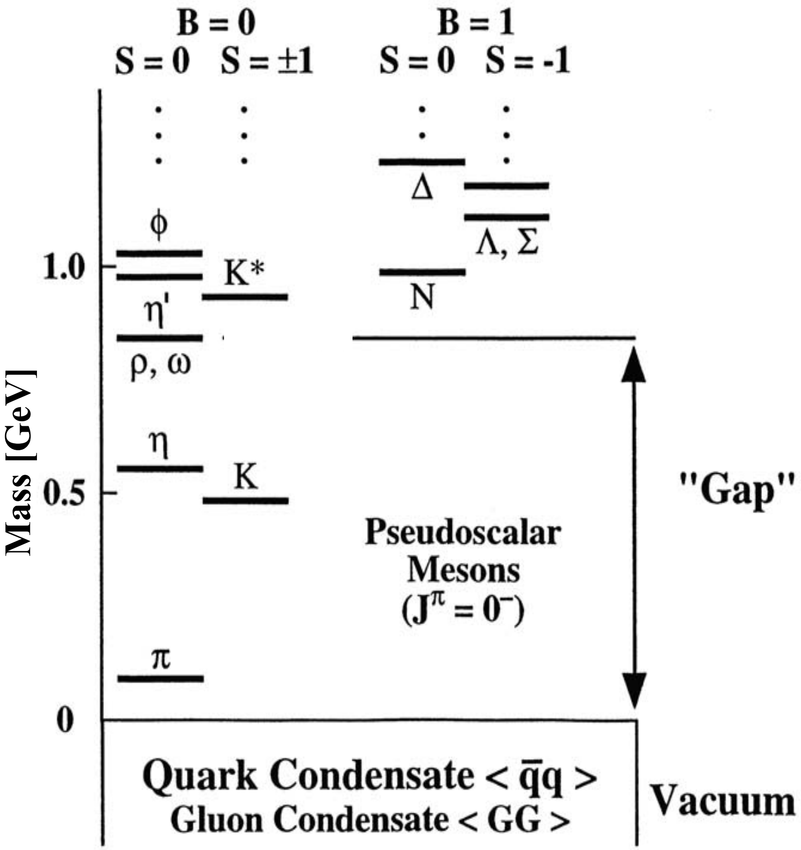
In-medium modifications of vector mesons in elementary reactions and heavy-ion collisions

Volker Metag
II. Physikalisches Institut
Universität Giessen
Germany

- **theoretical motivation and predictions**
- **medium modifications observed in elementary reactions: KEK-E325, Jlab-G7, CBELSA/TAPS**
- **medium modifications observed in heavy-ion collisions: DLS, HADES, CERES, NA60**
- **summary and conclusions**

Quark Matter 2006
Shanghai, China, Nov 12th-20th 2006

Motivation



- **hadrons = excitations of the QCD vacuum**
- **QCD-vacuum: complicated structure characterized by condensates**
- **in the nuclear medium: condensates are changed**

→ change of the hadronic excitation energy spectrum

G.E.Brown and M. Rho, PRL 66 (1991) 2720

$$\frac{m^*}{m} \approx \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} \approx 0.8\,(\rho \approx \rho_0)$$

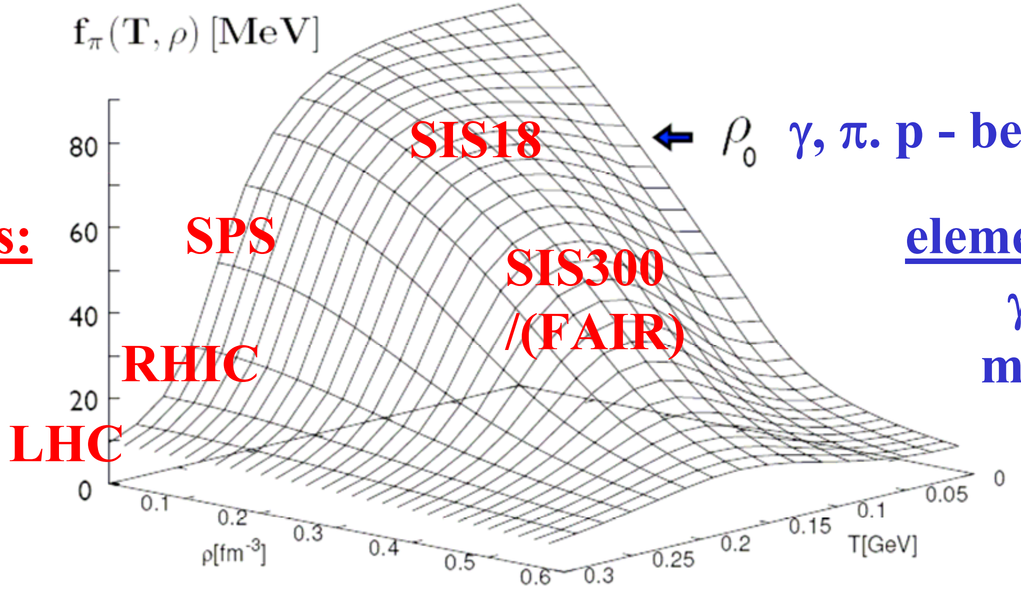
T.Hatsuda and S. Lee, PRC 46 (1992) R34

$$\frac{m_V^*}{m_V} = \left(1 - \alpha \frac{\rho_B}{\rho_0}\right) ; \; \alpha \approx 0.18$$

⇒ widespread theoretical and experimental activities to study in-medium modifications of hadrons

chiral condensate as function of baryon density ρ_B and temperature T

C. Ratti, M. Thaler, W. Weise, PRD73 (2006) 014019



← ρ_0 γ, π. p - beams

heavy ion reactions:

A+A→V+X

$m_V(\rho \gg \rho_0; T \gg 0)$

elementary reaction:

γ, π → V+X

$m_V(\rho=\rho_0; T=0)$

$$\frac{f_\pi^2(T,\rho)}{f_\pi^2(0)} \simeq \frac{\langle \bar{q}q \rangle_{T,\rho}}{\langle \bar{q}q \rangle_0} \simeq 1 - \frac{T^2}{8 f_\pi^2} - \frac{\sigma_N}{m_\pi^2 f_\pi^2}\rho + \ \dots$$

$\langle q\bar{q} \rangle$ **is not an observable!!**

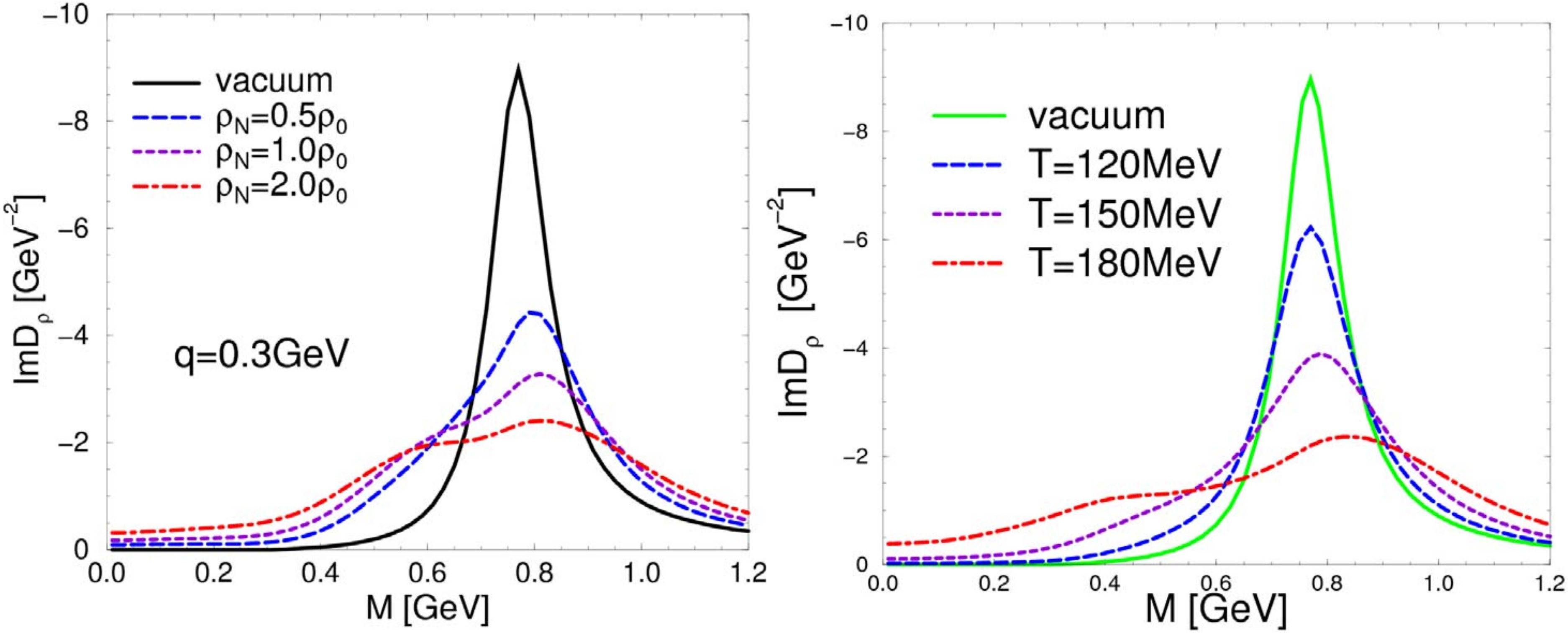
QCD sum rules: provide link between hadronic observables and condensates

$$\frac{Q^2}{24\pi^2}\int ds \frac{R(s)}{(s+Q^2)^2} = \frac{1}{16\pi^2}\left(1+\frac{\alpha_s}{\pi}\right) + \frac{1}{Q^4}\left[m_q\langle \bar{q}q \rangle + \frac{1}{24}\left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle\right] + \text{higher order terms}$$

hadronic spectral function: $R(s) \sim F^2 \frac{1}{\pi} \frac{\sqrt{s}\,\Gamma(s)}{\left(s - M_\rho{}^2\right)^2 + s(\Gamma(s))^2}$

ρ spectral function for different densities and temperatures

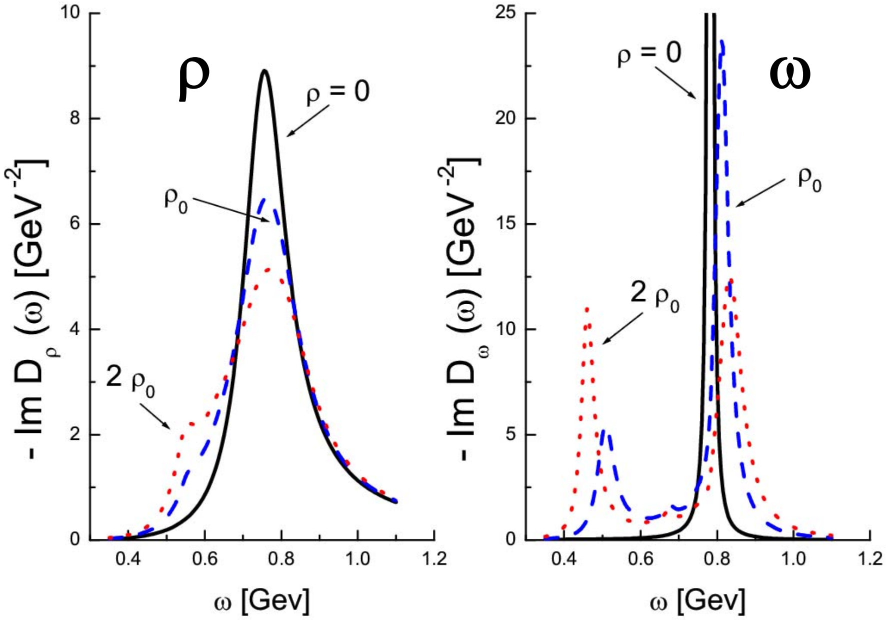
R. Rapp and J. Wambach, EPJA 6 (1999) 415



broadening and strength below vacuum pole mass

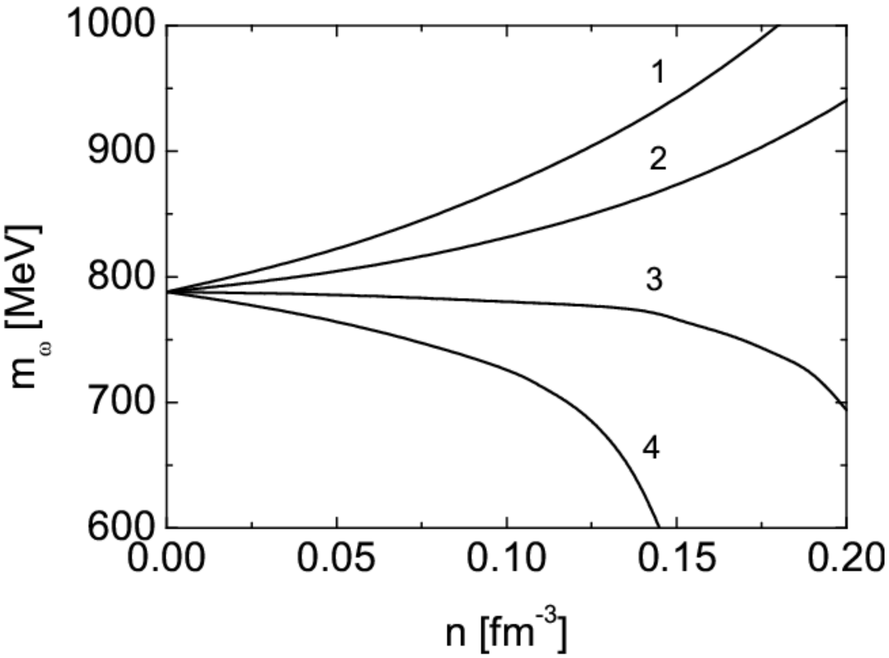
Model predictions for spectral functions of ρ and ω mesons

M. Lutz et al. , Nucl. Phys. A 706 (2002) 431



structure in spectral function due to coupling to baryon resonances

S. Zchocke et al. , Phys. Lett. B 562 (2003) 562



variation in ω-mass due to density dependence of 4-quark condensate

experimental approach: dilepton spectroscopy: $\rho, \omega, \phi \rightarrow e^+e^-$

reconstruction of invariant mass from 4-momenta of decay products:

$$m_\omega(\rho, T, \vec{p}) = \sqrt{(p_1 + p_2)^2}$$

essential advantage: no final state interactions !!

I. Information on medium modifications of mesons from elementary reactions

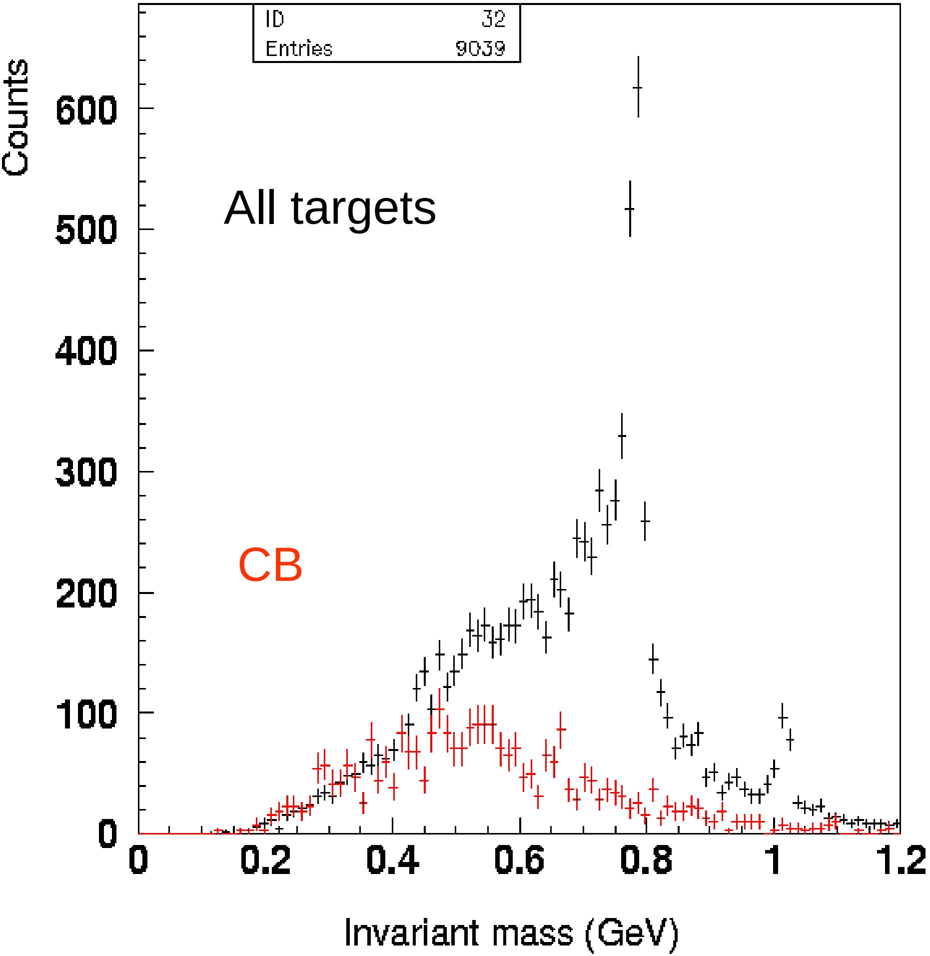
advantage: well controlled conditions:
important for theoretical interpretation
no time dependence of baryon density $\rho_B \neq \rho_B(t)$;T=0;

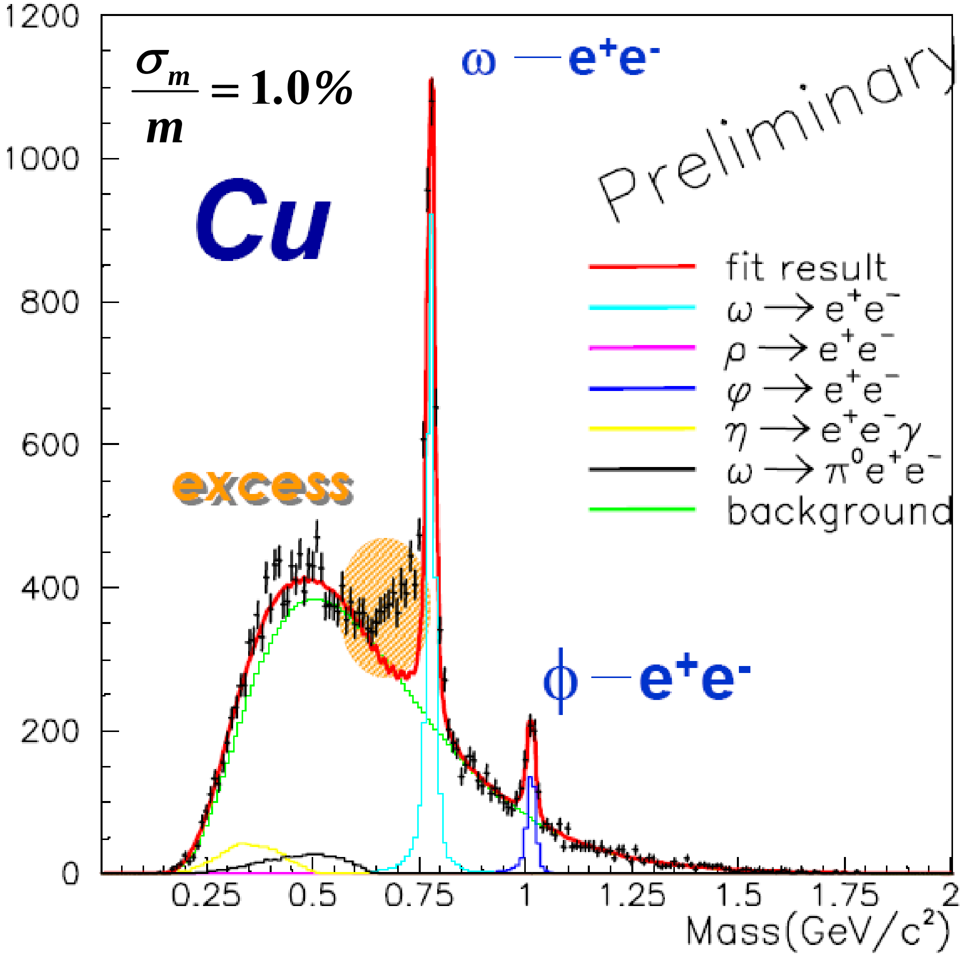
disadvantage: small medium effects since $\rho \leq \rho_0$ and T=0

JLAB-CLAS: G7 $\gamma A \rightarrow e^+e^- + X$

$E_\gamma = 0.6\text{-}3.8$ GeV

KEK-E325: p (12 GeV) $A \rightarrow \rho, \omega + X$





s. plenary talk by Ch. Djalali

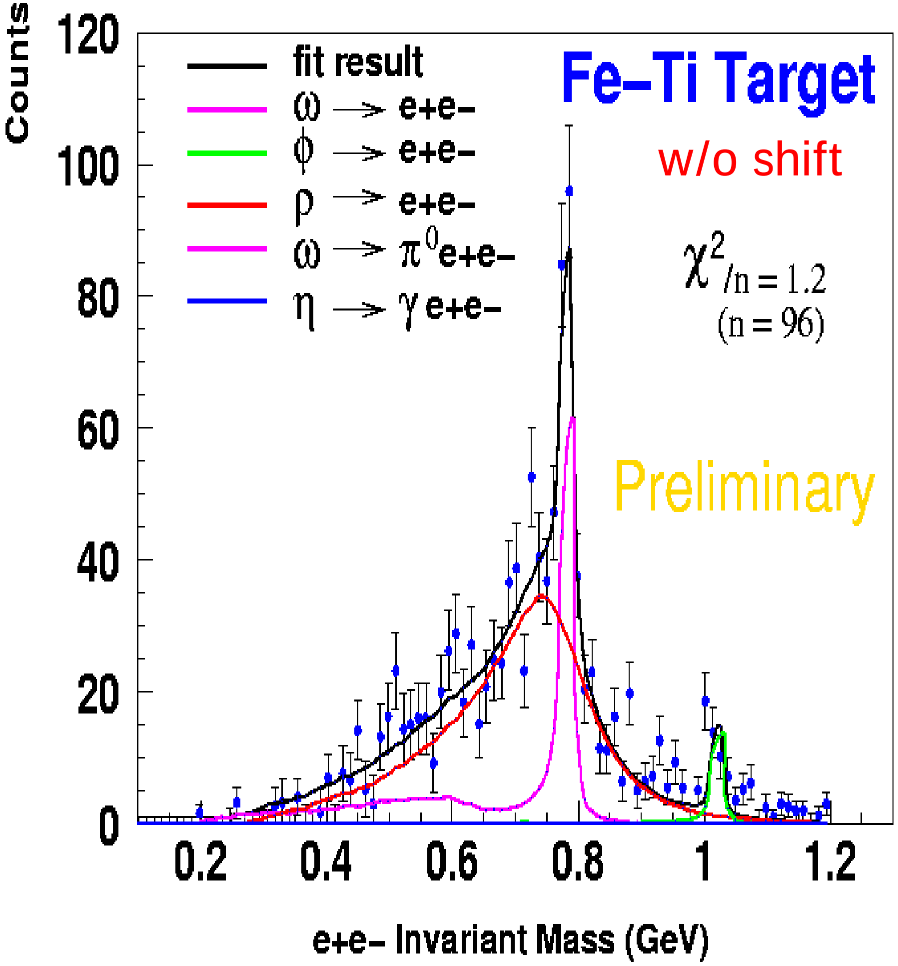
s. talk by M. Naruki

ω, φ -peaks observed;

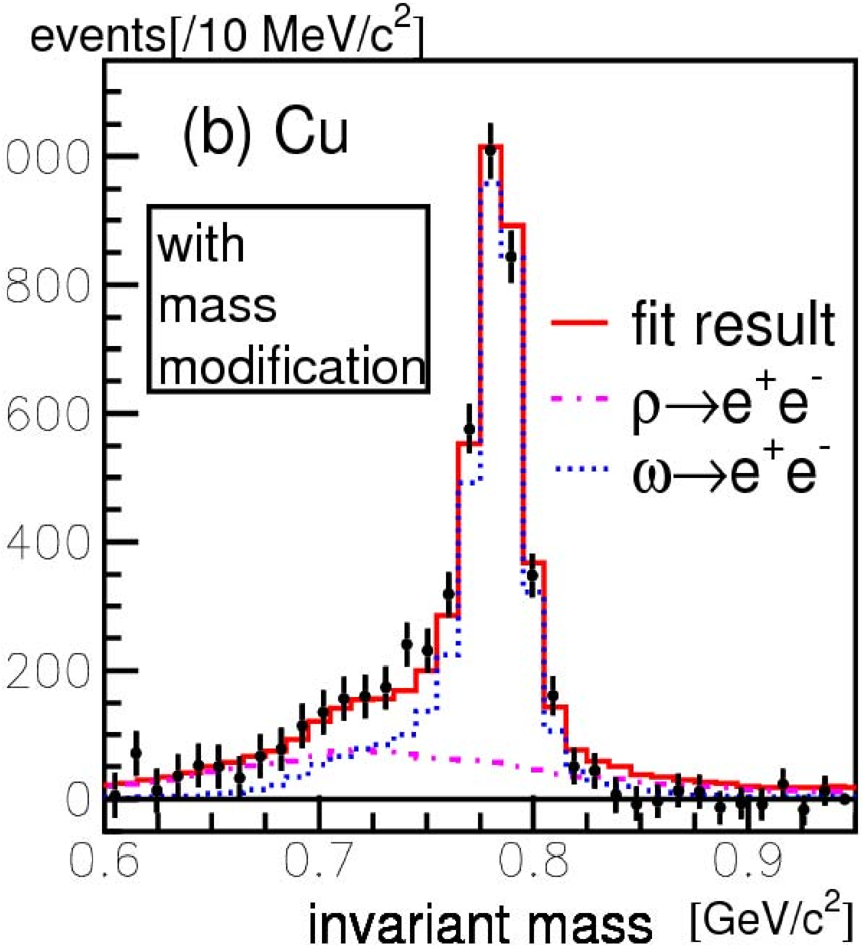
additional yield above combinatorial background assigned to $\rho \rightarrow e^+e^-$

comparison of JLAB and KEK results

JLAB-CLAS: G7 $\gamma A \rightarrow e^+e^- + X$



KEK-E325: p (12 GeV) $A \rightarrow \rho, \omega + X$



ρ slightly broadened; no mass shift

ρ shifted in mass: $m_\rho = m_0\left(1-0.092\frac{\rho}{\rho_0}\right)$; **no broadening!!**

No consistent picture!!

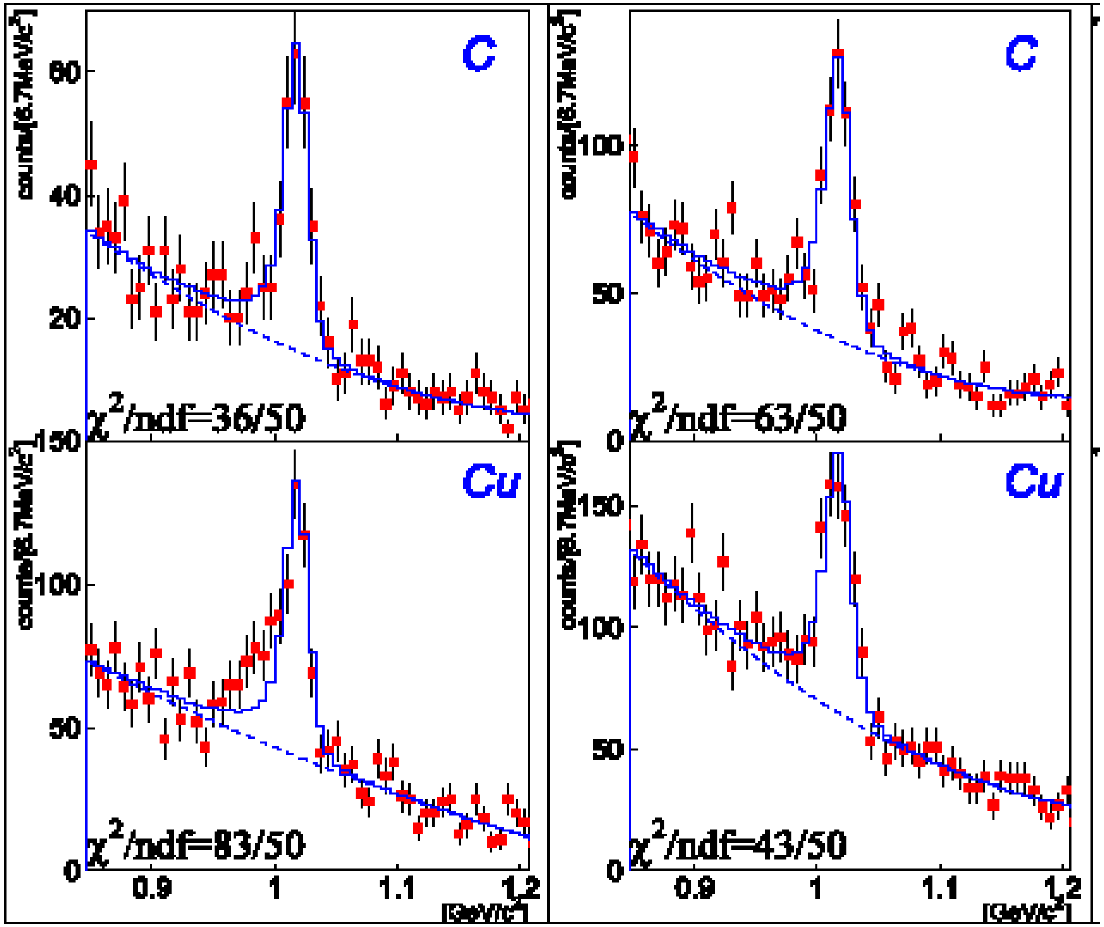
M. Naruki et al., PRL 96 (2006) 092301

Φ - meson in the nuclear medium

R.Muto et al., nucl-ex/0511019

KEK-E325: p (12 GeV) A→ ρ, ω +X; $\Phi \to e^+e^-$

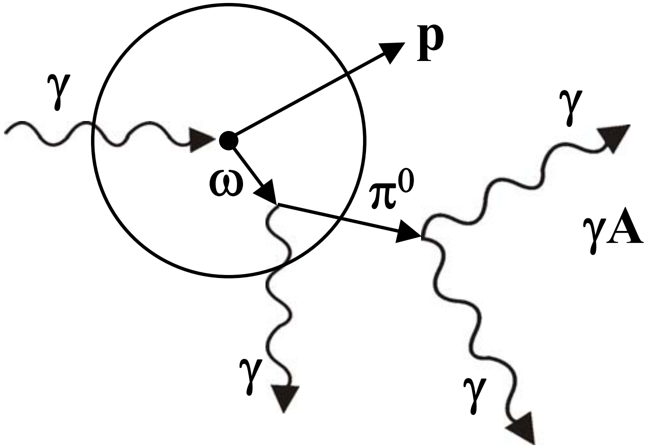
βγ<1.25 (Slow) 1.25<βγ<1.75



mass shift of Φ - meson for low recoil momenta in Cu: $m_\Phi = m_0\left(1-0.04\frac{\rho}{\rho_0}\right)$;

ω-mass in nuclei from photonuclear reactions

J.G.Messchendorp et al., Eur. Phys. J. A 11 (2001) 95



$$\gamma A \rightarrow \omega + X$$
$$\hookrightarrow \pi^0\gamma$$
$$\hookrightarrow \gamma\gamma$$

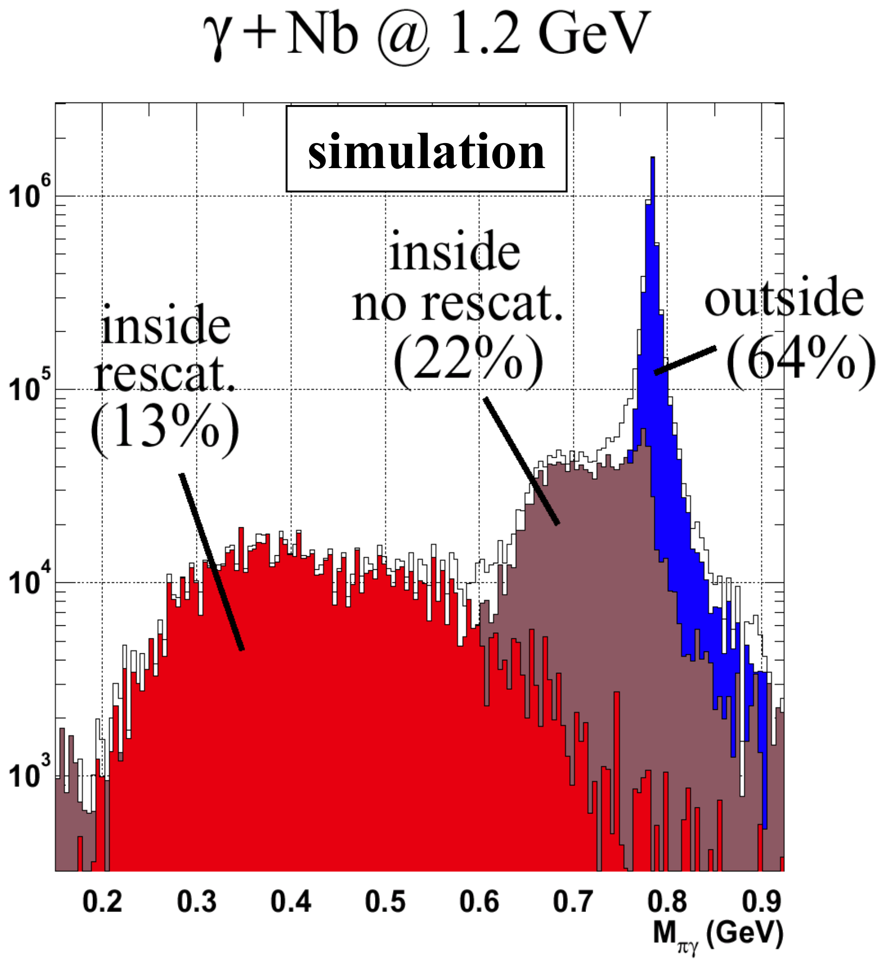
$$m_\omega = \sqrt{(p_\pi + p_\gamma)^2}$$

advantage:

- $\pi^0\gamma$ large branching ratio (8 %)
- no ρ-contribution ($\rho \rightarrow \pi^0\gamma : 7 \cdot 10^{-4}$)

disadvantage:

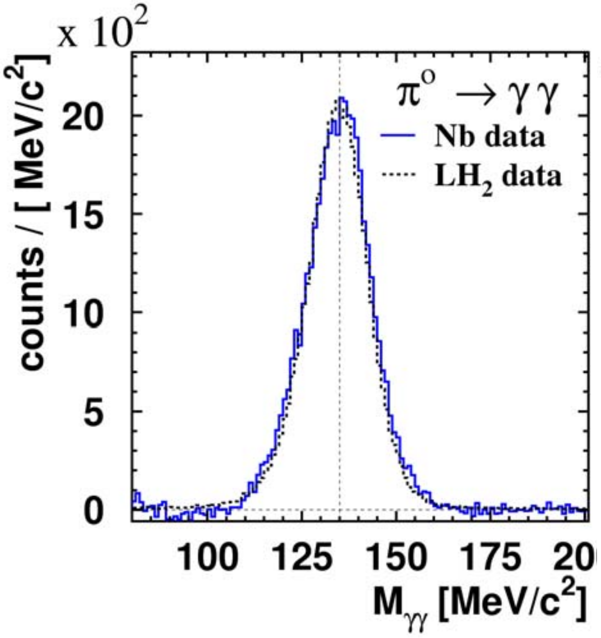
- π^0-rescattering


$\gamma + \text{Nb}$ @ 1.2 GeV

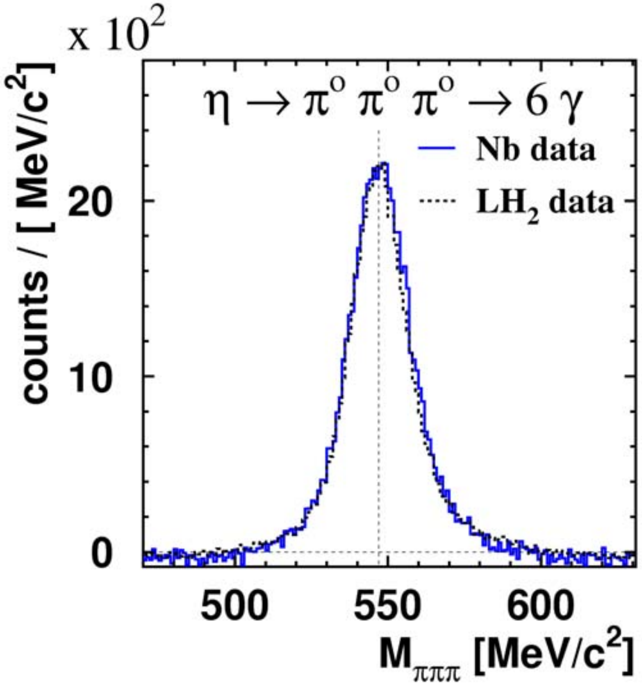
no distortion by pion rescattering expected in mass range of interest; further reduced by requiring T_π>150 MeV

comparison of meson masses and lineshapes for LH_2 and nuclear targets after background subtraction

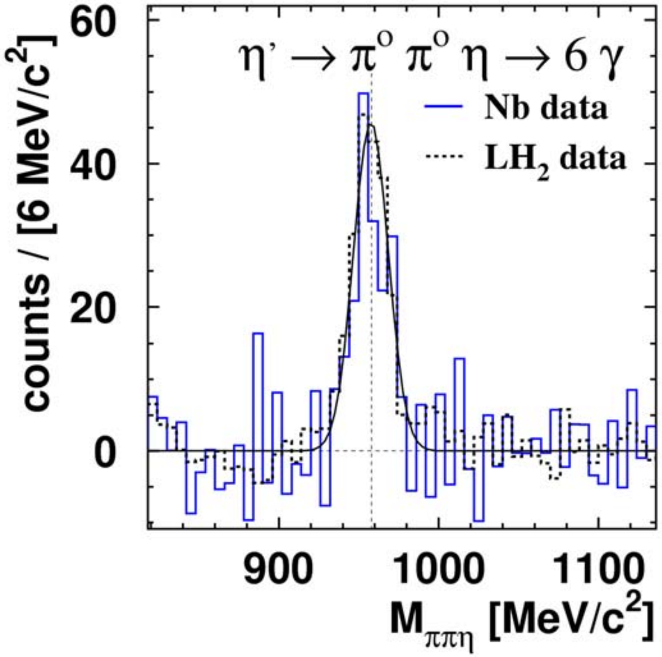
π^0



η



η'

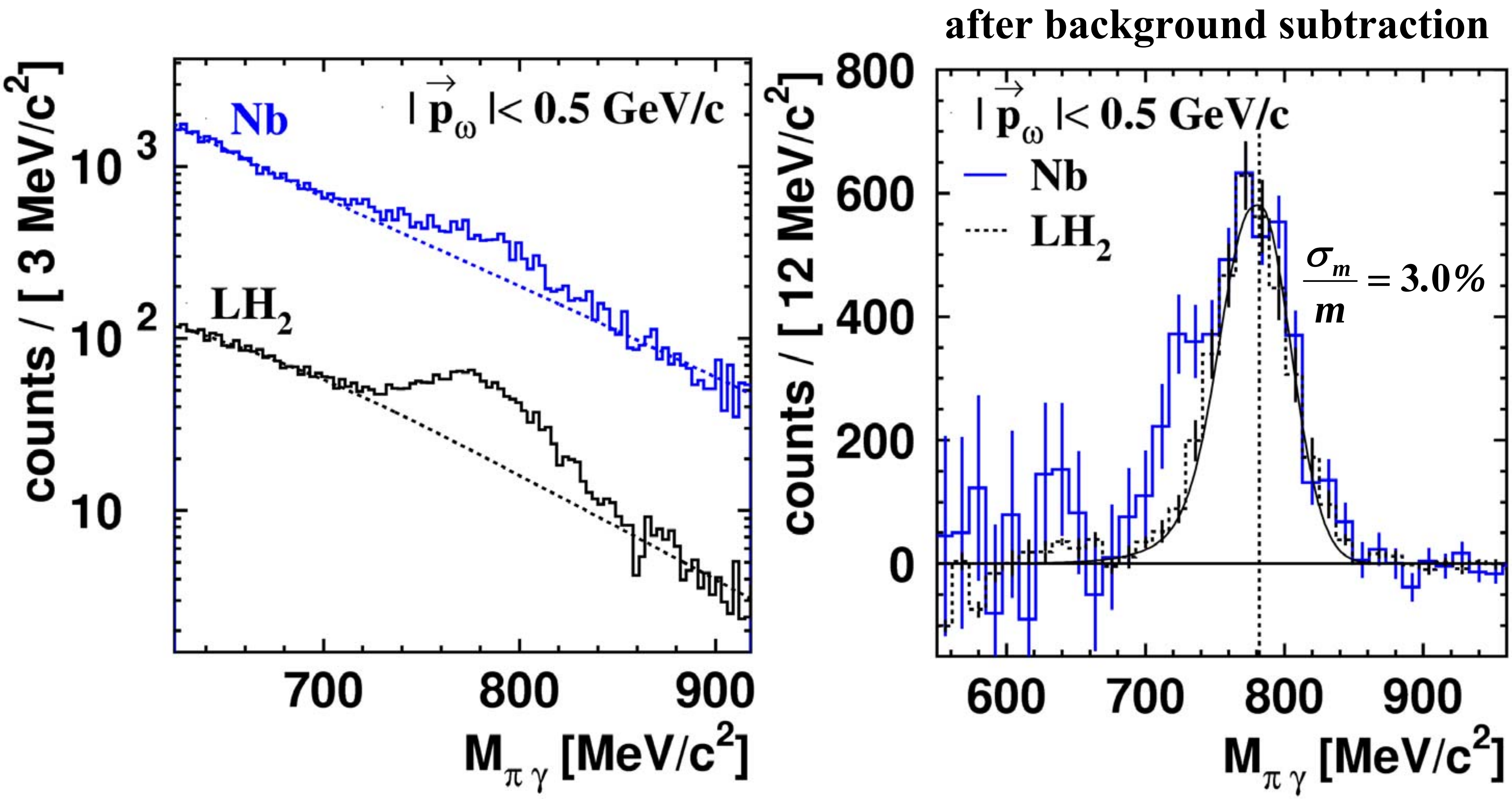


No change of mass and lineshape for longlived mesons (π^0, η, η') decaying outside nuclei

inclusive $\omega \to \pi^0 \gamma$ signal for LH_2 and Nb target

D. Trnka et al., PRL 94 (2005) 192203

after background subtraction



difference in line shape of ω signal for proton and nuclear target

consistent with $m_\omega = m_0 (1 - \alpha\, \rho/\rho_0)$ for $\alpha = 0.13$

refined analysis requiring recoil proton and p-ω coplanarity

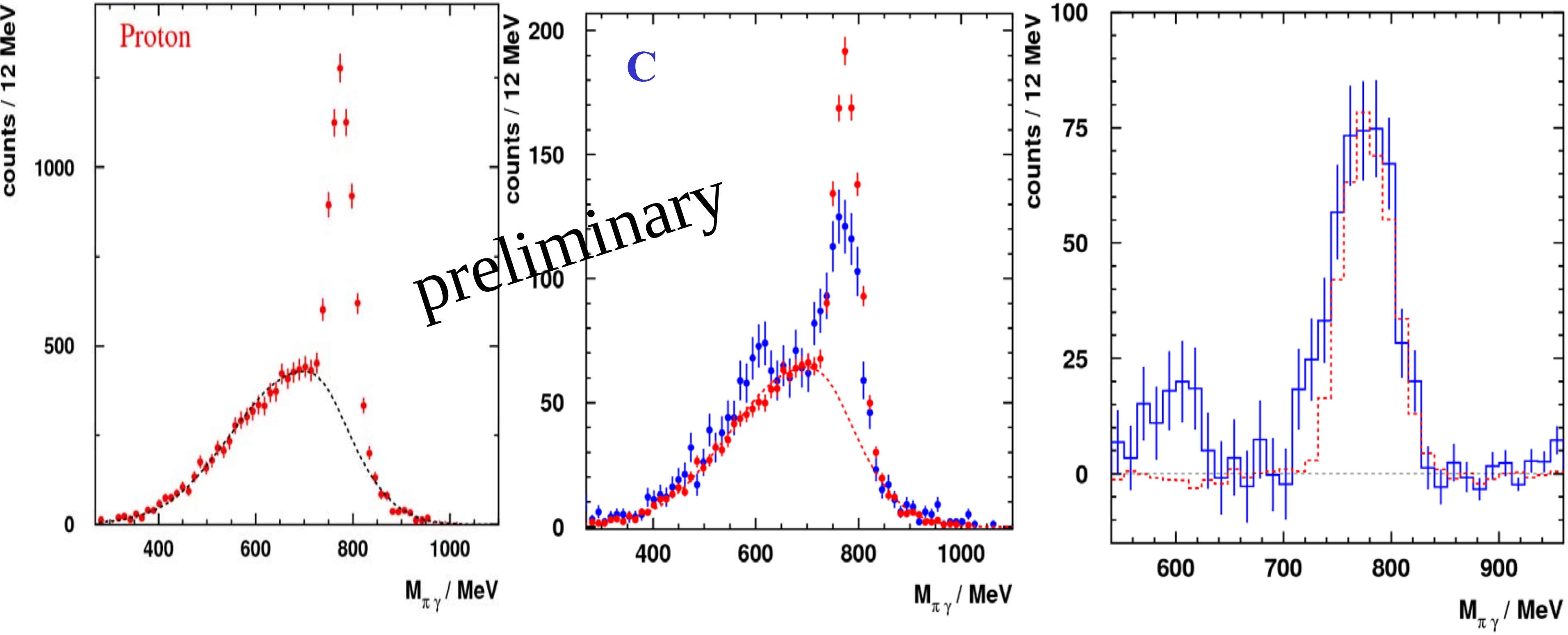
D. Trnka (Gießen) priv. com.

No background subtraction!!!

after LH_2 background subtraction

$|p_\omega| < 500$ MeV/c

$|p_\omega| < 500$ MeV/c



⇒ difference in ω - line shape for proton and nuclear target confirmed; no upward mass shift of ω meson!

⇒ additional structure at ≈ 600 MeV!! (also seen for heavier targets) fragmentation of ω strength or background ??? under investigation

II. Information on medium modifications of mesons from heavy-ion collisions

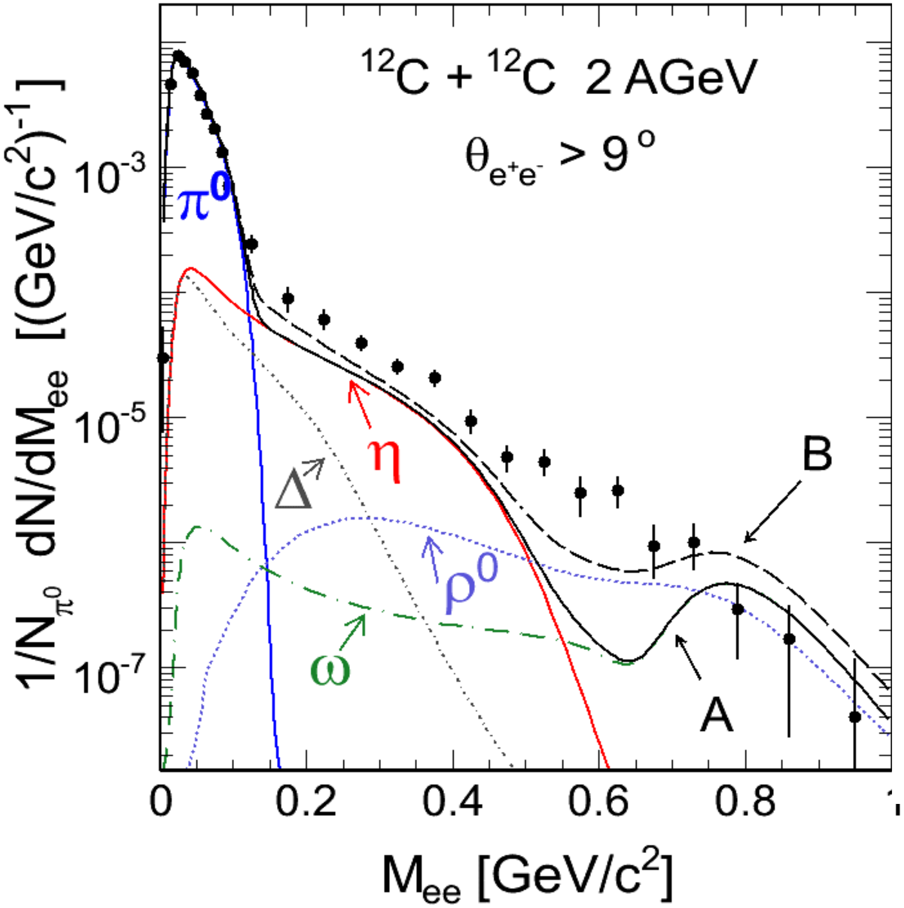
advantage: sizable effects due to high densities and temperatures

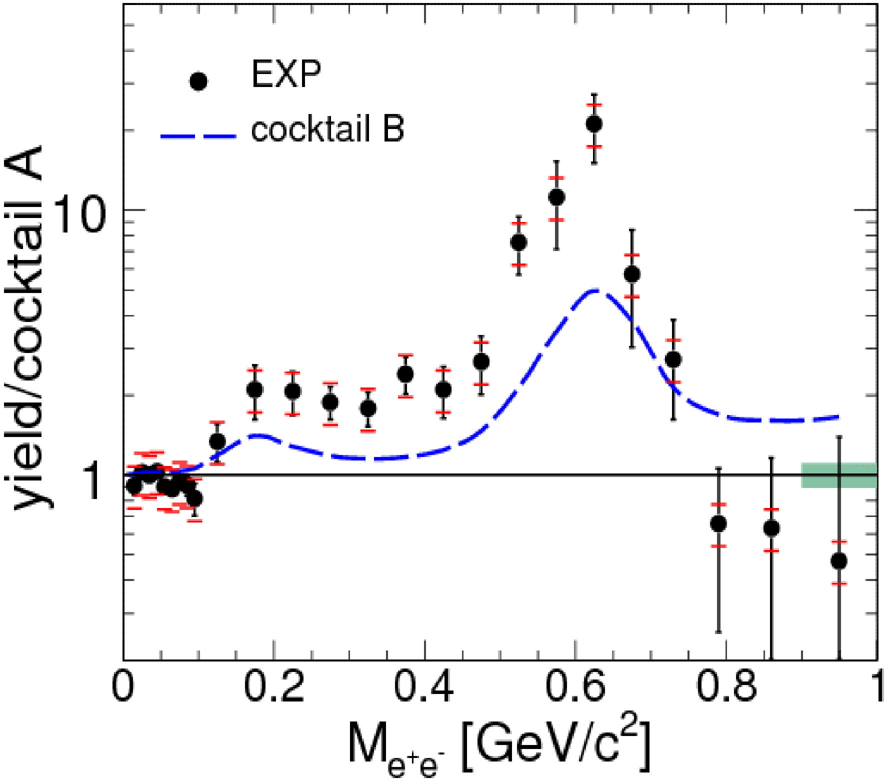
disadvantage: any signal represents an integration over the full
space-time history of the heavy-ion collision with
strong variations in densities and temperatures

HADES

s. talk by J. Markert

G. Agakichiev et al, subm. to PRL





sizable excess in dilepton yield relative to contributions from long-living mesons

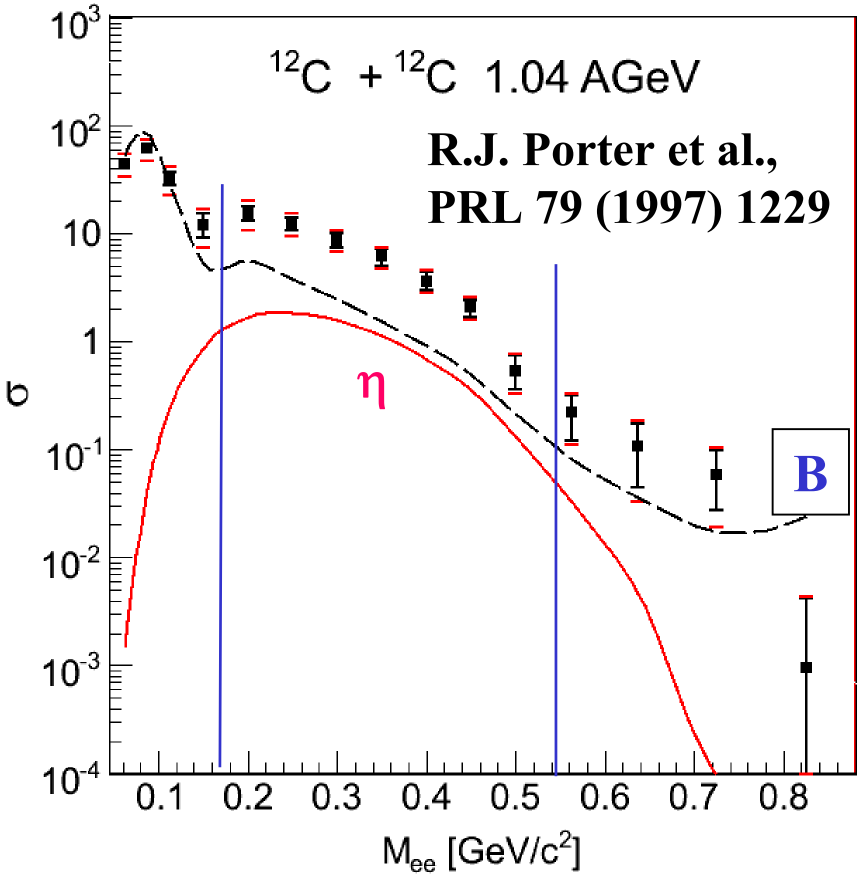
origin of excess-yield??

cocktail A: post freeze-out hadronic sources:
$\pi^0, \eta \to \gamma e^+e^-$; $\omega \to \pi^0 e^+e^-$; $\omega \to e^+e^-$;

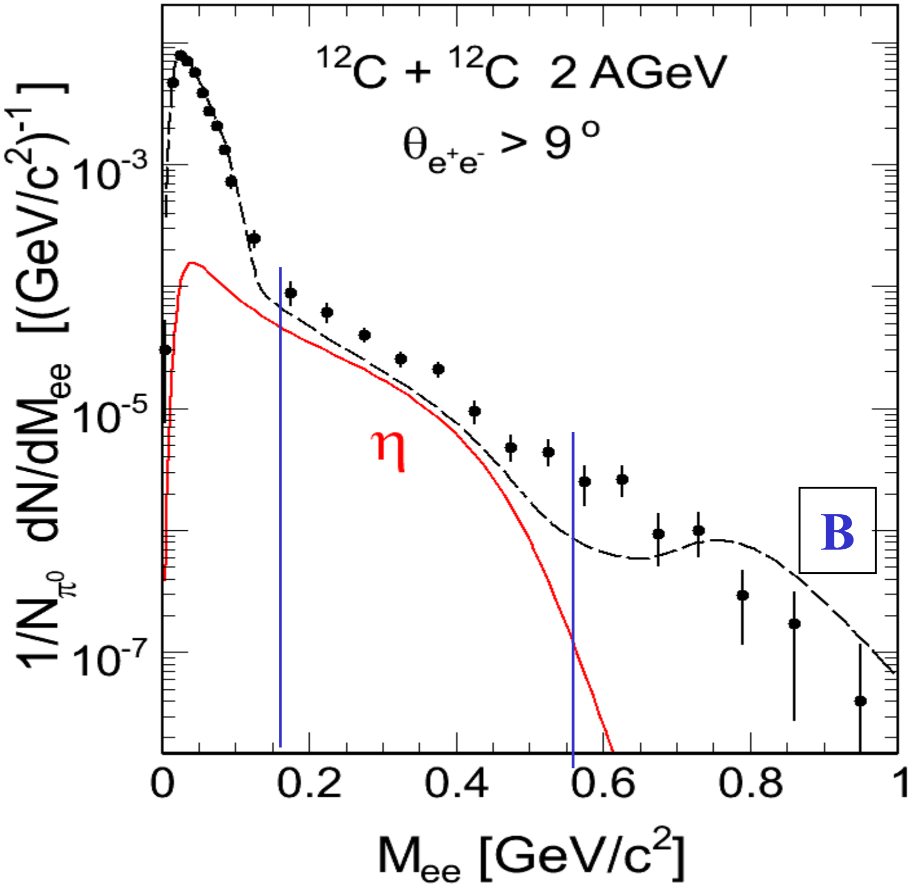
cocktail B: additional fireball sources:
$\Delta \to N e^+e^-$; $\rho \to e^+e^-$;

Dilepton production in C+C

DLS



HADES



for 170 MeV < M_{ee} < 550 MeV

F(1.04 AGeV) = 6.5 ± 0.5(stat) ± 2.1(sys)

F(2.0 AGeV) = 2.07 ± 0.21(stat) ± 0.38(sys)

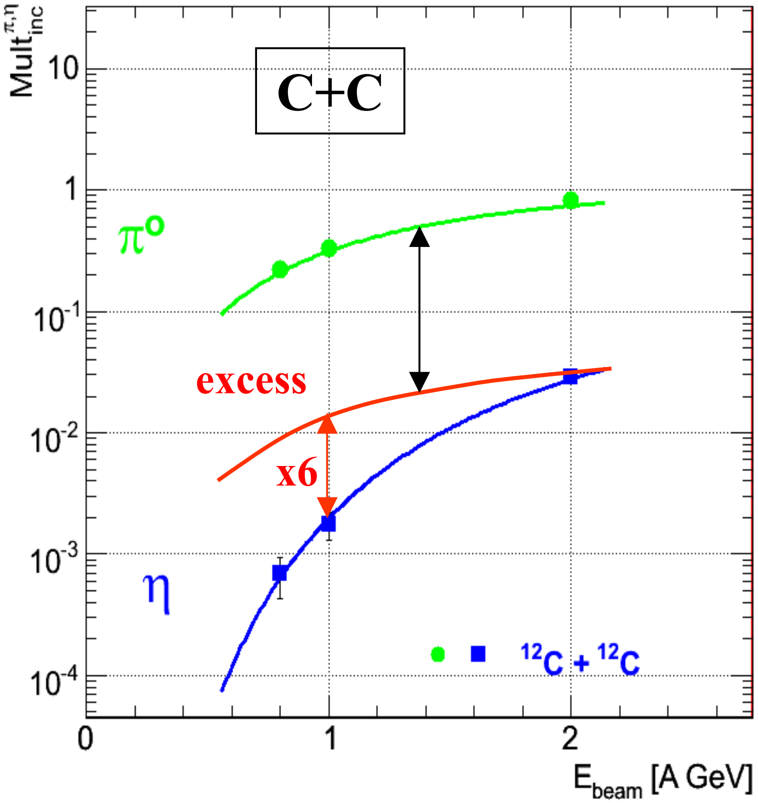
$$F = \frac{Y_{tot}}{Y_\eta} = \frac{Y_{exc} + Y_\eta}{Y_\eta} = \frac{Y_{exc}}{Y_\eta} + 1$$

$$\Rightarrow Y_{exc} = (F - 1)Y_\eta$$

comparison of excess yield with π⁰, η- cross section

TAPS data:
R. Averbeck et al., Z. Phys. A359 (1997) 65
R. Holzmanm et al., PRC 56 (1997) R2920

π and η multiplicities vs. E_{beam}



$$\frac{Y_{exc}(2.0\,AGeV)}{Y_{exc}(1.04\,AGeV)} = \frac{(F(2.0)-1)}{(F(1.04)-1)} \cdot \frac{Y_\eta(2.0)}{Y_\eta(1.04)}$$

$$= 2.5 \pm 0.5\,(stat) \pm 1.5\,(sys)$$

$$\frac{Y_\pi(2.0\,AGeV)}{Y_\pi(1.04\,AGeV)} = 2.3 \pm 0.3$$

excess yield scales with π^0 cross section !! and amounts to ≈ $2 \cdot 10^{-5}$ of the π^0-yield

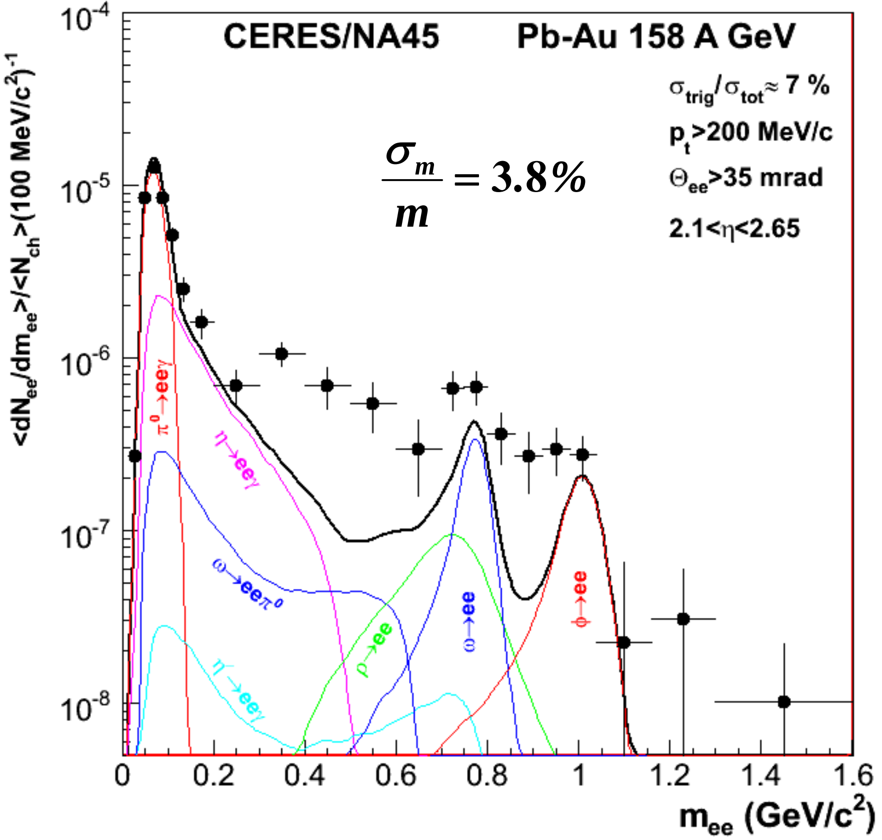
(assuming similar acceptances for the excess- and η-yields)

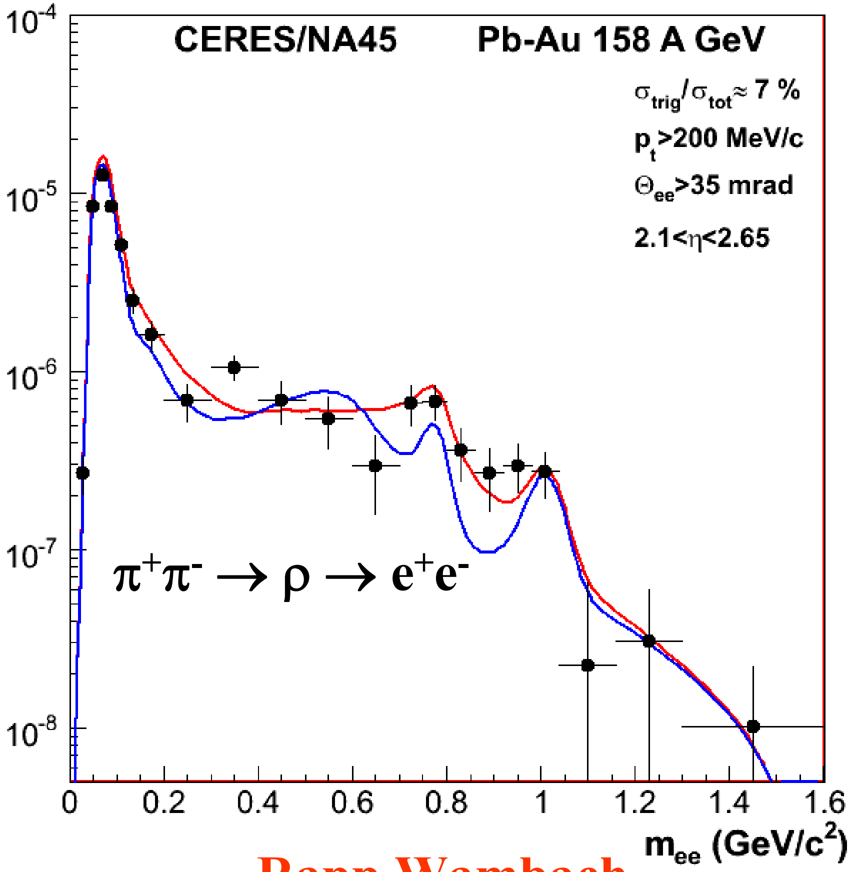
⇒ dilepton excess associated with excitation of baryon resonances !!

CERES: Pb + Au 158 AGeV

D.Adamova et al., subm. to PRL

data in comparison to
post freeze out hadronic cocktail



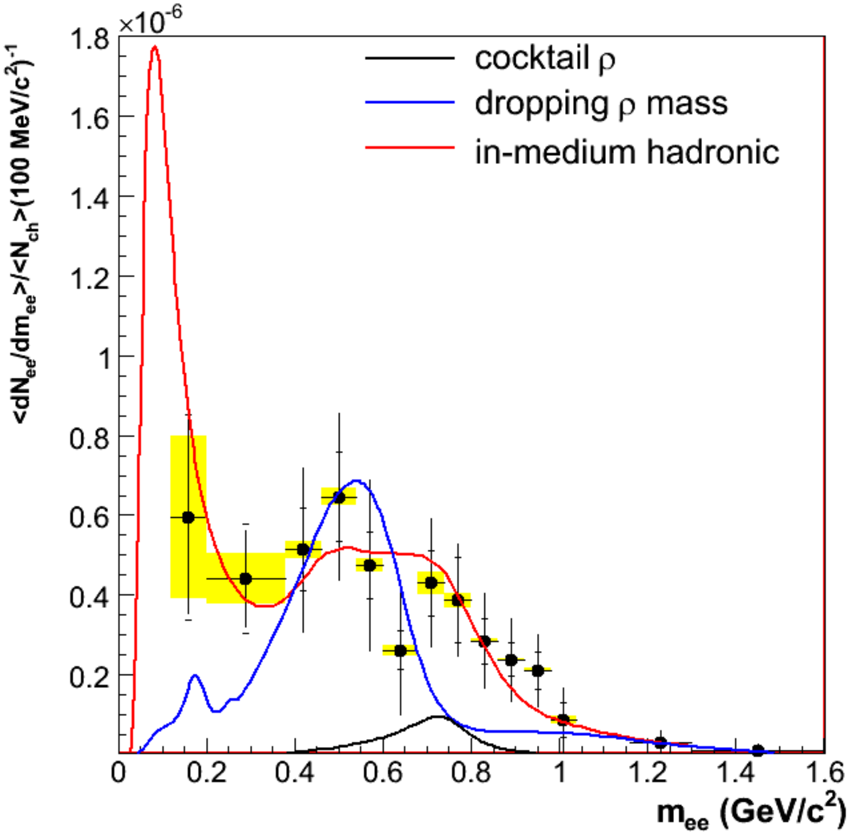


for $0.2 < m_{ee} < 1.1$ GeV/c^2
excess over hadronic decay contribution:
2.45 ± 0.30(stat) ± 0.38(syst) ±0.74(decays)

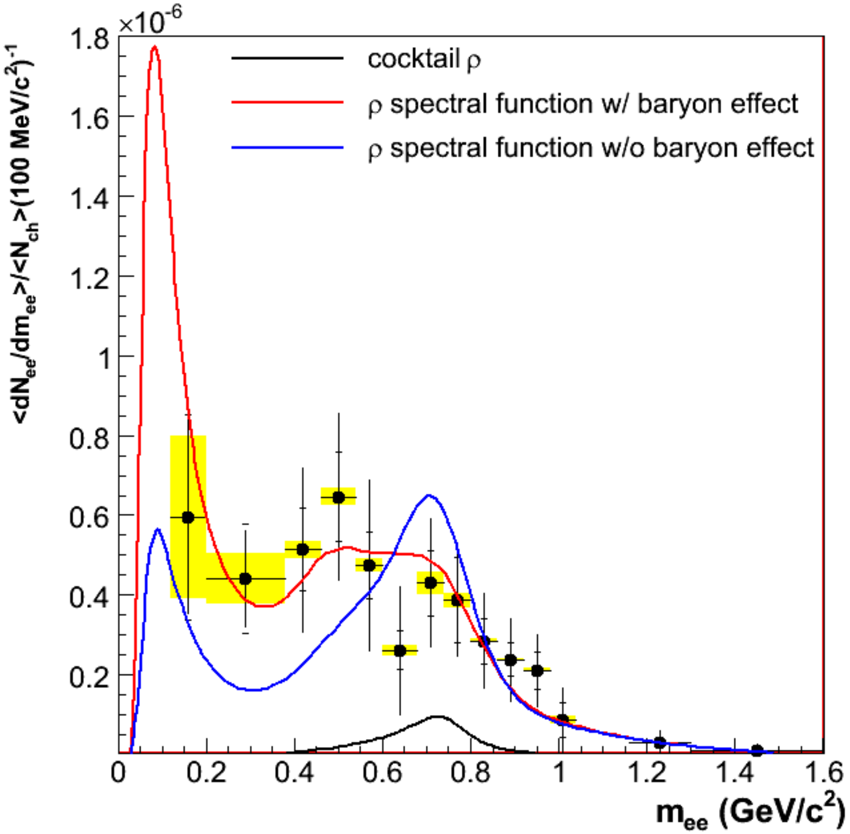
🟥 Rapp Wambach
broadened ρ spect. function

🟦 Brown Rho
dropping ρ mass

CERES e^+e^- pair yield after subtraction of hadronic cocktail excluding ρ



excess smeared out over wider mass range than expected for dropping ρ mass scenario



strength of di-lepton yield at low masses due to coupling to baryons

(similar to the observation by DLS, HADES)

NA60

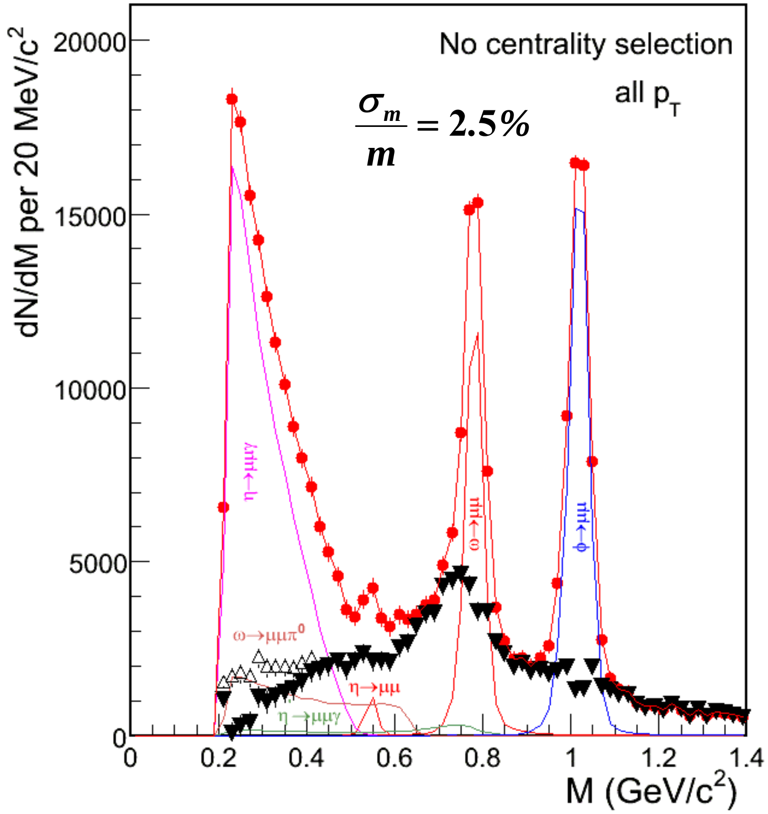
In+In 158 AGeV: ρ, ω, $\phi \rightarrow \mu^+ \mu^-$

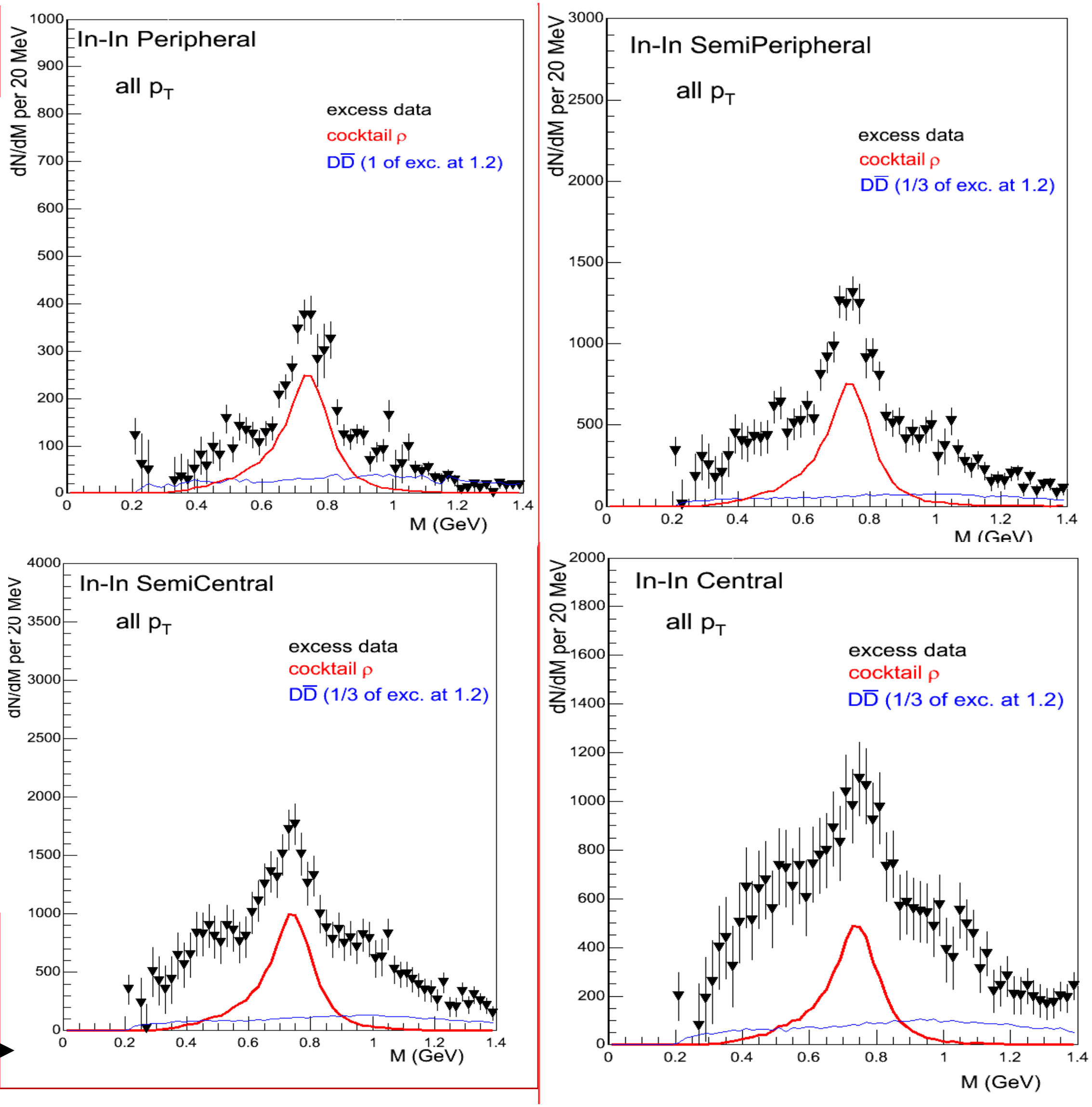
s. talk by J. Seixas

R. Arnaldi et al., PRL 96 (2006) 162302

after subtraction of hadronic cocktail

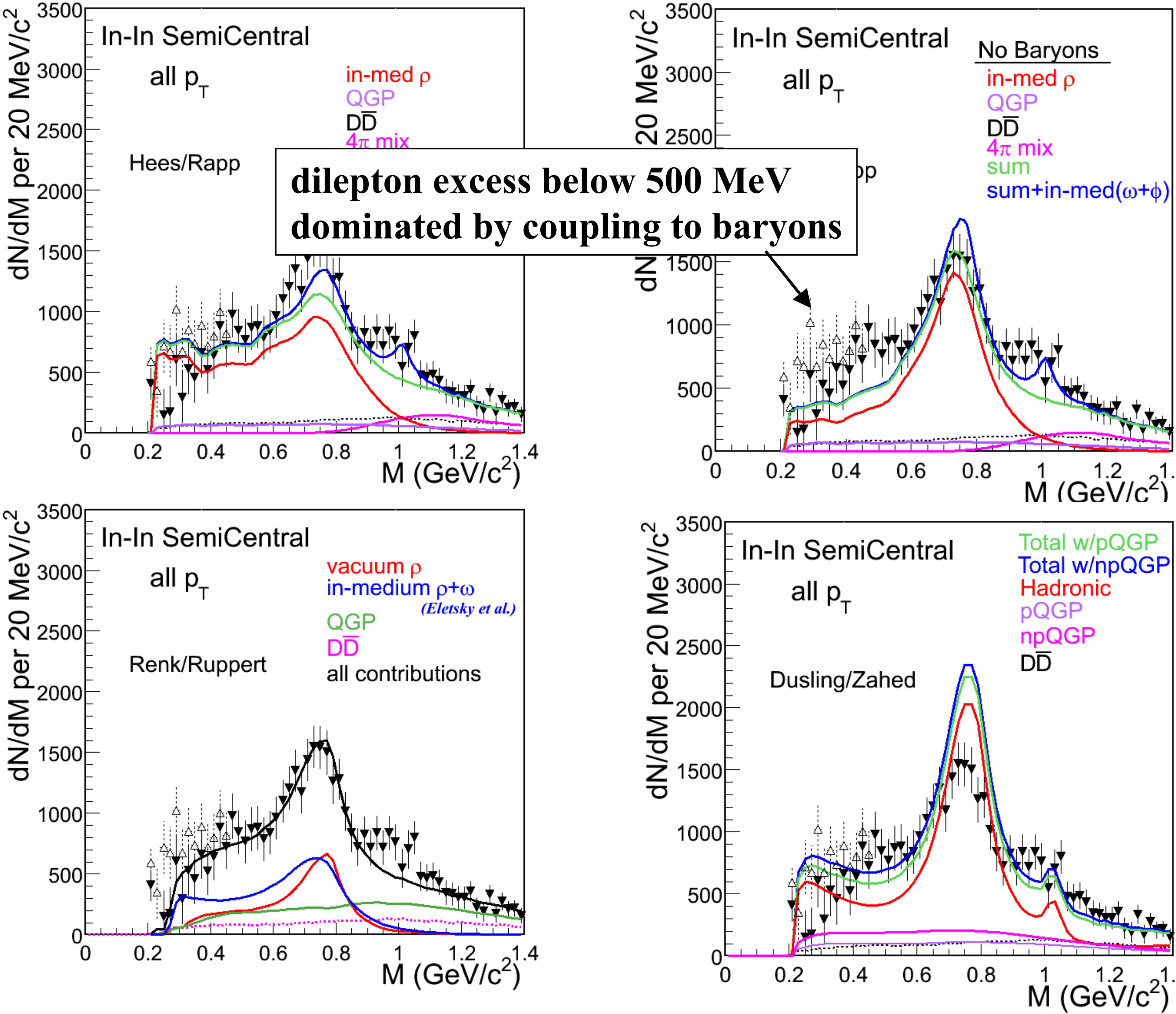
isolation of $\mu^+ \mu^-$ excess





excess increases with centrality →

⇒ broadening of ρ meson; no mass shift



dilepton excess below 500 MeV dominated by coupling to baryons

summary

current status of in-medium modifications of vector mesons

	KEK	**Jlab**	**CBELSA/TAPS**	**CERES**	**NA 60**
ω	–	–	mass shift: -14% $\Gamma_\omega(\rho=\rho_0)\approx 100$MeV	–	–
ρ	mass shift: -9% no broadening	no mass shift some broadening	–	broadening favored over density dependent mass shift	no mass shift strong broadening
Φ	mass shift: -4% $\Gamma_\phi(\rho_0)=47$MeV	–	–	–	–

despite of enormous progress in the experiments no fully consistent picture as yet
⇒ further precision experiments needed: HADES: $p\ A \rightarrow \rho, \omega + X$ on bound proton

emerging evidence from all heavy-ion experiments (DLS, HADES, CERES, NA60) that low mass part of dilepton excess ($m_{l+l-} \leq 500$ MeV) may be dominated by coupling to baryon resonances