Changes of hadron properties in medium
carry signals of the way in which
the vacuum changes in a nuclear environment
W. Weise, NPA 574 (1994) 347c

Medium Modifications of Hadrons and other Particles

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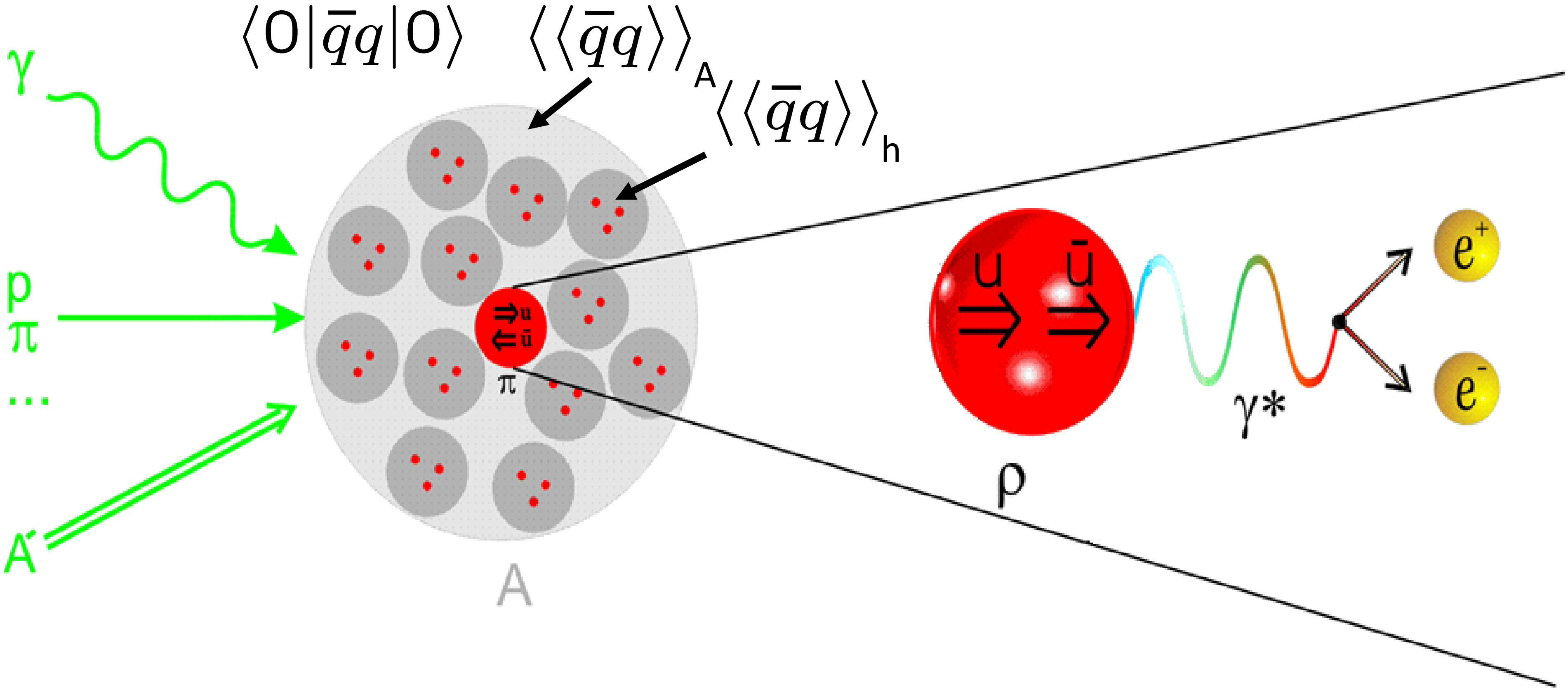
Technische Universität Dresden

QCD Sum Rules: condensates and hadron spectral functions
BUU: phi width adjusted to data
QED: Breit-Wheeler process

Nucleus as QCD Laboratory



Hadrons as Excitations of/above Vacuum
→ Probes of Changed QCD Vacuum?

QCD Condensates are not Condensates?

S. J. Brodsky, C. D. Roberts, R. Shrock, P. C. Tandy, arXiv:1202.2376
S. J. Brodsky, R. Shrock, Phys. Lett. B 666 (2008) 95
S. J. Brodsky, C. D. Roberts, R. Shrock, P. C. Tandy, Phys. Rev. C 82 (2010) 022201

If quark-hadron duality is a reality in QCD, then condensates, those quantities that have commonly been viewed as constant empirical mass-scales that fill all spacetime, are instead wholly contained within hadrons; i.e., they are a property of hadrons themselves

dynamical chiral symmetry breaking (DCSB) and the associated quark condensate must be a property of hadron wave functions, not of the vacuum

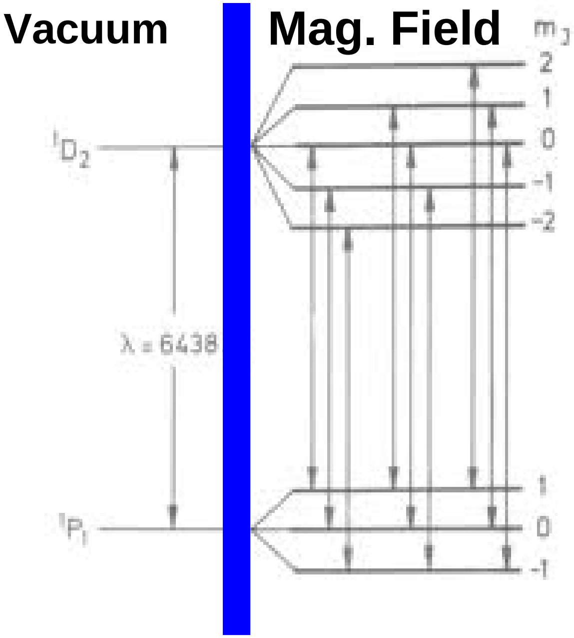
QCD condensates are completely contained within that domain which permits the propagation of the gluons and quarks that produce them; namely, inside hadrons.

any connection between the pion mass and a vacuum quark condensate is purely a theoretical artifice....
the pion's mass is a property of the pion

H. Reinhardt, H. Weigel, Phys.Rev. D85 (2012) 074029:

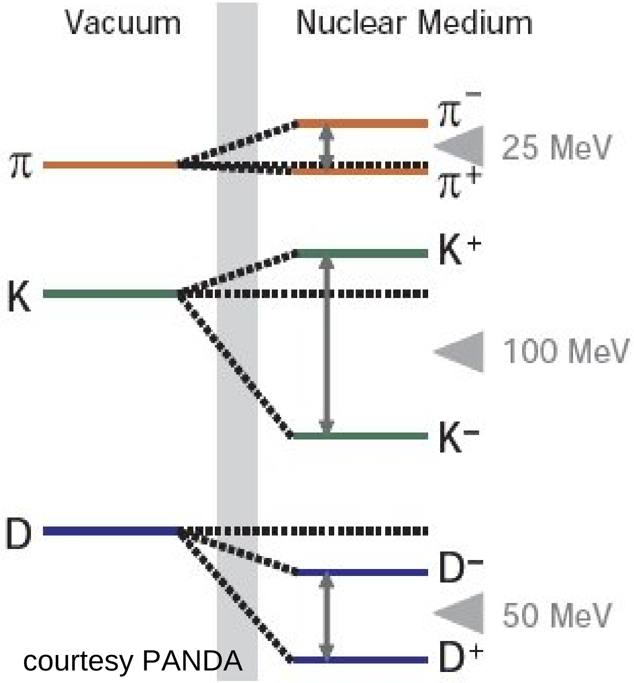
$\langle \bar{q} q \rangle \neq 0$ is a vacuum property

Zeeman & Stark Effects



shifts & splittings of atomic spectral lines

Hadrons in Nuclear Matter:
shifts of hadron energies („mass shifts“)?
new structures (ph exct) in spectral fncts?



courtesy PANDA

pA:
Scheinast et al.
(KaoS), PRL 2006

pA: CBM
p_bar A: PANDA

understanding
hadronic part
of QCD

QCD Vacuum

QCD: EoM for $\psi_{c,f}, A_{\hat{c}}$

$$\mathcal{O}_{i=0,\infty} = \{1, \bar{\psi}\psi, G^2, \cdots\}$$

spin-0

vacuum condensates: $O_{i,vac} = \langle 0|\mathcal{O}_i|0\rangle$

a priori undetermined mass-dimensioned parameters in OPE of color-singlet ccc‘s

vacuum $= |0\rangle =$ g.s. $=$ min. energy

frame dependent (Unruh)

Medium Modifications:

low n

T-n effects:

Zschocke et al. EPJA (2002)

$$\langle\langle \mathcal{O}_i \rangle\rangle = O_i(T, \mu) \approx O_{i,vac} + n O_{i,n}$$

Feynman-Hellmann, $\langle\langle \bar{q}q \rangle\rangle_\mu = -\frac{\partial p(\mu)}{\partial m_q}$

or sigma terms: $= \langle \bar{q}q \rangle + \sum_h n_h \frac{\sigma_h}{2m_q}$

prominent condensates:

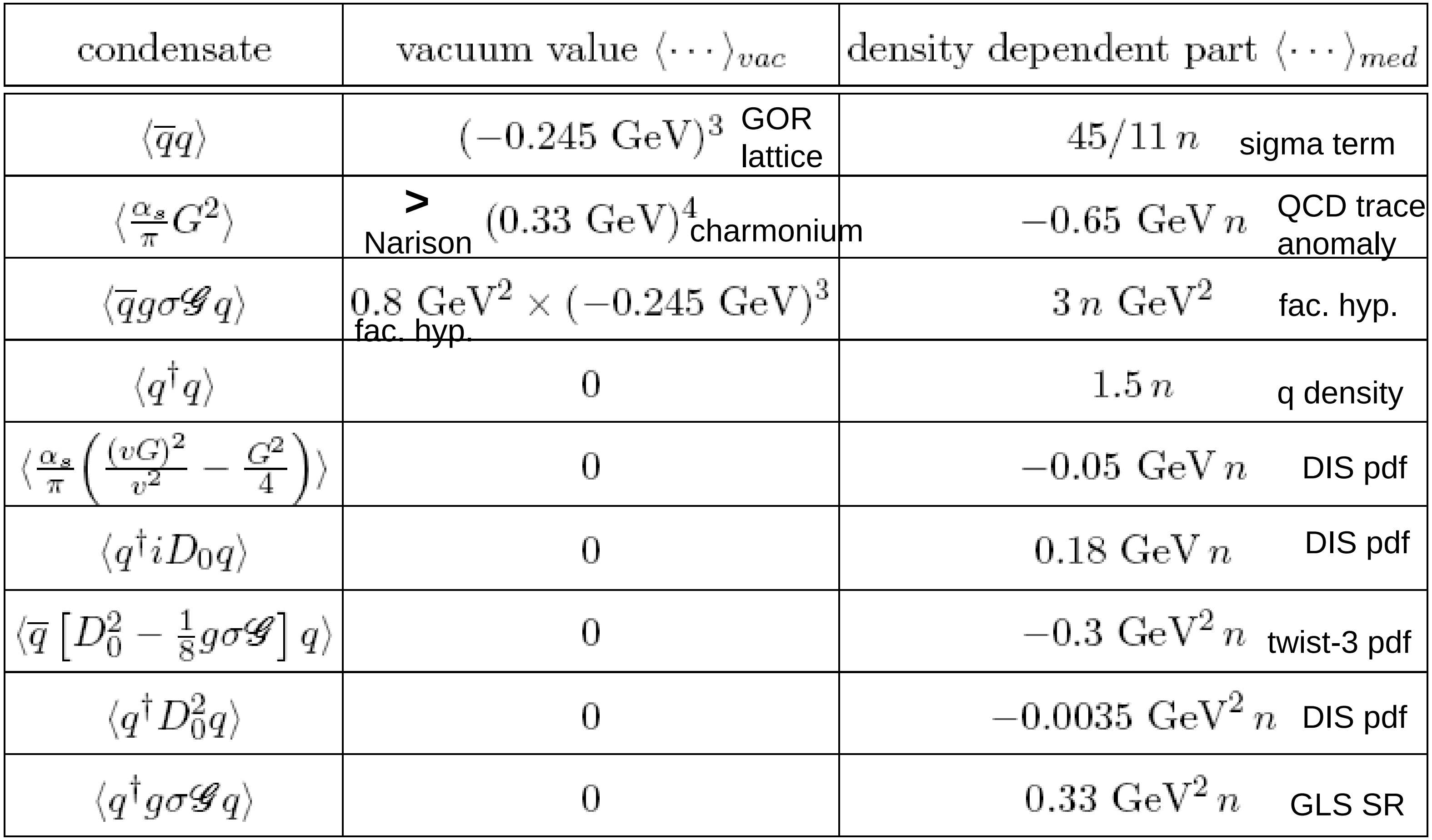
chiral condensate: $\langle \bar{q}q \rangle$

spontaneous symmetry breaking

gluon condensate: $\langle \frac{\alpha_s}{\pi} G^2 \rangle$

dilatation symmetry breaking

condensate = vacuum + density dep. part



	condensate	vacuum value $\langle\cdots\rangle_{vac}$	density dependent part $\langle\cdots\rangle_{med}$
	$\langle\bar{q}q\rangle$	$(-0.245\ \mathrm{GeV})^3$ GOR lattice	$45/11\, n$ sigma term
scalar	$\langle\frac{\alpha_s}{\pi}G^2\rangle$	> Narison $(0.33\ \mathrm{GeV})^4$ charmonium	$-0.65\ \mathrm{GeV}\, n$ QCD trace anomaly
	$\langle\bar{q}g\sigma\mathscr{G}q\rangle$	$0.8\ \mathrm{GeV}^2\times(-0.245\ \mathrm{GeV})^3$ fac. hyp.	$3\, n\ \mathrm{GeV}^2$ fac. hyp.
	$\langle q^\dagger q\rangle$	0	$1.5\, n$ q density
twist-2	$\langle\frac{\alpha_s}{\pi}\left(\frac{(vG)^2}{v^2}-\frac{G^2}{4}\right)\rangle$	0	$-0.05\ \mathrm{GeV}\, n$ DIS pdf
	$\langle q^\dagger iD_0 q\rangle$	0	$0.18\ \mathrm{GeV}\, n$ DIS pdf
	$\langle\bar{q}\left[D_0^2-\frac{1}{8}g\sigma\mathscr{G}\right]q\rangle$	0	$-0.3\ \mathrm{GeV}^2\, n$ twist-3 pdf
	$\langle q^\dagger D_0^2 q\rangle$	0	$-0.0035\ \mathrm{GeV}^2\, n$ DIS pdf
	$\langle q^\dagger g\sigma\mathscr{G}q\rangle$	0	$0.33\ \mathrm{GeV}^2\, n$ GLS SR

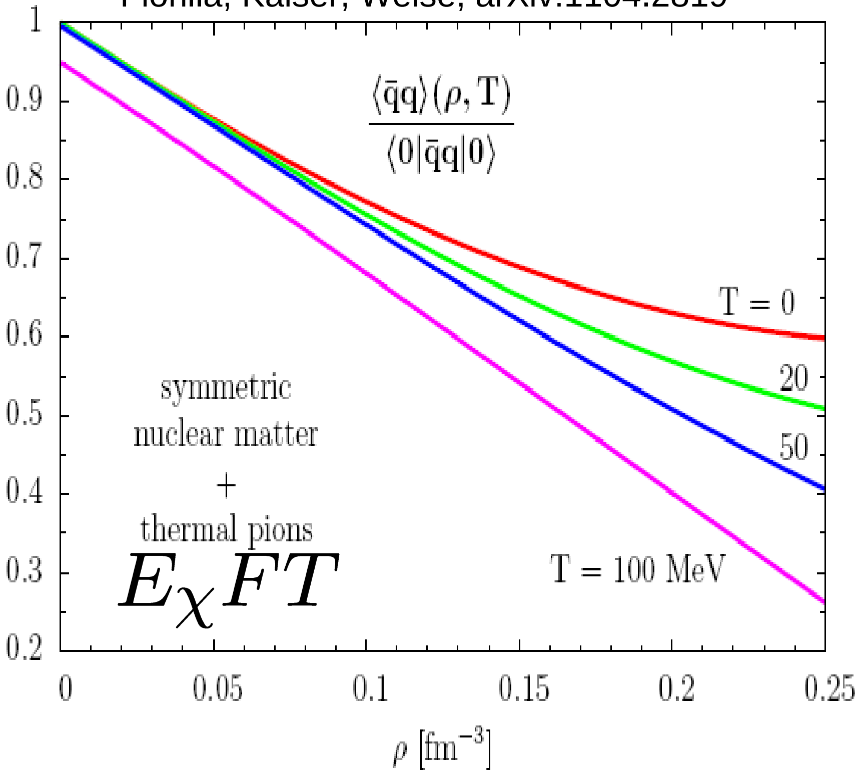
$$\langle\bar{q}q\rangle = -1.5\mathrm{fm}^{-3} = -10\times n_B$$

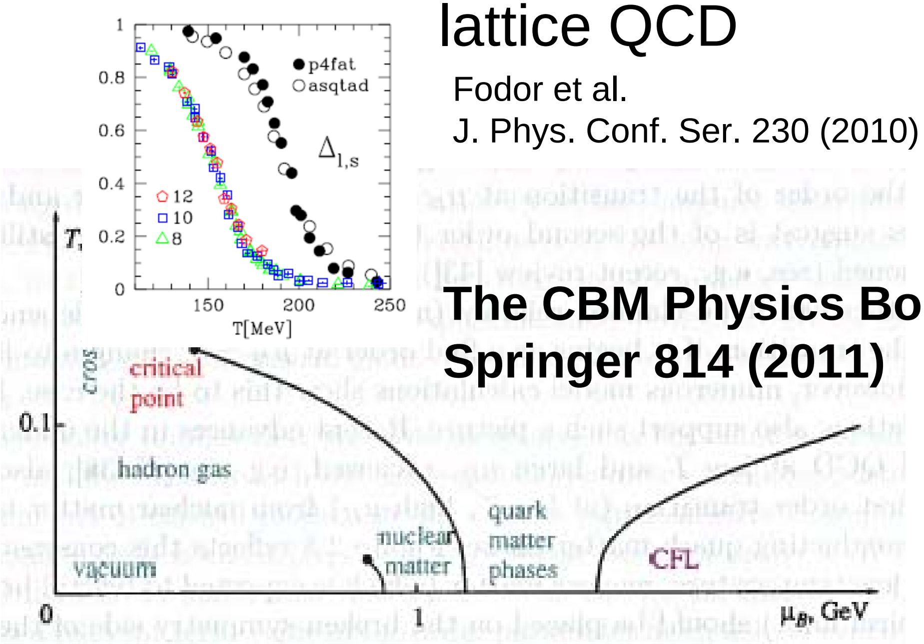
$$\langle\frac{\alpha_s}{\pi}G^2\rangle = 1.5\mathrm{GeV\,fm}^{-3} = 10\times e_0$$

if real condensate:
couples to gravity
10^{45} too large

Highlighting the Chiral Condensate

Fiorilla, Kaiser, Weise, arXiv:1104.2819





lattice QCD

Fodor et al.
J. Phys. Conf. Ser. 230 (2010)

The CBM Physics Book
Springer 814 (2011)

Brown-Rho (PRL 1991): $\frac{m(n)}{m_{vac}} = \left(\frac{\langle\bar{q}q\rangle_n}{\langle\bar{q}q\rangle_{vac}}\right)^x$

Hadrada, Yamawak Phy.Rep. (2003)

Kapusta-Shuryak (PRD 1994): $\left\{ \right.$
V-A mixing
shifts of pole masses
broadening (merging into continuum)

Hatsuda-Lee (PRC 1992): dropping mass of light vector mesons

if $\langle\langle\bar{q}q\cdots\bar{q}q\rangle\rangle = x\langle\langle\bar{q}q\rangle\rangle^2$

QCD Sum Rules: Predictions of Medium Modifications?

$$L(n) + \int_{-\infty}^{\infty} d\omega\, \omega^l \mathrm{Im}\Pi(\omega;n) e^{-\omega^2/M^2} = \underline{\sum_i \frac{c_i(n)}{M^{2i}}}$$

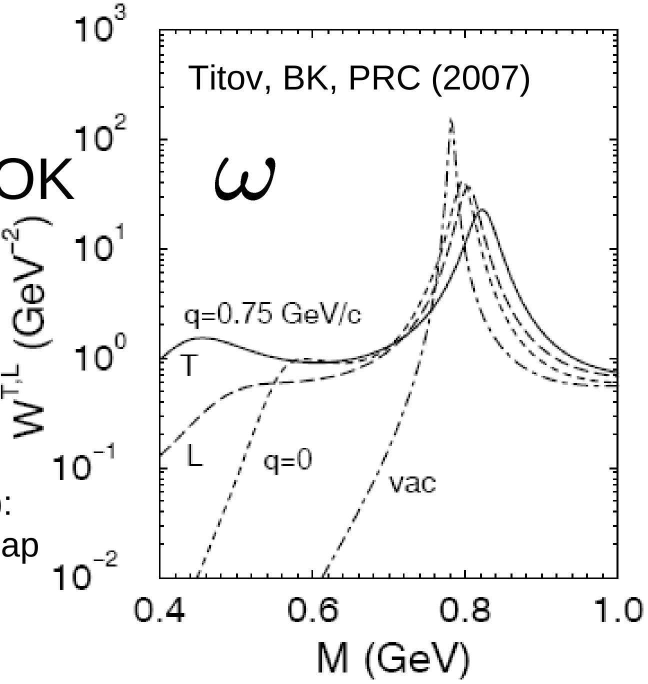
$c_i = \sum$ Wilson coeff. × condensates

(i) $\mathrm{Im}\Pi(\omega)$ as solution of integral eq. (Fredholm 1): too scarce information on <u>OBE side</u> $i < 6(8,12)$

(ii) MEM: Gubler, Morita, Oka, PRL (2011)

(iii) moments: mean (= center of gravity) – OK

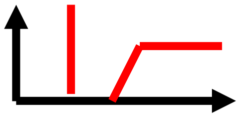
too large gap in powers of M
- variance (= width)
- skewness (= deformation)
- kurtosis (= up/down shot)


Titov, BK, PRC (2007)

(iv) insert hadronic model

Kwon, Weise, PRC (2010): another hierarchy+chiral gap

(v) pole + continuum ansatz



QCD sum rules: rho meson & VOC

hadron spectral moments ← QCD condensates (n,T)

$$\tilde{m}^2(M, s_+) \equiv \frac{\int_0^{s_+} ds\, \mathrm{Im}\,\Pi(s) e^{-s/M^2}}{\int_0^{s_+} ds\, \mathrm{Im}\,\Pi(s) s^{-1} e^{-s/M^2}}$$

center of gravity

s_+: cont. threshold

maximum flatness in Borel window

Kwon, Procura, Weise PRC (2008): $s_+ = 4\pi f_\pi^2$

$$\underbrace{m_q \langle \bar{q} q \rangle}_{\text{num. irrelevant}}, \langle \frac{\alpha_s}{\pi} G^2 \rangle, \langle O_4 \rangle \; \ldots$$

Hatsuda, Lee PRC (1992): $\langle O_4 \rangle \propto \langle \bar{q} q \rangle^2$

$$\langle O_4 \rangle = \langle O_4^{even} \rangle + \langle O_4^{odd} \rangle$$

$$\left. \begin{array}{ll} \psi_L \to e^{i\vec{\theta}_L \cdot \vec{\tau}} \psi_L, & \psi_R \to \psi_R \\ \psi_R \to e^{i\vec{\theta}_R \cdot \vec{\tau}} \psi_R, & \psi_L \to \psi_L \end{array} \right\}$$

chiral transformations

$\langle \bar{q} q \rangle$ is chirally odd

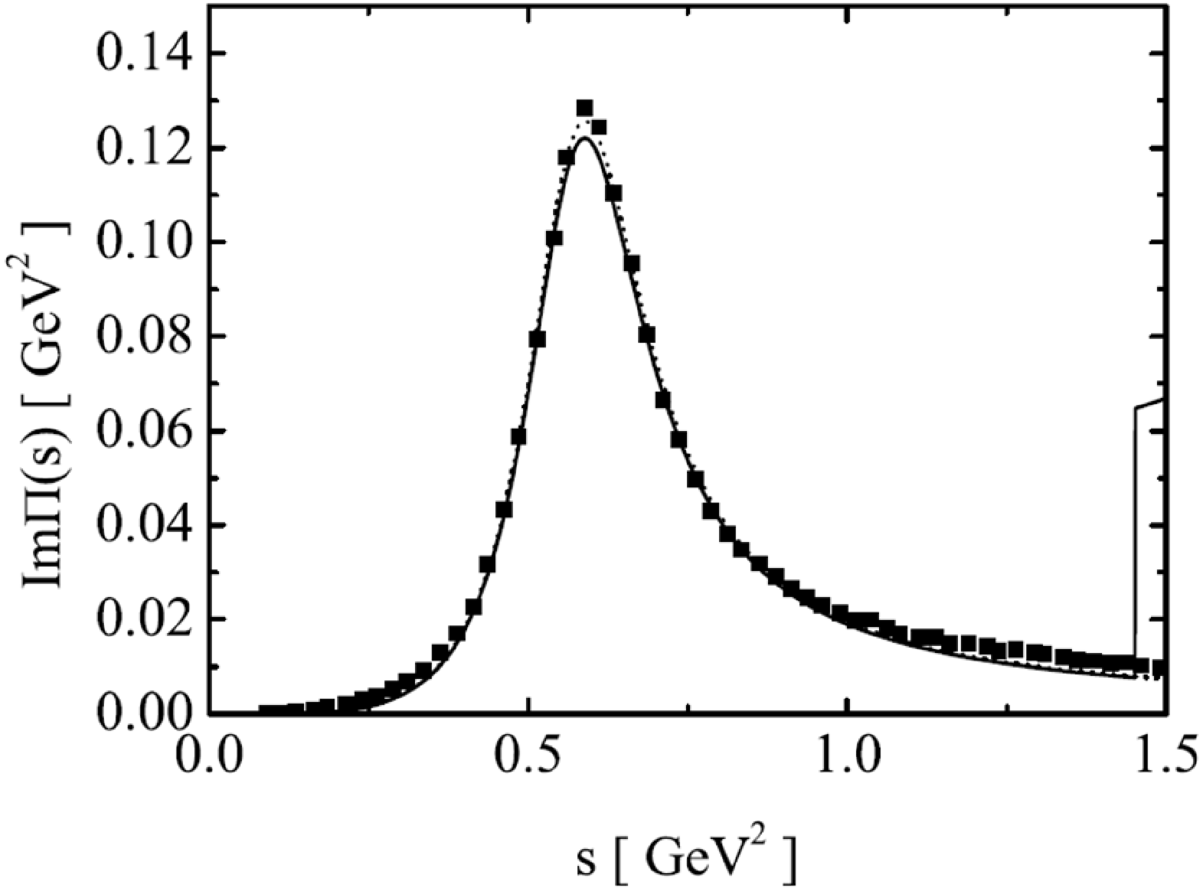
VOC: keep even conds., but set odd conds. to zero

Bordes, Dominguez, Pennarrocha, Schilcher JHEP (2006): $\langle O_4^{odd} \rangle = \frac{7}{9} \langle \bar{q} q \rangle^2$

reconstruct $\langle O_4^{even} \rangle$ from QCD sum rule $\overline{\tilde{m}^2} = m_\rho^2$

Hilger, Thomas, BK, Leupold PLB (2012)

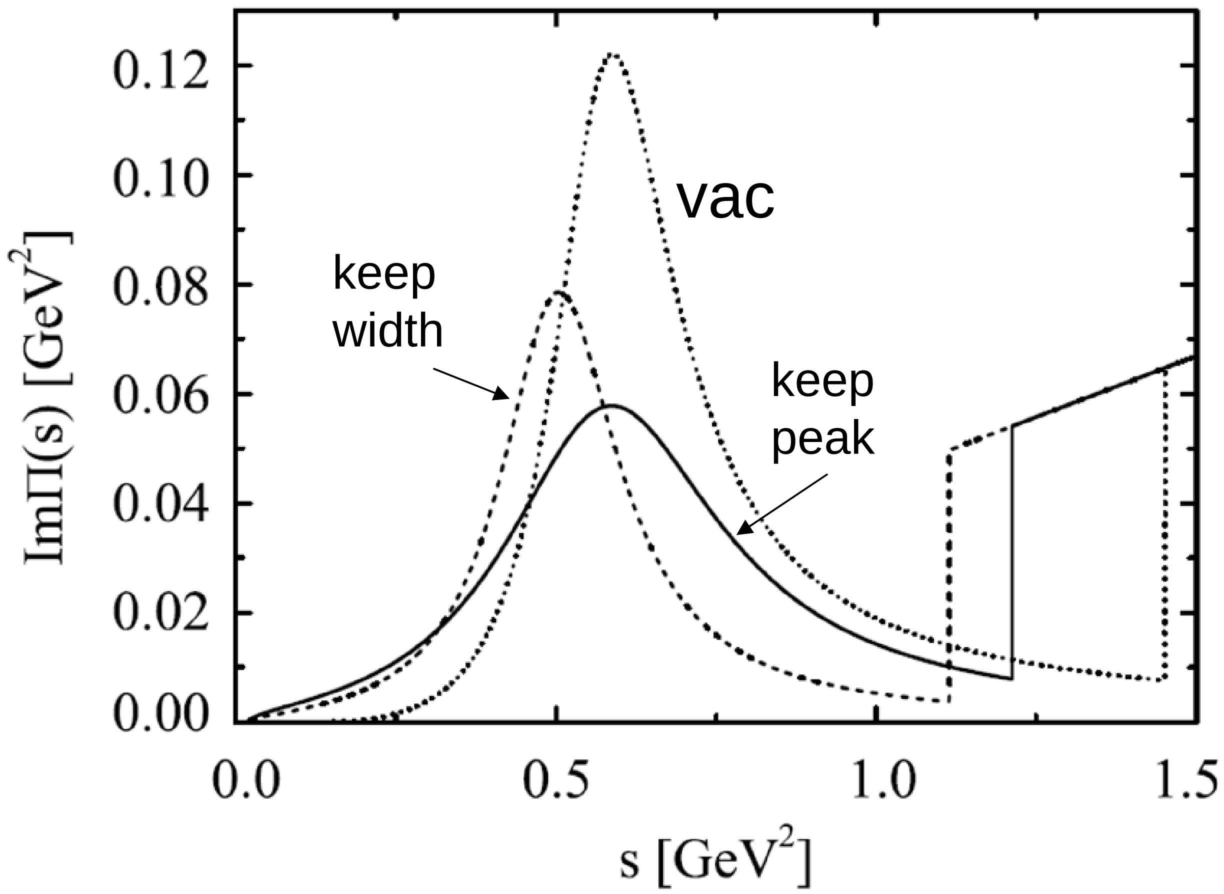
vacuum: parameterize the spectral function



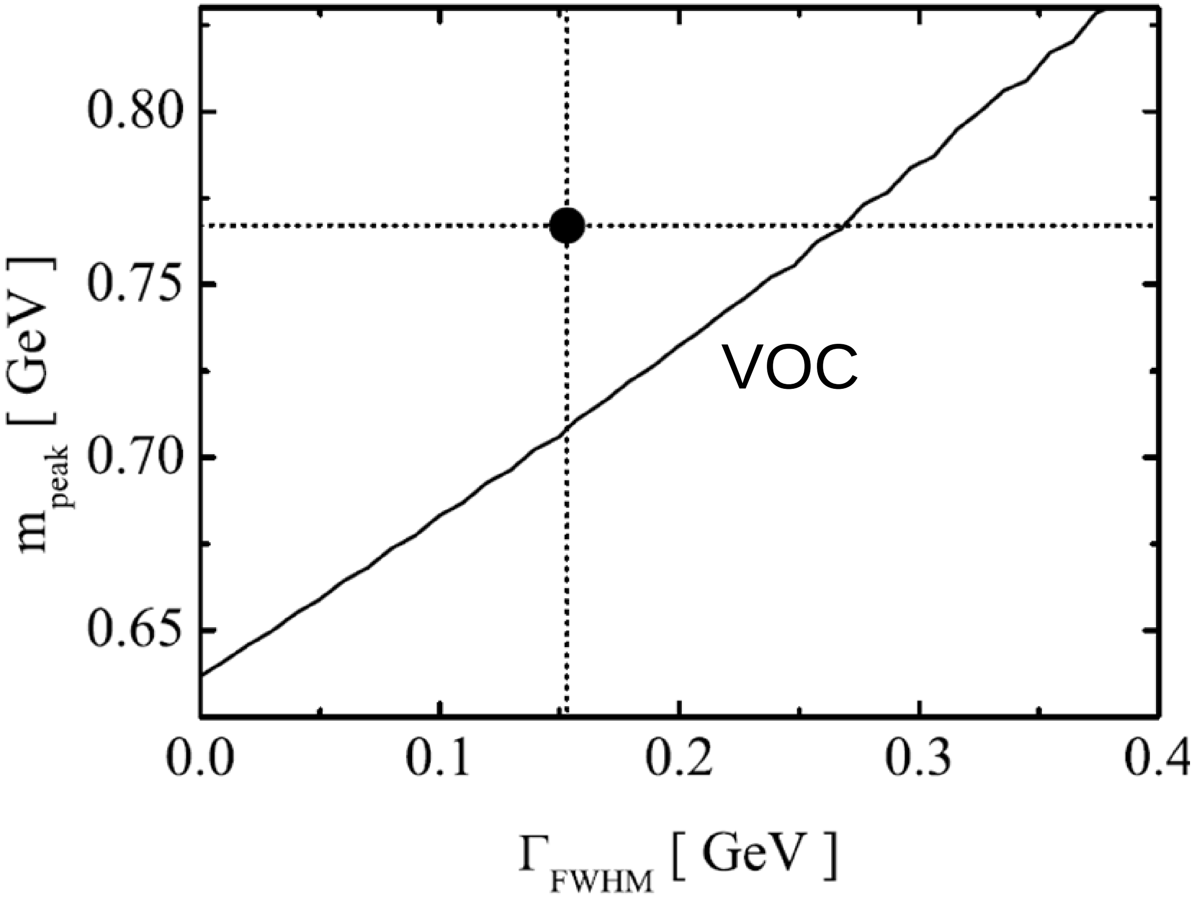
data: ALEPH (2005), $\tau \rightarrow \nu + n\pi$, even n

→ consistent QCD sum rule result

VOC



improvement of Leupold, Peters, Mosel NPA (1998)



NA60

VOC: minimum scenario of chiral restoration

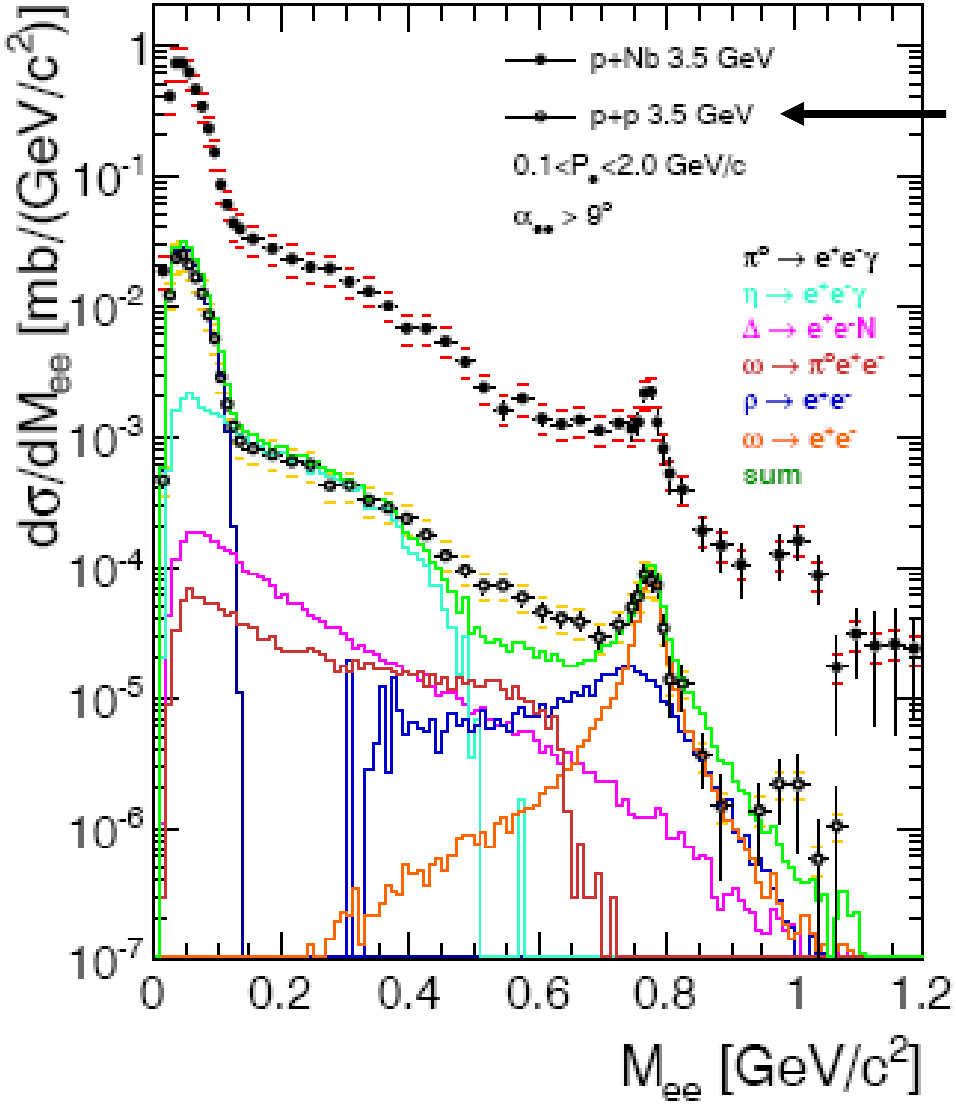
→ broadening as signal of chiral restoration

disclaimer: at chiral restoration more can happen

ω: much less influence of VOC

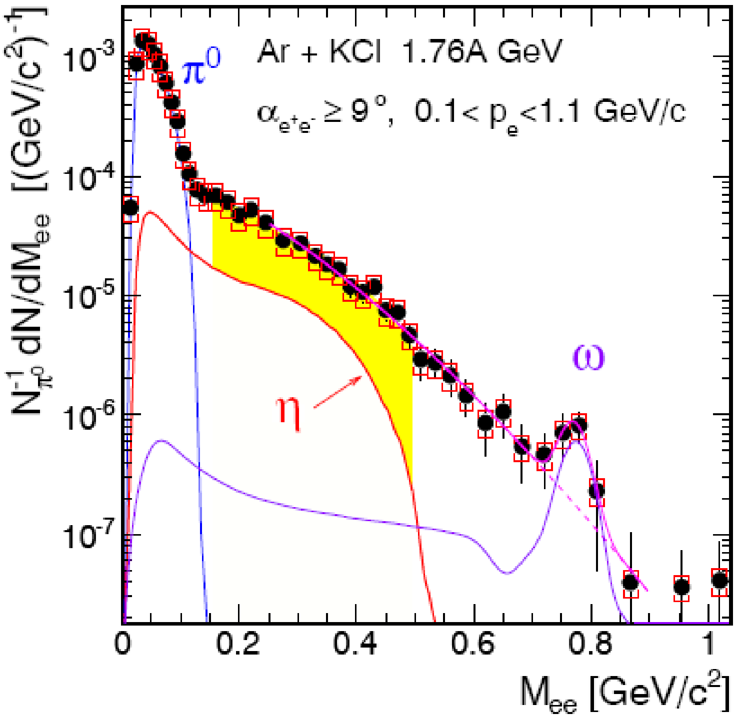
HADES: Hunting the rho Meson

arXiv:1205.1918



EPJA 48 (2012) 64

Phys.Rev. C84 (2011) 014902



Chiral Partners

$$\rho:\ j_\mu^V = \bar{q}\gamma_\mu\vec{\tau}q \xrightarrow[\text{transf.}]{\text{chiral}} \bar{q}\gamma_\mu\gamma_5\vec{\tau}q = j_\mu^A:\ a_1$$

with open charm

$$D^*(2007)^0:\ j_\mu^V = \bar{u}\gamma_\mu c \qquad \bar{u}\gamma_\mu\gamma_5 c = j_\mu^A:\ D_1(2420)^0$$

$$D_0^*(2400):\ j^S = \bar{u}c \qquad \bar{u}i\gamma_5 c = j^P:\ D^0(1865)$$

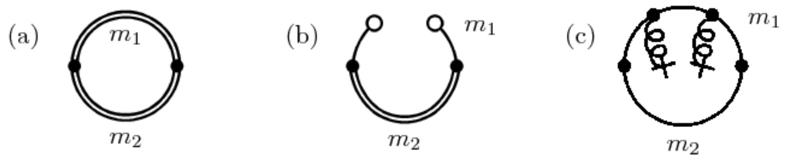
chiral QCD sum rules Hilger, BK, Leupold PRC (2011)

$\bar{q}Q$ and $q\bar{Q}$ mesons:

Wigner's nondegeneracy

splitting of spectral densities between chiral partners must be driven by order parameters of spontaneous chiral symmetry breaking only

light chiral limit: $m_q \to 0$



$$\frac{1}{\pi}\int_{-\infty}^{+\infty} d\omega\, \omega\, \Delta\Pi_{P-S}(\omega) = -\,2m_c\langle\bar{q}q\rangle\ ,$$

$$\frac{1}{\pi}\int_{-\infty}^{+\infty} d\omega\, \omega^3\, \Delta\Pi_{P-S}(\omega) = -\,2m_c^3\langle\bar{q}q\rangle + m_c\langle\bar{q}g\sigma\mathcal{G}q\rangle - m_c\,\langle\Delta\rangle$$

$$\frac{1}{\pi}\int_{-\infty}^{+\infty} d\omega\, \omega^5\, \Delta\Pi_{P-S}(\omega) = -\,2m_c^5\langle\bar{q}q\rangle + 3m_c^3\langle\bar{q}g\sigma\mathcal{G}q\rangle - 3m_c^3\,\langle\Delta\rangle + \ldots$$

$$\uparrow$$

$$\langle\bar{q}g\sigma\mathcal{G}q\rangle - 8\langle\bar{q}D_0^2q\rangle \equiv \langle\Delta\rangle$$

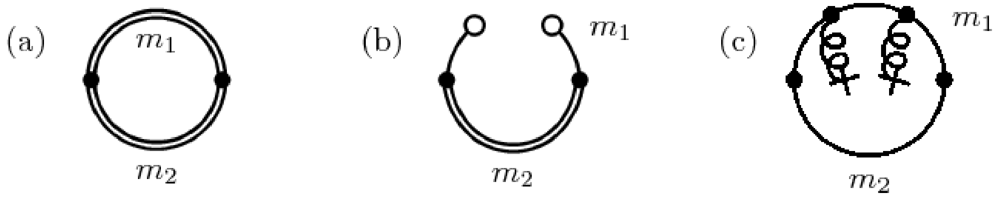
generalizes Weinberg‘s sum rule to P-S for qQ mesons

vacuum: $\langle\Delta\rangle = 0$ Narison PLB (2005)

r.h.s.: „order parameters“ of chiral symm. breaking

Hilger, Buchheim, BK, Leupold PPNP(2012): α_s

the case of V-A



$$\frac{1}{\pi}\int_{-\infty}^{+\infty} d\omega\, \omega\, \Delta\Pi_{V-A}(\omega) = 8 m_c \langle \bar q q\rangle \ ,$$

$$\frac{1}{\pi}\int_{-\infty}^{+\infty} d\omega\, \omega^3 \Delta\Pi_{V-A}(\omega) = 8 m_c^3 \langle \bar q q\rangle + 4 m_c \langle \Delta\rangle$$

$$\frac{1}{\pi}\int_{-\infty}^{+\infty} d\omega\, \omega^5 \Delta\Pi_{V-A}(\omega) = 8 m_c^5 \langle \bar q q\rangle - 4 m_c^3 \langle \bar q g \sigma \mathcal{G} q\rangle - 12 m_c^3 \langle \Delta\rangle + \ldots$$

different expressions for Π_T, Π_T/q^2

vacuum: $\langle \Delta \rangle = 0$

Hayashigaki, Terasaki 0411285
Reinders, Rubinstein, Yazaki PR (1985)

in contrast to Weinberg's sum rules: no Goldstone properties on r.h.s. (qQ currents are not conserved)

heavy quark symmetry: degeneracy of V – P, A - S

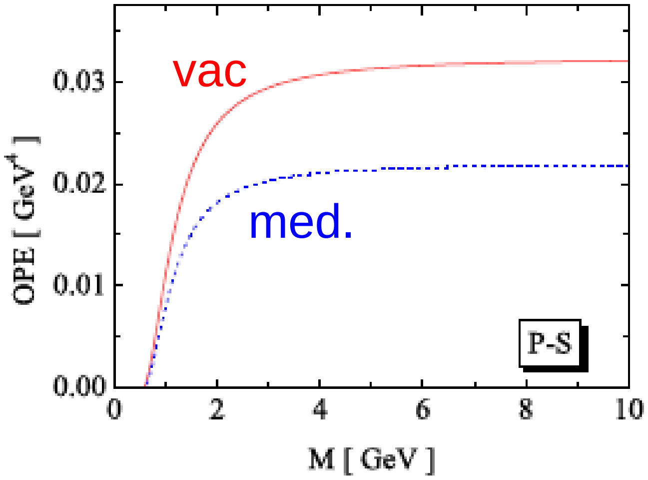
OBE sides: medium effects

$$\langle \bar{q}q \rangle = \langle \bar{q}q \rangle_0 + \frac{45}{11} n$$

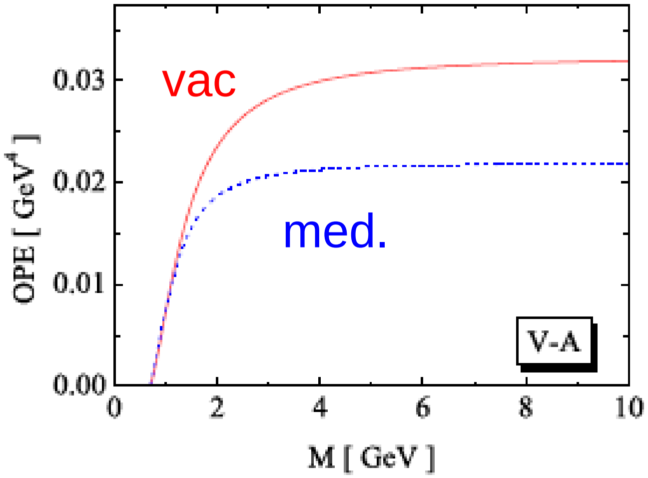
$$\langle \bar{q} g \sigma G q \rangle = 0.8\mathrm{GeV}^2 \langle \bar{q}q \rangle_0 + 3\mathrm{GeV}^2 n$$

$$\langle \Delta \rangle = 2.4\mathrm{GeV}^2 n$$

$$\langle \bar{q}q \rangle_0 = (-0.245\mathrm{GeV})^3$$



→ significant medium effects



elaboration of hadronic sides for light-light mesons

Kapusta, Shuryak PRD (1994)

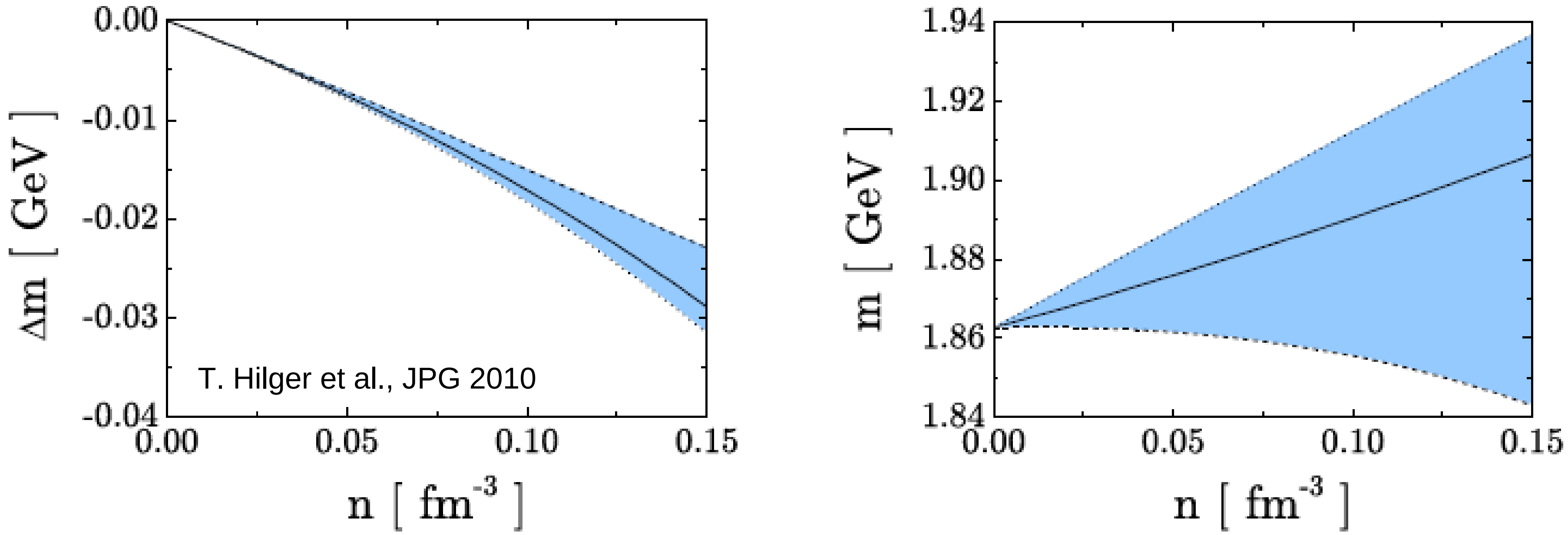
Open Charm Mesons in Nuclear Matter towards FAIR: CBM + PANDA

$$S_n(M) \equiv \int_{s_0^-}^{s_0^+} \mathrm{d}s\, s^n \Delta\Pi(s) \mathrm{e}^{-s^2/M^2}$$

$$j_{D+} = i\bar{d}\gamma_5 c,\; j_{D-} = i\bar{c}\gamma_5 d$$

$$\begin{aligned} \Delta m &\equiv \frac{1}{2}\frac{S_1 S_2 - S_0 S_3}{S_1^2 - S_0 S_2} , \\ m_+ m_- &\equiv -\frac{S_2^2 - S_1 S_3}{S_1^2 - S_0 S_2} , \\ m^2 &\equiv \Delta m^2 + m_+ m_- , \end{aligned}$$

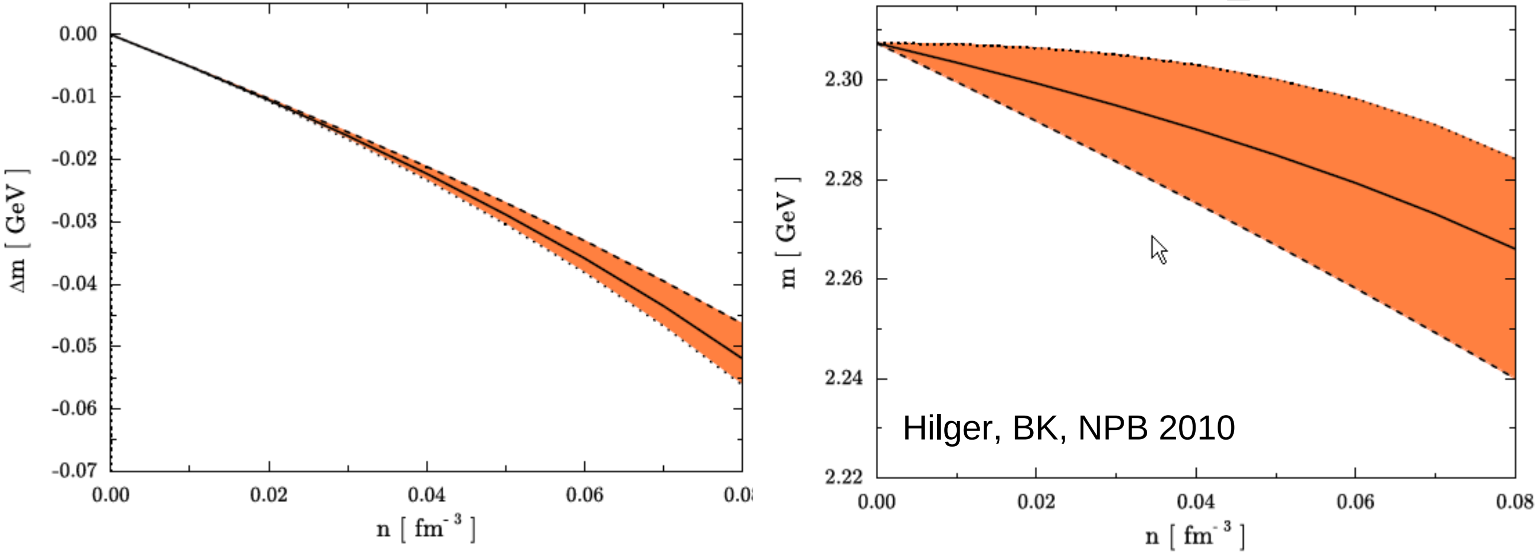
pseudo-scalar D - $\bar{D}$



T. Hilger et al., JPG 2010

scalar $D^* - \bar{D}^*$

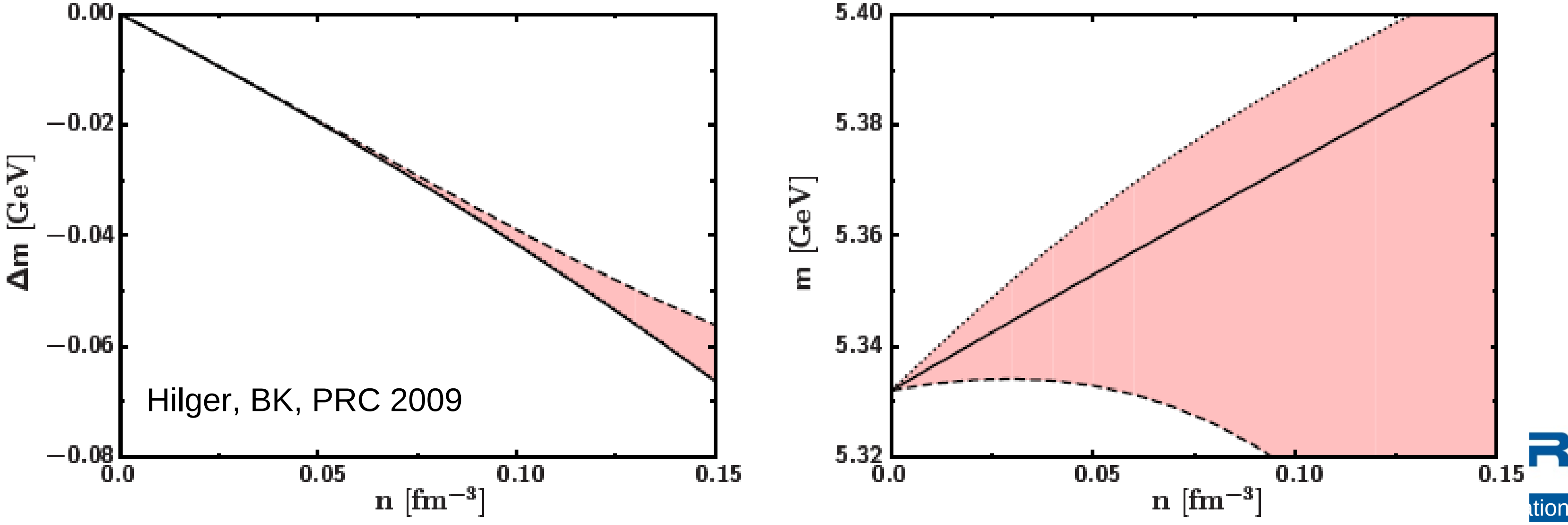
$j_{D^*} = \bar{d}c, \; j_{\bar{D}^*} = \bar{c}d$



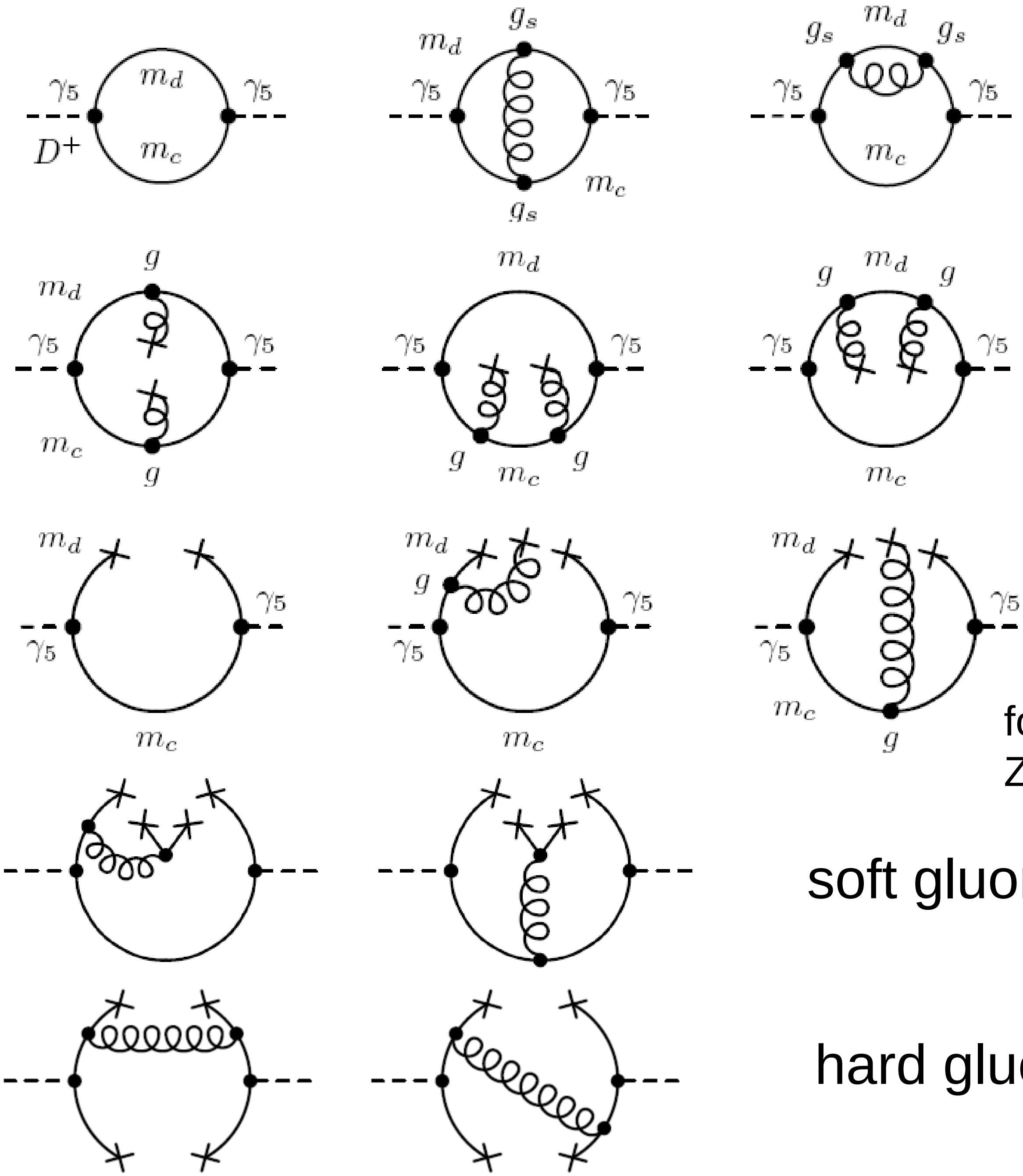
Hilger, BK, NPB 2010

pseudo-scalar $B - \bar{B}$

$j_{B+} = i\bar{b}\gamma_5 u, \; j_{B^0} = i\bar{b}\gamma_5 d$



Hilger, BK, PRC 2009



pert. contribution

gluon contribution

quark contribution

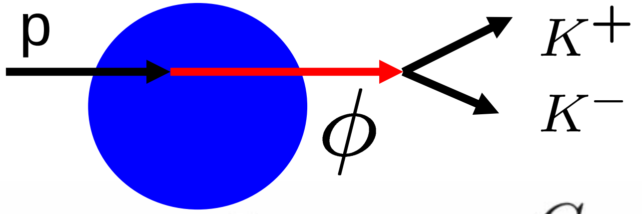
for details cf.
Zschocke, Hilger, BK EPJC (2011)

soft gluons

hard gluons

T. Buchheim

Width of Strangeonium

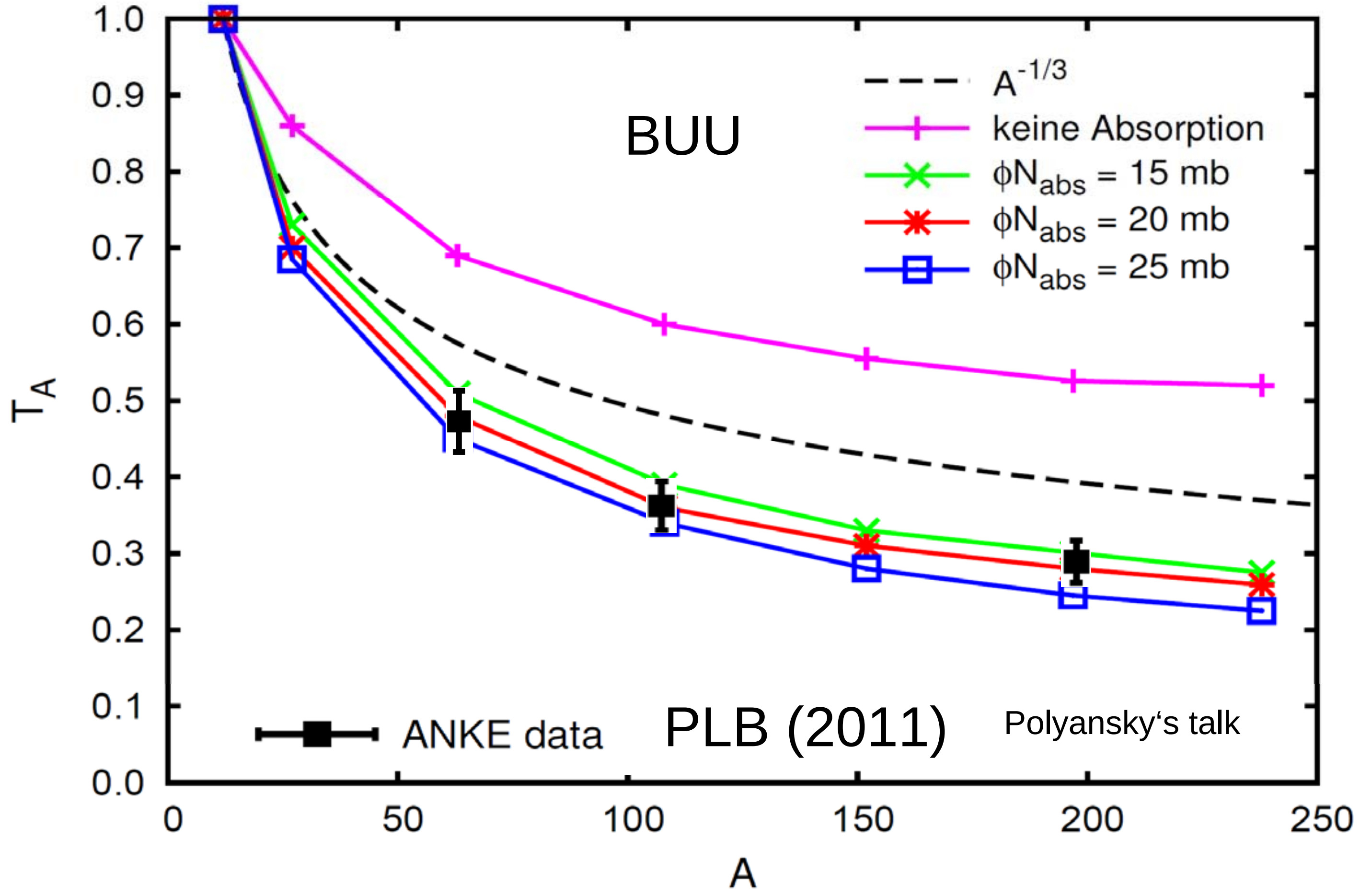


$pA \to X\phi$: Tansparency Ratio

$\hookrightarrow K^+K^-$

$$T_A = \frac{\sigma_{pA\to\phi X}}{A}\,\frac{C}{\sigma_{pC\to\phi X}}$$

proposed by Hernandez, Oset, ZPA (1992)



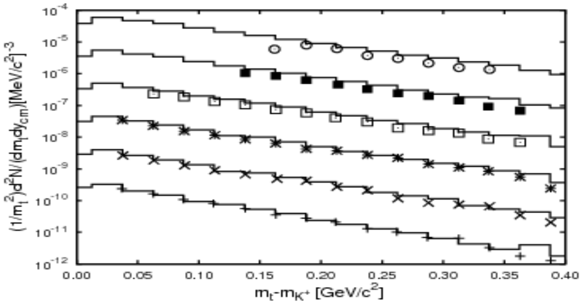
PLB (2011)

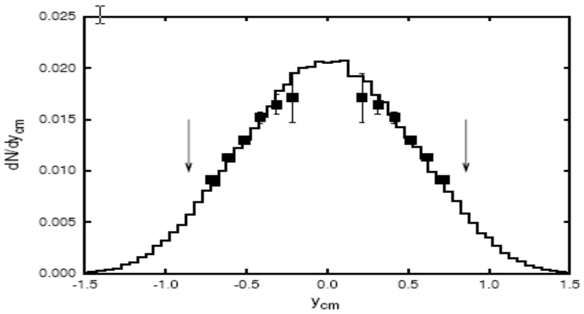
Polyansky's talk

Rossendorf BUU transport code for Ar(1.76 AGeV) + KCl

data: HADES PRC (2008)

Schade, Wolf, BK, PRC (2010)

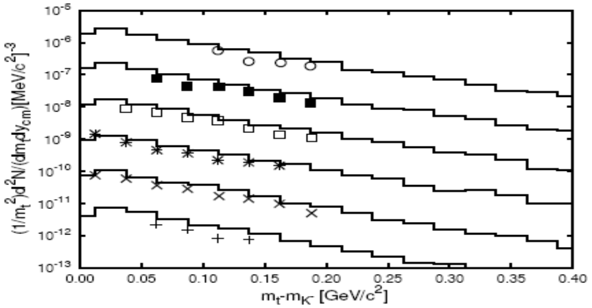


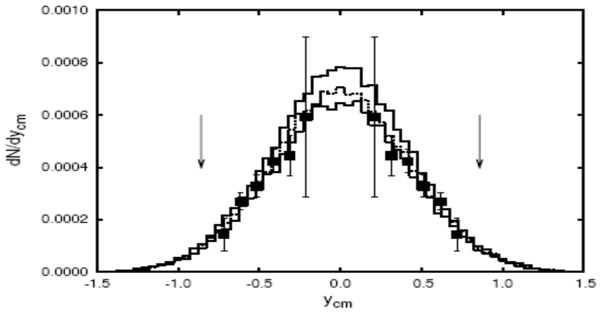


K+

$$\Delta m = 25 \text{ MeV}$$

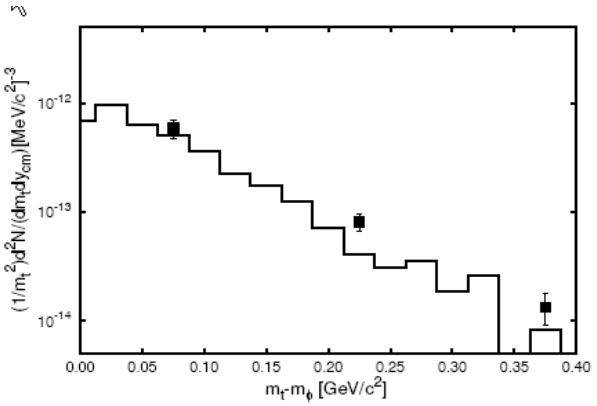
HADES, PRC (2010): 40 MeV

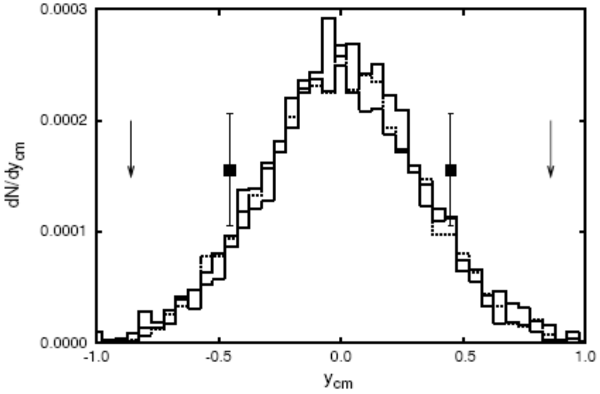




K-

$$\Delta m = -75 \text{ MeV}$$

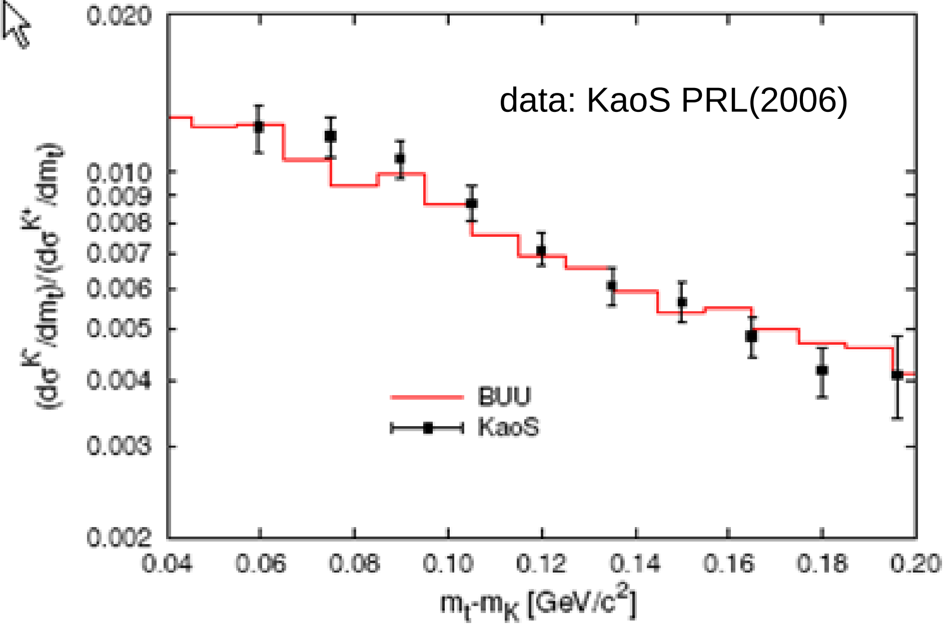




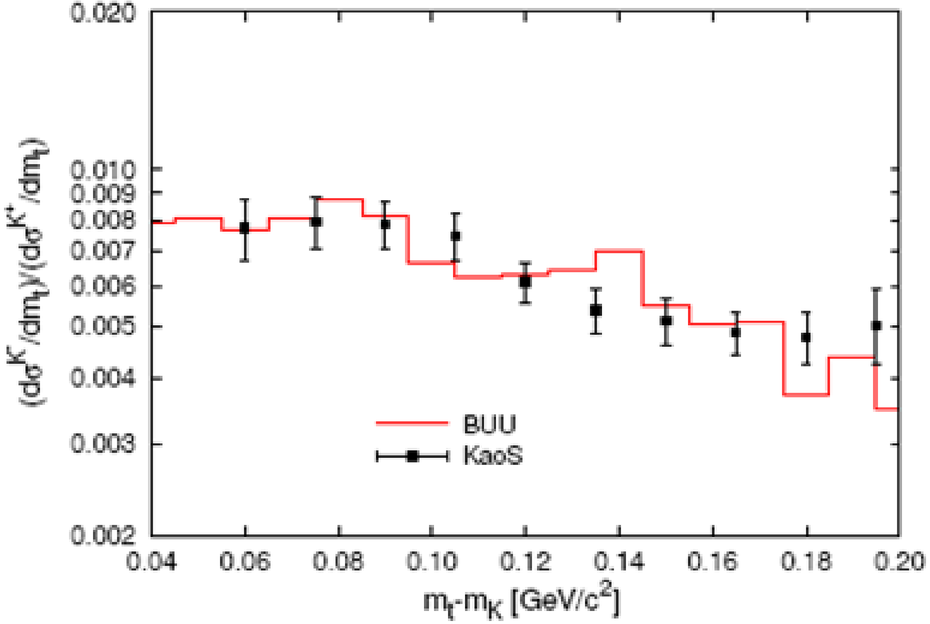
$$\phi$$

$$\Delta m = -22 \text{ MeV}$$

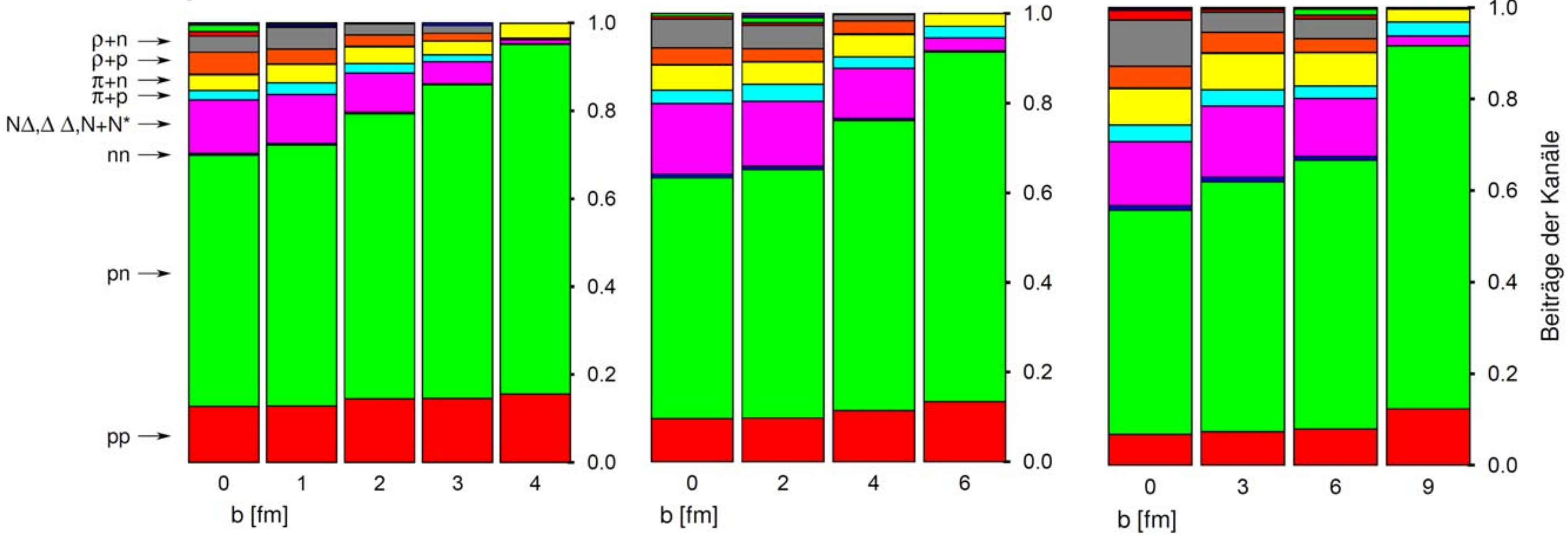
p(2.5 GeV) + C



p(2.5 GeV) + Au

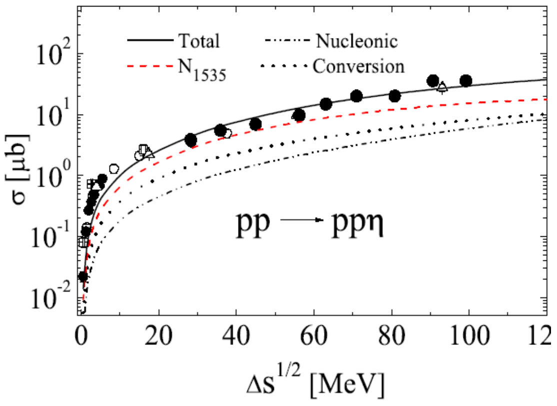


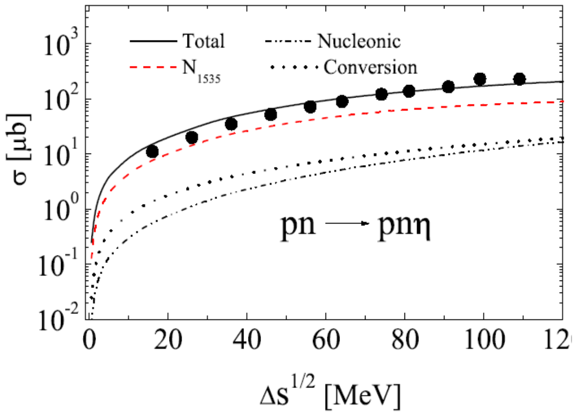
p(2.83 GeV) + C Cu Au

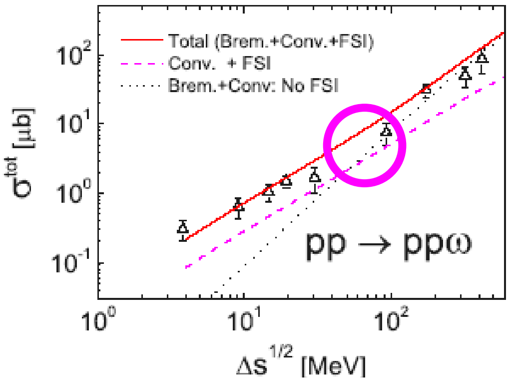


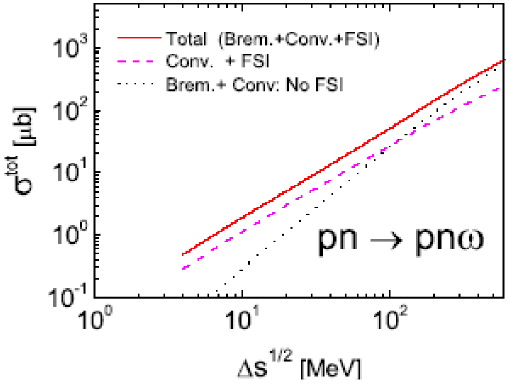
Aside: Effective Models at Work

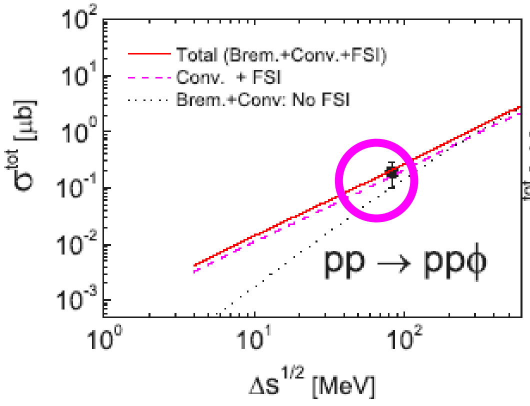
Kaptari, BK EPJA 2002, 2005, 2008, JPG 2004

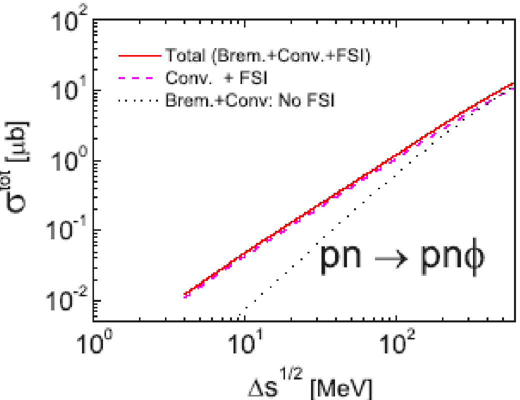




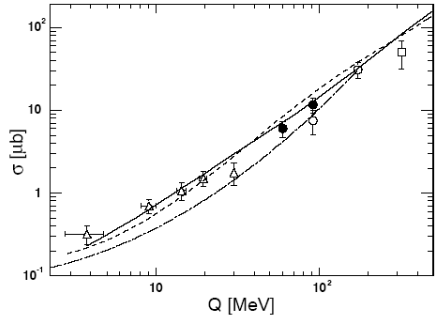




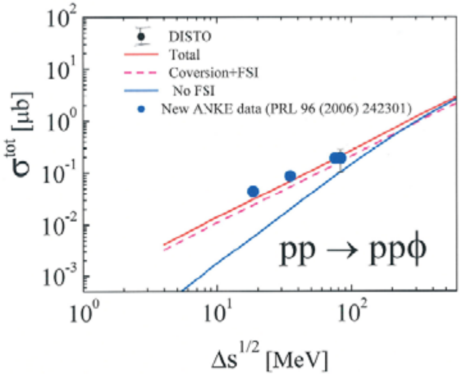


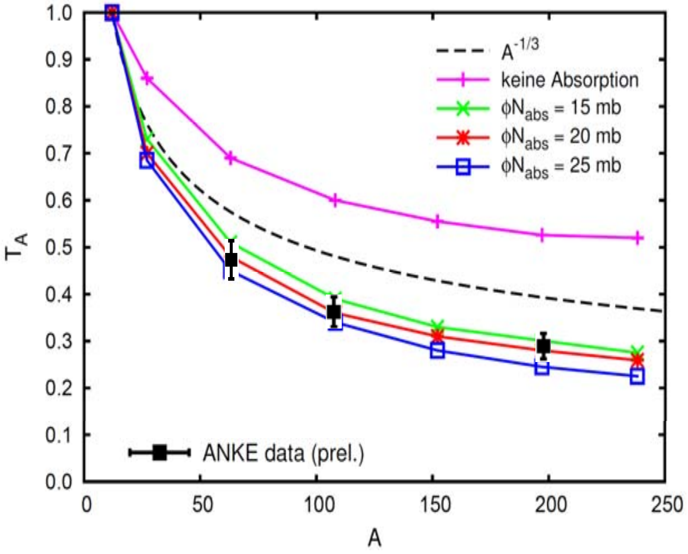


confirmed by ANKE



confirmed by ANKE





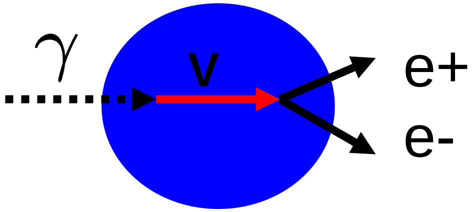
$$\Gamma_\phi = \langle \sigma_{abs} v n \rangle \sim 50 \text{ MeV}$$

in Valencia – Paryev models:

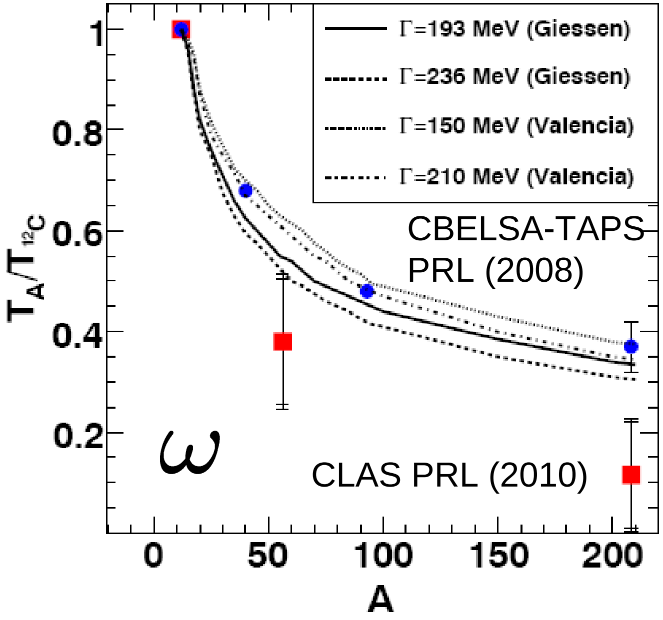
Oset, Cabrera,...

$$\Gamma_\phi = 45 - 73 \text{ MeV}$$

prediction of broadening:
Klingl, Wass, Weise, PLB (1998)

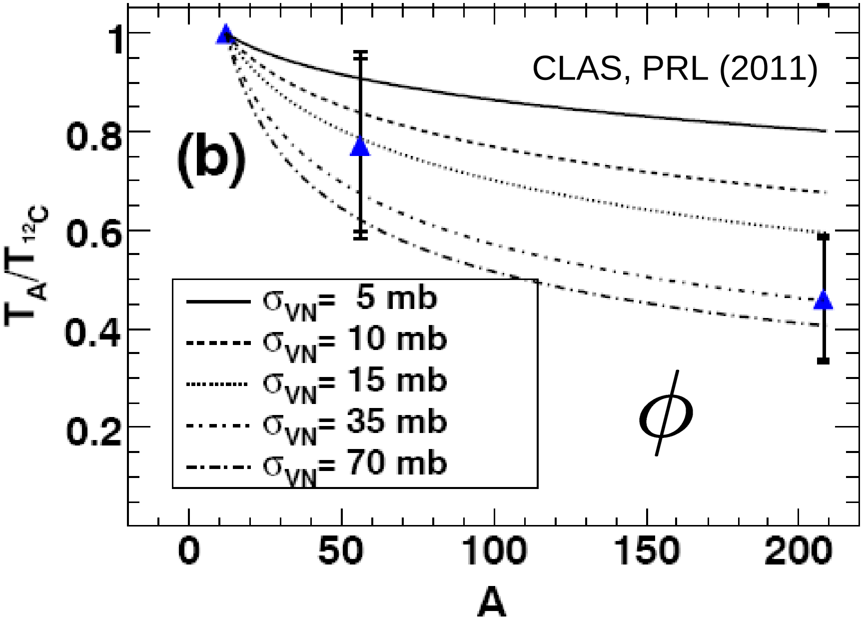


analog in omega and phi photo-production



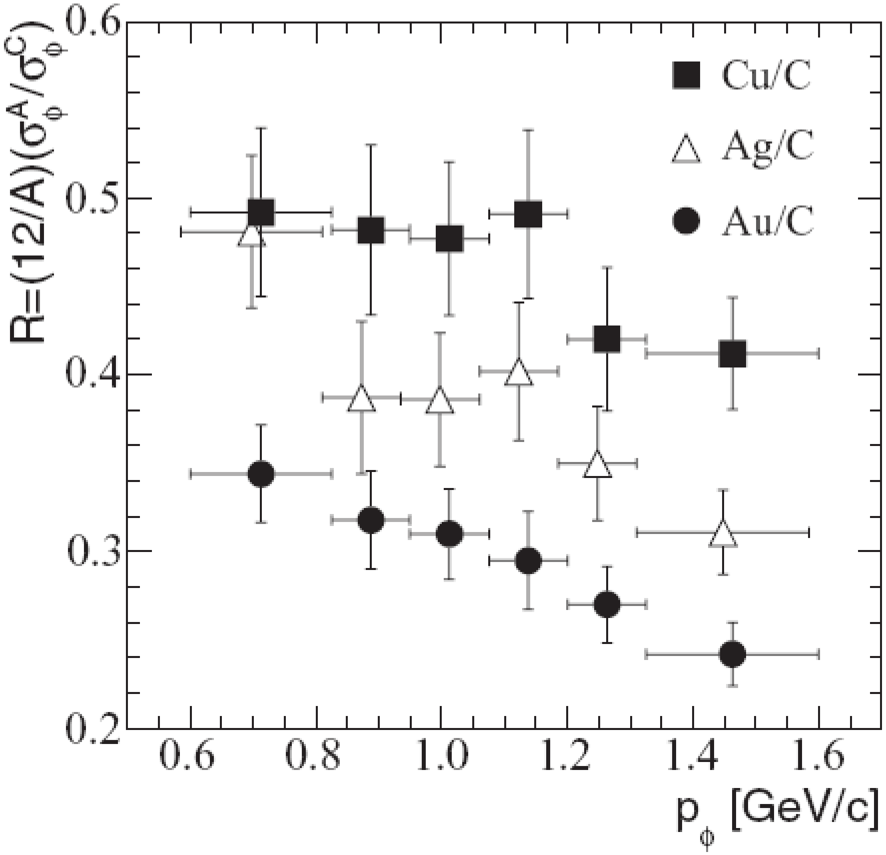
CBELSA-TAPS
PRL (2008)

CLAS PRL (2010)



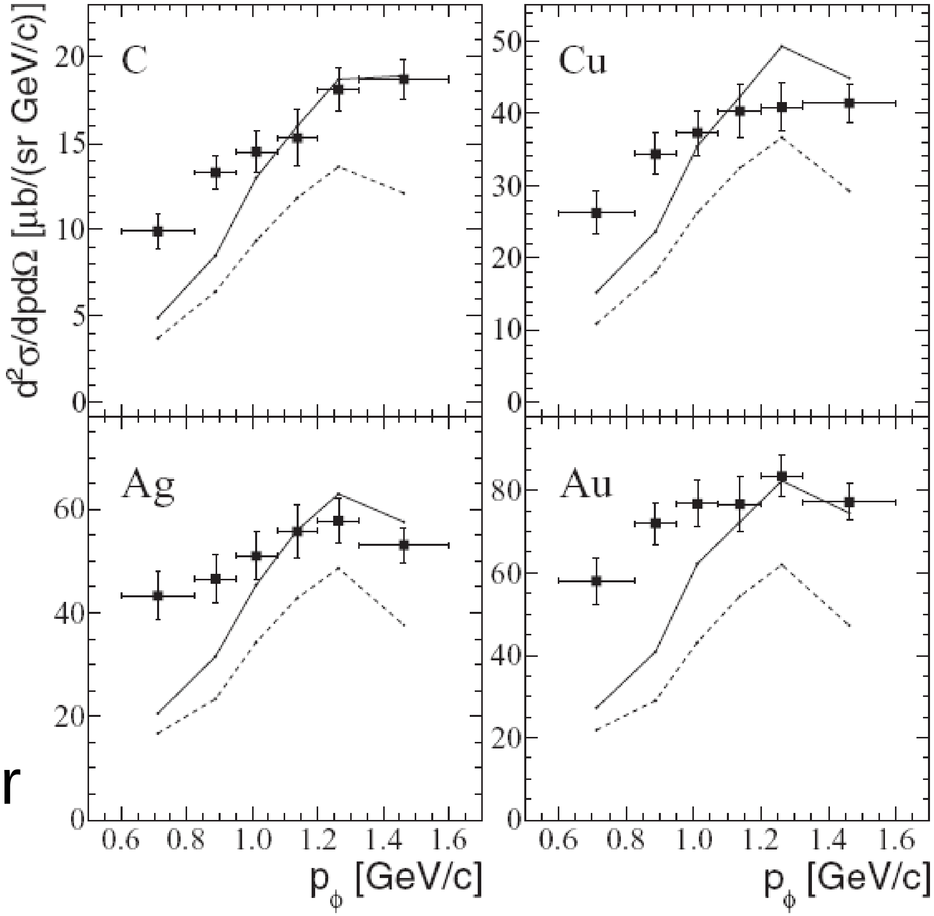
CLAS, PRL (2011)

Spring-8: Ishikawa et al., PLB (2005)

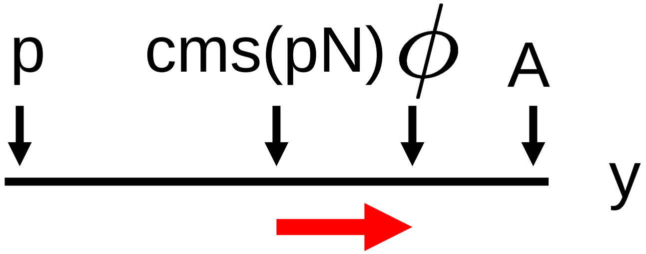


ANKE PRC (2012)

BUU: H. Schade



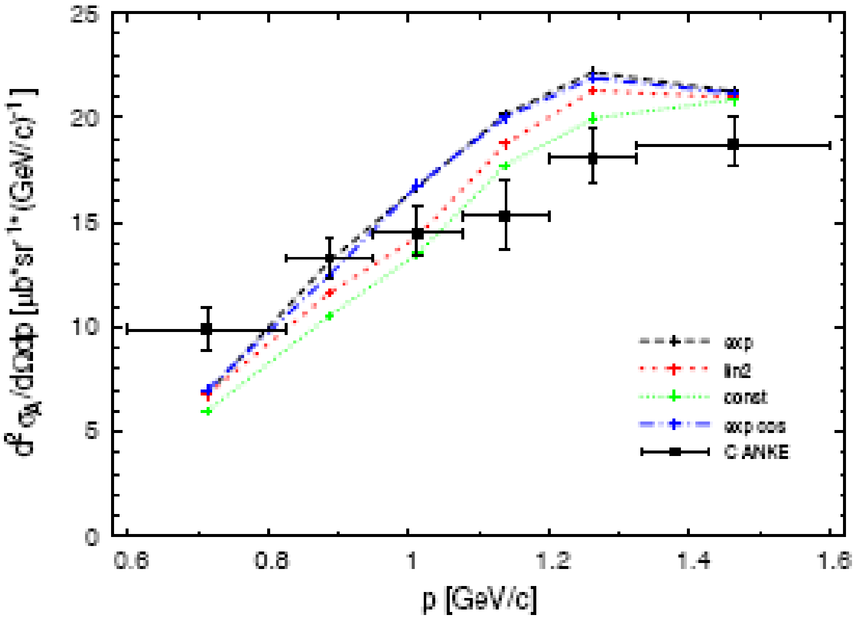
mystery: phi phase space

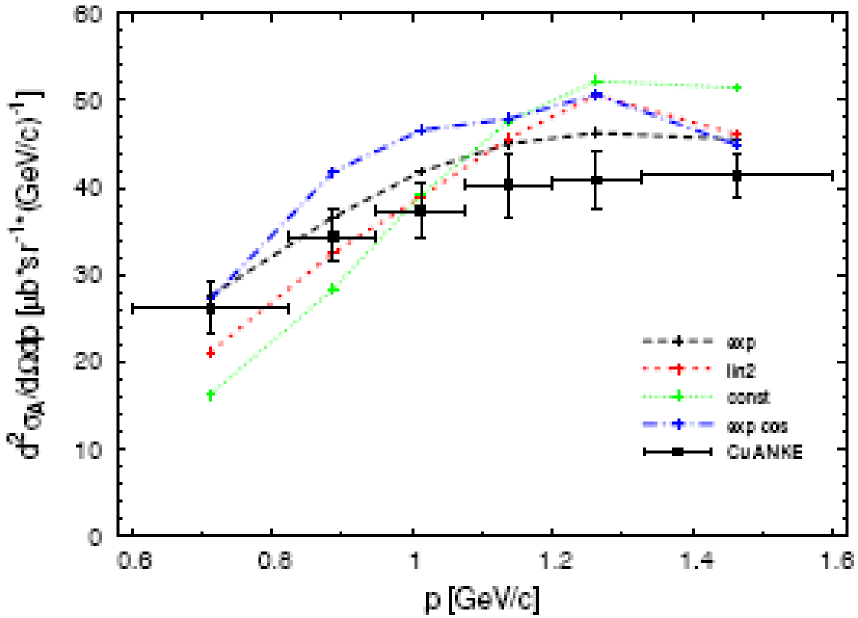


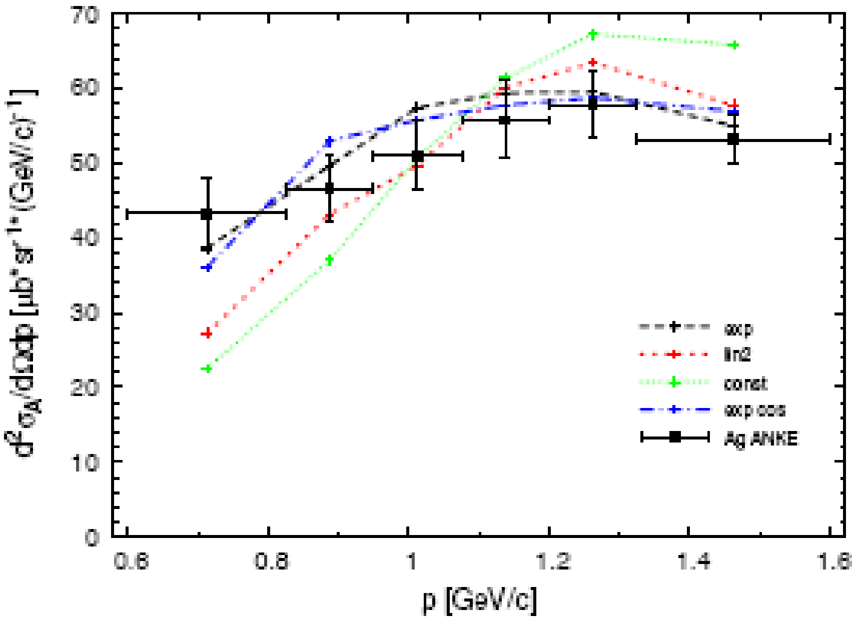
p cms(pN) ϕ A

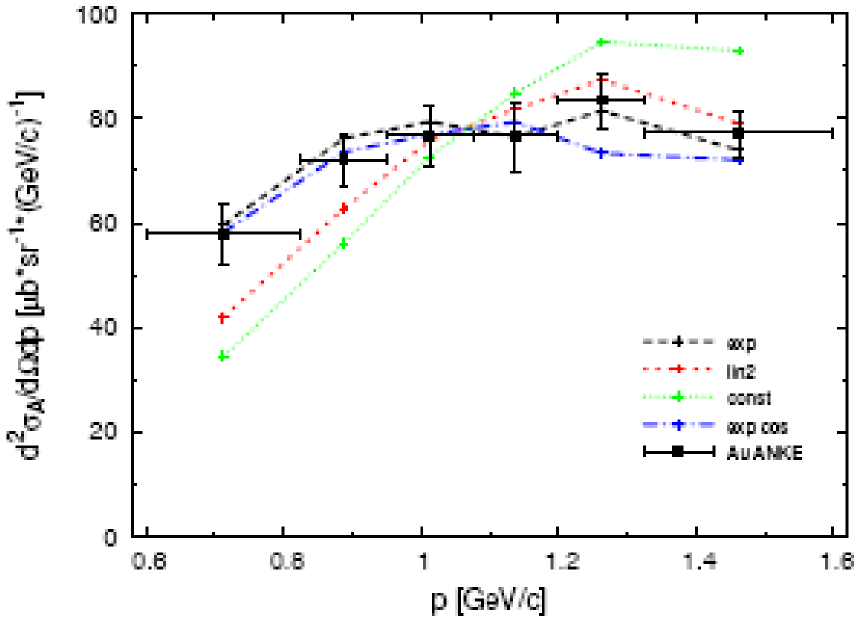
y

stopping power of nuclear matter


d²σ_A/dΩdp [µb*sr⁻¹*(GeV/c)⁻¹]
p [GeV/c]
0
5
10
15
20
25
0.6
0.8
1
1.2
1.4
1.6
exp
lin2
const
exp cos
C ANKE


d²σ_A/dΩdp [µb*sr⁻¹*(GeV/c)⁻¹]
p [GeV/c]
0
10
20
30
40
50
60
0.6
0.8
1
1.2
1.4
1.6
exp
lin2
const
exp cos
Cu ANKE

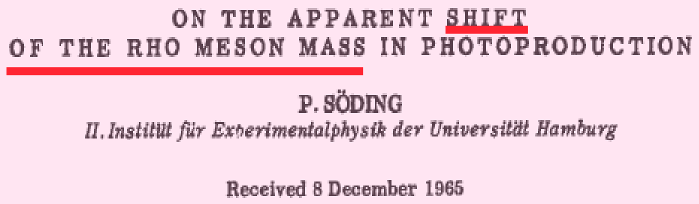

d²σ_A/dΩdp [µb*sr⁻¹*(GeV/c)⁻¹]
p [GeV/c]
0
10
20
30
40
50
60
70
0.6
0.8
1
1.2
1.4
1.6
exp
lin2
const
exp cos
Ag ANKE


d²σ_A/dΩdp [µb*sr⁻¹*(GeV/c)⁻¹]
p [GeV/c]
0
20
40
60
80
100
0.6
0.8
1
1.2
1.4
1.6
exp
lin2
const
exp cos
Au ANKE

Dropping Masses

QED: $m_*^2 = m_e^2(1 + a_0^2)$ Sengupta 1949

Phys. Lett. 19 (1966) 702



ON THE APPARENT SHIFT
OF THE RHO MESON MASS IN PHOTOPRODUCTION

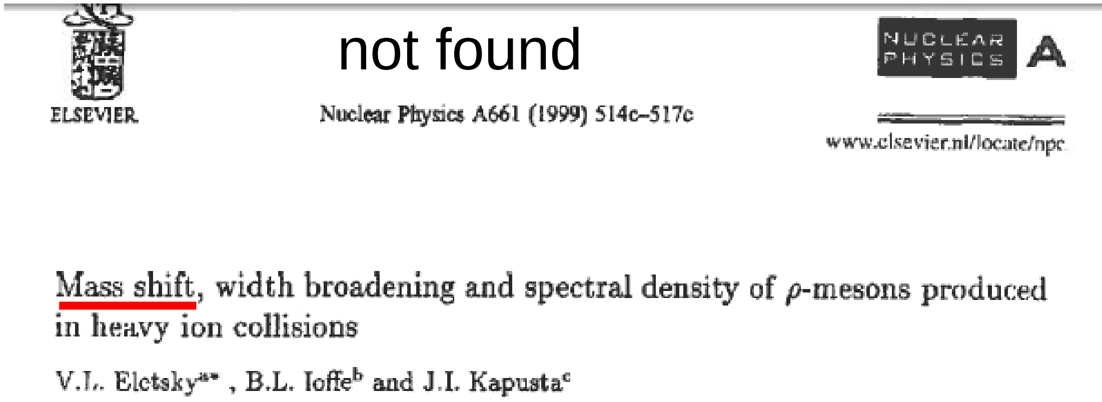
P. SÖDING
II. Institut für Experimentalphysik der Universität Hamburg

Received 8 December 1965

found

not yet found

not found



ELSEVIER

Nuclear Physics A661 (1999) 514c–517c

NUCLEAR PHYSICS A

www.elsevier.nl/locate/npe

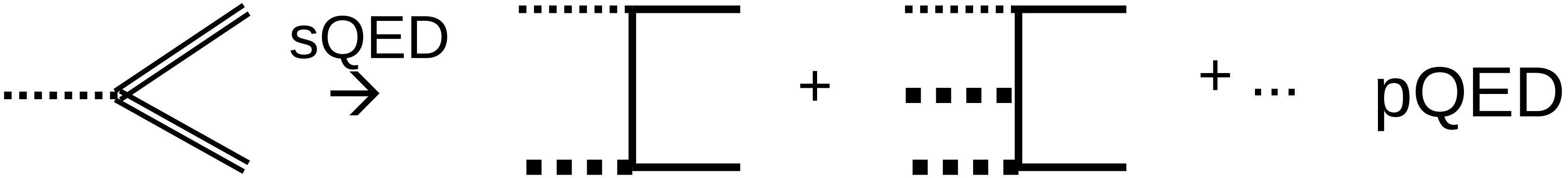
Mass shift, width broadening and spectral density of ρ-mesons produced in heavy ion collisions

V.L. Eletsky[a*], B.L. Ioffe[b] and J.I. Kapusta[c]

Brown-Rho, PRL 1991
Harada-Yamakawi, PR 2003
Ioffe, NPB 1981

$$m_{had} \propto |\langle \bar{q}q \rangle_{n,T}|^x$$

Mass Shift in QED
Example: Breit-Wheeler Process



sQED →

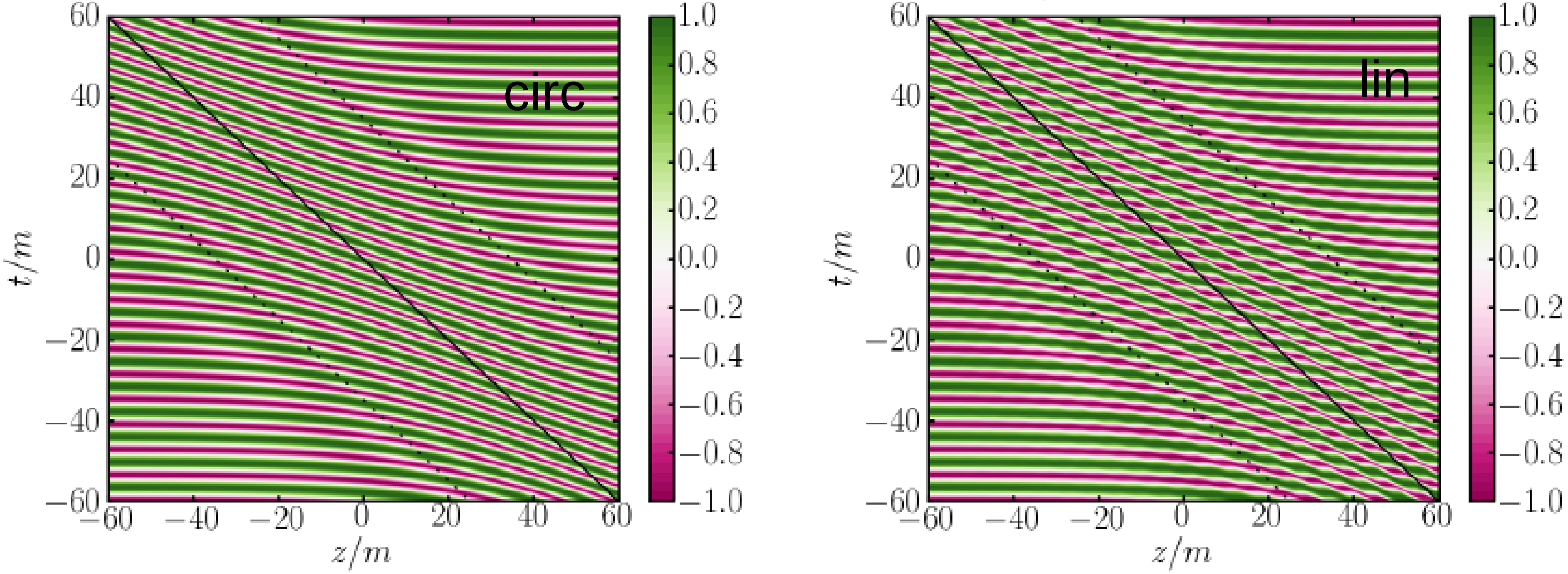
+ + …

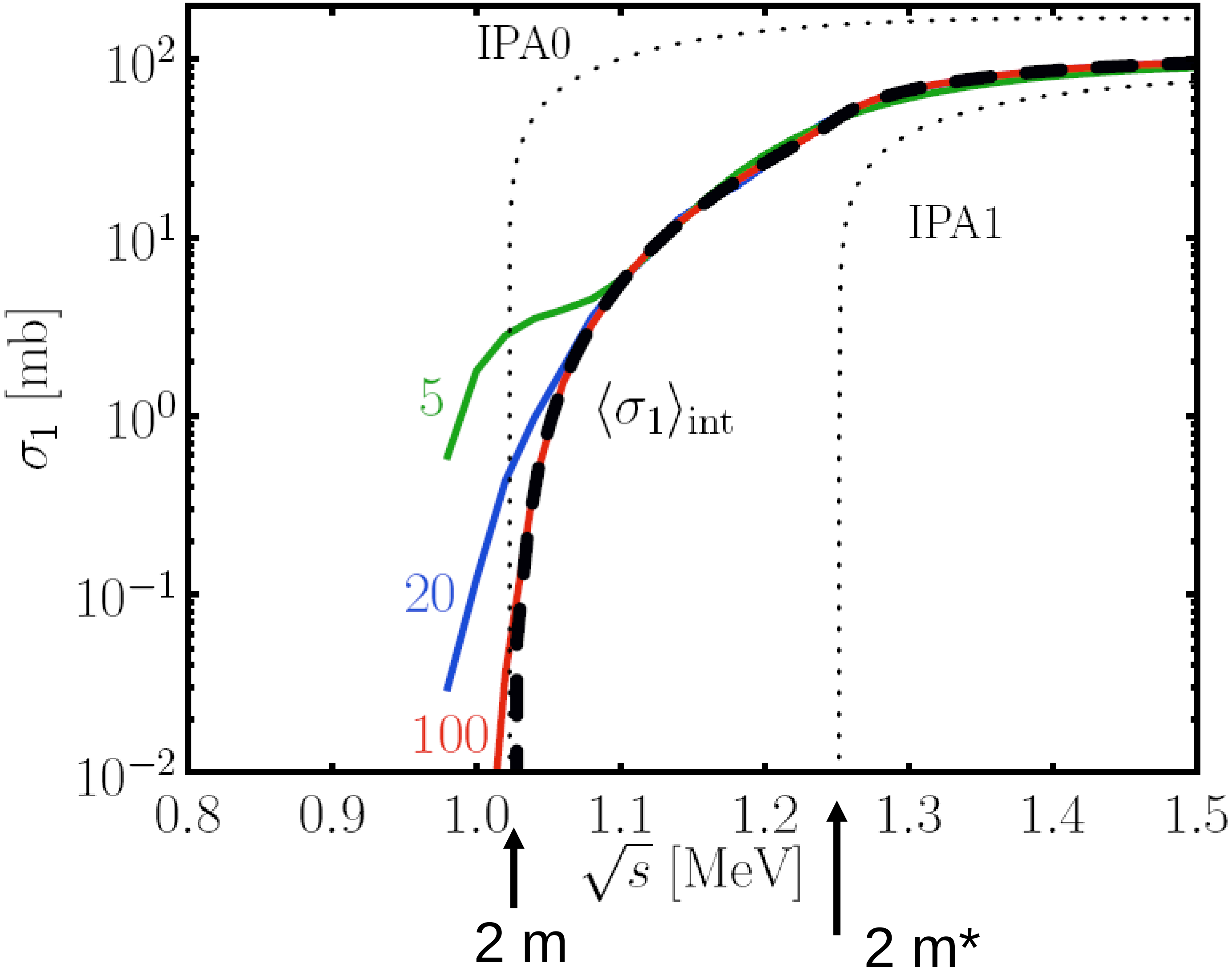
pQED

Breit-Wheeler n.l. Breit-Wheeler

Electron in Laser Pulses

D. Seipt, BK, arXiv:1010.3301

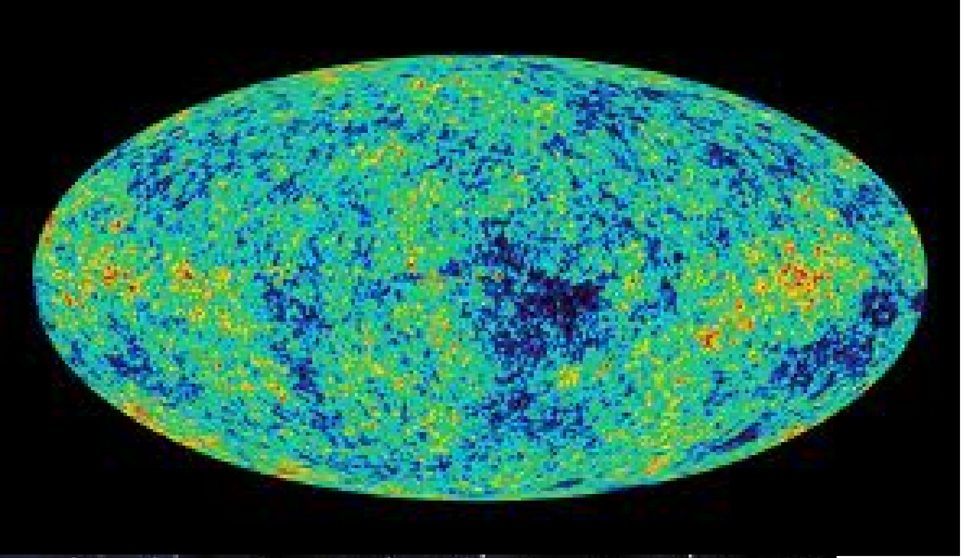


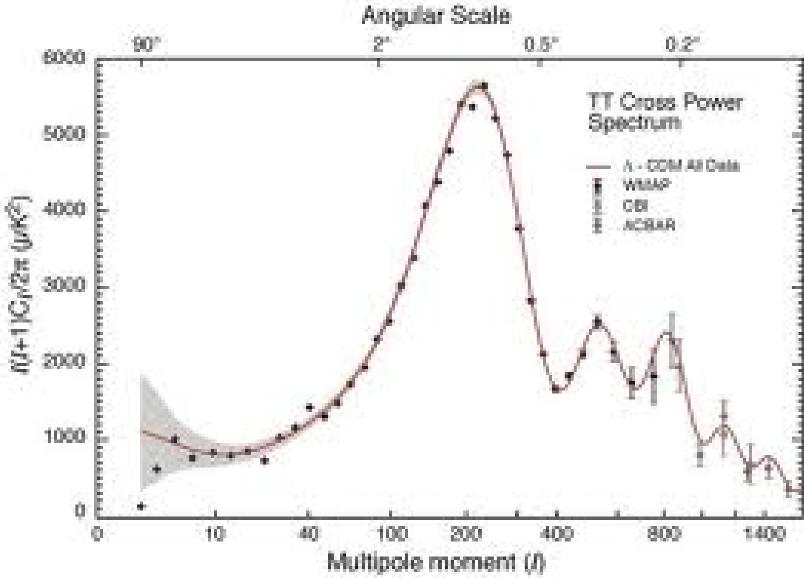


$e^{\pm}(\gamma)$

multi-photon effects & pulse shape and duration

Titov, Takabe, BK, Hosaka, PRL 2012
Nousch, Seipt, BK, Titov, arXiv 2012

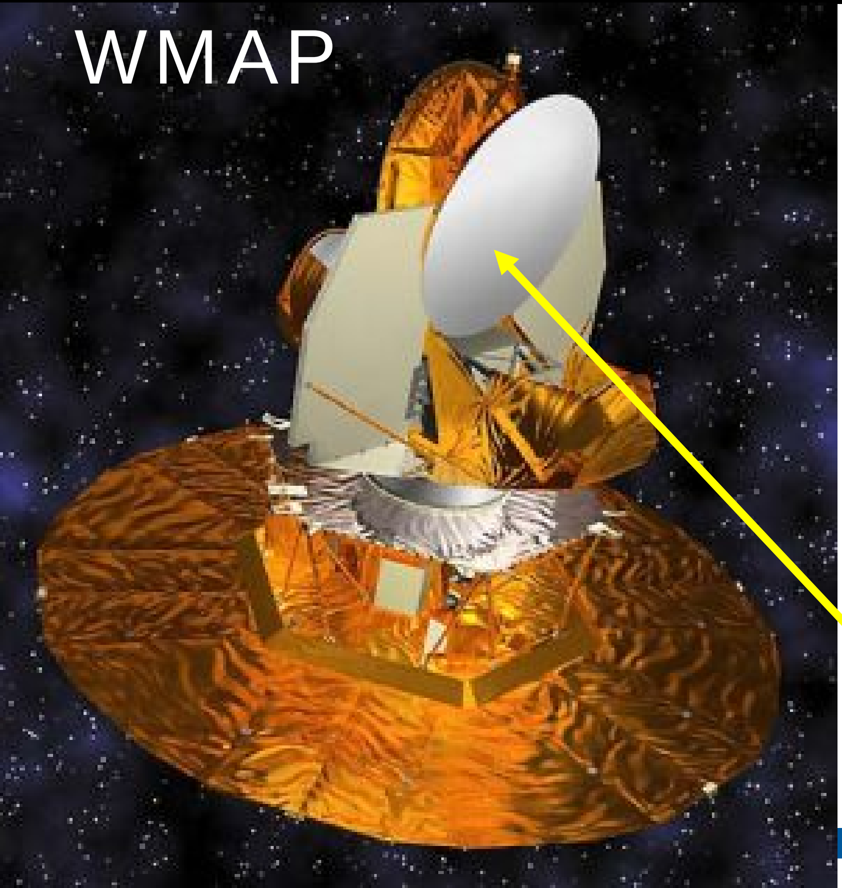




$$\Omega_\Lambda = \underbrace{0.7 \pm 0.05}$$

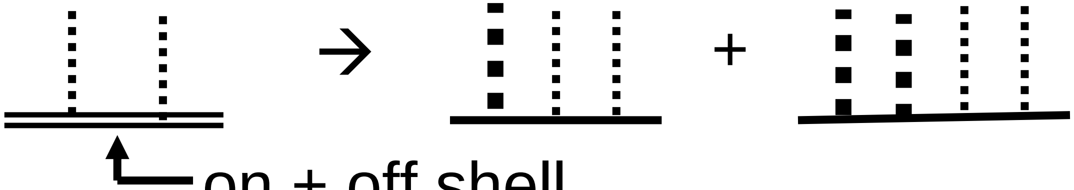
Dark Energy: $\frac{e_{vacuum}}{e_{tot}}$

or Einstein‘s constant or ?



sensors for the vacuum

Two-Photon Compton Process as a Signature of Unruh Effect

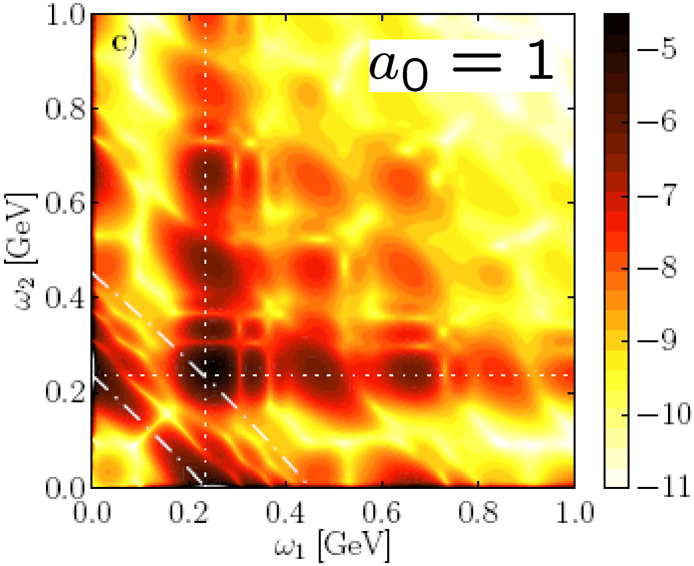


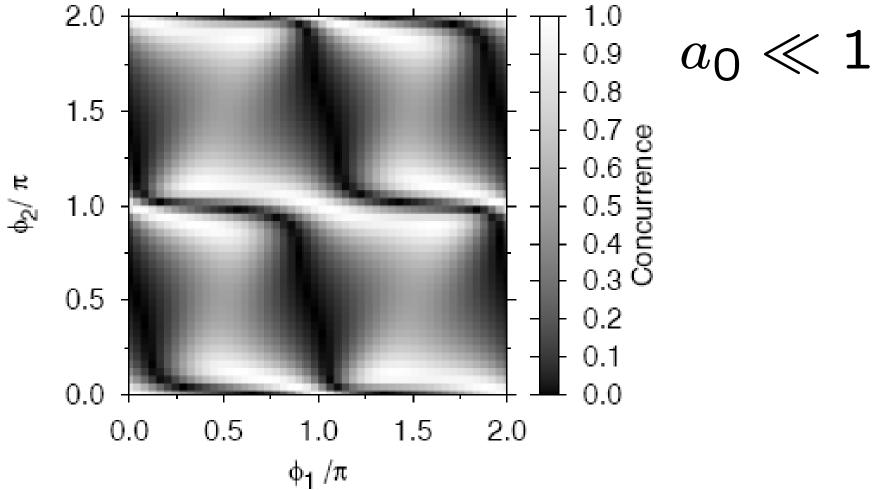
+ ... + exchange

on + off shell

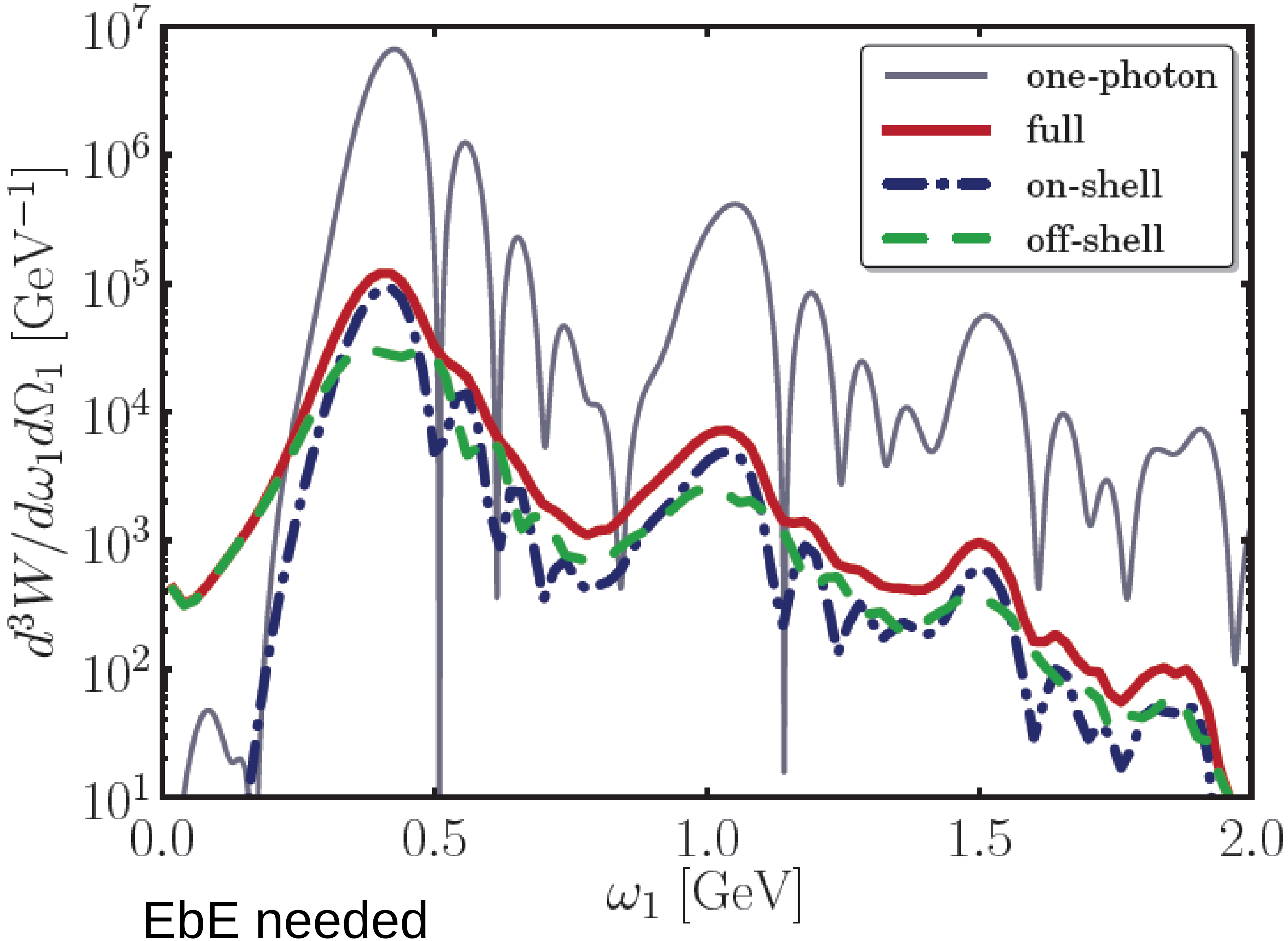
Chen, Tajima, PRL 1999
Thirolf et al., EPJD 2009
Schützhold, Schaller, Habs, PRL 2008
Schützhold, Maja, EPJD 2009

Unruh: frame dependence of vacuum
T_U ~ acceleration
accelerated electron emits entangled photon pairs





Suenert, diploma thesis Dresden 2010



EbE needed

FPA: D. Seipt, BK, PRD 2012
IPA: Lötstedt, Jentschura, PRL 2009, PRA 2009

Summary

QED: Breit-Wheeler process, Compton
m* effects are hardly measurable in laser pulses

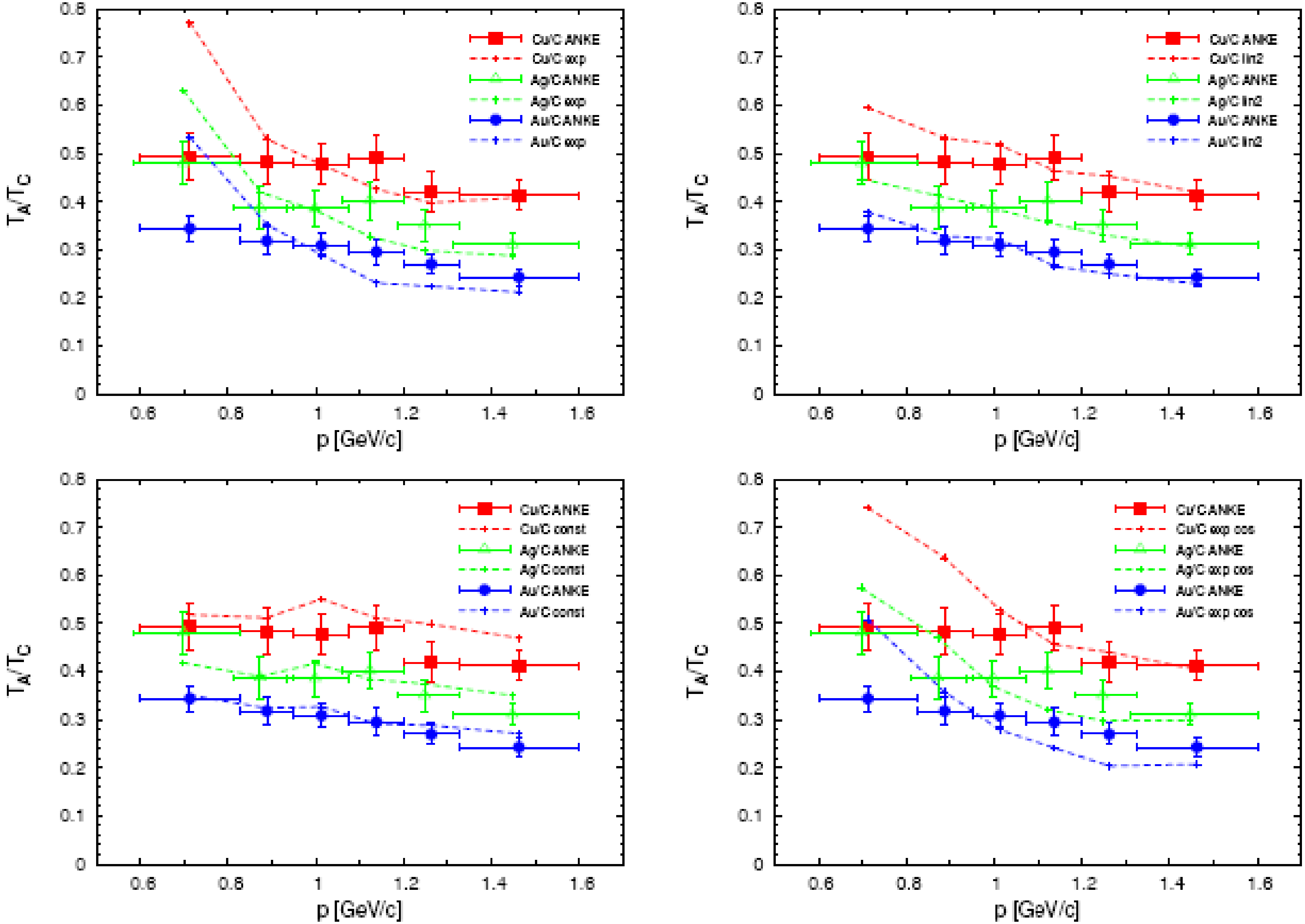
QCD: plenty of predictions of medium modifications,
medium changes of condensates (should) drive
medium modifications of hadrons

QCD sum rules: no direct link to shape of hadron spect. fncts.
rho & VOC: broadening as signal of chir. restoration
D – Dbar in nucl. matter due to chiral + qG +... conds.
V – A, S – P chir. partner SRs (-- „ --)

no direct link of QCD vacuum condensates to cosmic budget

phi (ANKE, CLAS) dramatic phi width in nucl. matter
(challenges to transport: sec. channels, phase space distr.)

Hayano, Hatsuda, Rev. Mod. Phys. (2010)
Leupold, Metag, Mosel, Int. J. Mod. Phys. (2010)
CLAS (Djalali, Wood, ...)



Cu/C ANKE
Cu/C exp
Ag/C ANKE
Ag/C exp
Au/C ANKE
Au/C exp
Cu/C ANKE
Cu/C lin2
Ag/C ANKE
Ag/C lin2
Au/C ANKE
Au/C lin2
Cu/C ANKE
Cu/C const
Ag/C ANKE
Ag/C const
Au/C ANKE
Au/C const
Cu/C ANKE
Cu/C exp cos
Ag/C ANKE
Ag/C exp cos
Au/C ANKE
Au/C exp cos
T_A/T_C
p [GeV/c]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.6
0.8
1
1.2
1.4
1.6

SU(2) chiral limit, leading order in n:

$$\frac{\langle\langle\bar{q}q\rangle\rangle_n}{\langle\bar{q}q\rangle_{vac}} = \left(\frac{f_\pi(n)}{f_{\pi,vac}}\right)^2 \left(\frac{m_\pi(n)}{m_{\pi,vac}}\right)^2$$

$$\left(\frac{m_\pi(n)}{m_{\pi,vac}}\right)^2 = 1 + \frac{2n}{f_{\pi,vac}^2}\left(2c_1 - c_2 - c_3 + \frac{g_A^2}{8m_N}\right)$$

$$\left(\frac{f_\pi(n)}{f_{\pi,vac}}\right)^2 = 1 + \frac{2n}{f_{\pi,vac}^2}\left(c_2 + c_3 - \frac{g_A^2}{8m_N}\right)$$

Thorsson, Wirzba, NPA (1995)
Meissner et al., Ann. Phys. (2002)

low-energy pi-A scattering, pionic atoms → chiral softening

$$\frac{\langle\langle\bar{q}q\rangle\rangle_n}{\langle\bar{q}q\rangle_{vac}} = 1 - 0.37\frac{n}{n_0}$$

Jido et al., PLB (2008)

---

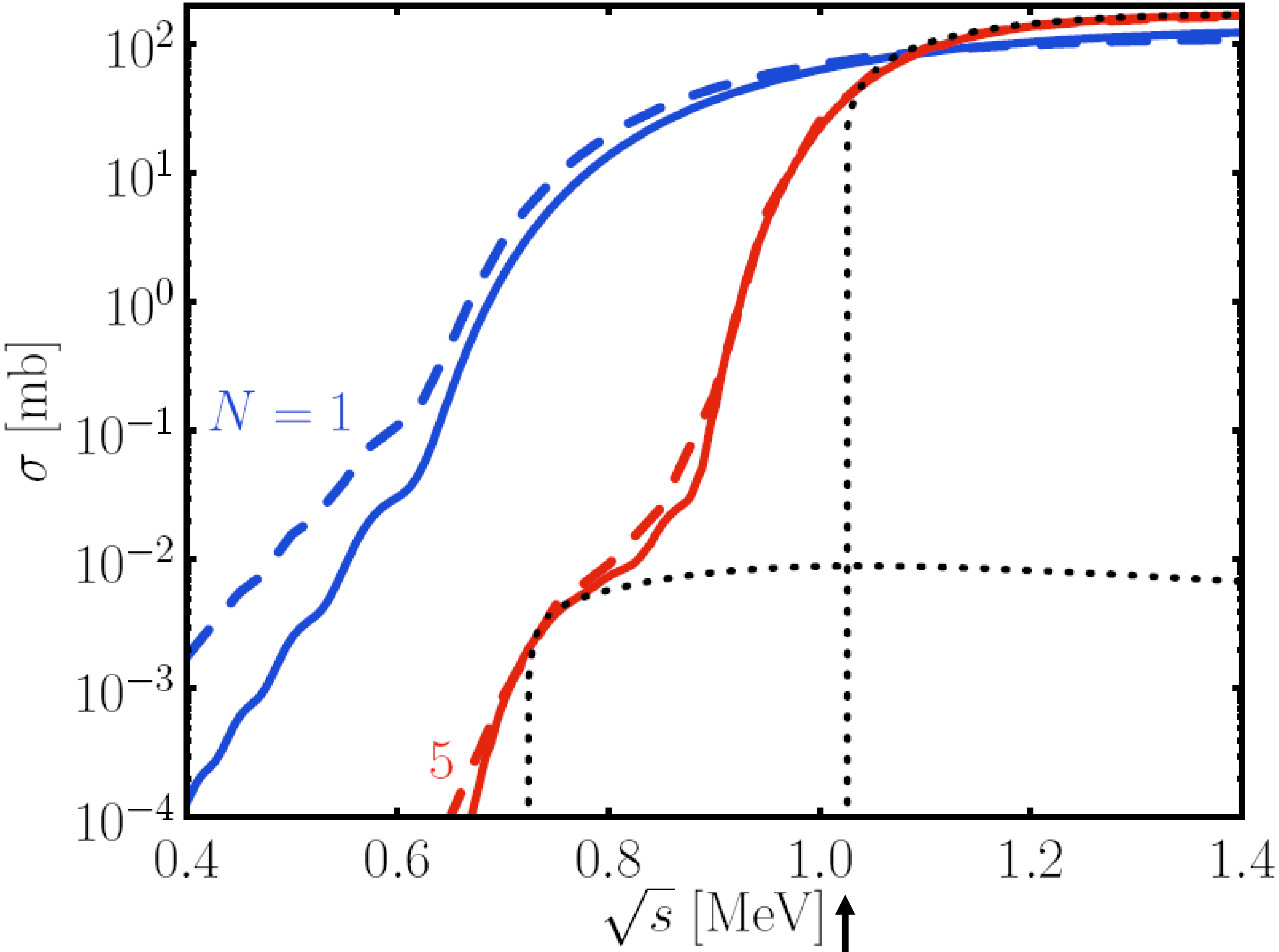
no rigorous relation of $\rho_{V,A}$ to $\langle\langle\bar{q}q\rangle\rangle$

$$\rho_V = (1-\epsilon(T))\rho_{vac}^V + \epsilon(T)\rho_{vac}^A$$
$$\rho_A = (1-\epsilon(T))\rho_{vac}^A + \epsilon(T)\rho_{vac}^V$$

Dey et al. PLB (1990)

in accordance with Weinberg‘s chiral sum rule

$$\int d\omega^2\omega^2(\rho_V(\omega) - \rho_A(\omega)) = -\frac{4\pi}{3}\alpha_s O_4$$

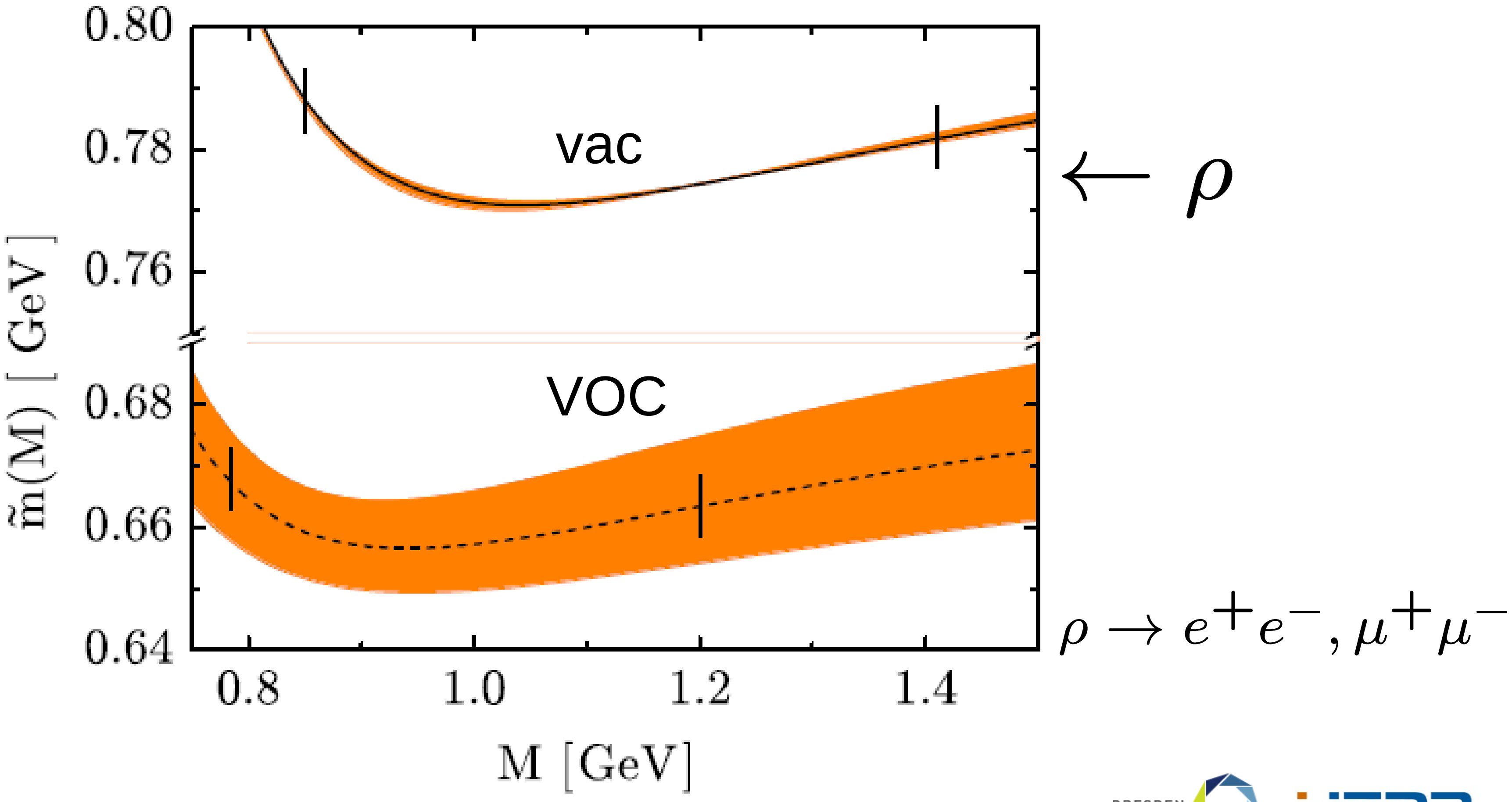

10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
σ [mb]
$N = 1$
5
0.4
0.6
0.8
1.0
1.2
1.4
$\sqrt{s}$ [MeV]

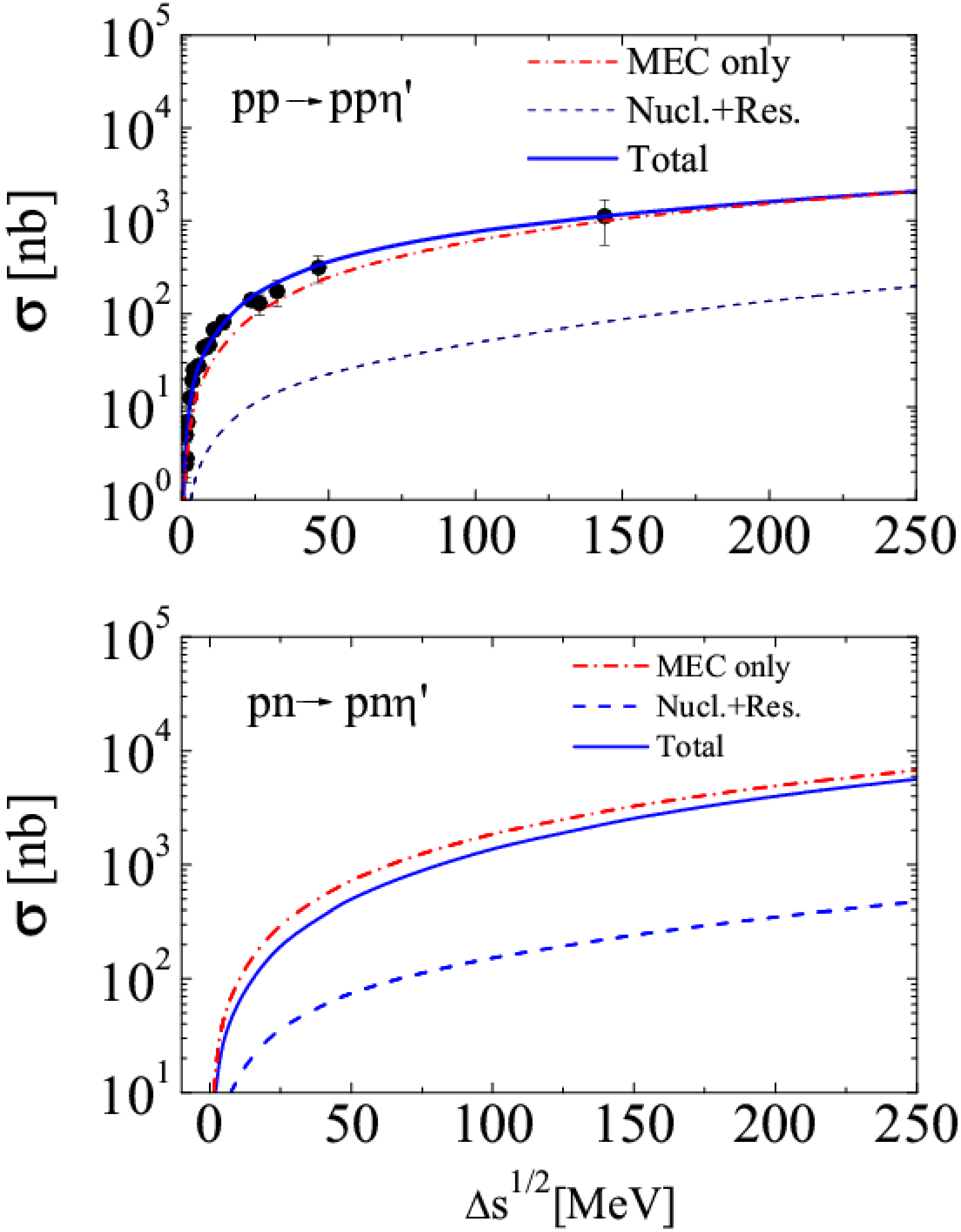
↑ 2 m

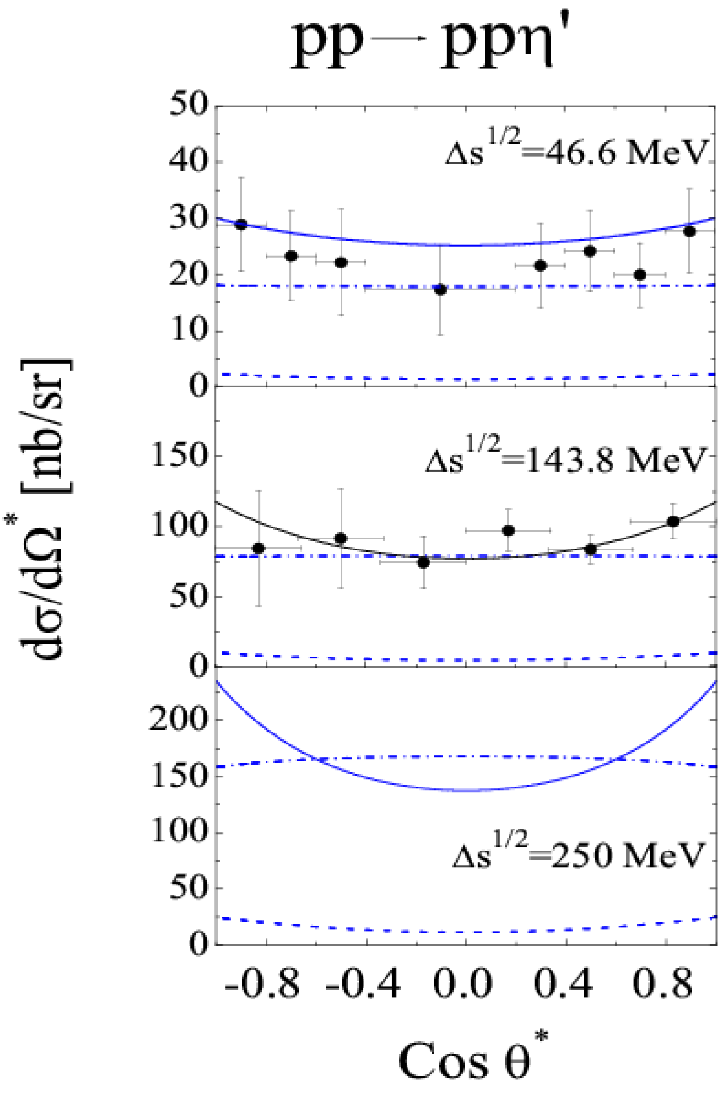
rho Meson and VOC

(vanishing of chirally odd condenstates: VOCOC = V(OC)^2→ VOC)

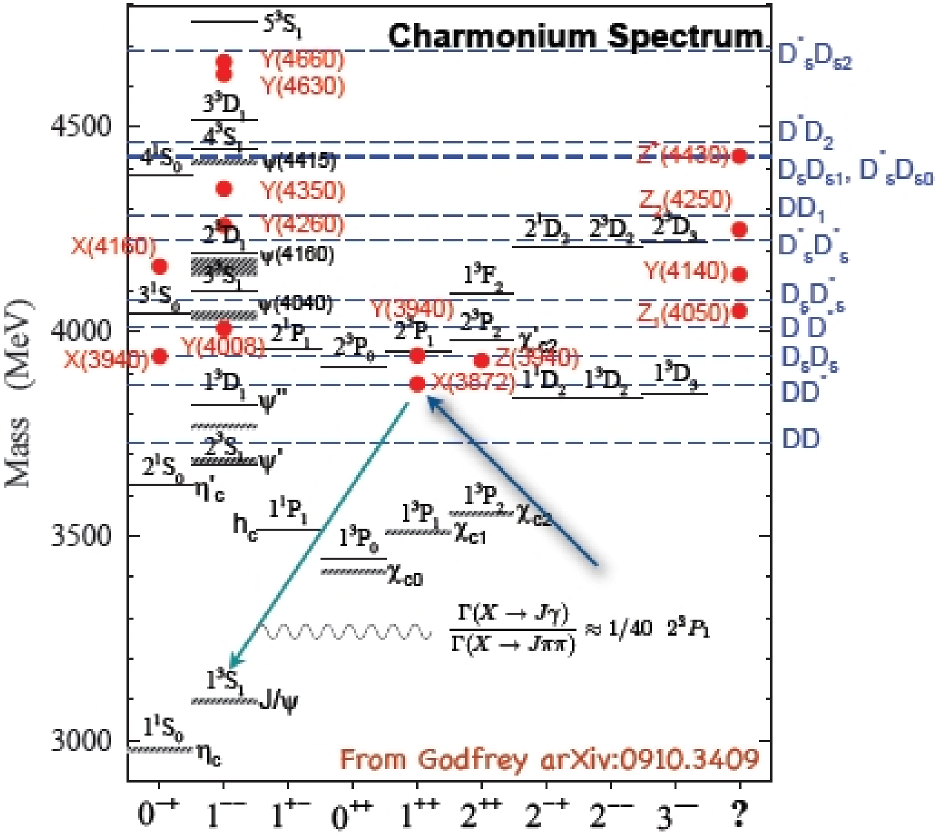
chiral restoration: <q̄ q> → 0 (large density/temperature)



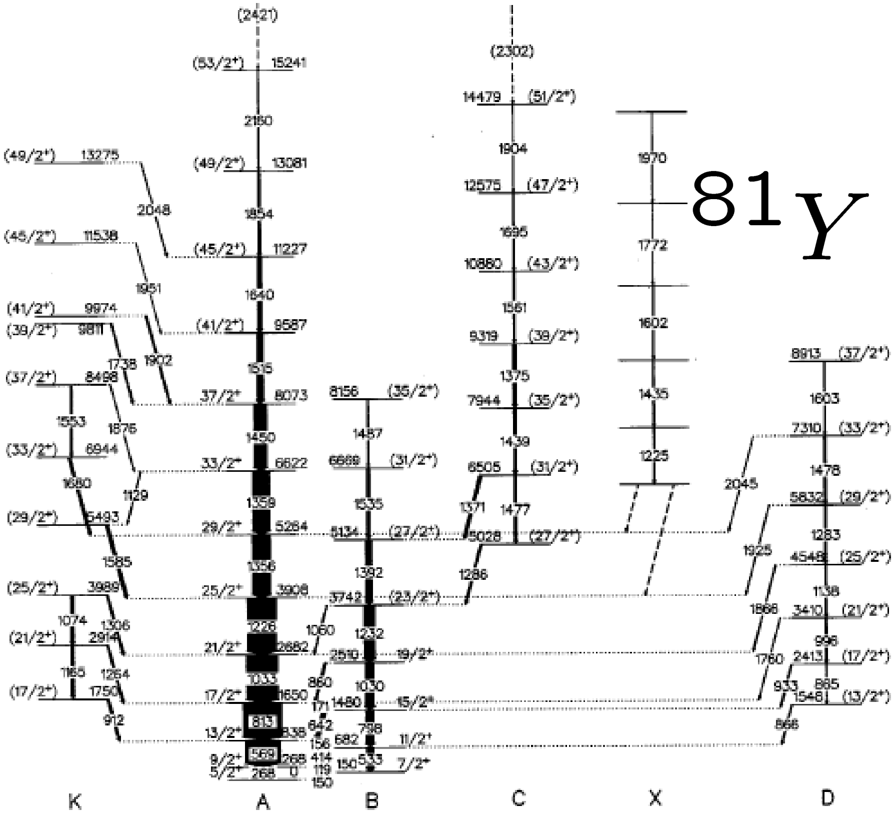

pp→ppη'
MEC only
Nucl.+Res.
Total
σ [nb]
10^0 10^1 10^2 10^3 10^4 10^5
0 50 100 150 200 250
pn→pnη'
MEC only
Nucl.+Res.
Total
σ [nb]
10^1 10^2 10^3 10^4 10^5
0 50 100 150 200 250
$\Delta s^{1/2}$[MeV]


pp→ppη'
$d\sigma/d\Omega^*$ [nb/sr]
$\Delta s^{1/2}$=46.6 MeV
0 10 20 30 40 50
$\Delta s^{1/2}$=143.8 MeV
0 50 100 150
$\Delta s^{1/2}$=250 MeV
0 50 100 150 200
-0.8 -0.4 0.0 0.4 0.8
Cos θ^*

Hadrons as Excitations of/above Vacuum



From Godfrey arXiv:0910.3409



vacuum
E = 0