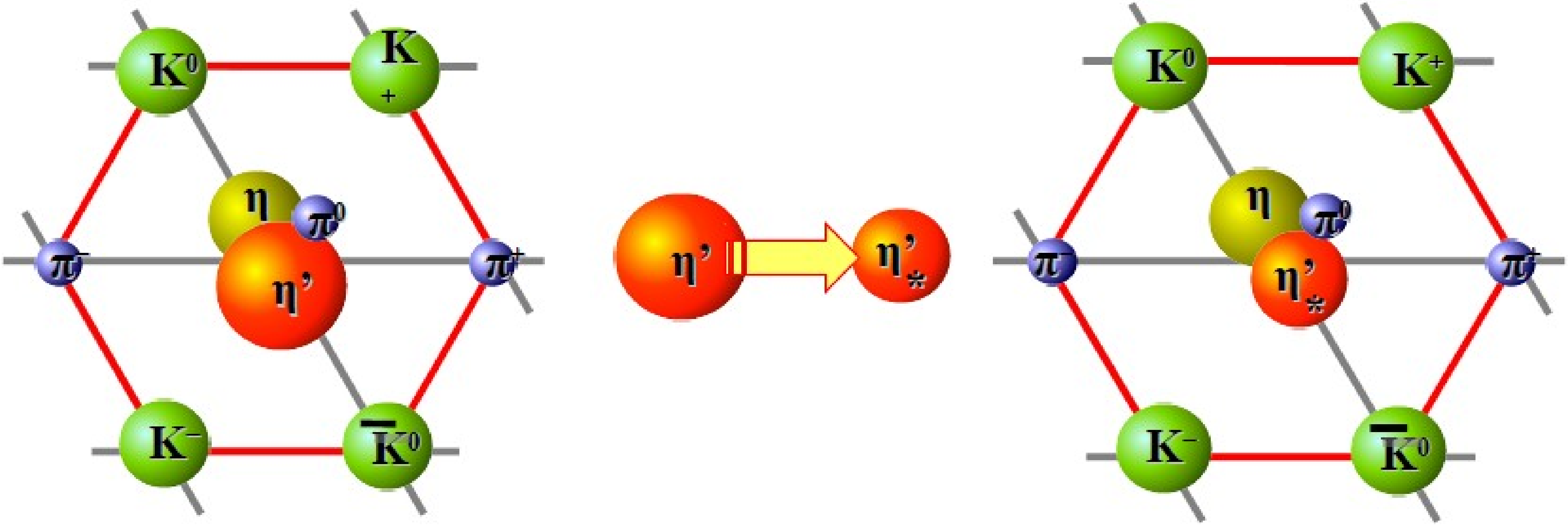
Significant in-medium η′ mass reduction in $\sqrt{s_m}$ = 200 GeV Au+Au collisions

T. Csörgő [1,2] R. Vértesi [2] J. Sziklai [1]

[1] **Dept. of Physics, Harvard University,** Cambridge, USA
[2] **MTA KFKI RMKI**, Budapest, Hungary



T. Csörgő. R. Vértesi. J. Sziklai, arXiv:0912.5526, Phys. Rev. Lett. (2010) in press
R. Vértesi, T. Csörgő, J. Sziklai, Nucl. Phys. A830: 631C (2009)

Outline

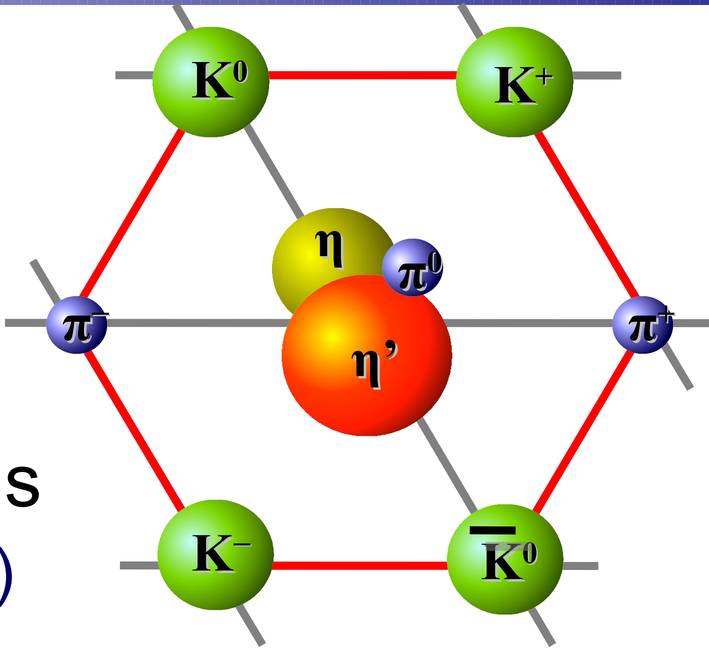
- Three-quark model, Chiral symmetry breaking
  - Restoration of symmetry in a hot, dense medium
- Role of the η' mass
  - Dilepton spectra in Heavy Ion Collisions
  - η' mass through $\pi^{\pm}$ Bose-Einstein correlations
- Possible experimental signatures
  - BEC measurements at RHIC
  - Dilepton excess found by PHENIX
- BEC-calculations for different models
  - Spectra, $\lambda^*(m_T)$, systematics…

Chiral Symmetry Breaking

- The three-quark model
  - SU(3) flavour-symmetry
  - Spontaneously broken

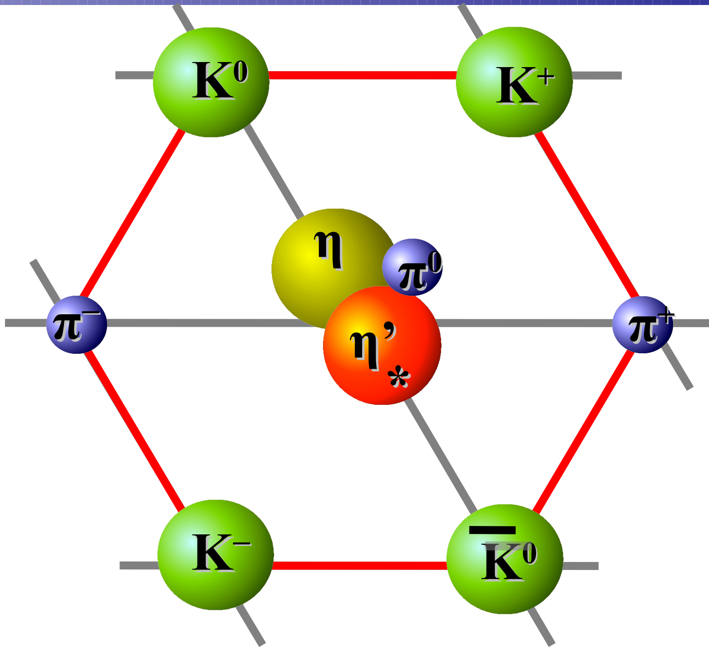
=> 9 Goldstone bosons

  - Corresponding to light mesons
    - There are only 8! (Meson-octet)



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

Restoration of the Symmetry in a Hot, Dense Medium



- High energy densities
  - Asymptotic freedom $\alpha_s \rightarrow 0$
  - Nontrivial topology vanishes
  - U(1) no more broken
  - SU(3) restored

Remark:

From SSB, one expects massless mesons.
However, the flavour symmetry is inexact.

- Mass reduction

$$m_{\eta'} = m_0 + \Delta m$$

Lower bound (Gell-Mann – Okubo):

$$m_0^2 = \frac{1}{3}\left(2m_K^2 + m_\pi^2\right); m_0 \approx 400MeV$$

Upper bound (S,NS isosinglet eigenstates):

$$m_S^2 = 2m_K^2 + m_\pi^2; \quad m_S \approx 700MeV$$

Δm is the extra mass from instantons in a not-so-dense medium

Signature: Particle Abundancy

- Hagedorn-model
  - Production of light mesons:

$$\sigma_i \sim (m/2\pi)^{3/2} e^{-m/T_H}$$

$T_H \sim 160$ MeV Hagedorn-temperature

- In case of a possible mass drop:
  - Number of η's would be small: $N_{\eta'} / N_{\pi^0} \sim 2\text{x}10^{-2}$
  - With a strongly reduced η' mass: $N_{\eta'} / N_{\pi^0} \sim 1$
    - An enhancement of a factor of 50 at maximum
    - Increased weight of strange states, rather 3 to 16

- Consequence of the reduced mass:
  An increased abundancy of η' mesons

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-p_T η' mesons are unable to get on-shell in the vacuum
  - Medium acts as a trap for low- p_T 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

Channels of Observation

- Leptonic decay $\eta' \rightarrow \ell^{+}\ell^{-}\gamma$
    - Increased η'/π proportion in the low-p_T range
    - Excess in the $\ell^{+}\ell^{-}$ spectrum under the ρ mass

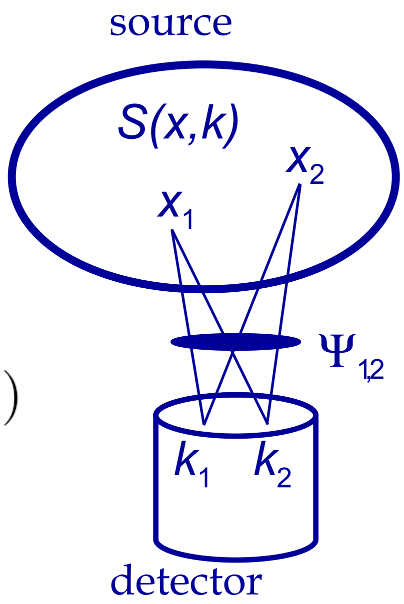
- η meson (BR=63%) $\eta' \rightarrow \eta\,\pi\,\pi$
    - Enhancement of η production
    - BEC of charged pions $\eta \rightarrow \pi^{0}\pi^{+}\pi^{-}$
        - Sensitive to the sources of the pions

- Direct measurement? $\eta' \rightarrow \gamma\gamma$
    - Would be convincing, however, poor S/B ratio ($\pi^{0}\rightarrow\gamma\gamma$)

HBT effect (BEC)

- Discovered and still used in astrophysics
- Consider two plane waves $$\Psi_1 = \mathrm{e}^{-ik_1x_1}$$ $$\Psi_2 = \mathrm{e}^{-ik_2x_2}$$
- 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: plane wave, no multiparticle-interactions, thermalization etc.

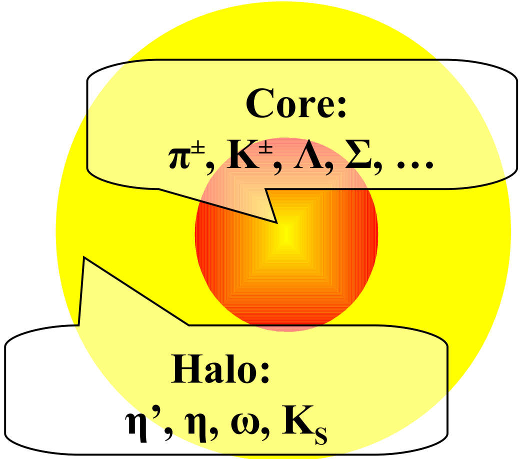
$\pi^\pm$ Correlations and the Core-Halo picture

- Pions from QM freezeout
  - Primordial (from phase transition)
  - Fast decaying resonances
  - Long-lived resonances (ω,η,η',K_S^0)

} Core

→ Halo

T. Cs, B. Lörstad, hep-ph/9411307


Core:
$\pi^\pm$, $K^\pm$, Λ, Σ, …

Halo:
η', η, ω, K_S

- Correlation

$$C(\Delta k, K) \simeq 1 + \lambda_* R_c(\Delta k, K) \qquad R_c(\Delta k, K) = \frac{|\tilde{S}_c(\Delta k, K)|^2}{|\tilde{S}_c(\Delta k = 0, K = p)|^2}$$

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

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

$$N = Cm_t^\alpha e^{-m_T/T_{eff}}, T_{eff} = T_{fo} + m\langle u_T\rangle^2$$

- Correlation measurent ↔ $\lambda^*(m_T)$ ↔ core−halo ratio

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 $p_{T,\eta'}^{2} + m_{\eta'}^{2} = p_{T,\eta'}^{*2} + m_{\eta'}^{*2}$
  - If $p_{T_{\eta'}}^{*} < \sqrt{m_{\eta'}^{2} - m_{\eta'}^{*2}}$, the η' can’t get onshell;

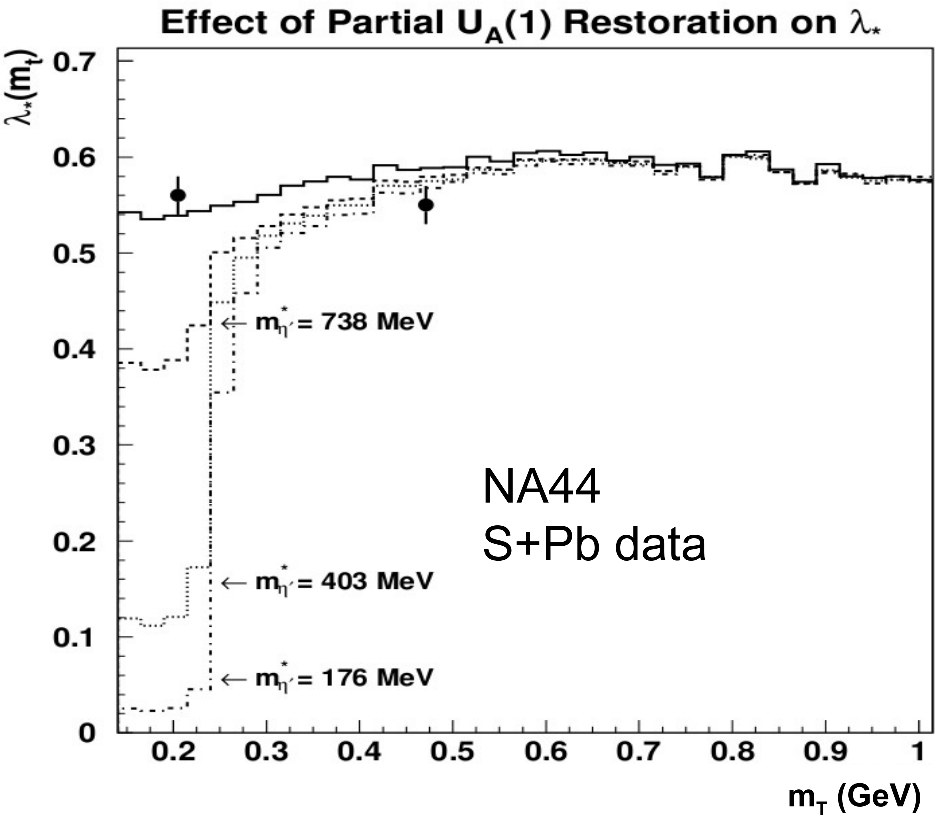
    a MB assumed:

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

- Parameters
  - From measurements $T_{FO} = 177\ \text{MeV}$, $\langle u_T \rangle = 0.48$
  - Conservative assumption $T_{FO}^{\eta'} = T_{FO}$ $T_{cond} = T_{FO}$
  - Hydrodynamical models α (related to d of expansion)
  - Looked for: **in-medium mass** $m_{\eta'}^{*}$ inverse slope B^{-1}
- Spectra from decays using JETSET

SPS data and simulation: No signal

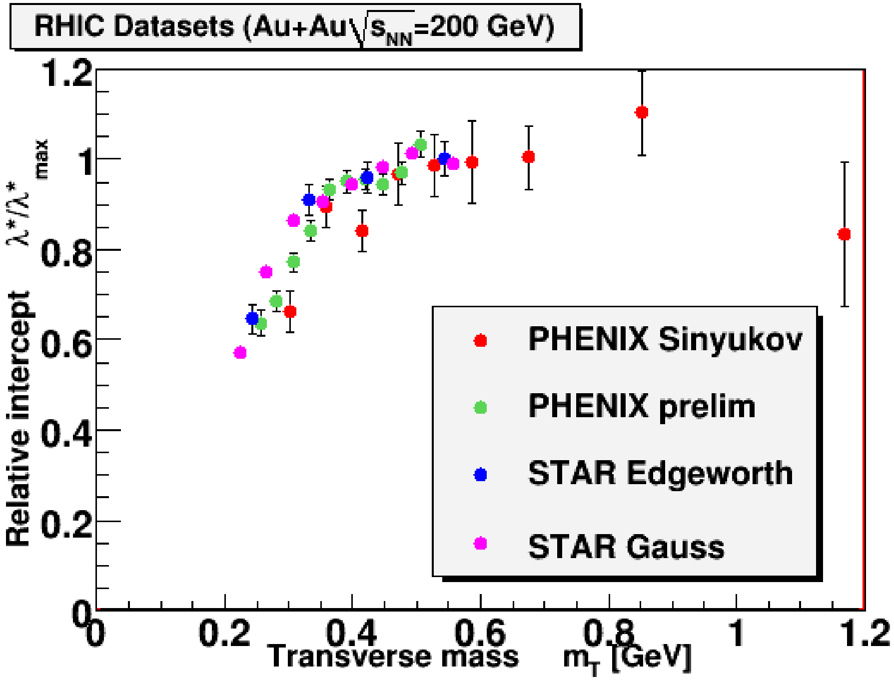
- Data:
  NA44 200 GeV S+Pb
- Resonances:
  FRITIOF
- Earlier, less refined modelling of condensate
- No sign of mass reduction



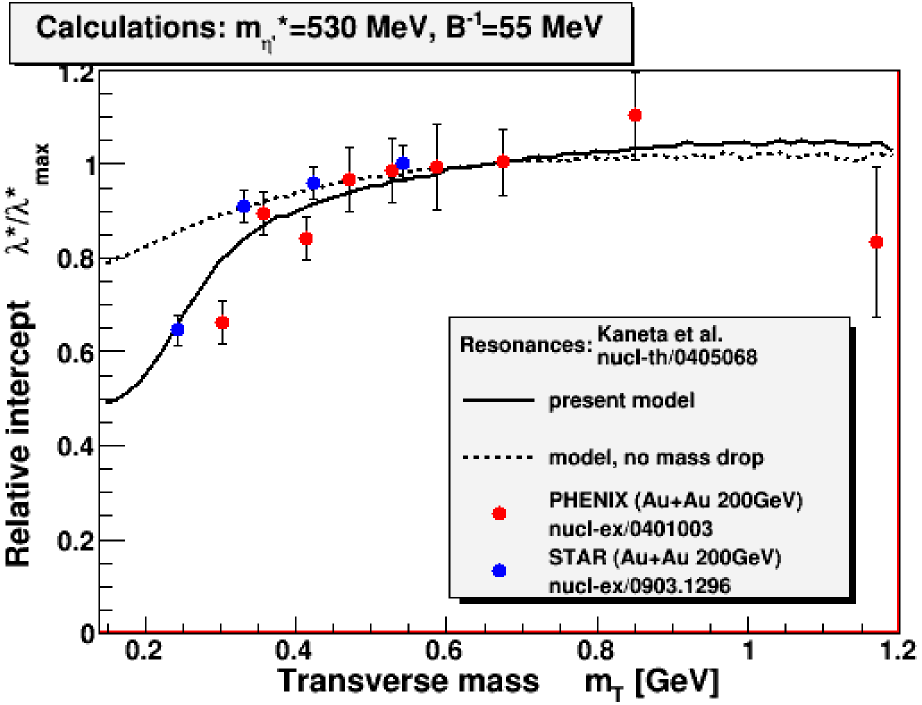
Signal of partial U(A)(1) symmetry restoration from two pion Bose-Einstein correlations
T. Csörgő, D. Kharzeev, S.E. Vance, hep-ph/9910436

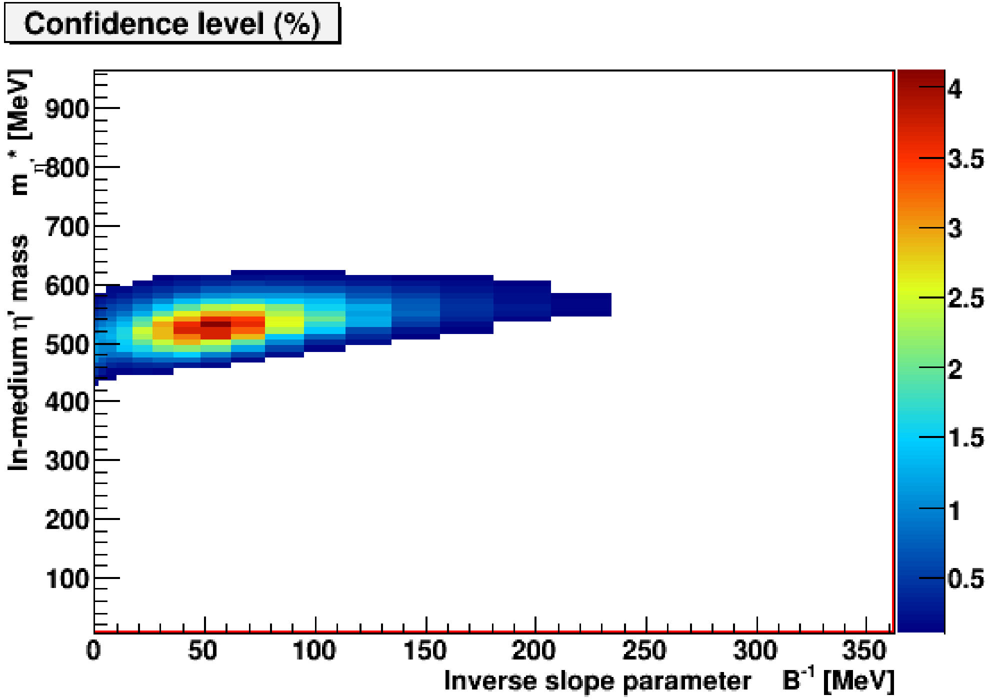
RHIC data

- Properties
  - Central Au+Au $s_{NN}^{1/2}$ = 200 GeV
  - Mid-rapidity $|\eta|<0.1$
  - $\pi^+\pi^+$ correlation measurements
  - $\lambda^*(m_T)/\lambda^*_{max}$ (different methods)
- Data used in the analysis
  - **PHENIX** Sinyukov 50%
  - **STAR** Edgeworth expansion (6th order, only even)
- Shown for comparison purposes
  - PHENIX preliminary
  - STAR Gauss



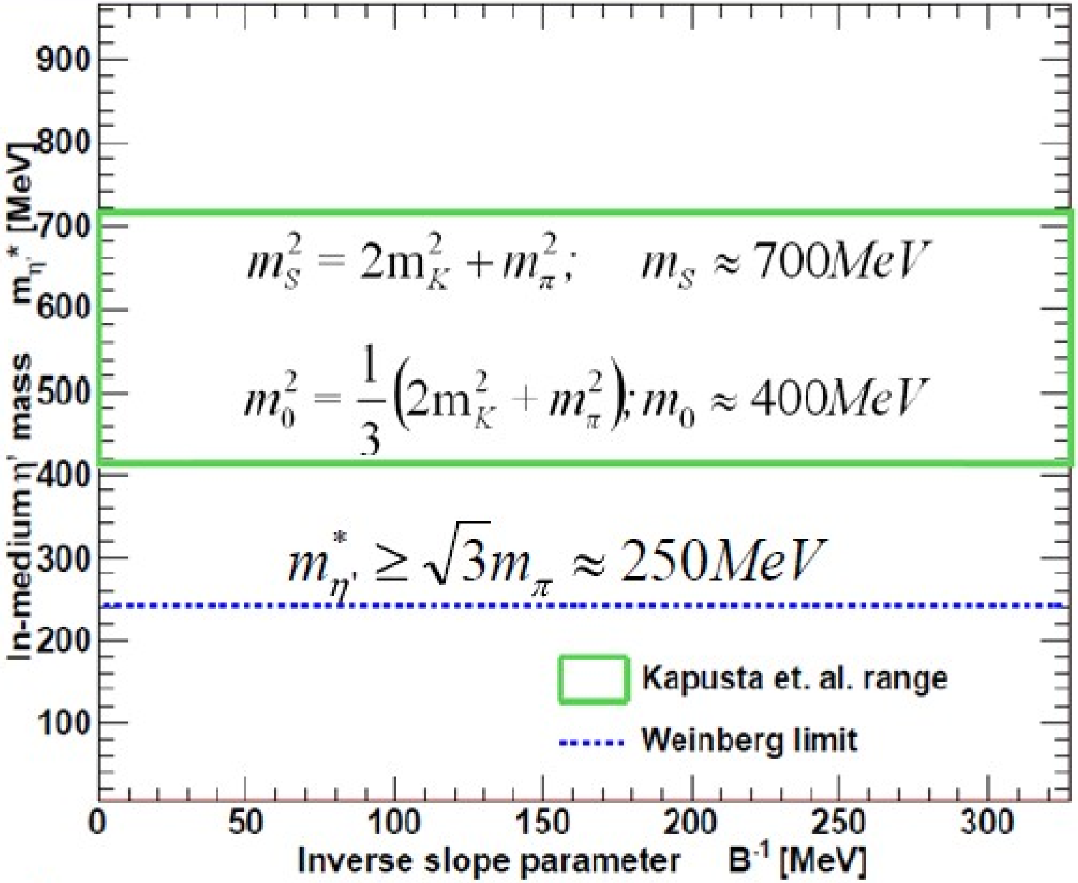
Finding the most likely mass





- Simulations all over the (B^{-1}, m^*) plain
  - Here: Resonance ratios of **Kaneta & Xu**, **arXiv:nucl-th/0405068**
- Mapping the confidence level
- Choose best $\lambda^*(m_T)/\lambda^*_{max}$ fit
  - By this model: $m_{\eta'}{}^*=530$ MeV

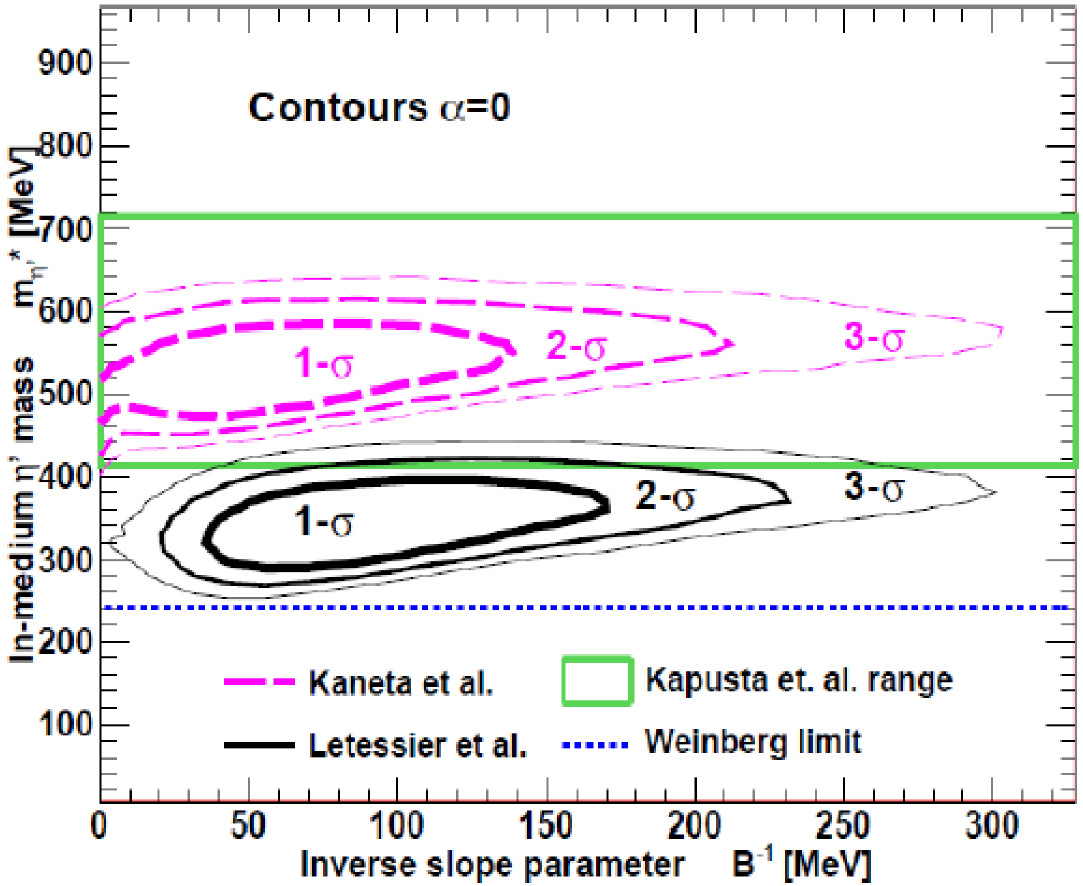
Limits for the η’ mass



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

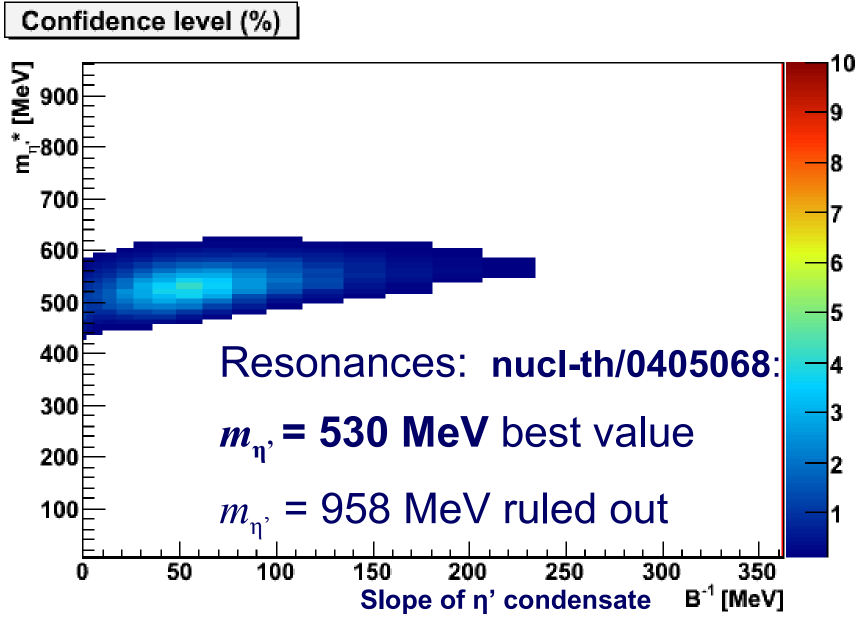
  Upper bound: S,NS isosinglet eigenstates; Lower bound: Gell-Mann – Okubo
- **Lower limit**: S. Weinberg, Phys. Rev. D 11, 3583 (1975).

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

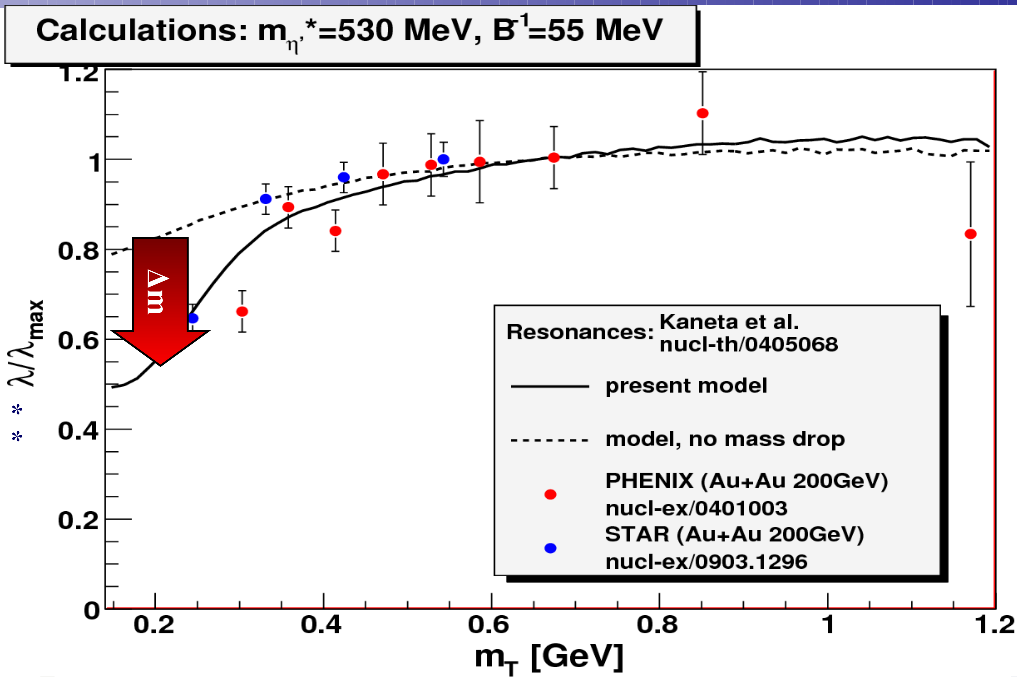
Results

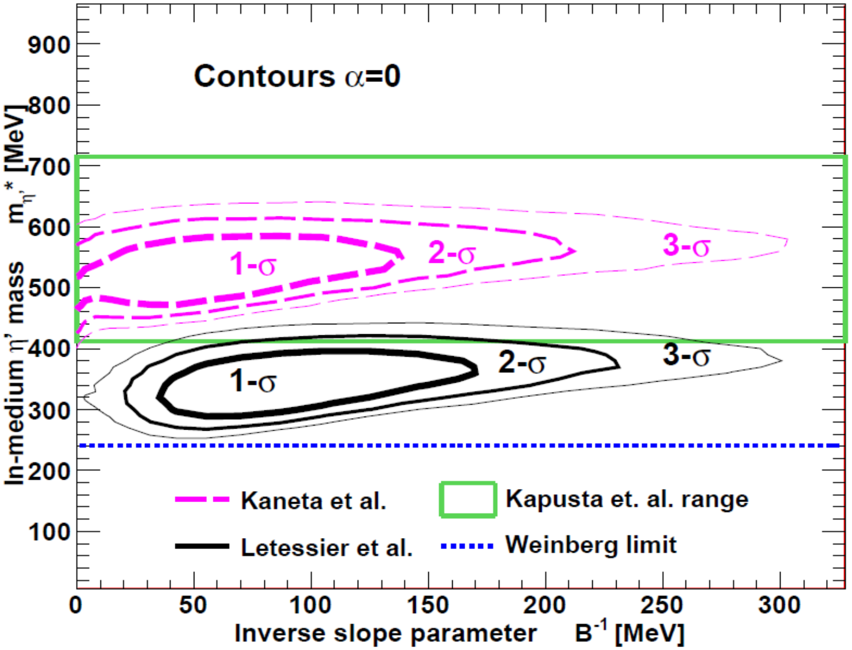


Resonances: **nucl-th/0405068:**

***$m_{\eta'}$* = 530 MeV** best value

$m_{\eta'}$ = 958 MeV ruled out





Resonance model	$m^*_{\eta'}$ (MeV)	χ^2 (CL %) ndf=11	$f_{\eta'}$	f_η	5-σ limit $m^*_{\eta'}$ (MeV)
ALCOR [17]	490^{+60}_{-50}	20.2 (4.29)	43.4	5.25	$\leq$ 700
Kaneta [18]	530^{+50}_{-50}	22.8 (4.12)	25.6	3.48	$\leq$ 730
Letessier [19]	340^{+50}_{-60}	18.9 (6.35)	67.6	4.75	$\leq$ 570
Stachel [20]	340^{+50}_{-60}	18.8 (6.38)	67.6	4.97	$\leq$ 570
UrQMD [16]	400^{+50}_{-40}	19.0 (6.14)	45.0	7.49	$\leq$ 660

Systematics

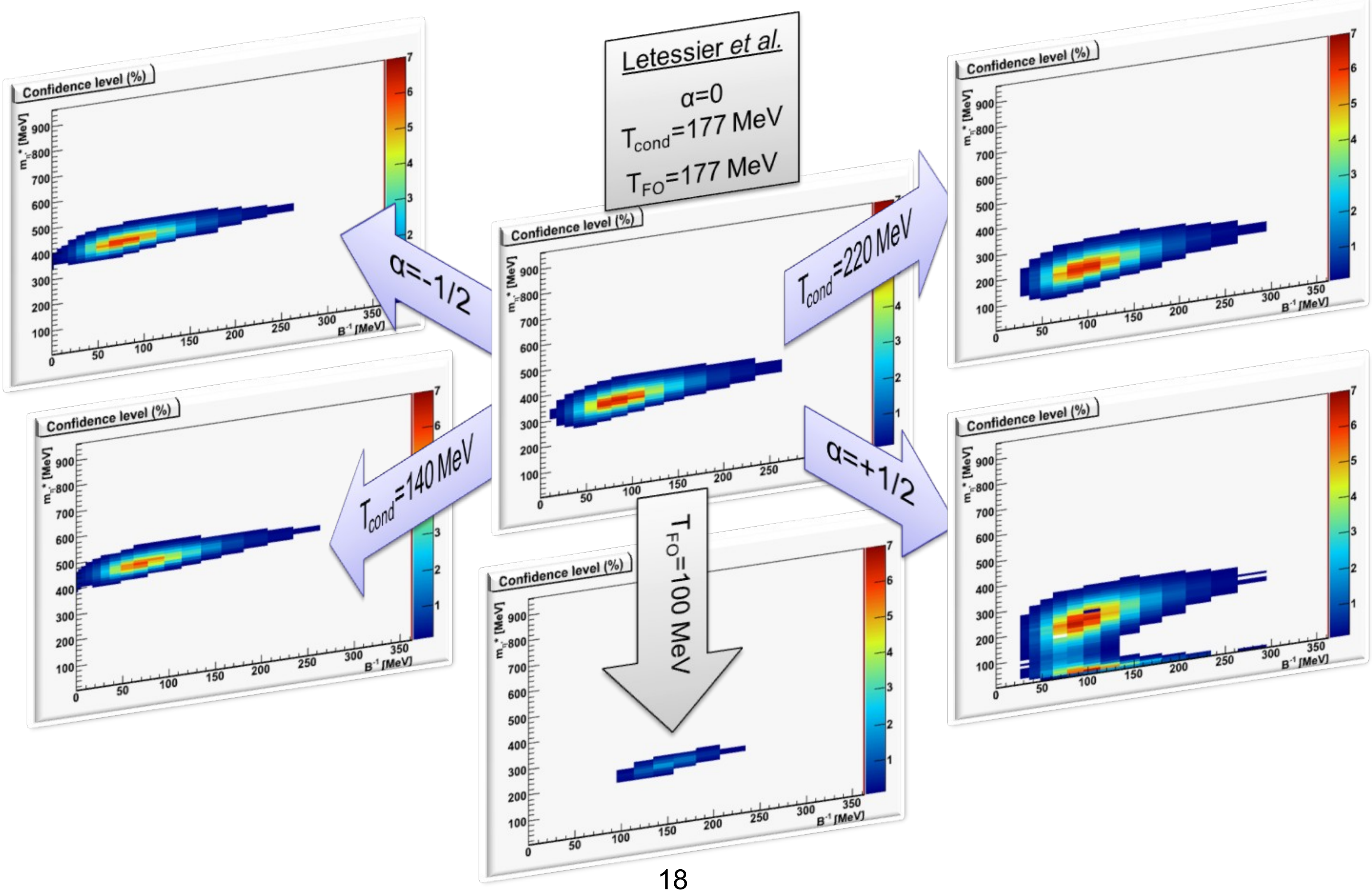
- Largest uncertainity: models for resonance ratios

- Modifying parameters in the widest reasonable range
  - $-1/2 \leq \alpha \leq +1/2$ (1)
  - $140\text{ MeV} \leq T_{cond} \leq 220\text{ MeV}$
  - $100\text{ MeV} \leq T_{FO} \leq 177\text{ MeV}$

  (altogether 17 x 1248 x 1000000 events simulated)

- An upper boundary can be determined for the η' mass: Each and every setup fails when $m^*_{\eta'} > 750\text{ MeV}$ (failure means CL<0.1%)

Systematics – a Visual Summary



Letessier *et al.*

α=0

T_{cond}=177 MeV

T_{FO}=177 MeV

α=-1/2

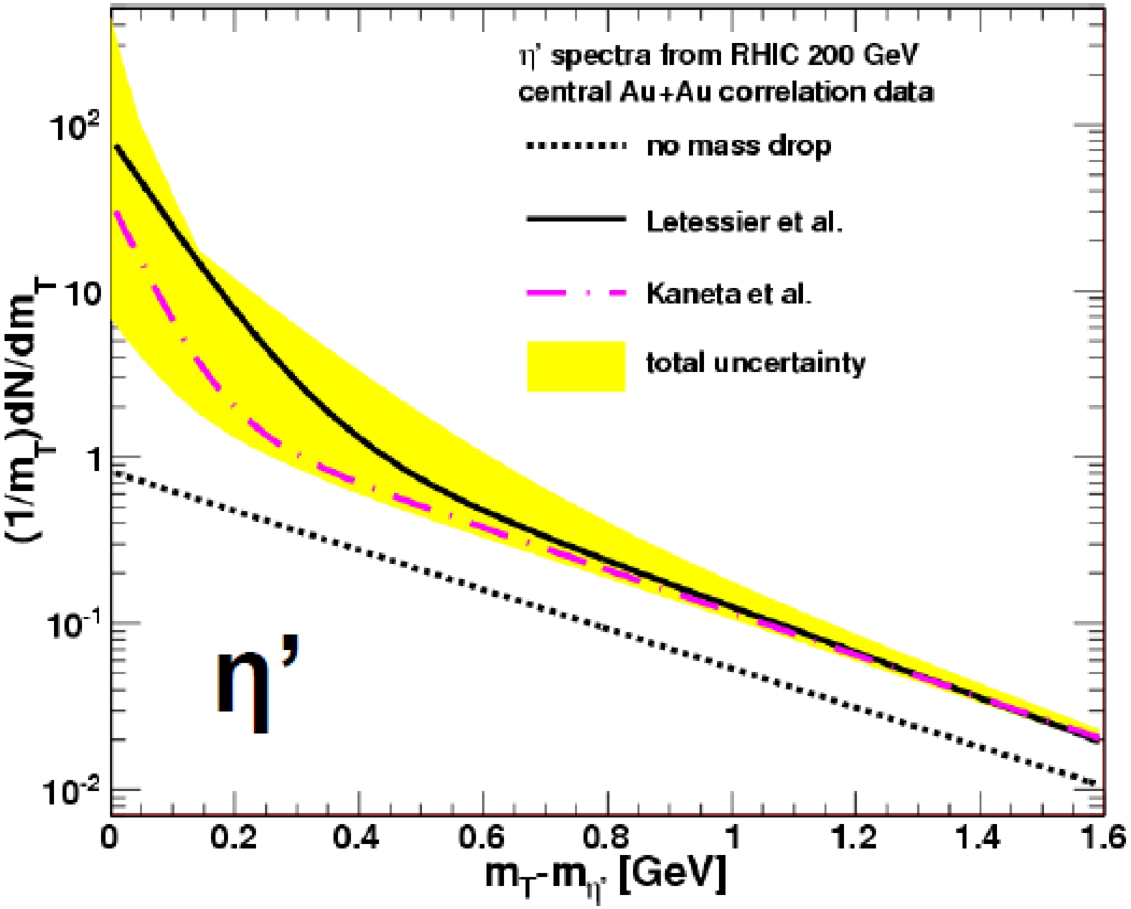
T_{cond}=220 MeV

T_{cond}=140 MeV

α=+1/2

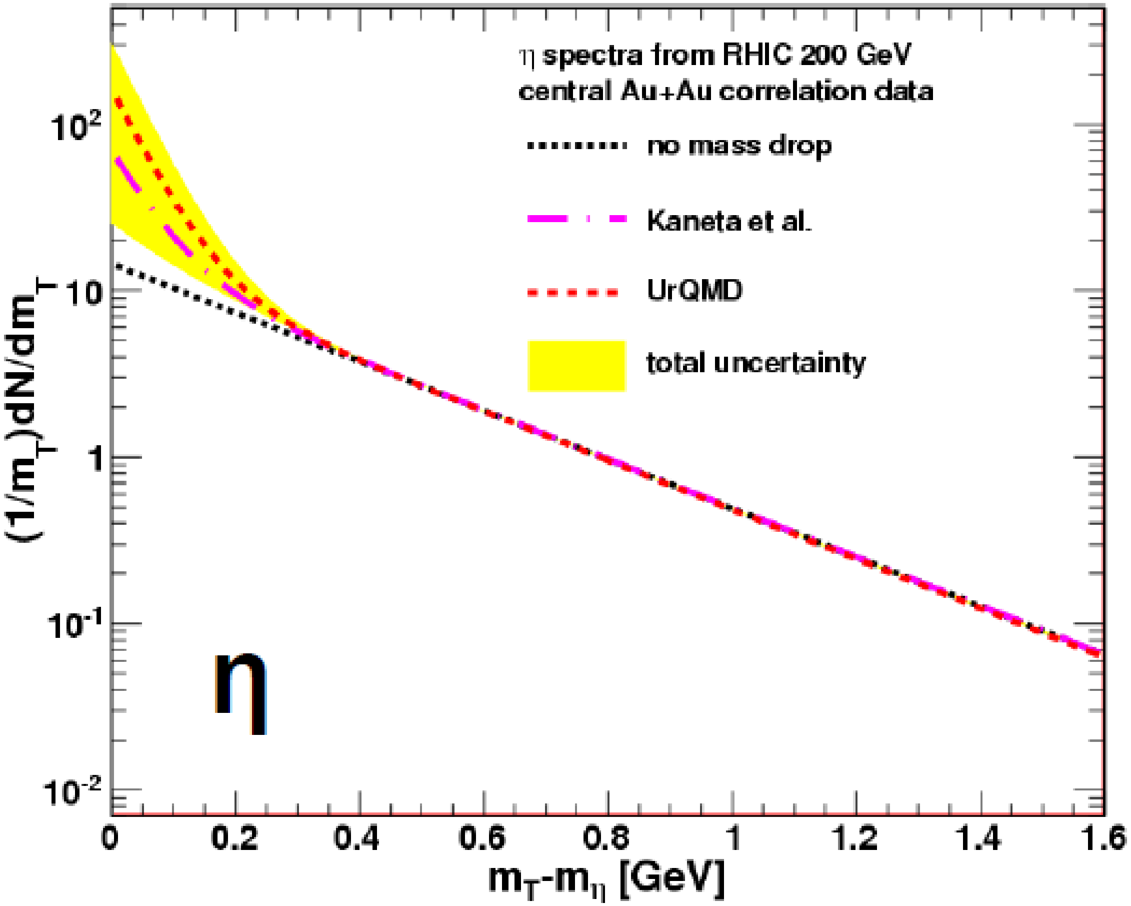
T_{FO}=100 MeV

Output: η' spectrum



- **An enhancement factor of 25 to 68** depending on model
- Enhancement **breaks** m_T –scaling at low-p_T
- **Possible explanation of the dilepton excess ➔ needs check!**

Output: η spectrum



- **An enhancement factor of 5.2 to 7.5** depending on model
- Enhancement at low-p_T ←→ Fits measured data at high-p_T
- **Possible explanation of the dilepton excess → needs check!**

Dilepton Excess in CERES

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

VOLUME 75, NUMBER 7 PHYSICAL REV

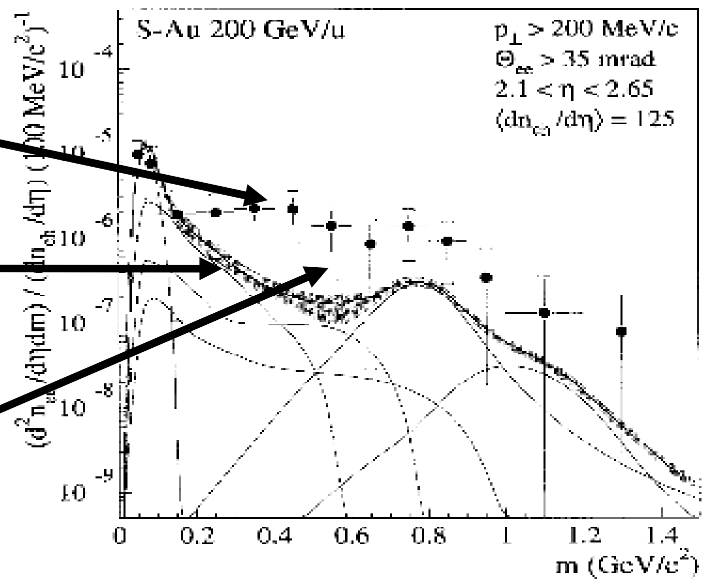
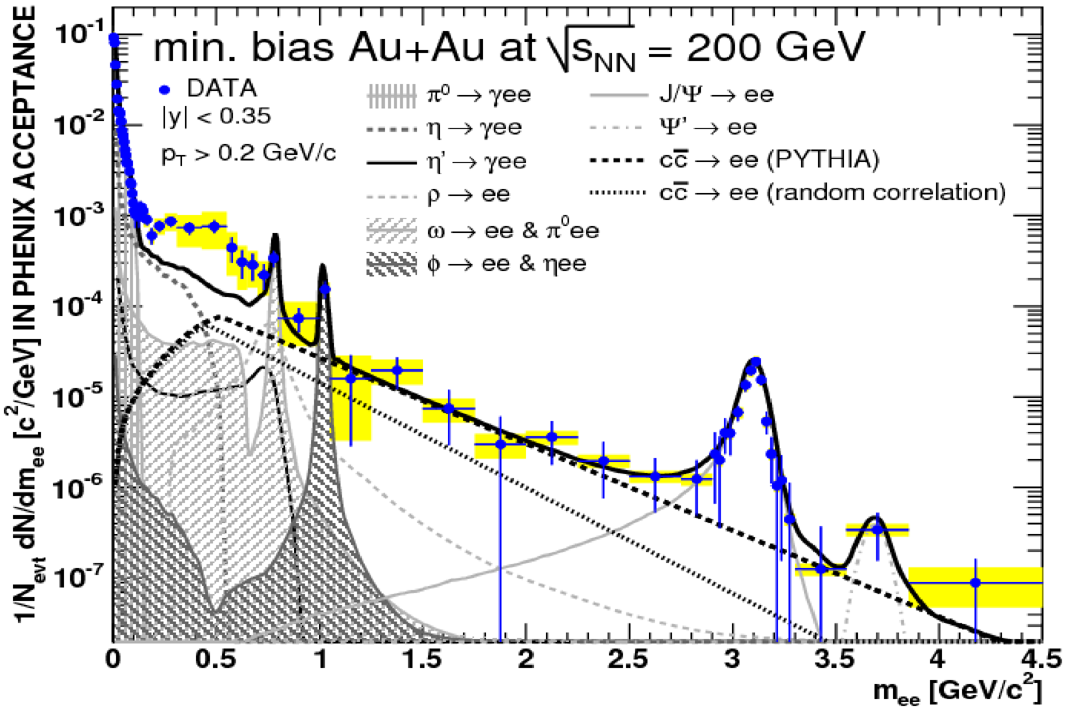


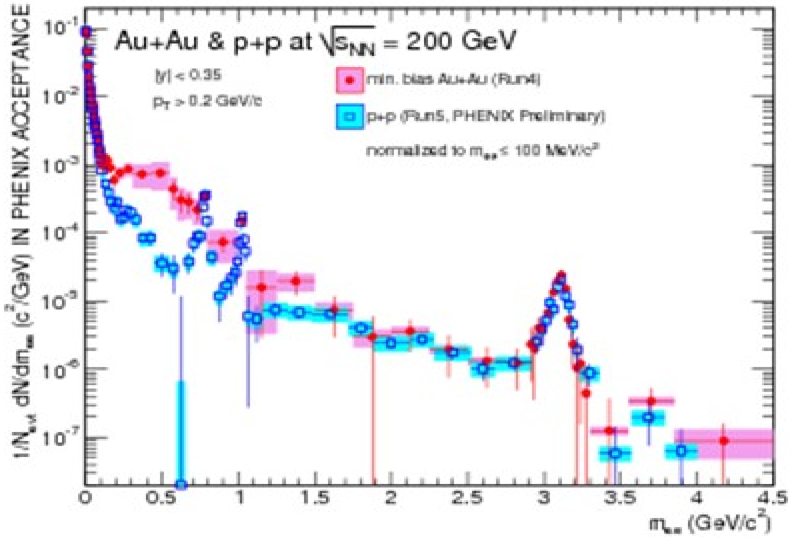
FIG. 4. Inclusive e^+e^- mass spectra in 200 GeV/nucleon S-Au collisions. For explanations see Fig. 2.

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

Dilepton Excess in PHENIX





A. Adare *et al.* (PHENIX cn.)
Phys.Lett.B670:313-320,2009.

S. Afanasiev *et al.* (PHENIX cn.)
e-Print: arXiv:0706.3034

- Au+Au invariant e+ e- pair yield

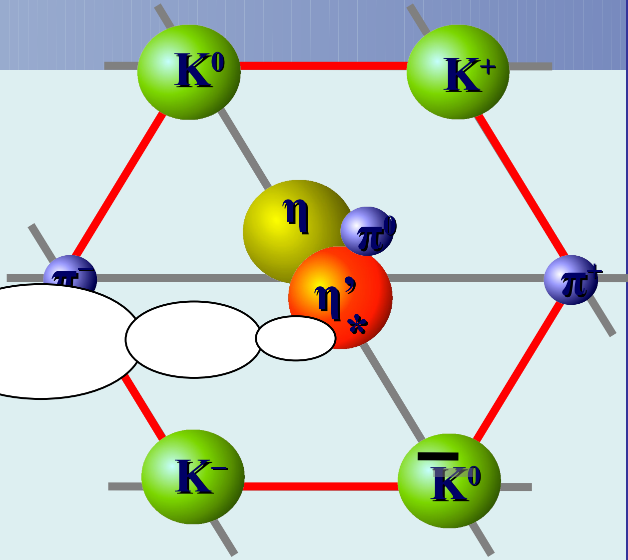
- Significant excess in PHENIX 200 GeV Au+Au measurements
- Not present in p+p data – in accordance with hadronic models
- Excess must be an effect of the hot, dense medium

Conclusion

$m^*_{\eta'} < m_{\eta'} - 200$ MeV

at the 99.9% confidence level

from PHENIX+STAR $\pi^+\pi^+$ correlation data + 6 models



- **A 5.4 σ effect, indirect observation**
- **Cross-check with direct γ + dilepton spectrum needed**
- **More λ^* data at low p_T is needed to reduce systematics**
- **Revitalize interest in chiral symmetry restoration**

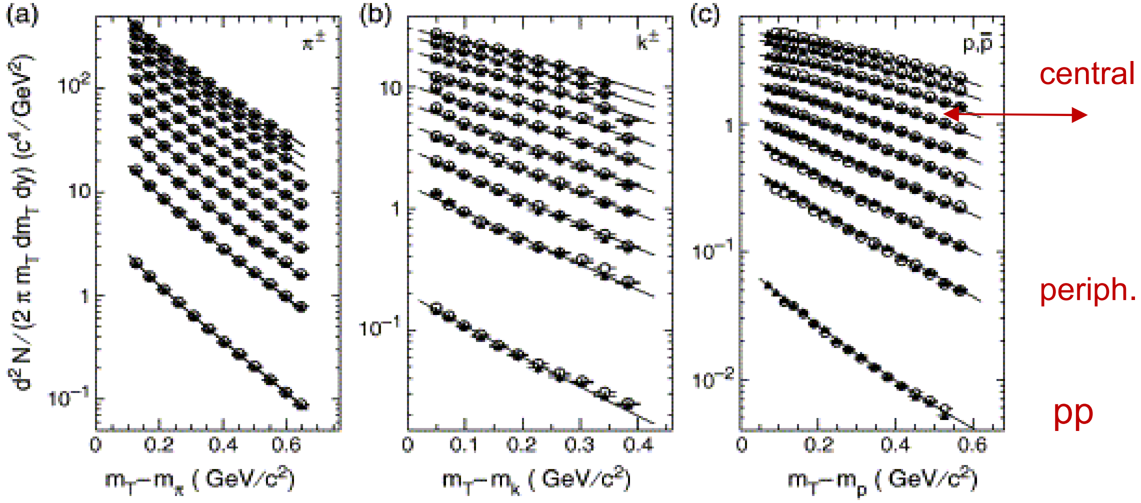
The End

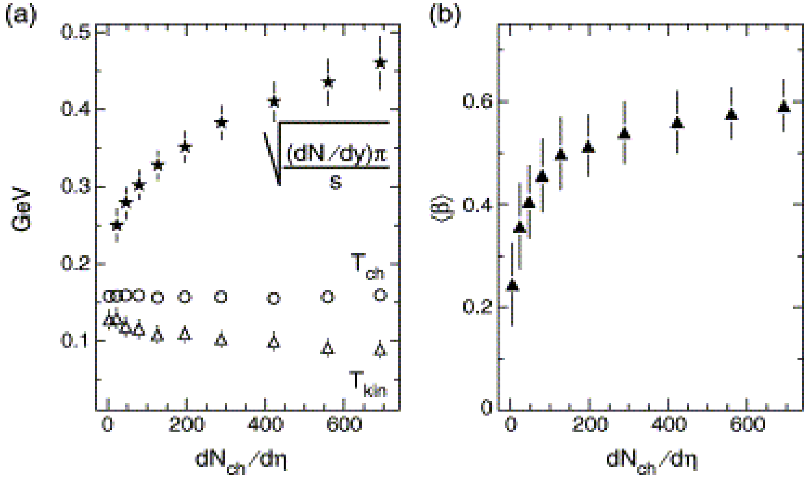
Thank You

for your attention

backup slides follow…

m_T-scaling

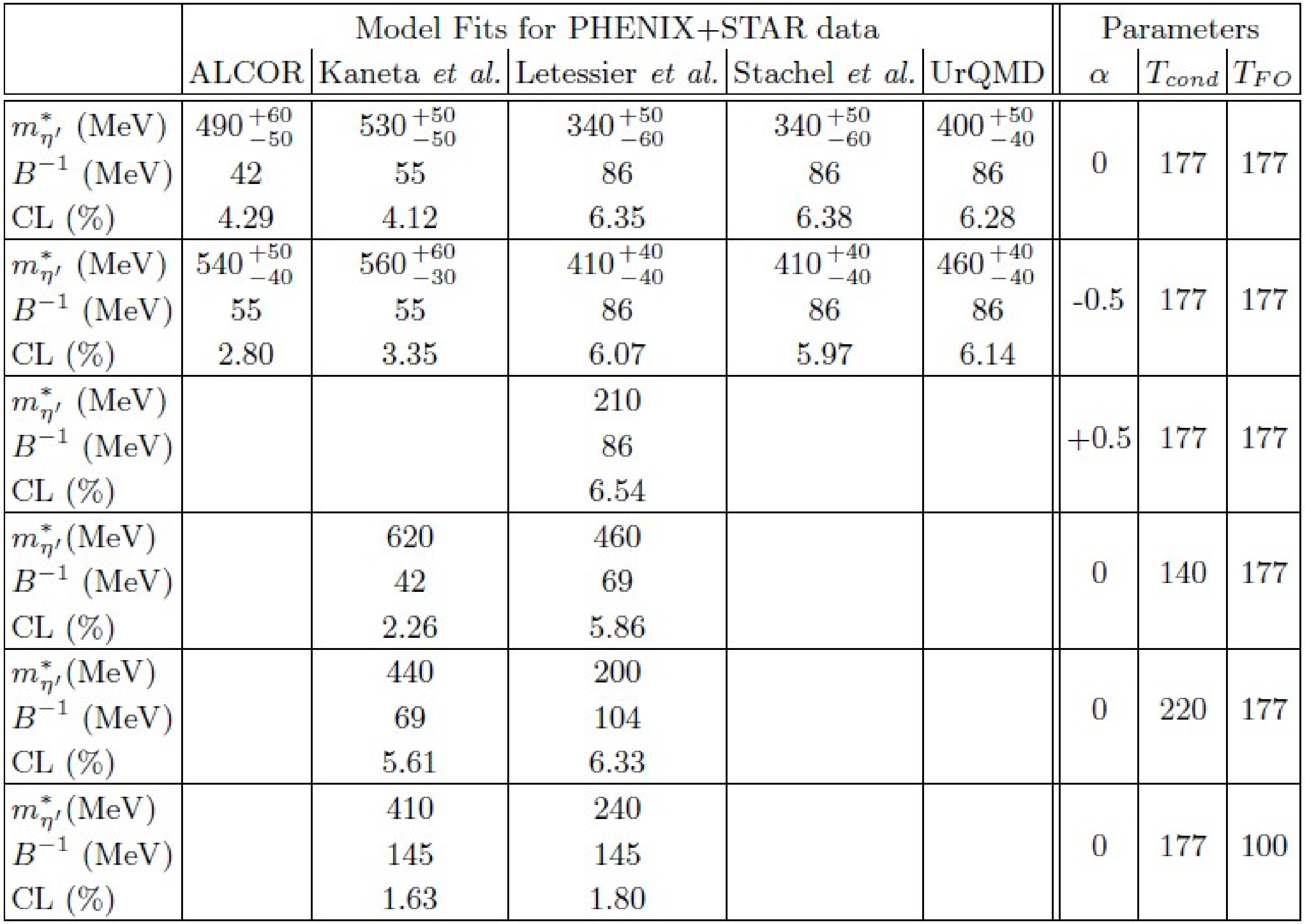




$$\frac{dN}{dp_t^2} \sim \exp\left(-\frac{m_t}{T}\right), \qquad m_t^2 = p_t^2 + m^2$$

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

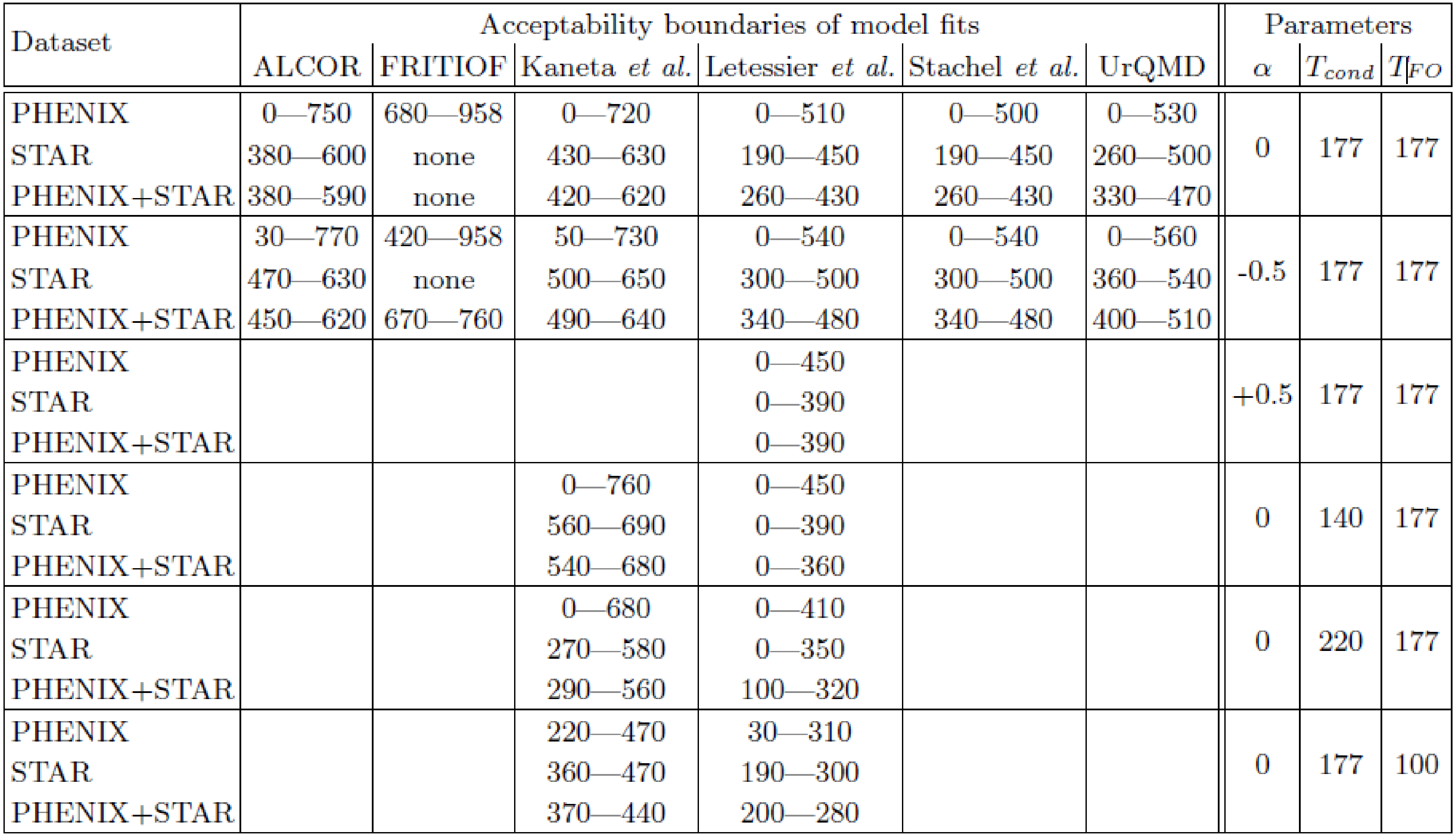
η' mass: Fitted values



	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.

Dilepton excess in details

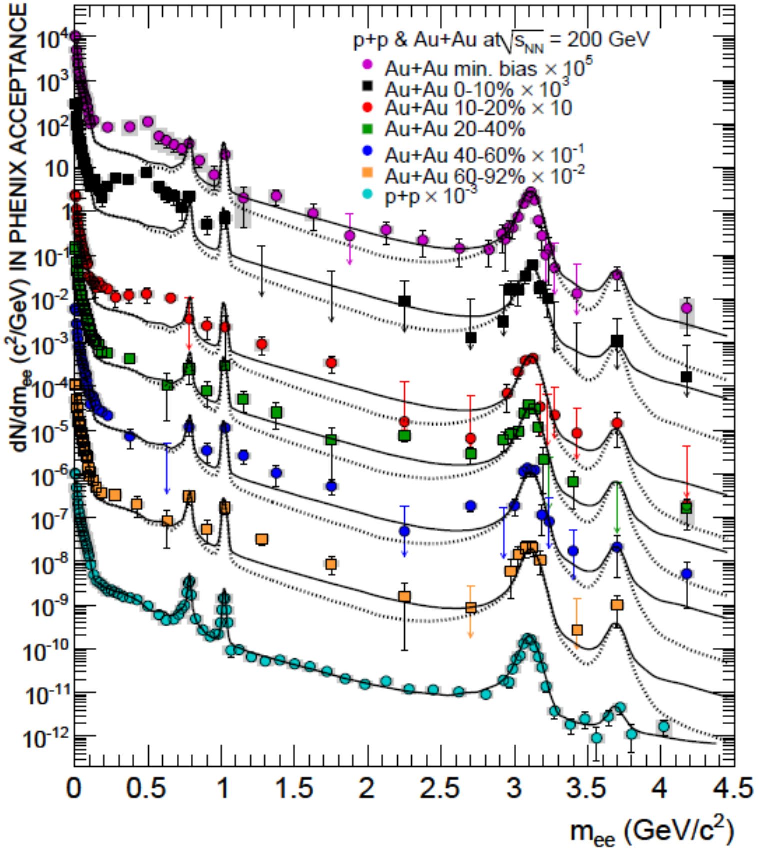


Fig.26: Invariant mass spectrum of e+e- pairs compared to expectations from the model of hadron decays for p+p and for different Au+Au centrality classes.

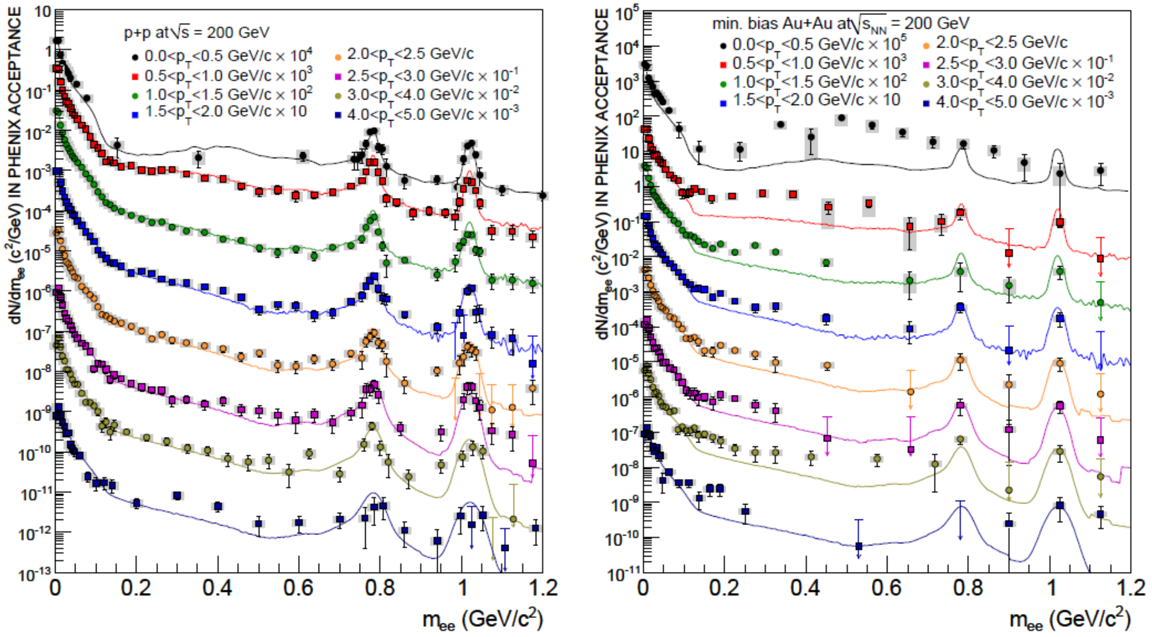
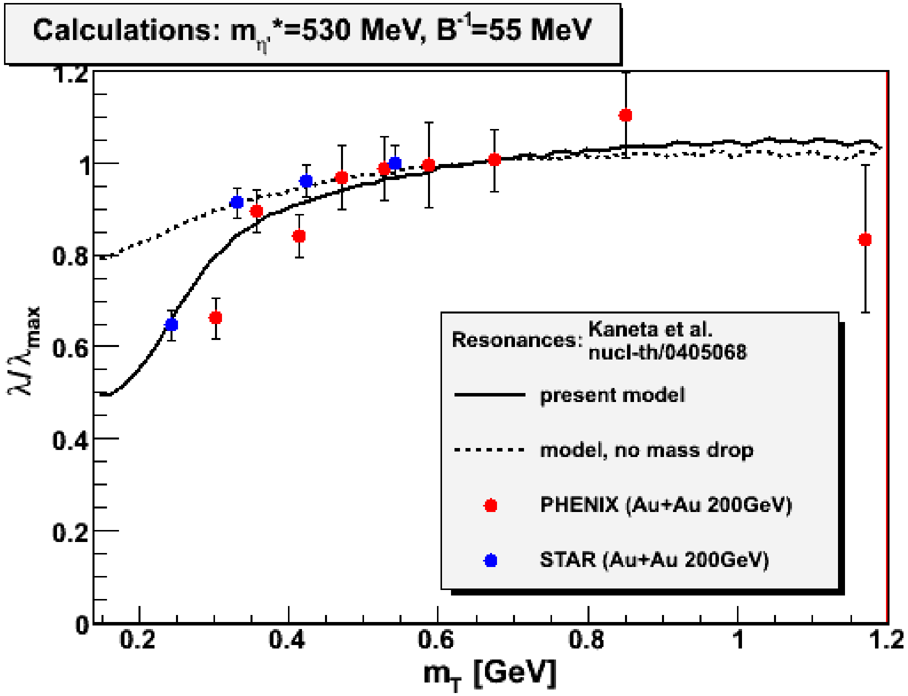
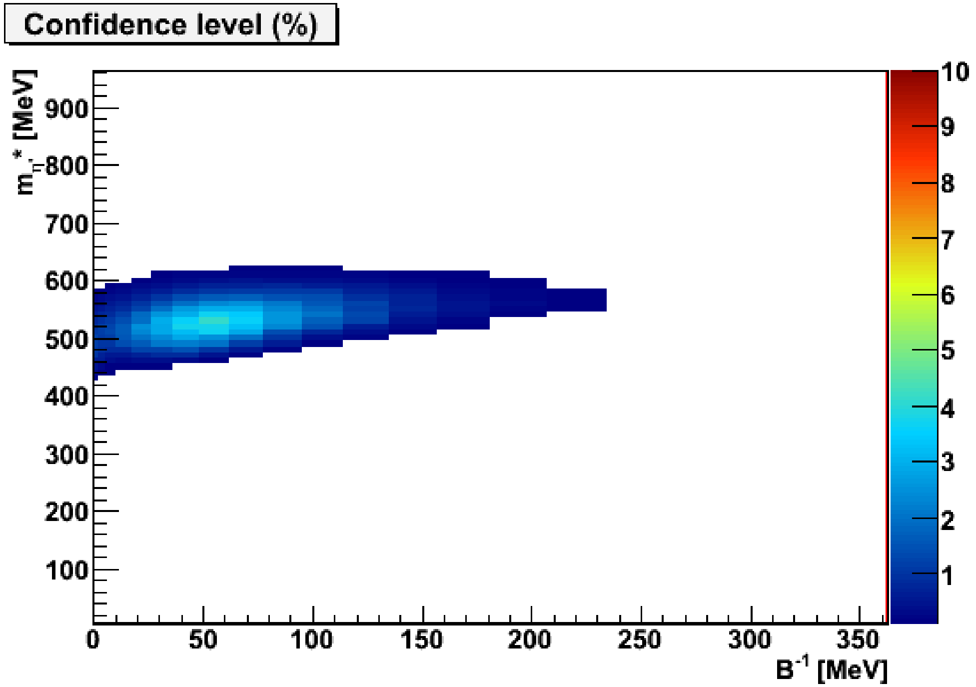


Fig.29: e+e- pair invariant mass distributions in p + p (left) and minimum bias Au+Au collisions (right). The pT ranges are shown in the legend.

Resonances: Kaneta-Xu vs. RHIC

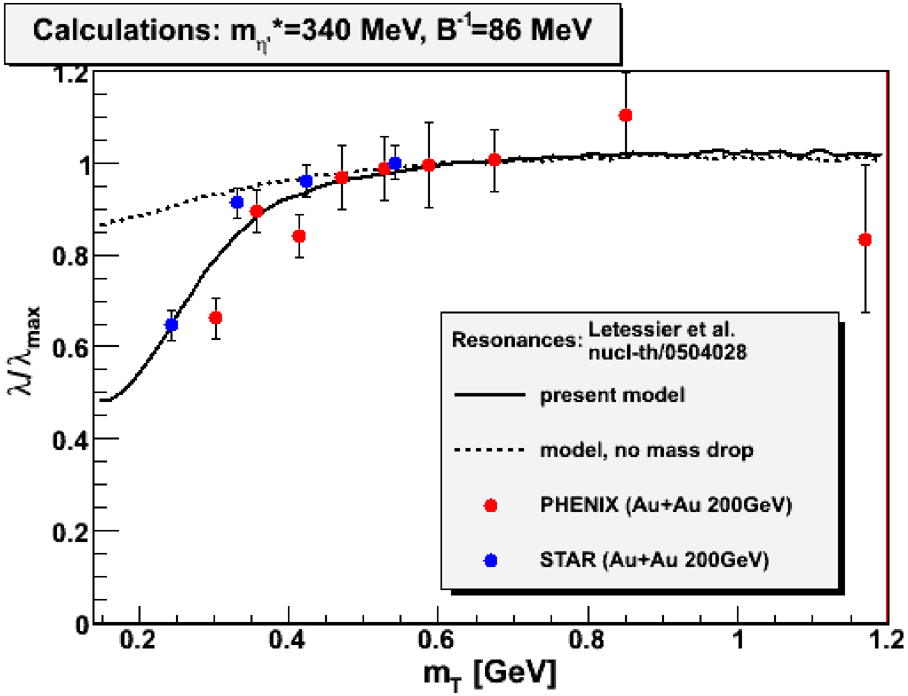


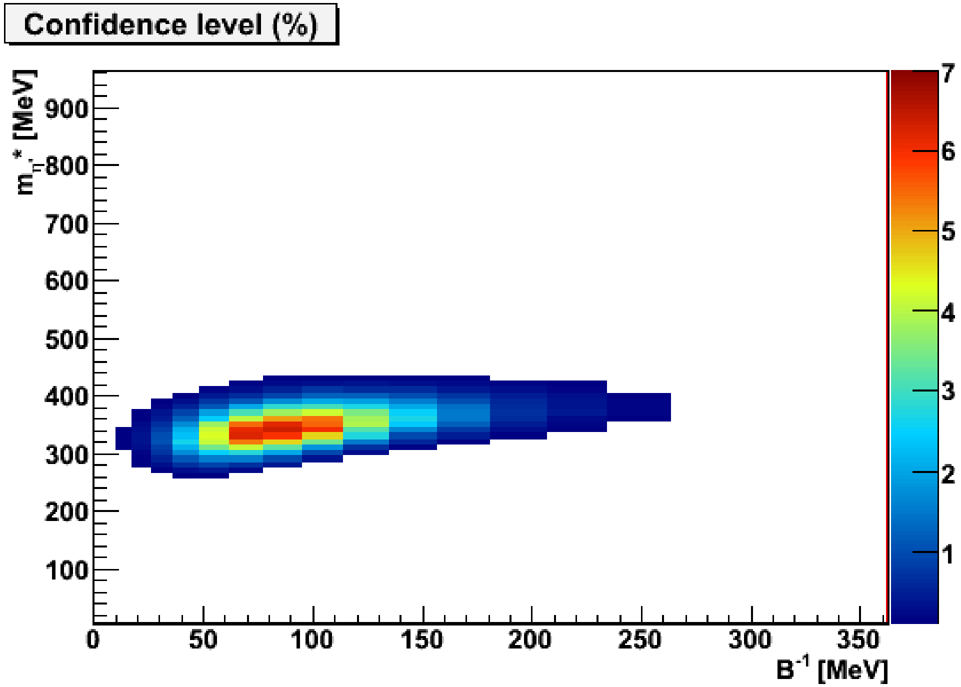


- Statistical chemical freezeout model
- Central mid-η 200 GeV Au+Au
- Describes PHENIX hadron spektrum well

Kaneta & Xu, arXiv:nucl-th/0405068

Resonances: Letessier-Rafelski vs. RHIC

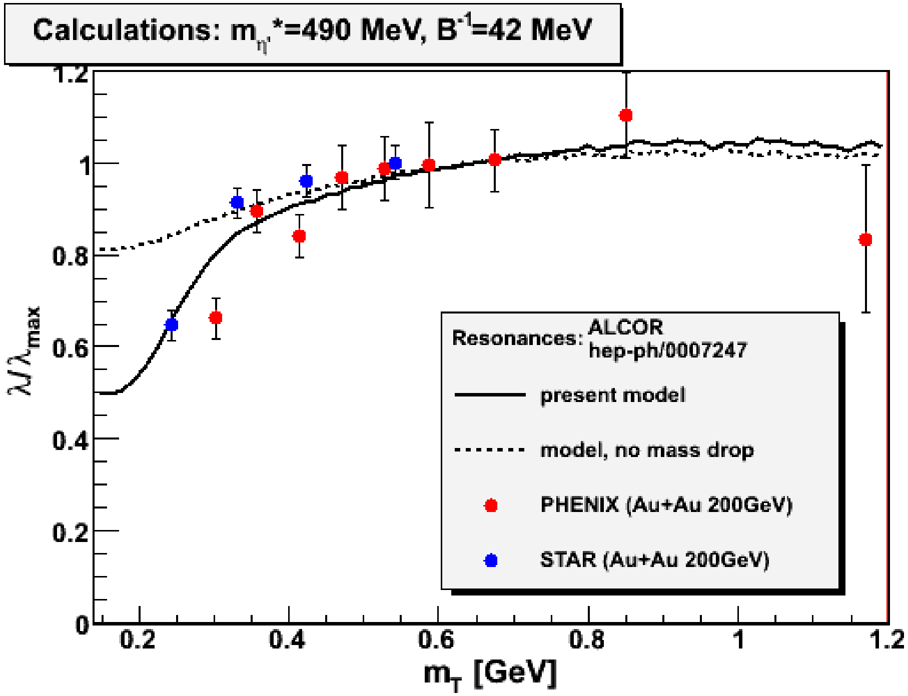


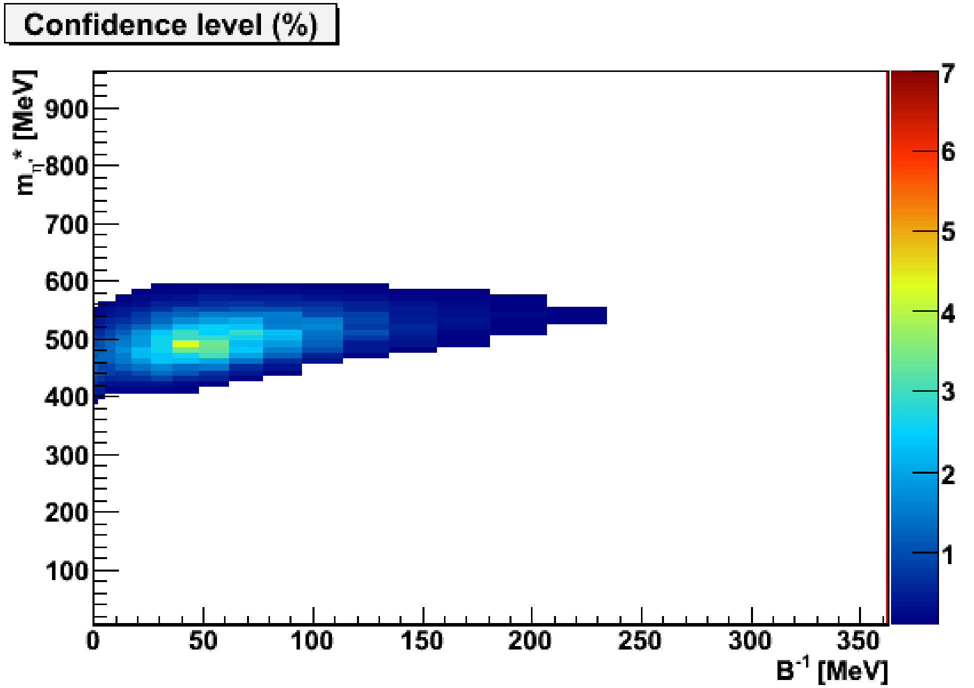


- Statistical chemical freezeout model
- Central mid-η 200 GeV Au+Au

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

Resonances: ALCOR vs. RHIC

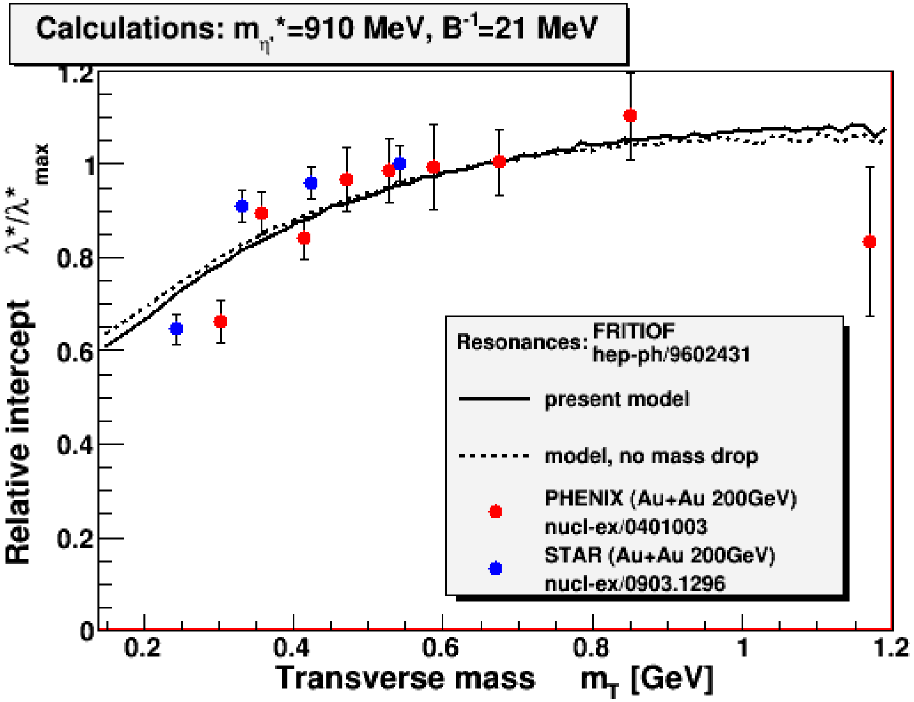




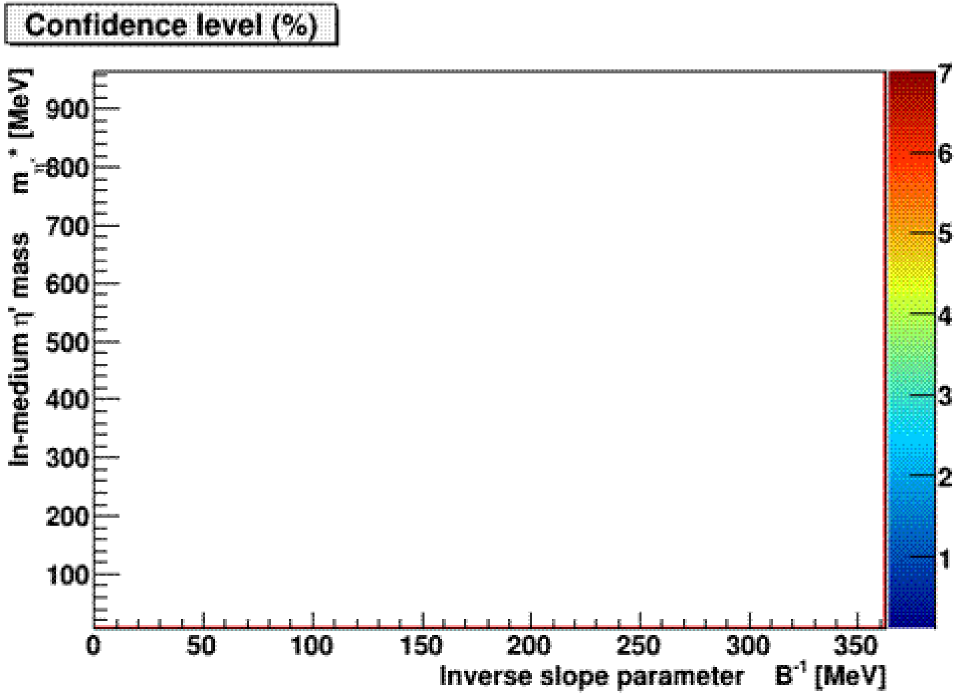
- Coalescence-model
- η'/ η ratio has to be fixed from other models
  (Kaneta, here)

P. Lévai, T.S. Biró, T. Csörgő, J. Zimányi, hep-ph/0007247

Resonances: FRITIOF vs. RHIC



Calculations: $m_{\eta'}^*$=910 MeV, B^{-1}=21 MeV

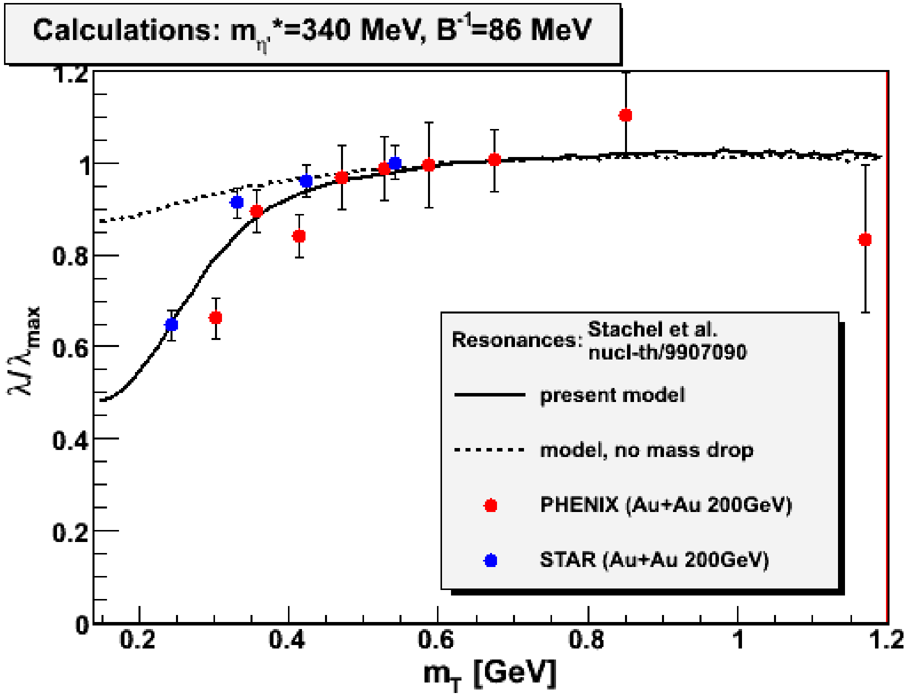


Confidence level (%)

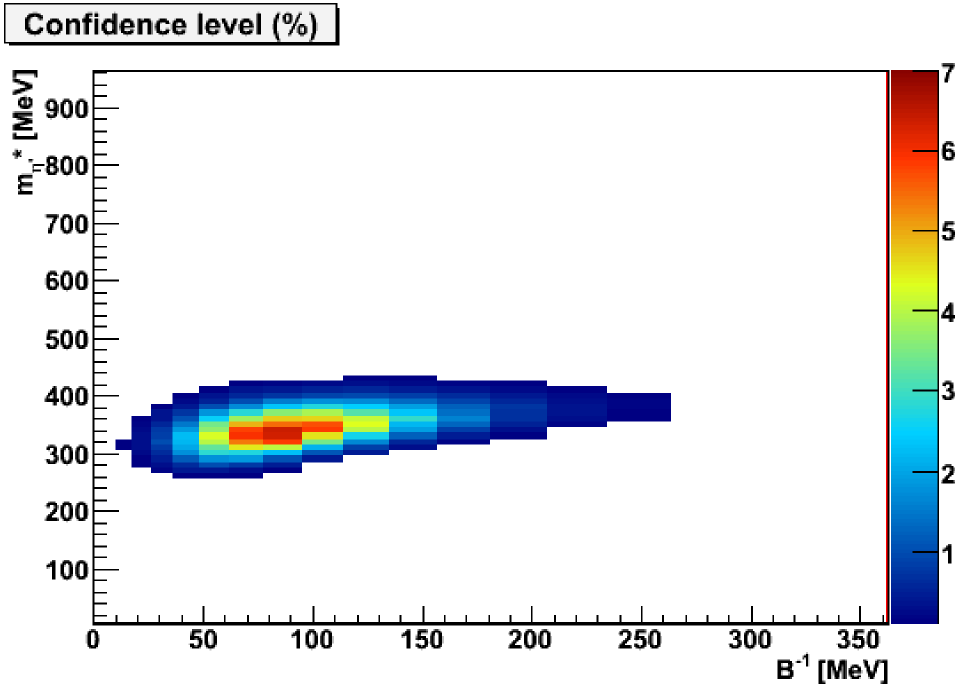
- 200 GeV mid-rapidity Au+Au simulation
- Note: Does not describe STAR data, neither the unified PHENIX+STAR dataset. For PHENIX data only, it is consistent with $m_{\eta'}$=958MeV.

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

Resonances: Stachel et al. vs. RHIC



Calculations: $m_{\eta'}^*$=340 MeV, B^{-1}=86 MeV

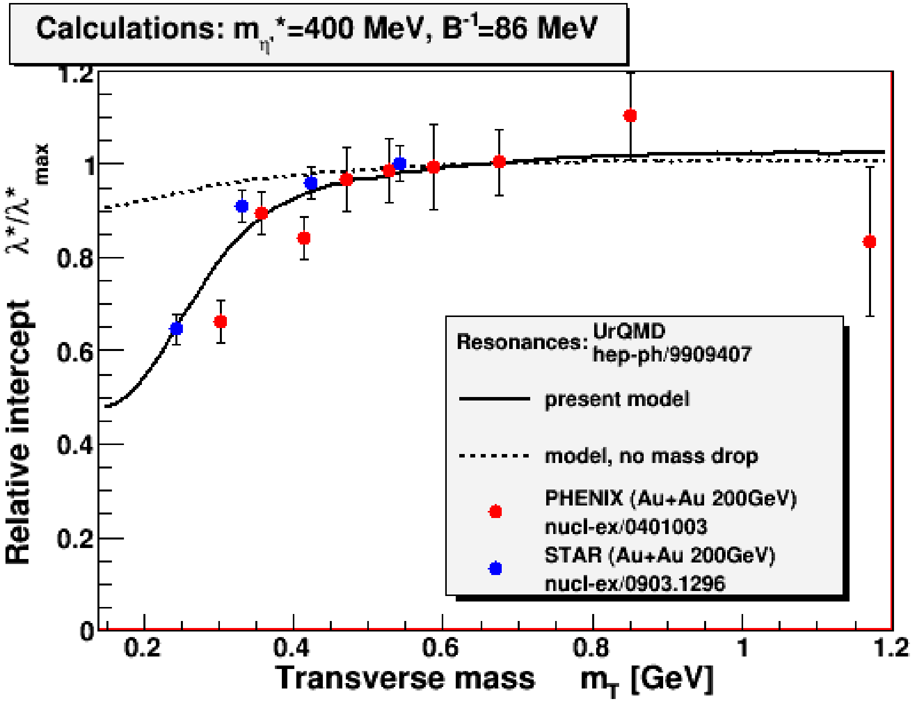


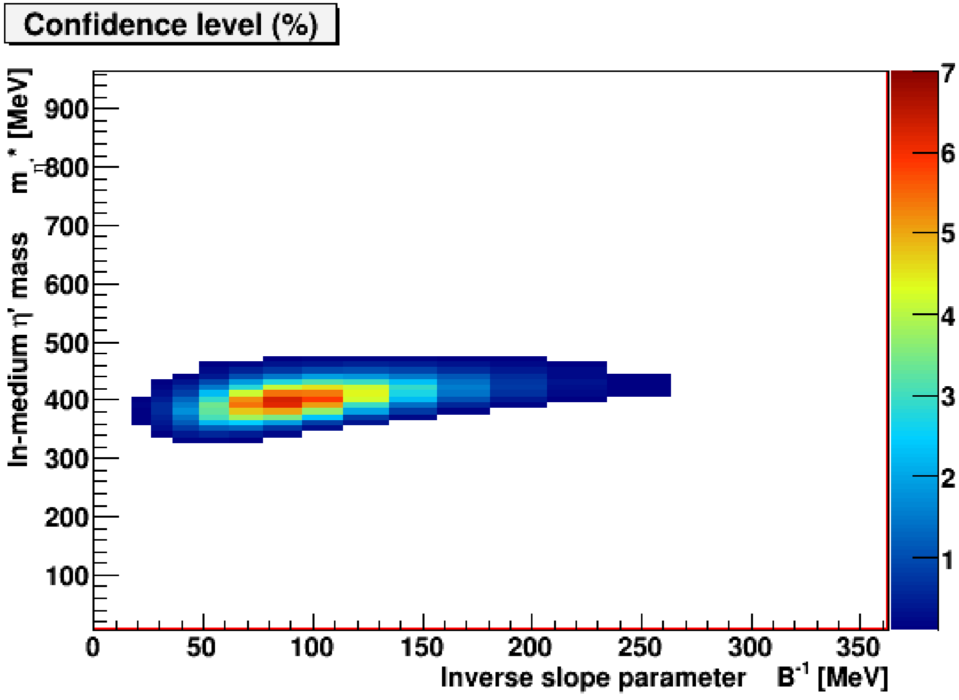
Confidence level (%)

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

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

Resonances: UrQMD vs. RHIC

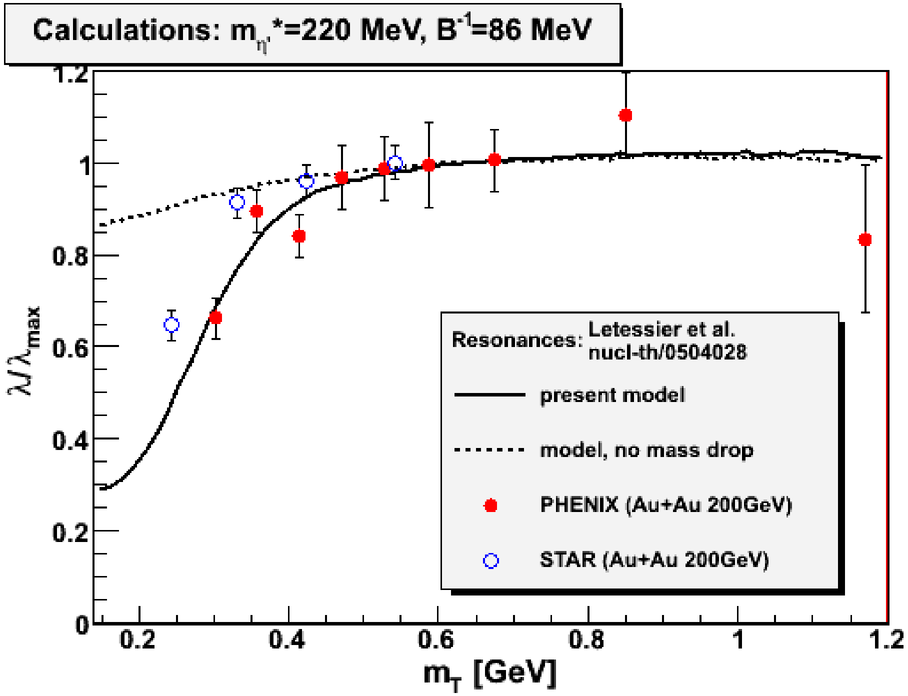


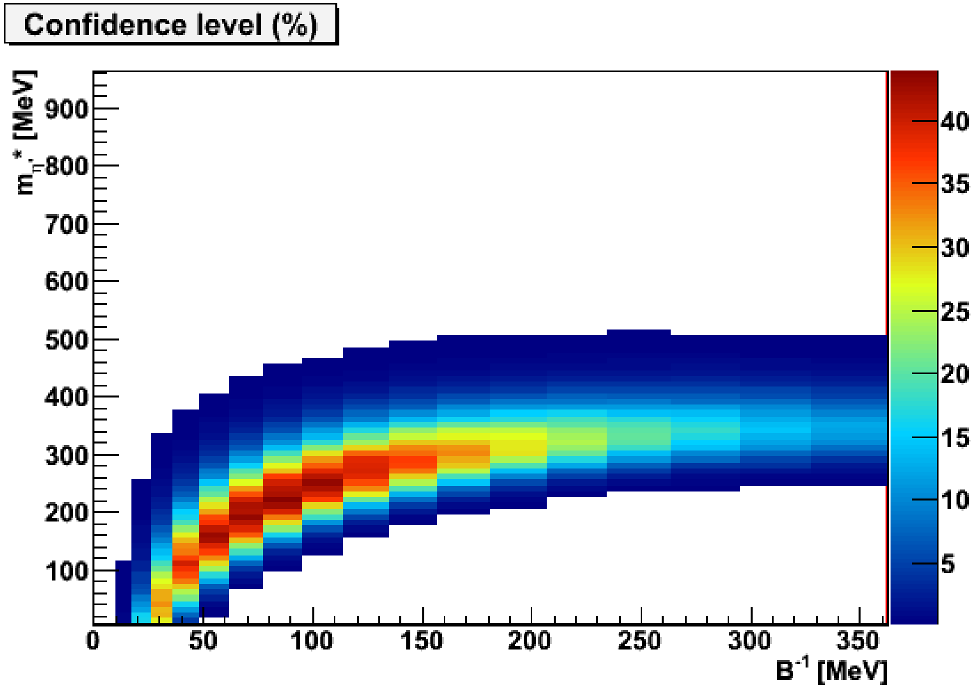


- 200 GeV midrapidity
- Au+Au, RHIC $\sqrt{s_{NN}}$ =200 GeV

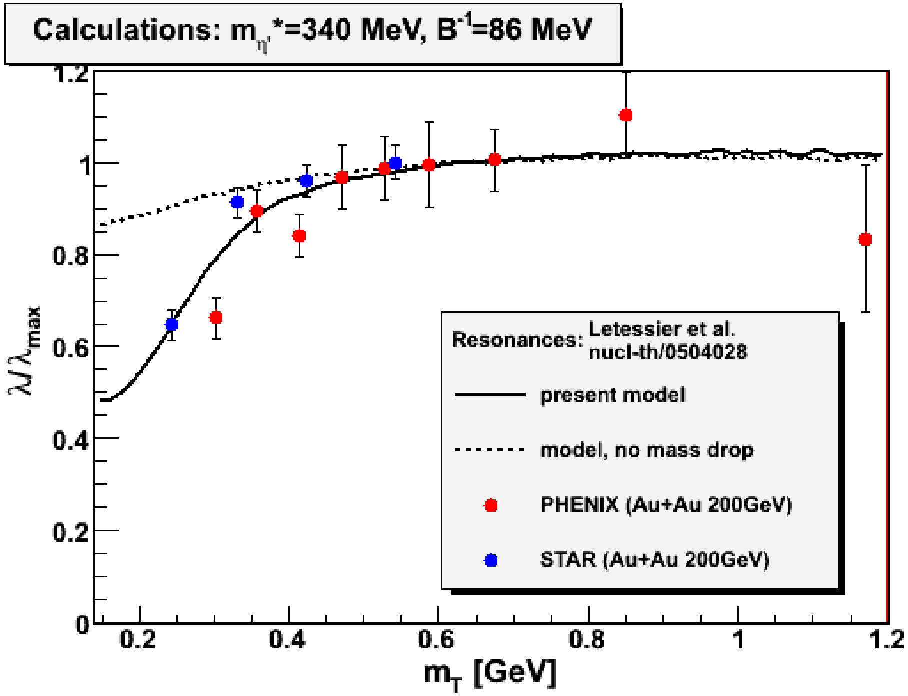
J. P. Sullivan et al., Phys. Rev. Lett. 70 (1993) 3000

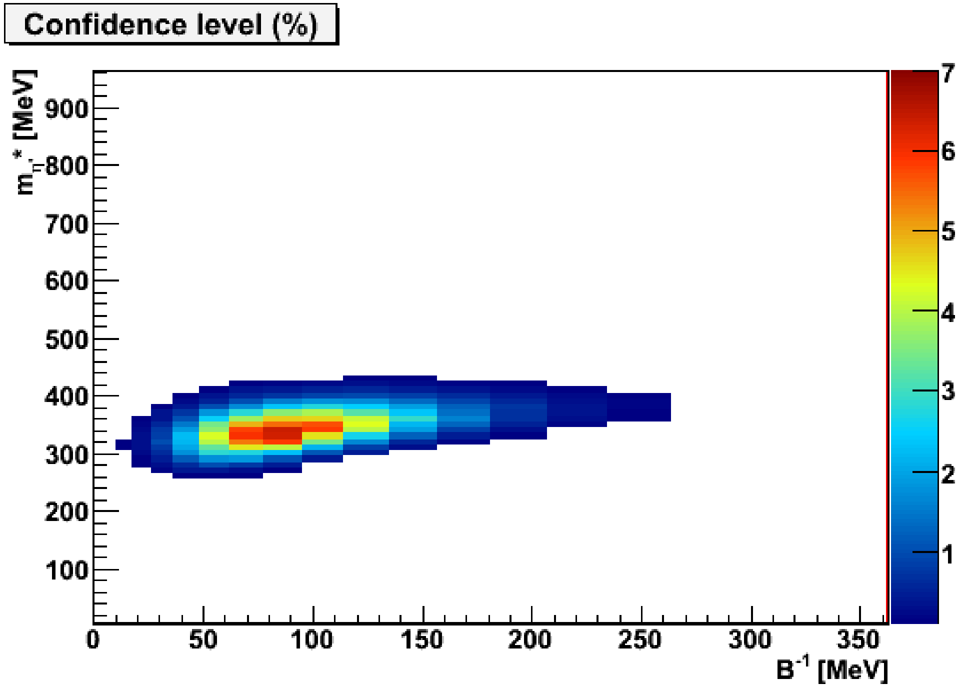
Rafelski vs. PHENIX



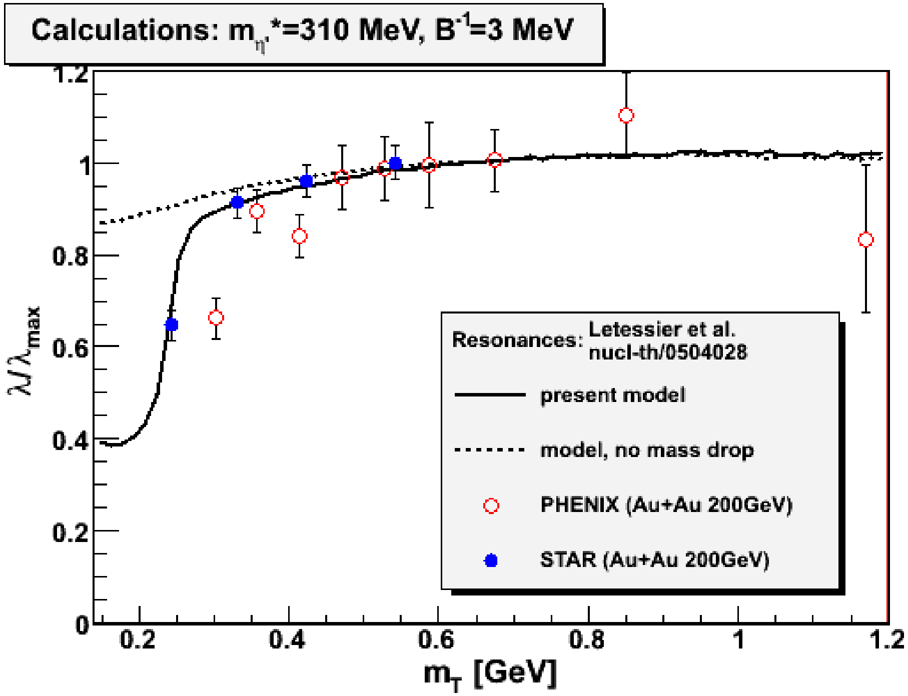


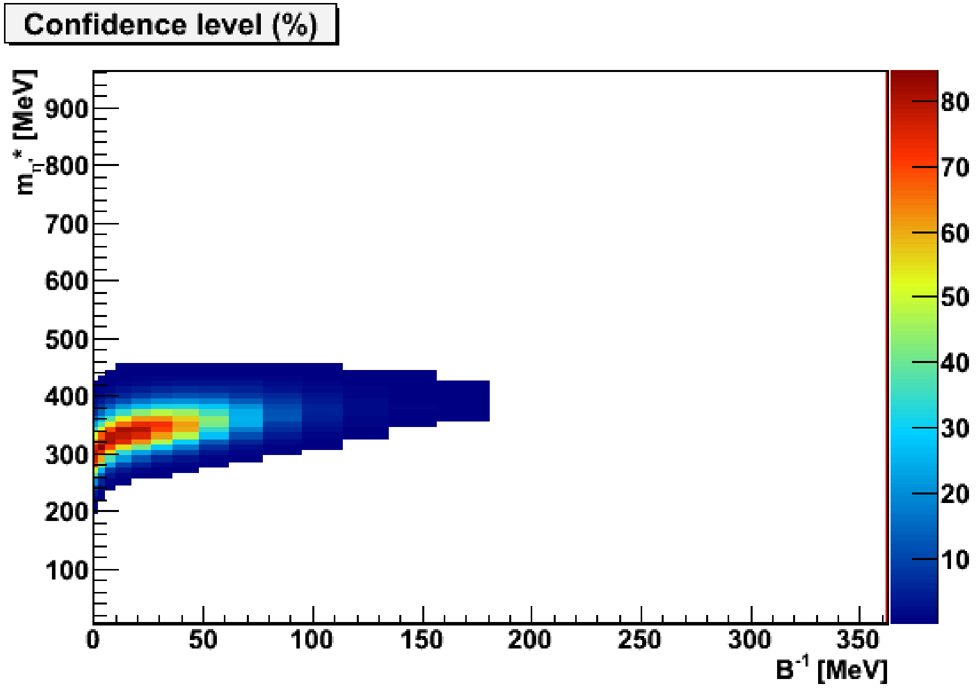
Rafelski vs. PHENIX & STAR



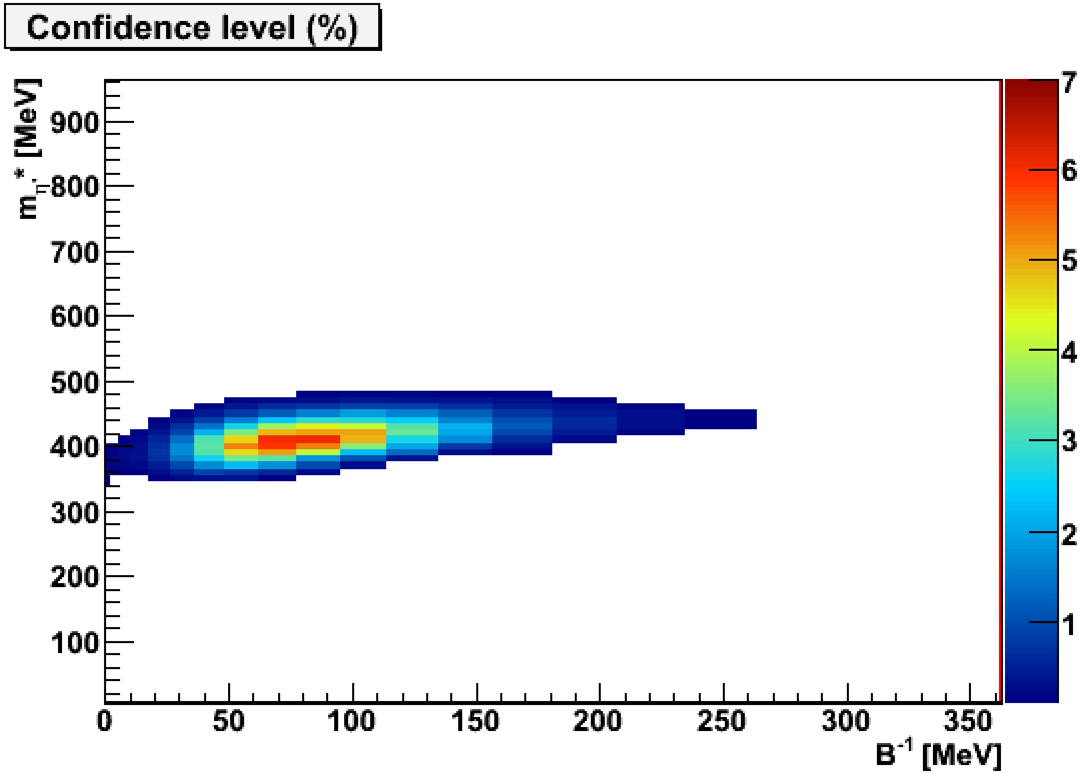


Rafelski vs. STAR

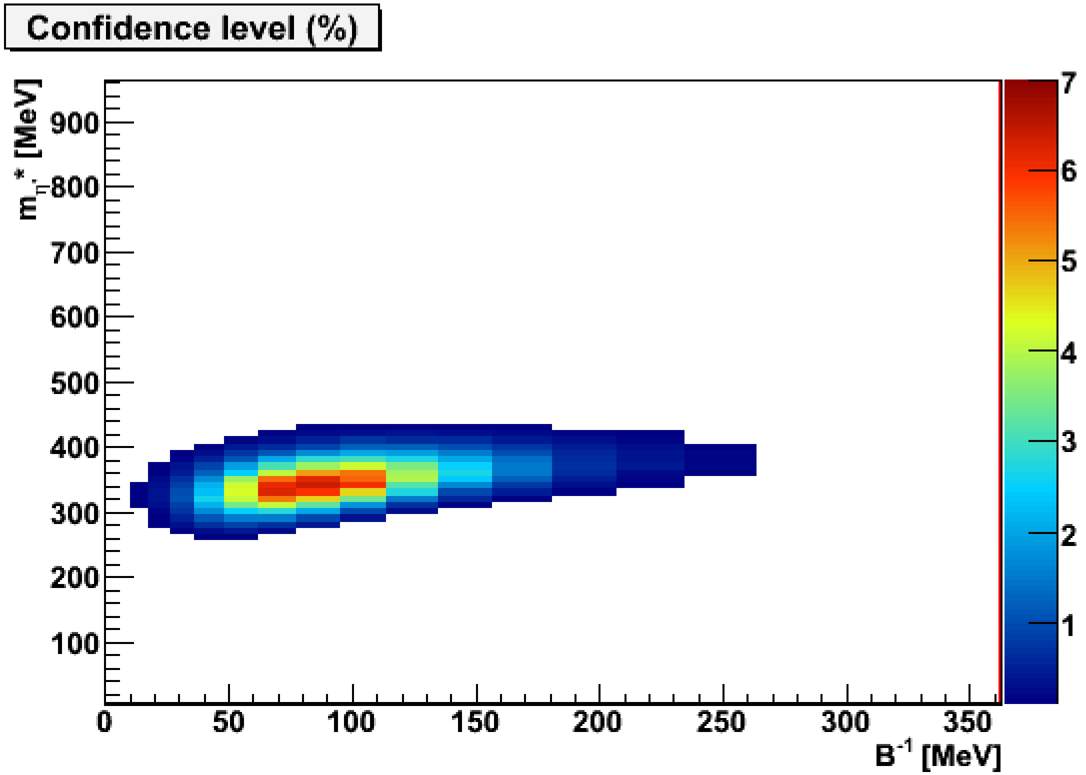




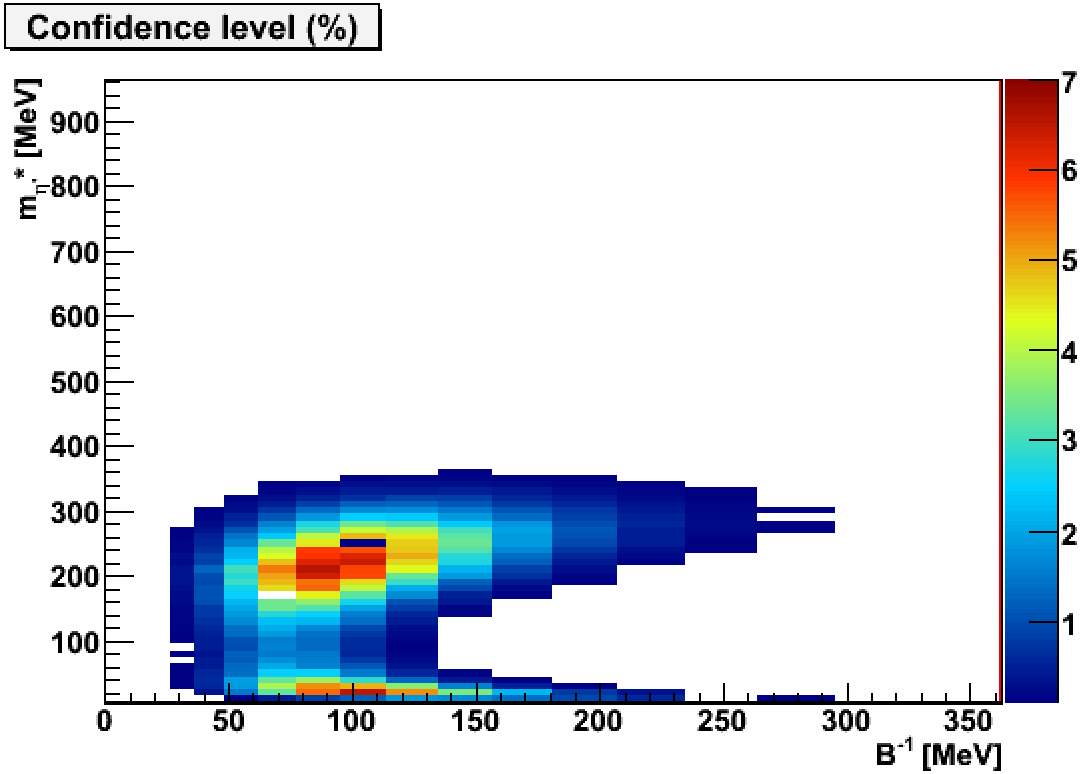
Systematics: Rafelski α=−1/2



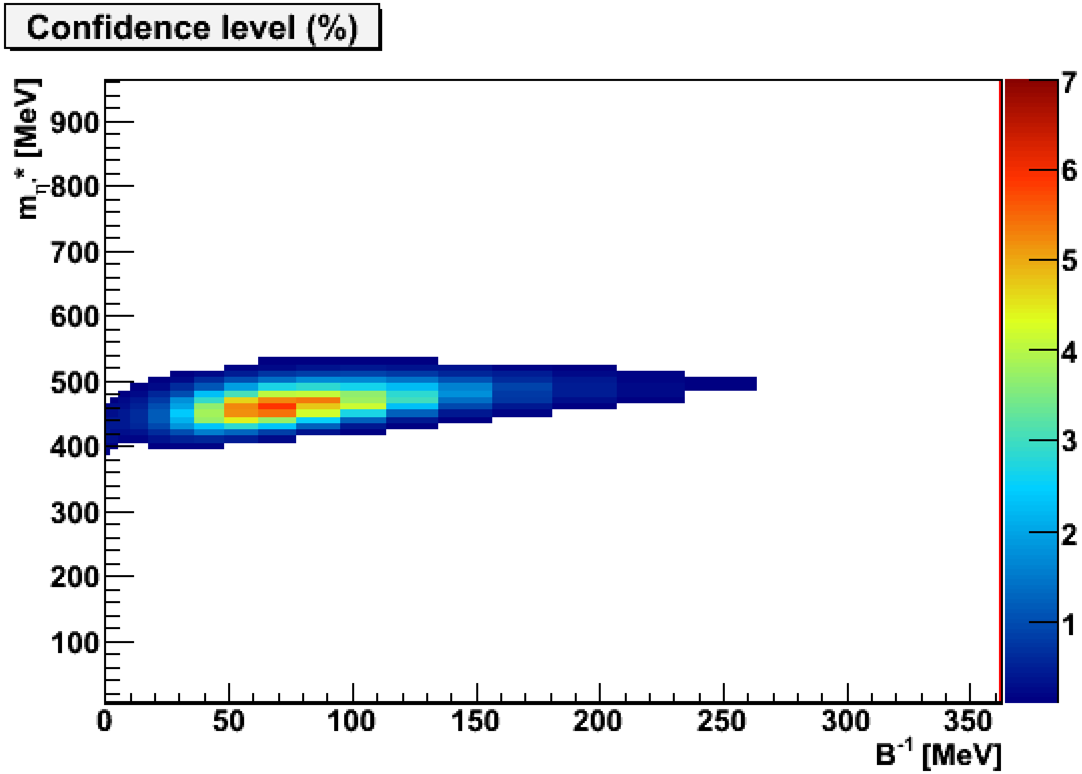
Systematics: Rafelski α=0



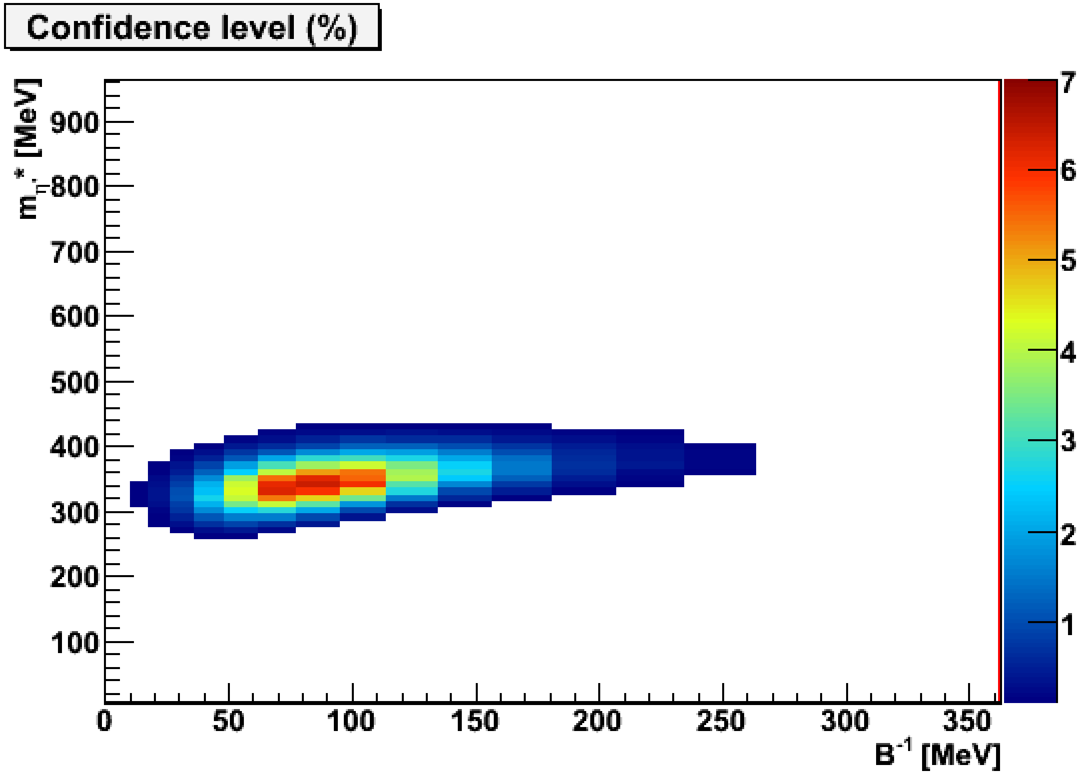
Systematics:
Rafelski α=+1/2



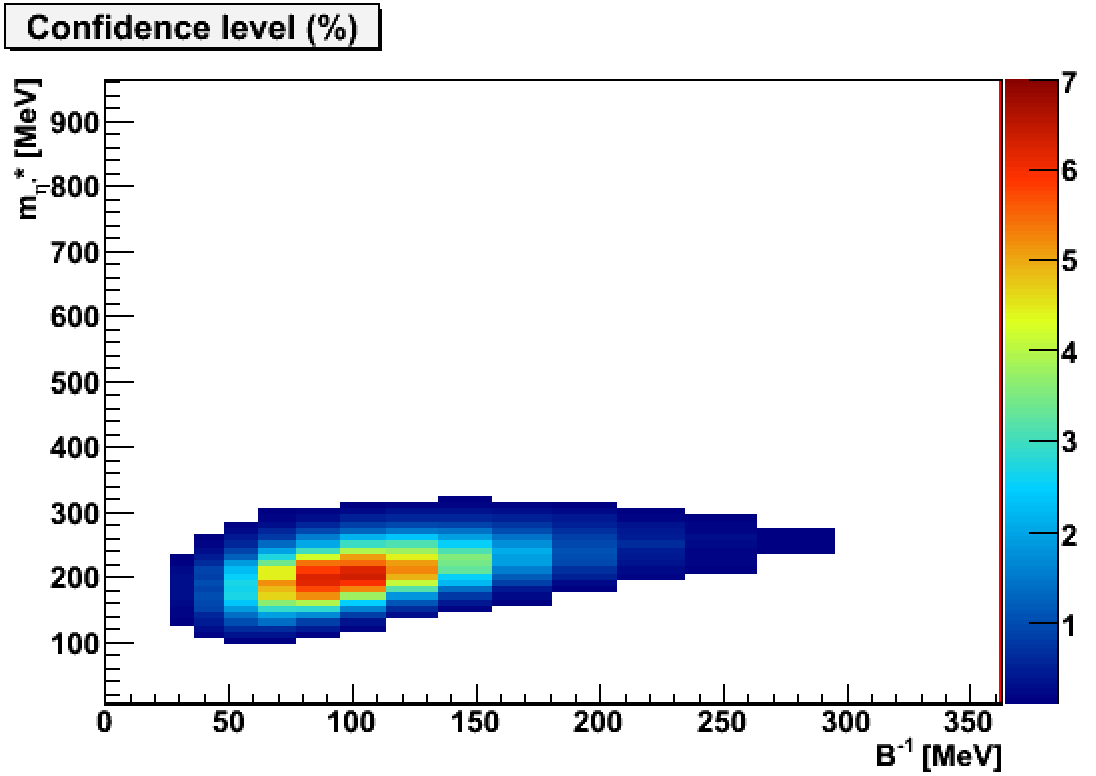
Systematics: Rafelski T'=140 MeV



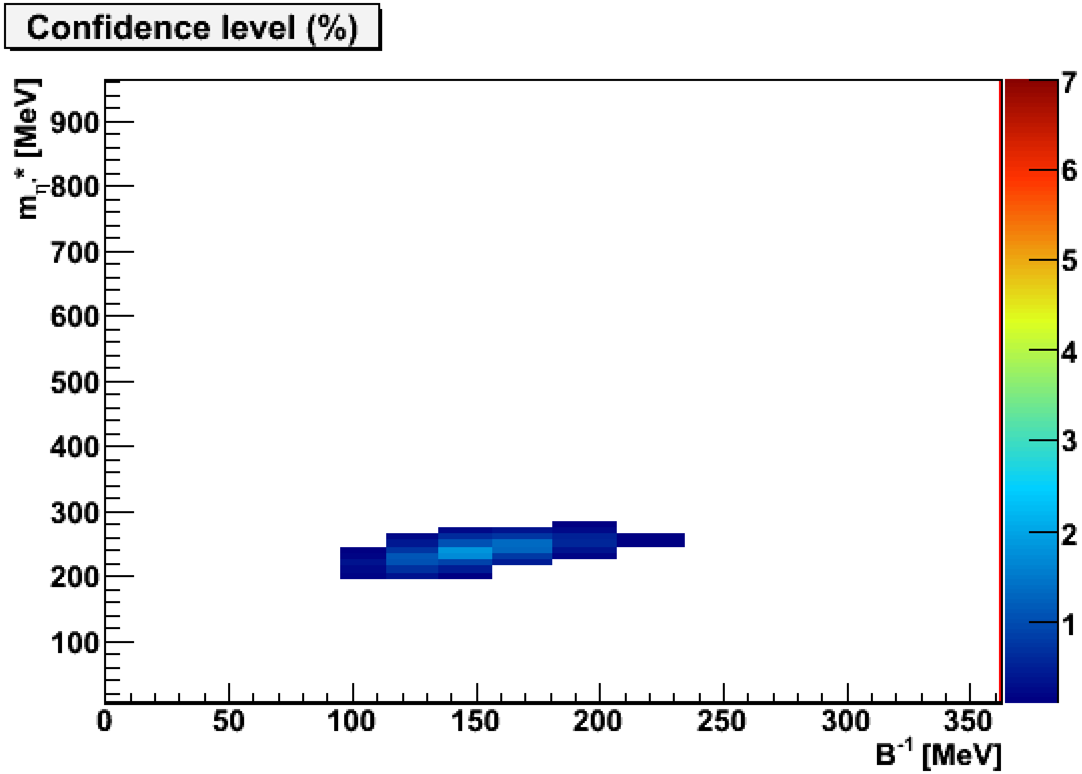
Systematics: Rafelski T’=177 MeV



Systematics: Rafelski T’=220 MeV



Systematics:
Rafelski T_{FO} =100 MeV



Systematics:
Rafelski T_{FO} =177 MeV