CEA - Saclay

Charmonium production: a tool for accessing the gluon distribution in the pion

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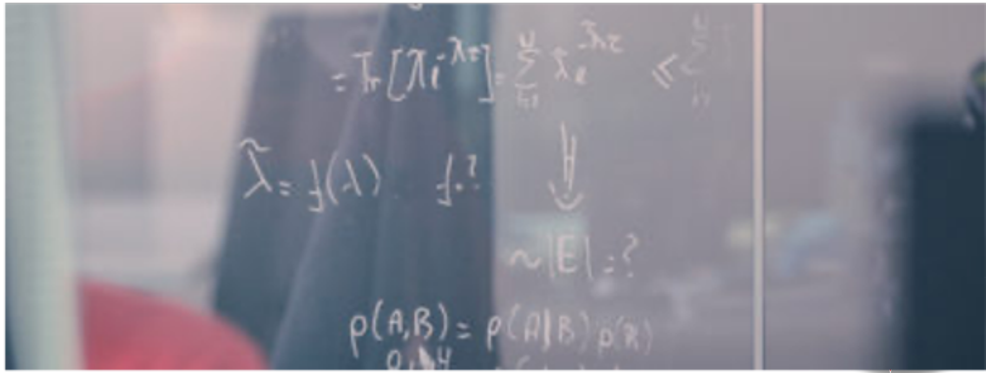
(collaboration with W.-C. Chang, C-.Y. Hsieh , Y.-S. Lian, J.-C. Peng, and T. Sawada)

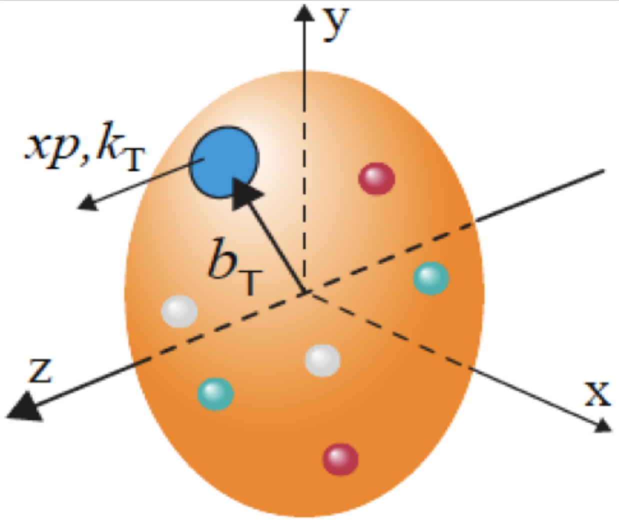
Parton distribution functions at a crossroad

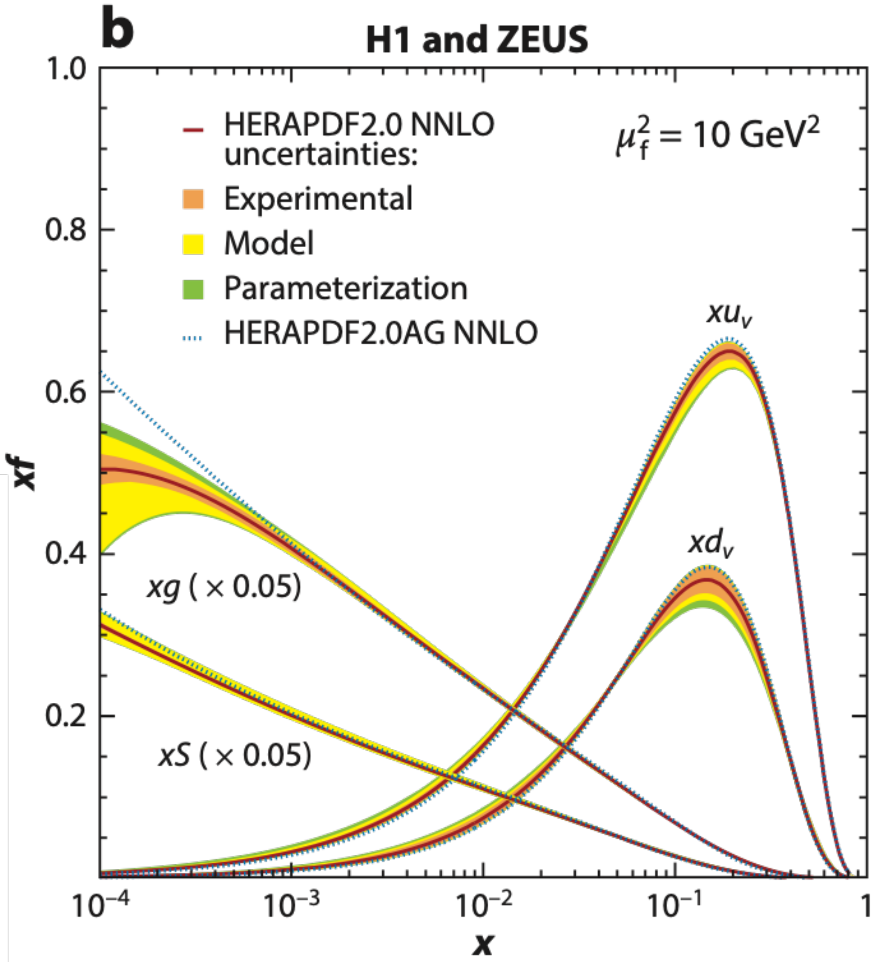
ECT* Trento, 18 – 22 September 2023



Hadron structure: the nucleon

- Main laboratory for QCD studies
  - More than 4 decades of extensive investigations
  - Hundreds of experiments
  - Parton distributions are well known
  - Perturbative QCD works really well
  - Aim at a full multidimensional picture : GPDs, TMDs:

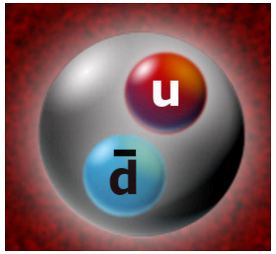


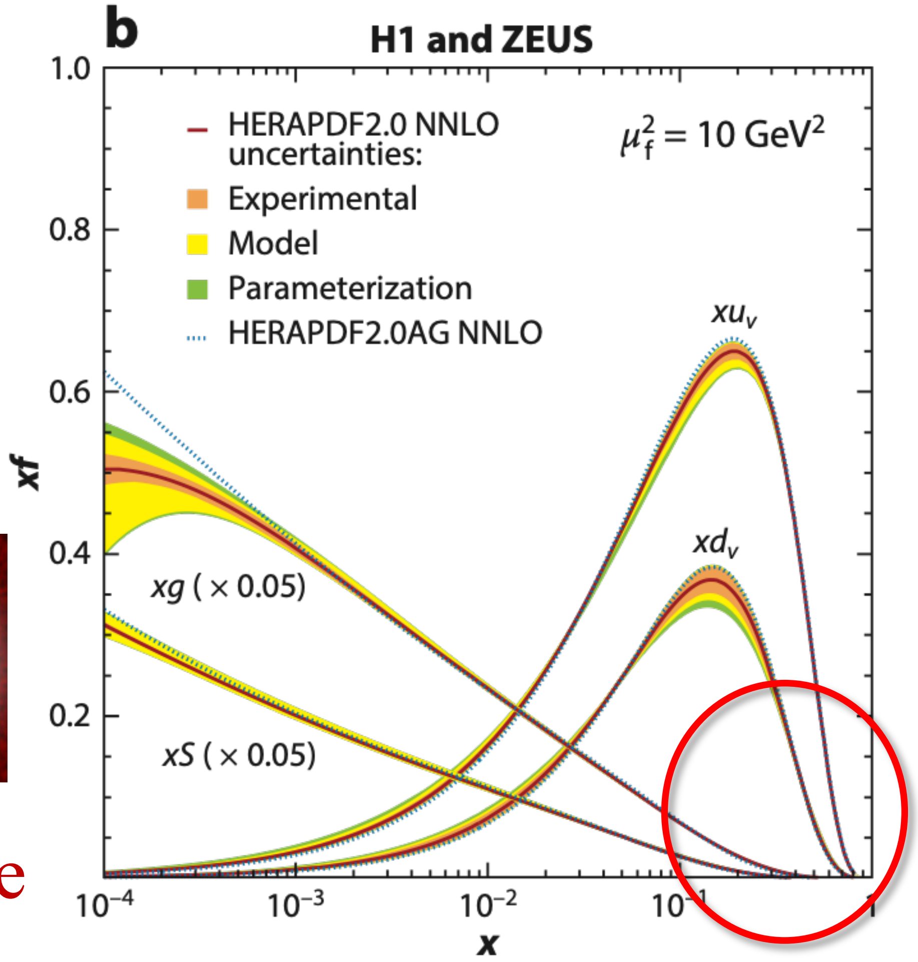


The nucleon structure is (almost) perfectly known –over few decades in x

Hadron structure: the pion and the kaon

- Laboratories for QCD studies
  - Absence of meson targets
  - Few experiments, few decades old
  - Pion parton distributions are quite uncertain
  - Kaon parton distribution are essentially unknown
  - Good news: new data from Compass + Amber, Jlab, EIC





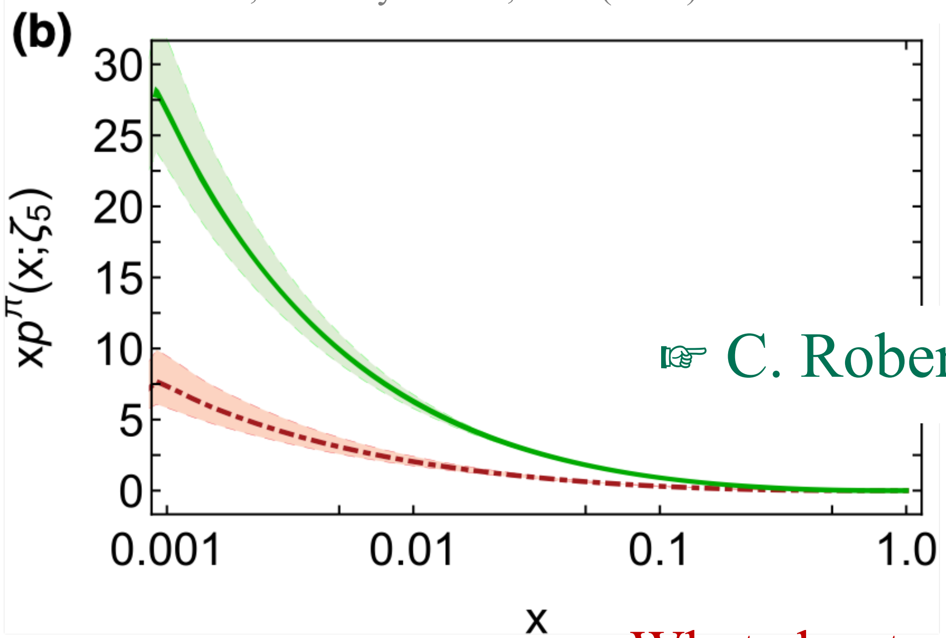
(☞ V. Andrieux, ☞ O. Denisov) Pion structure

Sharp contrast with the present knowledge on the pion. And on the kaon

Meson structure in the last few years - theory

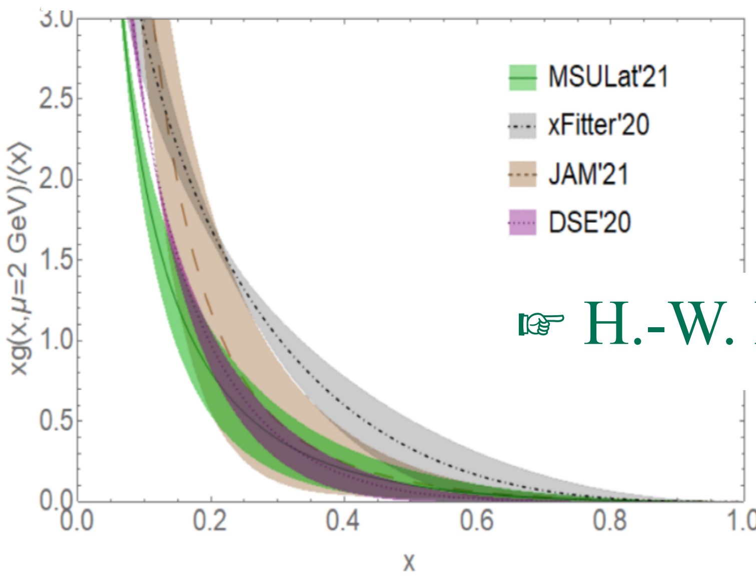
- Remarkable progress in theory
  - Continuum Schwinger method (CSM)
  - Lattice QCD
    - Aim at describing the properties of the two simplest hadrons (e.g. pion gluon PDF):

Cui et al., Eur.Phys.J C80,1064 (2020).



☞ C. Roberts

Z. Fan and H-W. Lin, Phys.Lett. B823, 136778 (2021)

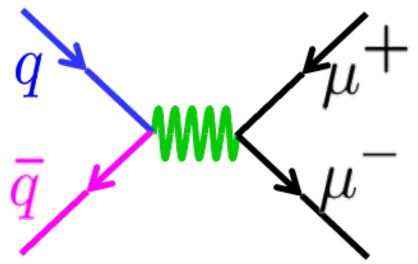


☞ H.-W. Lin

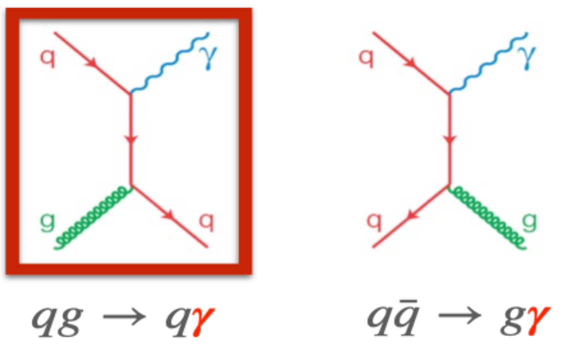
What about experimental info ?

Type of data used to infer the pion PDFs 1/2

- Drell-Yan process
  - Pros: well-known and clean process
  - Cons: low cross sections (em process)
  - Data available: NA3, NA10, E615…

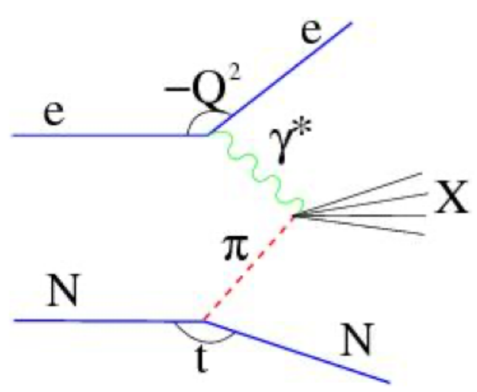


- Prompt-photon π-N production
  - Pros: sensitive to valence and gluon PDFs
  - Cons: high p_T, large background
  - Data available: CERN (WA70, NA24)



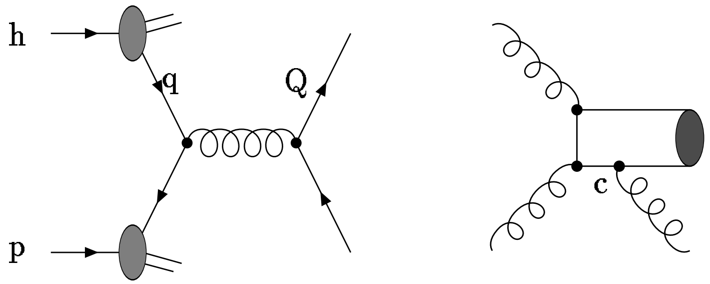
Type of data used to infer the pion PDFs 2/2

- Sullivan (Leading Neutron) process
  - Pros: gives access to lower x values of the PDFs (if high energy)
  - Cons: theoretical uncertainties
  - Data available: HERA (Zeus and H1) + JLab (to come)



- Charmonium production
  - Pros: sensitive to the gluon PDF, large cross sections
  - Cons: production mechanism
  - Data available: CERN: NA3, WA39, WA11

    FNAL: E537, E672, E705



$q\bar{q}$ gg

Four known methods of inferring the pion PDFs

Pion structure – global fits

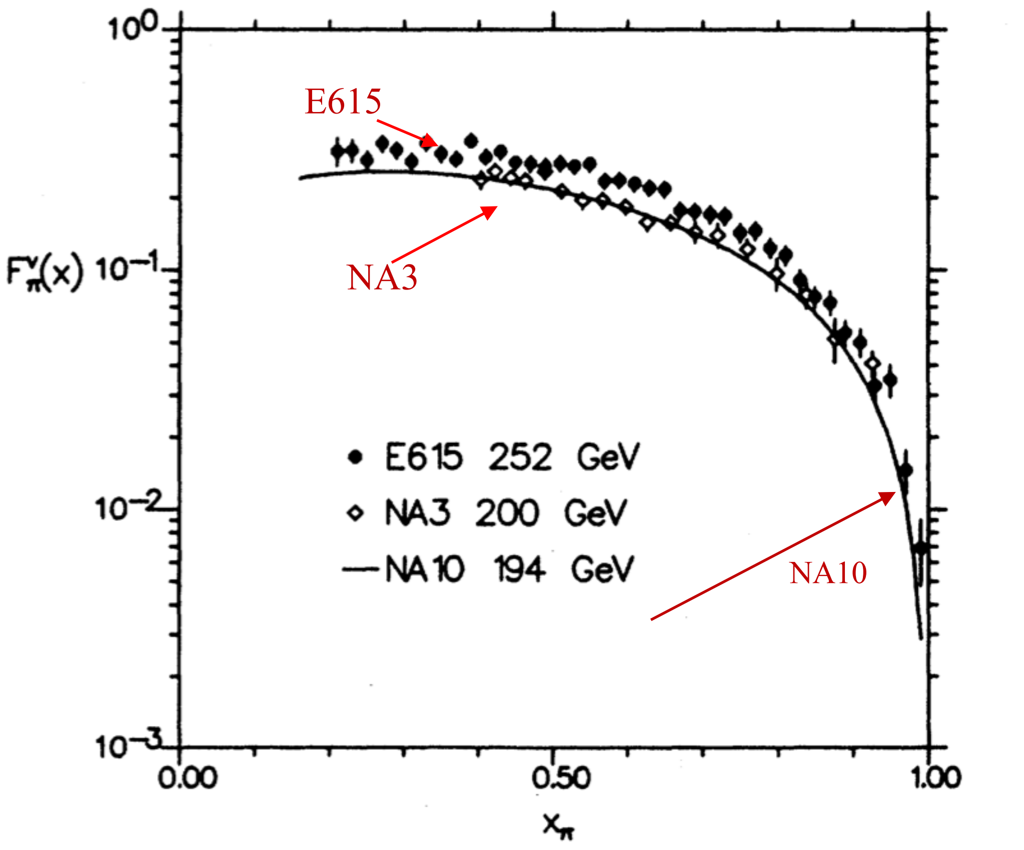
- Previous (3 decades old) global fits (+ a couple of others…)
  - SMRS Sutton, Martin, Roberts and Stirling (1992)
    - DY + Direct-photon production
  - GRV(S) Glück, Reya and Vogt (1992), Glück, Reya and Shienbein (1999)
    - Direct-photon production + DY

- Recent global fits
  - JAM Barry, Sato, Melnitchouk and Ji (2018, 2021)
    - DY + Sullivan process (+NLL corrections in 2021)
  - xFitter Novikov et al., (2020)
    - DY + Direct-photon production

Uncertainties in the present DY data (CERN vs FNAL)

- Differences

Conway et al., PRD 39, 92 (1989).



- Global fits normalizations

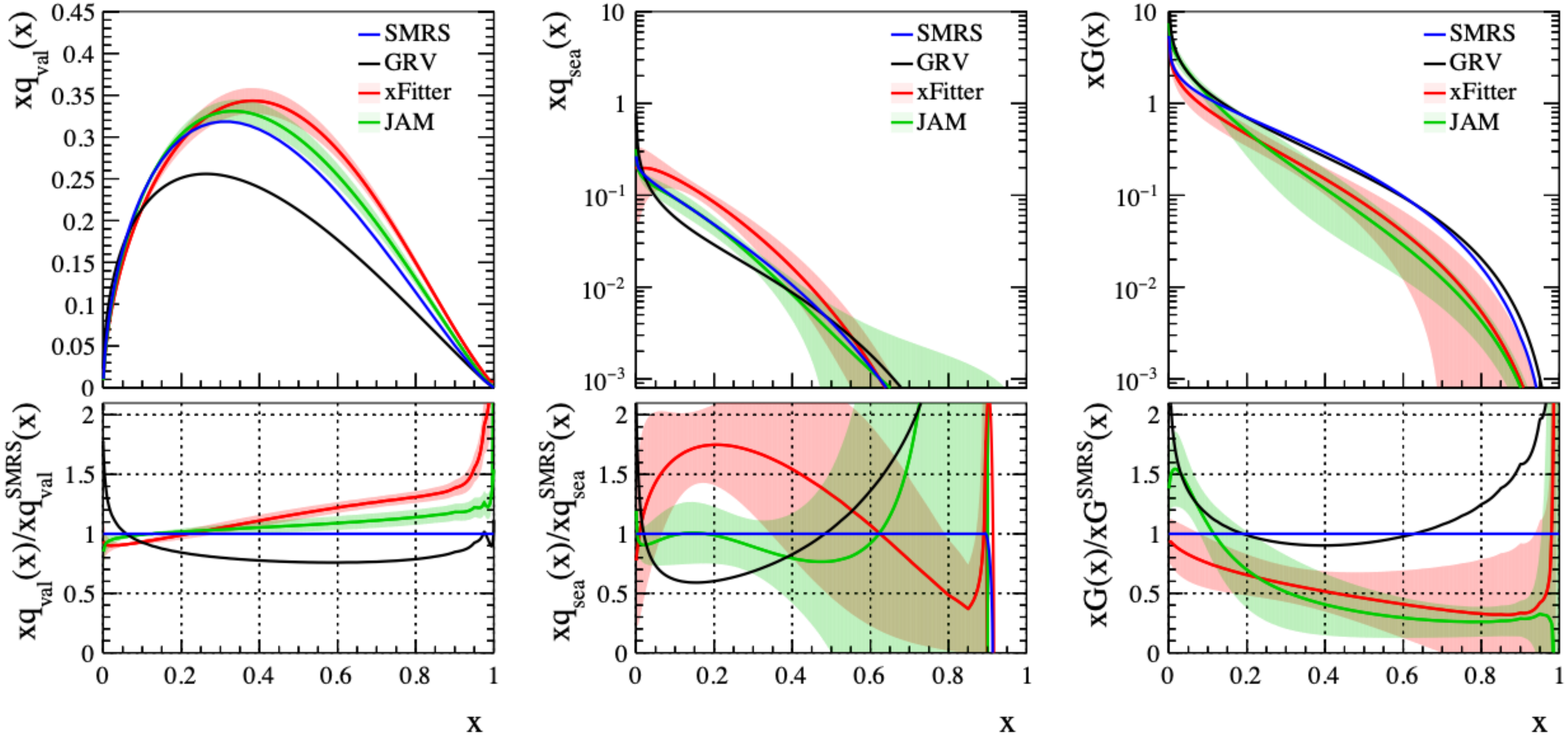
Exp / Global fit	xFitter	JAM	xFitter/JAM
E615	1.160	0.985	1.18
NA10-194 GeV	0.997	0.816	1.22
NA10-286 GeV	0.927	0.758	1.22
WA70 (prompt-γ)	0.737	-	
H1 LN	-	1.170	
Zeus LN	-	0.964	

Global fits – pion PDFs comparison

Fixed-target charmonium production and pion parton distributions

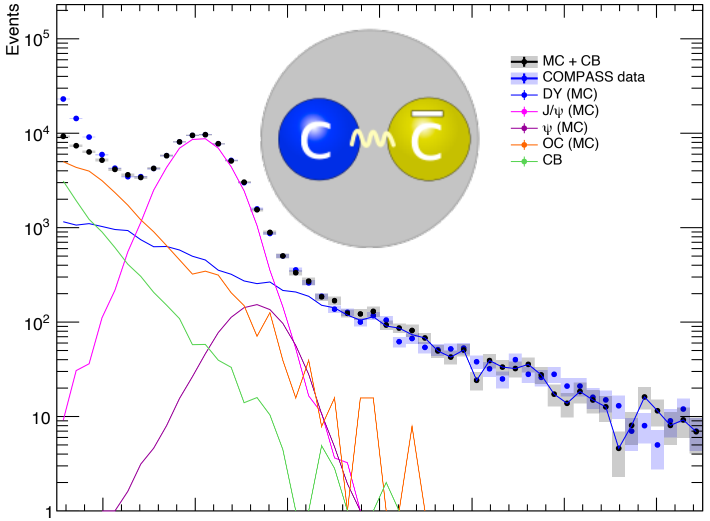
Wen-Chen Chang, Jen-Chieh Peng, Stephane Platchkov, and Takahiro Sawada
Phys. Rev. D **107**, 056008 – Published 7 March 2023

Valence   Sea   Gluons



Charmonium production

- Several advantages
  - Sensitive to valence and glue
  - Large cross sections, 30 – 50 times more than Drell-Yan
  - Fixed-target energies: dominated by 2 ---> 1 process
  - Large number of π-induced data (from 80s to 00s) on many targets



- Present descriptions for charmonium production
  - Color Evaporation Model
    - weight of each contribution (qqbar or GG) depends solely on the parton PDFs
    - Only one adjustable parameter
  - Non-Relativistic QCD (NRQCD)
    - effective field theory, based on factorization
    - separates pQCD (short distance processes) and npQCD (long-distance dynamics)

Are charmonium data compatible with the pion PDFs?

First step

- Compare the "Global Fits" results with the data, using CEM NLO.
  - Integrated cross sections
  - x_F – dependent cross sections

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

Wen-Chen Chang, Jen-Chieh Peng, Stephane Platchkov, and Takahiro Sawada
Phys. Rev. D **102**, 054024 – Published 24 September 2020

Experimental information used

- Data choice criteria
  - x_F distribution is available
  - Minimize nuclear effects ($A \leqslant 9$)
- Additional input
  - proton PDF: CT14nlo
  - nuclear PDFs: EPPS16

Data on heavier targets are also available

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

Experiment	$P_{\rm beam}$ (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]

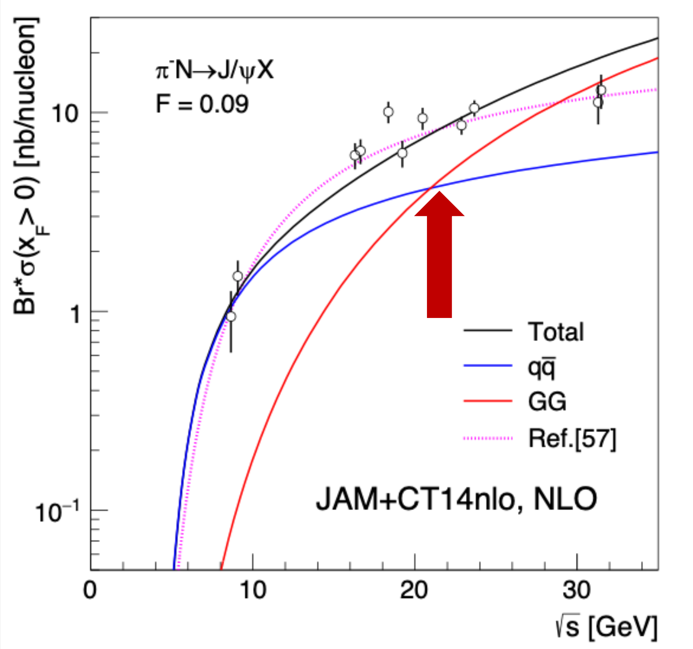
[a]Percentage of uncertainty in the cross section normalization.
[b]The numerical information was taken from figures.
[c]Information not available.

Eight data sets with π beam, published 1981 - 1996

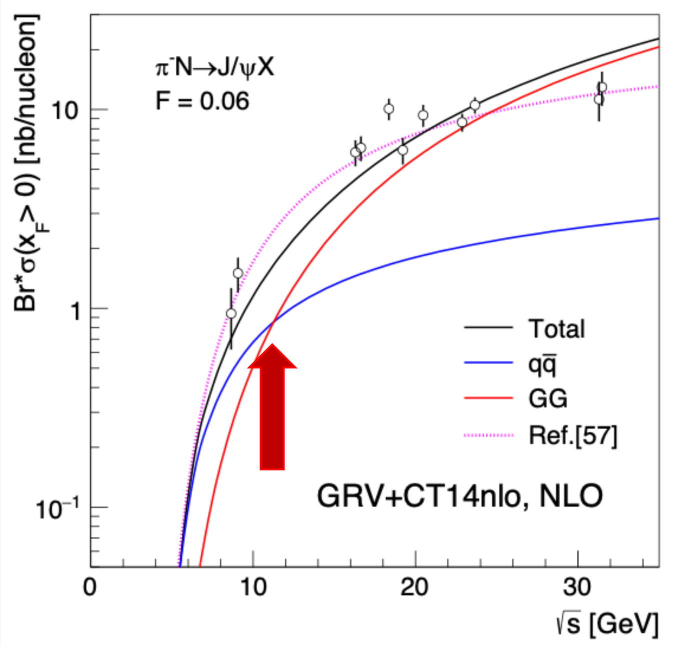
Integrated (x_F > 0) J/psi cross sections vs CEM NLO calculations

- Global fit dependence

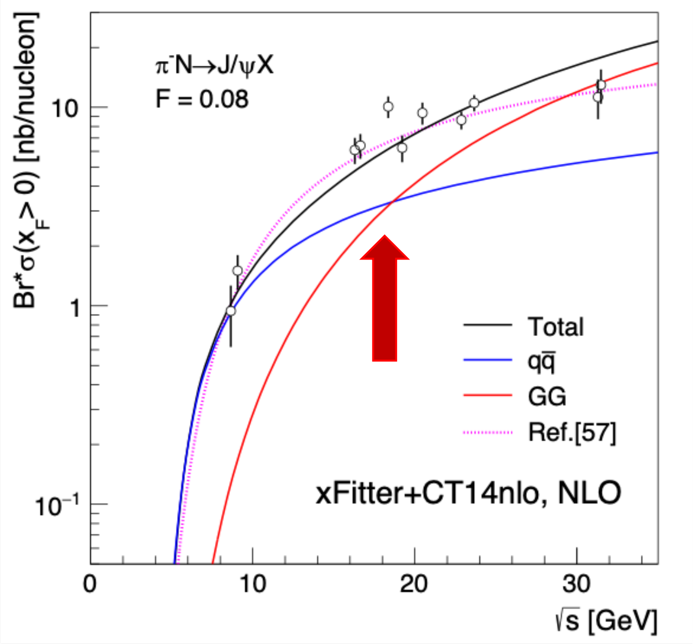
JAM



GRV



xFitter

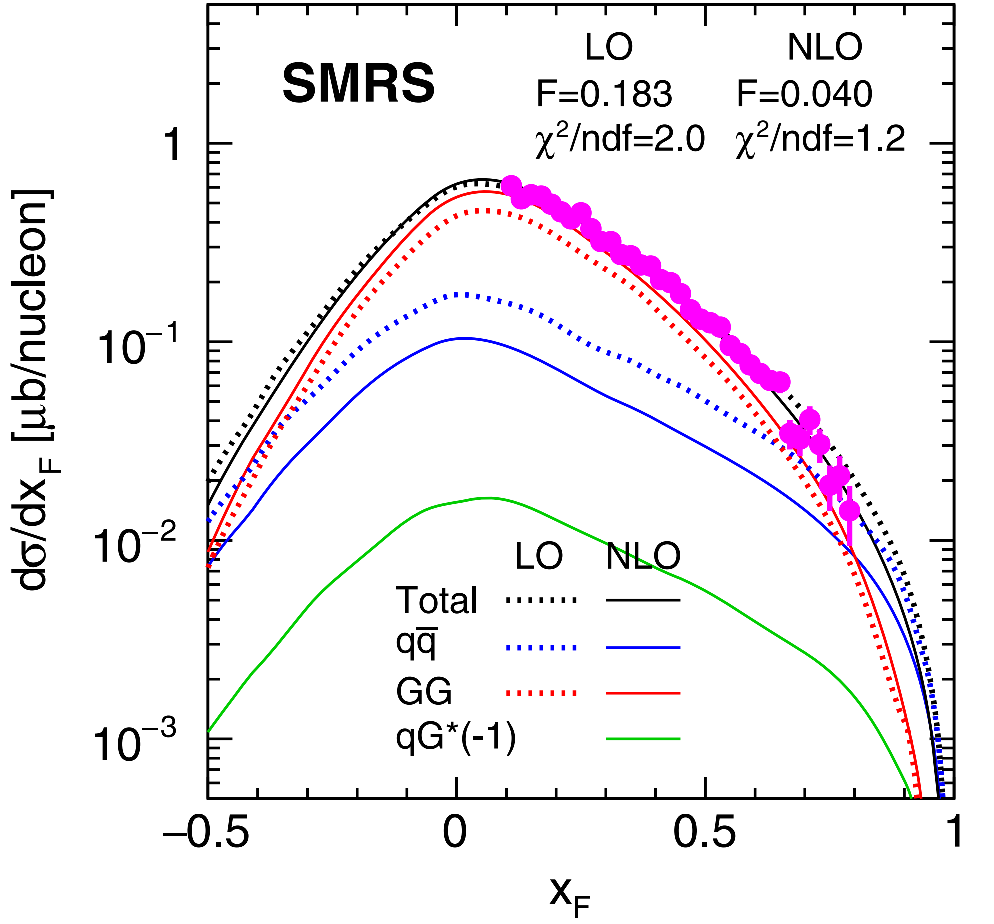


GG vs $q\bar{q}$ crossing: 21 GeV 12 GeV 20 GeV

Overall good agreement, but large GG vs $q\bar{q}$ variations

E672/E706: π + Be for E = 515 GeV

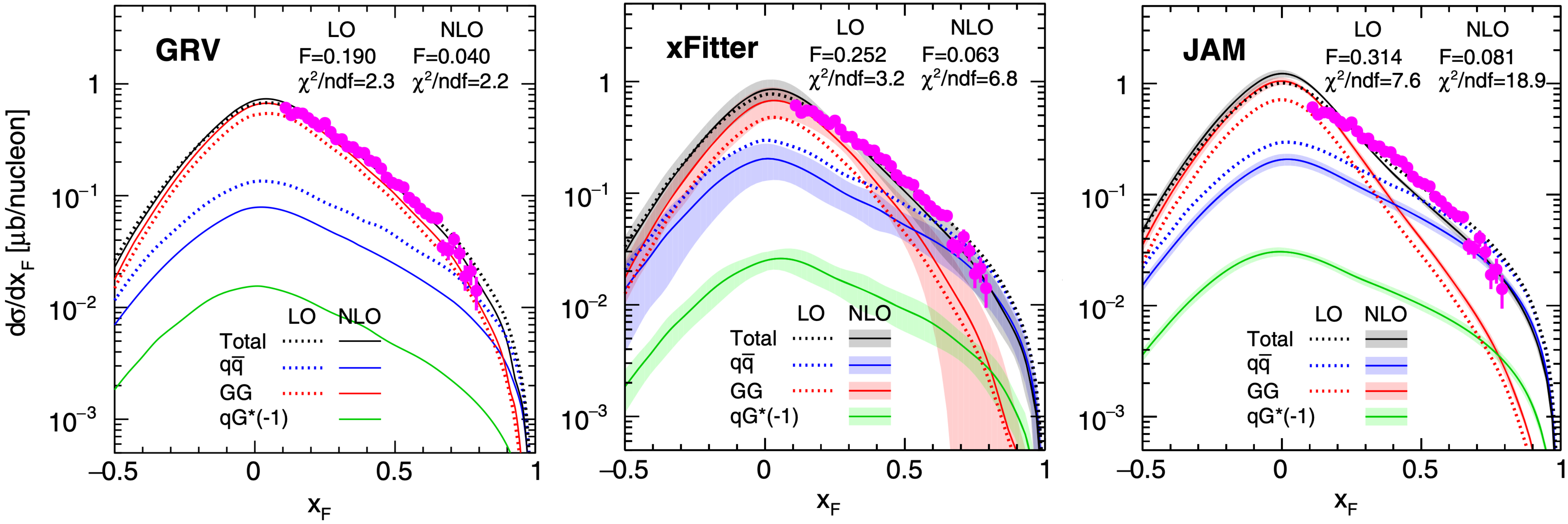
- CEM LO vs NLO



NLO: minor improvement in Chi2

E672/E706: π + Be for E = 515 GeV

- GRV vs xFitter vs JAM

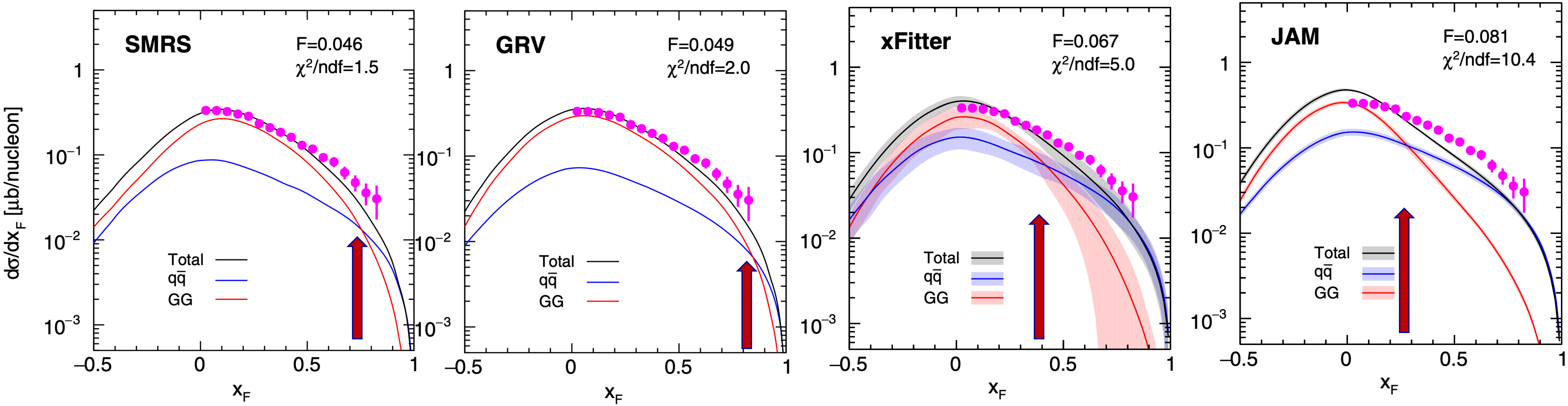


Different qq and GG contributions, and different χ^2/ndf

NA3: π + p for E = 280 GeV

- SMRS vs GRV vs xFitter vs JAM

arrows = crossing points



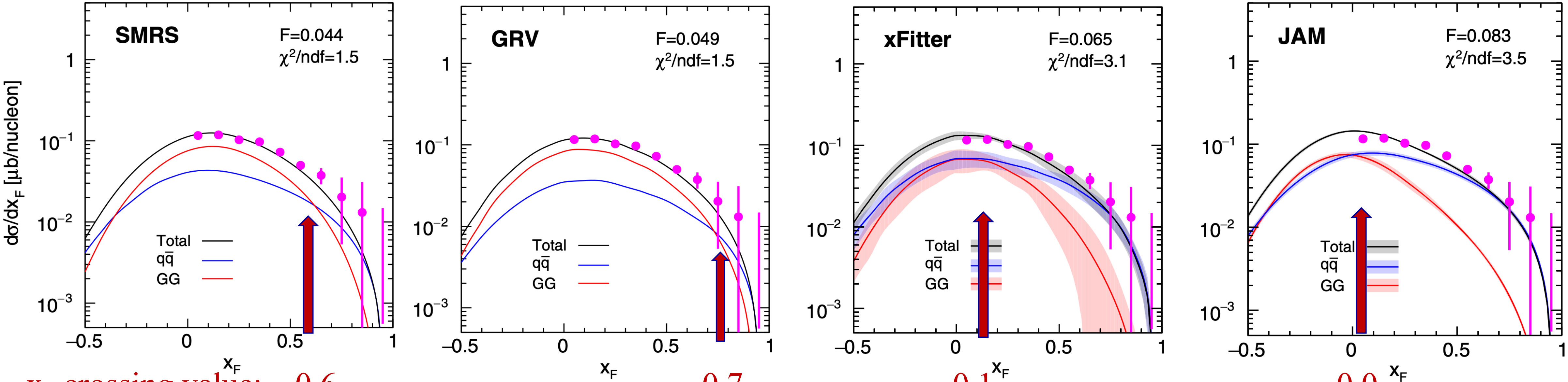
x_F crossing value = 0.7 0.8 0.4 0.3

Chi2 = 1.5 2.0 5.0 10

Smaller GG contribution ==> larger χ^2

E537: π + Be for E = 125 GeV

- SMRS vs GRV vs xFitter vs JAM



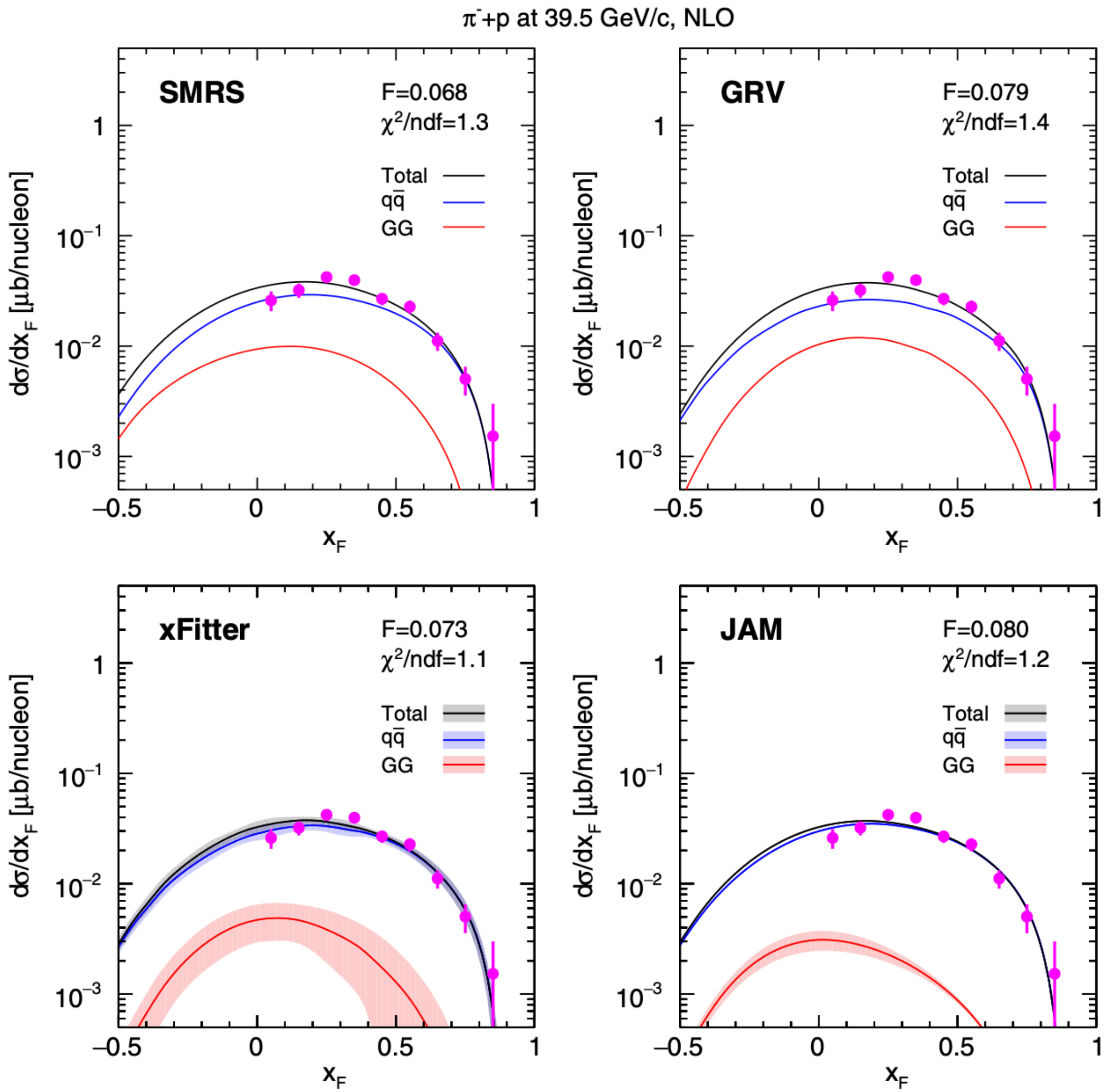
x_F crossing value: 0.6 0.7 0.1 0.0

$\chi^2 =$ 1.5 1.5 3.1 3.5

Smaller GG contribution ==> larger χ^2

Decreasing energy = decreasing GG contribution

WA39: π + p for E = 39.5 GeV



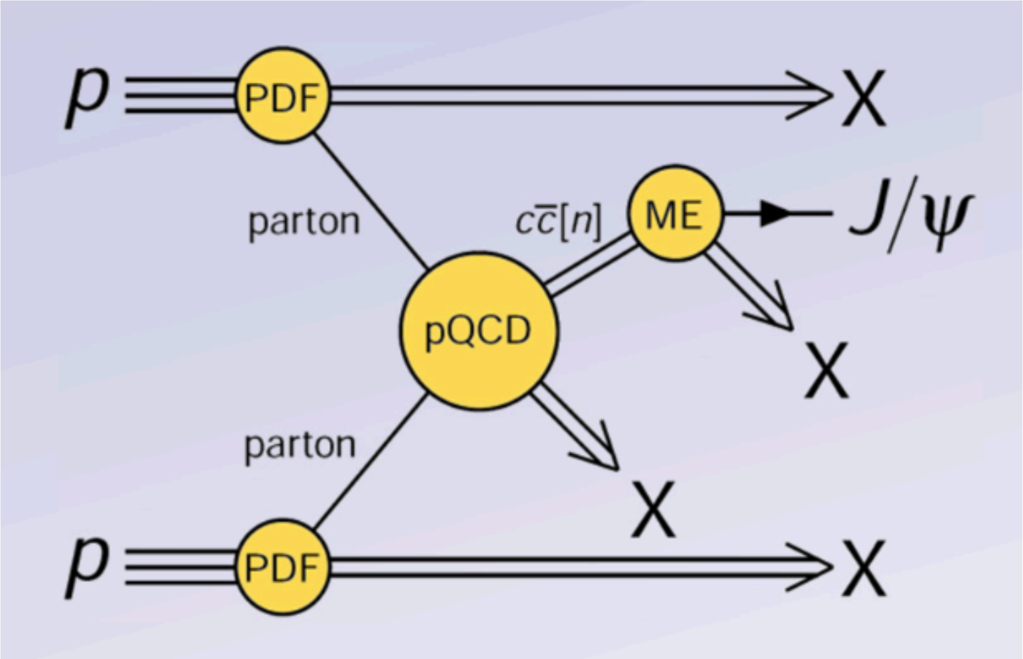
Are charmonium data compatible with the pion PDFs?

- Conclusions from the CEM NLO study
  - The gg fusion process becomes increasingly important with the increase of the (FT) energies
  - Data are sensitive to the amount of g(x) in the pion
  - Global fits with larger gluon contributions (GRV, SMRS) are favored

Would a different production model entail different conclusions?

Second step:

- Use NRQCD instead of CEM. Needed are:
  - Beam and Target PDFs
  - Short Distance cross sections (pQCD)
  - Long-Distance Matrix Elements (phen.)
  - Factorization



- Start with integrated cross sections only

Hsieh, Lian, Chang, Peng, Platchkov and Sawada, Chin. J. Phys. 73 (2021) 13

A word on the LDMEs…

- Sensitivity to the different subprocesses
  - Color Octet LDMEs (Color Singlet LDMEs are fixed to the values used in the literature)

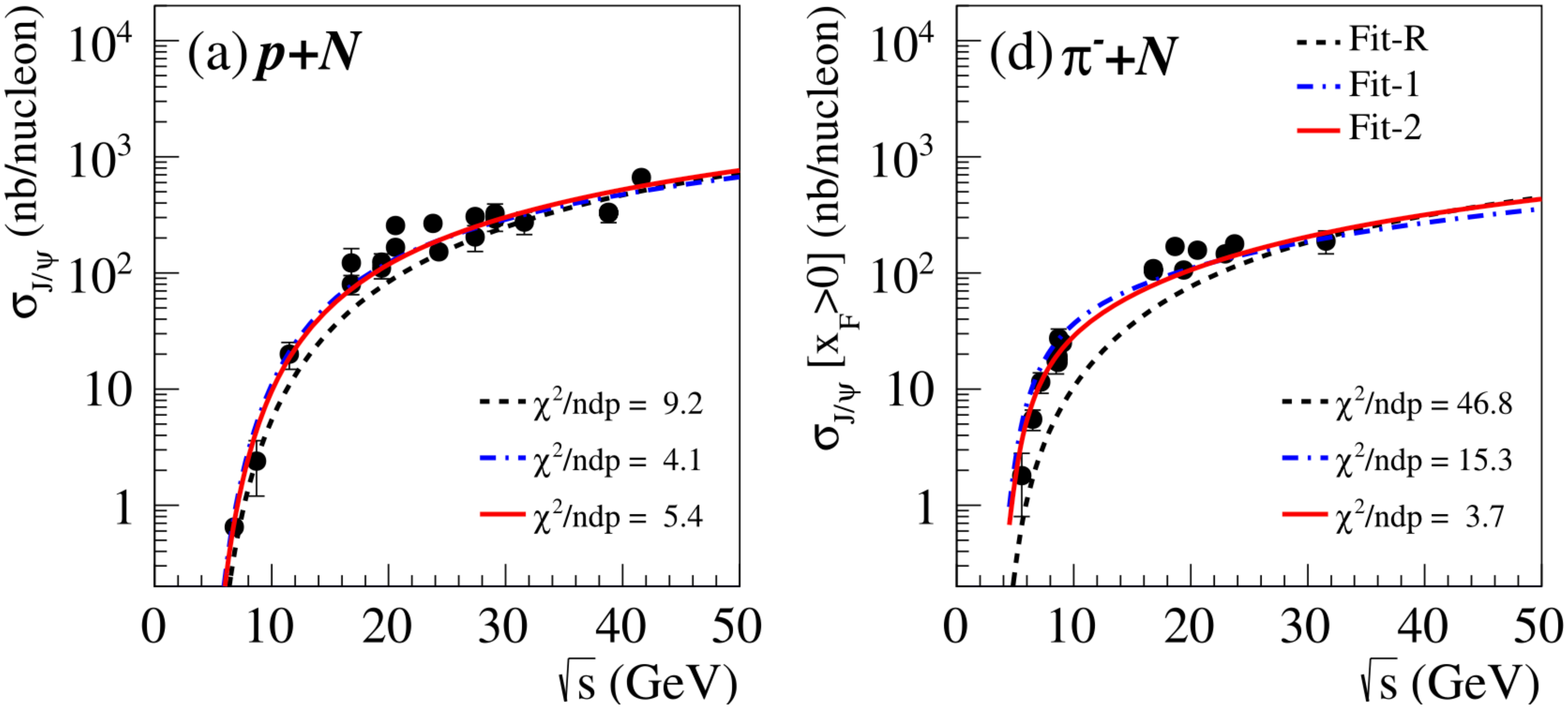
H	$q\bar{q}$	GG	qG
$J/\psi,\ \psi(2S)$	$\langle \mathcal{O}_8^H[^3S_1]\rangle\ (\alpha_s^2)$	$\Delta_8^H\ (\alpha_s^2)$	
		$\langle \mathcal{O}_1^H[^3S_1]\rangle\ (\alpha_s^3)$	
χ_{c0}	$\langle \mathcal{O}_8^H[^3S_1]\rangle\ (\alpha_s^2)$	$\langle \mathcal{O}_1^H[^3P_0]\rangle\ (\alpha_s^2)$	
χ_{c1}	$\langle \mathcal{O}_8^H[^3S_1]\rangle\ (\alpha_s^2)$	$\langle \mathcal{O}_1^H[^3P_1]\rangle\ (\alpha_s^3)$	$\langle \mathcal{O}_1^H[^3P_1]\rangle\ (\alpha_s^3)$
χ_{c2}	$\langle \mathcal{O}_8^H[^3S_1]\rangle\ (\alpha_s^2)$	$\langle \mathcal{O}_1^H[^3P_2]\rangle\ (\alpha_s^2)$	

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

- Data used: only integrated cross sections
  - π-induced J/ψ and ψ(2S)
  - p-induced J/ψ and ψ(2S)

NRQCD results – integrated cross sections

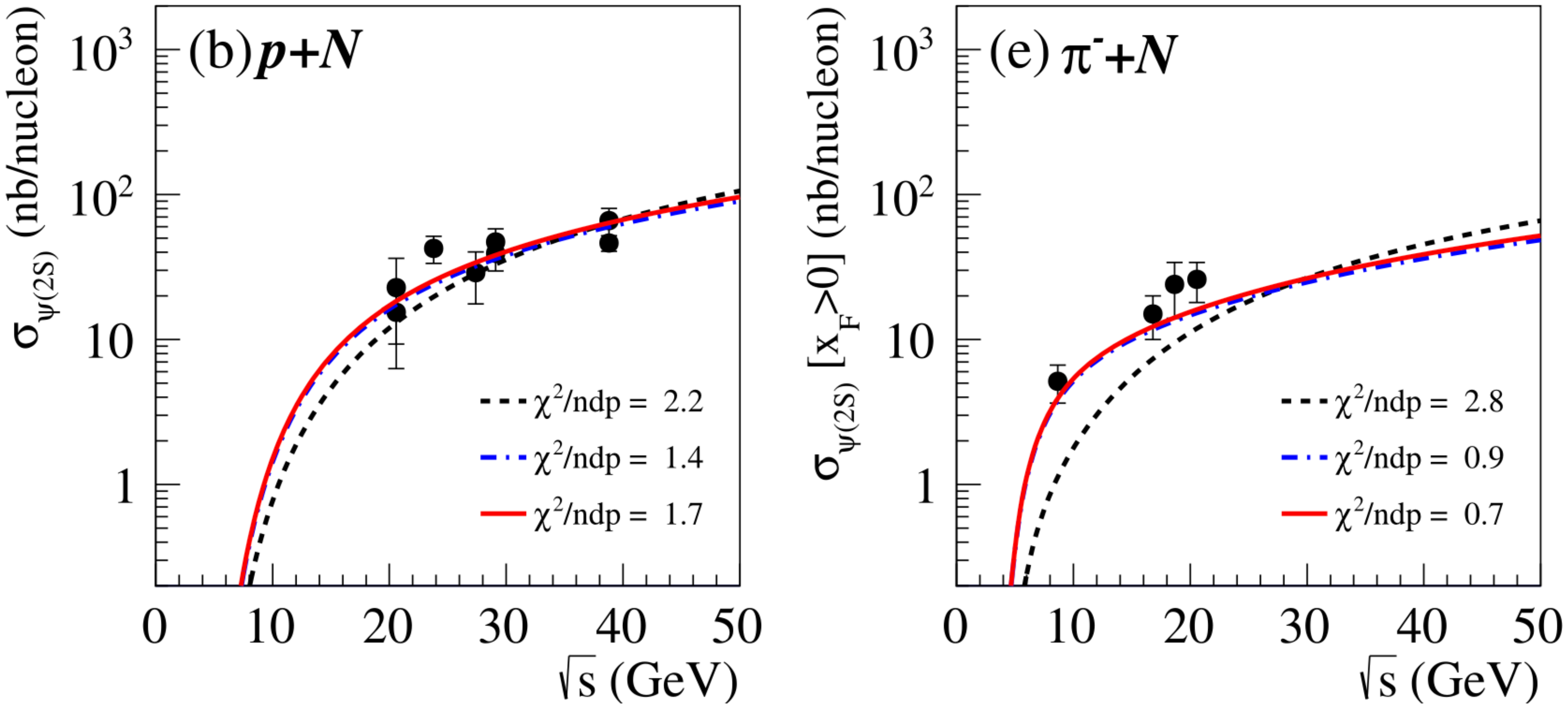
- Charmonium J/ψ data



Good common fit to both pion and proton-induced data

NRQCD results – integrated cross sections

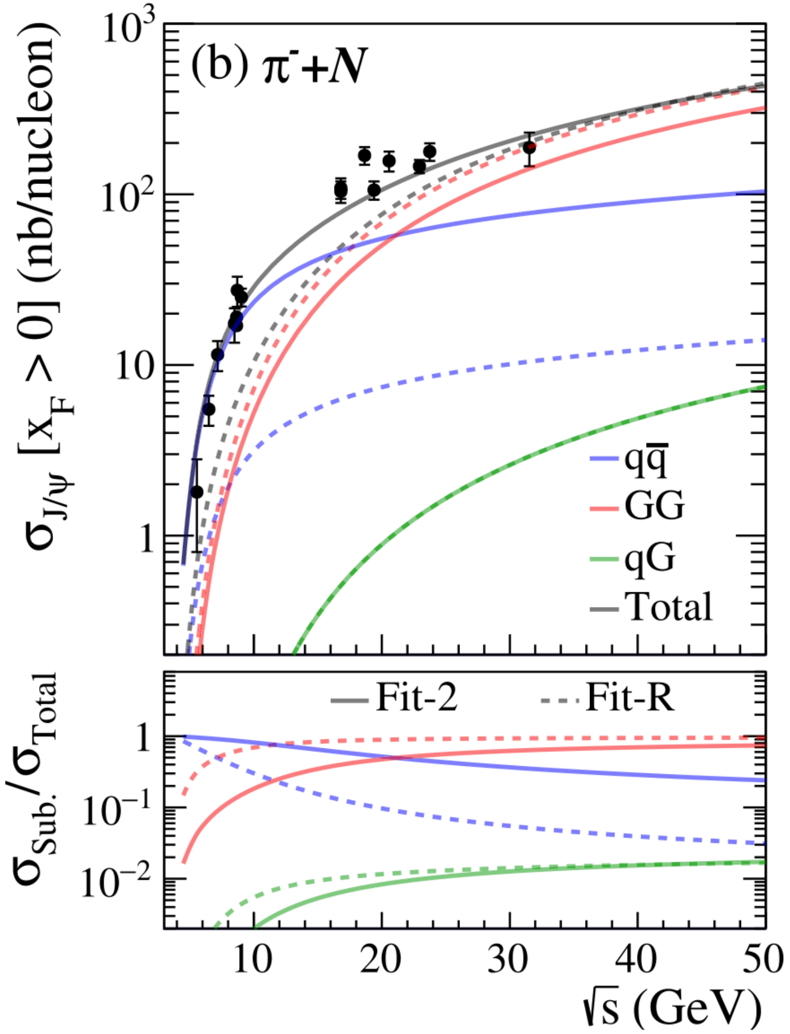
- Charmonium $\psi(2S)$ data



Good common fit to both J/ψ and ψ(2S) states

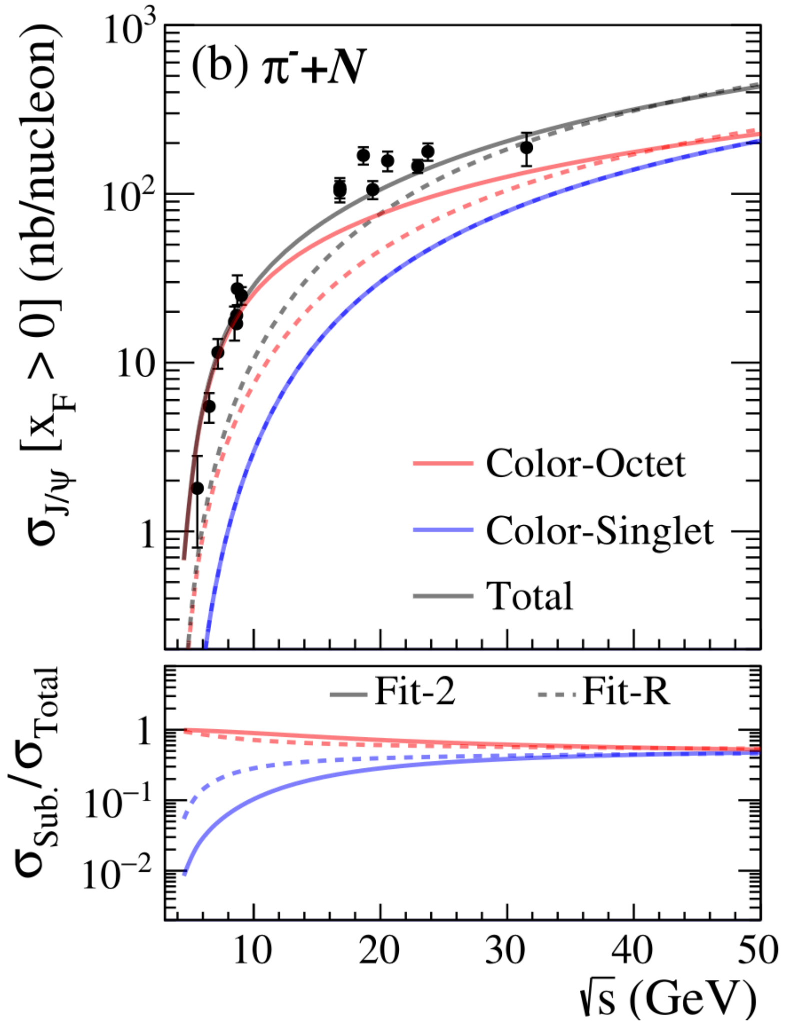
NRQCD results – integrated cross sections

- J/ψ subprocesses



NRQCD results – integrated cross sections

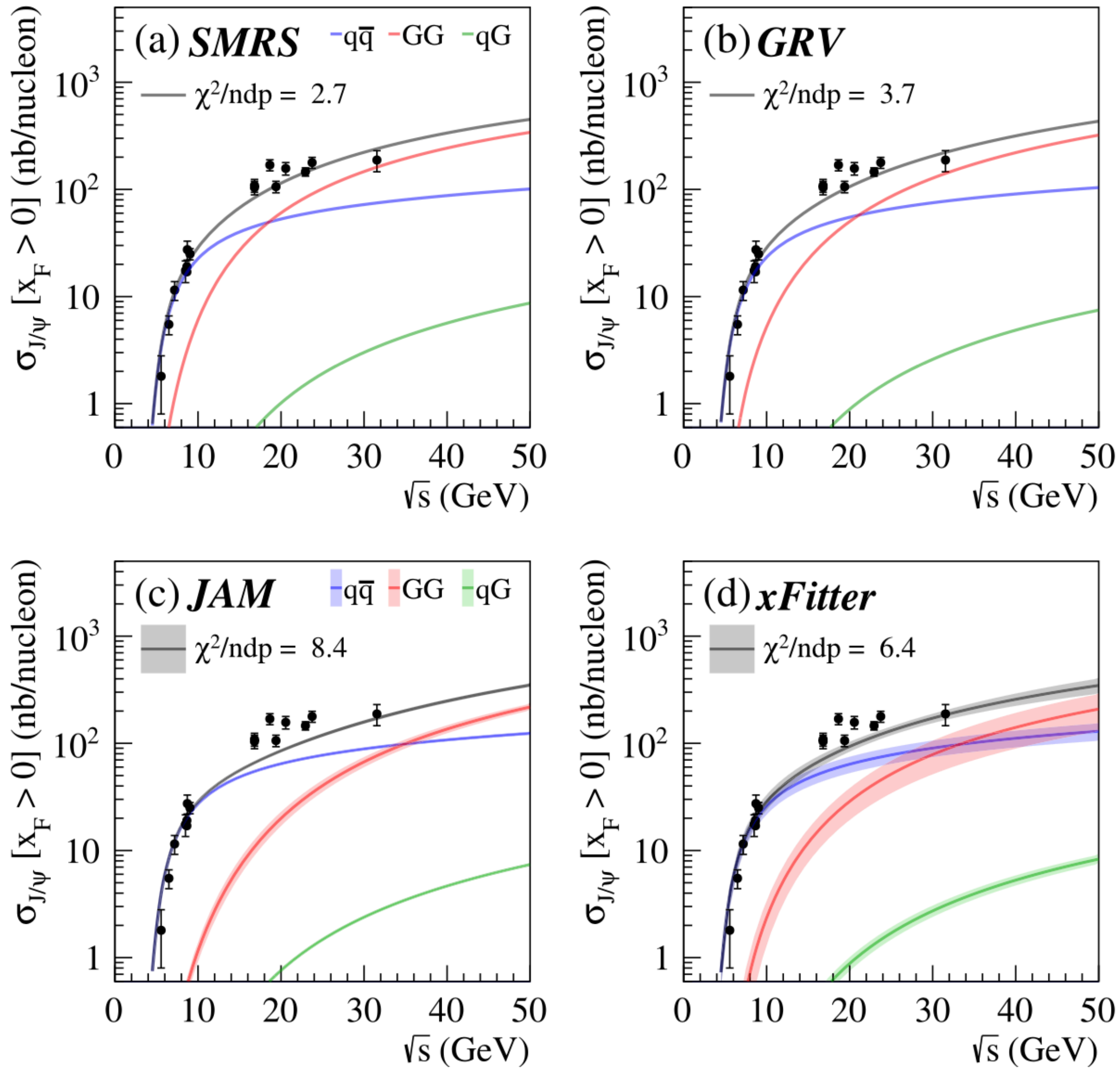
- J/ψ CO vs CS



The Color Octet process dominates the cross section

NRQCD results – integrated cross sections

- PDF dependence



Use of SMRS and GRV leads to better χ^2 values

Further study:

integrated cross section AND x_F-dependent data

NRQCD fits including x_F-dependent data

- Data used (Chang et al., PRD 107, 2023)
  - Atomic numbers < 10, both proton and pion-induced data, for J/ψ and $\psi(2S)$

TABLE II. Differential cross sections datasets for charmonium production [J/ψ, $\psi(2S)$ and $R_\psi(x_F)$] used in the study, listed in order of decreasing beam momentum.

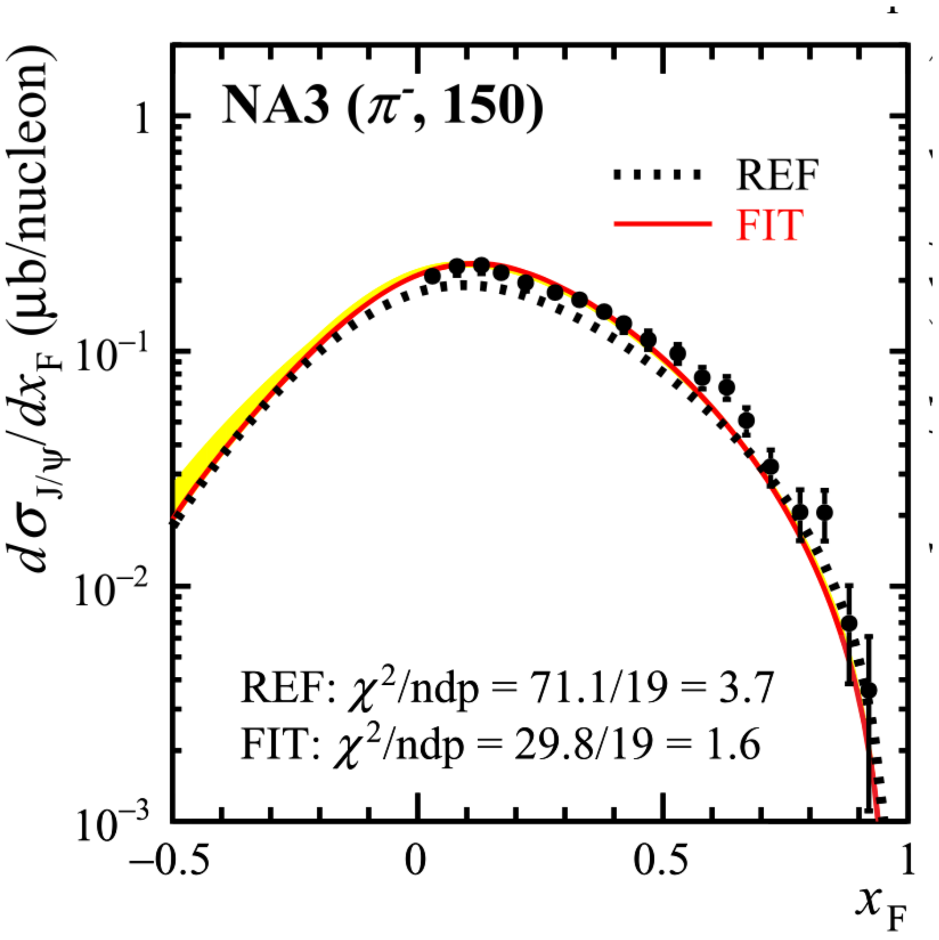
pion
164 points

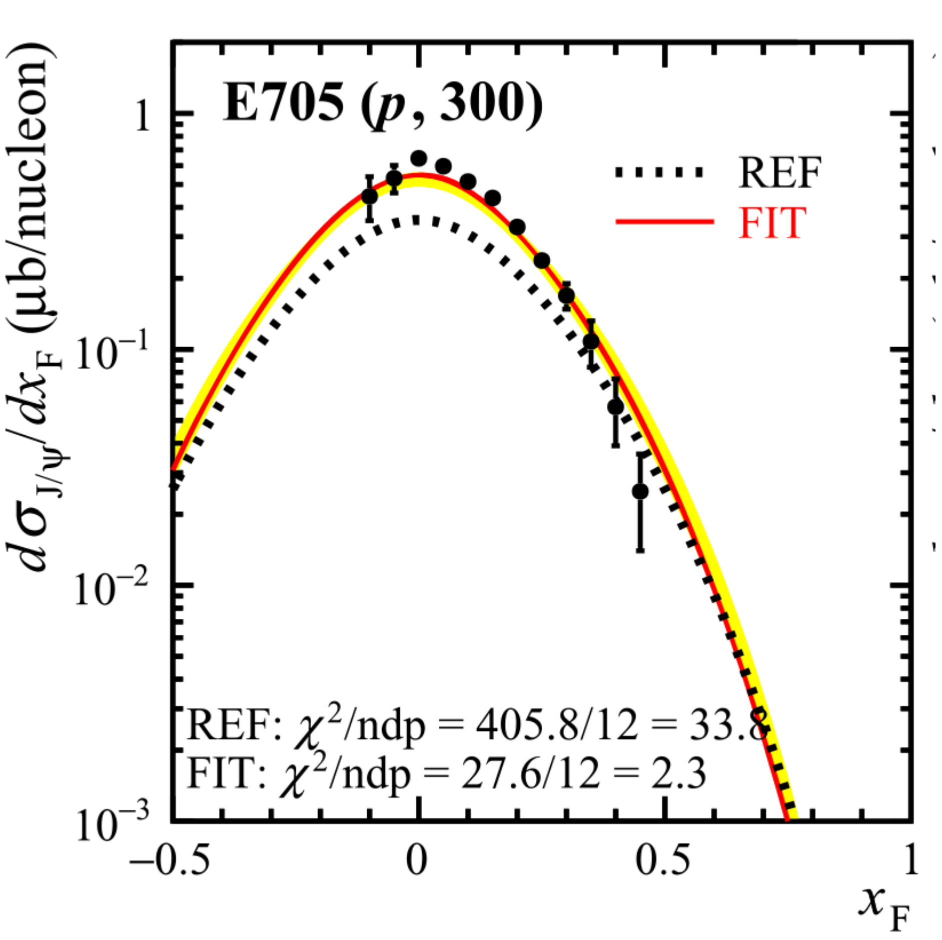
proton
82 points

Experiment	Beam	P_{beam} (GeV/c)	Target	Data	x_F	ndf	Norma.[a]	Reference
FNAL E672, E706	π	515	Be	$\sigma^{J/\psi}$	[0.11, 0.79]	35	12.0	[82]
FNAL E705	π	300	Li	$\sigma^{J/\psi}$	[−0.10, 0.45]	12	9.5	[83]
CERN NA3[b]	π	280	p	$\sigma^{J/\psi}$	[0.025, 0.825]	17	13.0	[84]
CERN NA3[b]	π	200	p	$\sigma^{J/\psi}$	[0.05, 0.75]	8	13.0	[84]
CERN WA11[b]	π	190	Be	$\sigma^{J/\psi}$	[−0.35, 0.75]	12	[c]10.0	[85]
CERN NA3[b]	π	150	p	$\sigma^{J/\psi}$	[0.025, 0.925]	19	13.0	[84]
FNAL E537	π	125	Be	$\sigma^{J/\psi}$	[0.05, 0.95]	10	6.0	[86]
CERN WA39[b]	π	39.5	p	$\sigma^{J/\psi}$	[0.05, 0.85]	9	15.0	[87]
FNAL E672, E706	π	515	Be	$\sigma^{\psi(2S)}$	[0.17, 0.73]	5	16.0	[82]
FNAL E615	π	253	W	$\sigma^{\psi(2S)}/\sigma^{J/\psi}$	[0.275, 0.975]	15		[88]
HERA-B	p	920	W	$\sigma^{\psi(2S)}/\sigma^{J/\psi}$	[−0.3, 0.075]	8		[78]
CERN NA50	p	450	W	$\sigma^{\psi(2S)}/\sigma^{J/\psi}$	[−0.075, 0.075]	4		[89]
FNAL E789	p	800	Au	$\sigma^{\psi(2S)}/\sigma^{J/\psi}$	[0.00, 0.12]	5		[90]
FNAL E771	p	800	Si	$\sigma^{\psi(2S)}/\sigma^{J/\psi}$	[0.00, 0.20]	6		[91]
FNAL E705	p	300	Li	$\sigma^{J/\psi}$	[−0.10, 0.45]	12	10.1	[83]
CERN NA3[b]	p	200	p	$\sigma^{J/\psi}$	[0.05, 0.75]	8	13.0	[84]

16 data sets

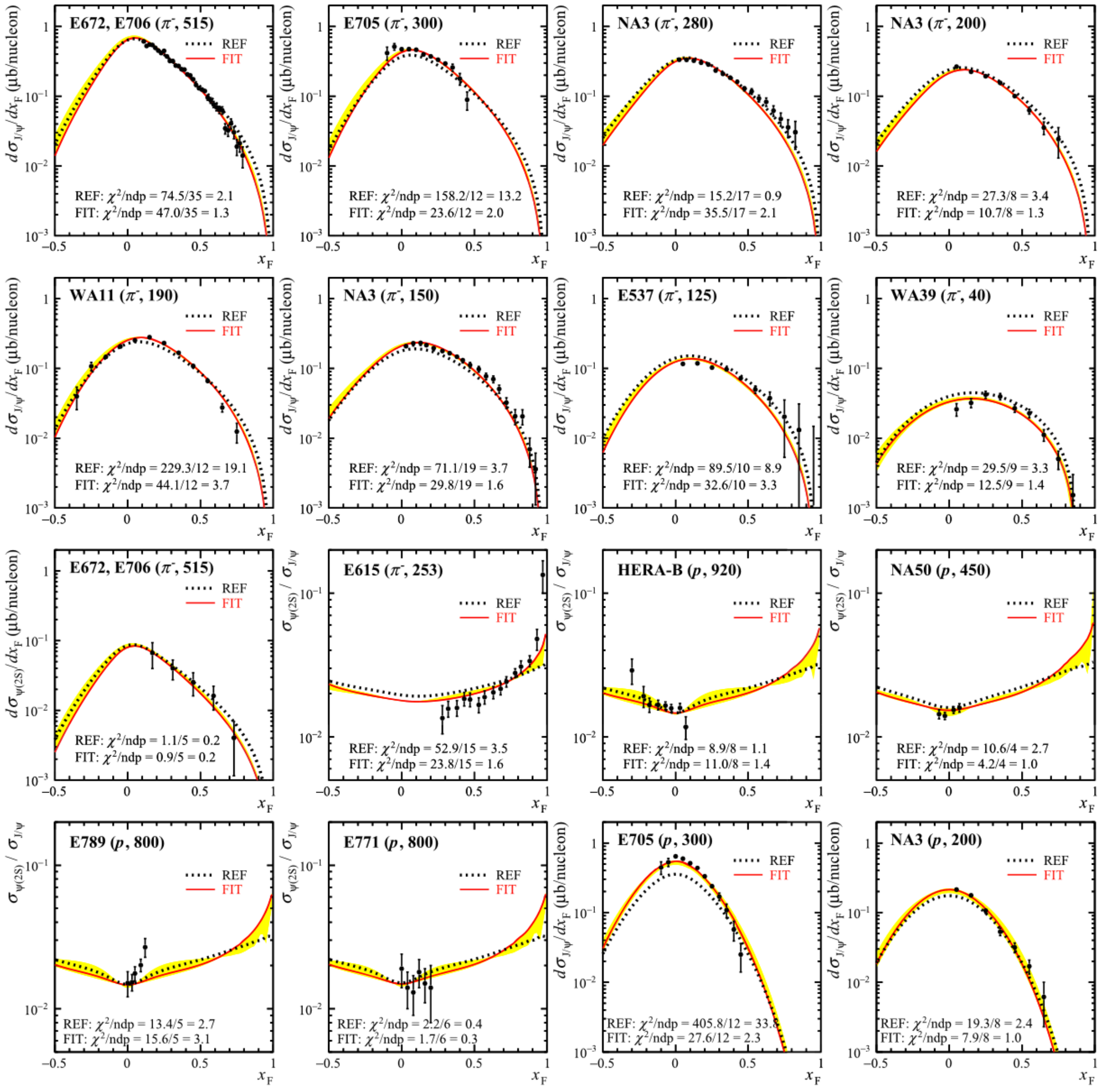
Fit results: examples for π and p-induced data





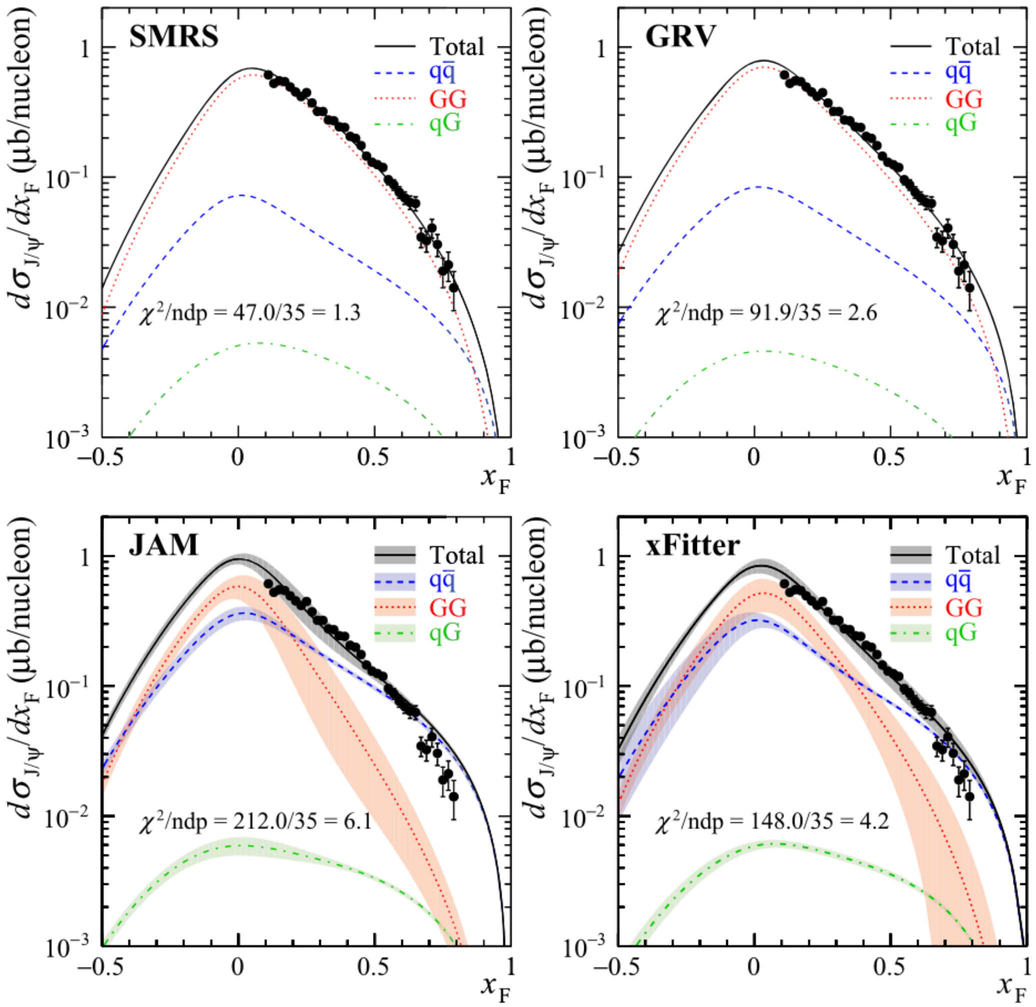
Good fit on both π and p data

Fit results: all data sets



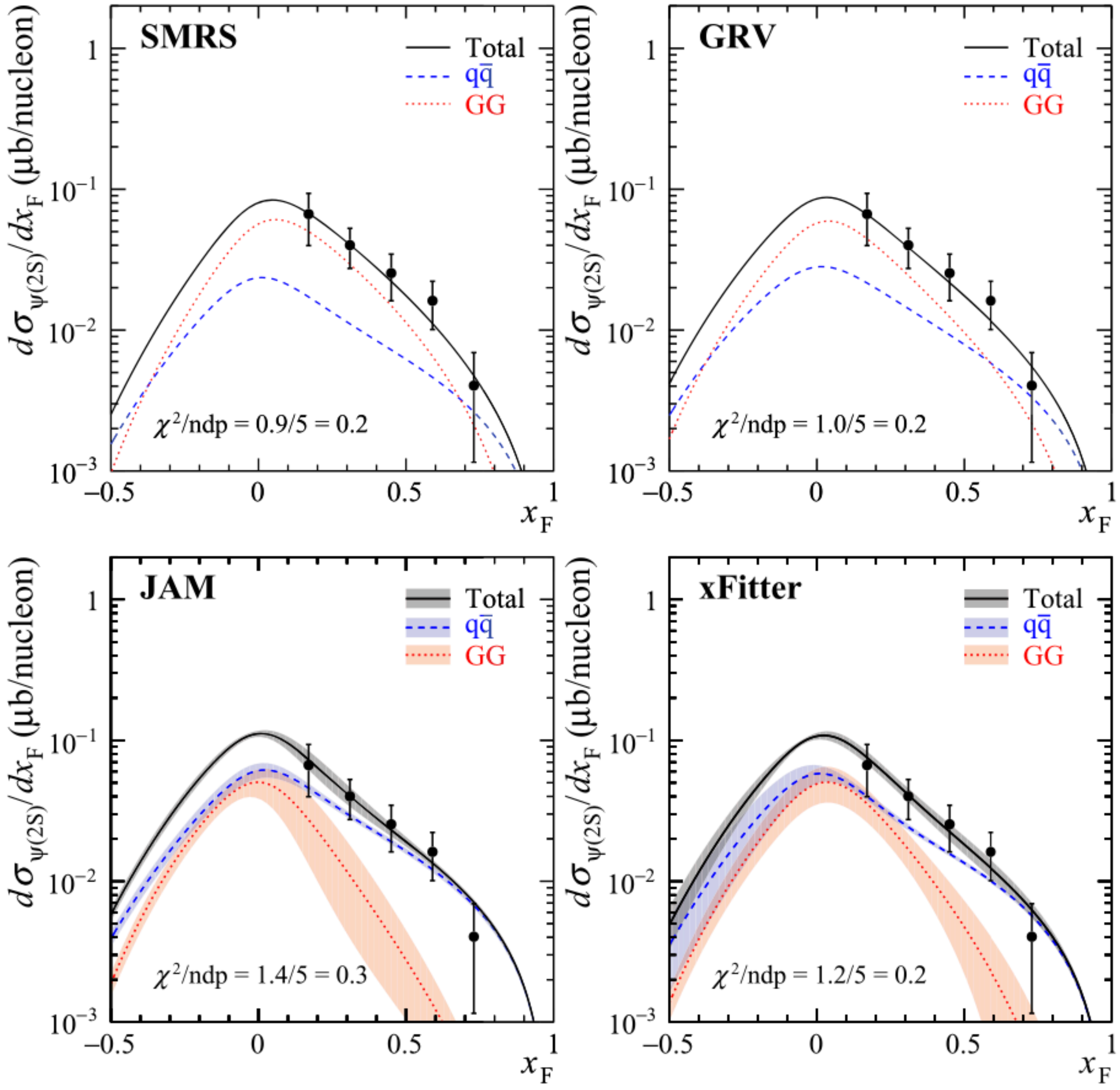
NRQCD fit results: dependence on the pion PDFs

- J/ψ π-induced data at 515 GeV/c



NRQCD fit results: dependence on the pion PDFs

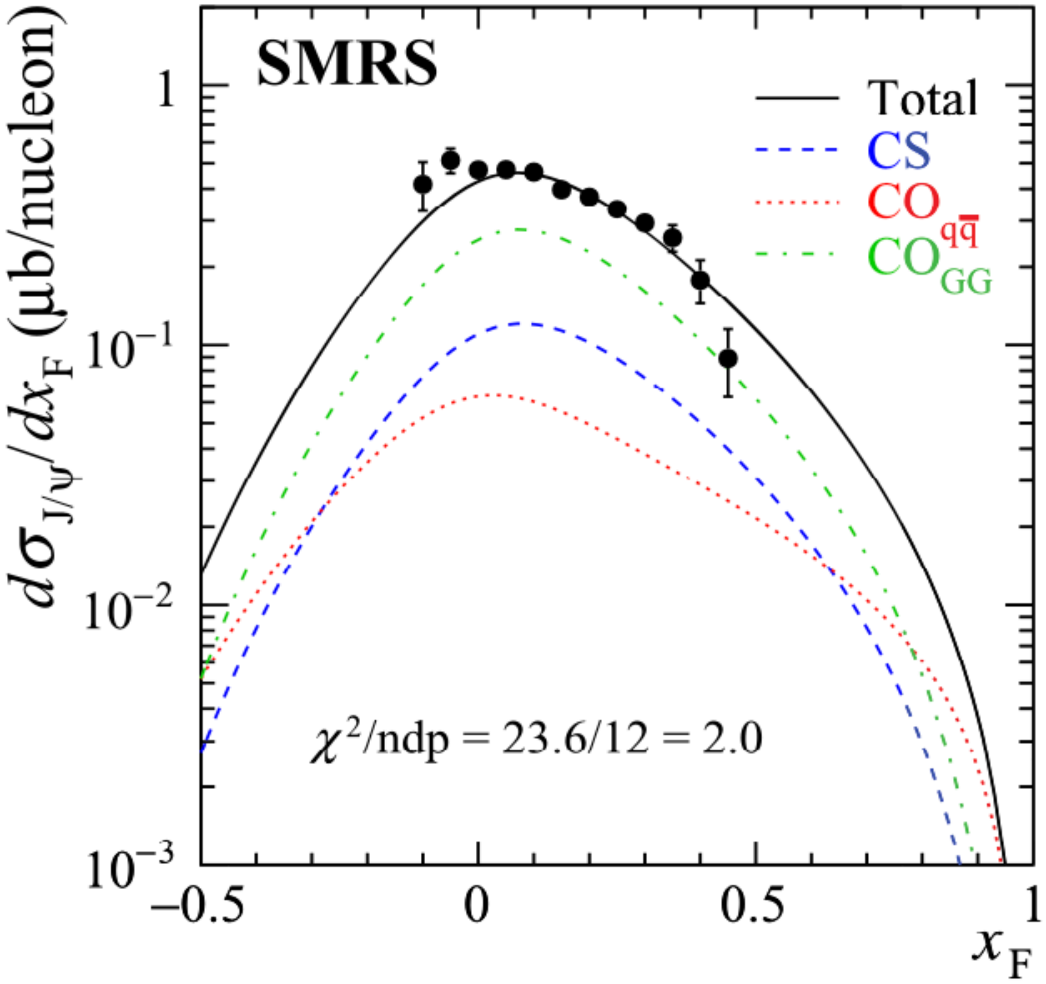
- $\psi(2S)$ π-induced data at 515 GeV/c



Data from E672/E706

E = 515 GeV

Sensitivity of the FT data to the CO component



Data from E705

E = 300 GeV

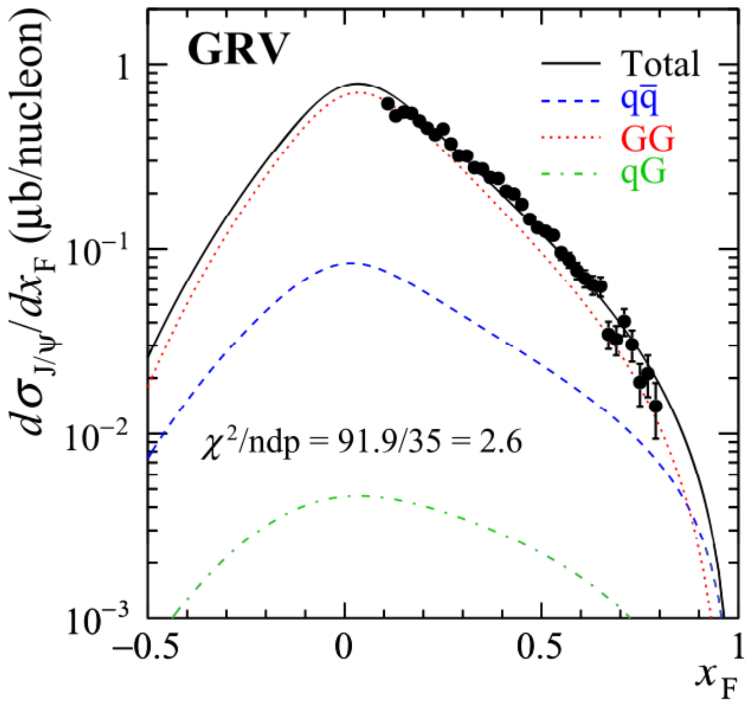
The CO *gg* contribution dominates the cross section

Comparison between J/ψ and ψ(2S)

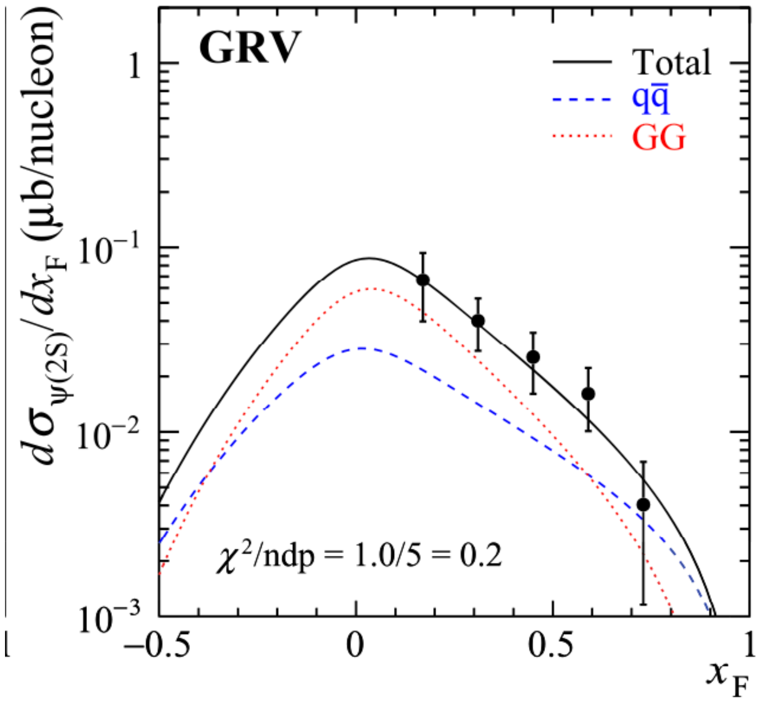
- π-induced data

at 515 GeV/c

J/ψ



ψ(2S)

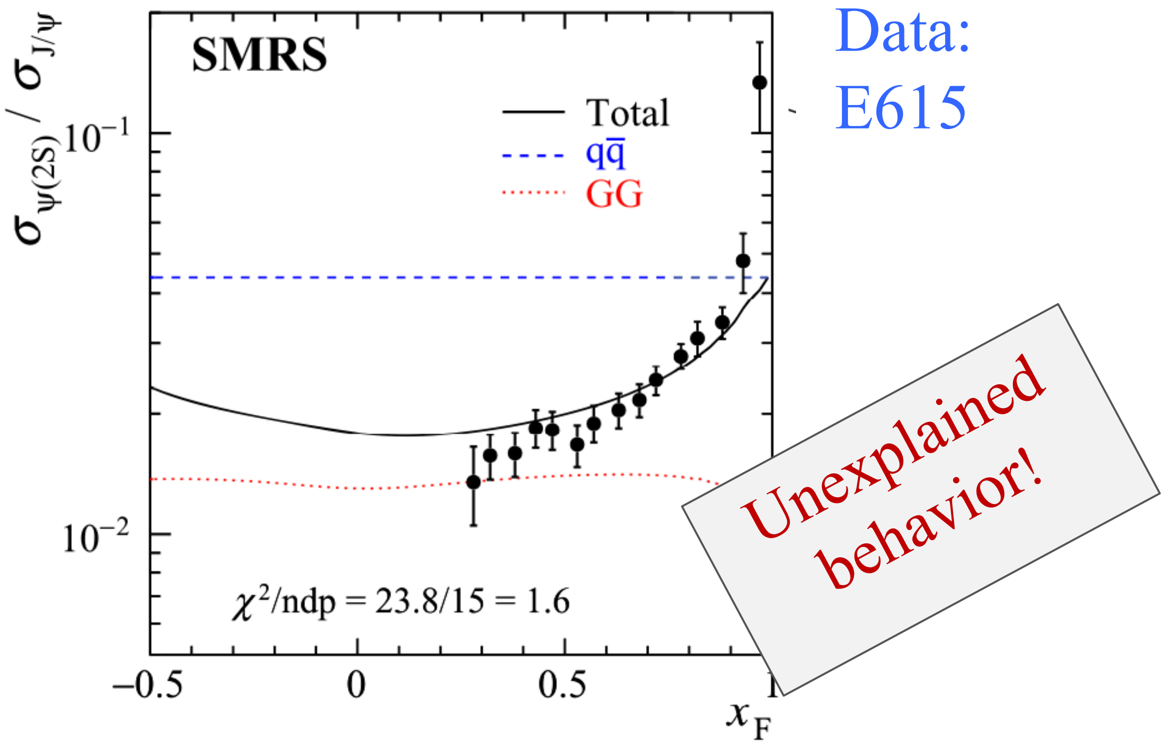


- Differences
  - size of cross section: about an order of magnitude!
  - larger $q\bar{q}$ contribution for ψ(2S) !

Further evidences for different J/ψ and ψ(2S) behaviors

- LDMEs (SMRS)
  - Δ_8 (J/ψ) = 0.0560±0.0016
    Δ_8 (ψ(2S)) = 0.0057±0.0003
    Ratio: = ~10
  - $\langle 0_8[^3S_1]$ (J/ψ) = 0.0259±0.0023
    $\langle 0_8[^3S_1]$ (ψ(2S)) = 0.0132±0.0009
    Ratio: = ~2 !

- Cross section ratio at E = 252 GeV

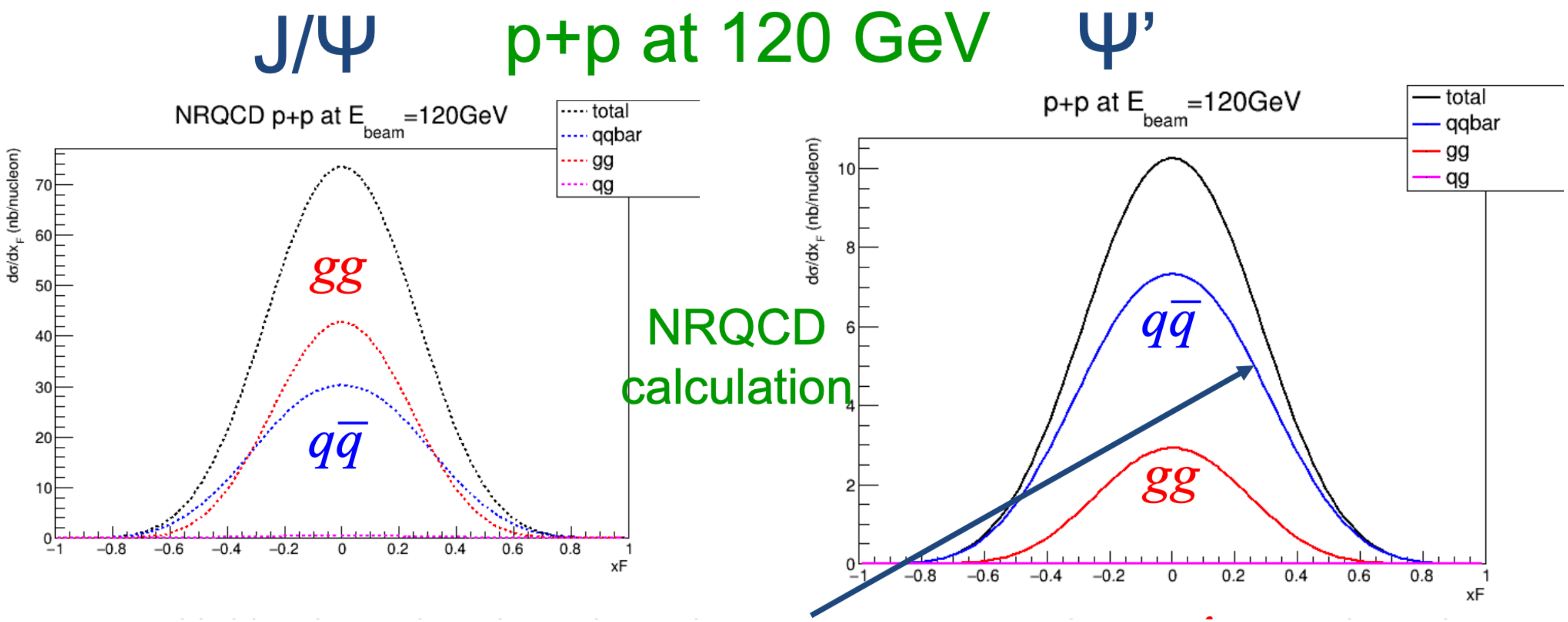


Data: E615

The $q\bar{q}$ contribution in ψ(2S) is much larger than in J/ψ
The behavior of the data cannot be explained using CEM

Comparison between J/ψ and ψ(2S) for p+p at 120 GeV

- Calculation: W.-C. Chang



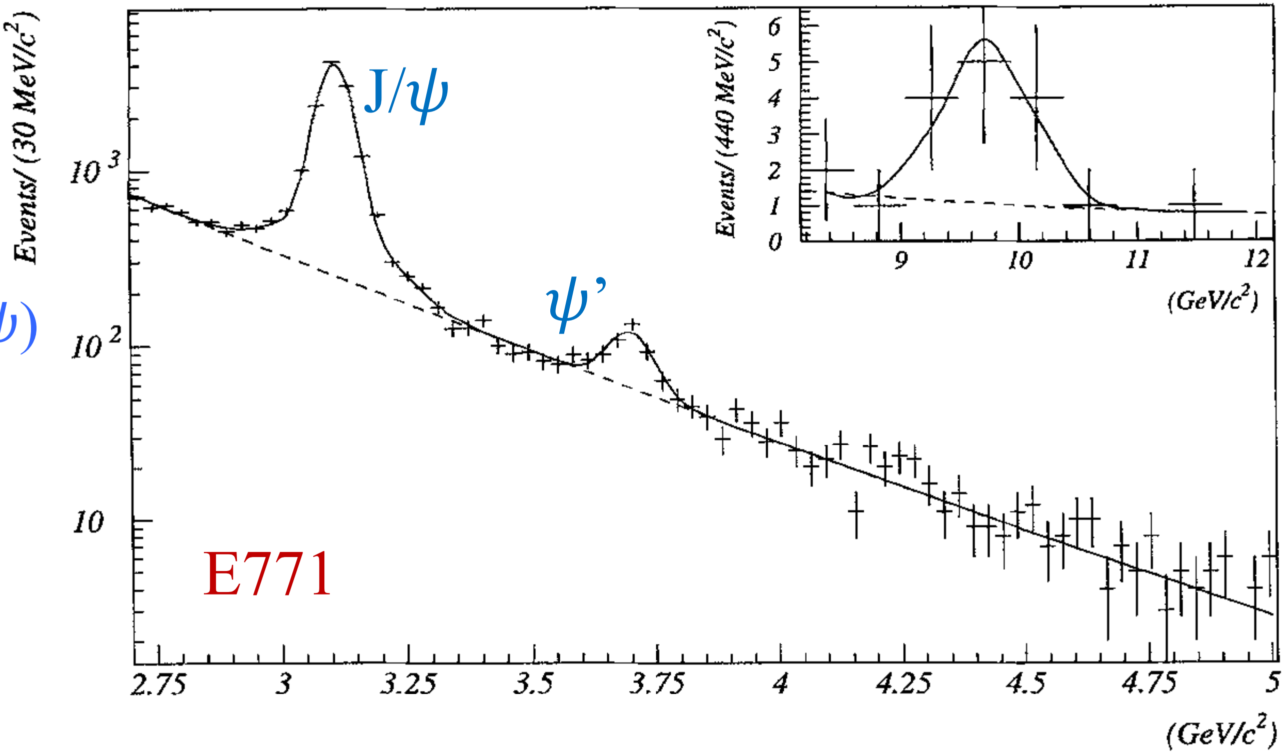
Combined use of J/ψ and ψ(2S) data would greatly help in separating $q\bar{q}$ and gg contributions

=> ψ(2S) could be considered as a Drell-Yan surrogate

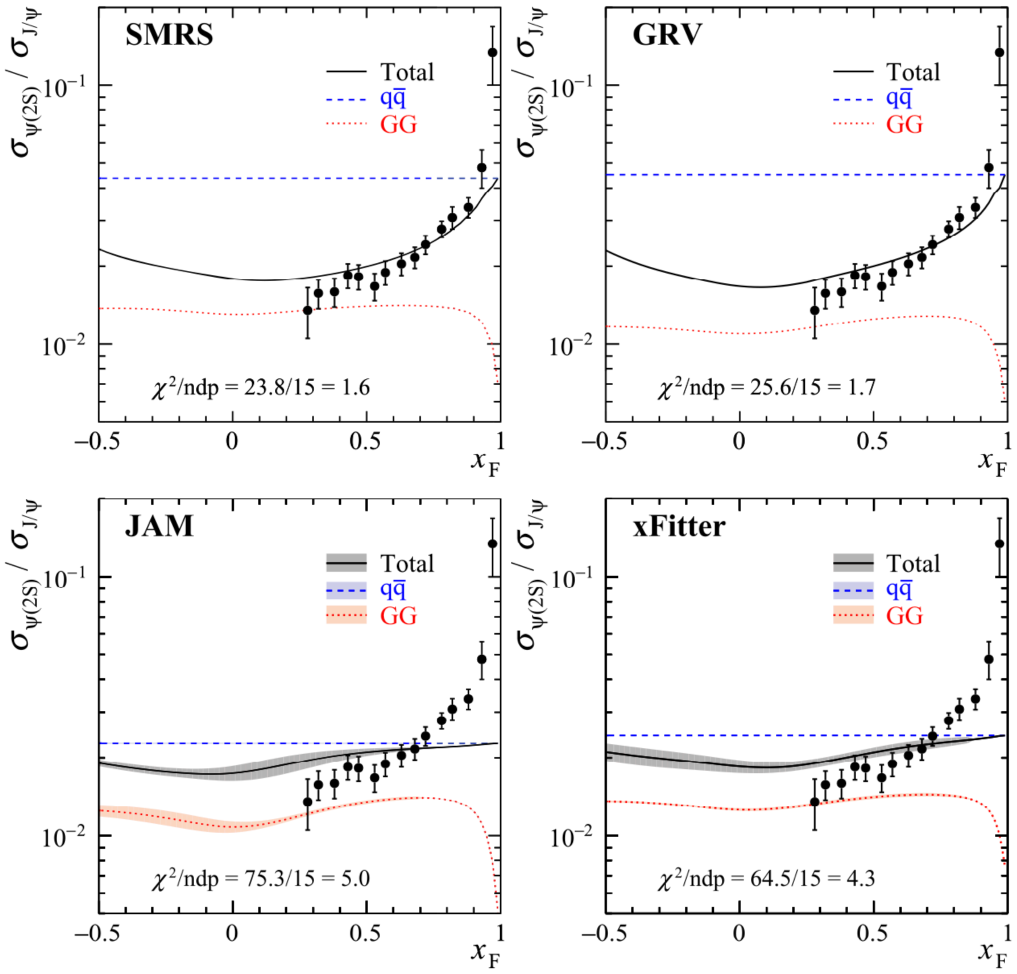
Why measure $\psi(2S)$ cross sections?

- Pros:
  - Different sensitivity to g(x) and q(x)
  - No feeddown contributions
- Cons:
  - Low counting rates (factor of 50 ! vs J/ψ)
  - Very good resolution required
- AMBER could/should? do it

E771 Collaboration / Physics Letters B 374 (1996) 271–276



Dependence on the pion PDFs



SMRS and GRV fits do (AGAIN!) a better job

LDMEs compared to collider energies fits values

- J/ψ production $\langle O_8^{J/\psi}[^3S_1]\rangle$ (GeV^3)

Present work	$(2.59\pm0.23)\times10^{-2}$	PRD 107, 2023
Buttenshoen-Kniehl	$(0.31\pm0.06)\times10^{-2}$	PRL 106, 2011
Chao, Ma et al.,	$(0.30\pm0.12)\times10^{-2}$	PRL 108, 2012
Zhang, Sun et al.,	$(1.00\pm0.30)\times10^{-2}$	PRL 114, 2015
Bodwin et al.,	$(1.10\pm1.00)\times10^{-2}$	PRL 114, 2015

- ψ(2S) production $\langle O_8^{\psi(2S)}[^3S_1]\rangle$ (GeV^3)

Present work	$(1.32\pm0.09)\times10^{-2}$	PRD 107, 1023
Gong, Wan et al.,	$(0.34\pm0.12)\times10^{-2}$	PRL 106, 2011
Buttenshoen-Kniehl, Fit1	$(0.15\pm0.01)\times10^{-2}$	PRD 107, 2023
Buttenshoen-Kniehl, Fit4	$(0.28\pm0.01)\times10^{-2}$	PRD 107, 2023

Price for a good fit: values for $\langle O_8[^3S_1]\rangle$ between a factor of 2.5 and 10 larger
(Note: high-energy fits are usually limited to values of p_T > 5 or 7 GeV/c)

Discussion

- The present NRQCD analysis could be further refined if the following items are considered:
  - Include higher order terms of NRQCD
  - Add data from heavier targets
  - Note: FT data are limited to small pT values ($\lesssim$ 4 GeV/c)

- An optional next step
  - Include charmonium production data in a global fit

Summary

- Conclusions
  - A common NRQCD fit to FT pion and proton-induced charmonium data is made
  - A good fit to J/ψ and $\psi(2S)$ data, as well as to their ratios
  - Better fit results for SMRS and GRV, in comparison with the recent JAM and xFitter PDFs
  - Explained by larger gluon contributions, particularly at large x_F
  - Use of either CEM or NRQCD leads to qualitatively similar results

- And a surprise
  - The data for $\psi(2S)$ favor a much larger $q\bar{q}$ contribution than that for J/ψ