TQCD Meeting 14/10/2020 @ Academia Sinica

Constraining pion PDFs with J/psi production

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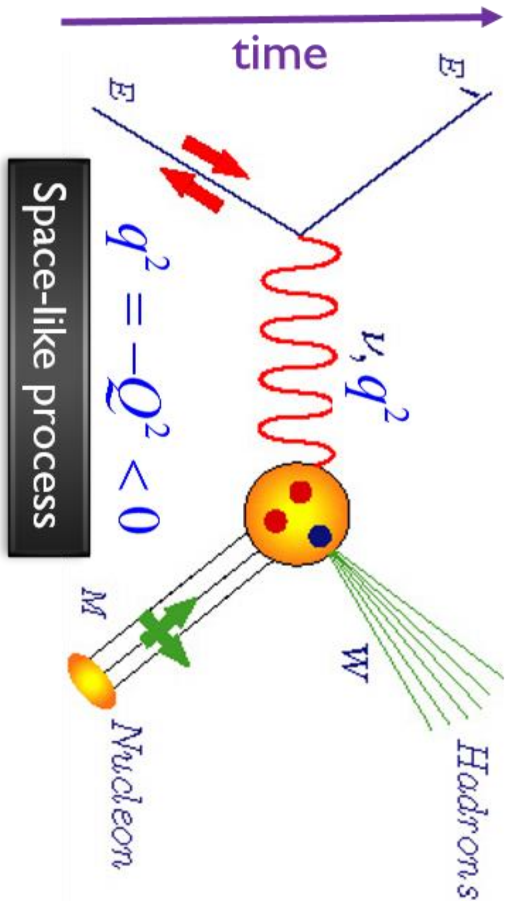
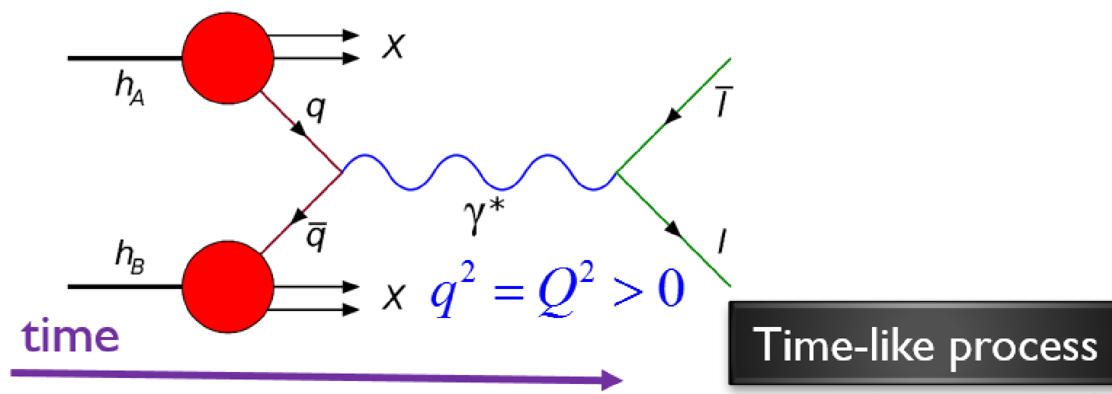
Phys. Rev. D 102, 054024 (2020); arXiv: 2006.06947

Why are Pions Important?

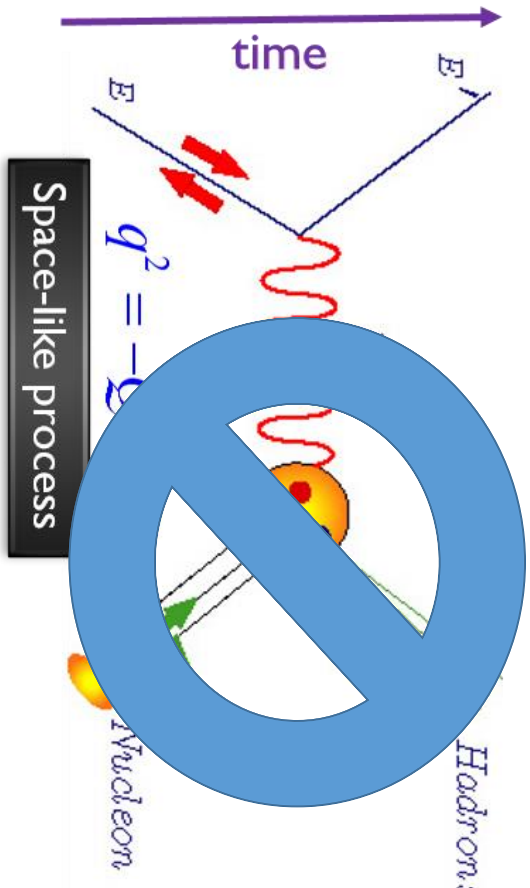
- Pions are the force carrier within the nucleus (Yukawa, 1935).
- Nambu-Goldstone bosons of spontaneous symmetry breaking of chiral symmetry $SU(3)_L * SU(3)_R$. The lightest QCD bound state.
- Pion cloud picture of nucleons is important in understanding the flavor asymmetry of sea quarks of nucleons.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

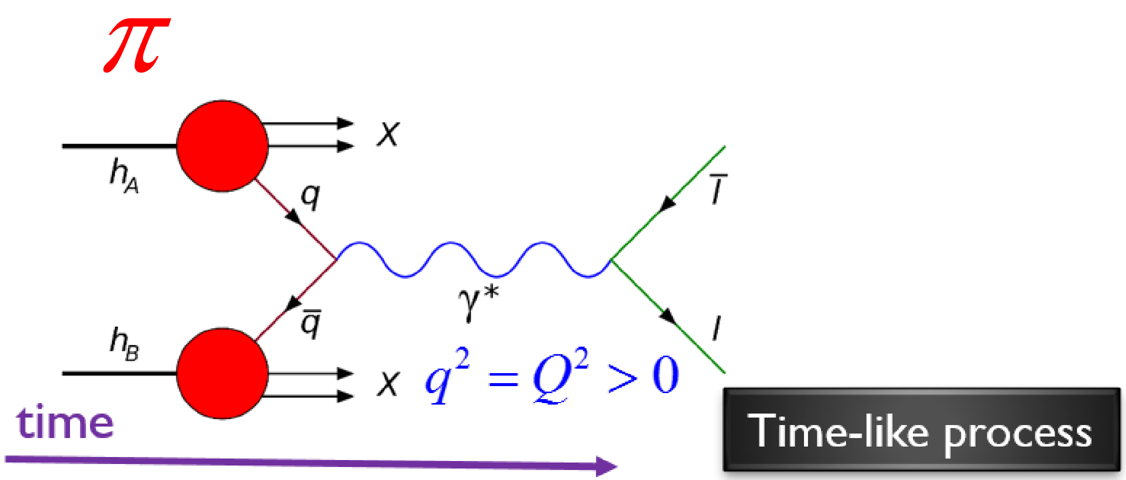
Experimental Approach for Proton PDFs





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!

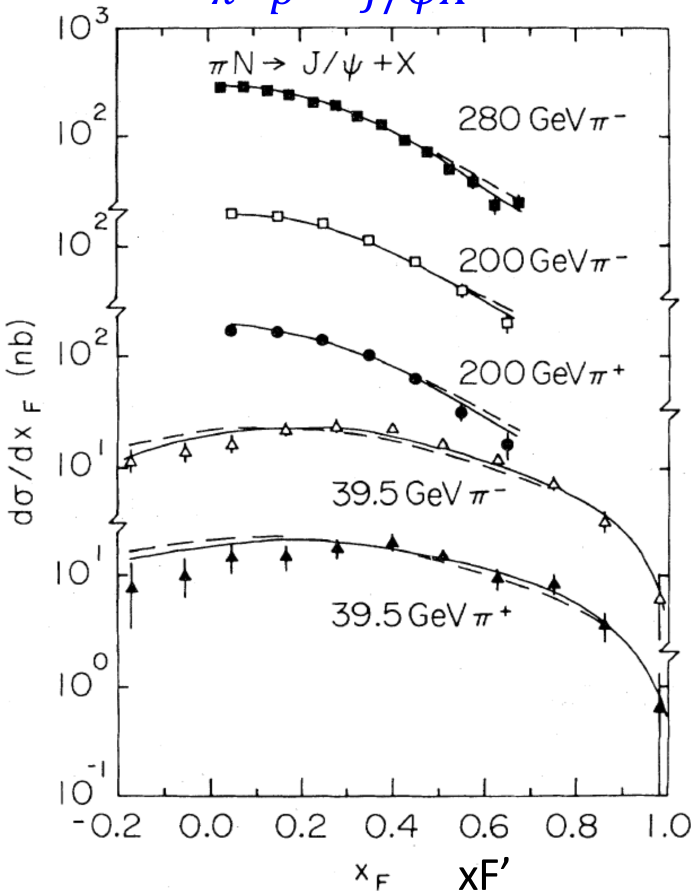
Pion-induced Reactions

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

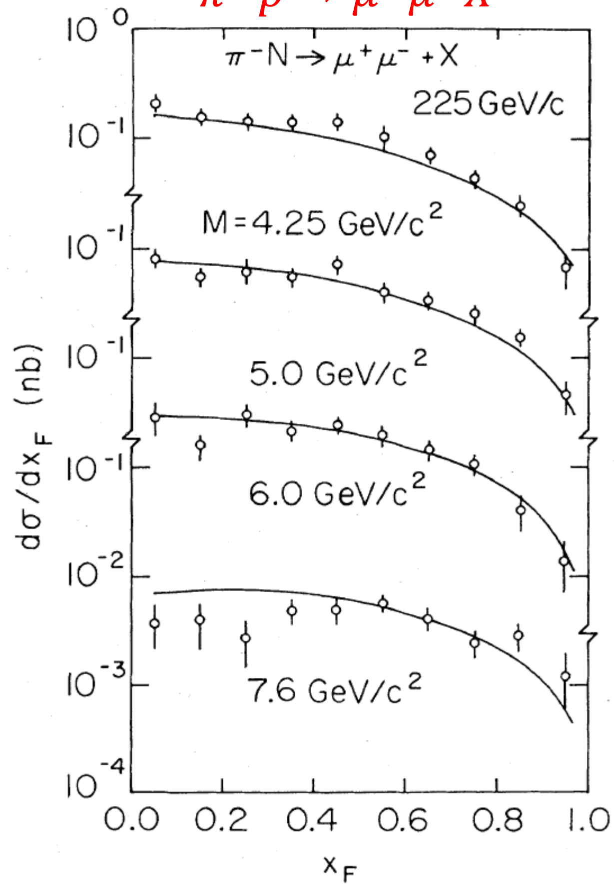
OW pion PDF

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

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



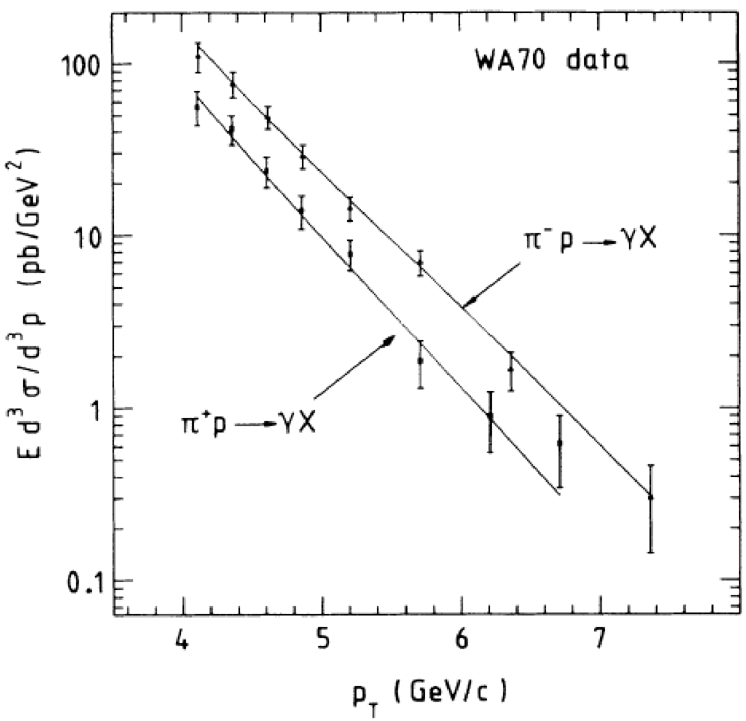
$\pi^{\pm}p \to \mu^{+}\mu^{-}X$



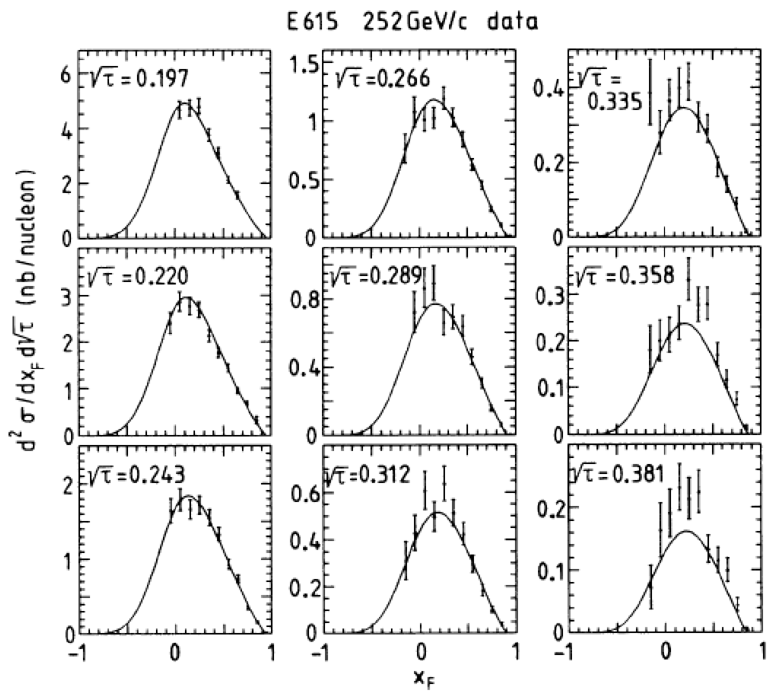
Fits to data of J/psi and DY production.

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

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



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



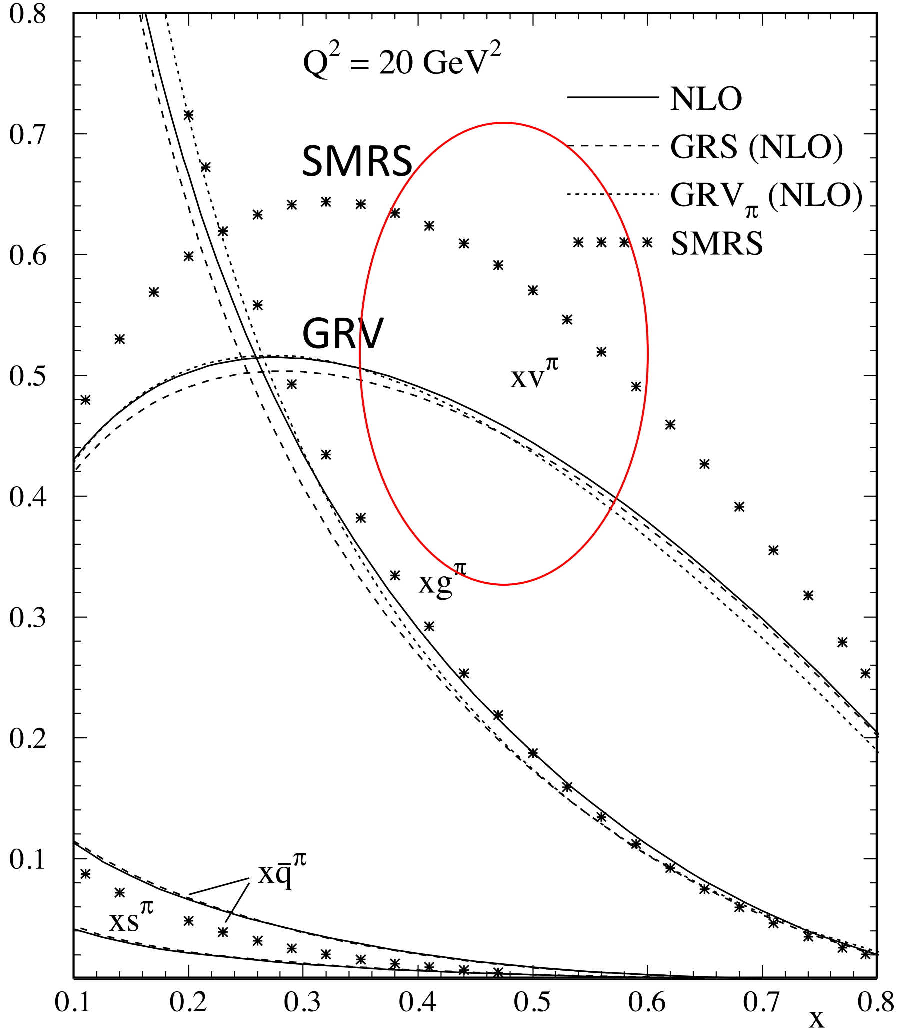
Fits to data of direct-γ and DY production.

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.

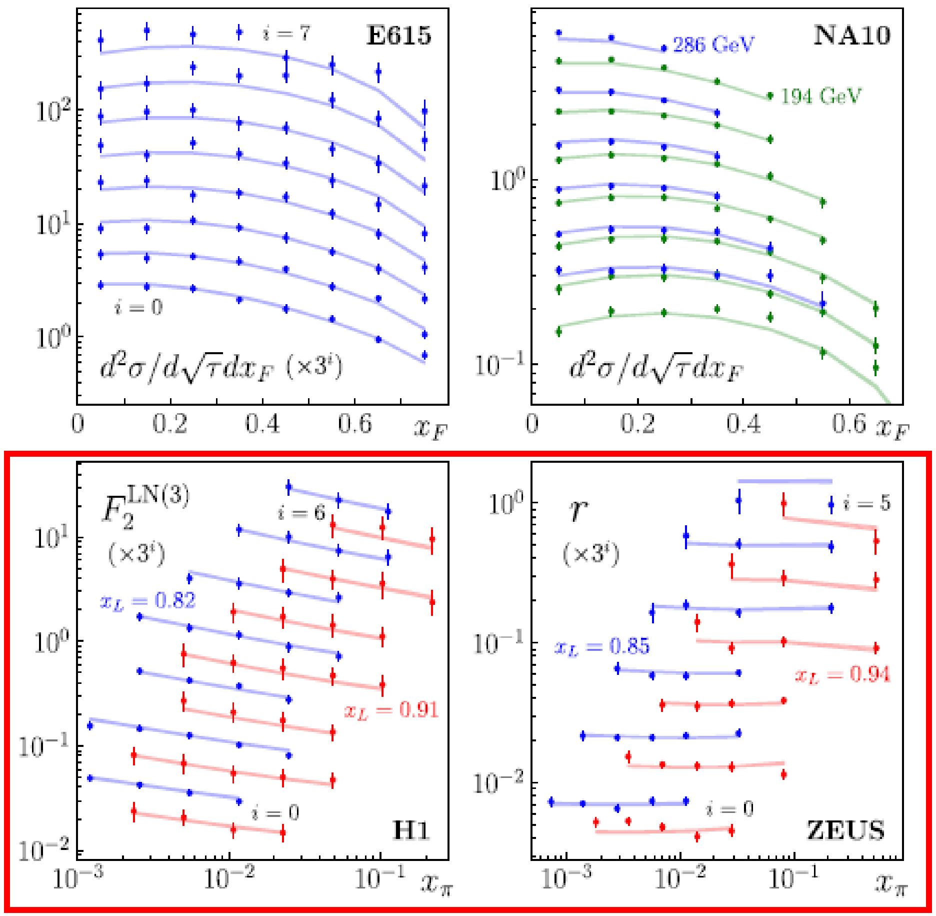
Pion PDFs (before 2018)

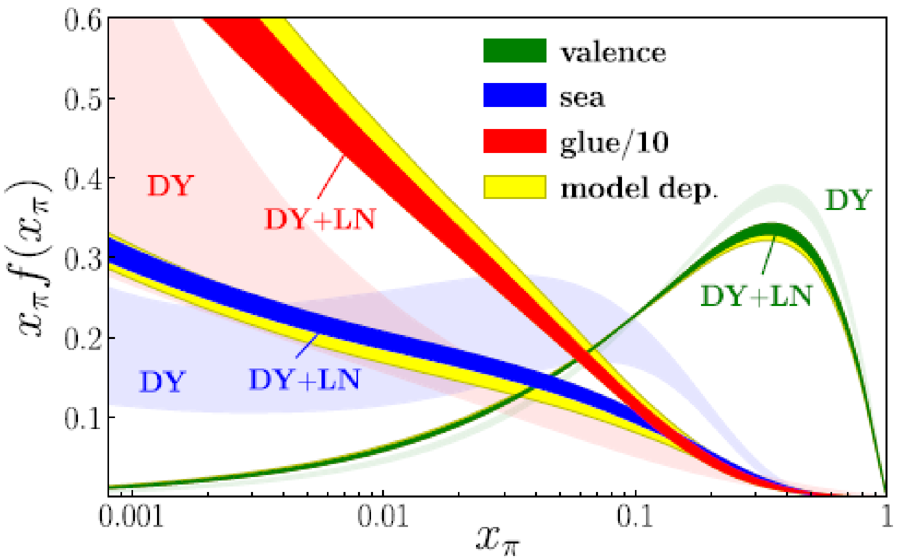


EPJC 10 (1999) 313

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

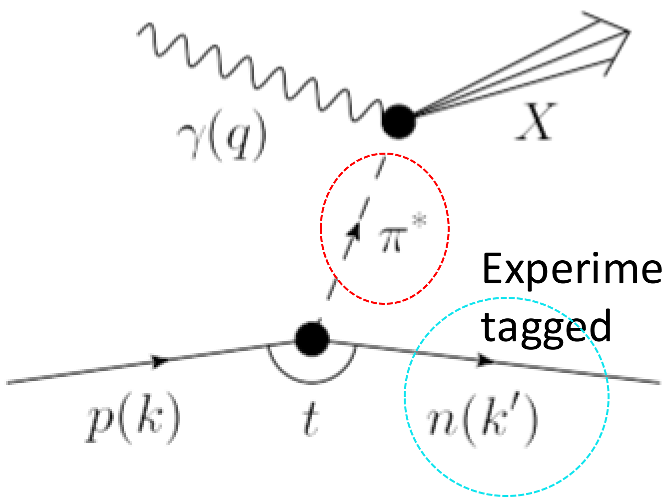
JAM18: Include leading neutron (LN) electroproduction from HERA [Barry et al., PRL 121, 152001 (2018)]



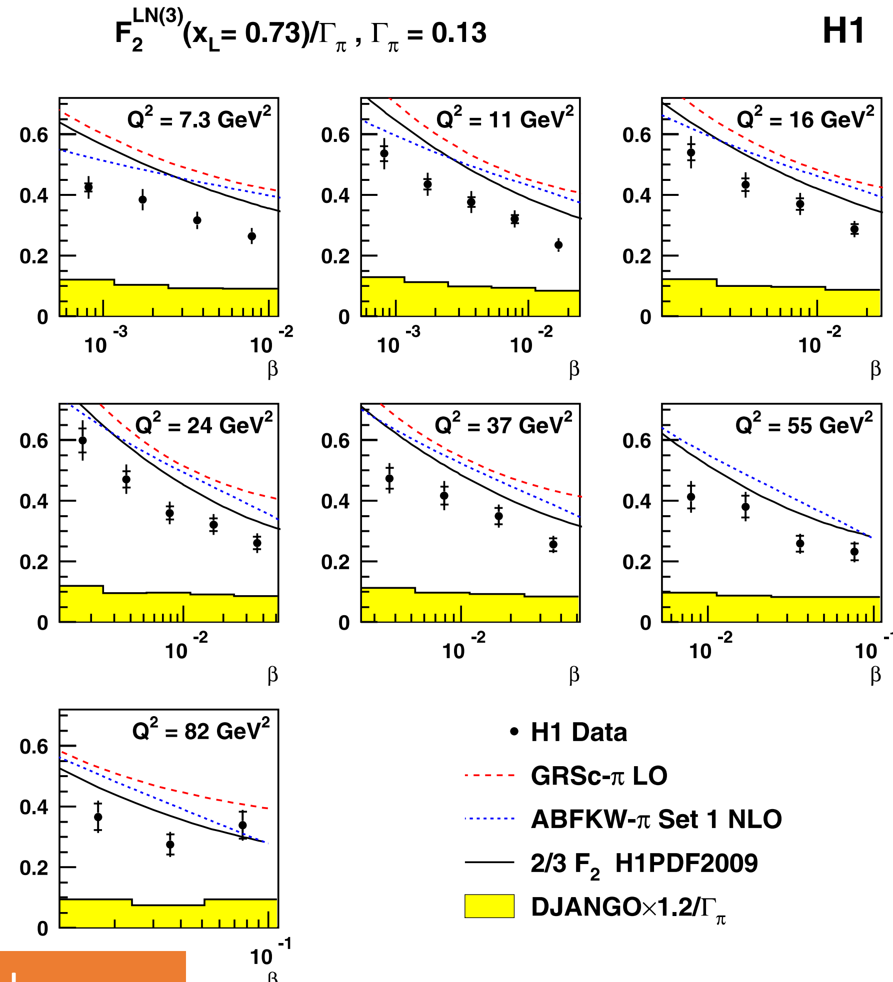


- Uncertainties are much reduced using DY+LN, as compared to DY alone.

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)

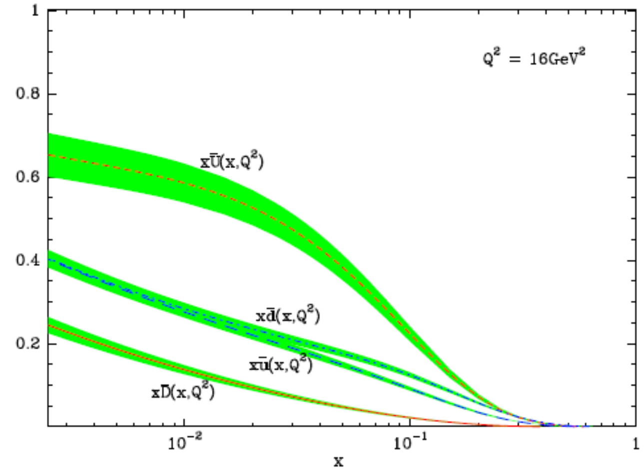
Statistical approach
[Bourrely and Soffer, NPA 981, 118 (2019)]

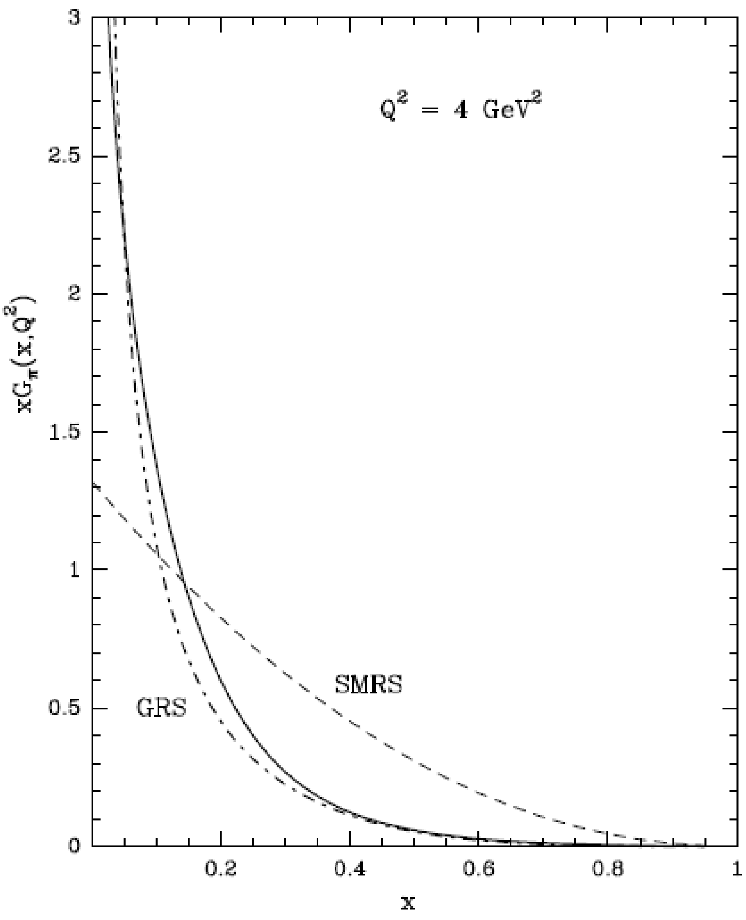
$$xQ^{\pm}(x) = \frac{A_Q X_Q^{\pm} x^{b_Q}}{\exp[(x - X_Q^{\pm})/\bar{x}] + 1}$$

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

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

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





xFitter:

[Novikov et al., PRD 102, 014040 (2020), 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.

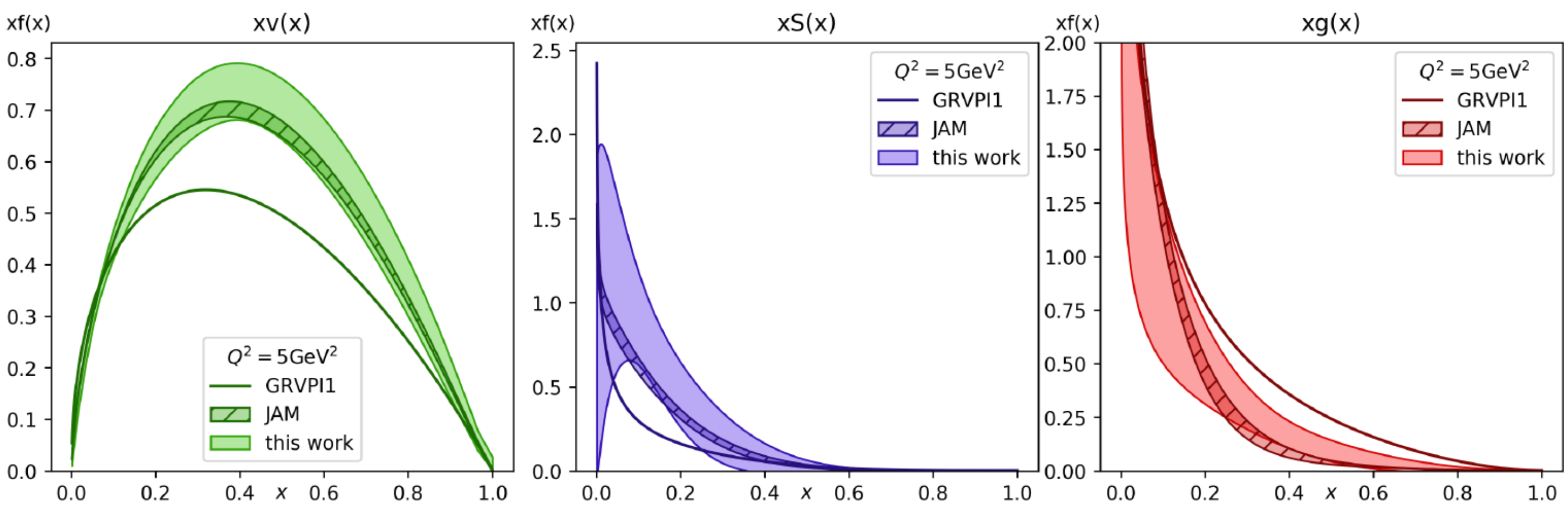


FIG. 3. Comparison between the pion PDFs obtained in this work, a recent determination by the JAM collaboration [26], and the GRVPI1 pion PDF set [22].

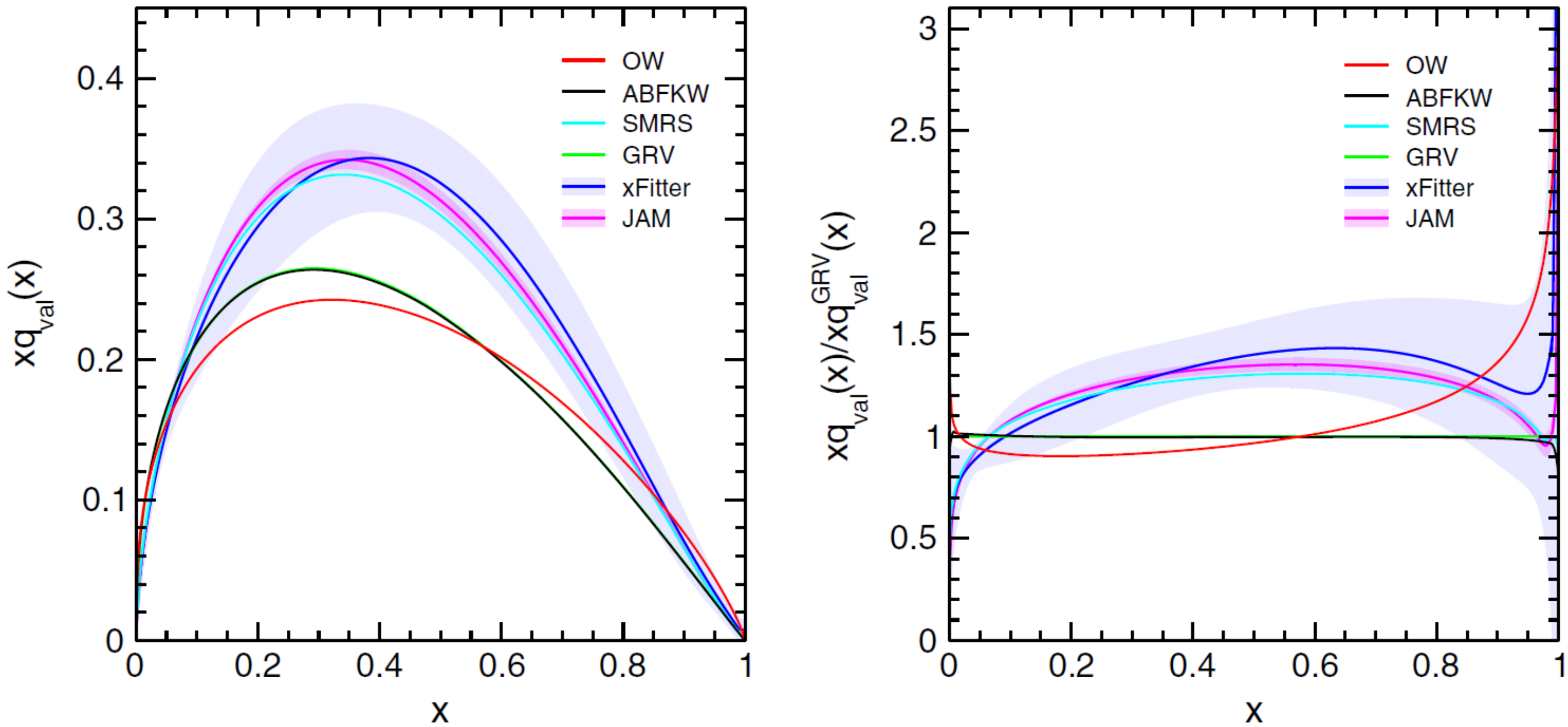
xFitter is consistent with JAM but disagrees with GRV.

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	*	*			PRD 2020

Pion PDFs: Valence Quarks

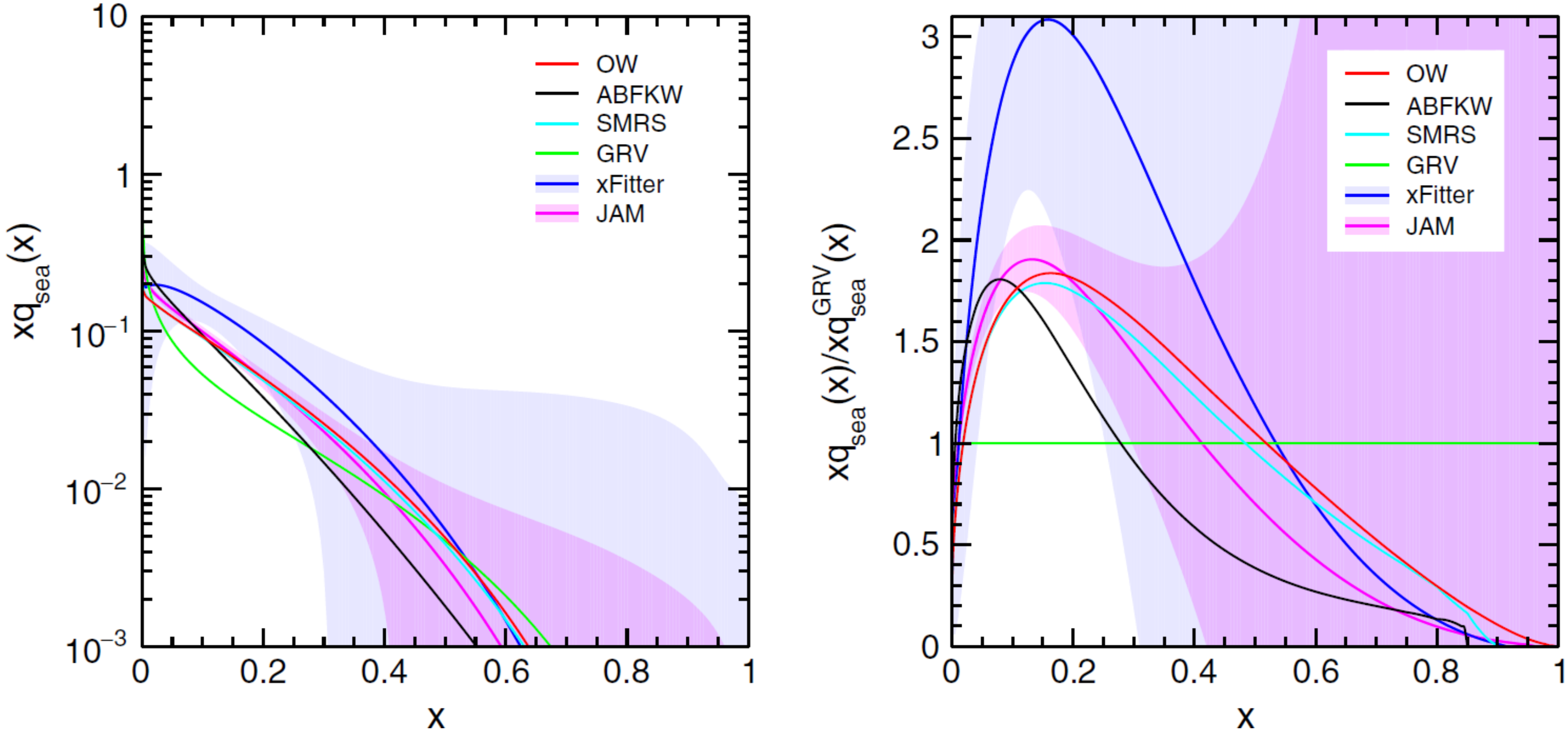
$$Q^2 = 9.6\ \mathrm{GeV}^2$$



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

Pion PDFs: Sea Quarks

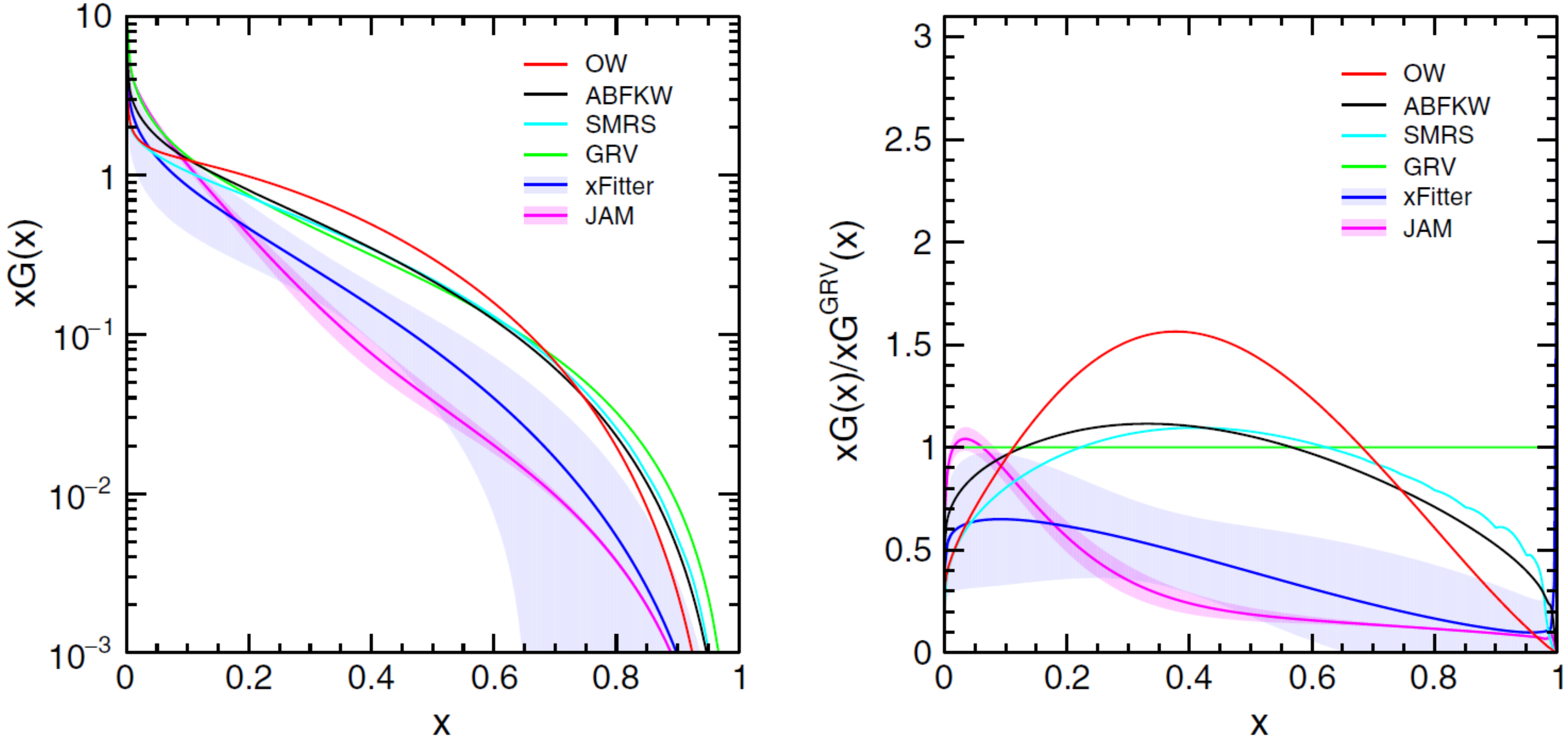
$$Q^2 = 9.6 \text{ GeV}^2$$



In the valence regions, the uncertainties of sea quarks are significant.

Pion PDFs: Gluons

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



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

Pion PDFs from Lattice QCD

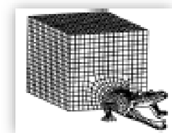
Z.H. Zhang et al., PRD 100, 034505 (2019)

Pion PDF

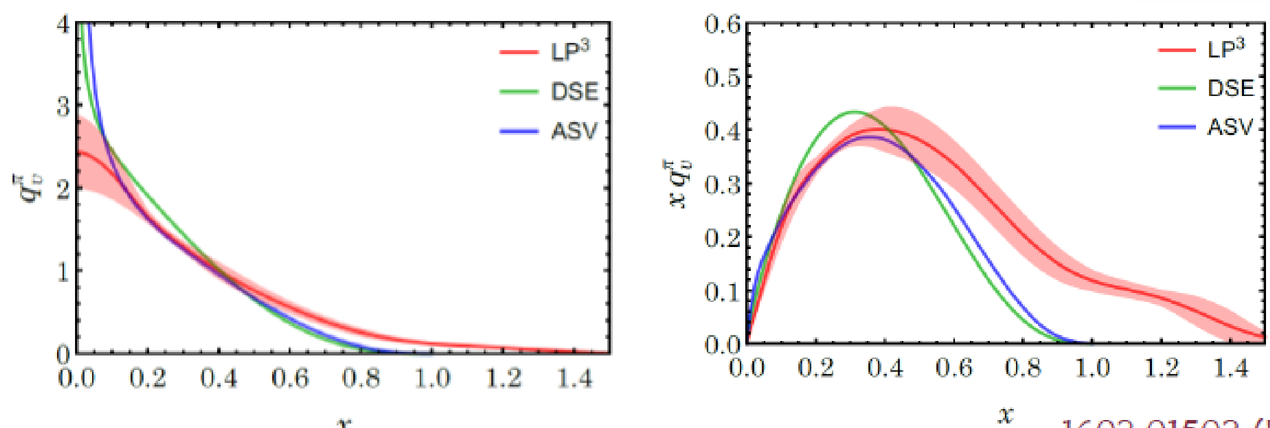
§ Not trivial to calculate in reality either

§ The first lattice exploratory study

1804.01483 (LP^3)



❧ $M_\pi \approx 310$ MeV, $a \approx 0.12$ fm ($M_\pi L \approx 4.5$)



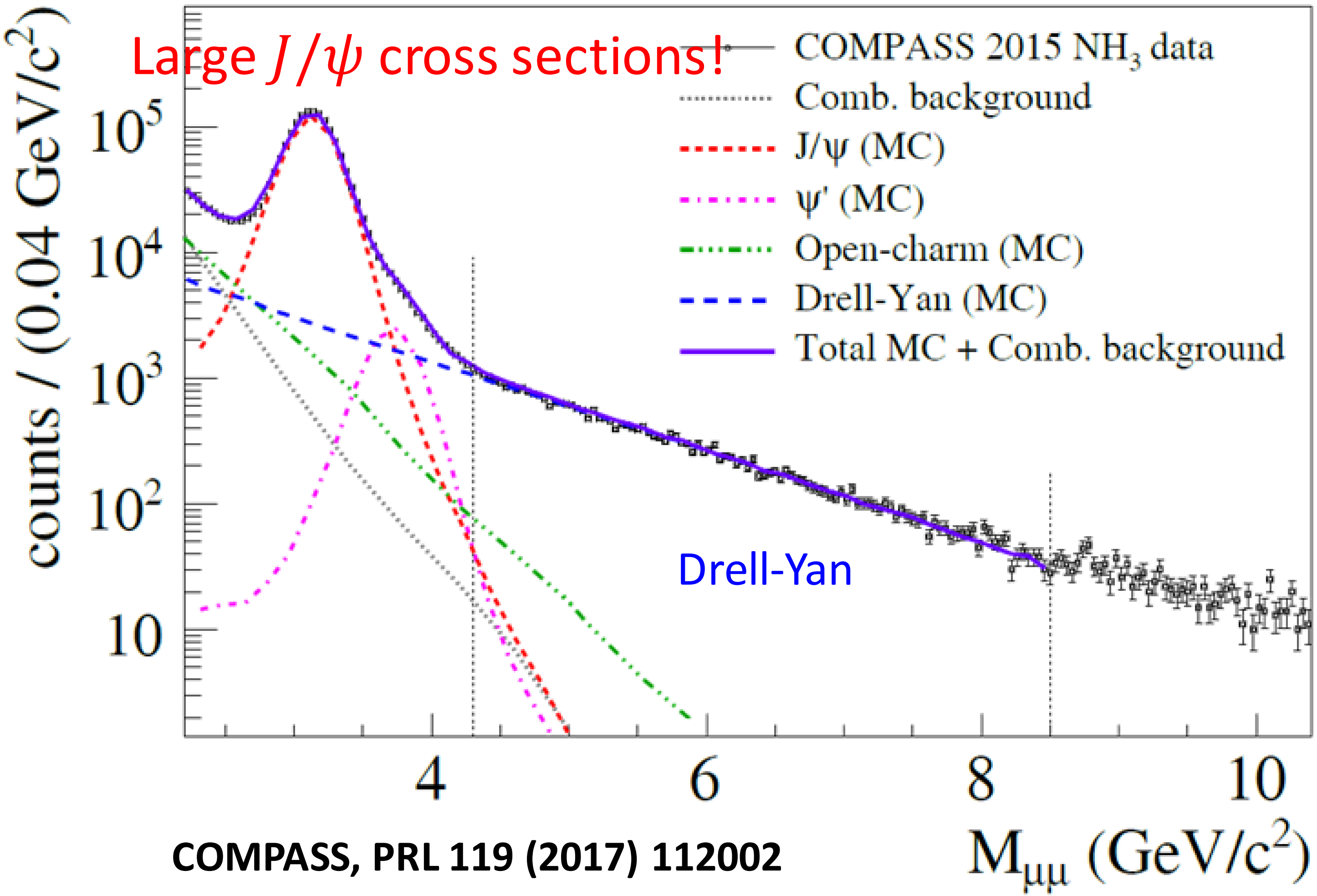
1602.01502 (DSE)
1009.2481(ASV)

§ Study of systematics needed

❧ Lattice-spacing, finite-volume, larger P_z, ...

H.W. Lin, JLAB pieic2018 workshop

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



COMPASS, PRL 119 (2017) 112002

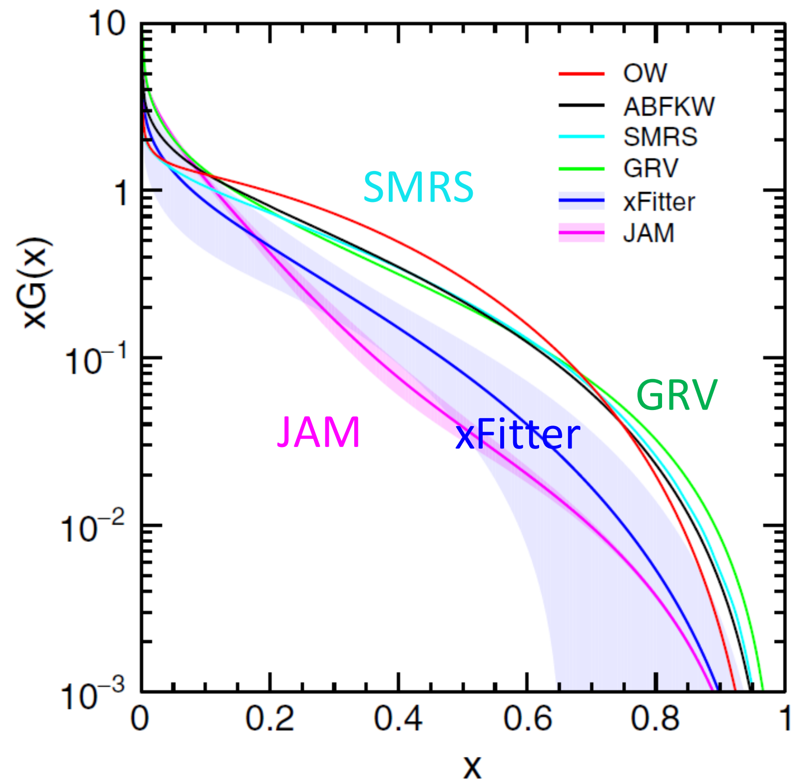
Pion-induced J/psi Production - Fixed-target Experiments

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

Goals of This Work

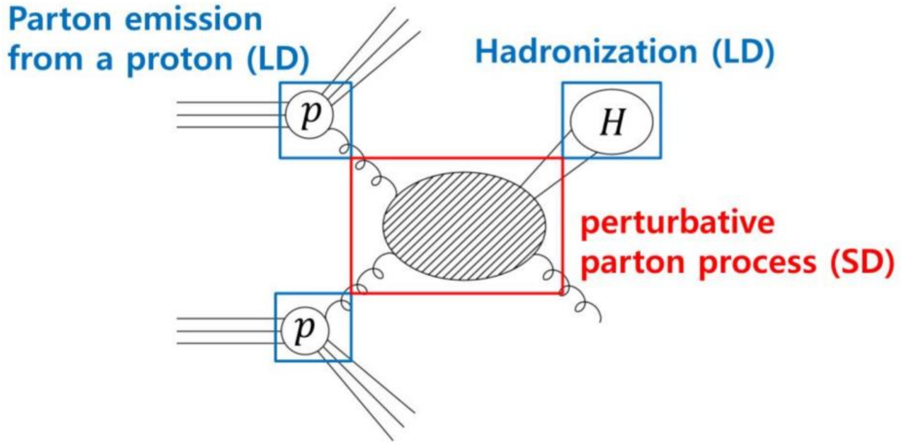
- **Color evaporation model** calculations of J/psi production: LO/NLO
- P**ion PDFs**: SMRS, GRV, xFitter and JAM with different gluon strength at large-x.
- Pion-induced $\sigma(\sqrt{s}, x_F)$ over a wide range of beam energy – [40, 515] GeV.

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



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 charmonium.
- **Non-relativistic QCD model (NRQCD)**: all pairs of different color and spin sates fragmenting with different probabilities – long-distance matrix elements (LDMEs).

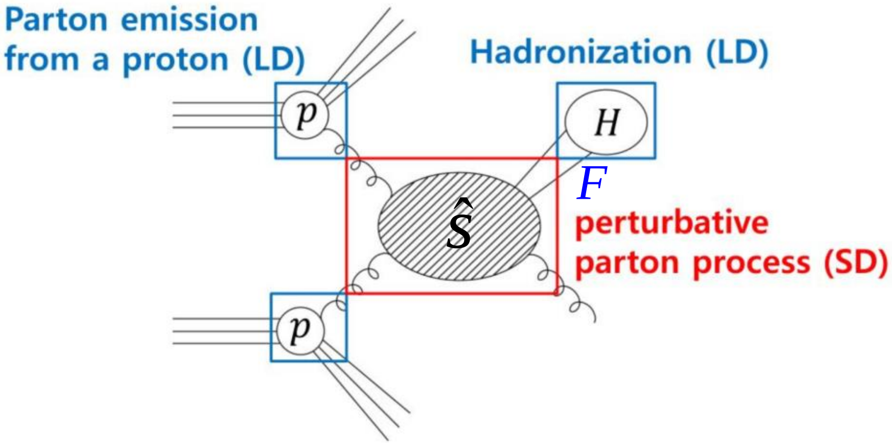


Color Evaporation Model

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

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

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

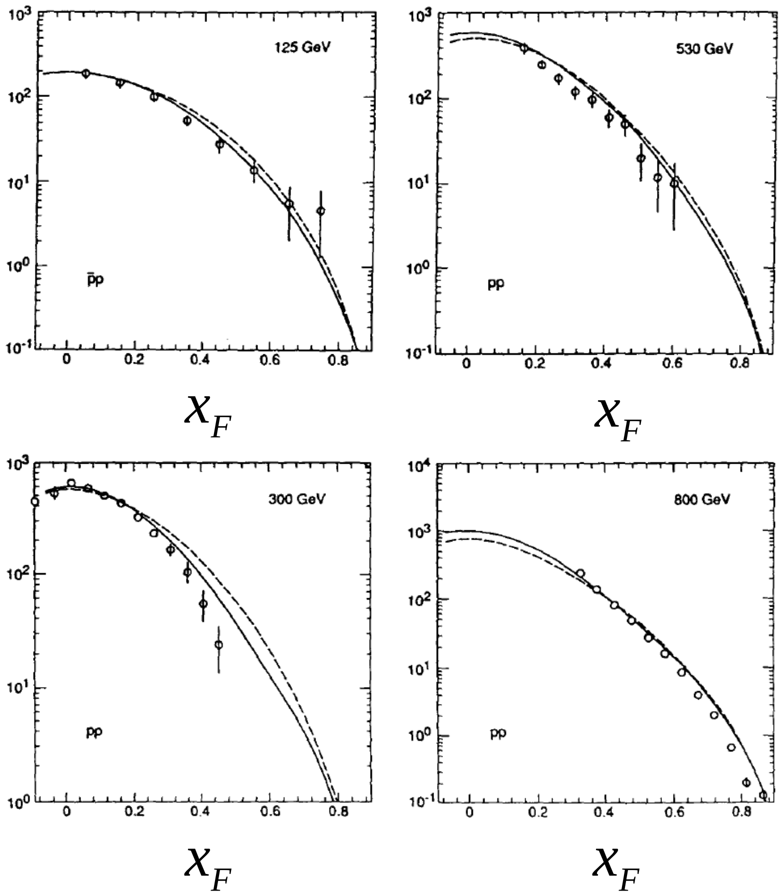


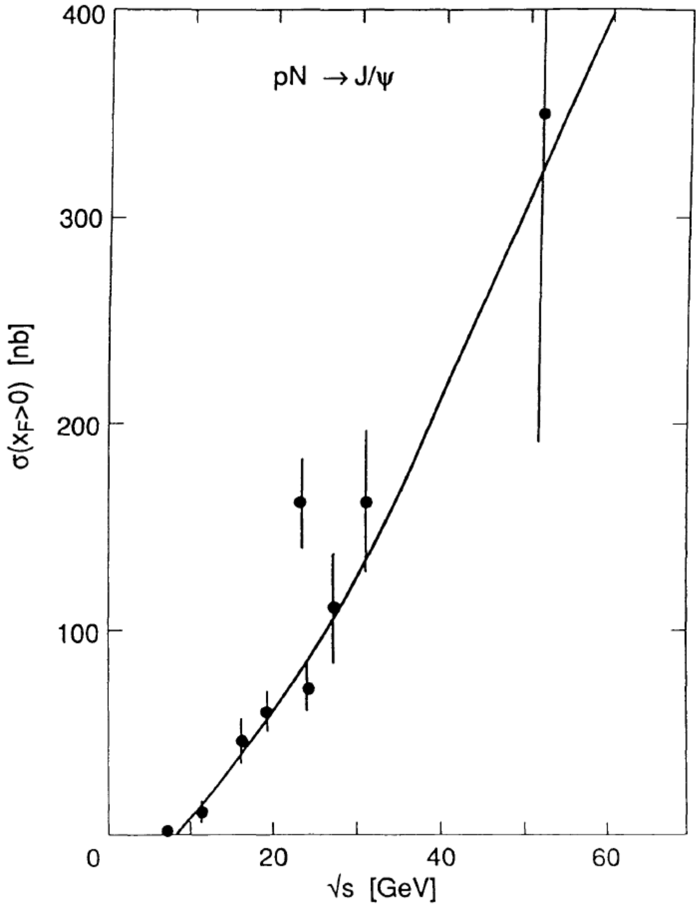
LO/NLO calculations of $\hat{\sigma}[ij \to c\bar{c}X]$:

- 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

pp: Data vs. CEM NLO

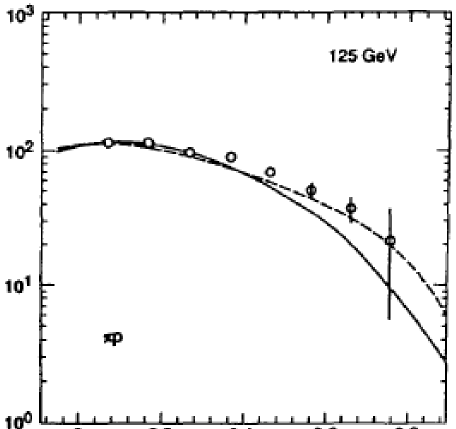
[Gavai et al., IJMPA 10, 3043 (1995)]



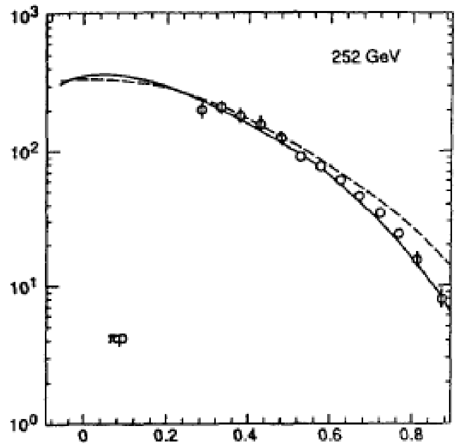


πp: Data vs. CEM NLO

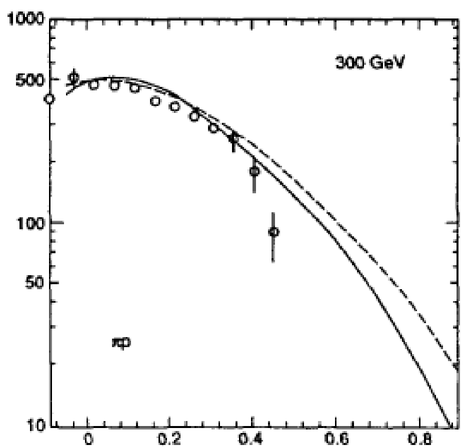
[Gavai et al., IJMPA 10, 3043 (1995)]



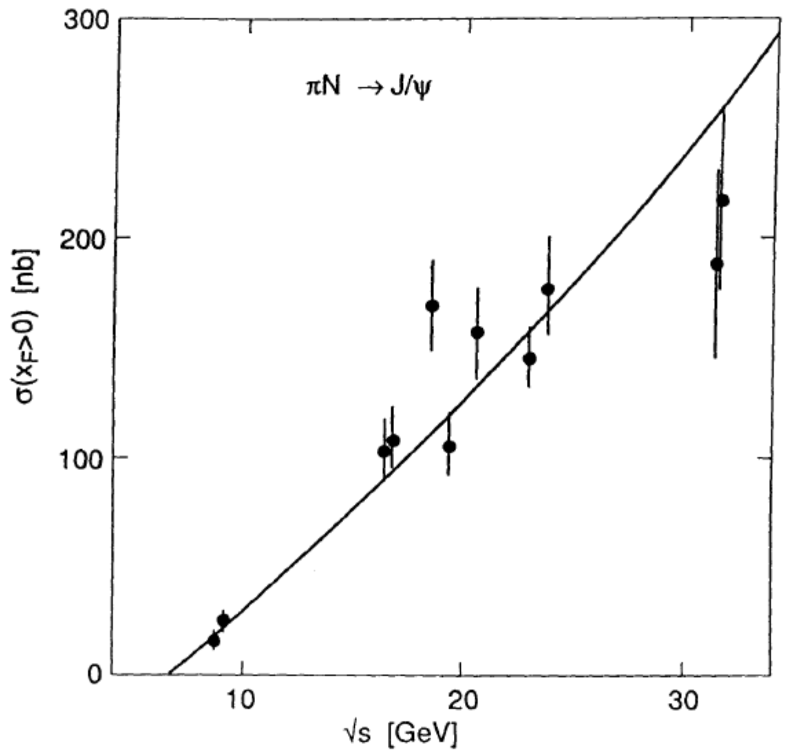
x_F



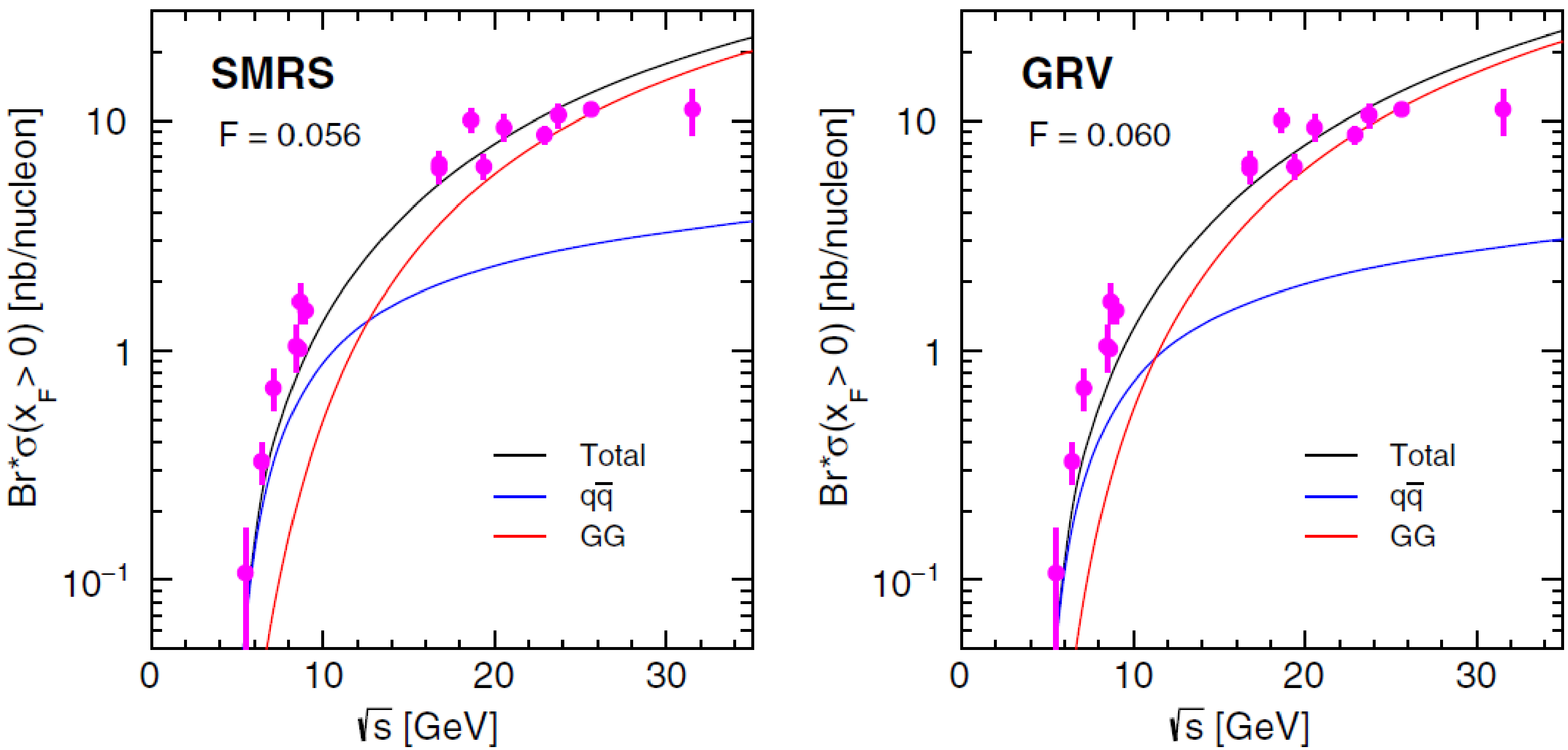
x_F



x_F

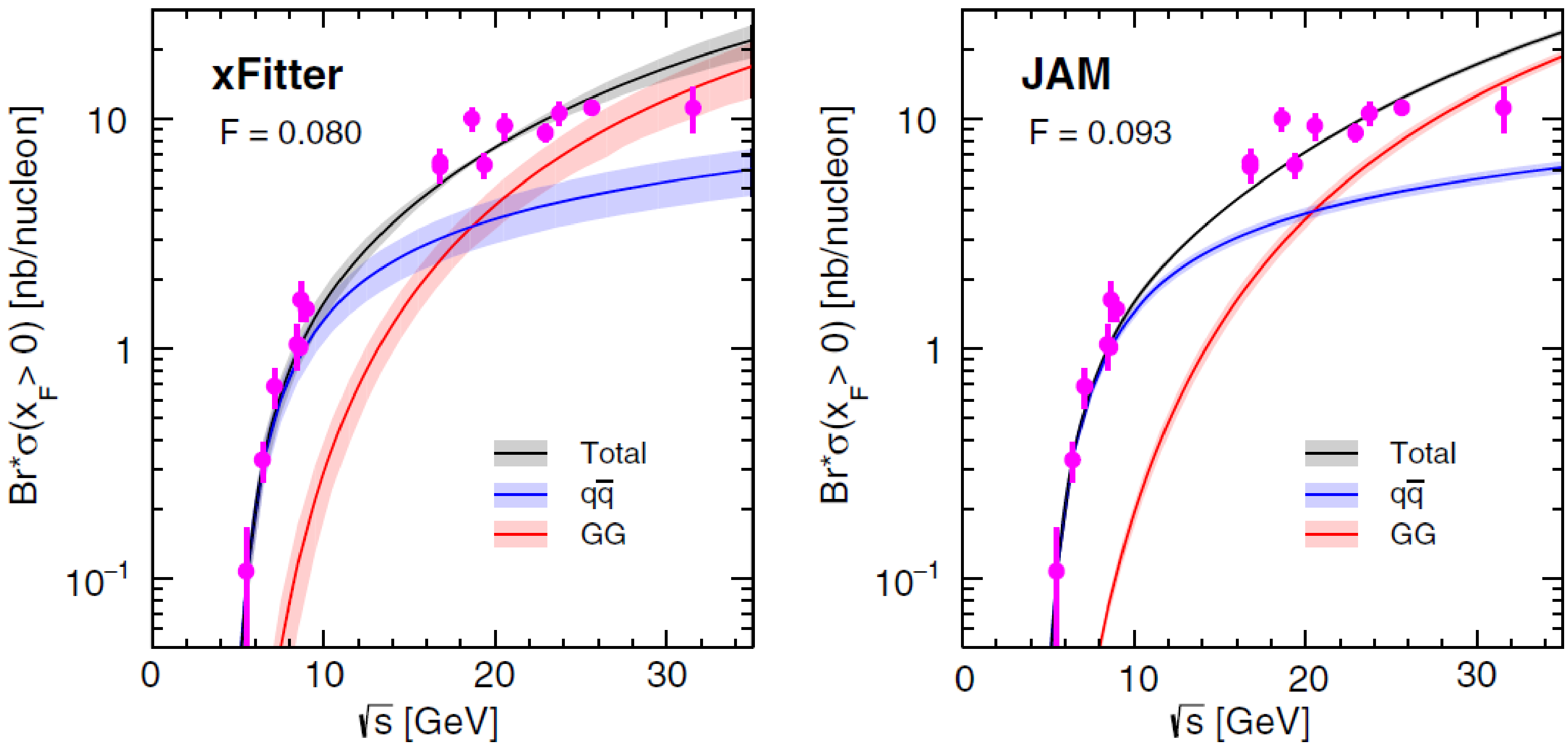


Data vs. CEM NLO
: Energy dependence



GG dominates at high energies while qqbar is important near threshold.

Data vs. CEM NLO
: Energy dependence



GG dominates at high energies while qqbar is important near threshold.

Data of $d\sigma/dx_F$

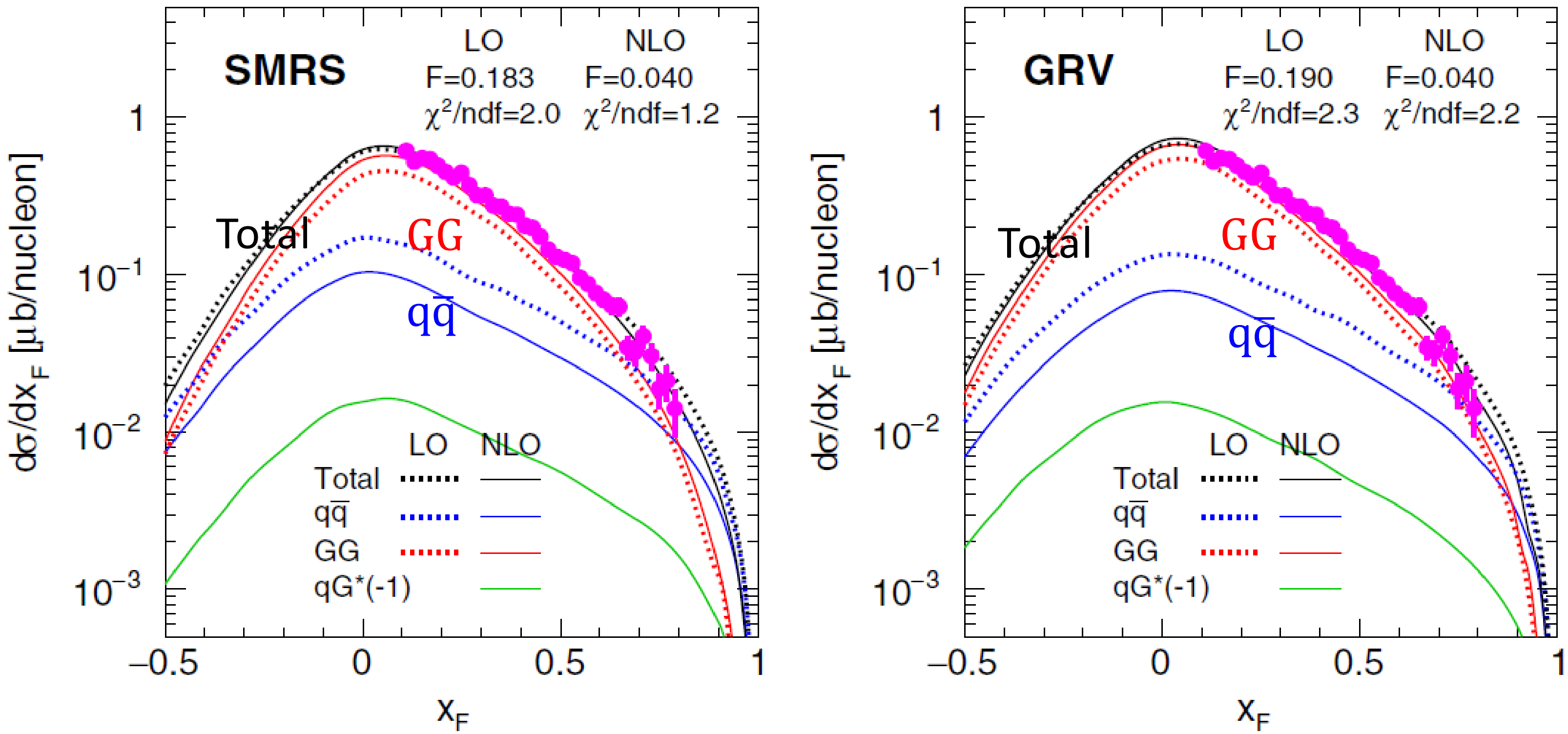
TABLE II. The J/ψ production datasets with π^- beam used in the analysis, listed in order of decreasing beam momentum.

Experiment	P_{beam} (GeV/c)	Target	Normalization[a]	References
FNAL E672, E706	515	Be	12.0	[68]
FNAL E705	300	Li	9.5	[69]
CERN NA3[b]	280	p	13.0	[70]
CERN NA3[b]	200	p	13.0	[70]
CERN WA11[b]	190	Be	[c]	[72]
CERN NA3[b]	150	p	13.0	[70]
FNAL E537	125	Be	6.0	[73]
CERN WA39[b]	39.5	p	15.0	[74]

Data vs. CEM LO/NLO

[$\pi^- + Be \rightarrow Jpsi + X$ at 515 GeV, PRD 53, 4723 (1996)]

m_c=1.5 GeV, μ_F=2m_c, μ_R=m_c,
hadronization parameter 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.

Data vs. CEM LO/NLO

[$\pi^- + Be \rightarrow Jpsi + X$ at 515 GeV, PRD 53, 4723 (1996)]

m_c=1.5 GeV, μ_F=2m_c, μ_R=m_c,
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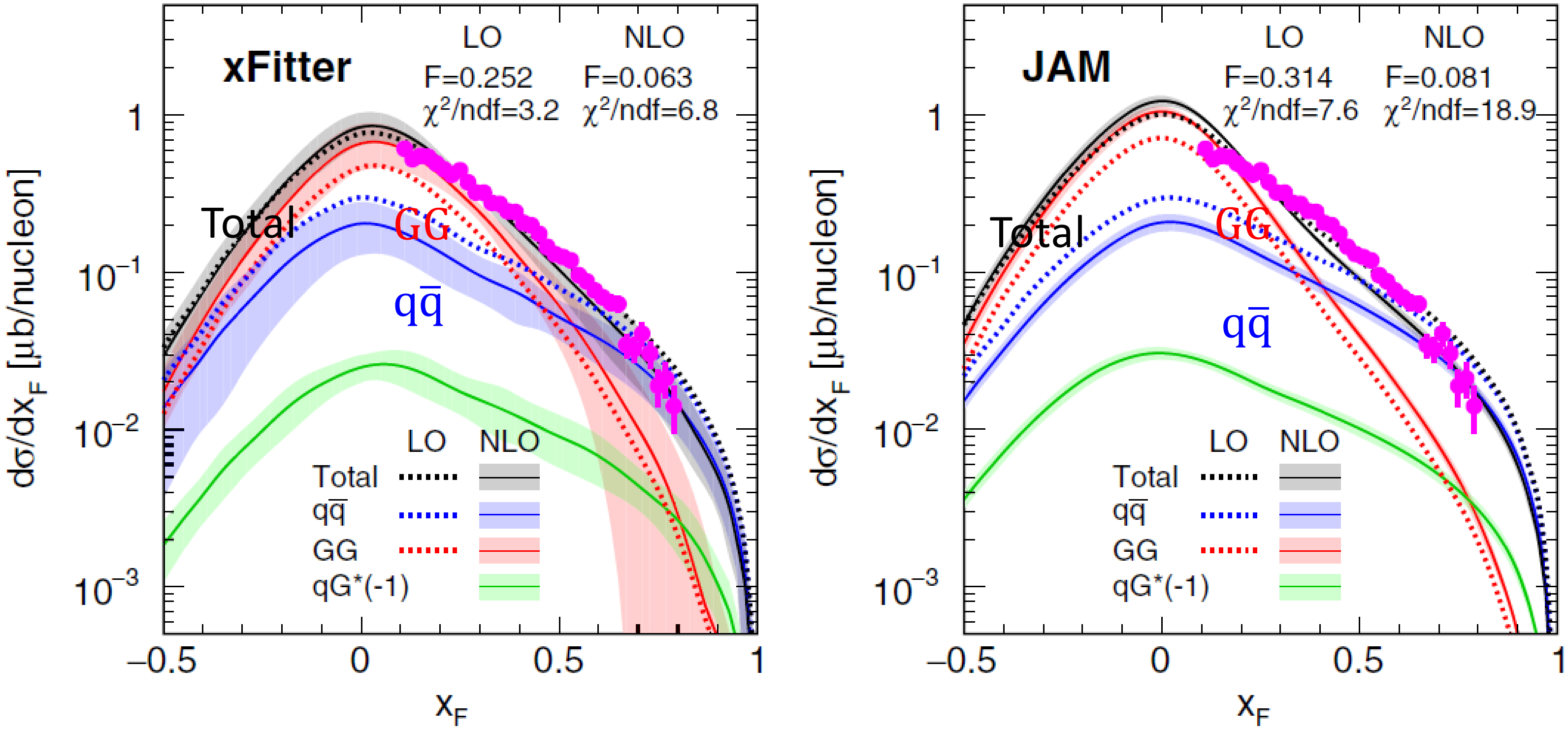
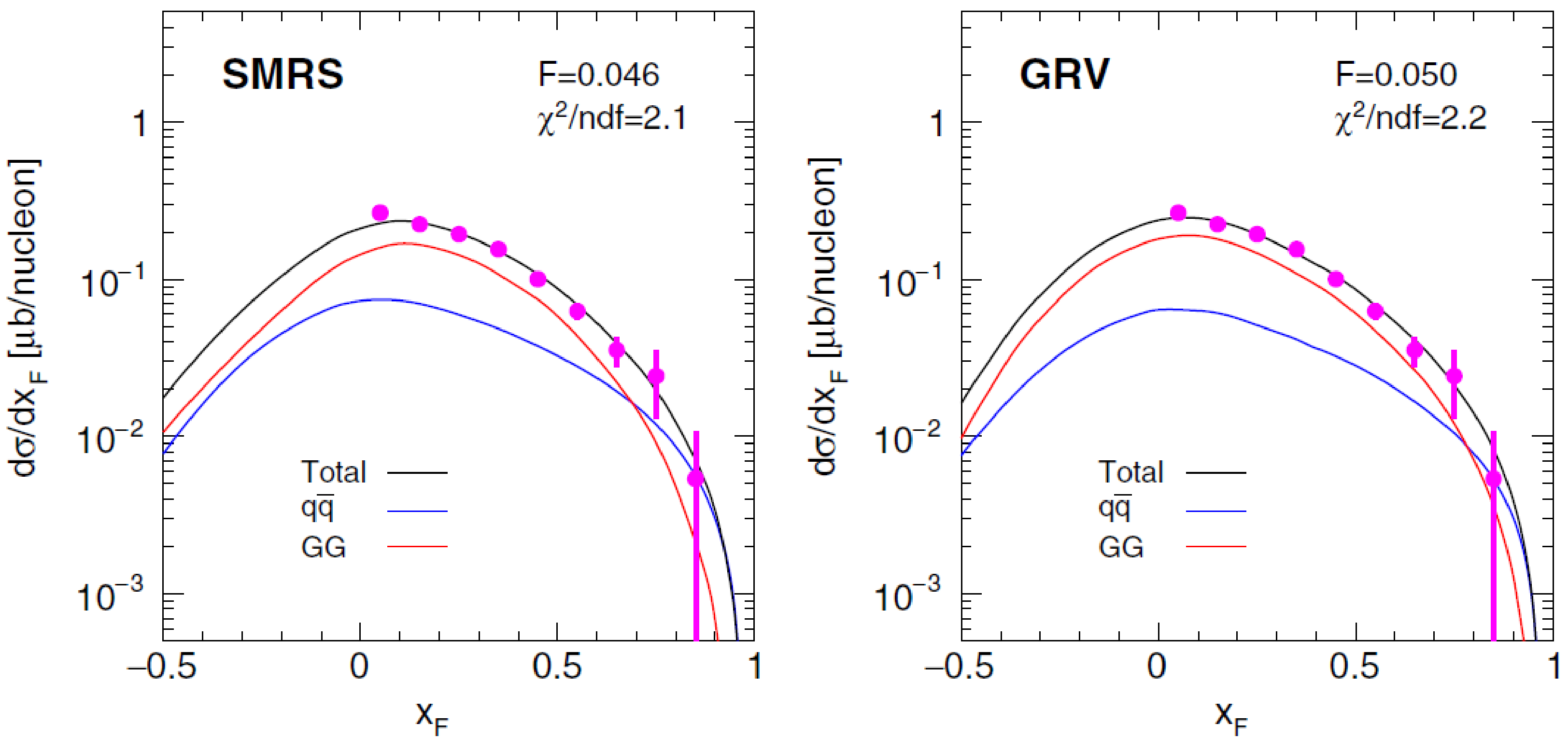


- The GG contribution dominates except at very forward or backward directions.
- The weighting of GG contribution is enhanced in the NLO calculations.

Data vs. CEM NLO

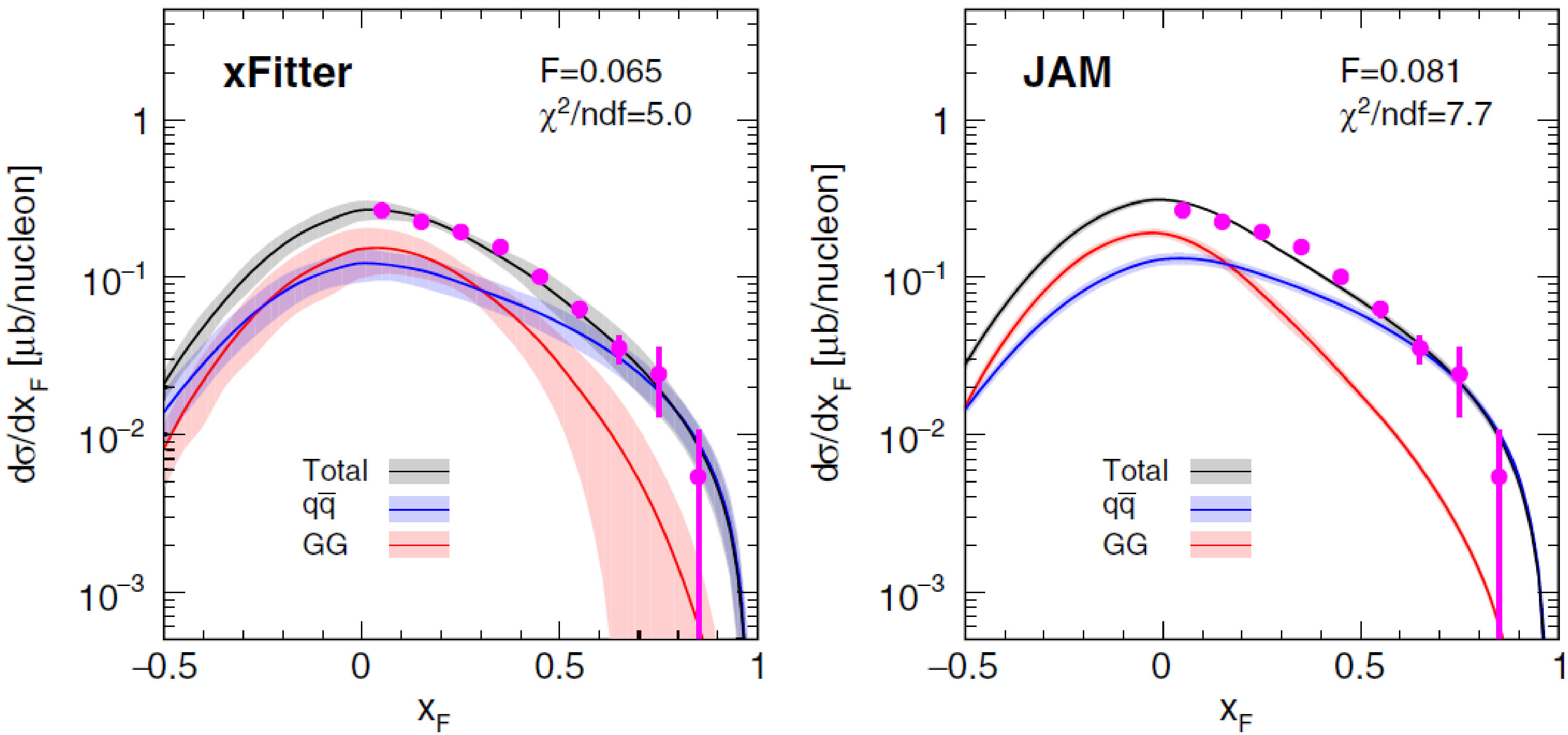
[$\pi^- + Pt \rightarrow Jpsi + X$ at 200 GeV, Z. Phys. C20,101(1983)]



- To well describe the data for xF>0.2, an appropriate weighting of GG and $q\bar{q}$ contributions is necessary.

Data vs. CEM NLO

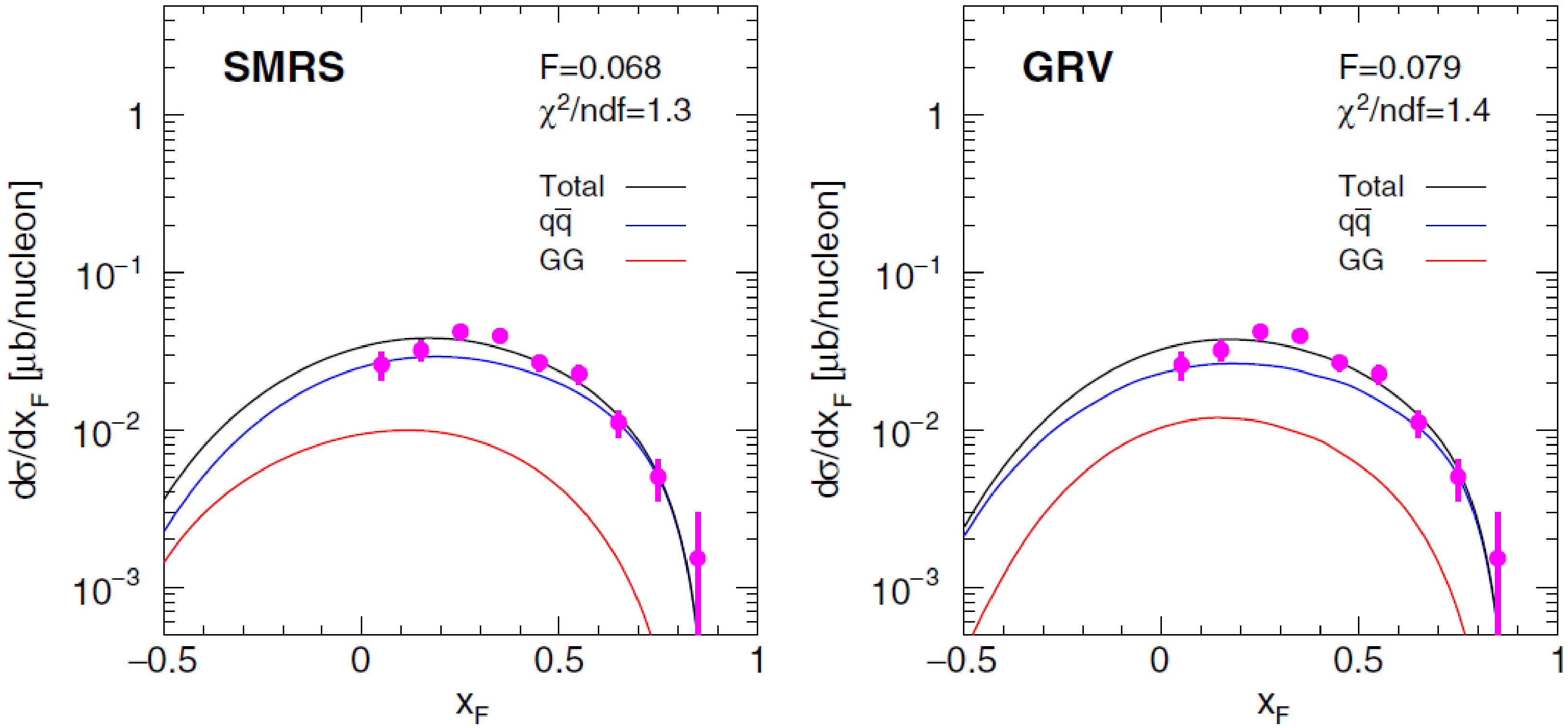
[$\pi^- + Pt \rightarrow Jpsi + X$ at 200 GeV, Z. Phys. C20,101(1983)]



- To well describe the data for xF>0.2, an appropriate weighting of GG and $q\bar{q}$ contributions is necessary.

Data vs. CEM NLO

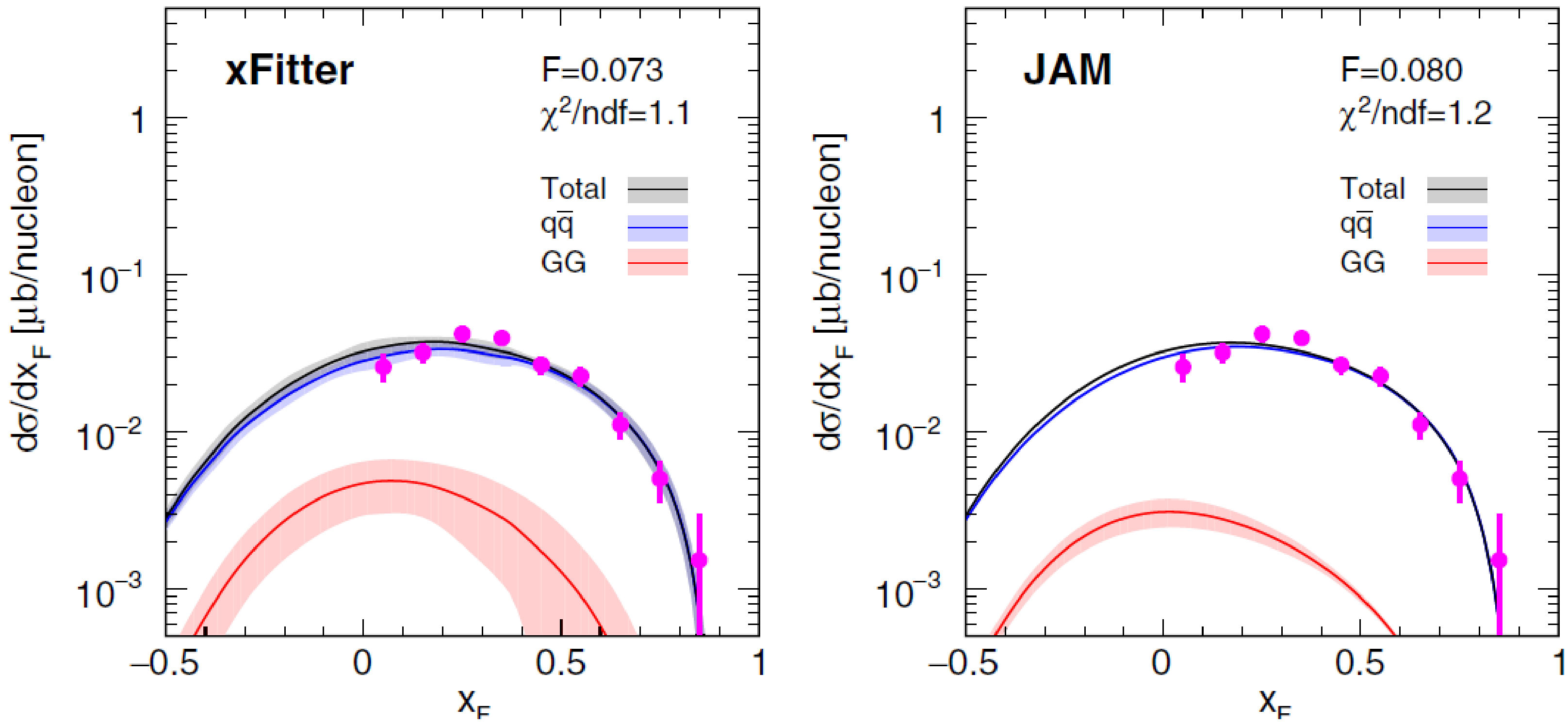
[$\pi^- + p \rightarrow Jpsi + X$ at 39.5 GeV, PLB 98, 220 (1981)]



- Calculations of all four PDFs describe the data well.

Data vs. CEM NLO

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

New Measurements at CERN

Timelines (meson PDFs only)

- Present: (2015 and 2018) data – improved knowledge:
  - Pion valence PDF
  - Kaon/Pion u(x) ratio measurement: with an upgraded beam identification (CEDAR) in 2018

Compass

----------- Future options ------------

- Near future (No RF needed): 1 year $\pi+/\pi-$ run immediately after LS2
  - valence – sea separation of the pion PDFs
  - direct photon production : measurement of $g_{\pi}(x)$

New experiment

- RF separation: dedicated runs with an intense kaon beam
  - Kaon valence PDF
  - Kaon sea and/or valence strange distribution
  - Direct photon production : measurement of $g_K(x)$

New experiment

Letter of Intent writing has started. Ideas and contributions from people outside COMPASS more than appreciated

S. Platchkov Argonne, PIEIC 2017 42

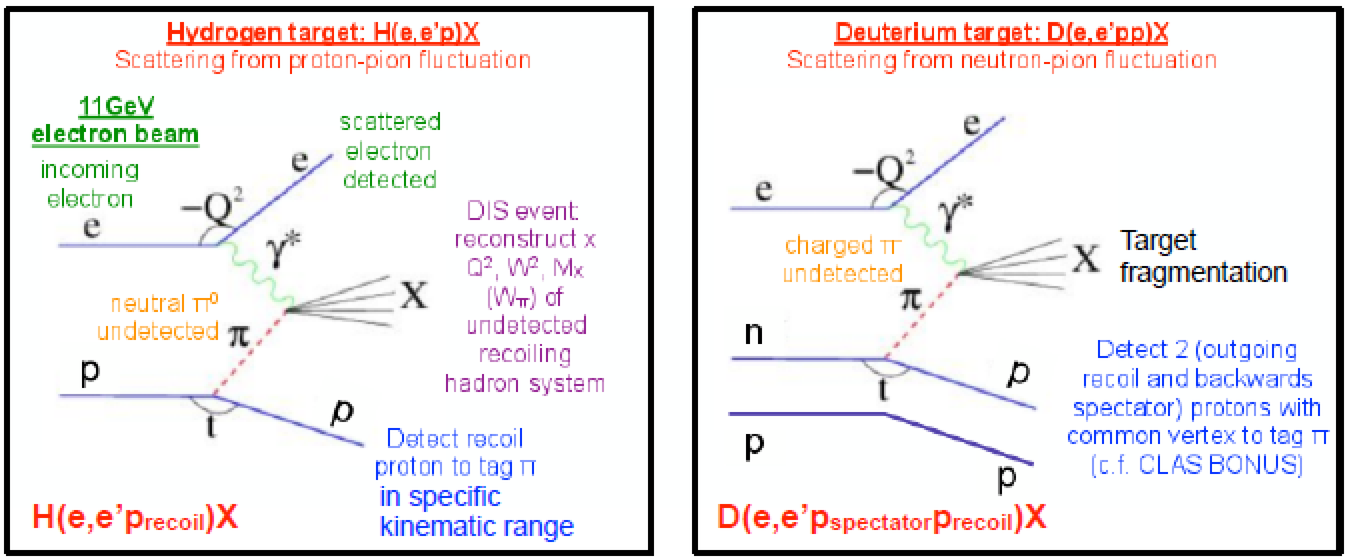
https://nqf-m2.web.cern.ch/

S. Platchkov, ANL pieic2017 workshop

New Measurements at JLAB

University of Glasgow

Pion TDIS Measurement in Hall A



- W^2 invariant mass squared, Q^2 virtuality exchanged photon, x Bjorken x
- t = 4-mom transfer squared at nucleon vertex = $k^2 = (p-p')^2$; p,p' initial,final proton momenta
- t must be small to extrapolate to pole ($|t| < 0.2 (GeV/c)^2$)
- <u>**The detected protons are low momentum (60MeV/c - 400MeV/c)**</u>
- **Access to both neutral and charged meson clouds**

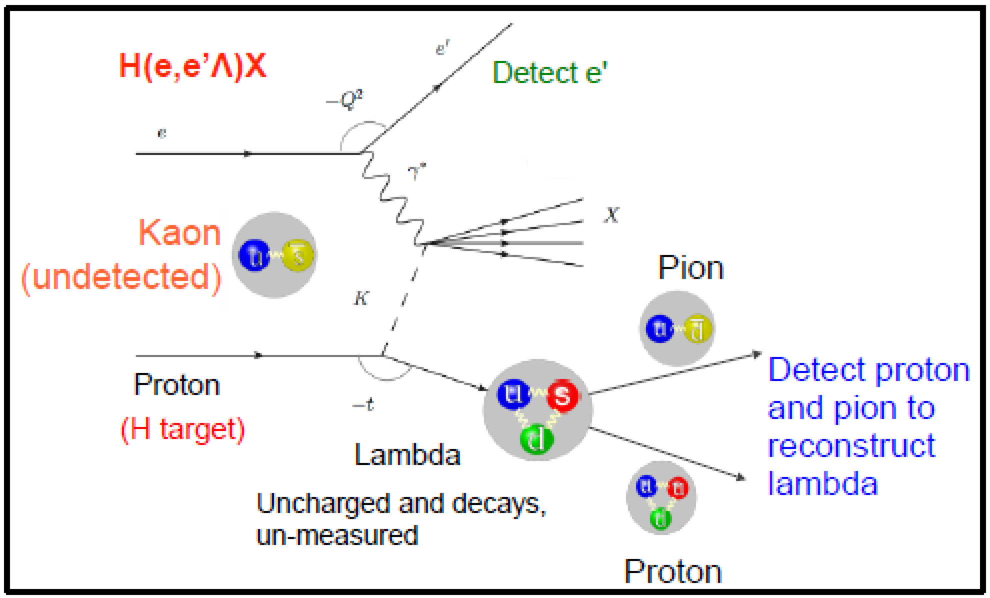
$8 < W^2 < 18$ GeV²
$1 < Q^2 < 3$ GeV²
$0.05 < x < 0.2$

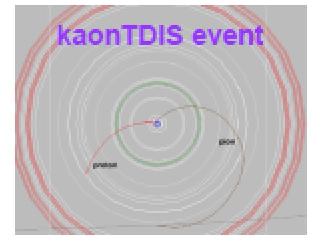
R.A. Montgomery, JLAB pieic2018 workshop

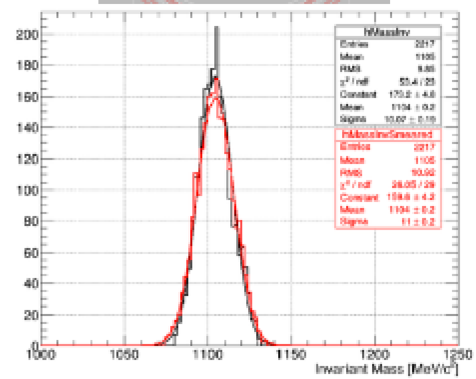
New Measurements at JLAB

University of Glasgow

Kaon TDIS Measurement in Hall A







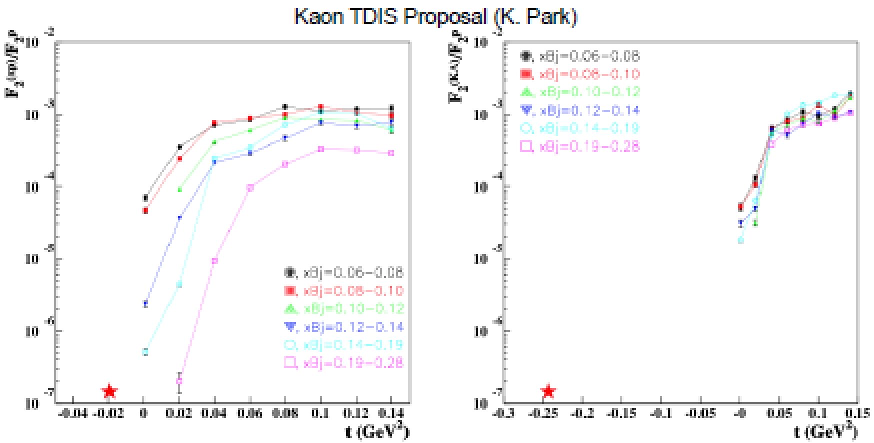
- Lambda reconstructed from pπ- invariant mass and track/vertex
- Proton and pion mostly emitted back to back, with angular and time correlation
- Protons, pions again low momentum in similar range as pion TDIS
- Kaon TDIS also background to pion TDIS (also e.g. $\Delta^0 \rightarrow p\pi^-$ and $\Sigma^0 \rightarrow \Lambda^0\gamma \rightarrow p\pi^-$ etc in pion exchange model) - would be useful to study
- Event generator written for kaon TDIS using chiral effective theory for strange quark asymmetry (arXiv:1610.03333 (2016)), splitting functions, all Feynman diagram contributions to s(bar) PDF in nucleon (K. Park, see proposal for details)

R.A. Montgomery, JLAB pieic2018 workshop

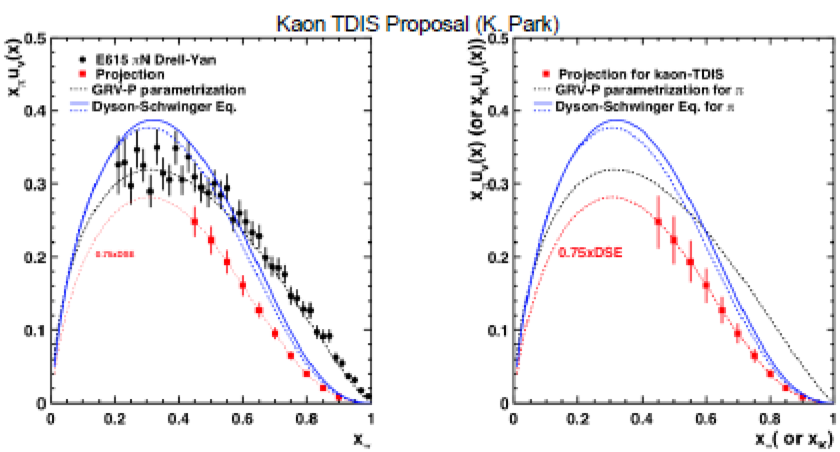
New Measurements at JLAB

University of Glasgow

Projected Results



- t-dependence for different x_{Bj}
- $F_2^{(\pi p)}(t,\Delta x)/F_2^p$ for momentum 100 - 400MeV/c
- $F_2^{(K\Lambda)}(t,\Delta x)/F_2^p$ for momentum <100MeV/c
- Statistical errors included
- As low a momentum reach of mTPC as possible essential for extrapolation to obtain shape of curve

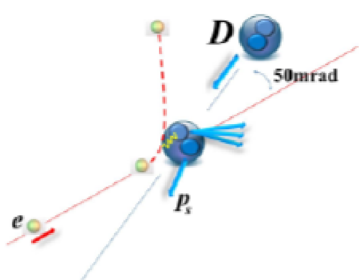


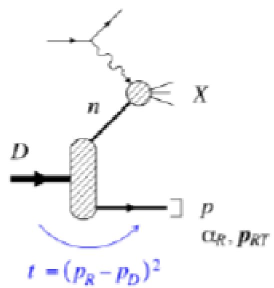
- Projected valence quark distribution as a function of $x_{\pi/K}$
- Results from Drell Yan E615
- GRV-P parameterisation and DSE for pion only
- 5% systematic uncertainty in pion flux assumed, total systematic uncertainty of 8.4% included

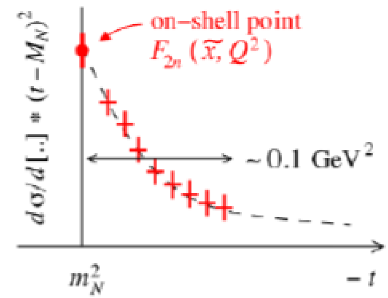
R.A. Montgomery, JLAB pieic2018 workshop

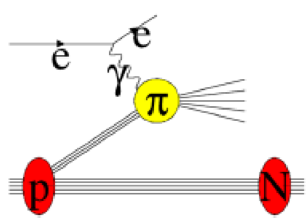
New Measurements at EIC

EIC – Versatility is Key









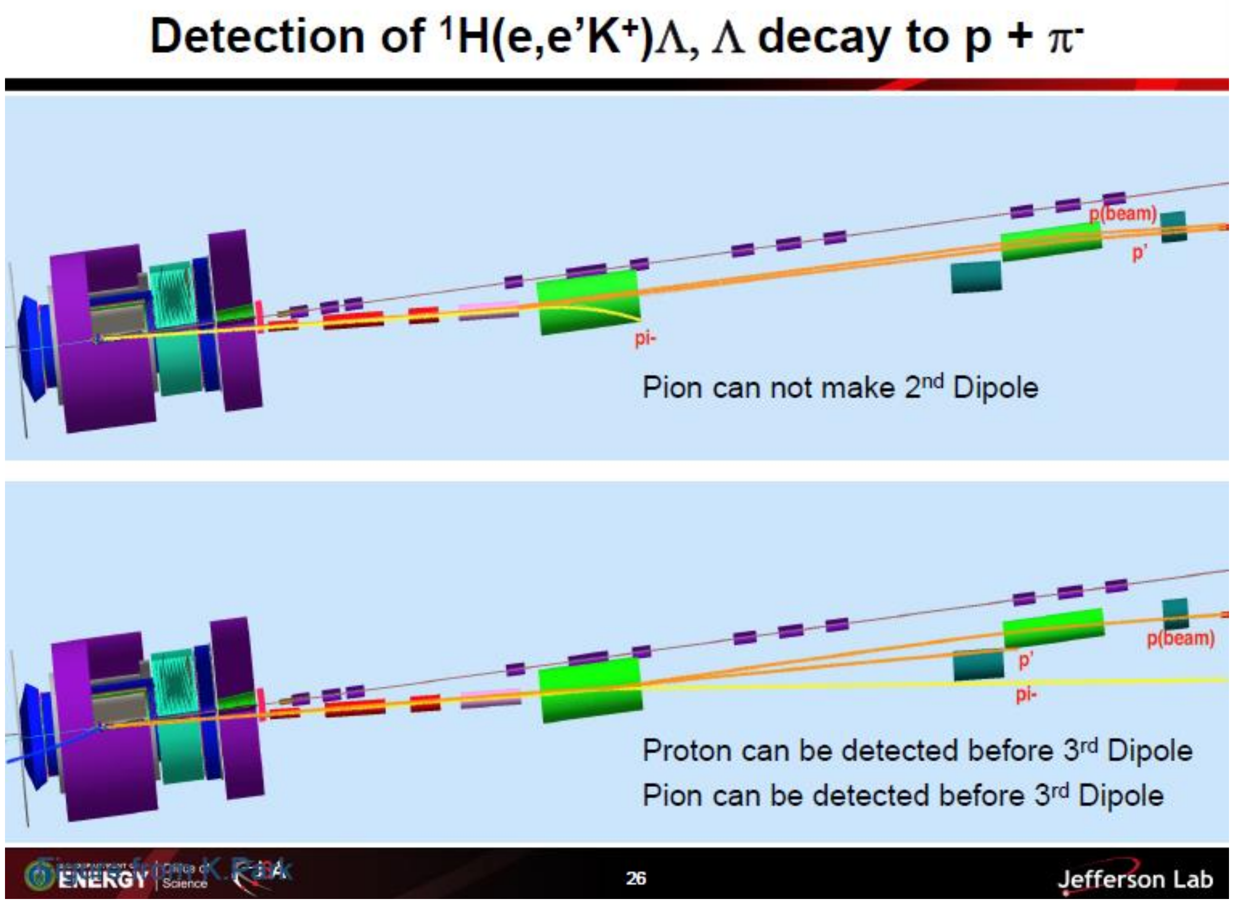
- Obtain F_2^n by tagging spectator proton from e-d, and extrapolate to on-shell neutron to correct for binding and motion effects.
- Obtain F_2^π and F_2^K by Sullivan process and extrapolate the measured t-dependence as compared to DSE-based models.

→ **Need excellent detection capabilities, and good resolution in –t**

ENERGY Office of Science JSA 22 Jefferson Lab

[R. Ent, DIS 2018]

New Measurements at EIC



[R. Ent, DIS 2018](#)

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. The current data favor the SMRS and GRV pion PDFs, containing relatively larger gluon content at large x.
- With the coming new data of meson-induced J/psi from COMPASS/AMBER and Tagged-DIS from JLAB and EIC, could be used to improve the less-known gluon/sea distributions in pion/kaon PDFs.