi + X at 515 GeV, PRD 53, 4723 (1996)]

NLO



- To well describe the data for xF>0.5, an appropriate weighting of GG and $q\bar{q}$ contributions is necessary.
- The agreement of CEM calculations and data is in the sequence of GRV, xFitter and JAM.

Data vs. CEM Calculations



- The fragmenting F factor is more or less stable across energy.
- GRV with the strongest large-x strength gives the best description.

Summary

- Pion PDFs have been 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 the color evaporation model, the high-energy large-x_F J/psi data are shown to be sensitive to the pion gluon distribution at x>0.1.
- With the coming new data of meson-induced J/psi from COMPASS/AMBER, all high-statistic fixed-target J/psi data sets could be used to improve the less-known gluon distributions in pion/kaon PDFs.