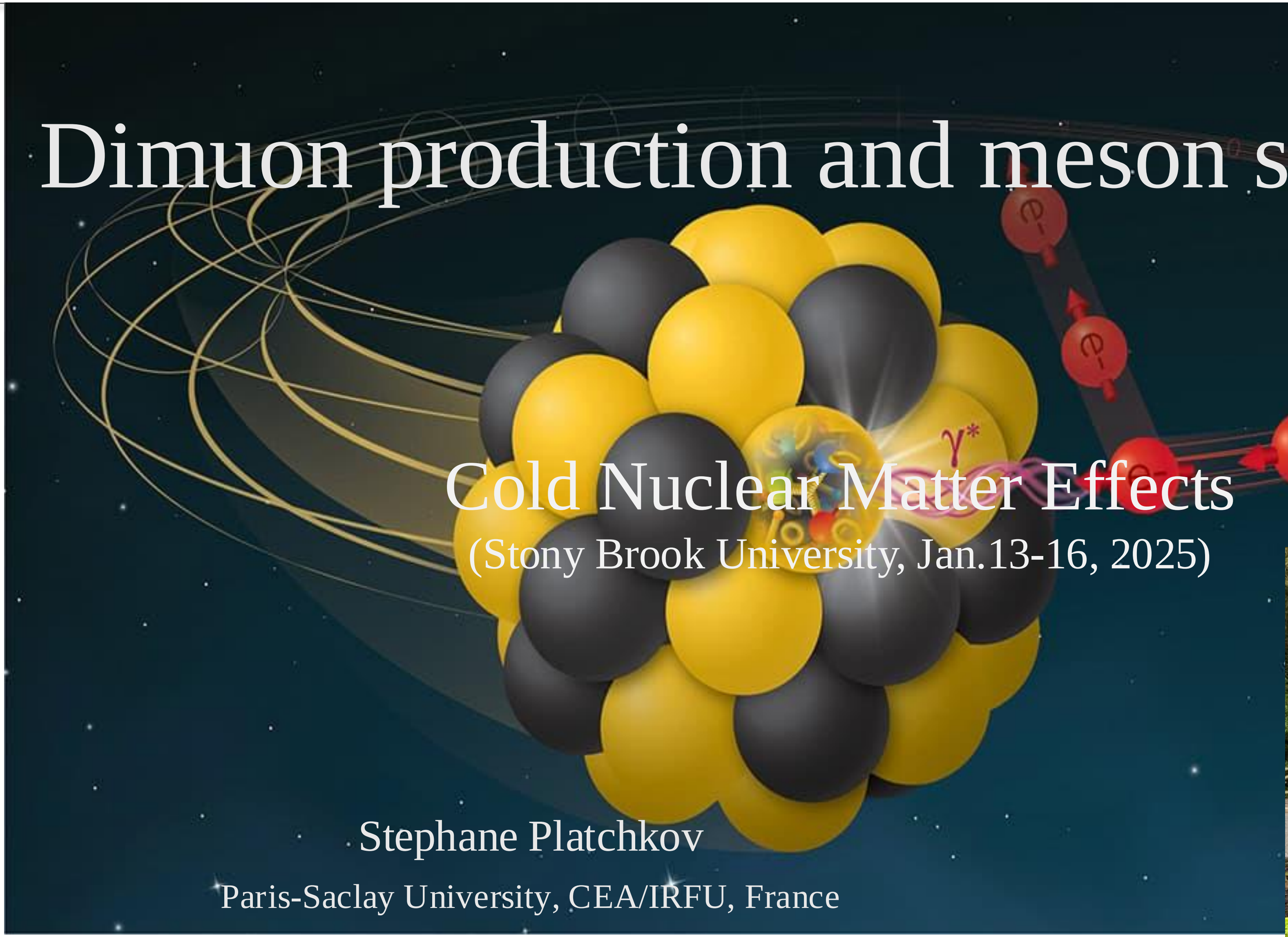


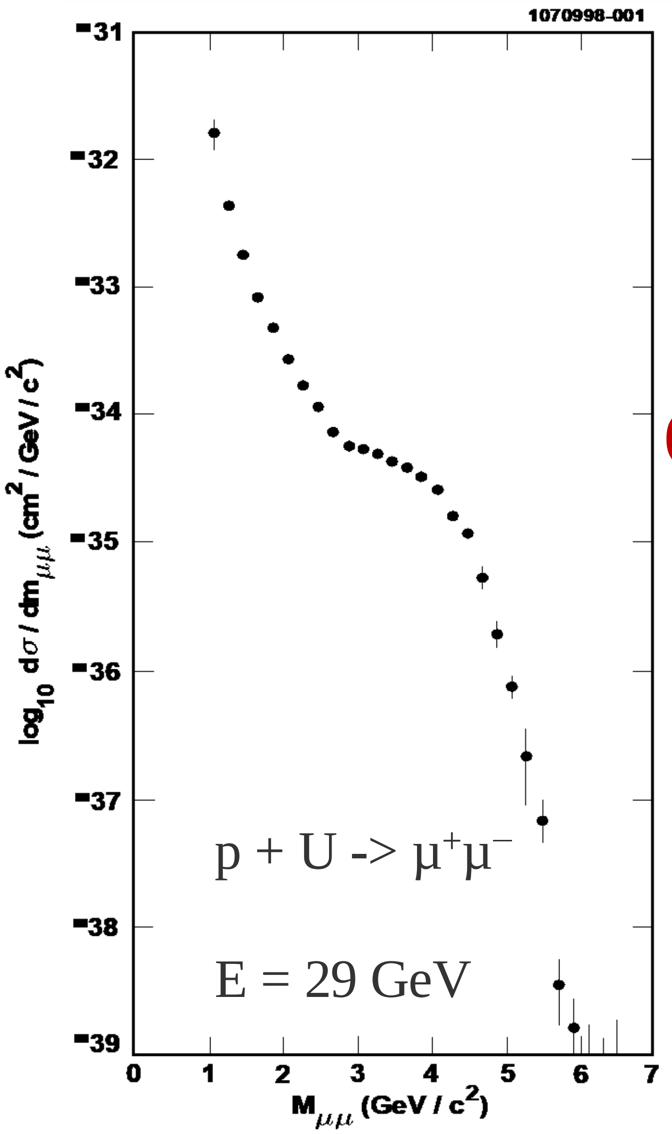
Dimuon production and meson structure

Cold Nuclear Matter Effects
(Stony Brook University, Jan.13-16, 2025)

Stephane Platchkov
Paris-Saclay University, CEA/IRFU, France

1968: first ever dimuon Drell-Yan-(Lederman) experiment

CEA - Saclay



- 1968: dimuon experiment at the AGS (BNL)

(Lederman's team was looking for the W)

… after discovering the K_L^0 at the Cosmotron (BNL) and the muon neutrino also at the AGS

Leon Lederman

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

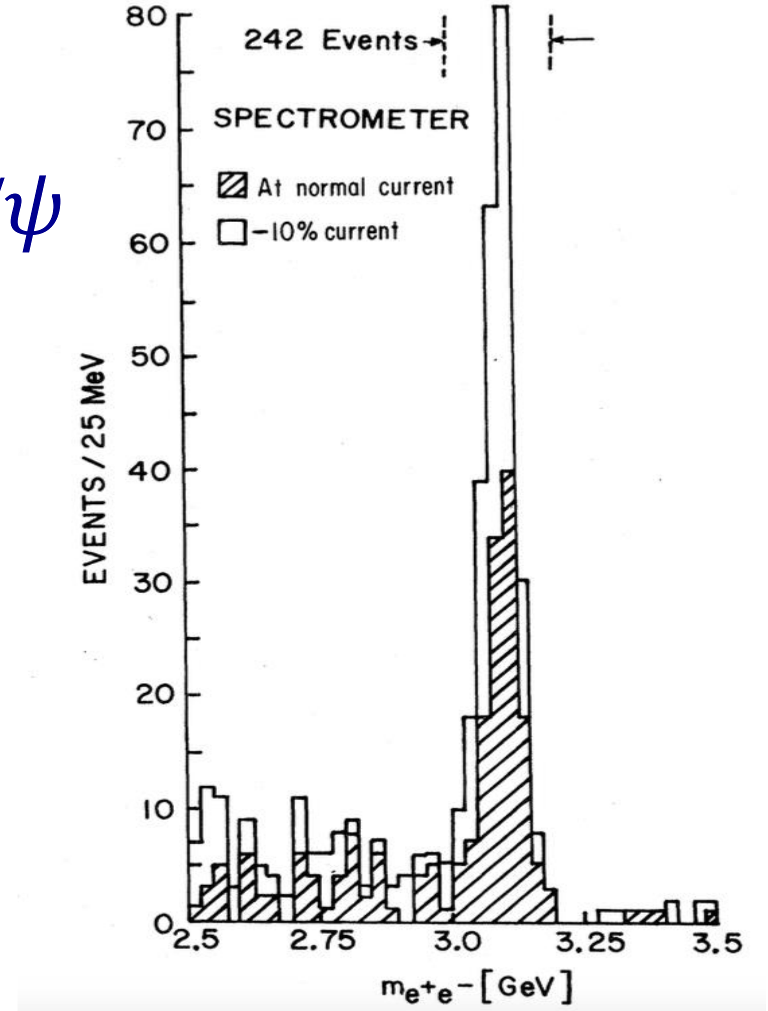
E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 8 September 1970)

- 1970: Explanation using the parton model by SLAC theorists, Sydney Drell and Tung-Mow Yan

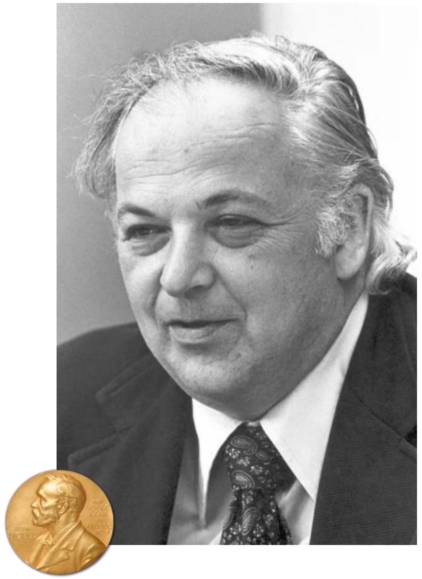
Dimuon experiments: “November revolution”

- 1974: discovery of the J/ψ both at the AGS and at SLAC

J/ψ



Sam Ting



Burton Richter

Nuclear effects: A-dependence

- Pioneering work in 1975:   James Cronin *et al.*,

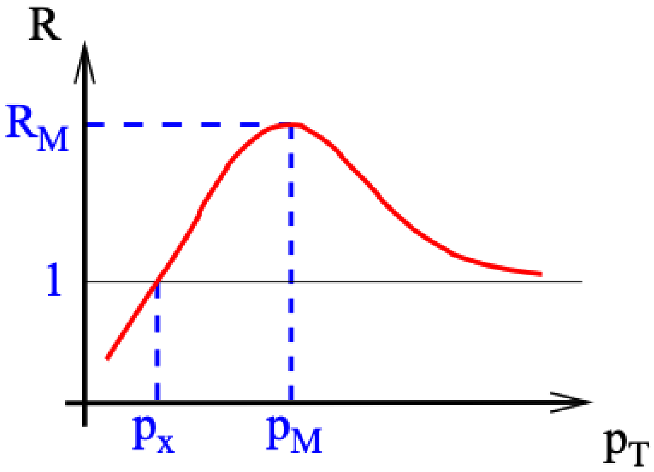
PHYSICAL REVIEW D   VOLUME 11, NUMBER 11   1 JUNE 1975

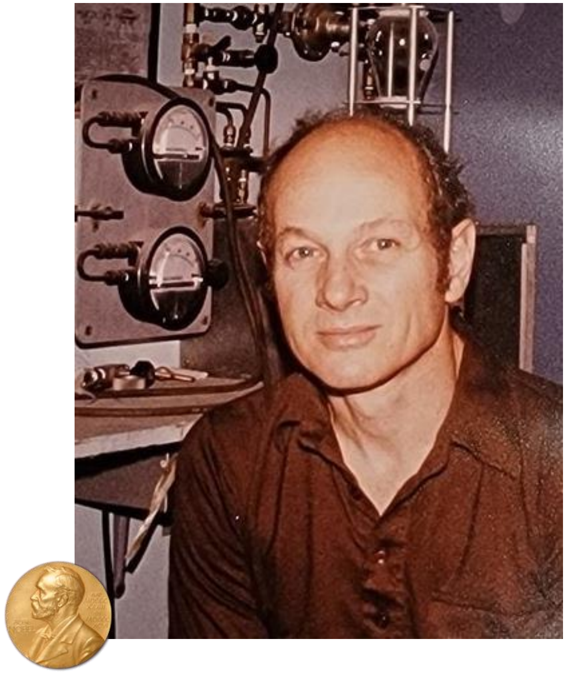
Production of hadrons at large transverse momentum at 200, 300, and 400 GeV *

J. W. Cronin, H. J. Frisch, and M. J. Shochet
The Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637

J. P. Boymond, P. A. Piroué, and R. L. Sumner
Department of Physics, Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 5 December 1974)

$$R(p_T) = \frac{B}{A}\frac{d\sigma_{pA}/d^2p_T}{d\sigma_{pB}/d^2p_T}$$





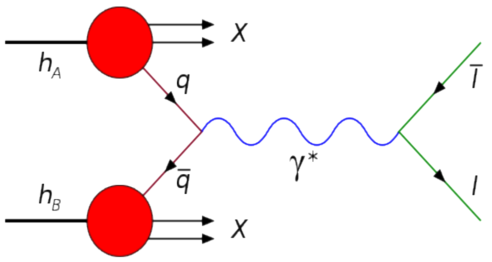
CP @AGS

James Cronin

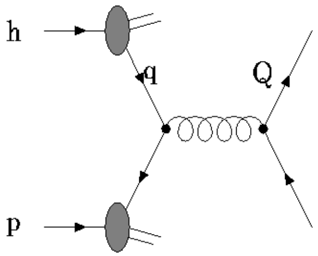
- Cronin effect: suppression at small p_T, compensated with an increase at larger p_T

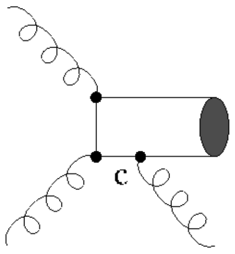
Dimuon production and meson structure

- Dimuon production
  - = > Drell-Yan, em process



  - = > Charmonium production, strong int.

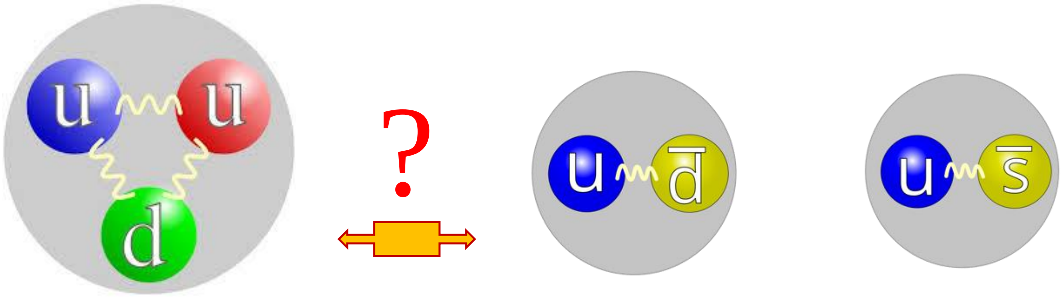




- Light meson structure
  - Absence of meson targets => data on the pion is scarce, kaon is essentially unknown
  - DY (old!) data extensively used, …but largely insufficient
  - J/ψ production 😀 is an additional tool for probing the pion PDFs!.

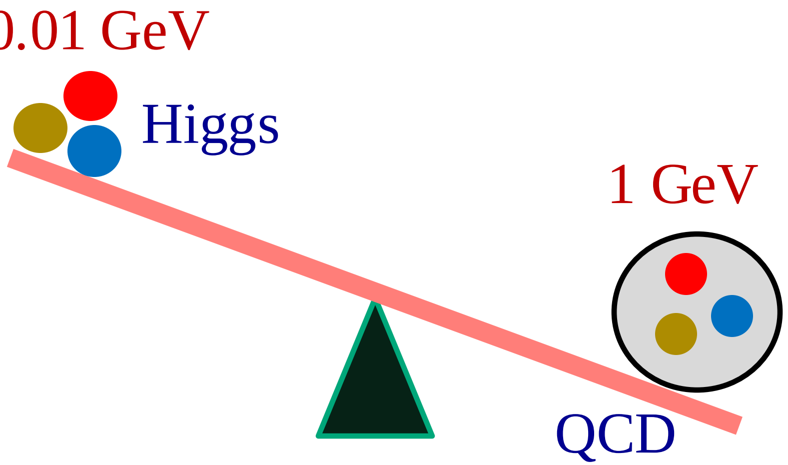
Properties of the light mesons: why?

- Light meson properties
  - Emerge from the properties of QCD: confinement, asymptotic freedom, …



Mass (MeV):	938	139	493
Radius (fm):	0.84	0.65	0.56

- Emergence of the hadron masses (EHM)
  - Higgs mechanism explain only 1% of the nucleon mass
  - EHM: must explain BOTH the nucleon and the pion/kaon

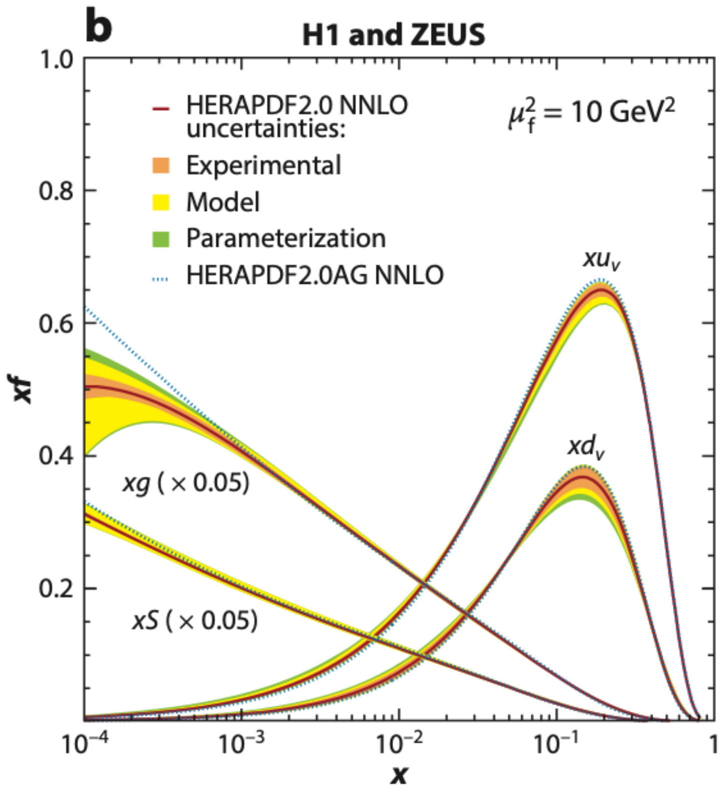


▸ Meson PDFs: input for π and K needed!

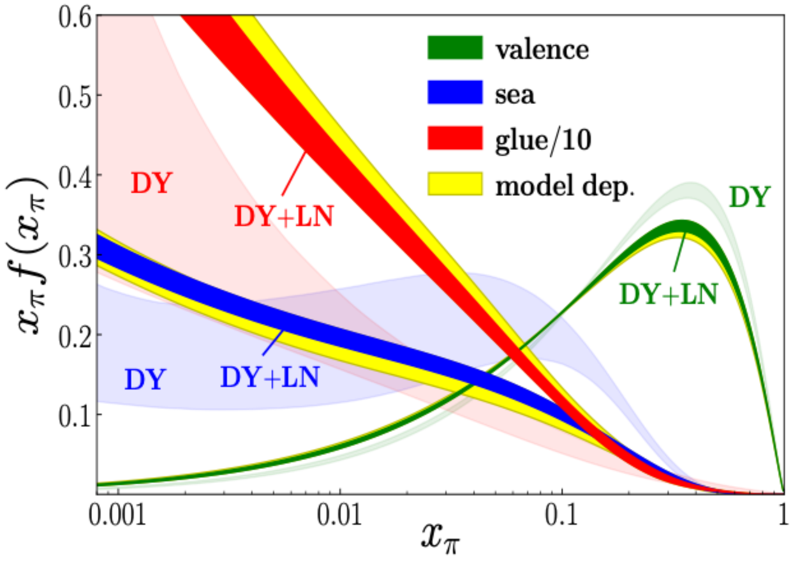
Craig Roberts: *“Thus, enigmatically, the properties of the massless pion are the cleanest expression of the mechanism that is responsible for almost all the visible mass in the universe.”*

PDFs of p, π, K: the present experimental knowledge

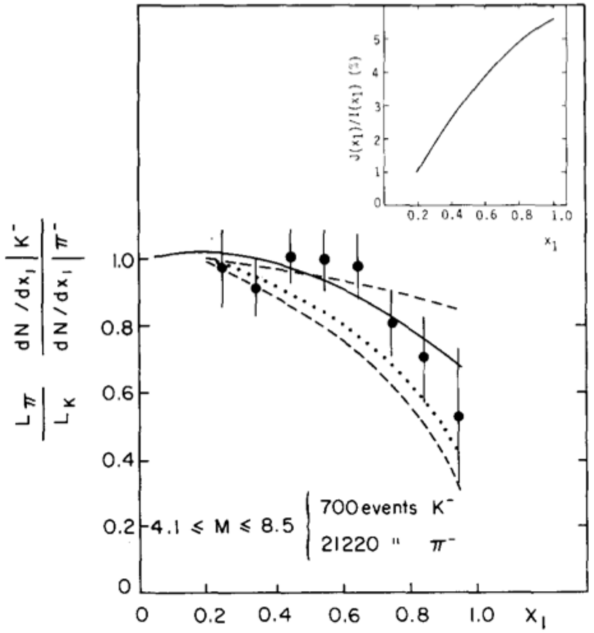
Proton	Pion	Kaon
Hundreds of data sets	Less than ten data sets	A single data set



JAM



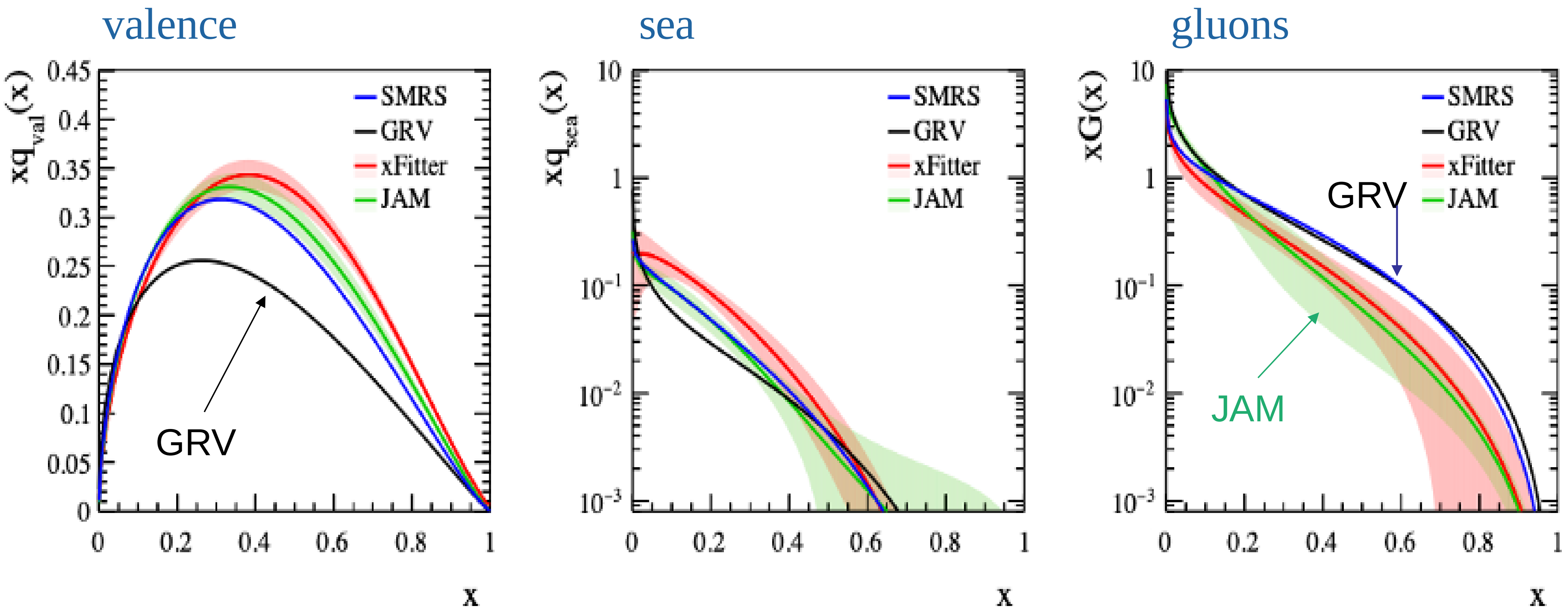
NA3



The parton structure of the two lightest mesons is nearly unknown

Present status of pion PDFs (global fits)

Chang, Peng, SP, Sawada. PRD 107, 056008 (2023).



Valence: need improvement. Sea and gluons: nearly unknown

Pion PDFs global fits

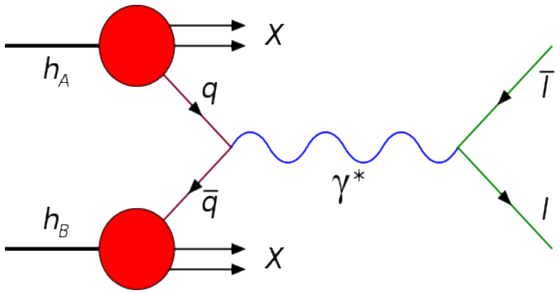
PDFs	Drell-Yan	Direct γ prod.	J/ψ prod.	Leading neutron	Year	nPDF	Eloss	Reference
SMRS	Yes	Yes	-	-	1992	$R(x_2)$	-	Sutton et al., PR D45
GRV	Yes	Yes	-	-	1992	-	-	Glück et al., Z.Phys. C53
xFitter	Yes	Yes	-	-	2020	nCTEQ15	-	Novikov et al., PR D102
JAM18	Yes	-	-	Yes	2018	EPPS16	-	Barry et al., PRL 121
JAM21 (NLL)	Yes	-	-	Yes	2021	EPPS16	-	Barry et al., PRL 127

J/ψ production data are not used in global fits

What can we learn from a comparison with the J/ψ data?

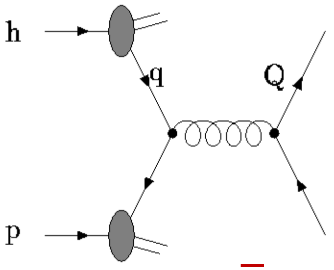
Main differences between DY and J/ψ production processes

- Drell-Yan process
  - 😀 Electromagnetic process
  - 😀 Well understood (up to NNLO)
  - 😀 Sensitive to valence (+ sea…) PDFs
  - 😟 Low cross sections



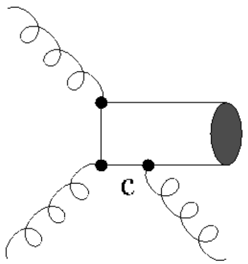
Drell-Yan

- J/ψ production
  - 😀 Strong interaction
  - 😀 Sensitive to valence and gluon PDFs
  - 😀 Large cross sections (~ x30-x40 !)
  - 😟 Production mechanism?



$q\bar{q}$

Annihilation



gg

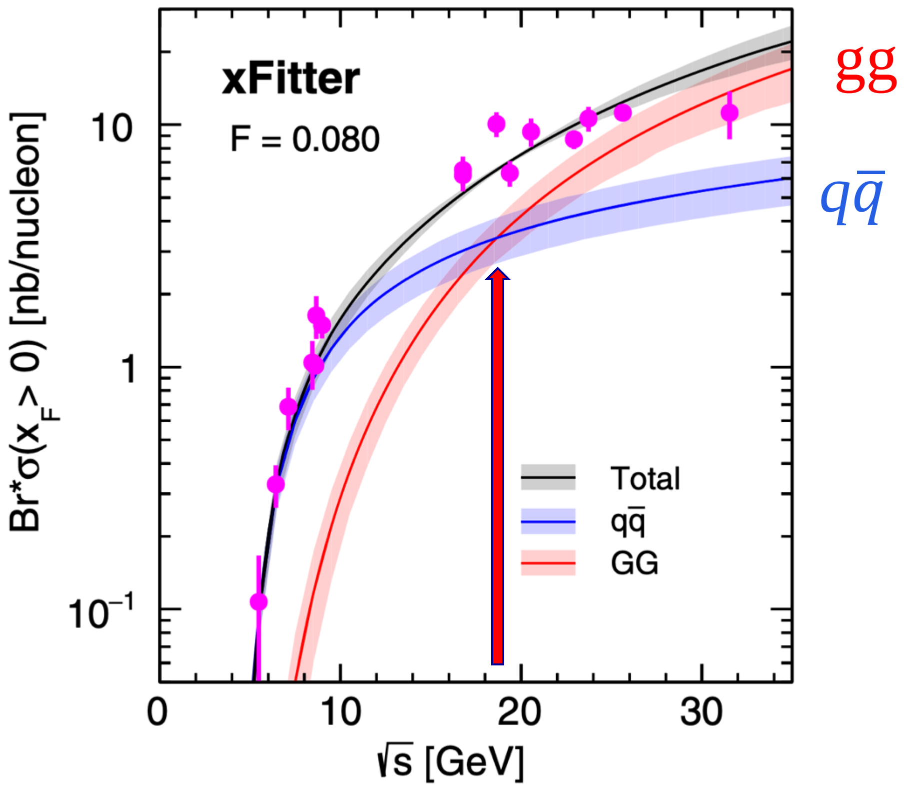
gg fusion

Significant number of meson-induced J/ψ production data!

PDF fit – total cross section vs $\sqrt{s}$

Chang, Peng, Sawada and SP, Phys.Rev. D102 (2020)

Pion-induced J/ψ production; calculations: CEM@NLO

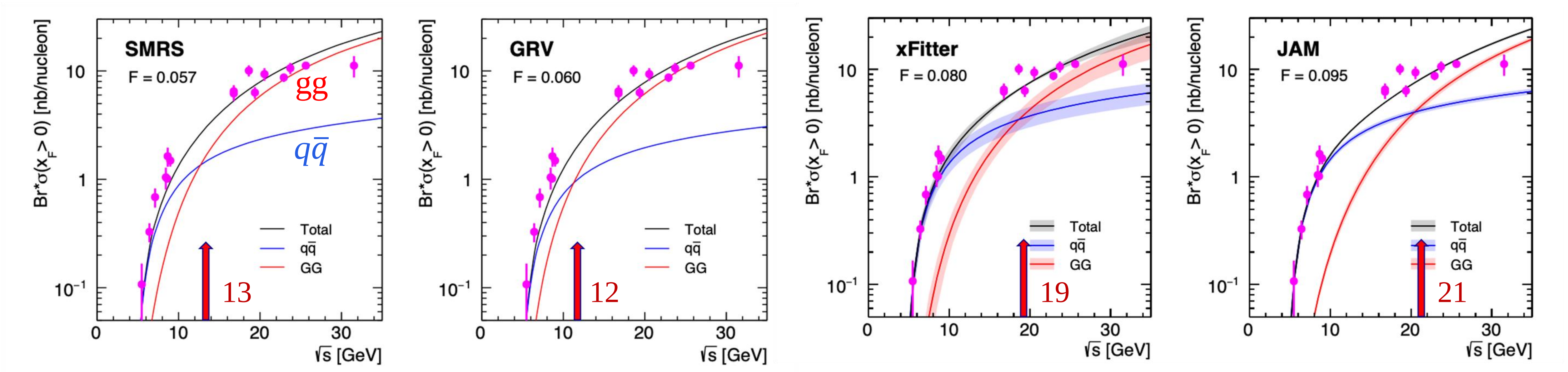


Available cross section data for light nuclei ($A \leq 9$)

The gg fusion term (arrow) is dominant above $\sqrt{s}$ =19 GeV

PDF fits comparison – total cross section

Pion-induced J/ψ production; calculations CEM@NLO

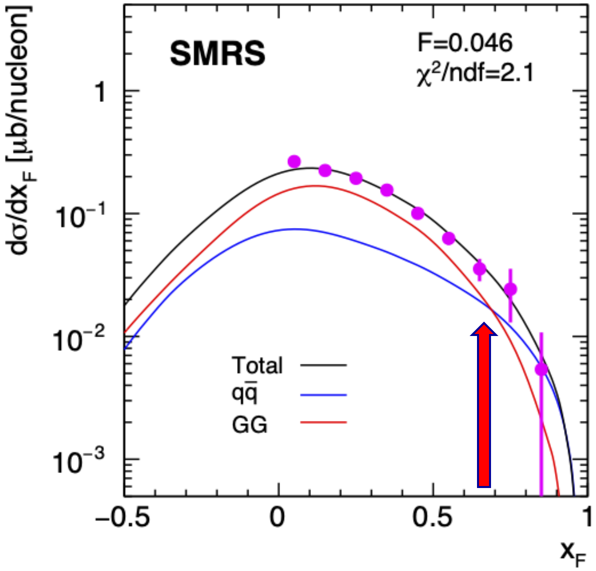


Quite different $q\bar{q}$ and gg contributions!
Data are very sensitive to the pion PDFs

PDF fit – x_F dependence

Pion-induced J/ψ production: calculations CEM@NLO

NA3: π^- 200 GeV



$x_F \simeq 0.70$

8 data sets

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

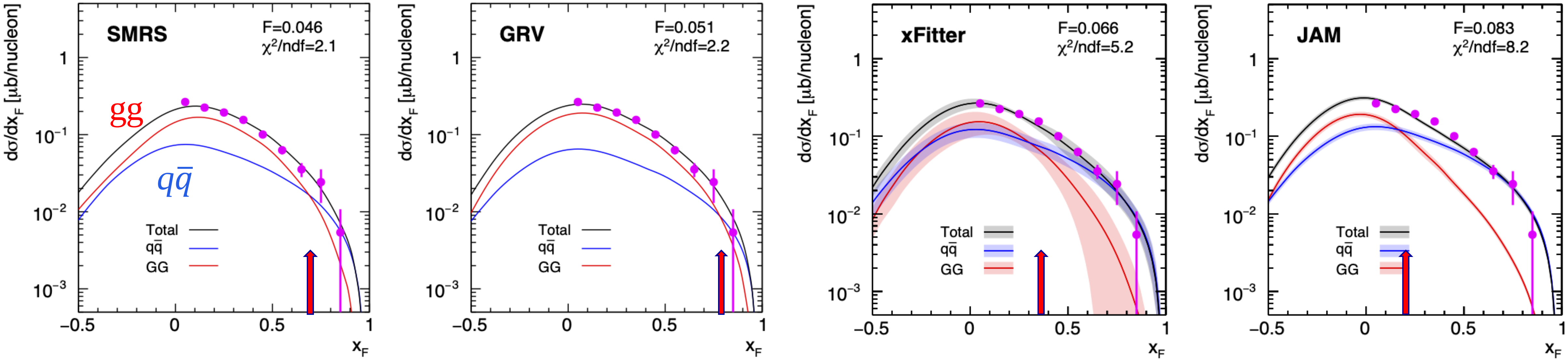
Experiment	P_{beam} (GeV/c)	Target	Normalization[a]	References
FNAL E672, E706	515	Be	12.0	[68]
FNAL E705	300	Li	9.5	[69]
CERN NA3[b]	280	p	13.0	[70]
CERN NA3[b]	200	p	13.0	[70]
CERN WA11[b]	190	Be	c	[72]
CERN NA3[b]	150	p	13.0	[70]
FNAL E537	125	Be	6.0	[73]
CERN WA39[b]	39.5	p	15.0	[74]

The GG fusion term is dominant up to $x_F \simeq 0.70$

PDF fits comparison – x_F dependence

Pion-induced J/psi production; calculations CEM@NLO

NA3, π^- 200 GeV



$x_F \simeq 0.70$
$\chi^2 = 2.1$

$x_F \simeq 0.78$
$\chi^2 = 2.2$

$x_F \simeq 0.36$
$\chi^2 = 5.2$

$x_F \simeq 0.20$
$\chi^2 = 8.2$

The data favors global fits with larger gluon PDFs

PDF fits comparison – Chi^2 comparison for all data sets

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

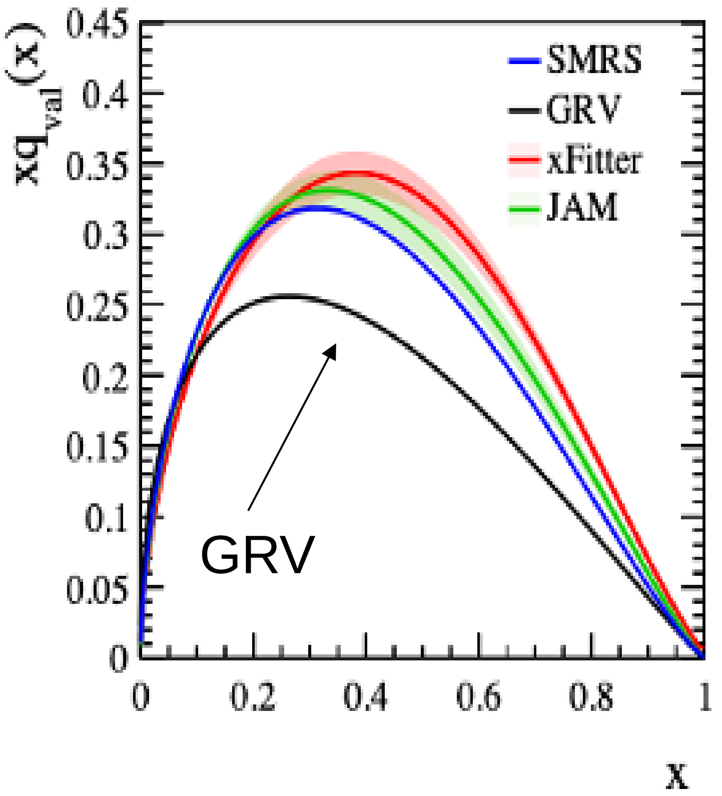
SMRS and GRV consistently provide better agreement with the data

Main reason: they have larger gluon densities for $x > 0.1$

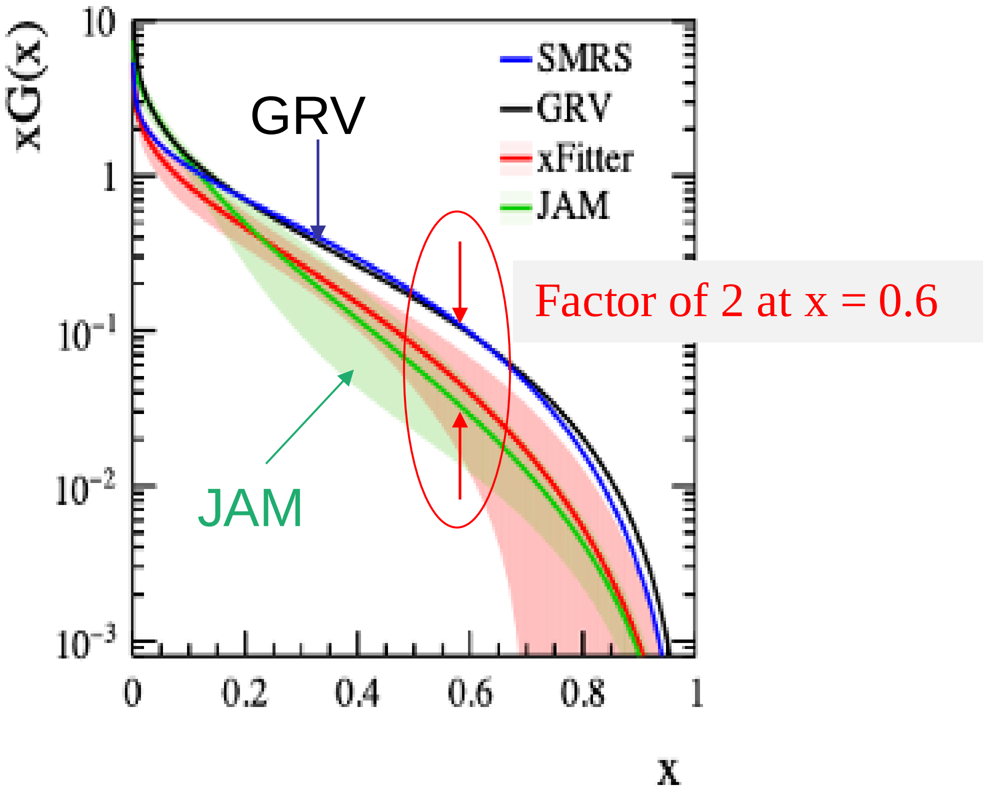
Pion global fits: differences

Chang, Peng, SP, Sawada. PRD 107 (2023)

valence



gluons



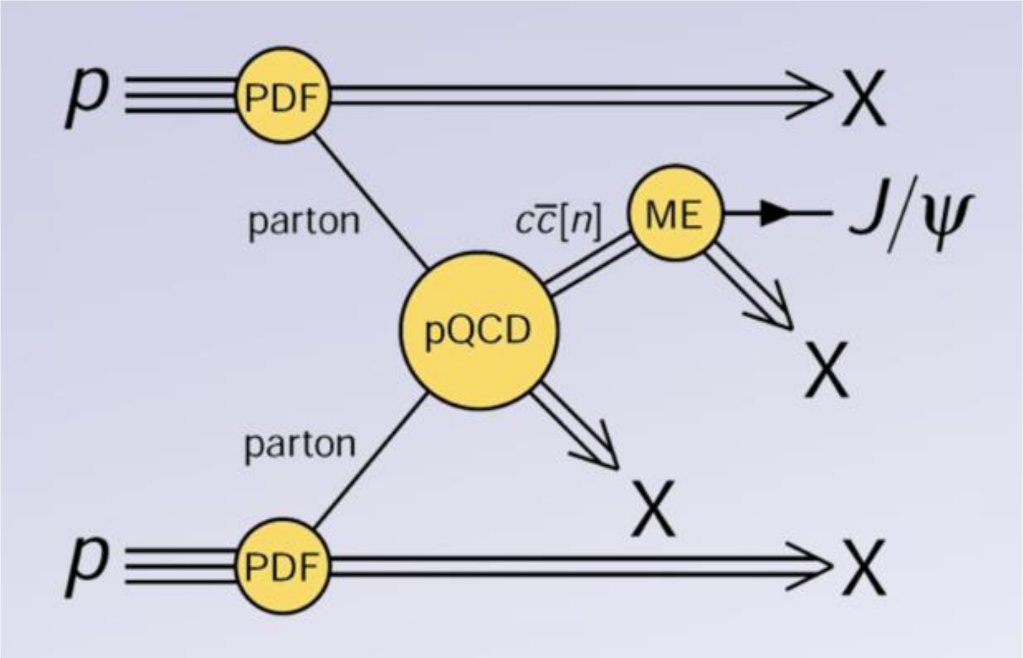
Large difference between the gluon distributions

Could it be there any bias due to the use of CEM?

- X-check: use NRQCD instead (Non-Relativistic QCD), a factorization-based approach:

  - Short-distance cross section: describes the purely partonic process (pQCD)
    😀 => well understood

  - Long-distance matrix elements (LDME): evolution to a color-neutral bound state
    😟 => purely phenomenological
    => LDMEs are fitted to the data



A short reminder on LDMEs (LO)

- Cross section for J/ψ (or ψ') production

Beneke and Rothstein, PRD 54, 2005(1996)

$$\hat{\sigma}(q\bar{q}\to\psi')=\frac{16\pi^3\alpha_s^2}{27(2m_c)^3 s}\delta(x_1x_2-4m_c^2/s)\langle\mathcal{O}_8^{\psi'}(^3S_1)\rangle$$

$$\hat{\sigma}(gg\to\psi')=\frac{5\pi^3\alpha_s^2}{12(2m_c)^3 s}\delta(x_1x_2-4m_c^2/s)\left[\langle\mathcal{O}_8^{\psi'}(^1S_0)\rangle+\frac{3}{m_c^2}\langle\mathcal{O}_8^{\psi'}(^3P_0)\rangle+\frac{4}{5m_c^2}\langle\mathcal{O}_8^{\psi'}(^3P_2)\rangle\right] = \Delta_8^{\psi'}$$

$$+\frac{20\pi^2\alpha_s^3}{81(2m_c)^5}\Theta(x_1x_2-4m_c^2/s)\langle\mathcal{O}_1^{\psi'}(^3S_1)\rangle z^2\left[\frac{1-z^2+2z\ln z}{(1-z)^2}+\frac{1-z^2-2z\ln z}{(1+z)^3}\right],$$

taken from theory

- Data used
  - p-induced J/ψ and ψ' production (light targets)
  - π-induced J/ψ and ψ' production (light targets)
  - Cross section ratio of ψ' and J/ψ (any target)

Two free LDMEs for J/ψ (… and two for ψ')

NRQCD fits to x_F-dependent data

Hsieh, liang, Chang, Peng, SP, Sawada, Ch.J.Ph. 73 (2021)
Chang, Peng, SP, Sawada. PRD 107 (2023)

- Data used
  - Atomic numbers < 10, both proton and pion-induced data, for both J/ψ and ψ'

pion
164 points

proton
82 points

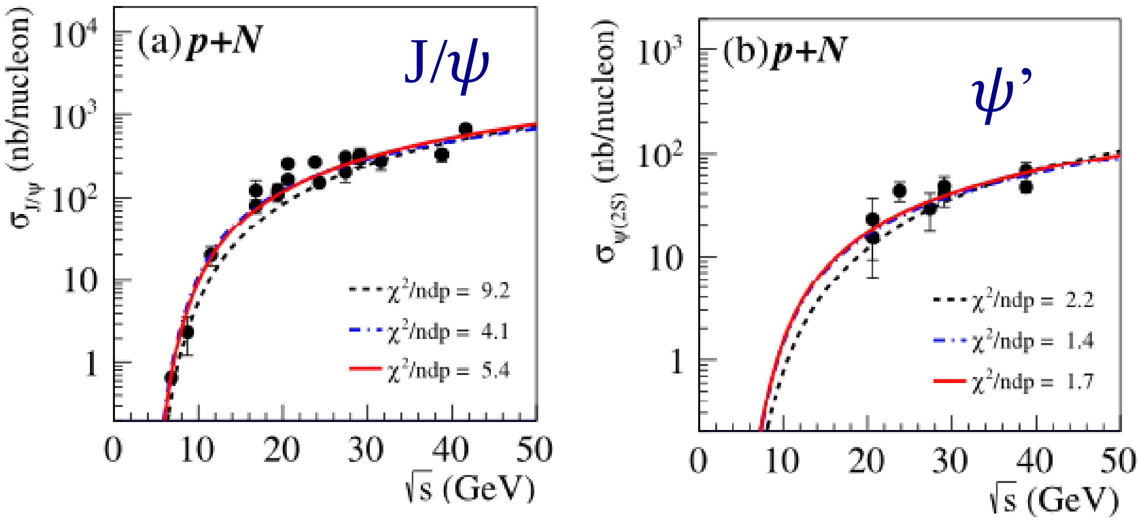
TABLE II. Differential cross sections datasets for charmonium production [J/ψ, $\psi(2S)$ and $R_\psi(x_F)$] used in the study, listed in order of decreasing beam momentum.

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]

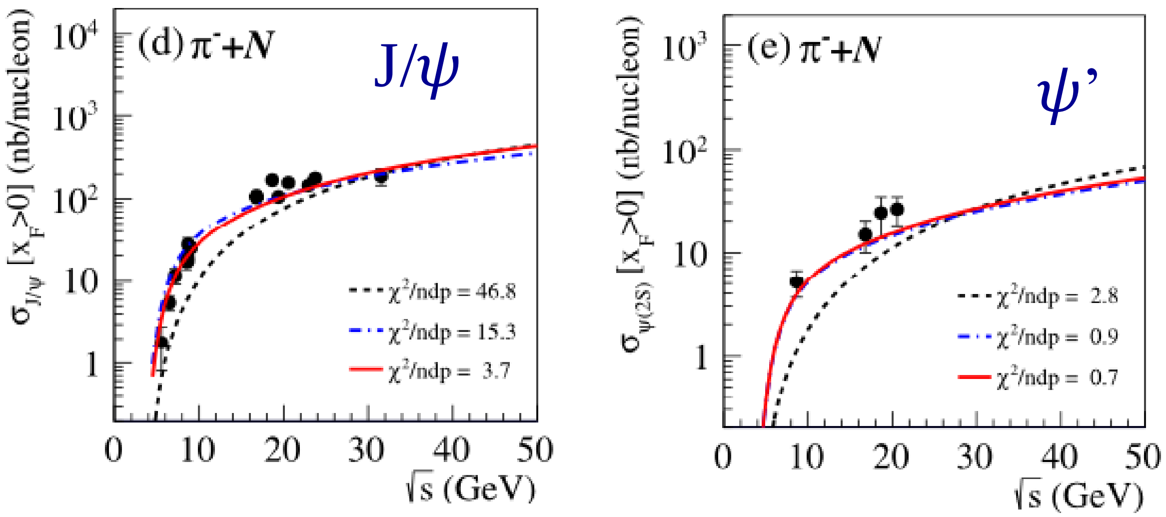
16 data sets, both pion- and proton-induced

Common fit to pion and proton-induced charmonium data

proton-induced



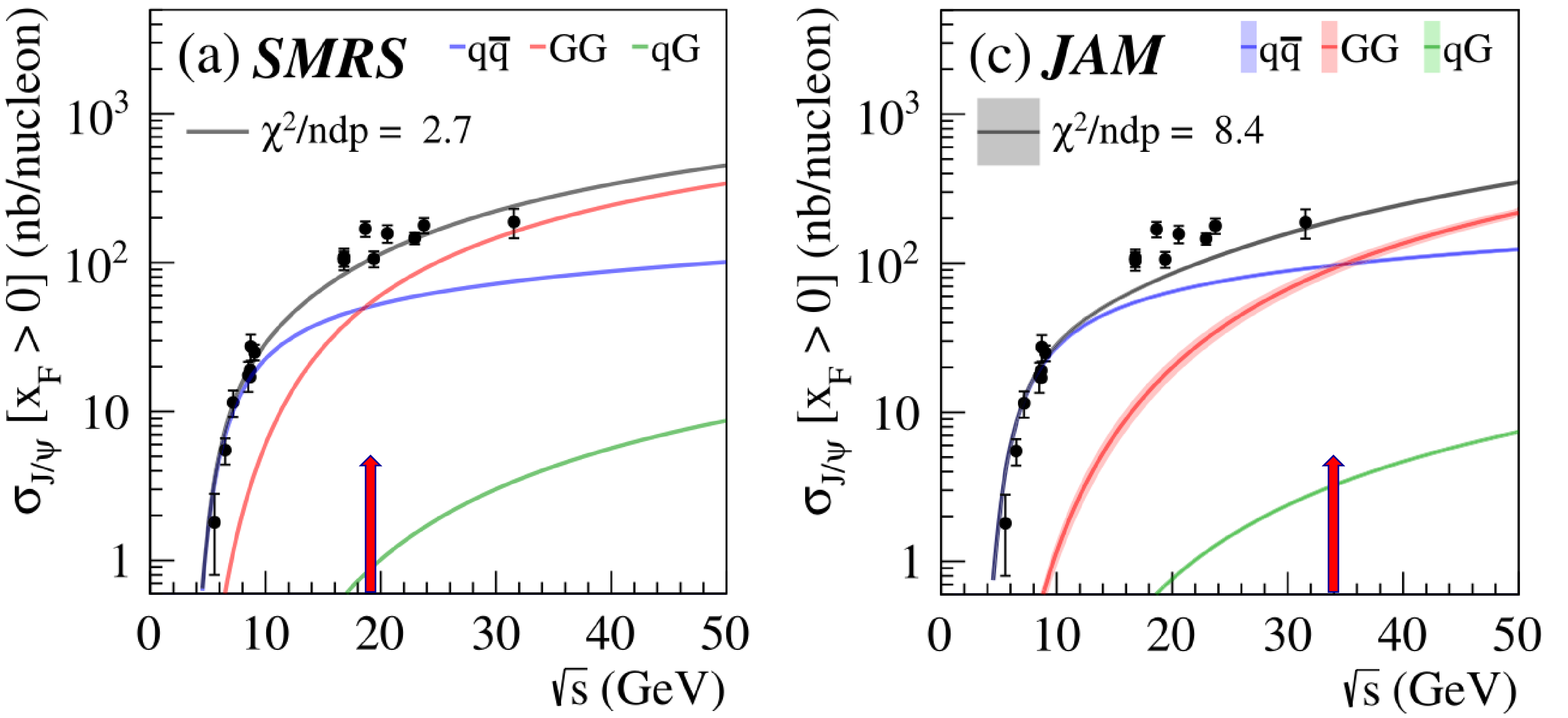
pion-induced



Proton data provide further constraint on the universal LDMEs

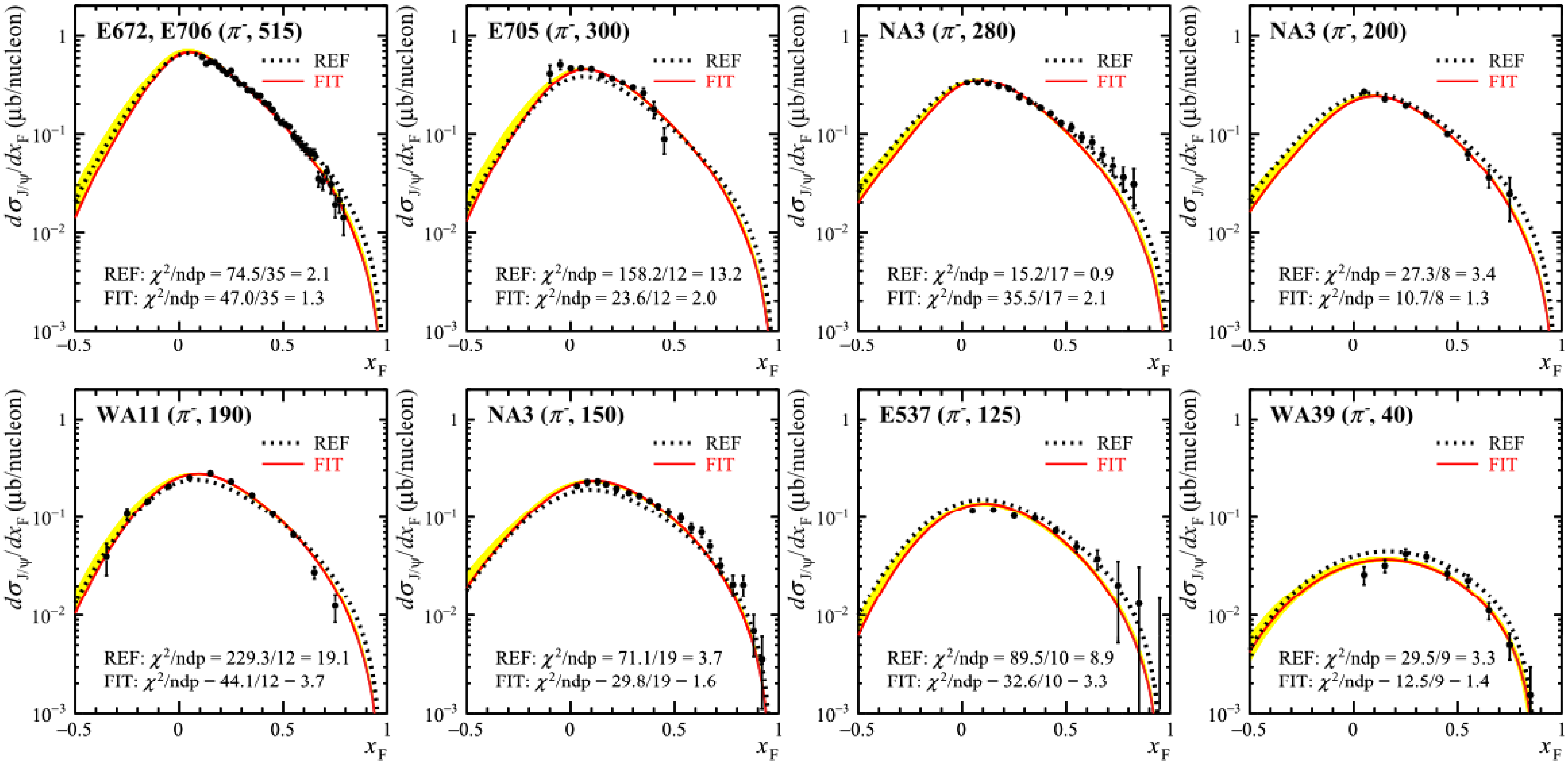
== > Good fit on all data!

NRQCD fit – total cross sections

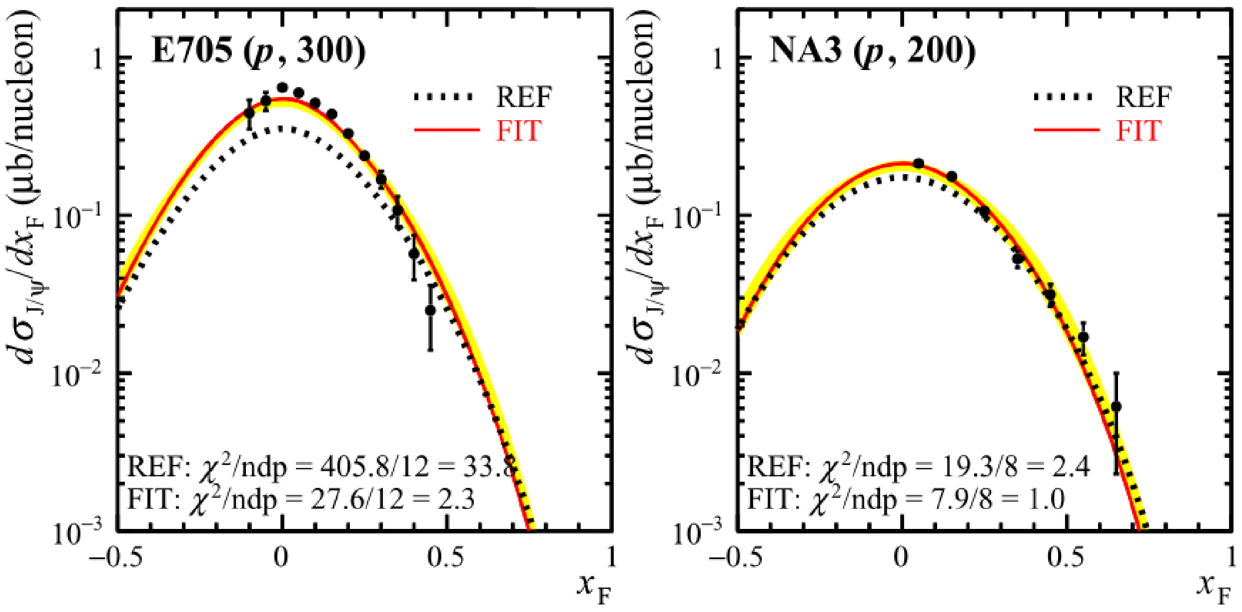


Larger gluon contribution for SMRS in comparison with JAM

x_F-dependence fit – pion beam



x_F-dependence fit – proton beam



Fit results for $\chi2$

Global FIT/ Comparison	SMRS	GRV	JAM	xFitter
$\chi2$ total/ndf	1.9	2.4	5.6	4.2
$\chi2$-ndp (pion)	1.8	2.4	5.9	4.5
$\chi2$-ndp (proton)	1.6	1.7	2.7	1.9

A comment on the ψ’ fits

- J/ψ vs ψ’ (Mass: 3.7 GeV vs 3.1 GeV)

Data from E706: $\pi^- + {}^9$Be at 515 GeV/c

- LDMEs
  - Δ_8 (J/ψ) = 0.052(2)

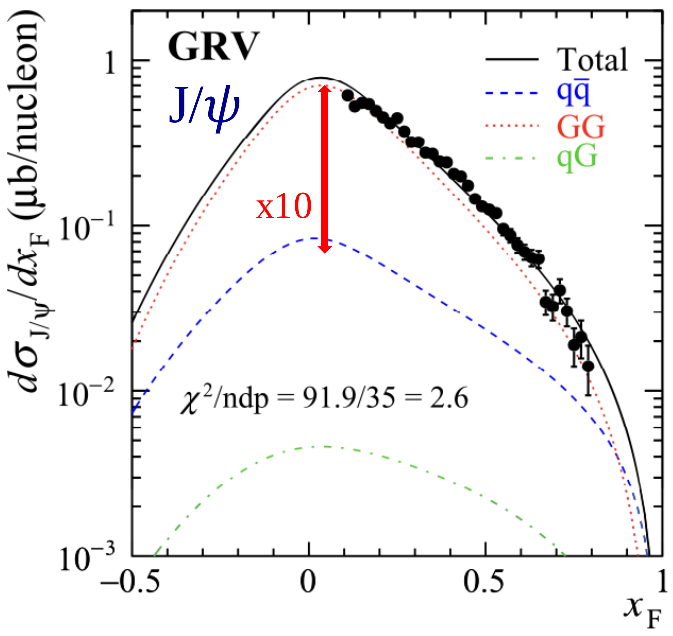
    Δ_8 (ψ’) = 0.004(1)

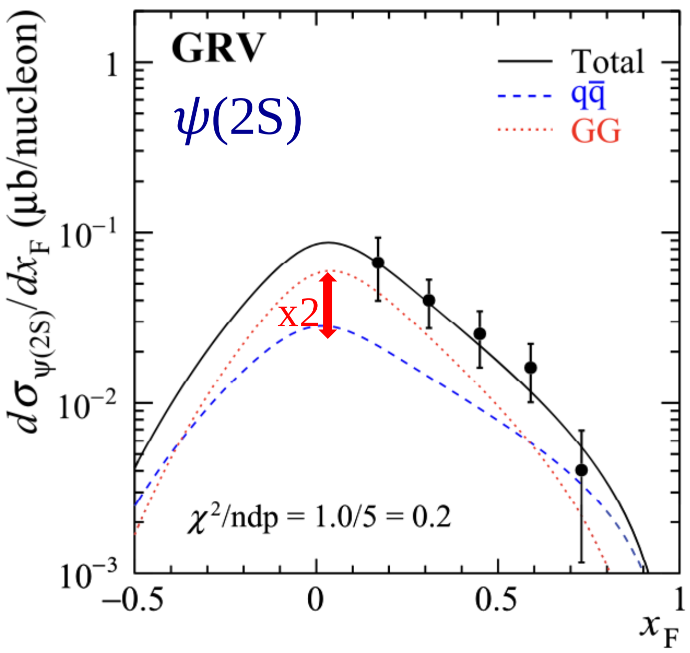
    Ratio = ~12

  - $O_8[^3S_1]$ (J/ψ) = 0.043(4)

    $O_8[^3S_1]$ (ψ’) = 0.021(2)

    Ratio: = ~2 !

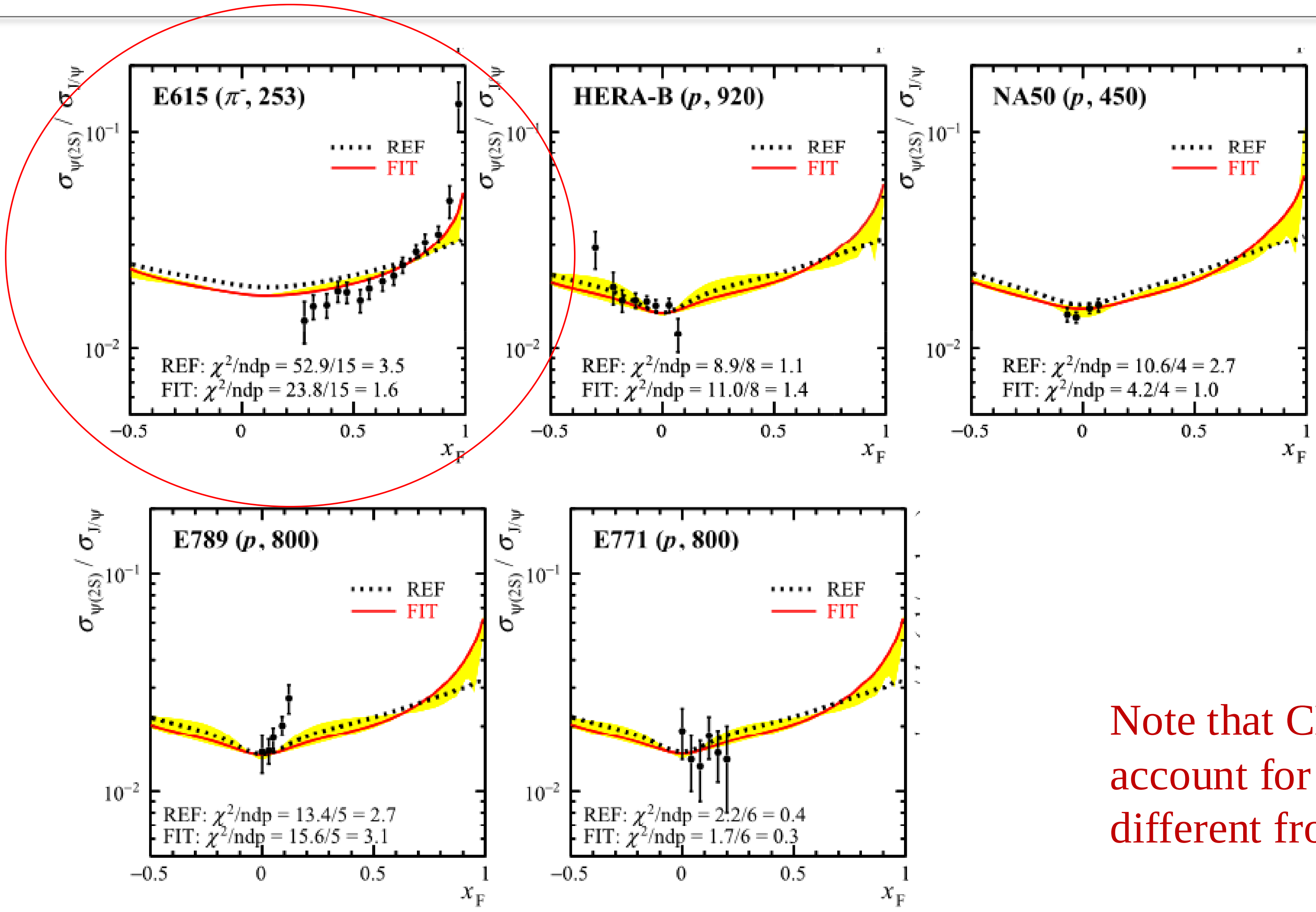




The $q\bar{q}$ contribution in ψ’ is much larger than that in J/ψ

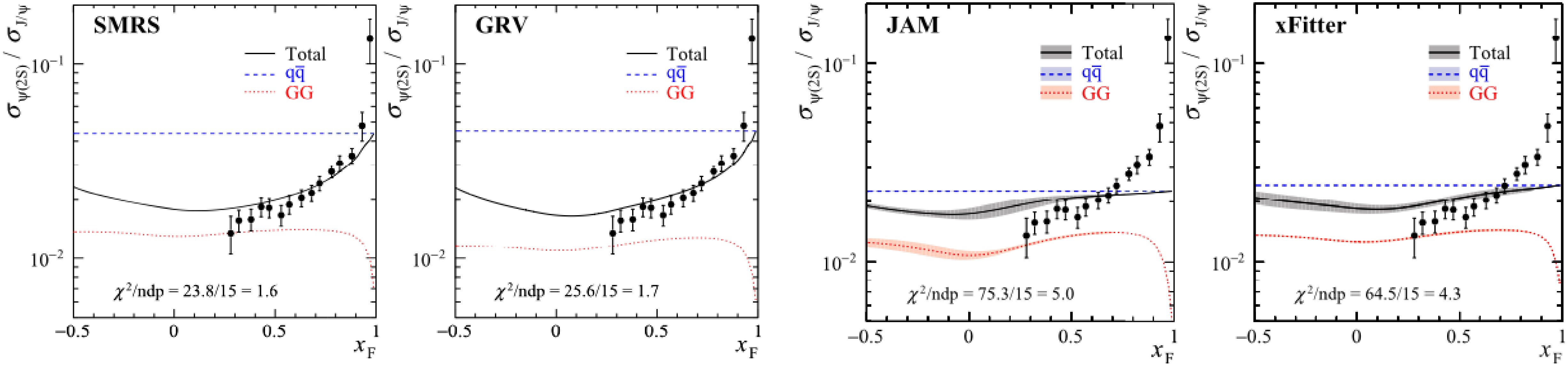
=> The ψ’ has a stronger sensitivity to the valence PDF

x_F-dependence fit – Ratio of J/ψ and ψ'



Note that CEM cannot account for a behavior different from a straight line

Ratio of J/ψ and ψ': comparison between the four pion PDFs

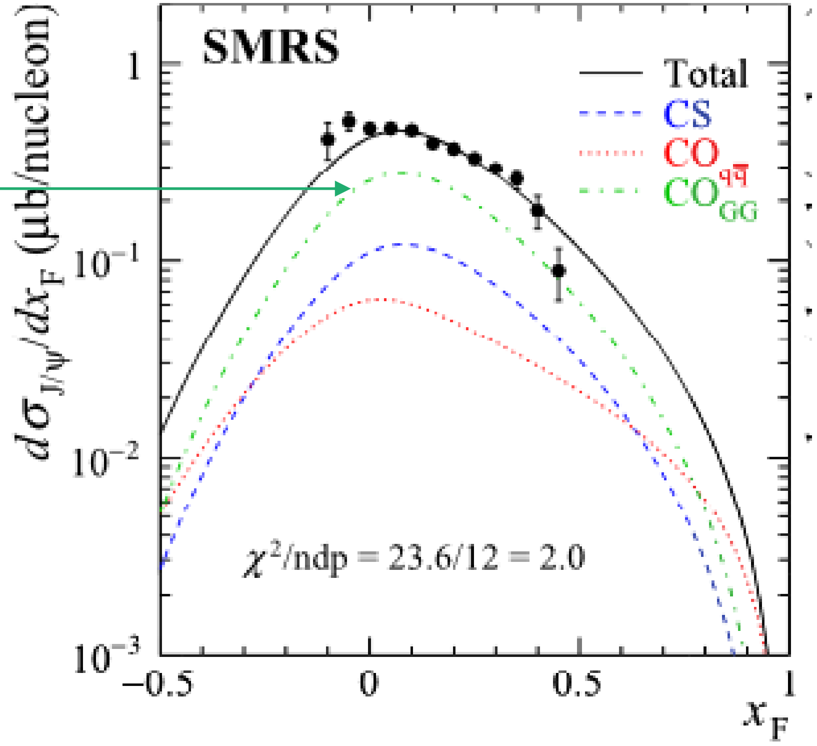


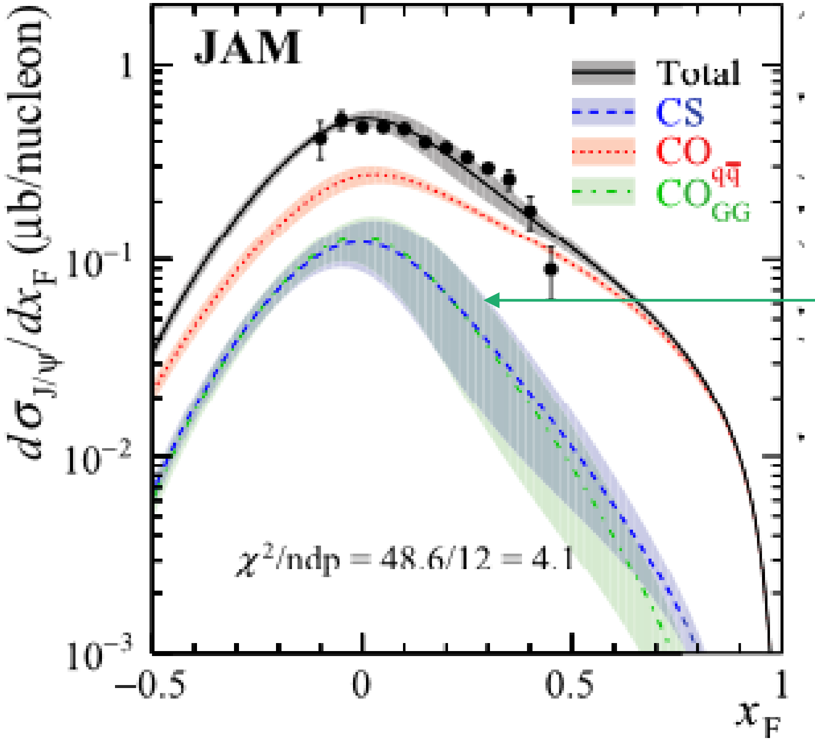
An additional strong constraint on the pion PDFs.

NRQCD fit: breakdown of CS and CO contributions

Data from E705, $\pi^- + \text{Li}$, 300 GeV

CO_{GG}





CO_{GG}

Very different CO contributions

A glimpse on the kaon PDFs

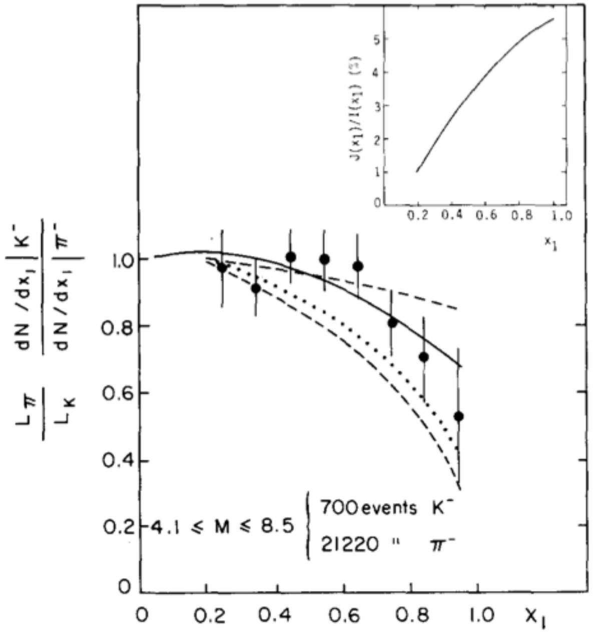
- Kaon-induced DY data vs recent QCD calculations

A single data set

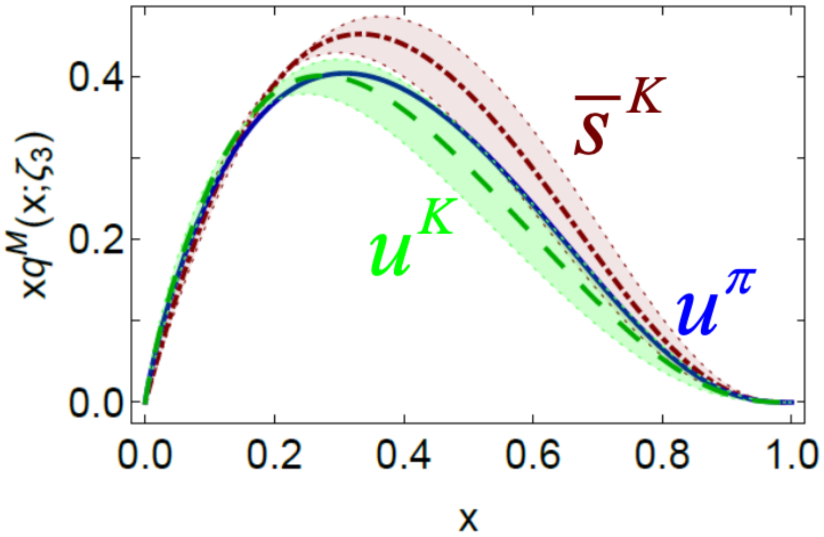
Cui et al., Eur.Phys.J. C80 (2020)

Han et al., Eur.Phys.J. C81 (2021)

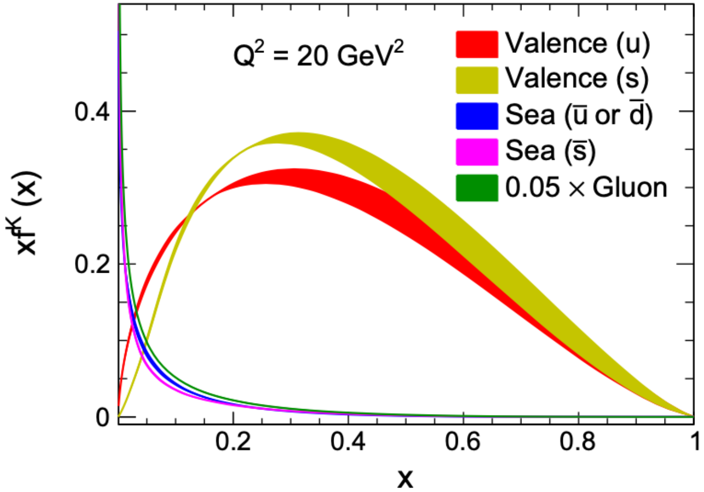
NA3



Continuum Schwinger Method



Maximum Entropy Method

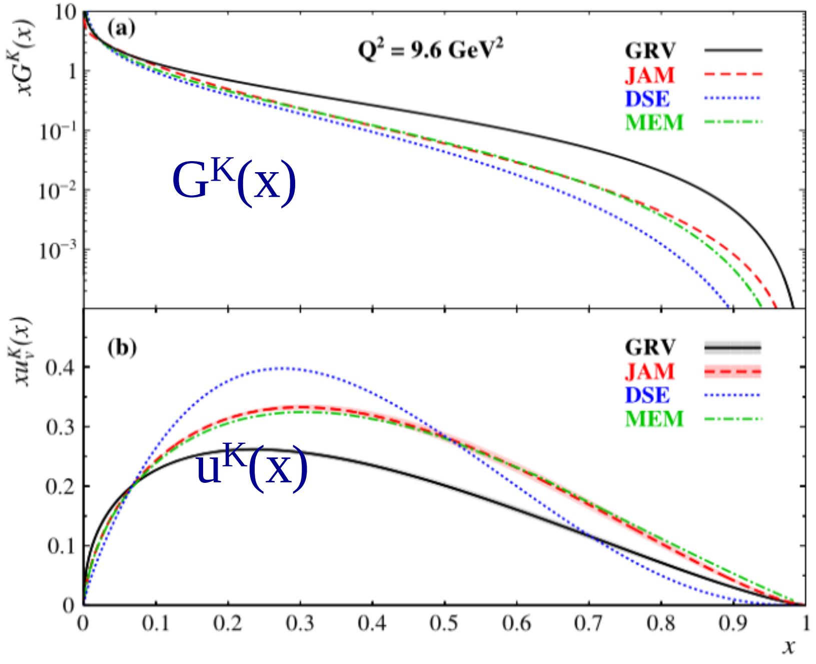


Are there additional J/ψ production data?

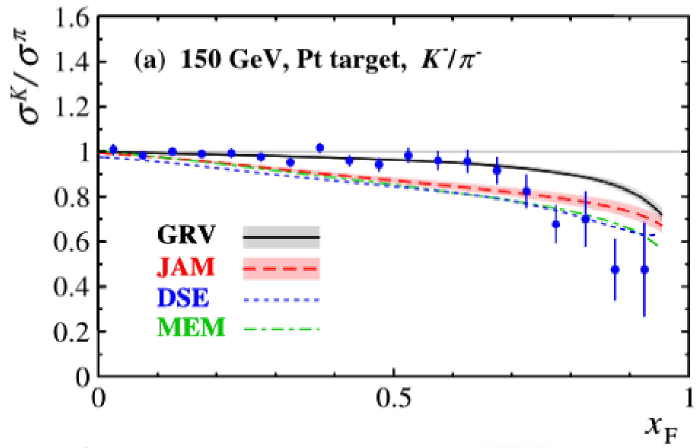
NA3 and WA39: kaon and pion-induced J/ψ production data

Chang, Peng, Sawada and SP, Phys. Lett. B855 (2024)

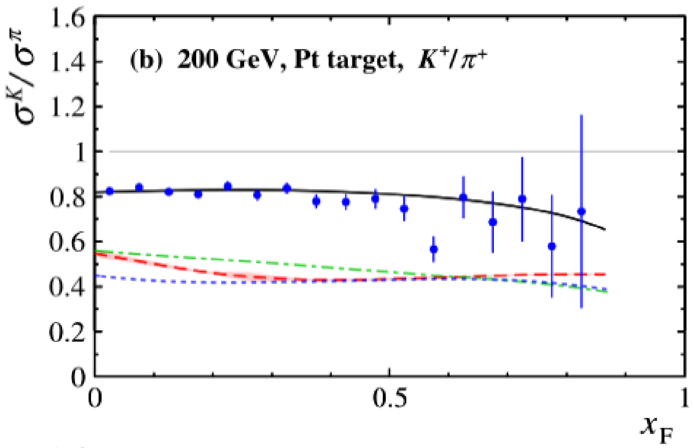
Kaon PDFs

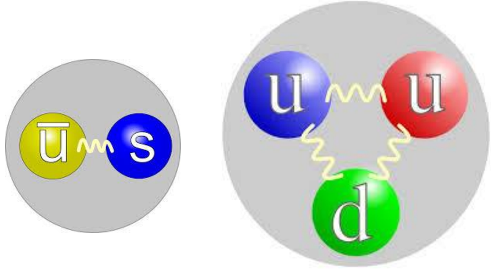


K^-/π^- ratio 150 GeV

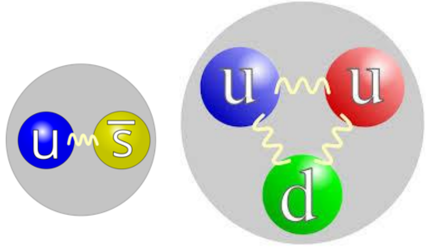


K^+/π^+ ratio, 200 GeV





$K^- + p$



$K^+ + p$

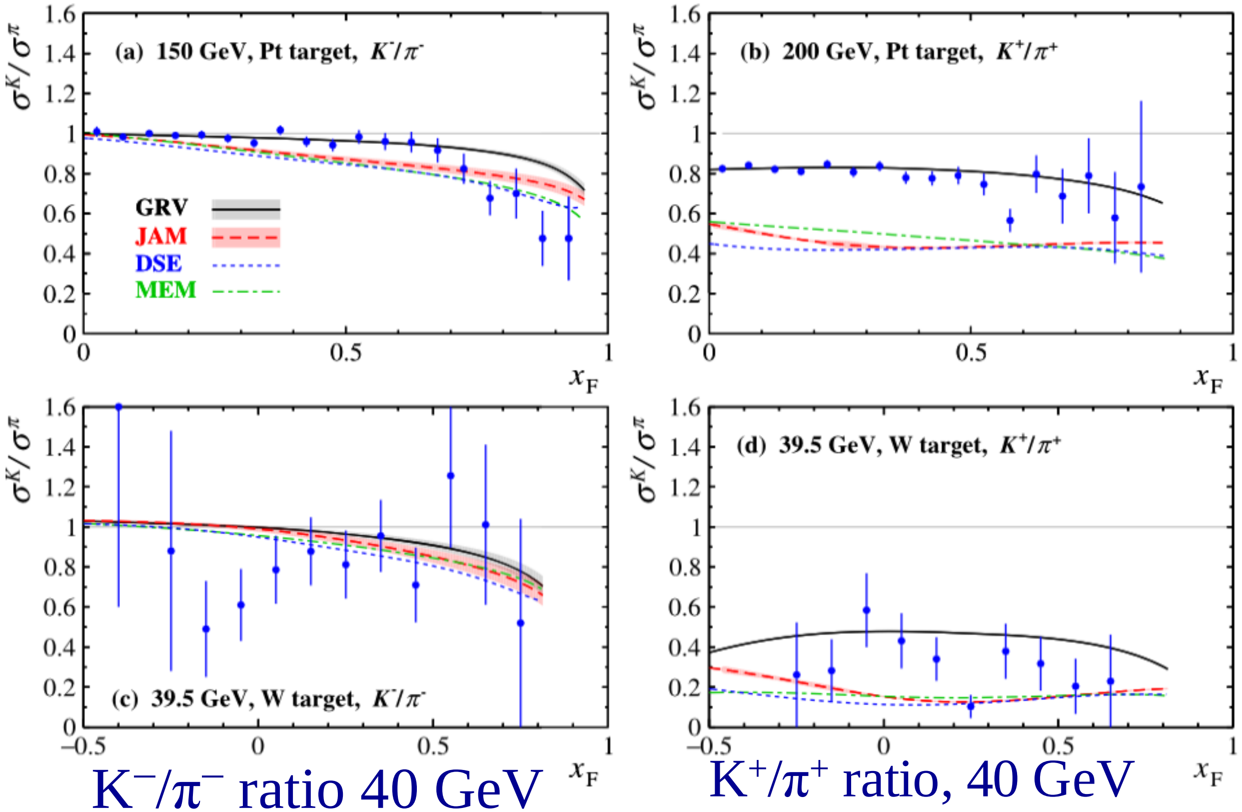
Data favor Kaon/pion PDFs with larger gluon content

NA3 and WA39: kaon and pion-induced J/ψ production data

Chang, Peng, Sawada and SP, Phys. Lett. B855 (2024)

K$^-$/π$^-$ ratio 150 GeV

K$^+$/π$^+$ ratio, 200 GeV



K$^-$/π$^-$ ratio 40 GeV

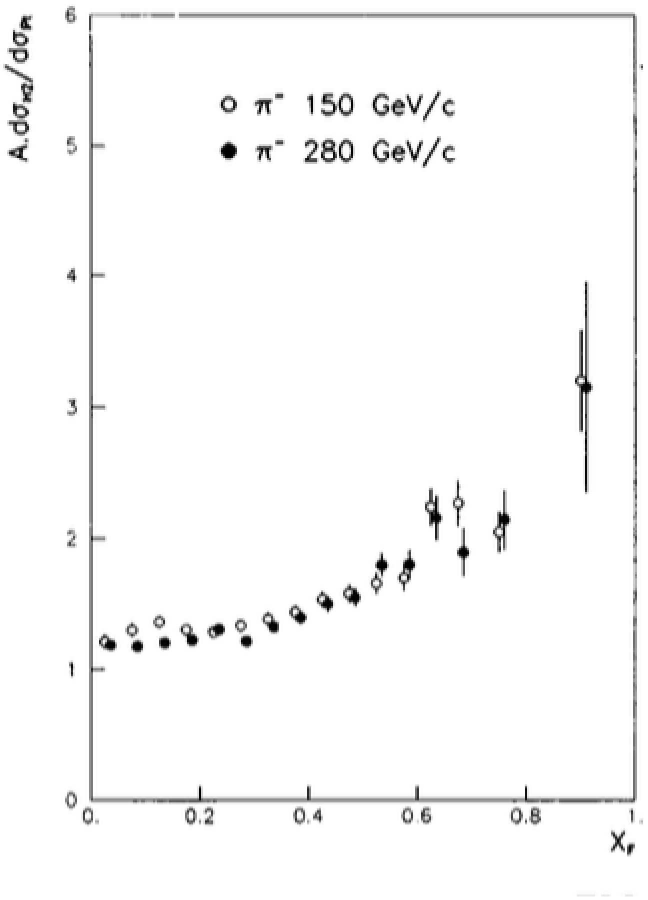
K$^+$/π$^+$ ratio, 40 GeV

Data favor Kaon/pion PDFs with larger gluon content

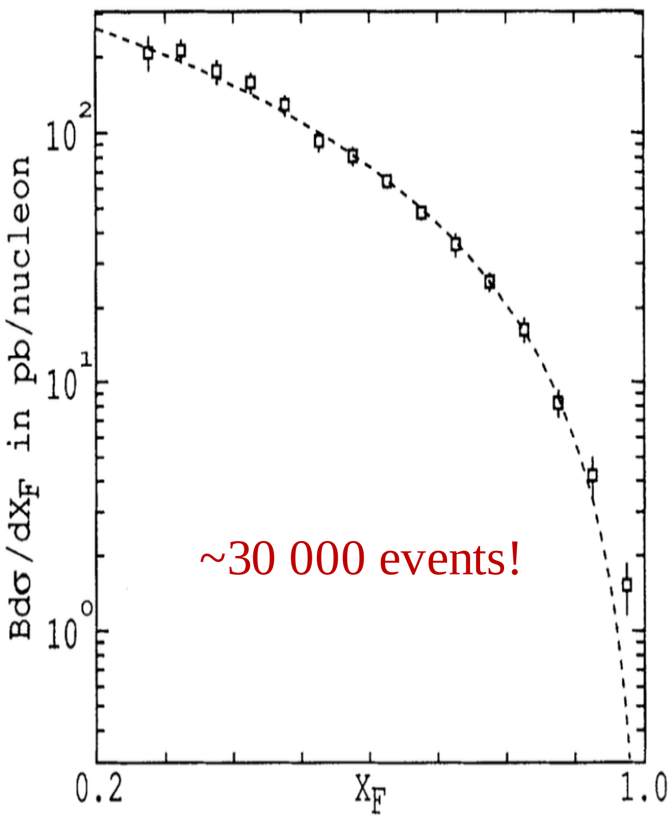
The importance of nuclear effects for J/ψ and ψ’ production

Eloss calculation

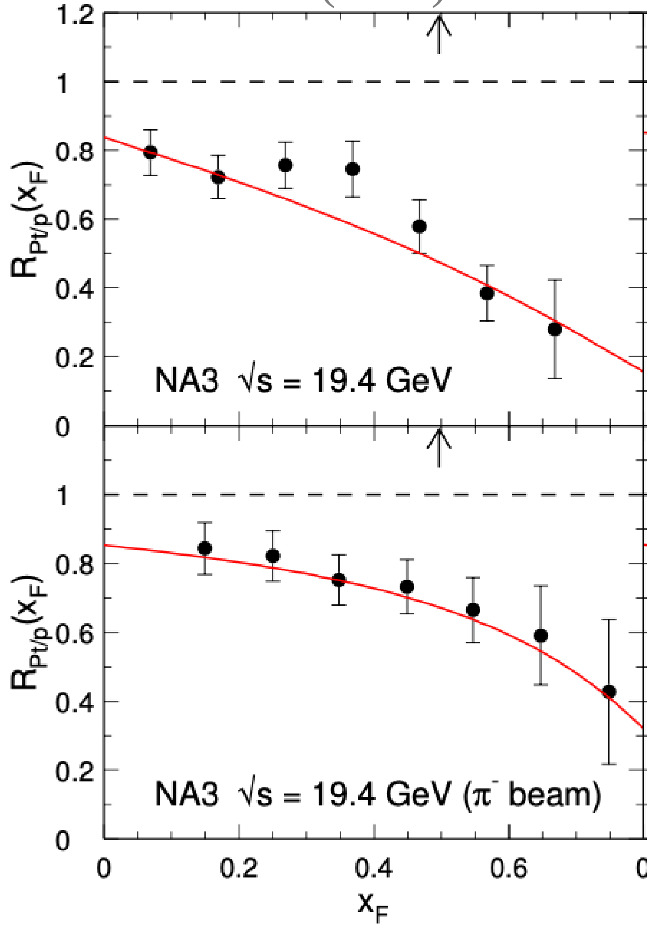
NA3 H/Pt ratio (1983)



E615 ψ’ data (1991)



Arleo and Peigné, JHEP 03 (2013)



Summary and Outlook

- Charmonium production:
  - complementary information on the light meson PDFs
  - Larger sets of data with high statistical accuracy
- Common NRQCD fit to p and π-induced data on both J/ψ and ψ' data
  - Charmonium production favors pion/kaon PDFs with larger gluon content.
- Next steps
  - Include DY and J/ψ production in a global fit of the pion PDFs
  - Further increase the amount of J/ψ data by including also data on heavy targets (mandatory condition: calculation of the E-loss effects)
- Last, but not least: new data from EIC, AMBER, JLab, etc…

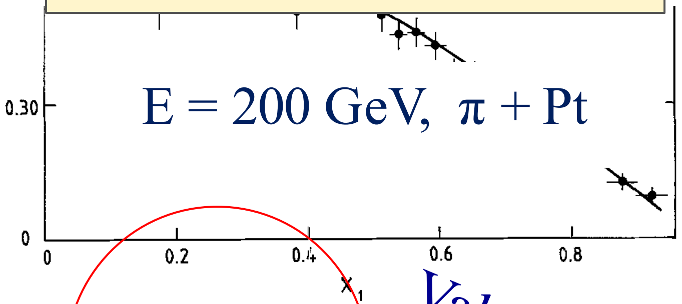
Thank you!

Spares

Drell-Yan

- DY data available today are nearly four decades old !
  - CERN : NA3(1983), NA10(1985); Fermilab: E537(1988), E615(1989)

Badier et al., Z.Phys. C18, 281 (1983).



Valence

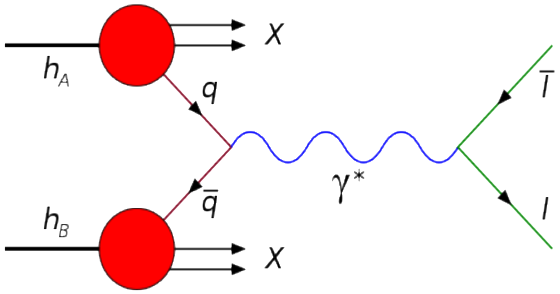
Sea

Fig. 1. a π^- 200 GeV data. The data points represent $F_\pi(x_1)$ as defined b[...] curve represents the valence structure function of the pion obtained from [...] function as defined by (2). **b** The data points represent $F_\pi(x_2)$ as defined [...] structure function $1.6u(x_2)+2.4d(x_2)$ for π^-. Solid curve represent the (v[...] curves have been scaled up by a factor $K=2.3$

Table 4. Result of the fit of the pion valence structure function with the data at $\langle M^2_{\mu\mu}\rangle = 25$ GeV^2. The π sea and nucleon valence and sea structur[...]

NA3

		σ	Correlation coefficients	Systema[...] pion sea
π^- — 150 GeV/c	$\alpha^\pi = 0.41$	0.05		∓0.03



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

E615

PAIRS PRODUCED BY . . .

NA3

[...]eral $m_{\mu\mu}$ intervals. The solid line is the cross sec[...] [...]ected from the structure-function determination.

3. *Pion structure*

NA10

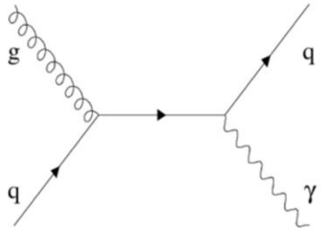
The results for the pion structure function are sh[...] Fig. 12(a). The parameters corresponding to the cu[...] given in Table I, column 1 and the projected va[...] the pion structure function in Table II. The para[...] [...]ation makes no allowance for scale-breaking eff[...] [...]ause these are very small as shown below.

E615

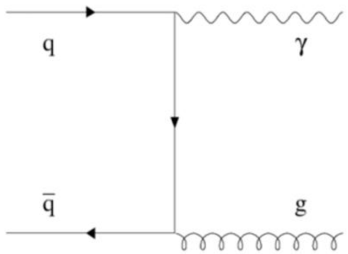
The data determine only the pion valence PDF …

Additional data used

- Direct photon production using meson beams (CERN)
  - provides constraints on the gluon PDFs,
  - NLO corrections known
  - insufficiently good statistics
  - data from 1985 (CERN WA70 experiment)

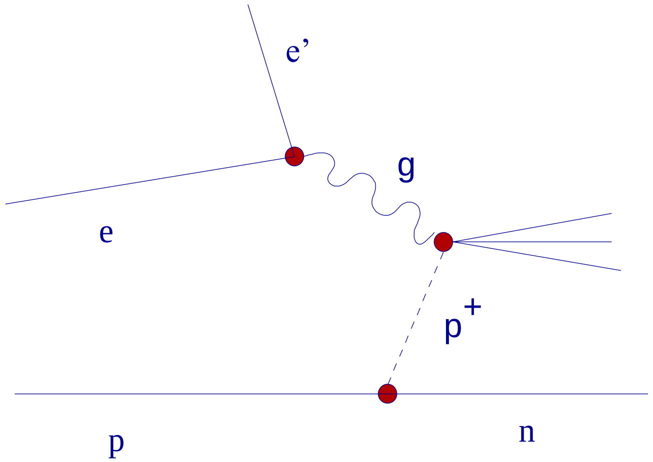


QCD Compton



Annihilation

- Leading neutron production (“Sullivan”): JLAB, EIC
  - extends kinematics to much lower x values
  - pion flux not well calibrated
  - the pion is off-shell



Leading neutron production

Pion valence PDF: Main "global" fits available

SMRS (NLO) 1992

Sutton, Martin, Roberts and Stirling, PRD 45, 2349 (1992).

ɔutions of Table VII which were fitted to the NA10 Drell-Yan
lata. The effect of varying the sea-quark distribution is shown.

effect of the variation of the sea is shown in Fig. 10. Further experiments with high-statistics π^+ and π^- beams, ideally with data below $x_\pi \sim 0.2$, are needed in order to more accurately determine the pion sea.

V. PION MOMENTS

In order to compare with lattice QCD calculations we calculate the first two moments of the pion valence-quark distributions:

$$2\langle xV_\pi\rangle = 2\int_0^1 dx\, xV_\pi\ , \quad (9)$$

$$2\langle x^2V_\pi\rangle = 2\int_0^1 dx\, x^2V_\pi\ . \quad (10)$$

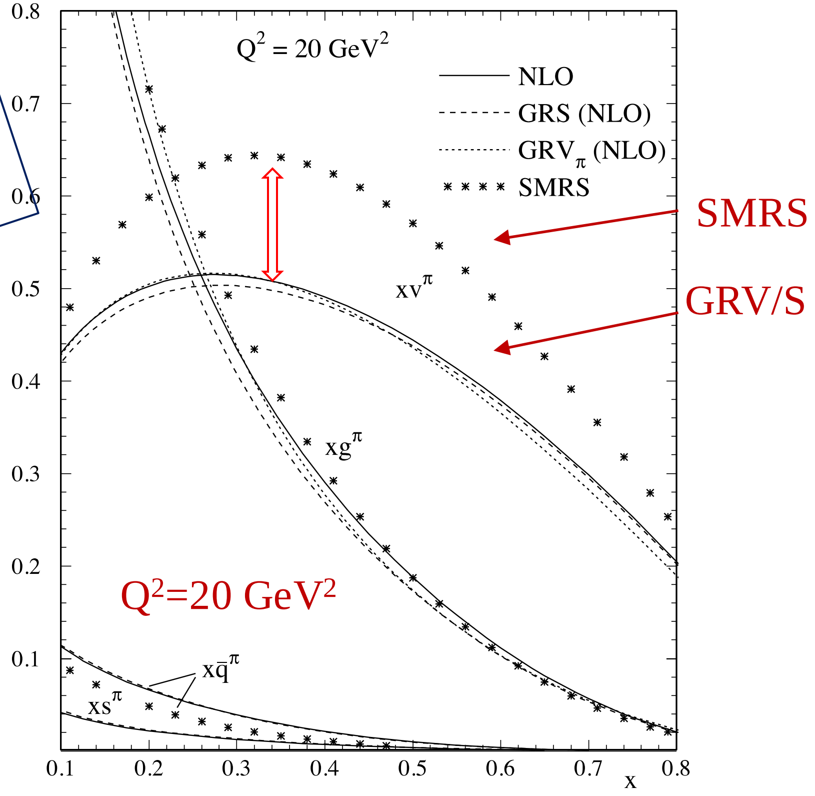
The Q^2 dependence of these moments for the distribu-

Mostly used pion PDF in Pythia: GRVPI 0/1

GRV/S (NLO) 1992,1999

GRV: Z Phys C53, 651 (1992).

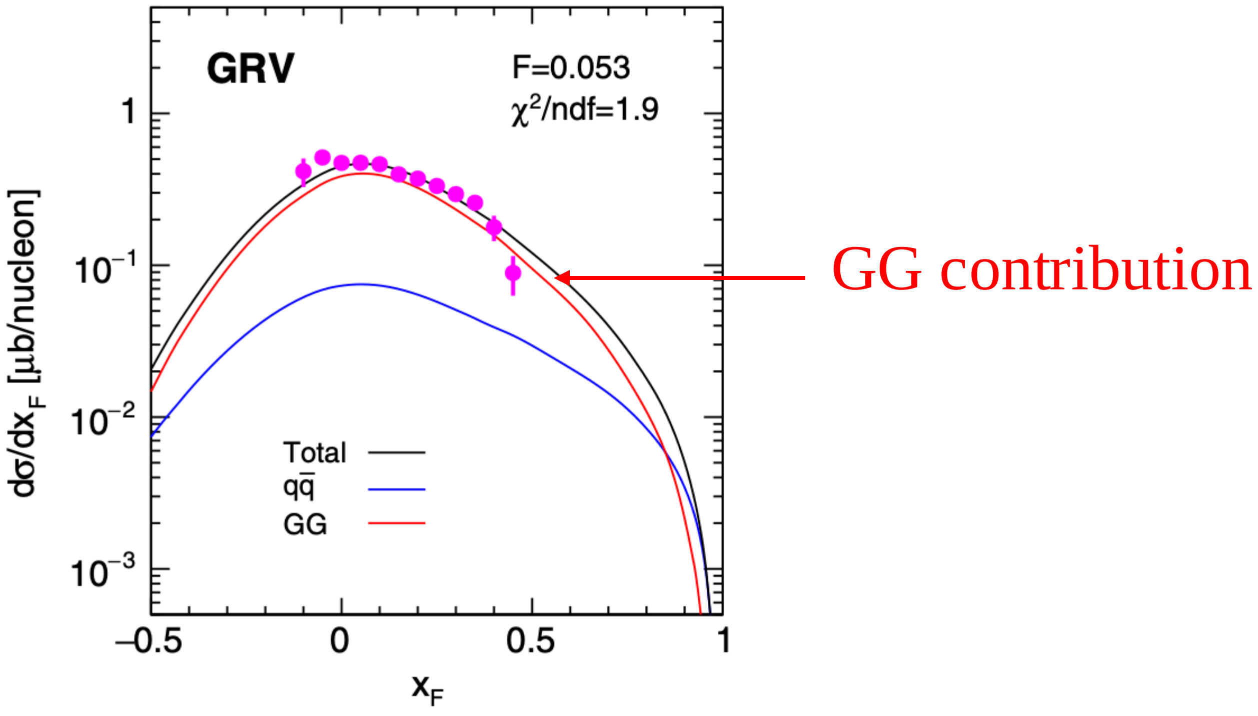
GRS: Eur Phys J C10, 313 (1999).



Global fits produce non-consistent results : 20% difference at x = 0.5 !

J/psi production

- CEM NLO calculation: π- + Li at 300 GeV/c, Fermilab E705 data



Strong sensitivity to the gluon-gluon fusion contribution

Fitted LDMEs – Comparison with LDMEs from literature

J/ψ Authors	Reference	Year	$O_1\,[^3S1]$ (GeV^3)	$O_8\,[^1S_0]$ ($10^{-2}\,GeV^3$)	$O_8\,[^3S_1]$ ($10^{-2}\,GeV^3$)	Comment
Present work	PR D107	2023	1.16	5.60±0.16	2.59±0.23	FT experiments
Butenschoen-Kniehl	PRL 106	2011	1.32	4.50±0.72	0.31±0.09	Fit on 26 data sets
Chao, Ma et al.,	PRL 108	2012	1.16	8.90±0.98	0.30±0.12	Polarization data
Gong, Wan et al.,	PRL 110	2013	1.16	9.70±0.90	-0.46±0.13	Polarization data
Bodwin, Chung et al.,	PRL 113	2014	1.32	9.90±2.20	1.10±1.00	Tevatron and LHC data
Zhang, Sun et al.,	PRL 114	2015	1.05	1.12±??	1.00±0.30	From LHCb data on η_c

$\psi(2S)$ Authors	Reference	Year	$O_1\,[^3S1]$ (GeV^3)	$O_8\,[^1S_0]$ ($10^{-2}\,GeV^3$)	$O_8\,[^3S_1]$ ($10^{-2}\,GeV^3$)	Comment
Present work	PR D107	2023	0.76	0.57±0.03	1.32±0.09	FT experiments
Gong, Wan et al.,	PRL 110	2011	0.76	-0.01±0.87	0.34±0.12	Polarization data
Bodwin, Chao et al.,	PR D93	2016	0.76	3.14±0.79	-0.16±0.28	Tevatron and LHC data
Butenschoen-Kniehl	PR D107	2023	0.76	0.84±0.10	0.286±0.01	1001 data points