Resonance production in a thermal model

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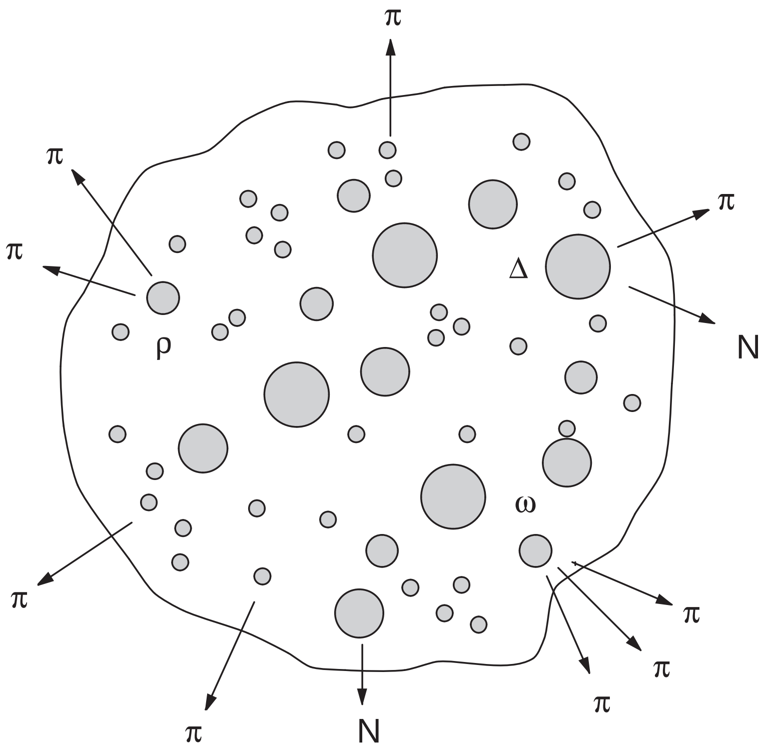


$$\sim e^{-(E-\mu)/T}$$

This is not the

Cracow model

Thermal model

Koppe (1948), Fermi (1950), Landau, Hagedorn, Rafelski, Bjorken, Gorenstein, Gaździcki, Heinz, Braun-Munzinger, Stachel, Redlich, Magestro, Csörgő, Becattini, Cleymans, Letessier,...

WB + WF, PRL 87 (2001) 272302; PRC 65 (2002) 064905 (our variant)
WB + A. Baran + WF, Acta Phys. Pol. B33 (2002) 4235 (review)
WB + WF + B. Hiller, **nucl-th/0306034**

1. $T_{\rm chem} = T_{\rm kin} \equiv T$, single freeze-out (short $\Delta\tau$, Appelshäuser, Lisa)

2. Complete treatment of resonances

3. Assumed freezeout hypersurface

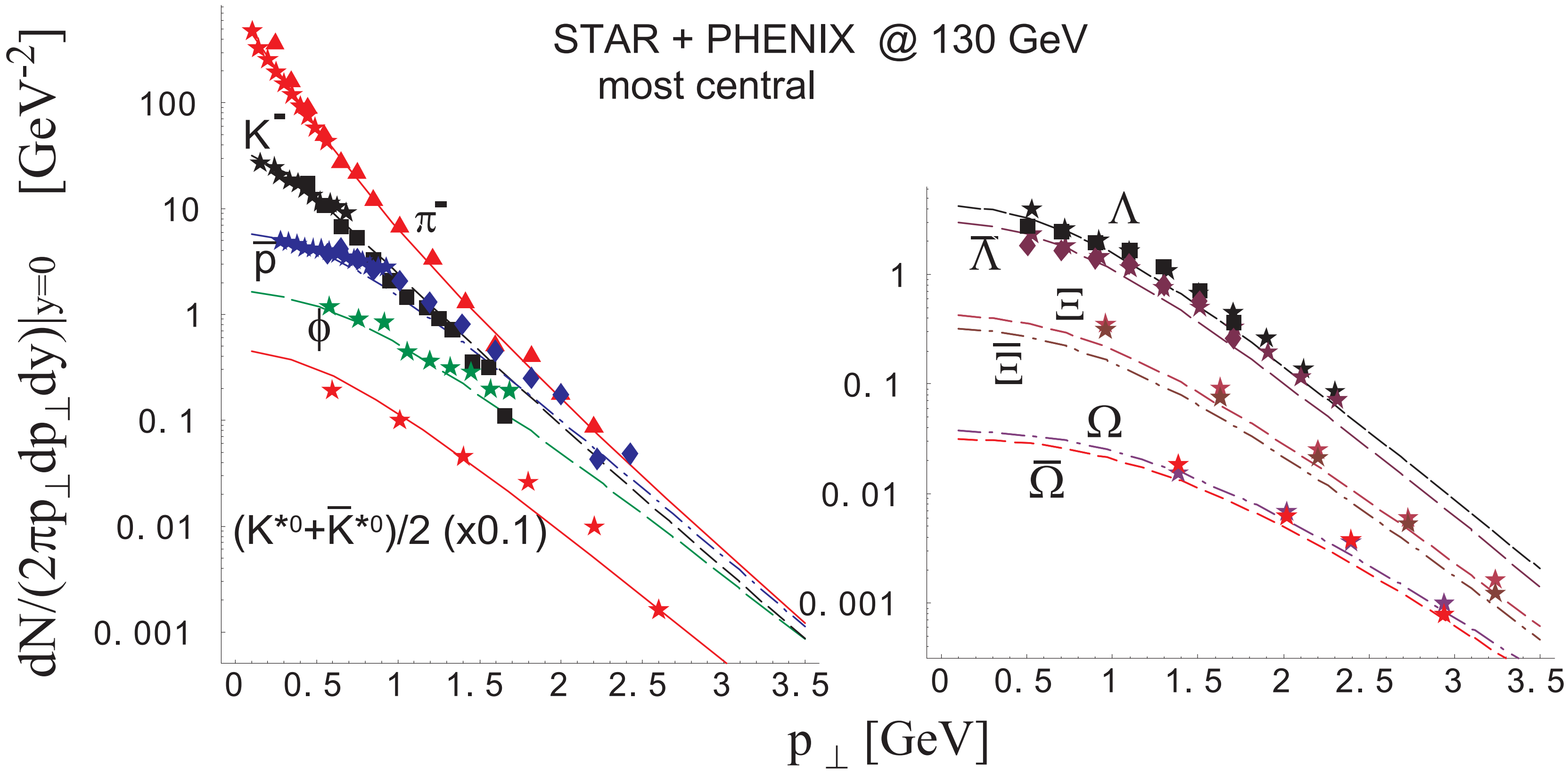
   $\sim$ Buda-Lund

4. 4 parameters: T,μ_B (fixed by the ratios of the particle abundances), invariant time at freeze-out τ (controls the overall normalization), transverse size $\rho_{\rm max}$ ($\rho_{\rm max}/\tau$ controls the slopes of the $p_\perp$ spectra)

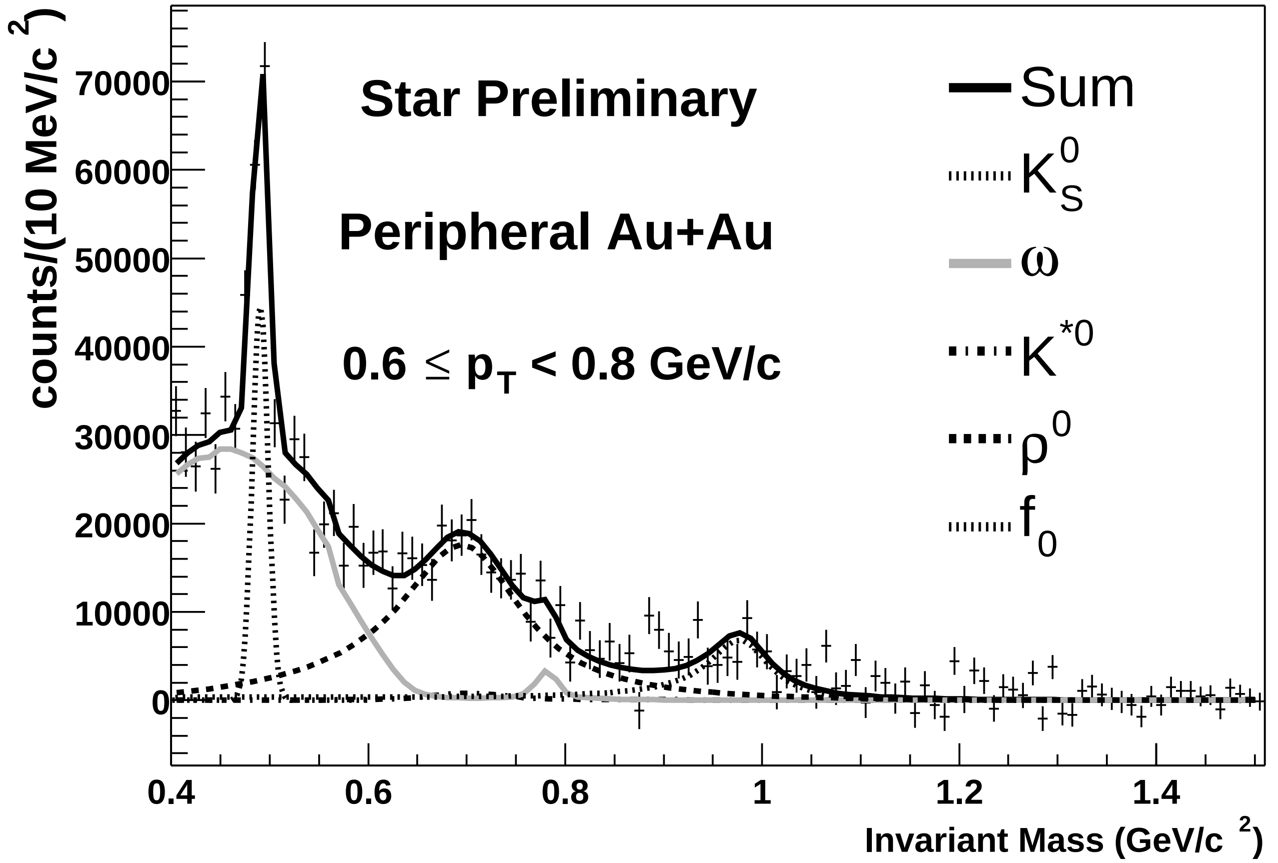
5. Hubble-like flow, $u^\mu = x^\mu/\tau$

Particle ratios @ 130 and 200 GeV →

T [MeV]	165 ± 7	160±5
μ_B [MeV]	41 ± 5	26±4
μ_S [MeV]	9	5
μ_I [MeV]	-1	-1
χ^2/DOF	1.0	1.5



$\pi^+\pi^-$ pairs from STAR (P. Fachini)



Can we explain this in the thermal model?

(positions of resonances, high vs. low M - yet another thermometer)

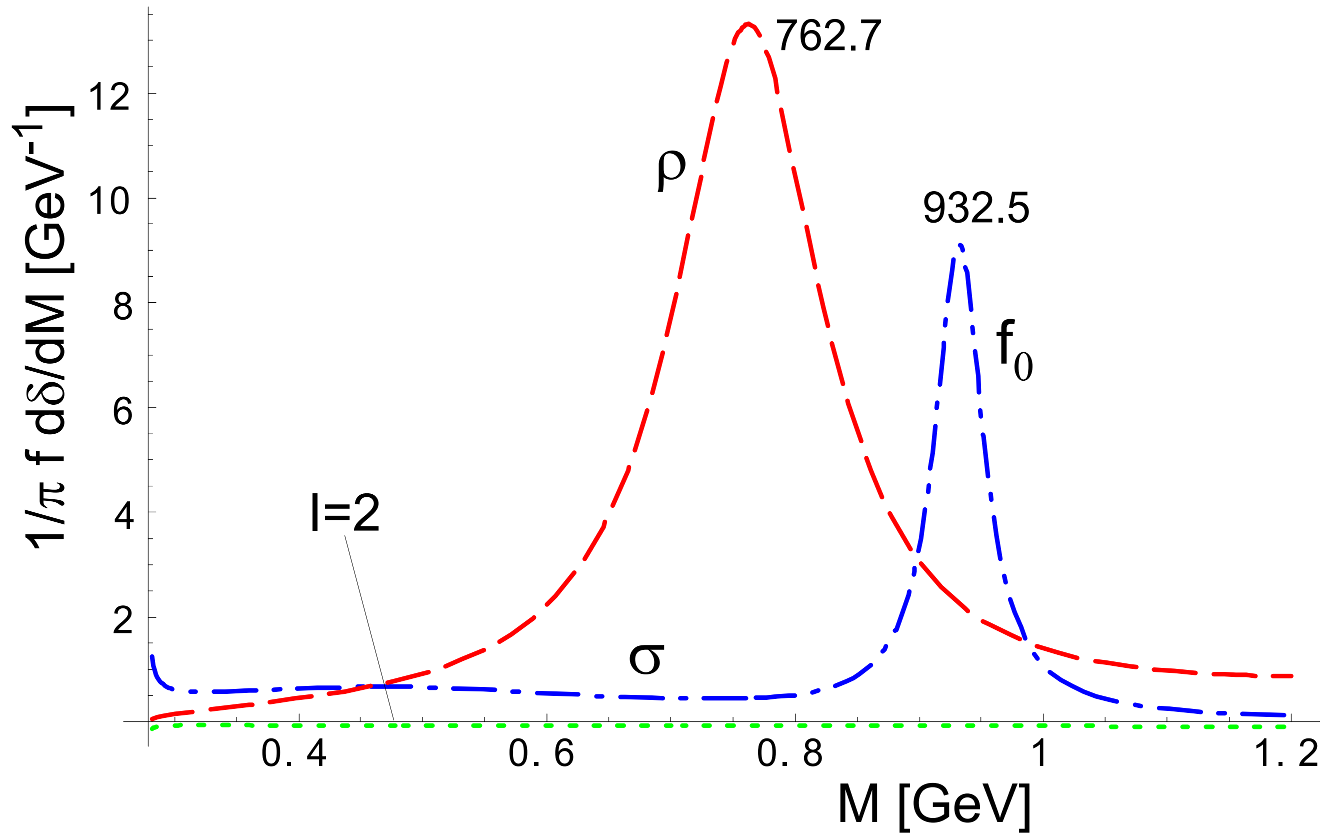
The phase-shift formula for the density of resonances

Beth,Uhlenbeck (1937); Dashen, Ma, Bernstein, Rajaraman (1974);
Weinhold (1998), Friman, Nörenberg;
WB,WF,B. Hiller, nucl-th/0306034; Pratt, Bauer, nucl-th/0308087

$$\frac{dn}{dM} = f \int \frac{d^3p}{(2\pi)^3} \frac{d\delta_{\pi\pi}(M)}{\pi dM} \frac{1}{\exp\left(\frac{\sqrt{M^2+\boldsymbol{p}^2}}{T}\right) \pm 1}$$

In some works the spectral function of the resonance is used *ad hoc* as the weight, instead of the derivative of the phase shift. For narrow resonances this does not make a difference, since then $d\delta(M)/dM \simeq \pi\delta(M - m_R)$, and similarly for the spectral function. For wide resonances, or for effects of tails, the difference between the correct formula and the one with the spectral function is signifcant

$d\delta_{\pi\pi}(M)/dM$ from experiment

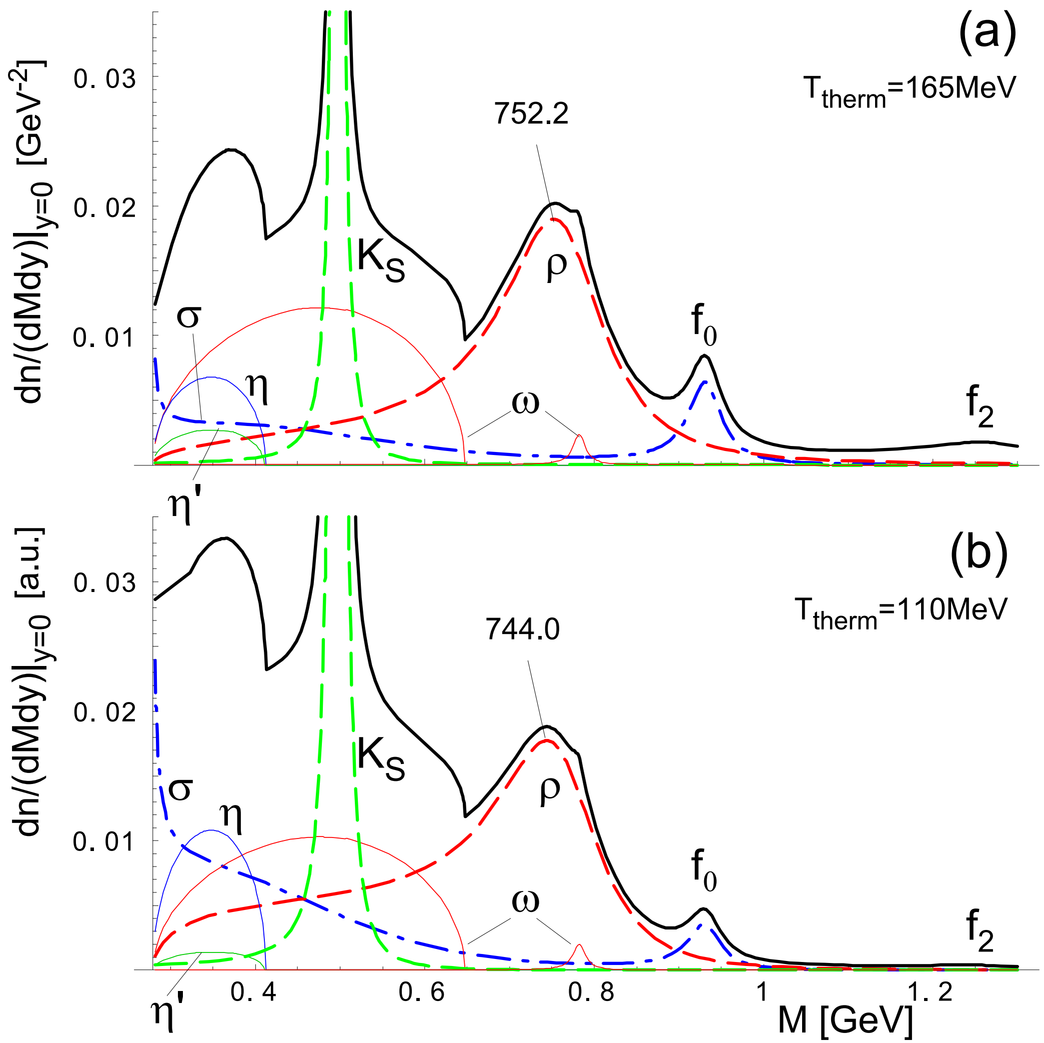


Small contribution from σ, negative and tiny contribution from $I = 2$, ρ-peak slightly shifted to lower M, $1/\sqrt{M - 4m_\pi^2}$ behavior for the σ

Warm-up calculation - static source

We compute the spectra at mid-rapidity, hence

$$\left.\frac{dn}{dMdy}\right|_{y=0} = \sum_i f_i \int_{0.2\mathrm{GeV}}^{2.2\mathrm{GeV}} \frac{p_\perp dp_\perp}{(2\pi)^2} \frac{d\delta_i(M)}{\pi dM} \frac{\sqrt{M^2+p_\perp^2}}{\exp\left(\frac{\sqrt{M^2+\boldsymbol{p}_\perp{}^2}}{T}\right)-1}$$

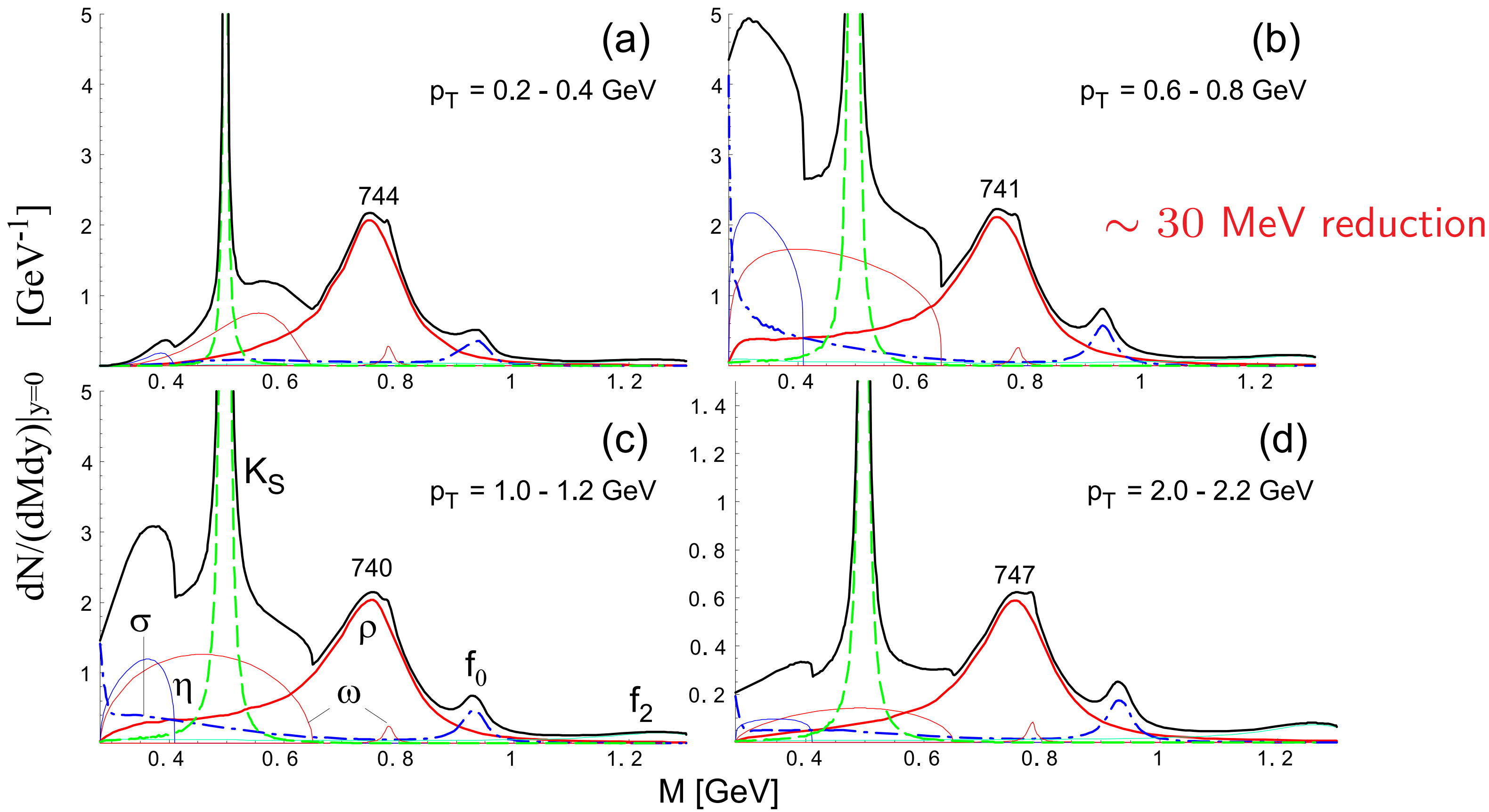


flat

steep

Cuts/flow + feeding from resonances

Flow has no effect on the invariant mass of a pair of particles produced in a resonance decay, since the quantity is Lorentz-invariant. Neverthelss, it affects the results since the kinematic cuts in an obvious manner break this invariance



The invariant $\pi^+\pi^-$ mass spectra in the single-freeze-out model for four sample bins in the trasverse momentum of the pair, p_T, plotted as a function of M. η indicates $\eta + \eta'$. All kinematic cuts of the STAR experiment are incorporated

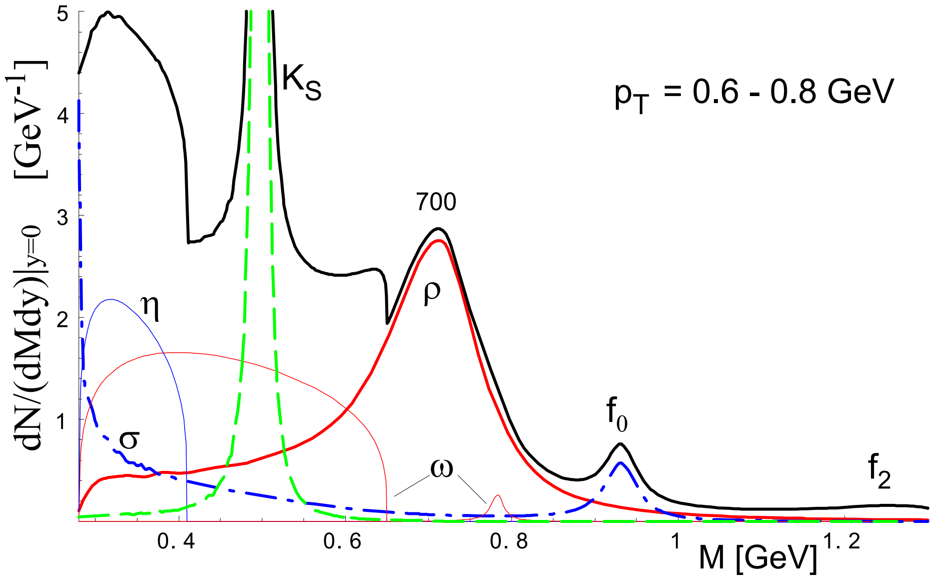
Resonanse decays

The calculation leads to the following enhancement factors coming from the decays of higher resonances: $d_{K_S} = 1.98$, $d_\eta = 1.74$, $d_\sigma = 1.13$, $d_\rho = 1.42$, $d_\omega = 1.43$, $d_{\eta'} = 1.08$, $d_{f_0} = 1.01$, and $d_{f_2} = 1.28$. Thus, the effects is strongest for light particles, K_S, η, ρ, and ω, while it is weaker for the heavier η' and scalar mesons.

Full model, with feeding from higher resonances and flow/cuts at $T = 165$ MeV is similar to the naive model at $T = 110$ MeV !

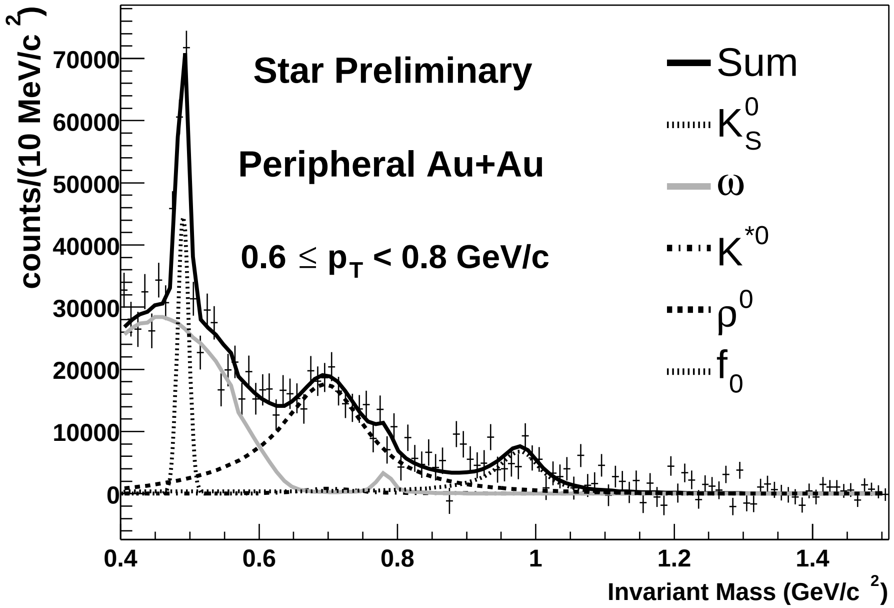
Medium effects?

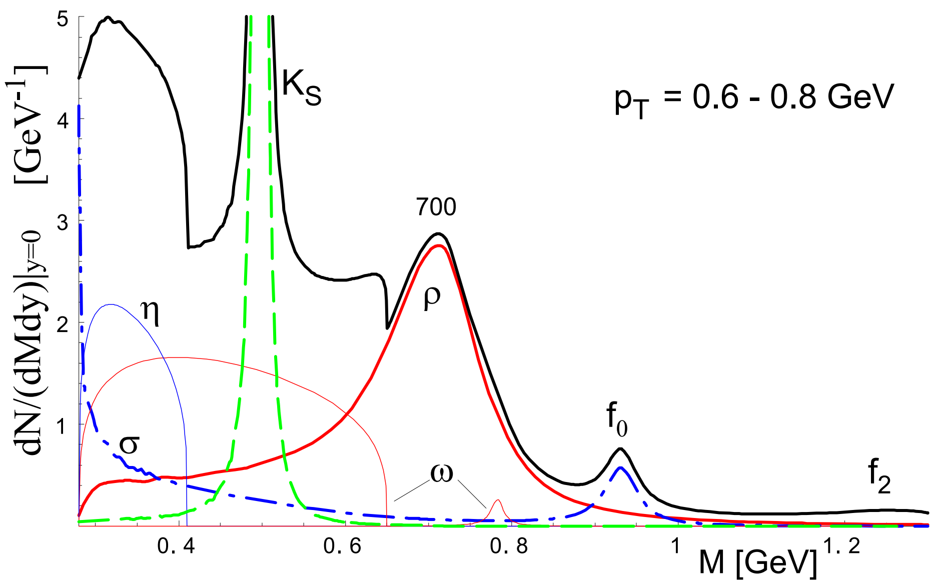
The position of ρ is lower than in the vacuum (medium effects, or other effects?)



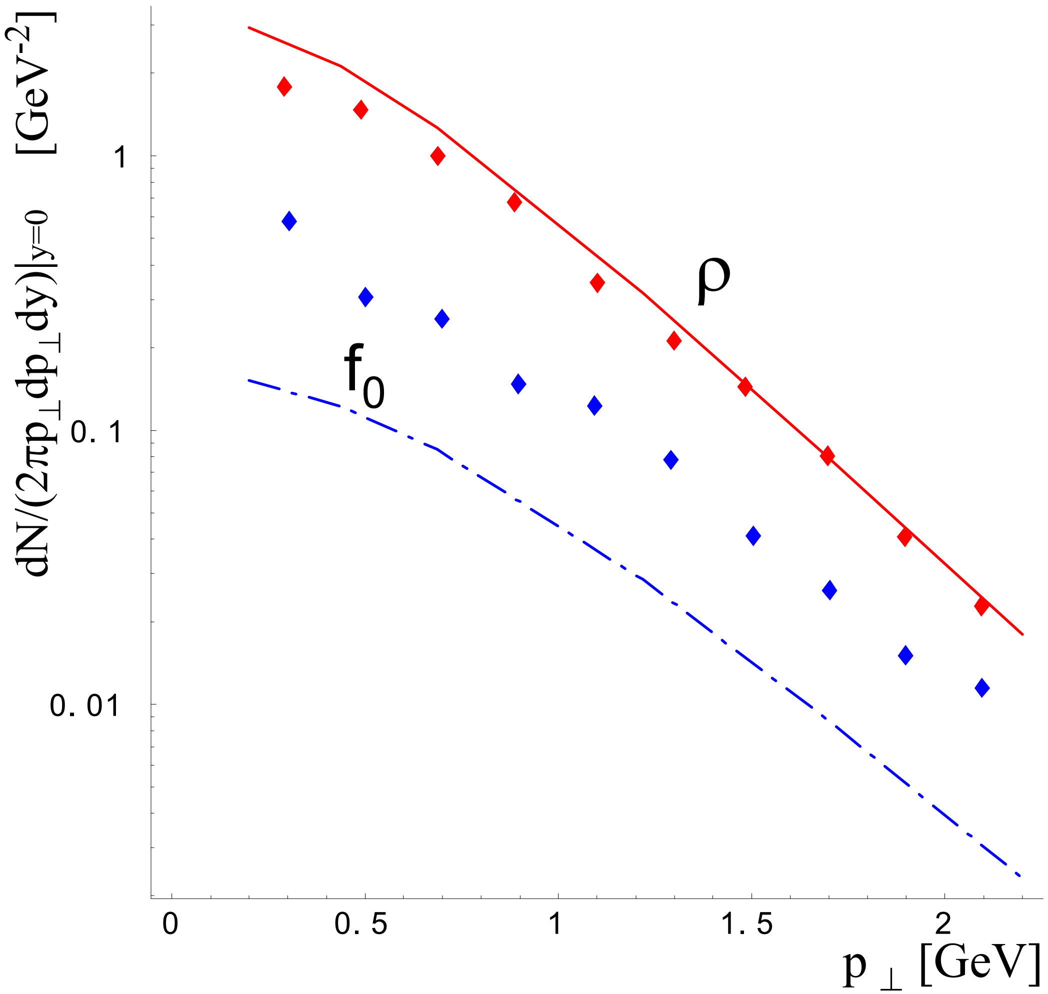
Our model + position of ρ shifted down from the vacuum value by 9%

STAR vs. thermal model





$p_\perp$ spectra of resonances

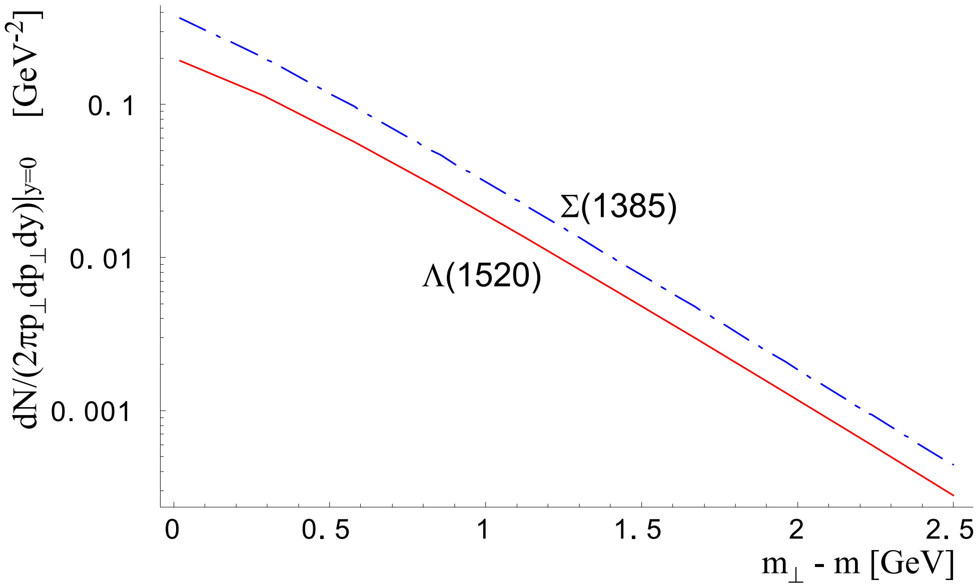


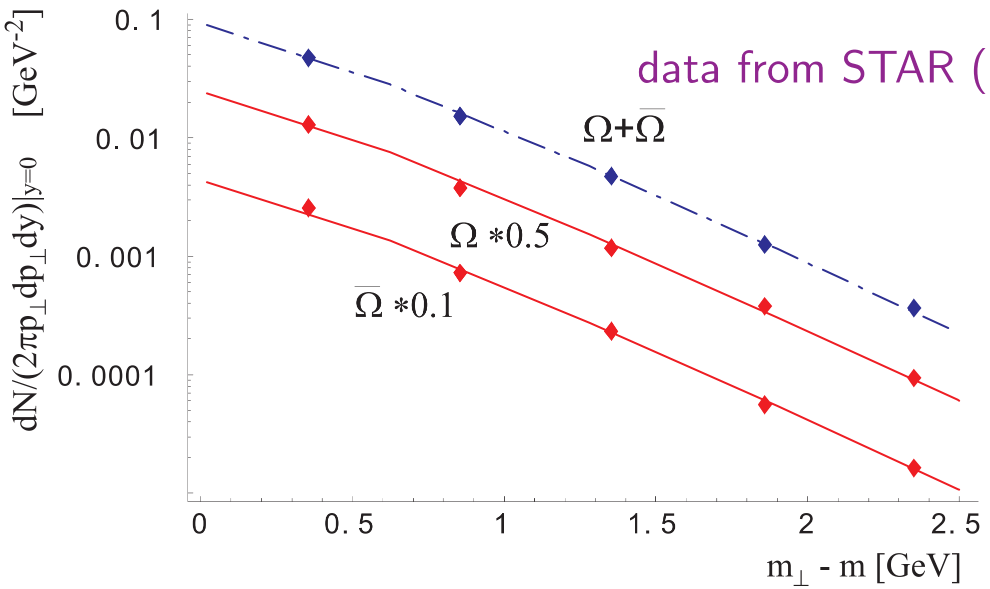
For f_0 experiment $>$ thermal model!

	$m_\rho^* = 770$ MeV	$m_\rho^* = 700$ MeV	Experiment
T [MeV]	$T = 165.6 \pm 4.5$	$T = 167.6 \pm 4.6$	
μ_B [MeV]	$\mu_B = 28.5 \pm 3.7$	$\mu_B = 28.9 \pm 3.8$	
η/π^-	0.120 ± 0.001	0.112 ± 0.001	
ρ^0/π^-	0.114 ± 0.002	0.135 ± 0.001	0.183 ± 0.028 (40-80%)
ω/π^-	0.108 ± 0.002	0.102 ± 0.002	
$K^*(892)/\pi^-$	0.057 ± 0.002	0.054 ± 0.002	
ϕ/π^-	0.025 ± 0.001	0.024 ± 0.001	
η'/π^-	0.0121 ± 0.0004	0.0115 ± 0.0003	
$f_0(980)/\pi^-$	0.0102 ± 0.0003	0.0097 ± 0.0003	0.042 ± 0.021 (40-80%)
$K^*(892)/K^-$	0.33 ± 0.01	0.33 ± 0.01	0.205 ± 0.033 (0-10%) 0.219 ± 0.040 (10-30%) 0.255 ± 0.046 (30-50%) 0.269 ± 0.047 (50-80%)
$\Lambda(1520)/\Lambda$	0.061 ± 0.002	0.062 ± 0.002	0.022 ± 0.010 (0-7%) 0.025 ± 0.021 (40-60%) 0.062 ± 0.027 (60-80%)
$\Sigma(1385)/\Sigma$	0.484 ± 0.004	0.485 ± 0.004	

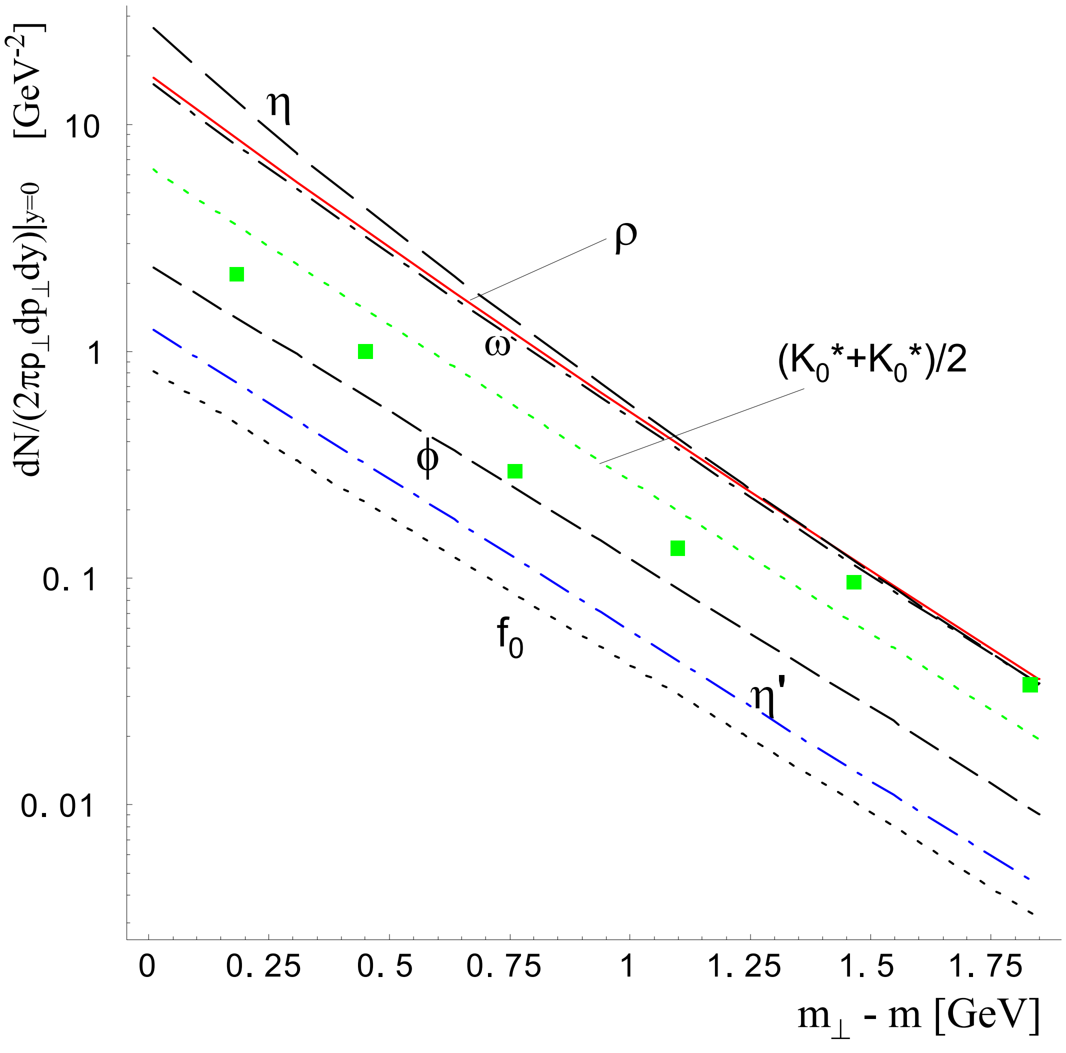
Model underpredicts ρ and f_0 with $T = 165$ MeV. Lower T would imply even less resonances!

Predictions





data from STAR (C. Suire, QM2002)


dN/(2πp⊥dp⊥dy)|y=0 [GeV-2]
10
1
0.1
0.01
0
0.25
0.5
0.75
1
1.25
1.5
1.75
m⊥ - m [GeV]
η
ρ
ω
(K0*+K0*)/2
φ
f0
η'

Summary

1. Shape of the $\pi\pi$ "spectral line" - new thermometer
2. Derivative of phase shift, not the spectral density as weight
3. Single freeze-out works, it gives similar results at 165MeV to the naive calculation at 110MeV
4. Kinematic cuts and flow important, resonance decays important
5. Not possible to place the ρ peak at the experimental value (medium effects?, other effects?)
6. Measure, please, the $\pi\pi$ spectra for most central events!

Back-up slides

The STAR cuts

The cuts in the STAR analysis of the $\pi^+\pi^-$ invariant-mass spectra have the following form (Fachini):

$$\begin{aligned} &|y_\pi| \leq 1, \\ &|\eta_\pi| \leq 0.8, \\ &0.2 \text{ GeV} \leq p_\pi^\perp \leq 2.2 \text{ GeV}, \end{aligned} \tag{1}$$

while the bins in $p_T \equiv |\boldsymbol{p}_\pi^\perp + \boldsymbol{p}_\pi^\perp|$ start from the range $0.2 - 0.4$ GeV, and step up by 0.2 GeV until $2 - 2.4$ GeV.

For two-body decays, the relevant formula for the number of pairs of particles 1 and 2 has the form

$$\begin{aligned} \frac{dN_{12}}{dM} \quad = \quad & \frac{d\delta_{12}}{dM}\frac{bm}{p_1^*}\int_{p_{1,\mathrm{low}}^\perp}^{p_{1,\mathrm{high}}^\perp} dp_1^\perp \int_{y_{1,\mathrm{low}}}^{y_{1,\mathrm{high}}} dy_1 \int_{p_{\mathrm{low}}^\perp}^{p_{\mathrm{high}}^\perp} dp^\perp \int_{y_{\mathrm{low}}}^{y_{\mathrm{high}}} dy \\ & \times C_2^0 C_1^\eta C_2^\eta \frac{\theta(1-\cos^2\gamma_0)}{|\sin\gamma_0|} S(p^\perp), \end{aligned} \tag{2}$$

Lowering the ρ mass

In order to show how the medium modifications will show up in the $\pi^+\pi^-$ spectrum, we have scaled the $\pi\pi$ phase shift in the ρ channel, according to the simple law

$$\delta_1^1(M)_{\rm scaled} = \delta_1^1(s^{-1}M)_{\rm vacuum}, \qquad (3)$$

Phase shift vs. spectral density