Hadron properties in dense nuclear matter

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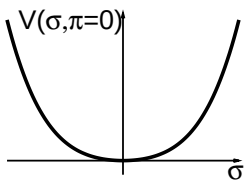
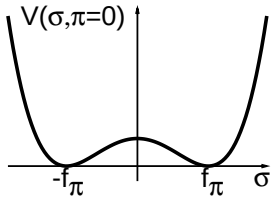
- Chiral symmetry restoration and the ρ and A1 mesons
- Spectral function of vector mesons in matter
- QMD
- $A_1 - \rho$ mixing
- Summary

Chiral Symmetry

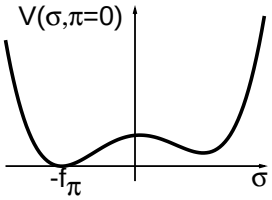
- for massless fermions: helicity
  spin has the same or opposite direction to the momentum, right-handed or left-handed particles
- $m_u \approx 4MeV$, $m_d \approx 7MeV$, $m_s \approx 150MeV$
  $m_q << m_p$, QCD is approximatelly chiral symmetric
  known before QCD (phenomenology of the weak interaction)
- The vacuum symmetric $\Rightarrow$ parity dublets
  not symmetric $\Rightarrow$ SSB $\Rightarrow < \bar{q}q >$ condensates in the vacuum



symmetry



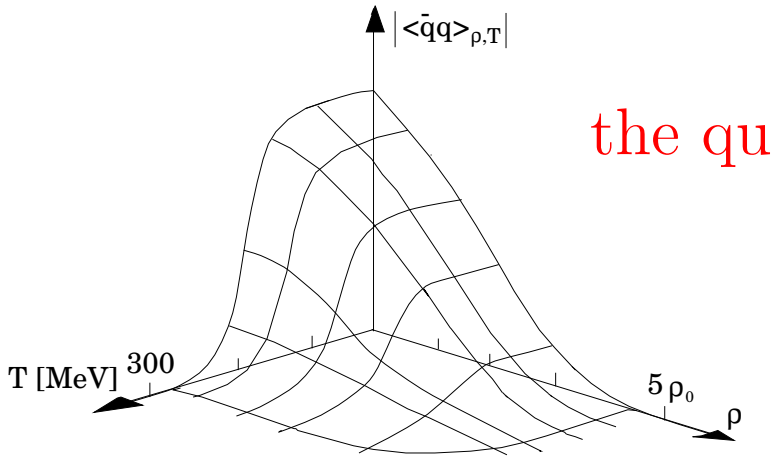
spontaneous



explicit breaking

Quark condensate

order parameter of the chiral phase transition: $< \bar{q}q >$

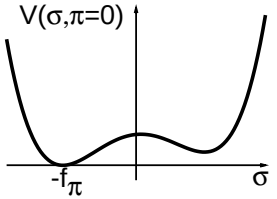


the quark condensate as a function of T and ρ

$$\frac{<\bar{q}q>_{\rho_o}}{<\bar{q}q>_{vac}} \approx 0.7$$

Proposed signals: disoriented chiral condensate (DCC) and change of hadron masses

- DCC: Large fluctuations in pion charges
  coherent decay of the false vacuum

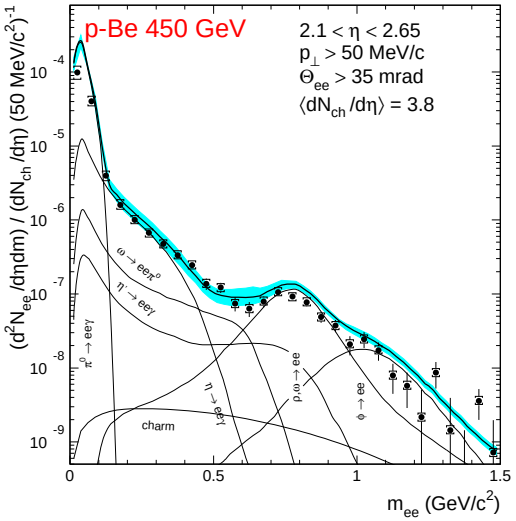


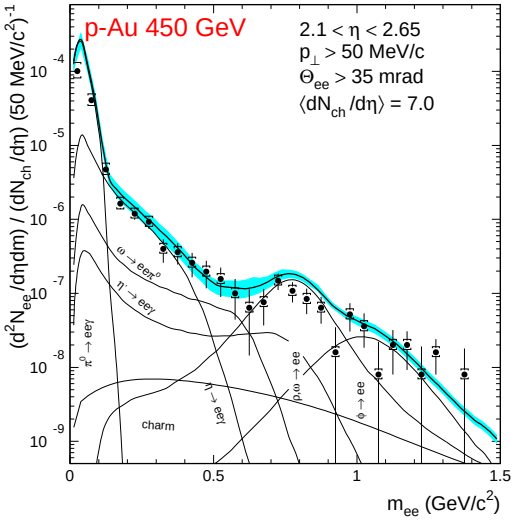
- Hadron masses: light vector meson masses shifted down
  $\Rightarrow$ dilepton production

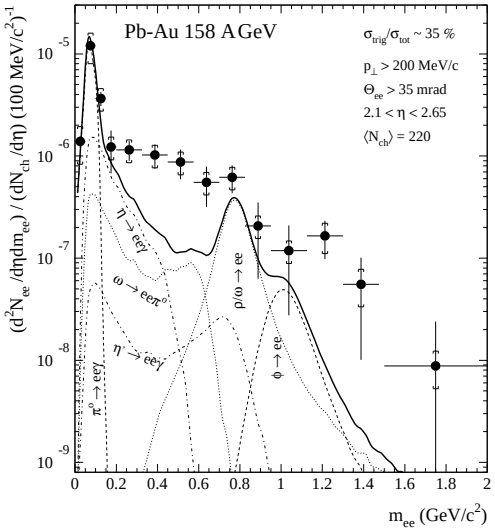
Chiral symmetry and vector mesons

- vector mesons can be observed by their dileptonic decay
- Chiral symmetry requires: in restored phase the spectral functions of parity partners (ρ and A_1) are the same.
- Two simplified scenarios for chiral restoration
  masses become equal
  spectral functions mix
- What do we know about the masses
  A_1: nothing, but in the vacuum
  ρ: QCD sum rules (mass shifts)
  hadronic models
- Study spectral functions

CERES data



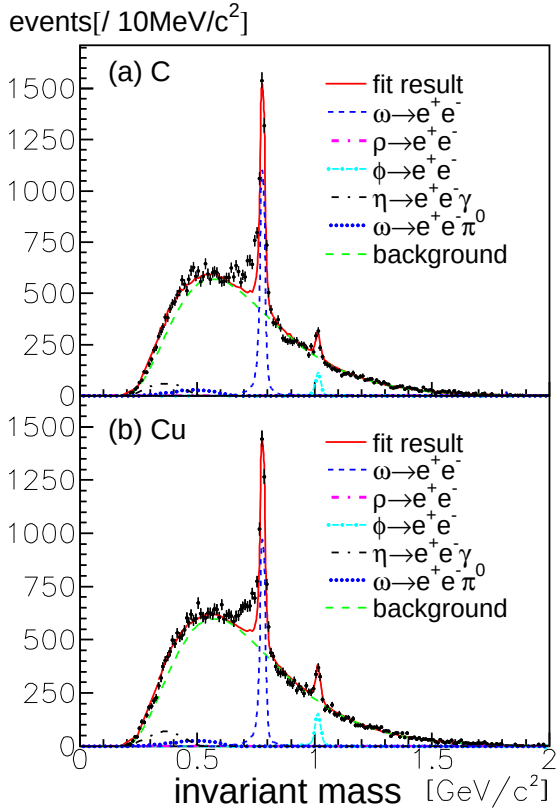




G. Agakichiev *et al.*
Eur. Phys. J. C4 (1998) 231

G. Agakichiev *et al.*
Phys. Lett. B422 (1998) 405

p + A 12 GeV at KEK

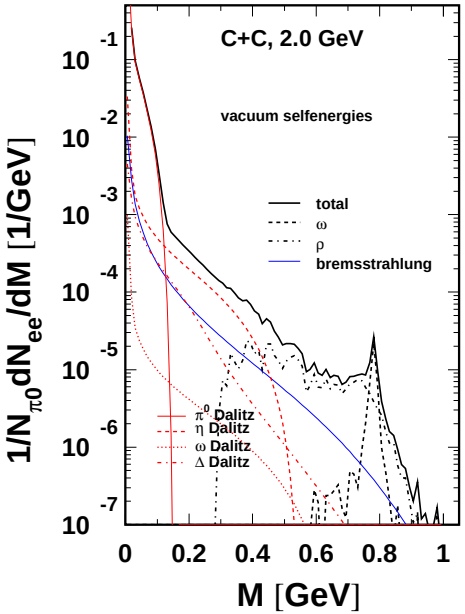


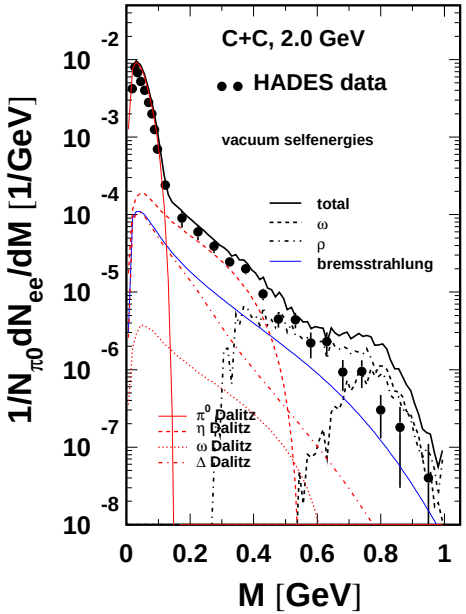
Naruki et al., Phys.Rev.Lett. 96 (2006) 092301

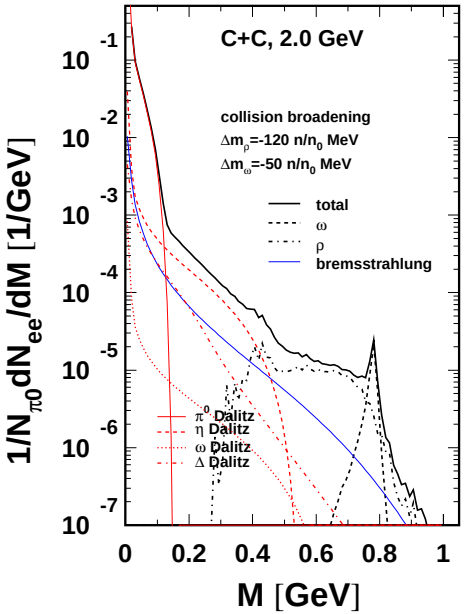
excess below the ω-mass, cannot be described by free coctail

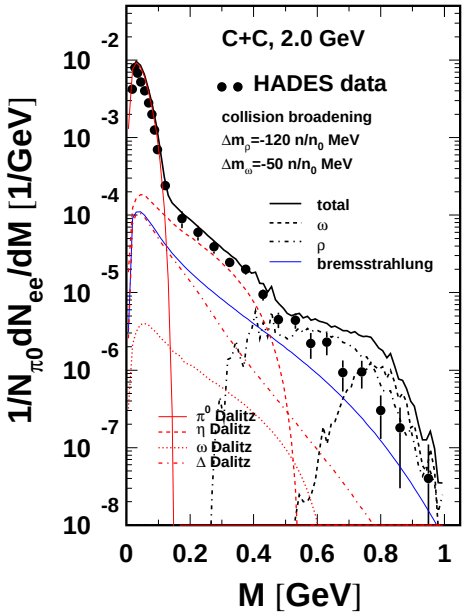
$m_v = m_{v_o} * (1 - 0.09\rho/\rho_o), \qquad v : \rho, \omega$

C + C 2 GeV

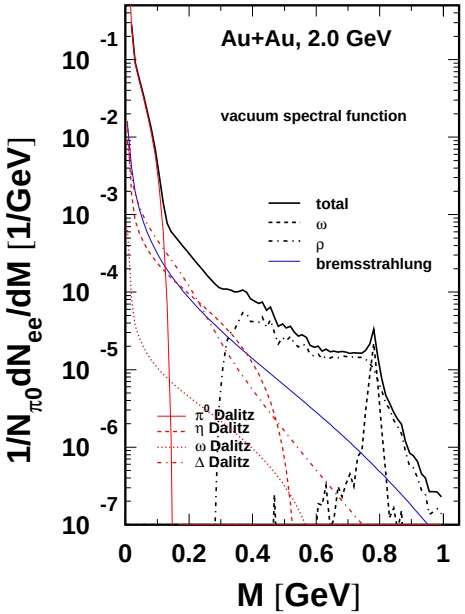

C+C, 2.0 GeV
vacuum selfenergies
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]

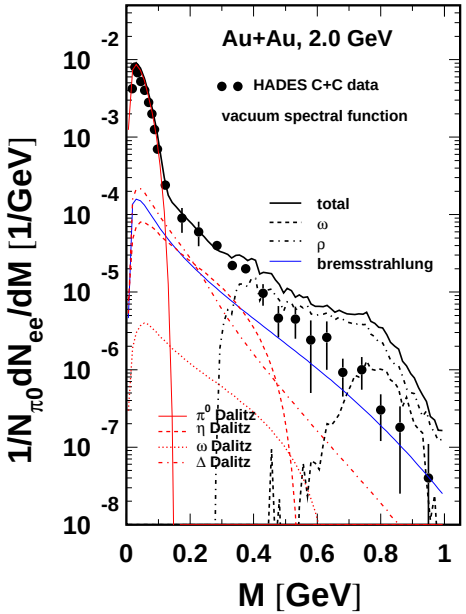

C+C, 2.0 GeV
HADES data
vacuum selfenergies
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]

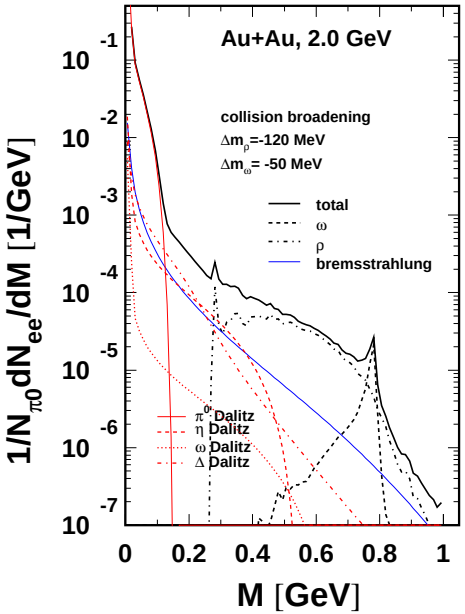

C+C, 2.0 GeV
collision broadening
Δmρ=-120 n/n0 MeV
Δmω=-50 n/n0 MeV
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]

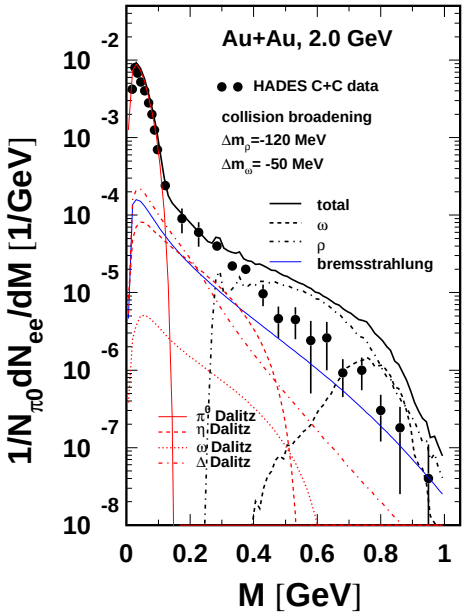

C+C, 2.0 GeV
HADES data
collision broadening
Δmρ=-120 n/n0 MeV
Δmω=-50 n/n0 MeV
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]

Au + Au 2 GeV


Au+Au, 2.0 GeV
vacuum spectral function
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]


Au+Au, 2.0 GeV
HADES C+C data
vacuum spectral function
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]


Au+Au, 2.0 GeV
collision broadening
Δmρ=-120 MeV
Δmω= -50 MeV
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]


Au+Au, 2.0 GeV
HADES C+C data
collision broadening
Δmρ=-120 MeV
Δmω= -50 MeV
total
ω
ρ
bremsstrahlung
π0 Dalitz
η Dalitz
ω Dalitz
Δ Dalitz
1/Nπ0dNee/dM [1/GeV]
M [GeV]

Self energy of vector mesons

- low density expansion
  $\langle n.m.|\mathcal{O}|n.m.\rangle = \langle 0|\mathcal{O}|0\rangle + \rho\langle N|\mathcal{O}|N\rangle$
- Modification of vector mesons in nuclear matter (after LSZ reduction)

  $\Delta\Pi = -4\pi\rho(1+\frac{m_V}{m_N})\langle NV|NV\rangle$

  $\langle NV|NV\rangle$: vector mesons' forward scattering amplitude off the nucleon
- goal: $T_{\omega N\to\omega N}$ and $T_{\rho N\to\rho N}$
  - not measurable
  - measurable: $T_{\pi N\to VN}$ and $T_{\pi N\to\pi N}$

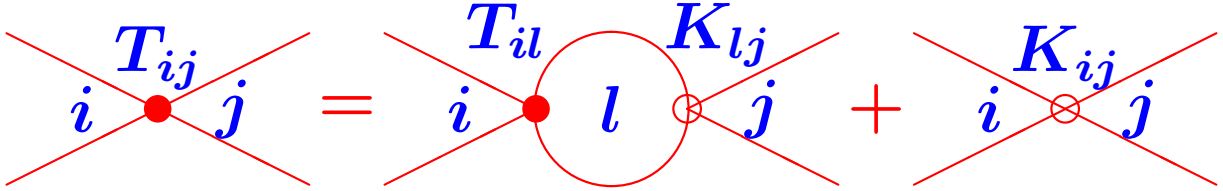
  $\Rightarrow$ coupled channels

Coupled channel approach

- goal: $T_{\omega N \to \omega N}$ and $T_{\rho N \to \rho N}$
  - not measurable
  - measurable: $T_{\pi N \to V N}$ and $T_{\pi N \to \pi N}$

  $\Rightarrow$ coupled channels

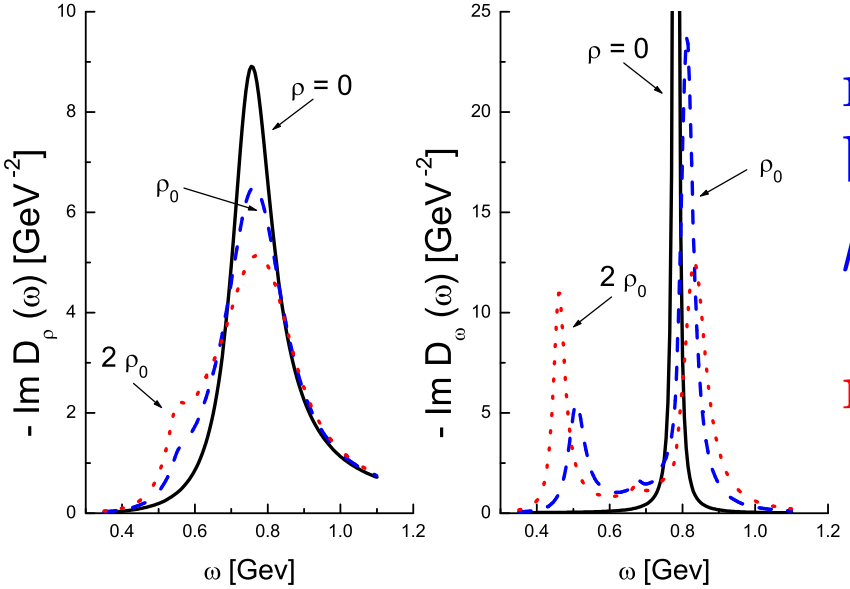
- Bethe-Salpeter equation



- channels:

  $\pi N, \rho N, \omega N, \eta N, \pi \Delta, \eta \Delta, K \Lambda, K \Sigma$

Vector mesons in nuclear matter

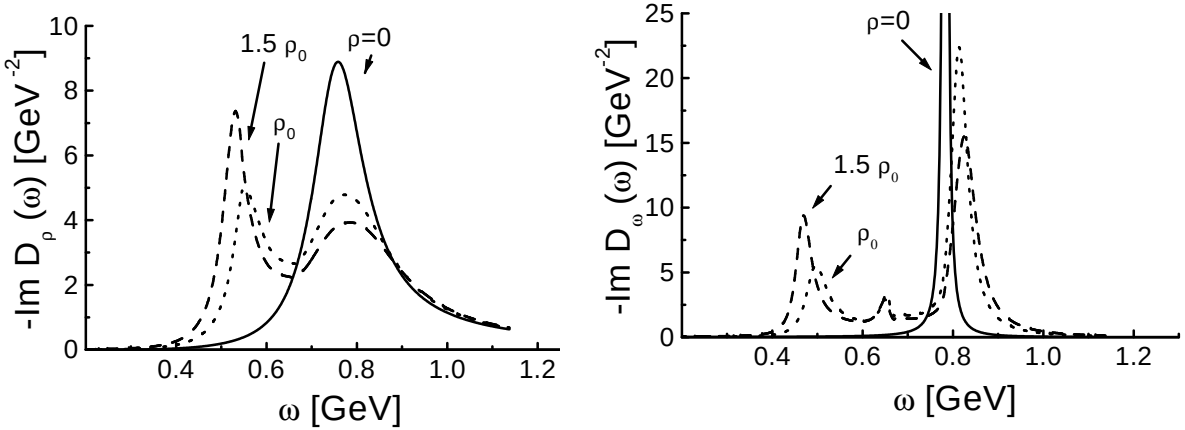


no mass shift, no simple broadening
but extra peaks: resonance-hole states
ρ spectrum is model-dependent (ω stable)

no clean signal for chiral restoration

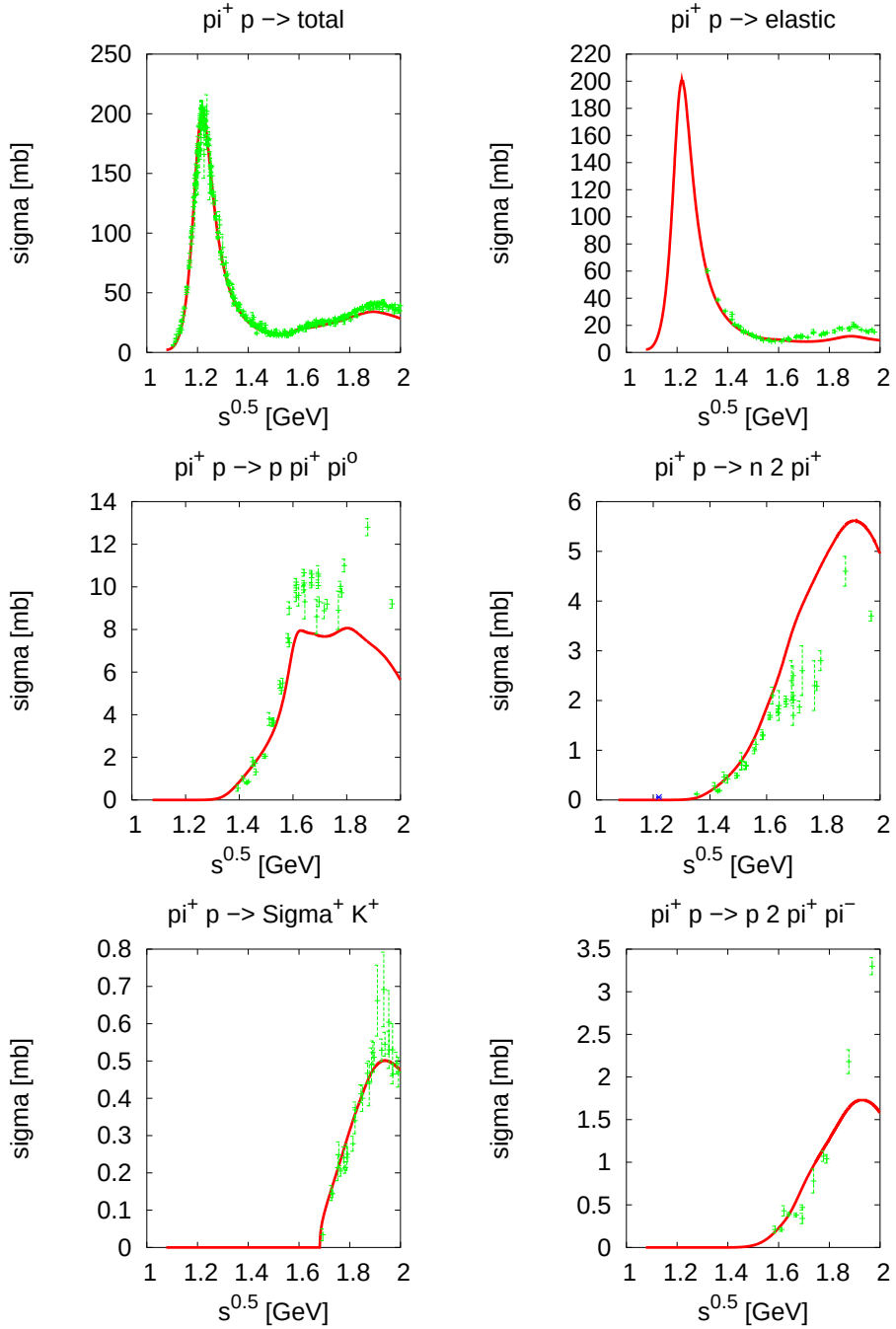
M. Lutz, Gy. Wolf, B. Friman; Nucl Phys. A706 (2002) 431.

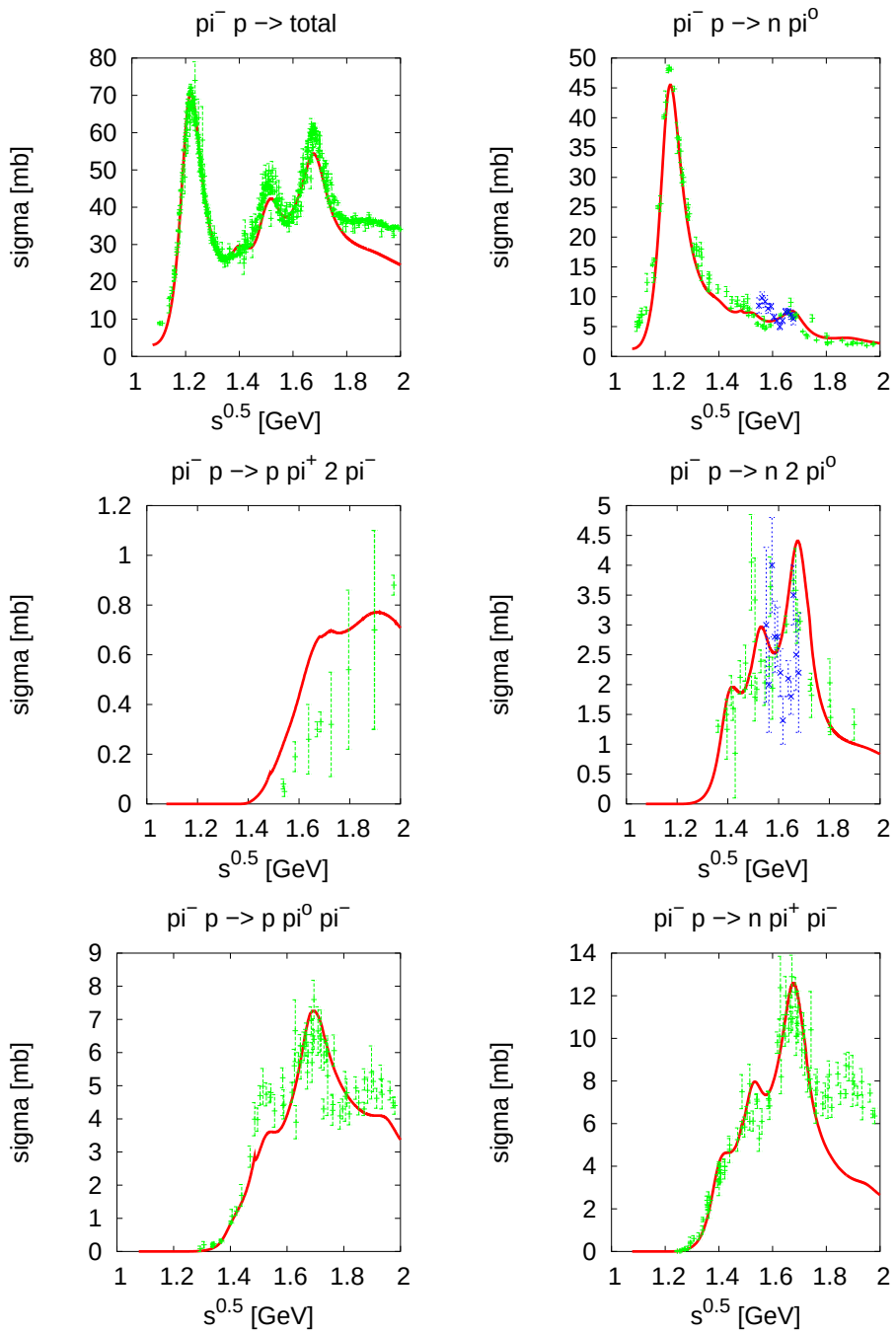
our old results:

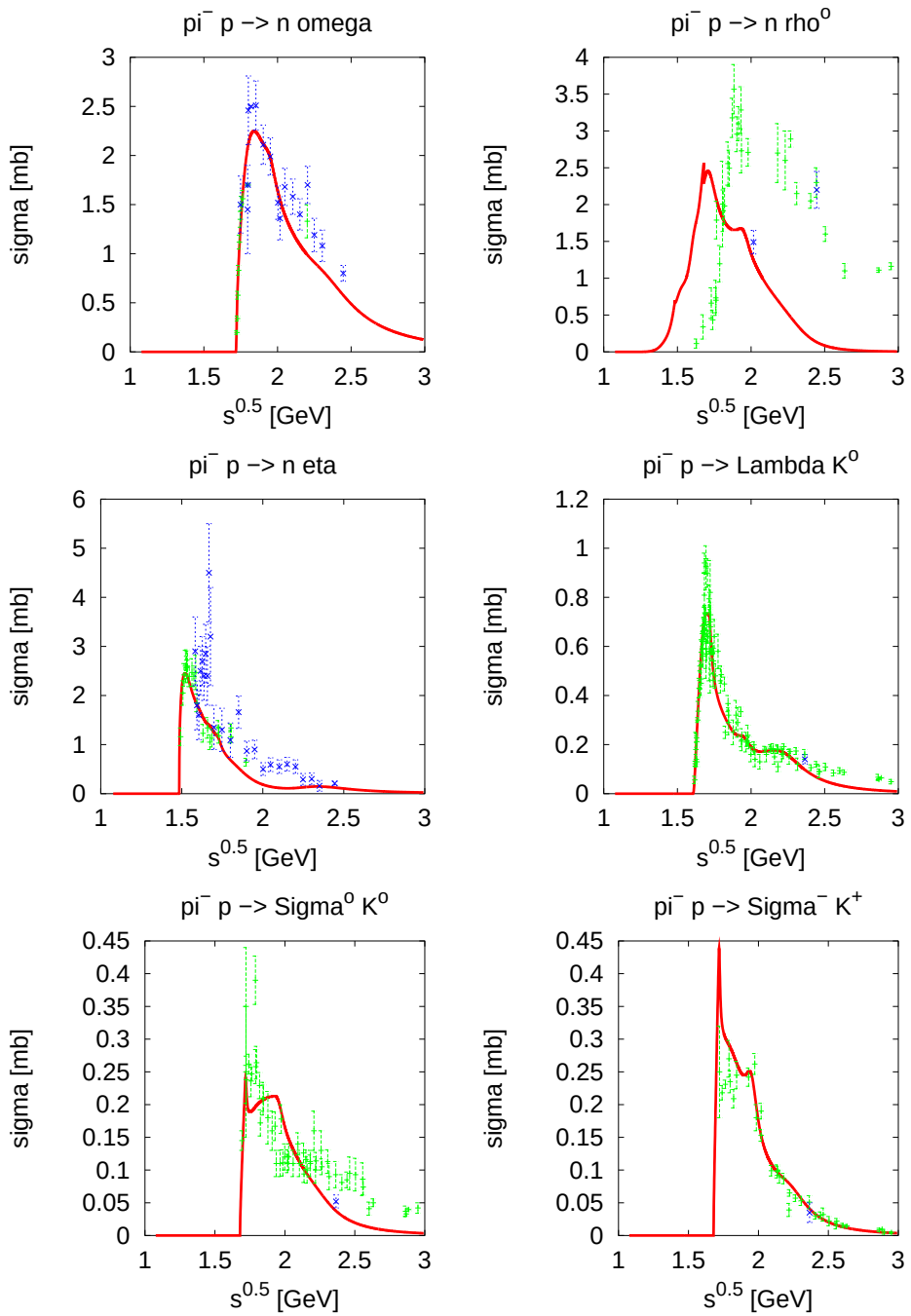


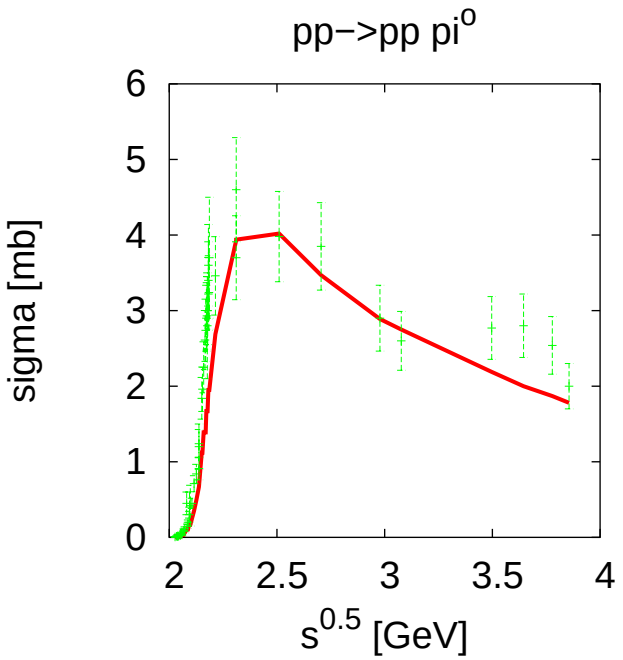
QMD

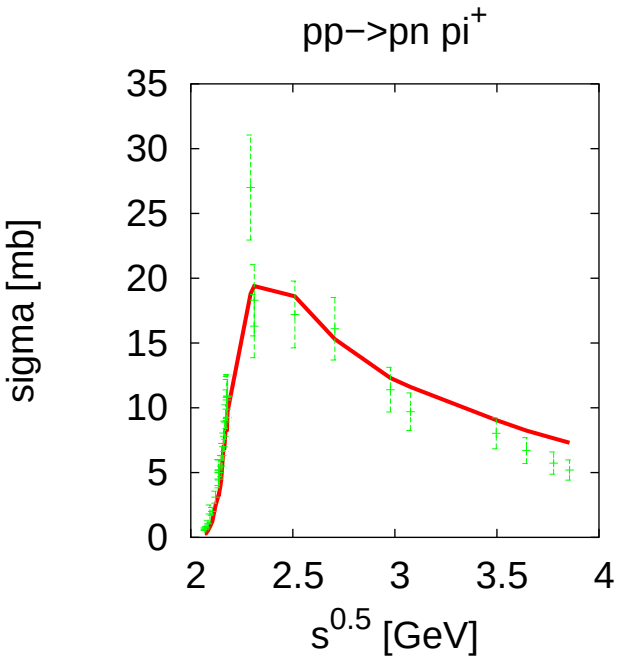
- Momentum dependent force between the particles
  Model describes rather well the flow data at 400 MeV Au+Au
- 24 baryon resonances + Λ and Σ baryons
  $\pi, \eta, \sigma, \rho, \omega$ and kaons
- Inelastic reactions:
  $NN \leftrightarrow NR, \quad MN \leftrightarrow R, \quad \pi\pi \leftrightarrow \rho, \quad \omega \leftrightarrow \rho\pi$
- Cross sections are resonance dominated, and added incoherently
- resonance parameters are fitted to π-nucleon scattering
- resonance production cross sections are fitted to nucleon-nucleon cross sections

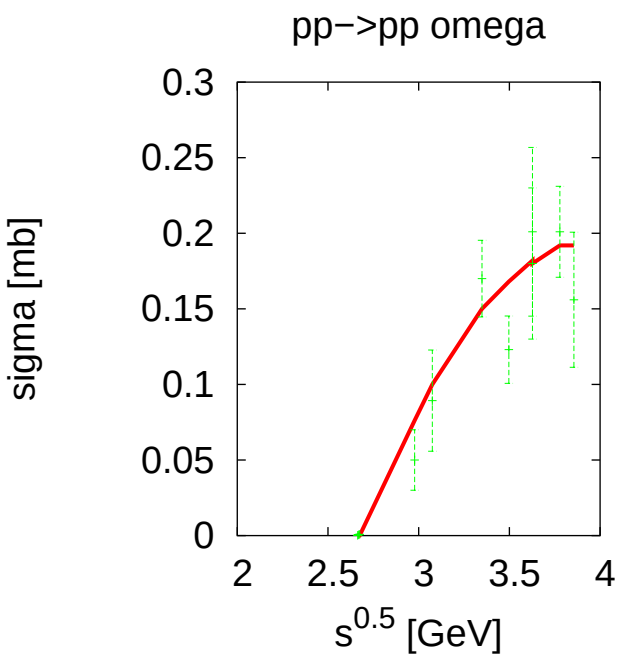

pi+ p -> total
sigma [mb]
s0.5 [GeV]
pi+ p -> elastic
sigma [mb]
s0.5 [GeV]
pi+ p -> p pi+ pi0
sigma [mb]
s0.5 [GeV]
pi+ p -> n 2 pi+
sigma [mb]
s0.5 [GeV]
pi+ p -> Sigma+ K+
sigma [mb]
s0.5 [GeV]
pi+ p -> p 2 pi+ pi−
sigma [mb]
s0.5 [GeV]

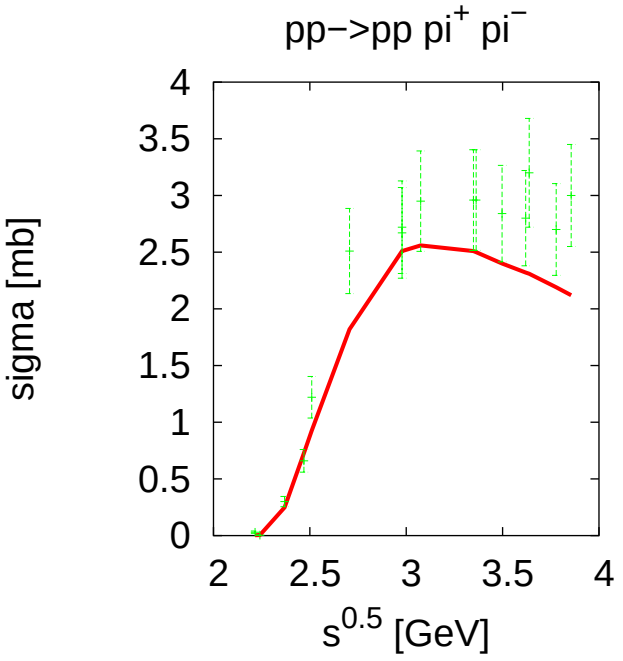

pi⁻ p –> total
sigma [mb]
s^0.5 [GeV]
pi⁻ p –> n pi^o
sigma [mb]
s^0.5 [GeV]
pi⁻ p –> p pi⁺ 2 pi⁻
sigma [mb]
s^0.5 [GeV]
pi⁻ p –> n 2 pi^o
sigma [mb]
s^0.5 [GeV]
pi⁻ p –> p pi^o pi⁻
sigma [mb]
s^0.5 [GeV]
pi⁻ p –> n pi⁺ pi⁻
sigma [mb]
s^0.5 [GeV]

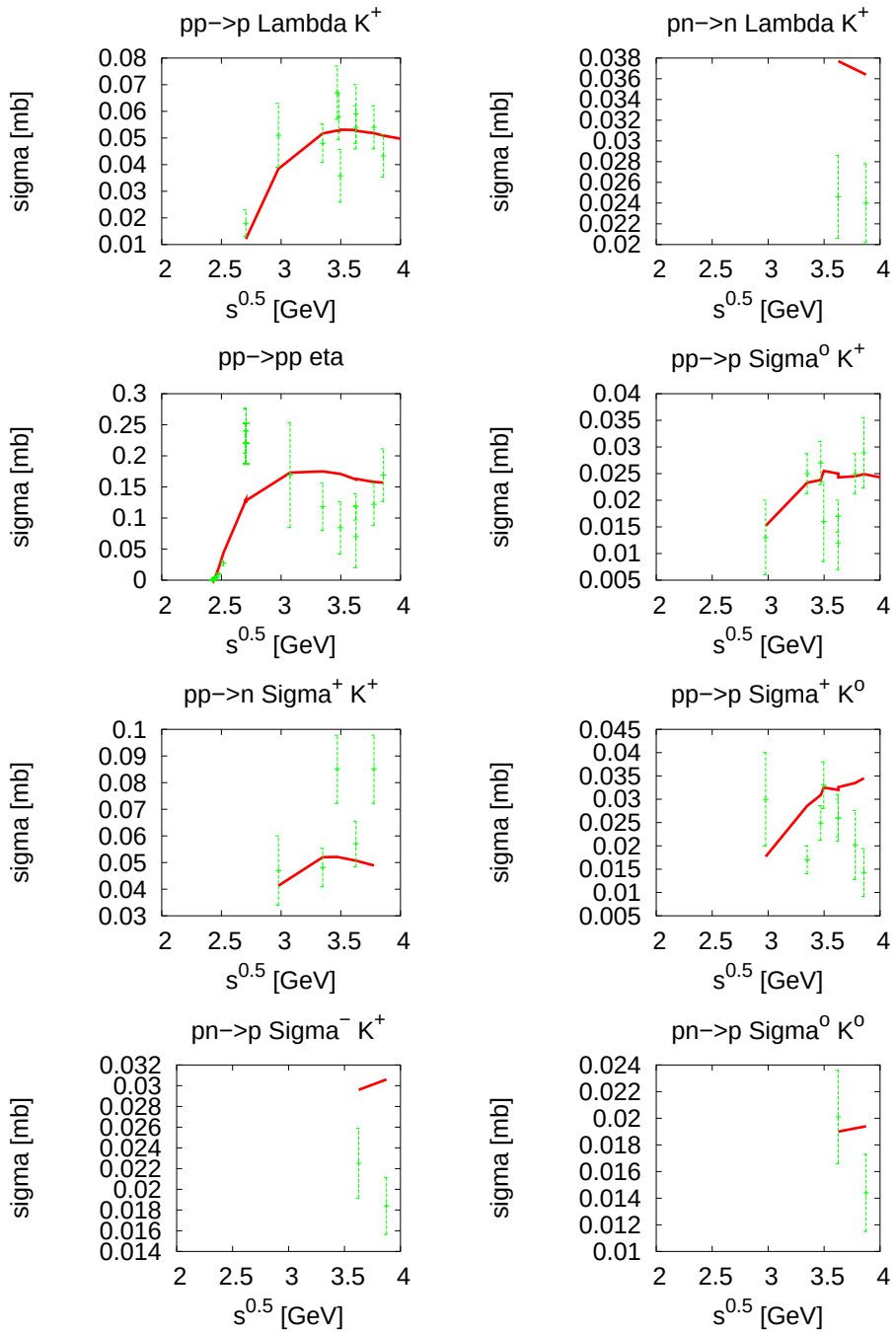

pi⁻ p –> n omega
sigma [mb]
s^0.5 [GeV]
pi⁻ p –> n rho^o
sigma [mb]
s^0.5 [GeV]
pi⁻ p –> n eta
sigma [mb]
s^0.5 [GeV]
pi⁻ p –> Lambda K^o
sigma [mb]
s^0.5 [GeV]
pi⁻ p –> Sigma^o K^o
sigma [mb]
s^0.5 [GeV]
pi⁻ p –> Sigma⁻ K⁺
sigma [mb]
s^0.5 [GeV]

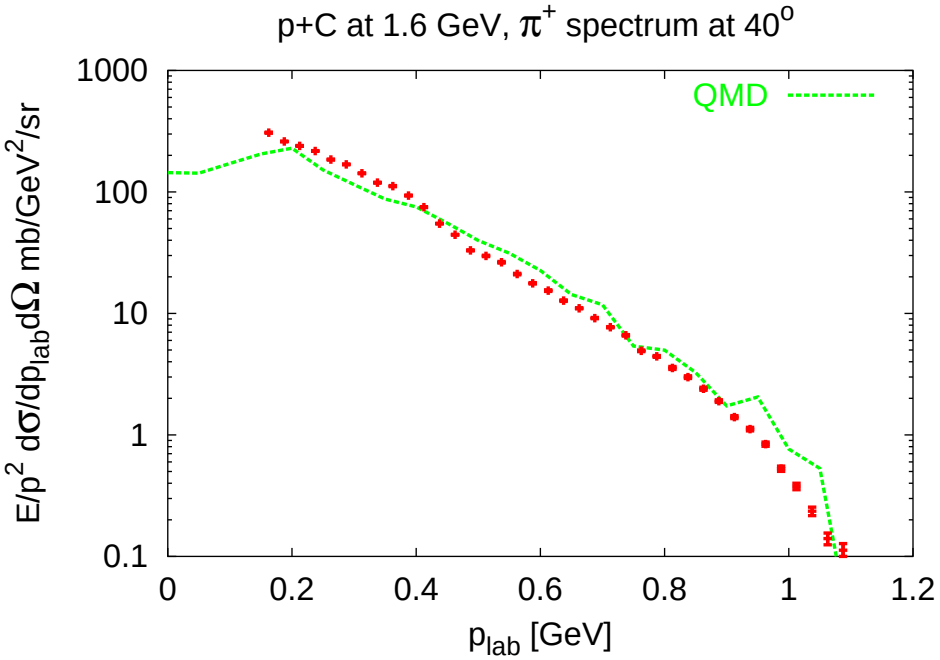

pp−>pp pi^o
sigma [mb]
s^0.5 [GeV]
0
1
2
3
4
5
6
2
2.5
3
3.5
4

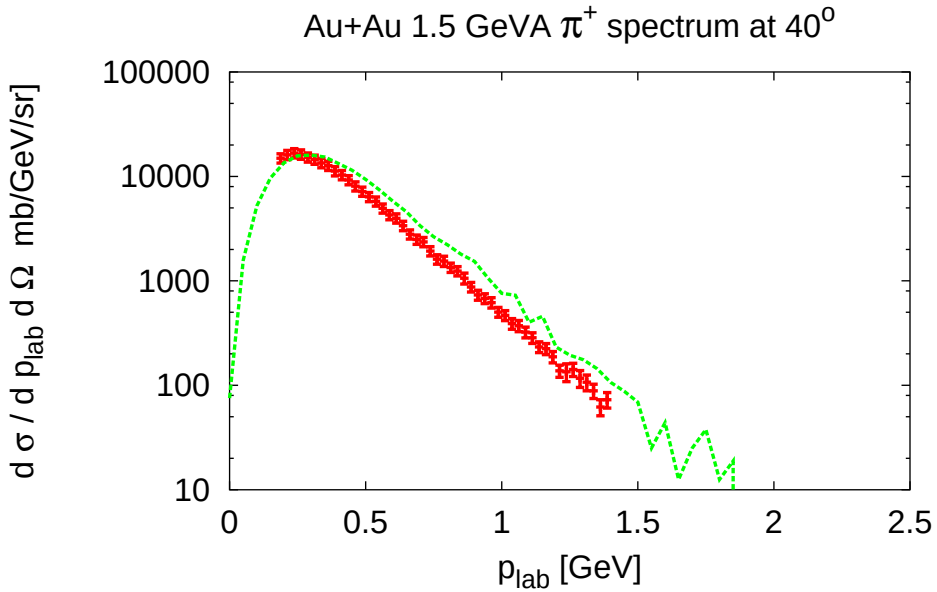

pp−>pn pi^+
sigma [mb]
s^0.5 [GeV]
0
5
10
15
20
25
30
35
2
2.5
3
3.5
4


pp−>pp omega
sigma [mb]
s^0.5 [GeV]
0
0.05
0.1
0.15
0.2
0.25
0.3
2
2.5
3
3.5
4


pp−>pp pi^+ pi^−
sigma [mb]
s^0.5 [GeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
2
2.5
3
3.5
4


pp−>p Lambda K+
pn−>n Lambda K+
pp−>pp eta
pp−>p Sigma0 K+
pp−>n Sigma+ K+
pp−>p Sigma+ K0
pn−>p Sigma− K+
pn−>p Sigma0 K0
sigma [mb]
s0.5 [GeV]


p+C at 1.6 GeV, π+ spectrum at 40o
QMD
E/p2 dσ/dplabdΩ mb/GeV2/sr
plab [GeV]
1000
100
10
1
0.1
0
0.2
0.4
0.6
0.8
1
1.2

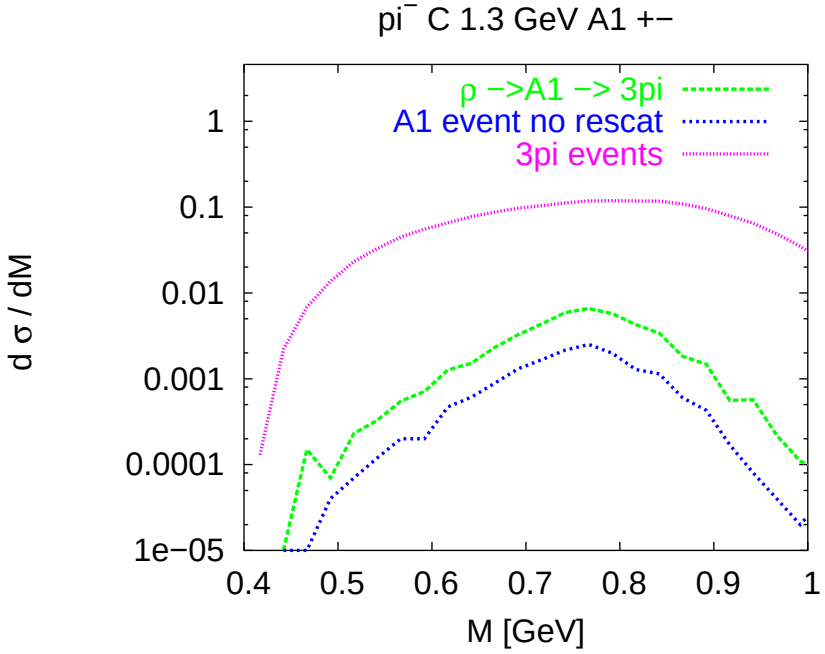

Au+Au 1.5 GeVA π+ spectrum at 40o
d σ / d plab d Ω mb/GeV/sr]
plab [GeV]
100000
10000
1000
100
10
0
0.5
1
1.5
2
2.5

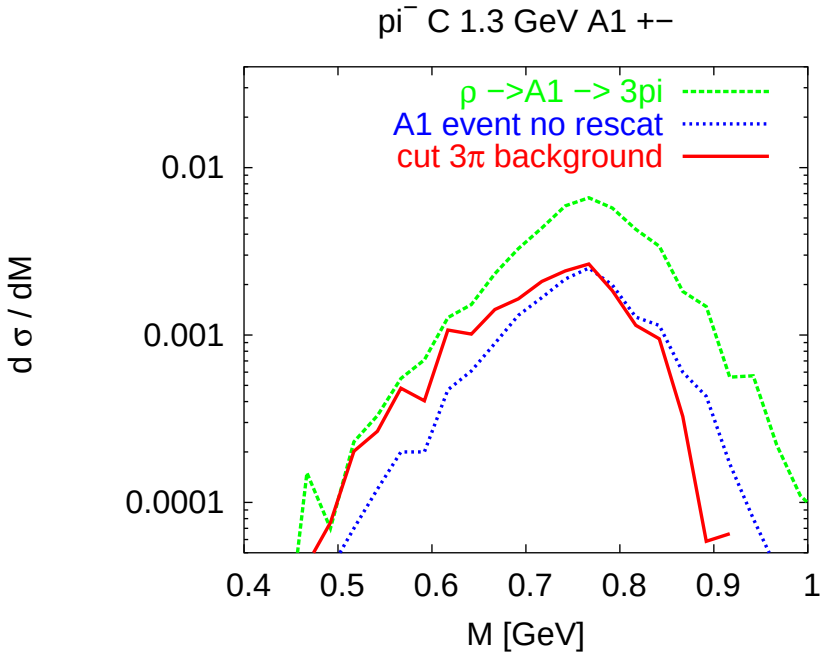
ρ-A1 mixing

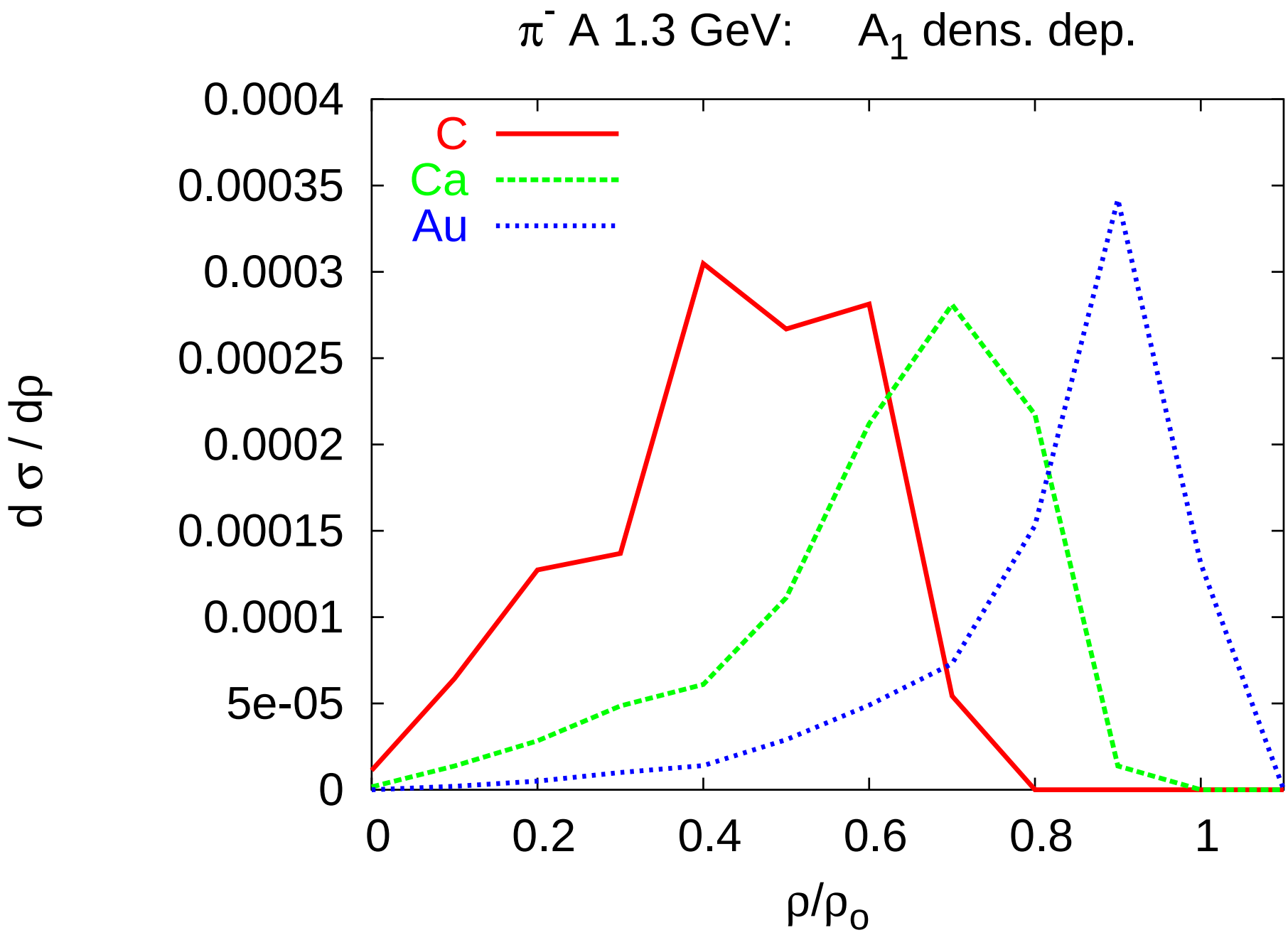
- $\overline{\Pi_\rho} = (1-x)\Pi^v_\rho + x\Pi^v_{A1}$ where $x = \frac{1}{2}0.3 * \frac{density}{normal\ density}$
  $\overline{\Pi_{A1}} = (1-x)\Pi^v_{A1} + x\Pi^v_\rho$ 0.3 comes from chiral symmetry
- Signal: 3π decay of A_1 with the mass of ρ-meson
- π-nucleus collisions
- 1 million central event

system	energy	A1	3 pions	A1 no rescatt.
$\pi^- Au$	1.3 GeV	6400	56 000	100
$\pi^- C$	1.3 GeV	1200	43 000	450
$\pi^- Ca$	1.3 GeV	3200	54 000	400
$\pi^- Ca$	1.1 GeV	3100	46 000	350
$\pi^- Ca$	1.5 GeV	2400	55 000	360

- Light system is prefered


pi⁻ C 1.3 GeV A1 +−
ρ −>A1 −> 3pi
A1 event no rescat
3pi events
d σ / dM
M [GeV]
1
0.1
0.01
0.001
0.0001
1e−05
0.4
0.5
0.6
0.7
0.8
0.9
1


pi⁻ C 1.3 GeV A1 +−
ρ −>A1 −> 3pi
A1 event no rescat
cut 3π background
d σ / dM
M [GeV]
0.01
0.001
0.0001
0.4
0.5
0.6
0.7
0.8
0.9
1


π^- A 1.3 GeV: A_1 dens. dep.
C
Ca
Au
0.0004
0.00035
0.0003
0.00025
0.0002
0.00015
0.0001
5e-05
0
0
0.2
0.4
0.6
0.8
1
d σ / dρ
ρ/ρ$_o$

Summary

- The in-medium modification of the ρ is contraversal
- A possible signal of chiral restoration in $A_1 - \rho$ mixing
- Needs very large statistics
- several theoretical uncertainties