

INDIRECT INDICATIONS OF

A 2ND QCD TRANSITION

IN $\sqrt{s_{NN}} = 200$ GEV AU+AU COLLISIONS AT RHIC

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Timeline from 1974 to 2024

T.D.Lee and G.C. Wick

S. Weinberg

R. Pisarski and F. Wilczek

RHIC proposal and CERN QGP press release

ZBCsL: quark coalescence @ CERN SPS

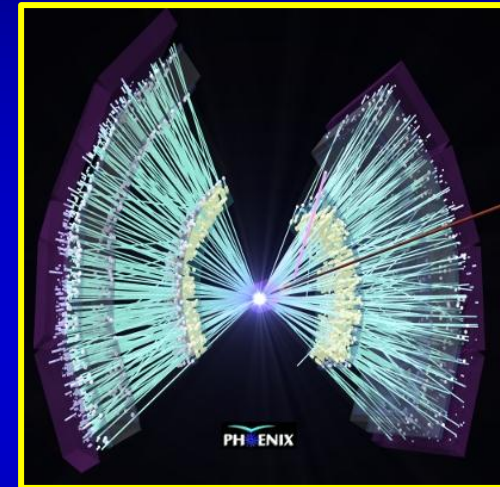
PHENIX and STAR data re-analysis @ RHIC

Indirect observation of $U_A(1)$ symmetry restoration by PHENIX

Based on: [arXiv:2407.08586](https://arxiv.org/abs/2407.08586), [Phys.Rev.C 110 \(2024\) 6, 6](https://doi.org/10.1103/PhysRevC.110.064911)

See also [Phys. Rev. C 97 \(2018\) 064911](https://doi.org/10.1103/PhysRevC.97.064911), and [Phys. Rev. C 108 \(2023\) 049905](https://doi.org/10.1103/PhysRevC.108.049905)

For detailed new results: see [my PHENIX talk at WPCF 2026](#) on May 22, 2026



1974 – T.D. Lee and 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](#)

[reference search](#) [841 citations](#)

[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](#)

[reference search](#) [798 citations](#)

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 $\eta \rightarrow 3\pi$ matrix element,

1984 – R. Pisarski and 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](#)

[reference search](#) [1,731 citations](#)

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.

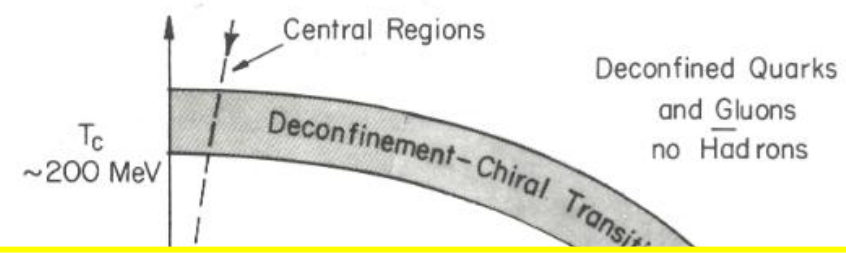
1984 – RHIC Proposal: One or two transitions on the phase diagram ?

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



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](#)

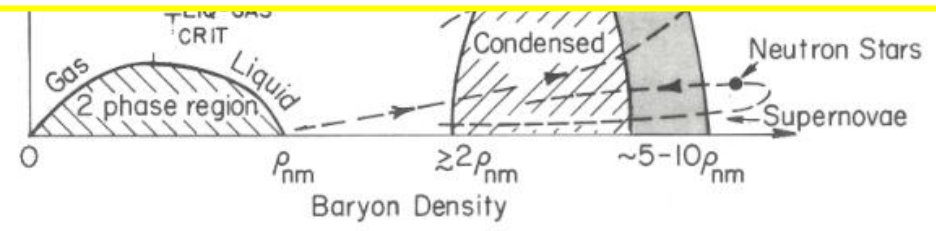


Fig. II.1 Phase diagram of Nuclear Matter (G. Baym, ref. 3). Temperature is plotted vs. net baryon density for an extended volume of nuclear matter in thermal equilibrium. Normal nuclear matter appears at the point 0, at zero temperature, and this is the neighborhood explored by low energy nuclear physics. 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.

1989: „NUCLEI, AS HEAVY AS BULLS, THROUGH COLLISION GENERATE NEW STATES OF MATTER” /T.D. LEE/



[Courtesy of the Tsung Dao \(T.D.\)
Lee Library](#)

Poem by Prof. T. D. Lee,
Nobel Laureate in Physics

Painting by Li Keran, 1989

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and Technology
© 2012 Shanghai Jiao Tong University,
Shanghai, China: All Rights Reserved

[Special thanks to: UNT Digital Library](#)

New emphasis:
on **plural** of state

At least two new states!

1996: RETURN OF THE PRODIGAL η' GOLDSTONE BOSON

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.

SIGNIFICANT

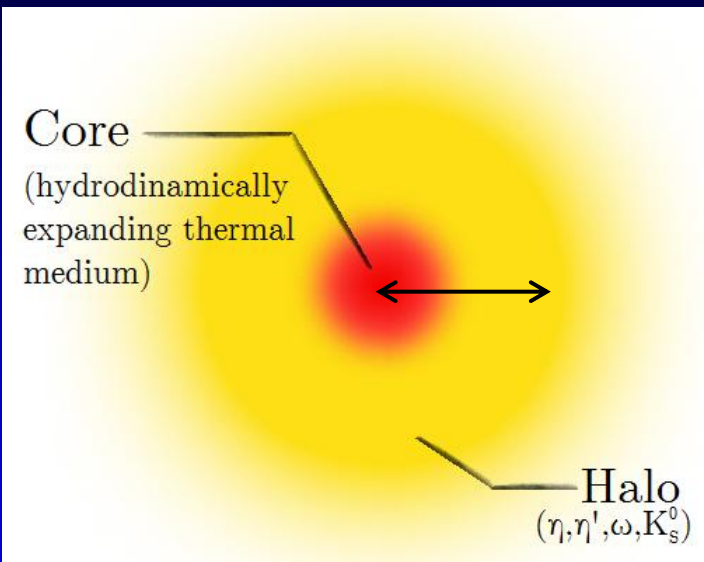
**in-medium η' modification,
predicted theoretically,
but**

How to observe it?

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.

in-medium η' modification: Photons? Dileptons? Enhanced production cross-section?

1996: Core/halo model, long-lived resonances



Resonance pions reduce the corr. strength [1, 2]

Core-Halo model: $S = S_C + S_H$

Primordial pions - Core $\lesssim 10$ fm

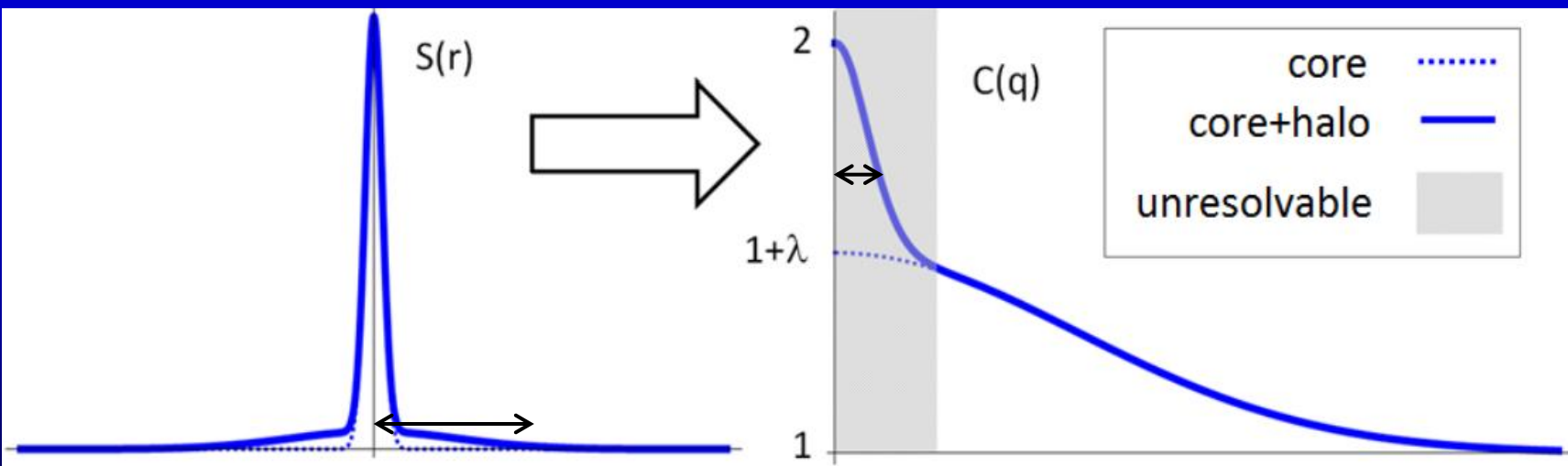
Resonance pions - from very far regions - Halo

Corr. strength \rightarrow C-H ratio: $\lambda = \left(\frac{N_C}{N_C + N_H} \right)^2$

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

Variance: halo dominated!

Precise measurement of λ important!



Precise measurement of λ is based on extrapolation to $Q = 0$, needs precise measurement of the shape of $C(q)$:

\rightarrow Levy expansion

M.B.de Kock, H.C.Eggers, T.Cs.:

PoS WPCF2011 (2011) 033

T. Novák et al (*WPCF 2015*):

Acta Phys.Polon.Supp. 9 (2016) 289

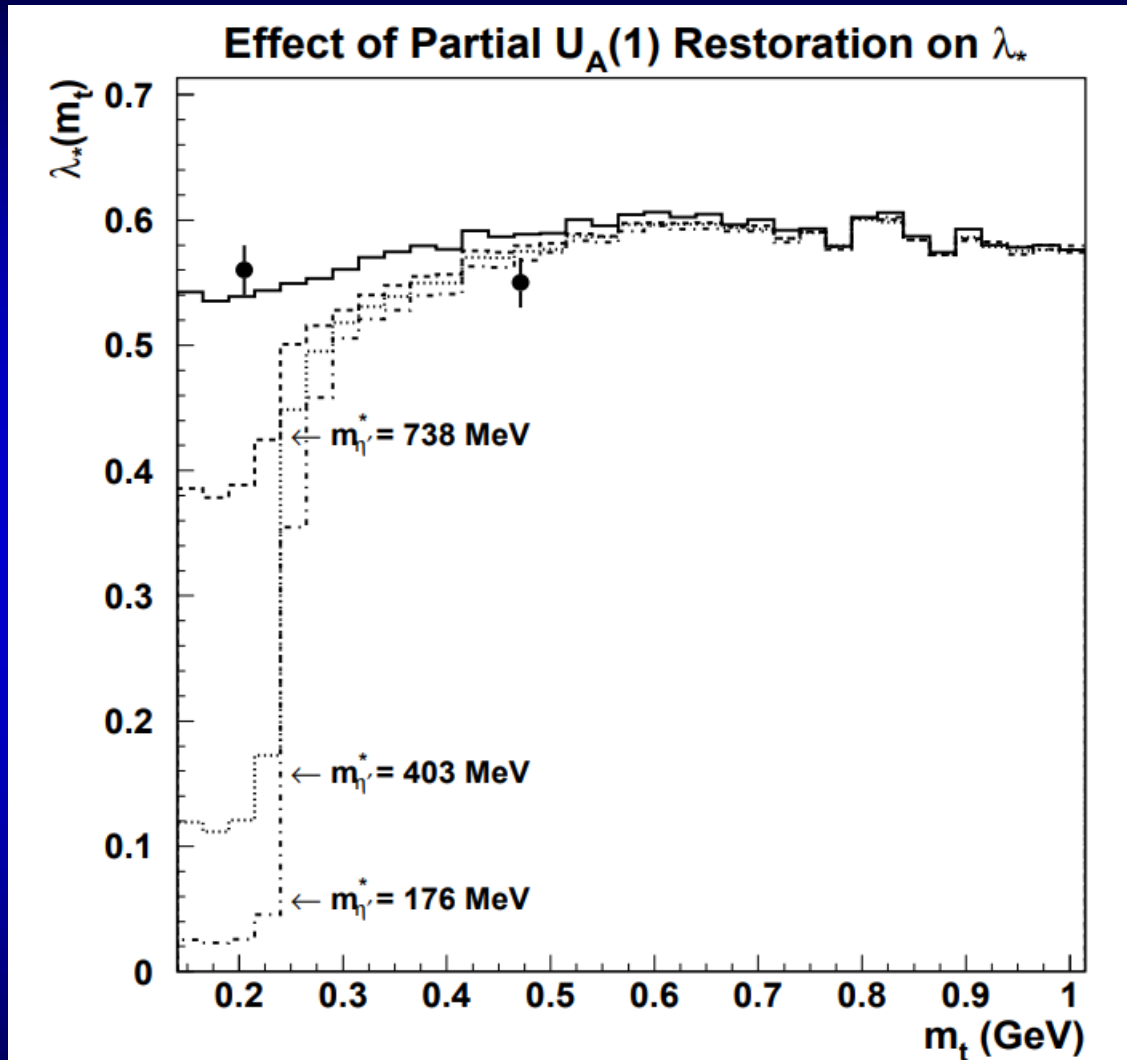
T. Cs., R. Paseschnik and A. Ster:

Eur. Phys. J. C 79 (2019) 1, 62

[1] J. Bolz et al: *Phys.Rev. D47 (1993) 3860-3870*

[2] T. Cs, B. Lörstad, J. Zimányi: [hep-ph/9411307](https://arxiv.org/abs/hep-ph/9411307), *Z.Phys. C71 (1996) 491-497*

1998: SENSITIVE TO IN-MEDIUM η' MASS MODIFICATION



NA44 S+Pb data + Monte Carlo,

NA44 $E_{\text{lab}} = 200$ 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

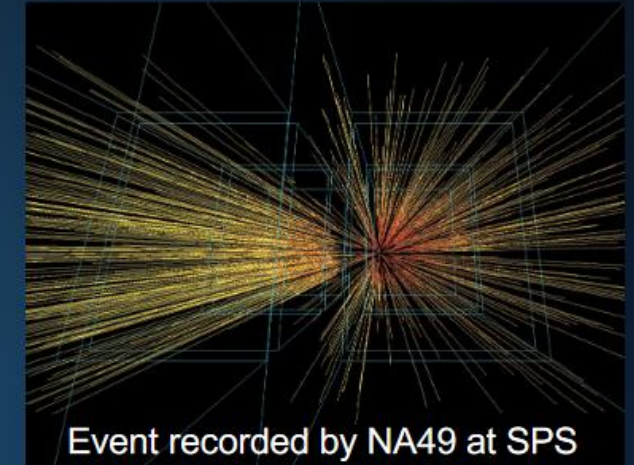
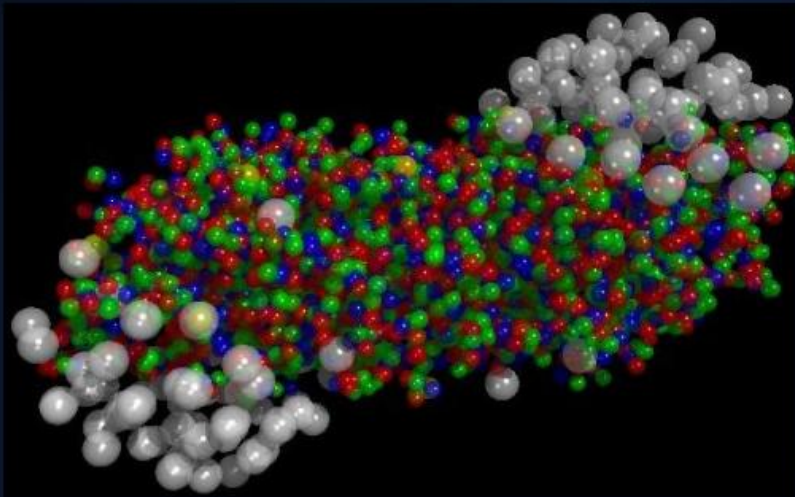
[nucl-th/9802074](#) [nucl-th]

in-medium η' modification: can it be switched on and off? Centrality? Energy? System size?

2000: „A NEW STATE OF MATTER, THE 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.



Luciano Maiani (CERN DG): “... We now have evidence of a new state of matter where quarks and gluons are no longer confined. ... There is still an entirely new territory to be explored concerning the physical properties of quark-gluon plasma. The challenge now passes to RHIC at BNL and later on to the LHC.”



**New emphasis:
Singular, only one new state ...**

2000 – CERN Press Release: How big is the mean free path of quarks ?

Quark liberation and coalescence at CERN SPS

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

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]

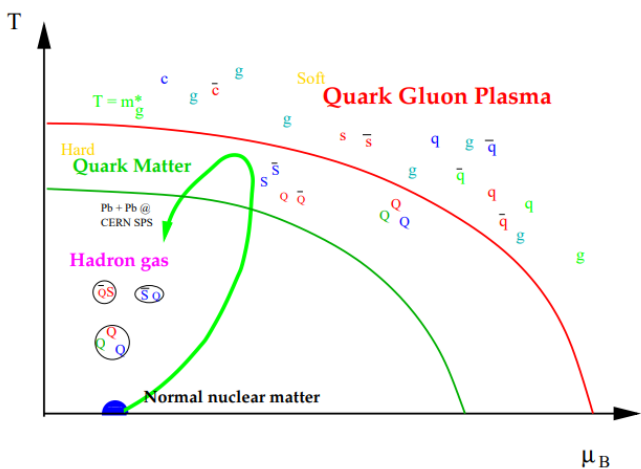
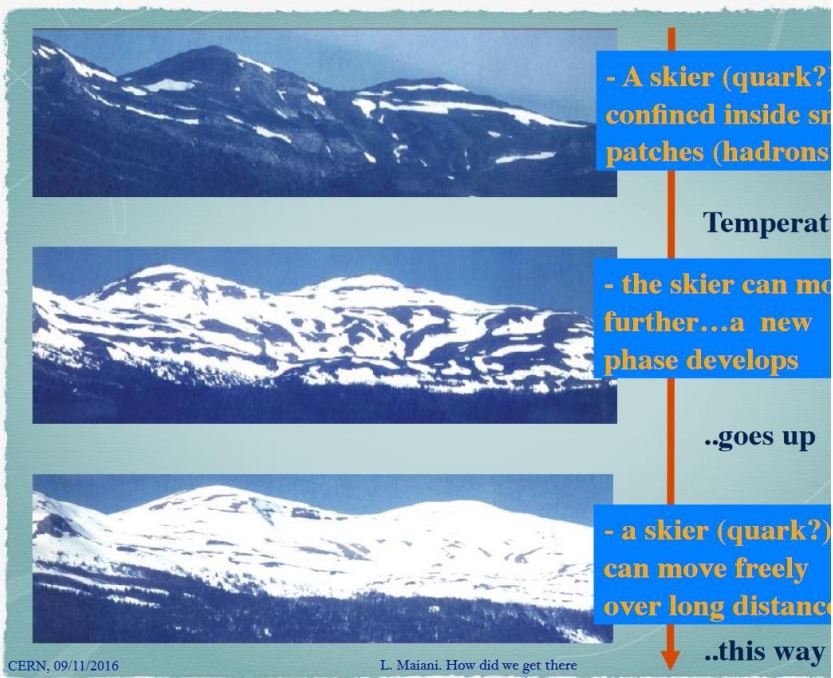


Figure 9. Illustration of the difference between Quark Matter consisting of dressed quarks, strange quarks and Quark Gluon Plasma which contains in a significant amount light and strange (undressed) (anti-)quarks as well as gluons .

$$T_{\text{slope}} = T_f + \frac{1}{2}m_0 \langle v_{\perp} \rangle^2 \quad (4)$$

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]

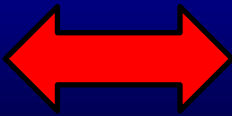
$$R_{\perp}^2 \approx \frac{R^2}{1 + \xi \langle v_{\perp} \rangle^2 (M_{\perp}/T_f)} \quad (5)$$

- 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.

U. W. Heinz: signs of hydro, it is a fluid, Mean free path tends to zero, with references to hydro results:

Nucl.Phys.A 685 (2001) 414-431, PRC54 (1996) 1390 Proc. NN2000, e-Print: hep-ph/0009170 [hep-ph]

L. Maiani, DG OF CERN : MEAN FREE PATH OF QUARKS tends to infinity (macroscopic)



T. Csörgő: Quark Matter, but not QGP!, Hard Quark Matter instead of soft QGP! Only ONE of the TWO transitions is seen: Nucl.Phys.B Proc.Suppl. 92 (2001) 62-74, e-Print: hep-ph/0011339 [hep-ph]

1963 – 2004 Applications of Levy source distributions

The variation of certain speculative prices

B Mandelbrot - Journal of business, 1963 - Springer

... The classic model of the temporal **variation** of **speculative prices** (Bachelier 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)

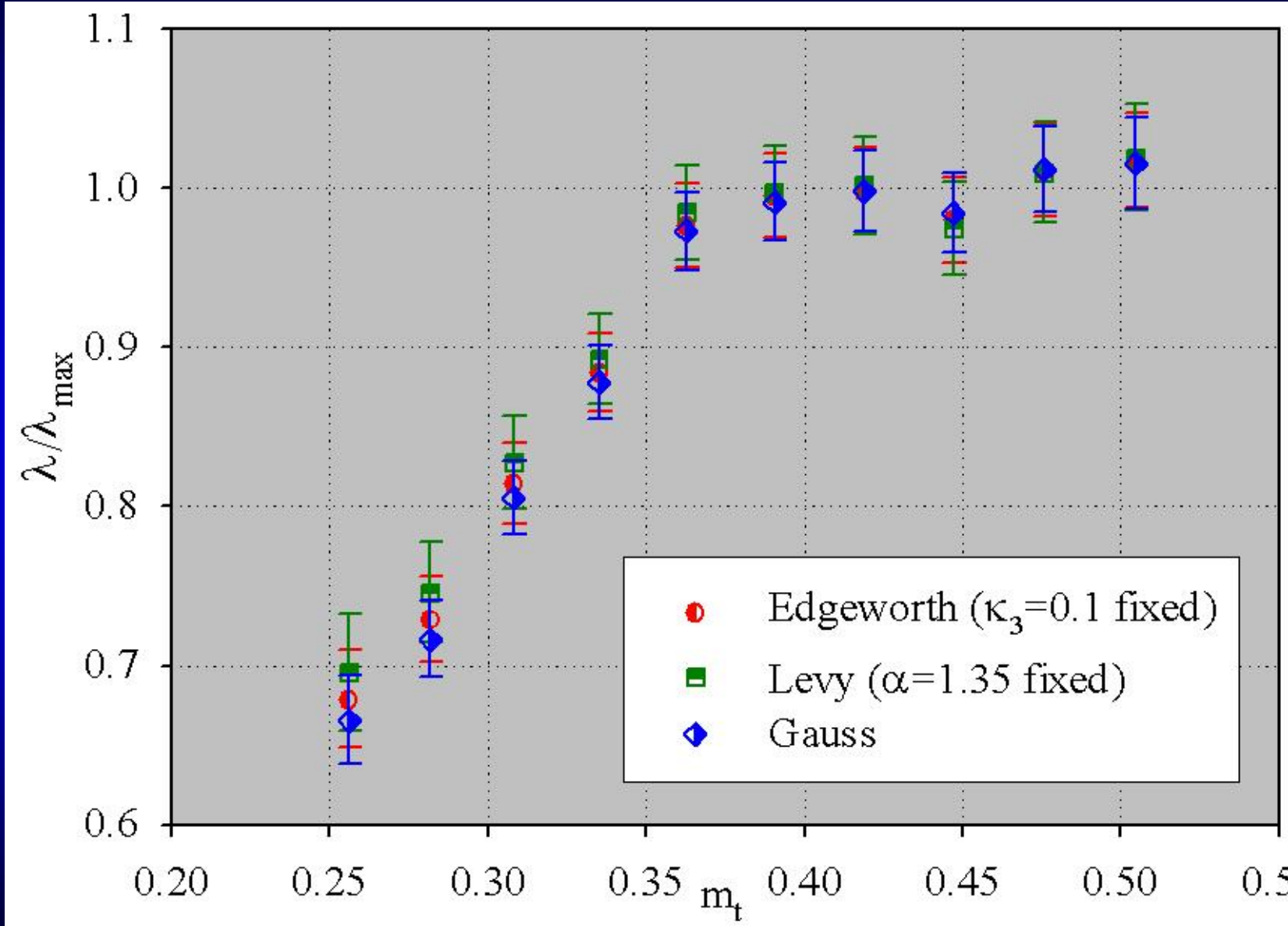
Published in: *Eur.Phys.J.C* 36 (2004) 67-78 • e-Print: nucl-th/0310042 [nucl-th]

 pdf  DOI  cite  claim

 reference search  156 citations

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

2005 – M. Csanád for PHENIX @ QM 2005, ELTE, Budapest, Hungary



M. Csanád for PHENIX Collaboration,
[arXiv:nucl-ex/0509042](https://arxiv.org/abs/nucl-ex/0509042):

λ / λ_{\max} is independent of
the method of extrapolation
of $C_2(q)$ to $q = 0$

Important systematic errors cancel

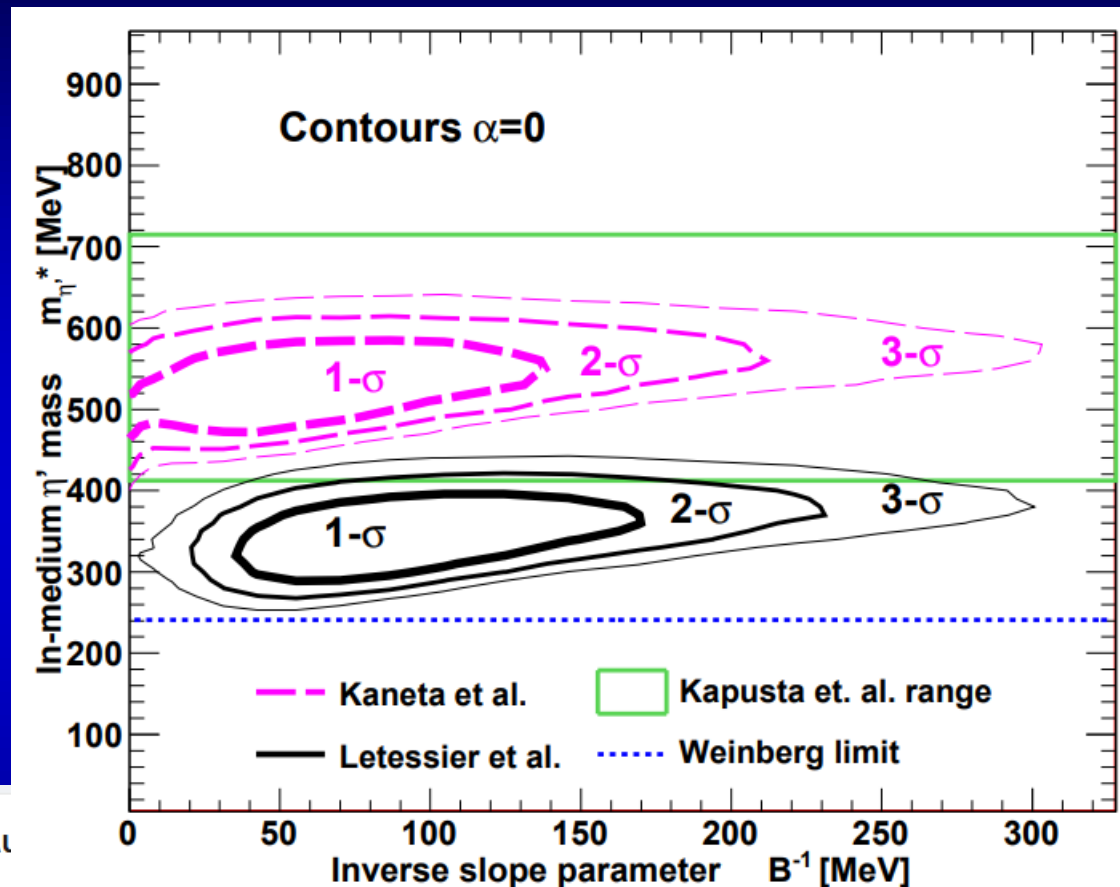
2010: RE-ANALYSIS OF PHENIX AND STAR DATA, AT LEAST 200 MEV LIMIT ON η' MASS DROP @ CL 99.9%

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)

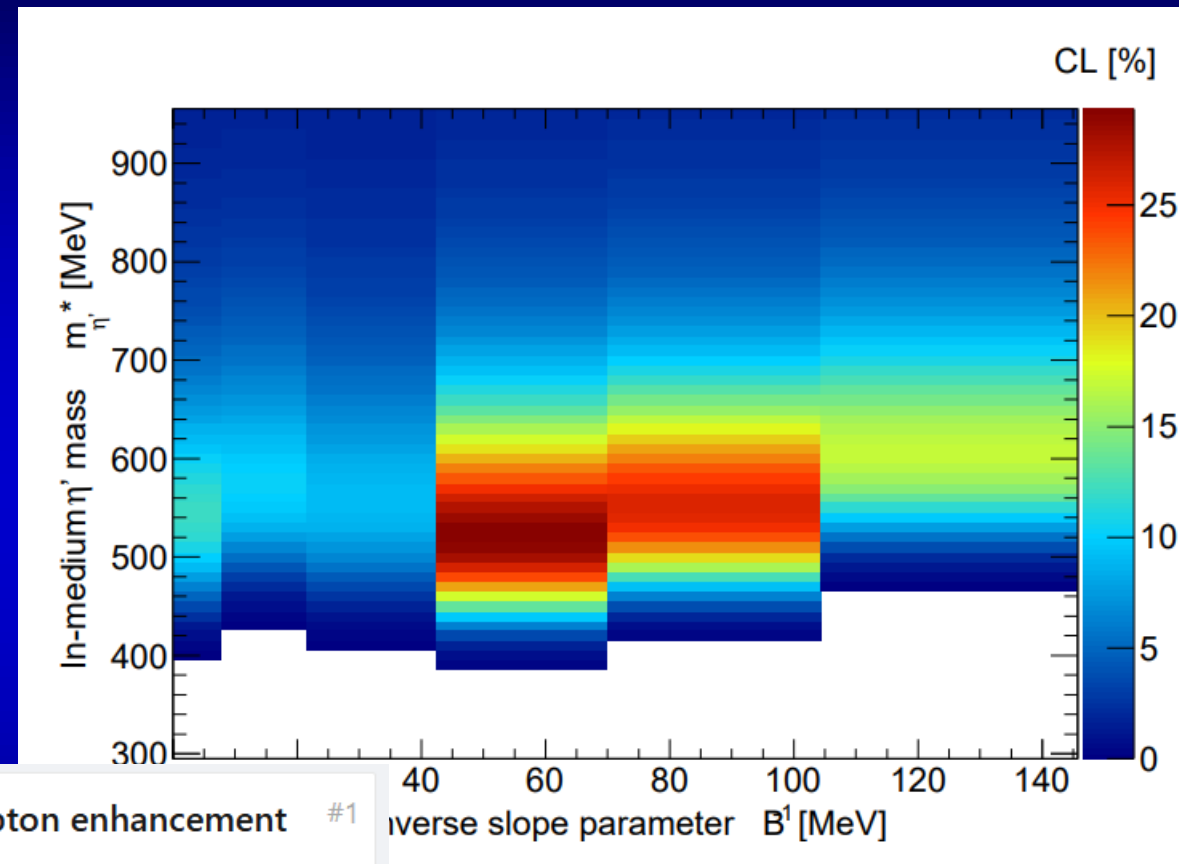
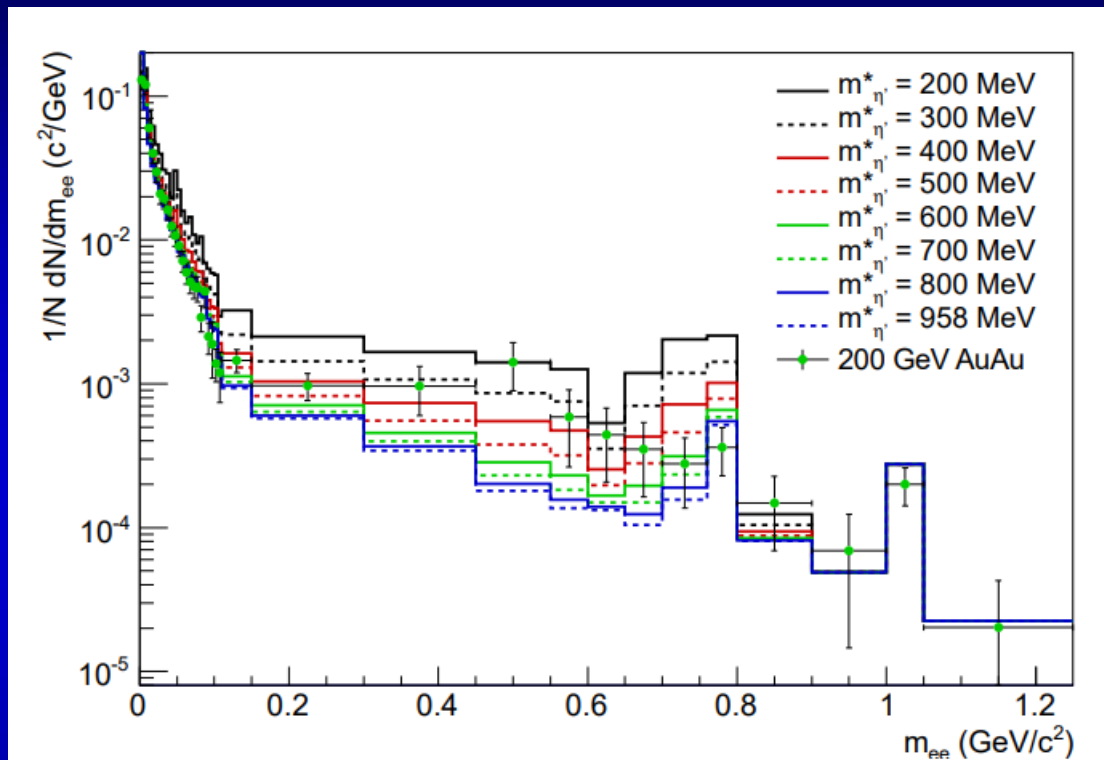
Published in: *Phys.Rev.Lett.* 105 (2010) 182301 • e-Print: 0912.5526 [nucl-ex]

pdf DOI cite claim

reference search 88 citations

in-medium η' modification: can it be switched on and off? YES!
Centrality? Energy? System size?

2013: RE-ANALYSIS, PHENIX 200 GEV AU+AU DIELECTRON, SENSITIVE, BUT NO NEED FOR MASS-SHIFT IN MIN BIAS



Effects of chain decays, radial flow and $U_A(1)$ restoration on the low-mass dilepton enhancement #1

in $\sqrt{s_{NN}} = 200$ GeV Au+Au reactions

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

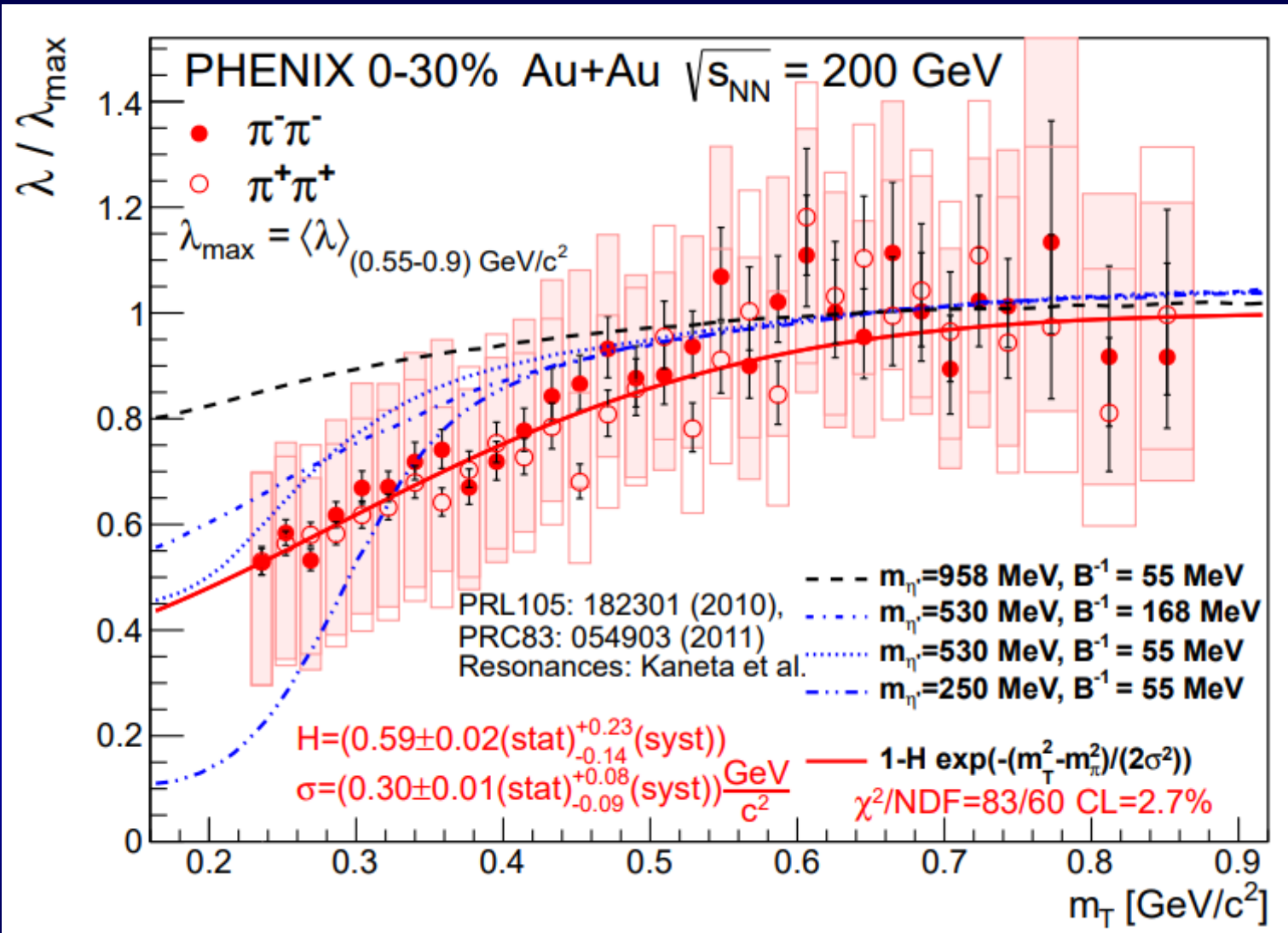
Published in: *Central Eur.J.Phys.* 11 (2013) 553-559 • e-Print: 1211.1166 [nucl-th]

[pdf](#) [DOI](#) [cite](#) [claim](#)

[reference search](#) [6 citations](#)

in-medium η' modification: is it significant? Not in PHENIX min bias Au+Au data...

2018: SENSITIVE TO IN-MEDIUM η' MASS MODIFICATION



PHENIX data + Monte Carlo,

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

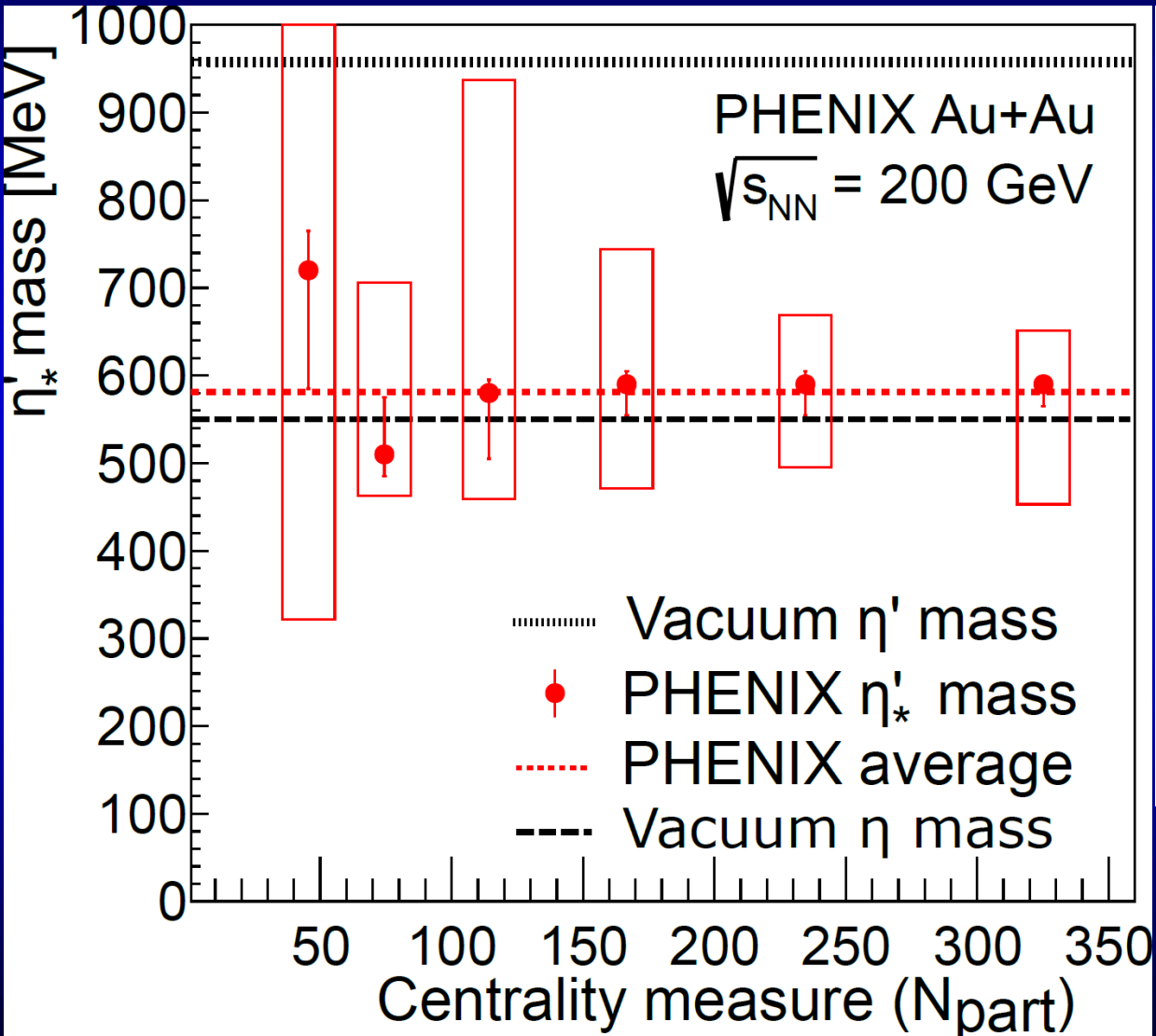
0-30 % Au+Au @ 200 GeV
Lévy Bose-Einstein

PHENIX data sensitive to
in-medium η' modification

centrality
dependence = ?

in-medium η' modification: It can be switched on/off with \sqrt{s} and/or system size

2024: „THIS IMPLIES A SECOND TRANSITION IN QCD ...” /PRC EDITORS/



EDITORS' SUGGESTION

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

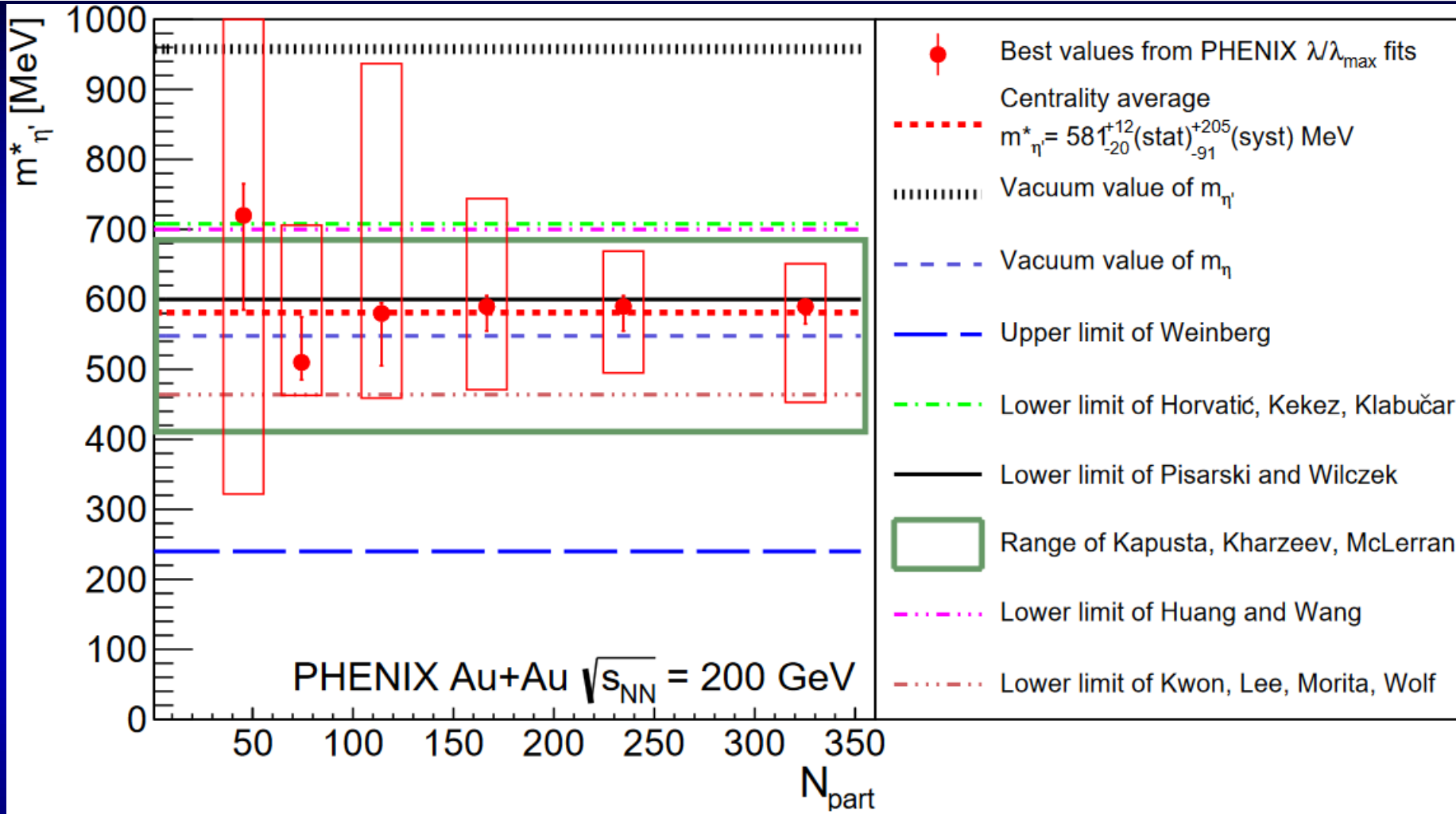
20 DECEMBER, 2024

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 \(2024\)](#)

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



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: $m^*(\eta') \sim m(\eta)$

DETAILS OF PHENIX RESULTS
<https://wpcf2026.elte.hu/press/>

SUMMARY AND CONCLUSIONS

Timeline from 1974 to 2024 summarized

From T.D.Lee (1974), S. Weinberg (1975) and F. Wilczek (1984)
through the RHIC proposal (1984) and
PHENIX and STAR Bose-Einstein data re-analysis (2010)
PHENIX dielectron spectra re-analysis (2013) to an

Indirect observation of a prodigal Goldstone boson (PHENIX , 2024):

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

**With $1 < \alpha < 2$ significantly, Levy shape describes data
decreasing with increasing N_{part}**

Unexpected scaling laws found

**Data not inconsistent with $U_A(1)$ symmetry restoration:
In-medium mass modification of η' with indirect method**

**Direct observation e.g. $\eta' \rightarrow \gamma + \gamma$ is particularly challenging
but also particularly rewarding:**

Challenge for B. Tamás (BST-70) !

SUMMARY AND CONCLUSIONS

Fro

**HAPPY 70TH BIRTHDAY,
to B. Tamás,
from Cs. Tamás and friends**

Indirect

**Cent
me**

W

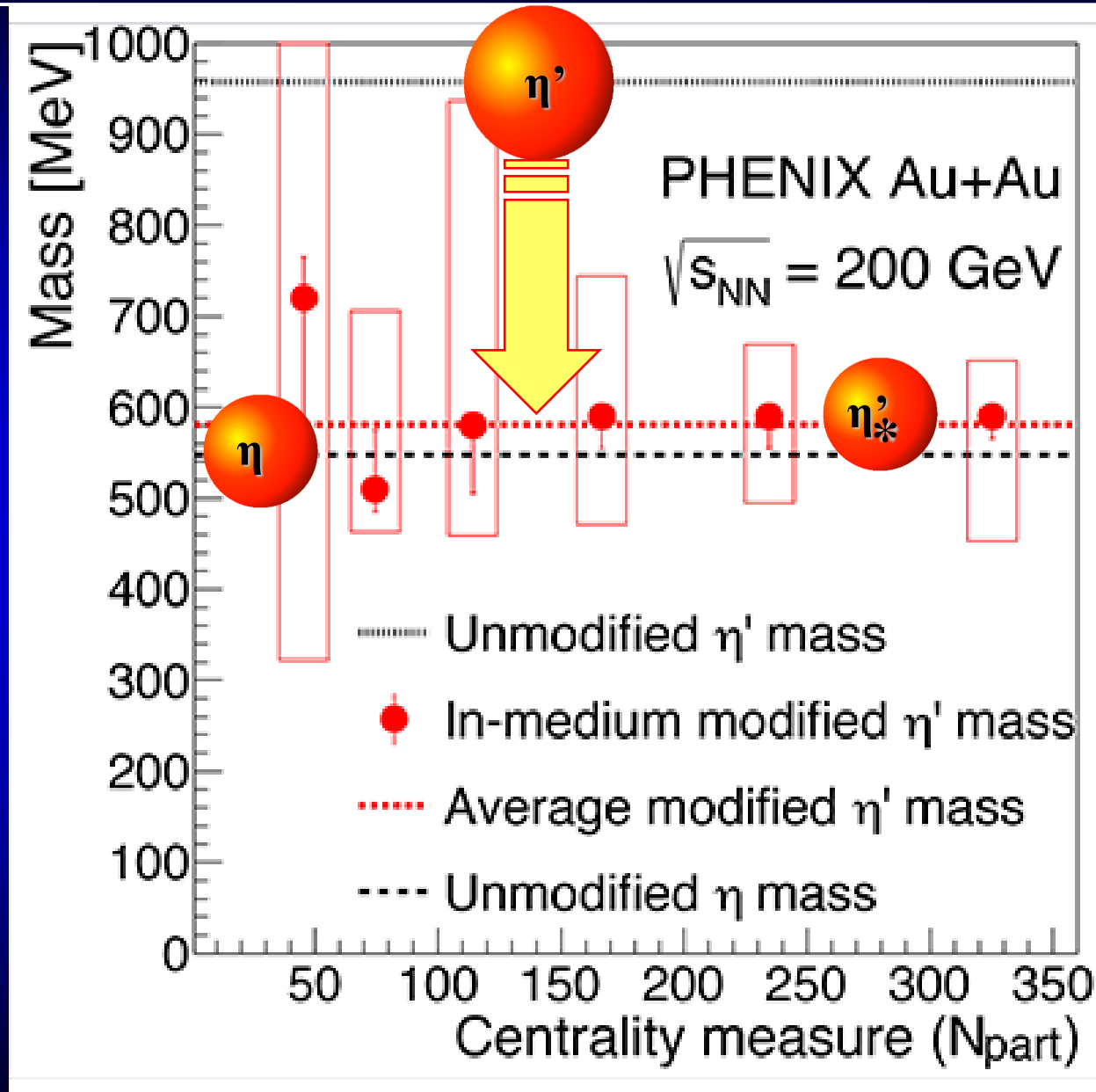
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In**

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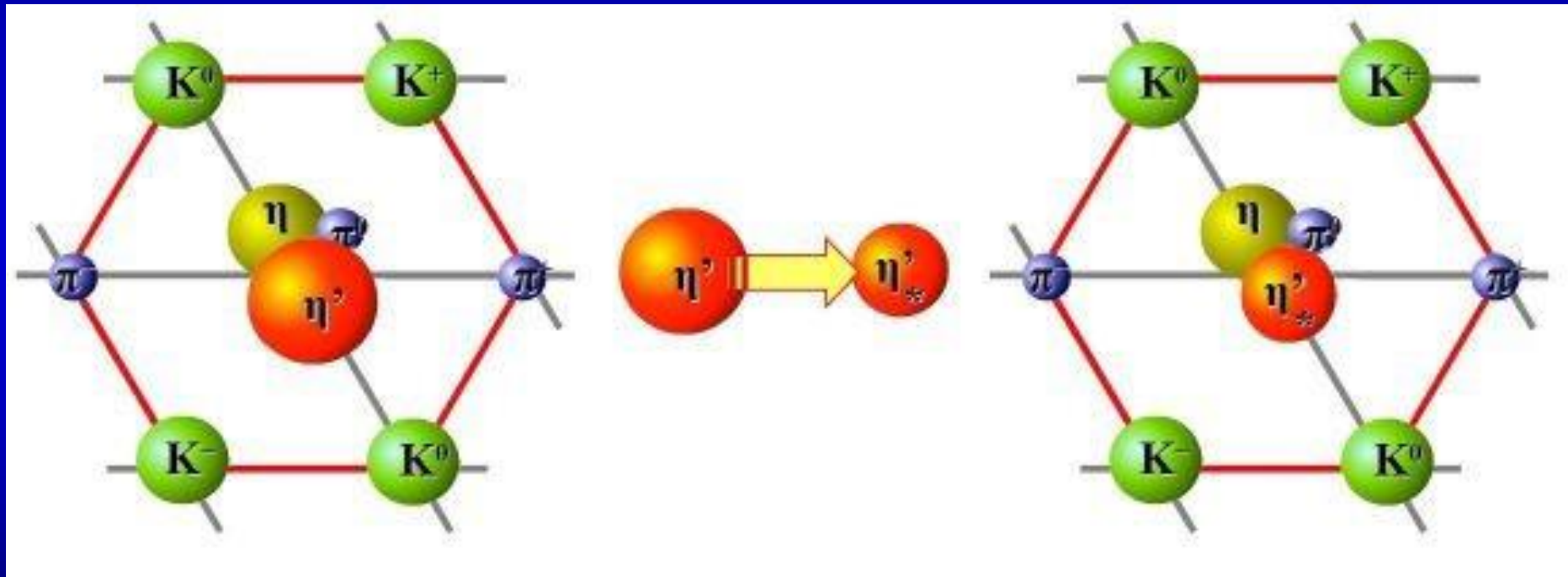
„THIS IMPLIES A SECOND TRANSITION IN QCD“



PRC Editors

Thank you for your attention!

Questions?



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](https://arxiv.org/abs/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

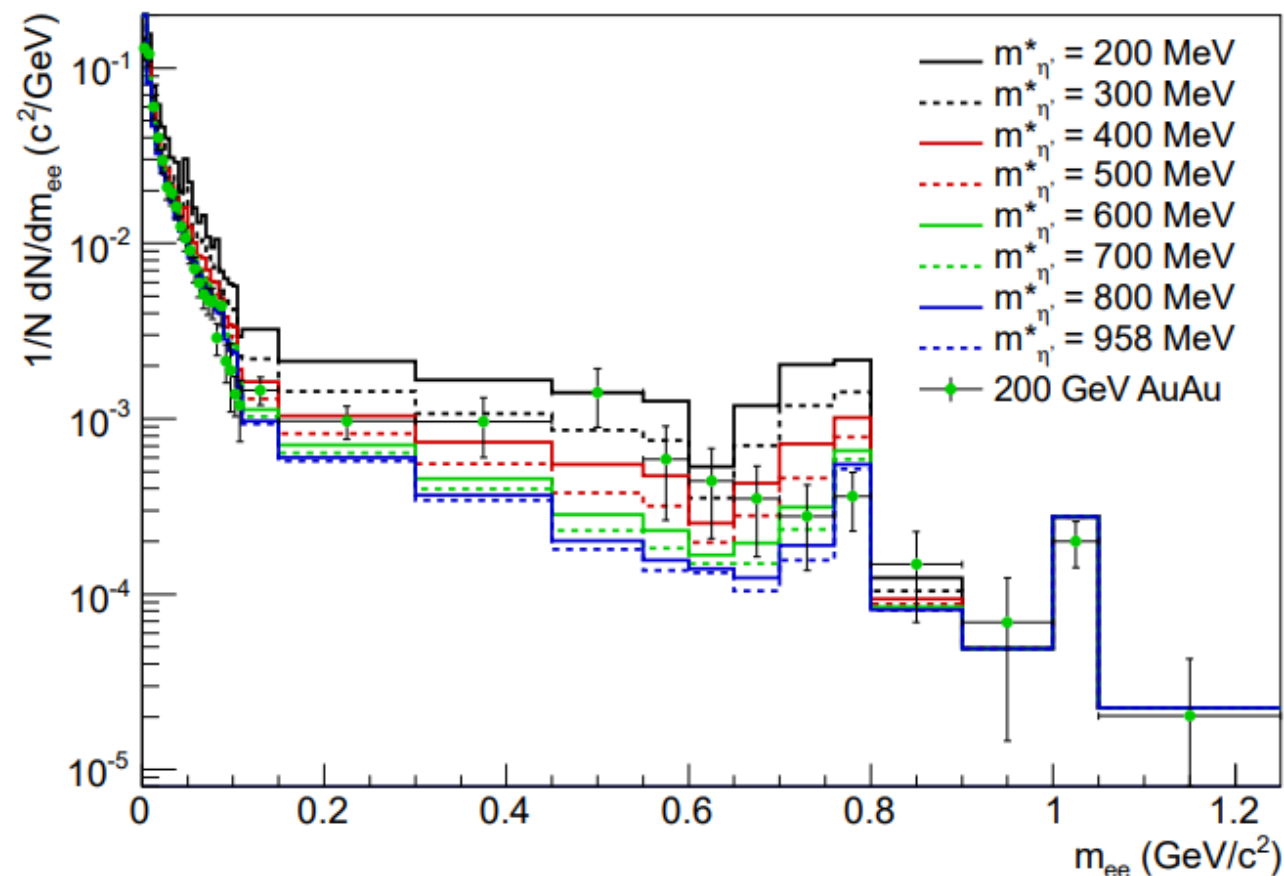


Figure 6: Dilepton cocktail in PHENIX acceptance, for different in-medium η' mass values. Points are PHENIX data of Ref. [1].

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

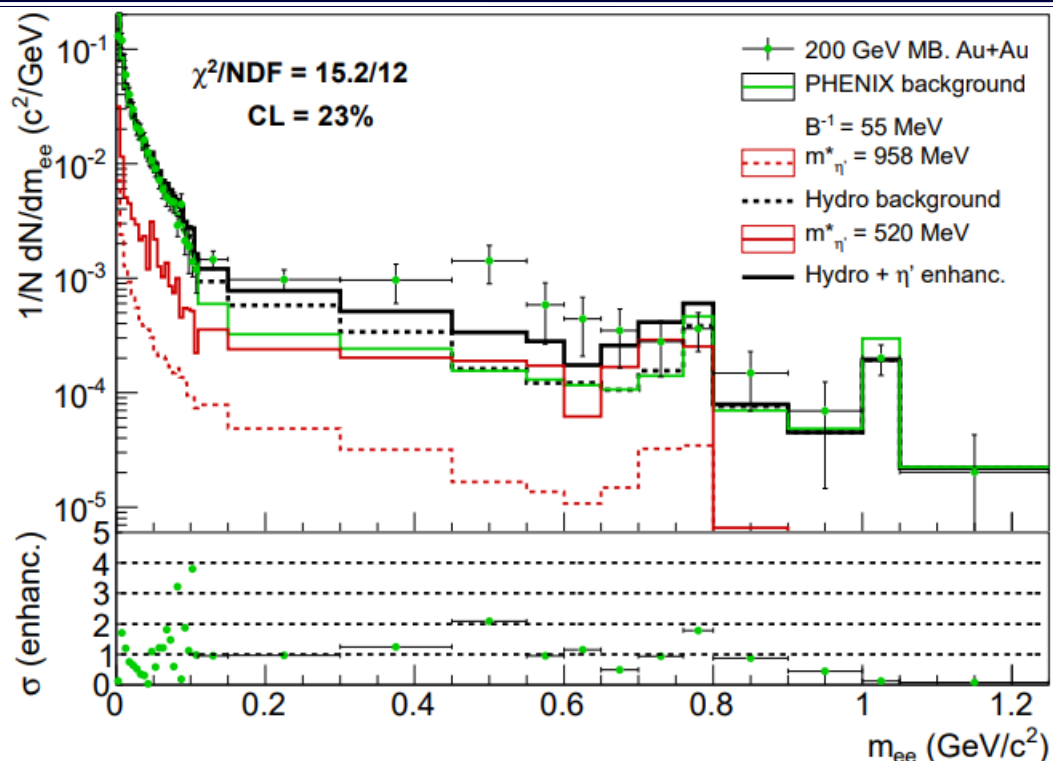


Figure 4: Dilepton spectra in PHENIX acceptance with the perfect hydrodynamics motivated spectrum of Eq. (4) including chain decays. The dashed red line is the contribution of the unmodified η' , the solid one is the contribution from the best fit, $m_{\eta'}^* = 520$ MeV. Dashed and solid black lines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

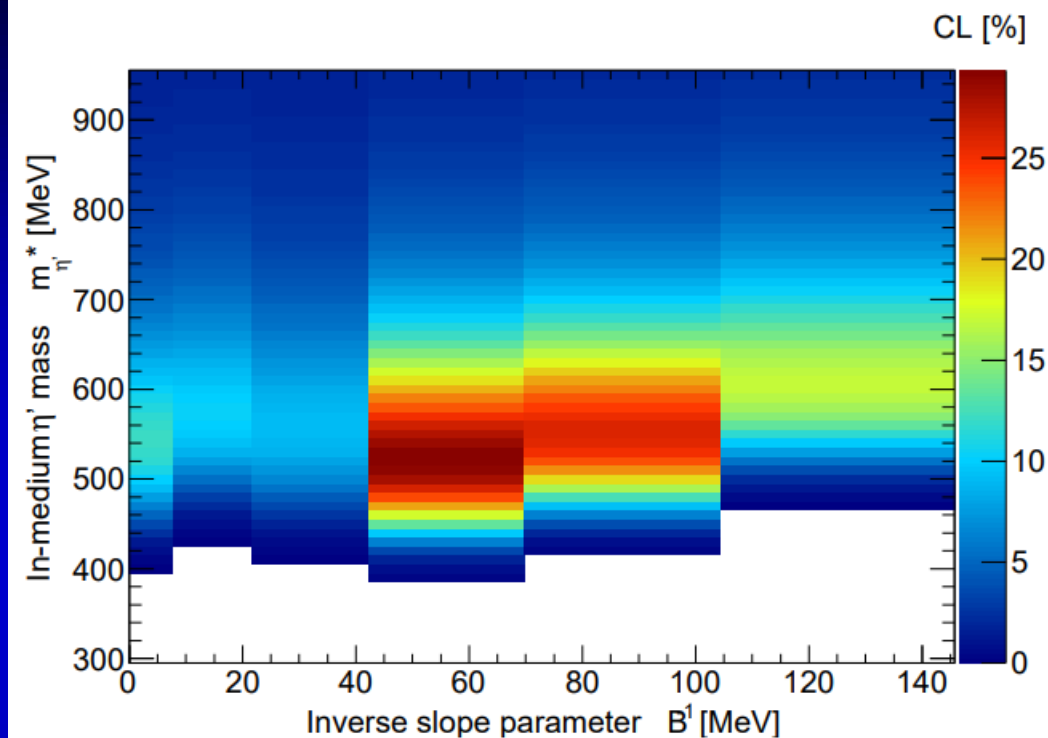


Figure 5: Preliminary confidence level map of the two η' spectrum parameter B^{-1} and $m_{\eta'}^*$. Best fit corresponds to $m_{\eta'}^* \approx 520$ MeV and $B^{-1} \approx 55$ MeV. The $m_{\eta'}^* < 380$ MeV region (white) corresponds to $CL < 0.1\%$ and can be excluded, but no upper limit can be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

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

10 → 60 % LEVY HBT VS MIN BIAS DIELECTRON

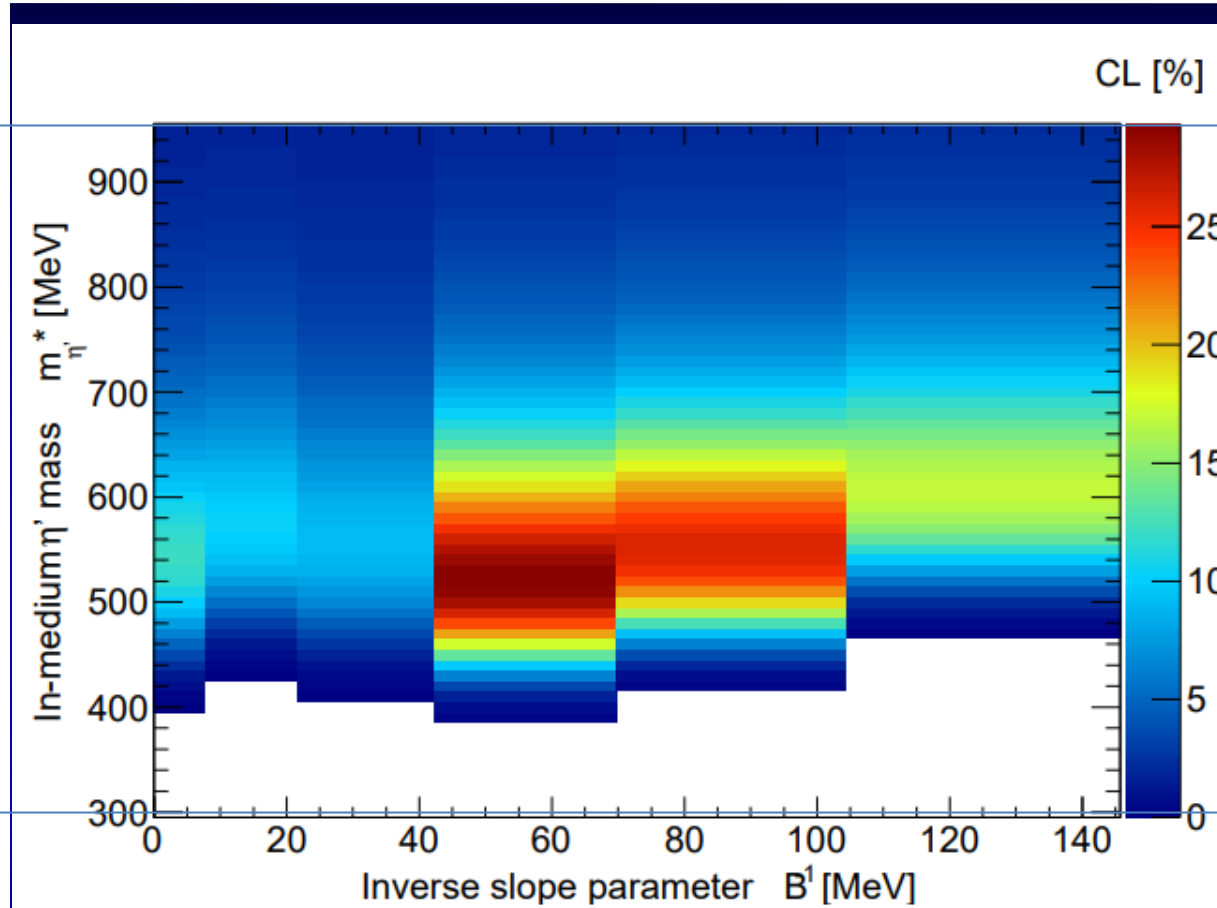
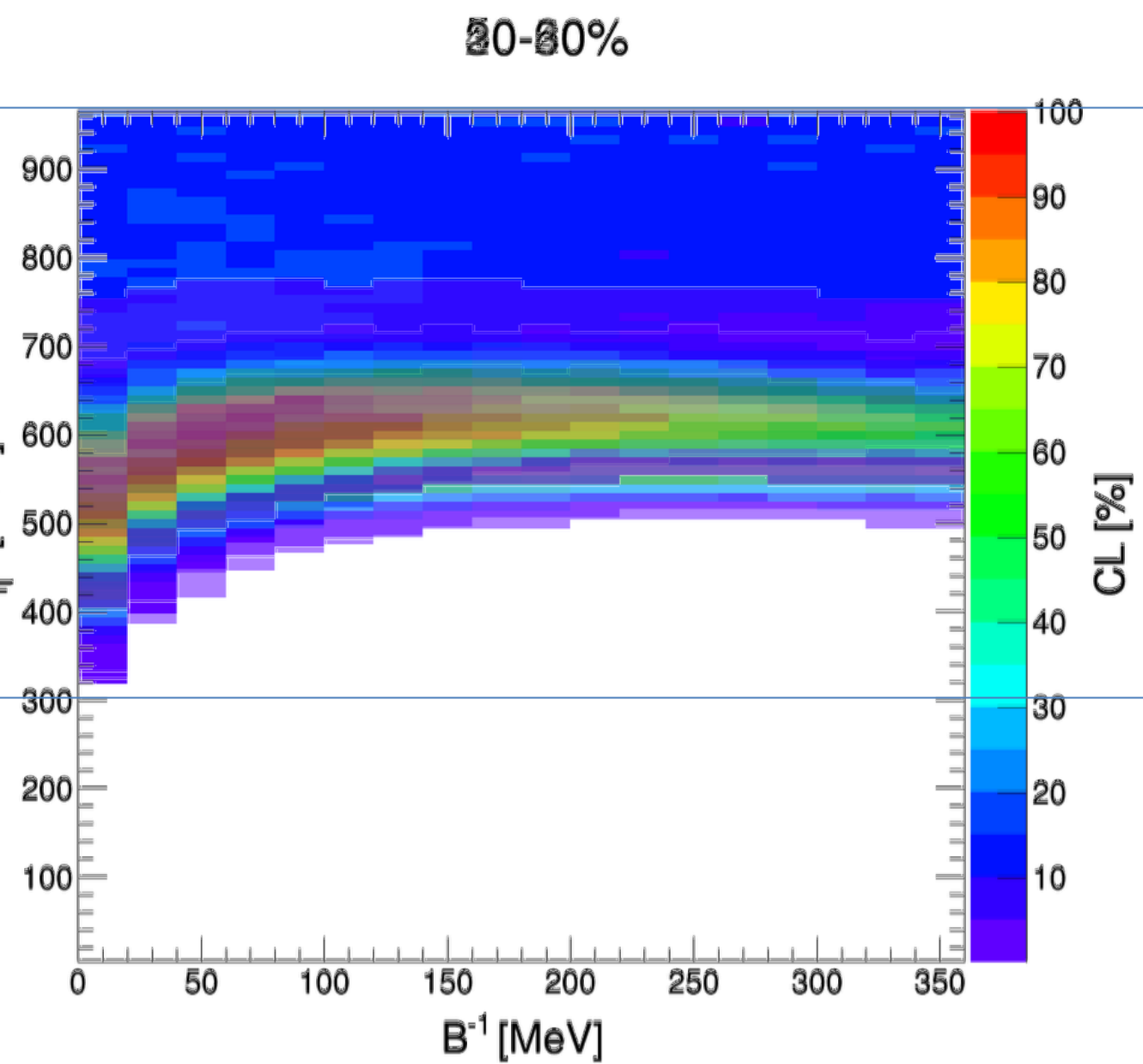
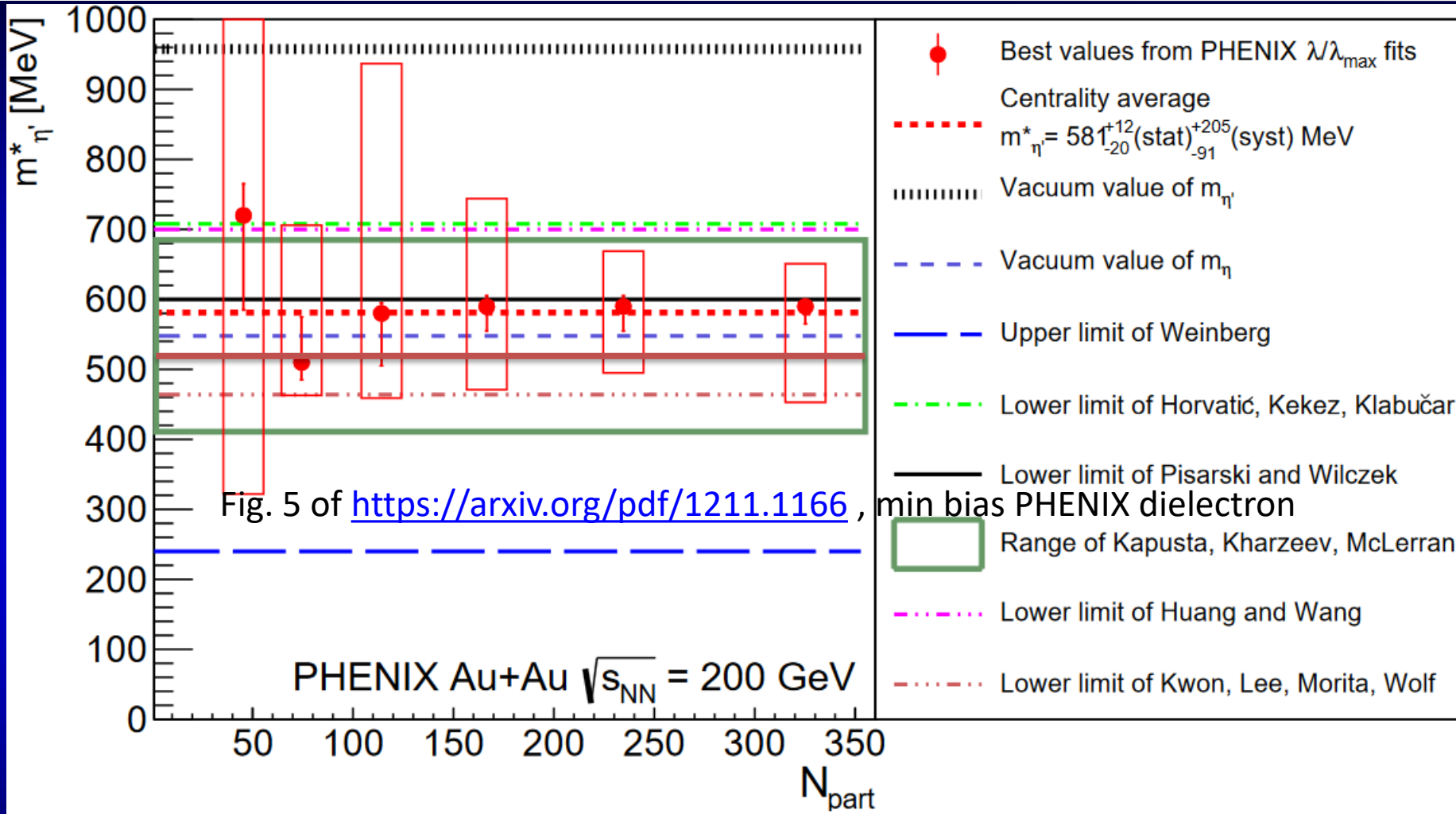


Figure 5: Preliminary confidence level map of the two η' spectrum parameter B^{-1} and $m_{\eta'}^*$. Best fit corresponds to $m_{\eta'}^* \approx 520$ MeV and $B^{-1} \approx 55$ MeV. The $m_{\eta'}^* < 380$ MeV region (white) corresponds to $CL < 0.1\%$ and can be excluded, but no upper limit

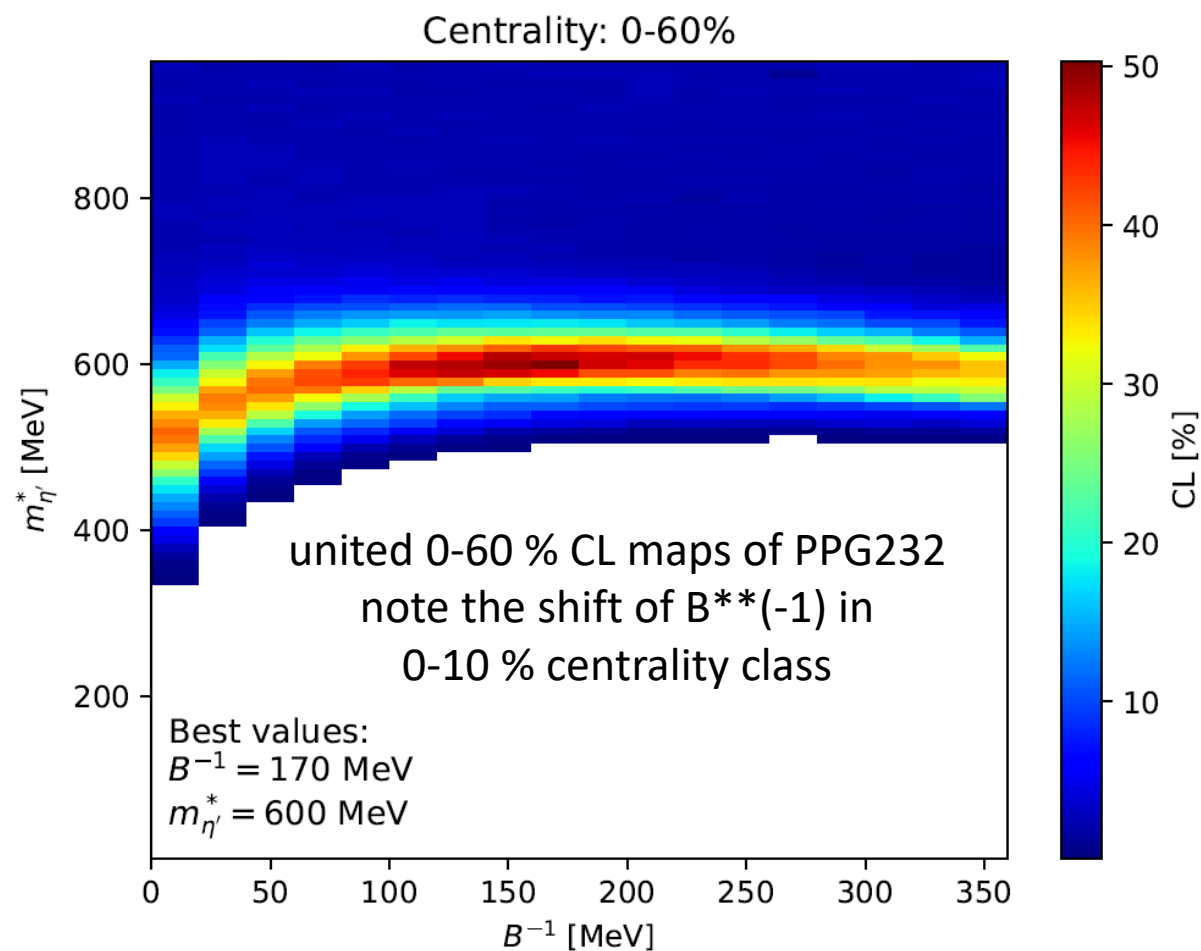
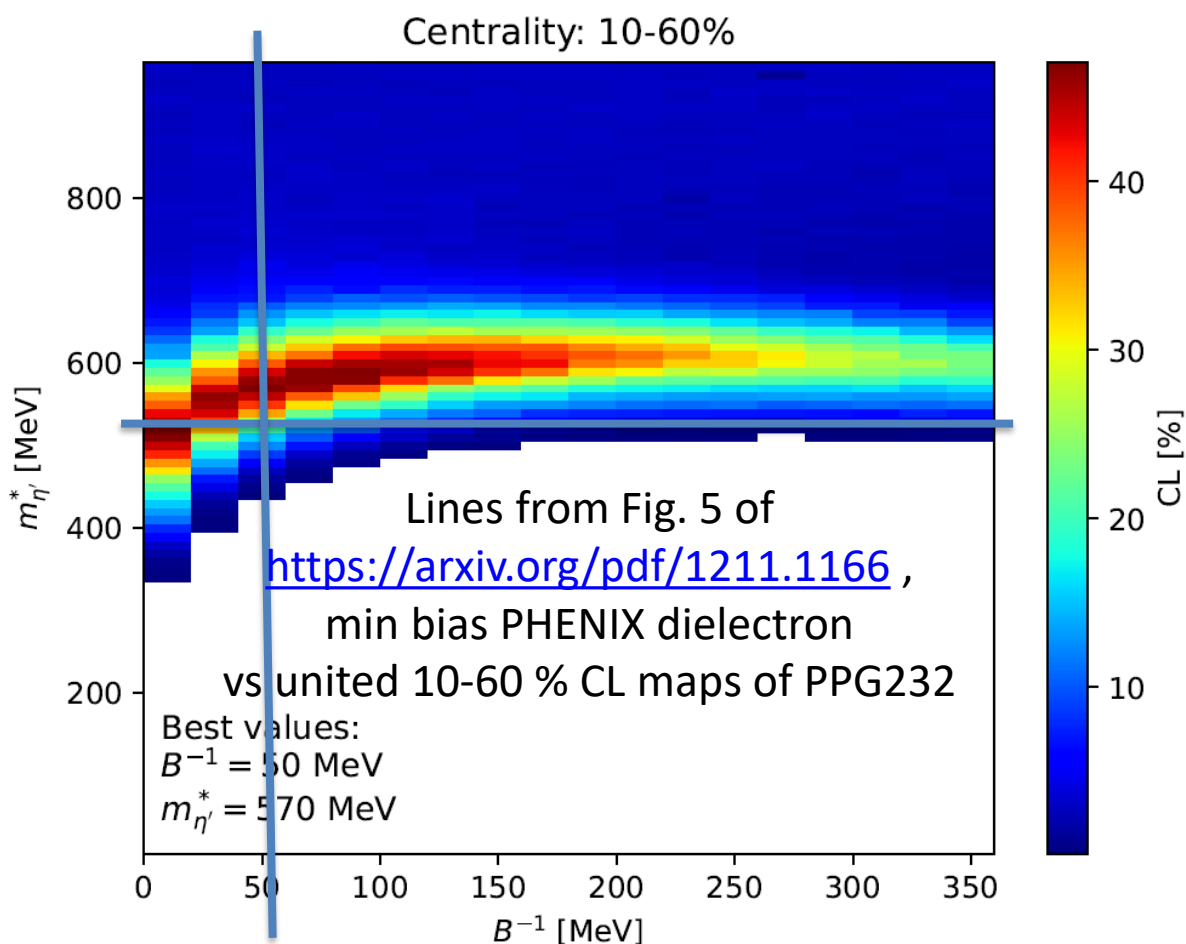
N_{part} DEPENDENCE OF IN-MEDIUM MASS OF η'



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:1211.1166³⁰

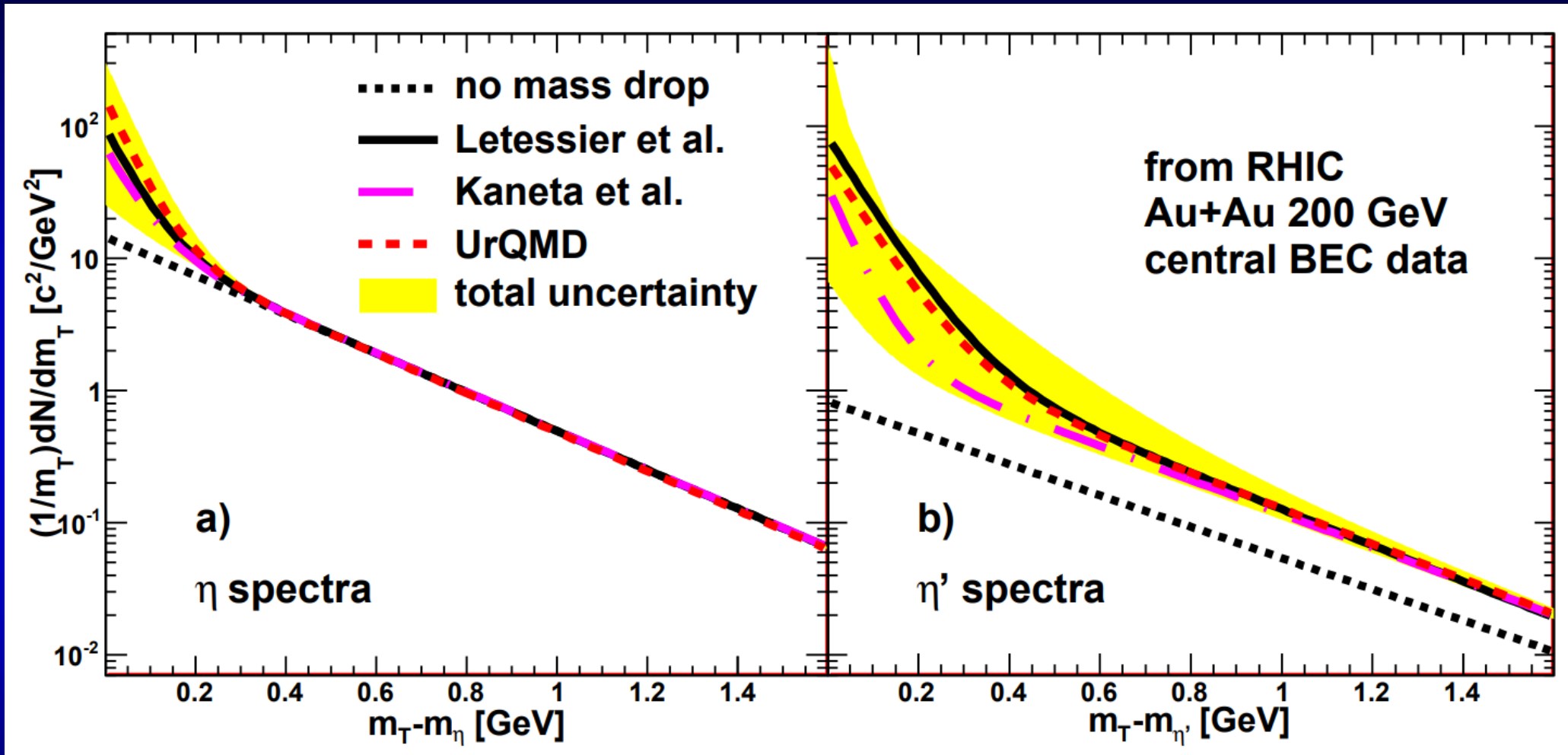
UNITING CL MAPS (10-60 %, 0-60 %) VS MIN. BIAS DIELECTRON

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

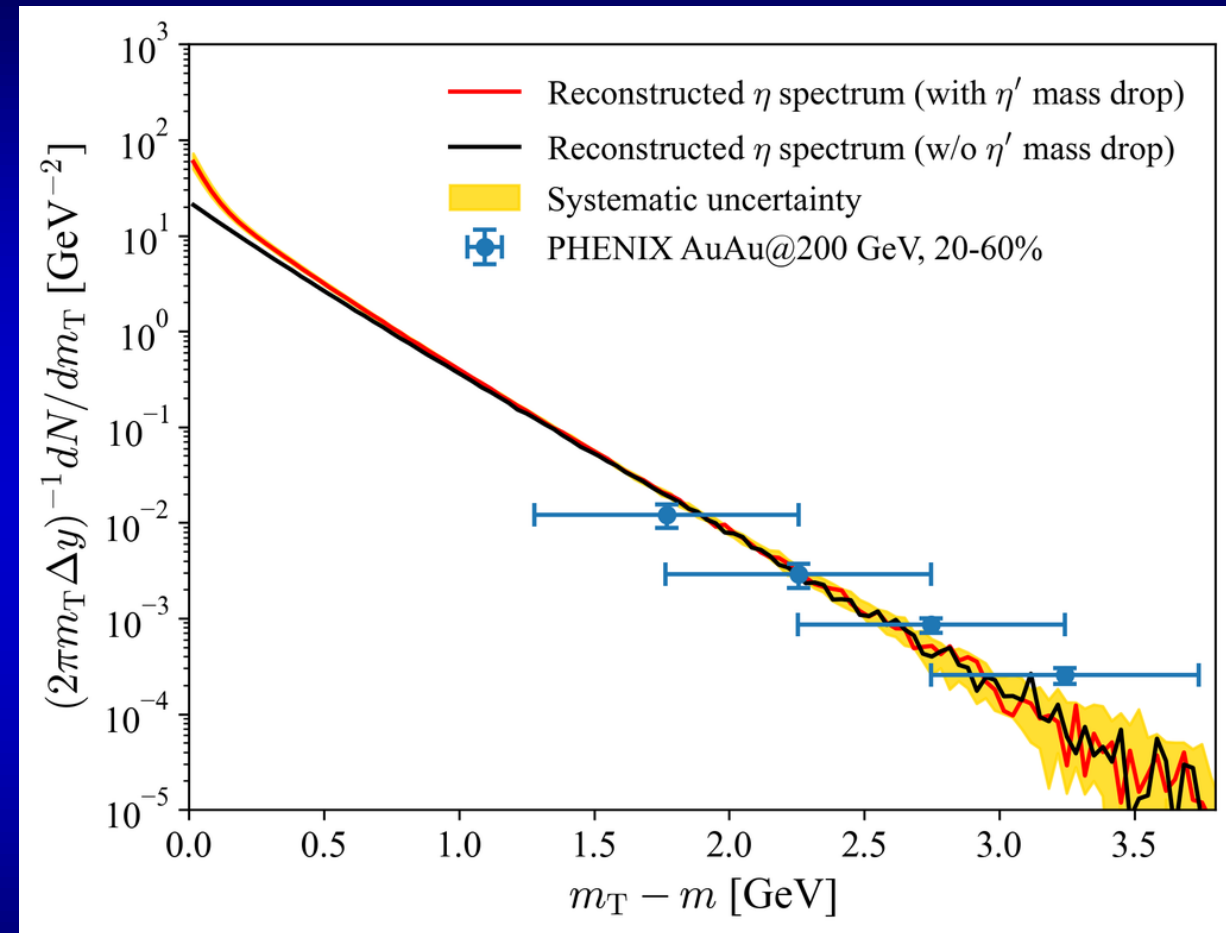
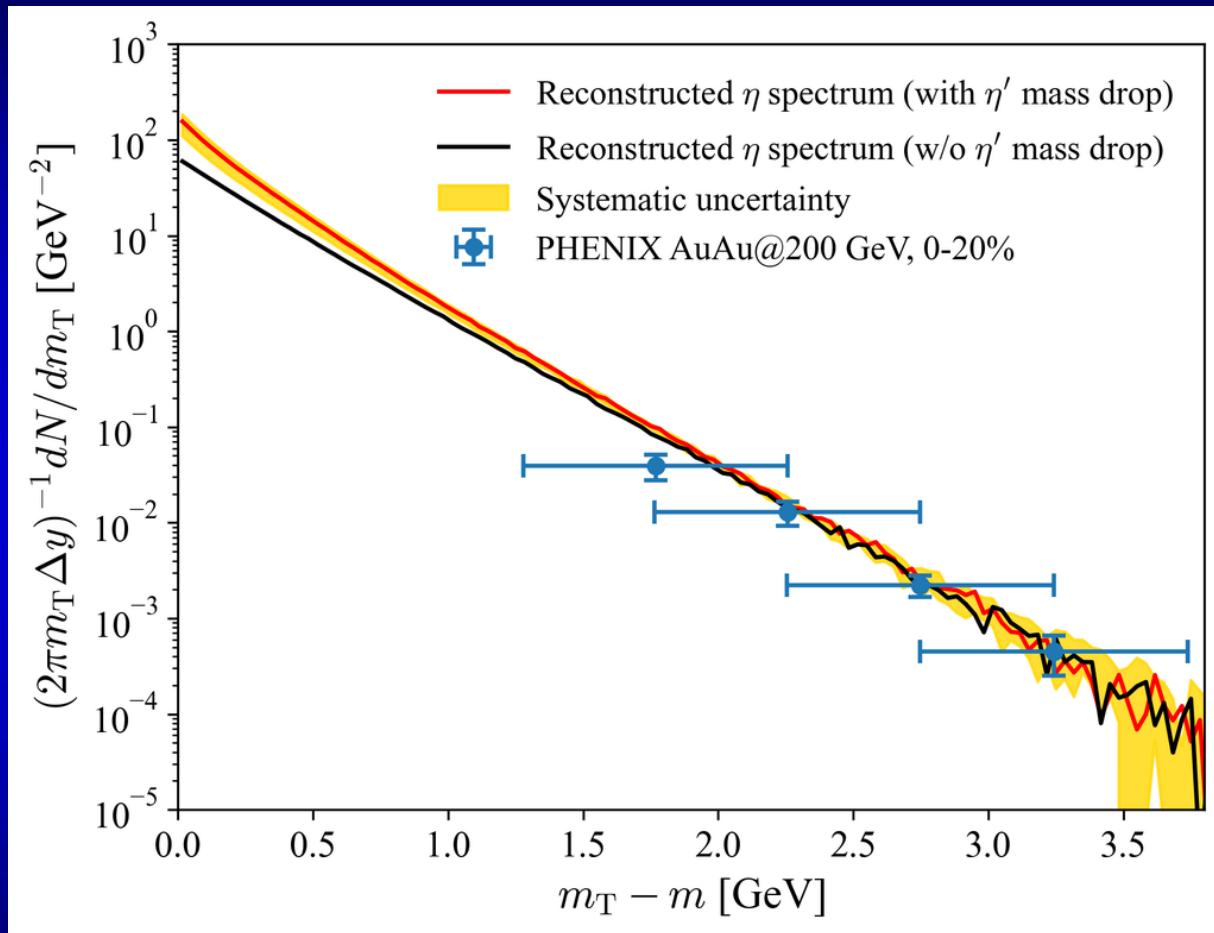


Indirect observation of an in-medium η' mass reduction in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions

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

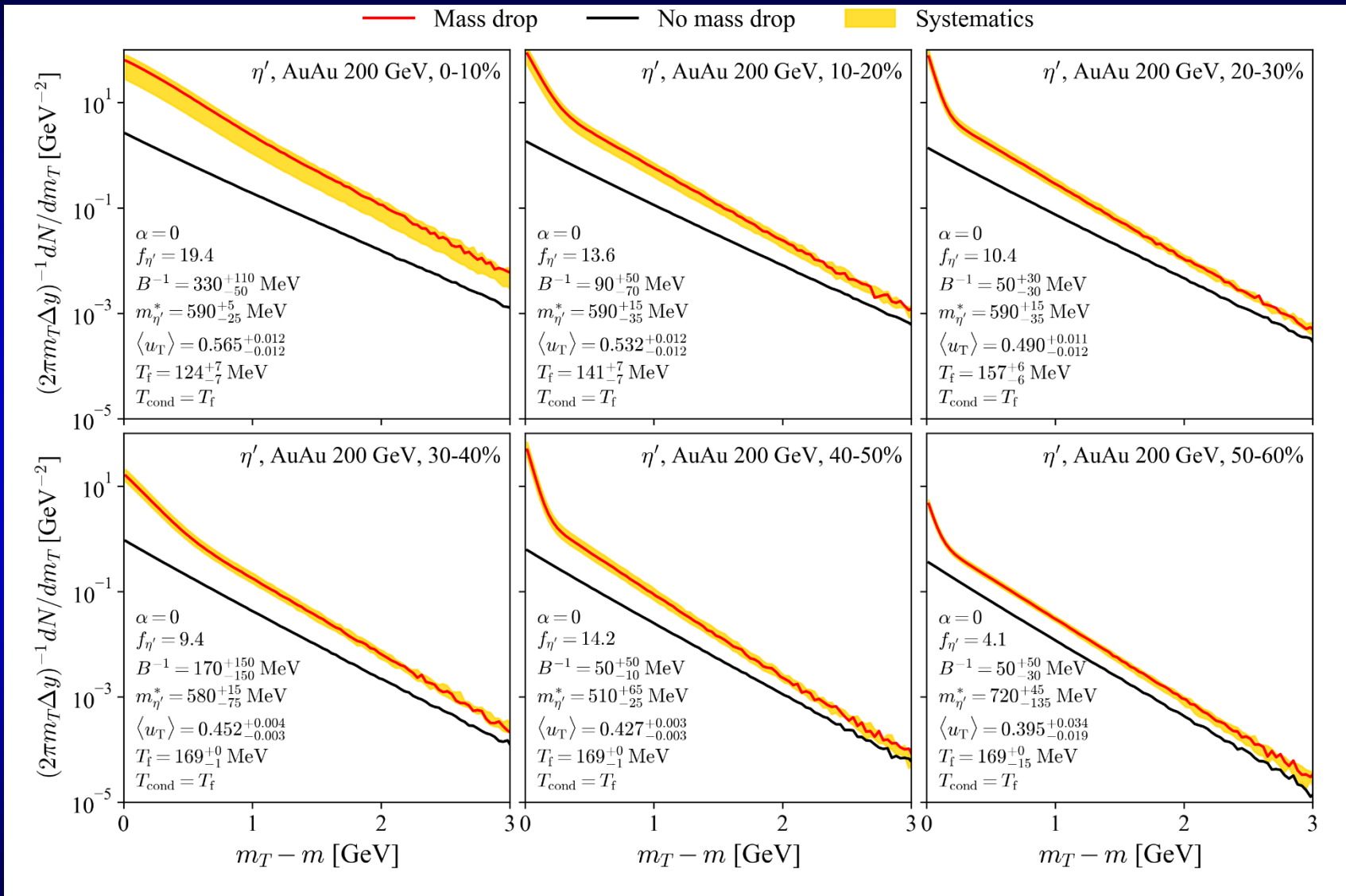
Published in: *Phys.Rev.Lett.* 105 (2010) 182301 • e-Print: 0912.5526 [nucl-ex]

NEW: CENTRALITY DEPENDENT η SPECTRA



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

NEW: CENTRALITY DEPENDENT η' SPECTRA

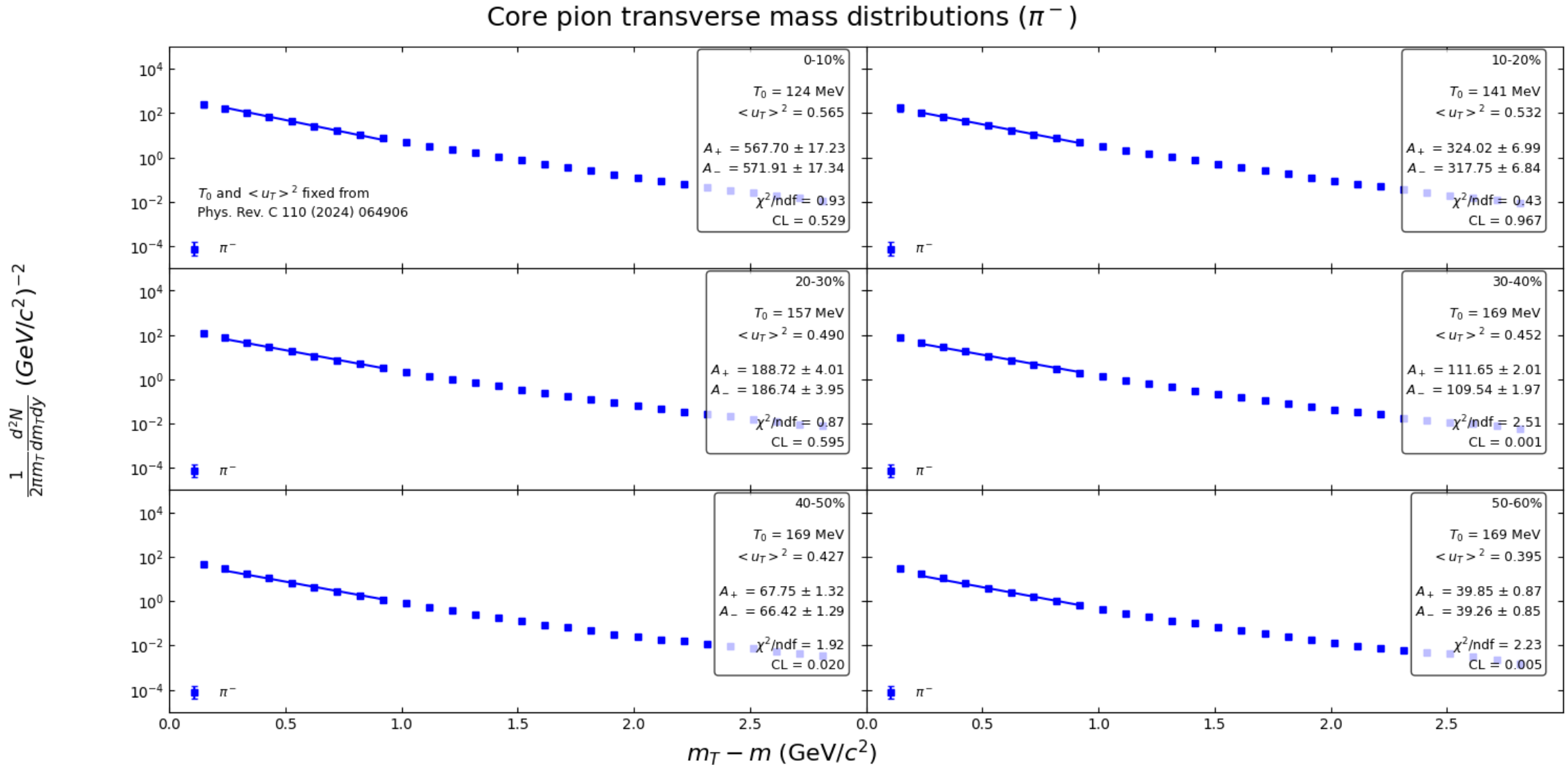


Enhancement factor $f_{\eta'}$,
determined similarly as in
Cs.T., R. Vértési and J. Sziklai,
Phys.Rev.Lett. 105 (2010) 182301
e-Print: [0912.5526](https://arxiv.org/abs/0912.5526) [nucl-ex]

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

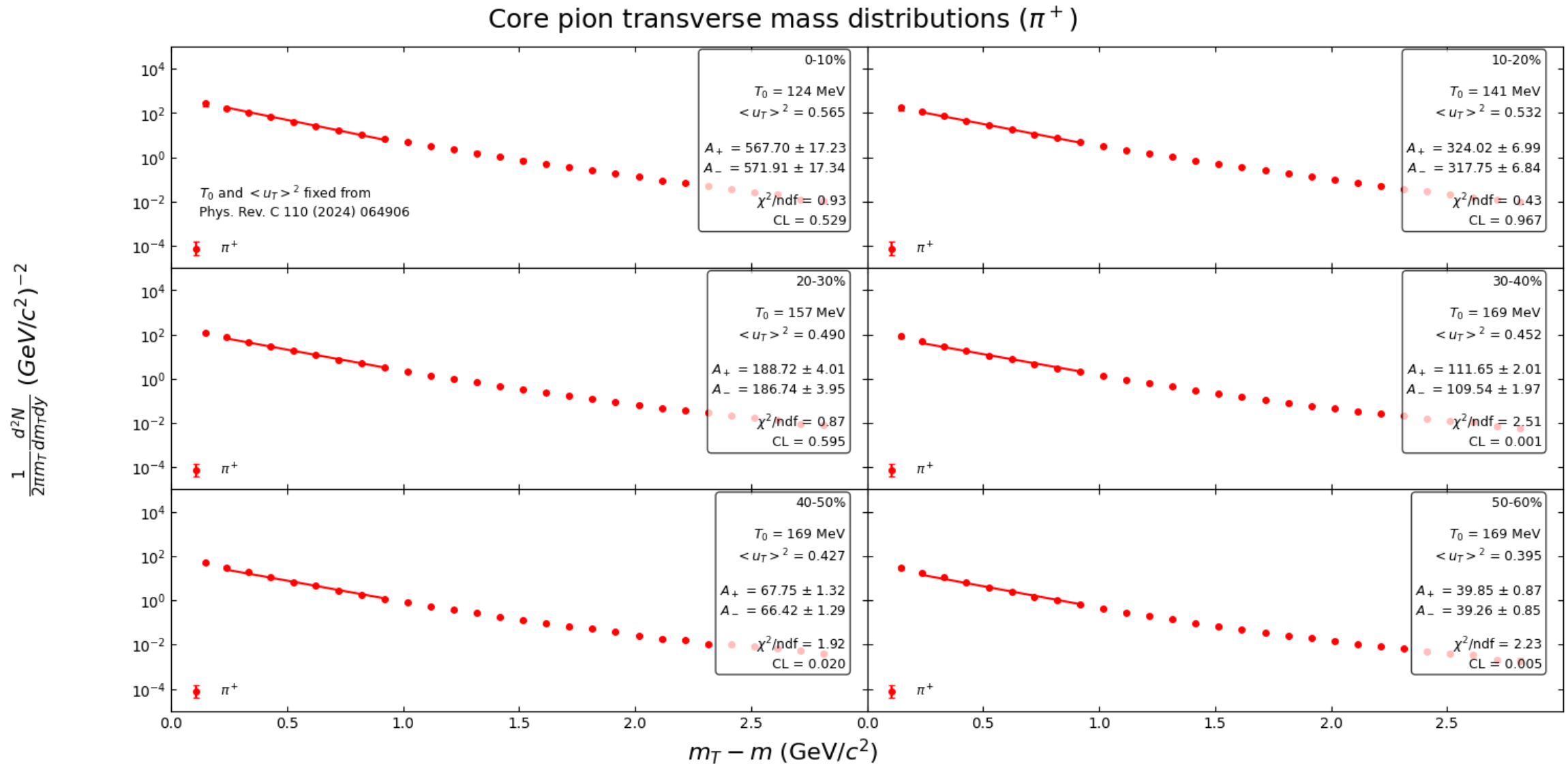
Q4: CAN WE REPRODUCE PION SPECTRA?

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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- Our results also suggest that the prediction of Ref. [64] slightly underestimates the in-medium mass change of the η' .

„THIS IMPLIES A SECOND TRANSITION IN QCD“

PRC Editors' Suggestion (2024/12)

Variables and Coulomb corrections for Levy $C_2(Q)$

$$Q \equiv |\mathbf{q}_{\text{LCMS}}| = \sqrt{q_{\text{out,LCMS}}^2 + q_{\text{side,LCMS}}^2 + q_{\text{long,LCMS}}^2}.$$

$$\sum_{i=\text{side,out,long}} R_i^2 q_i^2 \approx R^2 \left(\sum_{i=\text{side,out,long}} q_i^2 \right) = R^2 Q^2,$$

$$Q \equiv |\mathbf{q}_{\text{LCMS}}| = \sqrt{(p_{1,x} - p_{2,x})^2 + (p_{1,y} - p_{2,y})^2 + \frac{4(p_{1,z}E_2 - p_{2,z}E_1)^2}{(E_1 + E_2)^2 - (p_{1,z} + p_{2,z})^2}},$$

$$C_2(Q; \lambda, R, \alpha, N, \varepsilon) = 1 - \lambda + \lambda C_2^{(0)}(Q; \lambda, R, \alpha, N, \varepsilon) \times \frac{\sum_j w_j K(q_{\text{inv}})}{\sum_j w_j}$$

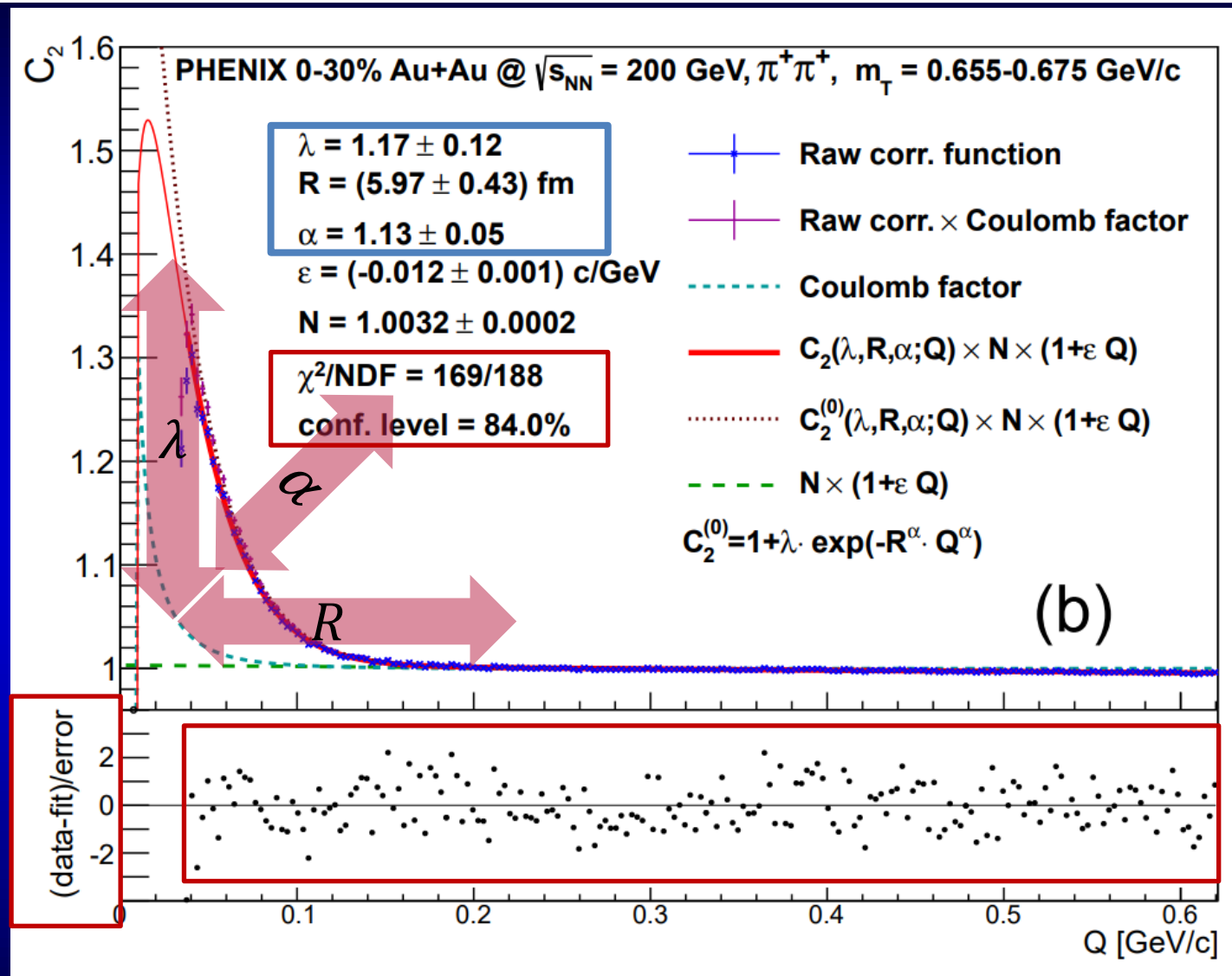
$$C_2^{(0)}(Q; R, \alpha, N, \varepsilon) = (1 + \exp(-R^\alpha Q^\alpha)) \times N \times (1 + \varepsilon Q),$$

From PHENIX, Phys.Rev.C 97 (2018) 6, 064911 and [2407.08586 \[nucl-ex\]](#)

**For recent results on Coulomb corrections for a Levy source, see:
M. Nagy, A. Purzsa et al, Eur.Phys.J.C 83 (2023) 11, 1015, arXiv:[2308.10745 \[nucl-th\]](#)**

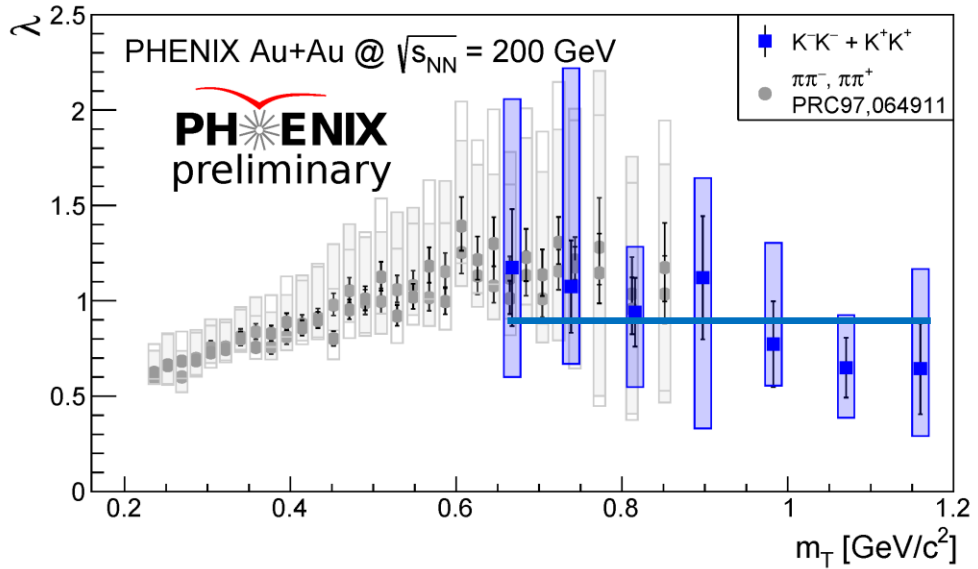
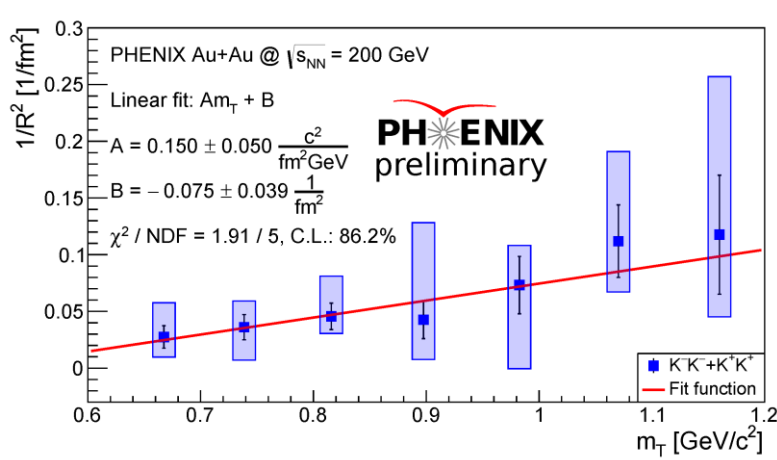
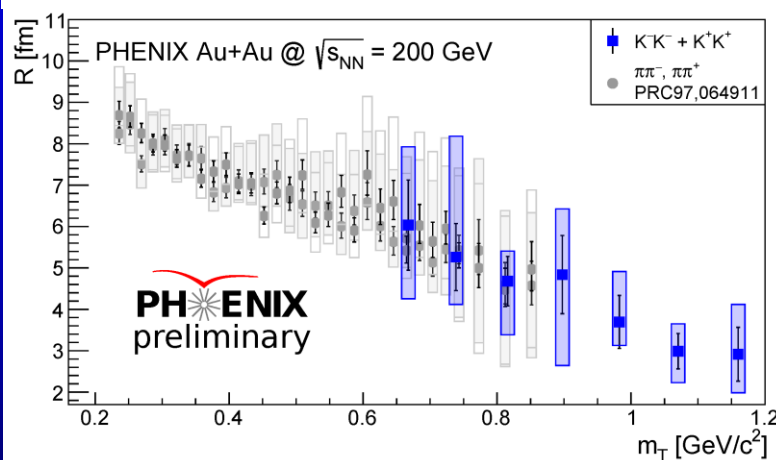
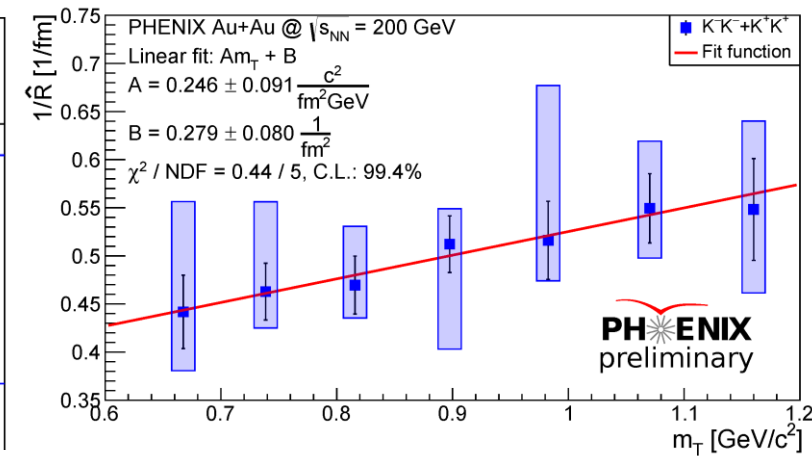
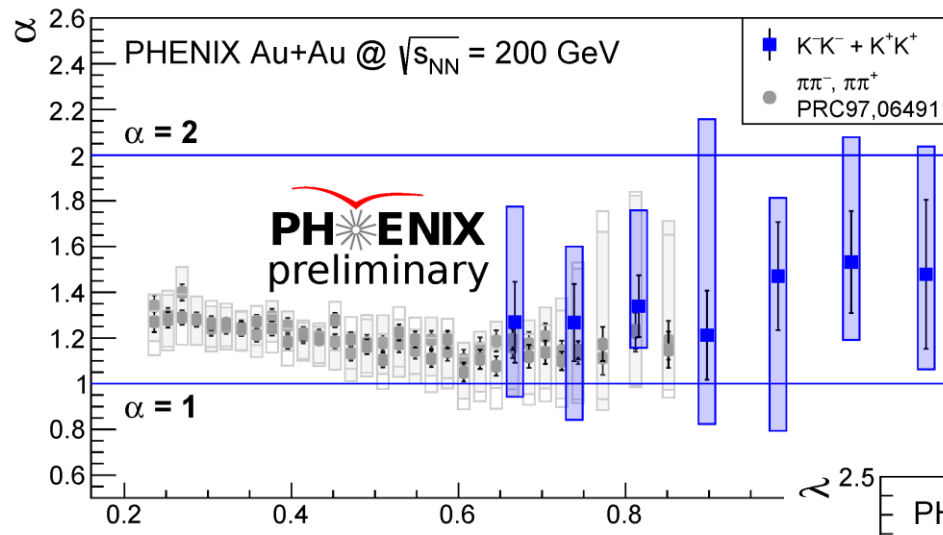
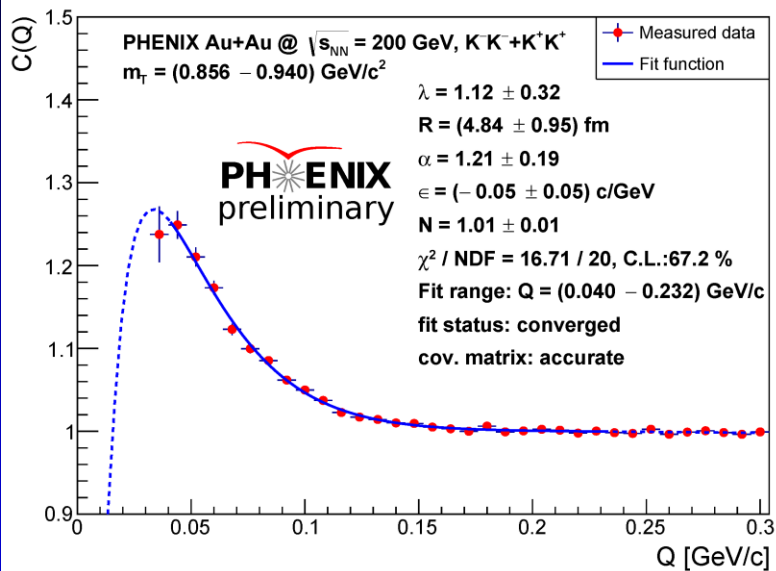
**For a recent review on Levy Bose-Einstein correlations in heavy ions:
M. Csanád and D. Kincses, Universe 10 (2024) 2, 54, arXiv:[2401.01249 \[hep-ph\]](#)**

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



$\sqrt{s_{NN}} = 200$ 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 %

Levy C(Q) for kaons: no $U_A(1)$, but new m_T scalings



PHENIX preliminary, charged KK correlations, $\sqrt{s_{NN}} = 200$ GeV min bias Au+Au:
 $\lambda(\text{KK}) \sim \lambda_{\text{max}}(\pi\pi)$, no $\lambda(\text{KK})/\lambda_{\text{max}}$ signal for $U_A(1)$, as expected.
 $\alpha(\text{KK}) \sim \alpha(\pi\pi)$: no anomalous diffusion??

HBT: Two-particle symmetrization, chaotic source

- or not ? Partial coherence: 3 vs 2 particle correlations

$$C_3(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \frac{N_3(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)}{N_1(\mathbf{k}_1)N_1(\mathbf{k}_2)N_1(\mathbf{k}_3)},$$

$$\lambda_2 = C_2(k_{12} \rightarrow 0) - 1,$$

$$\lambda_3 = C_3(k_{12} = k_{13} = k_{23} \rightarrow 0) - 1,$$

$$\kappa_3 = \frac{\lambda_3 - 3\lambda_2}{2\sqrt{\lambda_2^3}}.$$

$$p_c = \frac{N_{\text{coherent}}}{N_{\text{coherent}} + N_{\text{incoherent}}},$$

$$f_c = \frac{N_{\text{core}}}{N_{\text{core}} + N_{\text{halo}}}.$$

$$\lambda_2 = f_c^2 [(1 - p_c)^2 + 2p_c(1 - p_c)]$$

$$\lambda_3 = 2f_c^3 [(1 - p_c)^3 + 3p_c(1 - p_c)^2] + 3f_c^2 [(1 - p_c)^2 + 2p_c(1 - p_c)].$$

Three-body Coulomb correction in Riverside approximation,
domain of validity checked.

PHENIX preliminary data on three-pion Bose-Einstein: A.Bagoly, [poster at QM17](#) Partial coherence measurement possible!

B. Kurgyis for the PHENIX Collaboration, *Phys.Part.Nucl.* 51 (2020) 3, 263-266, [arXiv:1910.05019](#) [nucl-ex]

[arXiv:0604021](#): R. J. Glauber noted that partial coherence may be present, but swamped in a large background. Check it with three-particle vs two-particle Bose-Einstein correlations!

$$C_3(k_{12}, k_{13}, k_{23}) = K_3(k_{12}, k_{13}, k_{23})C_3^{(0)}(k_{12}, k_{13}, k_{23}).$$

$$C_3^{(0)}(k_{12}, k_{13}, k_{23}) = 1 + \ell_3 e^{-0.5(|2k_{12}R|^\alpha + |2k_{13}R|^\alpha + |2k_{23}R|^\alpha)} + \ell_2 \left(e^{|2k_{12}R|^\alpha} + e^{|2k_{13}R|^\alpha} + e^{|2k_{23}R|^\alpha} \right).$$

$$K_3(k_{12}, k_{13}, k_{23}) = K_2(k_{12})K_2(k_{13})K_2(k_{23}), \text{ where}$$

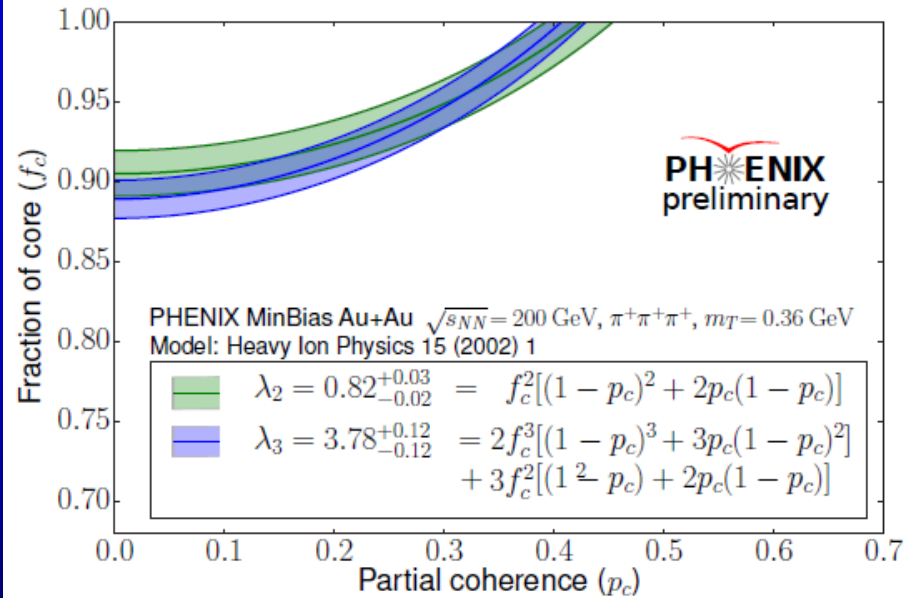
$$K_2(k) = \frac{\int d^4r S(\mathbf{r}, \mathbf{k}) |\Psi_{\mathbf{k}}^{(Coulomb)}(\mathbf{r})|^2}{\int d^4r S(\mathbf{r}, \mathbf{k}) |\Psi_{\mathbf{k}}^{(0)}(\mathbf{r})|^2}.$$

HBT: Two-particle symmetrization, chaotic source

- or not ? Partial coherence: 3 vs 2 particle correlations

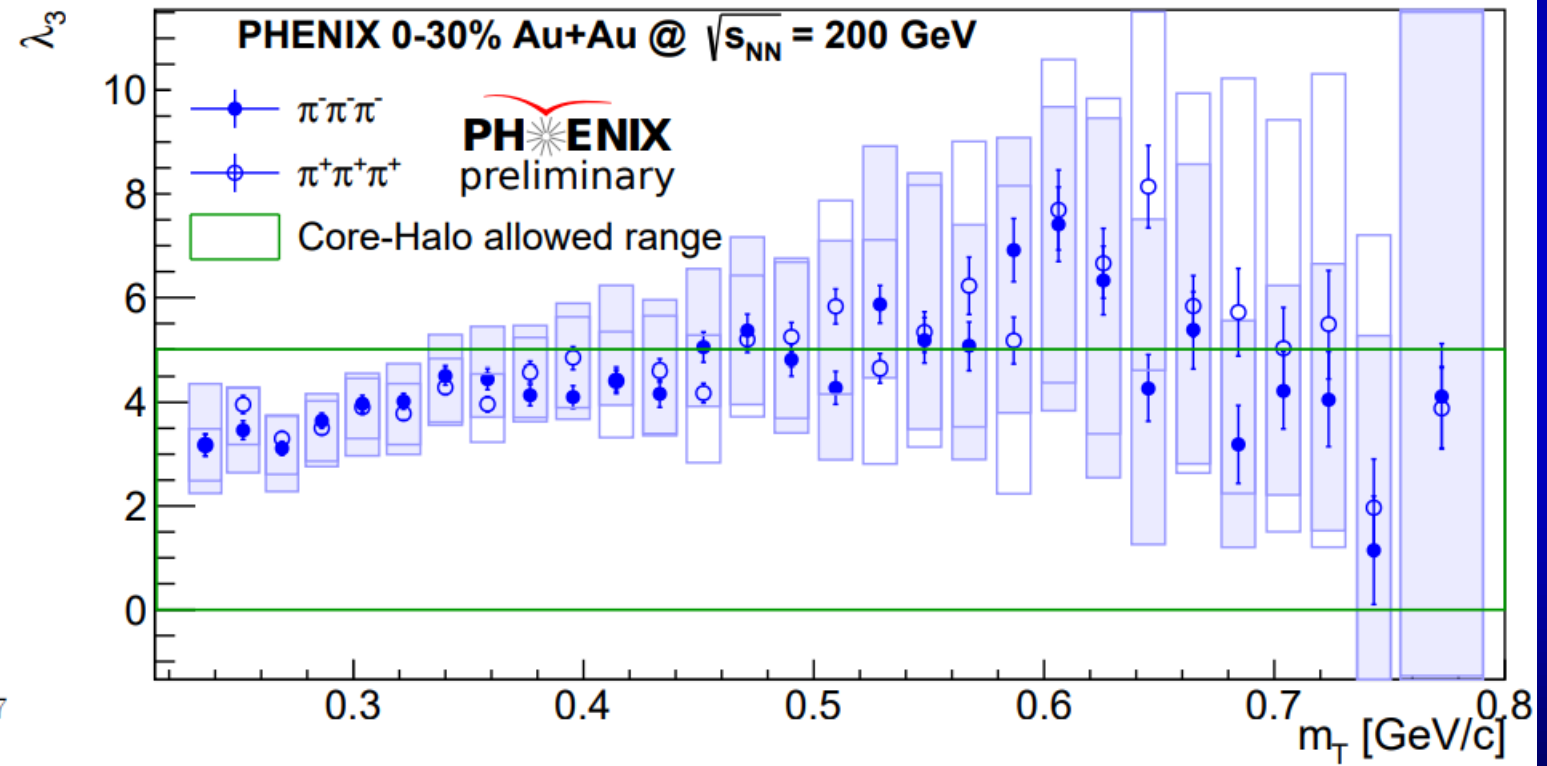
Partial coherence (p_c) vs fractional core (f_c)

- Simple theoretical model [5]: $\lambda_2(f_c, p_c)$, $\lambda_3(f_c, p_c)$
- Measured $\lambda_2^{\text{meas.}}$ \rightarrow
 $\lambda_2^{\text{meas.}} = \lambda_2(f_c, p_c) \Rightarrow f_c(p_c)$ (green lines)
- Measured $\lambda_3^{\text{meas.}}$ \rightarrow
 $\lambda_3^{\text{meas.}} = \lambda_3(f_c, p_c) \Rightarrow f_c(p_c)$ (blue lines)
- Example 2D plot at $m_T = 0.36 \text{ GeV}/c^2$:



$$\lambda_2 = f_c^2 [(1 - p_c)^2 + 2p_c(1 - p_c)]$$

$$\lambda_3 = 2f_c^3 [(1 - p_c)^3 + 3p_c(1 - p_c)^2] + 3f_c^2 [(1 - p_c)^2 + 2p_c(1 - p_c)] .$$

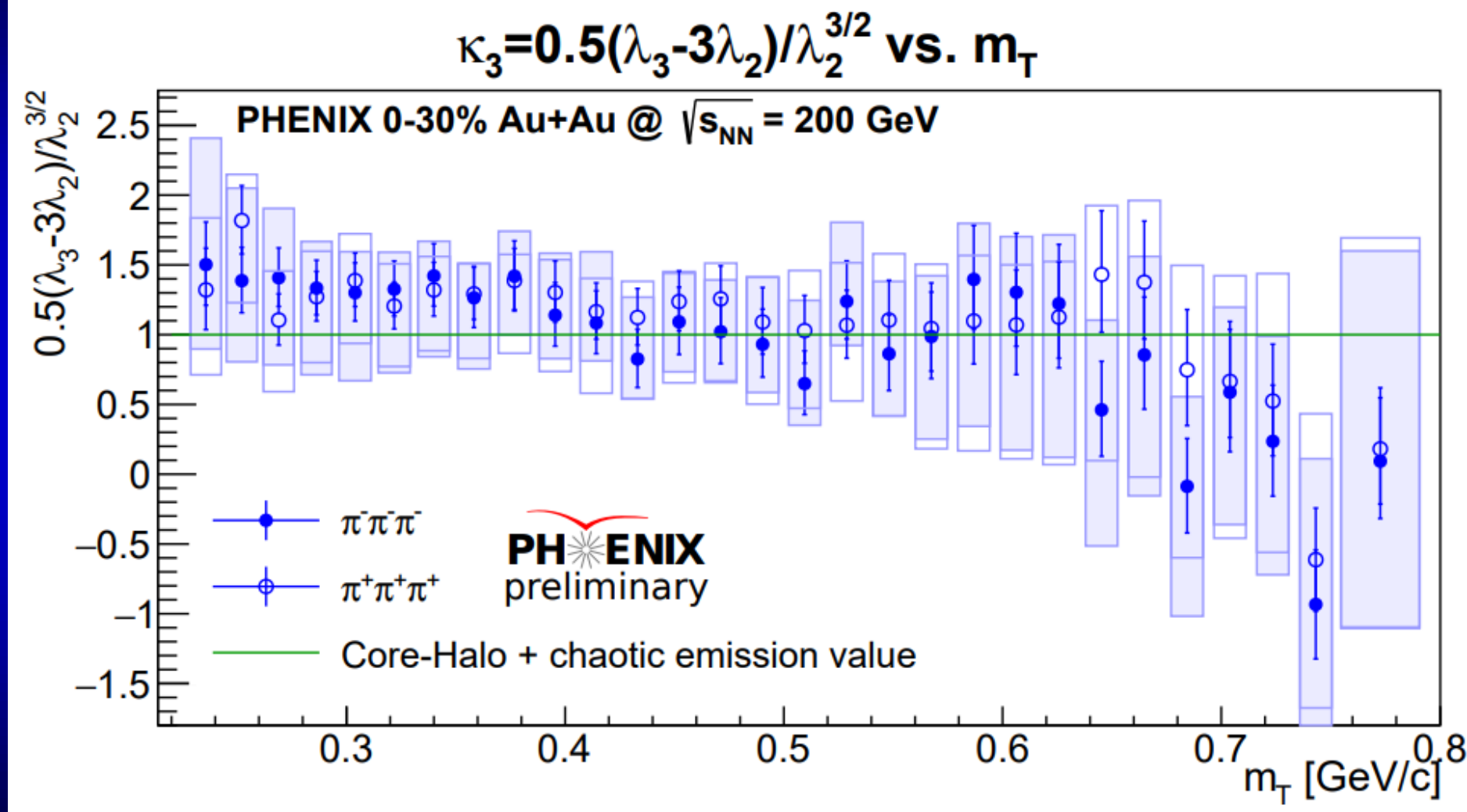


PHENIX preliminary data on three-pion Bose-Einstein: A.Bagoly, poster at QM17 Partial coherence measurement possible!

B. Kuryis for the PHENIX Collaboration, *Phys.Part.Nucl.* 51 (2020) 3, 263-266, arXiv:1910.05019 [nucl-ex]

HBT: Two-particle symmetrization, chaotic source

- or not ? Partial coherence: 3 vs 2 particle correlations



$$\kappa_3 = \frac{\lambda_3 - 3\lambda_2}{2\sqrt{\lambda_2^3}}$$

$\kappa_3 \sim 1$
within errors



No signal for
partial
coherence
($p_c > 0$), so

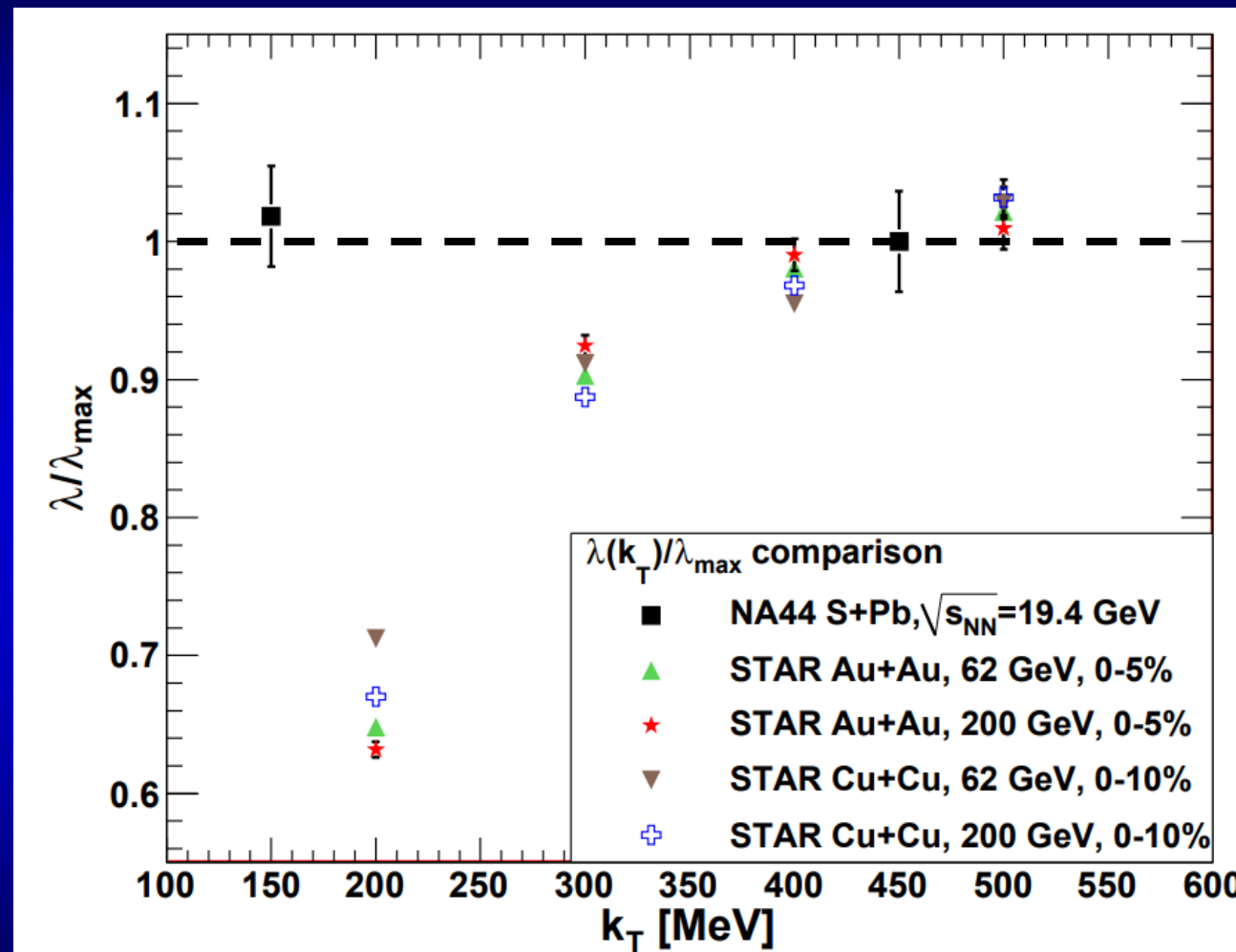


p_c cannot
mask $U_A(1)$

B. Kurgyis for the PHENIX Collaboration, *Phys.Part.Nucl.* 51 (2020) 3, 263-266, arXiv:1910.05019 [nucl-ex]

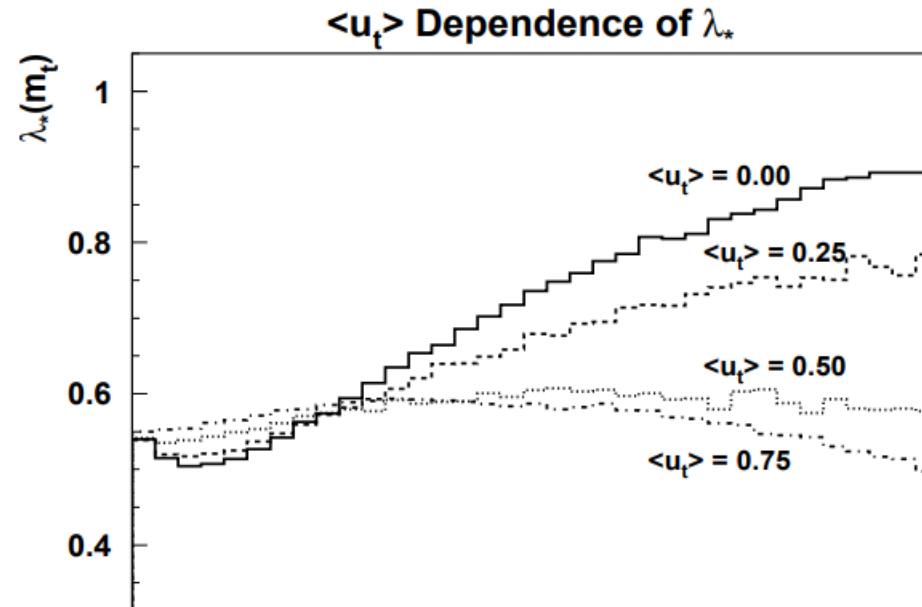
Can λ/λ_{\max} $U_A(1)$ restoration signal be switched off?

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. Vértési, T.Cs., J. Sziklai , [arXiv:2307.09573](https://arxiv.org/abs/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](https://arxiv.org/abs/nuc1-th/9802074) [nucl-th]

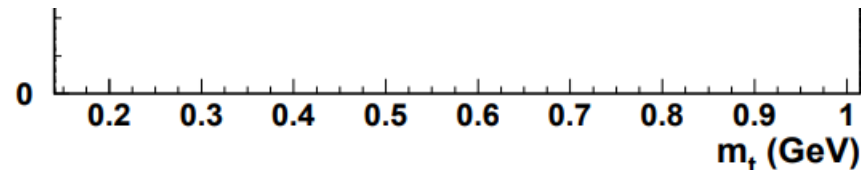
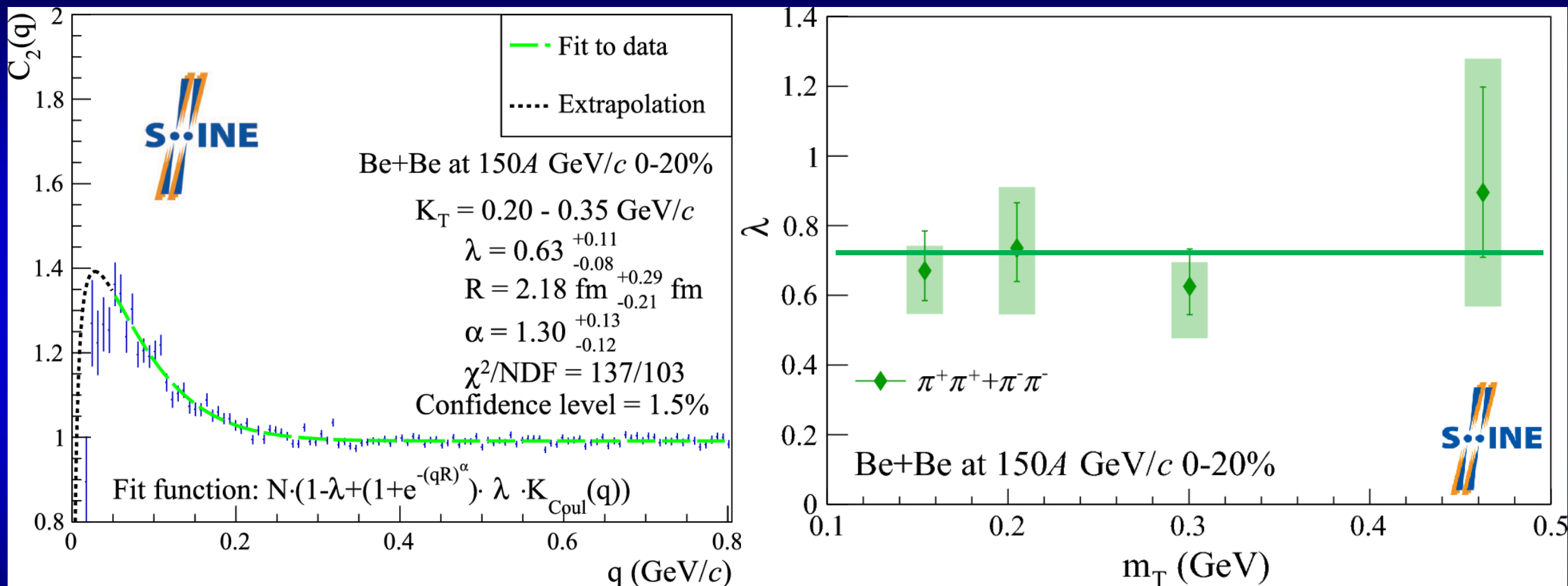


FIG. 3. Using the estimates of pion abundances given by Fritiof, $\lambda_*(m_t)$ is calculated using different average flow velocities in the m_t distribution. It is shown for $\langle u_t \rangle = 0.00$ by the solid line, for $\langle u_t \rangle = 0.25$ by the dashed line, for $\langle u_t \rangle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

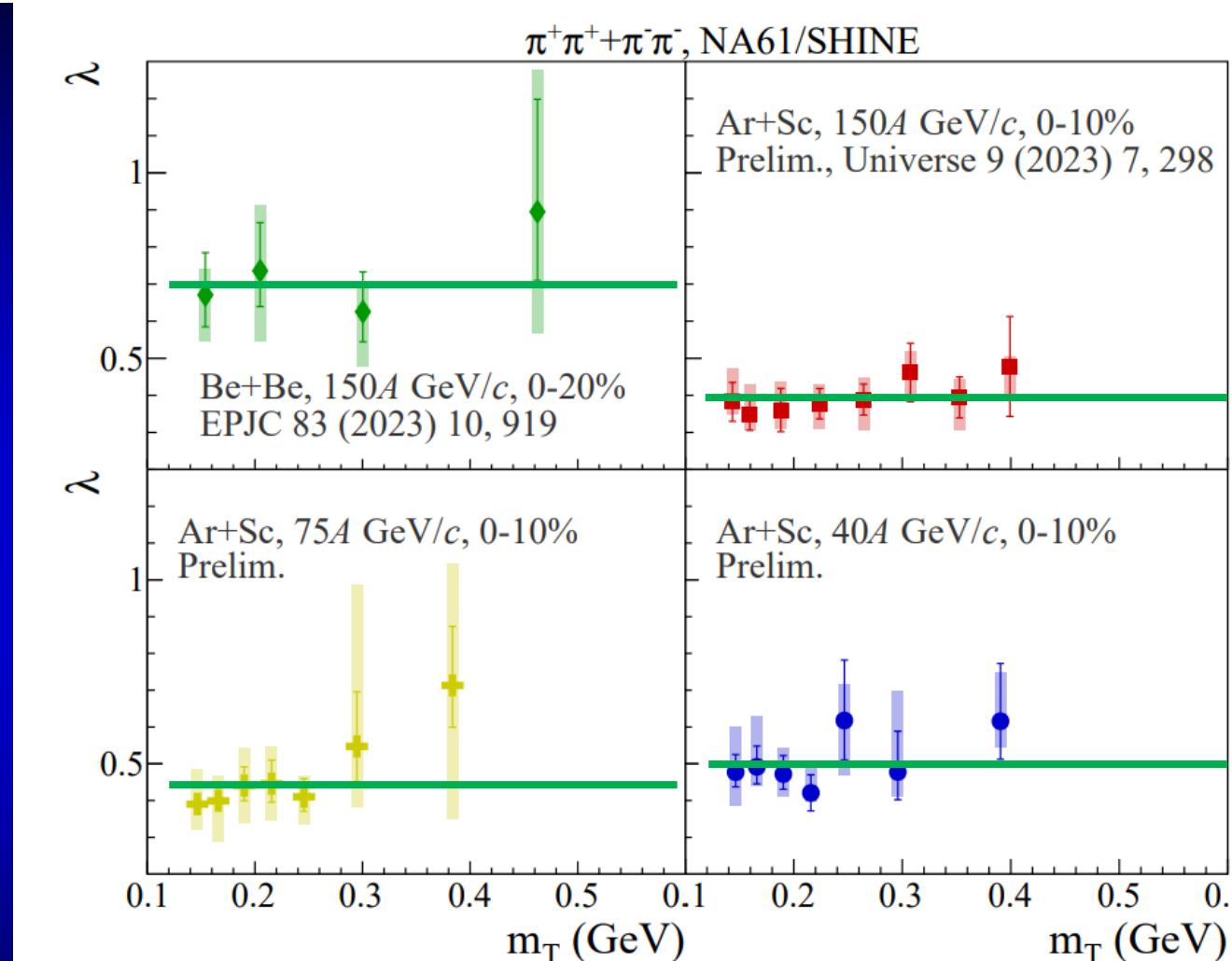
Yes, as known from the first papers, but confirmed by NA61!



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 systems (Be+Be) and relatively low energy, $\sqrt{s} < 20$ GeV.

NA61 data on charged $\pi\pi$ correlation in 150 AGeV Be+Be collisions
Eur.Phys.J.C 83 (2023) 10, 919, e-Print: [2302.04593](https://arxiv.org/abs/2302.04593) [nucl-ex]

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



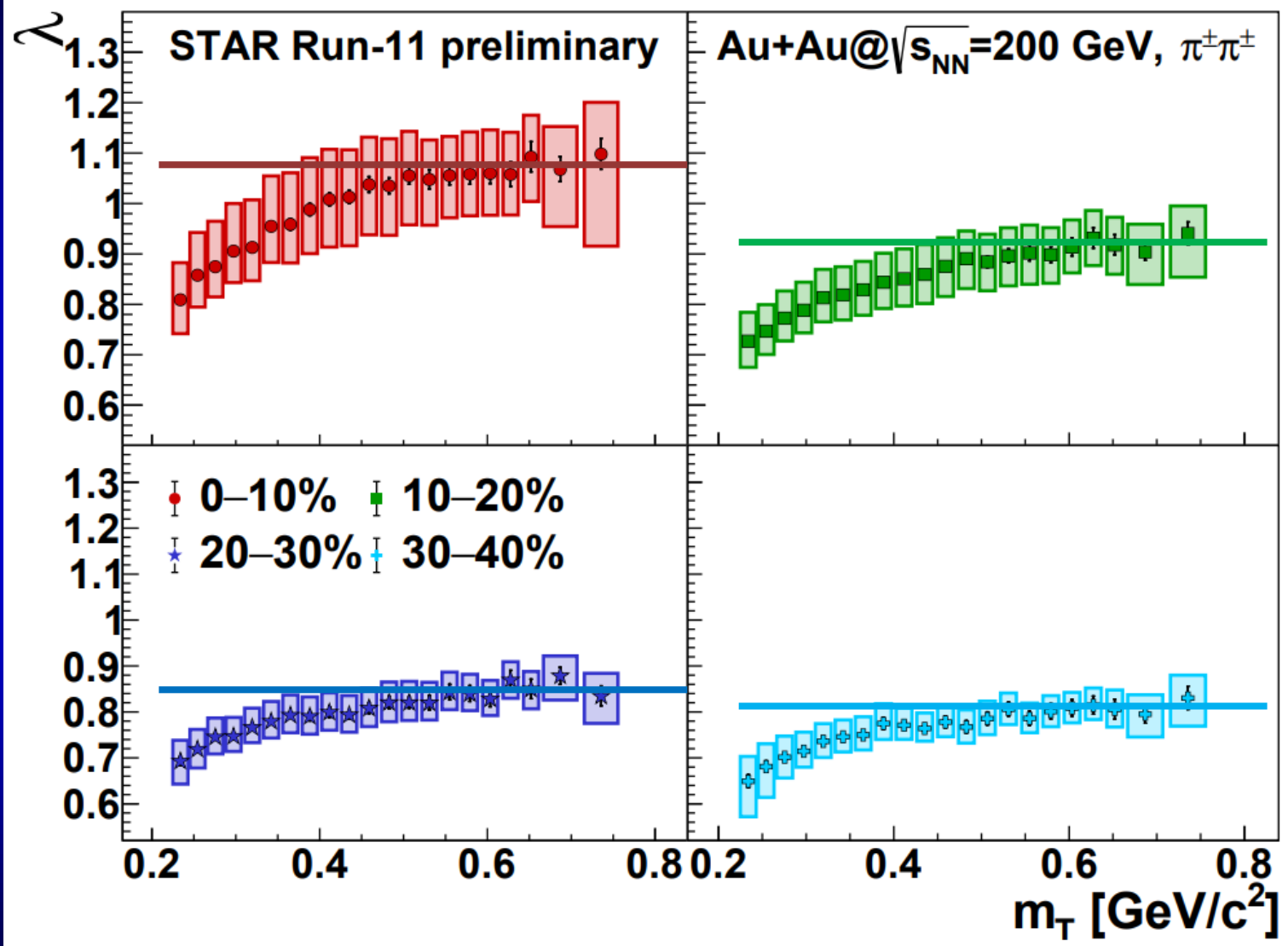
**NA61:
YES!**

**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 $E_{\text{lab}} \leq 150$ GeV Ar+Sc collisions

B. Pórfy for the NA61 Collaboration, e-Print: [2406.022423](https://arxiv.org/abs/2406.022423) [nucl-ex]

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

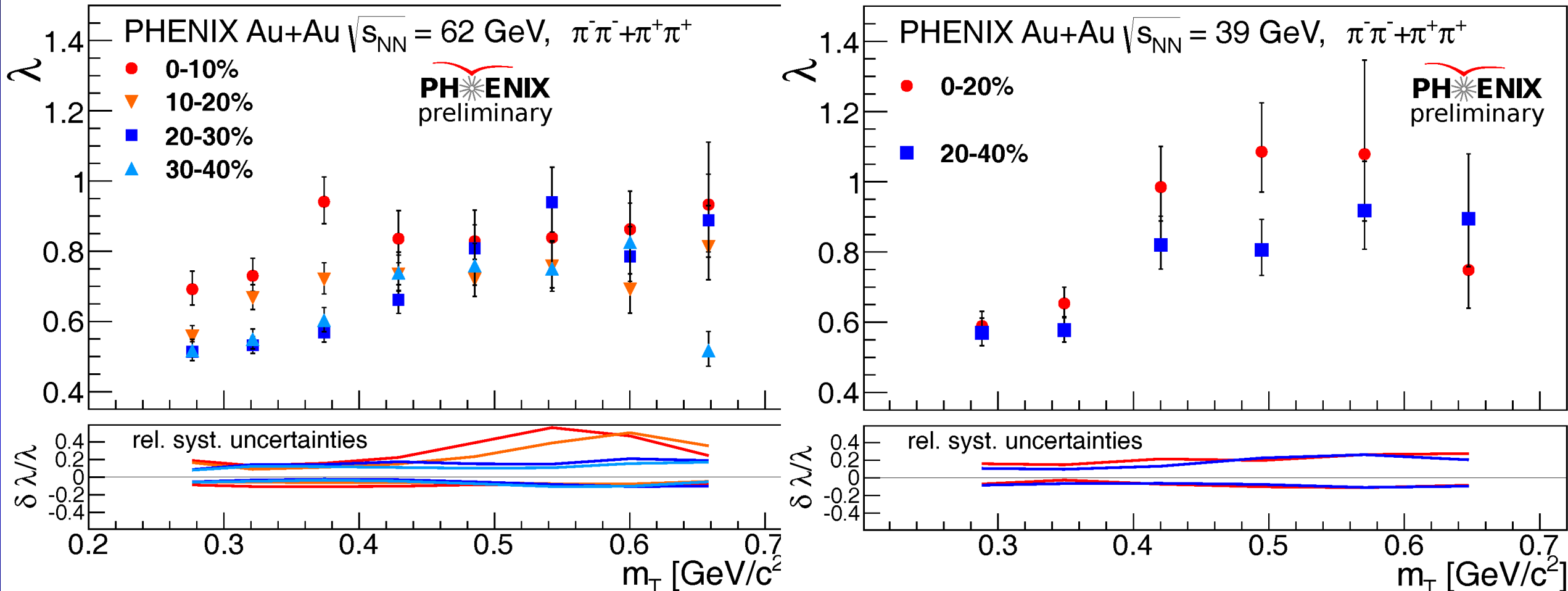


**STAR
preliminary:
YES!**

STAR preliminary, charged $\pi\pi$ 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](https://arxiv.org/abs/2401.11169) [nucl-ex] 53

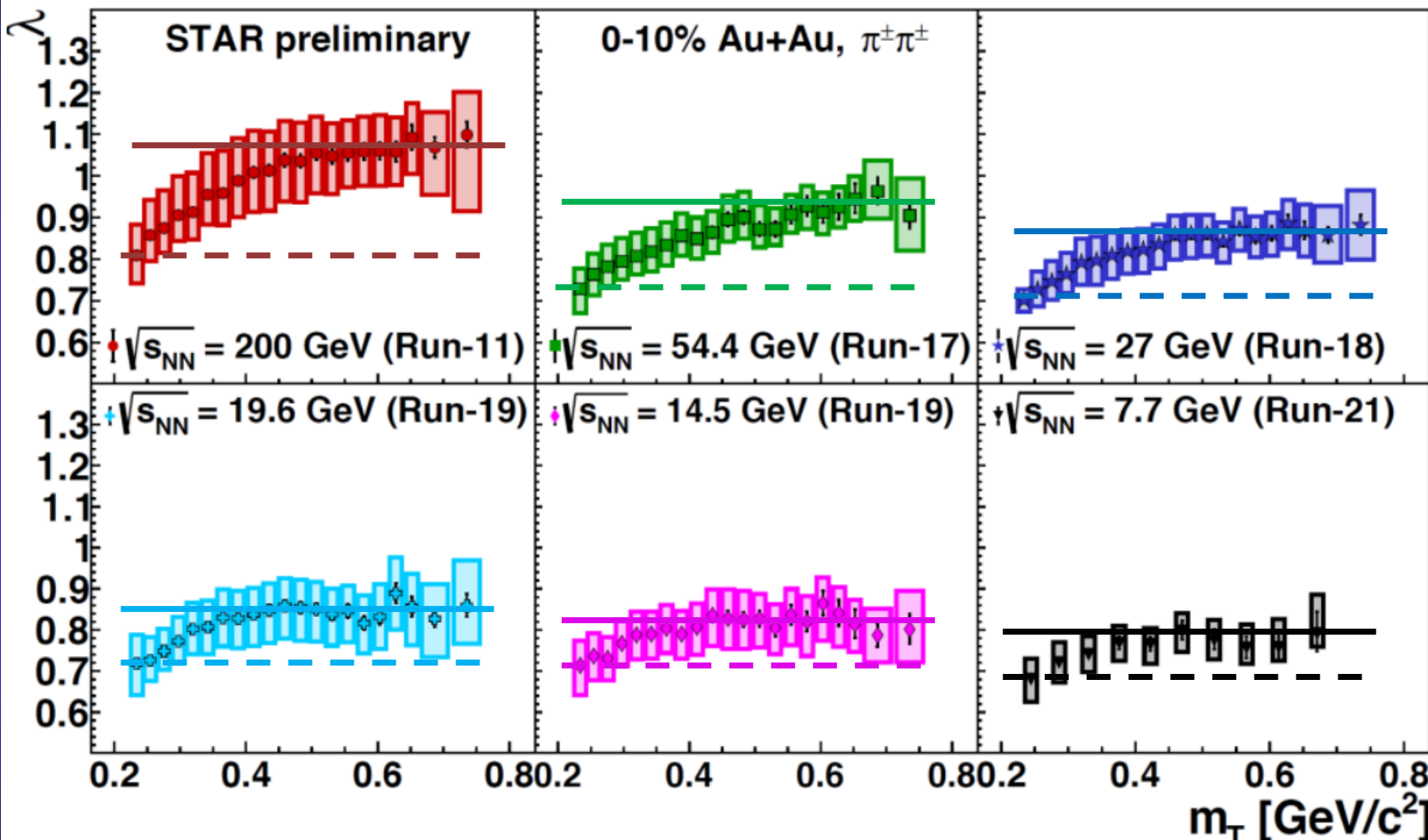
Can λ/λ_{\max} $U_A(1)$ restoration signal be switched off?



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.

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

NEW PAIR CUTS AND SYSTEMATIC ERRORS

TABLE I. The values of the coordinates for the pair cuts and the alternative values used to determine systematic uncertainties.

Pair cuts	DC			TOF east		TOF west		EM Cal		
	$\Delta\varphi_0$ [rad]	Δz_0 [cm]	$\Delta\varphi_1$ [rad]	$\Delta\varphi_0$ [rad]	Δz_0 [cm]	$\Delta\varphi_0$ [rad]	Δz_0 [cm]	$\Delta\varphi_0$ [rad]	Δz_0 [cm]	$\Delta\varphi_1$ [rad]
Default cut settings	.12	8.	.017	.12	12	.075	14.0	.12	16	.015
Loose drift chamber cut	.11	7.	.016	.12	12	.075	14.0	.12	16	.015
Strict drift chamber cut	.13	9.	.018	.12	12	.075	14.0	.12	16	.015
Loose ID detector cuts	.12	8.	.017	.11	11	.070	13.0	.11	15	.013
Strict ID detector cuts	.12	8.	.017	.13	13	.080	15.0	.13	17	.017

Systematic errors fully propagated to the very end
of this analysis chain:

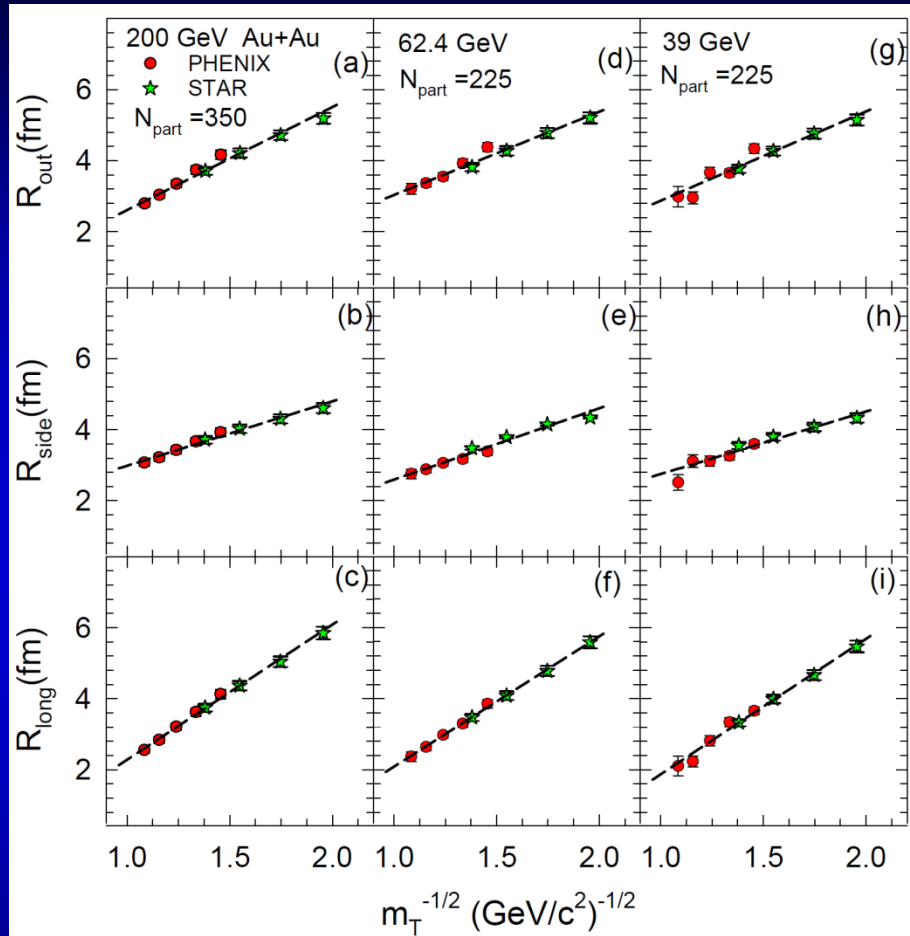
Cross-checks with three alternative syst error calculation methods.

Most conservative estimate of the systematic errors is shown.

Correlated error propagation is taken into account.

Improvements in Coulomb corrections not detailed
in this talk due to time limitations.

HBT: Signals of 3d hydro flow, ONLY for $\alpha = 2$



$$\frac{1}{\Delta\bar{\eta}^2} = \frac{1}{\Delta\eta^2} + \frac{M_t}{T_0},$$

$$\bar{R}_\perp^2 = \frac{R_G^2}{1 + \frac{M_t}{T_0} (\langle u_t \rangle^2 + \langle \frac{\Delta T}{T} \rangle_r)},$$

$$R_l^2 = \bar{\tau}^2 \Delta\bar{\eta}^2,$$

$$R_o^2 = \bar{R}_\perp^2 + \beta_t^2 \Delta\bar{\tau}^2,$$

$$R_s^2 = \bar{R}_\perp^2$$

$$R_s^2 = R_\perp^2,$$

$$R_o^2 = R_\perp^2 + \beta_t^2 [\cosh^2(\bar{\eta}) R_\perp^2 + \sinh^2(\bar{\eta}) R_\parallel^2],$$

$$R_{ol}^2 = -\beta_t \sinh(\bar{\eta}) \cosh(\bar{\eta}) (R_\perp^2 + R_\parallel^2),$$

$$R_l^2 = \cosh^2(\bar{\eta}) R_\parallel^2 + \sinh^2(\bar{\eta}) R_\perp^2,$$

Theory challenge for Levy $\alpha < 2$

Indication of hydro scaling behaviour of Gaussian R(side,out,long) at low m_T

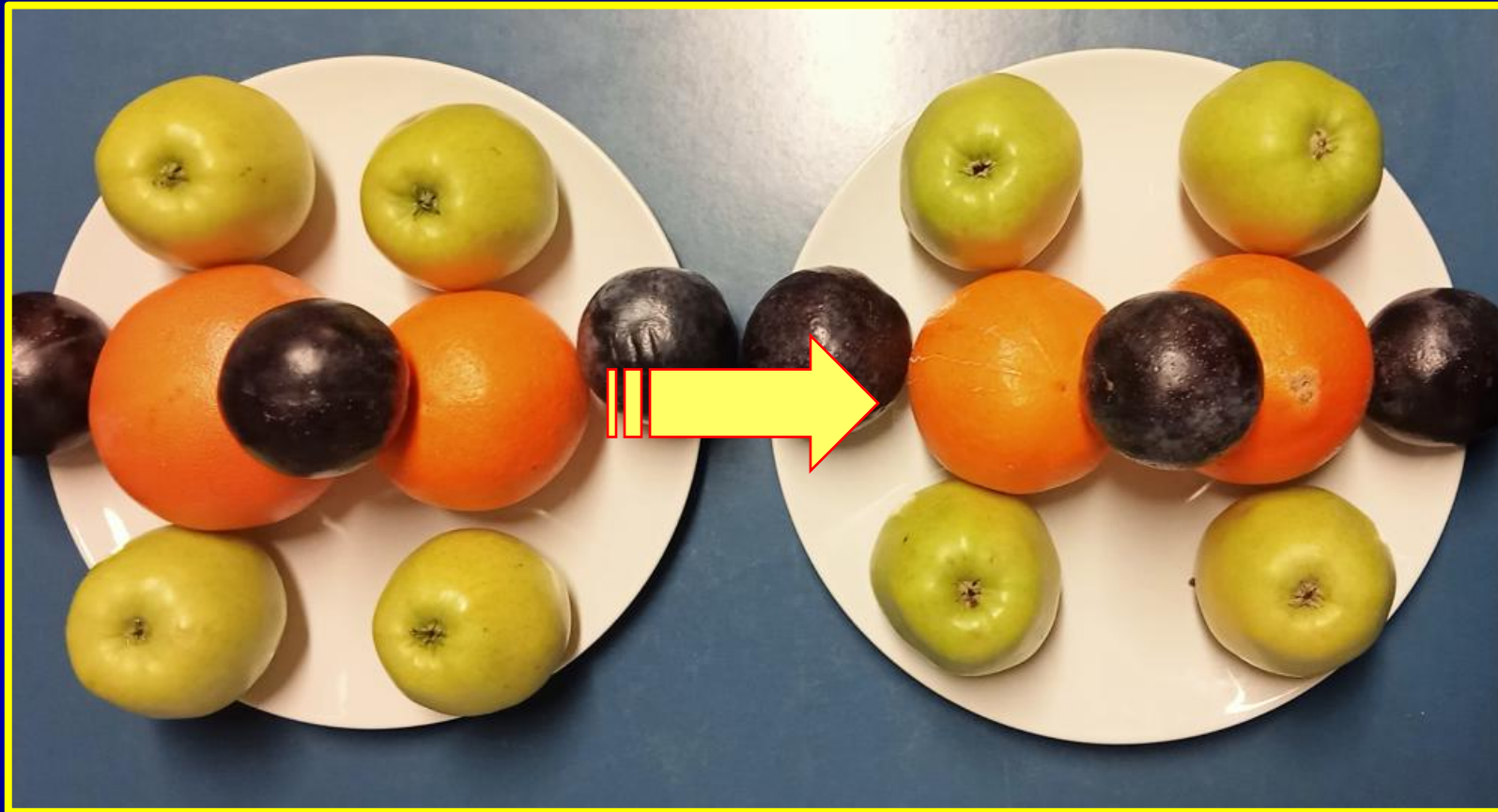
R_{long} m_T -scaling: Yu. Sinyukov and A. Makhlin: [Z.Phys. C39 \(1988\) 69](#)

$R_{side}, R_{out}, R_{long}$ m_T -scaling: T. Cs, B. Lörstad, [hep-ph/9509213](#) (shells of fire vs fireballs)

S. Chapman, P. Scotto, U. W. Heinz, [hep-ph/9408207](#)

$$\frac{1}{R^2} = \frac{1}{R_0^2} + \frac{m_T}{T_0} \cdot H_0^2$$

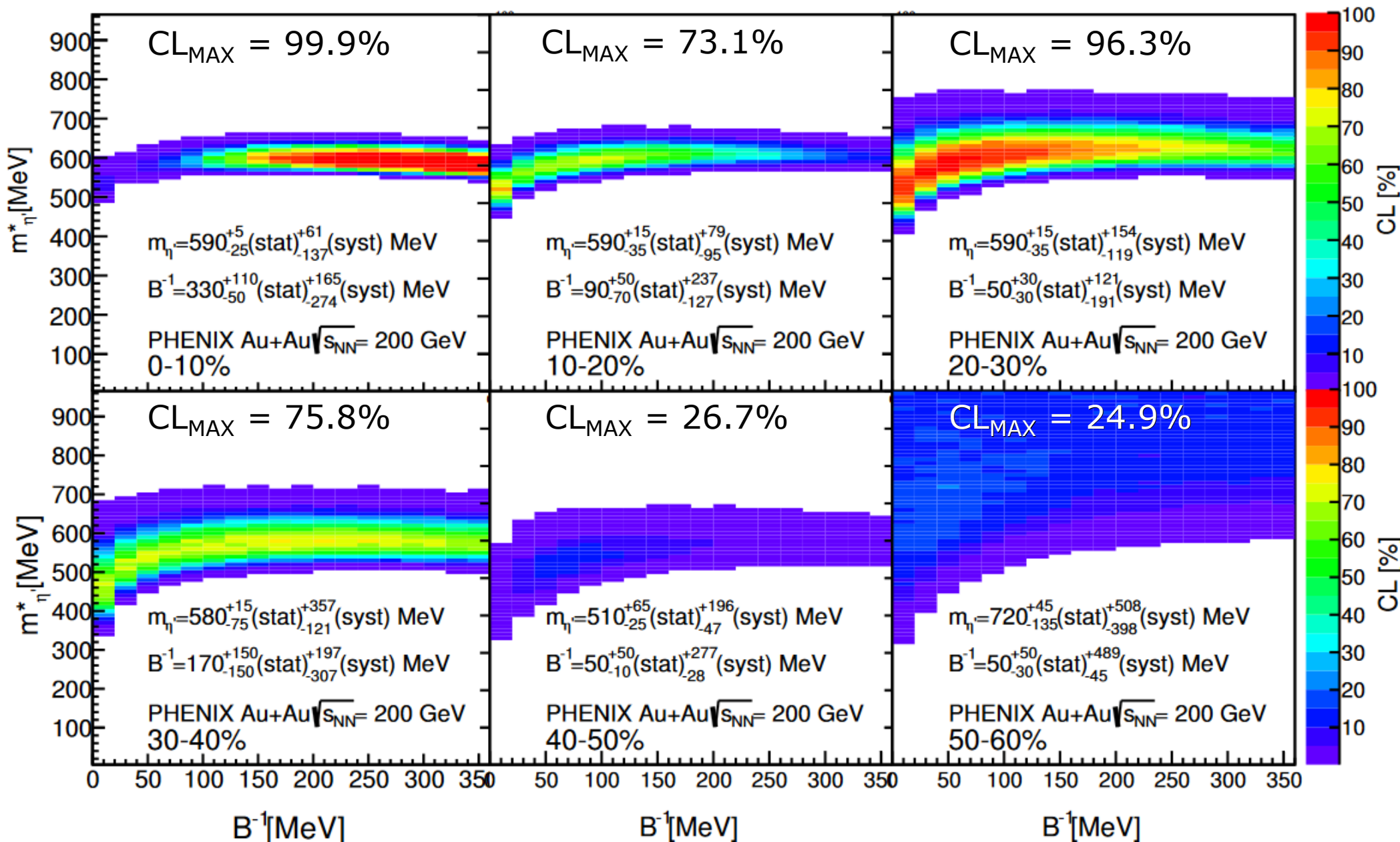
A DIRECT OBSERVATION: APPLICATION



DIRECT vs INDIRECT OBSERVATION



CONFIDENCE LEVELS (CL-S OR P-VALUES) FROM $\lambda/\lambda_{\text{MAX}}$ 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