Hadrons in Medium

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XIth Quark Confinement and the Hadron Spectrum
September 8-12, 2014
Saint-Petersburg State University, Russia

Outline

1. Motivations for studying hadrons in medium

2. Nucleon structure functions and e.m. form factors

3. Spectral properties of light vector mesons

4. Heavy flavor
    - — D-mesic nuclei
    - — J/Ψ nuclear bound states
    - — ~~Quarkonium in heavy-ion collisions~~ (Vairo and others)

5. Perspectives

Left out:

1. Energy losses in heavy-ion collisions, jet quenching
2. Pionic & Kaonic atoms, pions in medium
3. η’(980) mesic nuclei, hyperons in medium (hypernuclei)
4. Color transparency
5. Chiral magnetic effects

Motivations

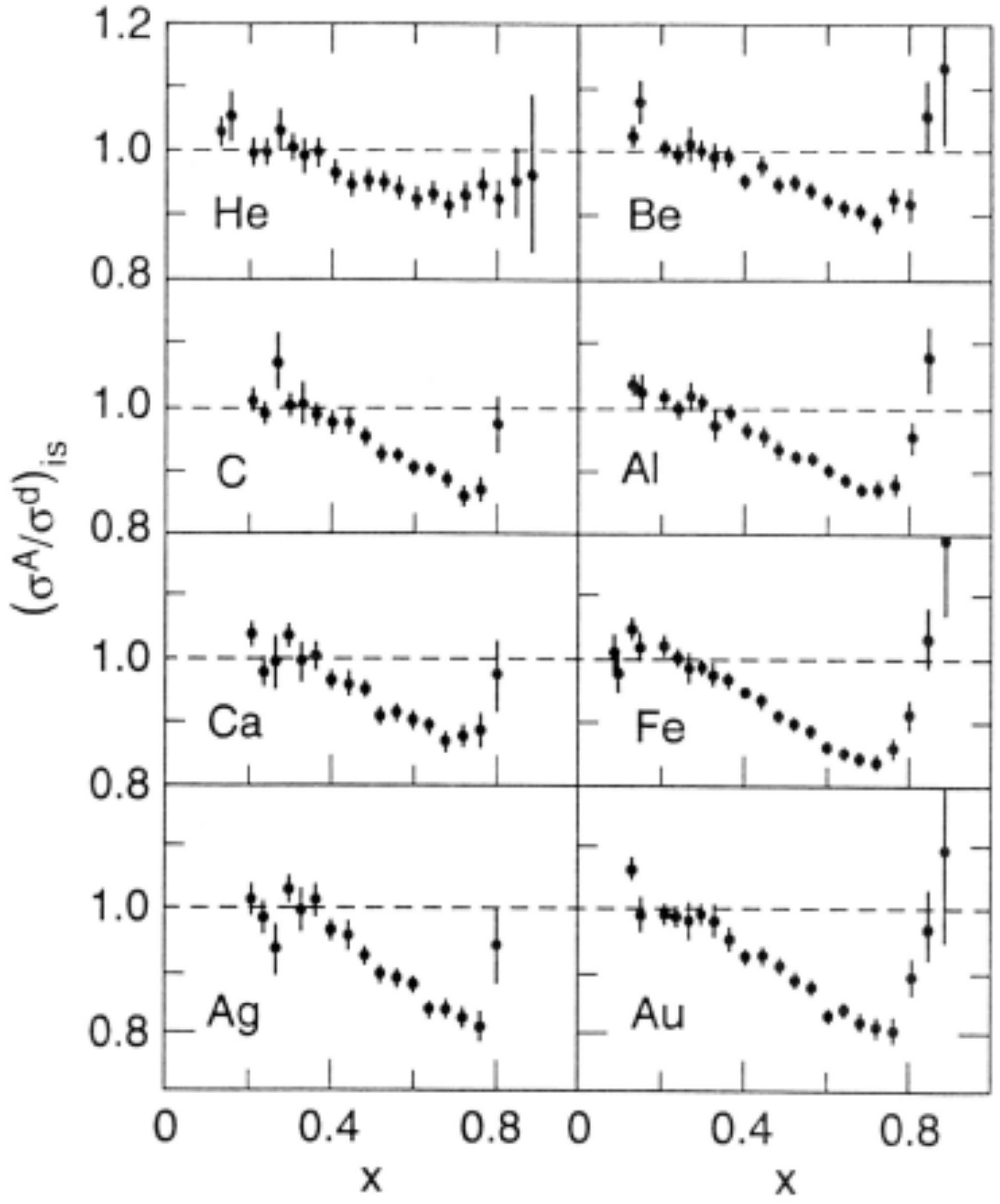
— for studying hadrons in medium

1. Understanding ground state of many-hadron systems like nuclei and dense stars
2. Change of intrinsic structure of hadrons
   — chiral symmetry & confinement
3. Production of new phases of QCD matter

Structure Functions

— of nucleons in nuclei

EMC Collab. (1983)



Ratio of nucleus A to deuterium A=2
DIS structure functions

$$\frac{\sigma_A}{\sigma_D} = \frac{F_2^A(x,Q^2)}{F_2^D(x,Q^2)}\,\frac{1+R_D}{1+R_A}\,\frac{1+\epsilon R_A}{1+\epsilon R_D} \approx \frac{F_2^A(x,Q^2)}{F_2^D(x,Q^2)}$$

Momentum fraction carried by quarks
inside a nucleus is different
from inside a free nucleon
(beyond trivial Fermi motion)

Structure Functions

— of nucleons in nuclei

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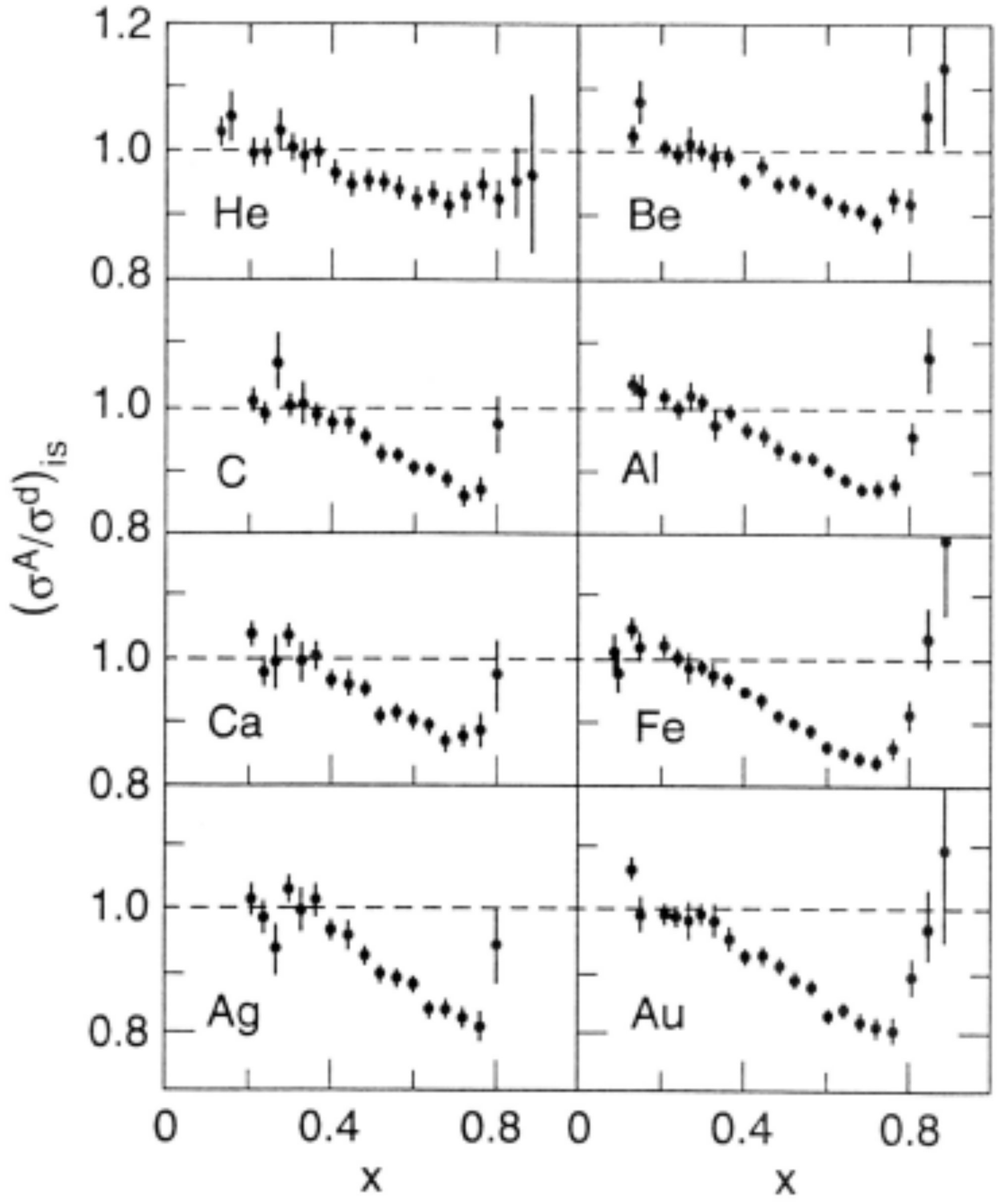

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An unexpected discovery

EMC effect — an unexpected discovery

Why unexpected?

A good deal of nuclear physics is understood with
nucleons in nuclei moving *independently*
in mean fields (shell model)

Why does the shell model work?

Shells ~ definite angular momentum

A nucleon must travel a distance comparable
to the diameter of the nucleus

BUT

$\sigma_{NN} \sim$ a few barns $\xrightarrow[\text{m.f.p.}]{}$ $\lambda_N = \dfrac{1}{\rho\,\sigma_{NN}} < 0.5\,\mathrm{fm}$

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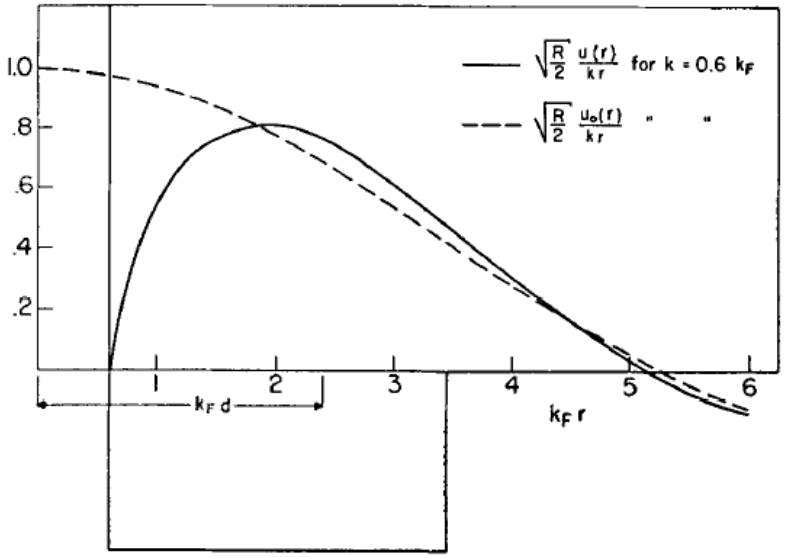
How can it work?

Answer

— Gomes, Walecka & Weisskopf (1958)

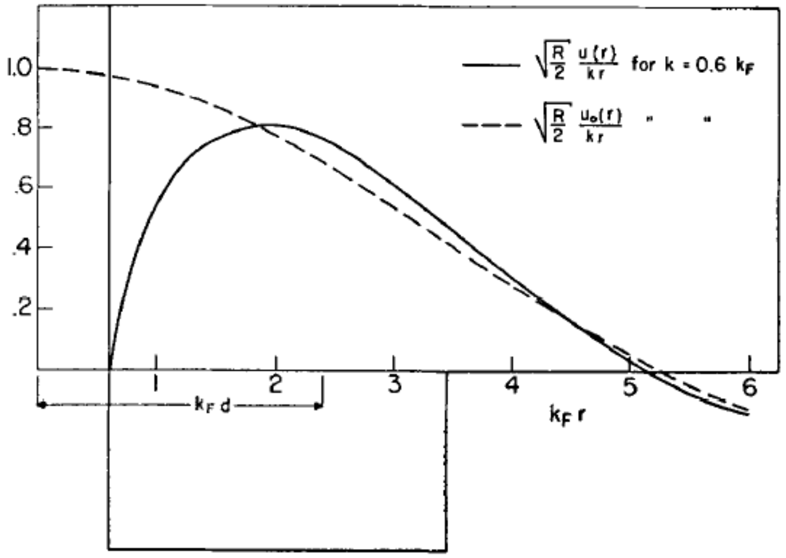


Interplay between the hard core of the nuclear force
and the Pauli exclusion principle

Pauli principle at the level of the nucleons:
Superposition of the quark structures in nuclei must be small

Answer

— Gomes, Walecka & Weisskopf (1958)



Interplay between the hard core of the nuclear force
and the Pauli exclusion principle

Pauli principle at the level of the nucleons:
Superposition of the quark structures in nuclei must be small

How small?

Answer*: r.m.s. radius $<$ 0.6 fm

Plenty of room for quark exchange & multiquark clusters

*GK & Th.A.J. Maris

Many new experiments after the 1983 EMC discovery

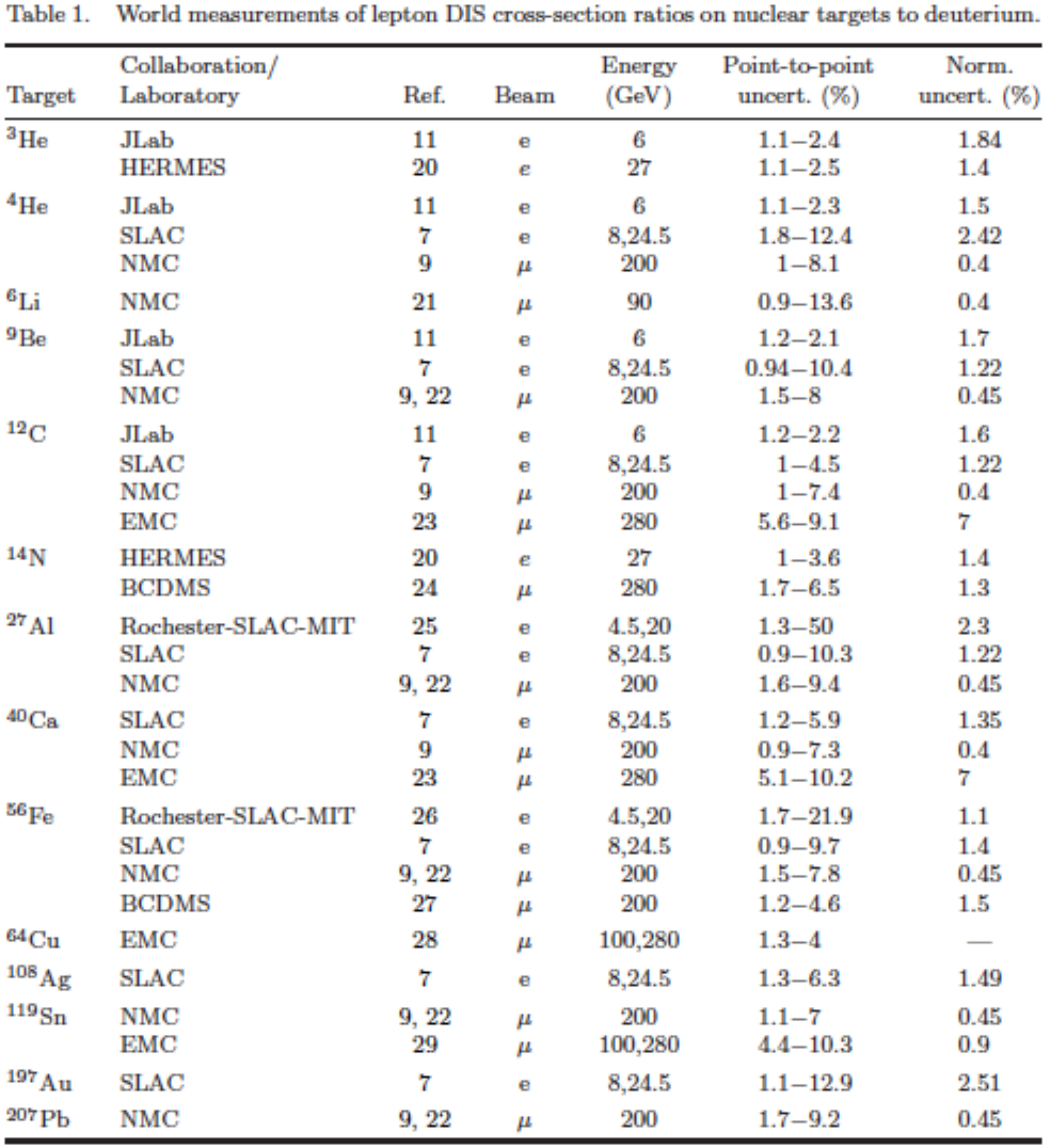
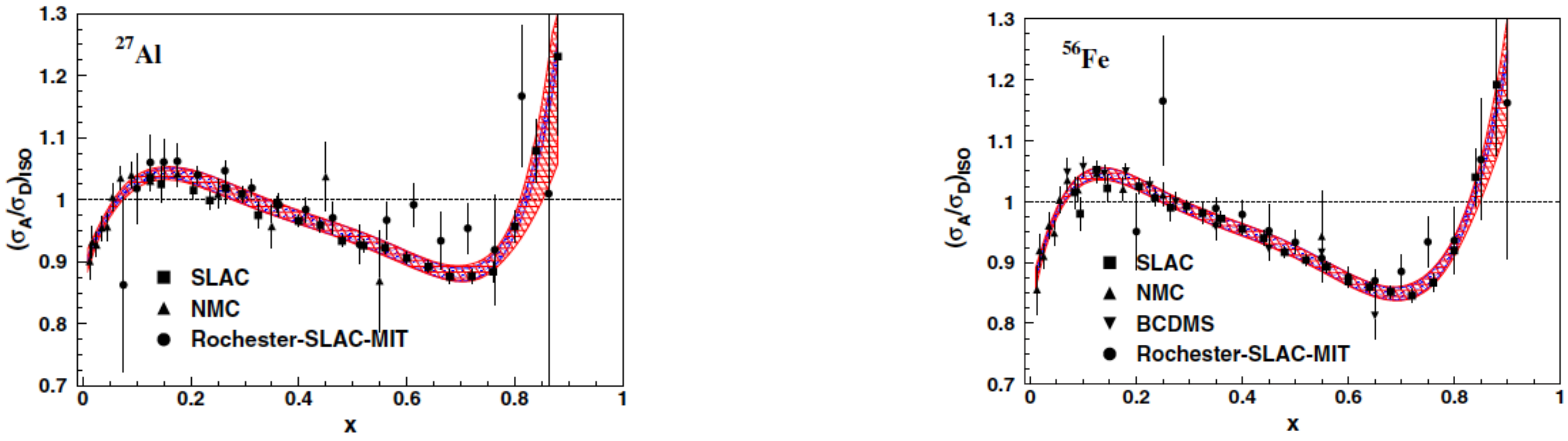


Table 1. World measurements of lepton DIS cross-section ratios on nuclear targets to deuterium.

Target	Collaboration/ Laboratory	Ref.	Beam	Energy (GeV)	Point-to-point uncert. (%)	Norm. uncert. (%)
^{3}He	JLab	11	e	6	1.1–2.4	1.84
	HERMES	20	e	27	1.1–2.5	1.4
^{4}He	JLab	11	e	6	1.1–2.3	1.5
	SLAC	7	e	8,24.5	1.8–12.4	2.42
	NMC	9	μ	200	1–8.1	0.4
^{6}Li	NMC	21	μ	90	0.9–13.6	0.4
^{9}Be	JLab	11	e	6	1.2–2.1	1.7
	SLAC	7	e	8,24.5	0.94–10.4	1.22
	NMC	9, 22	μ	200	1.5–8	0.45
^{12}C	JLab	11	e	6	1.2–2.2	1.6
	SLAC	7	e	8,24.5	1–4.5	1.22
	NMC	9	μ	200	1–7.4	0.4
	EMC	23	μ	280	5.6–9.1	7
^{14}N	HERMES	20	e	27	1–3.6	1.4
	BCDMS	24	μ	280	1.7–6.5	1.3
^{27}Al	Rochester-SLAC-MIT	25	e	4.5,20	1.3–50	2.3
	SLAC	7	e	8,24.5	0.9–10.3	1.22
	NMC	9, 22	μ	200	1.6–9.4	0.45
^{40}Ca	SLAC	7	e	8,24.5	1.2–5.9	1.35
	NMC	9	μ	200	0.9–7.3	0.4
	EMC	23	μ	280	5.1–10.2	7
^{56}Fe	Rochester-SLAC-MIT	26	e	4.5,20	1.7–21.9	1.1
	SLAC	7	e	8,24.5	0.9–9.7	1.4
	NMC	9, 22	μ	200	1.5–7.8	0.45
	BCDMS	27	μ	200	1.2–4.6	1.5
^{64}Cu	EMC	28	μ	100,280	1.3–4	—
^{108}Ag	SLAC	7	e	8,24.5	1.3–6.3	1.49
^{119}Sn	NMC	9, 22	μ	200	1.1–7	0.45
	EMC	29	μ	100,280	4.4–10.3	0.9
^{197}Au	SLAC	7	e	8,24.5	1.1–12.9	2.51
^{207}Pb	NMC	9, 22	μ	200	1.7–9.2	0.45

Table from the recent review:
S. Malace et al. (2014)

Qualitative universality



$x < 0.05 - 0.1$ Shadowing: depletion, depletion increases with A

$0.1 < x < 0.3$ Antishadowing: enhancement, no clear A dependence

$0.3 < x < 0.8$ EMC effect: depletion, depletion increases with A

$x > 0.8$ Fermi motion: strongly enhanced

Theory

Many ideas:

- Nuclear binding
- Pion excess in nuclei
- Multi-quark clusters

nuclear physics

- Dynamical rescaling
- Medium modification
- Short-range correlations

nucleon structure

… BUT not yet fully understood

Theory

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… BUT not yet fully understood

Possible scenario:

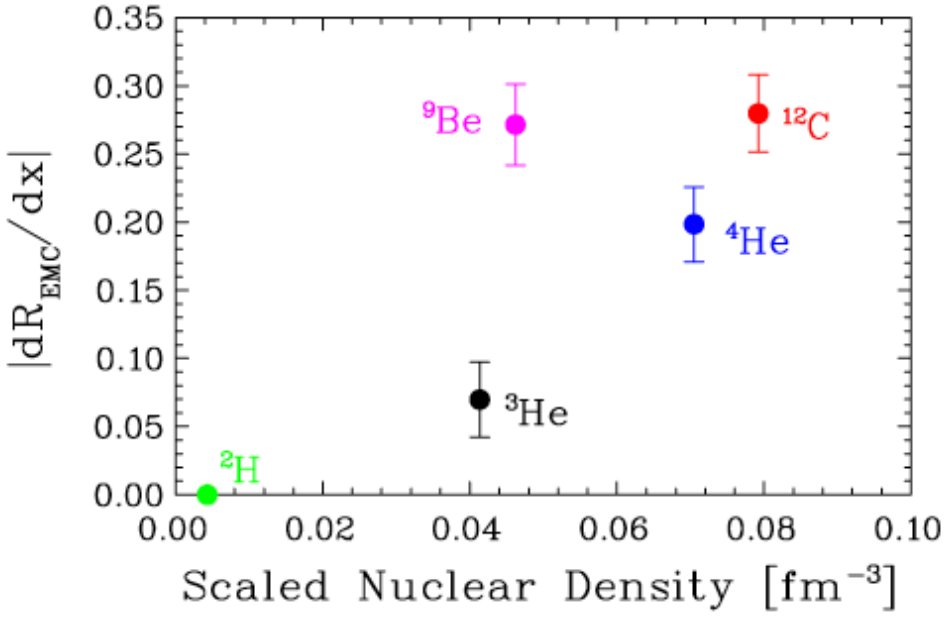
— several effects acting together, difficult to disentangle

Recent developments

Slope* of the ratio F_A/AF_D

- magnitude of the EMC effect

J. Seely et al. PRL (2009)

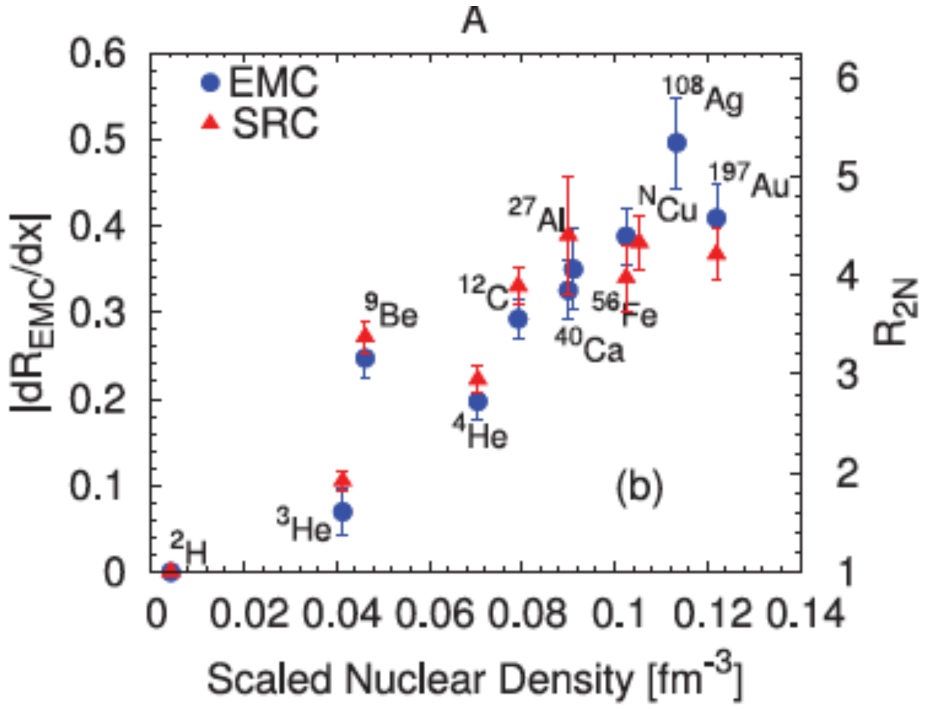


Effect in ^{4}He and ^{9}Be similar magnitude as in ^{12}C

2N short range correlations

- extracted from knockout reactions

J. Arrington et al. PRC (2012)



What matters is the <u>local</u> density the DIS happens

---

*in the liner region $0.35 < x < 0.7$

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Slope[*] of the ratio F_A/AF_D

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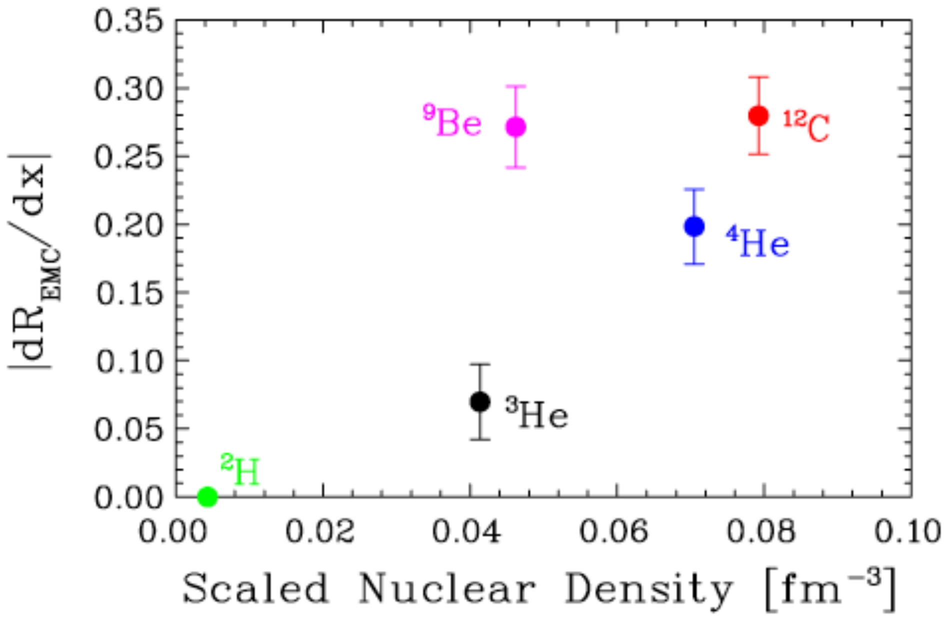

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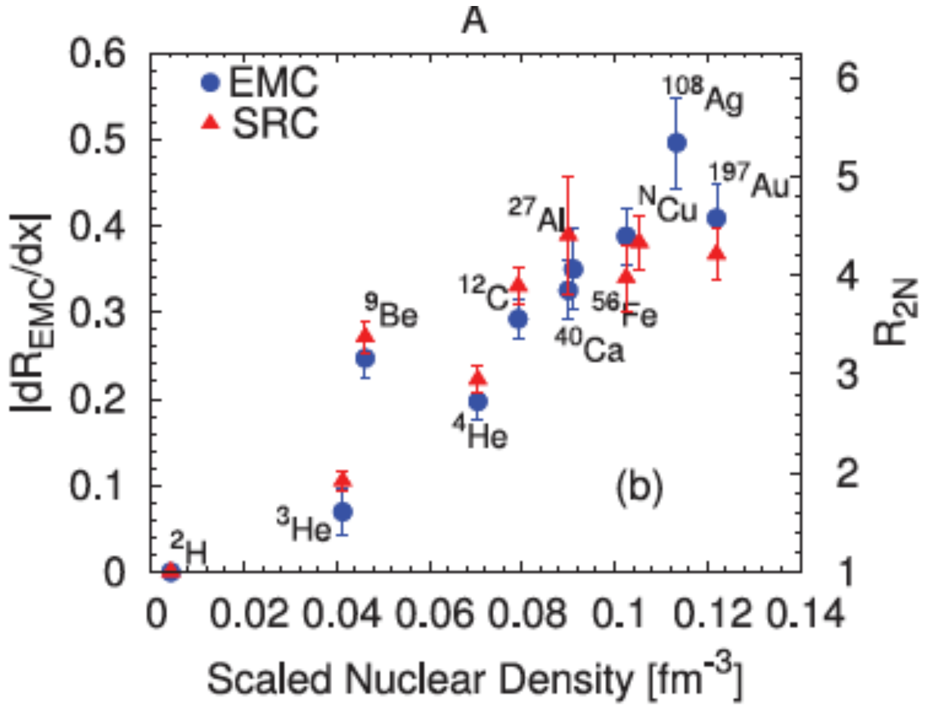


What matters is the local density the DIS happens

---

[*] in the liner region $0.35 < x < 0.7$

Recent review:
S. Malace et al. Int. J. Mod. Phys. 23, 1430013 (2014).

E.M. Form Factors

— of nucleons in nuclei

Magnetic and Electric Form Factors:

— encode fundamental properties of the proton and neutron, related to confinement and DCSB

— distribution of charge and magnetisation

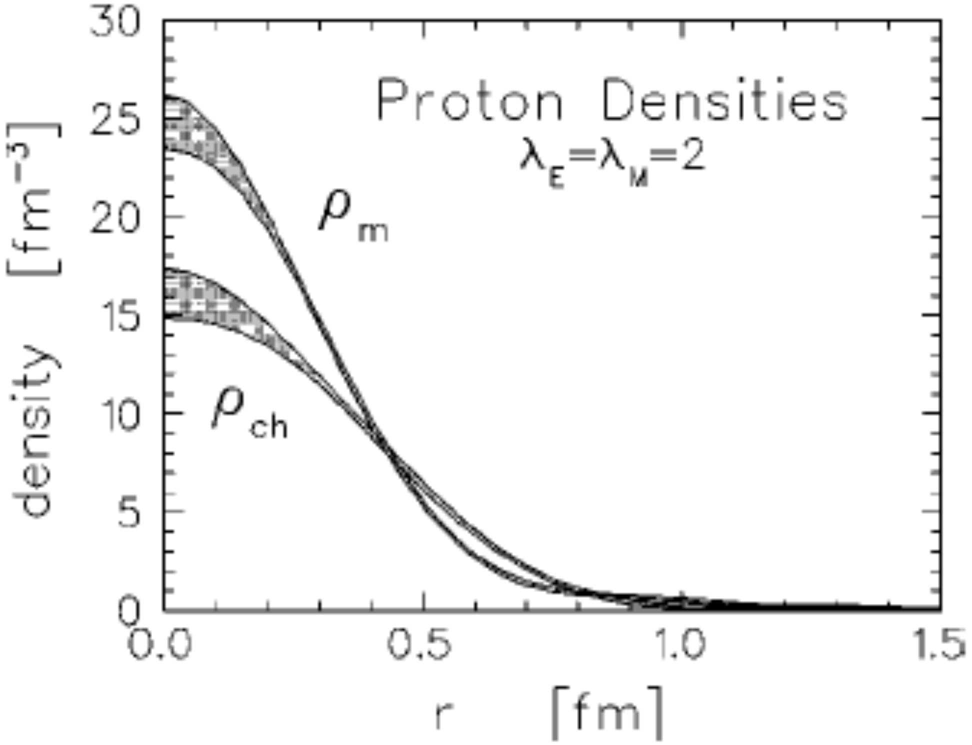
— information on quark core & pion cloud

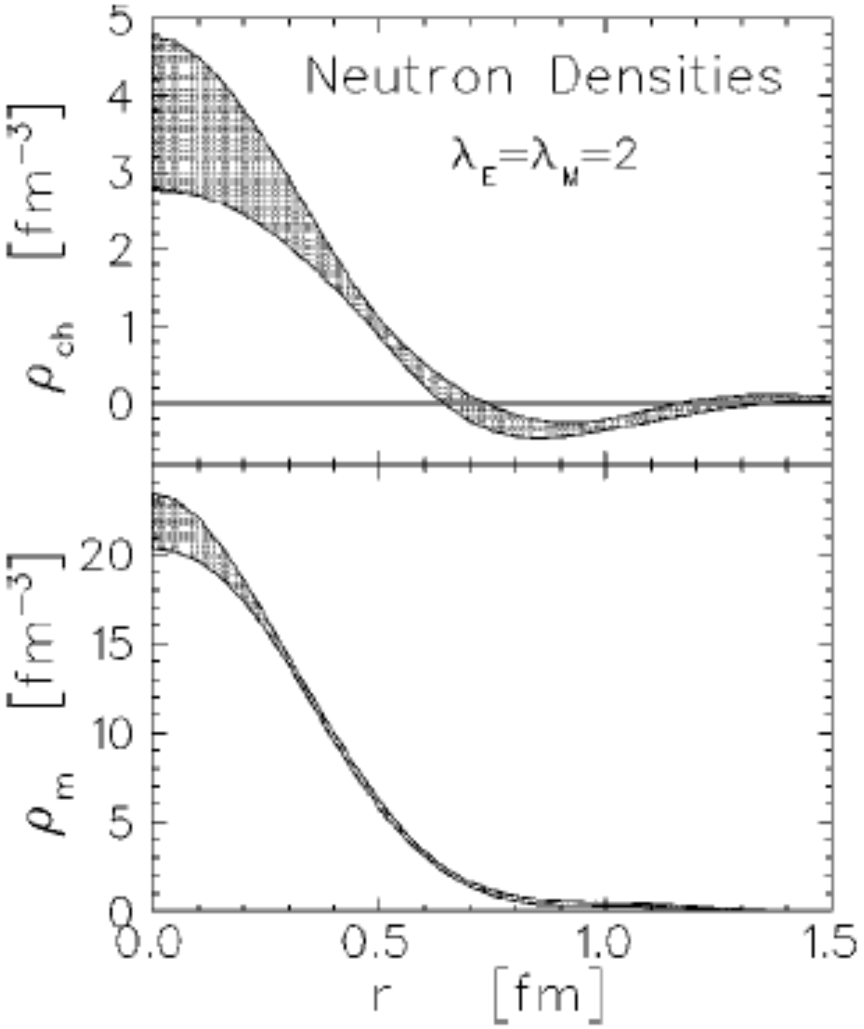
— going to medium, access to environmental changes

Extraction* of charge and magnetic densities

— from experimental from factors

Kelly, PRC (2002)





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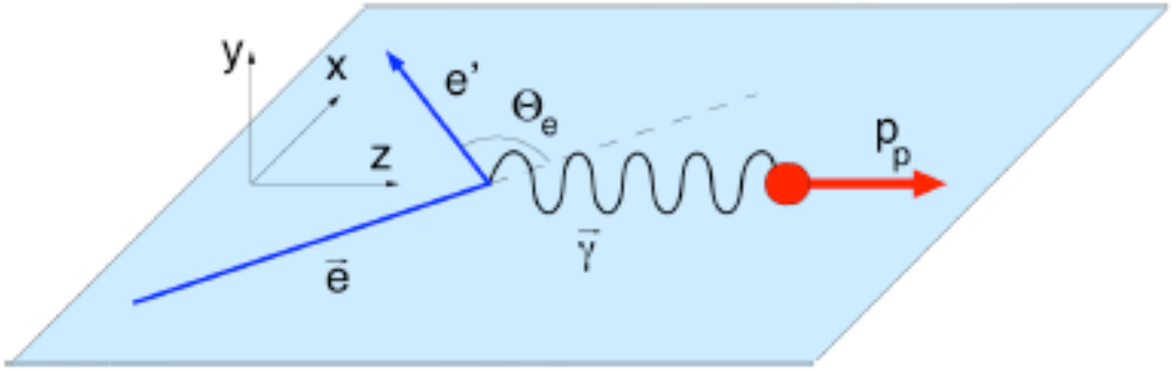
* Involves some model dependence

In-medium polarisation transfer

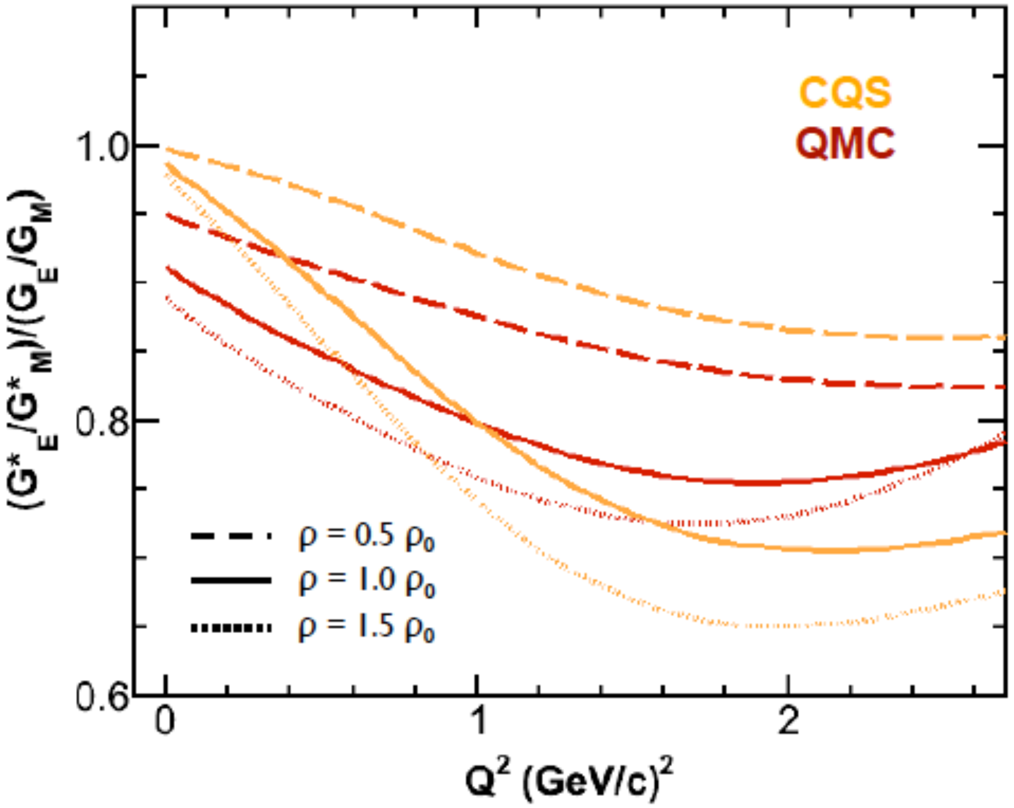
— change of form factors in medium



$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P'_x}{P'_z}\frac{(E_i+E_f)}{2m}\tan\frac{\theta_e}{2}$$

$$G(Q^2,\rho) = G(Q^2)\frac{G^*(Q^2,\rho)}{G^*(Q^2,0)}$$

Quark model predictions

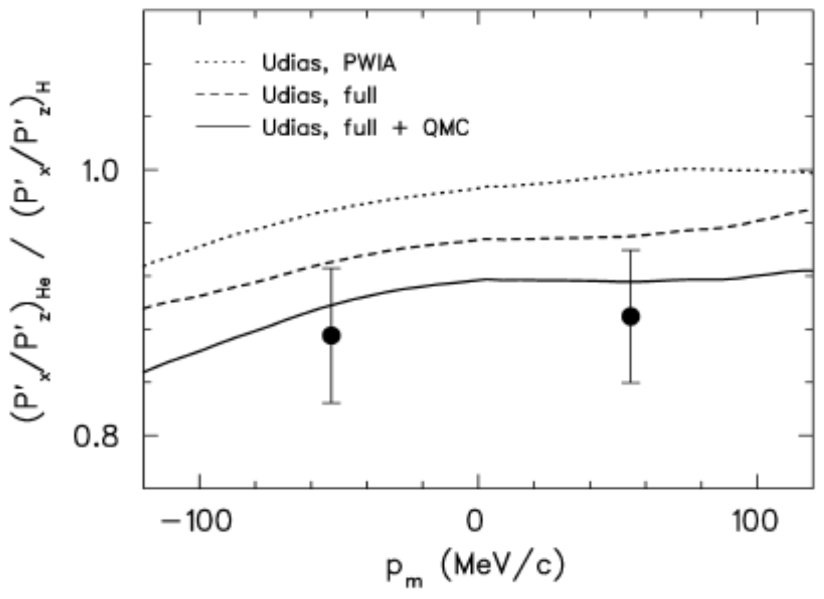


Measurements

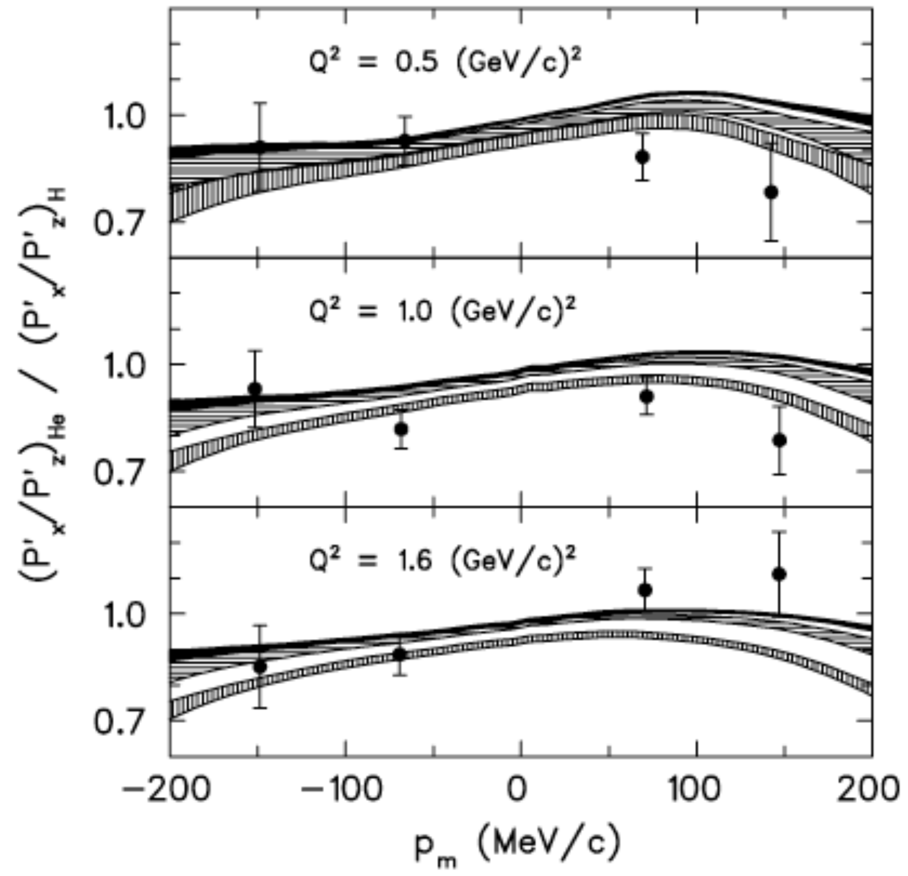
— MAMI & JLab

$$\boxed{R = \frac{(P'_x/P'_z)_{^4\mathrm{He}}}{(P'_x/P'_z)_{^1\mathrm{H}}}}$$

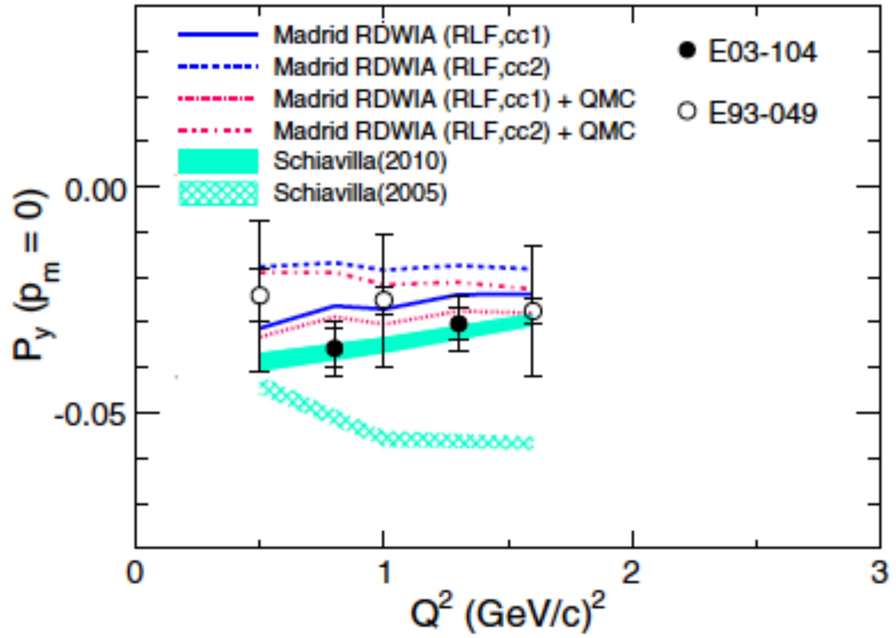
S. Dieterichet al. PLB (2001)



S. Strauch et al. PRL (2003)



S. P. Malace et al. PRL (2011)



Quark models and conventional nuclear physics
(or combination of both)
seem to be able explain the data!

Spectral Properties

— of light vector mesons

In-medium decay of light vector mesons in lepton pairs

— Early motivations:

1. masses of vector mesons are driven by DCSB
2. leptons (electrons, muons) interact weakly with the medium
3. clean information on masses and widths of vector mesons

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2. leptons (electrons, muons) interact weakly with the medium
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DCSB (Dynamical chiral symmetry breaking)

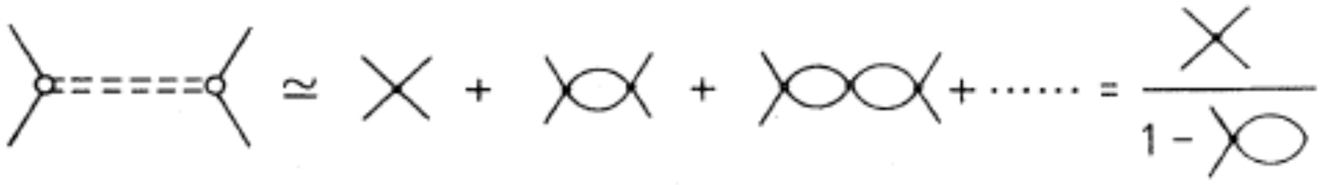
$$\langle \bar{q}q \rangle \simeq \left(1 - \frac{T^2}{8f_\pi^2} - 0.3\frac{\rho}{\rho_0}\right) \langle \bar{q}q \rangle_{\text{vac}}$$

Wambach (2003)

NJL

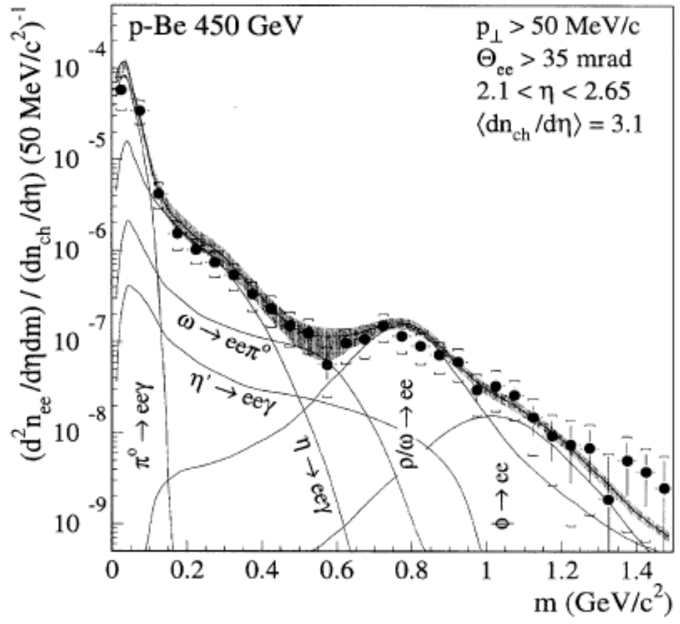
$M_q \sim \langle \bar{q}q \rangle$

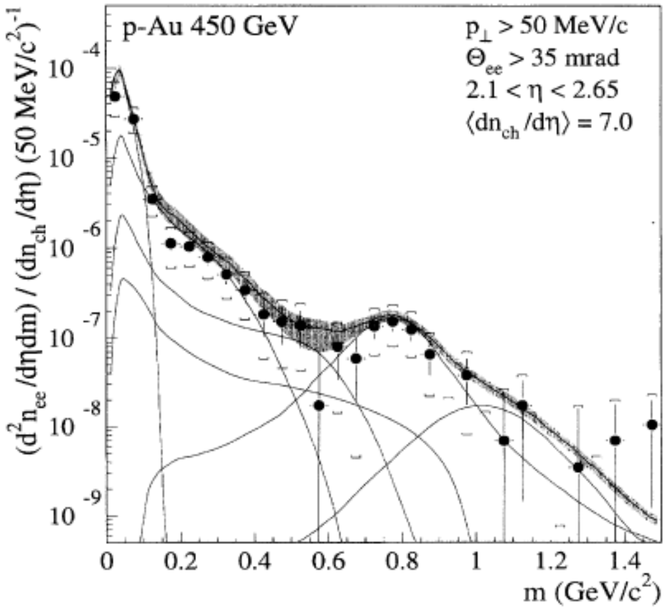
Mesons



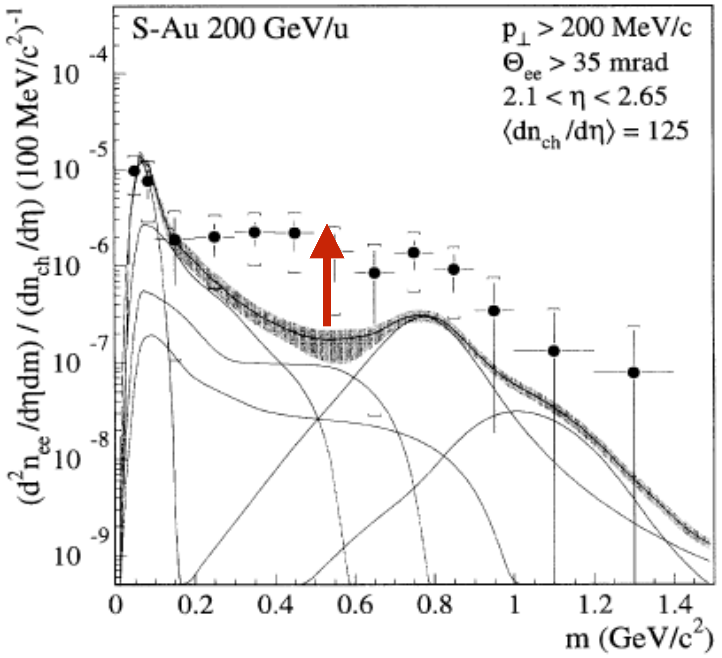
First experiments: CERES @ CERN-SPS

PRL (1995)

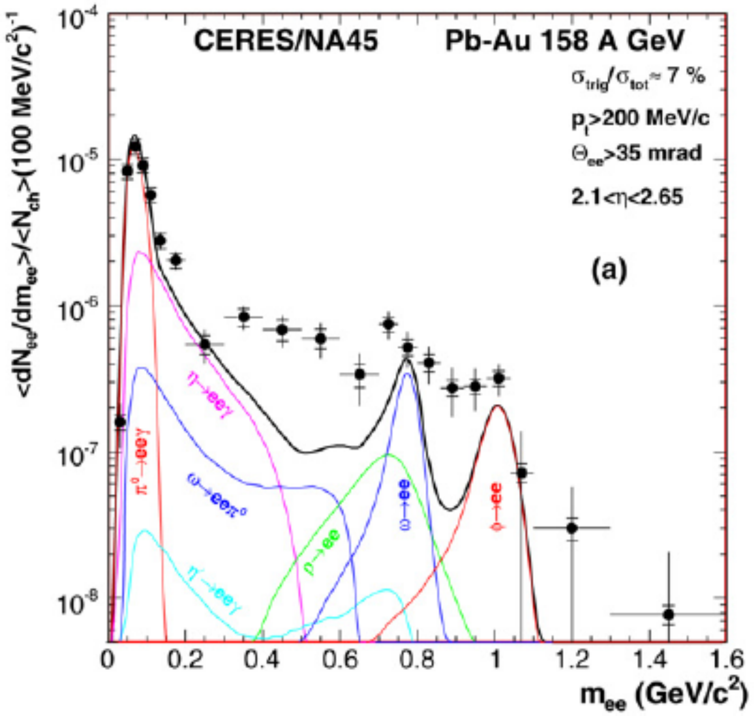


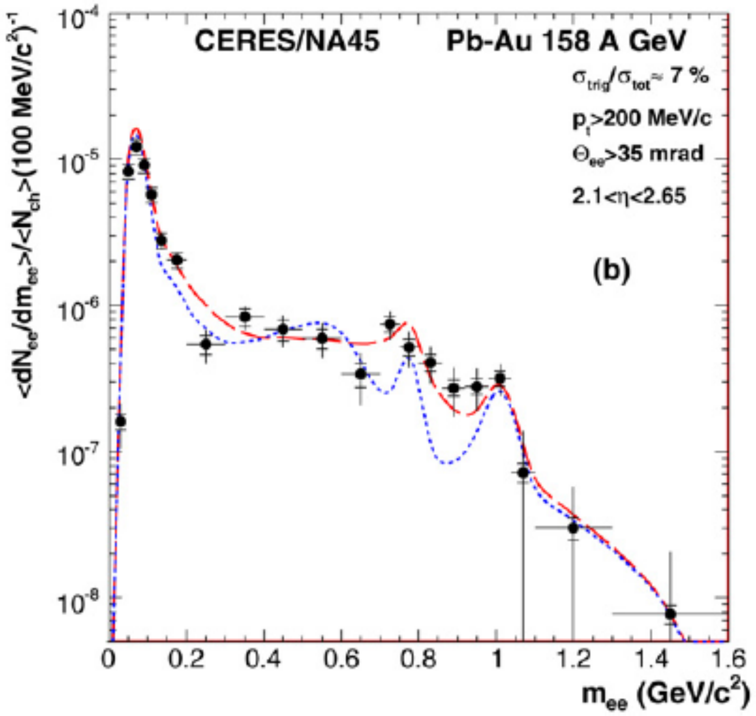


Many papers explaining the data in terms of a chiral restoration



PLB (2008)





Fit of data:

— Dashed: drop of rho mass

— Log-dashed: broadening of rho spectral function

data favor

Hadronic many-body explanations:

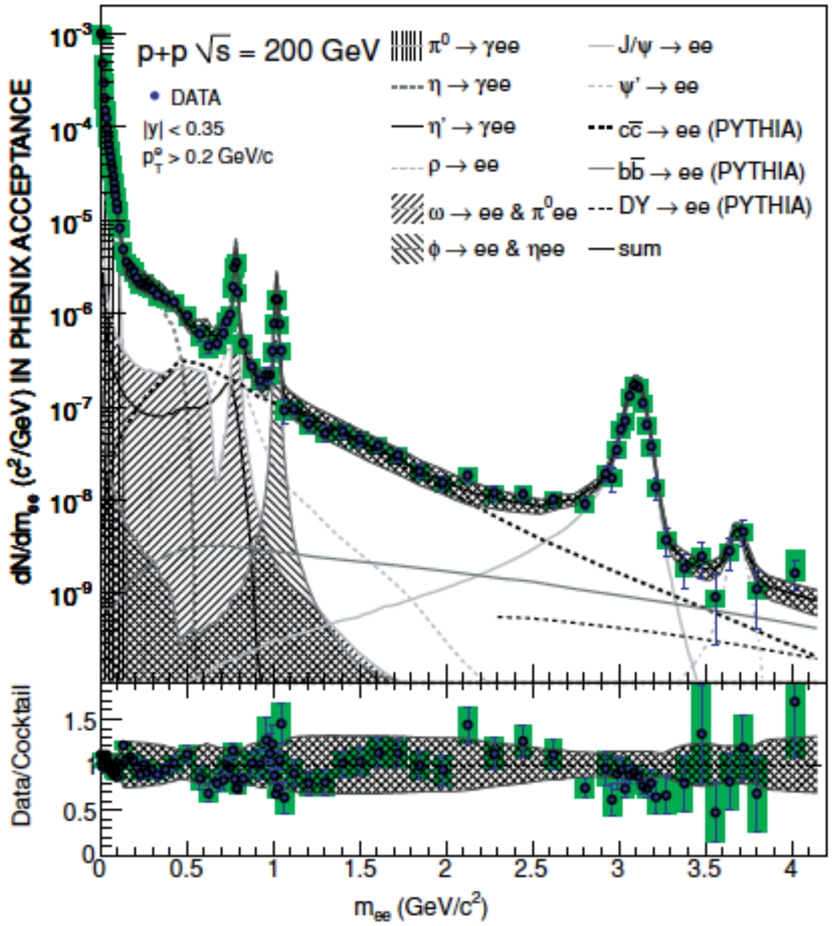
Well-constrained hadronic interactions in vacuum as input

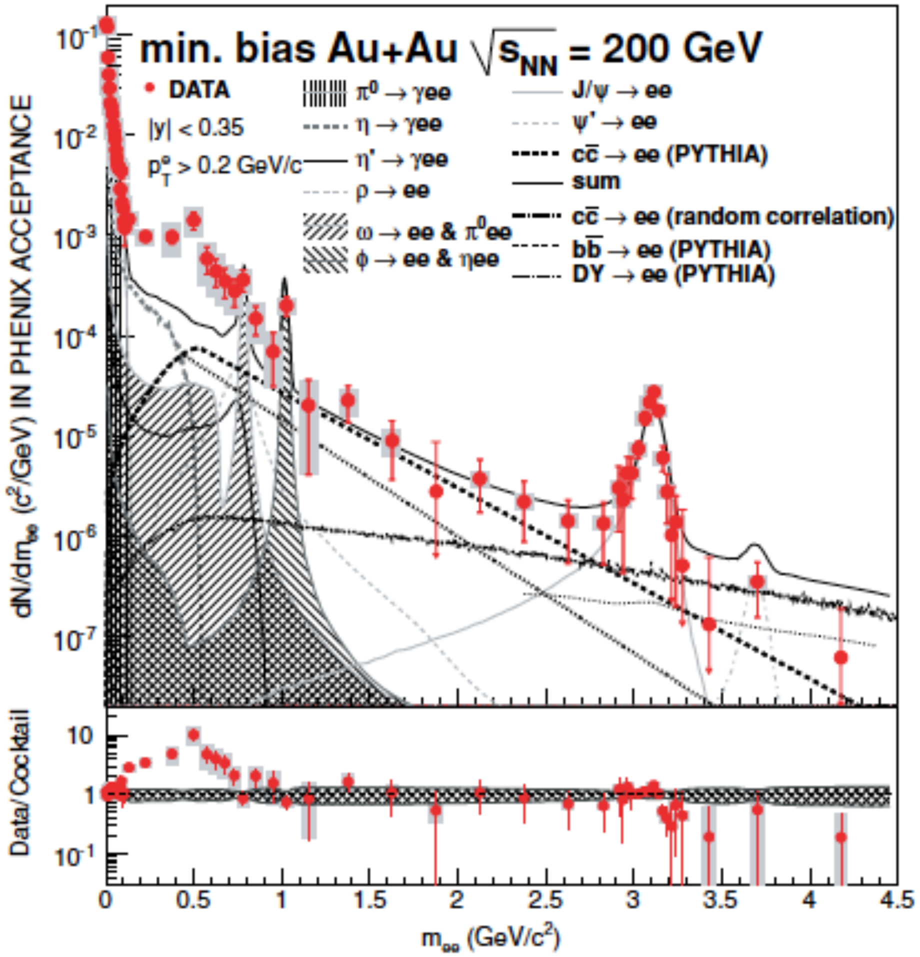
— broadening, with little mass shift (e.g. Rapp & van Hess)

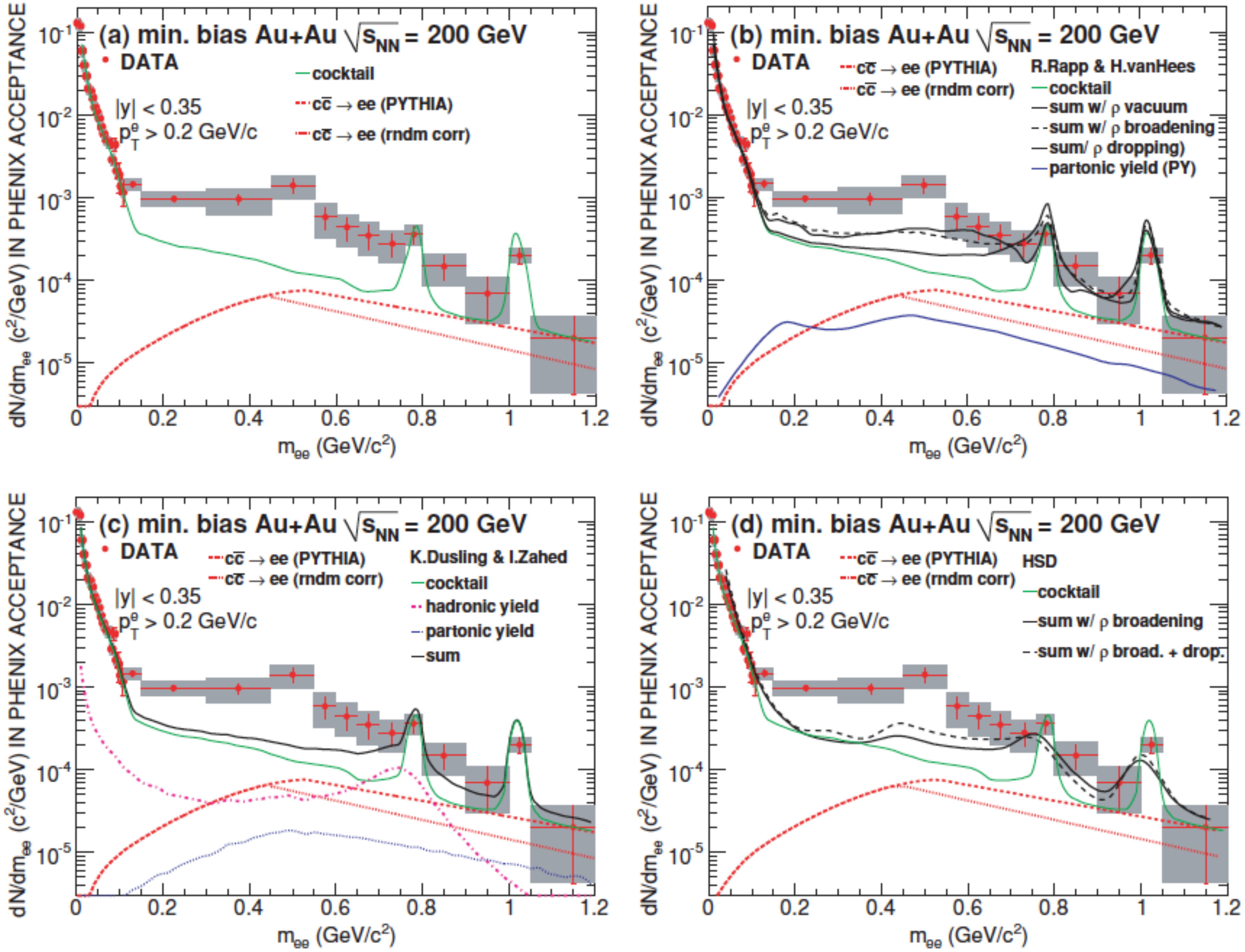
BUT

— Does not seem to be able to describe PHENIX data

PRC (2010)







On the other hand:

— STAR reports a much

smaller enhancemen

Alternative explanation

— P- & CP-odd effects

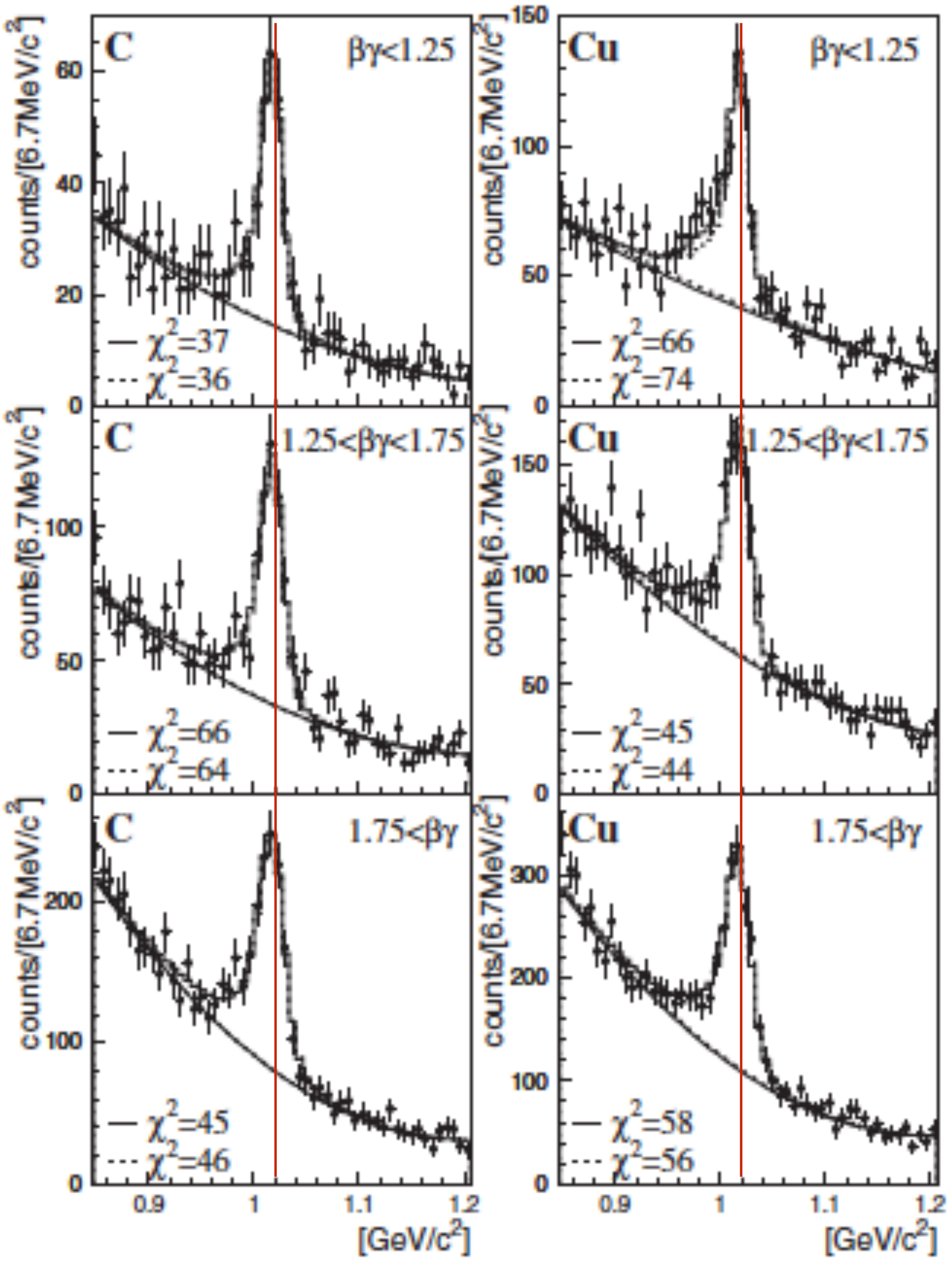
Talks by Andianov, Espriu

Recent review:

— S. Leupold, V. Metag and U. Mosel, Int. J. Mod. Phys. E 19, 147 (2010)

ϕ(1020) in medium

KEK-PS E325 Coll. (2007)



Extrapolation to nuclear matter density:

— Mass decreases 3.4%

— Width broadens 3.6 times

Relation to strangeness content in nucleon?
Talk of Gubler, Parallel V, Monday

Experiments on strangeness in nuclei:

— KLOE e^+e^+: Vasquez Doce, Parallel V, Monday

— HADES pp : Lapidus, Parallel VI, Tuesday

— ALICE LHC: Lea, Parallel VI, Tuesday

Heavy Flavor

— D-meson nuclear bound states

One of the most interesting QCD bound states

1. At the crossroads of the chiral $m_q = 0$ and pure-gluon $m_q = \infty$ worlds
2. Since $m_q \neq 0$ and $m_q \neq \infty$, challenge for EFTs with quark & gluon d.o.f.
3. Need go beyond rainbow-ladder in functional methods (DSE & BSE)
4. In medium, light quark is sensitive to chiral restoration

There is no direct experimental information
on their interactions with ordinary matter

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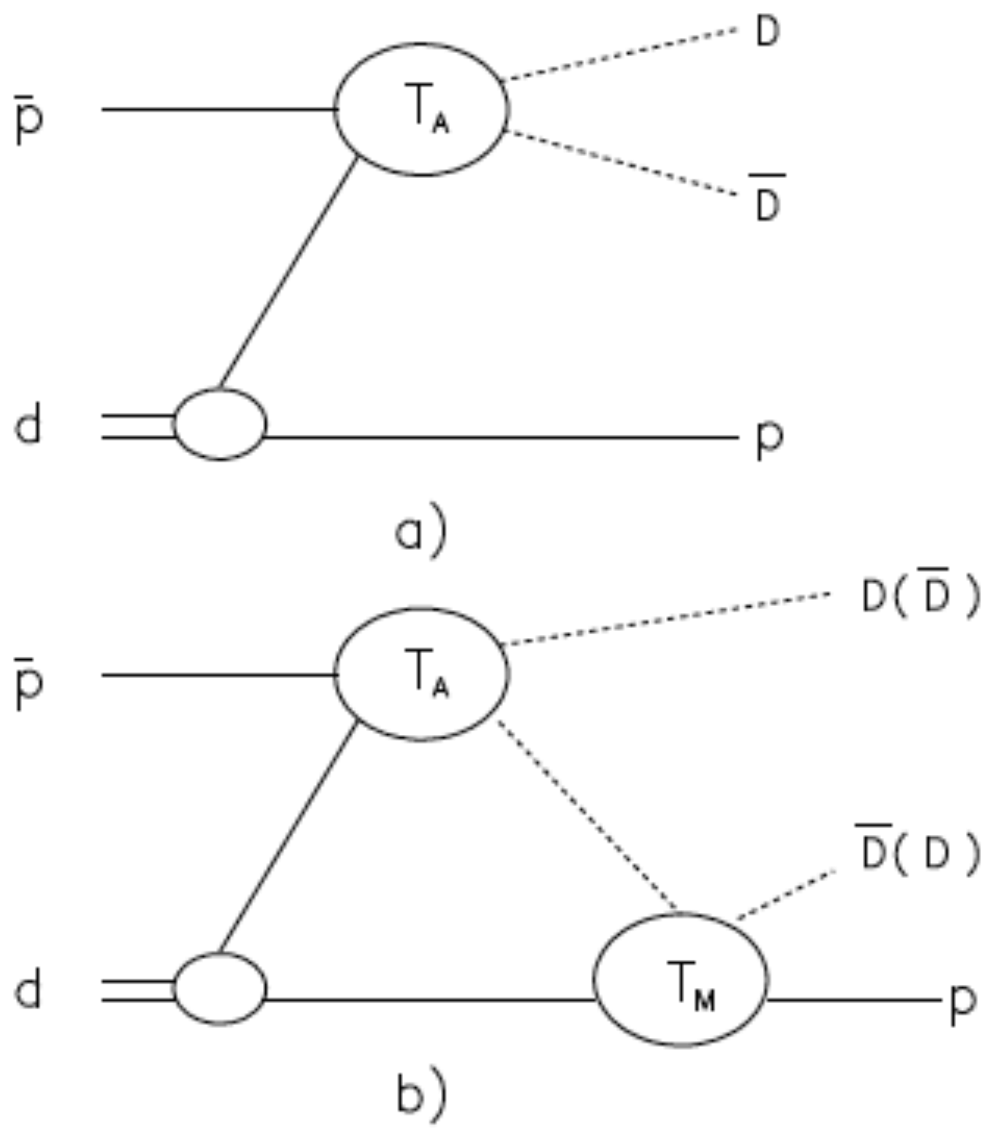
Experiments are underway

Antiproton annihilation on the deuteron

$\bar{\text{P}}$anda @ FAIR



J. Haidenbauer, GK, U.-G. Meissner, A. Sibirtsev

DN Interaction

— free space, low energies

Total cross sections:
($E_{c.m.}$ < 150 MeV)

$\bar{D}N$: 10 - 20 mb

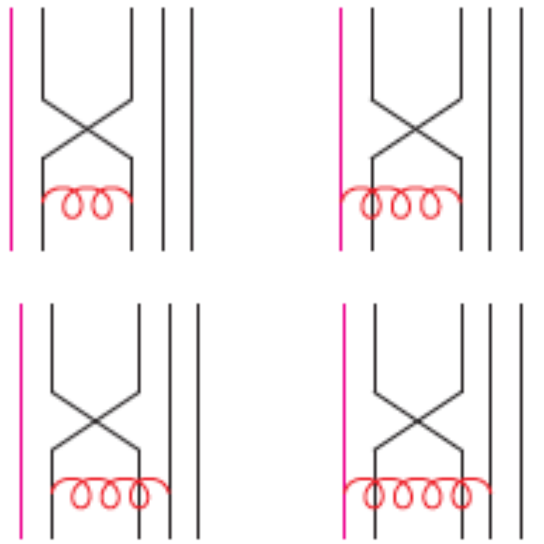
DN: 50 -100 mb

Similar to KN

Very short range

— Quark interchange

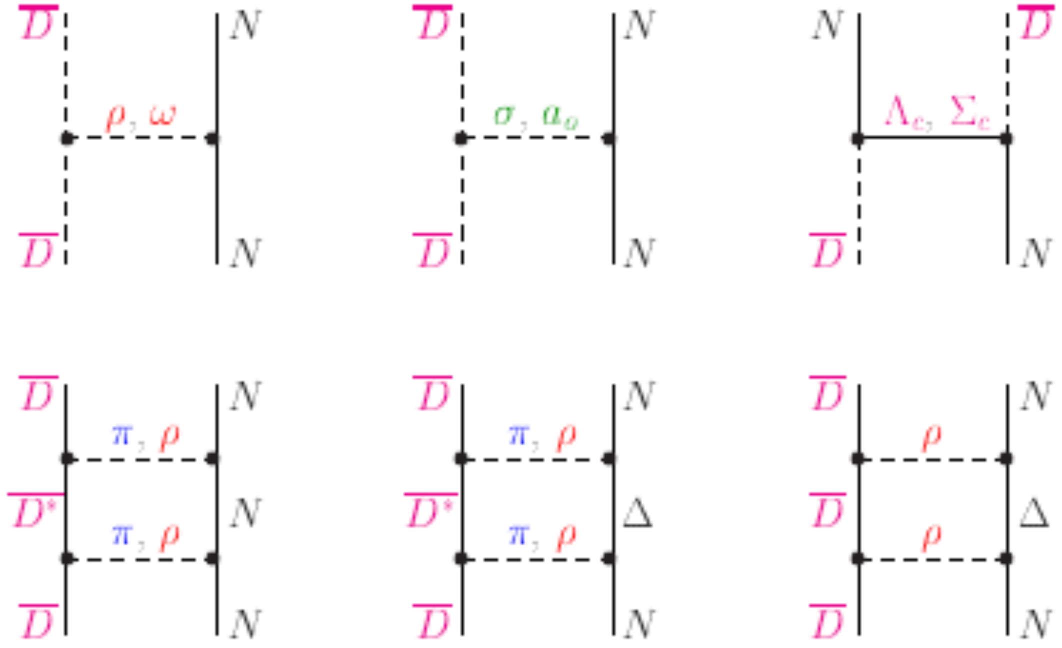
(Coulomb gauge QM, NRQM)



Medium-long range

— Meson-baryon Lagrangians

SU(4) flavor symmetry



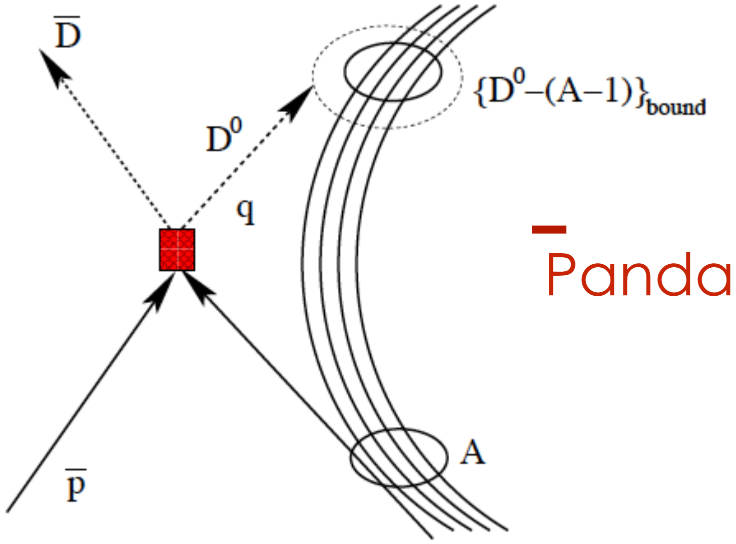
C.E. Fontoura, GK

J. Haidenbauer, GK, U.-G. Meissner, A. Sibirtsev

J. Haidenbauer, GK, U.-G. Meissner, L. Tólos

D-mesons

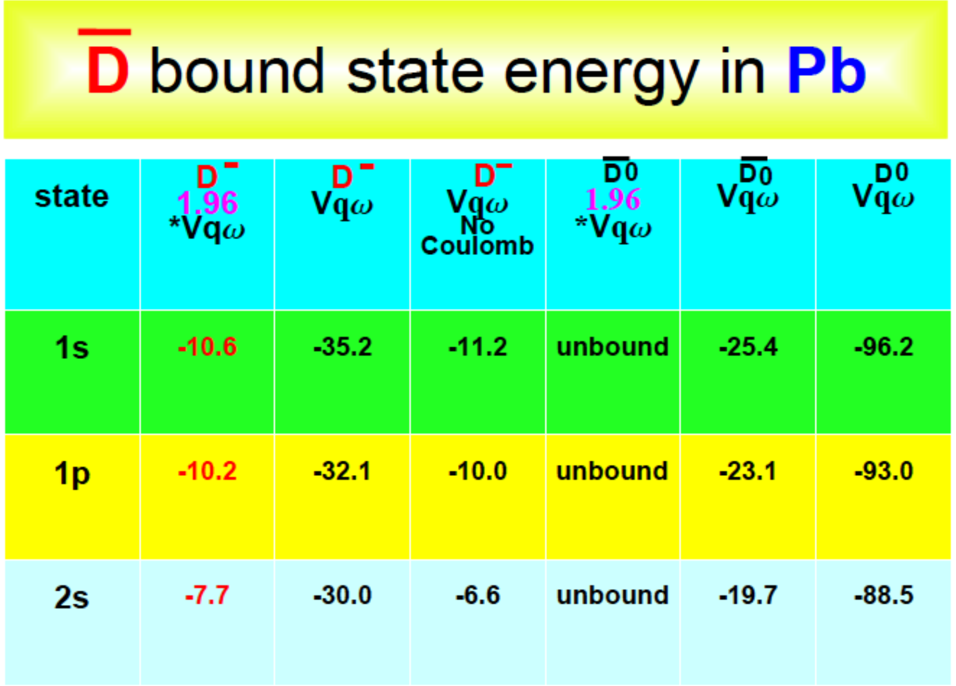
— bound to nuclei



$\bar{\text{P}}$anda @ FAIR

Quark-meson-coupling model

- Hartree MFT*, scalar + vector mean fields



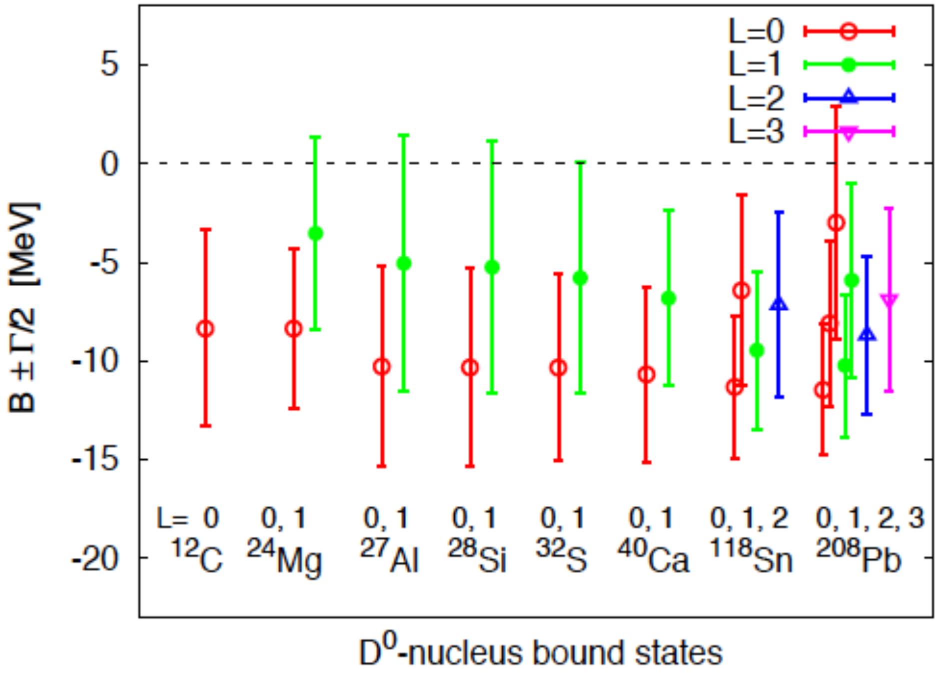
$\bar{D}$ bound state energy in Pb

state	D^- 1.96 *V_q^ω	D^- V_q^ω	D^- V_q^ω No Coulomb	$\bar{D}0$ 1.96 *V_q^ω	$\bar{D}0$ V_q^ω	D0 V_q^ω
1s	-10.6	-35.2	-11.2	unbound	-25.4	-96.2
1p	-10.2	-32.1	-10.0	unbound	-23.1	-93.0
2s	-7.7	-30.0	-6.6	unbound	-19.7	-88.5

Review
K. Saito et al. PPNP (2007)

EFT HQSS

- MFT, coupled channels



Review
L. Tolos, Int. J. Mod. Phys. E (2013)

<u>Quark model:</u>

— in vacuum, very few DN bound states (Caramés & Valcarce)
— in medium, many bound states
(drop quark masses + coupled channels) (Caramés et al. 2014)

*Fock terms do not change much size of mean fields
GK, K. Tsushima, T. Thomas

Heavy Flavor

— J/Ψ nuclear bound states

1. Nucleons and J/Ψ have no valence quarks in common
2. No Pauli Principle – no short-range repulsion
3. Interaction includes gluon van der Waals forces*
4. Probes the conformal scale anomaly
5. In medium, binding via D,D* loop
   — interaction of virtual D,D* with nucleons

J/Ψ binding in nuclear matter

— Bhanot-Peskin EFT theory

Brodsky, Schmidt & de Téramond

Second order Stark effect

—J/Ψ treated as a small color dipole

J/Ψ mass shift in medium, density ρ :

$$\Delta m_\psi(\rho) = -\frac{1}{9}\int dk^2 \left|\frac{d\psi(k)}{dk}\right| \frac{k}{k^2/m_c + \Delta\varepsilon} \langle \alpha_s E^2/\pi \rangle_N \frac{\rho}{2m_N}$$

$\Delta\varepsilon$: energy shift
octet – charmonium

$\psi(k)$: wave function
Cornell potential

$$\langle \alpha_s E^2/\pi \rangle_N = 0.5 \text{ GeV}$$

$$\Delta m_\psi = -8\,\text{MeV}$$

Sibirtsev & Voloshin: $\Delta m_\psi = -21\,\text{MeV}$

J/Ψ binding in nuclear matter

— Bhanot-Peskin EFT theory

Brodsky, Schmidt & de Téramond

Second order Stark effect

—J/Ψ treated as a small color dipole

J/Ψ mass shift in medium, density ρ :

$$\Delta m_\psi(\rho) = -\frac{1}{9}\int dk^2 \left|\frac{d\psi(k)}{dk}\right| \frac{k}{k^2/m_c + \Delta\varepsilon} \langle \alpha_s E^2/\pi\rangle_N \frac{\rho}{2m_N}$$

$\Delta\varepsilon$: energy shift
octet – charmonium

$\psi(k)$: wave function
Cornell potential

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$$V_0 > \frac{\pi^2\hbar^2}{8mR^2}$$

$$R = 5\,\text{fm} \to V_0 > 1\,\text{MeV}$$

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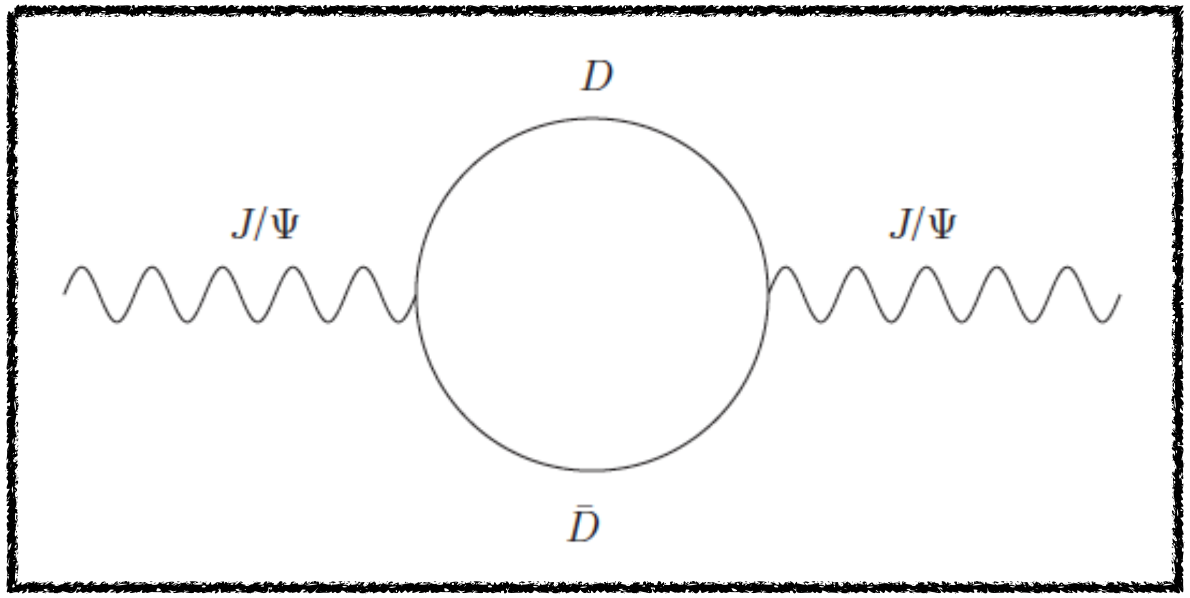
J/Ψ binding in nuclear matter
— D,D* loops

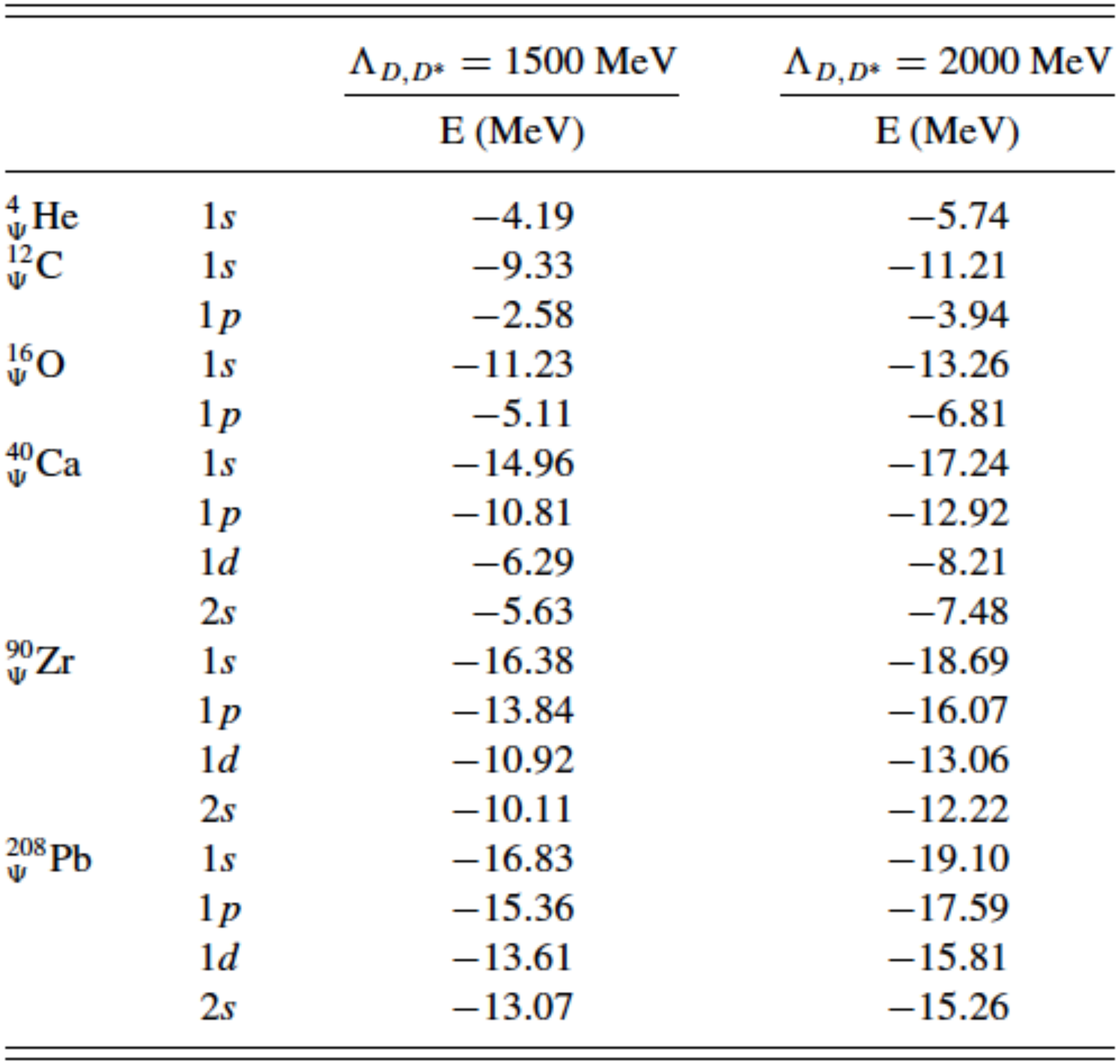


Calculation of selfenergy with effective Lagrangian

1. Coupling constants: SU(4) symmetry
2. Form factor: Quark model
3. In-medium masses of D, D*: QMC model

J/Ψ single-particle energies in nuclei

— solve a Klein-Gordon equation

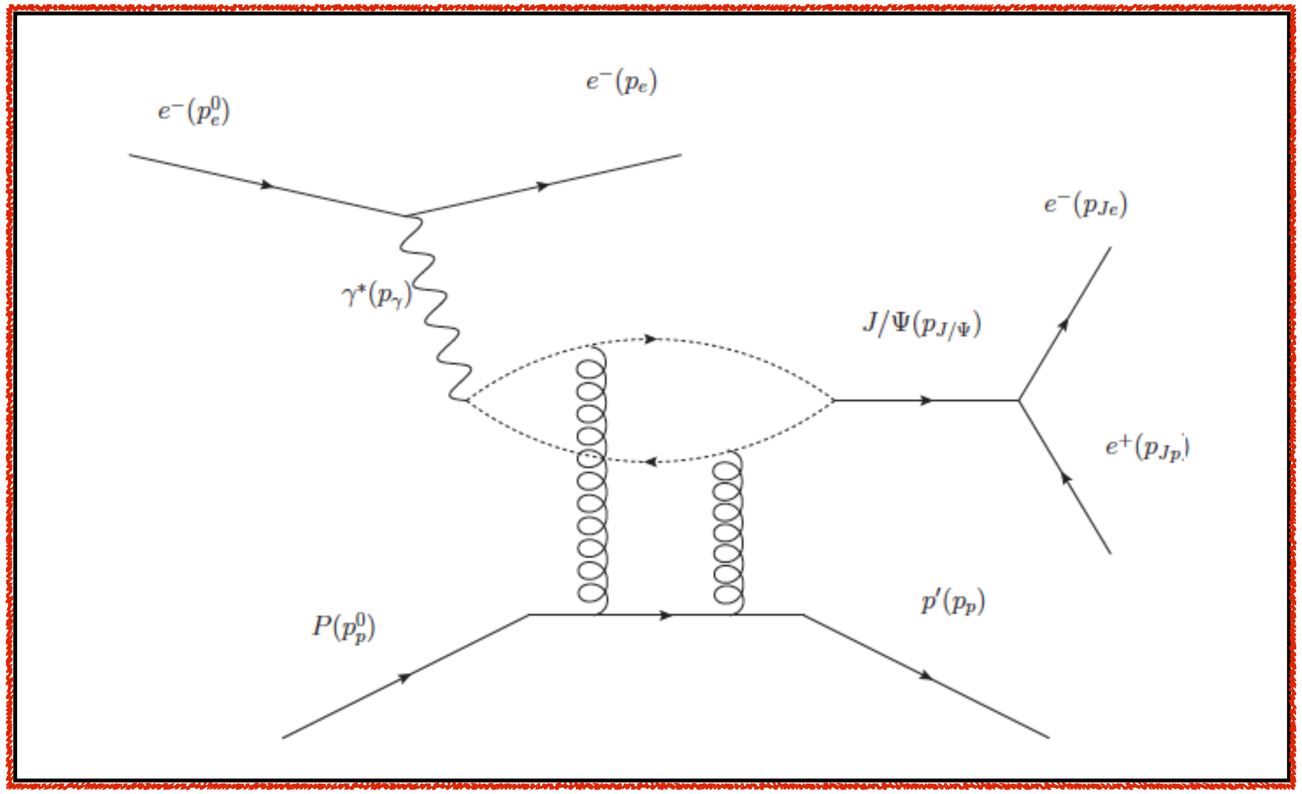


		$\Lambda_{D,D^*} = 1500$ MeV	$\Lambda_{D,D^*} = 2000$ MeV
		E (MeV)	E (MeV)
${}^{4}_{\Psi}$He	1*s*	−4.19	−5.74
${}^{12}_{\Psi}$C	1*s*	−9.33	−11.21
	1*p*	−2.58	−3.94
${}^{16}_{\Psi}$O	1*s*	−11.23	−13.26
	1*p*	−5.11	−6.81
${}^{40}_{\Psi}$Ca	1*s*	−14.96	−17.24
	1*p*	−10.81	−12.92
	1*d*	−6.29	−8.21
	2*s*	−5.63	−7.48
${}^{90}_{\Psi}$Zr	1*s*	−16.38	−18.69
	1*p*	−13.84	−16.07
	1*d*	−10.92	−13.06
	2*s*	−10.11	−12.22
${}^{208}_{\Psi}$Pb	1*s*	−16.83	−19.10
	1*p*	−15.36	−17.59
	1*d*	−13.61	−15.81
	2*s*	−13.07	−15.26

GK, A. W. Thomas & K. Tsushima
K. Tsushima, D. Lu, GK & A. W. Thomas

ATHENNA* coll.

— JLab @ 12 GeV

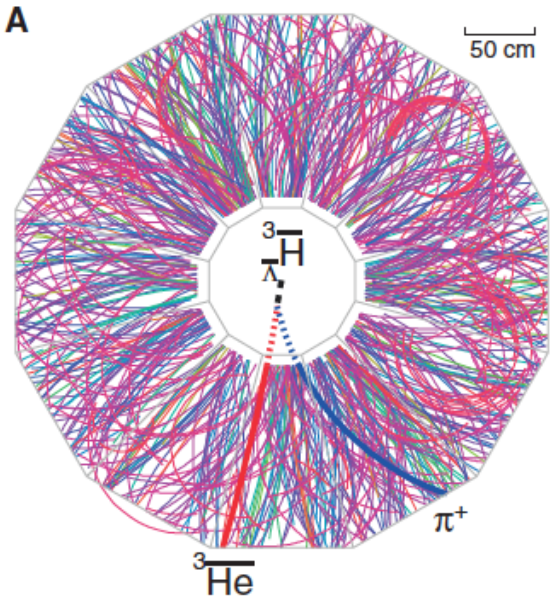


Z.-E. Meziani (Co-spokesperson/Contact)
N. Sparveris (Co-spokesperson)
Z. W. Zhao (Co-spokesperson)

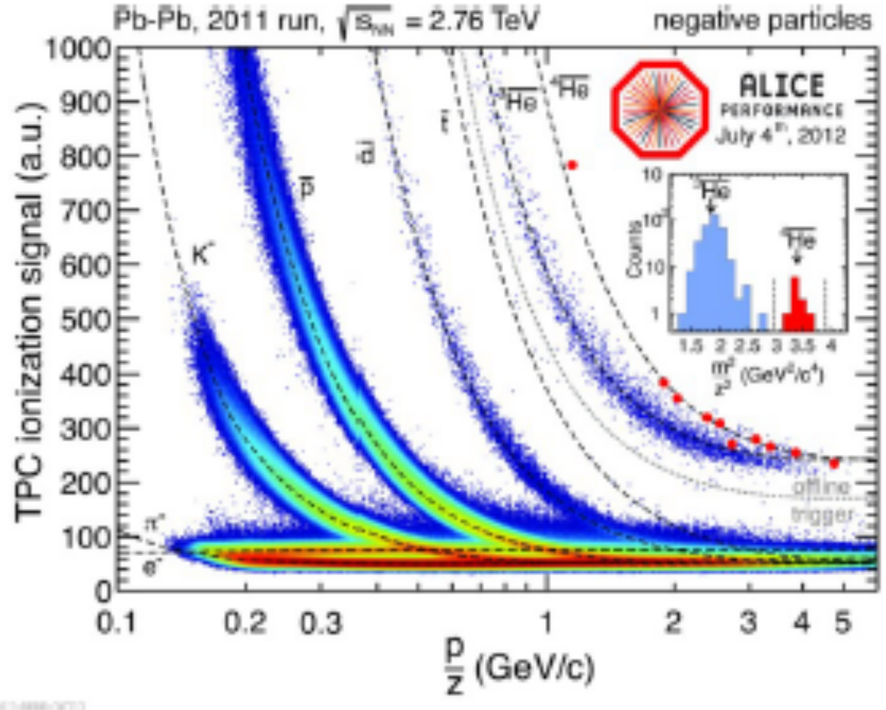
*A J/Ψ THreshold Electroproduction on the Nucleon and Nuclei Analysis

How about J/Ψ - N at the LHC?

— chances of a J/Ψ meeting one or two nucleons should not be smaller than of two antinucleons and one antiyperon meeting to form an antihypernucleus



Observation of an Antimatter Hypernucleus
The STAR Collaboration
Science **328**, 58 (2010);
DOI: 10.1126/science.1183980



See talk of Ramona Lea
Parallel VI, Tuesday

Need to detect in coincidence
the nucleon and decay products of J/Ψ

Perspectives (near future)

1. Expect progress with new experiments

   — LHC, PANDA & CBM @ FAIR, JLab @ 12 GeV, NICA, JPARC, …

2. Need improvements in theory, nonperturbative methods

   — control of cold nuclear matter effects (help from the lattice - sign problem), quark-gluon EFT heavy & heavy quarks