Status of the search for $U_A(1)$ symmetry restoration at RHIC and LHC energies

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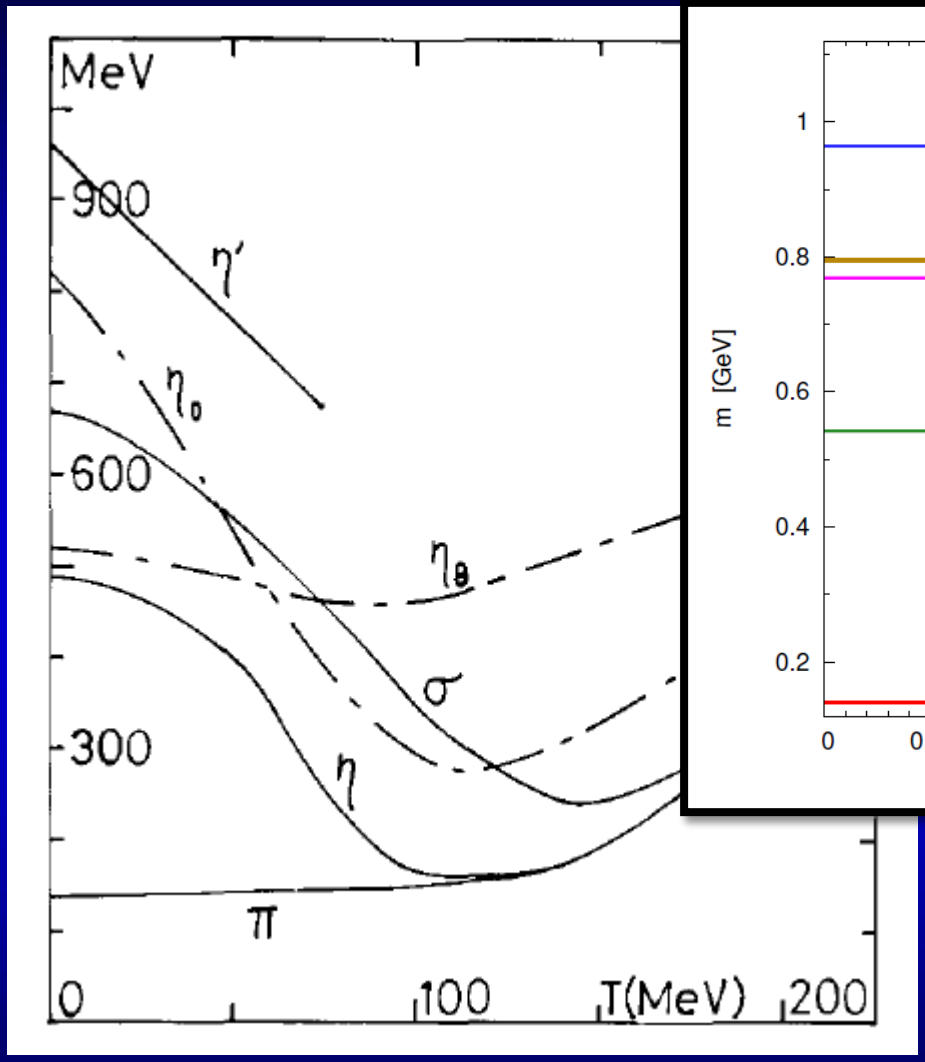
Introduction
CERES: dilepton spectrum at SPS
Indirect observation method and null result at CERN SPS

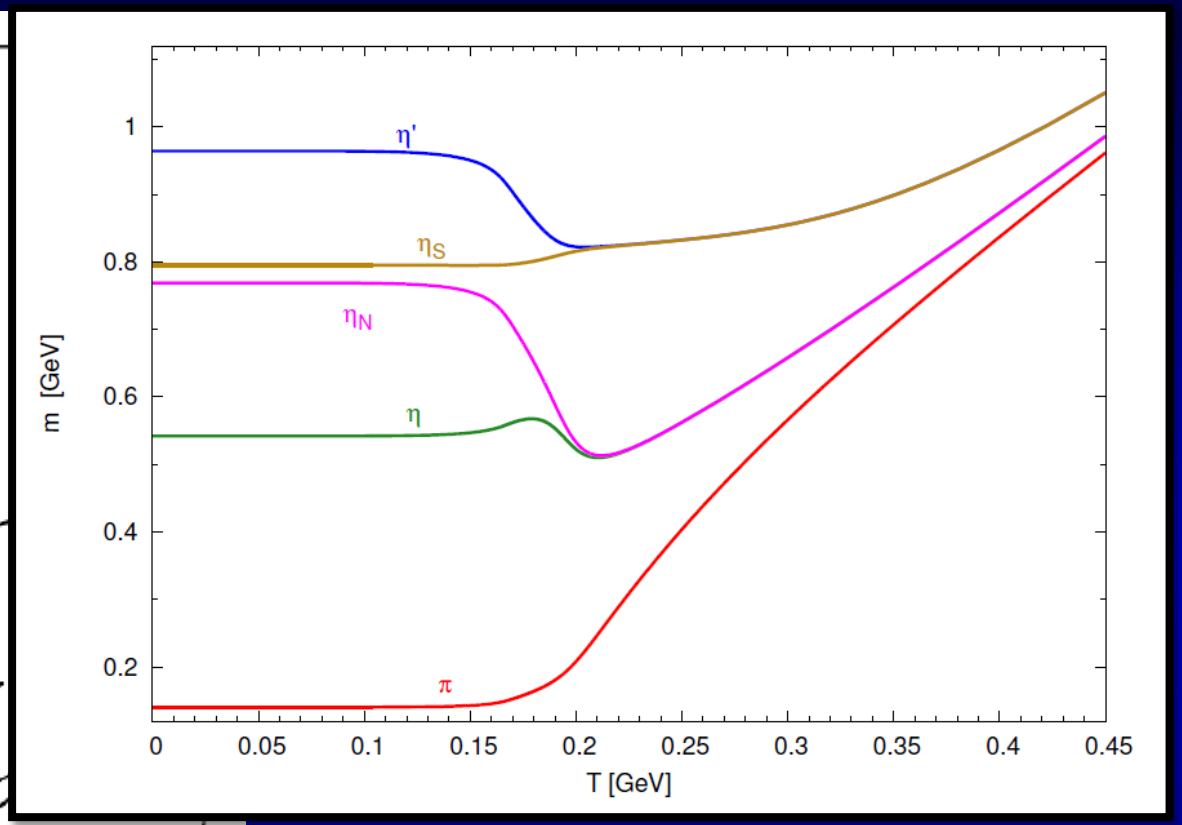
Indirect observation in Bose-Einstein correlations at RHIC
Expectations for LHC
Implications for dilepton spectra and for direct photon spectra
New experiments being proposed
Summary

arXiv:nucl-th/9802074
arXiv:0912.0258
arXiv:0912.5526
arXiv:1211.1166

Motivation: Kunihiro's prediction



T. Kunihiro, PLB 219 (1989) 363



P. Kovács, Zs. Szép, Gy. Wolf, 2015 Zimányi Winter School
arXiv:1601.05291

Density and temperature effects

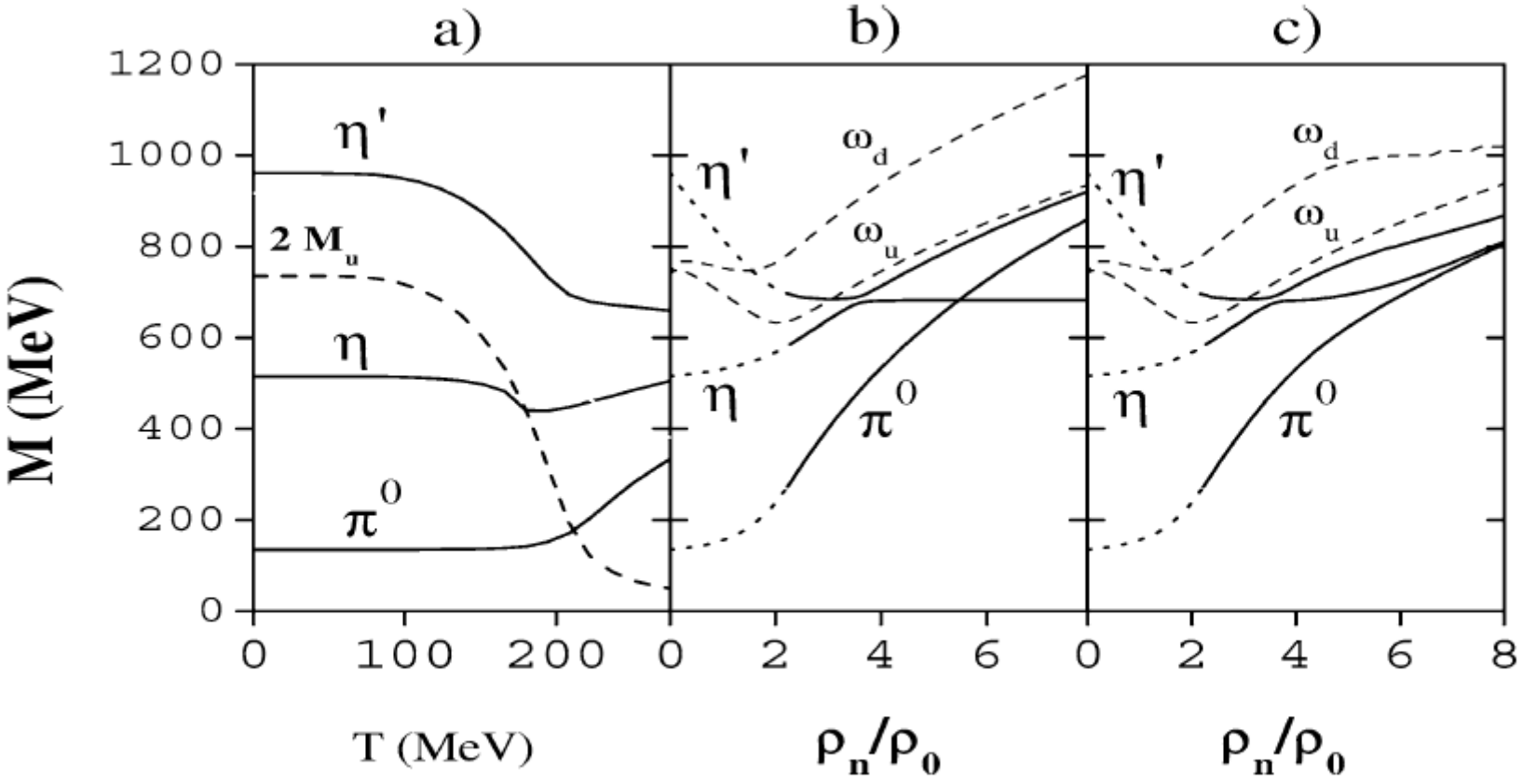
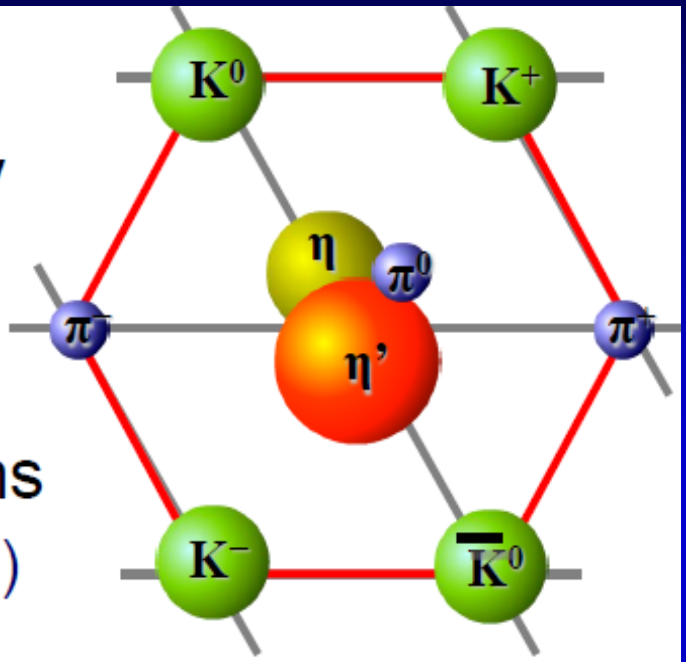


Fig. 2. η, η' and π^0 masses as function of temperature (a) and density: (b) case I; (c) case II.

P. Costa, M. C. Ruivo, Yu. L. Kalinovsky, PLB 560 (2003) 171

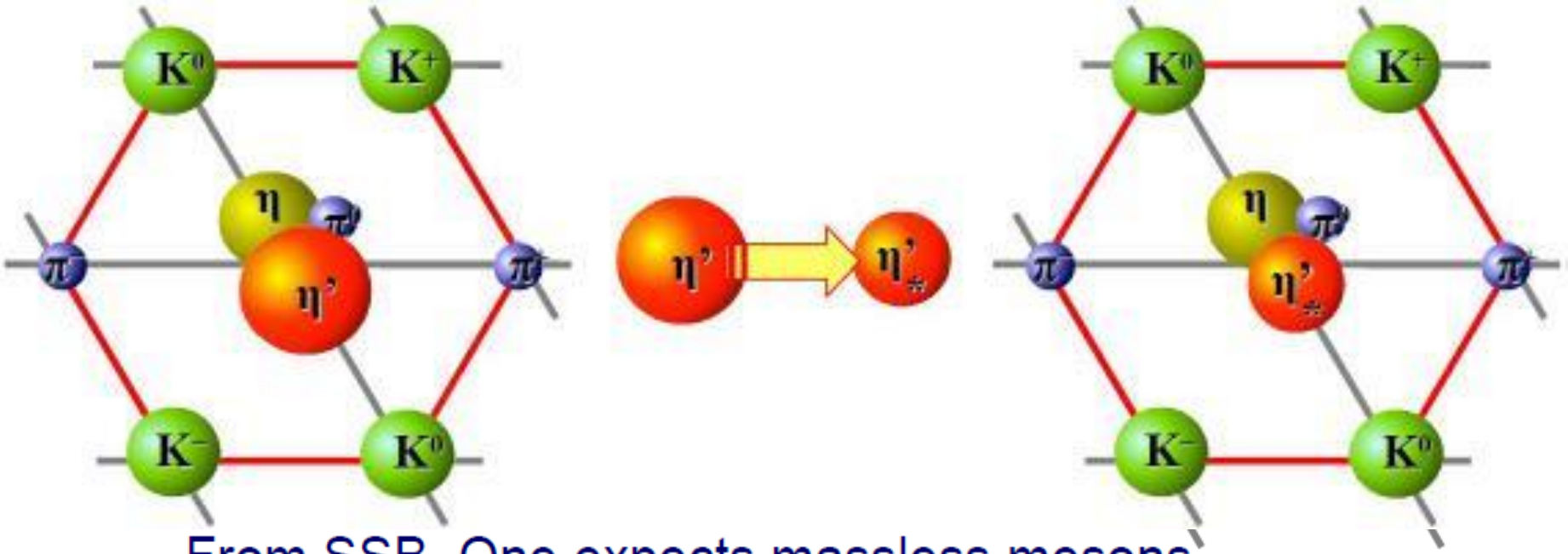
Why η'? Chiral and $U_A(1)$ symmetry

- The three-quark model
  - SU(3)xU(1) 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 $U_A(1)$ symmetry



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

- Mass reduction

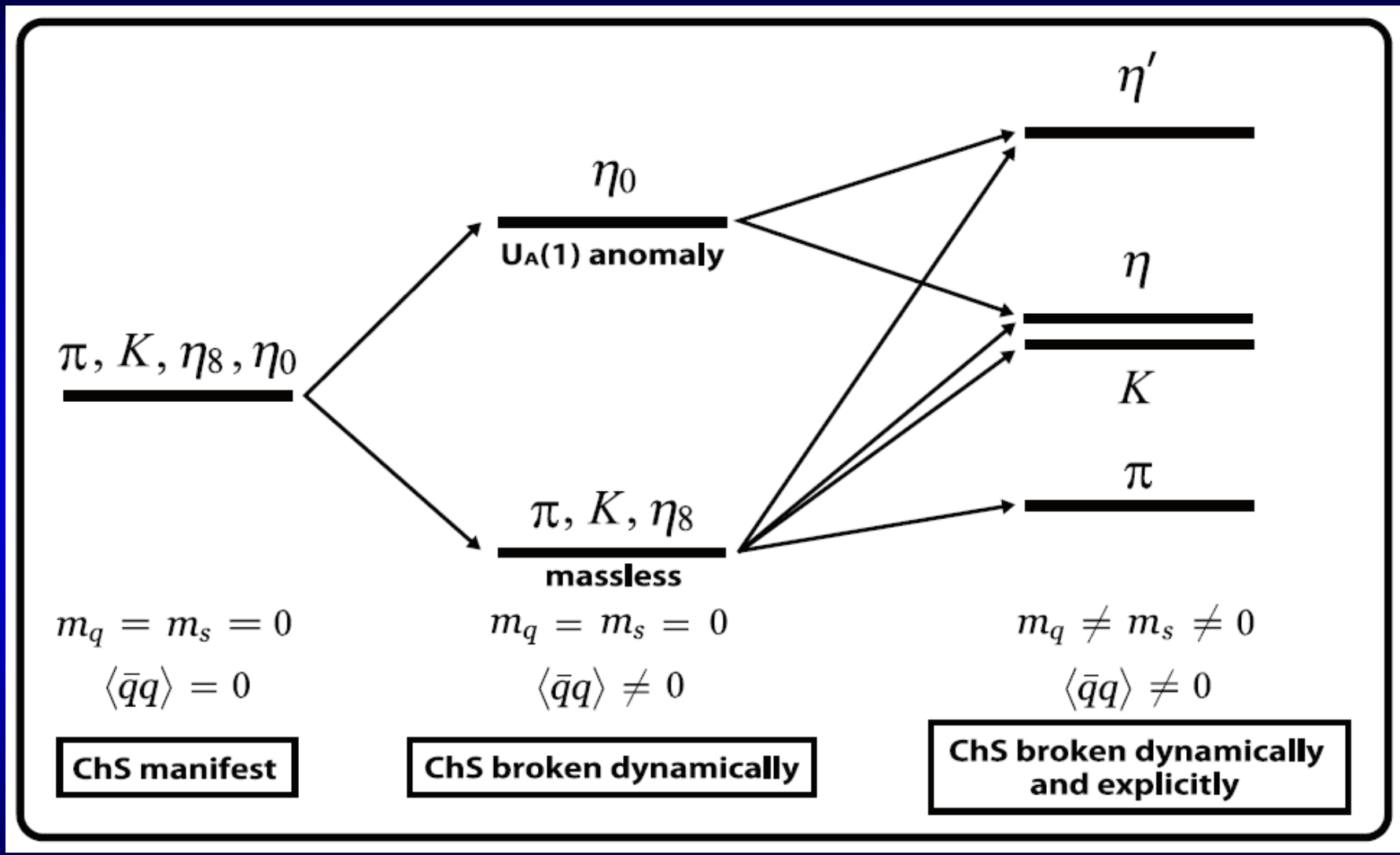
$$m_{\eta'} = m_0 + \Delta m$$

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

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

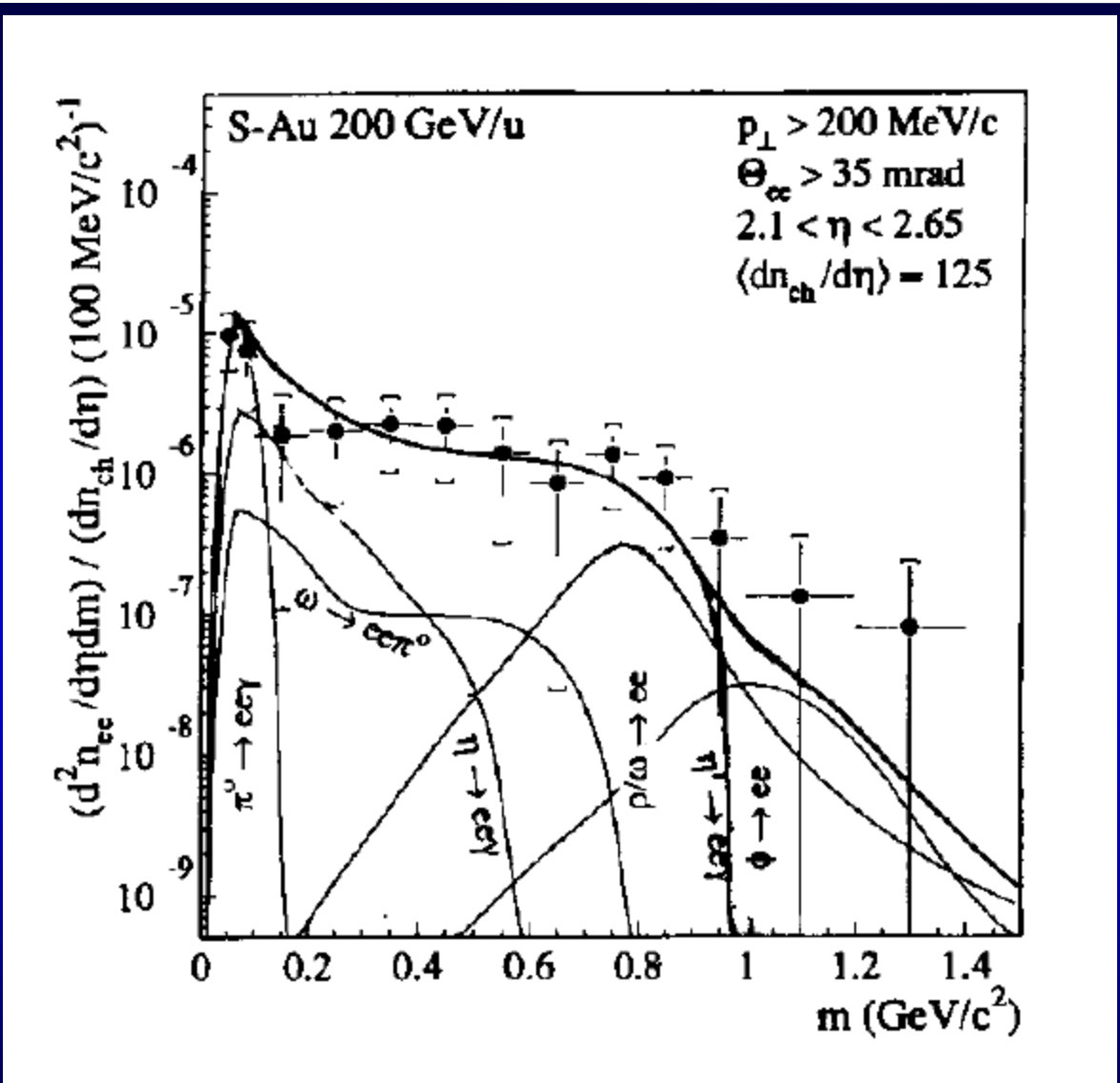
Δm : extra mass from instantons in a not-so-dense medium

Motivation: mass hierarchy



Nagahiro, Jido et al, arXiv:1211.2506

Motivation: CERES data at CERN SPS



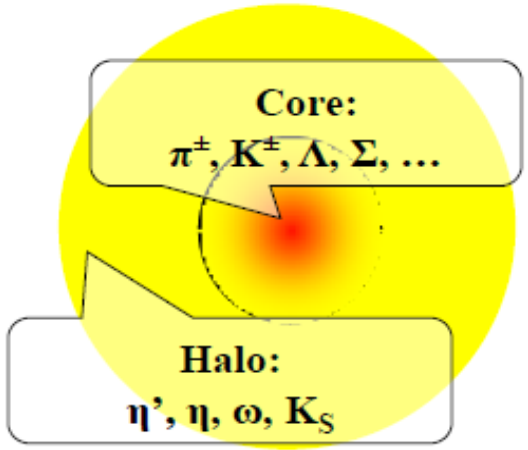
Kapusta, Kharzeev, McLerran: hep-ph/9507343

Core/halo picture for Bose-Einstein

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

Core

Halo



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

$$N^{\pi^+}_{halo} = N_{\omega\to\pi^+} + N_{\eta\to\pi^+} + N_{\eta'\to\pi^+} + N_{K^0_S\to\pi^+}$$

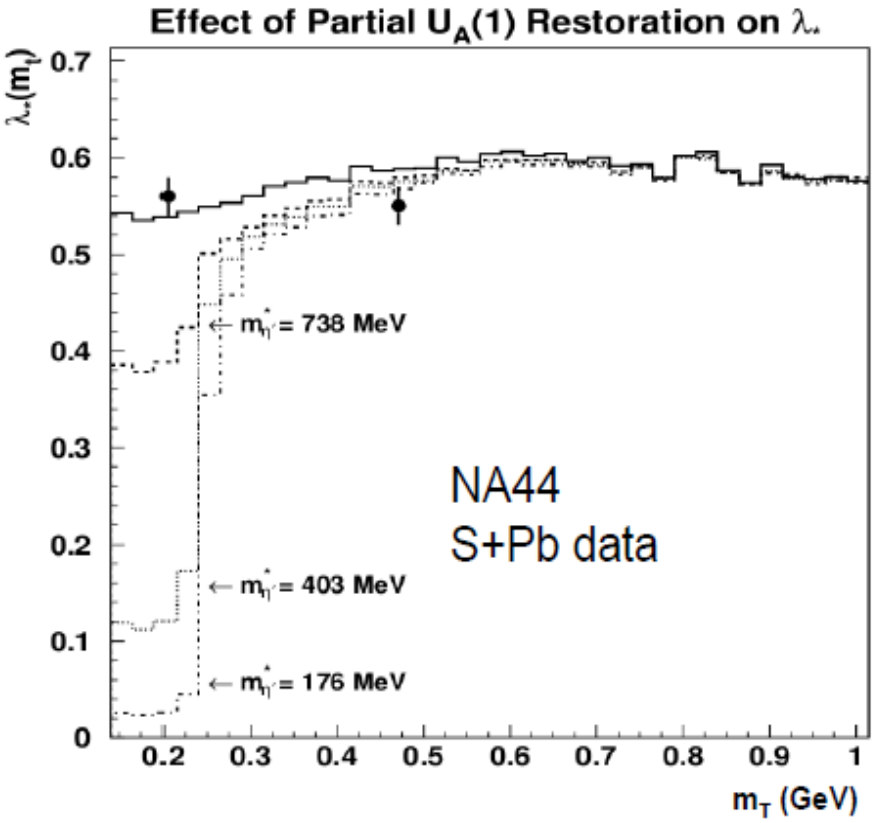
$$N = C m_t^{\alpha} e^{-m_T/T_{eff}}, T_{eff} = T_{fo} + m\langle u_T \rangle^2$$

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

T. Cs, B. Lörstad, PRC 54 (1996) 1390

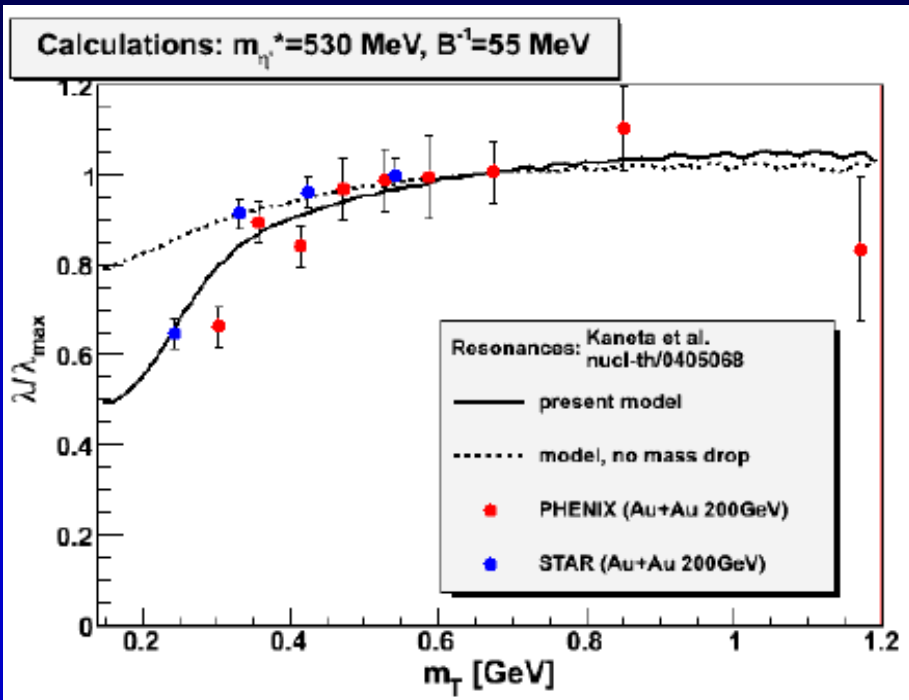
Result at SPS: no in-medium $\eta'_* \rightarrow \eta'$

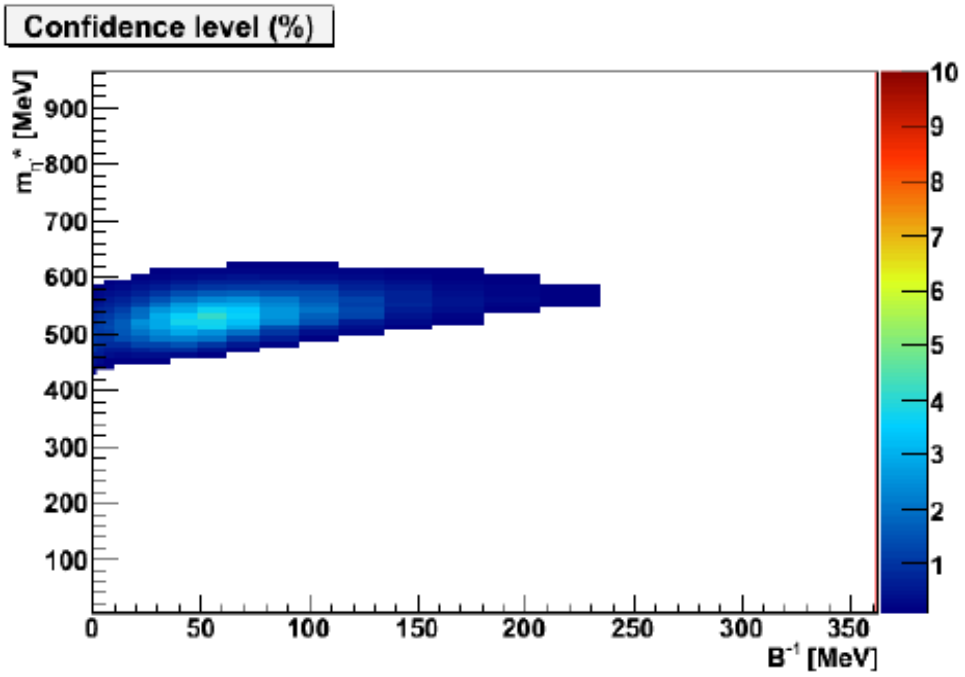
- Data:
  NA44 200 GeV S+Pb
- Resonances:
  FRITIOF
- Earlier, less refined modelling of condensate
- No sign of mass reduction



T. Cs, D. Kharzeev, S. E: Vance, hep-ph/9910436
S. E. Vance, T. Cs, D. Kharzeev, Phys. Rev. Lett. 81 (1998) 2205

Example results, based on Kaneta & Xu

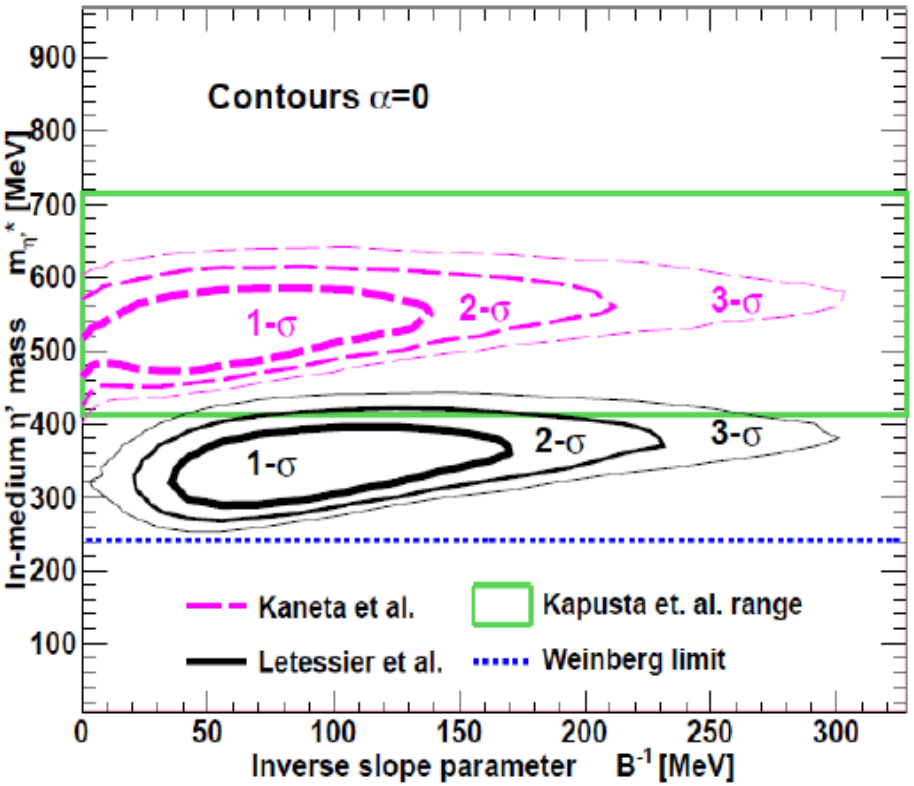




- Statistical chemical freezeout model
- Central mid-η 200 GeV Au+Au
- Describes PHENIX hadron spektrum well

Resonance model:
Kaneta and Xu, nucl-th/0405068

Femtoscopic Analysis: Results at RHIC



- Framed region: Kapusta et al., arXiv:nucl-th/9507343 .
- Lower limit: S. Weinberg, Phys. Rev. D 11, 3583 (1975).
- Sigma-contours from model calculations

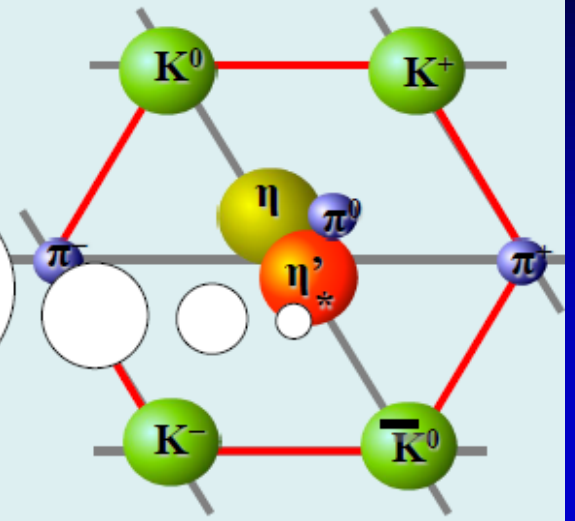
T. Cs, R. Vértesi, J. Sziklai, Phys. Rev. Lett. 105 (2010) 182301
Details: R. Vértesi, T. Cs, J. Sziklai, Phys. Rev. C38 (2011) 054903

Conclusions of femtoscopic study

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

at the 99.9% confidence level

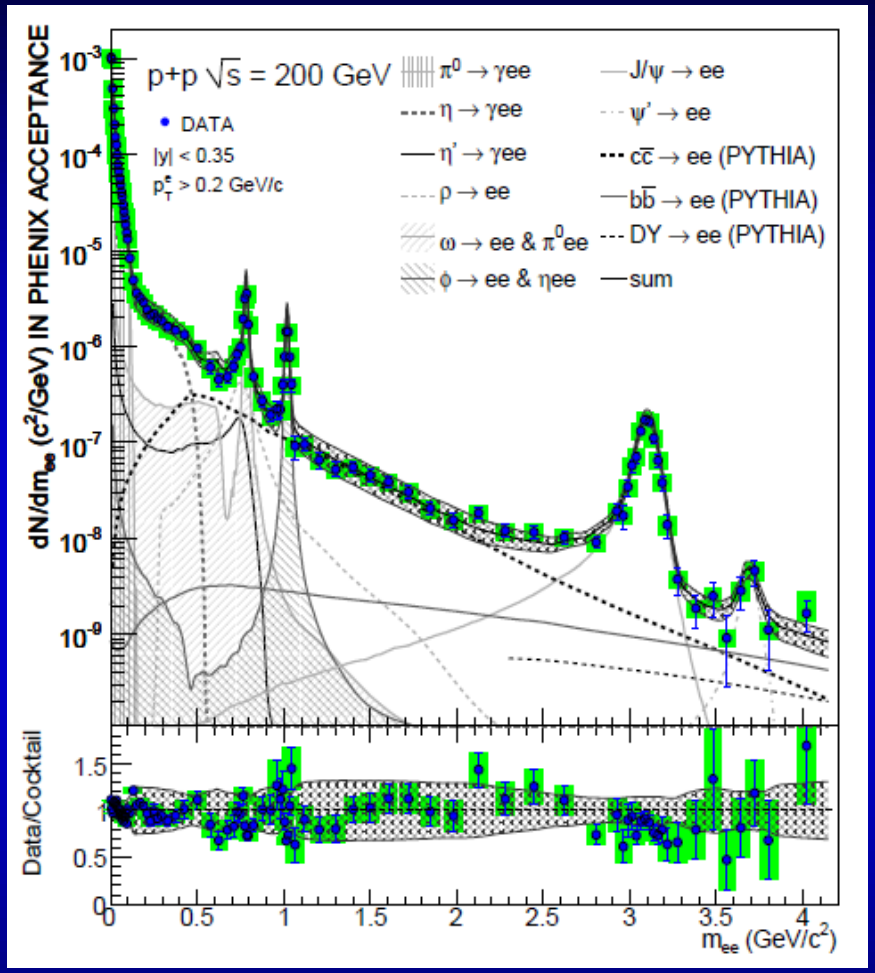
from PHENIX+STAR $\pi^+\pi^+$ correlation data + 6 models

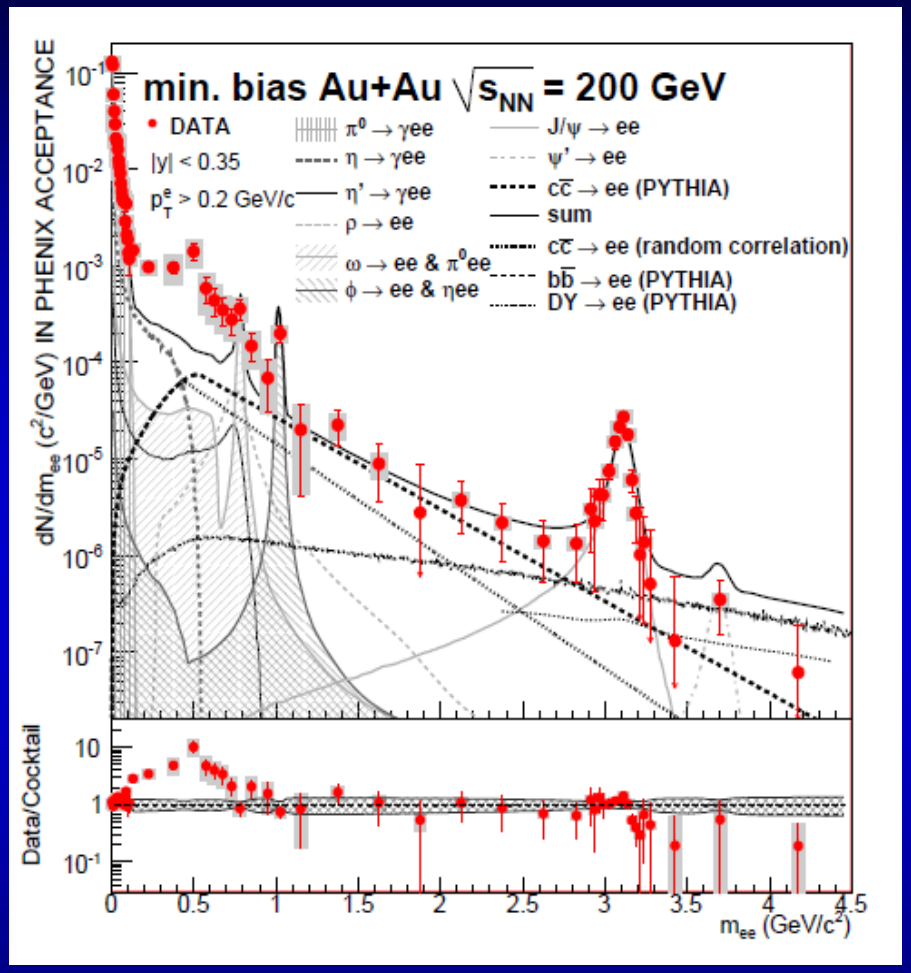


- Cross-check with dilepton spectrum needed
- More λ^* data at low p_T is needed to reduce systematics
- Revitalize interest in chiral symmetry restoration

T. Cs, R. Vértesi, J. Sziklai, Phys. Rev. Lett. 105 (2010) 182301
Details: R. Vértesi, T. Cs, J. Sziklai, Phys. Rev. C38 (2011) 054903

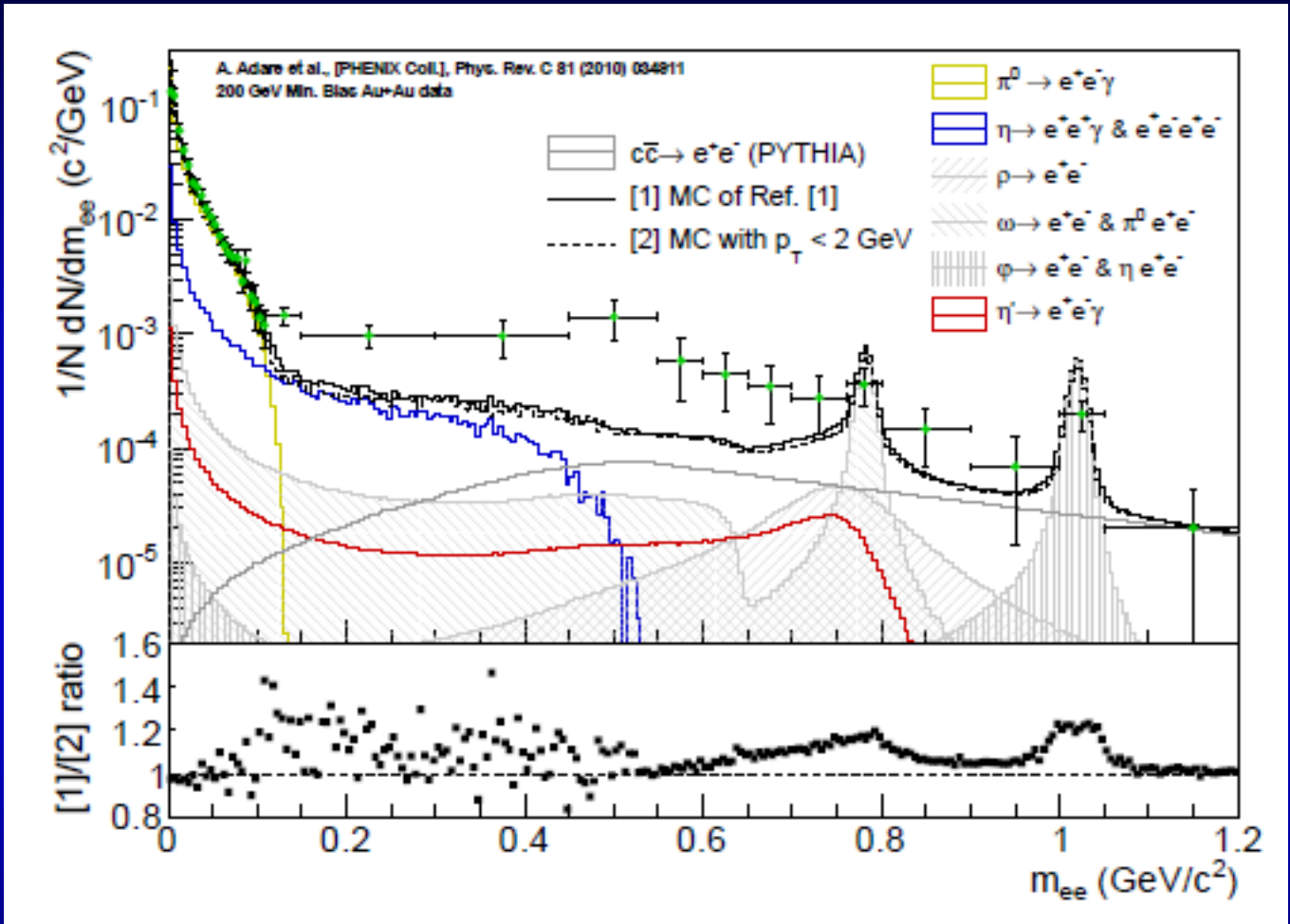
200 GeV Au+Au: low mass dileptons





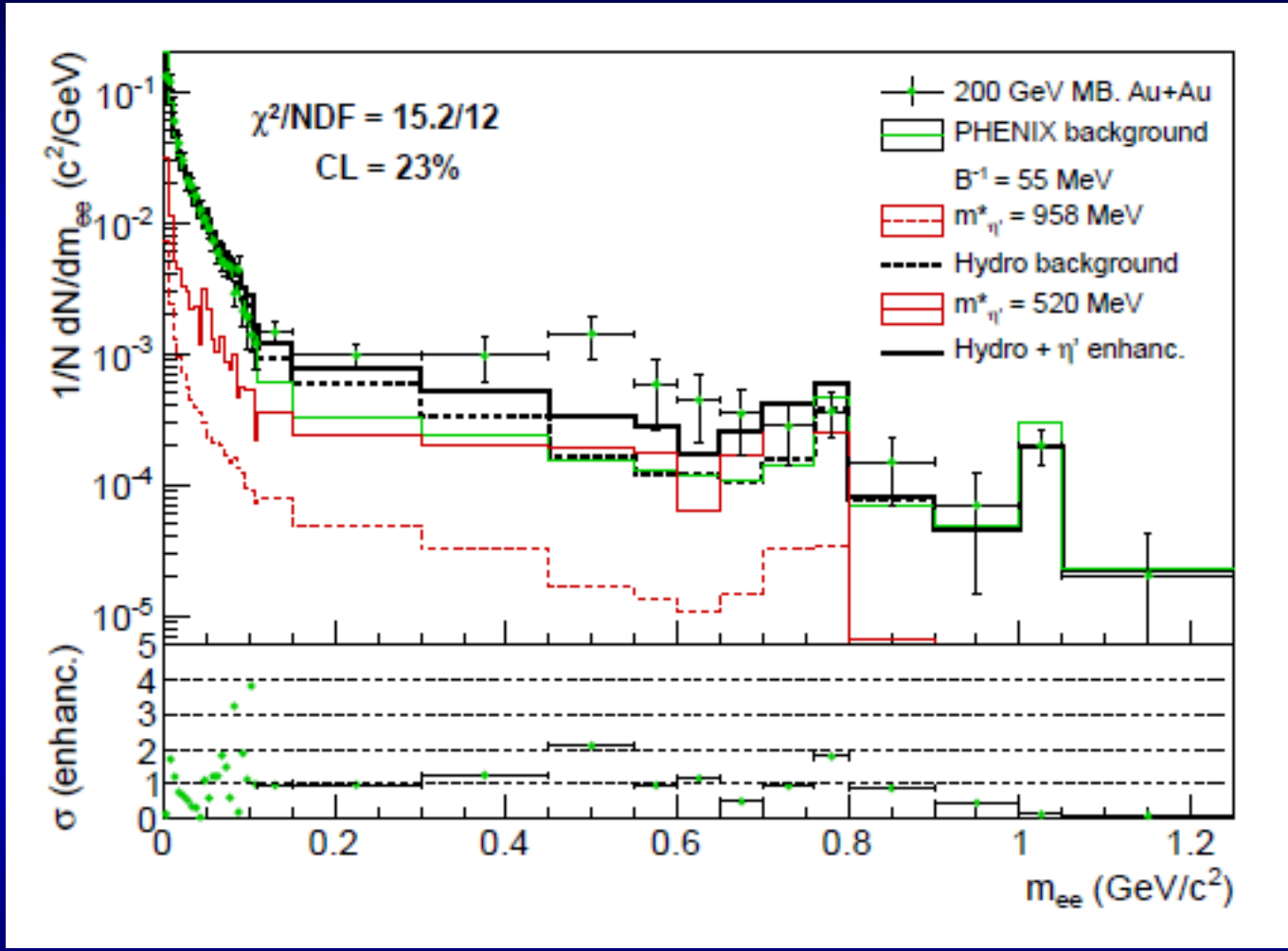
In low mass region, $0.12 < m_{ee} < 1.2$ GeV region:
excess of dileptons, that are expected from hadronic phase
S. Afanasiev et al, PHENIX, arXiv:0912.0244v1 [nucl-ex]

Return to dilepton spectra at RHIC



PHENIX cocktail reproduced and also calculated with $p_t < 2$ GeV
lower panel indicates that the dilepton enhancement is soft
→ make sure that hydro /flow effects are included in background

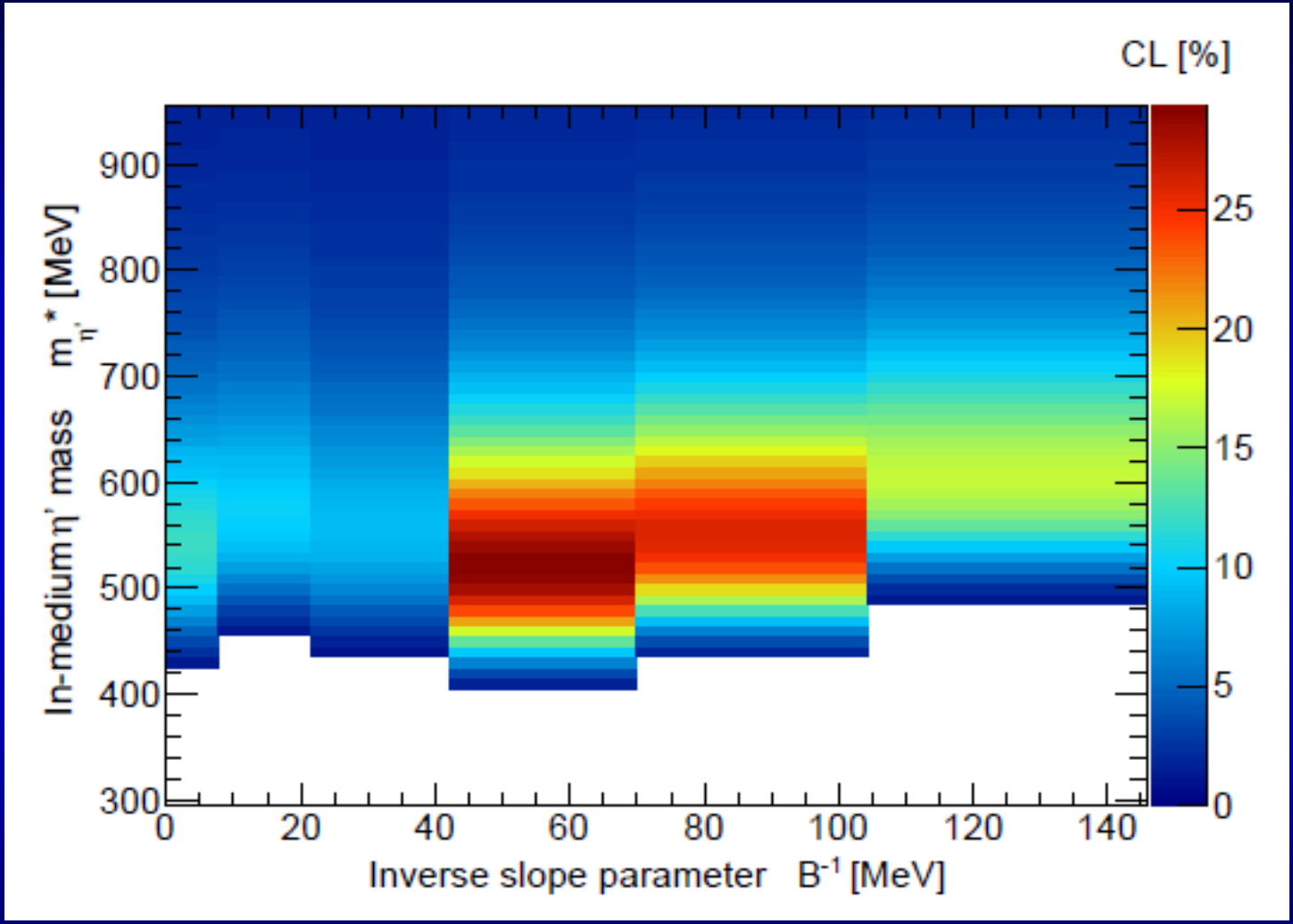
Hydro background + all chain decays



Hydro background is different from PHENIX default

In-medium η' mass drop: acceptable fit but systematics

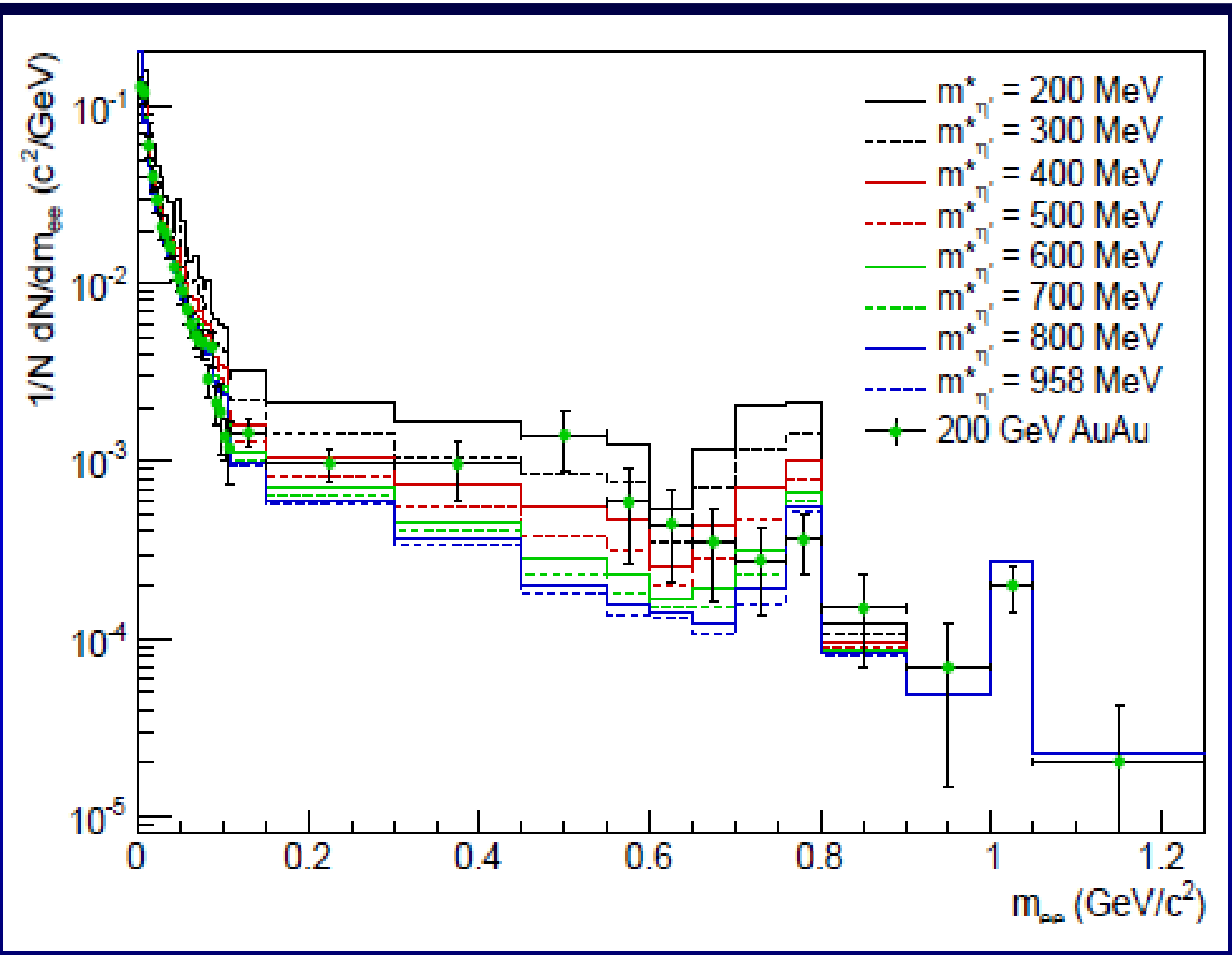
Parameter scan from dilepton data



η' mass values below 400 excluded at 99.9 % CL

consistent with femtoscopy, but B^{-1} scan is preliminary

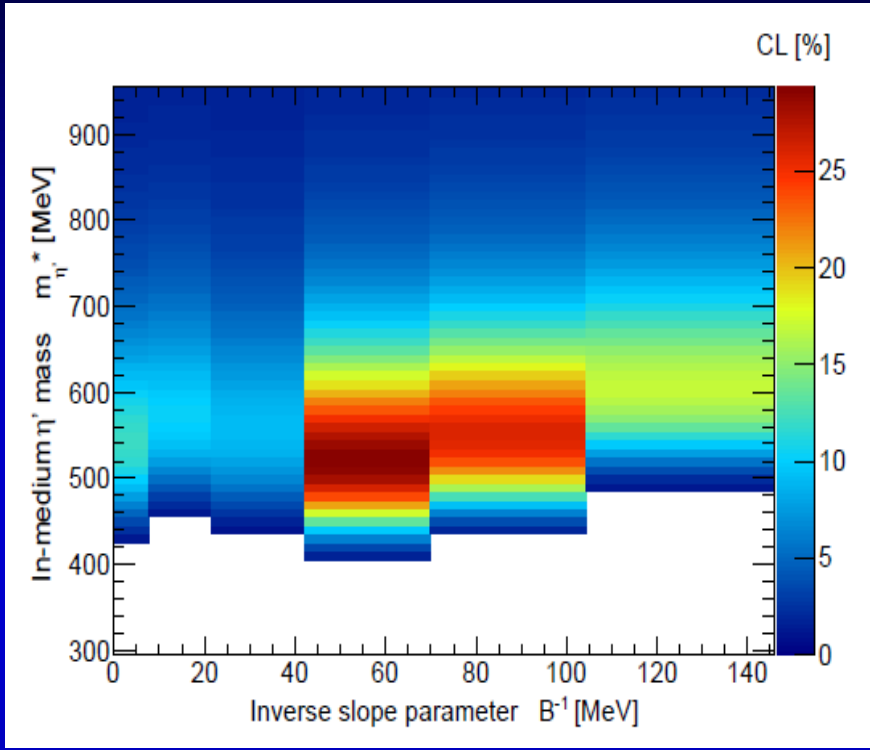
η' mass scan vs dilepton data

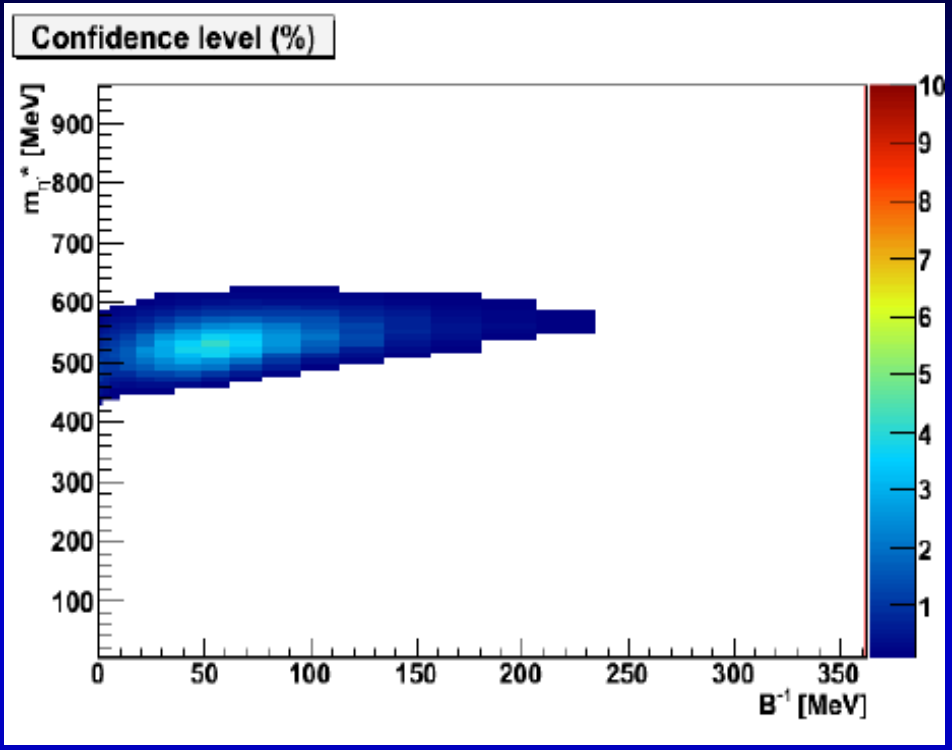


m*(η') ~ 400-600 MeV
B^{-1} fixed to 55 MeV (best)
Needs update for new PHENIX data

M. Vargyas, CsT, R. Vértesi,
CEJP 11 (2013) 553-559
arXiv:1211.1166

What have we learned so far?





Final femtoscopy/BE and first dilepton spectrum analysis
→ **consistent** picture of in-medium η' mass modification
at 99.9 % CL: 400 < m(η'*) < 758 MeV
→ dilepton and femtoscopy analysis is **complementary**
→ details available in centrality and pt dependence of dileptons
Needs **cross-checks**, density effect at **J-PARC**

200 GeV Au+Au: new PHENIX results

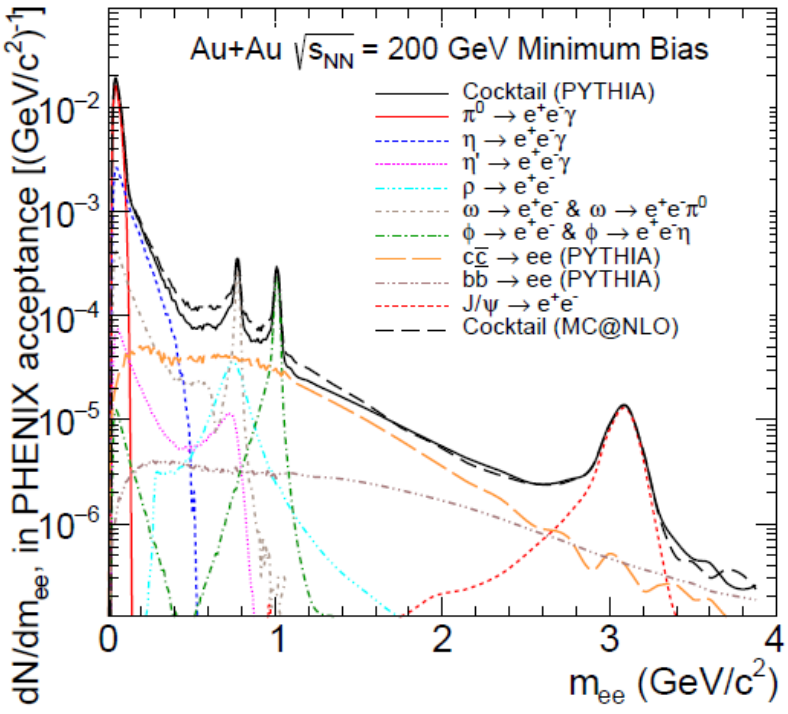


FIG. 27. (Color online) Cocktail of hadronic sources for the 2010 run (black solid line) using the PYTHIA generator for the open heavy flavor contributions. The individual components of the cocktail are also shown. For comparison, the total cocktail using MC@NLO is shown (black dashed line).

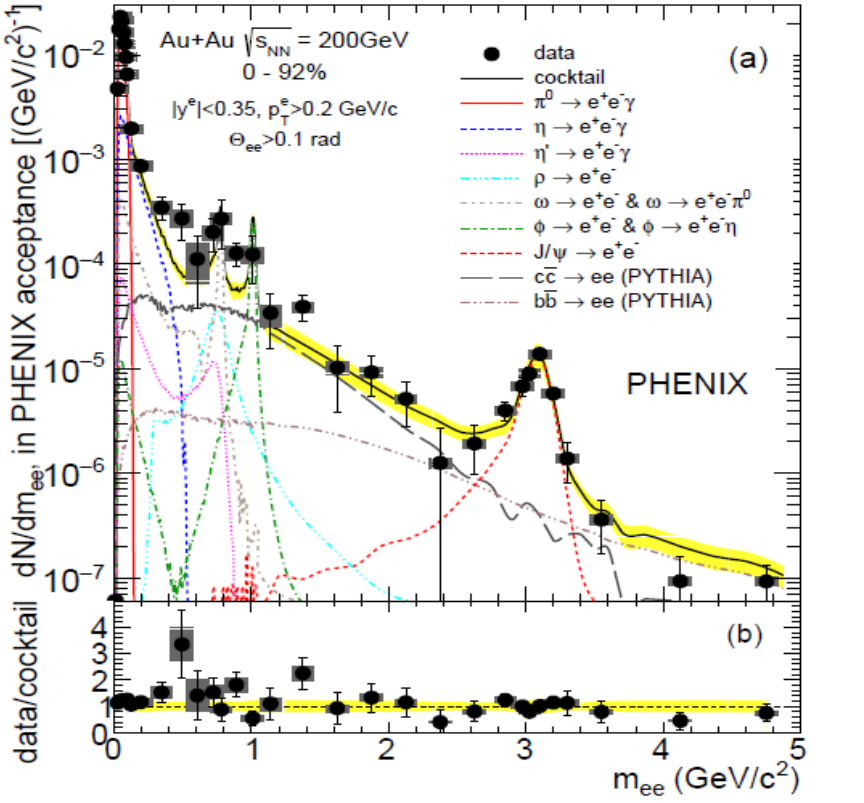


FIG. 28. (Color online) Invariant mass spectrum of e^+e^- pairs in MB Au+Au collisions within the PHENIX acceptance compared to the cocktail of expected decays.

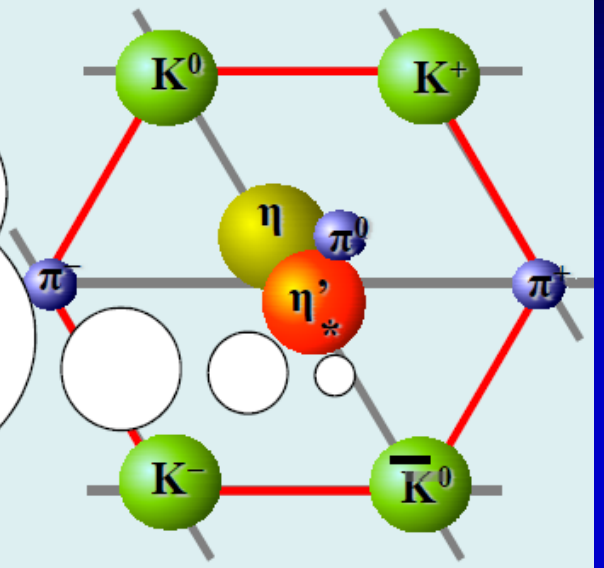
In low mass $0.12 < m_{ee} < 1.2$ GeV region: **excess** of dileptons, but ρ **modification**! heavy flavour e^+e^-: **PYTHIA < MC@NLO** !
PHENIX, PRC93 (**2016**) 1, 014904 arXiv:1509.04667 → ongoing η' analysis

Conclusions, T>0

400 MeV < $m^*_{\eta'}$ < 758 MeV

at the 99.9% confidence level

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



- **Cross-check with dilepton spectrum needs more detail**
- **Cross-check with photon spectrum needed**
- **Revitalize interest in chiral symmetry restoration**

Recent theoretical results

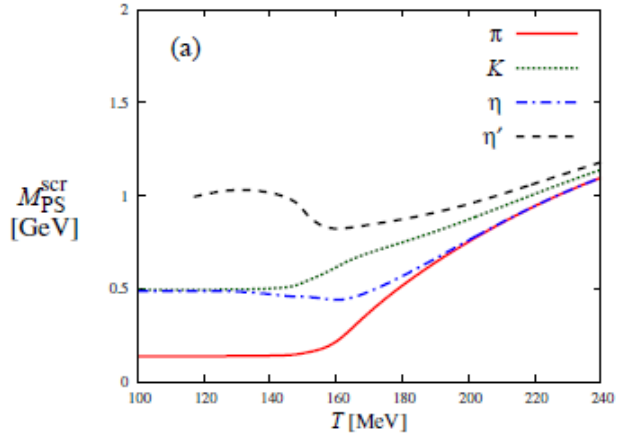


Fig. 3: T dependence of meson screening masses for (a) pseudoscalar mesons π, K, η, η' and (b) scalar mesons a_0, κ, σ, f_0 calculated with the realistic parameter set (A). Model results are denoted by lines. In model calculations, the channel mixing is taken into account.

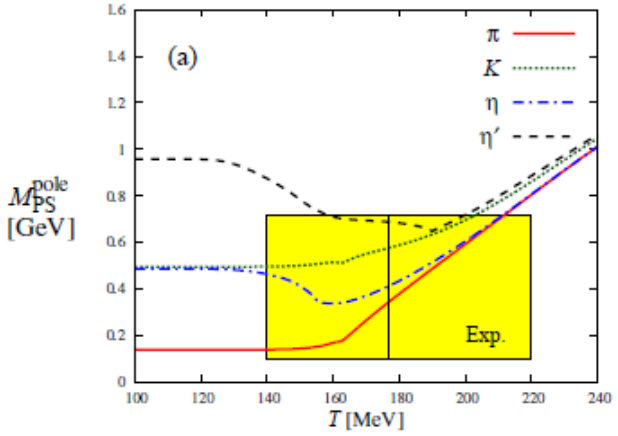


Fig. 4: Model prediction on T dependence of meson pole masses for (a) pseudoscalar mesons π, K, η, η' and (b) scalar mesons a_0, κ, σ, f_0. In model calculations, the parameter set (A) is taken and the channel mixing is taken into account. Model results are denoted by lines. For η' meson in panel (a), the experimental data [1] is shown by the rectangle with the thin dotted vertical line $T = 177$ MeV; see the text for the explanation.

arXiv:1609.04575

Recent theoretical results 2.

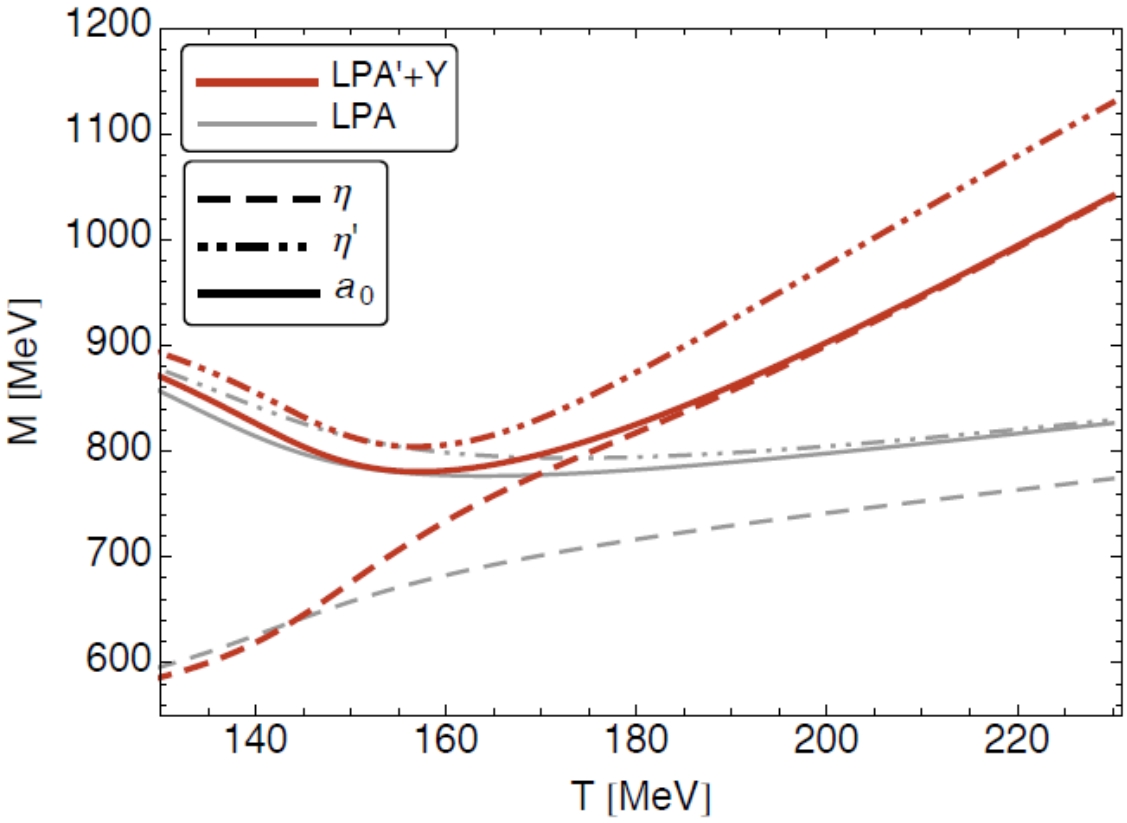
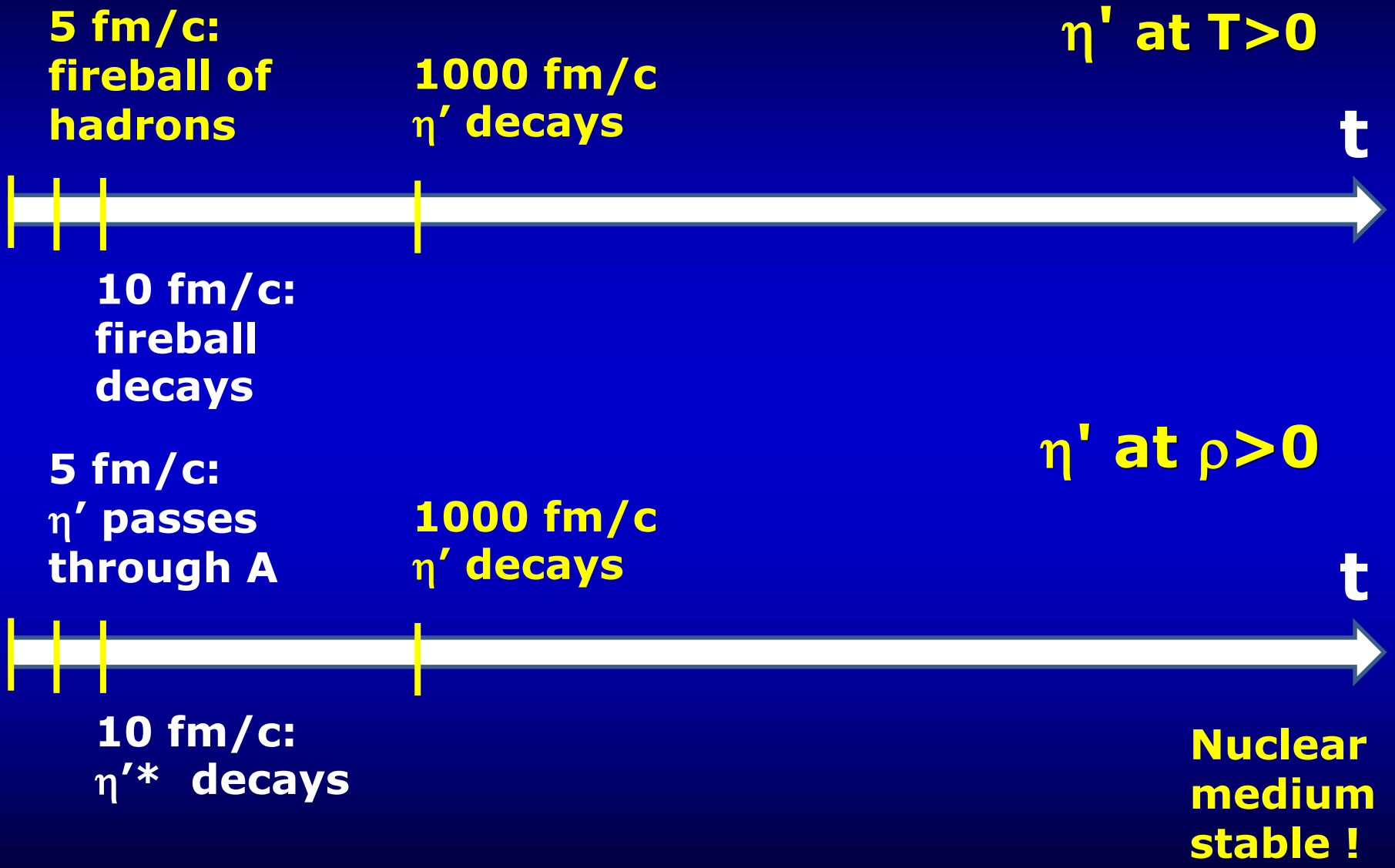


Figure 7. The masses of η-, η'- and a_0-meson at large temperatures. While the a_0-meson (solid lines) degenerates with the η'-meson in LPA (thin dotted-dashed gray line), it degenerates with the η-meson in LPA′+Y (dashed red dark line).

arXiv:1610.08478

η' at T>0 vs η' at ρ>0, time scales



TAPS results at T=0, finite density

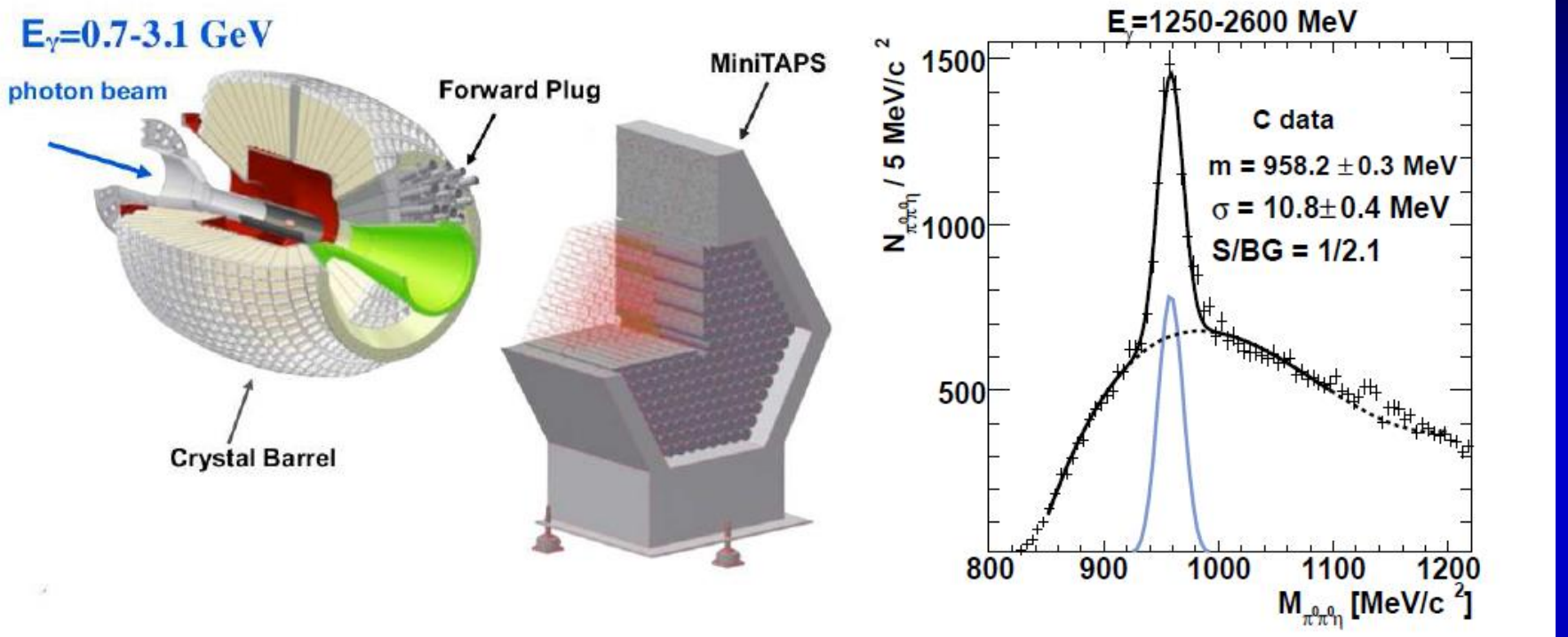
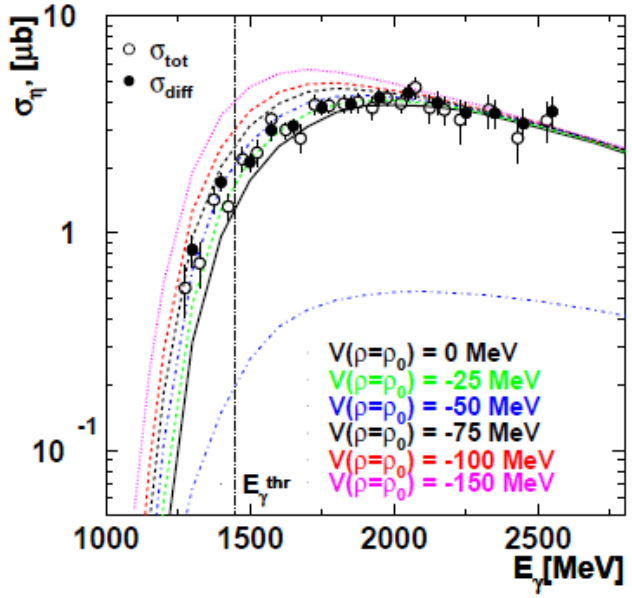
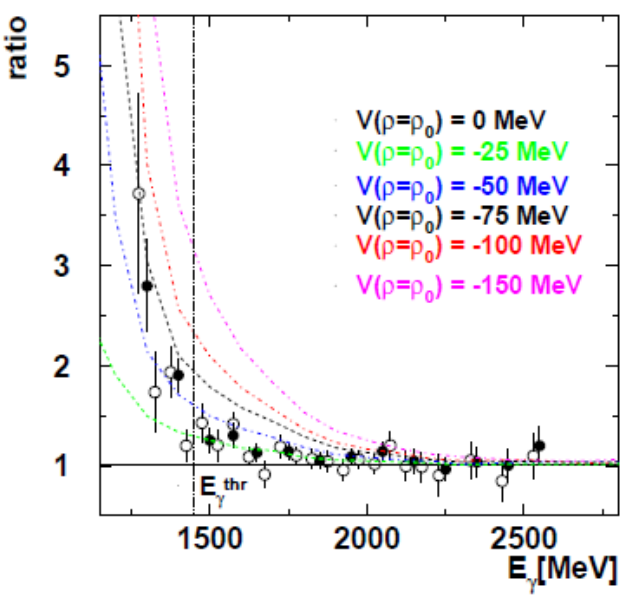
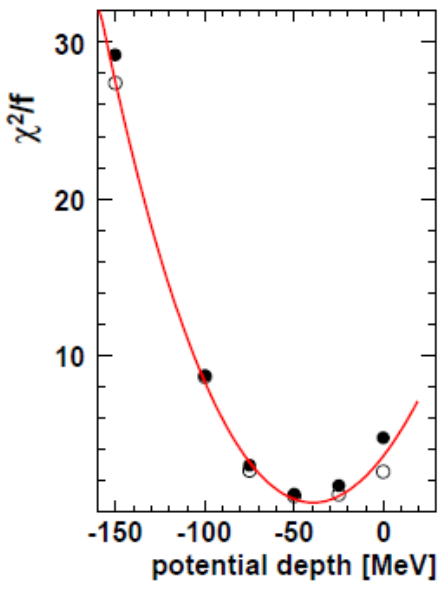


FIG. 1. (Color online) Left: Setup used in the experiment in 2009. Right: The $\pi^0\pi^0\eta$ invariant mass distribution measured in photoproduction off carbon in the incident photon energy range of 1250-2600 MeV. The solid curve represents a fit to the data using a Gaussian function combined with a polynomial function for the background. The fit parameters are: σ=10.8±0.4 MeV (corresponding to the instrumental resolution), m=958.2±0.3 MeV/c^2; S/BG is the signal (S) to background (BG) ratio within a $\pm 3\sigma$ interval.

TAPS results







real part: $V(\rho_0) = -37 \pm 10$ (stat) $\pm$ 10(syst) MeV
imaginary part: $W(\rho_0) = -10 \pm 2.5$ MeV
$\Gamma(\rho_0) = 20 \pm 5$ MeV
Mass at PDG value, width broadening by factor of 100!
but: η' is not stopped in A

Indirectly: η' in hot hadronic matter:

Femtoscopy and dilepton analysis at RHIC

If $m^*(\eta') < m(\eta') = 958$ MeV
two-pion Bose-Einstein correlations indicate a **hole** in $\lambda(m_t)$
in the low transverse mass, $0 < m_t - m < 0.25$ GeV region:
Method: S. Vance, CsT, D. Kharzeev, PRL **81** (1998) 2205-2208, nucl-th/9802074
Data: PHENIX: PRL93 (2004) 152302 nucl-ex/0401003 + new arxiv:1602.04578
STAR: PRC80 (2009) 024905 arXiv:0903.1296 [nucl-ex]

Dilepton spectra:
In low mass region, $0.12 < m_{ee} < 1.2$ GeV region:
excess of dileptons, that are expected from hadronic phase
Data:
PHENIX: PRC **81** (2010) 034911, arXiv:0912.0244
STAR: PRL **113** (2014) 022301
STAR: PRL **113** (2014) 049903
PHENIX: PRC**93** (2016) 1, 014904, arXiv:1506.07834

Indirect observation of η' modification
HBT: CsT, R. Vértesi, J. Sziklai, PRL **105** (2010) 182301, arXiv:0912.5526
HBT: R. Vértesi, CsT, J. Sziklai, PRC **38** (2011) 054903, arXiv:0912.0258
Dilepton: M. Vargyas, CsT, R. Vértesi, CEJP **11** (2013) 553 arXiv:1211.1166
Dilepton: CsT, G. Kasza, M. Vargyas… in preparation

Summary

Indication of a hadronic phase
where η and η' are like identical twins
$U_A(1)$ restoration

Bose-Einstein and **dilepton** analysis
consistent and **complementary**

$400 < m(\eta'_*) < 759$ MeV at 99.9 % CL

but ongoing dilepton analysis of
recent PHENIX and STAR data

needs confirmation:
γ channels, T dependence at RHIC

new measurements:
Density dependence at J-PARC

Thank you for your attention!

Backup slides – Discussion