Irfu
Institut de recherche
sur les lois fondamentales
de l'Univers

Drell-Yan and SIDIS measurements connected to the EMC effect

S. Platchkov

CEA/IRFU-DPhN, Université Paris-Saclay

EMC – First data, published in March 1983

Volume 123B, number 3,4 PHYSICS LETTERS 31 March 1983

THE RATIO OF THE NUCLEON STRUCTURE FUNCTIONS F_2^N FOR IRON AND DEUTERIUM

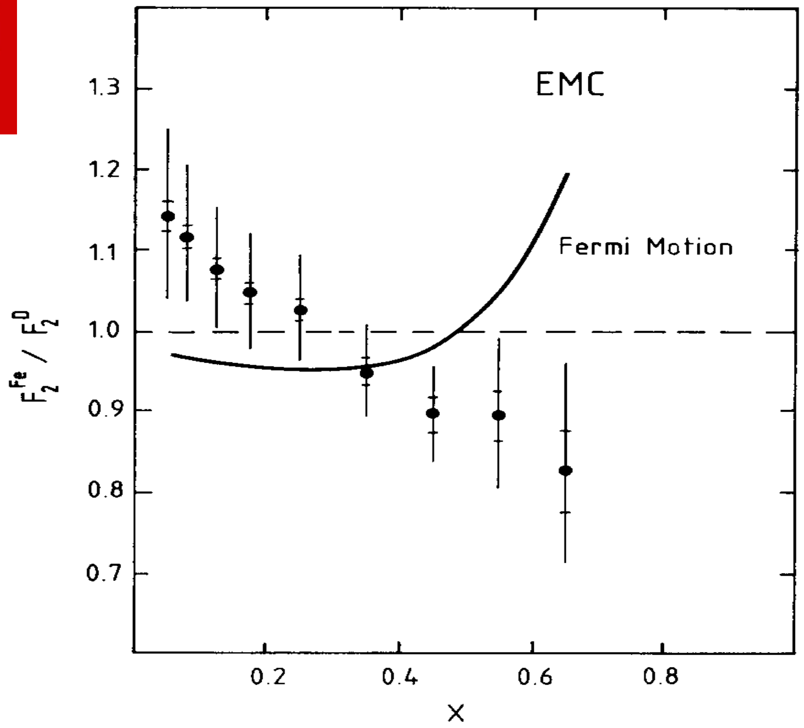
The European Muon Collaboration

J.J. AUBERT [h], G. BASSOMPIERRE [f], K.H. BECKS [m], C. BEST [j,1], E. BÖHM [d], X. de BOUARD [f], F.W. BRASSE [b], C. BROLL [f], S. BROWN [g], J. CARR [j,2], R.W. CLIFFT [j], J.H. COBB [e,3], G COIGNET [f], F. COMBLEY [k], G.R. COURT [g], G D'AGOSTINI [h], W D. DAU [d], J.K. DAVIES [i,4], Y. DÉCLAIS [f], R.W. DOBINSON [a], U. DOSSELLI [a,5], J. DREES [m], A.W. EDWARDS [a], M. EDWARDS [j], J. FAVIER [f], M I FERRERO [ℓ,6], W. FLAUGER [b], E. GABATHULER [a], R. GAMET [g], J. GAYLER [b], V GERHARDT [b,7], C. GÖSSLING [b], J. HAAS [c], K. HAMACHER [m], P. HAYMAN [g], M. HENCKES [m,8], V. KORBEL [b], U. LANDGRAF [c], M. LEENEN [a,9], M. MAIRE [f], H MINSSIEUX [f], W. MOHR [c], H.E. MONTGOMERY [a], K. MOSER [c], R P. MOUNT [i,10], P.R. NORTON [j], J McNICHOLAS [i,11], A M OSBORNE [a], P PAYRE [f], C. PERONI [ℓ], H. PESSARD [f], U PIETRZYK [m], K. RITH [c], M. SCHNEEGANS [f], T. SLOAN [e], H E. STIER [c], W. STOCKHAUSEN [m], J.M. THÉNARD [f], J.C. THOMPSON [j], L URBAN [f,12], M. VILLERS [i], H. WAHLEN [m], M WHALLEY [k,13], D. WILLIAMS [g], W.S.C WILLIAMS [i], J. WILLIAMSON [k] and S.J. WIMPENNY [g]

CERN [a]–DESY (Hamburg) [b]–Freiburg [c]–Kiel [d]–Lancaster [e]–LAPP (Annecy) [f]–Liverpool [g]–Marseille [h]–Oxford [i]–Rutherford [j]–Sheffield [k]–Turin [ℓ]–Wuppertal [m]

CERN
Hints from high energy muons

J.J. Aubert et al. / Nucleon structure functions



"The observed x dependence of this ratio is in disagreement with existing theoretical predictions"

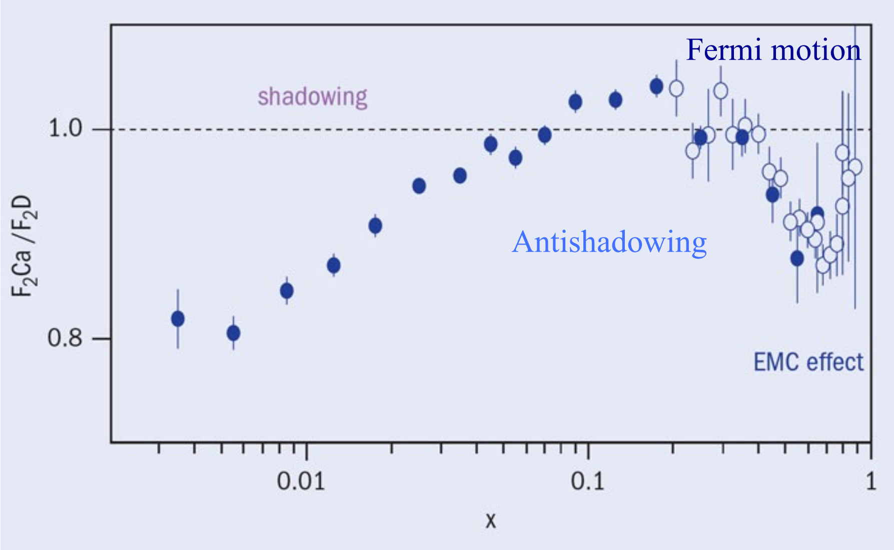
The EMC effect in 2013

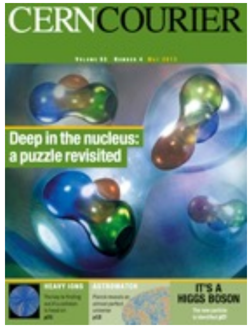
- Universal shape
- ~Independent of Q^2
- Effect increases with: either A? or the nuclear density?

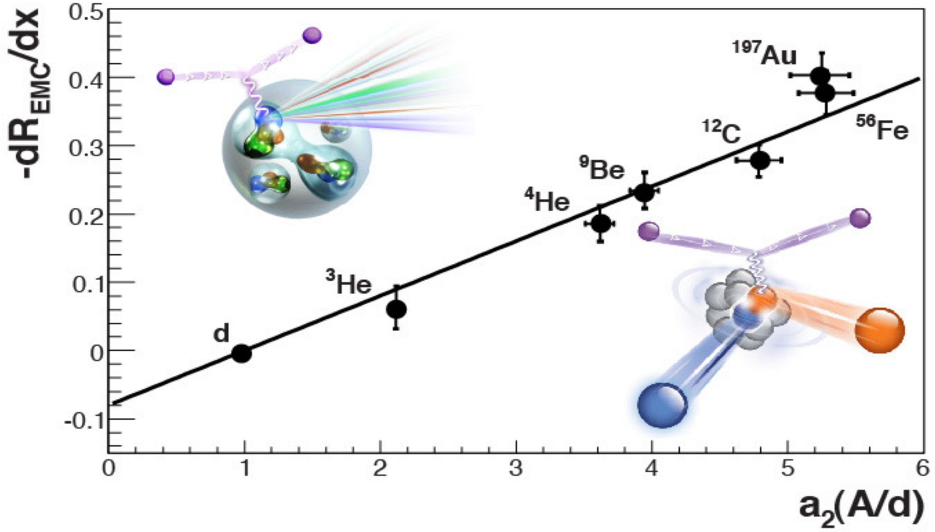
CERN COURIER

Apr 26, 2013

The EMC effect still puzzles after 30 years





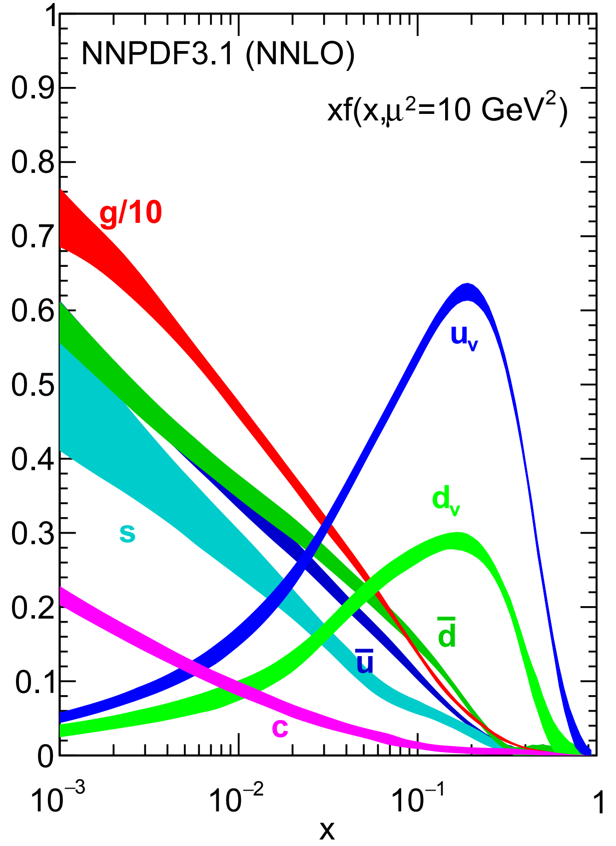


D. Higinbotham, G. Miller, O. Hen and K. Rith, CERN Courier, 2013:

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

The EMC effect - 40 years later

- The simplest definition of the EMC effect:
  - The PDFs in nuclei are different than the PDFs in free nucleons
- Additional (yet unanswered) questions:
  - Are valence quark PDFs and sea quarks PDFs in nuclei modified differently or not?
  - Is the EMC effect flavor-dependent?
  - Is the EMC effect on quarks similar to that on the gluons?
  - Are the Transverse Momentum Distributions (TMDs) also modified?



The EMC effect - 40 years later

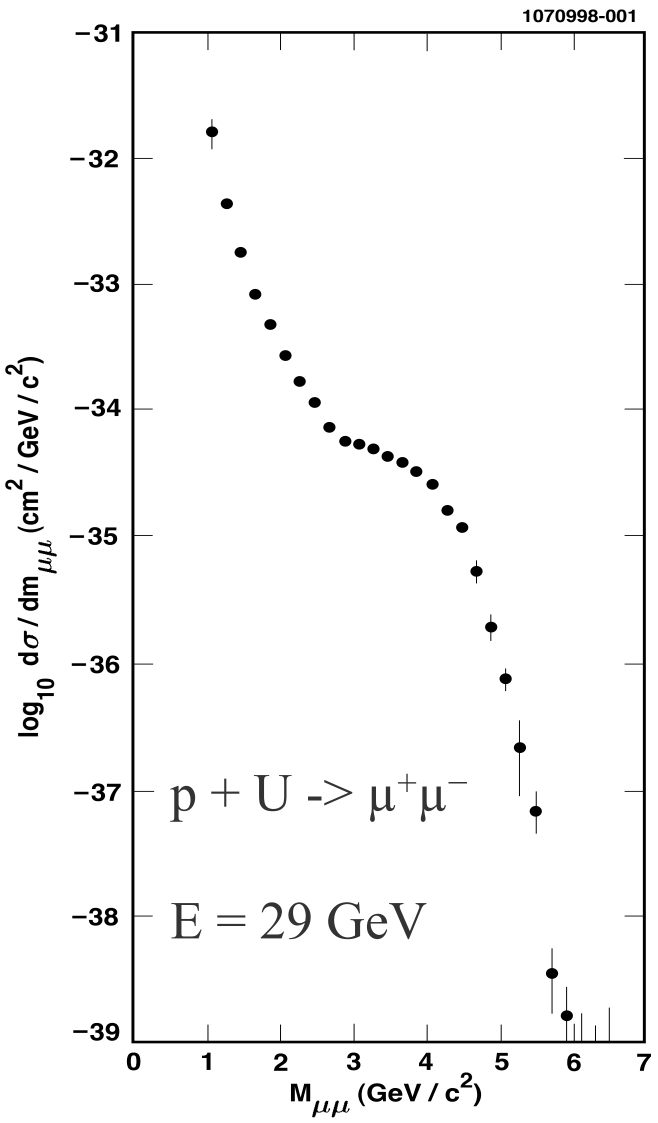
- Additional (and un-answered) questions:
  - Are valence quark PDFs and sea quarks PDFs in nuclei modified differently or not?
  - Is the EMC effect flavor-dependent?
  - Is the EMC effect on quarks similar to that on the gluons?
  - Are the Transverse Momentum Distributions (TMDs) also modified?

Dedicated Drell-Yan experiments could provide an answer (first three questions)

Could be probed using SIDIS (TMDs question)

The Drell-Yan (-Lederman) process

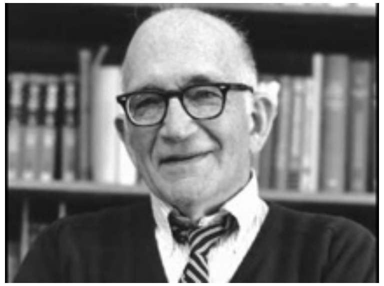
Christenson et al., PRL 25 (1970) 1523



- First "dimuon" experiment at the AGS : in 1968 !
  Leon Lederman's team was looking for the W
  - Rapid fall-off: ~$M_{\mu\mu}^{-4}$
  - Shoulder at around 3-4 GeV was unexplained: the authors missed two great discoveries: J/ψ… and the partonic substructure of the nucleon

- Explanation by Drell and Yan (1970)
  - Process explained using Feynman's parton model
  - First application of the parton model besides the SLAC DIS exp't

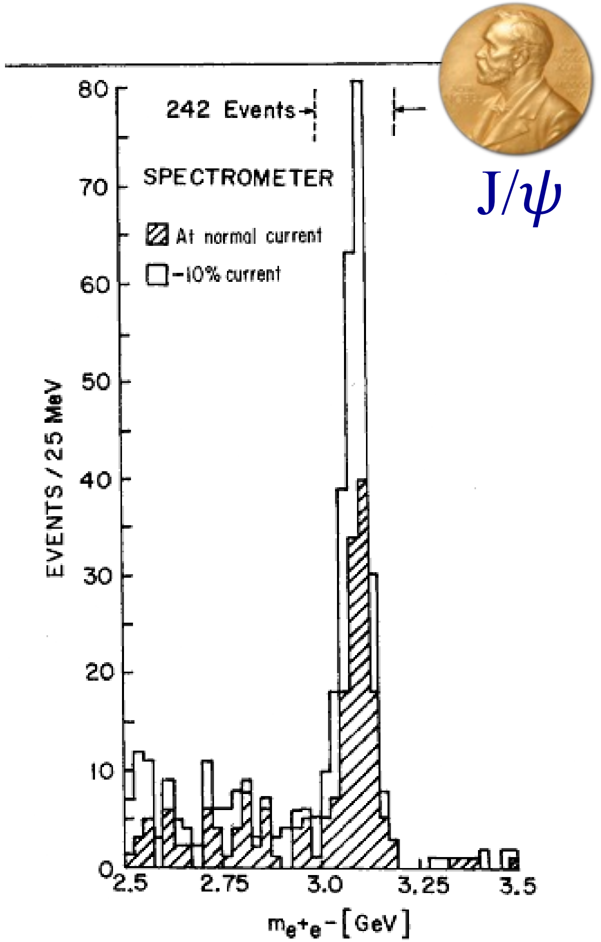
Drell and Yan, PRL 25 (1970) 316



Dimuon experiments – a celebrated historical background

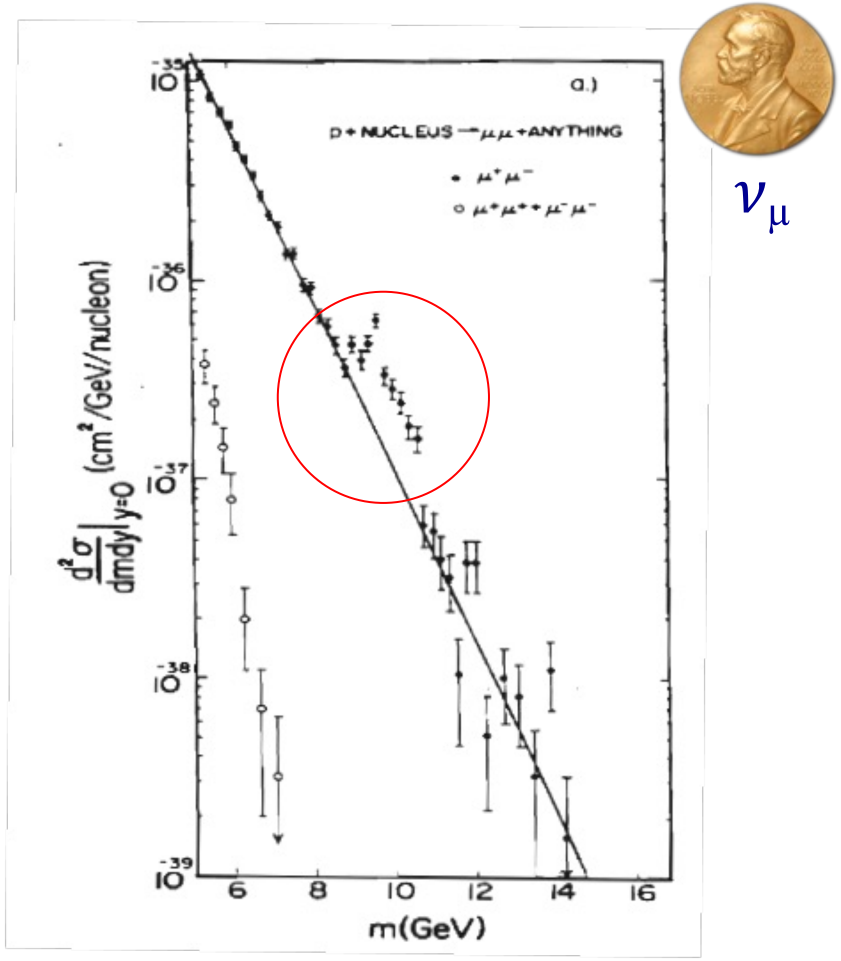
- Discovery of the J/ψ

"1974: Ting, Richter



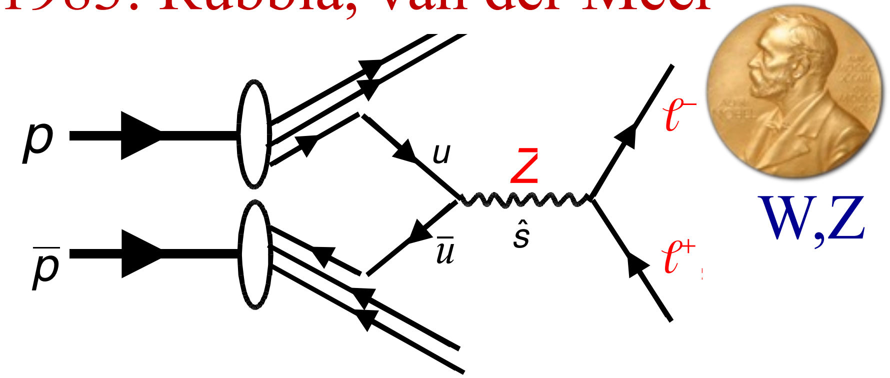
- Discovery of the Υ

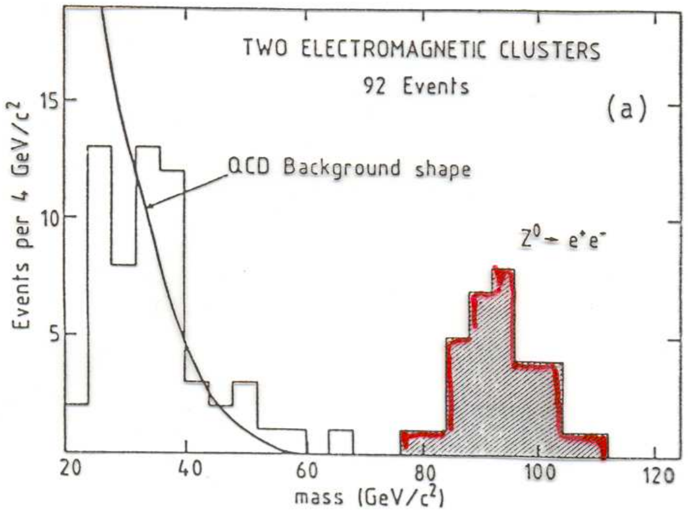
1977: Lederman



- Discovery of the W,Z

1983: Rubbia, van der Meer

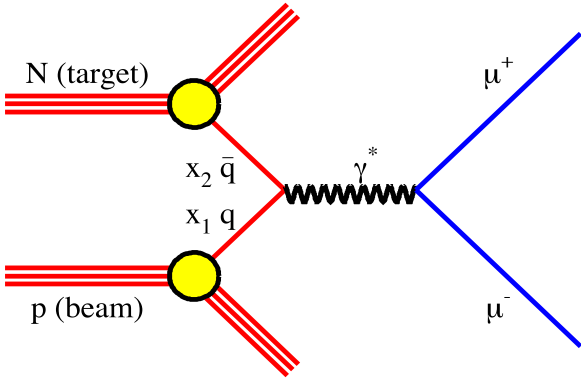




Drell-Yan cross section

- Convolution of beam and target PDFs

$$\frac{d^2\sigma}{dx_1 dx_2} \propto \sum_{i=u,d,s} e_i^2 \left[f_i^{\pi}(x_1,Q^2).\bar{f}_i^{A}(x_2,Q^2) + \bar{f}_i^{\pi}(x_1,Q^2).f_i^{A}(x_2,Q^2) \right]$$



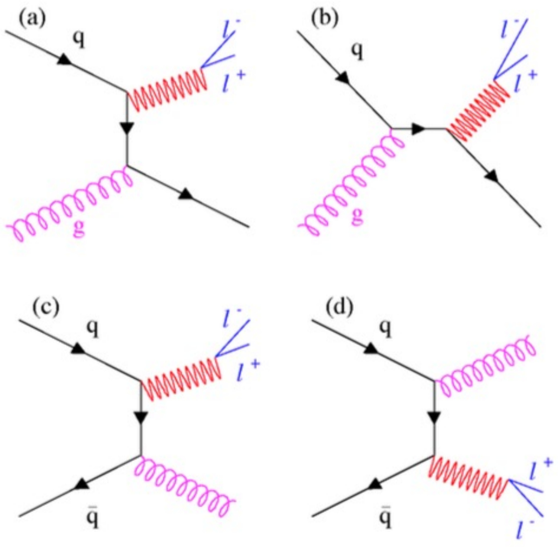
- At order (α_s^0) : a purely electromagnetic process

- NLO (α_s^1) corrections are well known

- NNLO (α_s^2) corrections are also known

QCD Compton

Gluon production

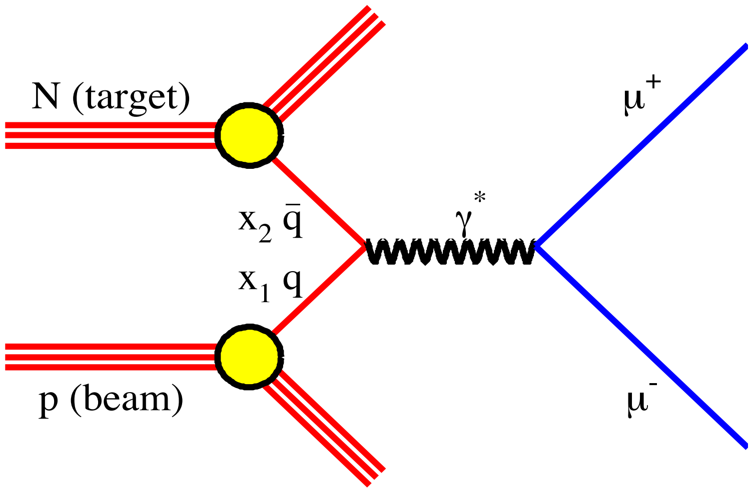


Drell-Yan is a well understood process

Drell-Yan cross section

- Convolution of beam and target PDFs

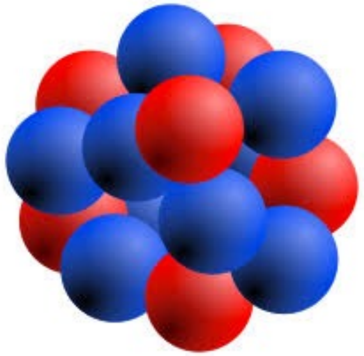
$$\frac{d^2\sigma}{dx_1 dx_2} \propto \sum_{i=u,d,s} e_i^2 \left[f_i^{\pi}(x_1,Q^2).\bar{f}_i^{A}(x_2,Q^2) + \bar{f}_i^{\pi}(x_1,Q^2).f_i^{A}(x_2,Q^2) \right]$$



- DY process: quark – antiquark annihilation

  - Pion beam (π^-) + proton target : $(\bar{u}d) + (uud)$: probes u valence quarks in the target
  - Pion beam (π^+) + proton target : $(u\bar{d}) + (uud)$: probes d valence quarks in the target
  - Proton beam + proton target : $(uud) + (uud+\bar{u}_s u_s)$: probes sea quarks in the target

Nuclear effects – possible studies using dimuon production



- Separate valence and sea nuclear effects with DY (DIS is sensitive to both)
  - Pion beams : probe mainly valence quarks
  - Proton beams probe mainly sea quarks

- Separate different flavors (DIS is not sensitive to the individual flavors)
  - Pion (π^-) beam : probes (preferentially) valence u quarks
  - Pion (π^+) beam : probes (preferentially) valence d quarks
  - Can probe the flavor dependence of the nuclear mean field

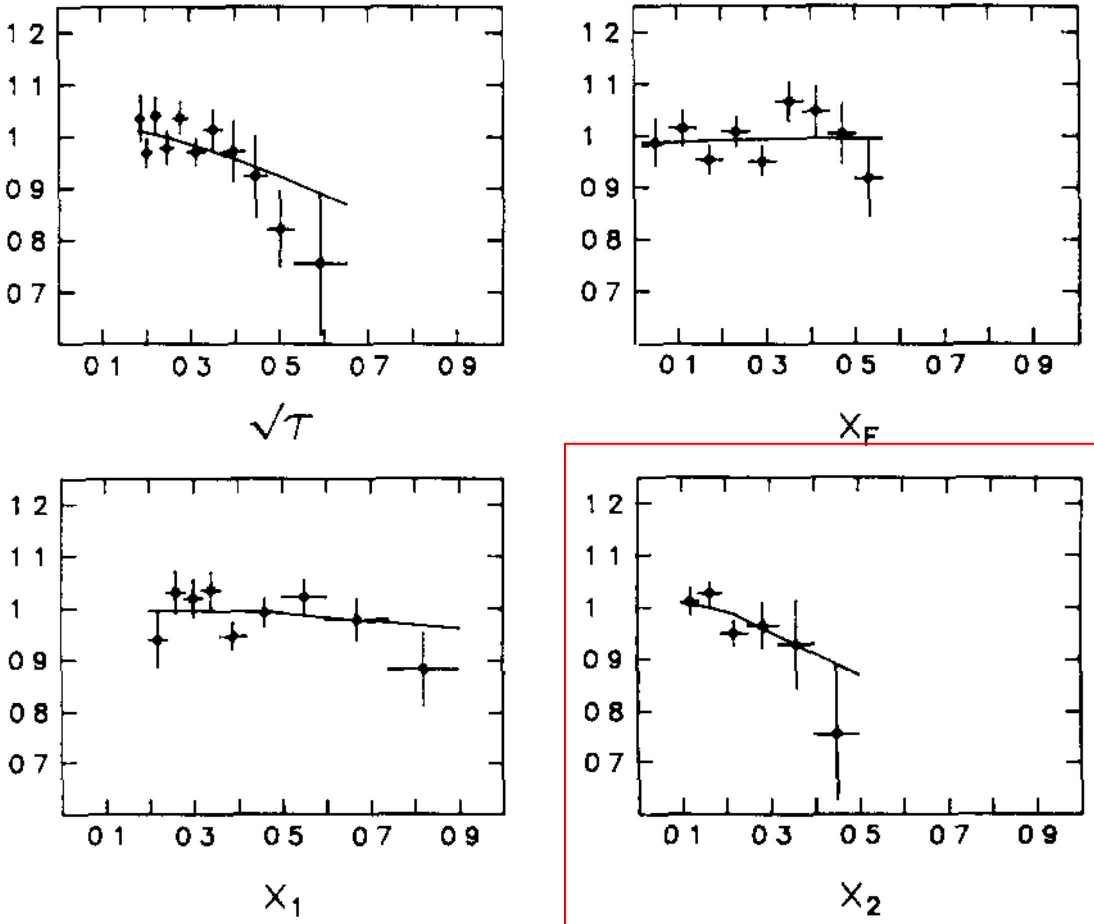
- Access the gluon distribution in nuclei?
  - Assuming that the J/ψ production is well understood

NA10 results, 1987

- Beam: π^-
- Targets: ^{2}D, W
- Energies: 140, 286 GeV

Bordalo et al, PL B193, 368 (1987)

$$\frac{\sigma(\pi^- W \rightarrow \mu^+\mu^- + X)}{\sigma(\pi^- D \rightarrow \mu^+\mu^- + X)}$$



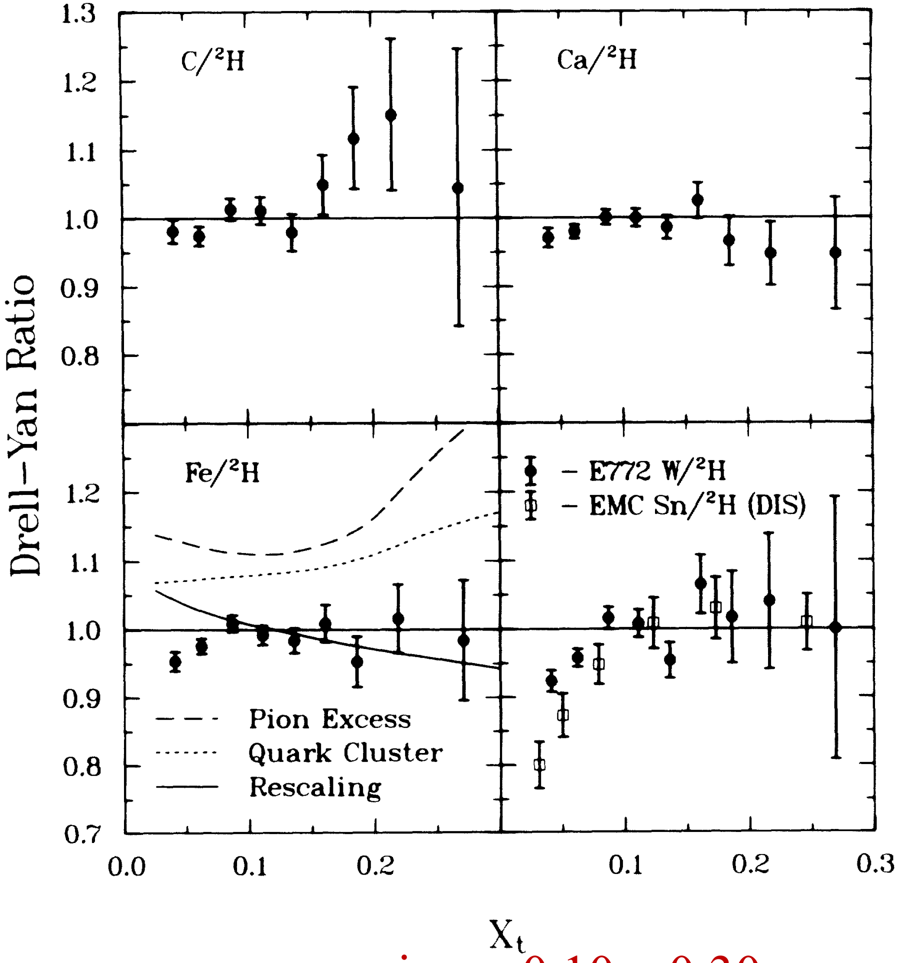
"The x_2 distribution indicates an effect (slope) quite similar in shape and magnitude to that reported by DIS experiments"

x_2 region: ~0.10 – 0.45

E772 results, 1990

- Beam: protons
- Targets: ^{2}H (50 cm) C, Ca, Fe, W
- Energy: 800 GeV
- Goal: probe antiquark distribution in nuclei

Alde et al, PRL 64, 368 (1990)



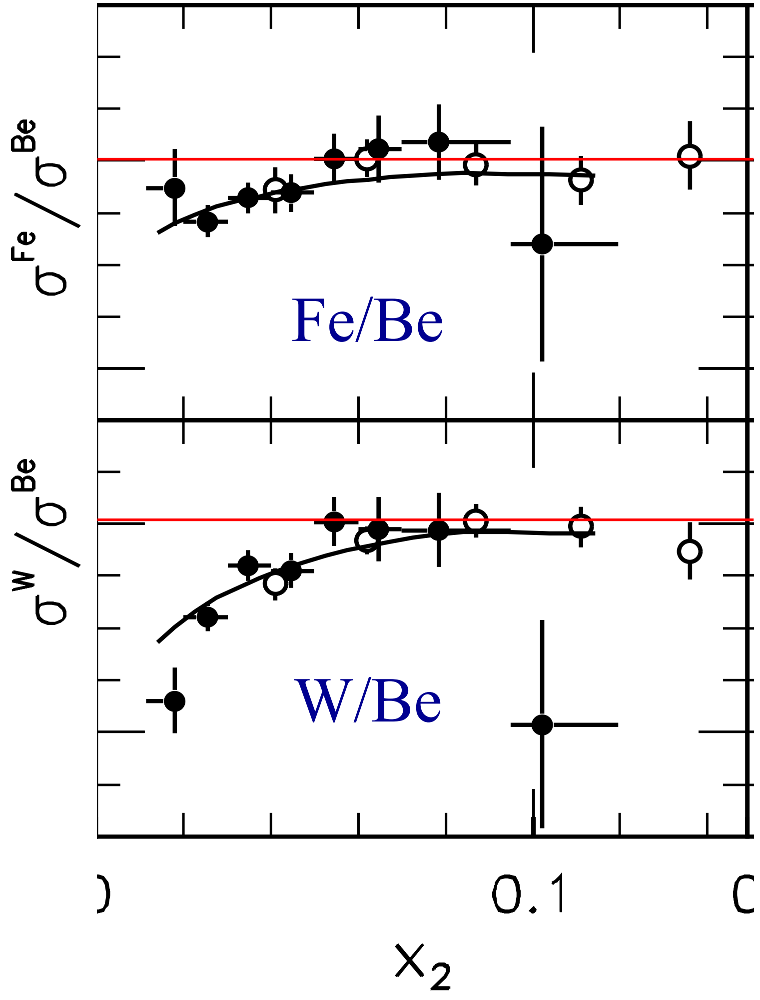
"In summary, this experiment has shown almost no nuclear dependence in the production of continuum dimuon pairs....
This implies no modification of the antiquark sea in the range 0.1 – 0.3."

x_2 region: ~0.10 – 0.30

E886 results, 1999

Vasiliev et al, PRL 83, 2304 (1999)

- Beam: protons
- Targets: Be, Fe, W
- Energy: 800 GeV
- Goal: access the shadowing region



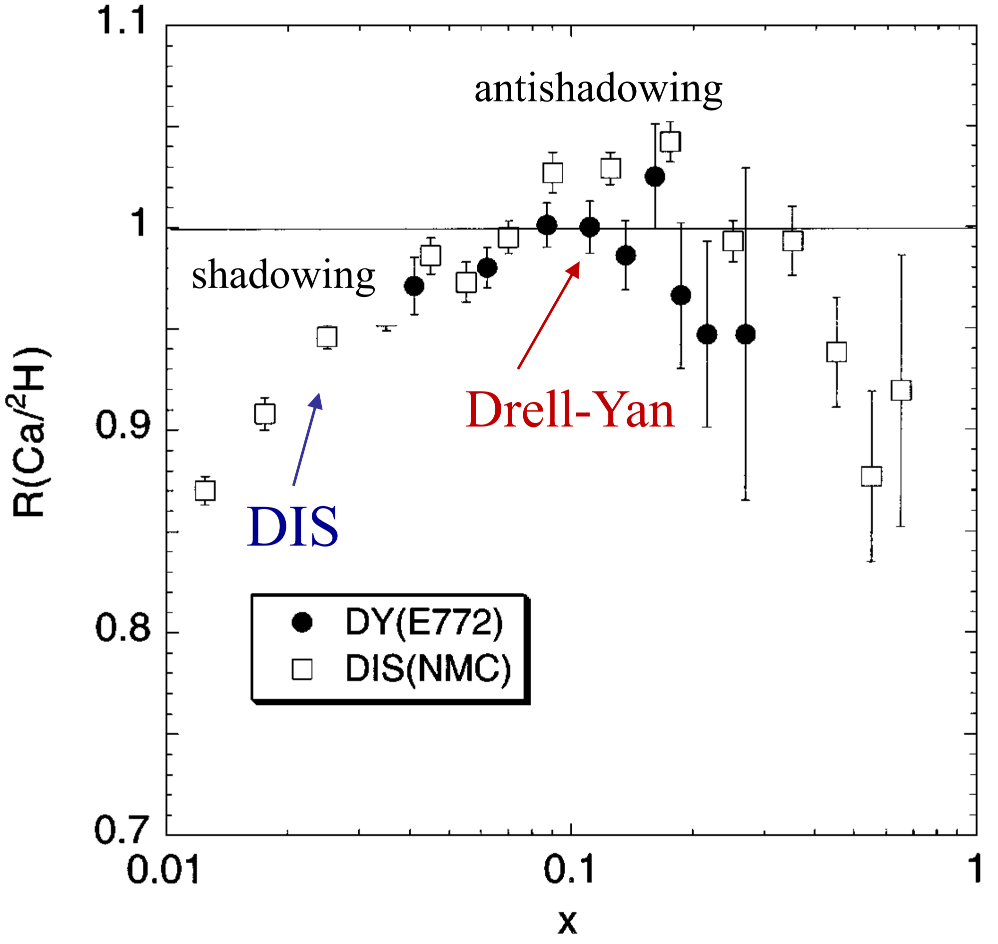
x_2 region: ~0.01 – 0.12

" ...the shadowing observed in Drell-Yan has been demonstrated to be quantitatively similar to that in DIS."

Comparison EMC/E772 – anti-shadowing region

- Observations
  - no enhancement of the DY antiquarks distribution
- DY (proton beam):
  - interacts mainly with antiquarks in the target
- DIS (lepton beam):
  - Sensitive to the charge weighted sum of all quarks

McCaughey, Moss, Peng, ARNPS49, 217 (1999)

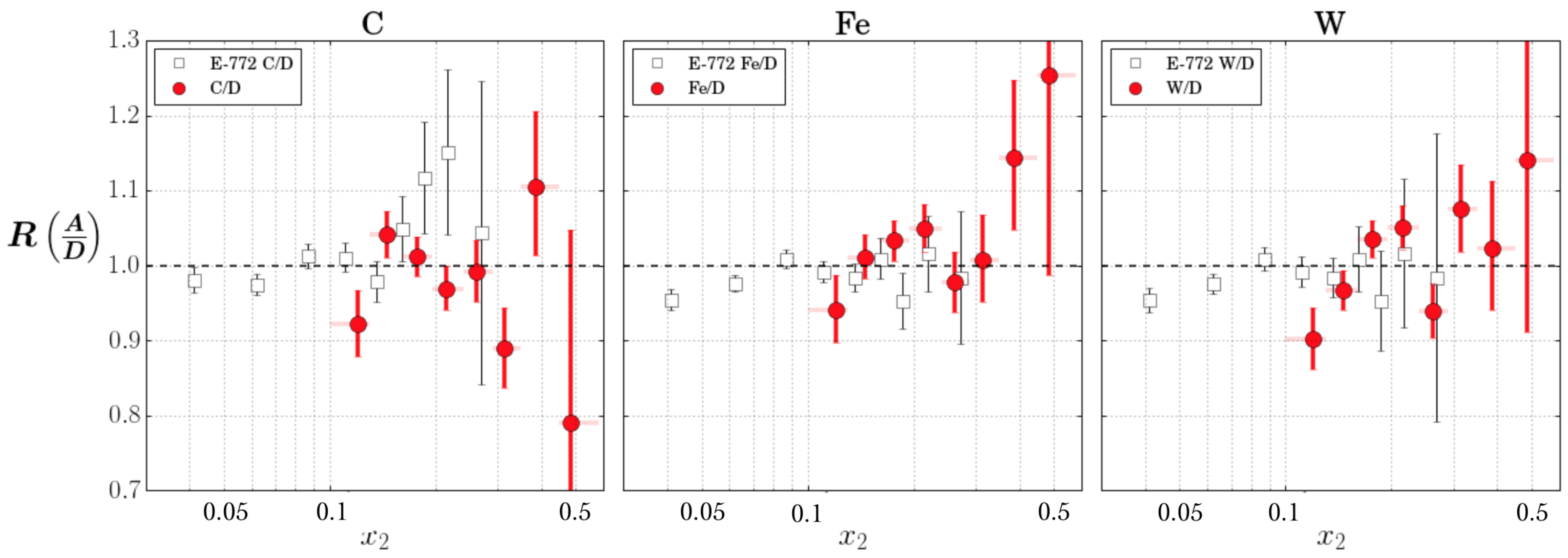


Are valence and sea nuclear effects identical?

Nuclear effects from SeaQuest 2017 (PhD thesis, preliminary!)

- Beam: protons   Targets: D, C, Fe, W
- Energy: 120 GeV   Statistics: = 61 000 ev (~30%)

B. Dannowitz, PhD UIUC (2017)



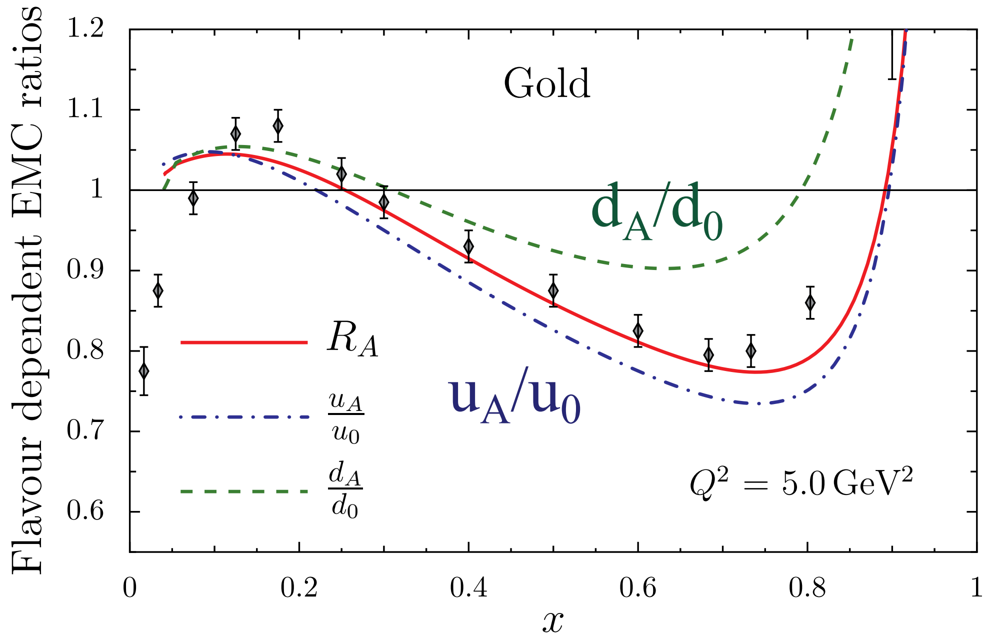
"This implies that perhaps the nuclear modification that leads to the DIS phenomenon known as the EMC effect is exclusively an effect of the valence quarks and does not originate from the quark sea."

x_2 region: ~0.10 – 0.50

Flavor dependence of the EMC effect

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

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



Free nucleon PDFs: u_0, d_0
Medium modified PDFs: u_A, d_A

DIS data are not sensitive to the flavor-dependence.

Flavor-dependent EMC : existing DY data

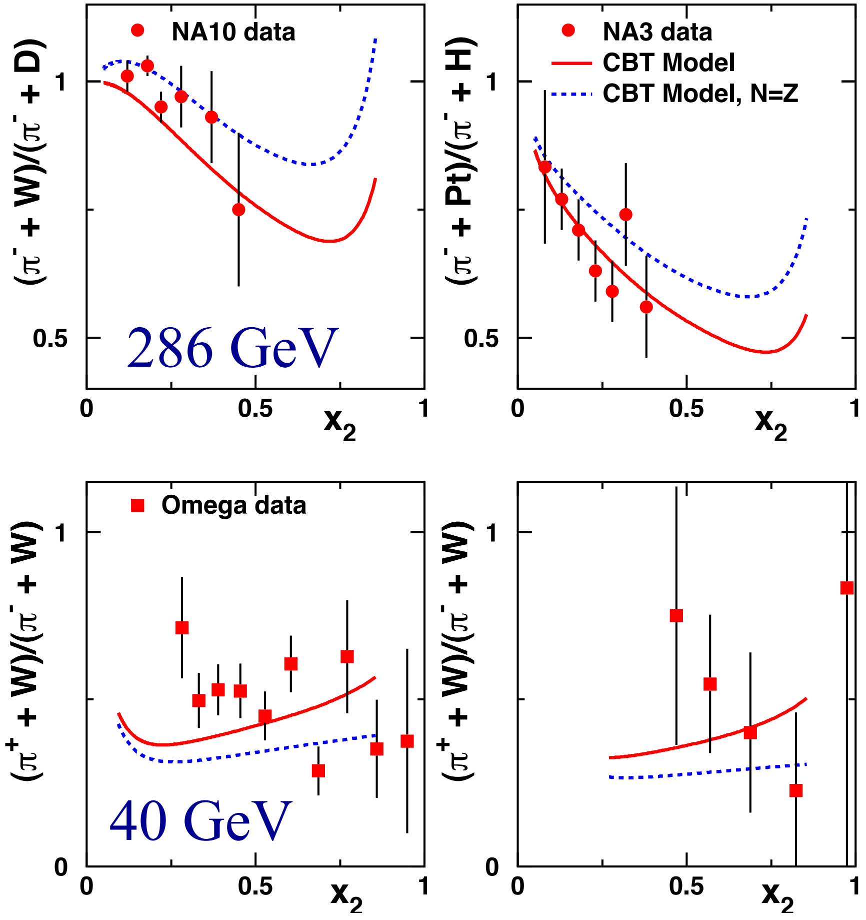
- Available data
  - NA3: H_2, Pt
  - NA10: ^{2}H, W

- Available π^+ and π^- data
  - NA3: 2063 and 5067 events
  - WA39: few hundreds events

Dutta et al., Phys. Rev. C 83, 042201 (2011)

$$\frac{\pi^- + W}{\pi^- + D}$$

$$\frac{\pi^+ + W}{\pi^- + W}$$



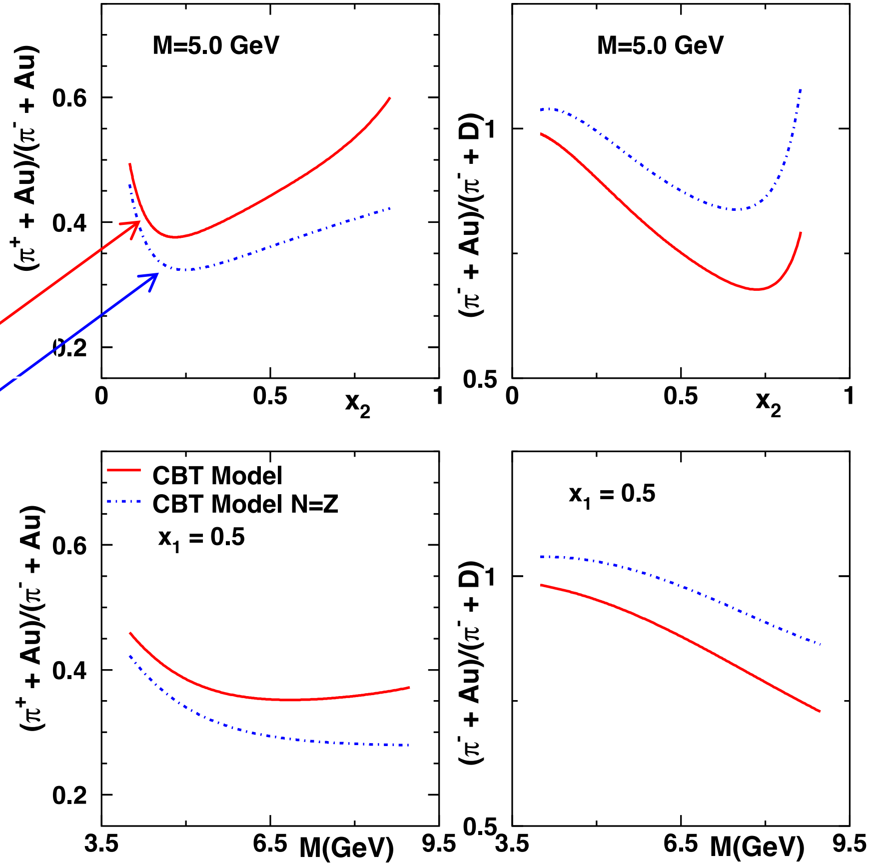
Flavor dependence of EMC effect – predictions at 160 GeV

Dutta et al., Phys. Rev. C 83, 042201 (2011)

- Pion-induced Drell-Yan for E = 160 GeV.
- Two options:
  - $R_{\pm} = \frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)}$ $\frac{\pi^+ + Au}{\pi^- + Au}$
  - $R^-_{A/D} = \frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$ $\frac{\pi^- + Au}{\pi^- + D}$

With flavour-dependence

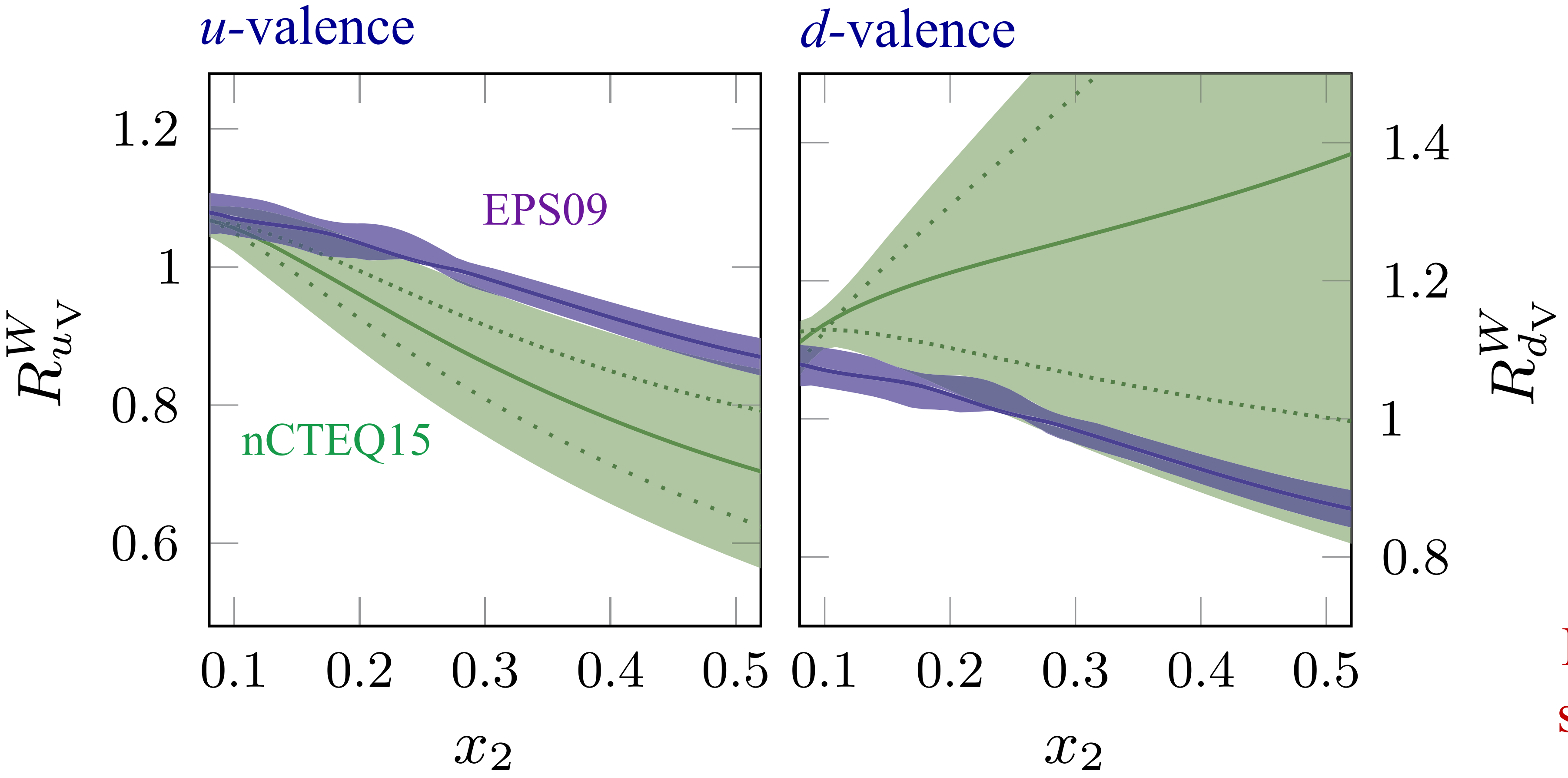
Without flavour-dependence



Valence quark PDF ratios for $^{184}W/^{2}H$

Paakkinen, Eskola, Paukkunen, PL B768, 7 (2017)

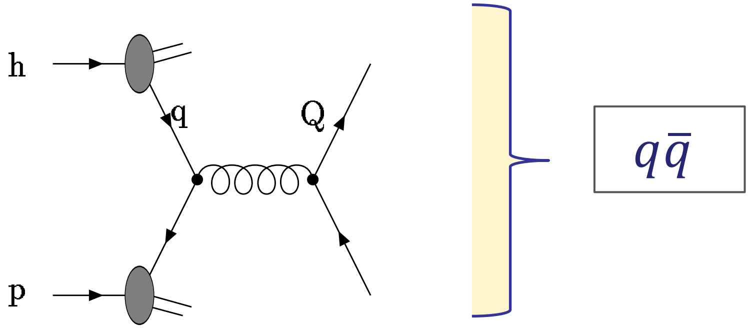
- Derived using global fits to the DIS and DY pion data
  - EPPS09 : u/d symmetric
  - nCTEQ15: independent *u* and *d* PDFs

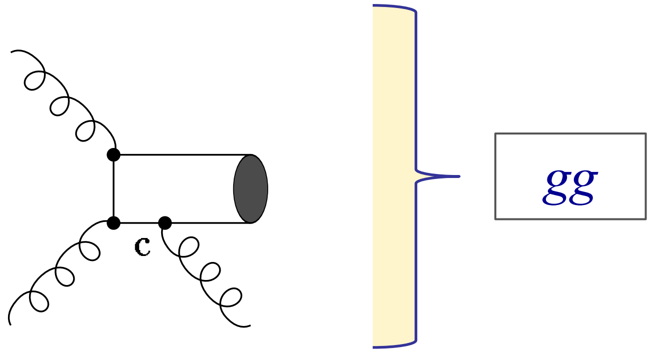


More precise data should add further constraints

J/ψ production mechanism

- J/ψ are produced through two main processes:
  - $q\bar{q}$ annihilation
  - gluon-gluon fusion gg (+g)
- J/ψ production advantages
  - Large cross sections (strong process)
  - Access to quark and gluon distributions in nuclei
  - Access to quark and gluon distributions in the beam



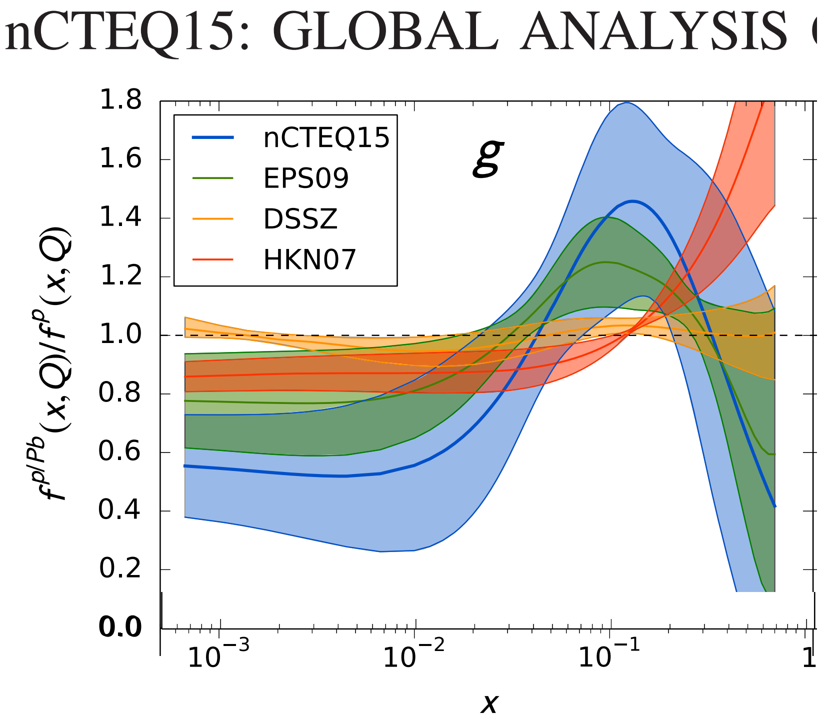


Gluon distributions in nuclei ?

PHYSICAL REVIEW D **93,** 085037 (2016)

nCTEQ15: Global analysis of nuclear parton distributions with uncertainties in the CTEQ framework

K. Kovařík,[1] A. Kusina,[2] T. Ježo,[3] D. B. Clark,[4] C. Keppel,[5] F. Lyonnet,[4] J. G. Morfín,[6] F. I. Olness,[4] J. F. Owens,[7] I. Schienbein,[2] and J. Y. Yu[4]



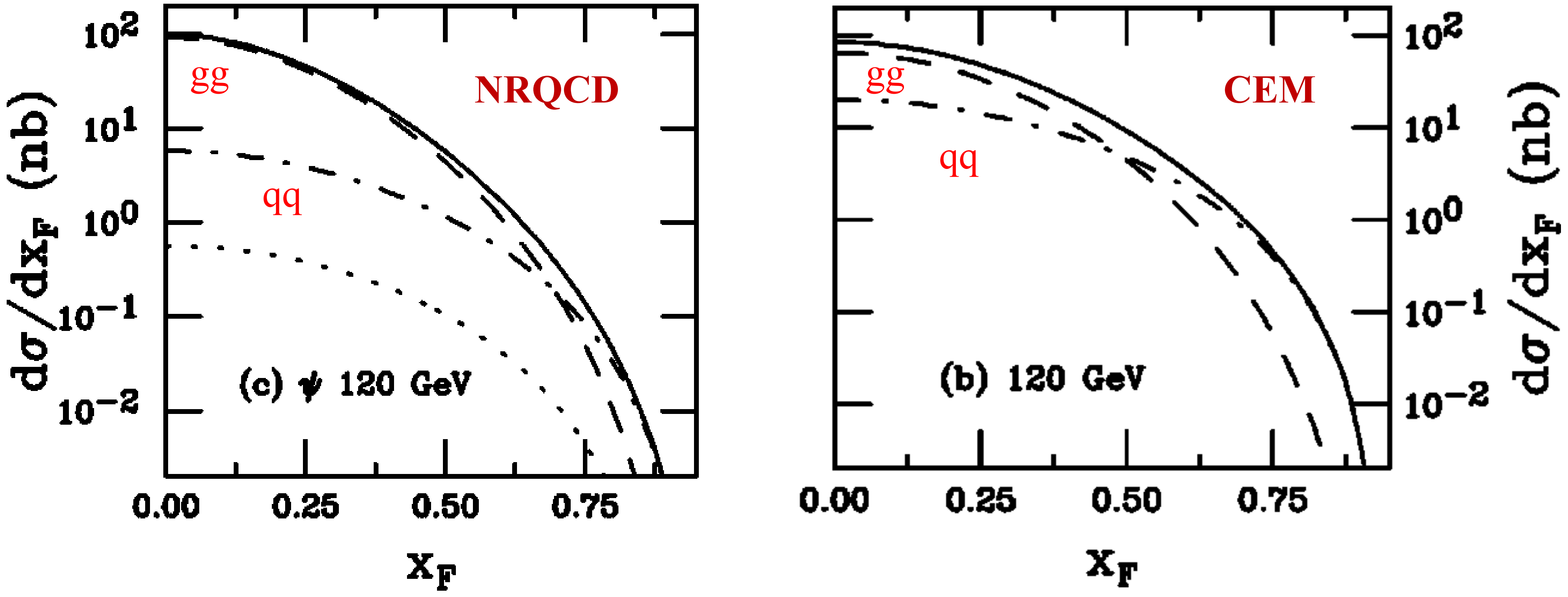
- Extraction of gluon PDFs from J/ψ cross section:
  - Difficulty 1: J/ψ production mechanism
  - Difficulty 2: J/ψ suppression: competition with the medium-modified gluon PDF

Measuring the glue in nuclei is still a - rewarding - challenge

Do we understand the J/ψ production mechanism?

R. Vogt, Phys. Rev. C61, 035203 (2000)

- Two models: CEM and NRQCD
  - Comparison: somewhat different results



Model dependence: prevents a reliable PDF determination

J/ψ – can we get rid of the production models ?

Yes! look at the production cross section for K$^+$ and K$^-$

$$K^-(\bar{u}s)+p(uud)\propto gg+\left[\bar{u}_v^K u_v^p\right]+\left[\bar{u}_v^K u_s^p+s_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

$$K^+(u\bar{s})+p(uud)\propto gg+\left[---\right]+\left[u_v^K\bar{u}_s^p+\bar{s}_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K\bar{u}_s^p+s_s^K\bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

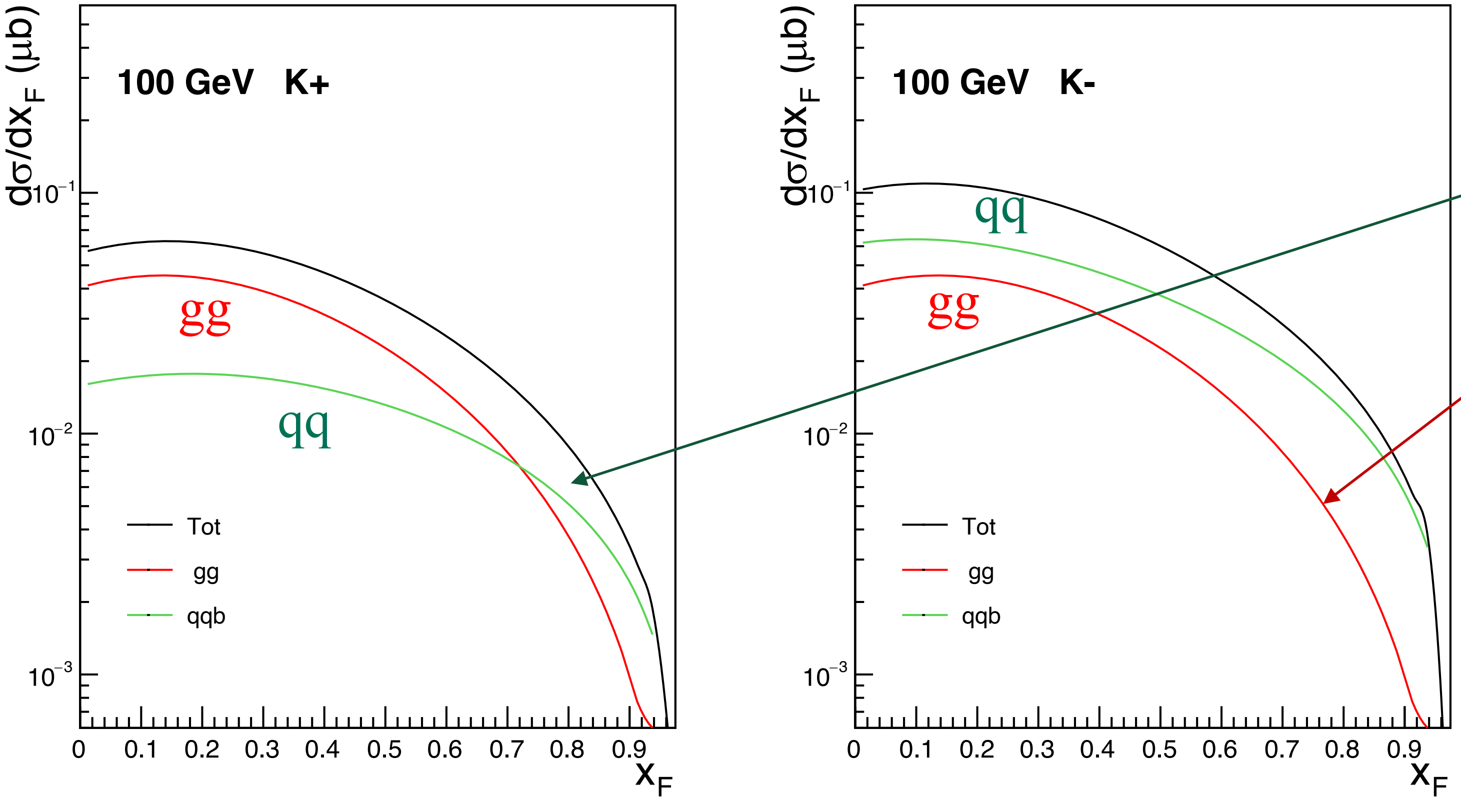
The cross section difference isolates solely the valence-valence term :

$$\sigma(K^-)-\sigma(K^+)\propto\bar{u}_v^K u_v^p$$

The cross section difference between K$^-$and K$^+$ is independent of any model

Kaon-induced J/ψ production

CEM calculations



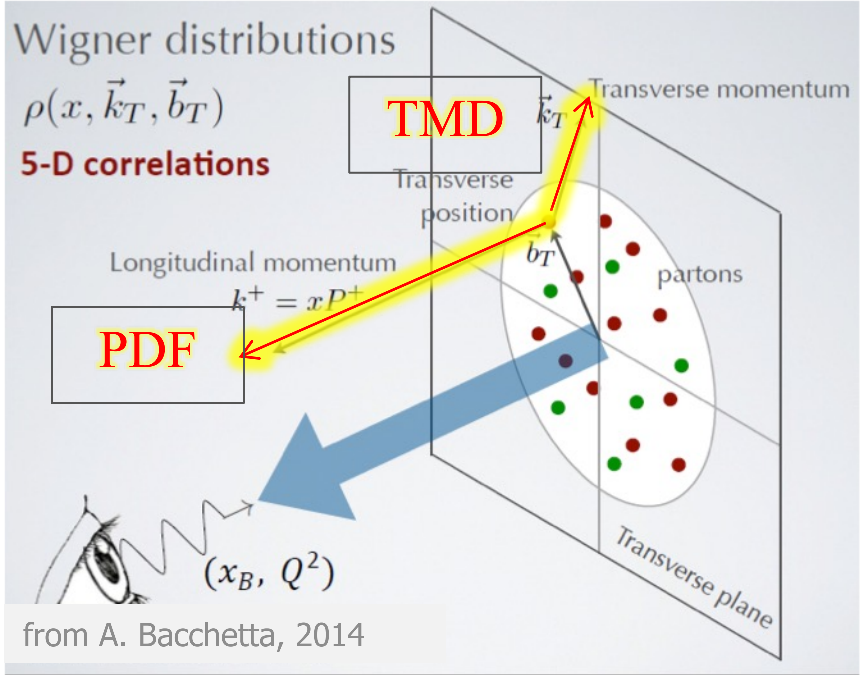
identical val-sea and sea-sea contributions

identical gg contributions

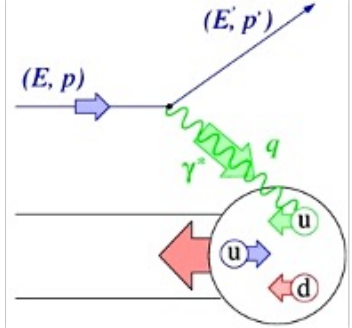
Cross sections for K$^-$ and for K$^+$ for light and heavy nuclei.

$$\frac{\sigma^A(K^-) - \sigma^A(K^+)}{\sigma^p(K^-) - \sigma^p(K^+)} = \frac{\bar{u}_V^K u_V^A}{\bar{u}_V^K u_V^p} = \frac{u_V^A}{u_V^p}$$

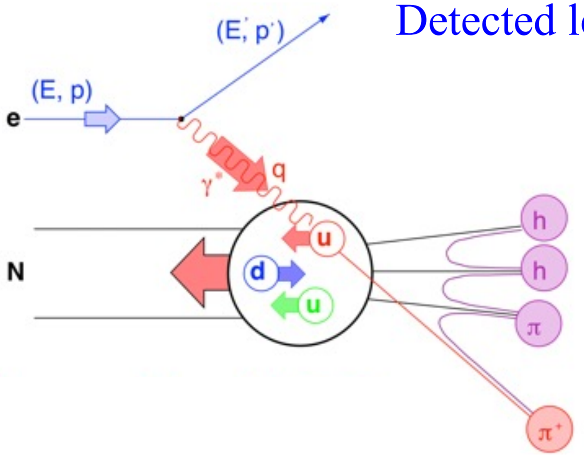
Tools for investigating the hadron structure



Deep Inelastic Scattering (DIS)

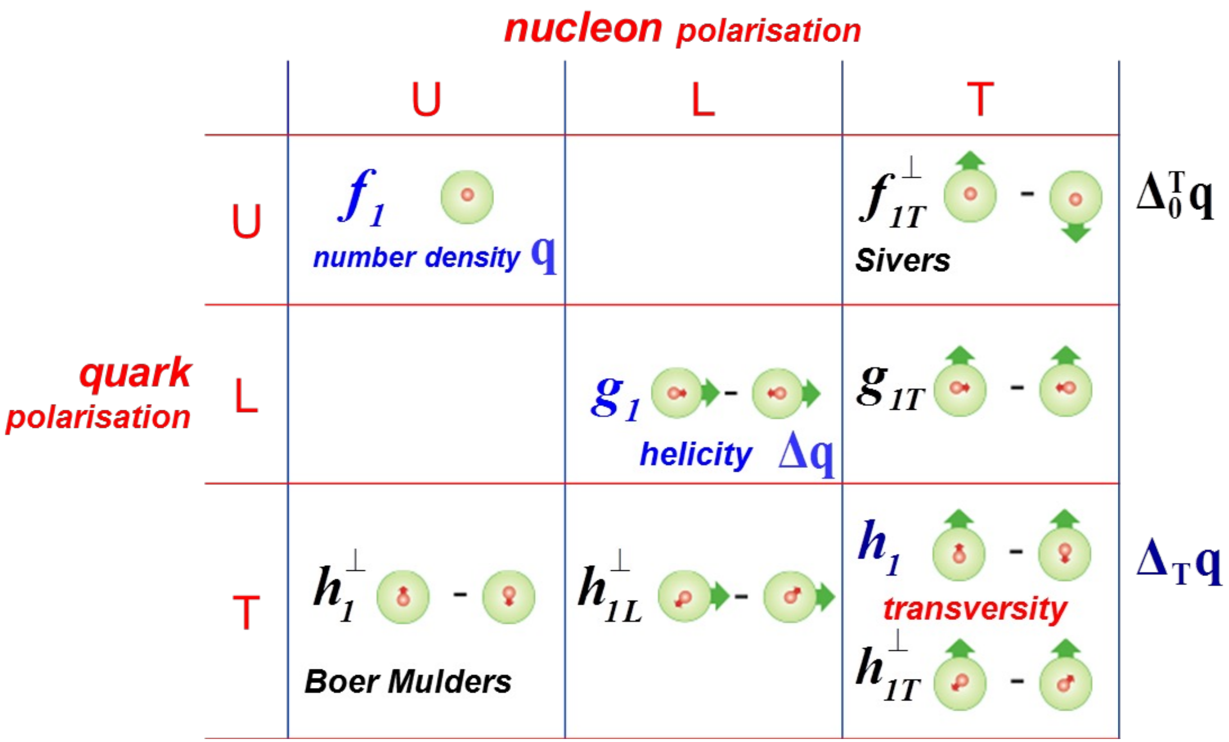


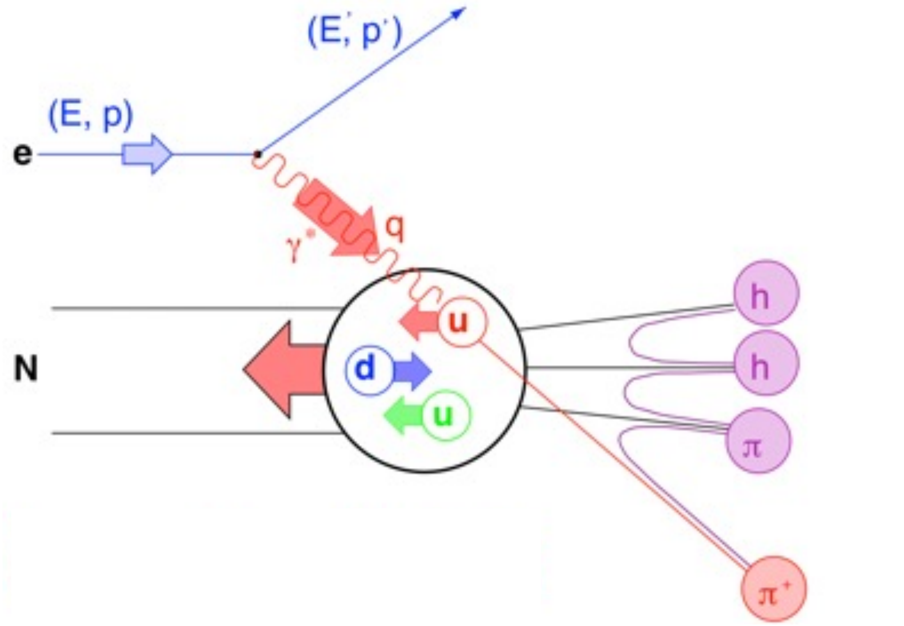
Semi-Inclusive DIS



SIDIS and Transverse Momentum Dependent PDFs (LT)

- EMC effect: are the TMDs in nuclei different than the TMDs in the nucleon?



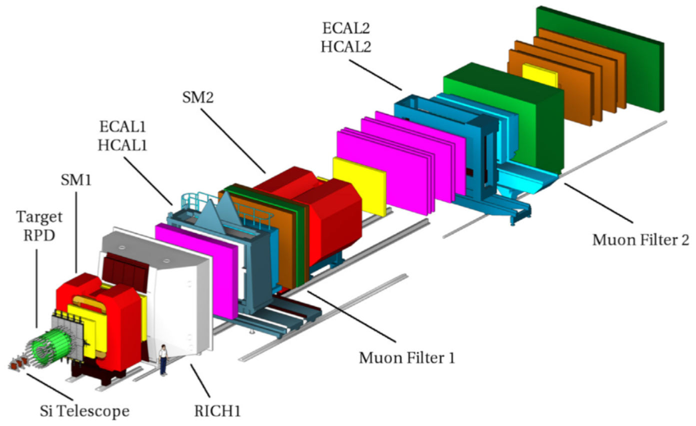


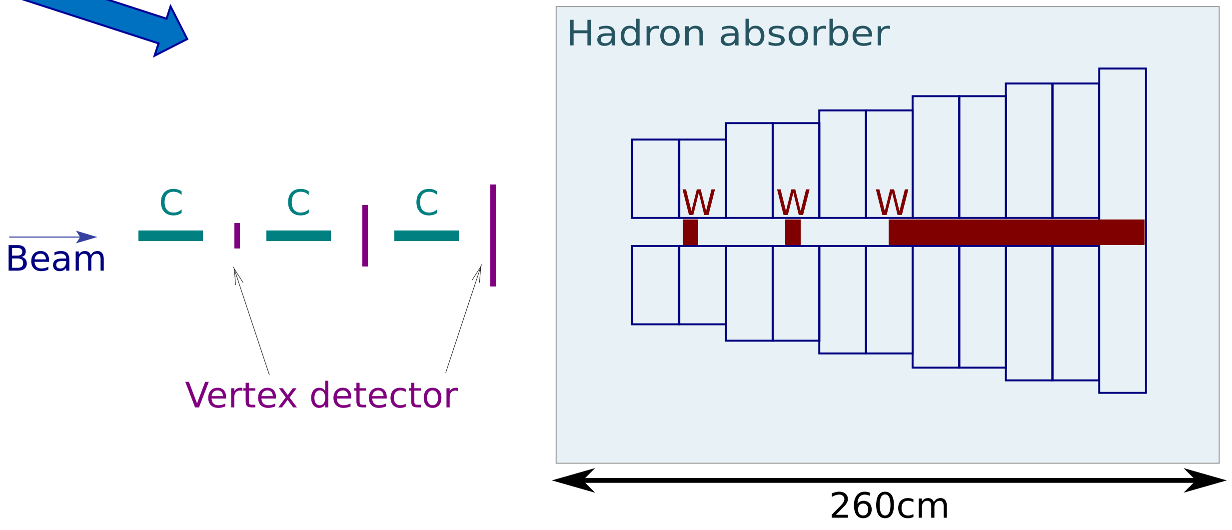
Detected hadron

- Answer is difficult: needed is large statistics, polarization, quark fragmentation, etc…

AMBER experiment at CERN

- Dimuon setup
  - Proposal is accepted
  - Energy: 190 GeV
  - Beams: Positive and Negative hadrons
  - Targets: ^{12}C and ^{184}W





Summary

- Drell-Yan experiments shed further lights on the EMC effect.

- CERN + AMBER experiment: only place in the world with
  - 1) mesons beams (pions, kaons) ; also proton and antiproton beams
  - 2) positive or negative beam charge
  - 3) large and uniform acceptance (and there are planned improvements...)