Heavy Ion Collisions

In Medium Dileptons

- Intro (VK)
- From pp to pA to AA (Tetyana)
- Various details of the in medium rho/omega spectral function calculation (Ralf)
- Transport (Theory vs reality) Stefan
- Ingredients to the Gumbo (how dileptons are calculated in a transport code) Janus
- Effects of time evolution (Hendrik)
- Photons and v_2 (Hendrik)
- What do we need to declare success (VK, all)

Thermodynamics and Resonances

Resonances are nothing but interactions among the long lived particles (pions, nucleons):

Virial Expansion a la Beth Uhlenbeck
(see e.g. Landau, Stat.Mech, or Prakash et al. PLB 245 (1990))

$$\Delta P = \frac{\int d^3 q}{(2\pi)^3} \int d\epsilon \exp(-\beta \sqrt{q^2+\epsilon^2}) \sum_i \frac{1}{\pi} g_i \frac{\partial \delta_i(\epsilon)}{\partial \epsilon}$$

Limit of narrow width

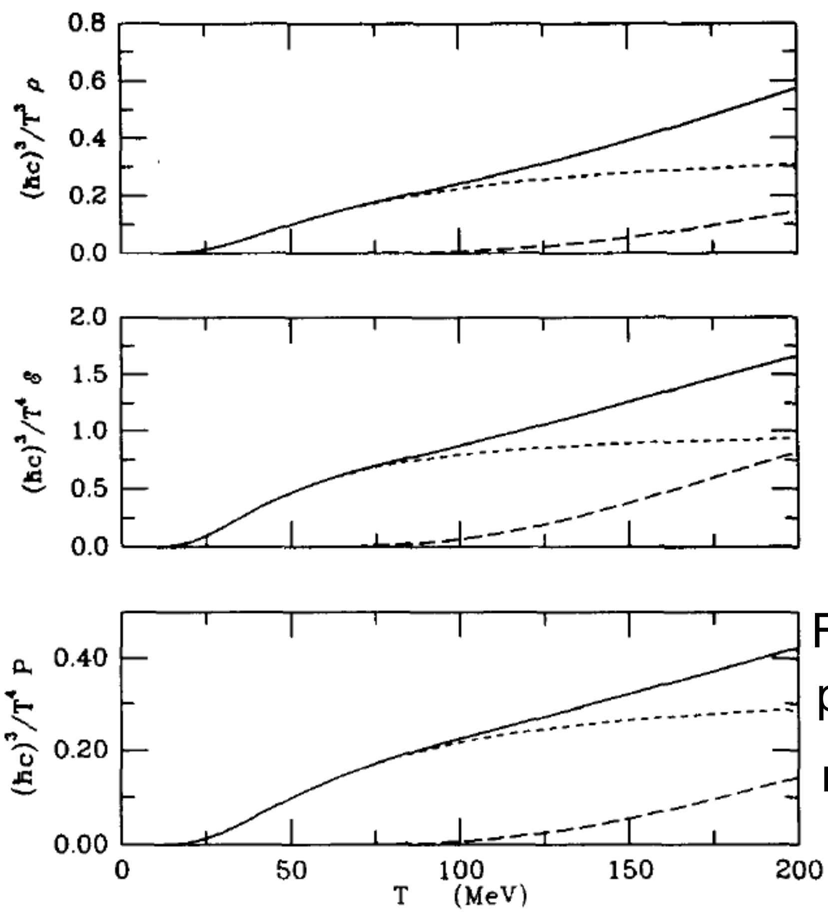
Phase shift resonance $\delta(E) = \frac{\pi}{2} + \arctan\left(\frac{E-M_R}{\Gamma/2}\right) \rightarrow \pi\,\delta(M_R - E)$

$$\Delta P \rightarrow \sum_i g_i \int \frac{d^3 q}{(2\pi)^3} \exp(-\beta \sqrt{q^2+M_R})$$

Appears just as a gas of resonances

Necessary ingredients: Narrow witdh, “proper” resonances

Thermodynamics and Resonances



Works well for the rho meson!

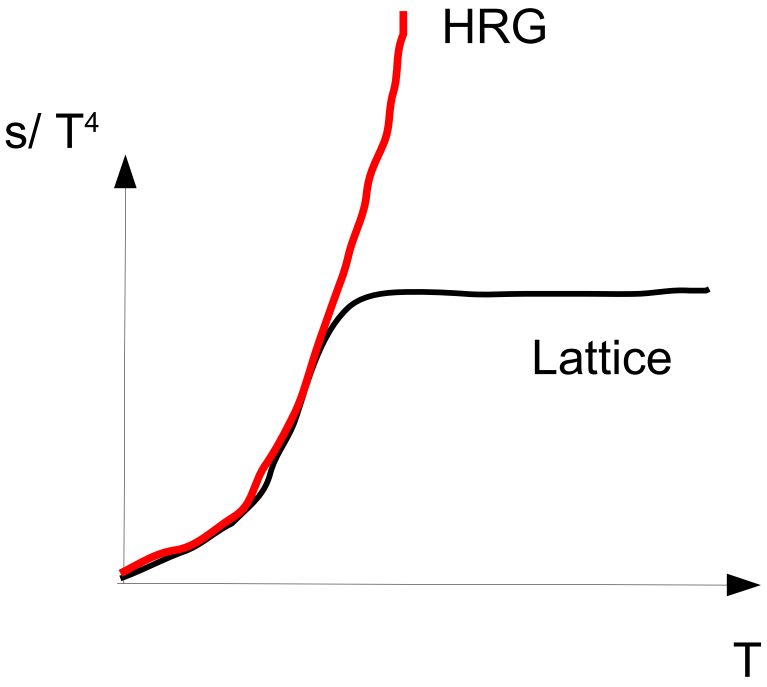
Fully interacting system

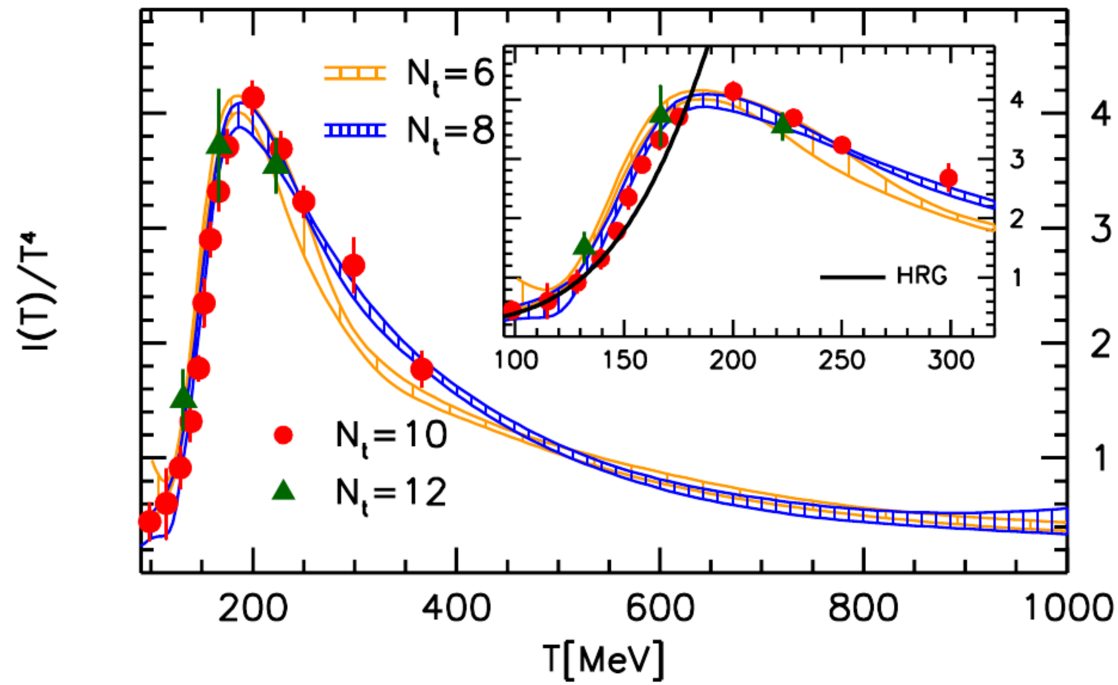
pions

rhos

Prakash et al, PLB 245 (1990)

Resonances and the EOS



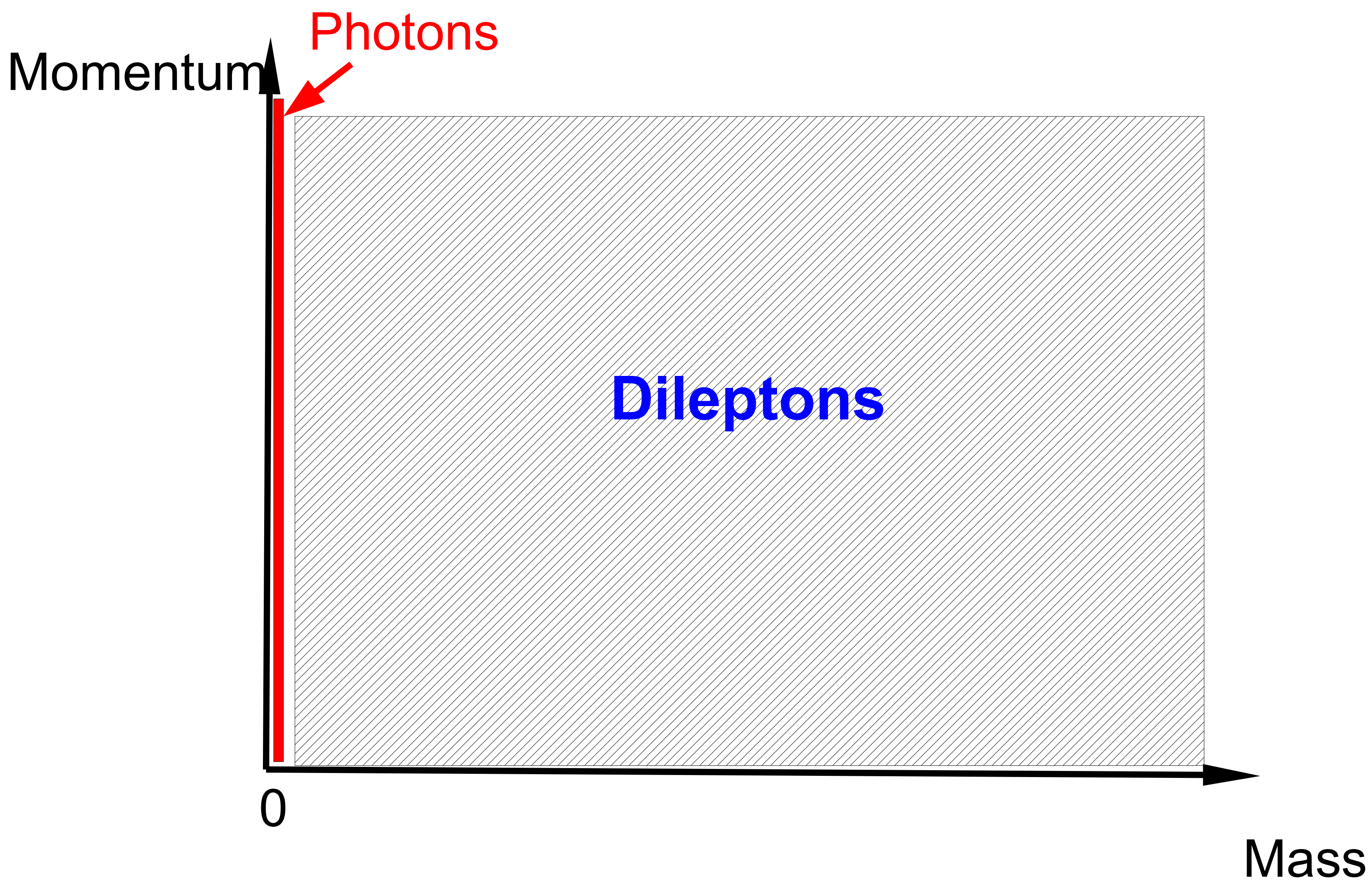


Wuppertal/Budpest LQCD

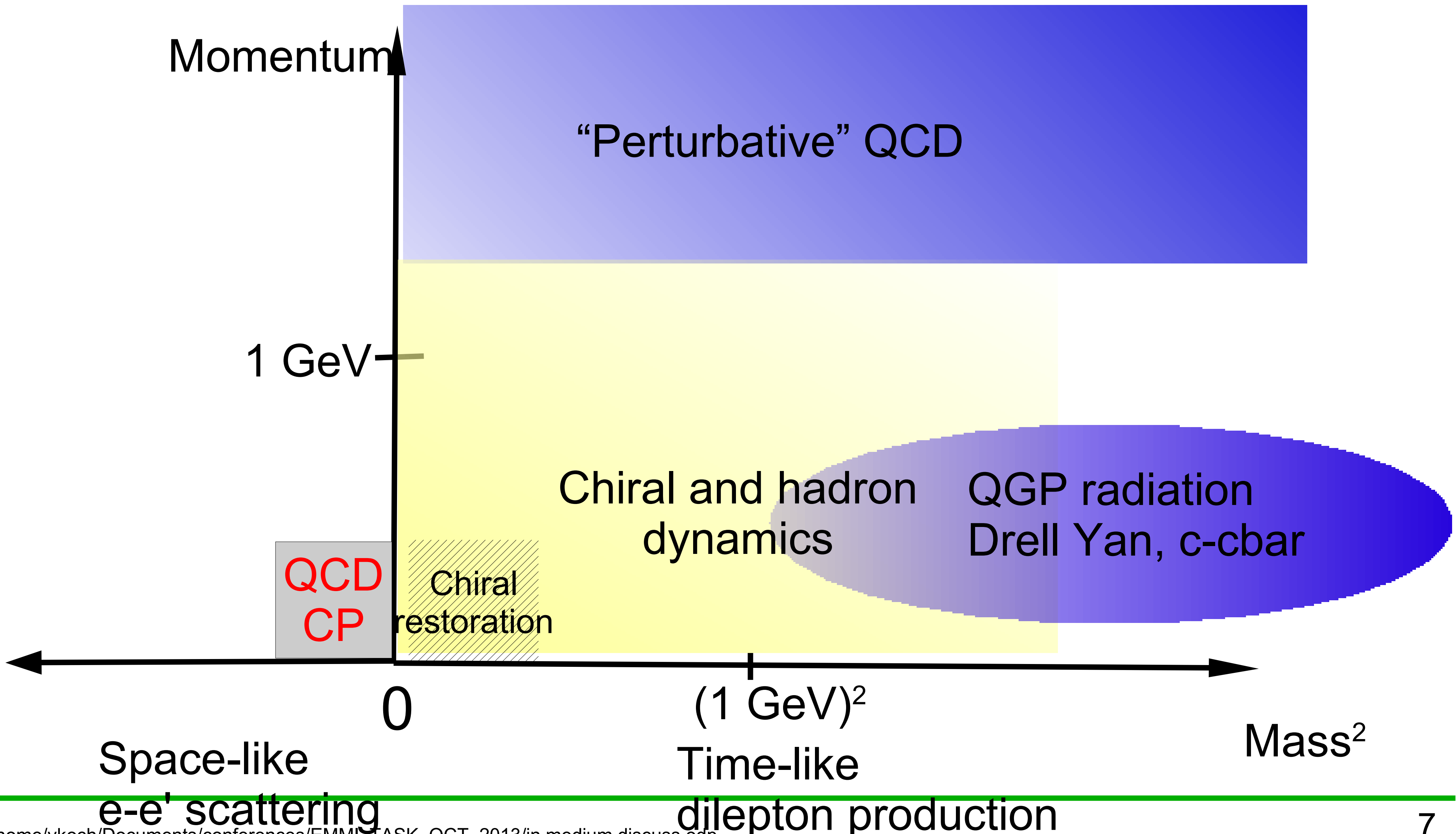
EOS reasonably well described by HRG up to $T \sim T_c$

For $T > T_c$ QCD predicts **LESS** degrees of freedom than HRG

Dilepton
The versatile photon



The Dilepton production landscape



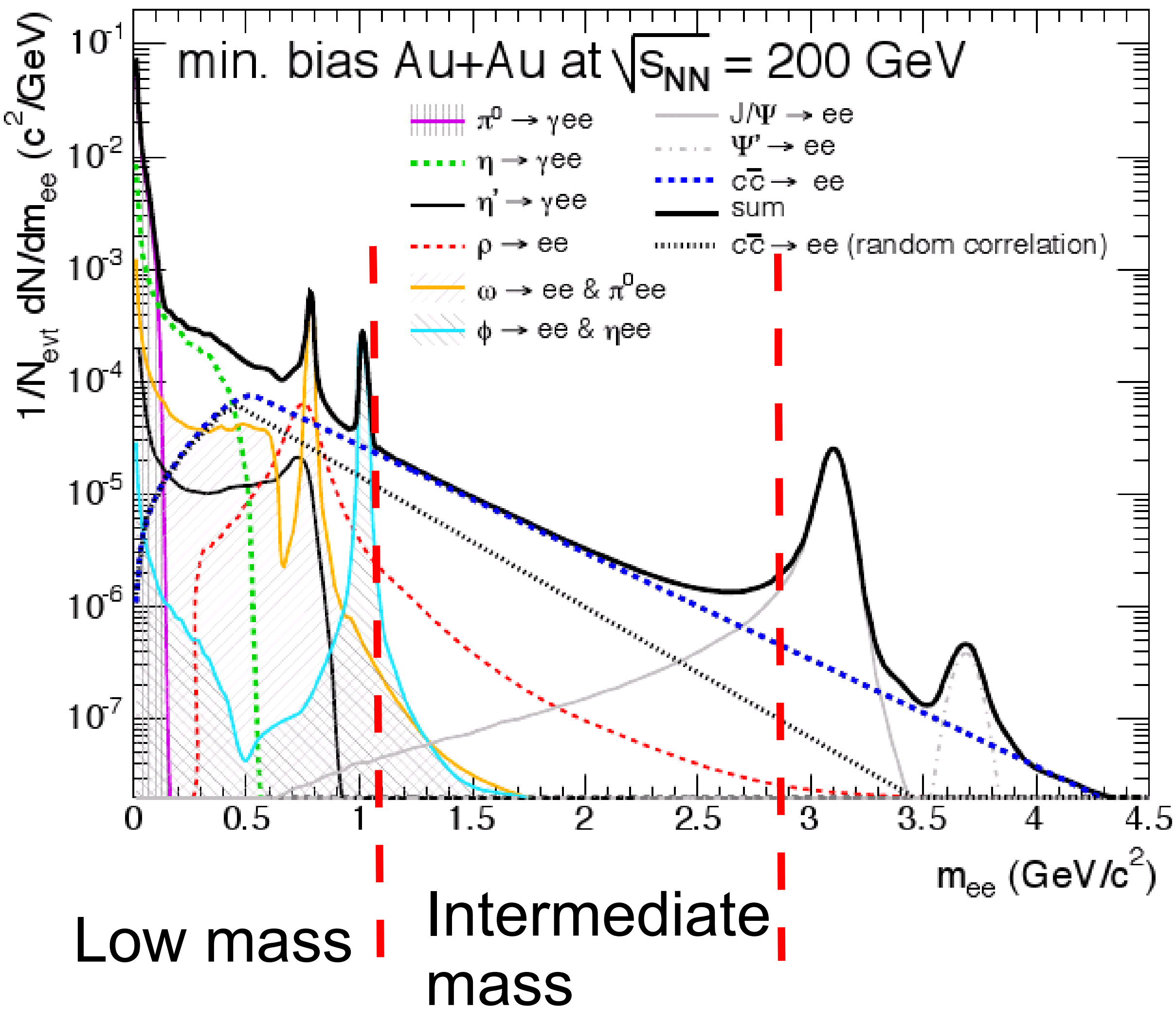
Dileptons (dis) advantages

- Good:
  - Penetrating probe
  - Dynamic range (M, p_t)
- Bad:
  - Penetrating probe: Measure only time integrals
  - Rare

Production channels

- Quark annihilation (the holy grail?)
- Pion annihilation (the dull background?)
- Resonance decays
  - N(1520), a1, ω, etc. (Note: many are 3 body decay)
- Multi-particle channels
- Exotica
  - DCC, collective Bremsstrahlung
- Drell-Yan
- "c-c_{bar} decays"

Elementary Production channels



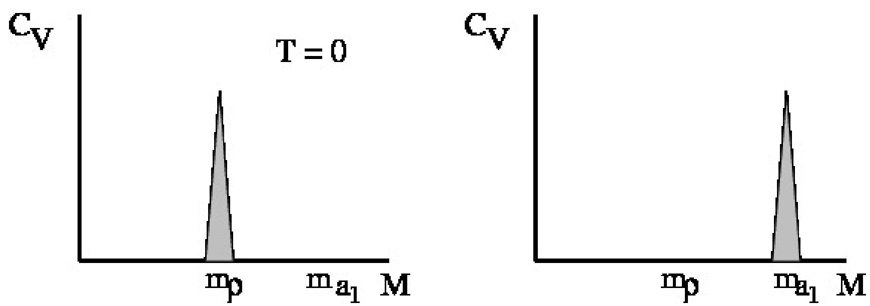
Thanks to T. Ullrich

Low mass dileptons

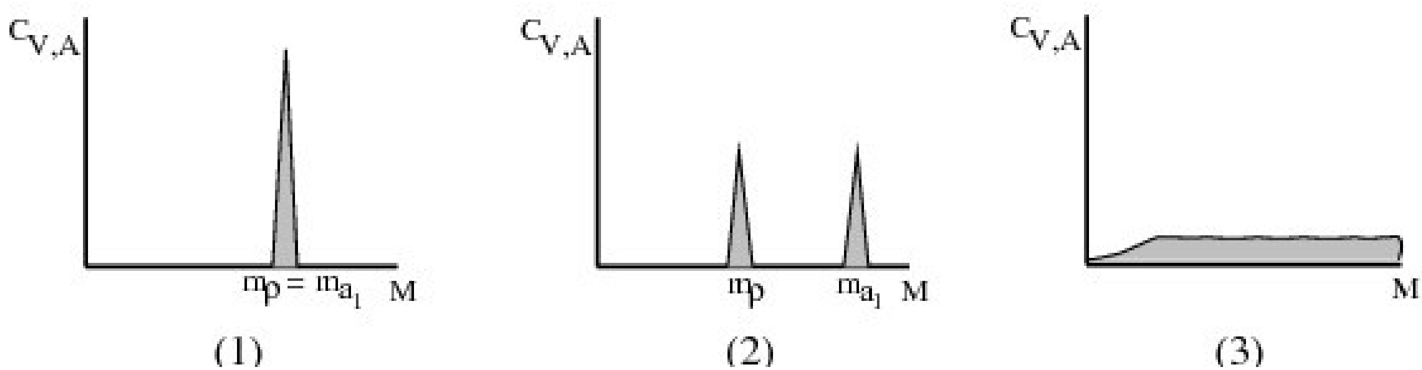
Chiral symmetry restoration:

QCD vacuum: Chiral symmetry spontaneously broken!

T=0



$T>T_c$

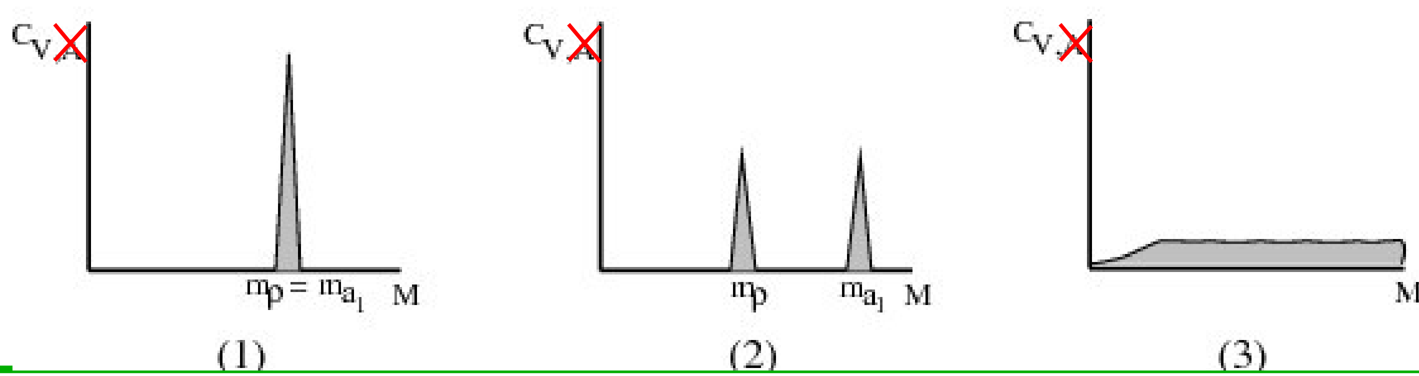


Dileptons and chiral symmetry

Dileptons measure both isovector-vector and isoscalar vector current

Good!! Not so good

Dileptons do NOT measure the isovector AXIAL current

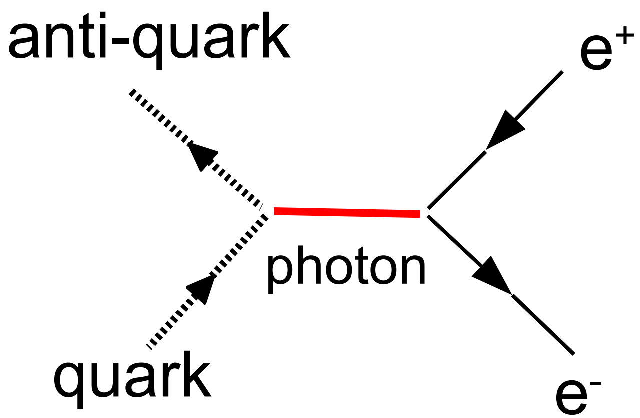


Calculating Dilepton Production

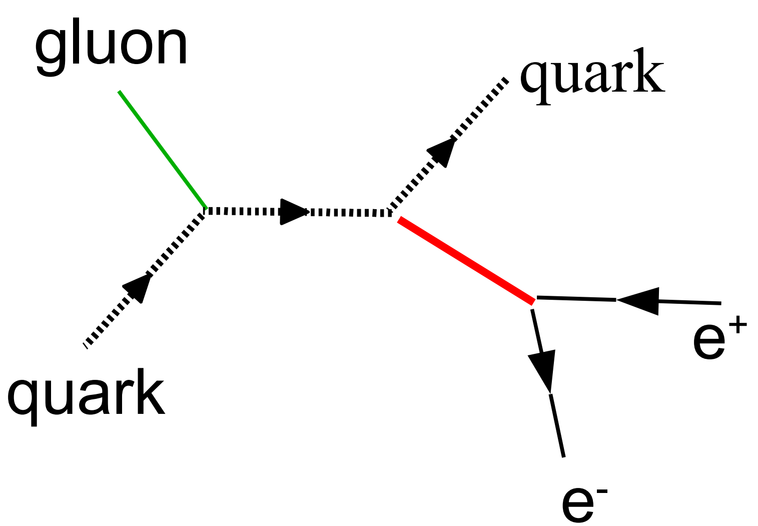
- Elementary production channels
- Many body (medium) effects
- Collision / Expansion dynamics

Elementary channels
(partons)

q-qbar annihilation:

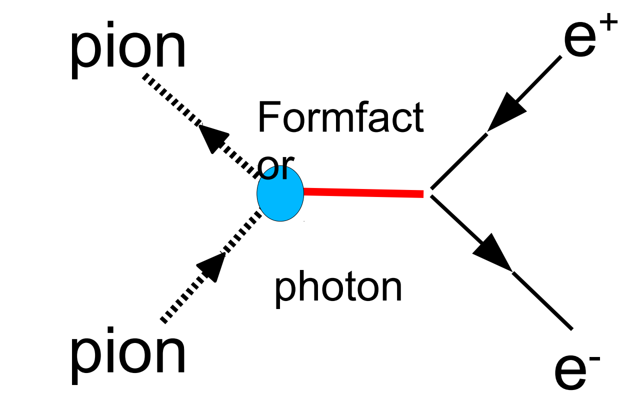


Compton
"scattering"

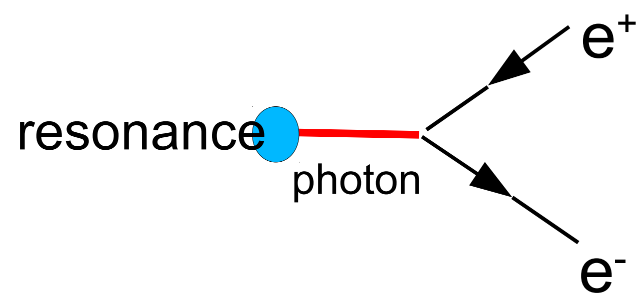


Elementary channels
(hadrons)

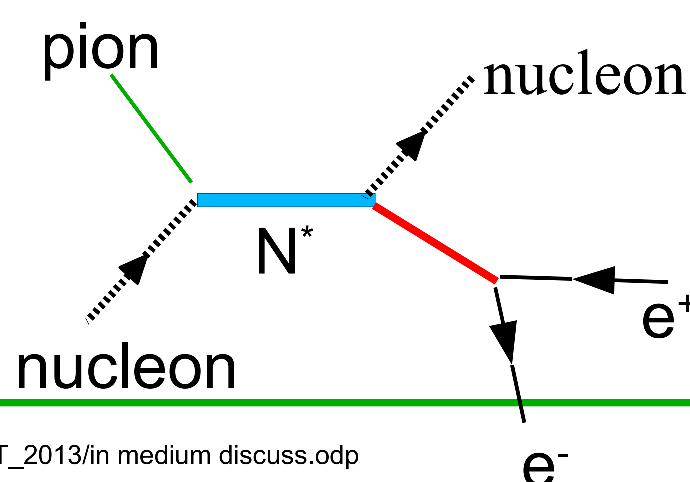
Pion annihilation



"Direct decay"

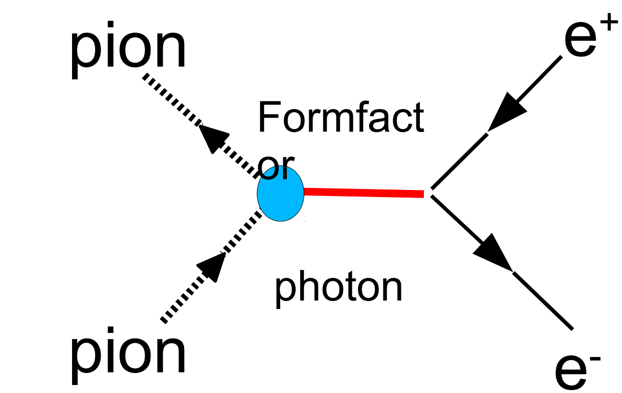


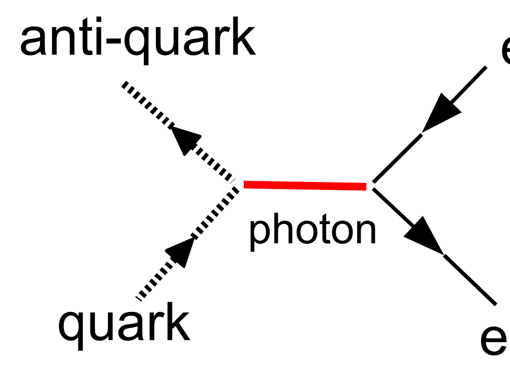
Dalitz decay



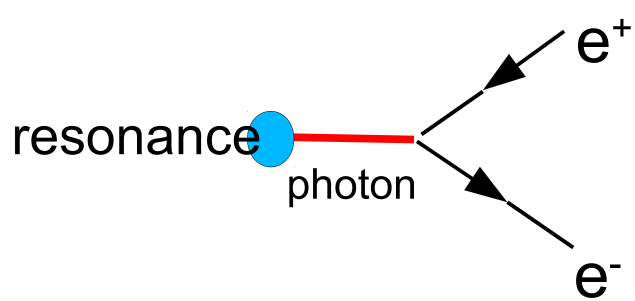
Elementary channels
(hadrons)

Pion annihilation

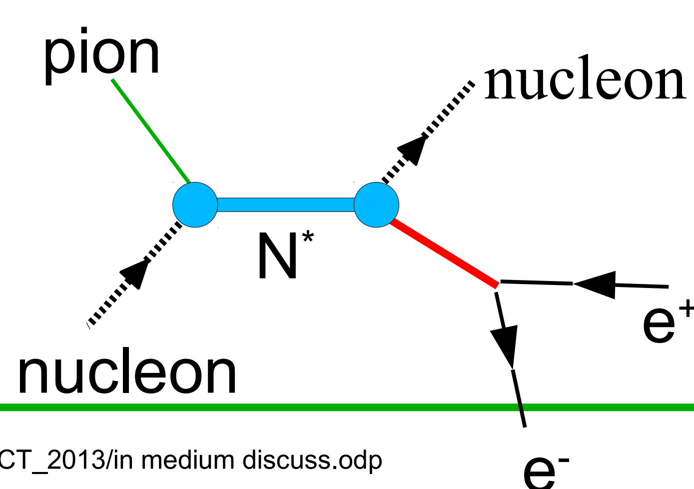


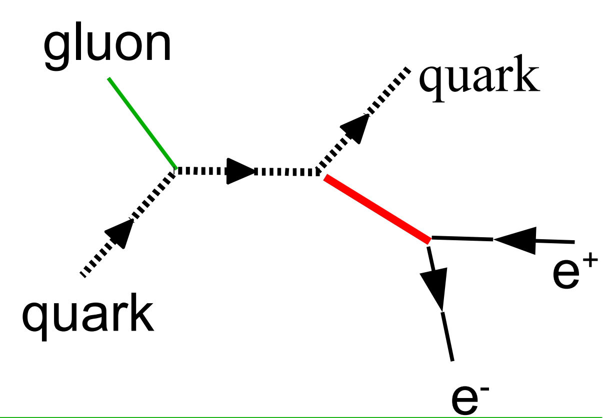


Direct decay



Dalitz decay





Many body / medium effects

General approache:

- Calculate dilepton production from current-current correlator (e.g. Gale&Kapusta)

$$E_+ E_- \frac{d^6 R}{d^3 p_+ d^3 p_-} = \frac{2}{(2\pi)^6} \frac{e^2}{k^4} \left[p_+^\mu p_-^\nu + p_+^\nu p_-^\mu - g^{\mu\nu} (p_+ \cdot p_- + m_l^2) \right] \mathrm{Im}\, \Pi_{\mu\nu}^R (k) \frac{1}{e^{\beta\omega} - 1}$$

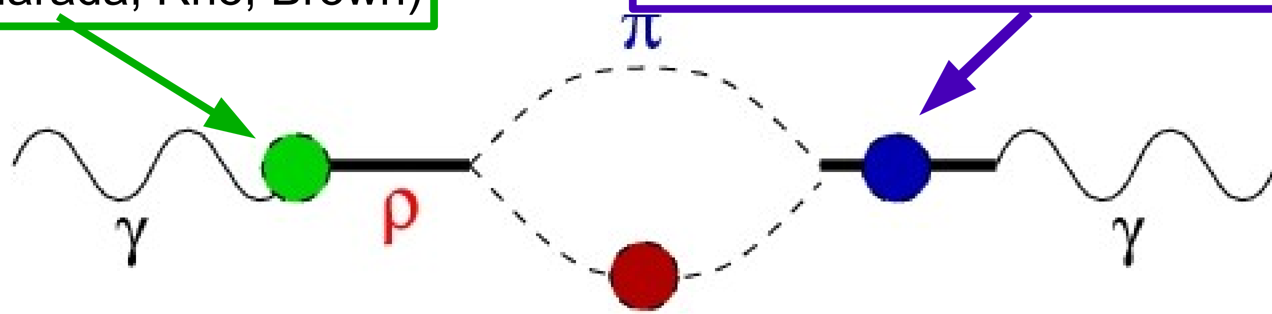
"Trivial" QED + kinemantics

All the good stuff:
- Strong interaction physics
- Manybody physics

In medium correlator

Coupling of ρ to photon
(gauge invariance)
(Song et al, Harada, Rho, Brown)

Dressing of the ρ itself
(s-wave resonances)
a_1, baryon resonances (N 1520)
(Song et al, Friman et al, Mosel et al, Rapp et al)



Dressing of intermediate
pion states
(Delta-hole, thermal pions,..)
(Friman et al, Ko et al, Rapp et al)

Dressing of the rho

- microscopic calculation of self energy (C. Song et al, Chanfray et al, Leupold et al,...
  - dominant channel: coupling to N(1520) (Mosel et al)
    - support from photo absorption data
- impulse/low density approximation for rho optical potential (Kapusta et al.)

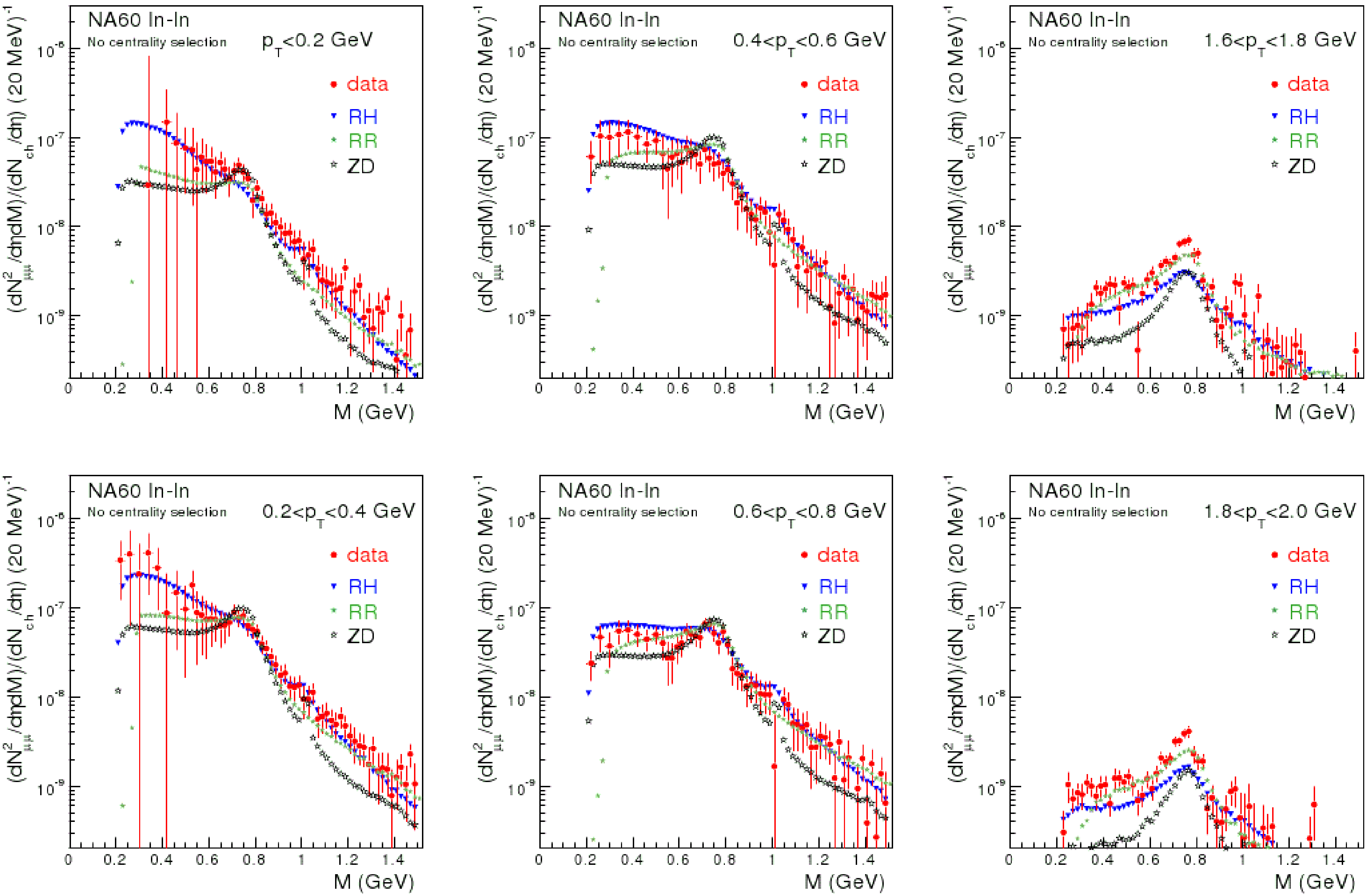
$$\Pi_{ab}(E,p) = -4\pi \int \frac{d^3k}{(2\pi)^3} n_b(\omega) \frac{\sqrt{s}}{\omega} f_{ab}^{(cm)}(s)$$

Non-relativistically:: $\Pi_{ab} = -4\pi f_{ab}^{(b \text{ rest frame})} \rho_b$

Expansion dynamics

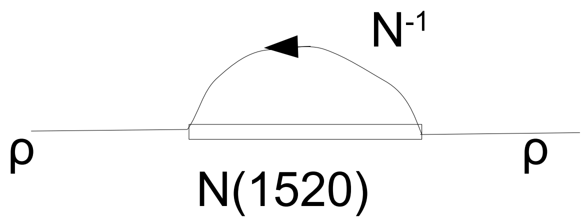
- Fireball, constrained by entropy
  - $V(t)$, $T(t)$, $\mu(t)$
    - constant T, μ, μ_π $\mu_{K,eta,...}$ over Volume
    - NO longitudinal flow field
- Hydro (valid at SPS energies ?)
- Transport

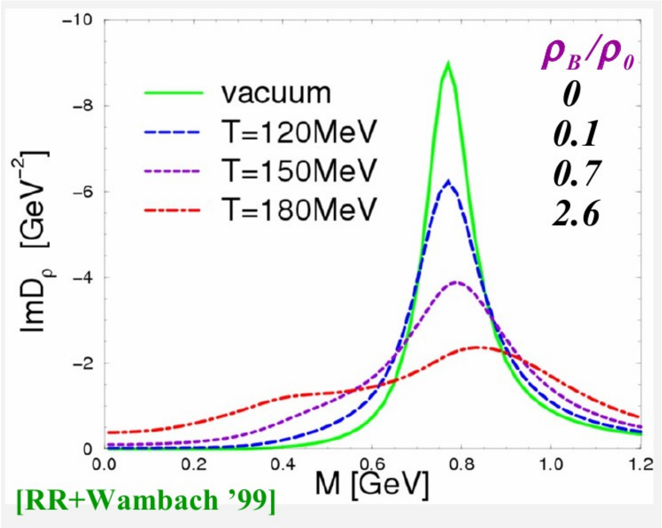
NA 60 favors broadening



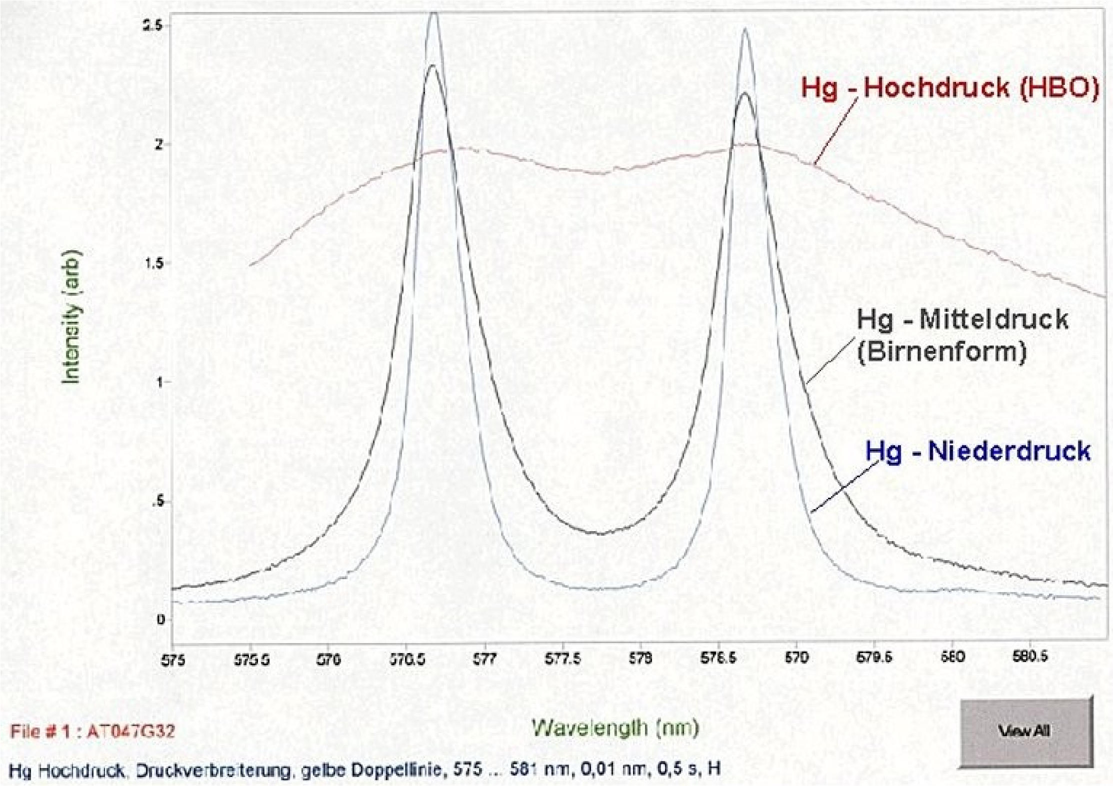
Melting/Broadening of Resonances

- Deconfinement
- Change of hadronic part of the wave function
  - Example Λ(1405), rho?
- Mixing with other hadrons
  - Example rho





Broadening of Resonances

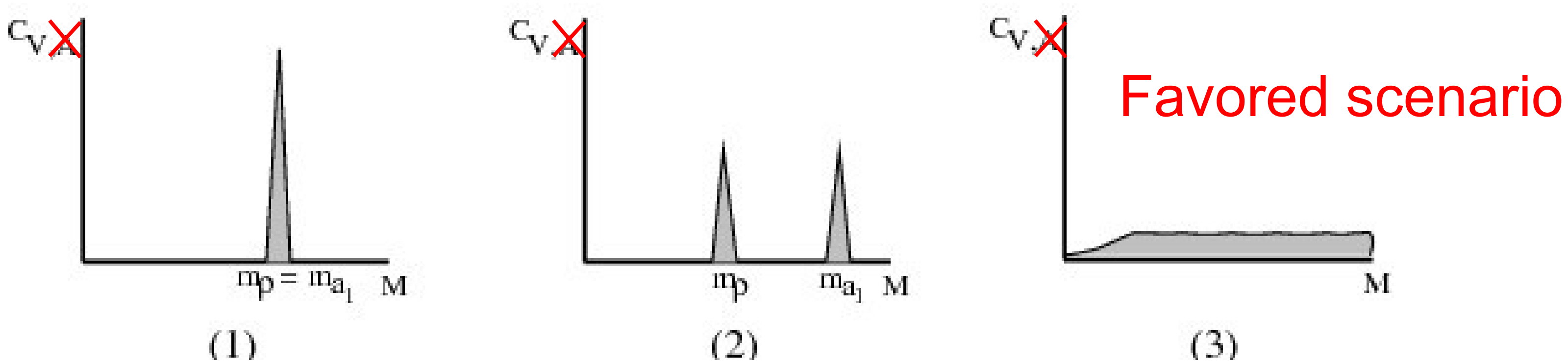


"Chiral restoration" in real life ….

Low mass dileptons

- Well explained by broadening of rho
  - Baryons are essential
- Dropping masses dis-favored

- What about chiral symmetry?



Closing the deal

- Are we done ? SPS RHIC (PHENIX?) described by in medium spectral function
- HADES? Looks as if resonances play important role (see Tetayana's talk)
- What do we need to declare success?
  - Expansion dynamics controlled
  - Channels controlled
  - Are we treating the resonances correctly?
  - Re-tune spectral function approach to incorporate p-p, p-A, pi-N ….

Resonance → Nρ Branching Ratios

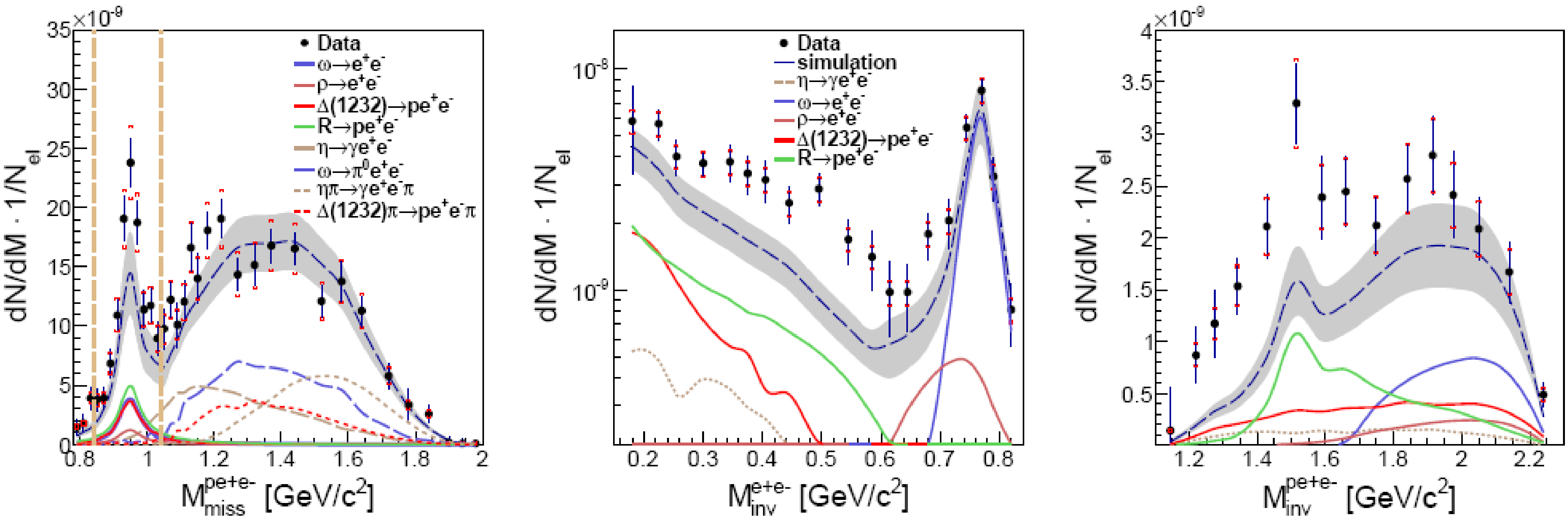
	GiBUU12	UrQMD09	KSU12	KSU92	BnGa12	CLAS12	PDG12	
N(1520)3/2⁻	21	15	20.9(7)	21(4)	10(3)	12.7(4.3)	20(5)	D13
N(1720)3/2⁺	87	73	1.4(5)	87(5)	10(13)	47.5(21.5)	77.5(7.5)	P13
Δ(1620)1/2⁻	29	5	26(2)	25(6)	12(9)	37(12)	16(9)	S31
Δ(1905)5/2⁺	87	80	<6	86(3)	42(8)		>60	F35

Partial courtesy of Piotr Salabura, Sept 2013

CLAS12: V. Mokeev *et al*, Phys Rev C **86**, 035203 (2012); V. Mokeev, PC
BnGa12: A.V, Anisovich *et al*, Eur Phys J A **48**, 15 (2012)
GiBUU12: J. Weil *et al*, Eur Phys J A **48**, 111 (2012); J. Weil, PC
KSU92: D.M. Manley and E.M. Saleski, Phys Rev D **45**, 055203 (1992)
KSU12: M. Shrestha and D.M. Manley, Phys Rev D **86**, 055203 (2012)
PDG12: J. Beringer *et al* [RPP] Phys Rev D **86**, 010001 (2012)
UrQMD09: K. Schmidt *et al*, Phys Rev C **79**, 4002 (2009)

Results for ppe+e- channel

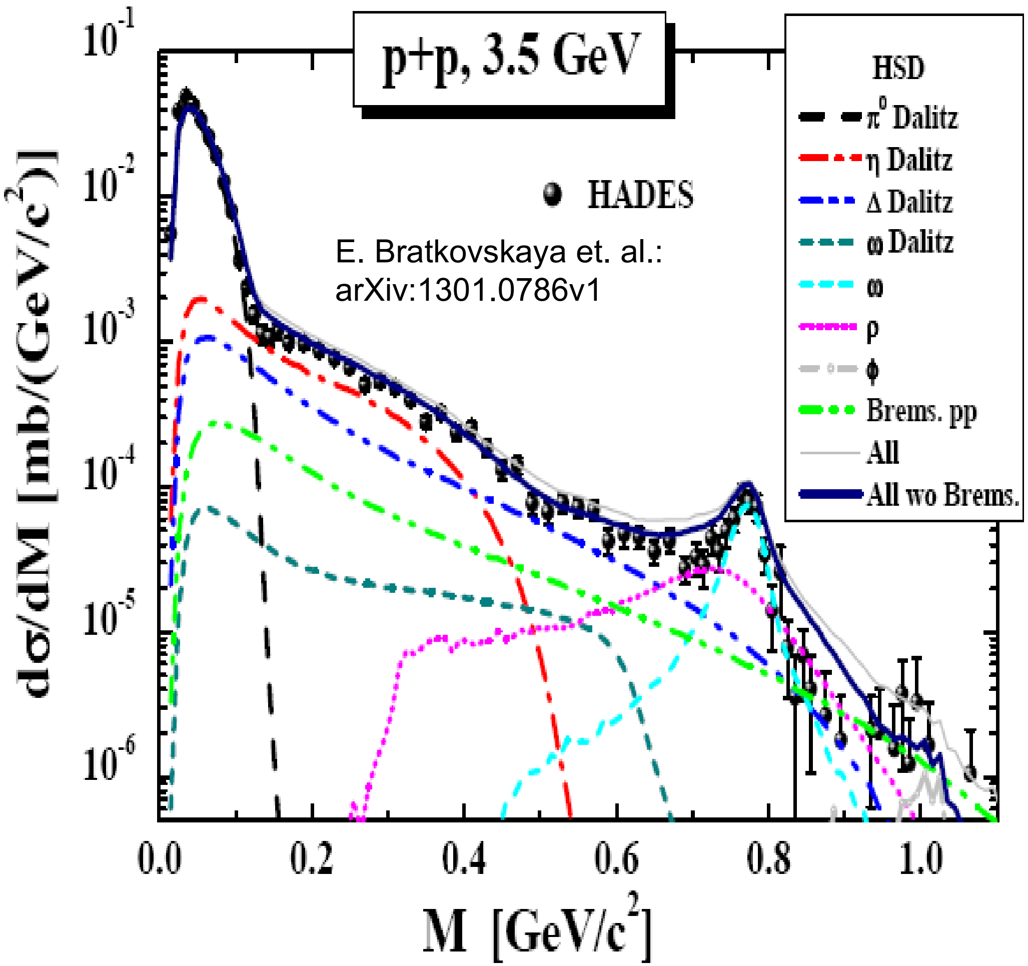
„QED" : point like $R \rightarrow N\gamma^*$ vertex

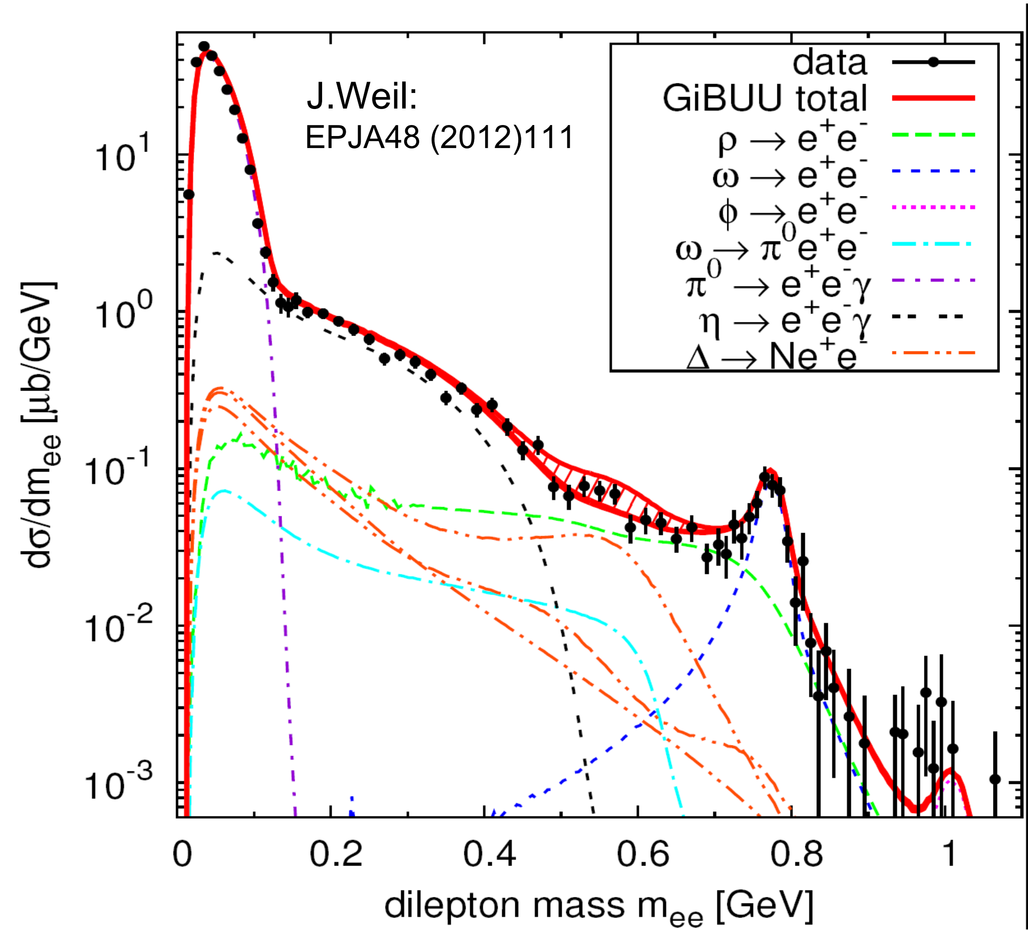


- Significant contribution from higher (than Δ) mass resonances

- Addtional strength below VM pole needed – off shell ρ meson coupling ! – extended interaction vertex
- low mass resonances : Δ(1232), N(1440), N(1520) ?

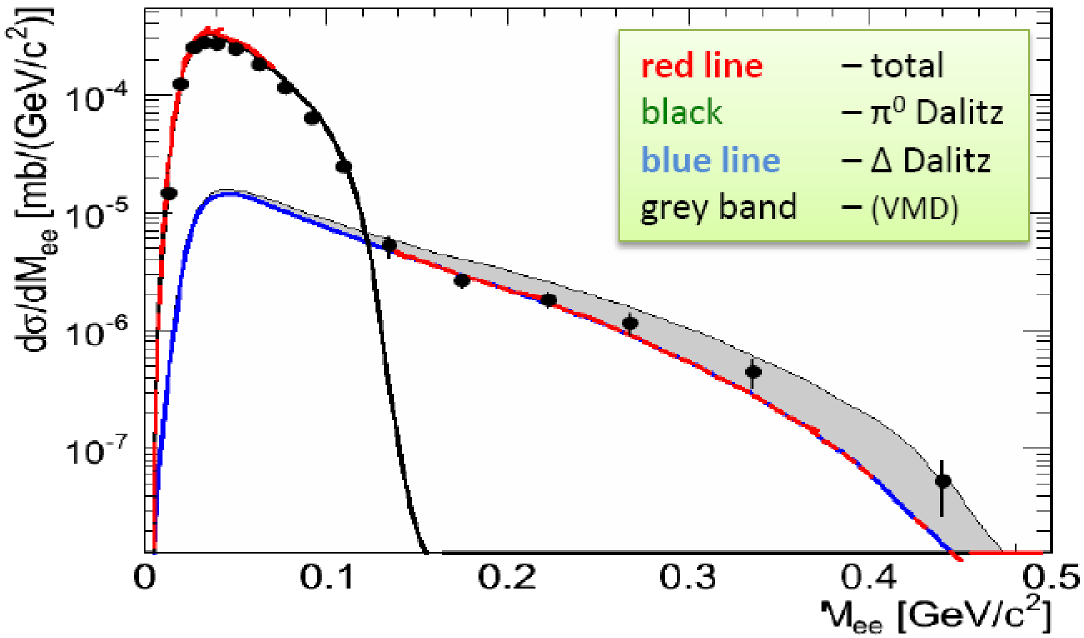
e+e- sources in pp @ 3.5 GeV





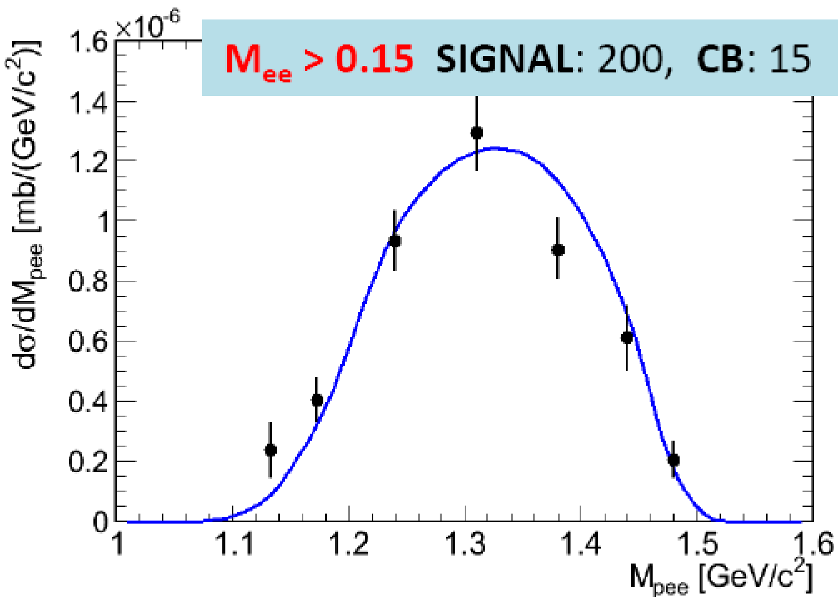
- Many uncertainties: inclusive cross sections π, Δ, η , ω/ρ (fixed now by HADES)
  Δ→pe+e- transition (Dalitz decay); rates, em. Transition Form-Factors
  ρ - spectral function !

p+p→pΔ$^+$ → p pe+e- Dalitz decay

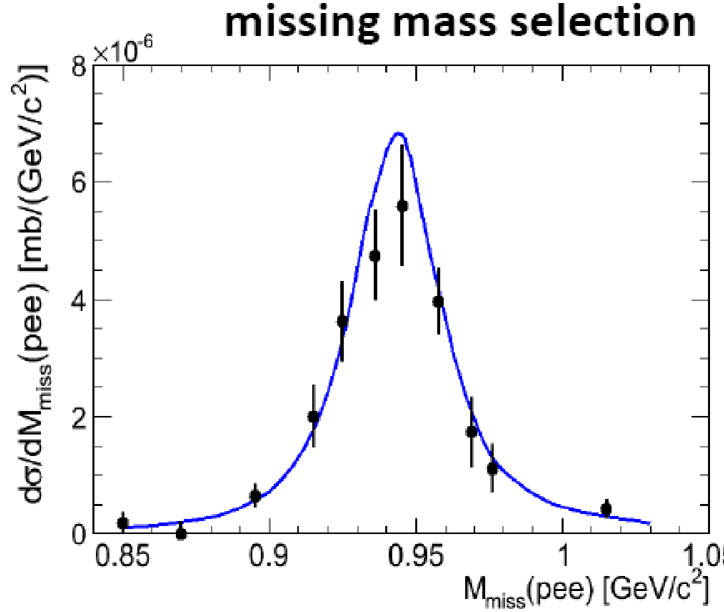


Mass distributions

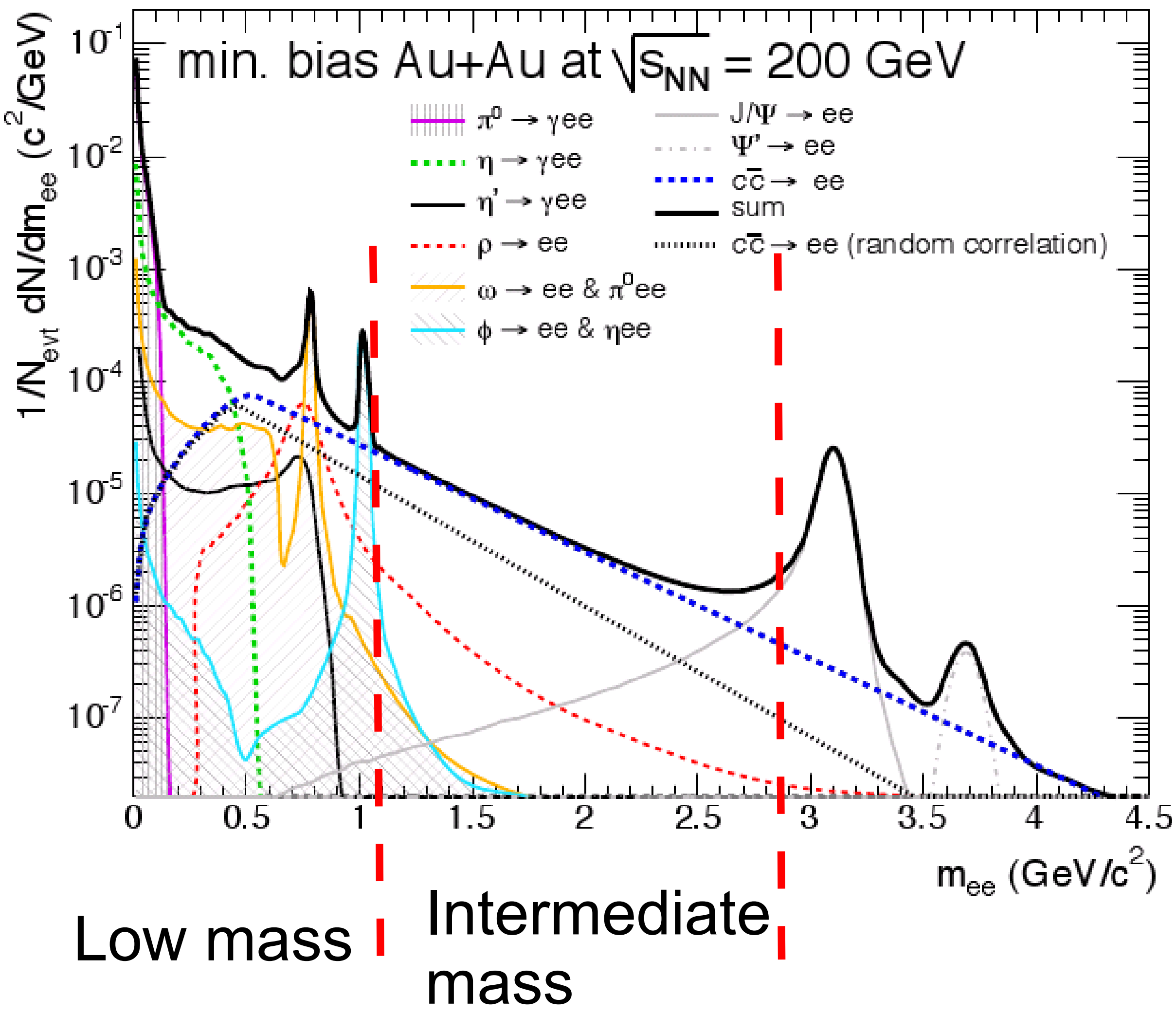
G_M (q^2) impact moderate



missing mass selection



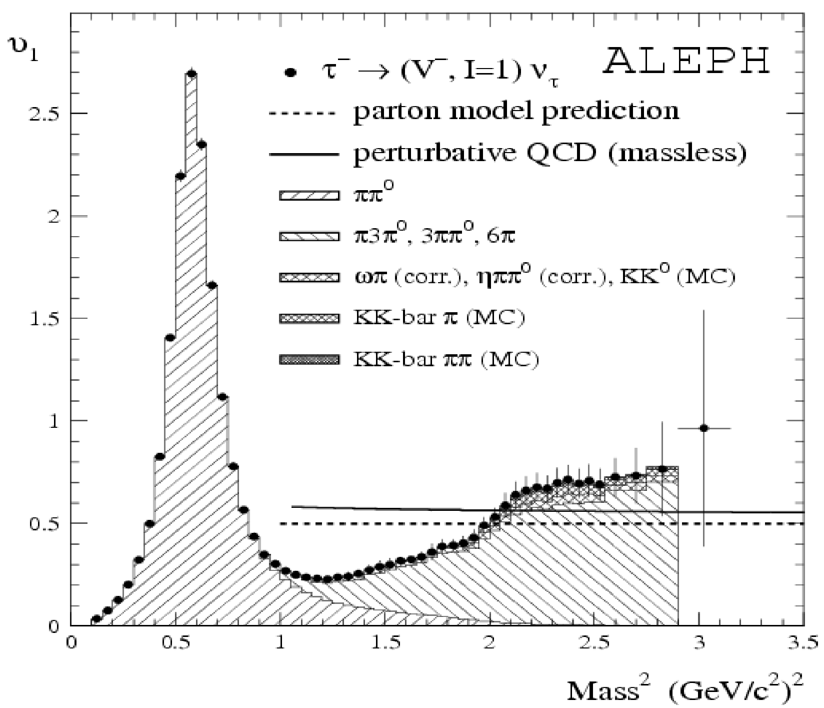
Intermediate mass



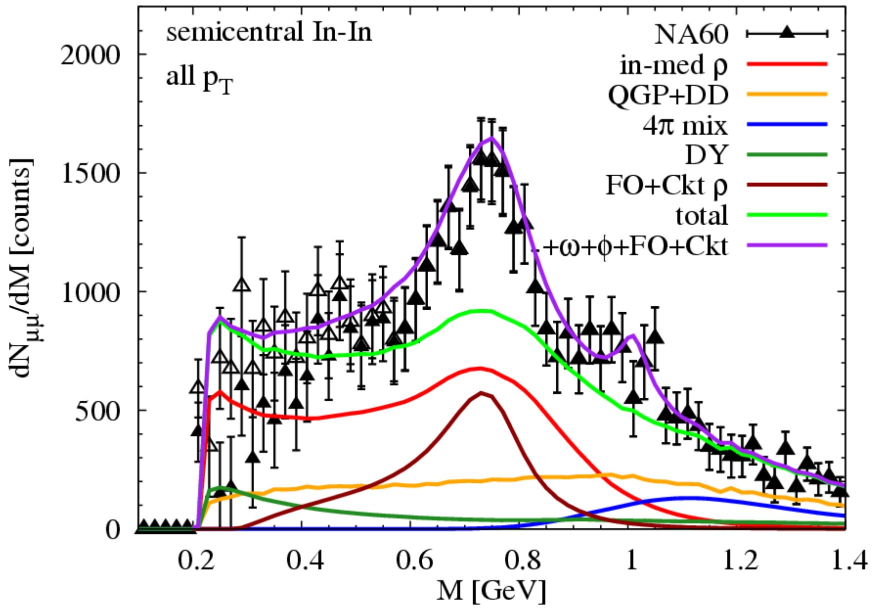
Thanks to
T. Ullrich

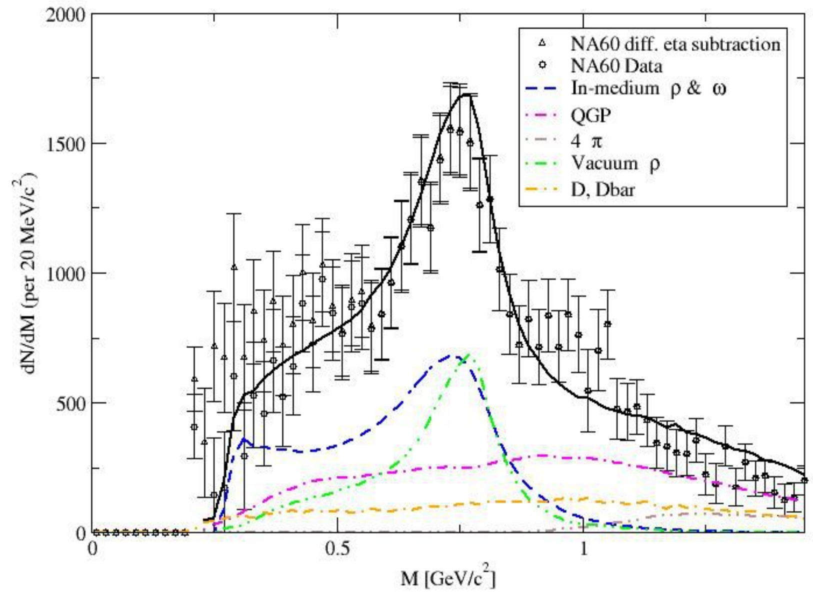
Intermediate mass

- Contributions from both q-qbar and multi-pion (a_1 etc) channels
  - Can we disentangle this?



Intermediate Mass M>1GeV



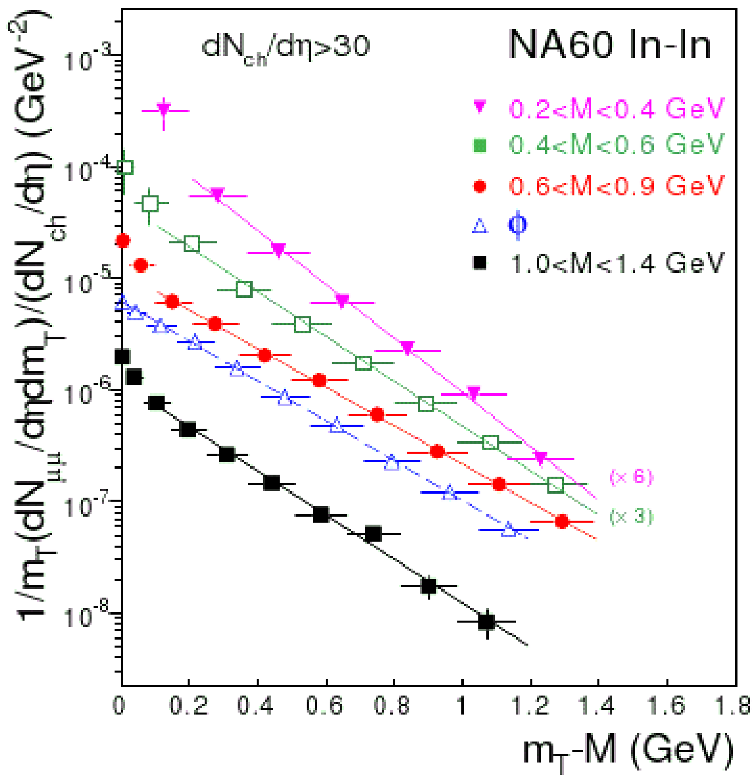


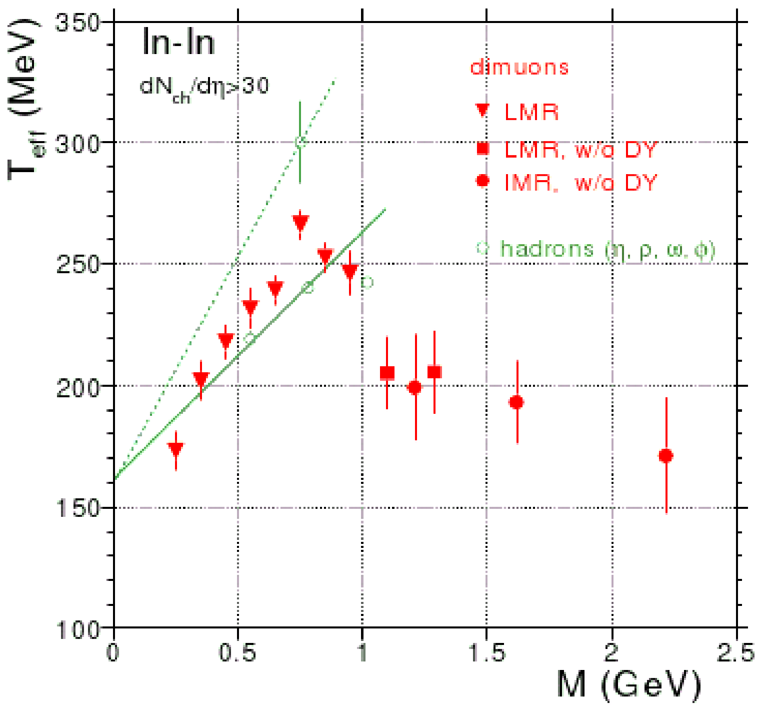
van Hess, Rapp

Renk, Rupert

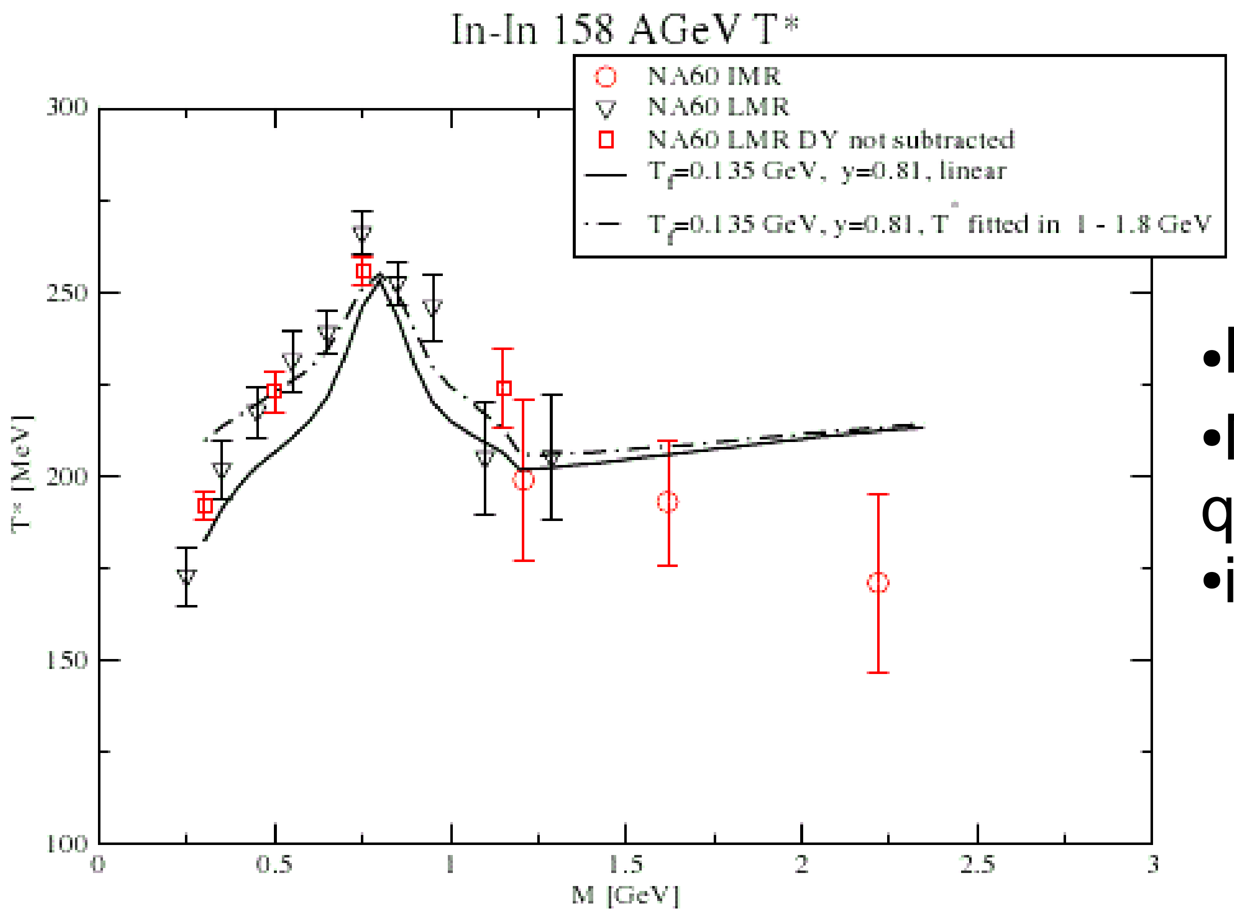
"multi pion" vs QGP

NA60 p_t slopes



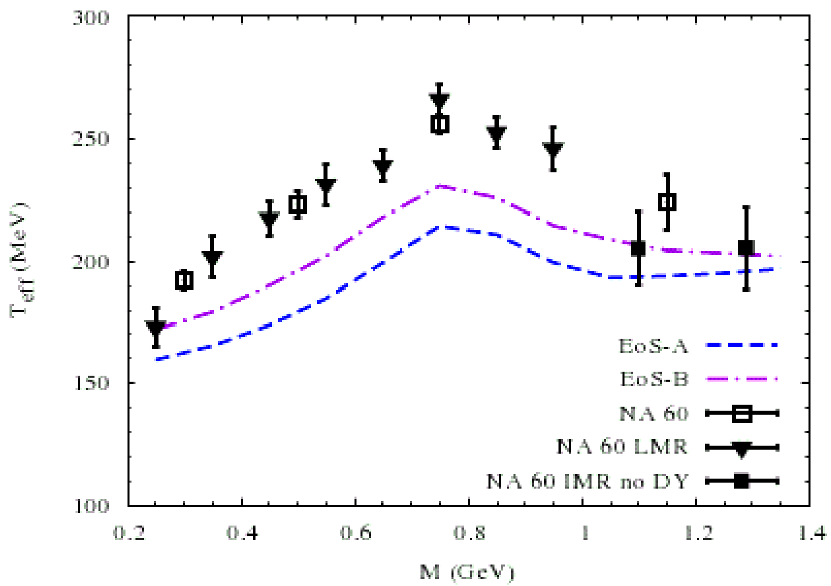


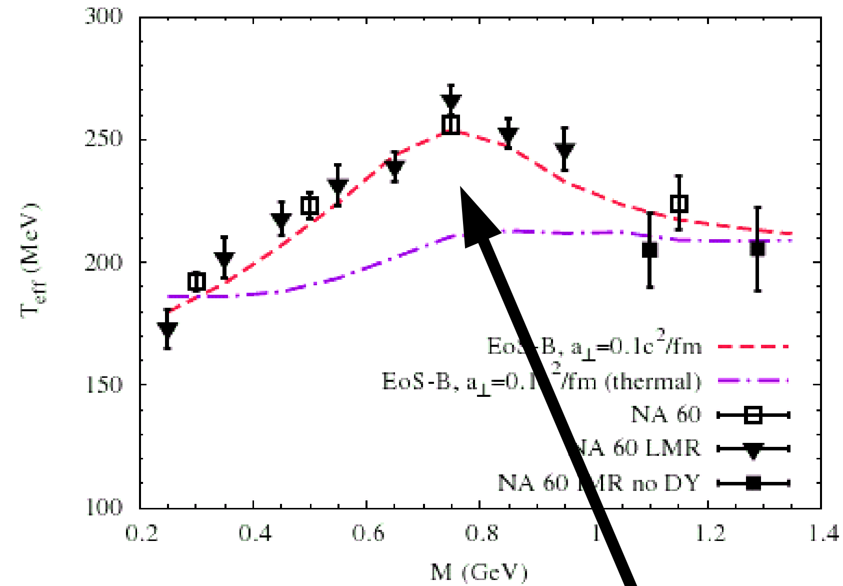
Renk, Ruppert et al



- Deviation for p_t<1 GeV
- M>1 GeV dominated by q-qbar
- initial high Temp is essentia

van Hees and Rapp





Primordial (“hard”) rho absolutely essential

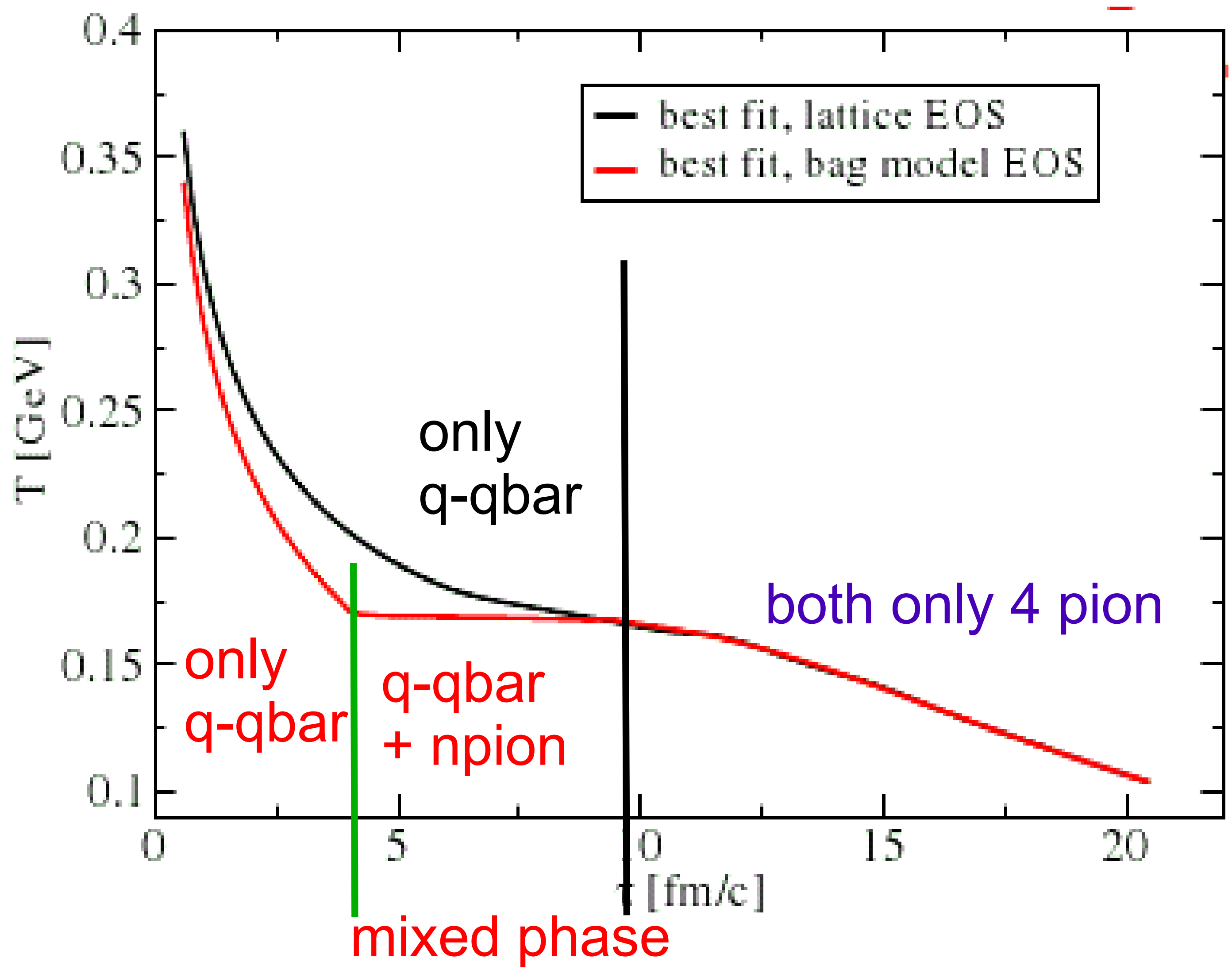
(equivalent hard *pion* equally important for pion spectrum)

Data can be reproduced with:

- primordial rho-meson
- increased initial acceleration
- EOS with low T_c=160 MeV (EOS B)

Expansion dynamics and intermediate mass

T. Renk

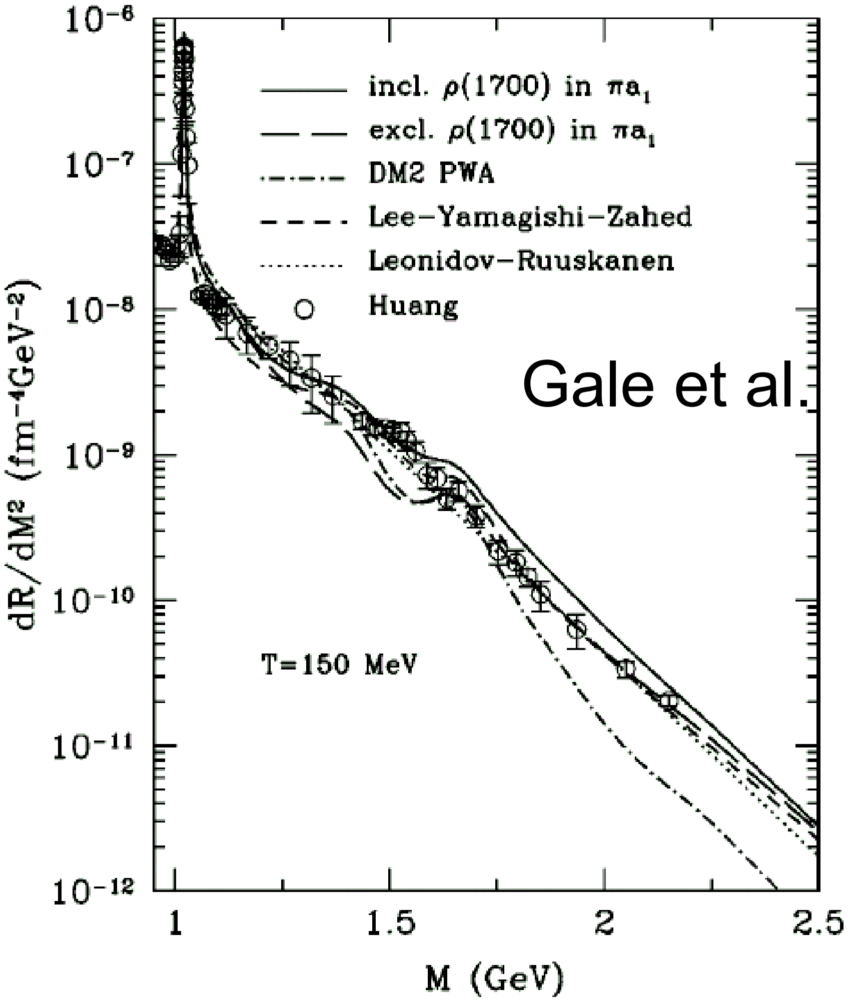


So what is it?

q-q_bar annihilation ?

Multi-pion hadronic reactions?

Meet Bob
(aka Duality)



Gale et al.

Rate(QGP) = Rate(Hadrons) = **Bob**

Renk, Rupert et al: Bob Q-qbar

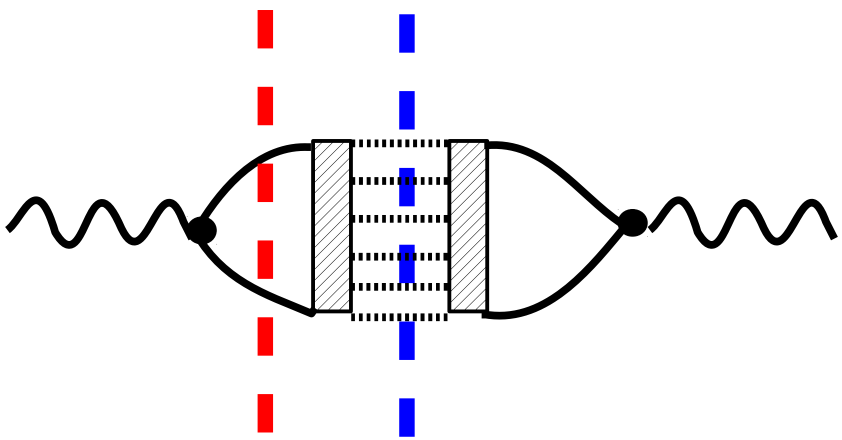
Van Hees and Rapp: Bob Multipion

Duality

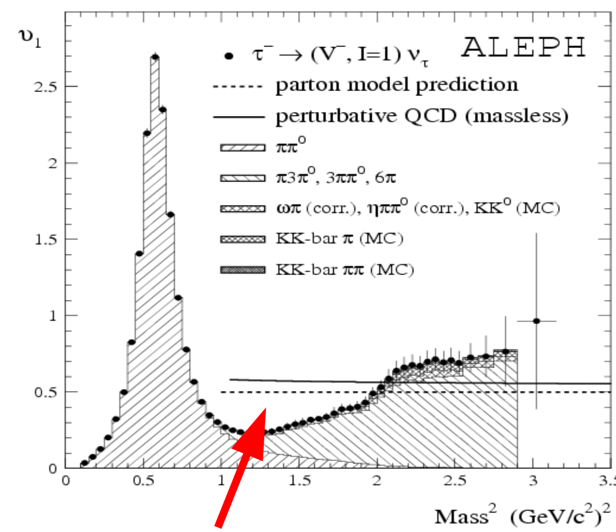
$$E_+ E_- \frac{d^6 R}{d^3 p_+ d^3 p_-} = \frac{2}{(2\pi)^6} \frac{e^2}{k^4} \left[p_+^{\mu} p_-^{\nu} + p_+^{\nu} p_-^{\mu} - g^{\mu\nu} (p_+ \cdot p_- + m_l^2) \right] \mathrm{Im}\, \Pi_{\mu\nu}^{R} (k) \frac{1}{e^{\beta\omega} - 1}$$

Extract from e^+e^- or tau-decay data

(Z. Huang PLB 95)



q-qbar cut n-pion cut

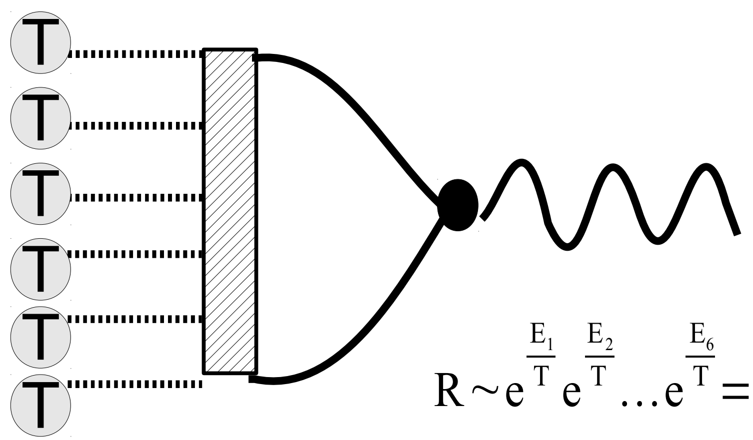


Location of break in p_t-slopes

Production Rate

$$\frac{dR}{d^4q} \sim \int d^3p_1 \ldots d^3p_n \left| M(p_1, \ldots, p_n; e^+ e^-) \right|^2 f(p_1) \ldots f(p_n) \delta^4(p_1^\mu + \ldots + p_n^\mu - q^\mu)$$

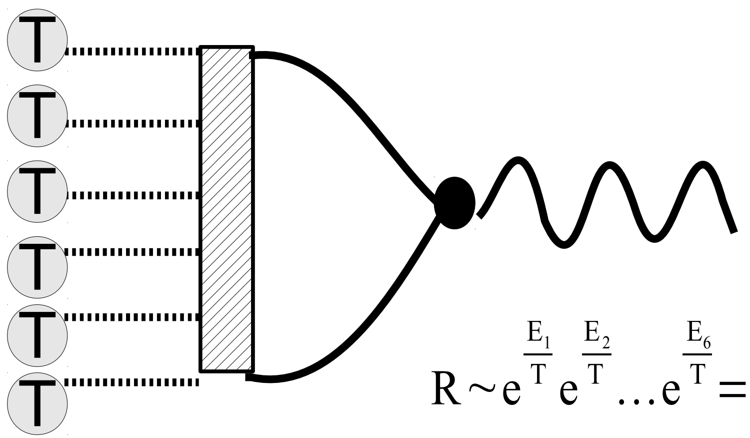
$$f(p) \sim \exp\left(\frac{-E(p)}{T} \right)$$



$$R \sim e^{\frac{E_1}{T}} e^{\frac{E_2}{T}} \ldots e^{\frac{E_6}{T}} = e^{\frac{\sum E_i}{T}} = e^{\frac{E_\gamma}{T}}$$

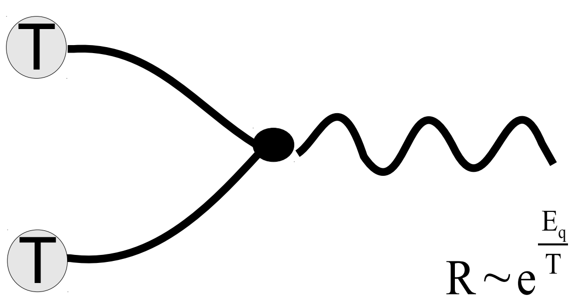
Duality

n-pion



$$R \sim e^{\frac{E_1}{T}} e^{\frac{E_2}{T}} \ldots e^{\frac{E_6}{T}} = e^{\frac{\sum E_i}{T}} = e^{\frac{E_\gamma}{T}}$$

q-qbar



$$R \sim e^{\frac{E_q}{T}} e^{\frac{E_{\bar{q}}}{T}} = e^{\frac{E_\gamma}{T}}$$

Dilepton and the QCD CP

- Massless “modes” at CP since it is a second order phase transition
- Mode is mixture of “sigma” amd “omega"
- However these may likely be space-like modes
  - $M^2 \rightarrow O^{-}$

Nambu model
(Fuji et al, hep-ph/0401028,0403039)

Sigma remains massive at CP; CP driven by spacelike p-h exitations

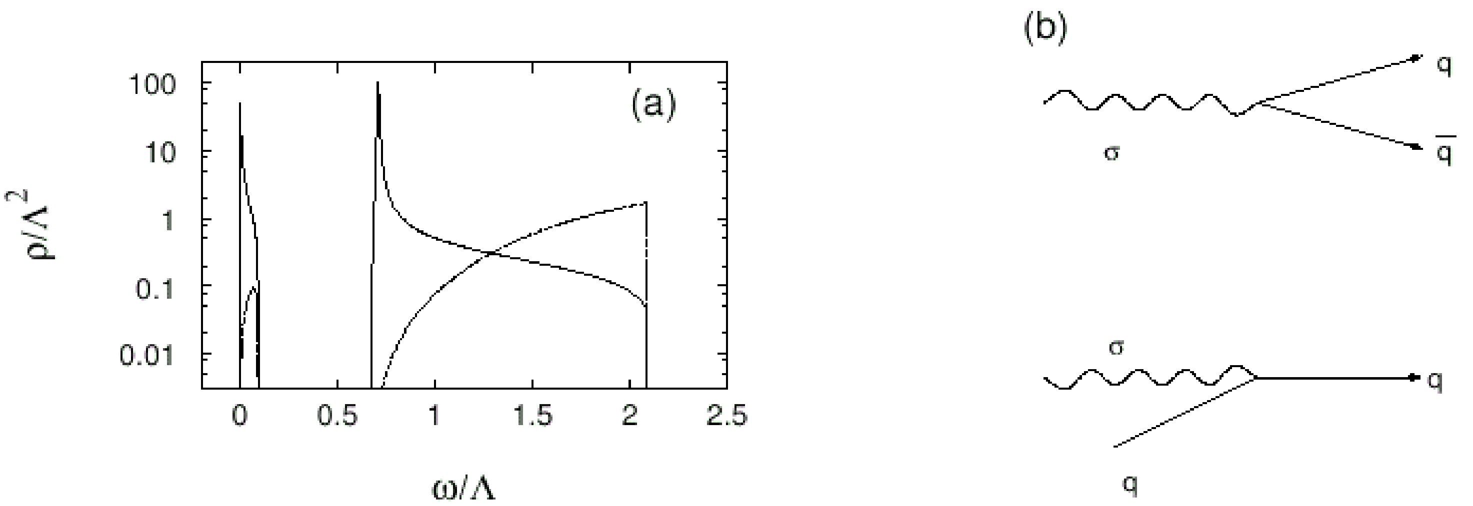


Fig. 2. (a) Spectral function in the scalar channel (solid) with $|\boldsymbol{q}|/\Lambda = 0.1$ at a CEP with $m/\Lambda = 0.01$. The free gas spectrum (dashed) is also shown for reference. (b) Typical processes contributing to the spectrum.

Nambu model
p-h excitations

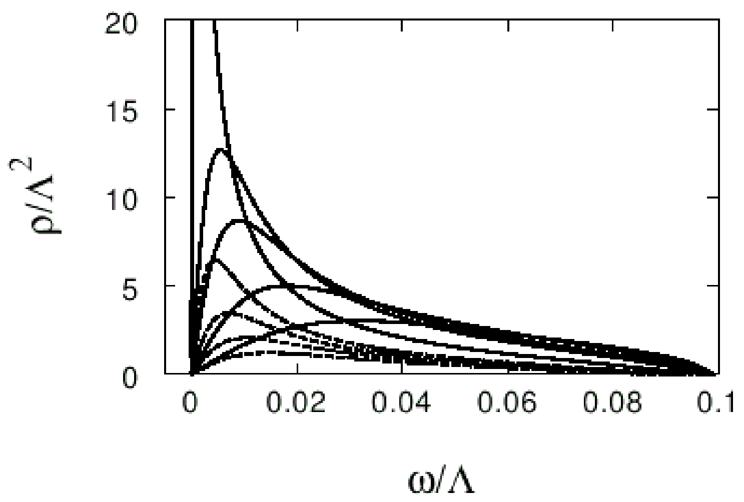
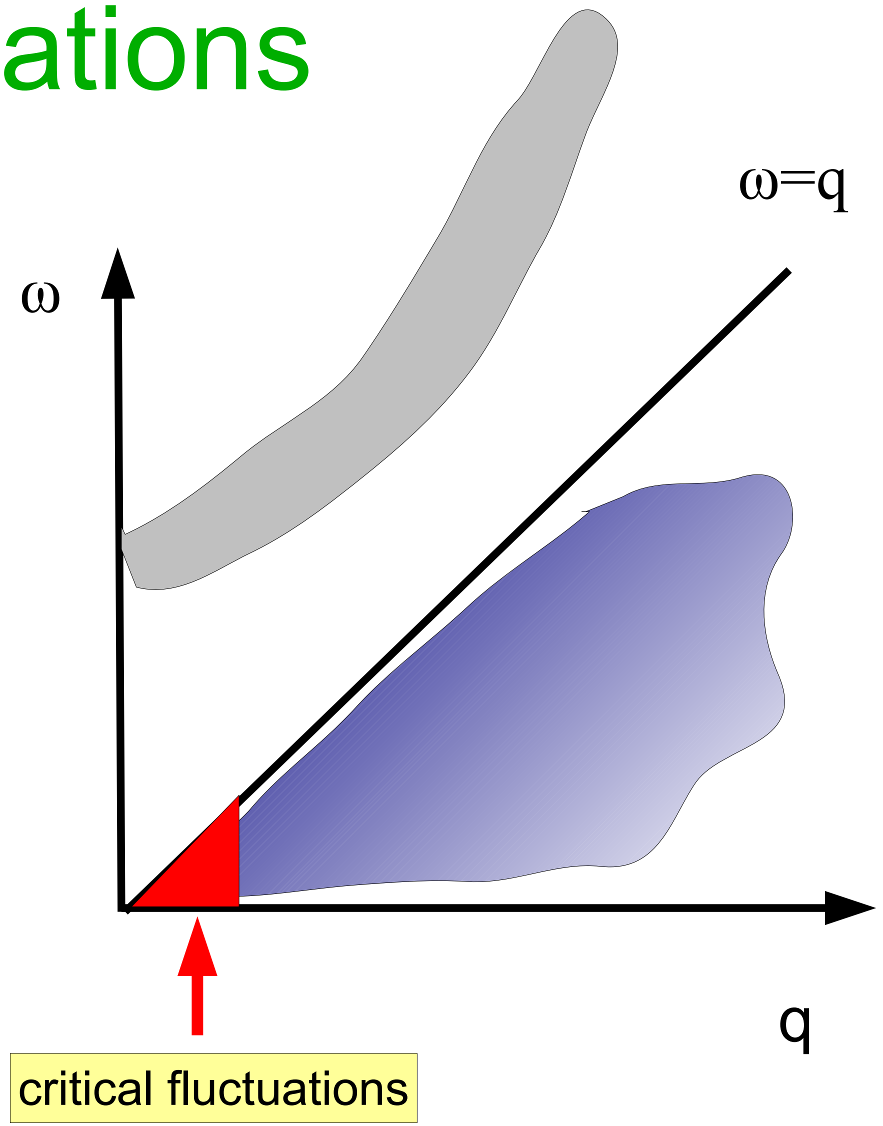


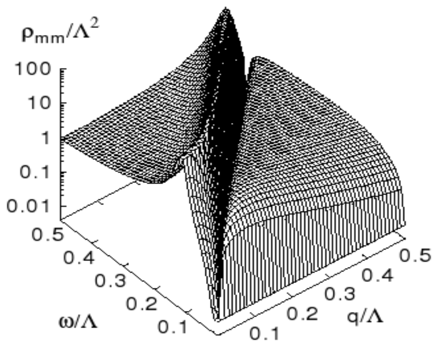
Fig. 3. Spectral function in the spacelike momentum region with $|\boldsymbol{q}|/\Lambda = 0.1$, $T = T_c$ and $m/\Lambda = 0.01$ for several μ (see text).



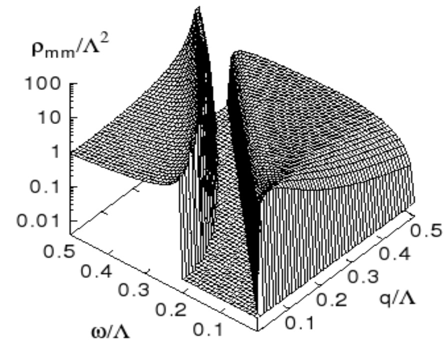
CP is and the chiral transition

Chiral transition m_q=0

T>T_c



(a)

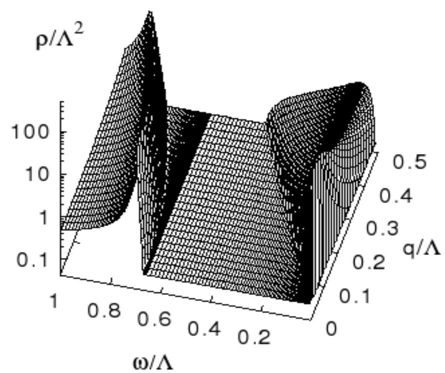


(b)

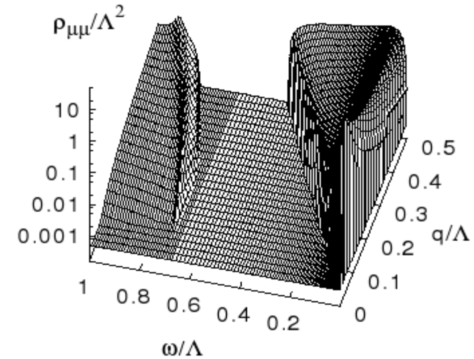
T<T_c

Critical point m_q>0

Massive Scalar



Scalar



Vector (Baryon-density)

Dileptons and Critical Point

- Not accessible since fluctuations are space-like
- Same for charge fluctuations!
- May provide model constraints
-

The Dilepton production landscape