Probing the pion's parton structure with AMBER (Phase-1 experiments)

Stephane Platchkov, Apr. 27, 2021
(On behalf of the AMBER collaboration)

Non-official logo!

Physics potential of AMBER – Phase 1 (“DY” = Dimuon production)

- Three main advantages of CERN + COMPASS:
  - 1) mesons beams (Amber phase-1: pions, later: kaons)
  - 2) both positive and negative – very important!
  - 3) Large and uniform acceptance spectrometer

Only place in the world!

- Three main physics goals of AMBER phase-1:
  - 1) Separate valence and sea pion PDFs
  - 2) Access gluon distribution in the pion using J/ψ and ψ’ production

and

  - 3) Study the flavor dependence of the nuclear mean field

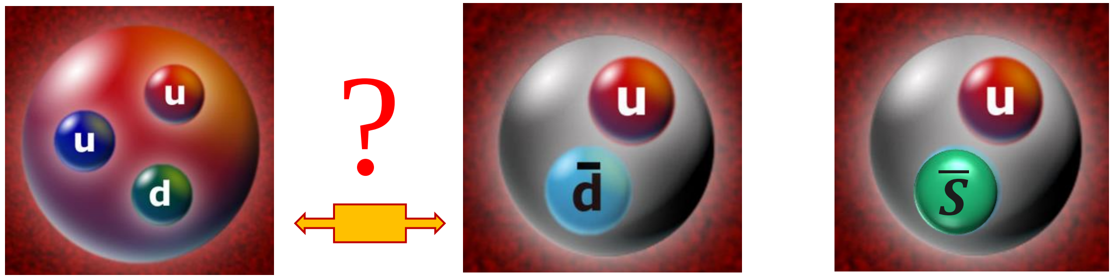
Fall 2020: official approval by SPSC!

Goal #1:

Separate valence and sea contributions in the pion

Properties of the lightest mesons (pion and kaon)

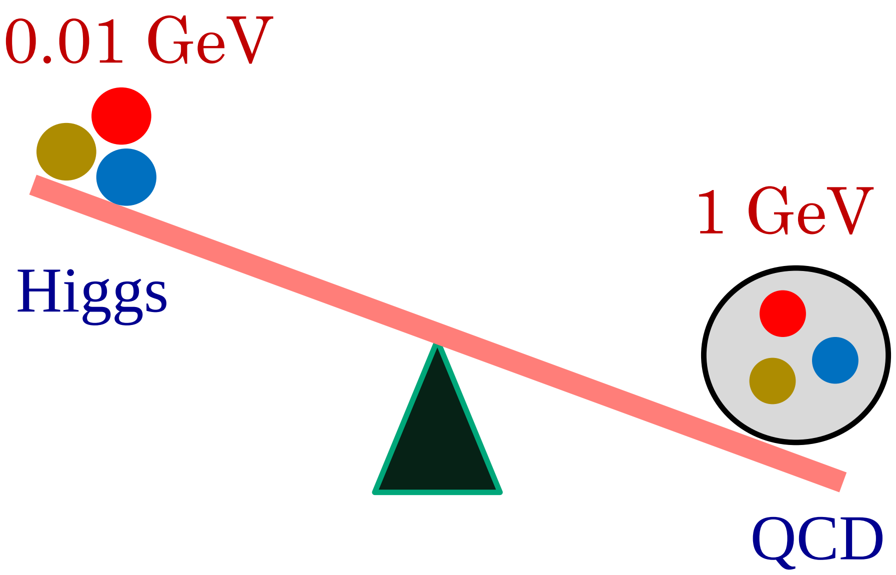
- Light meson properties
  - How the (simplest) light mesons compare to the nucleon?



M (MeV):	938	135	493
Rch (fm):	0.841(2)	0.659(4)	0.560(31)

- Help understanding the emergence of hadron masses
  - Higgs mechanism can't explain hadron masses
  - EHM: explain the heavy nucleon and the light pion

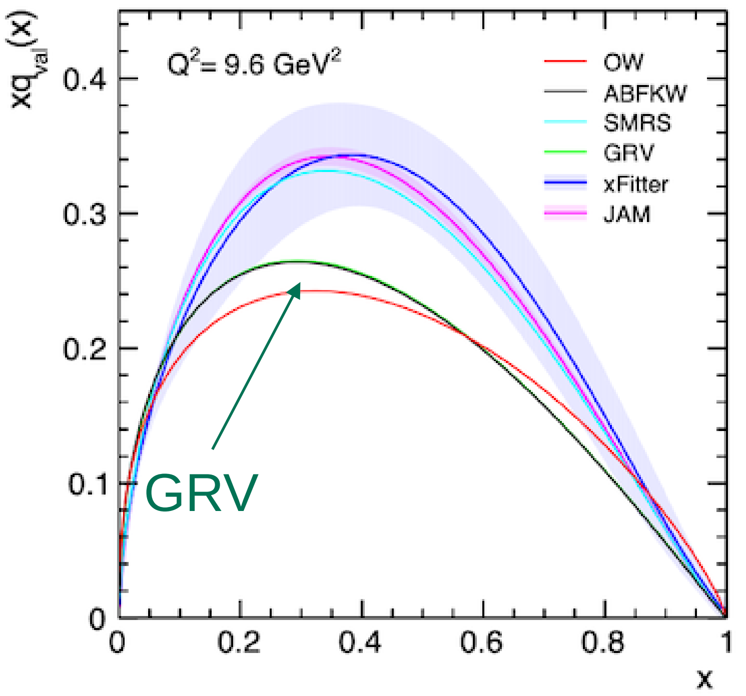
    ▸ Meson PDFs: Important input



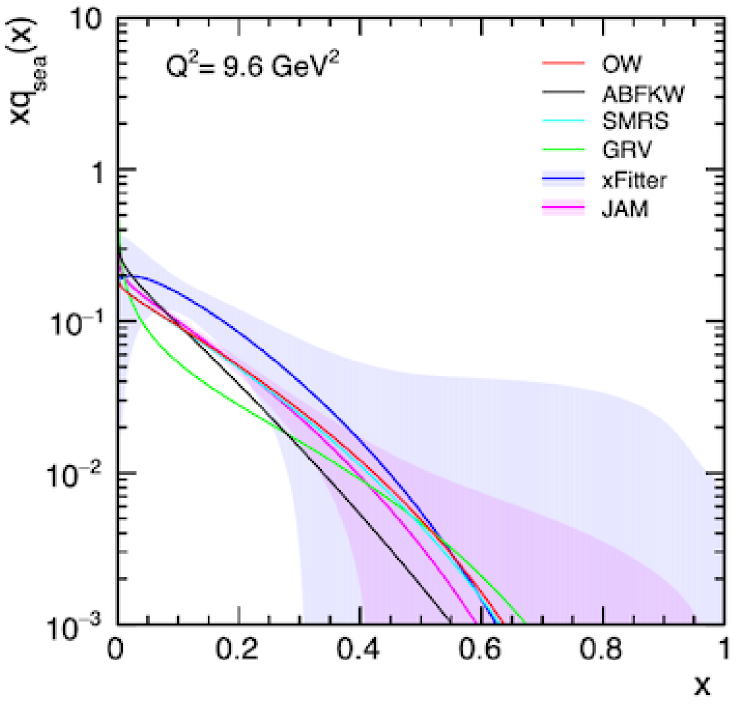
Present status of pion PDFs (global fits ≃ experiment)

Chang, Peng, SP, Sawada. PRD 102, 054024 (2020).

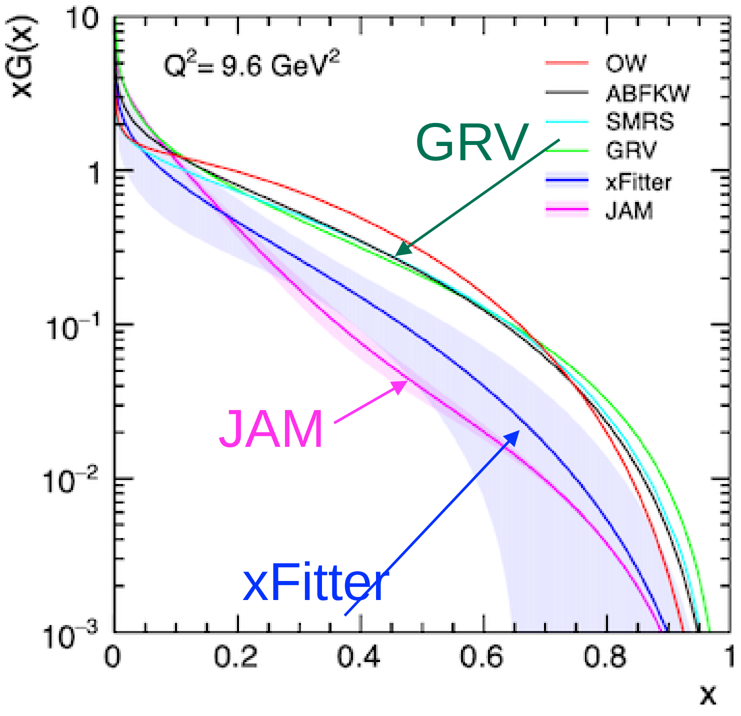
valence



sea



gluons



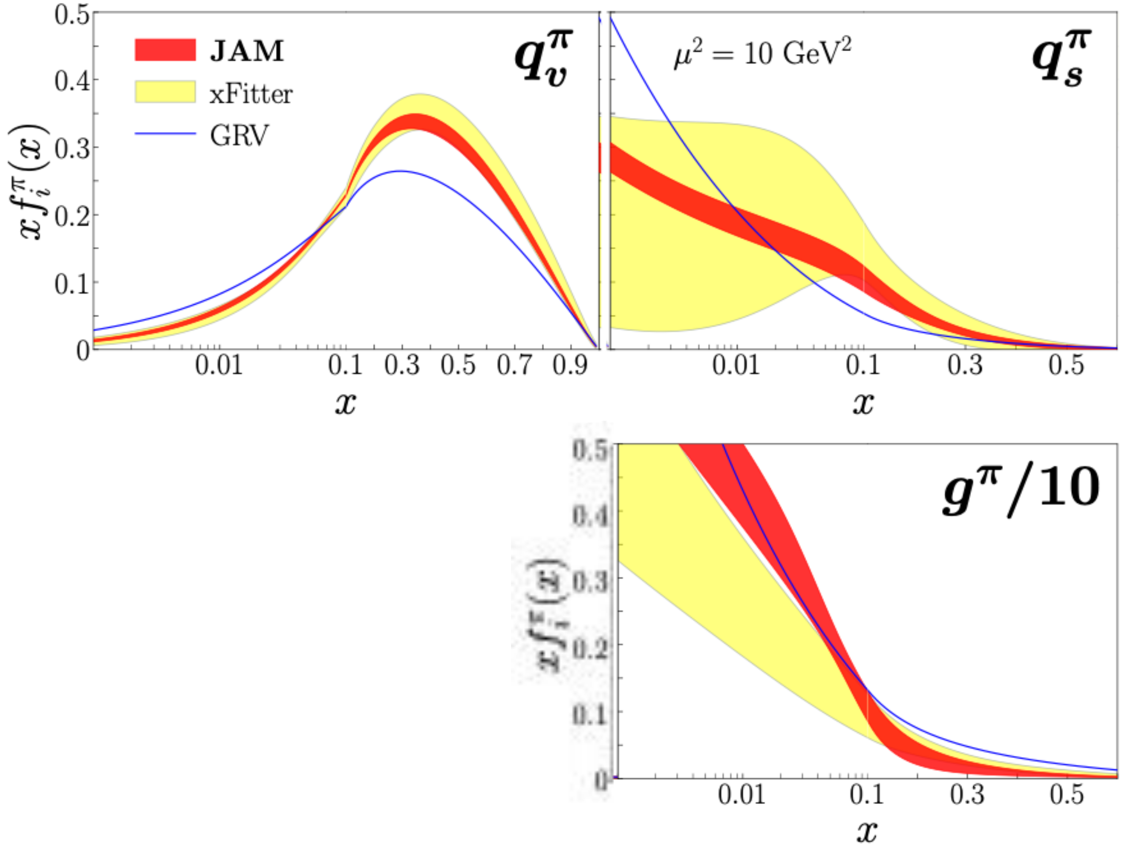
Valence: must be checked and improved. Sea and gluons: nearly unknown

Pion PDFs (very recent progress…)

N. Cao, P. Barry, N. Sato, and W. Melnitchouk, arXiv:2103.02159 (2021).

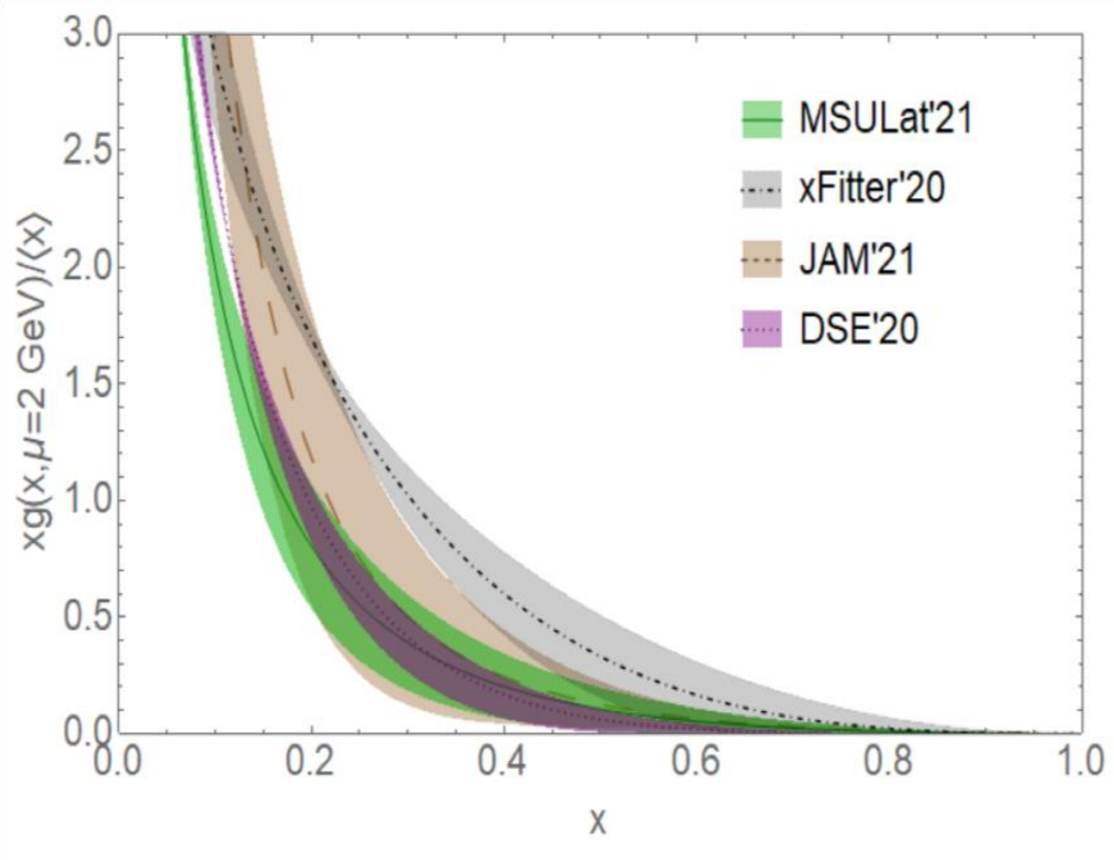
Z. Fan and H-W. Lin, arXiv:2104.06372 (2021).

global fit (JAM21)



First multidimensional global fit by JAM21 (March 2021)

gluons



First pion glue lattice QCD calculation (April 2021)

Pion sea/valence : the only available results (NA3, 1983)

- Only measurement: NA3 (π^-/ π^+ on a ^{195}Pt target)
  - π^- : 200 GeV (4.7k)
  - π^+ : 200 GeV (1.7k)
    - ► Insufficient statistics!

- Requirements for a new measurement
  - Beams of π^- and π^+
  - Good control of σ(abs) normalization
  - Statistics: $\gtrsim$ order of magnitude !

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

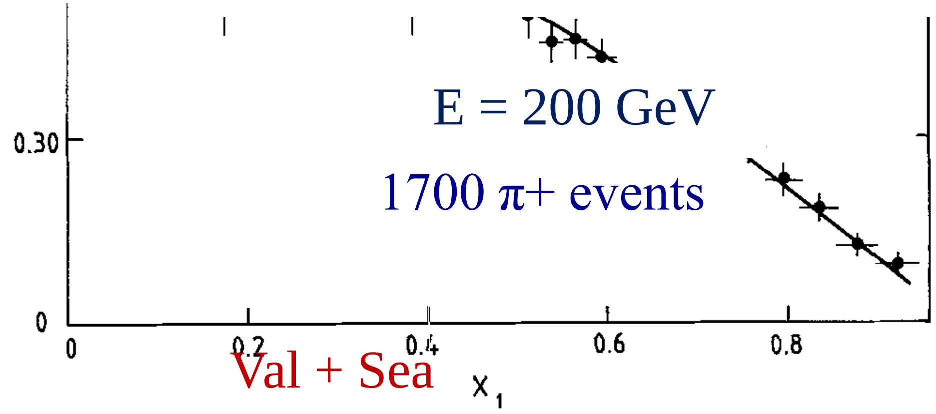


Fig. 1. a π^- 200 GeV data. The data points represent $F_\pi(x_1)$ as defined b
curve represents the valence structure function of the pion obtained from
function as defined by (2). **b** The data points represent $F_\pi(x_2)$ as defined
structure function $1.6u(x_2)+2.4d(x_2)$ for π^-. Solid curve represent 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

σ	Correlation coefficients	Systema
		pion sea
		±0.03

The available π^+ statistics will be increased to $\gtrsim$ 20 000

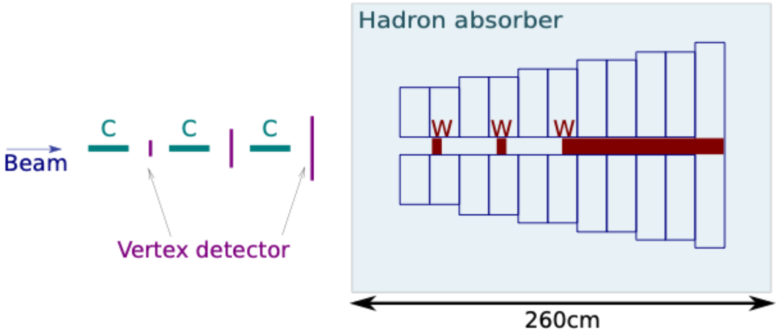
Drell-Yan: available data and expected statistics

Table 7: Statistics collected by earlier experiments (top rows), compared with the achievable statistics of the proposed experiment (bottom rows), in 213 days (π^+ beam) + 67 days (π^- beam).

Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H_2	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120 cm D_2	286 140	π^-	65×10^7	4.2 – 8.5 4.35 – 8.5	7800 3200
	12 cm W	286 194 140	π^-	65×10^7	4.2 – 8.5 4.07 – 8.5 4.35 – 8.5	49600 155000 29300
COMPASS 2015 COMPASS 2018	110 cm NH_3	190	π^-	7.0×10^7	4.3 – 8.5	35000 52000
This exp	75 cm C	190	π^+	1.7×10^7	4.3 – 8.5 4.0 – 8.5	21700 31000
		190	π^-	6.8×10^7	4.3 – 8.5 4.0 – 8.5	67000 91100
	12 cm W	190	π^+	0.4×10^7	4.3 – 8.5 4.0 – 8.5	8300 11700
		190	π^-	1.6×10^7	4.3 – 8.5 4.0 – 8.5	24100 32100

Amber advantages

- ✓ ^{12}C (3 x 25 cm) target
- \- control reinteraction

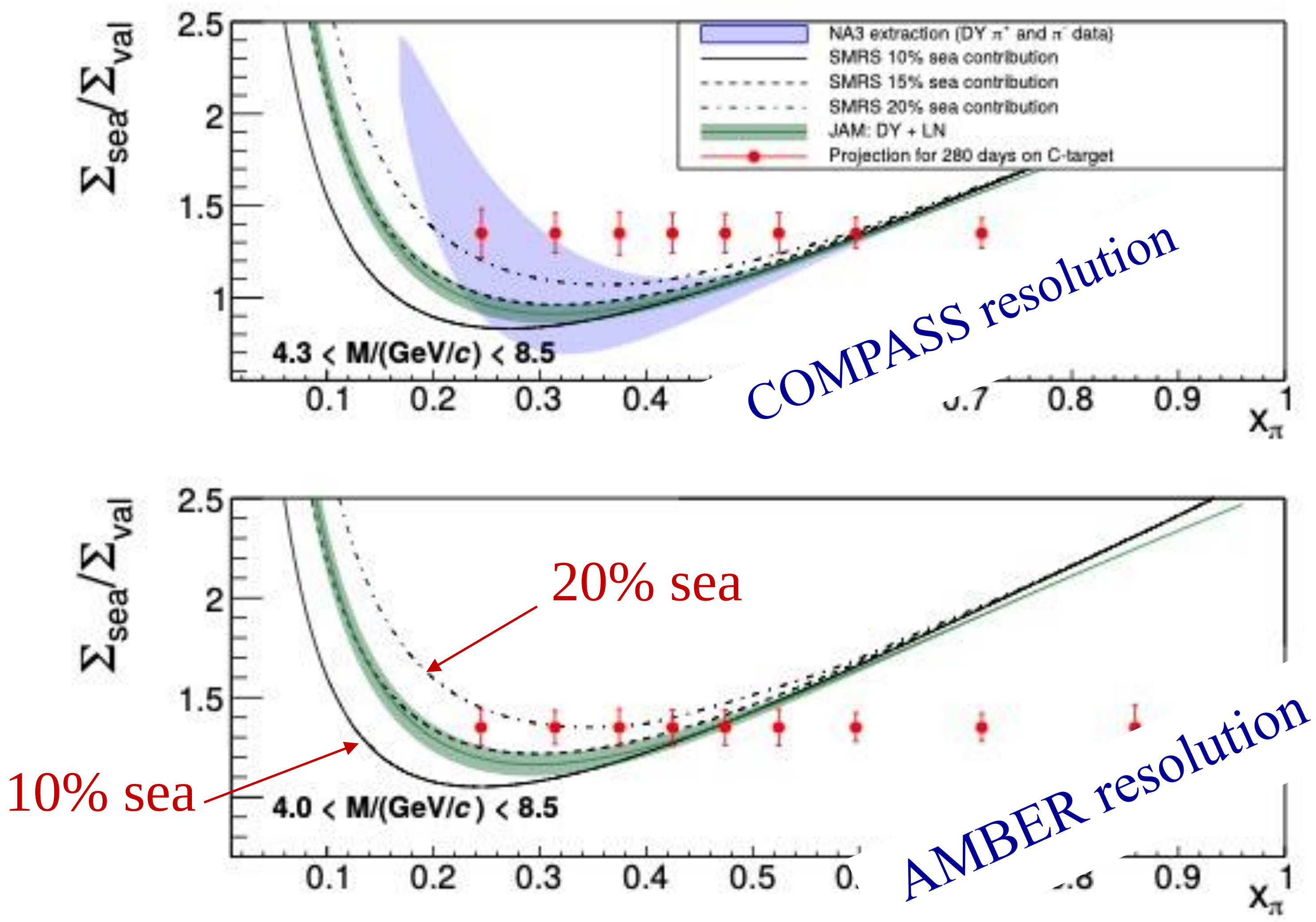


- ✓ Improvement in statistics:
  - π– : x 19
  - π+ : x 18

Expected results, emphasizing valence/sea separation

$$S^{pD}_{sea} = 4s^{p^+D} - s^{p^-D}$$ no valence

$$S^{pD}_{val} = -s^{p^+D} + s^{p^-D}$$ only valence



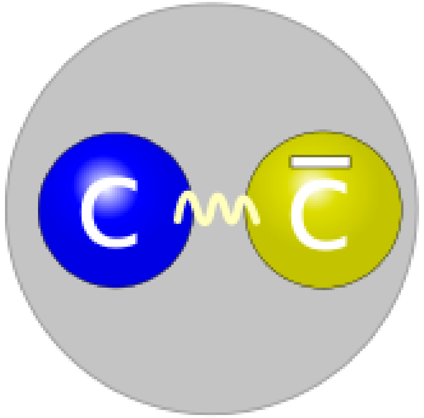
Goal #2:

Access the gluons in the pion using charmonium production

Charmonium production: pros and cons

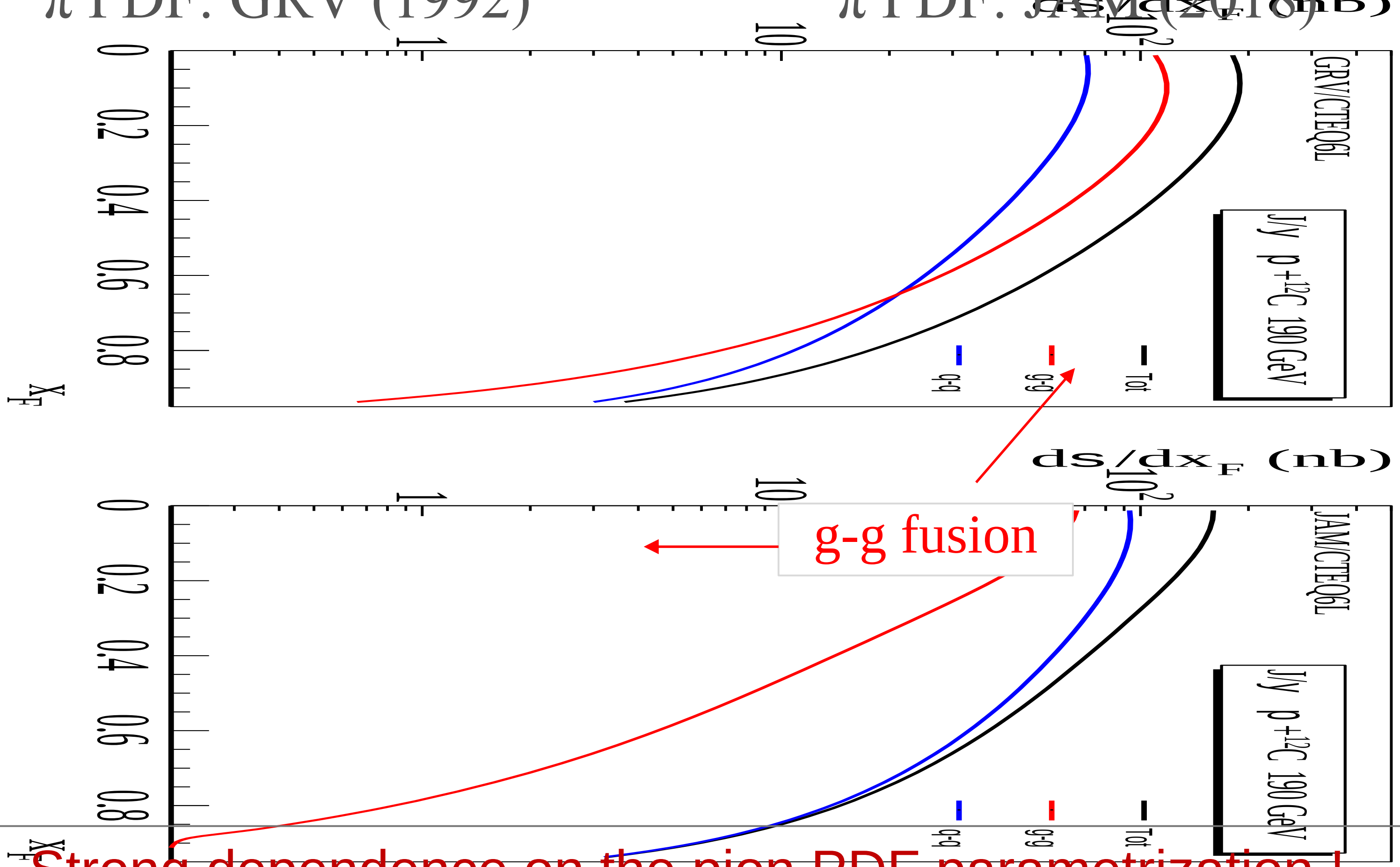
- Extremely attractive observable, linked to the gluon distribution
  - J/ψ has large cross sections: factor of 30-50 larger than Drell-Yan
  - AMBER will measure x_F, p_T, λ distributions with huge statistics (> 1 M events)
  - Fixed target energies: production is dominated by 2 --> 1 process
  - AMBER@CERN: simultaneous measurements of (π^+ and p) and π^-
  - No new FT data since two decades!

- However!
  - The J/ψ production mechanism is not well known
  - Fixed-target energies: $p_T \leqslant M(J/\psi)$; for LHC $p_T >> M(J/\psi)$;
    - Additional effects may contribute



π + ^{12}C cross section for two PDF "global" fits (CEM at LO)

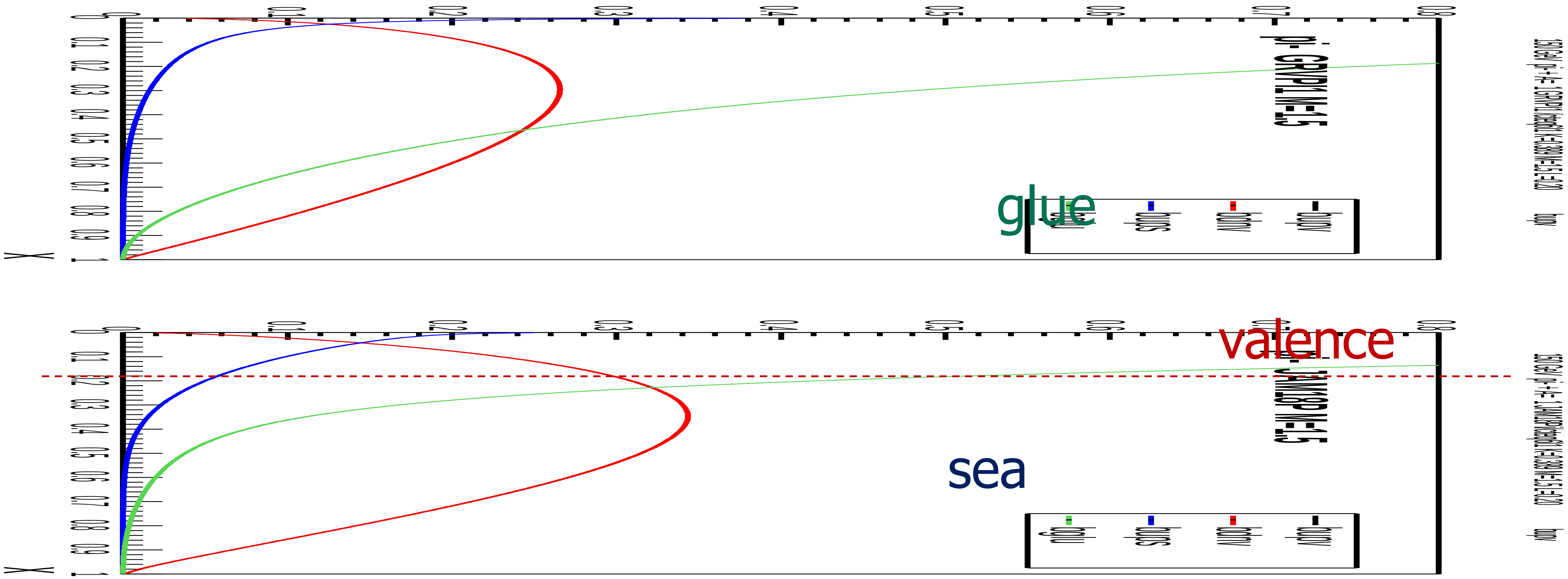
π PDF: GRV (1992) π PDF: JAM (2018)



g-g fusion

Strong dependence on the pion PDF parametrization !

GRV(1992) vs JAM(2018) pion PDFs

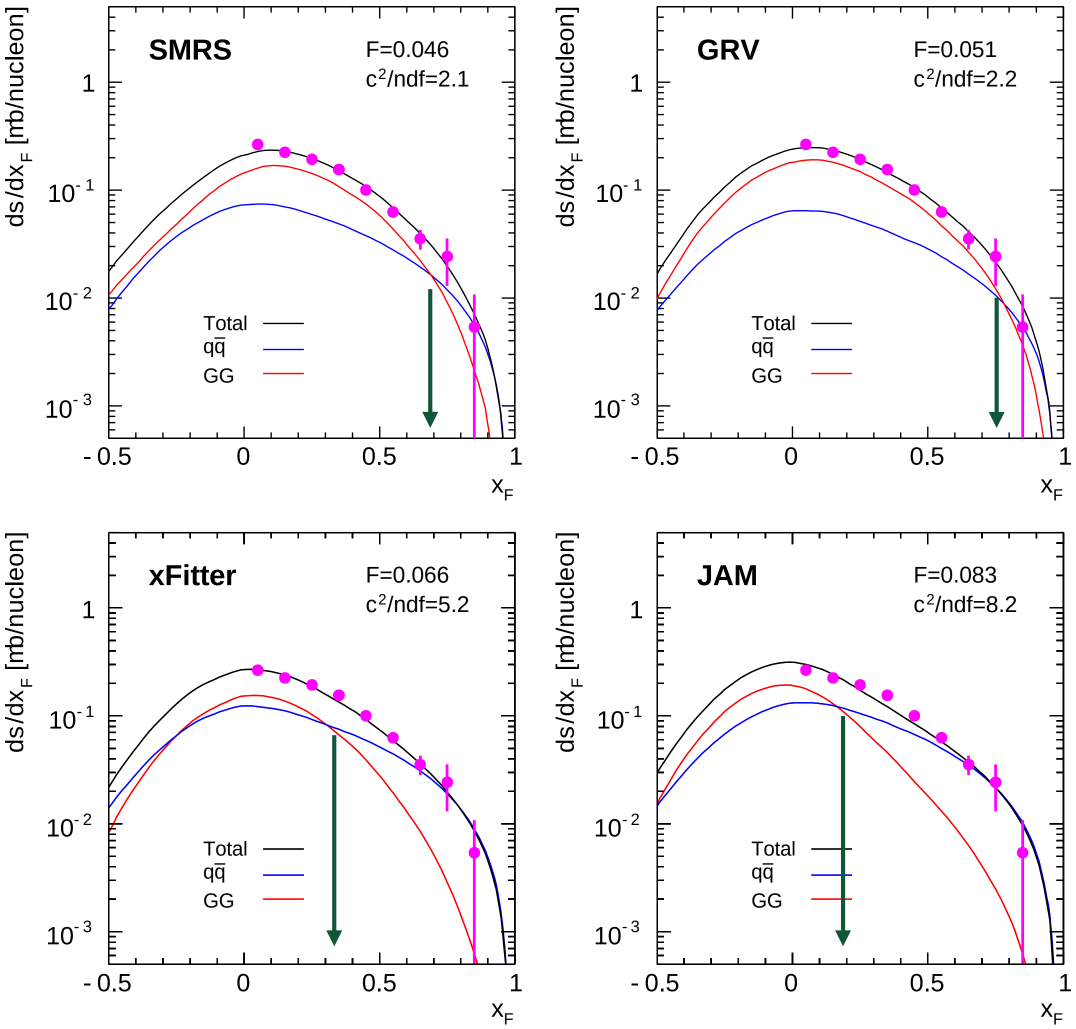


The two global fits provide different PDFs: valence, gluon, sea

NLO CEM calculation for a H_2 target (NA3)

- NLO CEM calculation for J/ψ cross section
  - pion beam, E = 200 GeV
  - Target = Hydrogen
- 4 different pion PDFs:
  - SMRS, GRV, xFitter, JAM

Chang, Pen, SP, Sawada, Phys.Rev. D102,054024(2020)



Result: very different magnitudes of the $q\bar{q}$ and gg contributions

Polarization

- J/ψ is a 1^{--} particle; its third component is $J_z = 0, +1, -1$.
  - $\alpha = +1$: 100% transverse polarization ($J_z = \pm 1$)
  - $\alpha = 0$: unpolarized
  - $\alpha = -1$: 100% longitudinal polarization ($J_z = 0$)

$$\frac{d\sigma}{d(\cos\theta)} \propto 1 + \alpha \cos^2\theta,$$

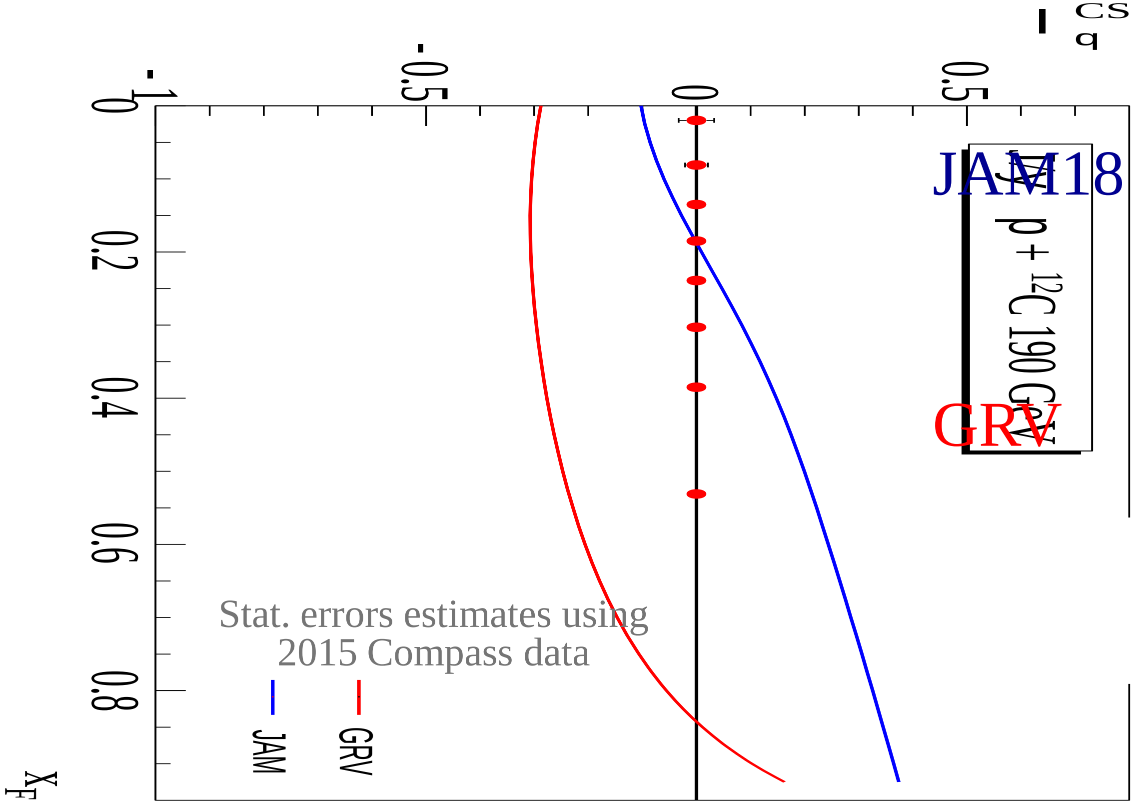
- Polarization is a fundamental observable
  - angular momentum, chirality, parity conservations preserve the properties of the J/ψ: from production to the 2μ decay
  - Nature wants to help us, for $q\bar{q}$: $\alpha \simeq +1$, but for gg: $\alpha \simeq -1$
  - Key variable for understanding the bound state formation

Polarization: expected results (Cheung and Vogt, priv. comm.)

- ICEM xF-dependent predictions
  - with minimal model-dependence

$$\lambda_\vartheta^{CS} \approx +0.4 \text{ for } q\bar{q}$$
$$\lambda_\vartheta^{CS} \approx -0.6 \text{ for } gg$$

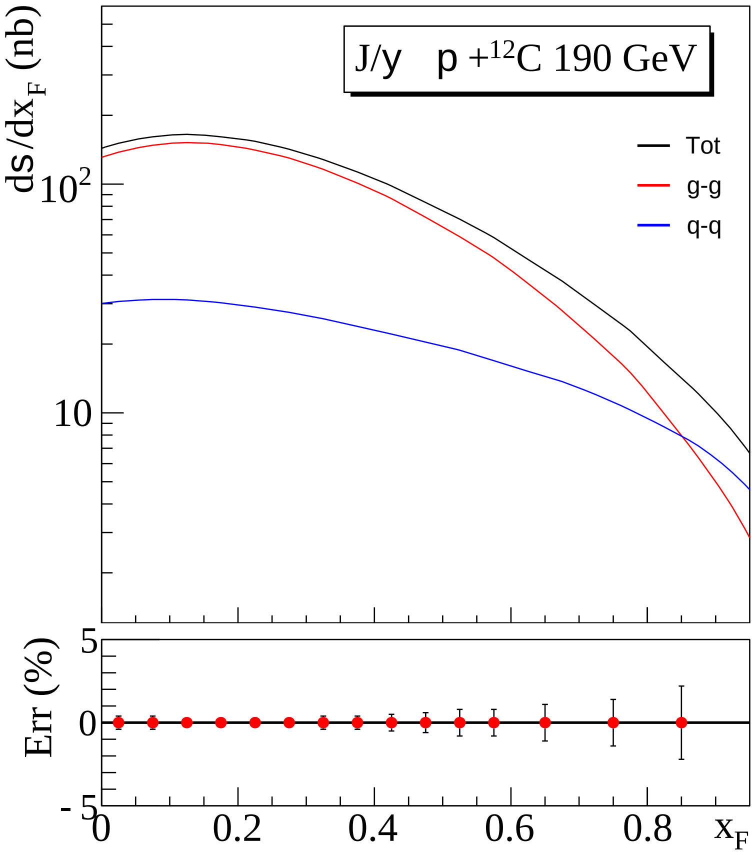
  - The difference between the two predictions results from the different amount of $q\bar{q}$ and gg contributions as a function of x_F.



The polarization value as a function of x_F is sensitive to the shape differences between gg and $q\bar{q}$ contributions to the cross section

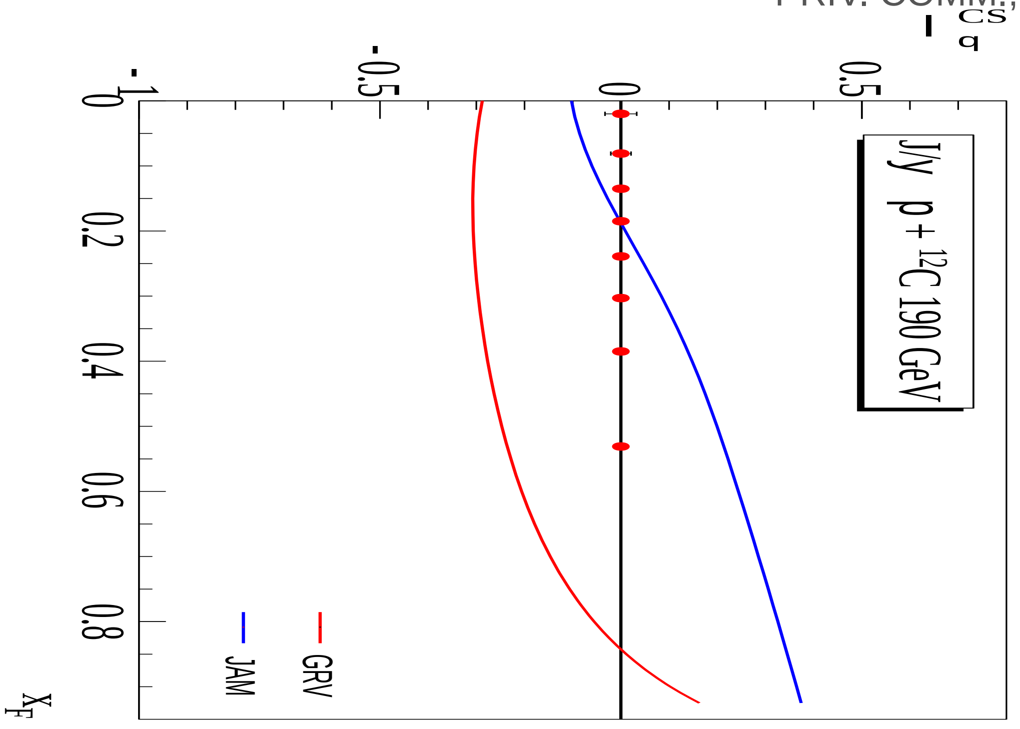
J/ψ measurements at COMPASS++/AMBER

Cross section (ICEM)



Polarization (ICEM)

CHEUNG AND VOGT, PRIV. COMM., 2020



Multidimensional analysis of both cross section and dilepton decay angles should provide constraint on the gg and $q\bar{q}$ fractions

Estimated J/ψ statistics

Experiment	Target type	Beam energy (GeV)	Beam type	J/ψ events
NA3 [76]	Pt	150	π^-	601000
		280	π^-	511000
		200	π^+	131000
			π^-	105000
E789 [127, 128]	Cu	800	p	200000
	Au			110000
	Be			45000
E866 [129]	Be, Fe, Cu	800	p	3000000
NA50 [130]	Be	450	p	124700
	Al			100700
	Cu			130600
	Ag			132100
	W			78100
NA51 [131]	p	450	p	301000
	d			312000
HERA-B [132]	C	920	p	152000
This exp	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

Comments

Cross sections not published, only plots available

x_F and p_T cross sections available

Only ratios of cross sections available

Only A-dependent studies of total cross sections

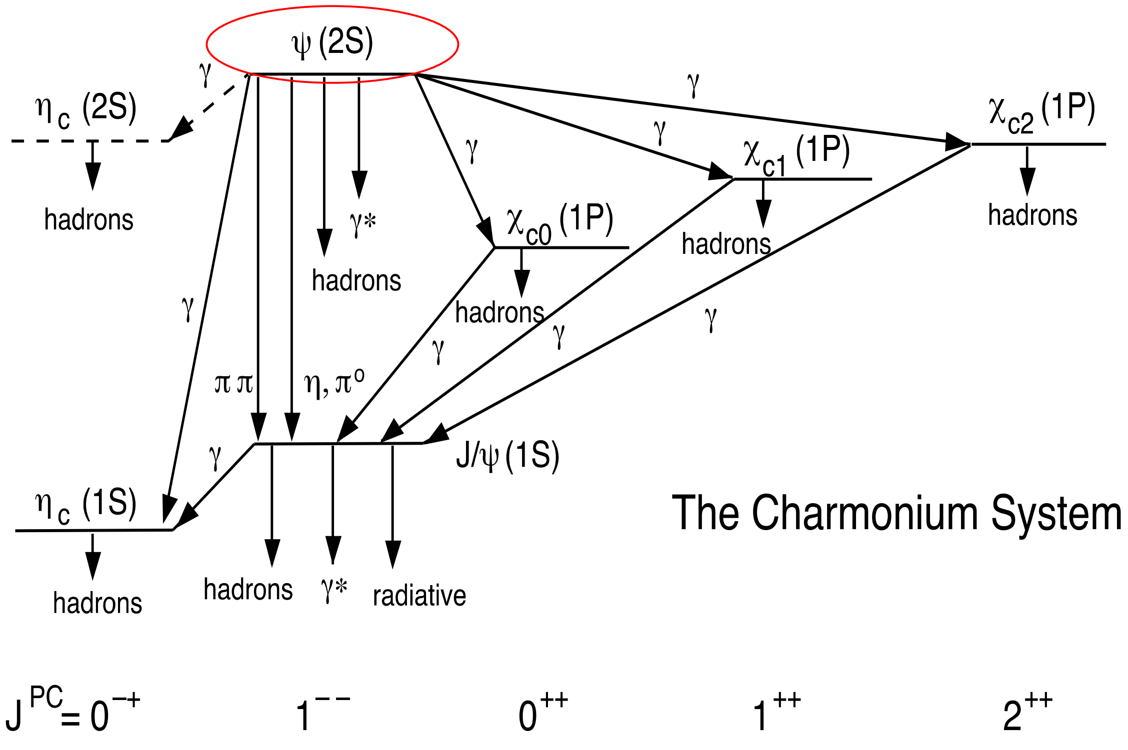
Only A-dependent studies of total cross sections
x_F and p_T cross sections available
…

Estimations based on Compass preliminary numbers

Largest statistics ever (between 0.5M and 1.8 events/target/beam)

ψ’ production

- Pros
  - No feed-down contributions. Consequences:
    - $q\bar{q}$ and gg contributions could reach their maximum polarization values
  - Measure: x_F and p_T distributions + polarization
  - AMBER could provide the largest ψ’ data set ever.
- Cons
  - Lower cross section (~1/7) smaller BR (~1/8):
  - Ratio (ψ’/J/ψ) $\simeq$ 0.018 !



The Charmonium System

Requirements: Good mass resolution (≤ 100 MeV) – need vertex detectors and/or dedicated runs without absorber (AMBER II)

ψ’ production – expected statistics

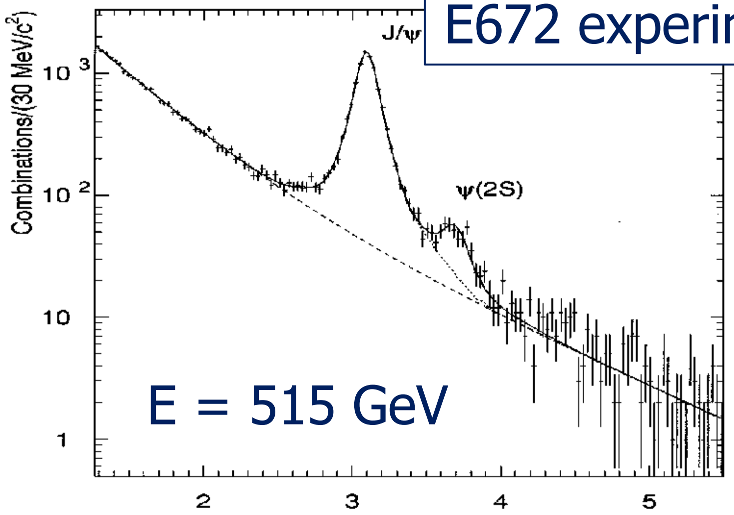
- AMBER – 6 complementary measurements!

Target	Energy	Beam	Nb of ψ’
^{12}C	190 GeV	π^+	21 600
		π^-	32 400
		p	27 000
^{184}W		π^+	9 000
		π^-	12 600
		p	12 600

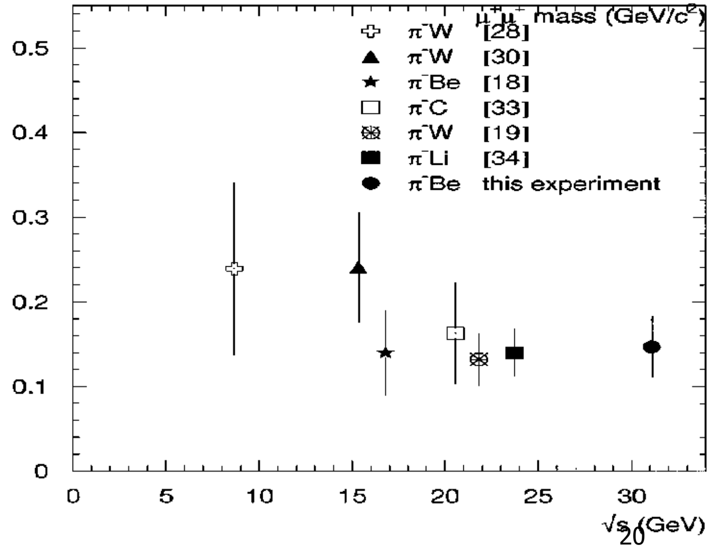
Improved statistics on two targets and with three different beams

Gribushin et al., PRD 53,4723 (1996)

E672 experiment



$$\frac{\sigma(\psi')}{\sigma(J/\psi)}$$

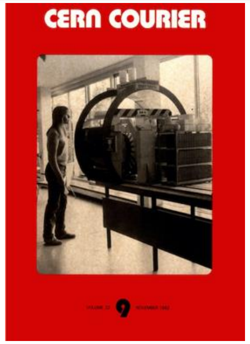


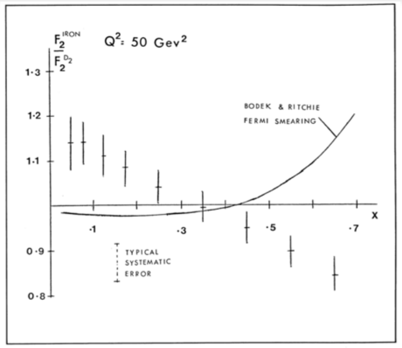
Goal #3:

Flavor dependence of the EMC effect

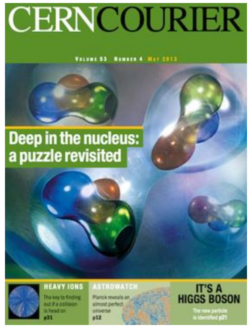
EMC effect – a longstanding nuclear physics issue

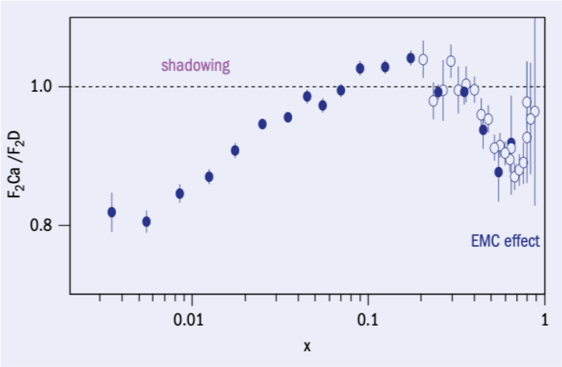
1982





2013



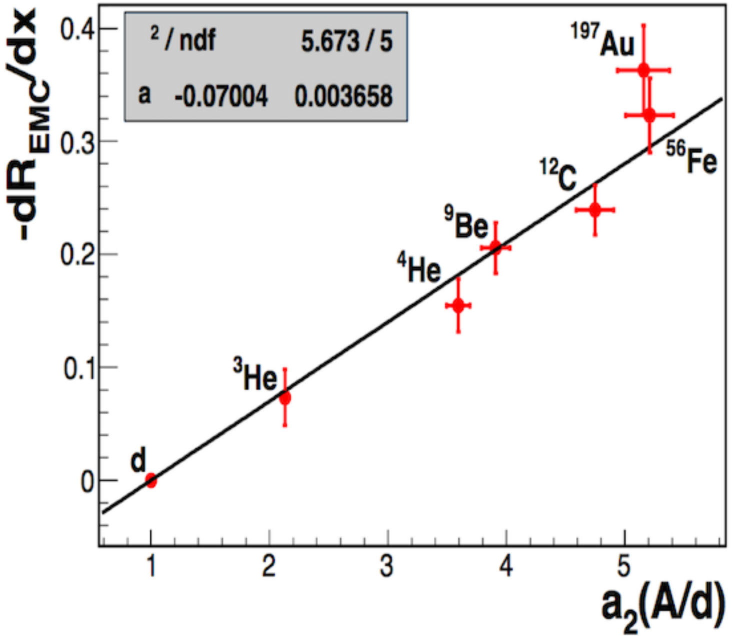


"Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day."

REVIEWS OF MODERN PHYSICS, VOLUME 89, OCTOBER–DECEMBER 2017

Nucleon-nucleon correlations, short-lived excitations, and the quarks within

O. Hen, G. Miller, E. Piasetzky, L. Weinstein

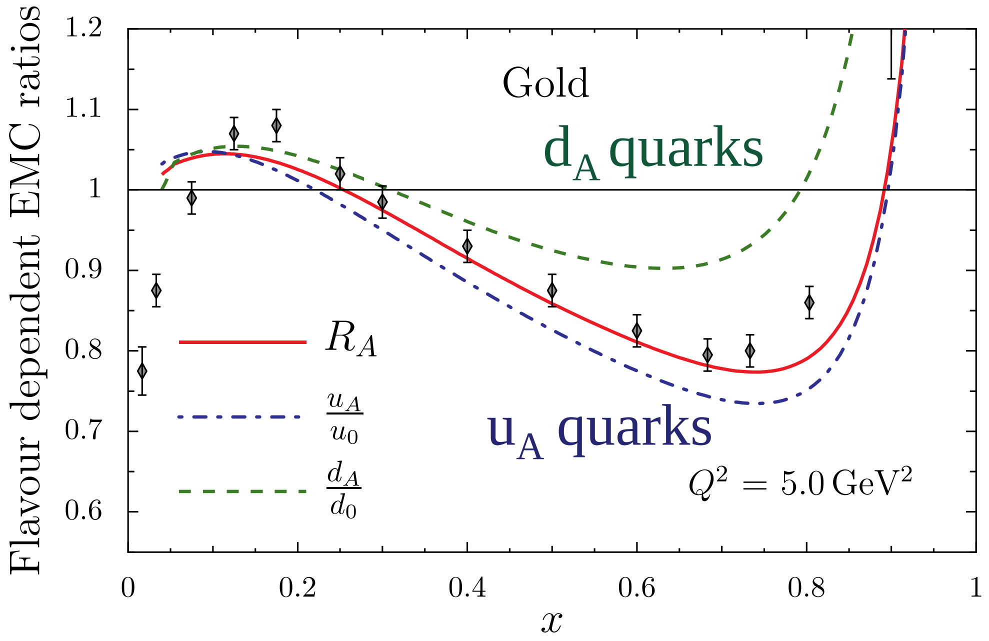


How can AMBER contribute ("for free") ?

Flavor-dependence of the EMC effect

- Cloët, Benz and Thomas (2009):
  - use nuclear matter within a covariant Nambu–Jona-Lasinio model
  - Compute the flavour-dependence of the nuclear PDFs
    - "…for N≠Z nuclei, the u and d quarks have distinct nuclear modifications."

Cloët, Benz and Thomas, PRL 102, 252301 (2009)

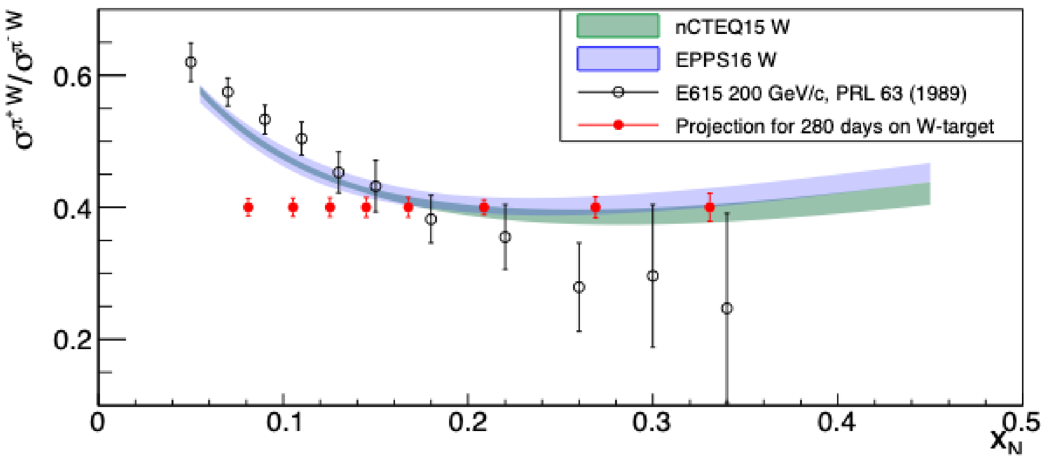


- Isovector-vector mean-field force
  - Appears in nuclei with N ≠ Z
  - *u* quarks feel additional attraction, *d* quarks feel additional repulsion

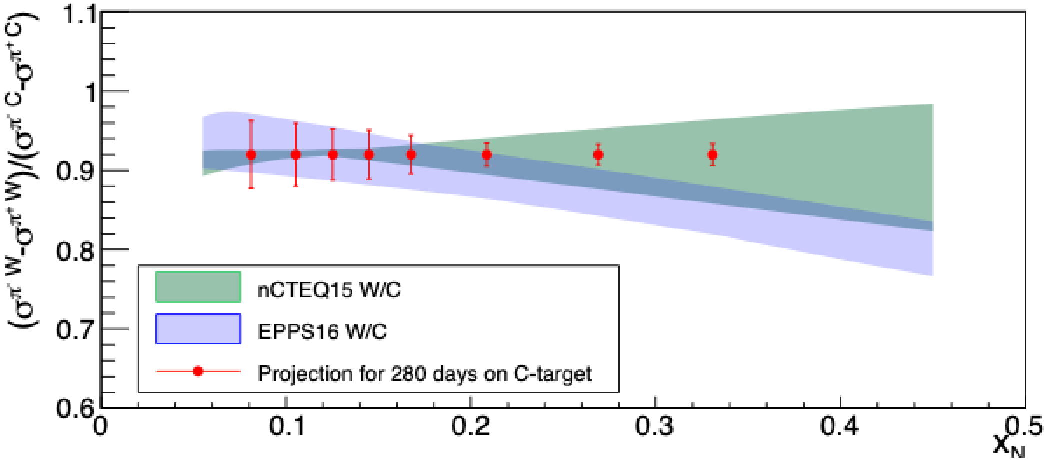
Can be accessed ONLY through parity-violating DIS (JLAB) or with AMBER@CERN

AMBER – expected results

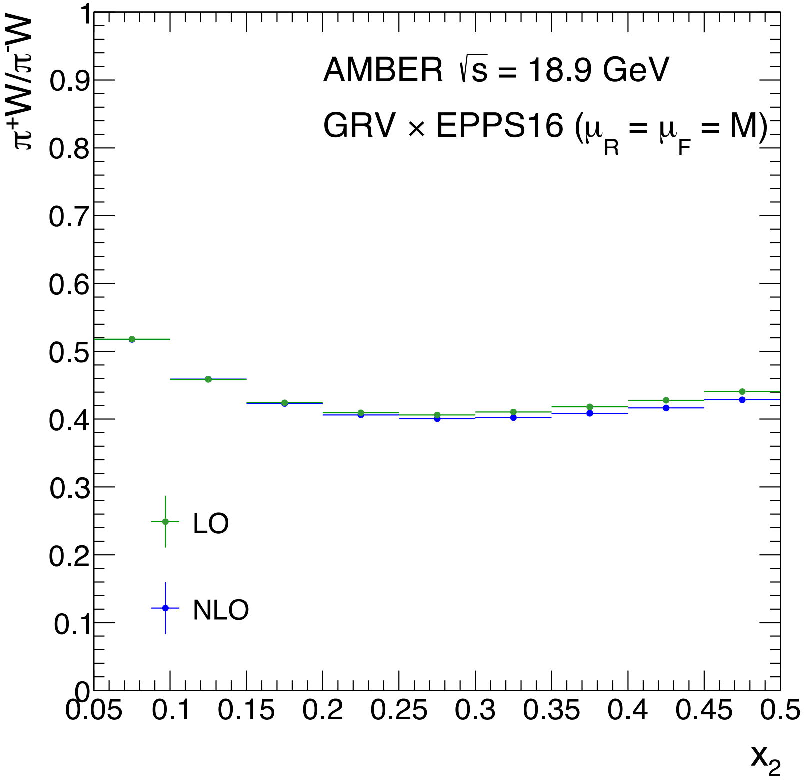
$\sigma_W^{\pi+} / \sigma_W^{\pi-}$



$$\frac{\sigma_W^{\pi-} - \sigma_W^{\pi+}}{\sigma_C^{\pi-} - \sigma_C^{\pi+}}$$



$\sigma_W^{\pi+} / \sigma_W^{\pi-}$ LO vs NLO



LO/NLO: minimal effect

Summary

- Map out the pion parton structure at large x, x > 0.1
  - 1) DY data : separate valence and sea distributions in the pion
  - 2) J/ψ and ψ' data : study pion-induced production –

    infer pion valence and gluon distributions
    - AMBER@CERN is unique for these meson PDFs measurements
- Nuclear dependence at large x
  - Improve our knowledge of the EMC effect – first look at the flavor dependence of the nuclear mean field
    - AMBER@CERN is unique for this nuclear stricture measurement

These three fundamental measurements will be achieved using the same data set