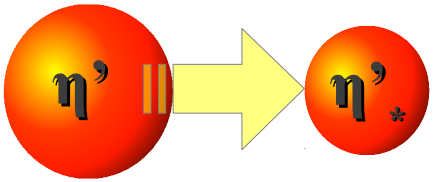
AGS-RHIC Users' Meeting
June 12-15, 2012
Brookhaven National Laboratory

An indirect observation of the

In-medium reduction of the η' mass

In √sNN = 200 GeV Au+Au collisions at RHIC



Róbert **Vértesi**, Tamás **Csörgő**, János **Sziklai**

Wigner Research Centre for Physics, Budapest Hungary

Details:

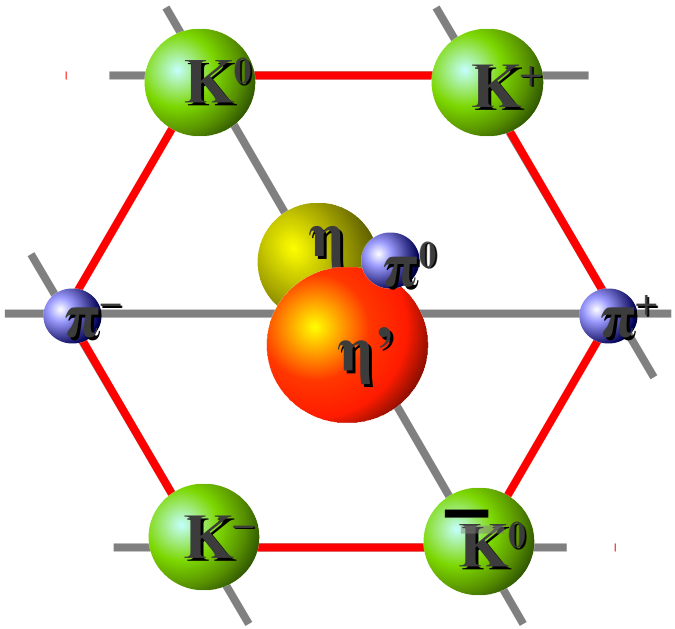
PRL 105, 182301 (2010), arXiv:**0912.5526**

PRC 83, 054903 (2011), arXiv:**0912.0258**

InsideRHIC magazine, 01/11/2011.

Chiral Symmetry Breaking

- Three-quark model
  - $U(3)_L \times U(3)_R$ symmetry
  - Spontanously broken
    => 9 Goldstone-bosons
  - Associated with light mesons
  - There are only 8! (meson-octet)



- Chiral anomaly

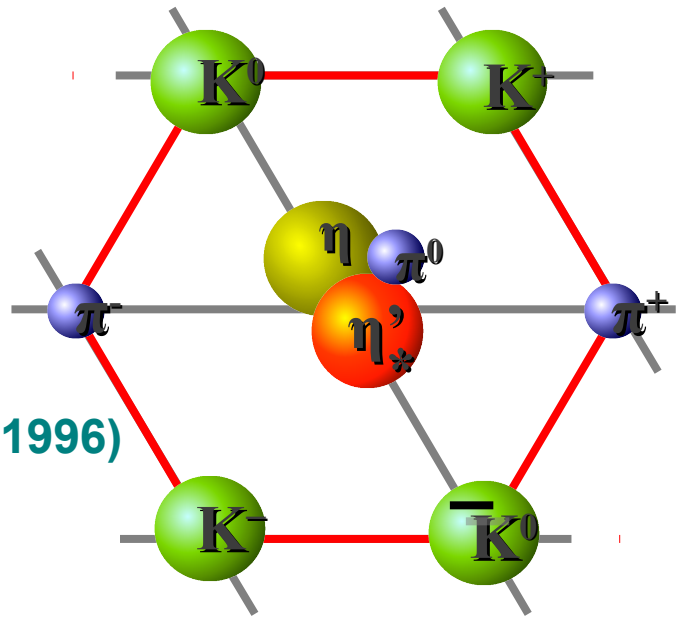
  $U(3)_L \times U(3)_R \sim SU(3)_L \times SU(3)_R \times U_V(1) \times U_A(1)$

  - $U_A(1)$ explicitly broken
  - Distinct topological vacuum-states
  - Tunneling between them – quasiparticles (instantons)
  - 9th boson gains mass – η' (958 MeV)

Restoration of the Symmetry in a Hot, Dense Medium

- High energy densities
  - Strong coupling (α_s) decreases
  - Nontrivial topology vanishes
  - $U_A(1)$ not broken anymore

J. I. Kapusta et al., Phys. Rev. D 53, 5028 (1996)



- Reduced in-medium mass

Δm : mass from non-trivial vacuum structure: $m_{\eta'} = m_0 + \Delta m$

Lower limit (Gell-Mann – Okubo): $m_0^2 = \frac{1}{3}\left(2m_K^2 + m_\pi^2\right); m_0 \approx 400 MeV$

Upper limit (S,NS isosinglet eigenstates): $m_S^2 = 2m_K^2 + m_\pi^2; m_S \approx 700 MeV$

- Necessary condition: Chiral transition separates from deconfinement, phase transition is a smooth cross-over

Z. Fodor, S. Katz, arXiv:0908.3341 [hep-ph].

Signature: Particle Abundance

- Direct observation is not likely: $\tau_{\eta'} >> \tau_{medium}$
- Production of light mesons: Hagedorn model

$$\sigma_i \sim \left(m/2\pi\right)^{3/2} e^{-m/T_H}$$ T_H~170 MeV Hagedorn temperature

  - Normally $N_{\eta'}$ would be small: $N_{\eta'} / N_{\pi^0} \sim 2\text{x}10^{-2}$
  - Reduced-mass in-medium η'_*: $N_{\eta'} / N_{\pi^0} \sim 1$
  - Maximal enhancement of a factor 50.
  - However, increased weight of strange states: 3 to 16
  - η'_* expected to decouple and survive into η'
- Consequence: increased multiplicity of η' mesons
- Observation channels:
  - Decay to leptons, photons: $\eta' \to ee\gamma$, $\eta' \to \gamma\gamma$ …
  - Into low momentum pions: $\eta' \to \pi + \pi - \eta$ BR= 43%

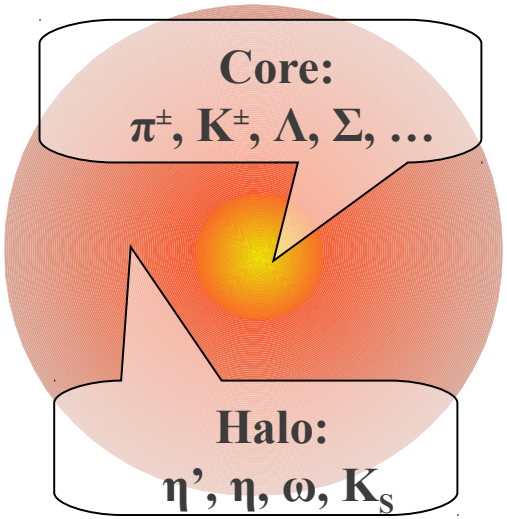
    $\eta \to \pi^+ \pi^- (\pi^0 / \gamma)$ BR= 28%

Observation: $\pi^{\pm}$ correlations

- Pions from freezeout of quark matter
  - Primordial (from phase transition)
  - Fast decaying resonances
  - Long-life resonances (ω,η,η',K_S^0)

} **Core**

→ **Halo**



- Bose–Einstein correlation

$$C(\Delta k, K) \simeq 1 + \lambda_* R_c(\Delta k, K)$$

$$R_c(\Delta k, K) = \frac{|\tilde{S}_c(\Delta k, K)|^2}{|\tilde{S}_c(\Delta k = 0, K = p)|^2}$$

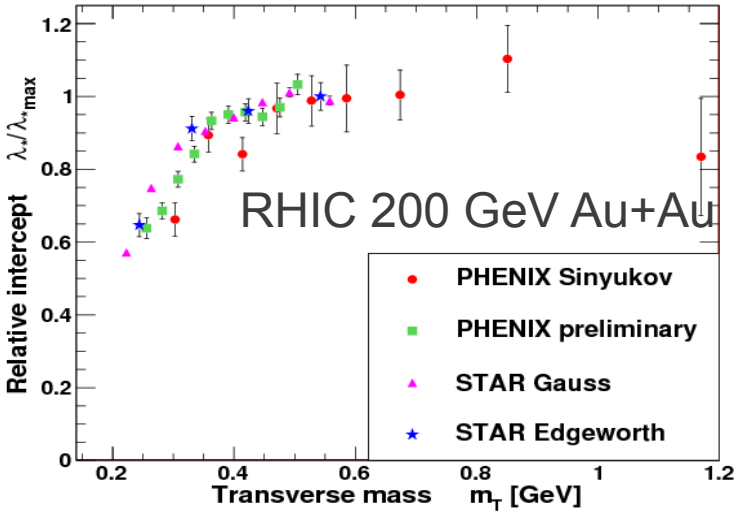
- Intercept

$$\lambda_*(m_t) = \left[\frac{N_{core}^{\pi^+}(m_t)}{N_{core}^{\pi^+}(m_t) + N_{halo}^{\pi^+}(m_t)}\right]^2$$

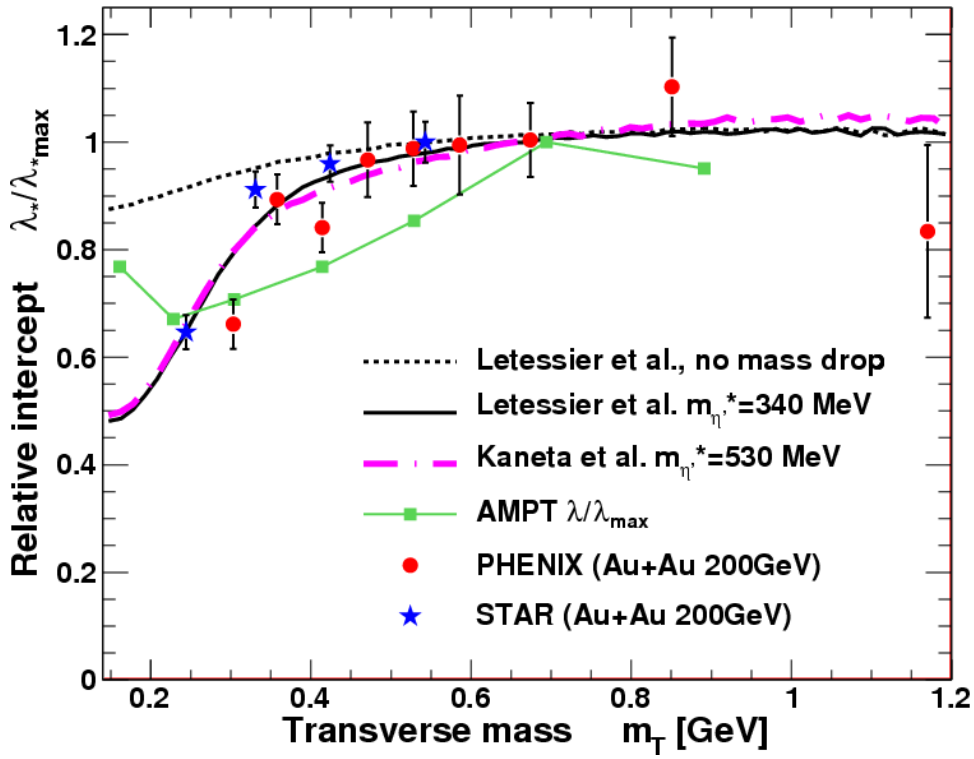
$$N_{halo}^{\pi^+} = N_{\omega\to\pi^+} + N_{\eta\to\pi^+} + N_{\eta'\to\pi^+} + N_{K_S^0\to\pi^+}$$

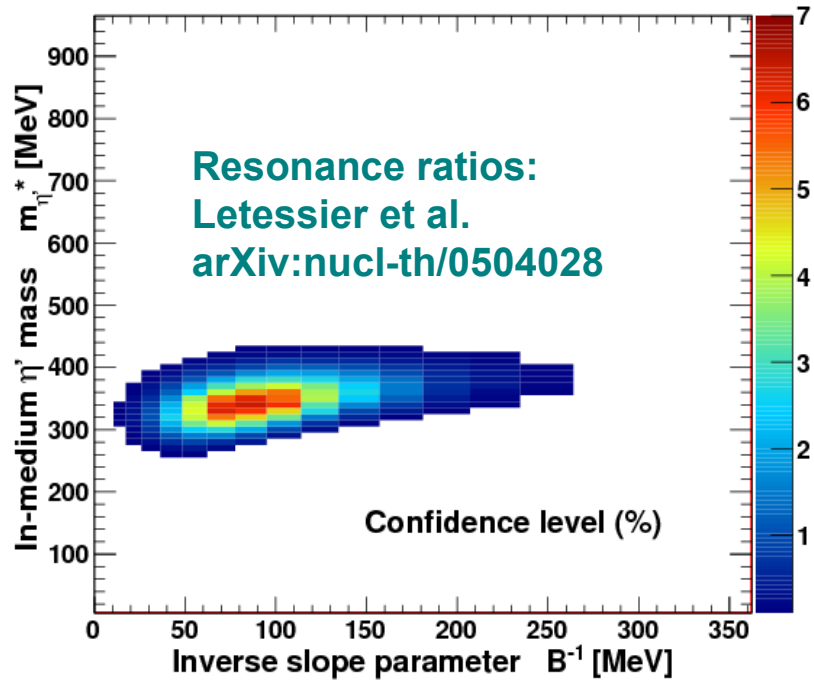
- Correlation measurent ↔ $\lambda^*(m_T)$

  ↔ core−halo ratio ↔ $N_{\eta'}$



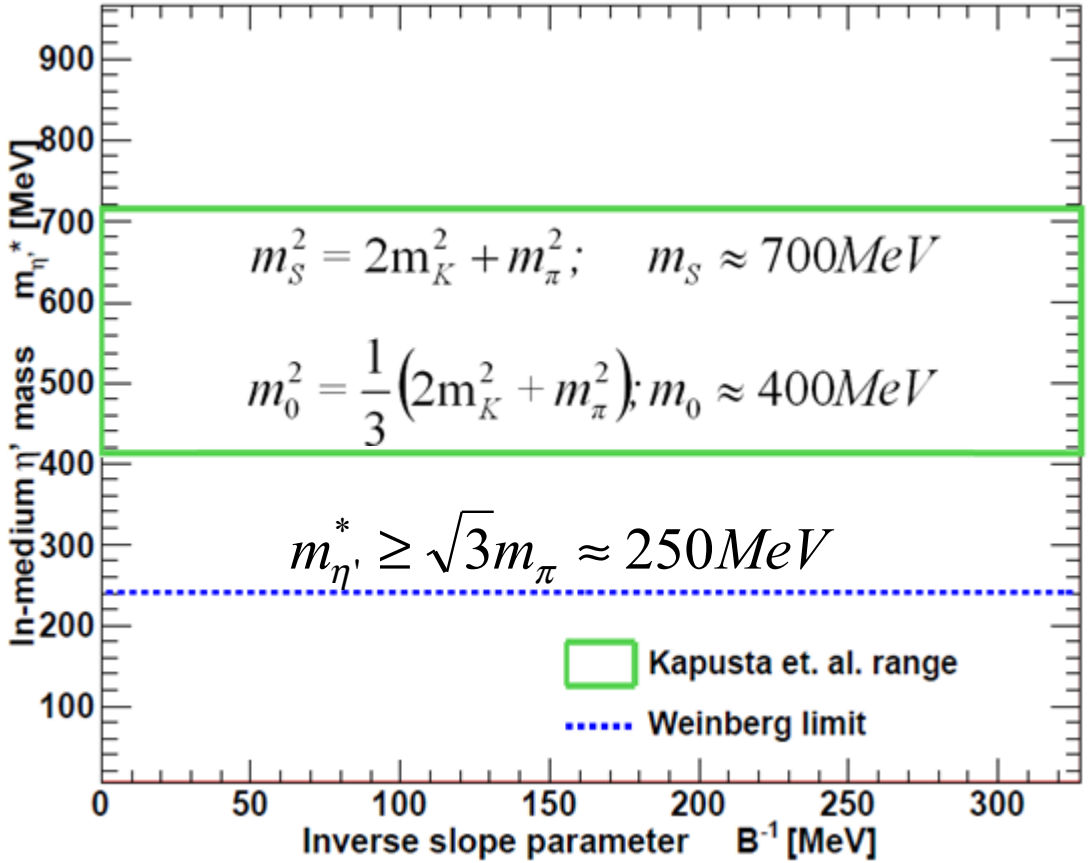
Simulations: Finding the in-medium mass





- **Different assumptions for in-medium masses m^* and slope parameters B^{-1}**
  - **No single setup allows** $m_{\eta'}^* > 760$ MeV by CL=99.9% !
  - **Best** $\lambda^*(m_T)/\lambda^*_{max}$ **fit:** $m_{\eta'}^* = 340^{+50}_{-60}{}^{+280}_{-140} \pm 45$ MeV
- Main systematics: Resonance ratios (ALCOR, FRITIOF, Kaneta et al, Letessier et al., Stachel et al., uRQMD)
- Other systematics: α, T_{FO}, T_{cond}, $\langle u_T \rangle$, centrality and y definition, ω contribution

Limits for the η' mass

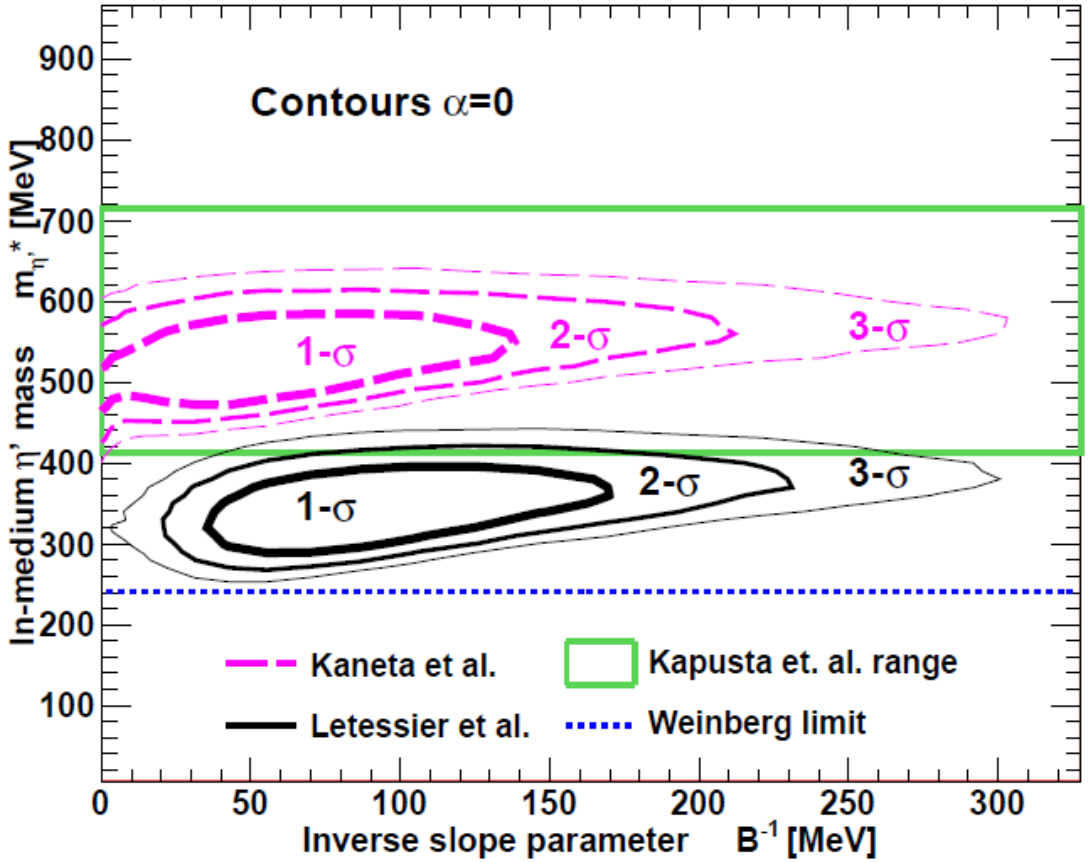


- **Framed region**: Kapusta et al., arXiv:nucl-th/9507343 .

  Upper bound: S,NS isosinglet eigenstates; Lower bound: Gell-Mann – Okubo

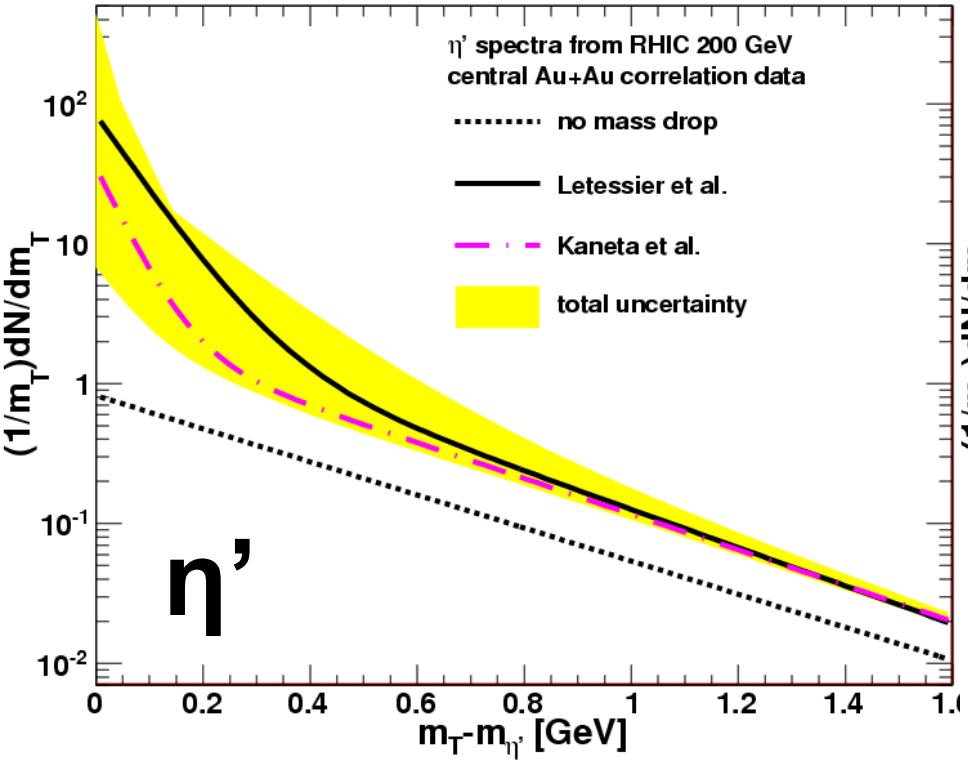
- **Lower limit**: S. Weinberg, Phys. Rev. D 11, 3583 (1975).

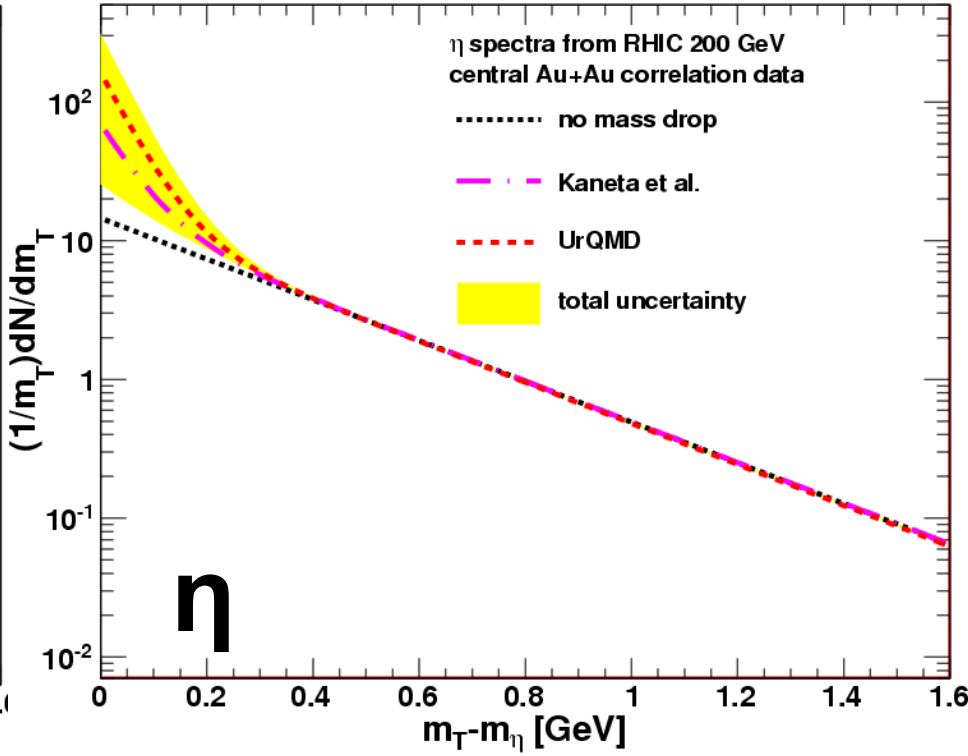
Results vs. Predictions



- **Sigma-contours** from model calculations
- **All in** or slightly below the **limits** of Kapusta et al.
- All above the lower limit of Weinberg

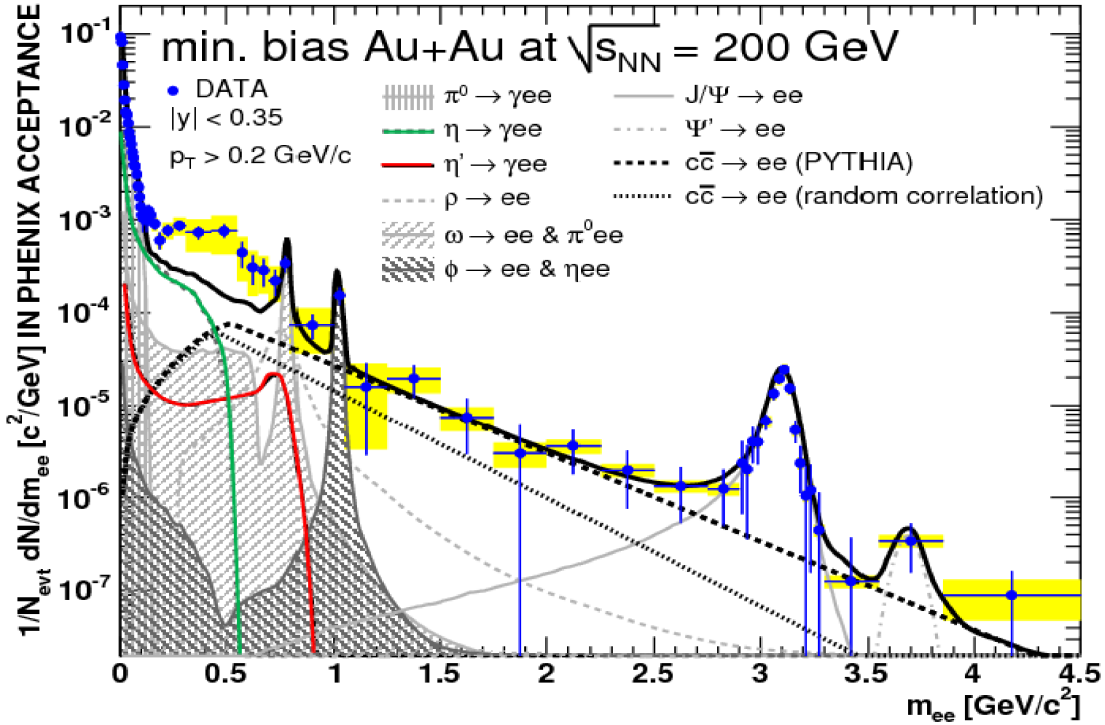
Output: η' and η spectra

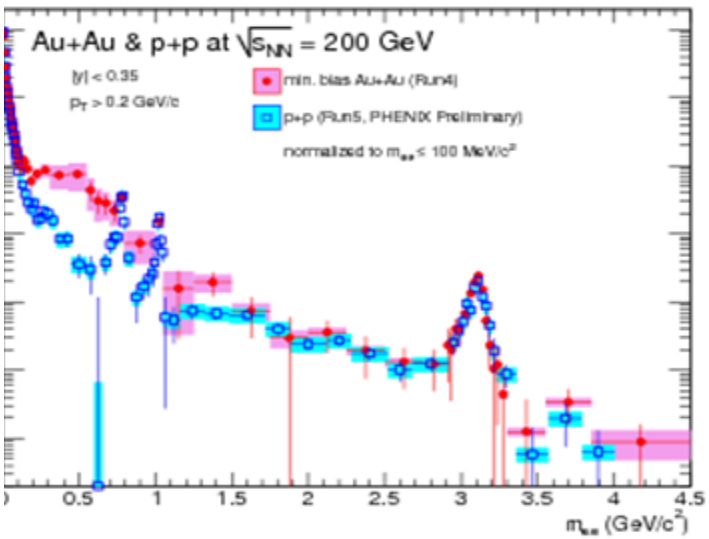




- Strong enhancement of **η'** : factor of **25** to **68** depending on model
- Translates into an **5.2** to **7.5** enhancement of **η**
- Effect mostly at **low-p_T** →← Fits the measured η data at higher p_T
- Possible explanation of the PHENIX dilepton excess → needs check!

Dilepton Excess in PHENIX



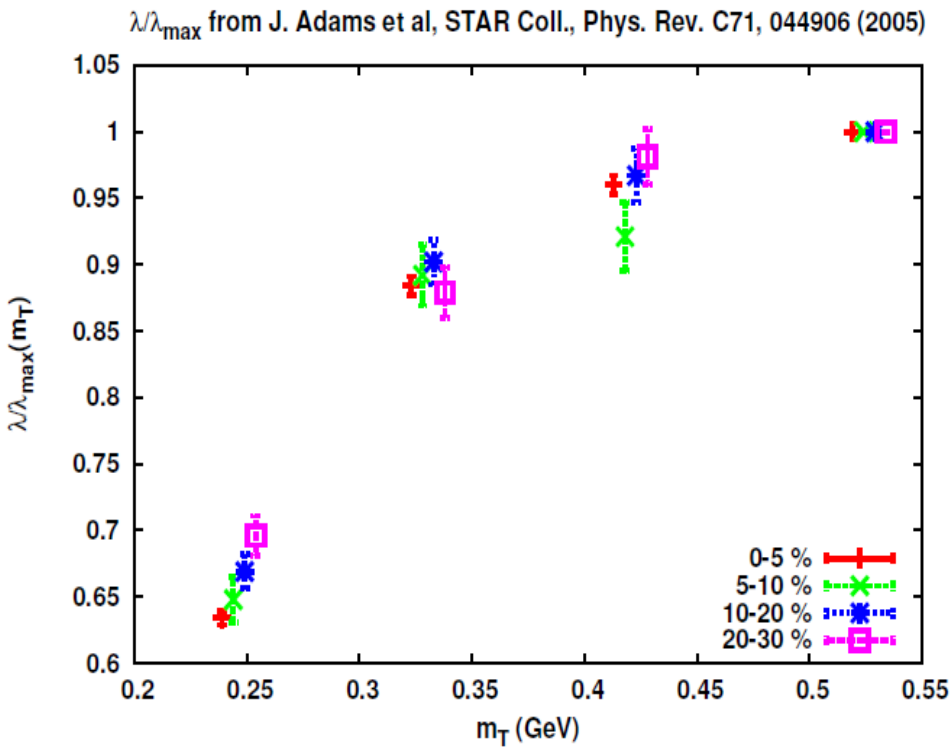


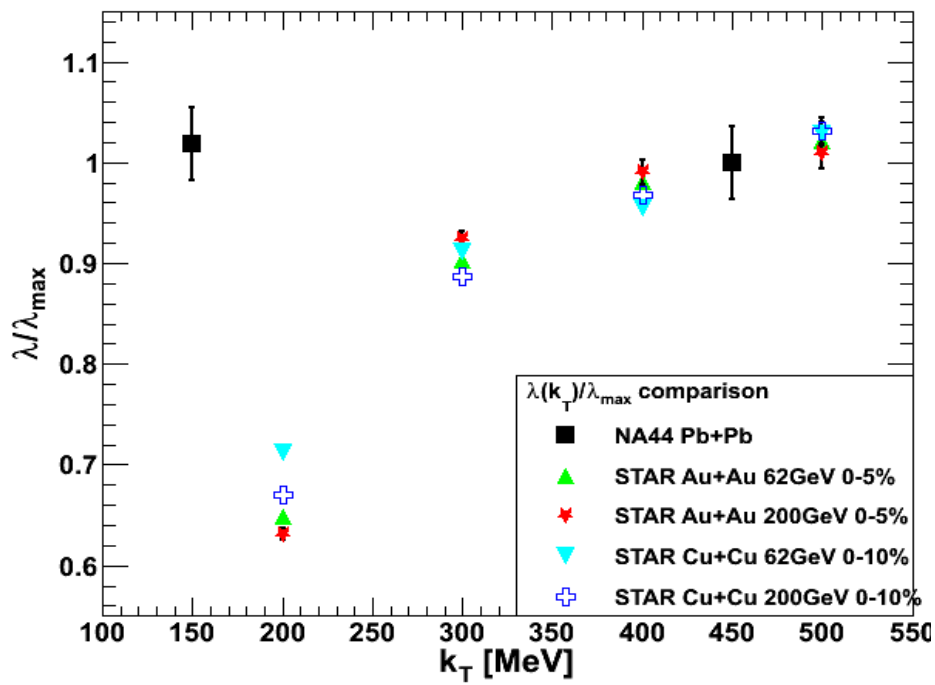
Au+Au invariant e+ e- pair yield

A. Adare *et al.* (PHENIX cn.)
Phys.Rev.C81:034911,2010

- **Significant excess in PHENIX 200 GeV Au+Au measurements**
- **Not present in p+p data – in accordance with hadronic models**
- **Excess must be an effect of the hot, dense medium**
- **Estimations: low-pT η', η enhancement is a promising candidate**

Centrality, system size and energy dependence



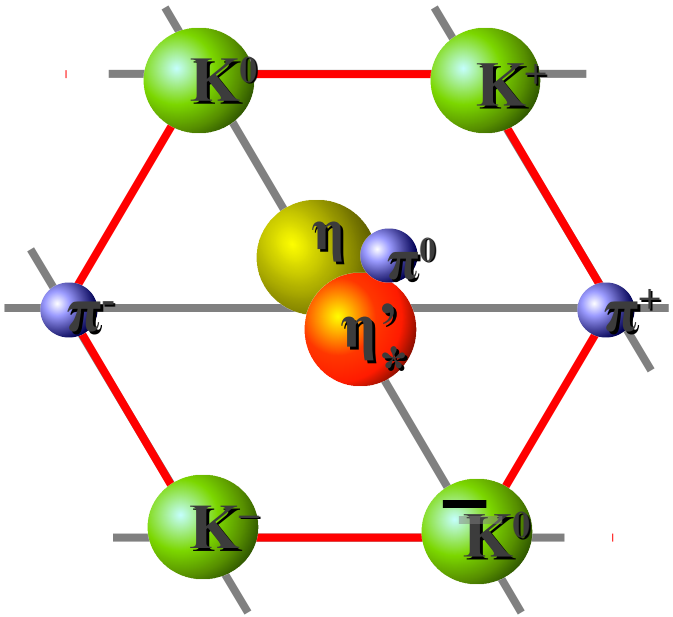


Larger dip = larger η' enhancement, lower supposed η' mass

- **SPS :** no effect seen in NA44 S+Pb 19.4 GeV data
- **STAR**: effect is present at all RHIC energies and centralities
  - Effect is slightly bigger for more central reactions (<9.8% PHENIX-STAR)
  - Also for bigger colliding nuclei and larger energies (~15% altogether)

Summary

- **Mass of the η' observed to drop with at least 200 MeV**
  - From PHENIX and STAR correlation data
  - Within the considered wide model class using 6 different models
  - To the confidence level of CL=**99.9%**



- **Best description of data if**

$$m^*_{\eta'} = 340^{+50}_{-60}{}^{+280}_{-140} \pm 45 \text{ MeV}$$

- **We determined the low-p_T spectra of the η' és η mesons**

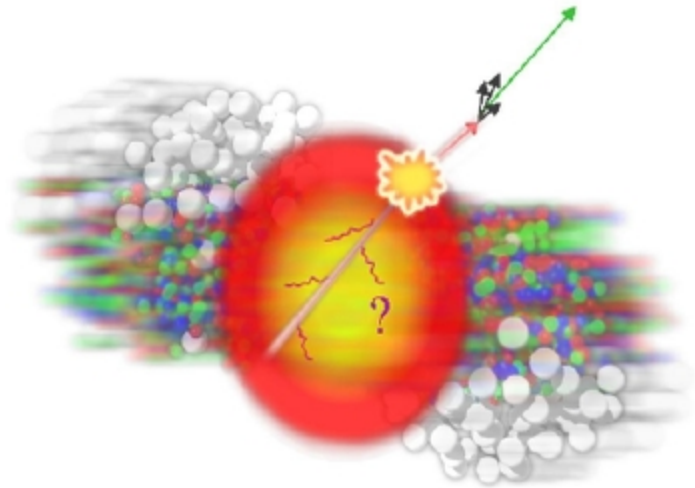
- Revitalize interest in chiral symmetry restoration
  - Confirms the **cross-over** character phase transition
  - **Cross check needed** via other channels (especially the dileptons)
  - Dedicated **low-p_T** λ^* measurements are needed to reduce systematics

The End

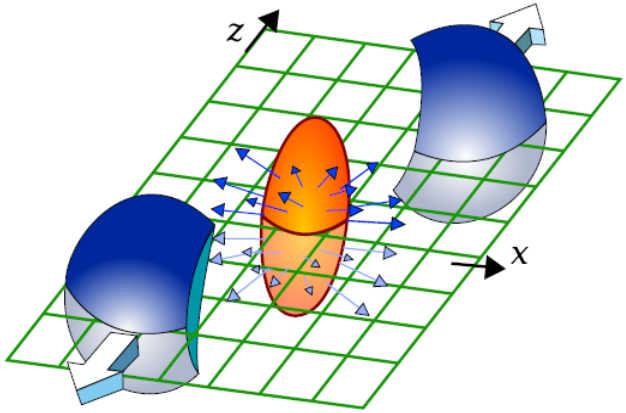
backup slides follow…

Hot nuclear matter

- Extremely dense
  - Au+Au: jet suppression
    Phys.Rev.Lett. 88, 022301 (2002)
  - No effect in d+Au
  - → Strongly interacting, new state of matter
    Phys. Rev. Lett. 91, 072303 (2003)
    $\lambda \sim 3$ fm (5 GeV-es jet)



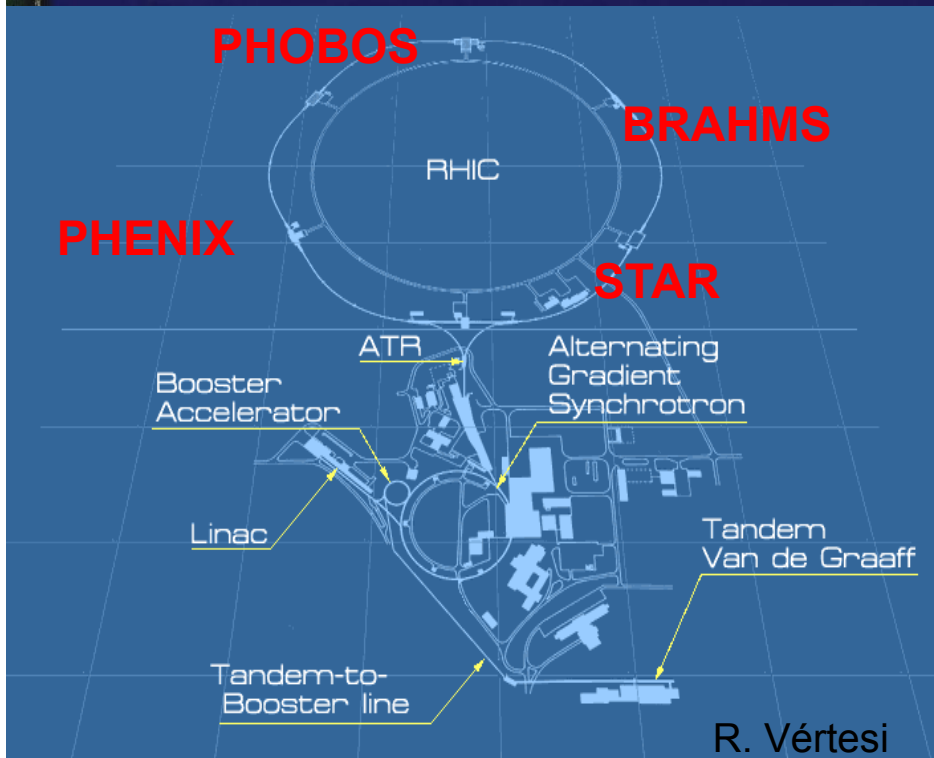
- Perfect fluid of quarks
  Nucl Phys. A757, 184757, 184 (2005)
  - Contradicts expectations
  - Degrees of freedom: quarks
  - Viscosity consistent with theoretical limit
    $\eta/s \sim \hbar/4\pi$, $cs = 0.35c$



- Quark Gluon Plasma (sQGP)
  Phys.Rev.Lett. 104, 132301 (2010)
  - Thermal radiation, Tinit~4 x 1012 K
  - New phase: above Haggedorn temperature
    Tinit>300 MeV>>THagedorn, εinit~15 GeV/fm3 , pinit ≥ 1.5 GeV/fm3

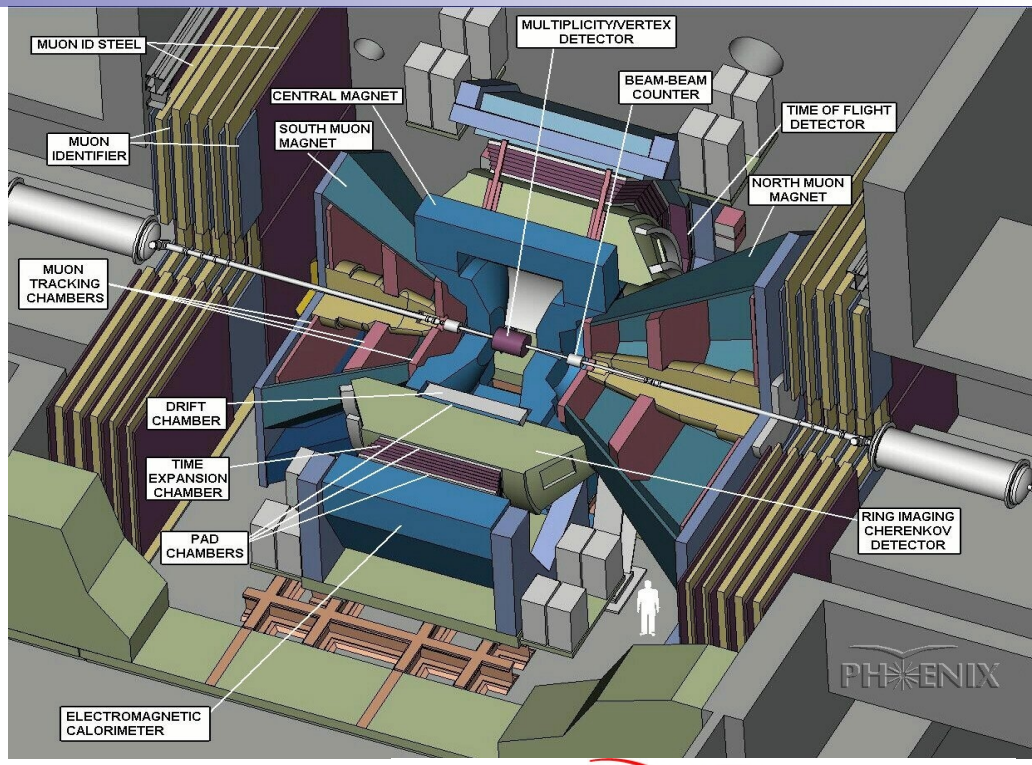
The RHIC facility

- Two independent rings
  - 3,9 km long each
- Collides heavy ions...
  - **Au+Au**, **Cu+Cu**, ...
  - $\sqrt{s_{NN}}$= 7,7 – 200 GeV
- ...and protons
  - **p+p** up to $\sqrt{s}$ = 500 GeV
  - Different polarizations
- Asymmetric setups
  - **d+Au**
- 4 experiments
  - All different capabilities
  - PHENIX, STAR (the „large" ones)
  - PHOBOS, BRAHMS (completed)



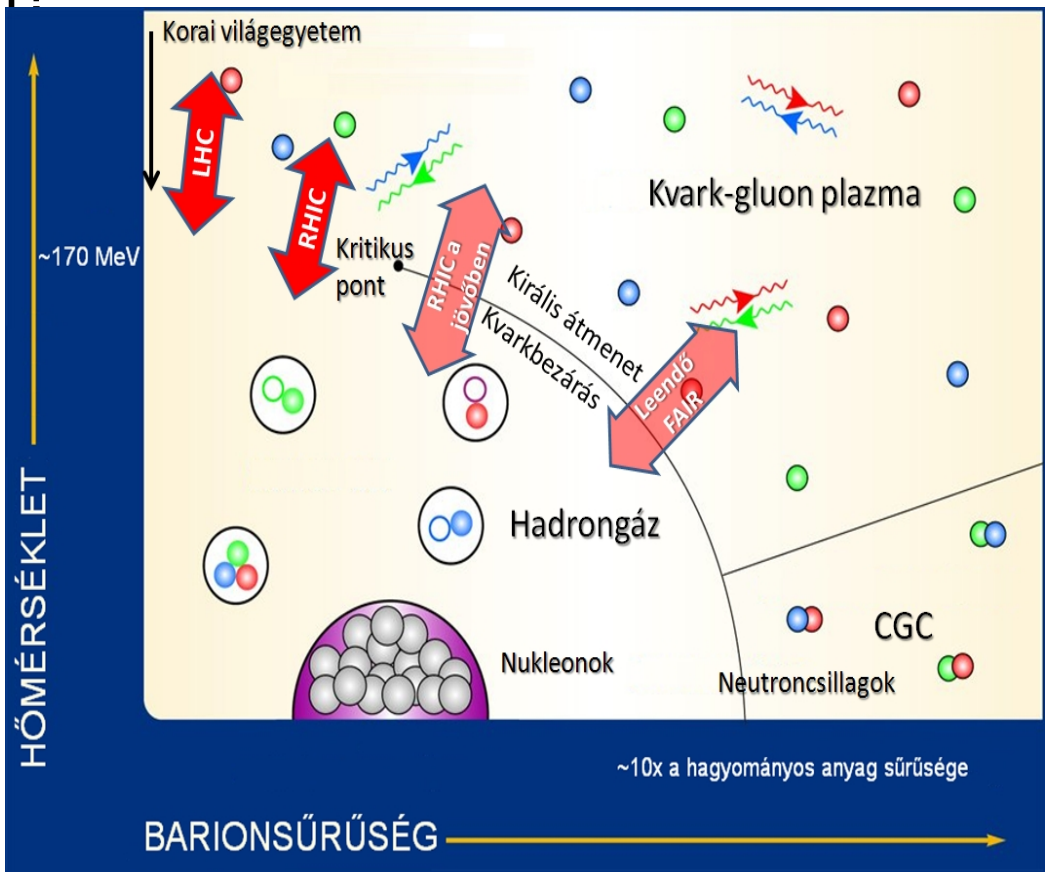
The PHENIX experiment

- Tracking system
  - Gas chambers at mid-rapidity
  - Dipole magnet
  - Measuring spectra and correlation of charged hadrons ($\pi\pm$, $K\pm$, $p,\bar{p}$)
- Calorimetry
  - $\pi 0$, η
  - direct photons
- Identifying leptons
  - $e+e-$ pairs, $\mu\pm$ (forward region)
  - heavy quarkonia (J/ψ)
- International collaboration
  - ... Countries involved



QCD phase diagram

- How does matter transform?
  - Type of phase transition?
  - Critical point?
  - Relation of deconfinement and chiral transition?
- RHIC programme
  - Lower energies: Mapping the phase diagram
  - In-medium properties of mesons
  - And a lot more…



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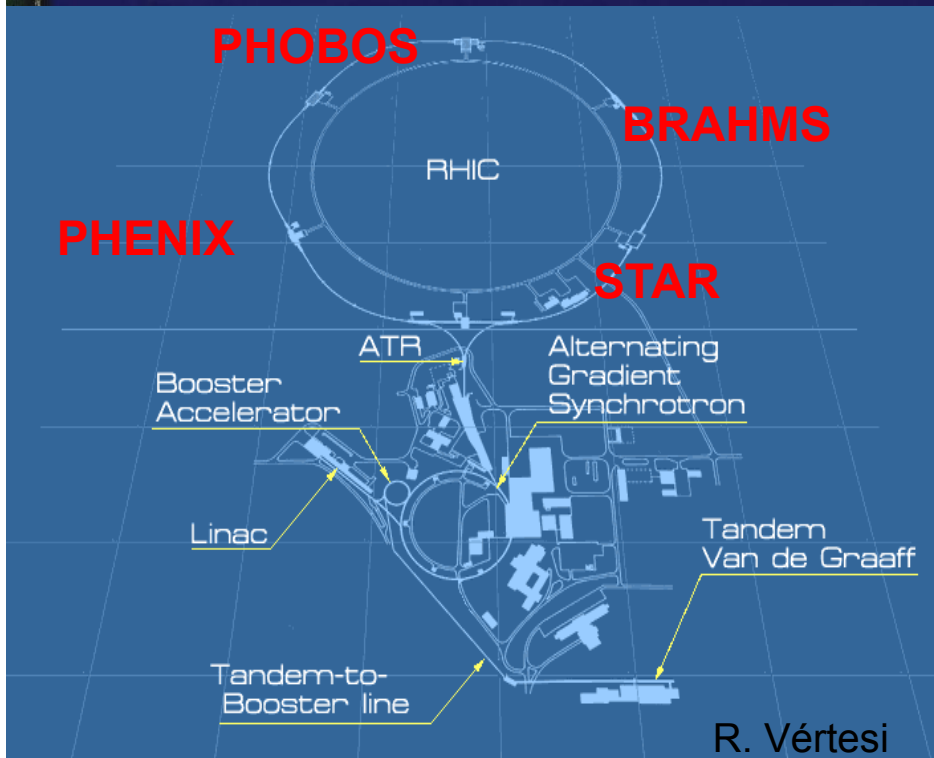

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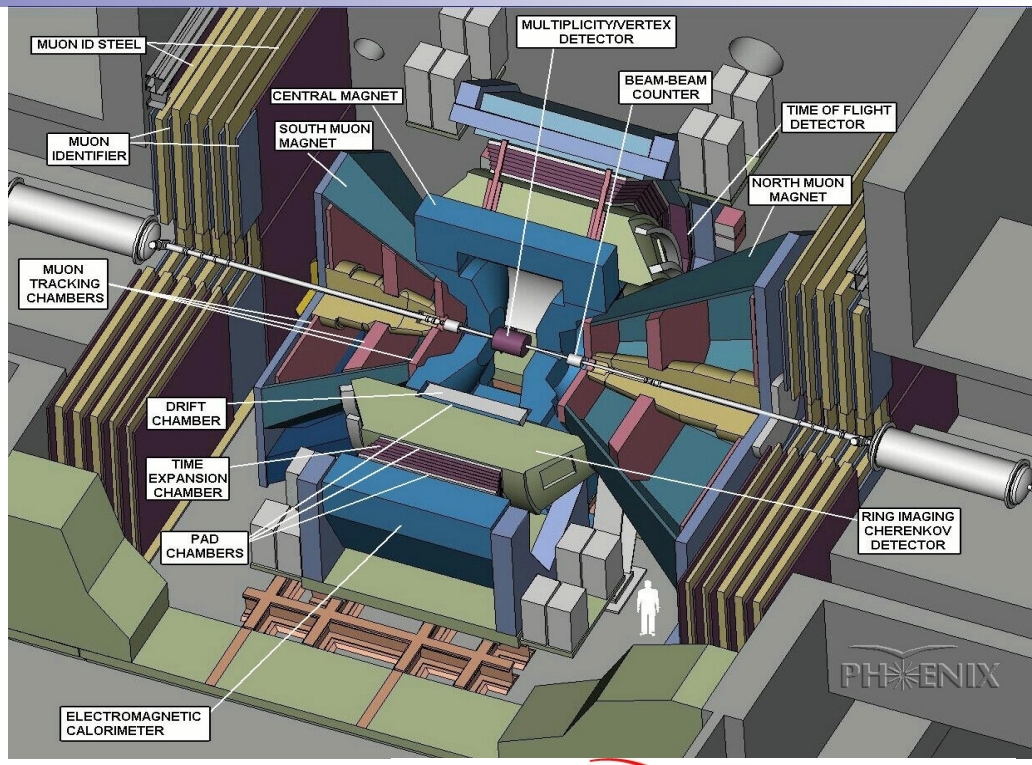

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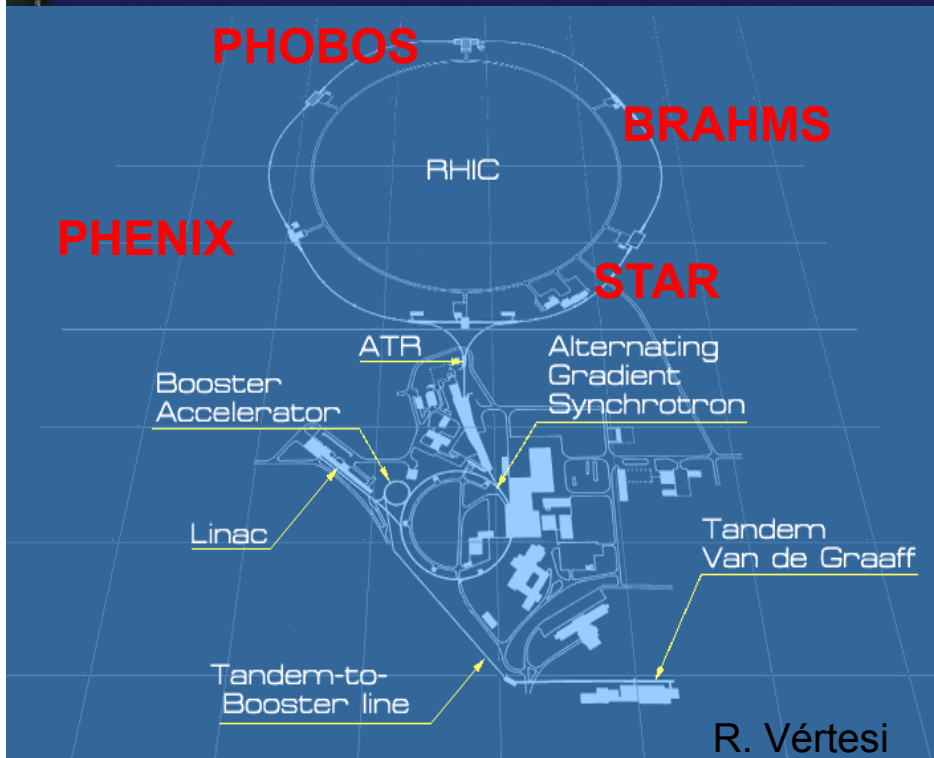

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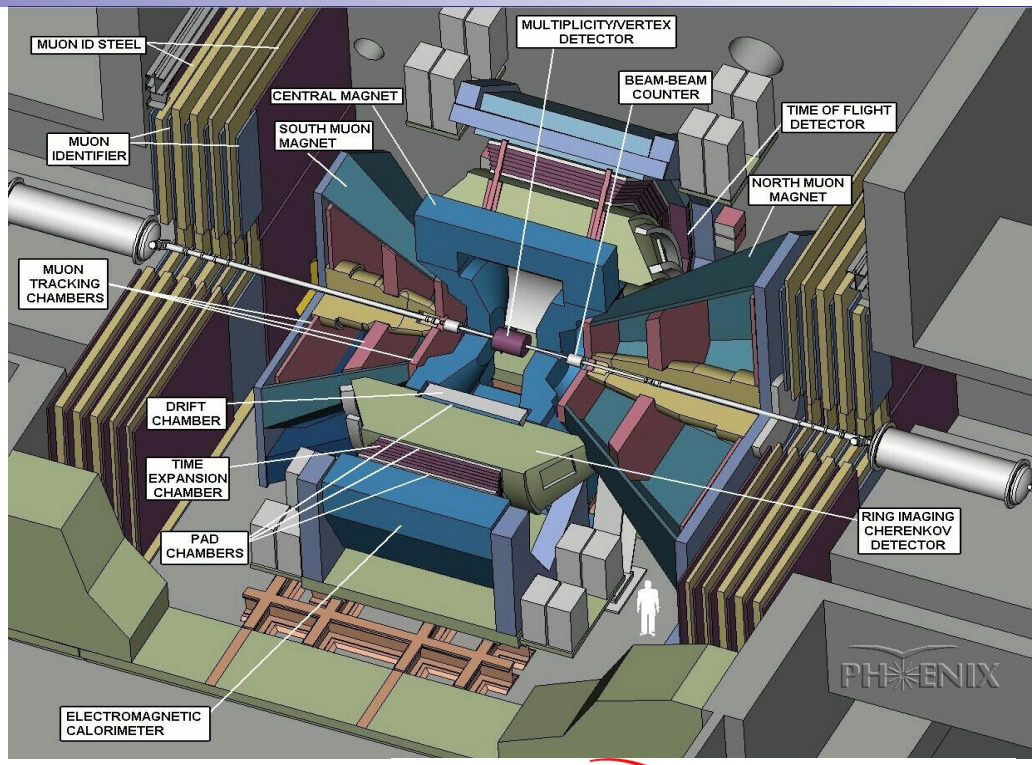
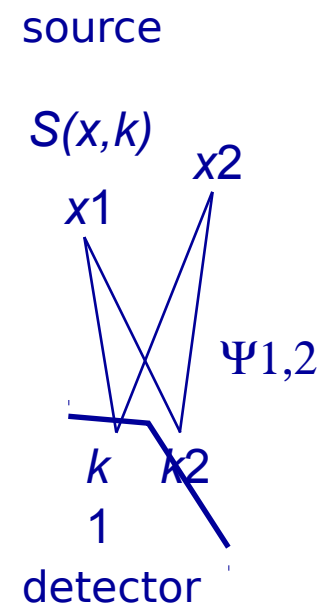


HBT effect (BEC)

- Discovered and still used in Astrophysics
- Consider two plain vawes: $\Psi_1 = \mathrm{e}^{-ik_1x_1}$

  $\Psi_2 = \mathrm{e}^{-ik_2x_2}$
- Bosons: symmetrization needed

$$\Psi_{1,2} = \frac{1}{\sqrt{2}}(\mathrm{e}^{-ik_1x_1}\mathrm{e}^{-ik_2x_2} + \mathrm{e}^{-ik_1x_2}\mathrm{e}^{-ik_2x_1})$$



- Spectra: $N_1(k_1) = \int S(x_1,k_1)|\Psi_1|^2 \mathrm{d}x_1$

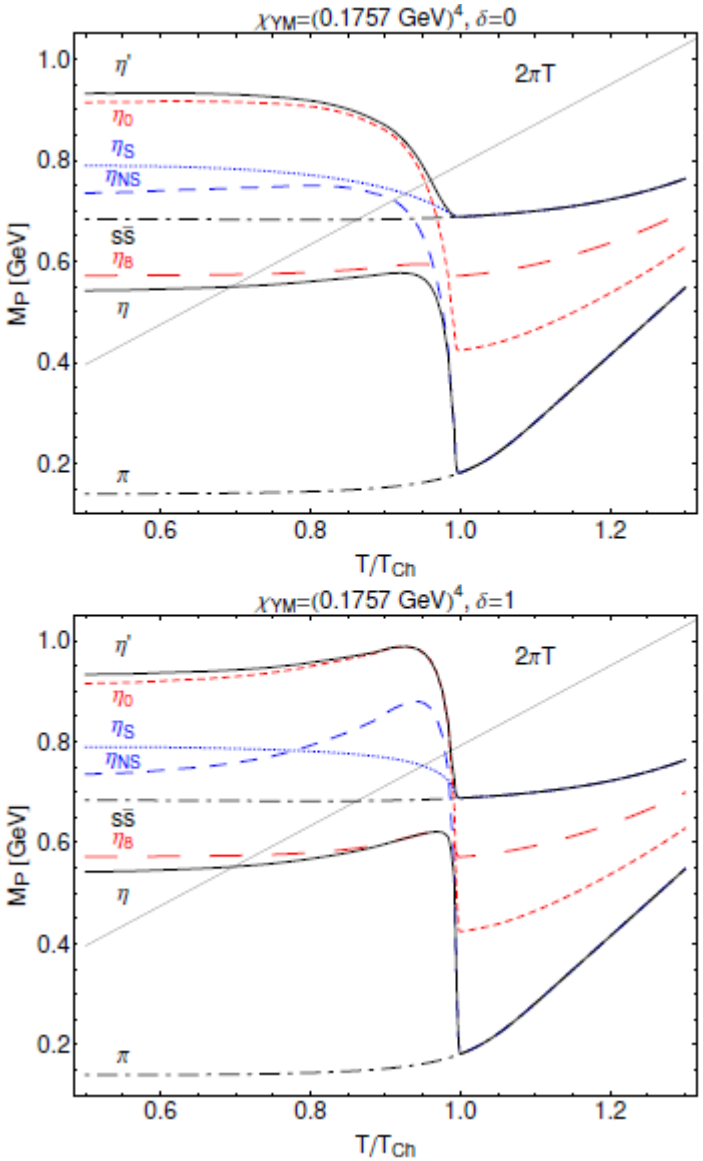
$$N_2(k_1,k_2) = \int S(x_1,k_1)S(x_2,k_2)|\Psi_{1,2}|^2 \mathrm{d}x_1\mathrm{d}x_2$$

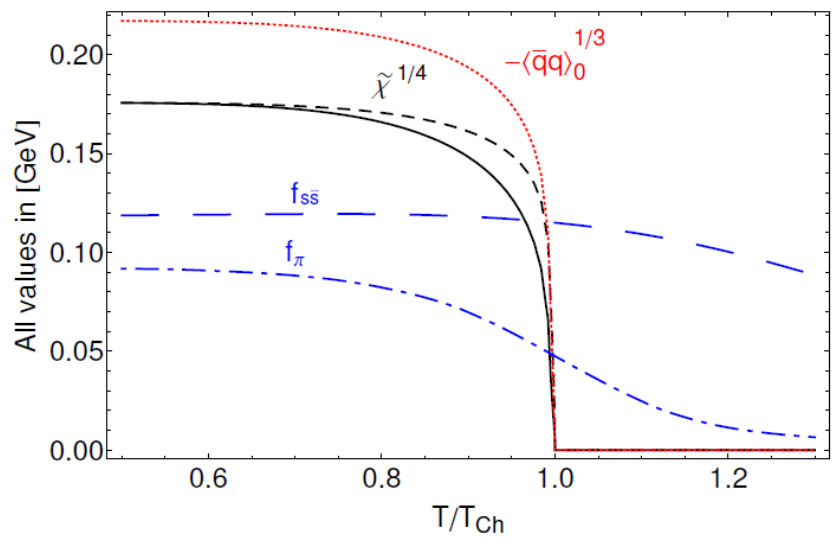
- Correlation:

$$C(k,\Delta K) = \frac{N_2(k_1,k_2)}{N_1(k_1)N_2(k_2)} \qquad \Delta K = k_1 - k_2 \qquad k = (k_1+k_2)/2$$

Simplified picture: plain wave, no multiparticle-interactions, thermalization etc.

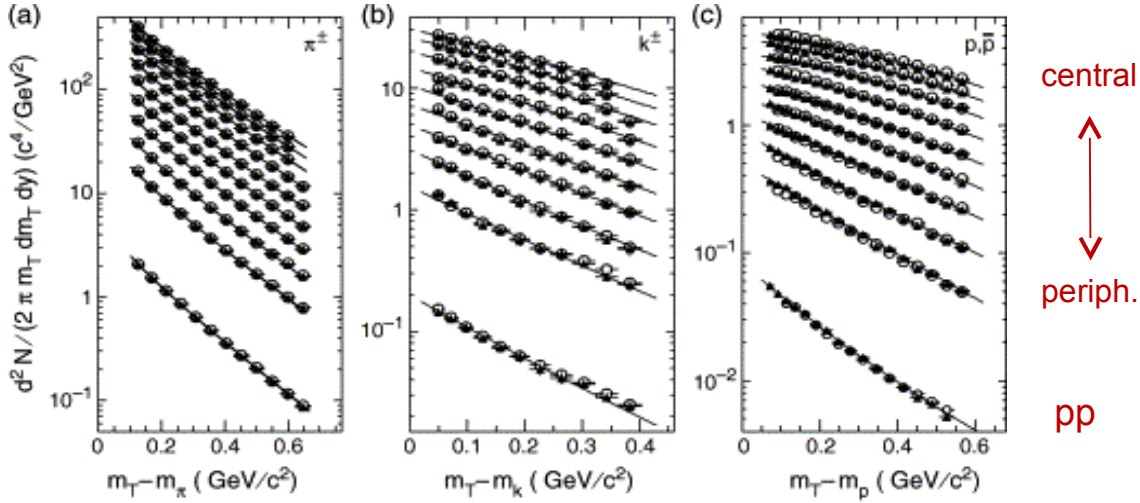
Meson masses and χch vs. T/Tch

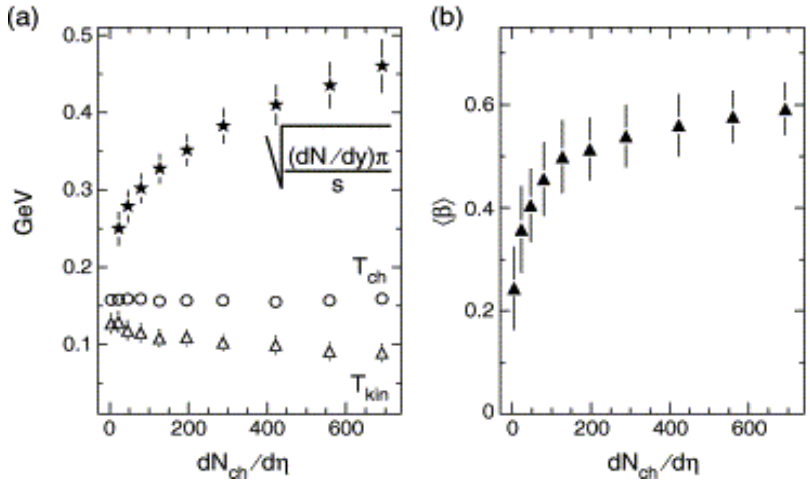




S. Benic, D. Horvatic, D. Kekez, D. Klabucar, e-Print: arXiv:1105.0356 [hep-ph]

mT-scaling





$$\frac{dN}{dp_t^2} \sim \exp\left(-\frac{m_t}{T}\right), \qquad m_t^2 = p_t^2 + m^2$$

E. Shuryak, Prog.Part.Nucl.Phys.53:273-303,2004.

Dilepton Excess in CERES

- Measurement
- Model calculations
- Excess
  in the range b/w the π and ρ mass

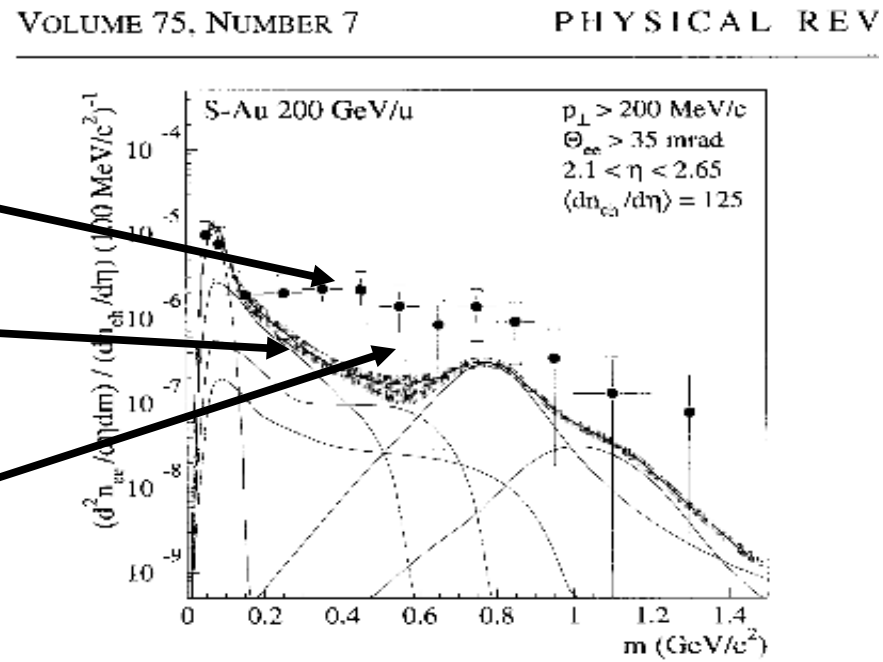


FIG. 4. Inclusive e^+e^- mass spectra in 200 GeV/nucleon S-Au collisions. For explanations see Fig. 2.

Invariant e+ e- pair yield measurements compared to hadronic model yealds

e+ e- pair production in Pb - Au collisions at 158-GeV per nucleon.
CERES cn. (G. Agakichiev et al.). Jun 2005. 39pp.
Eur.Phys.J.C41:475-513,2005. e-Print: nucl-ex/0506002

current understanding: broadening of the ρ width

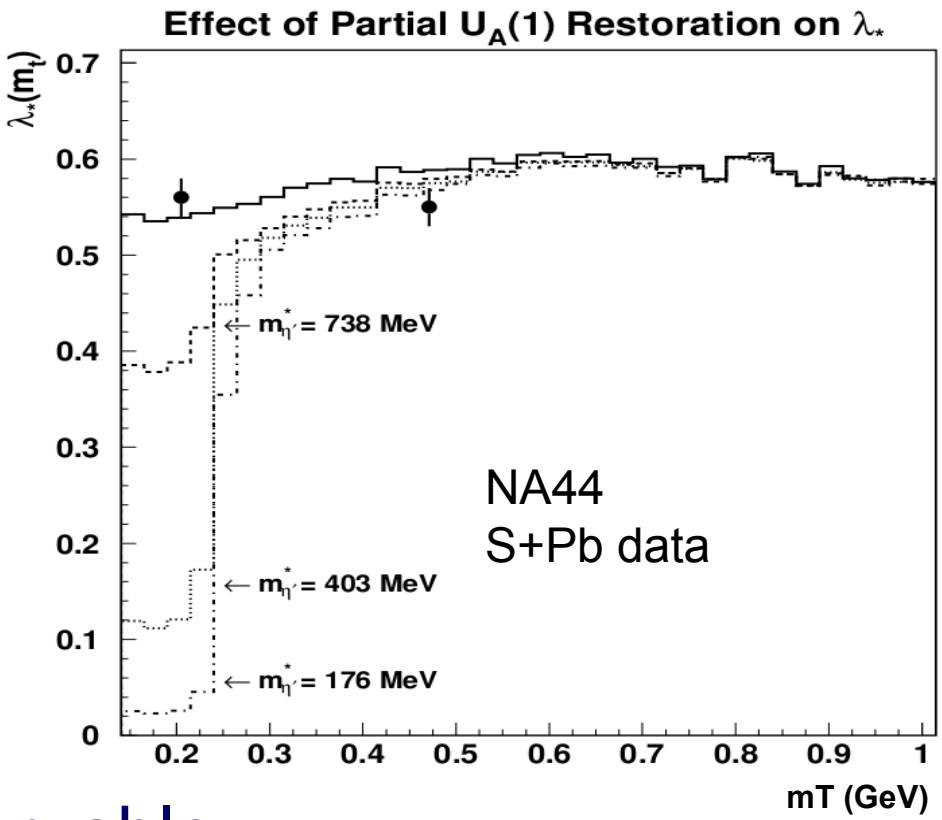
The η' through Phase Transition

- Hadronization
  - Reduced-mass η' mesons produced with a decreased mass with an increased abundancy
- Decoupling from non-Goldstonic matter
  - Mean free path for annihilation is large
  - Long lived
- ”Condensate” in the medium
  - Low-pT η' mesons are unable to get on-shell in the vacuum
  - Medium acts as a trap for low- pT η's
- As medium dissolves, the η's regain their original mass

The Return of the prodigal Goldstone boson. J. I. Kapusta, D. Kharzeev, L. D. McLerran Phys.Rev.D53:5028-5033,1996. Hep-ph/9507343

SPS data and simulation: No signal

- Simulation
  - NA44 S+Pb √s=19.4 GeV
  - Midrapidity
- Simulation
  - Simpler modell
  - FRITIOF parameters

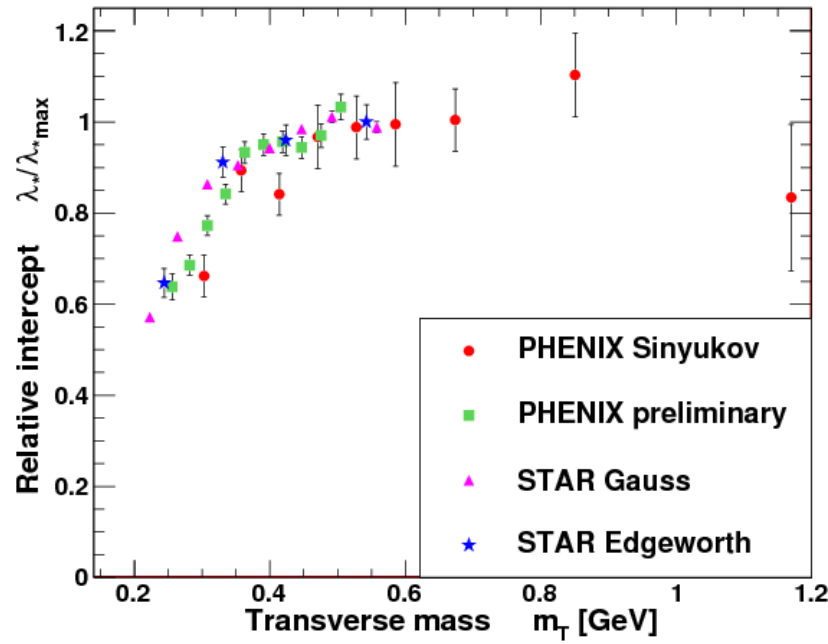


- No mass reduction is observable in NA44 S+Pb 19.4 GeV data

S.E. Vance, T. Csörgő, D. Kharzeev, Phys.Rev.Lett.81:2205-2208,1998.

RHIC data and simulation: There is!

- RHIC data used in analysis
  - **PHENIX** and **STAR**
  - $\pi^+\pi^+$ correlation → $\lambda^*(m_T)/\lambda^*_{max}$
  - Cental Au+Au $\sqrt{s_{NN}}$=200 GeV
  - Midrapidity $|\eta|<0.1$



- Simulation and fits
  - Resonance ratios from 6 differend models
    ALCOR, FRITIOF, Kaneta et al., Letessier et. al., Stachel et al., UrQMD
  - Simulation of the η' condensate
  - Fitting the in-medium mass and ($m_{\eta'}$*) a slope parameter (B^{-1})
  - Other parameters from measurements, models (α, T_{FO}, Tcond, $\langle u_T \rangle$)
  - Systematic studies over the widest reasonable region

Simulating the Condensate

- Resonance ratios from different models
  ALCOR, FRITIOF, Kaneta *et al.*, Letessier *et. al.*, Stachel *et al.*, UrQMD.
- η' excess:

$$\frac{N^*_{\eta'}}{N_{\eta'}} = \left(\frac{m^*_{\eta'}}{m_{\eta'}}\right)^{\alpha} e^{-\left(\frac{m^*_{\eta'} - m_{\eta'}}{T_{FO}}\right)}$$

- Restored η' mass: $p^2_{T,\eta'} + m^2_{\eta'} = p^{*2}_{T,\eta'} + m^{*2}_{\eta'}$
  - If $p^*_{T_{\eta'}} < \sqrt{m^2_{\eta'} - m^{*2}_{\eta'}}$ t get onshell, **trapped** until fireball dissolution
  - After trap decays. a **Maxwell-Boltzmann** distribution is assumed:

$$f(p_x, p_y) = \left(\frac{1}{2\pi m_{\eta'} B^{-1}}\right) \exp\left(-\frac{p_x^2 + p_y^2}{2 m_{\eta'} B^{-1}}\right) \quad ; \quad p^2_{T,\eta'} = p_x^2 + p_y^2$$

- Parameters
  - From measurements *TFO* = 177 MeV, <*uT*> = 0.48
  - Conservative assumption *TFO*η' =*TFO* *Tcond*=*TFO*
  - Hydrodynamical models α (related to the dimension of expansion)
  - Looked for: in-medium mass *m*η'* inverse slope *B*-1
- Spectra from decays using JETSET

Systematics and Results

- Largest uncertainity: models for resonance ratios
- Modifying parameters in the widest reasonable range
  - $-1/2 \leq \alpha \leq +1/2$ (1)
  - $140\ \mathrm{MeV} \leq Tcond \leq 220\ \mathrm{MeV}$
  - $100\ \mathrm{MeV} \leq TFO \leq 177\ \mathrm{MeV}$

(altogether 17 x 1248 x 1000000 events simulated)

- Other effects
  - Centrality, rapidity cutoff, ω resolution
- An upper boundary can be determined for the η' mass:
  Each and every setup fails when m*η' > 750 MeV
  (failure means CL<0.1%)

fit result summary and enhancement factors

Resonance model	$m^*_{\eta'}$ (MeV)	B^{-1} (MeV)	$\frac{\chi^2}{ndf}$ (CL %)	$f_{\eta'}$	f_η
ALCOR [17]	490^{+60}_{-50}	42	1.83 (4.29)	43.4	5.25
Kaneta *et al.* [18]	530^{+50}_{-50}	55	2.07 (4.12)	25.6	3.48
Letessier *et al.* [19]	340^{+50}_{-60}	86	1.72 (6.35)	67.6	4.75
Stachel *et al.* [20]	340^{+50}_{-60}	86	1.71 (6.38)	67.6	4.97
UrQMD [16]	400^{+50}_{-40}	86	1.73 (6.14)	45.0	7.49

The most probable values of the $B-1$, $m*$ fits for different resonance multiplicity models (errors only systematic) and the corresponding integrated enhancement factors.

η' mass: Fitted values

	Model Fits for PHENIX+STAR data					Parameters		
	ALCOR	Kaneta *et al.*	Letessier *et al.*	Stachel *et al.*	UrQMD	α	T_{cond}	T_{FO}
$m^*_{\eta'}$ (MeV)	490^{+60}_{-50}	530^{+50}_{-50}	340^{+50}_{-60}	340^{+50}_{-60}	400^{+50}_{-40}	0	177	177
B^{-1} (MeV)	42	55	86	86	86			
CL (%)	4.29	4.12	6.35	6.38	6.28			
$m^*_{\eta'}$ (MeV)	540^{+50}_{-40}	560^{+60}_{-30}	410^{+40}_{-40}	410^{+40}_{-40}	460^{+40}_{-40}	-0.5	177	177
B^{-1} (MeV)	55	55	86	86	86			
CL (%)	2.80	3.35	6.07	5.97	6.14			
$m^*_{\eta'}$ (MeV)			210			+0.5	177	177
B^{-1} (MeV)			86					
CL (%)			6.54					
$m^*_{\eta'}$(MeV)		620	460			0	140	177
B^{-1} (MeV)		42	69					
CL (%)		2.26	5.86					
$m^*_{\eta'}$(MeV)		440	200			0	220	177
B^{-1} (MeV)		69	104					
CL (%)		5.61	6.33					
$m^*_{\eta'}$(MeV)		410	240			0	177	100
B^{-1} (MeV)		145	145					
CL (%)		1.63	1.80					

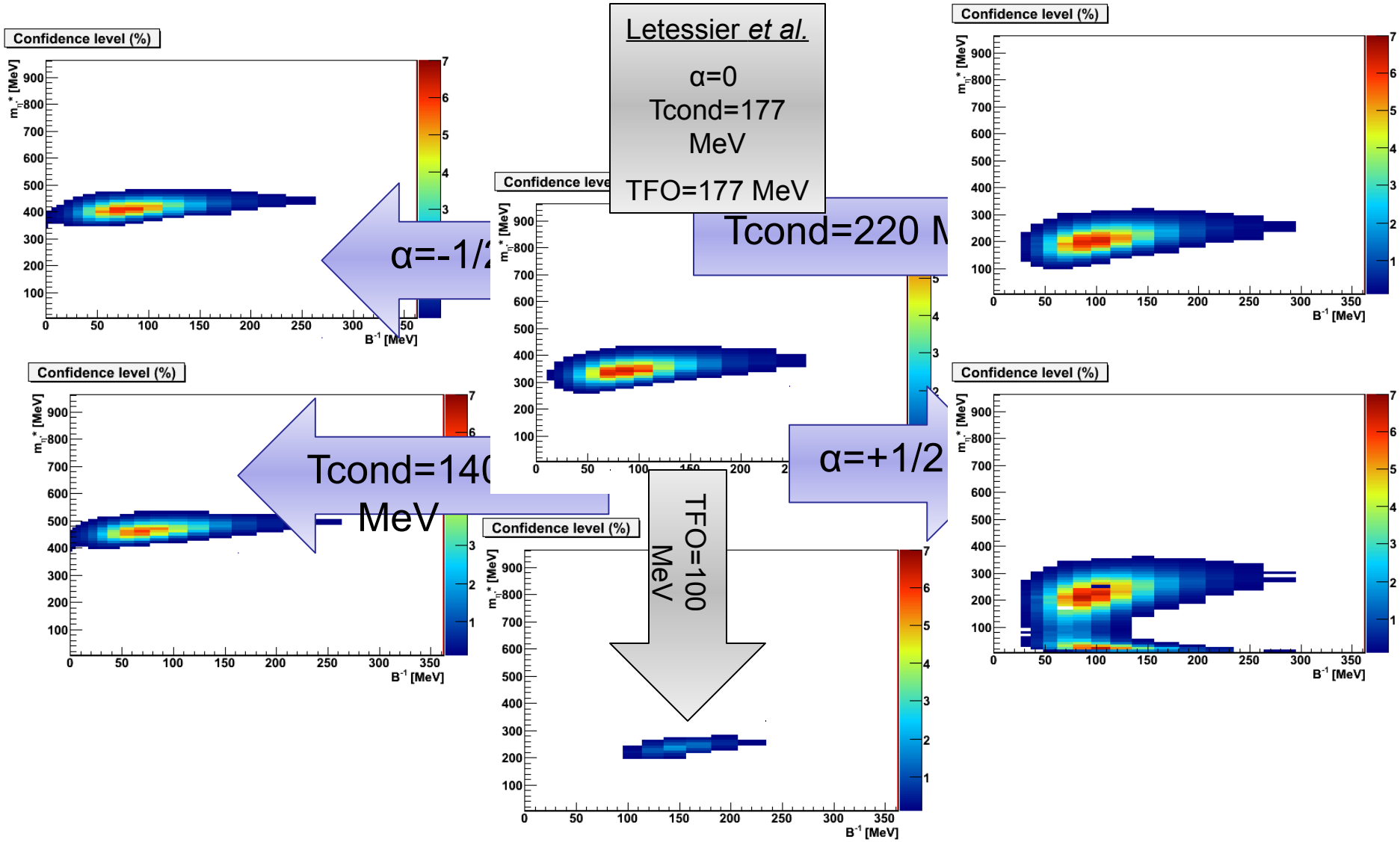
TABLE II: Fitted values of the modified η' mass on the STAR+PHENIX combined dataset, for different resonance models and parameters. The Fritiof model has CL$<$ 0.1% and therefore not shown here. 1-σ boundaries of the fits are given only for $m^*_{\eta'}$ and for the $\alpha = 0$ and $\alpha = -0.5$ simulations, not for all the systematic checks.

η' mass: Acceptability boundaries

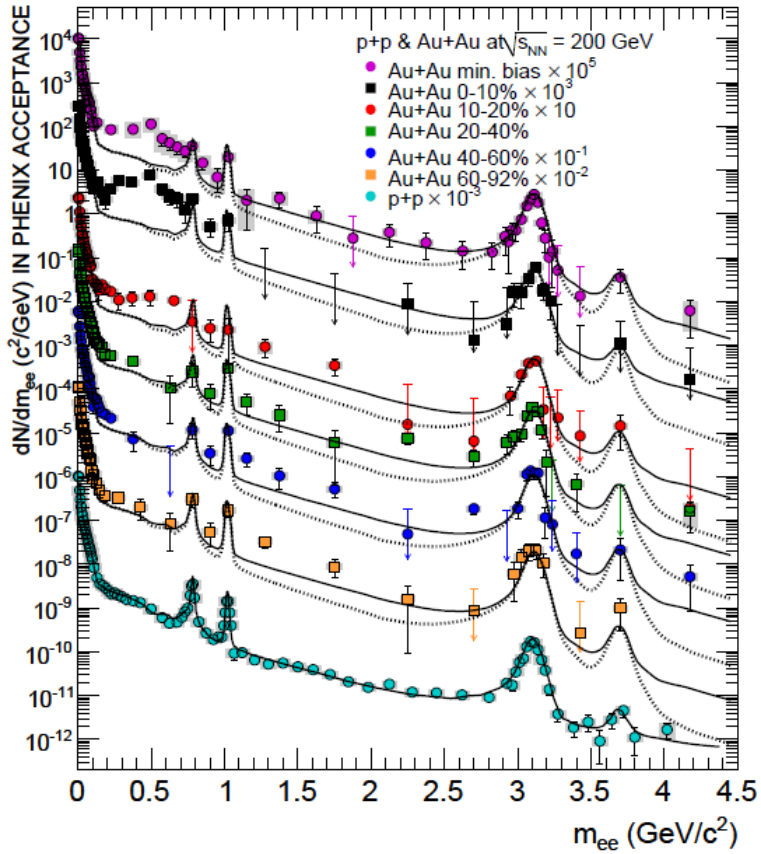
Dataset	Acceptability boundaries of model fits						Parameters		
	ALCOR	FRITIOF	Kaneta *et al.*	Letessier *et al.*	Stachel *et al.*	UrQMD	α	T_{cond}	T_{FO}
PHENIX	0—750	680—958	0—720	0—510	0—500	0—530	0	177	177
STAR	380—600	none	430—630	190—450	190—450	260—500			
PHENIX+STAR	380—590	none	420—620	260—430	260—430	330—470			
PHENIX	30—770	420—958	50—730	0—540	0—540	0—560	-0.5	177	177
STAR	470—630	none	500—650	300—500	300—500	360—540			
PHENIX+STAR	450—620	670—760	490—640	340—480	340—480	400—510			
PHENIX				0—450			+0.5	177	177
STAR				0—390					
PHENIX+STAR				0—390					
PHENIX			0—760	0—450			0	140	177
STAR			560—690	0—390					
PHENIX+STAR			540—680	0—360					
PHENIX			0—680	0—410			0	220	177
STAR			270—580	0—350					
PHENIX+STAR			290—560	100—320					
PHENIX			220—470	30—310			0	177	100
STAR			360—470	190—300					
PHENIX+STAR			370—440	200—280					

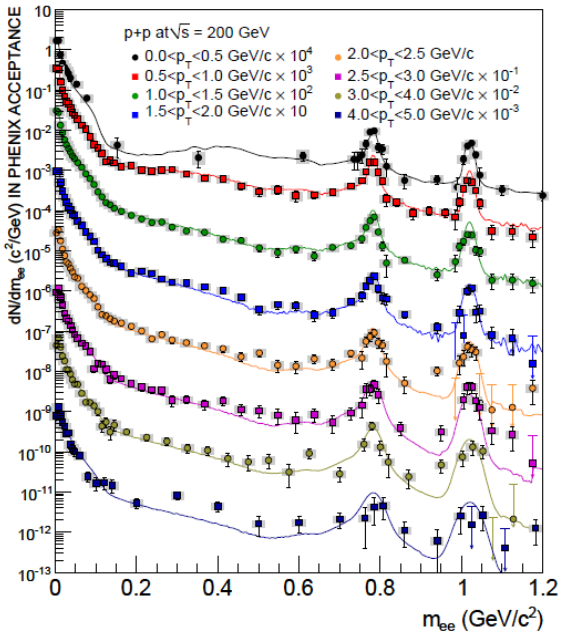
TABLE III: Acceptability boundaries of the modified η' mass on the PHENIX, STAR, and the STAR+PHENIX combined datasets, for different resonance models and parameters. A fit is considered acceptable if CL$\geq$ 0.1%. There is no model and no sane set of parameters that contradict with an $m^*_{\eta'} \leq 760$ MeV assumption for the combined PHENIX+STAR dataset. However, all the models except for the FRITIOF, the one that completely fails on the STAR dataset, require an $m^*_{\eta'} \leq 640$MeV.

Systematics – a Visual Summary



Dilepton excess in details





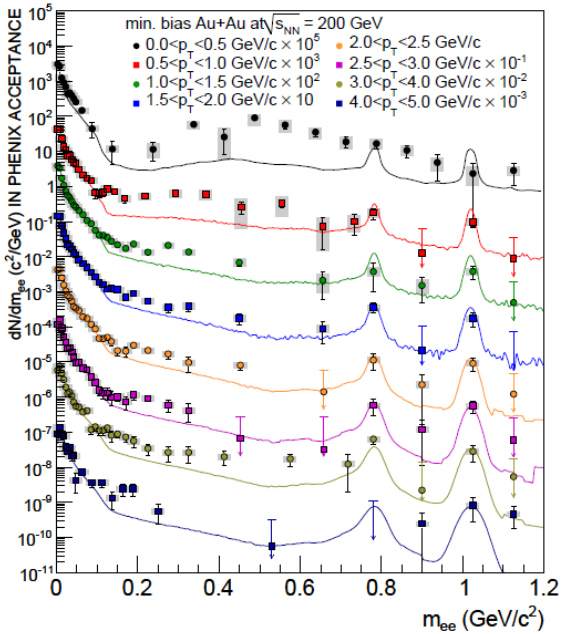
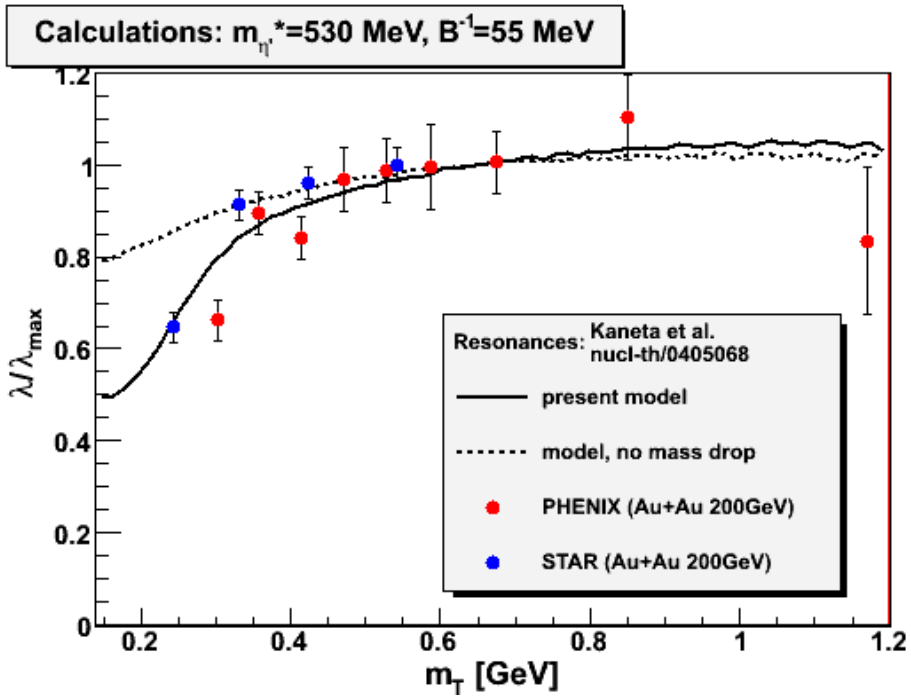
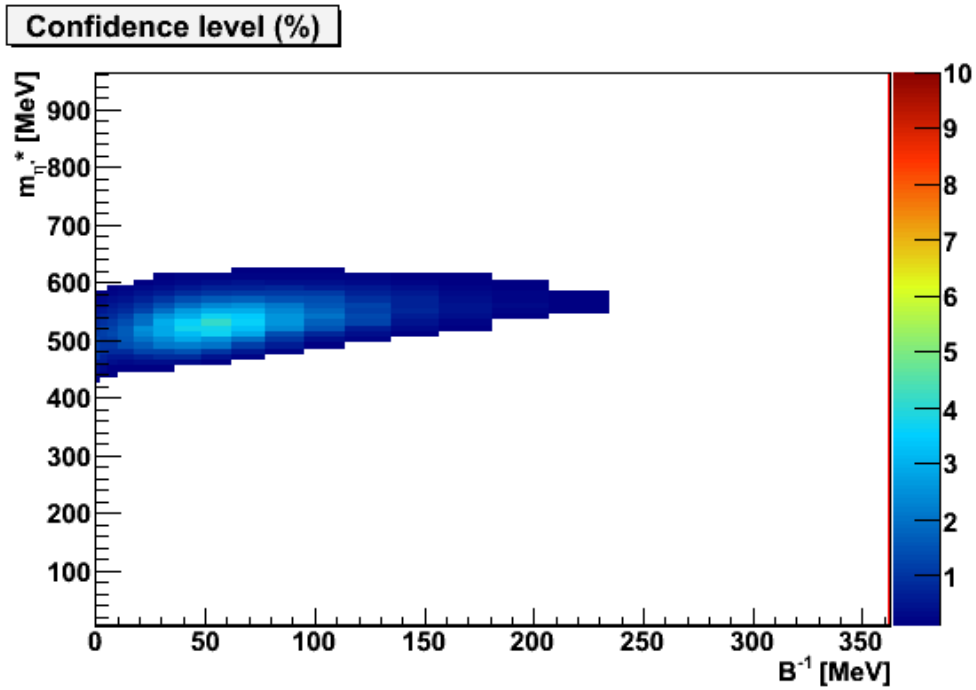


Fig.26: Invariant mass spectrum of e+e- pairs compared to expectations from the model of hadron decays for p+p and for different Au+Au centrality classes.

Fig.29: e+e- pair invariant mass distributions in p + p (left) and minimum bias Au+Au collisions (right). The pT ranges are shown in the legend.

Resonances: Kaneta-Xu vs. RHIC

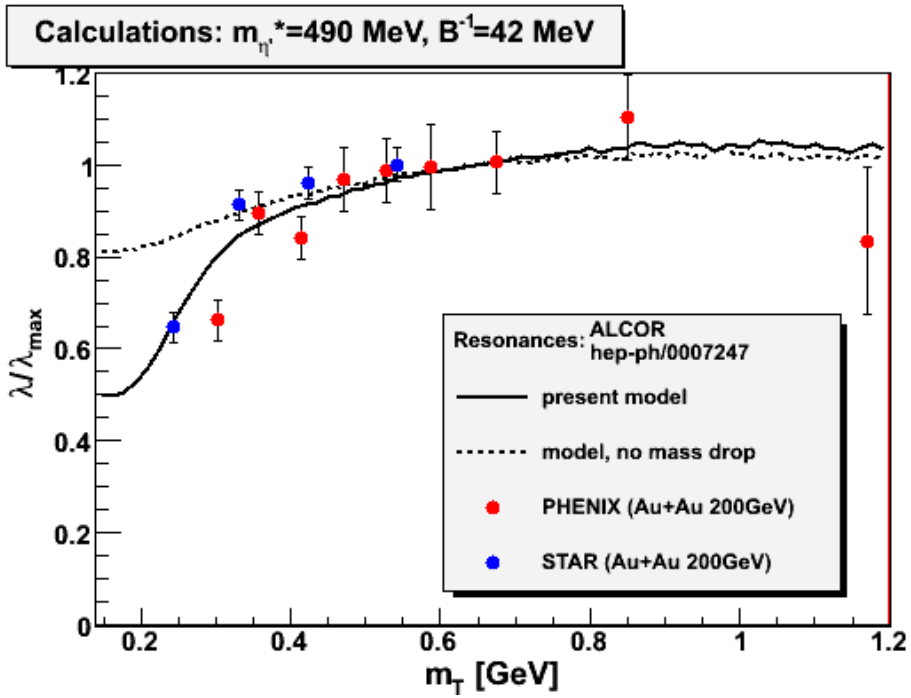


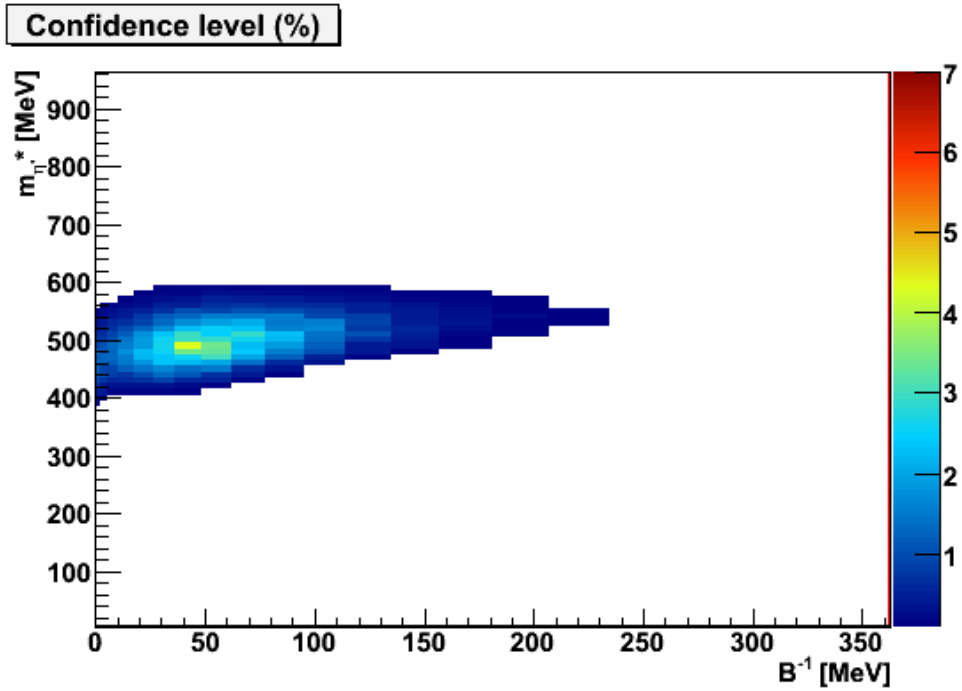


- Statistical chemical freezeout model
- Central mid-η 200 GeV Au+Au
- Describes PHENIX hadron spektrum well

Kaneta & Xu, arXiv:nucl-th/0405068

Resonances: ALCOR vs. RHIC

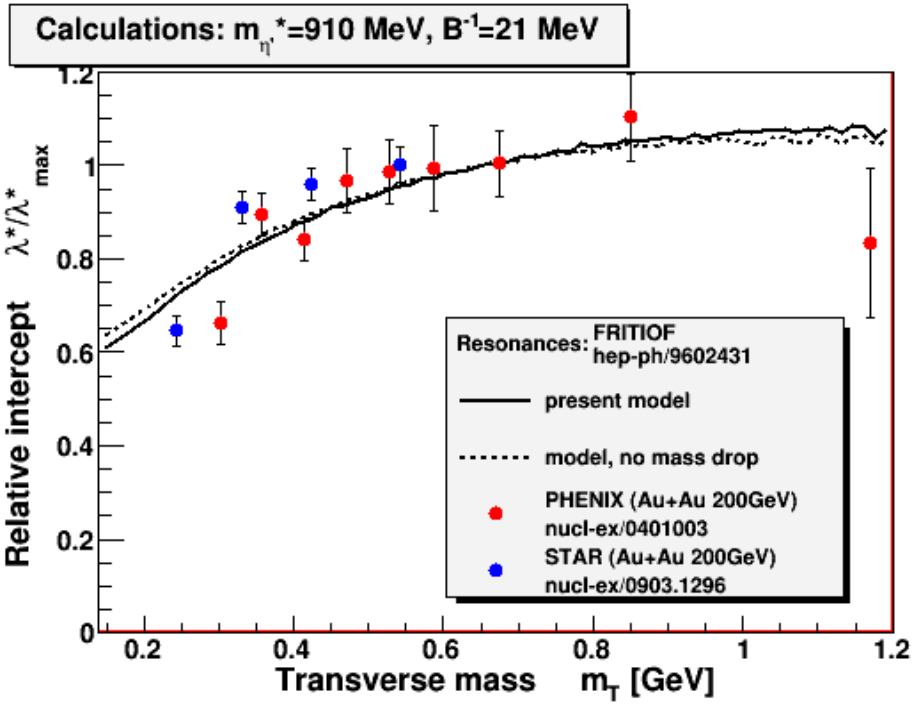


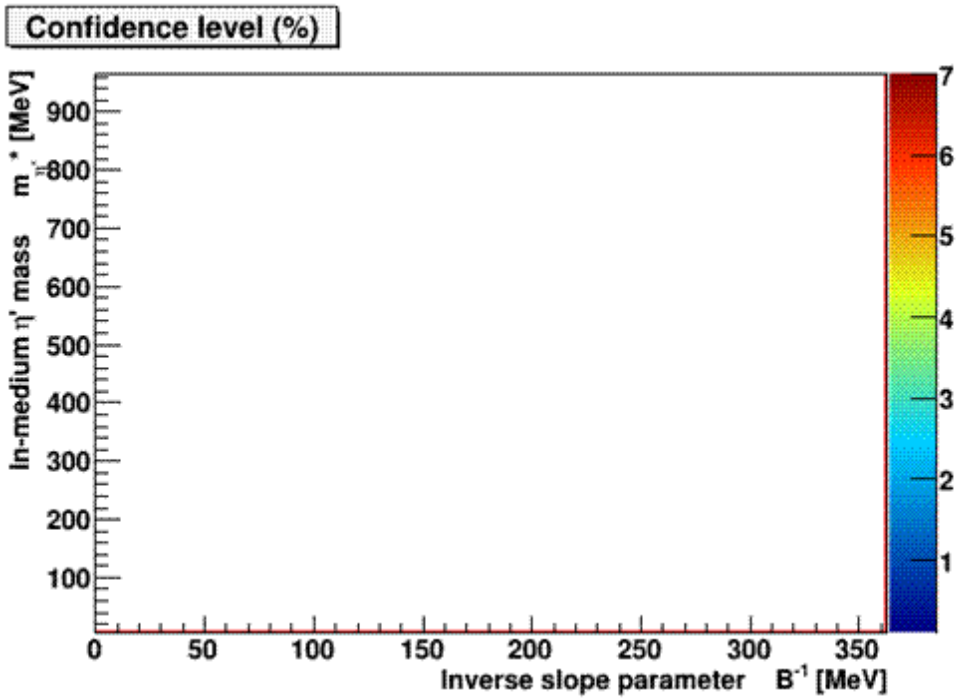


- Coalescence-model
- η'/ η ratio has to be fixed from other models (Kaneta, here)

P. Levai, T.S. Biro, T. Csorgo, J. Zimanyi, hep-ph/0007247

Resonances: FRITIOF vs. RHIC

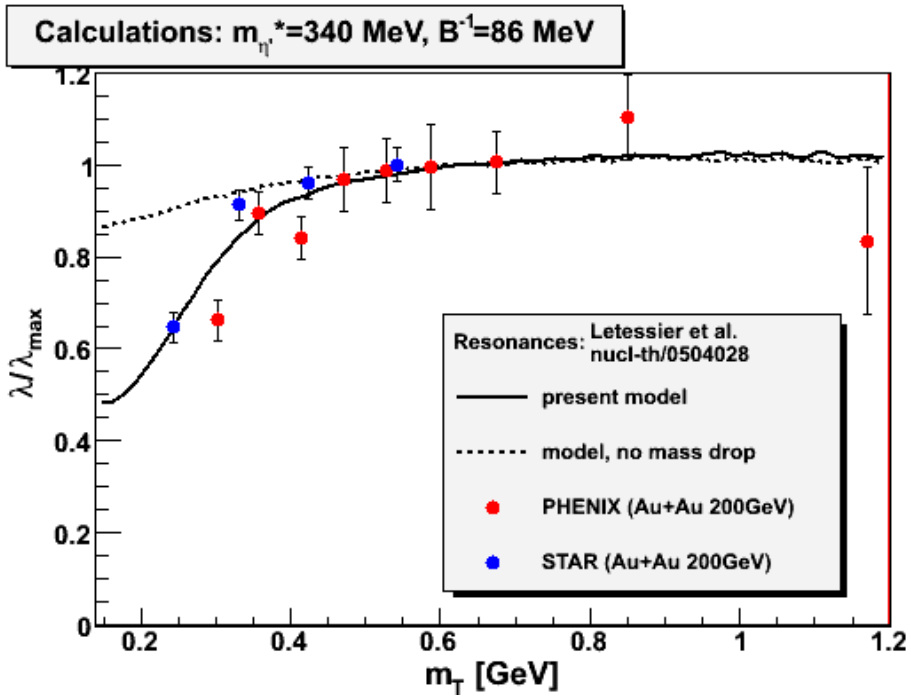


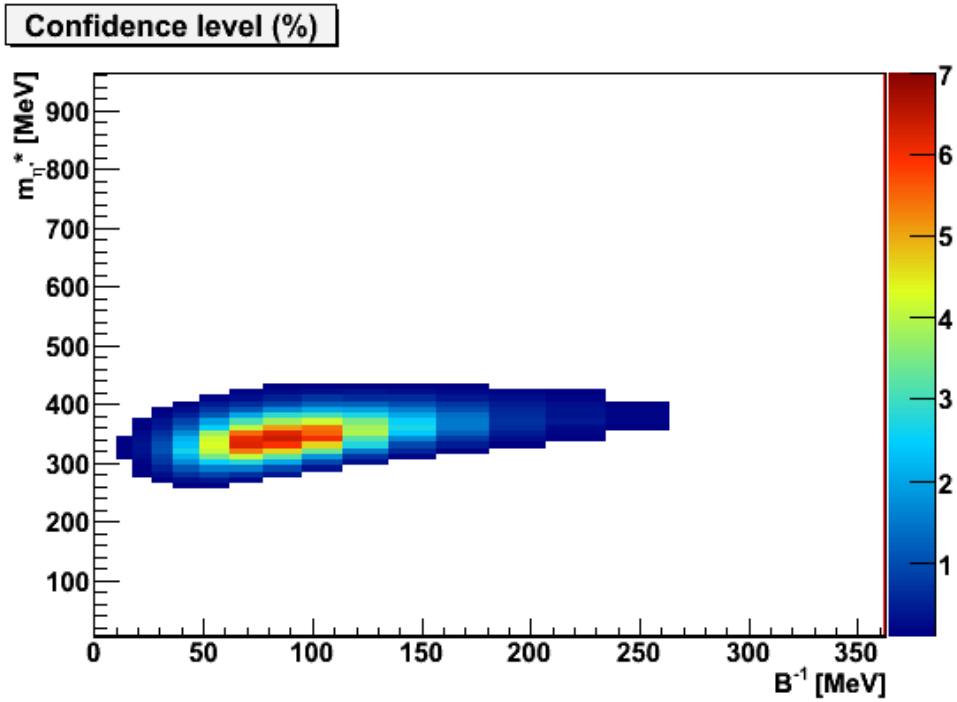


- 200 GeV mid-rapidity Au+Au simulation
- Note:Does not describe STAR data, neither the unified PHENIX+STAR dataset. For PHENIX data only, it is consistent with mη'=958MeV.

B. Anderson et al., Nucl. Phys. B 281 (1987) 289.

Resonances: Letessier-Rafelski vs. RHIC

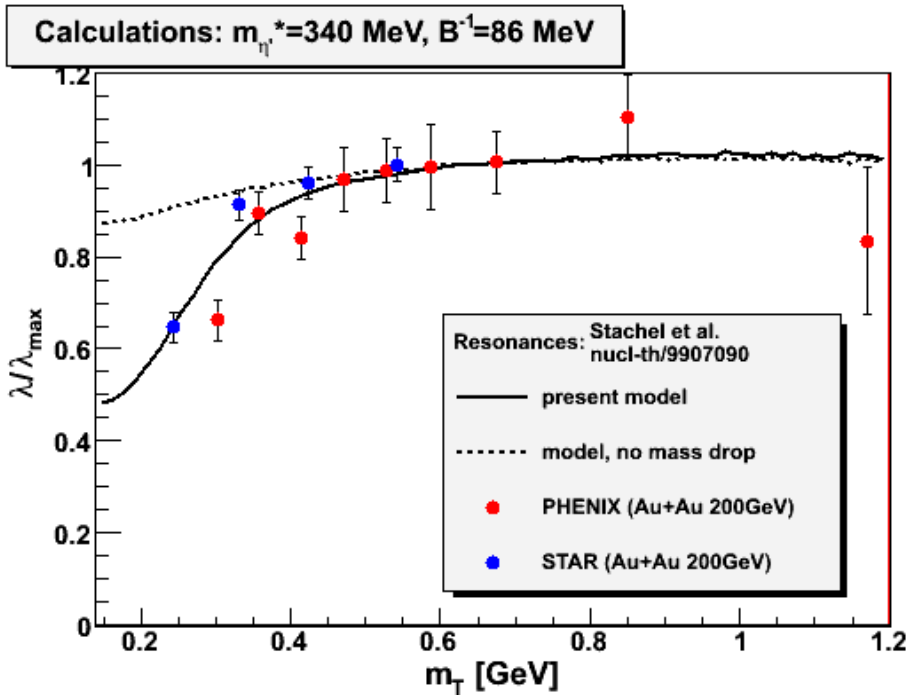


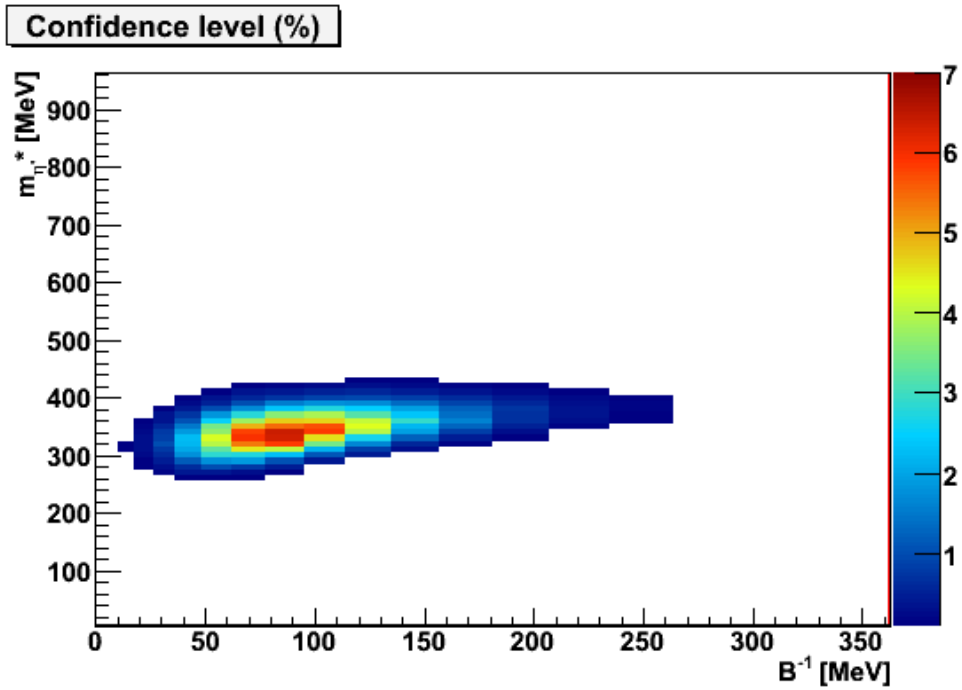


- Statistical chemical freezeout model
- Central mid-η 200 GeV Au+Au

J.Letessier J.Rafelski, arXiv:nucl-th/0504028

Resonances: Stachel et al. vs. RHIC

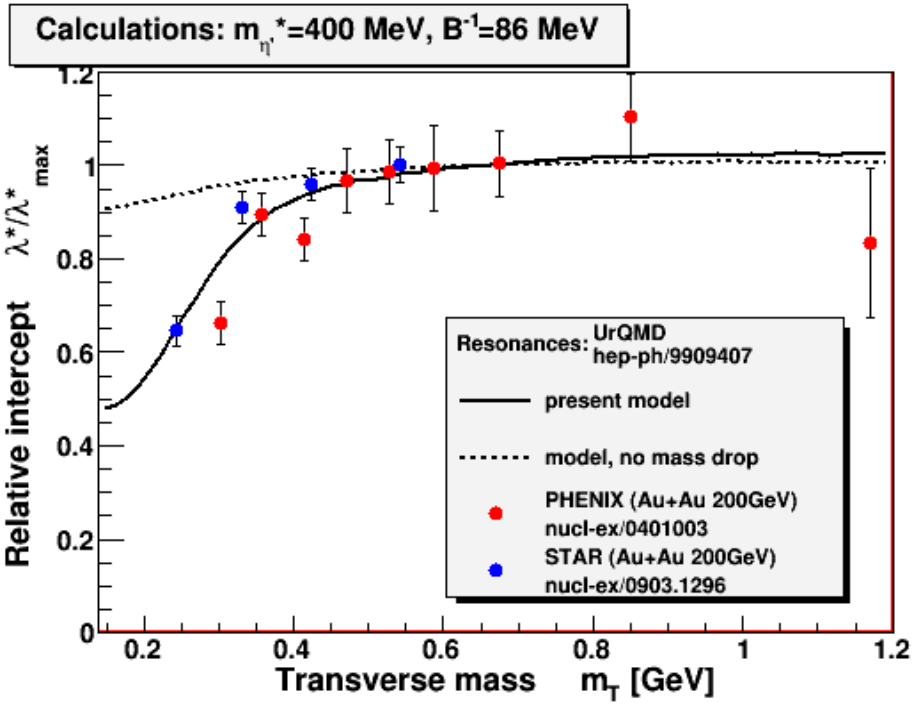


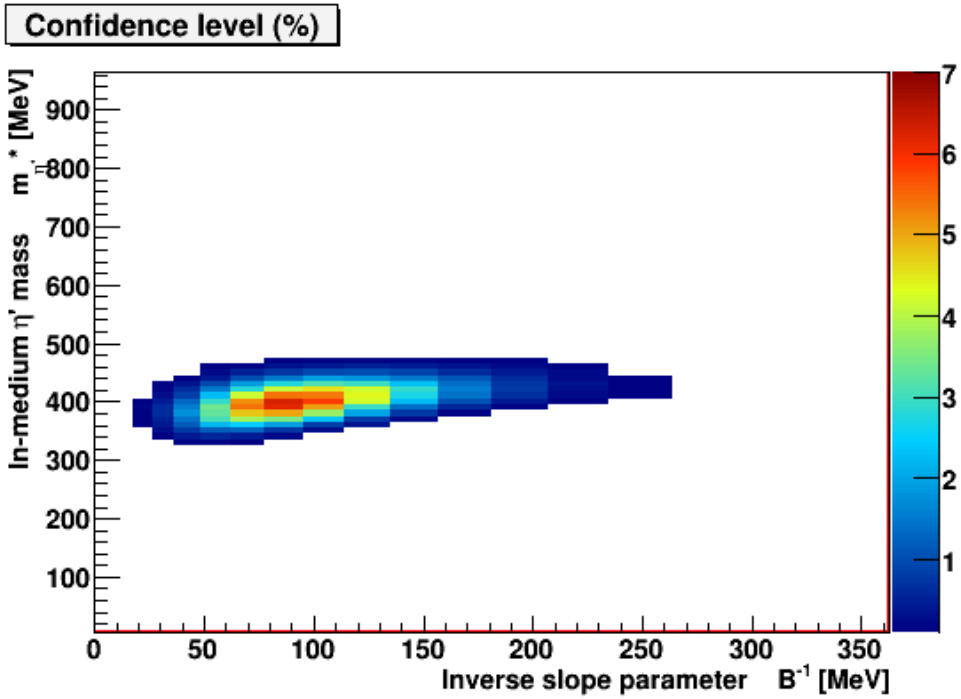


- Statistical chemical freezeout model
- Central mid-η 200 GeV Au+Au

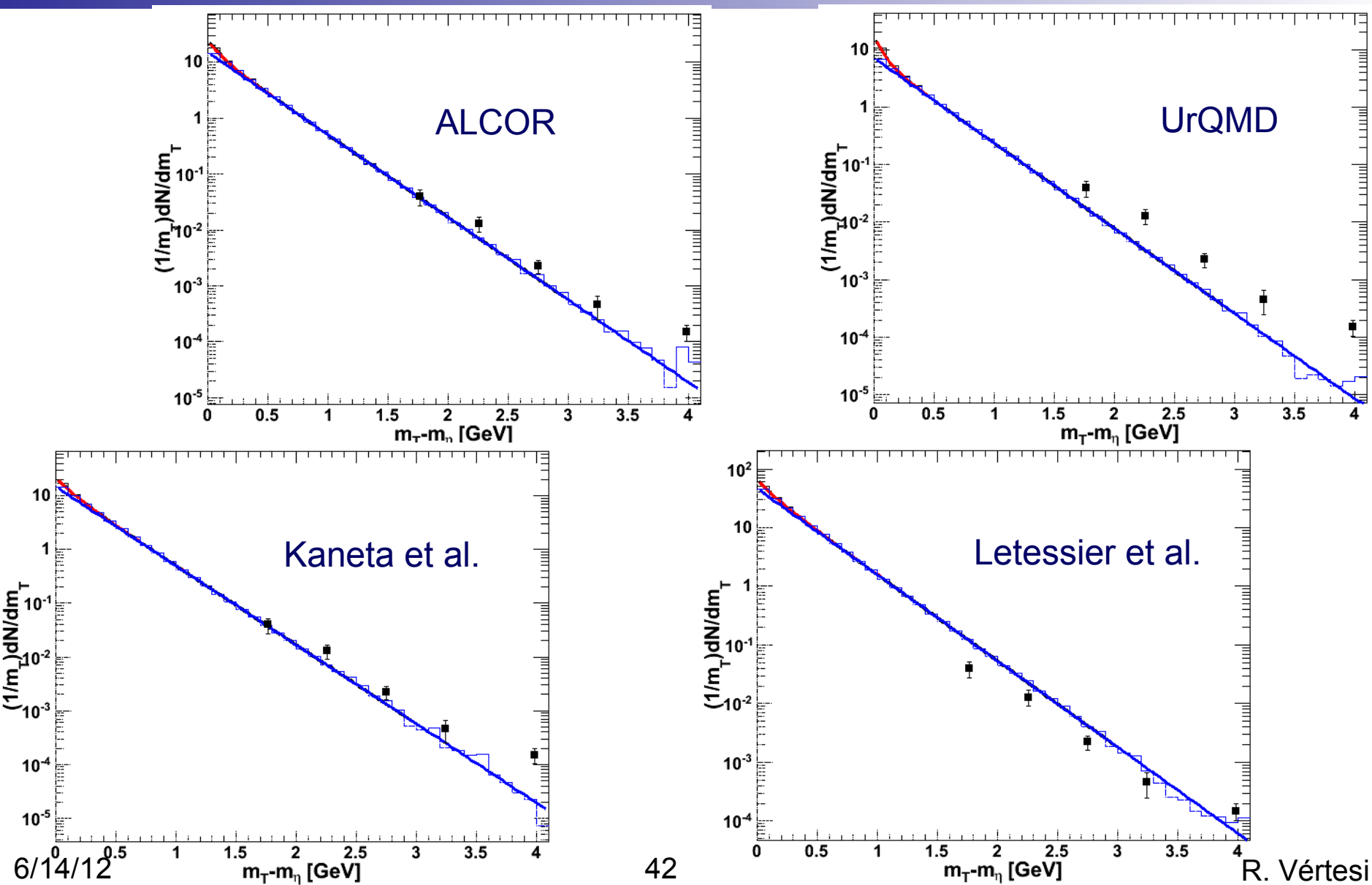
J.Stachel *et al.*, arXiv:nucl-th/9907090

Resonances: UrQMD vs. RHIC





- 200 GeV midrapidity
- Au+Au, RHIC √sNN=200 GeV

J. P. Sullivan et al., Phys. Rev. Lett. 70 (1993) 3000

η spectra – model vs. data