A FIZIKAI VÁKUUM TULAJDONSÁGAI ÉS VÁLTOZÁSAI

ELSŐ ÉS KÖZVETETT PILLANTÁSOK AZ ŐSANYAG MÁSODIK ÚJ ÁLLAPOTÁRA

Csörgő Tamás [1,2]

[1] HUN-REN Wigner FK, Budapest és
[2] MATE Műszaki Intézet, KRC, Gyöngyös

1974-től 2024-ig
T.D.Lee és G.C. Wick
S. Weinberg
R. Pisarski és F. Wilczek
A RHIC terve és a CERN QGP sajtóanyaga
ZBCsL: kvark koaleszcencia @ CERN SPS
PHENIX és STAR adatok újra elemzése @ RHIC
Az $U_A(1)$ szimmetria helyreállásának közvetett megfigyelése a PHENIX-ben

Alapjai: arXiv:2407.08586, Phys.Rev.C 110 (2024) 6, 6
Közlemények Phys. Rev. C 97 (2018) 064911, és Phys. Rev. C 108 (2023) 049905

Részletes szakmai eredmények: PHENIX előadás a WPCF 2026-on, ELTE, 2026. V. 22.

1974 – T.D. Lee és G.C. Wick

Vacuum Stability and Vacuum Excitation in a Spin 0 Field Theory #1

T.D. Lee (Columbia U.), G.C. Wick (Columbia U.) (Jan, 1974)

Published in: *Phys.Rev.D* 9 (1974) 2291-2316

DOI cite claim

Tsung-Dao Lee

Nobel Prize in Physics 1957

Prize motivation: "for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"

Lee and G. C. Wick, published more than 50 years ago, in 1974, in Physical Review D, the leading particle physics journal of the American Physical Society. According to the conjectured physical picture, the *empty space, the so-called vacuum actually more resembles a medium whose properties can be changed*. Thus empty space has properties, for example, it has a temperature. For a medium, consider water as an example. Water has a temperature. In winter time, below the freezing point, water freezes to ice. When put on fire, and its temperature increases above the boiling point, water turns to steam.

1975 – S. Weinberg

The U(1) Problem

#1

Steven Weinberg (Harvard U.) (Mar, 1975)

Published in: *Phys.Rev.D* 11 (1975) 3583-3593

DOI cite claim

Steven Weinberg

Nobel Prize in Physics 1979

Prize motivation: "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"

The 1974 prediction of G. C. Wick and T. D. Lee has been extended in 1975 by S. Weinberg,

Abstract

A detailed analysis of the problems associated with the conserved U(1) axial vector current in quark-gluon models is presented. It is shown that such models involve a light isoscalar pseudoscalar boson, with a mass less than $\sqrt{3}m_\pi$. The existence of this boson would produce a strong off-shell variation in the $\eta \to 3\pi$ matrix element,

1984 – R. Pisarski és F. Wilczek

Remarks on the Chiral Phase Transition in Chromodynamics

#1

Robert D. Pisarski (Santa Barbara, KITP), Frank Wilczek (Santa Barbara, KITP) (Dec, 1983)

Published in: *Phys.Rev.D* 29 (1984) 338-341

DOI cite claim

Frank Wilczek

Nobel Prize in Physics 2004

Prize motivation: "for the discovery of asymptotic freedom in the theory of the strong interaction"

Abstract

The phase transition restoring chiral symmetry at finite temperatures is considered in a linear σ model. For three or more massless flavors, the perturbative ε expansion predicts the phase transition is of first order. At high temperatures, the $U_A(1)$ symmetry will also be effectively restored.

1984 – RHIC tervezet: Két új halmazállapot is felfedezhető

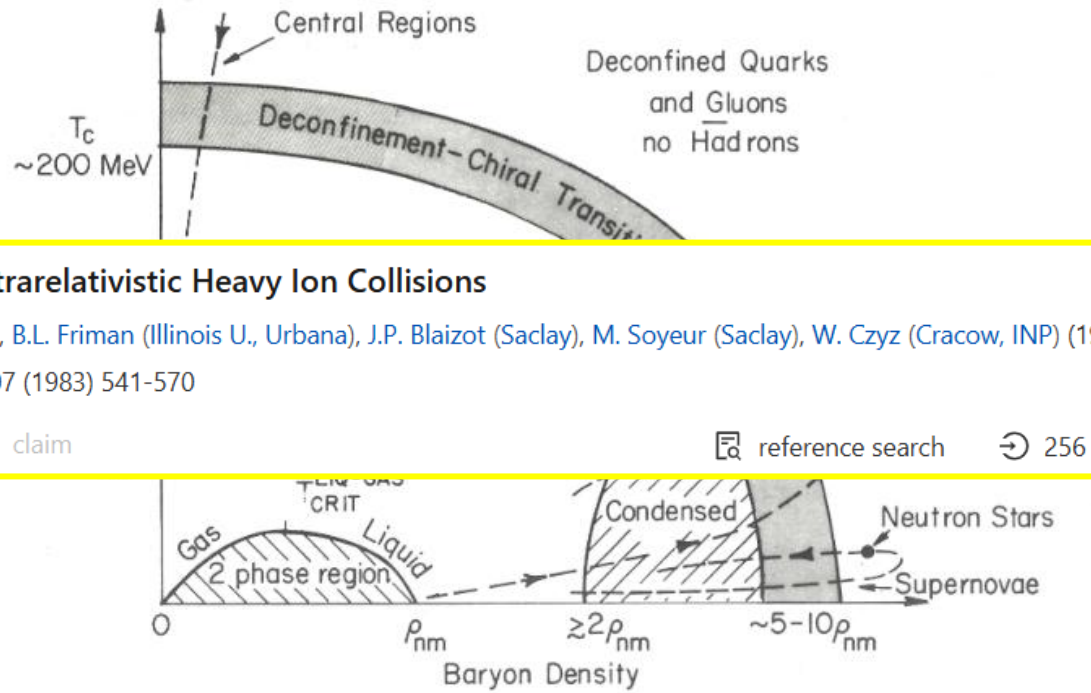
BNL 51801
UC-28
(Particle Accelerators and High
Voltage Machines — TIC-4500)

RHIC AND QUARK MATTER

PROPOSAL
for a
RELATIVISTIC HEAVY ION COLLIDER
at
BROOKHAVEN NATIONAL LABORATORY

August 1984

bnl aui



Hydrodynamics of Ultrarelativistic Heavy Ion Collisions #2

G. Baym (Illinois U., Urbana), B.L. Friman (Illinois U., Urbana), J.P. Blaizot (Saclay), M. Soyeur (Saclay), W. Czyz (Cracow, INP) (1983)

Published in: *Nucl.Phys.A* 407 (1983) 541-570

DOI cite claim reference search 256 citations

Fig. II.1 Phase diagram of Nuclear Matter (G. Baym, ref. 3). Temperature is plotted vs. net baryon density for an extended volume of nuclear matter in thermal equilibrium. Normal nuclear matter appears at the point ρ_{nm} at zero temperature, and this is the neighborhood explored by low energy nuclear physics. The region of the phase transitions corresponding to deconfinement (at temperature T_C) and chiral symmetry restoration is indicated T_F. The two critical temperatures may well be coincident. The confinement force couples quarks to form hadrons. The chiral force binds the collective excitation to Goldstone bosons. Above T_C, hadrons dissolve into quarks and gluons. Above T_F quarks are massless. The indicated trajectories show two avenues for probing the quark-gluon plasma with high energy nucleus-nucleus collisions: by reaching high baryon densities among the hot, compressed fragments of the colliding nuclei, and at very high temperatures in the central rapidity region among thermally produced particles where conditions may approximate those of the early universe.

NEHÉZION ÜTKÖZÉSEK – SZILAJ BIVALY TÜRKÖLÉSEK – ÚJ ŐSANYAG GERJESZTÉSEK /T.D. LEE, 1989/

A Tsung Dao (T.D) Lee Könyvtár szívességéből

T. D. Lee verse és
Li Keran festménye, 1989

Az UNT Digital Library fogadja hálás köszönetünket

Új hangsúly:
Többes számú
gerjesztések!

Legalább két új halmazállapot!

1996: A TÉKOZLÓ η′ BOZON VISSZATÉR

The Return of the prodigal Goldstone boson #2

Joseph I. Kapusta (Minnesota U.), D. Kharzeev (CERN and Bielefeld U.), Larry D. McLerran (Minnesota U.) (Jun, 1995)

Published in: *Phys.Rev.D* 53 (1996) 5028-5033 • e-Print: hep-ph/9507343 [hep-ph]

pdf DOI cite claim reference search 154 citations

After an η' is produced it must survive subsequent hadronic interactions until it has escaped the matter. The η' lifetime in vacuum is about 1000 fm/c; if there were no interactions with surrounding particles, it would certainly survive the time it takes for the hadronic matter produced in heavy ion collisions to dissipate.

Szignifikáns

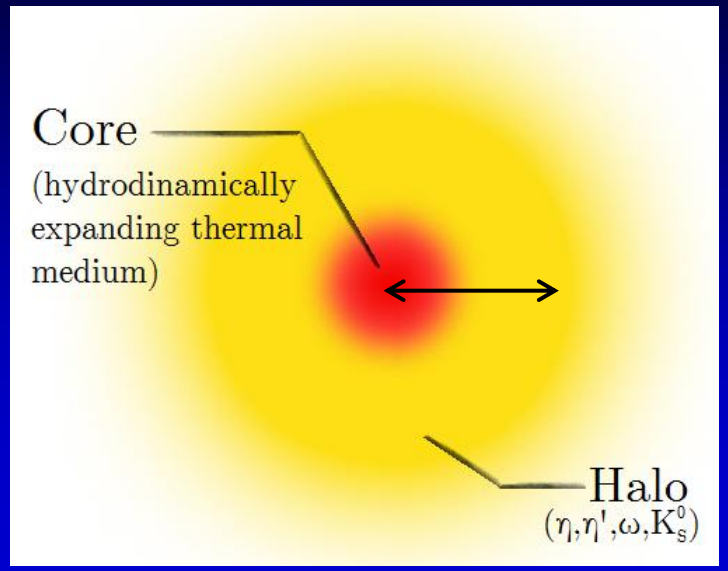
közegbeli η′ módosulás, elméleti jóslata, de

Hogyan figyelhető meg?

We should emphasize that unlike the case for the ρ meson, and to a lesser degree for the ω and ϕ, the η' and the η mesons almost always decay after the surrounding hadronic matter has blown apart. Therefore one cannot expect to directly see the effect of the mass shift of the η' or the η meson: the only effect will be due to an enhanced production cross section.

Közegben módosult η′ megfigyelése: Fotonok? Dileptonok? Megnövekedett darabszám?

1996: Fő/háló modell, hosszú életű részecskék

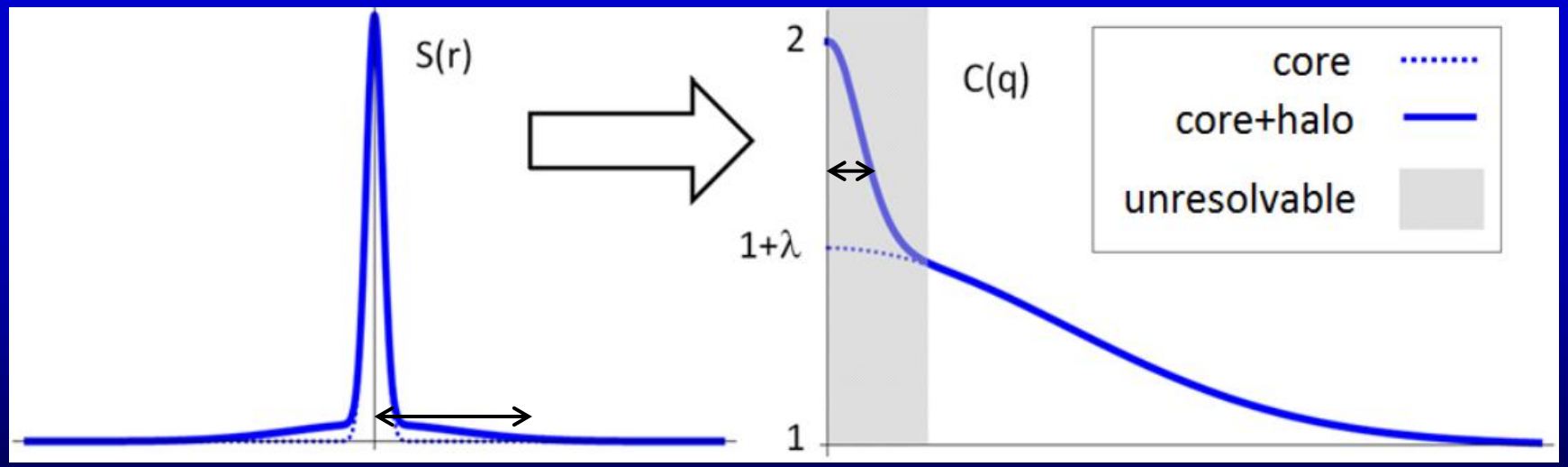


Resonance pions reduce the corr. strength [1, 2]
Core-Halo model: $S = S_C + S_H$
Primordial pions - Core $\lesssim$ 10 fm
Resonance pions - from very far regions - Halo
Corr. strength→C-H ratio: $\lambda = \left(\frac{N_C}{N_C+N_H}\right)^2$

$R = \sqrt{\langle x^2\rangle - \langle x\rangle^2}.$

Szórás: <u>háló</u> dominált!

Pontos λ mérés: fontos !



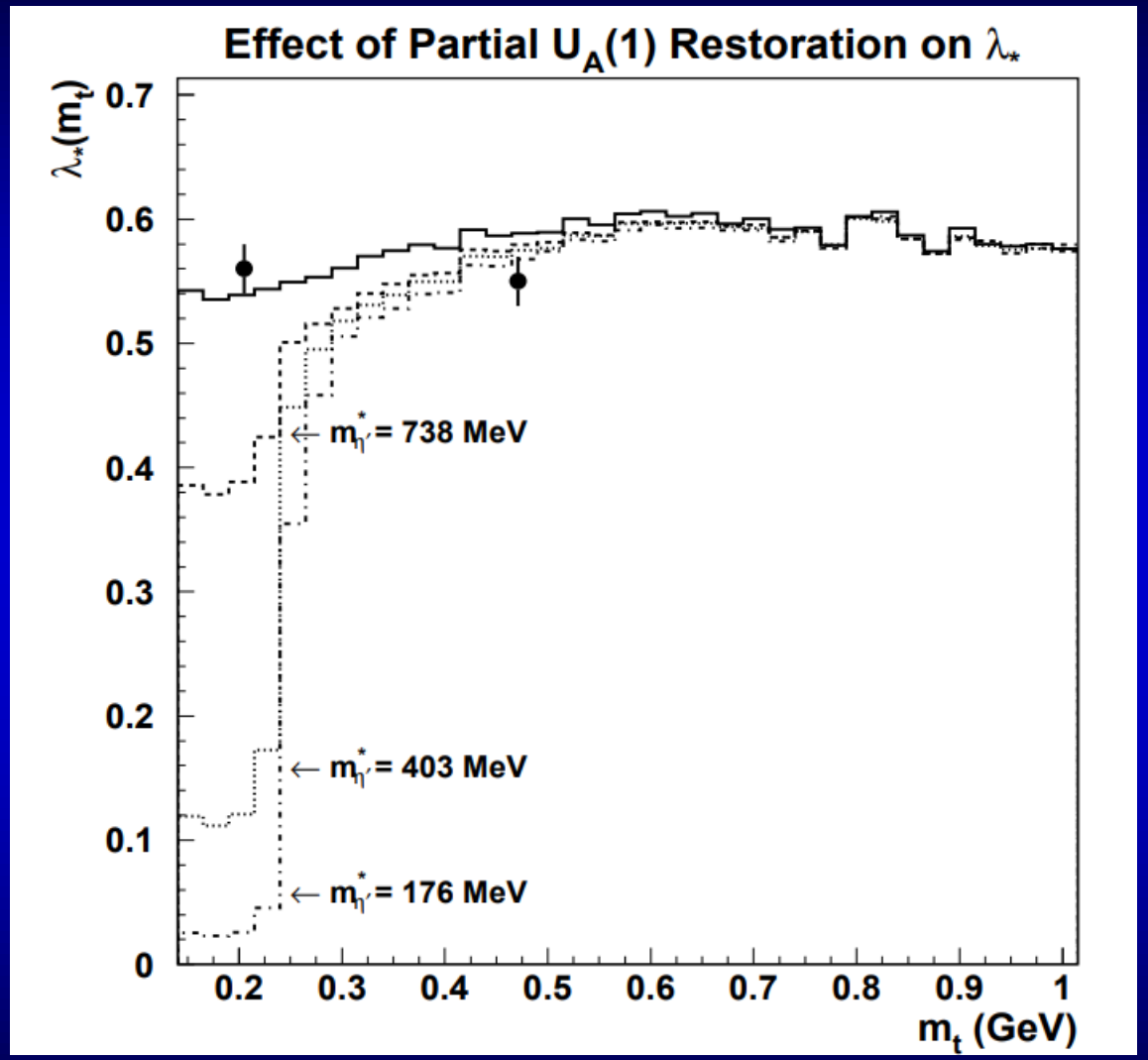
Pontos λ mérés fontos, ez a Q = 0 pontba való extrapoláción alapul. Kell a C(q) alakjának pontos meghatározása:

→ Lévy sorfejtés

[1] J. Bolz et al: Phys.Rev. D47 (1993) 3860-3870
[2] T. Cs, B. Lörstad, J. Zimányi: <u>hep-ph/9411307</u>, Z.Phys. C71 (1996) 491-497

M.B.de Kock, H.C.Eggers, T.Cs.: *<u>PoS WPCF2011 (2011) 033</u>*
T. Novák et al *(WPCF 2015)* : *<u>Acta Phys.Polon.Supp.</u>* <u>9 (2016) 289</u>
T. Cs., R. Paseschnik and A. Ster: *<u>Eur. Phys. J. C</u>* <u>79 (2019) 1, 62</u>

1998: ÉRZÉKENY AZ η' TÖMEG KÖZEGBELI MÓDOSULÁSÁRA



NA44 S+Pb data + Monte Carlo,

NA44 E_{lab} = 200 AGeV (SPS)

S+Pb data sensitive to

in-medium η' modification, but

NO EFFECT

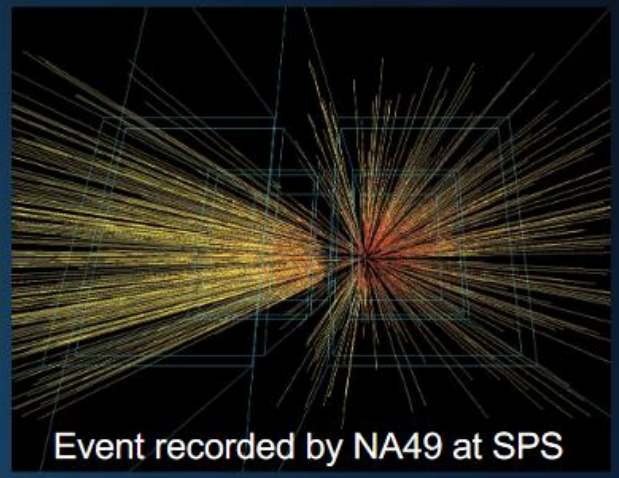
S. Vance, T. Cs, D. Kharzeev,
PRL 81 (1998) 2205-2208
nucl-th/9802074 [nucl-th]

Közegbeli η' módosulás: Lehet-e ki és bekapcsolni? Centralitás? Energia? Rendszer méret?

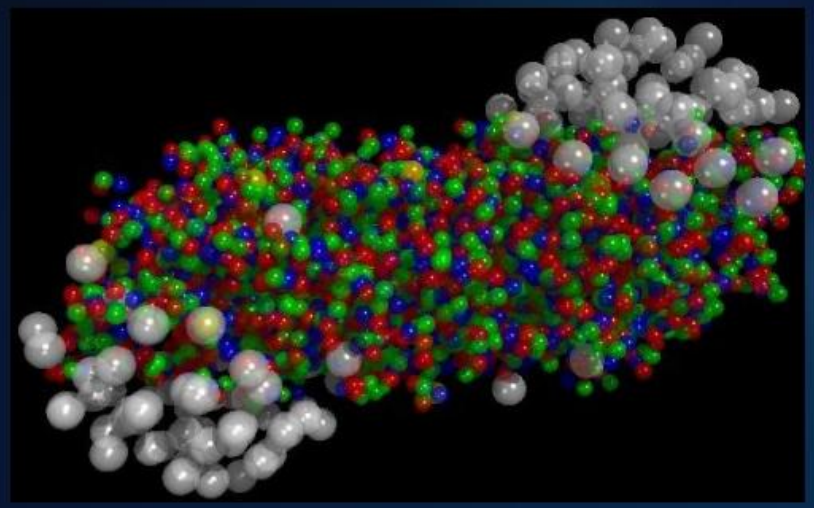
2000: „EGY ÚJ HALMAZÁLLAPOT, A QGP” /CERN/

CERN, February 2000: first evidence of a new state of matter, the quark-gluon plasma

- Combined data from the 7 experiments on CERN's HI programme
- Proves an important prediction of the QCD theory. An important step forward in the understanding of the early evolution of the Universe.



Event recorded by NA49 at SPS



Luciano Maiani (CERN DG): “… We now have evidence of a new state of matter where quarks and gluons … onfined. … There is still an entirely new territory to b… concerning the physical properties of quark-g… er. The challenge now passes to RHIC at BNL and late… the LHC."

Új hangsúly:
Egyes szám, egyetlen egy új állapot …

2000 – CERN Sajtótájékoztató: Mekkora a kvarkok szabad úthossza?

Quark liberation and coalescence at CERN SPS

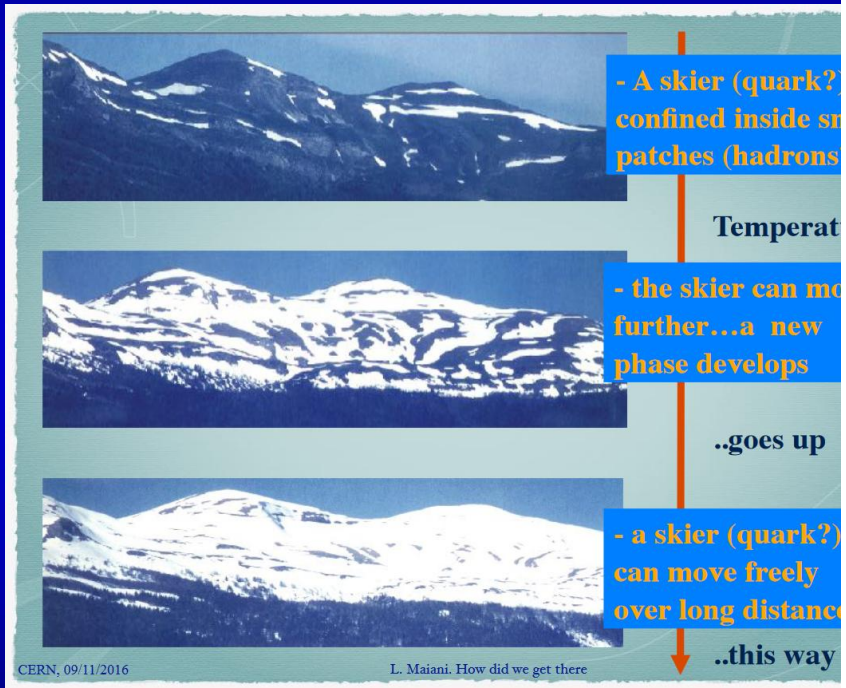
J. Zimanyi (Budapest, RMKI), T.S. Biro (Budapest, RMKI), T. Csorgo (Budapest, RMKI), P. Levai (Bu

Published in: *Phys.Lett.B* 472 (2000) 243-246 • e-Print: hep-ph/9904501 [hep-ph]

New form of matter at CERN SPS: Quark matter but not quark gluon plasma #7

T. Csorgo (Budapest, RMKI) (Jun, 2000)

Published in: *Nucl.Phys.B Proc.Suppl.* 92 (2001) 62-74 • Contribution to: 9th International Workshop on Multiparticle Production: New Frontiers in Soft Physics and Correlations on the Threshold of the New Millenium (Torino 2000), 62-74 • e-Print: hep-ph/0011339 [hep-ph]



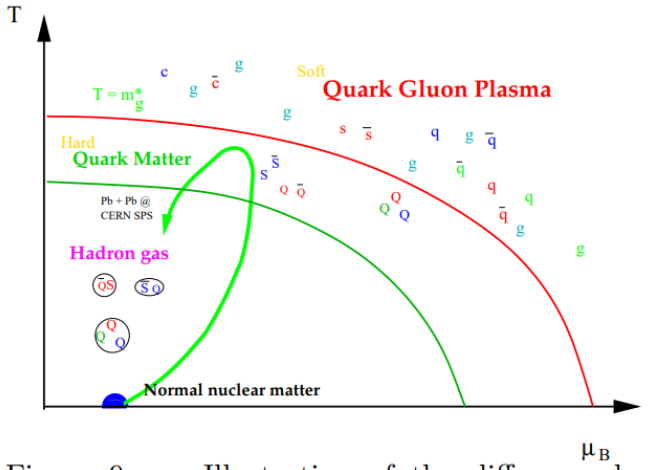


Figure 9. Illustration of the difference between Quark Matter consisting of dressed quarks, strange quarks and Quark Gluon Plasma which contains in a significant amount light and strange (undressed) (anti-)quarks as well as gluons .

$$T_{\mathrm{slope}} = T_{\mathrm{f}} + \tfrac{1}{2} m_0 \langle v_\perp \rangle^2 . \qquad (4)$$

Such an approximately linear rest mass dependence is indeed observed. Figure 3 shows clearly that the spectra contain a collective flow component; inverse slopes of 300 MeV or more as seen e.g. for the protons can obviously not be interpreted as hadronic temperatures (see Figures 1 and 2). There is some scatter between the data from different

in coordinate space. Collective expansion tends to reduce the size of the regions within which particles can develop such correlations; thermal motion, controlled by the thermal velocity $\sim \sqrt{T/M_\perp}$, smears out the flow velocity gradients and thus acts in the opposite direction. This leads to a characteristic dependence of the size of the effective emission region for correlated pairs on their transverse mass $M_\perp$; its transverse size is controlled by the transverse flow velocity, $\langle v_\perp \rangle$ as shown by the approximate formula [21,16,17]

$$R_\perp^2 \approx \frac{R^2}{1 + \xi \langle v_\perp \rangle^2 (M_\perp / T_{\mathrm{f}})} . \qquad (5)$$

16. T. Csörgő, B. Lörstad, Nucl. Phys. A 590 (1995) 465c; Phys. Rev. C 54 (1996) 1390.
17. R. Scheibl and U. Heinz, Phys. Rev. C 59 (1999) 1585.

L. Maiani, a CERN főigazgatója:
A kvarkok szabad úthossza
a végtelenhez tart (makroszkópikus)

U. W. Heinz: folyadékviselkedés jelei,
A kvarkok szabad úthossza a nullához tart,
Hivatkozással hidrodinamikai eredményeinkre:
Nucl.Phys.A 685 (2001) 414-431,PRC54 (1996) 1390
Proc. NN2000, e-Print: hep-ph/0009170 [hep-ph]

T. Csörgő: Kvarkanyag, de nem QGP!,
A tulajdonságok eltérnek a várttól! A két átmenet közül csak egy figyelhető meg:
Nucl.Phys.B Proc.Suppl. 92 (2001) 62-74, e-Print: hep-ph/0011339 [hep-ph]

1963 – 2004: Lévy alakú források a C(Q) mérésére

The variation of certain speculative prices

B Mandelbrot - Journal of business, 1963 - Springer

… The classic model of the temporal **variation** of **speculative prices** (Bacheller 19(0) assumes that successive **changes** of a **price** Z(t) are independent Gaussian random variables. But, …

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Note number of citations: 11865 (and increasing)

Bose-Einstein correlations for Levy stable source distributions #1

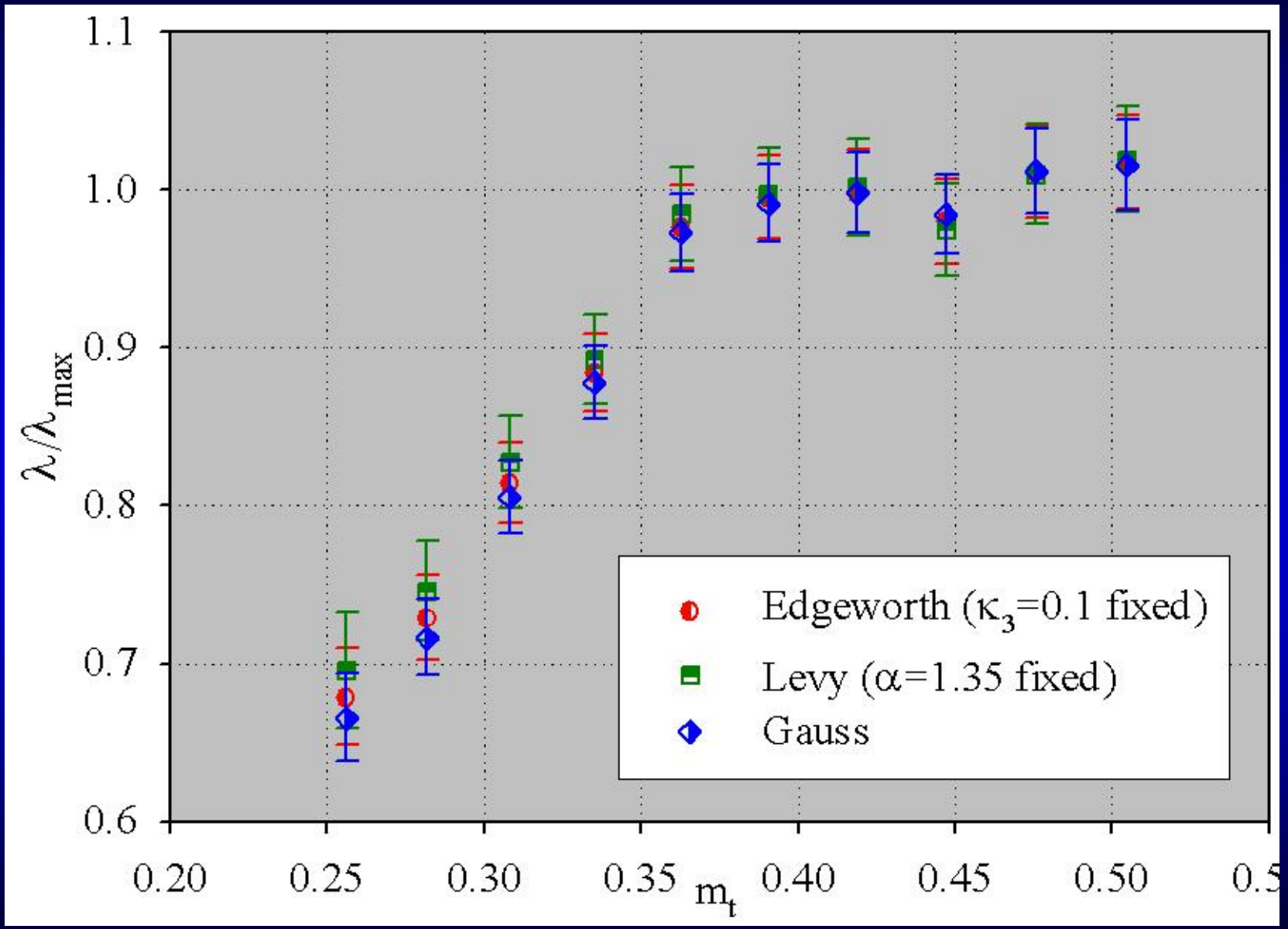
T. Csorgo (Budapest, RMKI), S. Hegyi (Budapest, RMKI), W.A. Zajc (Columbia U.) (Oct, 2003)

Published in: *Eur.Phys.J.C* 36 (2004) 67-78 • e-Print: nucl-th/0310042 [nucl-th]

pdf DOI cite claim reference search 156 citations

Levy stable source distributions in HEP: Cs.T., S. Hegyi and W.A. Zajc (2004)

2005 – Csanád Máté, PHENIX @ QM 2005, ELTE, Budapest



M. Csanád for PHENIX Collaboration, arXiv:nucl-ex/0509042:
λ / λ_{max} is independent of the method of extrapolation of $C_2(q)$ to $q = 0$
Important systematic errors cancel

2010: PHENIX ÉS STAR ADATOK ÚJRA ELEMZÉSE, LEGALÁBB 200 MEV AZ η' TÖMEG CSÖKKENÉSE @ CL 99.9%

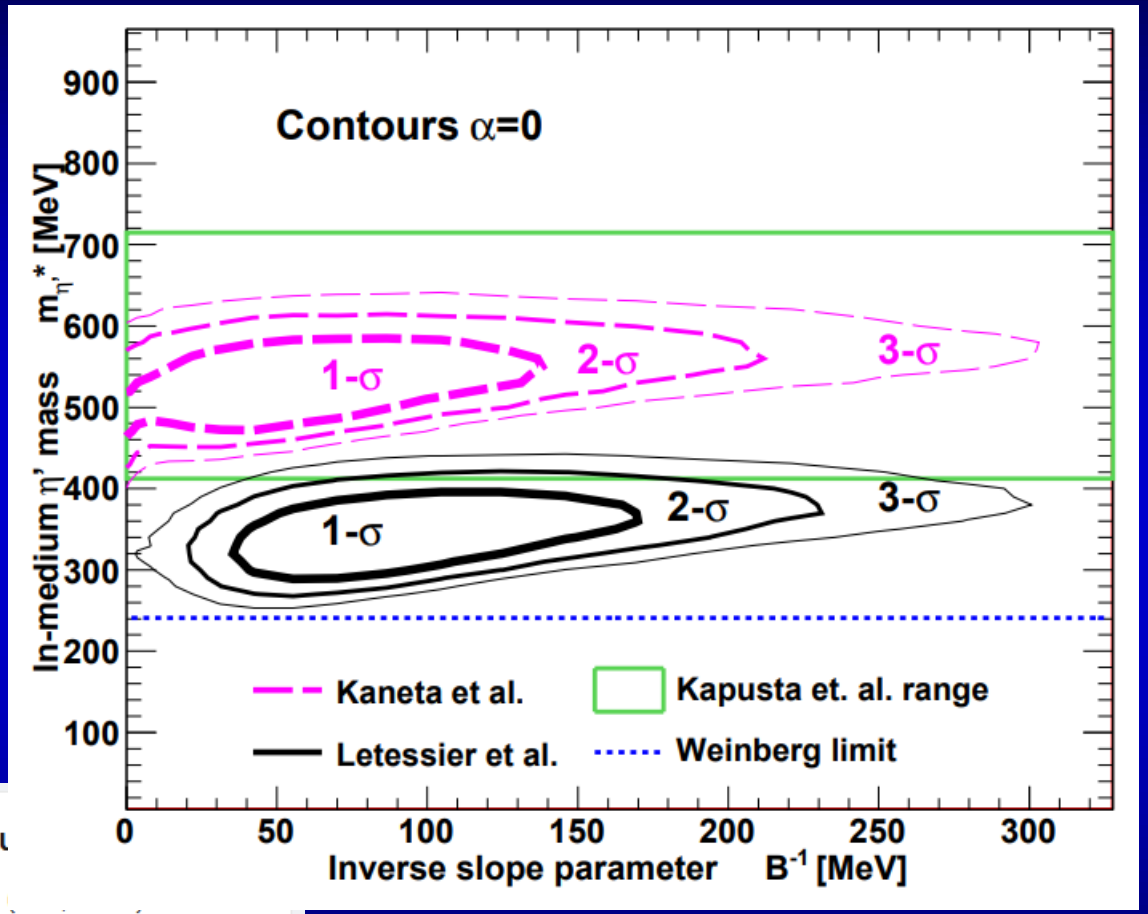
PHENIX and STAR 200 GeV Au+Au data @RHIC

sensitive to

in-medium η' modification, At least 200 MeV mass drop

EFFECT FOUND

- but without unique minimum



Indirect observation of an in-medium η ' mass reduction in $\sqrt{s_{NN}} = 200$ GeV Au+Au

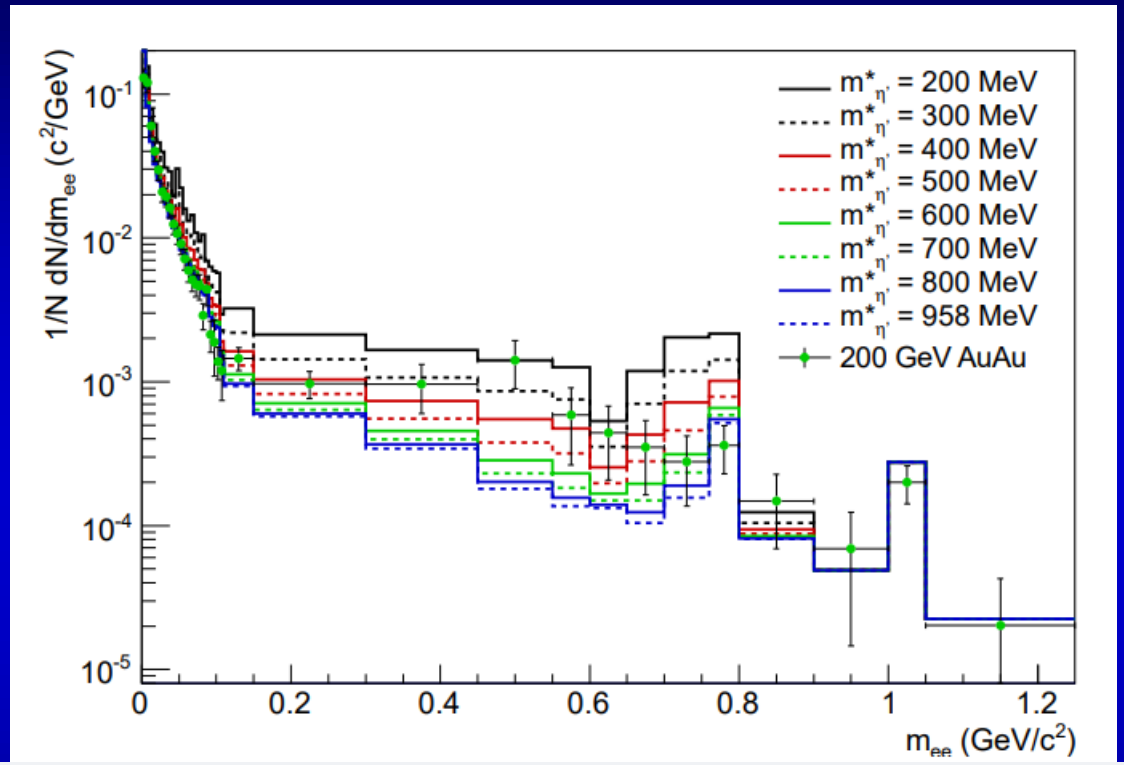
T. Csorgo (Harvard U., Phys. Dept. and Budapest, RMKI), R. Vertesi (Budapest, RMKI), J. Sziklai (Budapest, RMKI)

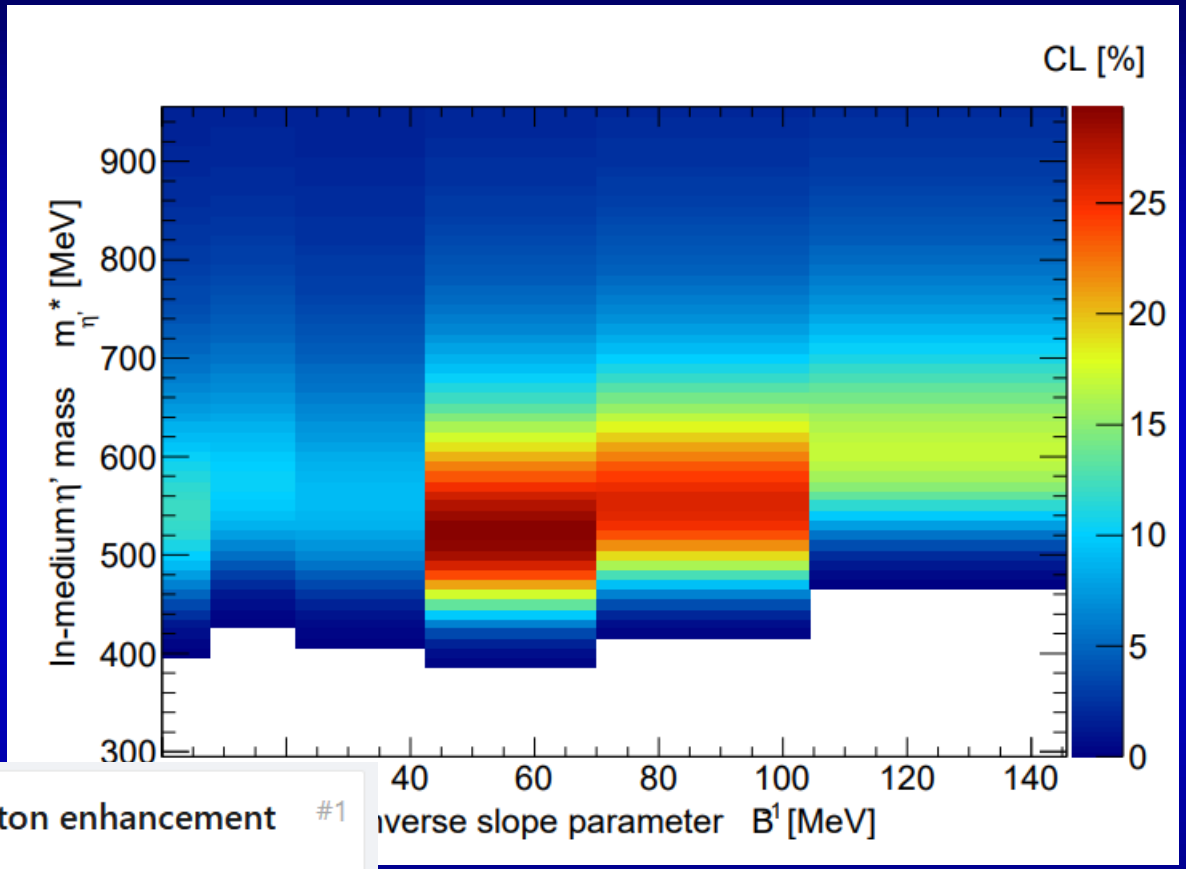
Published in: *Phys.Rev.Lett.* 105 (2010) 182301 • e-Print: 0912.5526 [nucl-ex]

pdf DOI cite claim reference search 88 citations

közegbeli η' tömegcsökkenés: lehet-e ki és bekapcsolni? IGEN!
Centralitás? Energia? Rendszer méret?

2013: A PHENIX 200 GEV AU+AU DIELEKTRON MÉRÉS, MINIMUM BIAS ADATOK ÚJRAELEMZÉSE: ÉRZÉKENY, DE...





Effects of chain decays, radial flow and $U_A(1)$ restoration on the low-mass dilepton enhancement in $\sqrt{s_{NN}} = 200$ GeV Au+Au reactions #1

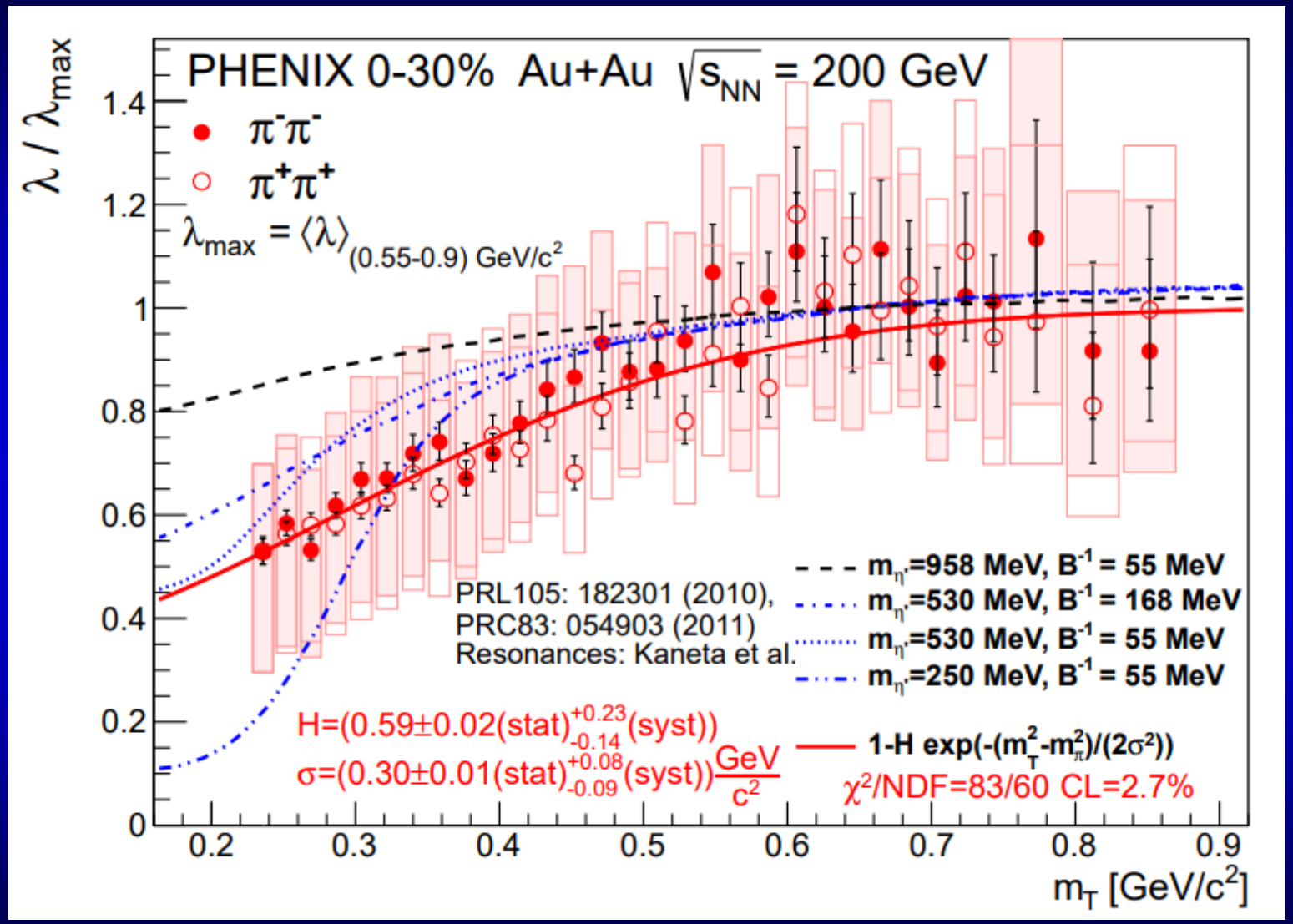
Marton Vargyas (Eotvos U.), Tamas Csörgő (Hungarian Acad. Sci., Budapest), Robert Vertesi (Rez, Nucl. Phys. Inst.) (Nov, 2012)

Published in: *Central Eur.J.Phys.* 11 (2013) 553-559 • e-Print: 1211.1166 [nucl-th]

pdf DOI cite claim reference search 6 citations

közegbeli η' módosulás: Szignifikáns vajon? A PHENIX min bias Au+Au adatokban nem ...

2018: 0-30 % CENTRALITÁSÚ ADATOK ÉRZÉKENYSÉGE



PHENIX data + Monte Carlo,

PHENIX Phys. Rev. C 97 (2018) 064911:

0-30 % Au+Au @ 200 GeV
Lévy Bose-Einstein

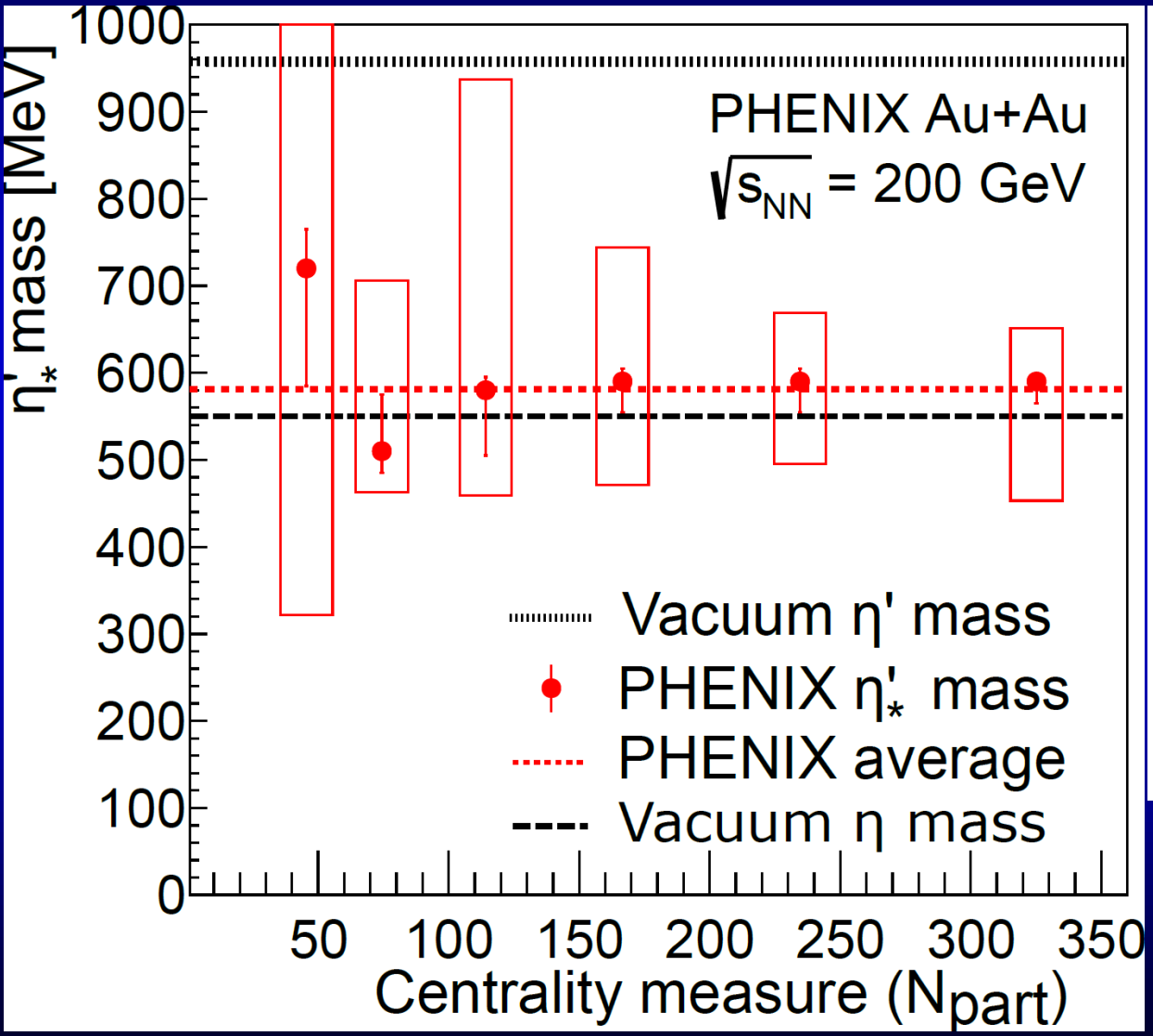
PHENIX data sensitive to

in-medium η' modification

centrality dependence = ?

közegbeli η' tömegcsökkenés: lehet-e ki és bekapcsolgatni? IGEN!
Centralitás? Energia? Rendszer méret?

2024: „MÁSODIK QCD ÁTMENETRE UTAL …”
/A PRC SZERKESZTŐINEK AJÁNLÁSA SZERINT/



EDITORS' SUGGESTION

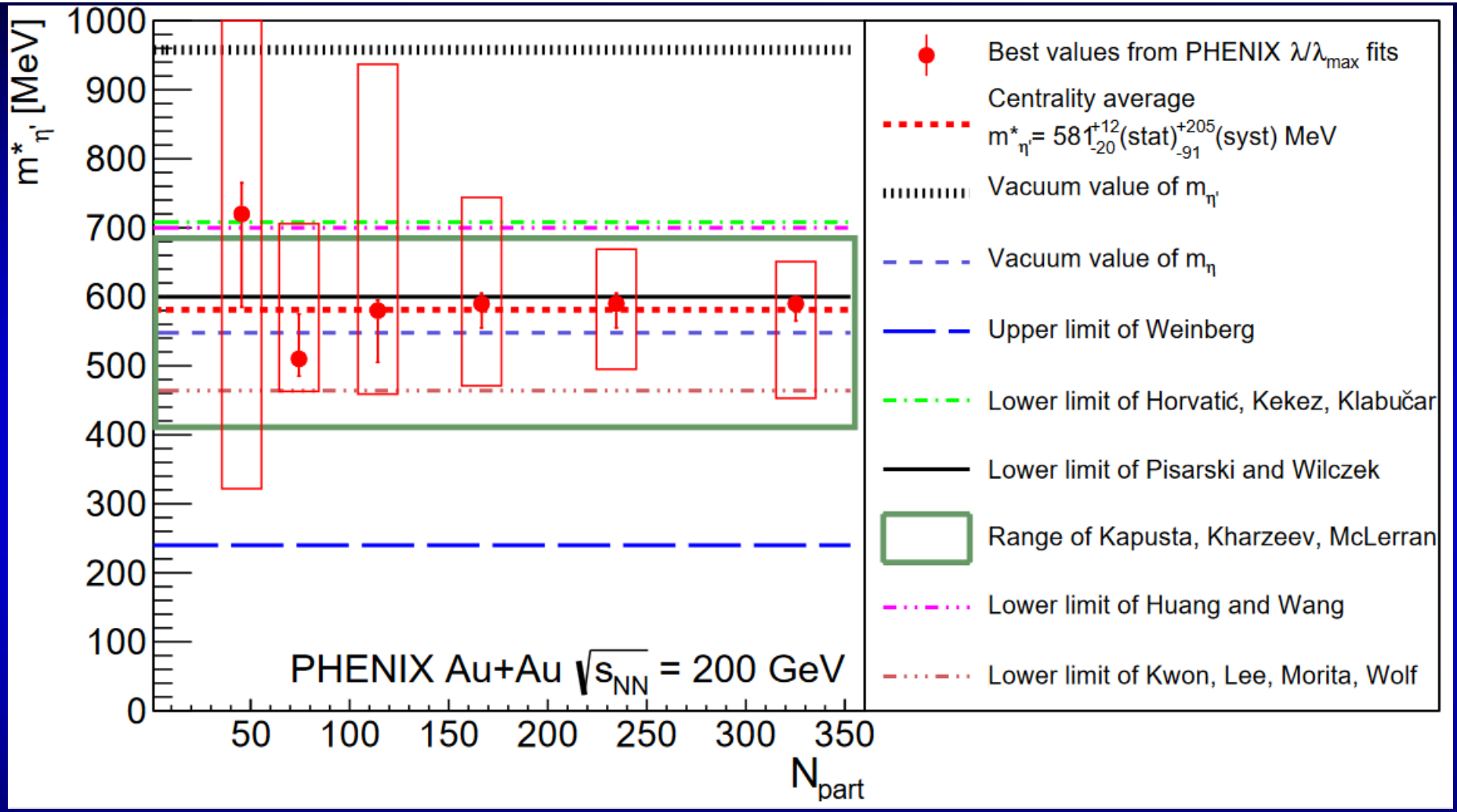
Centrality dependence of Lévy-stable two-pion Bose-Einstein correlations in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions

20 DECEMBER, 2024

Color deconfinement and chiral-symmetry restoration have long been predicted by QCD theory. Color deconfinement in the form of a nearly perfect fluid of quarks was reported by all four RHIC experiments in 2005. Now, the PHENIX Collaboration details two-pion Lévy-stable Bose-Einstein correlation data in Au+Au collisions at the top RHIC energy. They report a significant reduction of the mass of the η' meson in hot and dense hadronic, color-confining matter. This implies a second transition in QCD by the return of the so-called prodigal Goldstone boson—a specific kind of partial chiral-symmetry restoration—and calls for further, challenging experimental studies, aiming at direct measurements of identified η' spectra in high-energy heavy-ion collisions.

N. J. Abdulameer *et al.* (PHENIX Collaboration)
Phys. Rev. C **110**, 064909 (2024)

A KÖZEGBEN MÓDOSULT η′ TÖMEGE ÉS A CENTRALITÁS



In-medium mass of η′ is determined with the help of Levy Bose-Einstein correlation measurements and Monte-Carlo simulations to be similar to the vacuum mass of η in each centrality class: indirectly, return of the prodigal Goldstone boson η′
Centrality dependent selection power, successful: KHM, KLMW, PW: $m^*(\eta') \sim m(\eta)$

A MAGYAR PHENIX EREDMÉNY SAJTÓANYAGAI

https://wpcf2026.elte.hu/press/

MAGYAR AGRÁR- ÉS ÉLETTUDOMÁNYI EGYETEM

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Hírek

Létrehozva: 2026 január 20.

Első pillantást vethettek az ősanyag második új formájára

A Magyar Agrár- és Élettudományi Egyetem (MATE) Kutatási Kiválósági Programjai keretében támogatott, Csörgő Tamás fizikus, az Európai Akadémia tagja által vezetett kutatócsoport eredménye kiemelten jelent meg az Amerikai Fizikai Társulat vezető magfizikai lapjában, a Physical Review C-ben, a lap szerkesztőinek ajánlásával. A közvetett,

Első pillantást vethettek az ősanyag második új formájára

2026.06.01.

Beszámoló az ELTE-n lezajlott femtoszkópiai konferenciáról és a PHENIX kísérlet eredményeiről

Tovább

ÖSSZEGZÉS

Idővonal 1974-től 2024-ig
T.D.Lee (1974), S. Weinberg (1975) és F. Wilczek (1984)
A RHIC tervezete (1984)
PHENIX és STAR Bose-Einstein adatok újra elemzése (2010)
PHENIX dielectron spectrum újra elemzése (2013)

A tékozló bozon visszatért,
Első, közvetett észlelés (PHENIX , 2024)

Centrality dependent Levy stable Bose-Einstein correlations measured in $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions by PHENIX

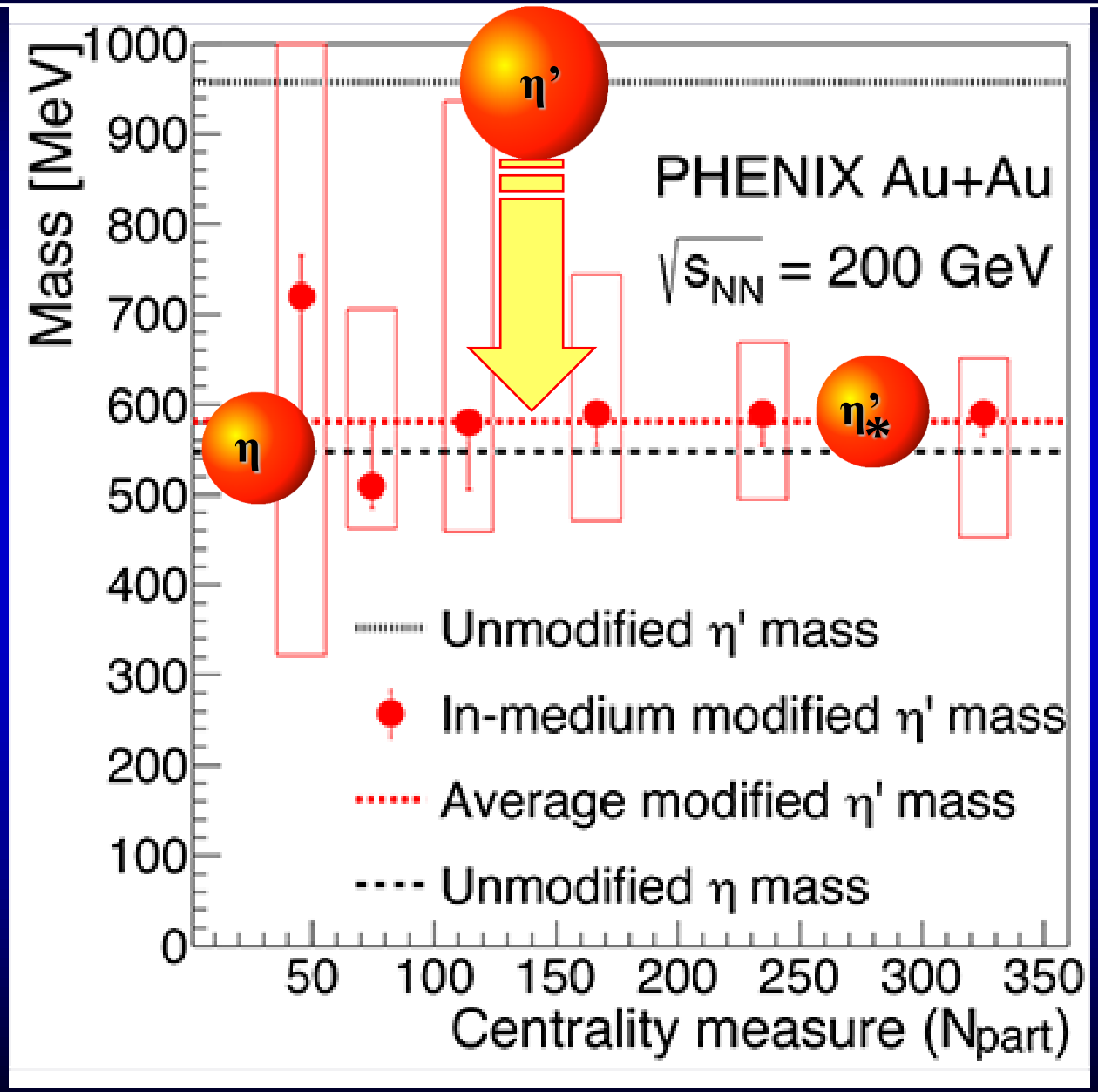
Közvetlen észlelés pl: $\eta' \rightarrow \gamma + \gamma$ óriási kihívás,
Egyben óriási lehetőség:

Kihívás a fiatalok számára !

20

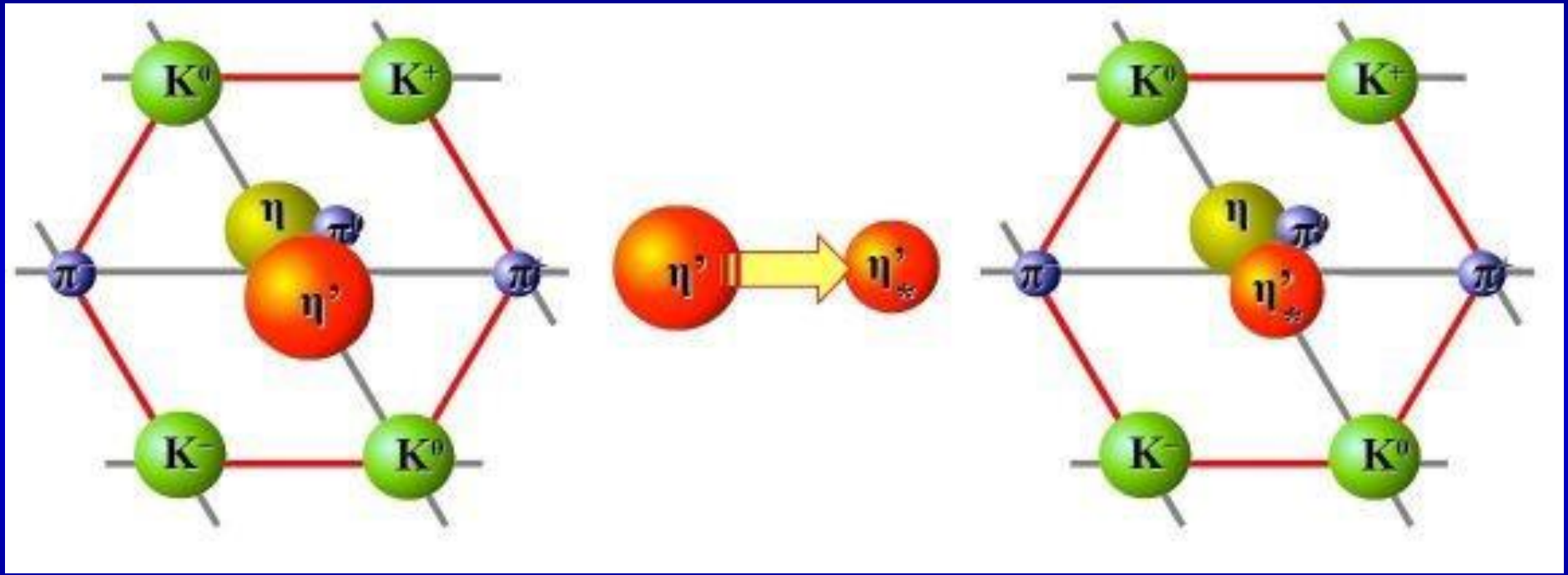
„THIS IMPLIES A SECOND TRANSITION IN QCD”

PRC Editors



Köszönöm a figyelmet!

Kérdések?



Hasonlat: Eta néni és Etike ...

Partially supported by NKFIH and MATE KKP FRG and HUN-REN Wigner RCP, Hungary
and by the PHENIX funding agencies and organizations listed at https://www.bnl.gov/rhic/phenix.php

Q&A: EXPECTED QUESTIONS AND THEIR ANSWERS

Q1: CAN WE SEE THE η′ MASS IN DILEPTON SPECTRA?

The Return of the prodigal Goldstone boson

Joseph I. Kapusta (Minnesota U.), D. Kharzeev (CERN and Bielefeld U.), Larry D. McLerran (Minnesota U.) (Jun, 1995)

Published in: *Phys.Rev.D* 53 (1996) 5028-5033 • e-Print: hep-ph/9507343 [hep-ph]

After an η' is produced it must survive subsequent hadronic interactions until it has escaped the matter. The η' lifetime in vacuum is about 1000 fm/c; if there were no interactions with surrounding particles, it would certainly survive the time it takes for the hadronic matter produced in heavy ion collisions to dissipate.

We should emphasize that unlike the case for the ρ meson, and to a lesser degree for the ω and ϕ, the η' and the η mesons almost always decay after the surrounding hadronic matter has blown apart. Therefore one cannot expect to directly see the effect of the mass shift of the η' or the η meson: the only effect will be due to an enhanced production cross section.

Q2: INDIRECT SIGNAL IN DILEPTON SPECTRUM?

A2: IN-MEDIUM η′ MASS VS PHENIX MIN BIAS DILEPTON

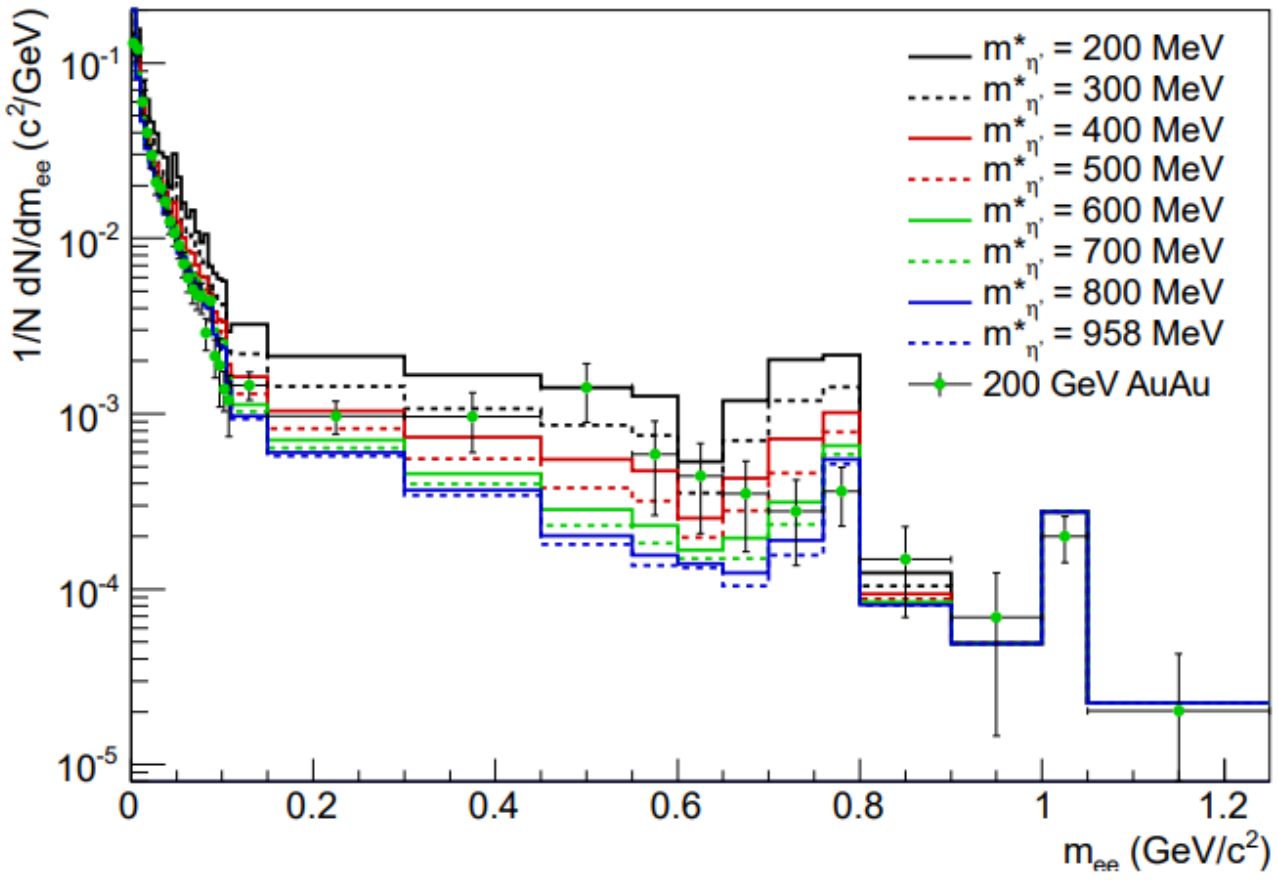


Figure 6: Dilepton cocktail in PHENIX acceptance, for different in-medium η' mass values. Points are PHENIX data of Ref. [1].

Cross-check with earlier dielectron analysis of arXiv:1211.1166, 200 GeV min bias Au+Au

CL (OR P-VALUE) MAPS FROM PHENIX MIN BIAS DILEPTON

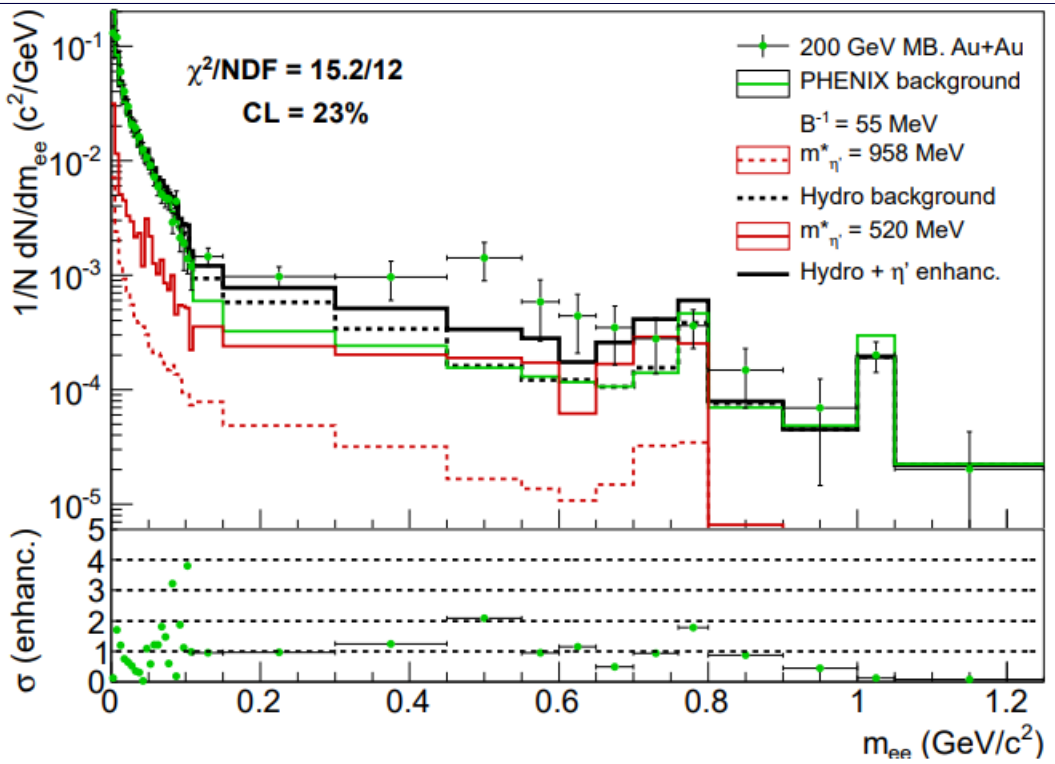


Figure 4: Dilepton spectra in PHENIX acceptance with the perfect hydrodynamics motivated spectrum of Eq. (4) including chain decays. The dashed red line is the contribution of the unmodified η', the solid one is the contribution from the best fit, $m^*_{\eta'}$=520 MeV. Dashed and solid black lines are the corresponding total cocktails. Points are PHENIX data, the green line is the reproduced cocktail [1].

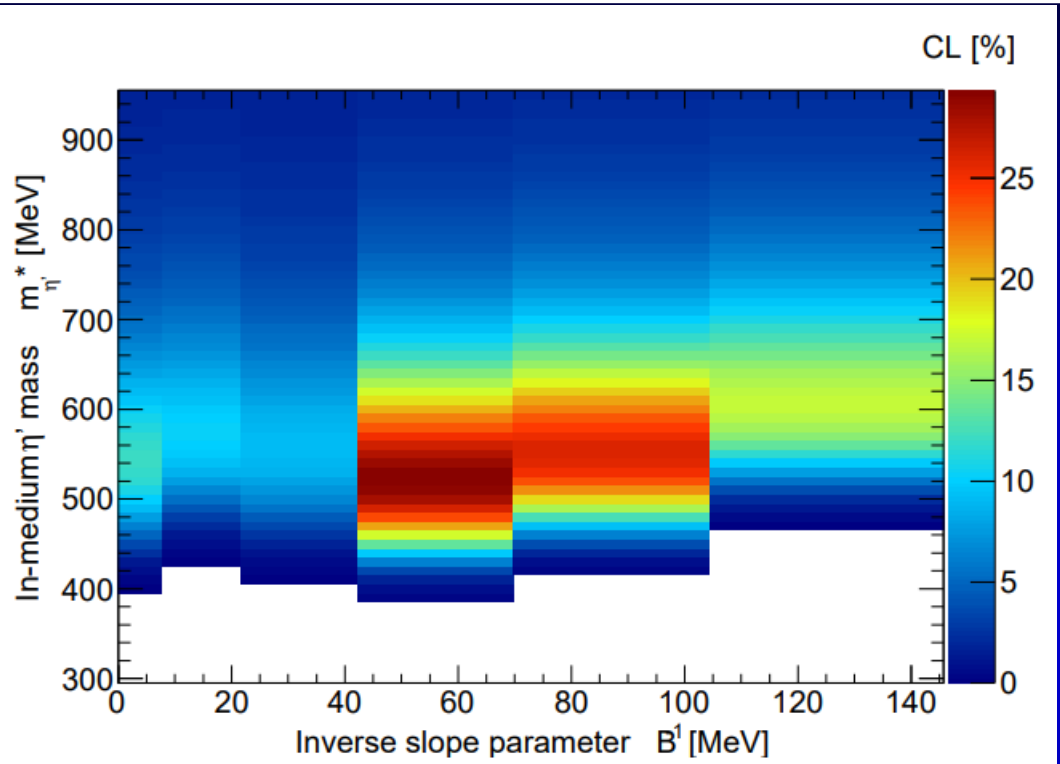
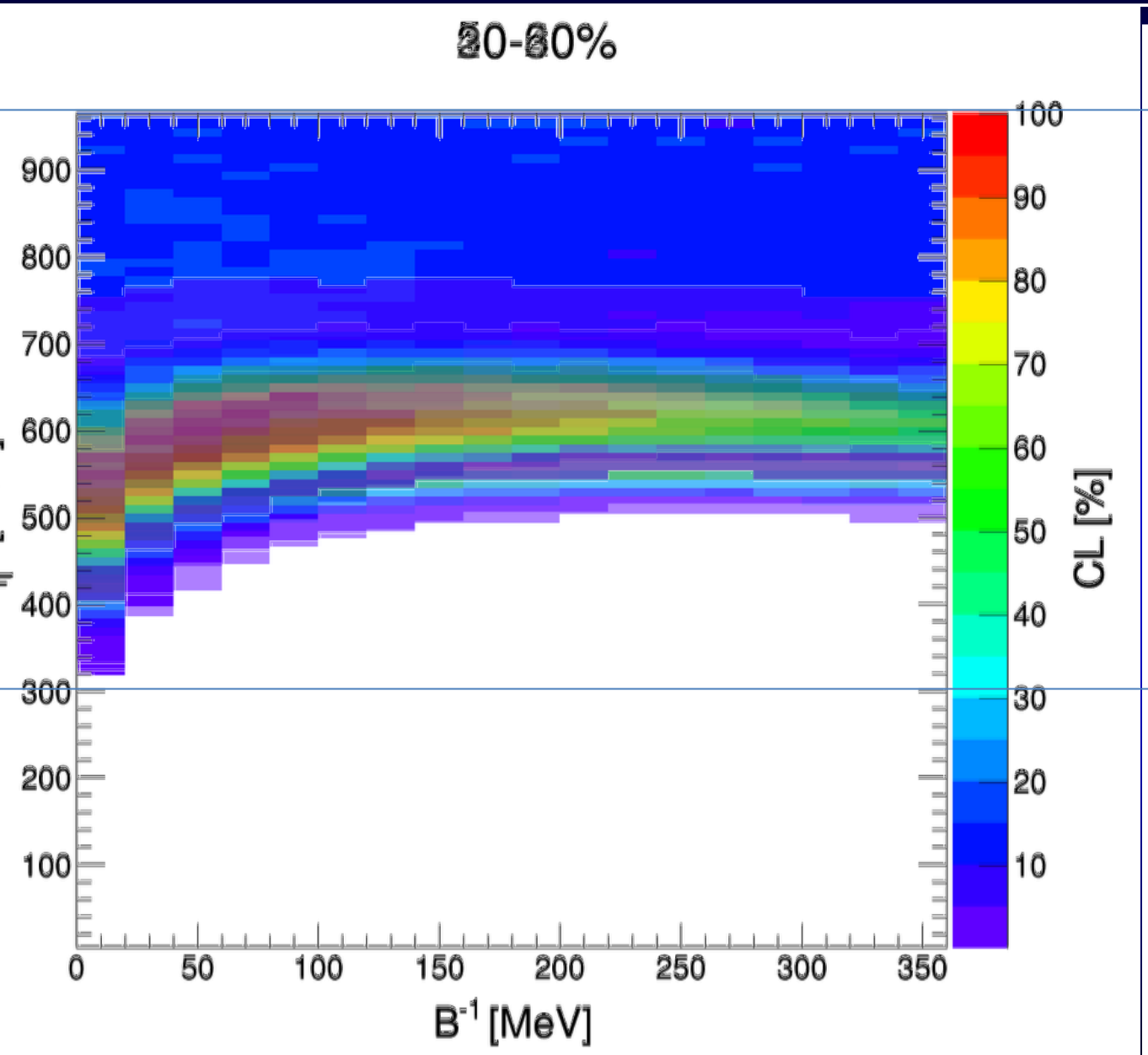


Figure 5: Preliminary confidence level map of the two η' spectrum parameter B^{-1} and $m^*_{\eta'}$. Best fit corresponds to $m^*_{\eta'}\approx$520 MeV and $B^{-1}\approx$55 MeV. The $m^*_{\eta'}<$380 MeV region (white) corresponds to CL<0.1% and can be excluded, but no upper limit can be given.

Cross-check with earlier dielectron analysis of rXiv:1211.1166, 200 GeV min bias (0-92%) Au+Au

10 → 60 % LEVY HBT VS MIN BIAS DIELECTRON



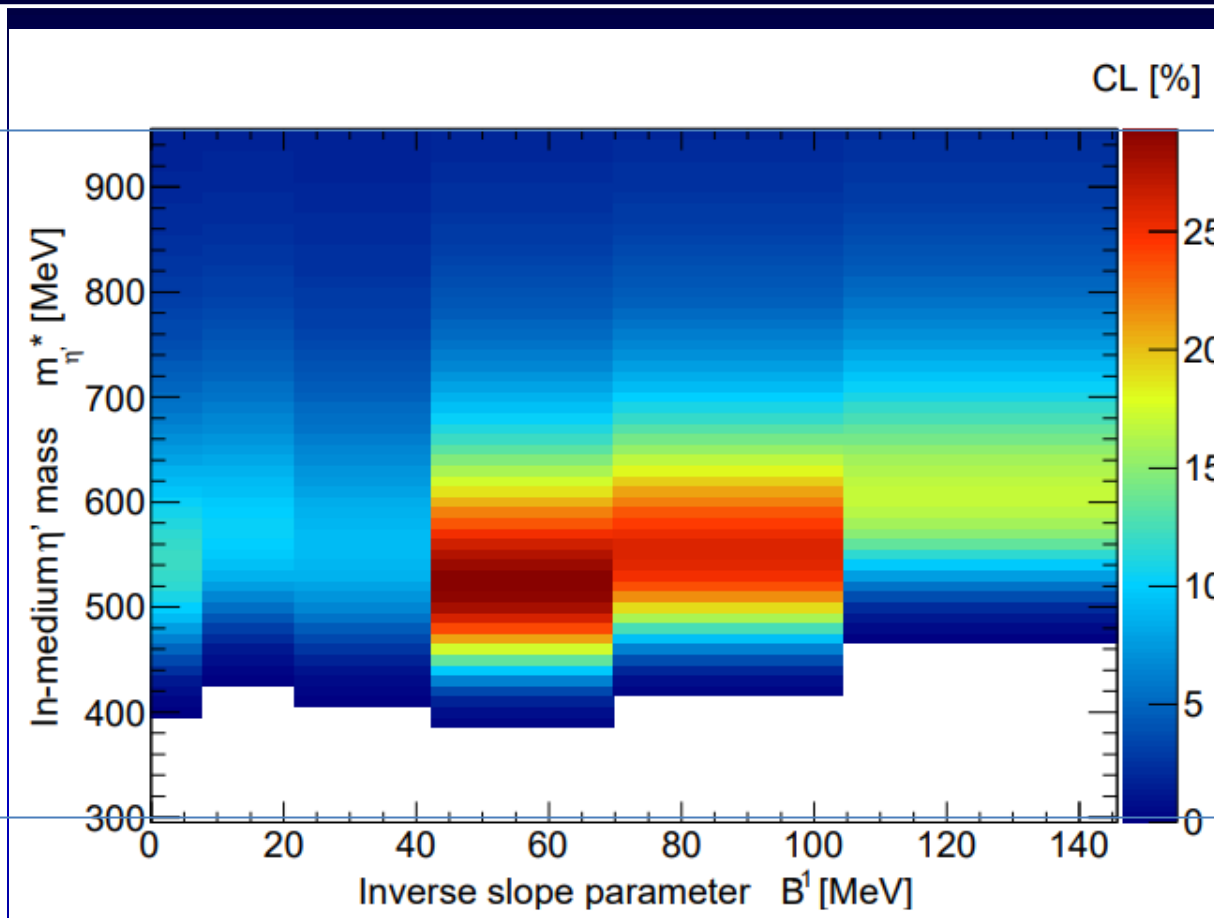


Figure 5: Preliminary confidence level map of the two η' spectrum parameter B^{-1} and $m^*_{\eta'}$. Best fit corresponds to $m^*_{\eta'}$≈520 MeV and B^{-1}≈55 MeV. The $m^*_{\eta'}$<380 MeV region (white) corresponds to CL<0.1% and can be excluded, but no upper limit

N_{part} DEPENDENCE OF IN-MEDIUM MASS OF η′

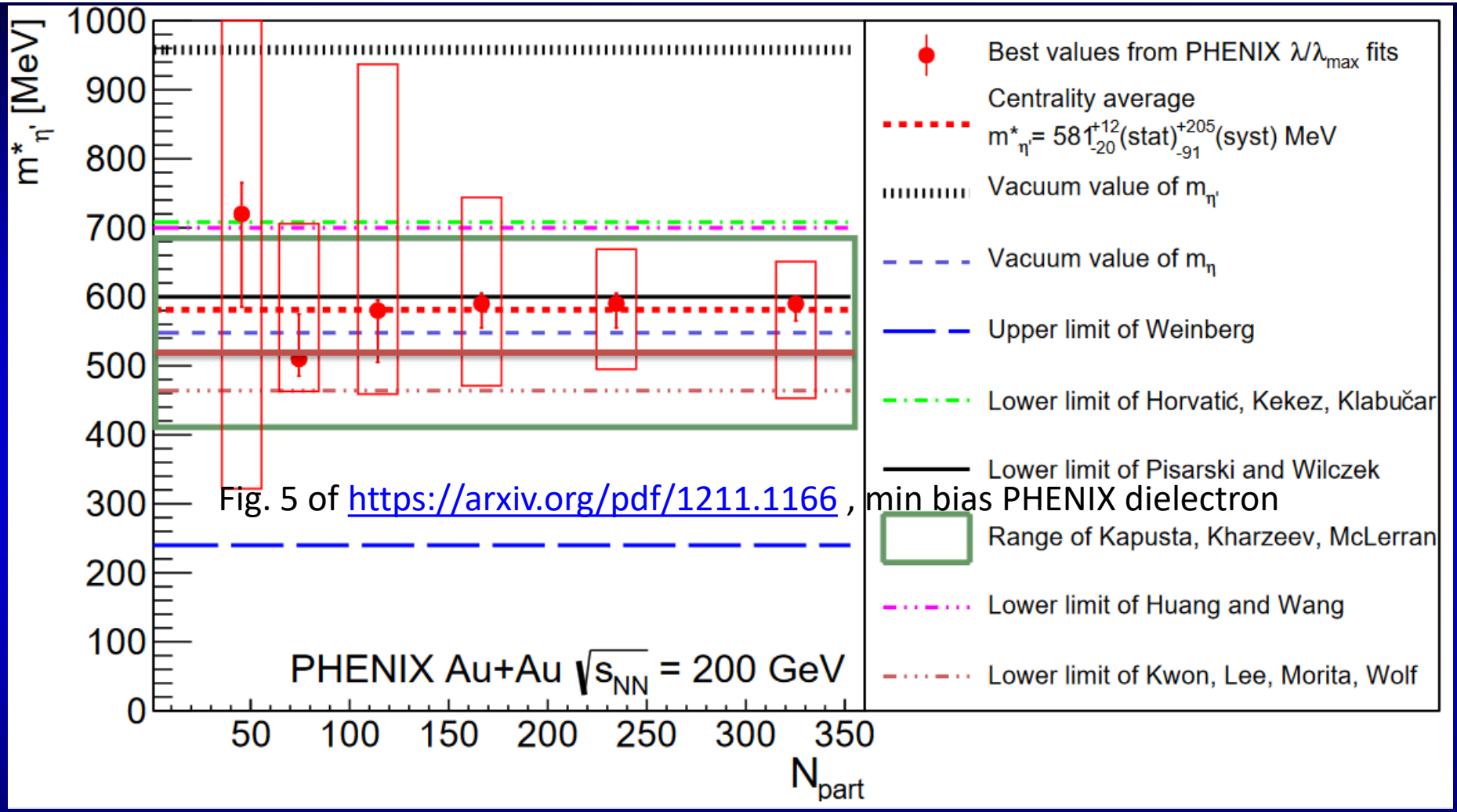


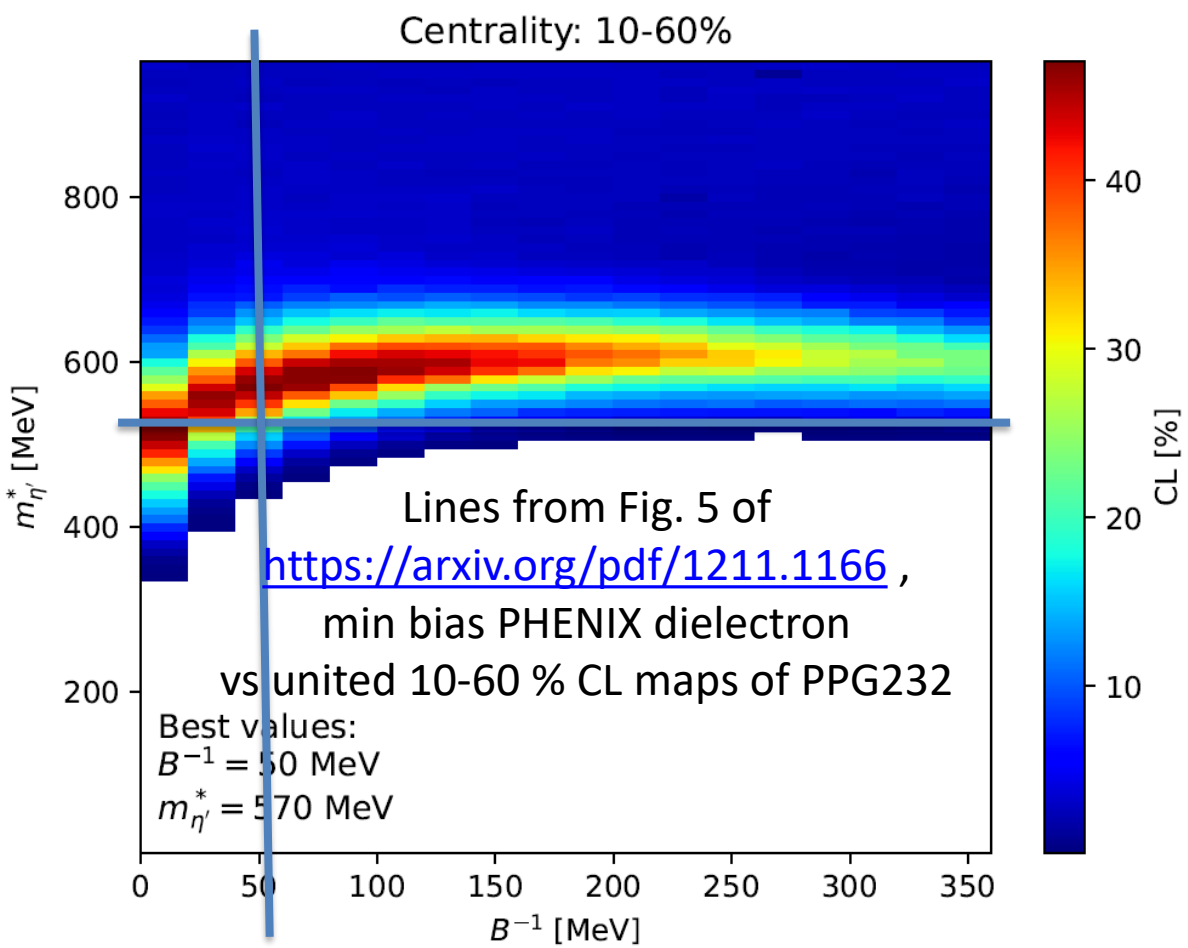
Fig. 5 of https://arxiv.org/pdf/1211.1166 , min bias PHENIX dielectron

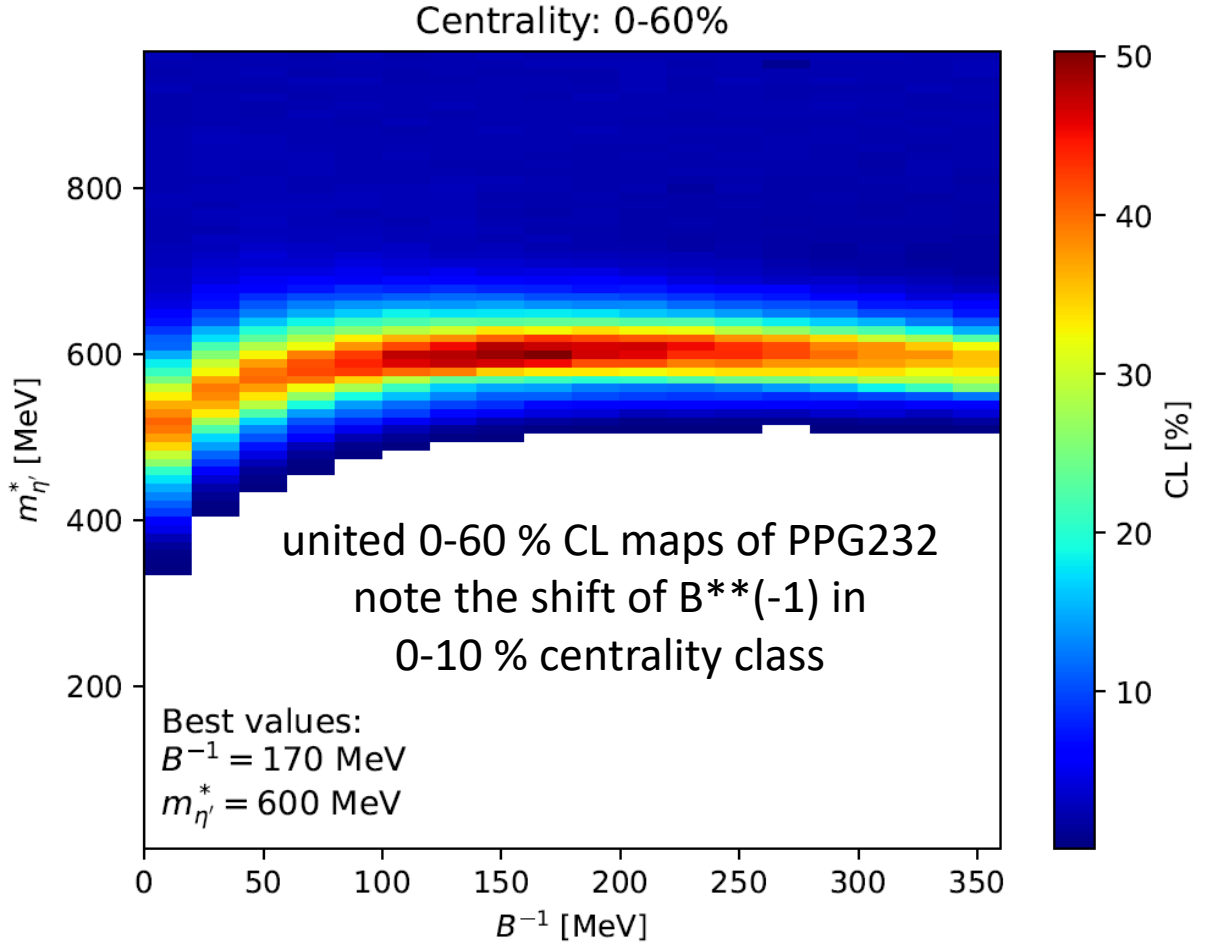
In-medium mass of η′ is determined with the help of Levy Bose-Einstein correlation measurements and Monte-Carlo simulations to be similar to the vacuum mass of η in each centrality class: indirectly, return of the prodigal Goldstone boson η′

Centrality average consistent with earlier (0-92%) dielectron analysis of arXiv:1211.1166

UNITING CL MAPS (10-60 %, 0-60 %) VS MIN. BIAS DIELECTRON

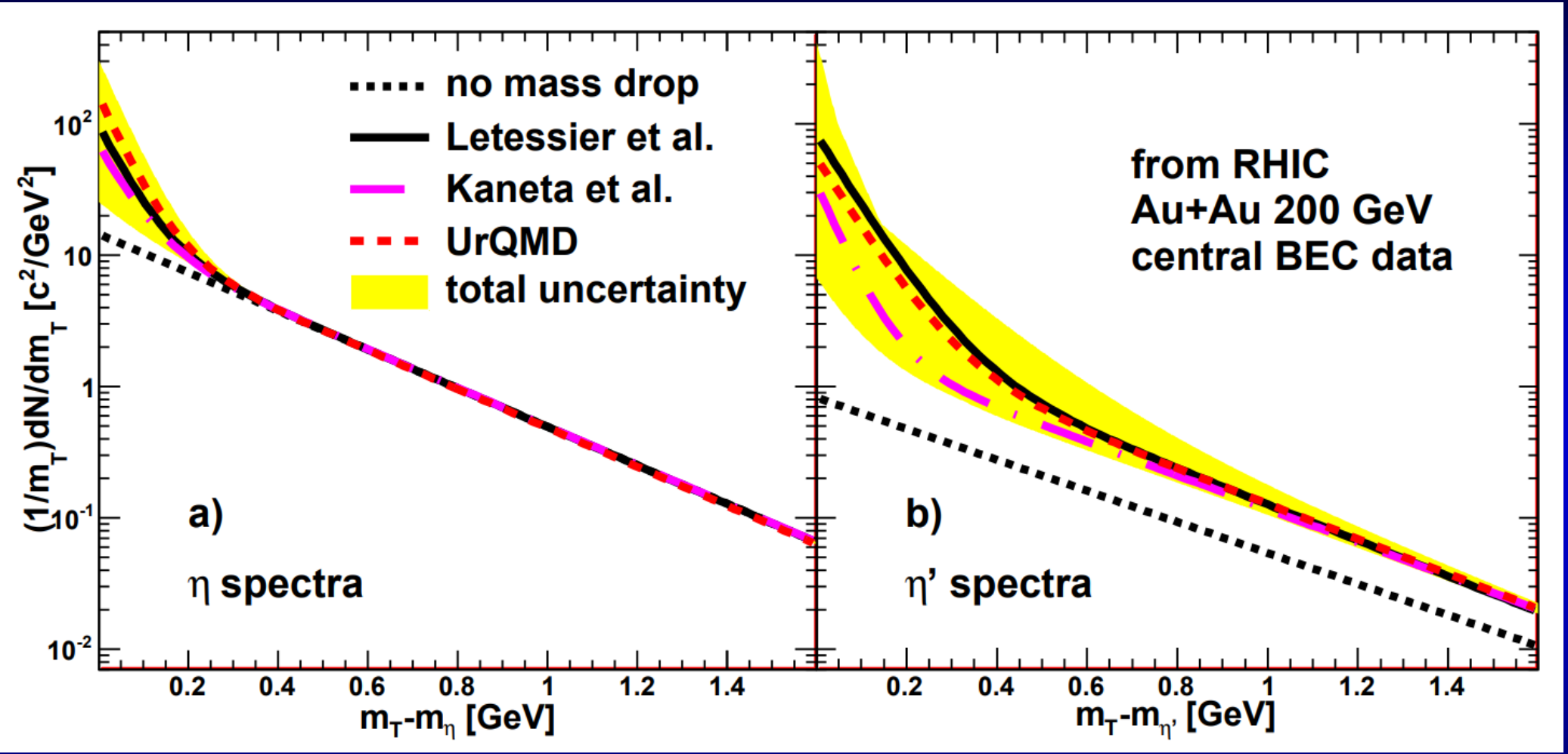
NOTE: IF CL(i) IS A UNIFORMLY DISTRIBUTED RANDOM VARIABLE IN INTERVAL (0,1)
THEN (CL(1)+ CL(2) + … + CL(n))/n IS ALSO A UNIFORMLY DISTRIBUTED IN (0,1)
SO CL MAPS FOR VARIOUS CENTRALITY CLASSES CAN BE AVERAGED OVER
RESULT YIELDS AN EFFECTIVE CL MAP FOR THE MERGED CENTRALITY CLASSES





Q3: CAN WE RECONSTRUCT THE η AND η' SPECTRA?

A3: INDIRECTLY RECONSTRUCTED η AND η' SPECTRA

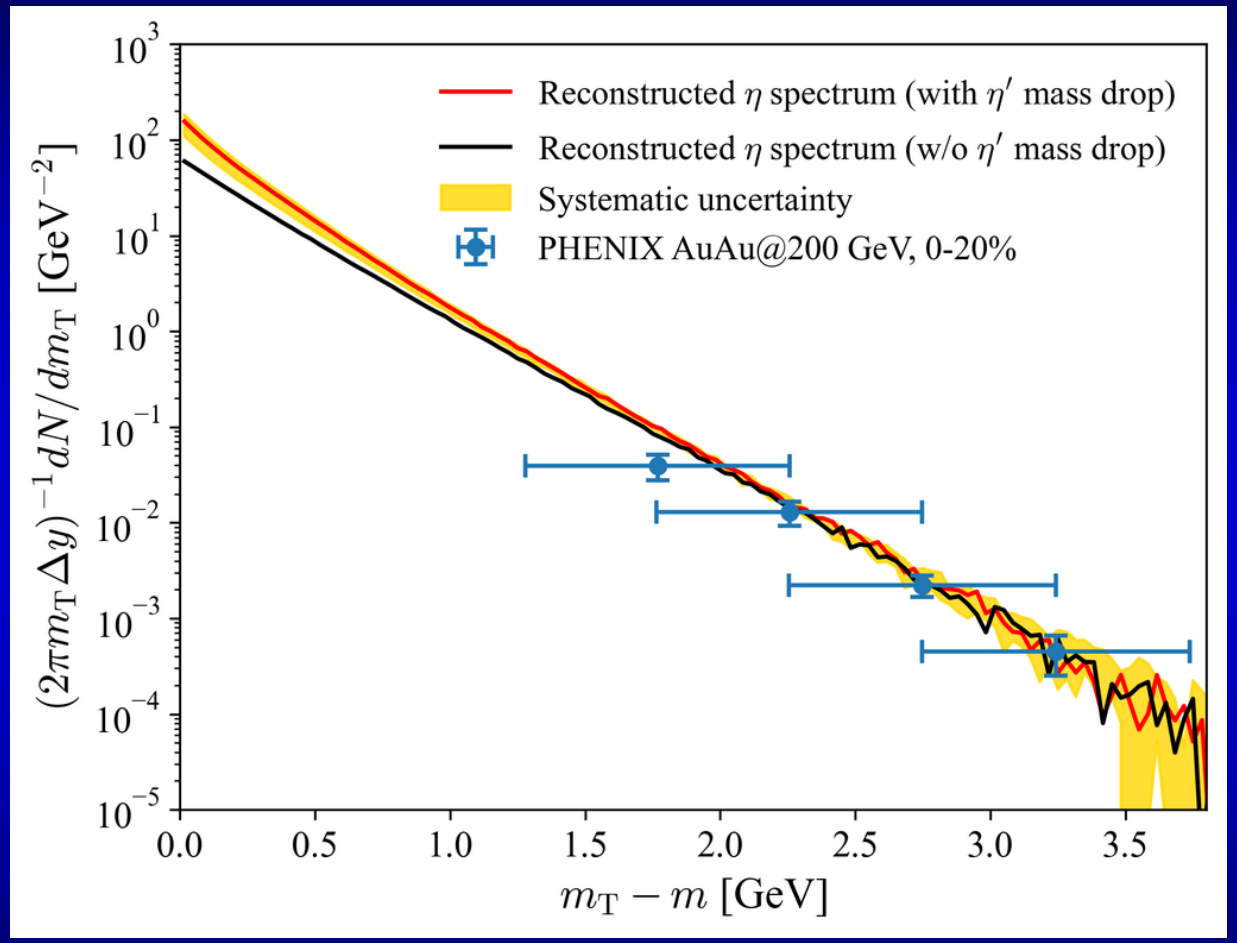


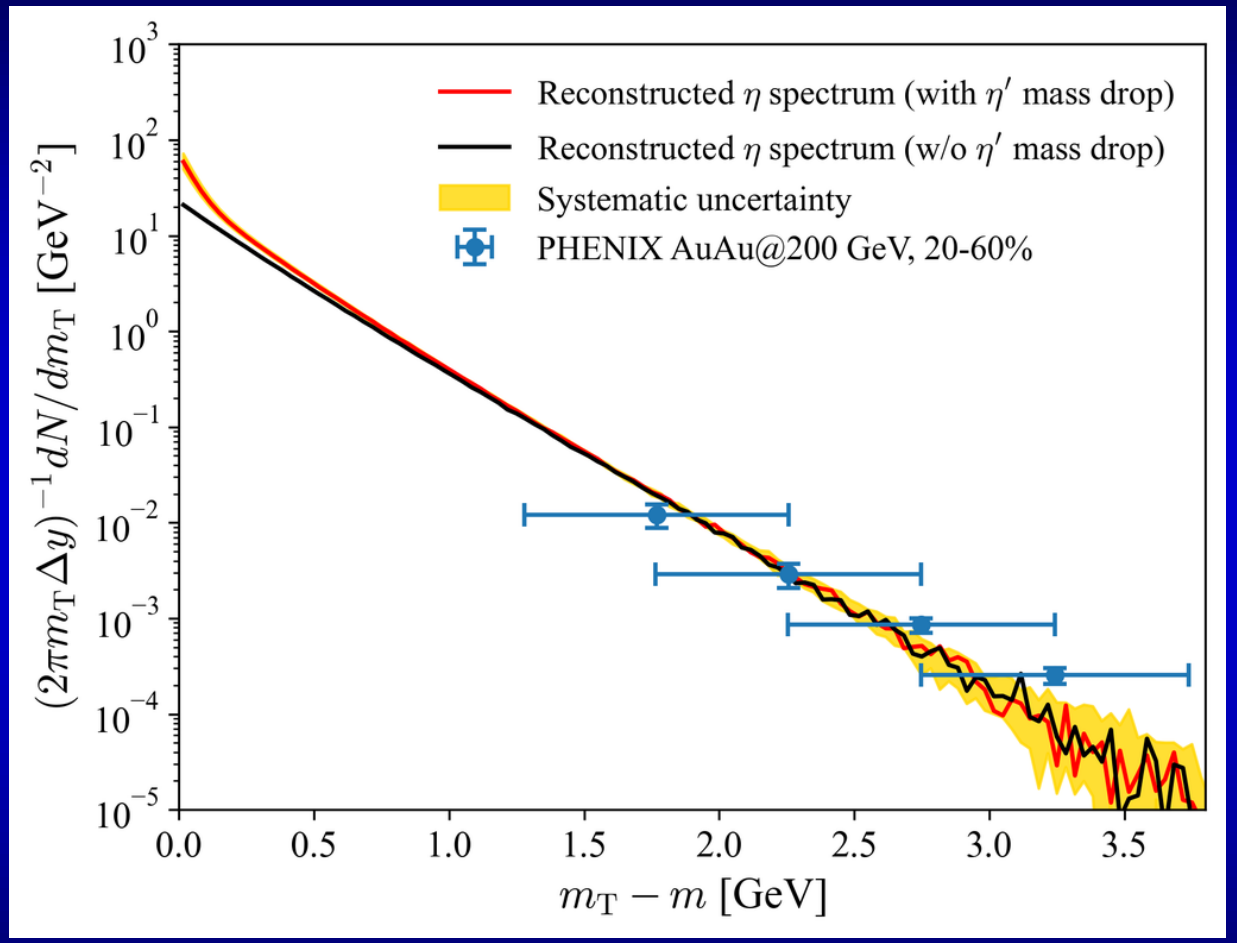
Indirect observation of an in-medium η ' mass reduction in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions

T. Csorgo (Harvard U., Phys. Dept. and Budapest, RMKI), R. Vertesi (Budapest, RMKI), J. Sziklai (Budapest, RMKI) (Dec, 2009)

Published in: *Phys.Rev.Lett.* 105 (2010) 182301 • e-Print: 0912.5526 [nucl-ex]

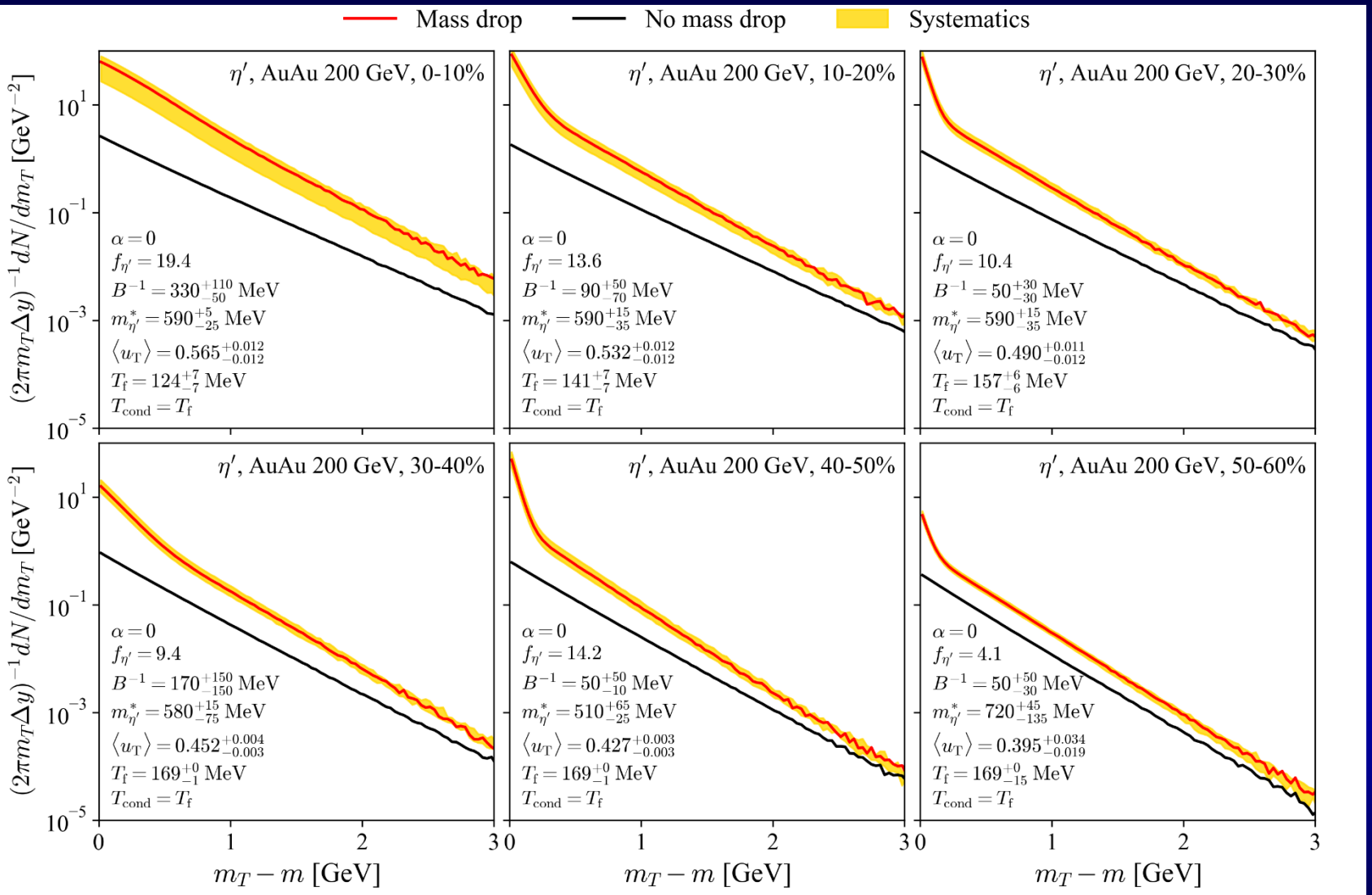
NEW: CENTRALITY DEPENDENT η SPECTRA





η AND η' SPECTRA, G. KASZA AND T. CS. IN PREPARATION

NEW: CENTRALITY DEPENDENT η′ SPECTRA



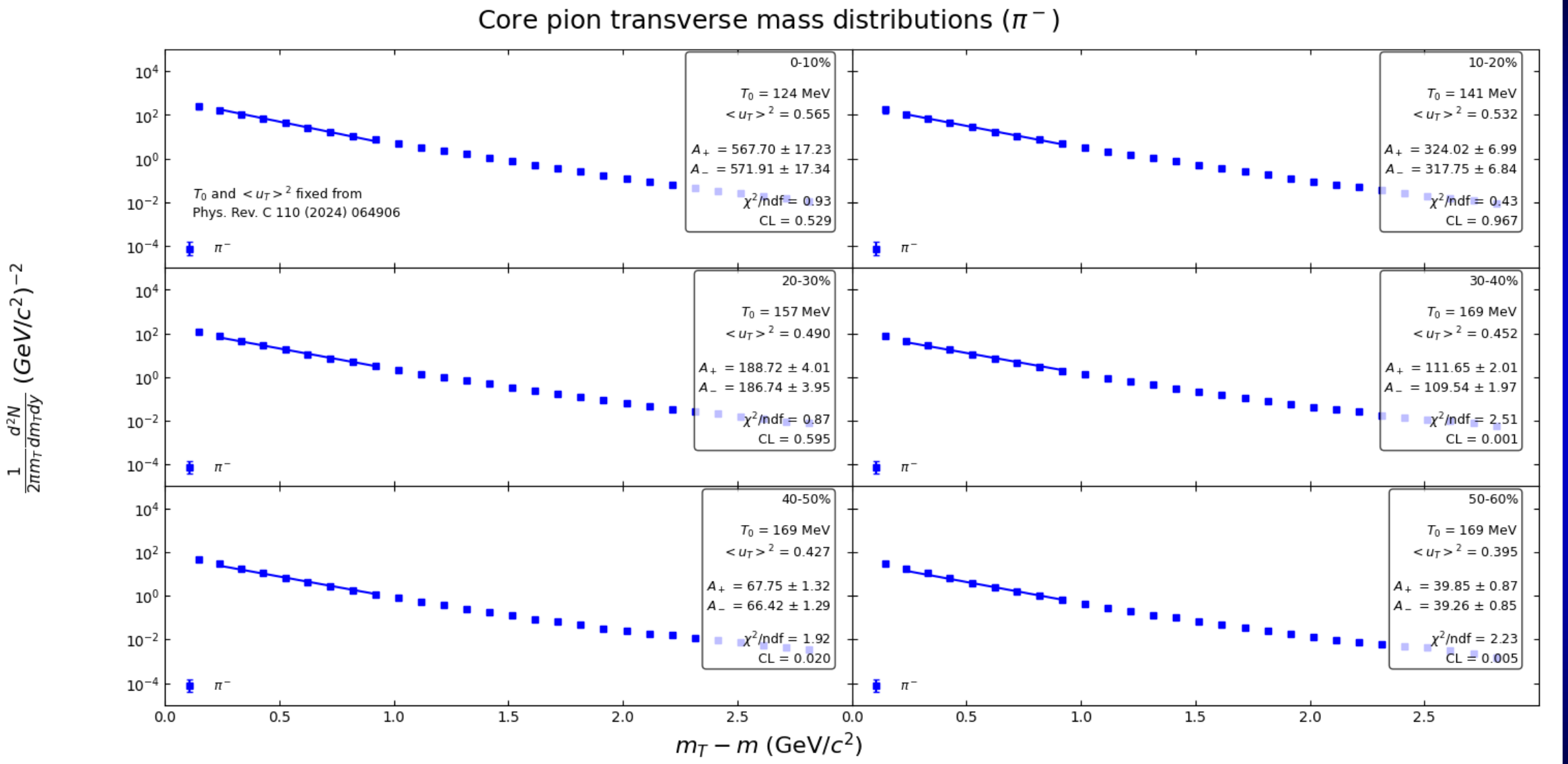
Enhancement factor $f_{\eta'}$ determined similarly as in Cs.T., R. Vértesi and J. Sziklai, *Phys.Rev.Lett.* 105 (2010) 182301
e-Print: 0912.5526 [nucl-ex]

Enhancement factor $4 < f_{\eta'} < 20$, greatest in most central collisions

η AND η′ SPECTRA, G. KASZA AND T. CS. IN PREPARATION

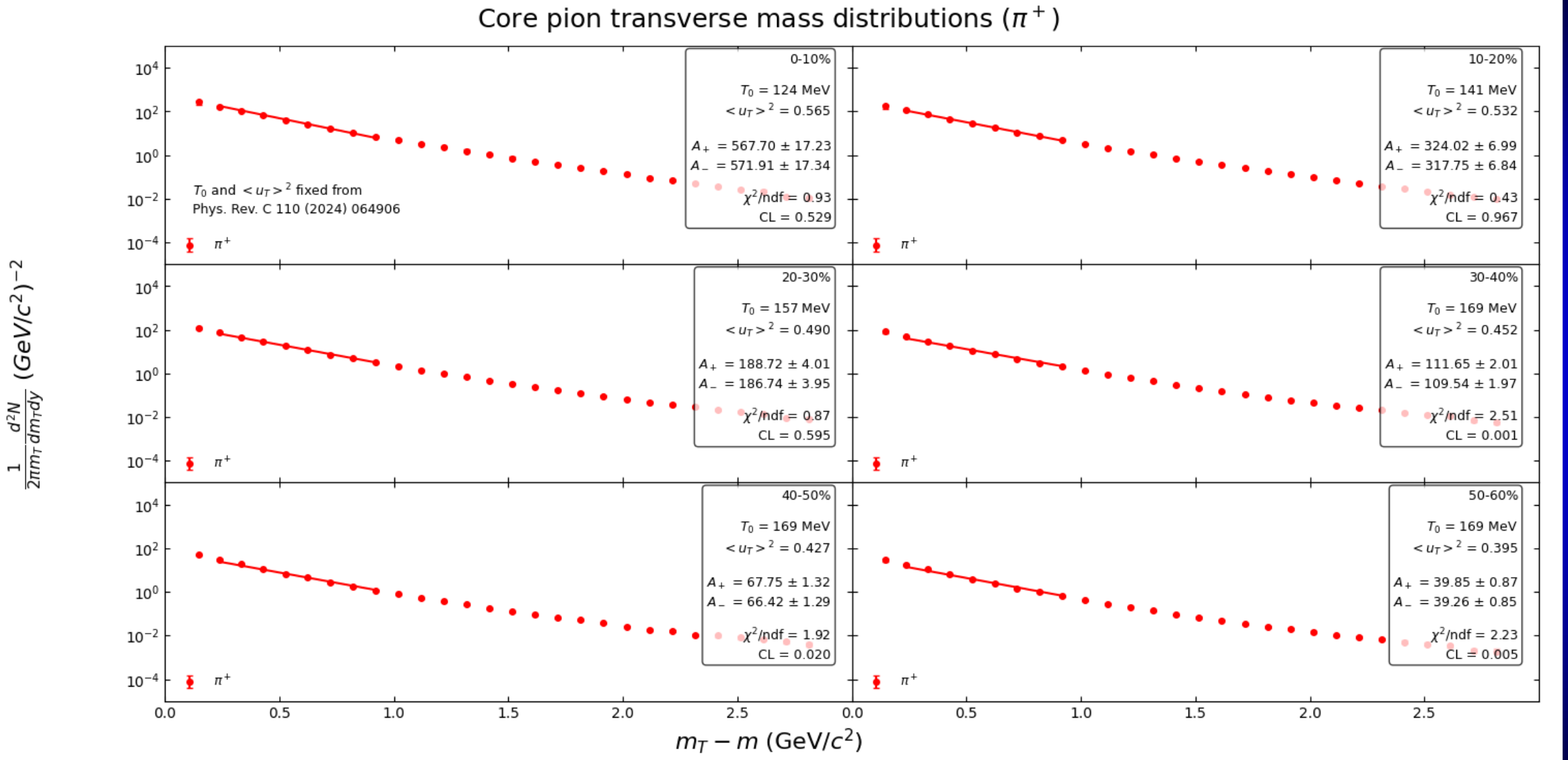
Q4: CAN WE REPRODUCE PION SPECTRA?

A4: CROSS-CHECK: CORE-HALO CORRECTED π^- SPECTRA



π^- SPECTRA OK, T. NOVÁK AND T. CS. IN PREPARATION

A4: CROSS-CHECK: CORE-HALO CORRECTED π^+ SPECTRA



π^+ SPECTRA OK, T. NOVÁK AND T. CS. IN PREPARATION

BACKUP SLIDES

CENTRALITY DEPENDENCE OF IN-MEDIUM MASS OF η′

Centrality	$m^*_{\eta'}$	(stat)	(syst)
0%–10%	590	$^{+5}_{-25}$	$^{+61}_{-137}$
10%–20%	590	$^{+15}_{-35}$	$^{+79}_{-95}$
20%–30%	590	$^{+15}_{-35}$	$^{+154}_{-119}$
30%–40%	580	$^{+15}_{-75}$	$^{+357}_{-121}$
40%–50%	510	$^{+65}_{-25}$	$^{+196}_{-47}$
50%–60%	720	$^{+45}_{-135}$	$^{+508}_{-398}$

In-medium mass of η′ determined indirectly from Levy Bose-Einstein correlations.

Similar to the vacuum mass of η (548 MeV) in each centrality class!

Lower, than the vacuum mass of η′ (958 MeV) except the 50-60% centrality class!

- The Kapusta-Kharzeev-McLerran prediction [43] is in agreement with our measurements in each investigated centrality class.
- The lower limit of Kwon, Lee, Morita, and Wolf [58] is also consistent with our measurement in each investigated centrality class.
- Our measured centrality-average value of $m^*_{\eta'}$ is slightly below, but consistent with, the lower limit predicted by Pisarski and Wilczek [42].
- However, the upper limit of Weinberg [55] is several standard deviations below the central values obtained in each investigated centrality class.
- The lower limit predictions of Horvatić, Kekez and Klabučar [56] and of Huang and Wang [57] are excluded except in the 50%–60% centrality class.
- Our results also suggest that the prediction of Ref. [64] slightly underestimates the in-medium mass change of the η'.

CENTRALITY DEPENDENCE OF IN-MEDIUM MASS OF η′

R. D. Pisarski and F. Wilczek, Remarks on the Chiral Phase Transition in Chromodynamics, Phys. Rev. D **29**, 338 (1984).
J. I. Kapusta, D. Kharzeev, and L. D. McLerran, The Return of the prodigal Goldstone boson, Phys. Rev. D **53**, 5028 (1996), arXiv:hep-ph/9507343.

Y. Kwon, S. H. Lee, K. Morita, and G. Wolf, Renewed look at η' in medium, Phys. Rev. D **86**, 034014 (2012), arXiv:1203.6740 [nucl-th].

Z. Huang and X.-N. Wang, Partial U(1)A restoration and eta enhancement in high-energy heavy ion collisions, Phys. Rev. D **53**, 5034 (1996), arXiv:hep-ph/9507395.

S. Weinberg, The U(1) Problem, Phys. Rev. D **11**, 3583 (1975).
D. Horvatić, D. Kekez, and D. Klabučar, η' and η mesons at high T when the $U_A(1)$ and chiral symmetry breaking are tied, Phys. Rev. D **99**, 014007 (2019), arXiv:1809.00379 [hep-ph].

G. Kovács, P. Kovács, and Z. Szép, One-loop constituent quark contributions to the vector and axial-vector meson curvature mass, Phys. Rev. D **104**, 056013 (2021), arXiv:2105.12689 [hep-ph].

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„THIS IMPLIES A SECOND TRANSITION IN QCD”

PRC Editors’ Suggestion (2024/12)

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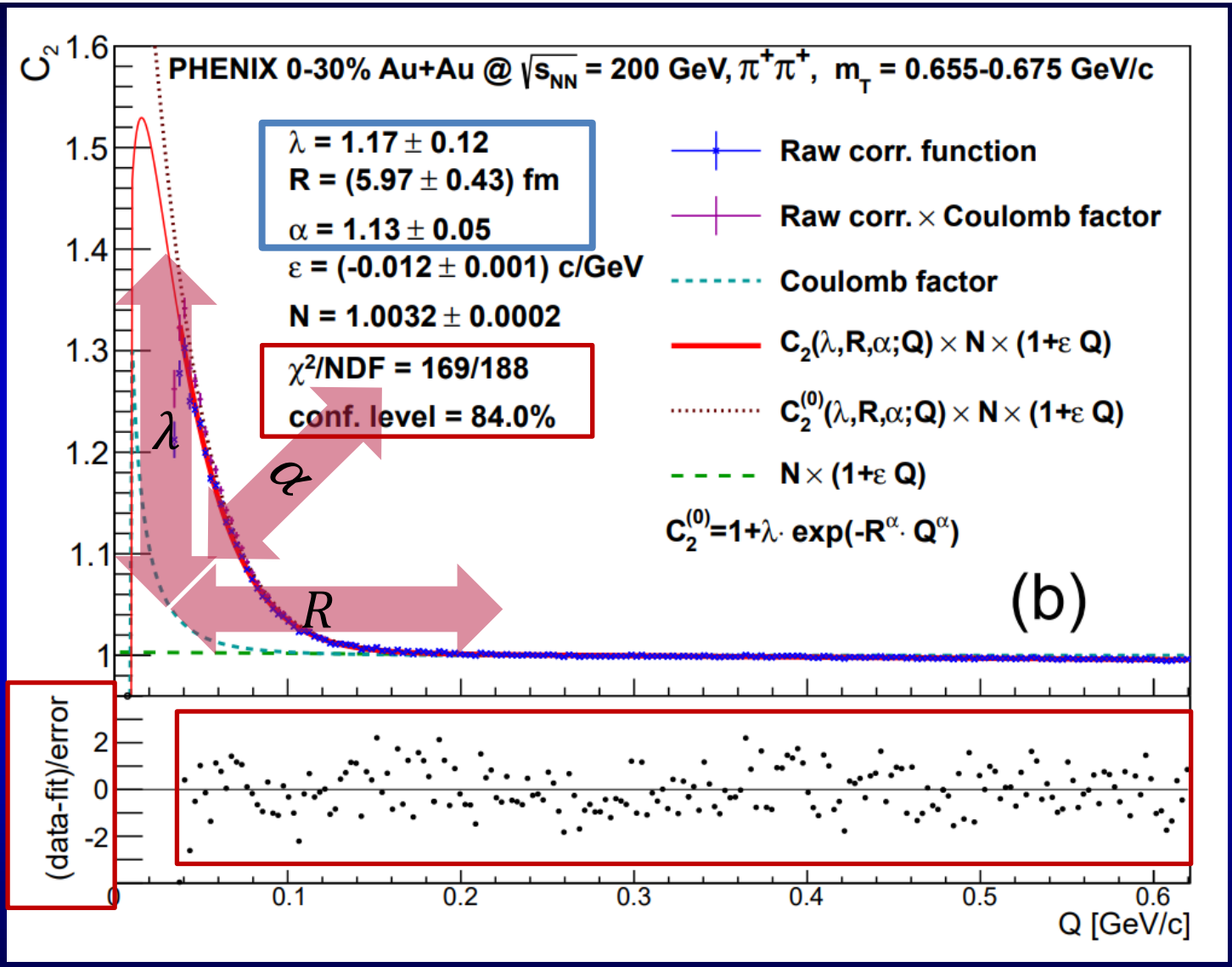
Quality plot for Levy fits of $C_2(Q)$

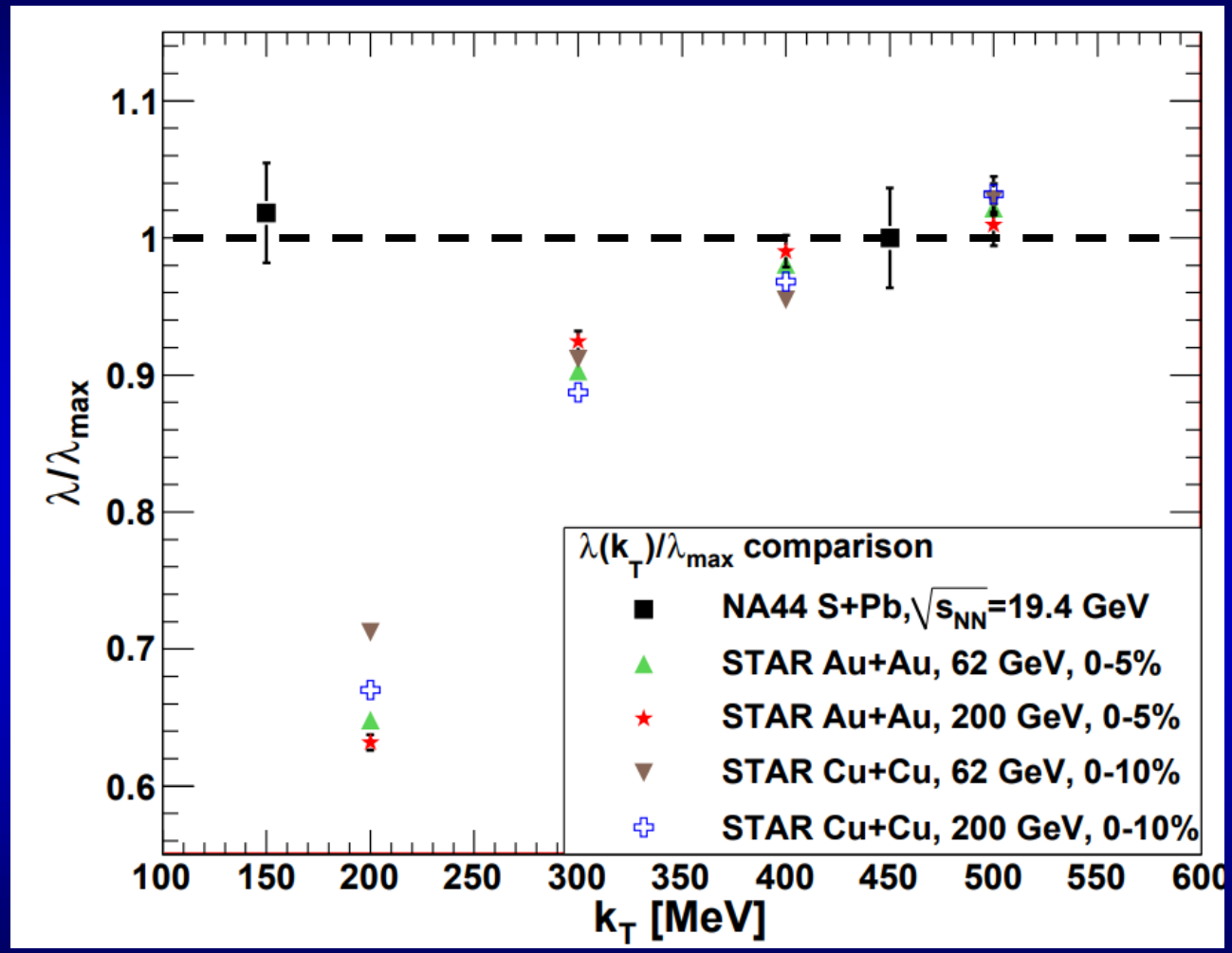


√s_{NN} = 200 GeV 0-30 % Au+Au collisions, from Phys.Rev.C 97 (2018) 6, 064911

Note the good fit quality, p-value or CL > 0.1 %

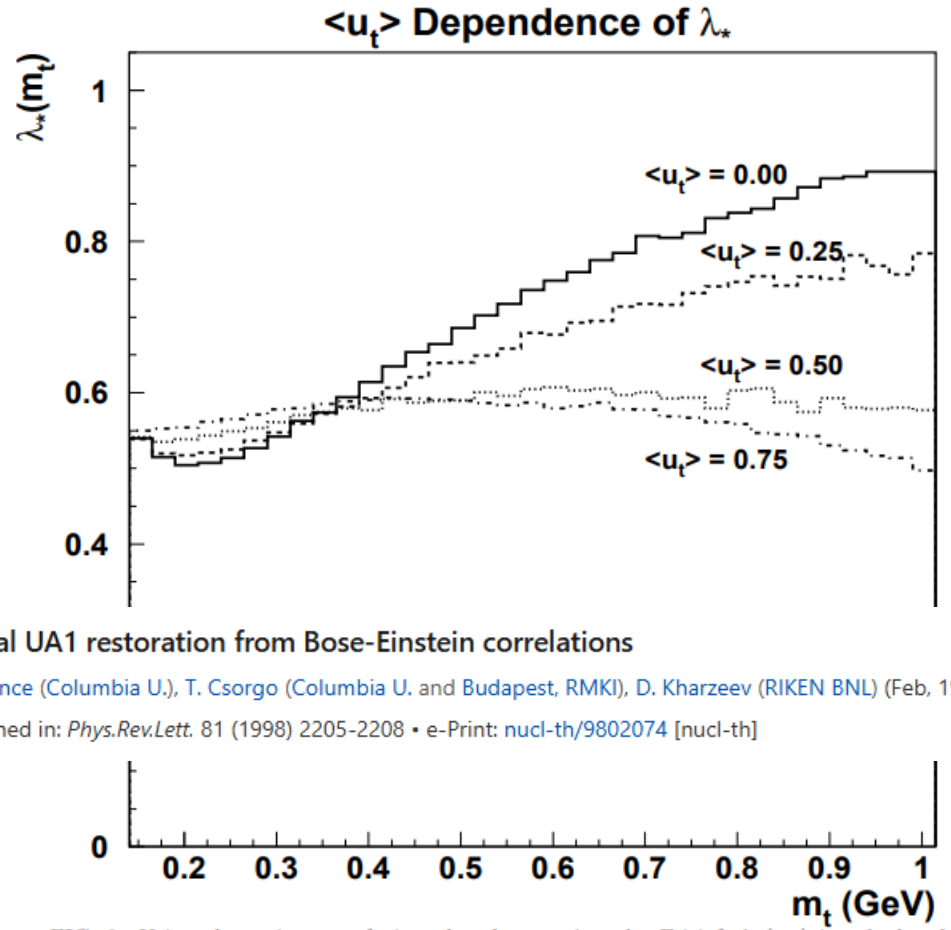
Can λ/λ_{max} $U_A(1)$ restoration signal be switched off?

Yes, as known from the first papers!



NA44 data on charged pion Bose-Einstein correlation indicate a null effect in S+Pb at $\sqrt{s_{NN}}$ = 19.4 GeV ! Contrasted to STAR data on charged pion B-E correlation in $\sqrt{s_{NN}}$ = 62 and 200 GeV Au+Au collisions: suppression signal of $U_A(1)$ restoration. R. Vértesi, T.Cs., J. Sziklai , arXiv:2307.09573 [nucl-ex]

Can $\lambda(m_T)$ be used for other things?



Partial UA1 restoration from Bose-Einstein correlations

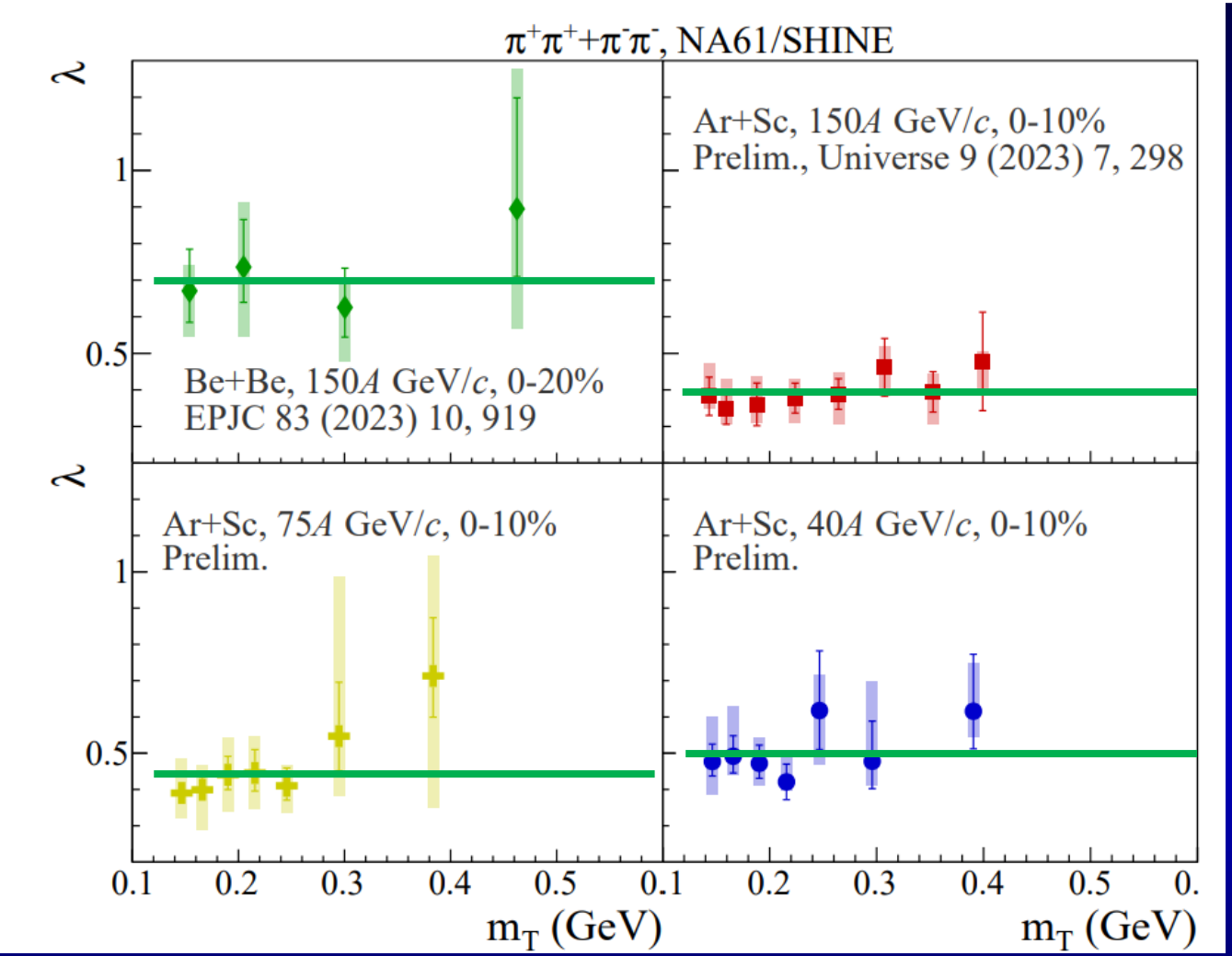
S.E. Vance (Columbia U.), T. Csorgo (Columbia U. and Budapest, RMKI), D. Kharzeev (RIKEN BNL) (Feb, 1998)

Published in: *Phys.Rev.Lett.* 81 (1998) 2205-2208 • e-Print: nucl-th/9802074 [nucl-th]

FIG. 3. Using the estimates of pion abundances given by Fritiof, $\lambda_*(m_t)$ is calculated using different average flow velocities in the m_t distribution. It is shown for $\langle u_t \rangle = 0.00$ by the solid line, for $\langle u_t \rangle = 0.25$ by the dashed line, for $\langle u_t \rangle = 0.50$ by the dotted line and for $\langle u_t \rangle = 0.75$ by the dashed-dotted line.

Yes, at $0.4 < m_T < 1$ GeV, $\lambda(m_T)$ measures radial flow !

Can λ/λ_{max} $U_A(1)$ restoration signal be switched off?

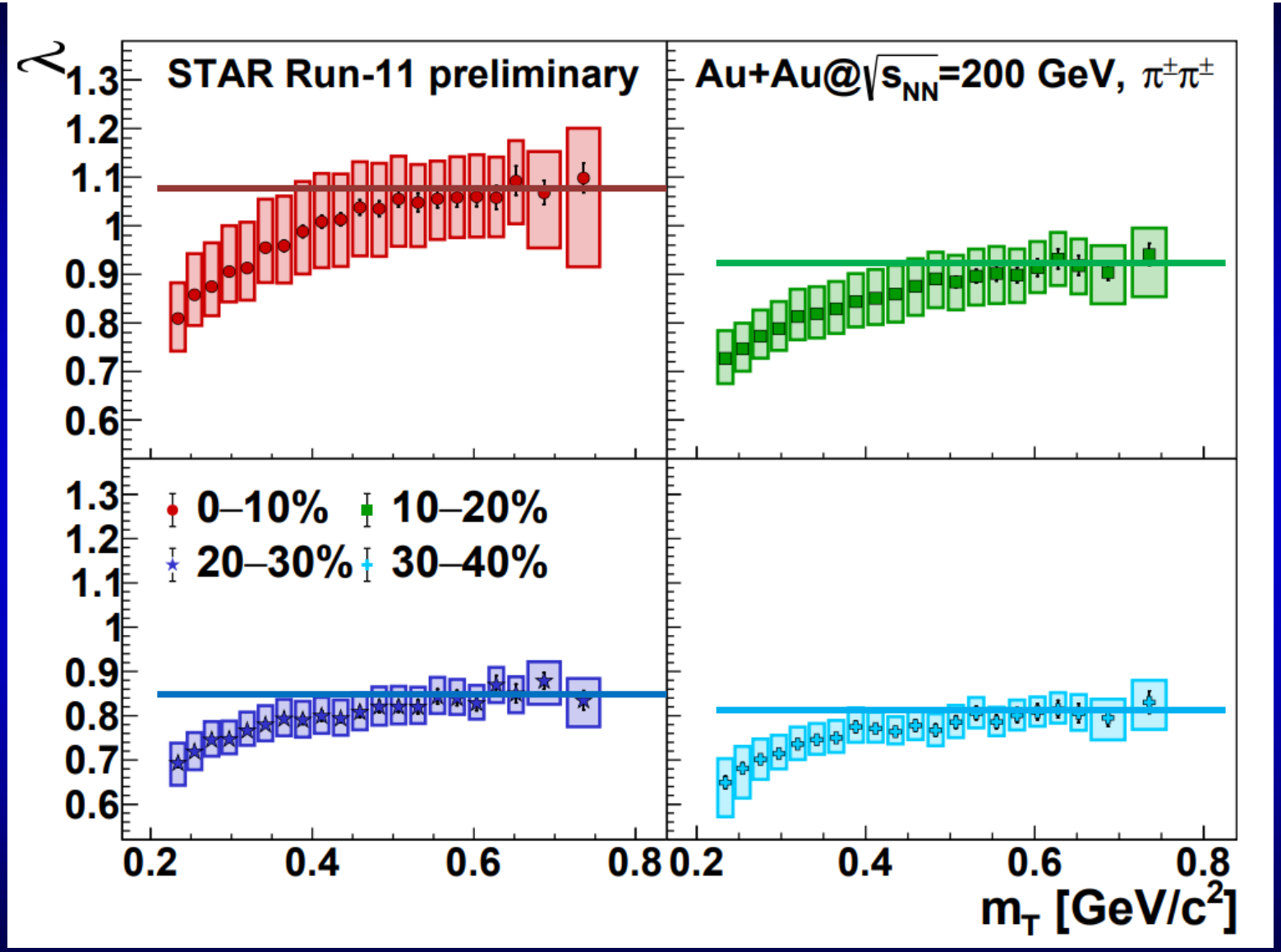


NA61: YES!

NA61 data: no signal of decrease of λ/λ_{max} for m_T < 0.5 GeV, no signal of $U_A(1)$ symmetry restoration
Small AND intermediate systems (Be+Be and Ar+Sc) and relatively low energy, $\sqrt{s}$ < 20 GeV.

NA61 data on charged $\pi\pi$ correlation in 150 AGeV Be+Be and $E_{lab} \leq$ 150 GeV Ar+Sc collisions
B. Pórffy for the NA61 Collaboration, e-Print: 2406.022423 [nucl-ex]

Is $\lambda(m_T)/\lambda_{max}$ confirmed in $\sqrt{s_{NN}}$ = 200 GeV Au+Au?

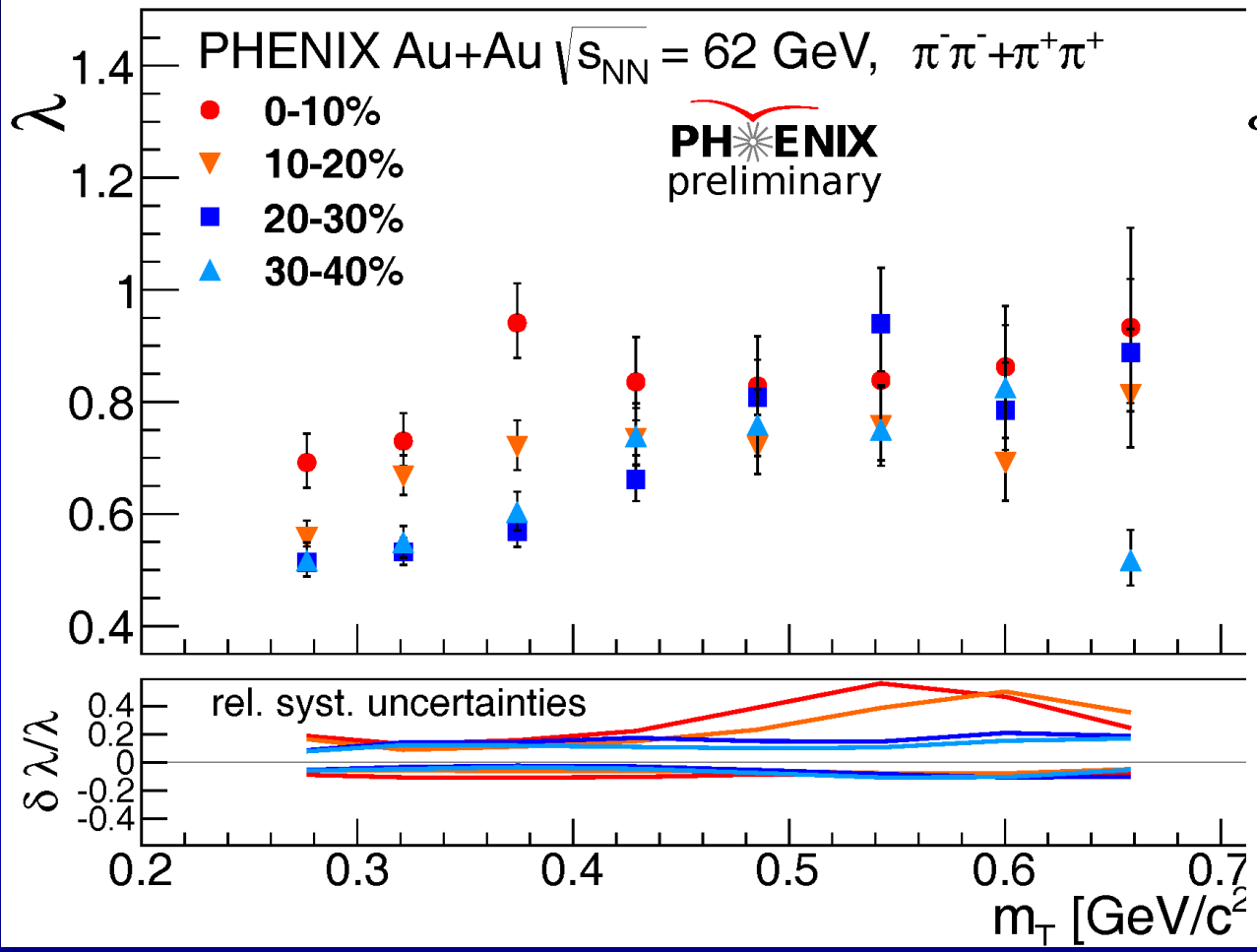


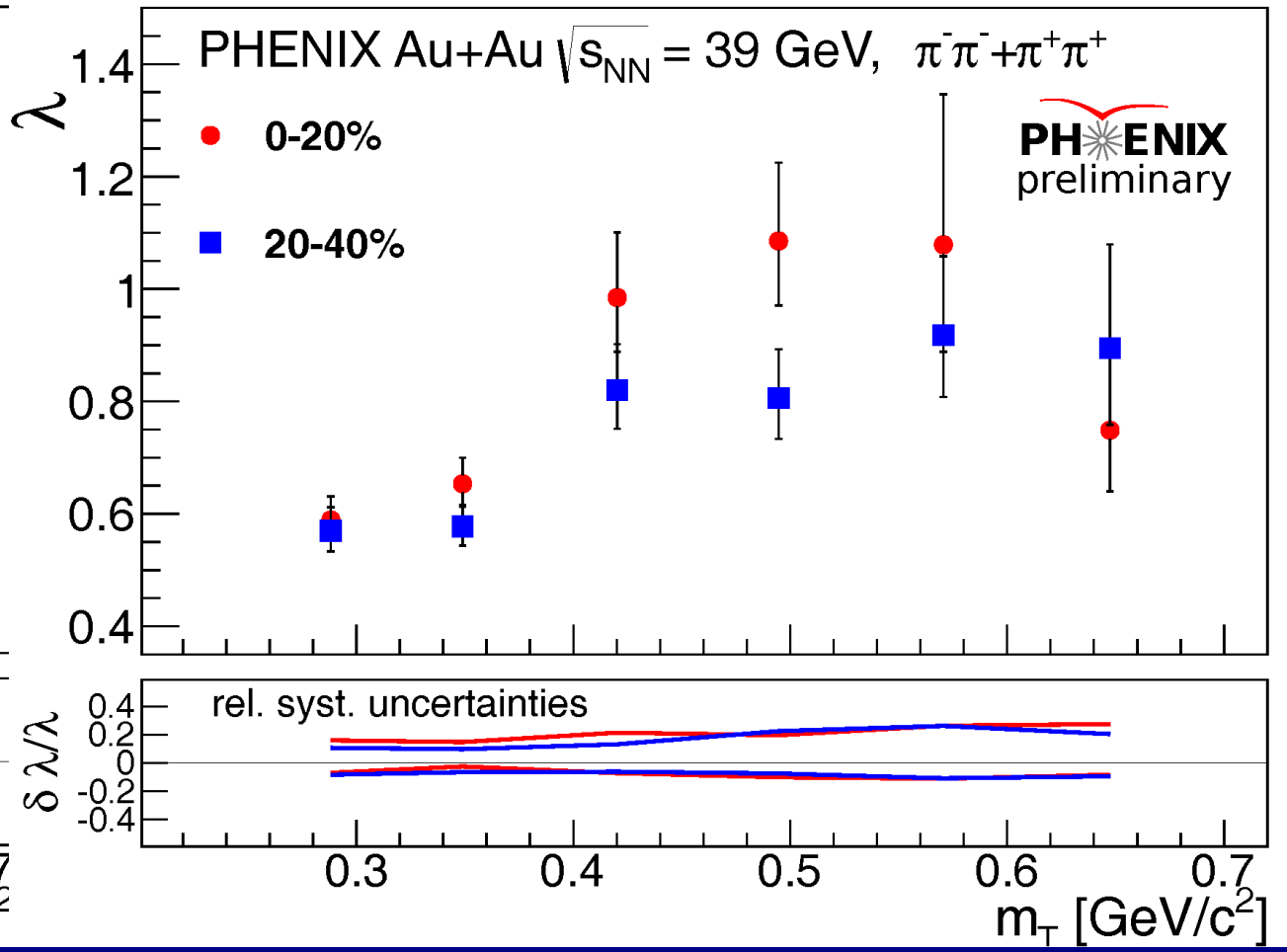
STAR preliminary: YES!

STAR preliminary, charged ππ correlation in 0-10%, 10-20%, 20-30% and 30-40% Au+Au @ 200 GeV

D. KIncses for the STAR Collaboration, Universe 10 (2024) 3, 102, e-Print: 2401.11169 [nucl-ex]

Can λ/λ_{max} $U_A(1)$ restoration signal be switched off?



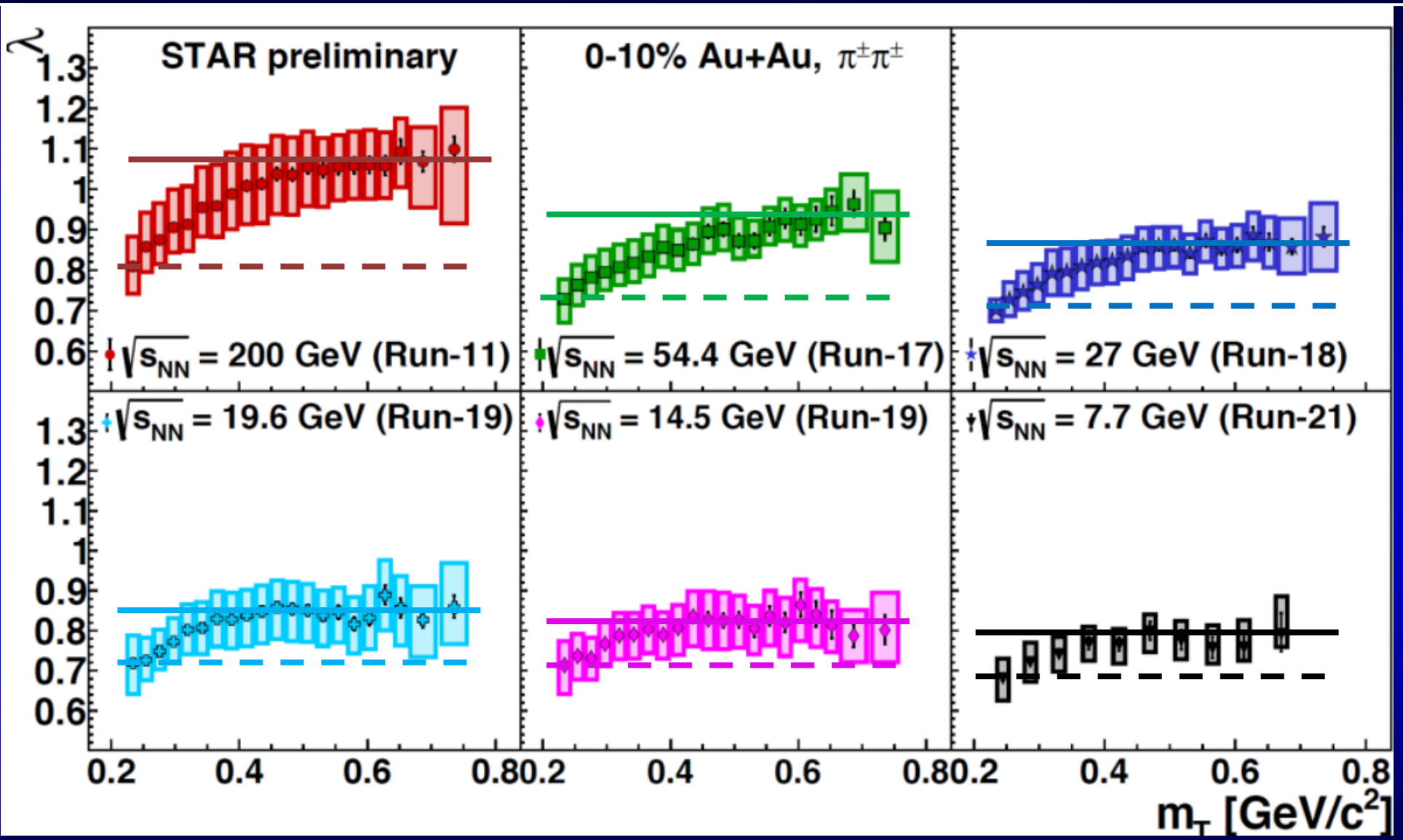


PHENIX preliminary data: qualitatively a of decrease of λ/λ_{max} for m_T < 0.5 GeV, but limited statistics!

both at $\sqrt{s_{NN}}$ = 39 and 62 GeV: greater magnetic field, less momentum resolution at low m_T as compared to Run-10 Au+Au data.

D. Kincses for the PHENIX Collaboration, Universe 4 (2018) 1, 11, e-Print: 1711.06891 [nucl-ex]

Excitation function of $\lambda(m_T)/\lambda_{max}$ in Au+Au@RHIC BES?

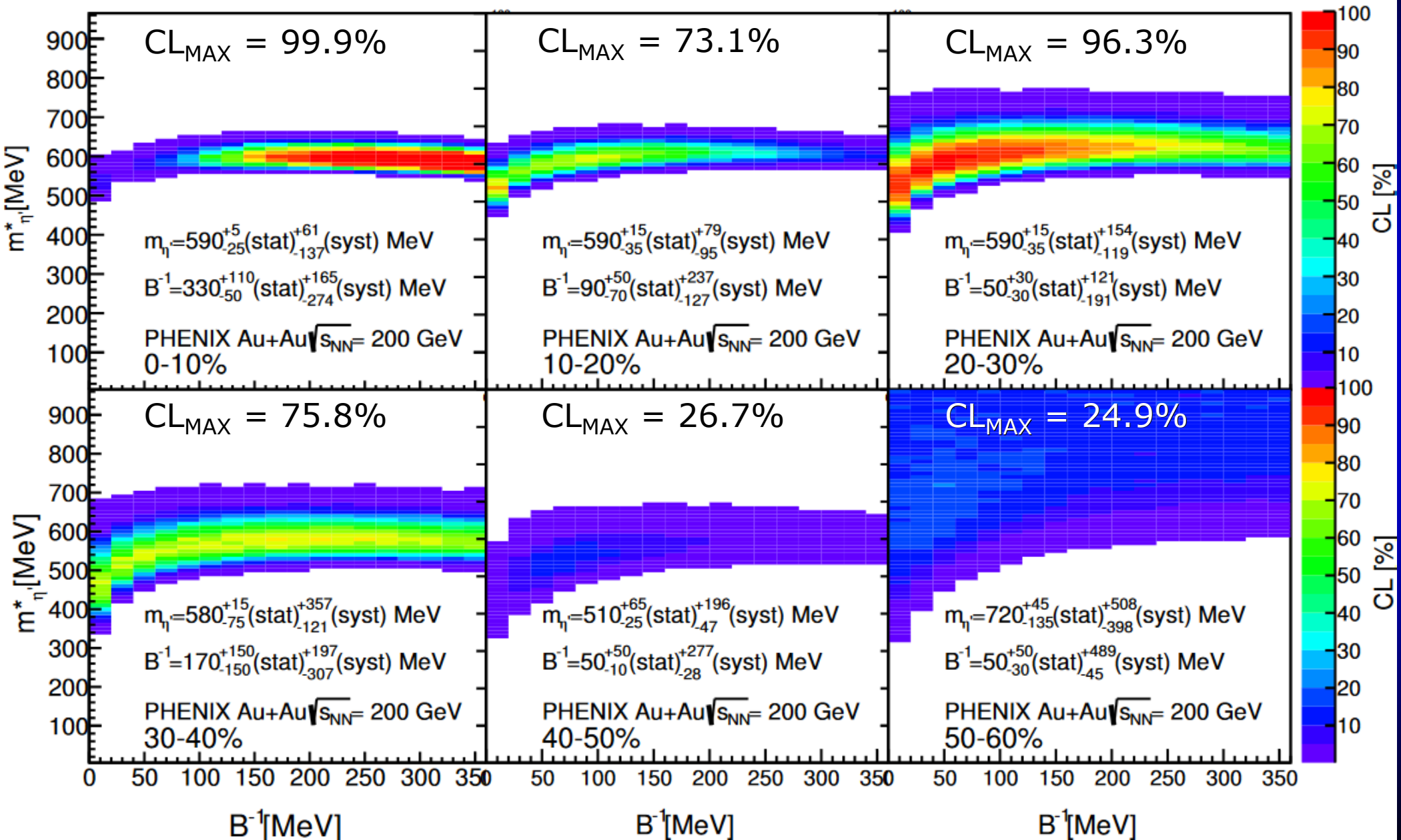


STAR preliminary: in 0-10% Au+Au, $\lambda_{min}/\lambda_{max}$ decreases with decreasing $\sqrt{s_{NN}}$

Note: the results obtained in assuming a Gaussian might be altered if one utilizes Lévy-stable source. M. Csanád and D. Kincses, J.Phys.G 52 (2025) 2, 025102

STAR preliminary, charged ππ correlation in 0-10% Au+Au @ 200, 54.4, 27, 19.6, 14.5 and 7.7 GeV
D. Kincses for the STAR Collaboration, Universe 10 (2024) 3, 102, e-Print: 2401.11169 [nucl-ex]

CONFIDENCE LEVELS (CL-S OR P-VALUES) FROM λ / λ_{MAX} MAPS



Maps out allowed regions & best values

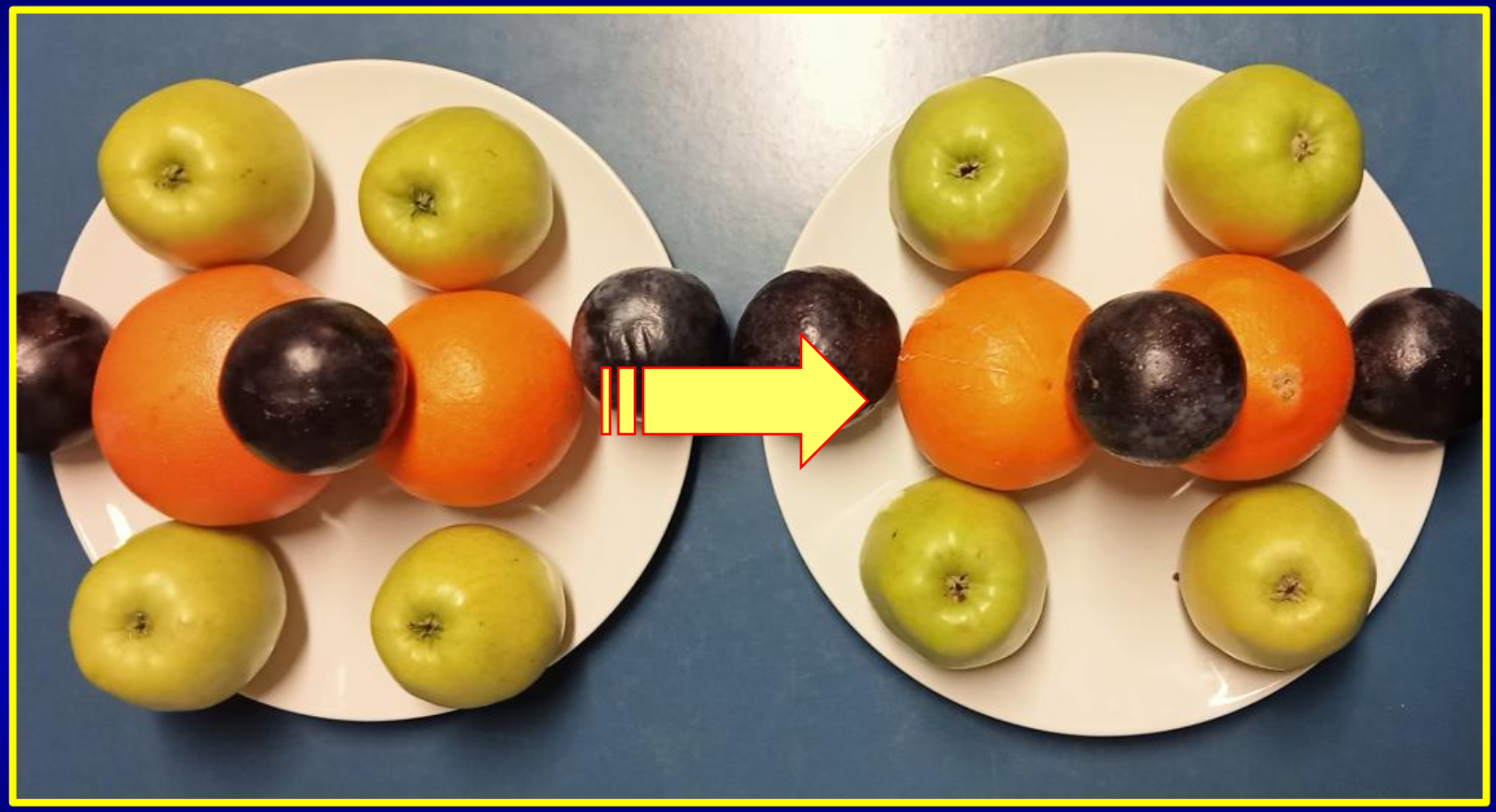
in-medium η′ mass modification

CL_{MAX} = CL of the peak (best fit)

Colored region allowed with CL > 0.1 %

Selective, except in 50-60 % centrality class

A DIRECT OBSERVATION: APPLICATION



DIRECT vs INDIRECT OBSERVATION