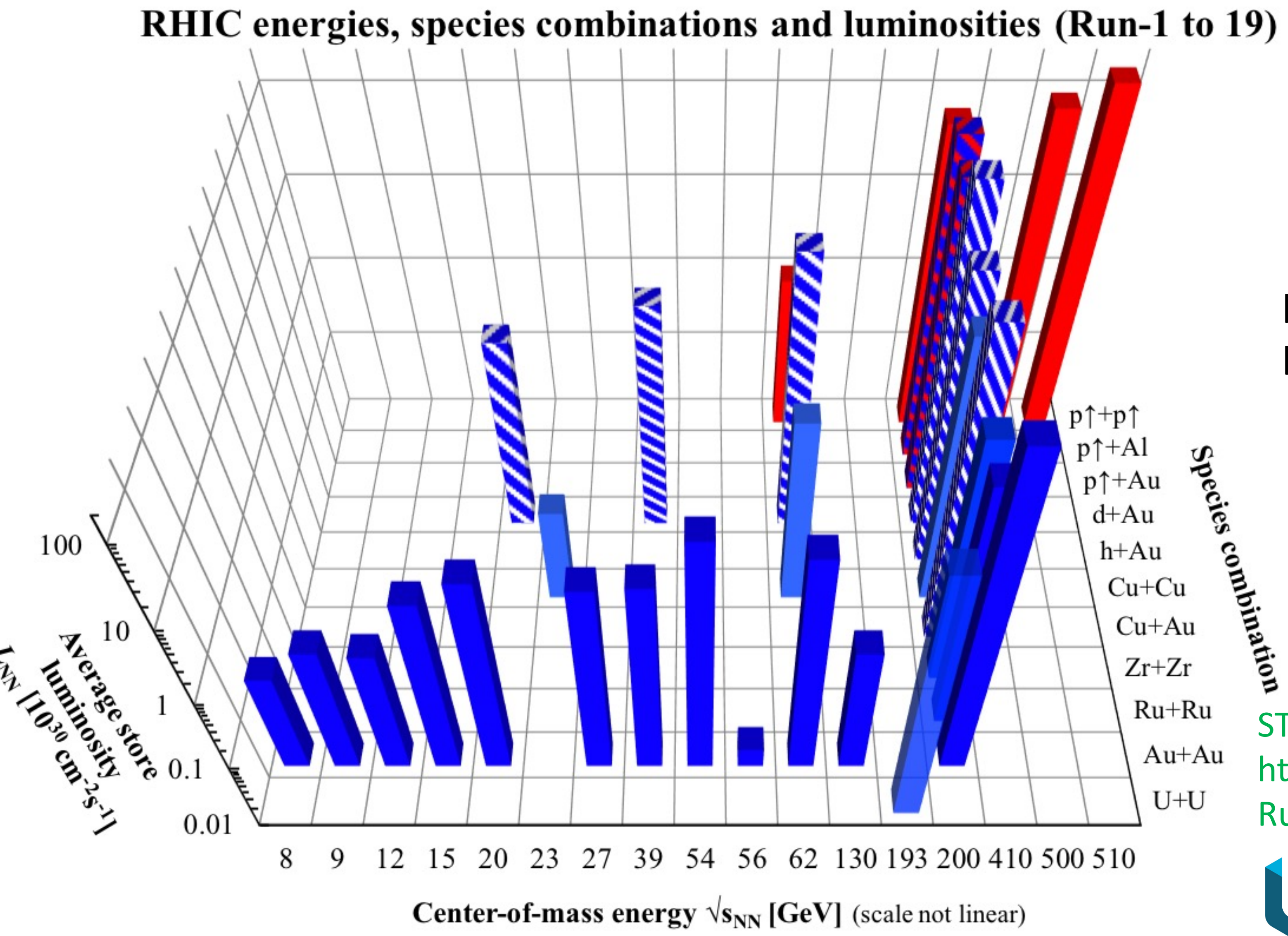
RHIC HI Program (focus on dilepton)

Zhangbu Xu



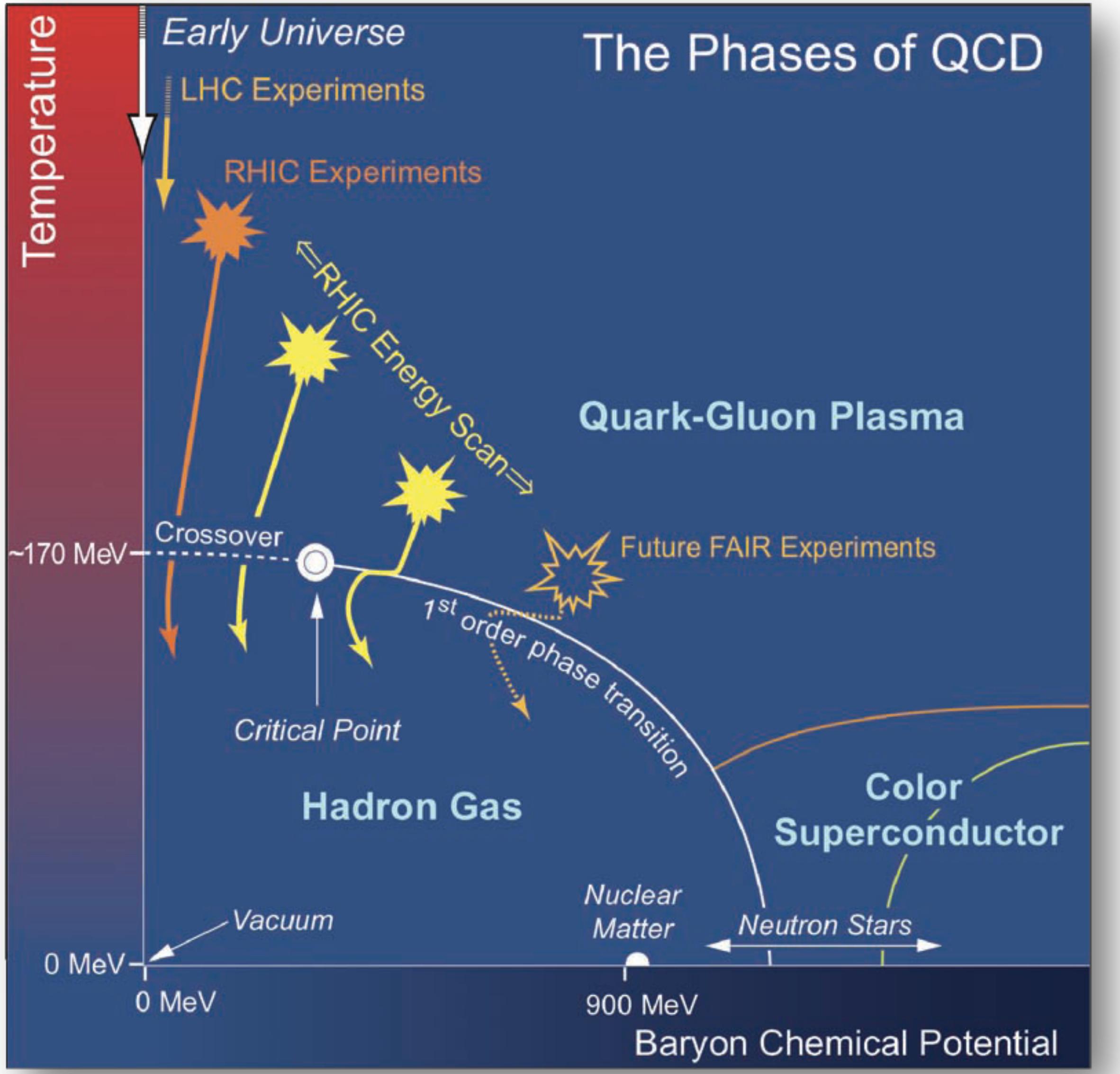
present highlights of the RHIC heavy ion program, from both STAR and PHENIX, in particular in the areas of di-lepton production and heavy flavor physics.

STAR Beam Use Request (2023-2025) June 2021: https://drupal.star.bnl.gov/STAR/files/STAR_Beam_Use_Request_Runs22_25.pdf

Brookhaven National Laboratory

In part supported by U.S. DEPARTMENT OF ENERGY Office of Science

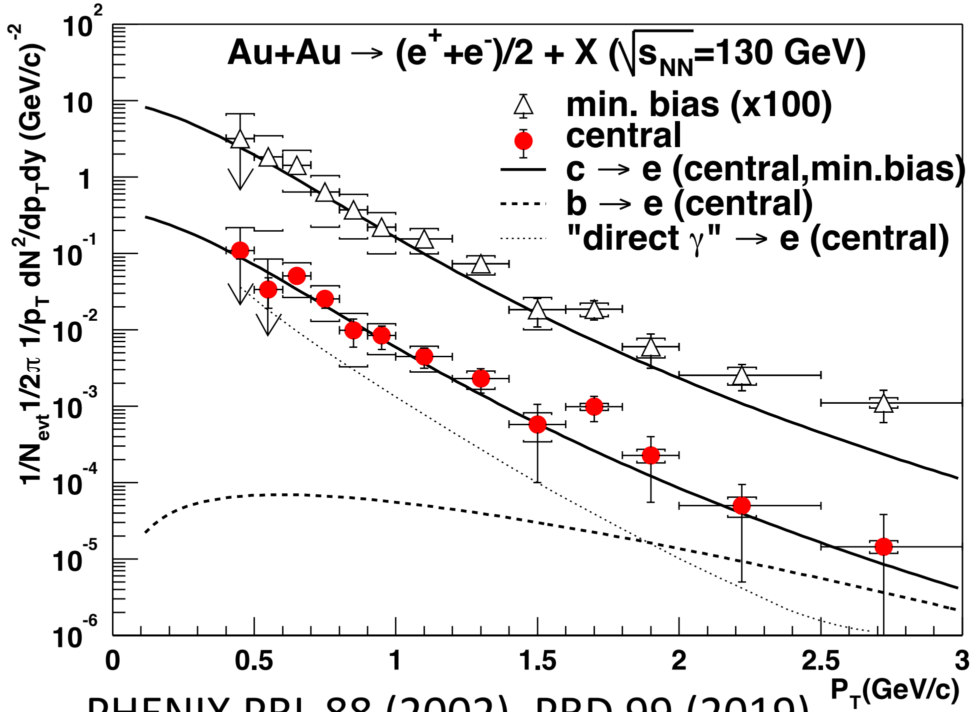
Outline



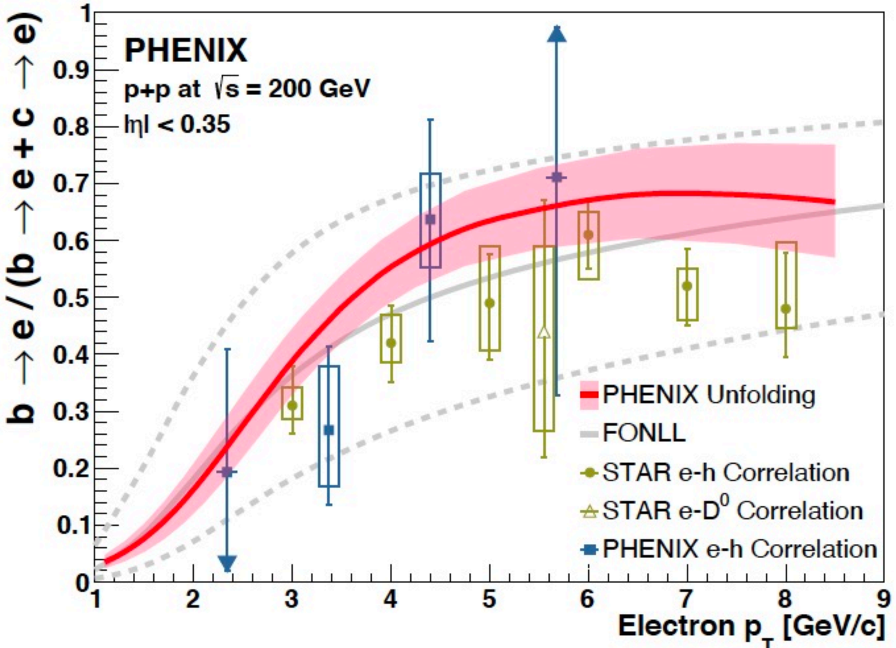
US Long Range Plan 2007

- J/Ψ probes of temperature and color screening effect
- Dilepton as a probe of penetrating thermometer and chiral symmetry restoration
- Breit-Wheeler Process and Vacuum Birefringence, Diffractive process (J/Ψ) in UPC and hadronic collisions
- Magnetohydrodynamics, any sensible tools?

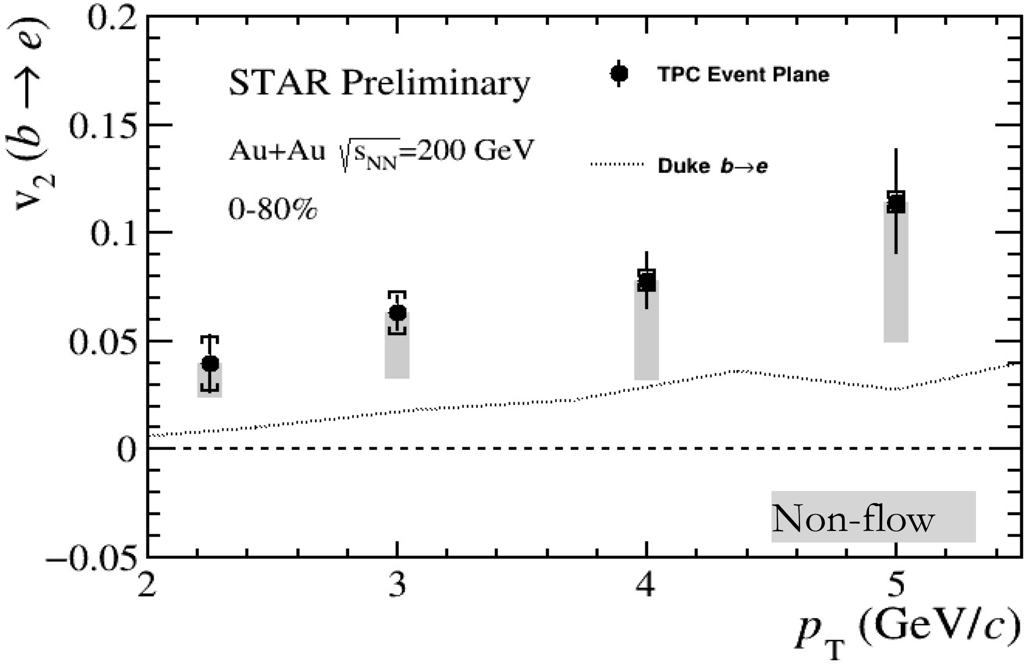
Open charm and bottom



PHENIX PRL 88 (2002), PRD 99 (2019)



From first paper by PHENIX in 2002 to current measurements of displaced secondary vertex (both PHENIX and STAR), full charm reconstructions (STAR)



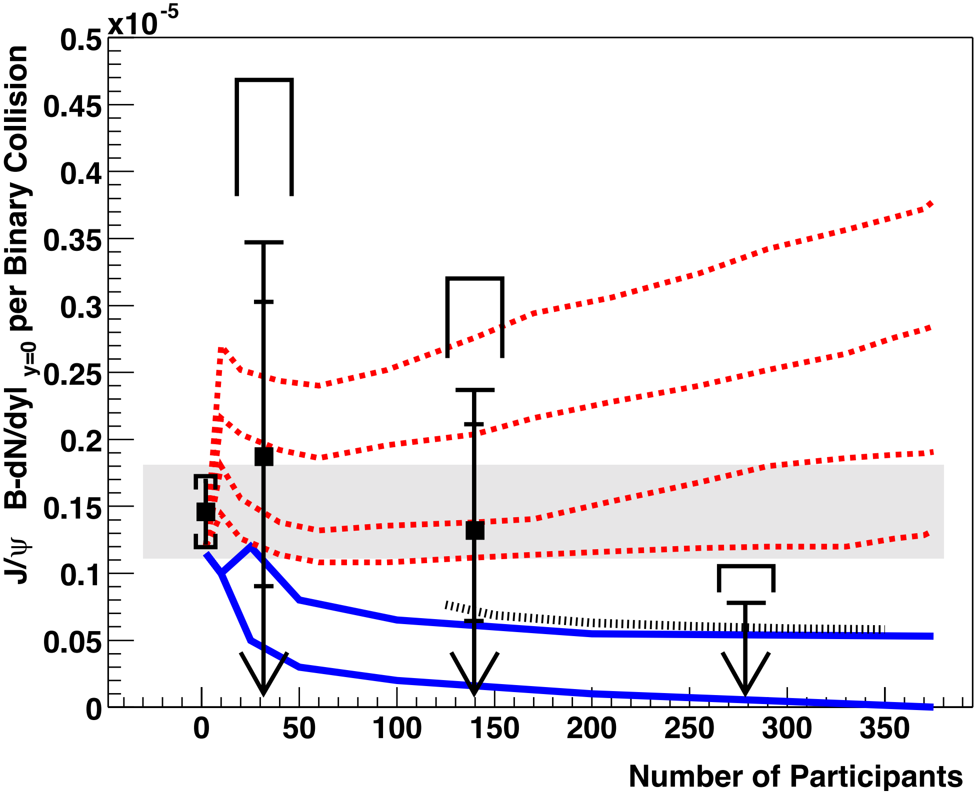
Matthew Kelsey, QM19

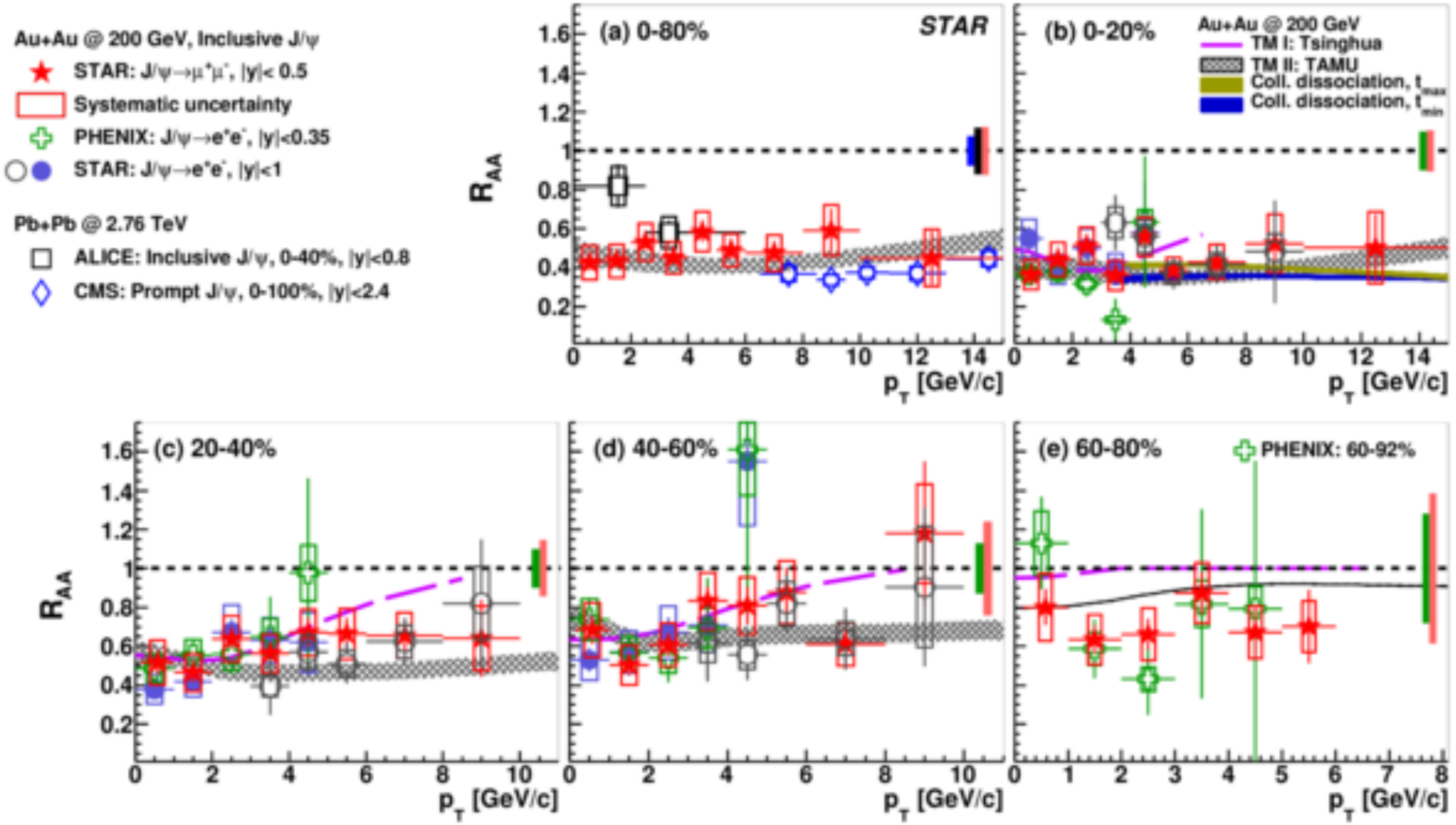
- Using HFT displaced vertex for heavy-flavor decay topology
- Observation of Λ_c/D enhancement: arXiv:1910.14628, PRL
- New charmed electron $v_{1,2}$ are consistent with D^0 measurements

Quarkonia, best probes of free quarks

STAR with latest PHENIX data, PLB 797 (2019)

PHENIX, PRL (2002)



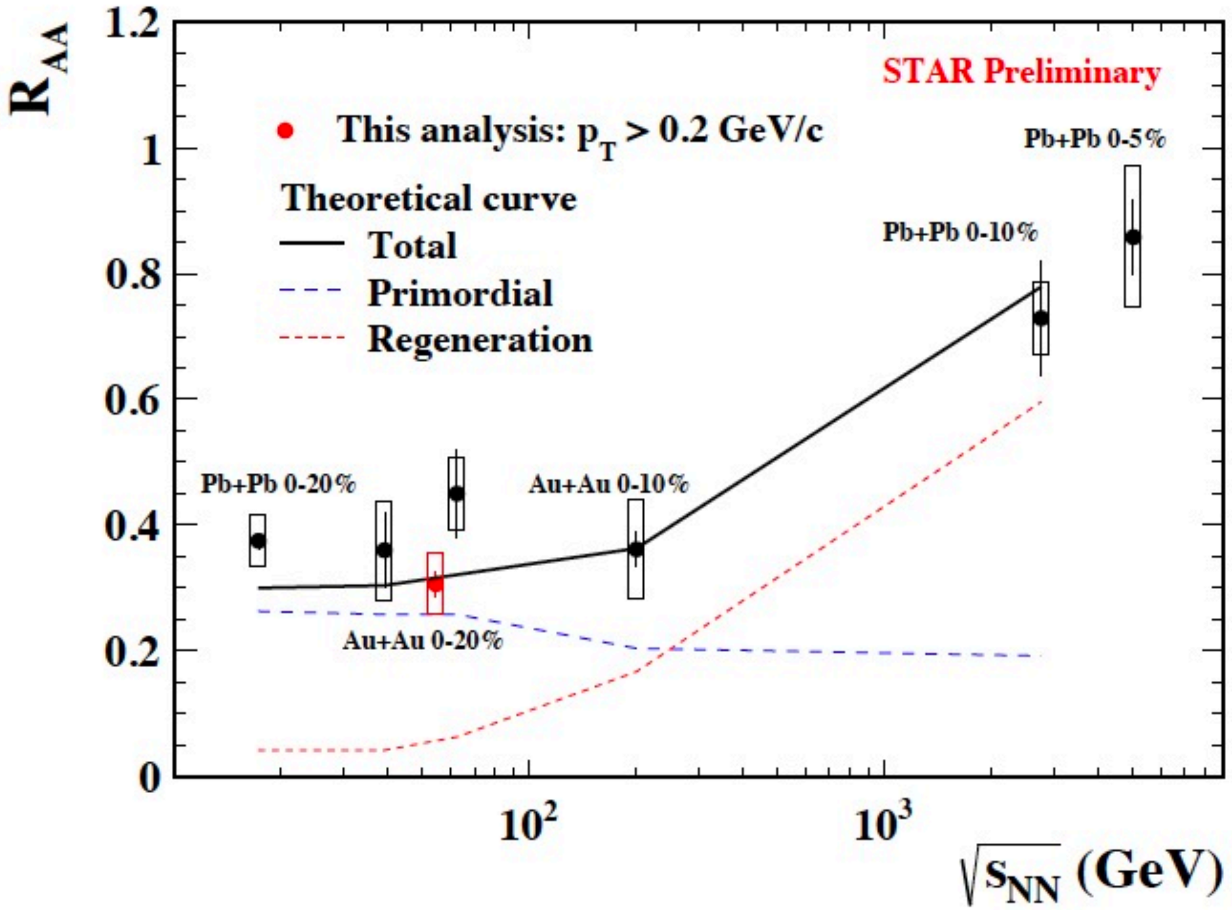


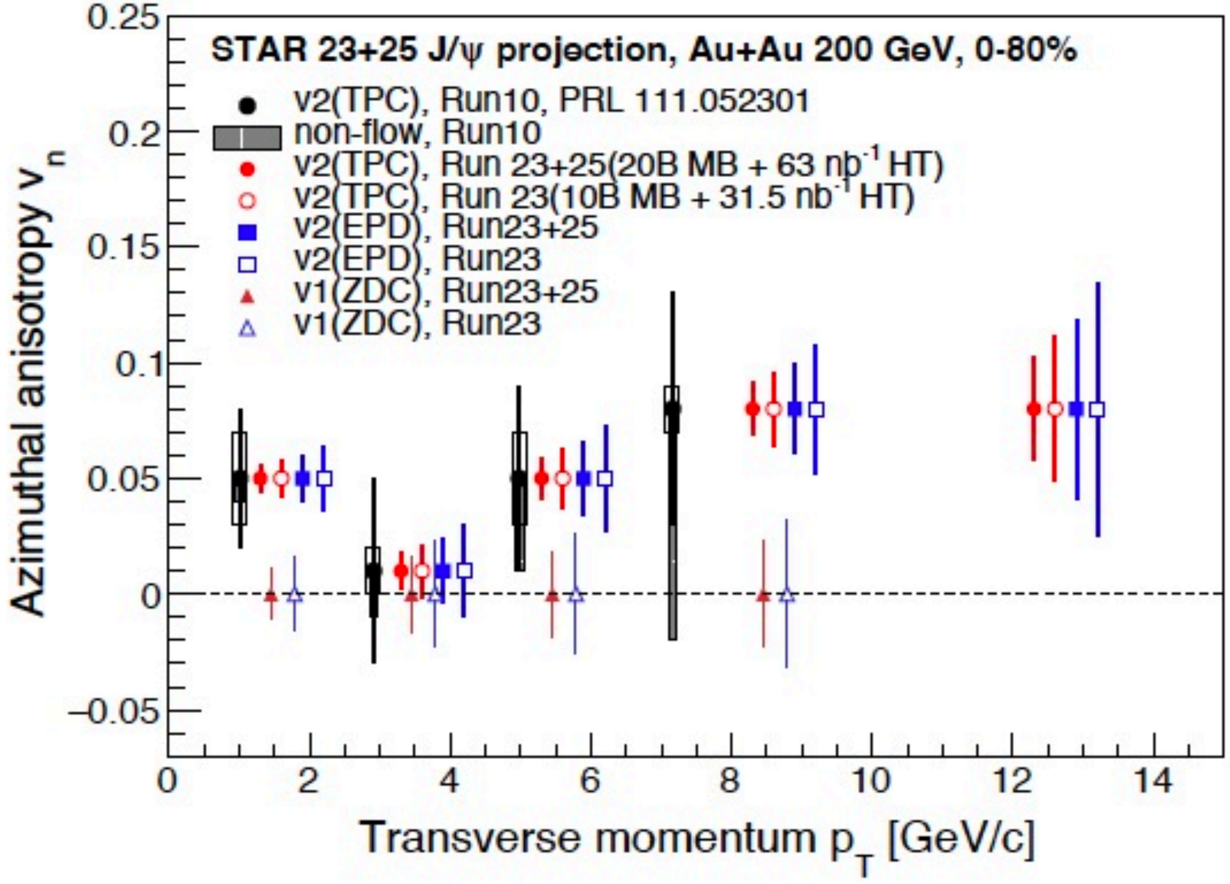
- **Less suppression at low p_T at LHC than at RHIC**
- **Similar suppression at high p_T**
- **Consistent with color screening, quark coalescence**

Upsilon states with STAR, PHENIX and sPHENIX

Any Quarkonium flow signs at RHIC?

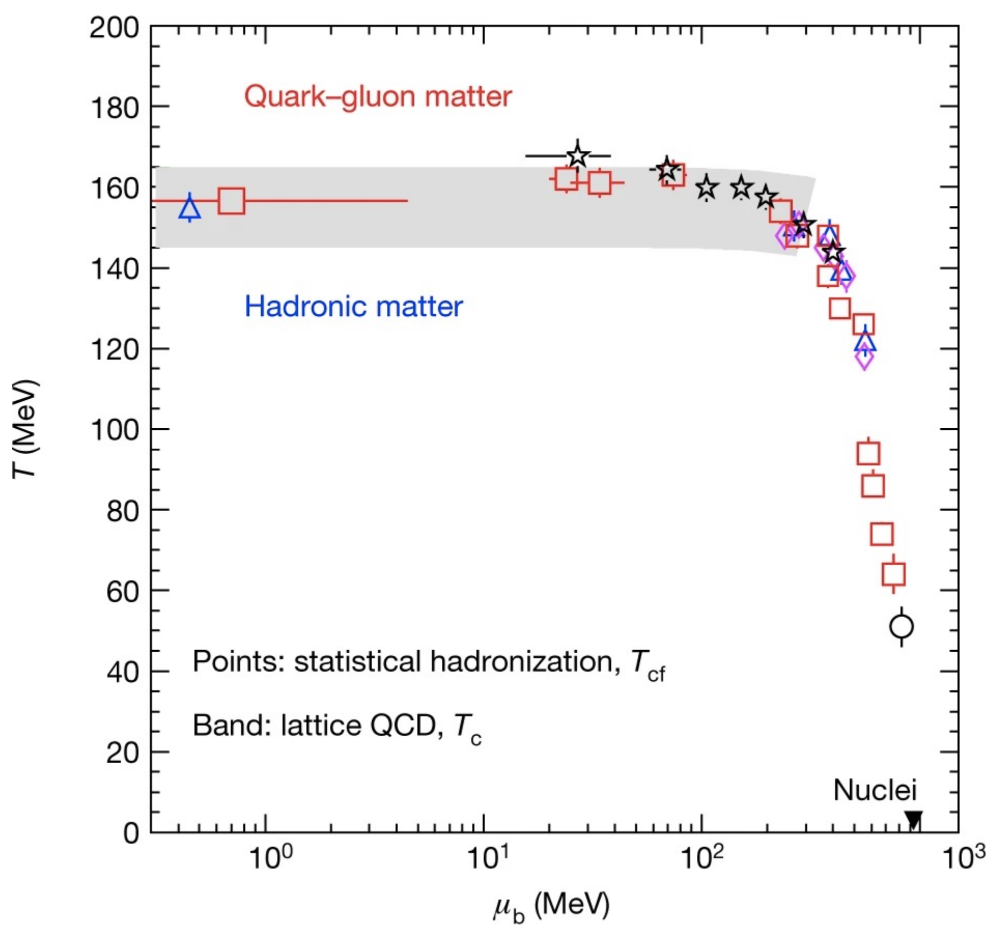
STAR BUR 2023-25





Are we there yet? Color screening of heavy quarkonia?
Matsui/Salz, PLB (1986)

Temperature from Chemistry



A. Andronic et al., NATURE 561 (2018)

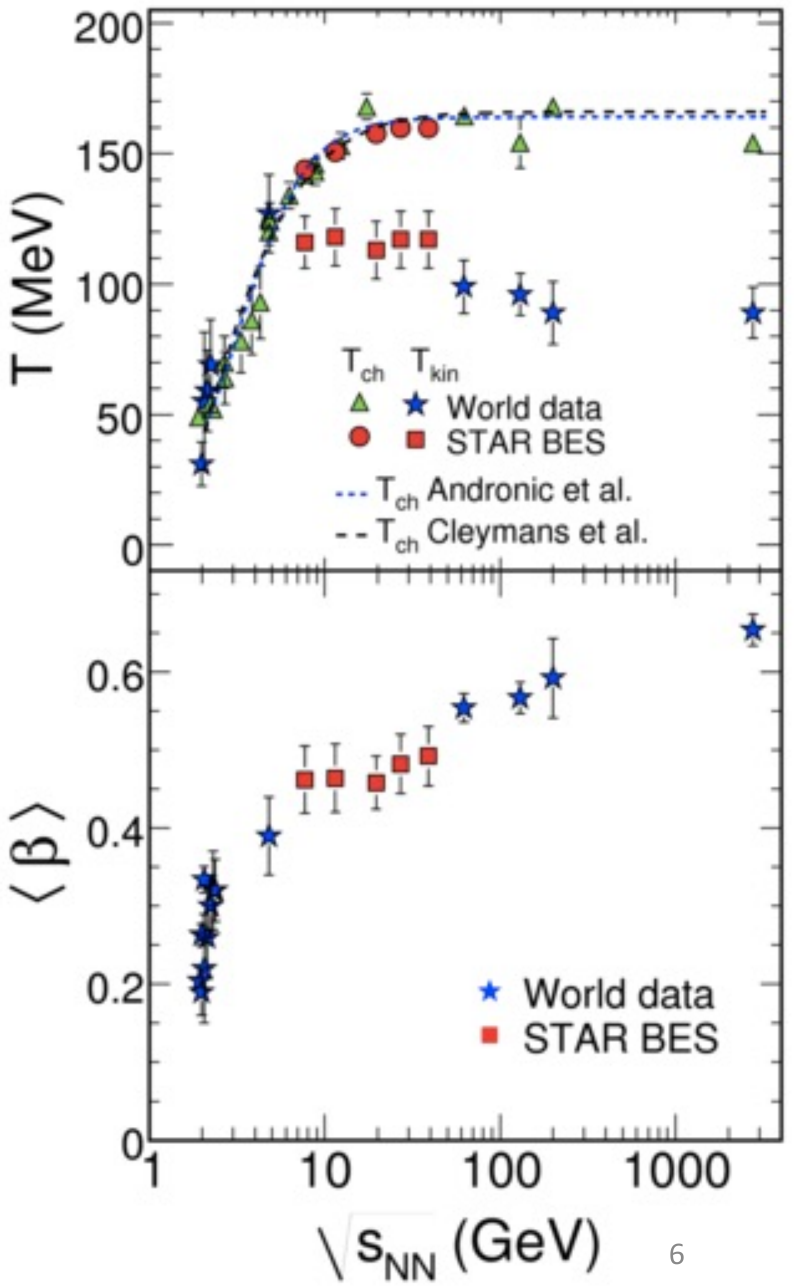
From particle yields and momentum spectra, obtain temperatures and chemical potentials at freeze-out

Whether the chemical freeze-out is at the phase transition boundary is still in debate.

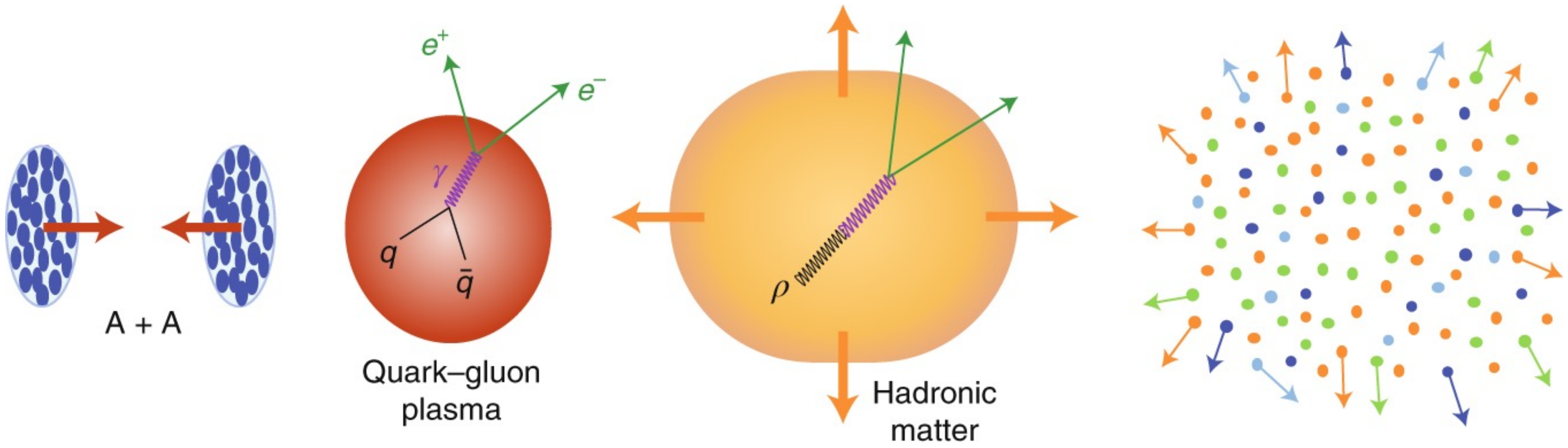
Regardless, RHIC data cover a large range from μ_B = 20MeV to 700MeV with large PID coverage over rapidity-azimuthal-p_T

A foundation to search for Critical Point

STAR, PRC 96 (2017)



Fireball Spectroscopy



R. Rapp, Nature Physics, 15 (2019) 990

The hot fireballs also emit real and virtual photons, which — contrary to hadrons — penetrate the QCD medium and thus carry information on the interior of the fireball

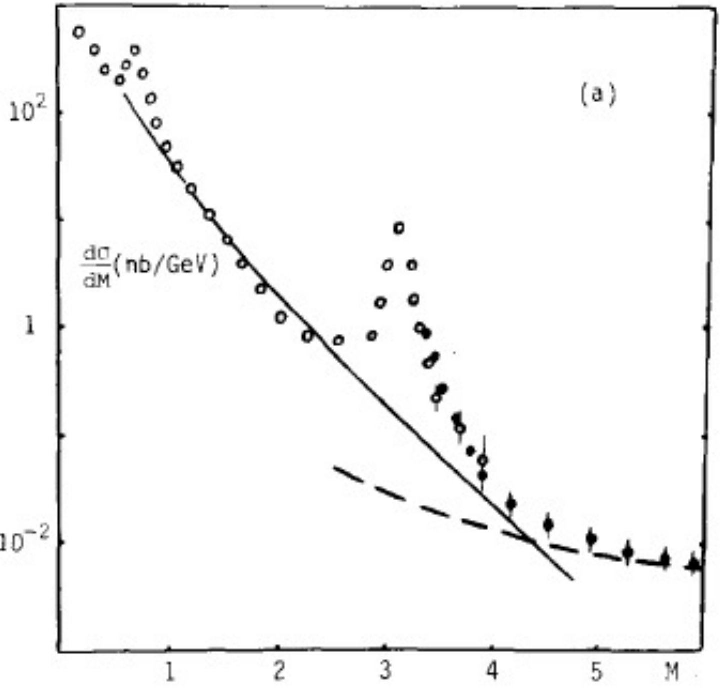
QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS

E.V. SHURYAK

Institute of Nuclear Physics, Novosibirsk, USSR

Received 16 March 1978

The best known example is dilepton production ($\mu^+\mu^-$, e^+e^-), in which deviations from the Drell–Yan model [1] for dilepton mass $M \lesssim 5$ GeV reach a factor



October 2018 at Shuryak 70th Birthday

Thermal dilepton radiation at intermediate masses at the CERN-SpS

Ralf Rapp, Edward Shuryak

Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794-3800, USA

Received 14 September 1999; accepted 16 November 1999

We investigate the significance of thermal dilepton radiation in the intermediate-mass region in heavy-ion reactions at CERN-SpS energies. Within a thermal fireball model for the space-time evolution, the radiation from hot matter is found to dominate over hard 'background' processes (Drell–Yan and open charm) up to invariant masses of about 2 GeV, with a moderate fraction emerging from early stages with temperatures $T \simeq 175$–200 MeV associated with deconfined matter.

arXiv:1005.3531, unpublished

Production of soft e^+e^- Pairs in Heavy Ion Collisions at RHIC by Semi-coherent Two Photon Processes

Pilar Staig and Edward Shuryak

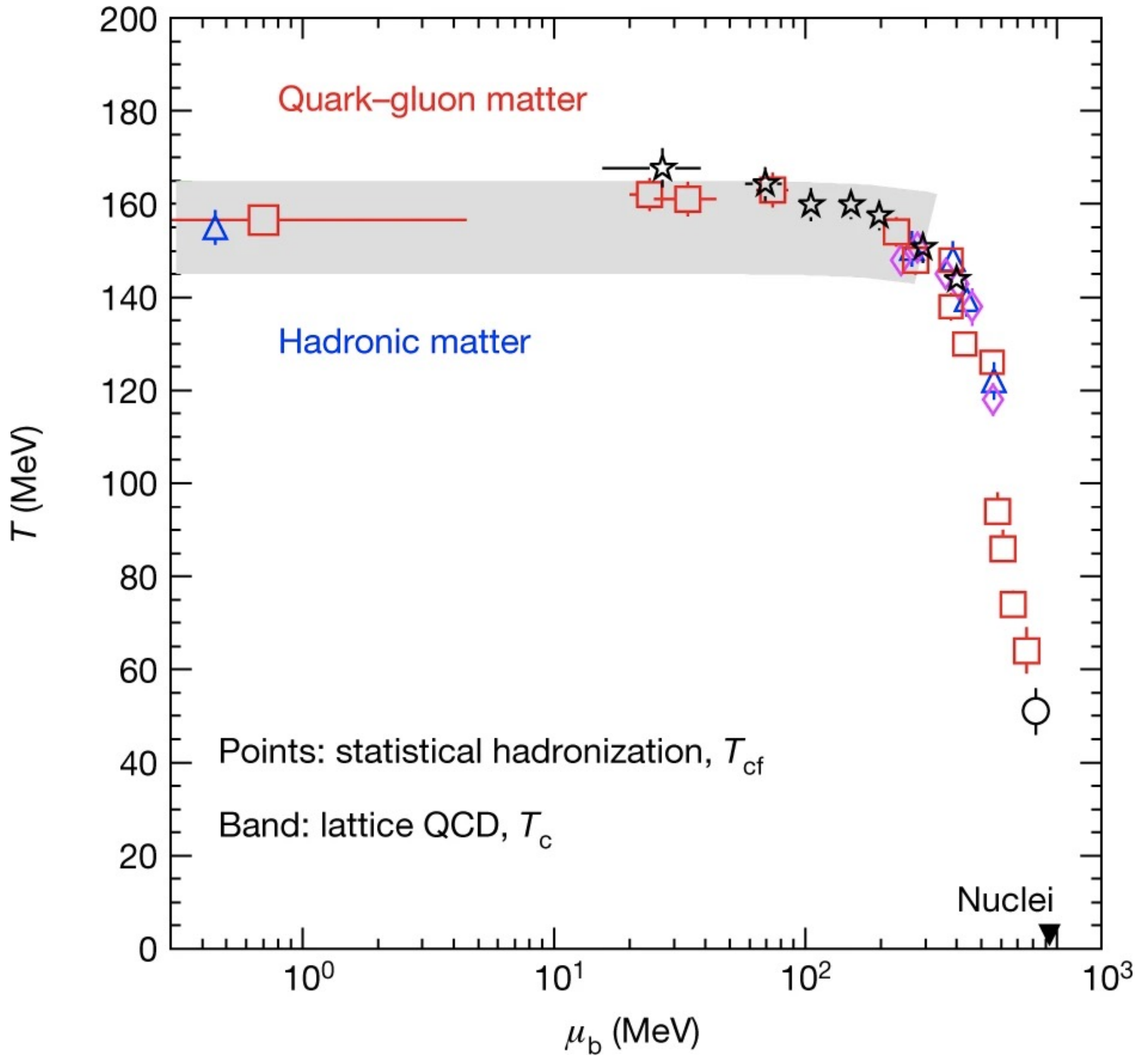
PHYSICAL REVIEW C **90**, 014905 (2014)

Magneto-sonoluminescence and its signatures in photon and dilepton production in relativistic heavy ion collisions

Gökçe Başar,[1] Dmitri E. Kharzeev,[1,2] and Edward V. Shuryak[1]

Among the phenomena that we study are magneto-sonoluminescence [MSL, the interaction of magnetic field $\vec{B}(x,t)$ with the sound perturbations of the stress tensor $\delta T_{\mu\nu}(x,t)$] and magneto-thermoluminescence [MTL, the interaction of $\vec{B}(x,t)$ with smooth average $\langle T_{\mu\nu}\rangle$]. We calculate the rates of these process and find that they can dominate the photon and dilepton production at early stages of heavy ion collisions. We also point out the characteristic signatures of MSL and MTL that can be used to establish their presence and to diagnose the produced matter.

QCD phase diagram with penetrating thermometer



A. Andronic et al., NATURE 561 (2018)

NATURE PHYSICS 15 (2019) 1040, HADES Collaboration

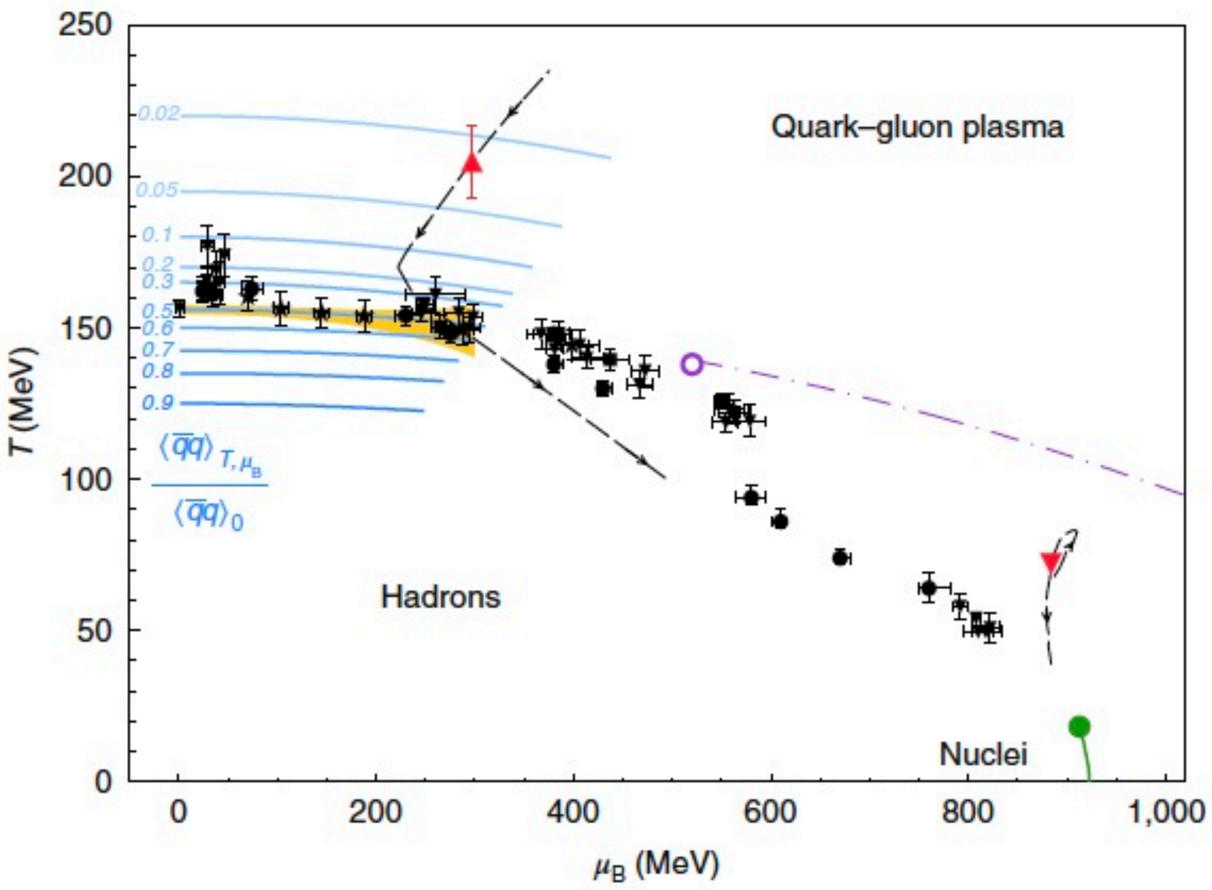
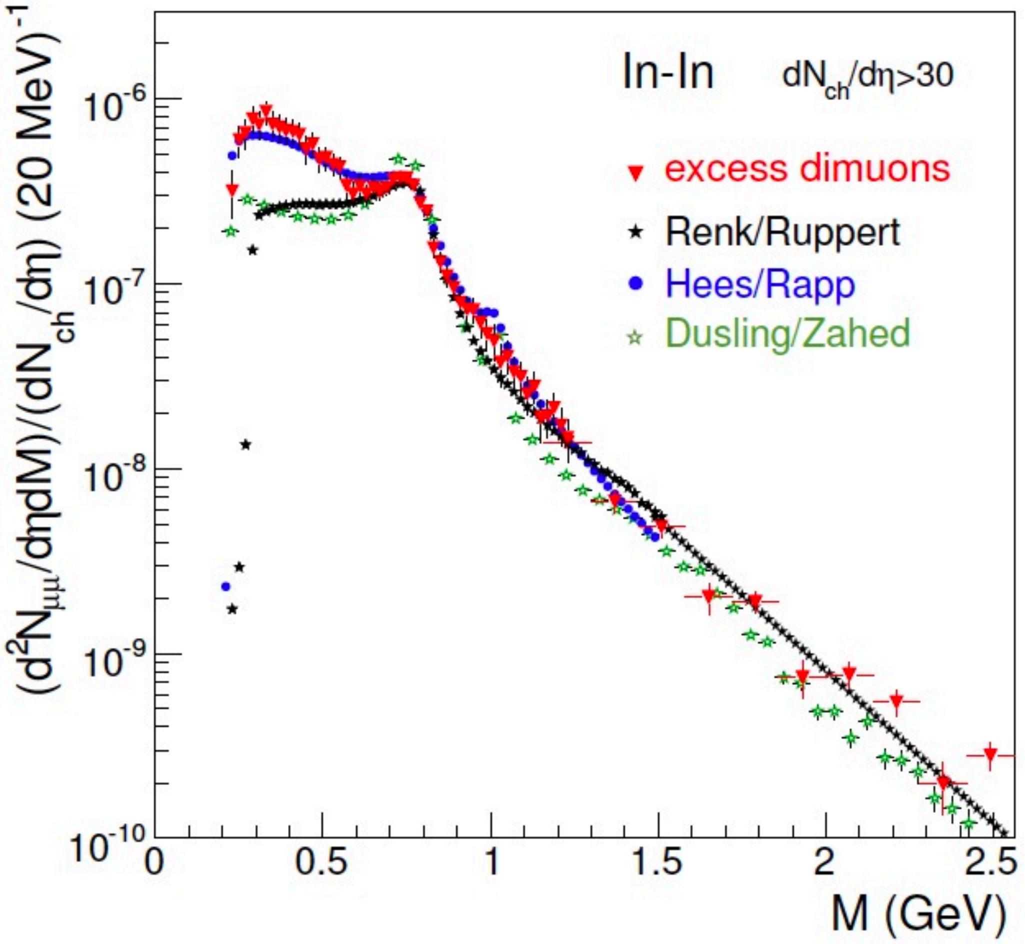


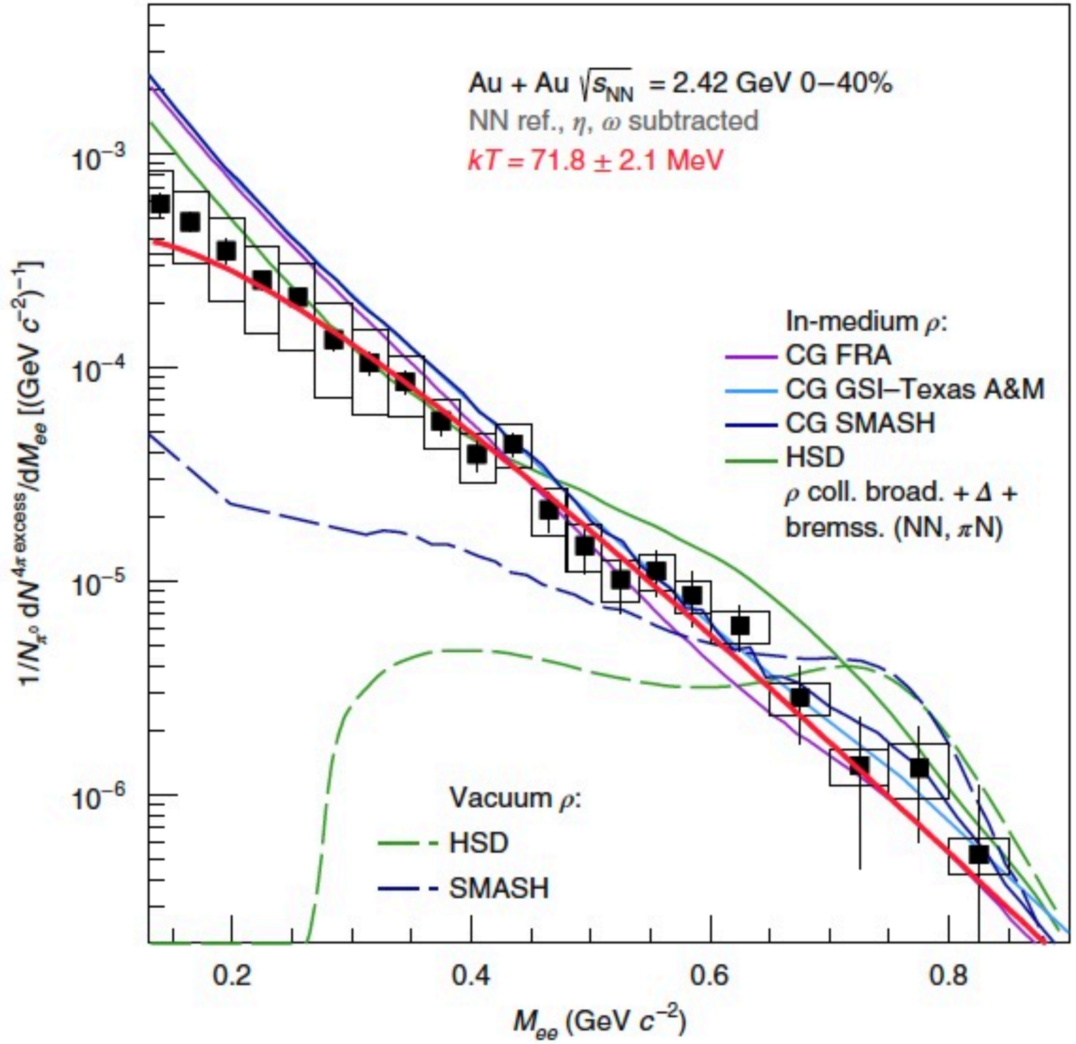
Fig. 1 | The conjectured QCD phase diagram of strong-interaction matter.

Dilepton invariant mass spectra

Thermal radiation and ρ spectral broadening



ρ→e+e-



NA60, AIP. Conf. Proc. 1322 (2010) 1-10

Electron Identification at STAR (and ALICE)

TPC dE/dx: large hadron background

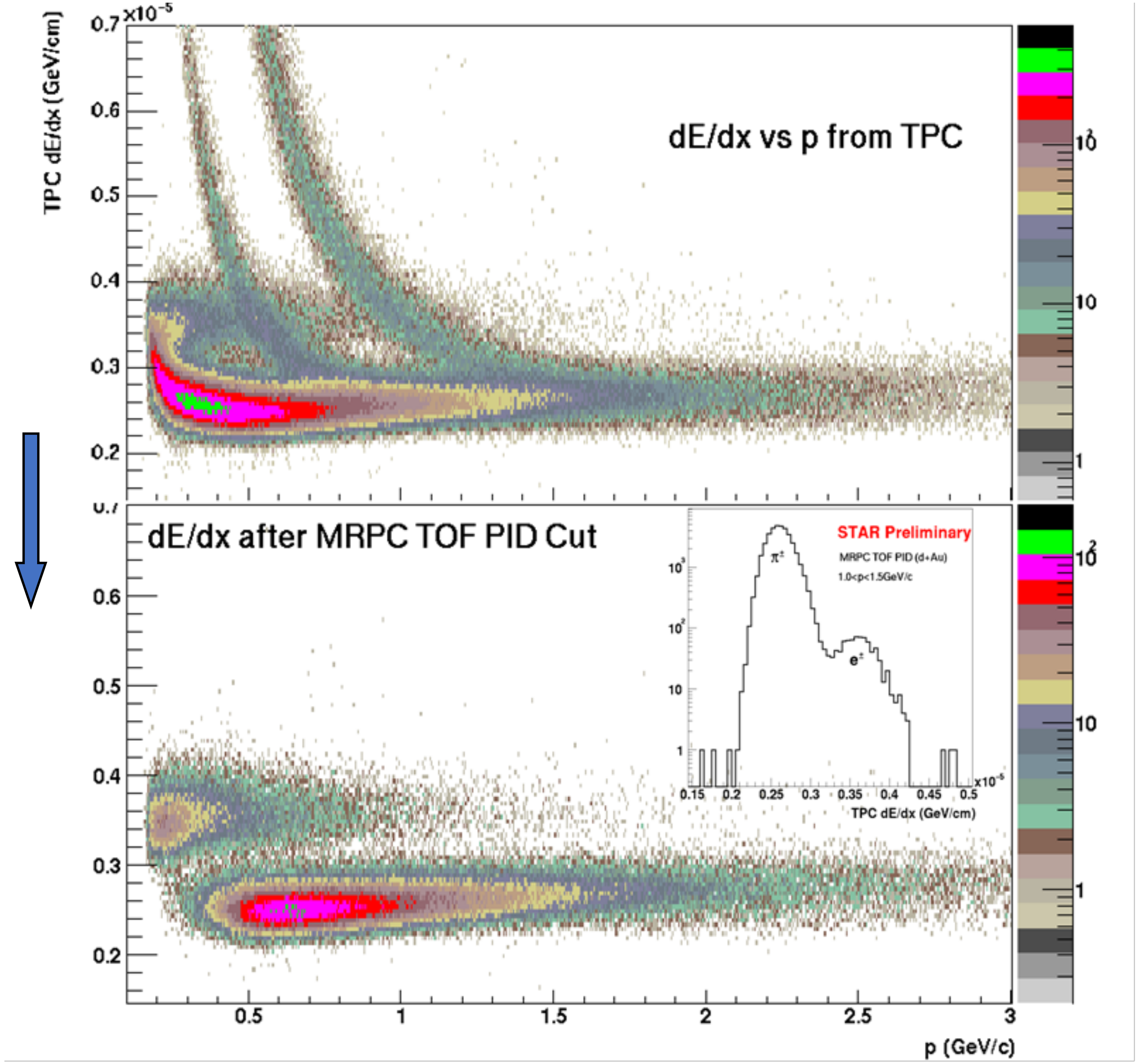
EMC: p_T>~2.0 GeV/c

A prototype TOF tray (TOFr) in 2003
TOF is NOT always the obvious choice,
Became upgrade item (STAR),
but it has proven to be crucial for STAR
ALICE3 has inner and outer TOF

|1/β-1|<0.03

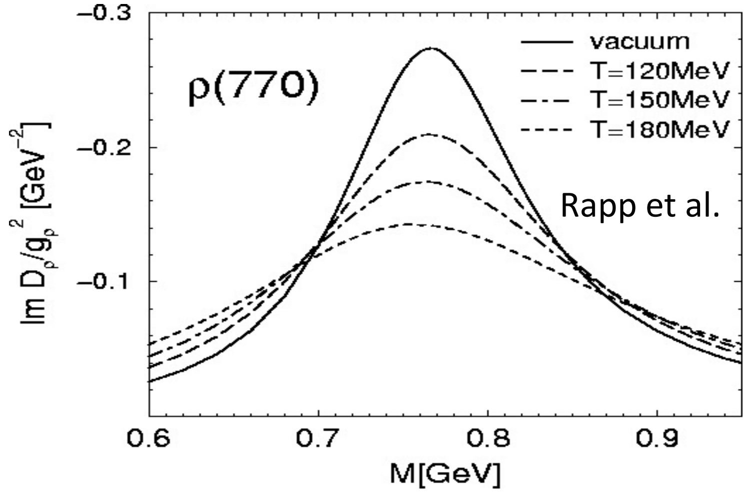
Not able to do without TOF!

nucl-ex/0505026, M. Shao et al.
X. Dong PHD Thesis (USTC 2005)
L. Ruan PHD Thesis (USTC 2004)

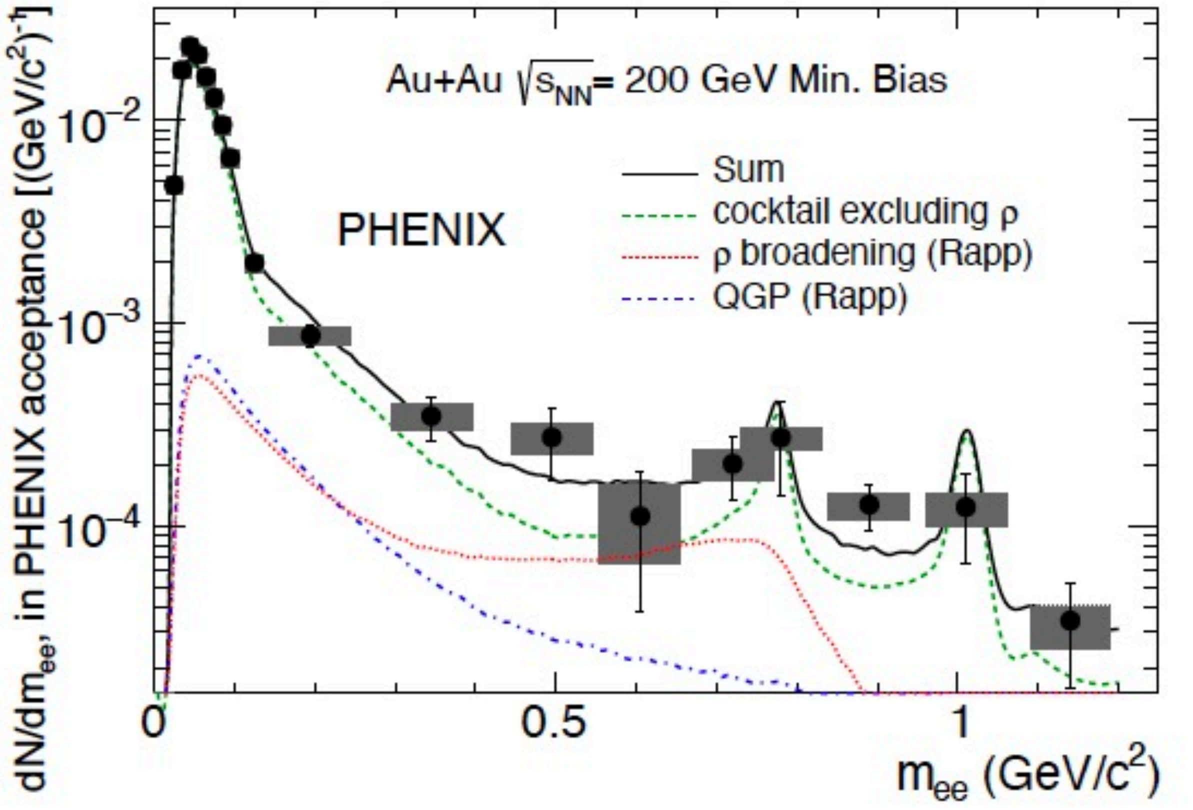


QCD phase transition is a chiral phase transition

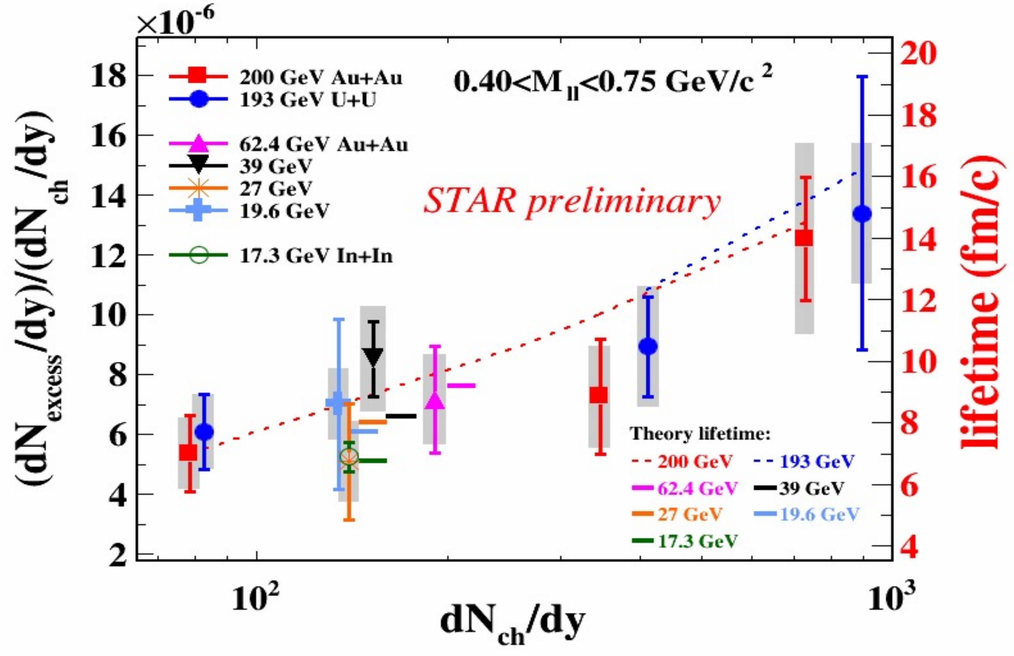
Golden probe of chiral symmetry restoration:
change vector meson ($\rho \to e^+e^-$) spectral function
STAR data (RHIC and SPS):
Consistent with continuous QGP radiation and broadening of vector meson in-medium



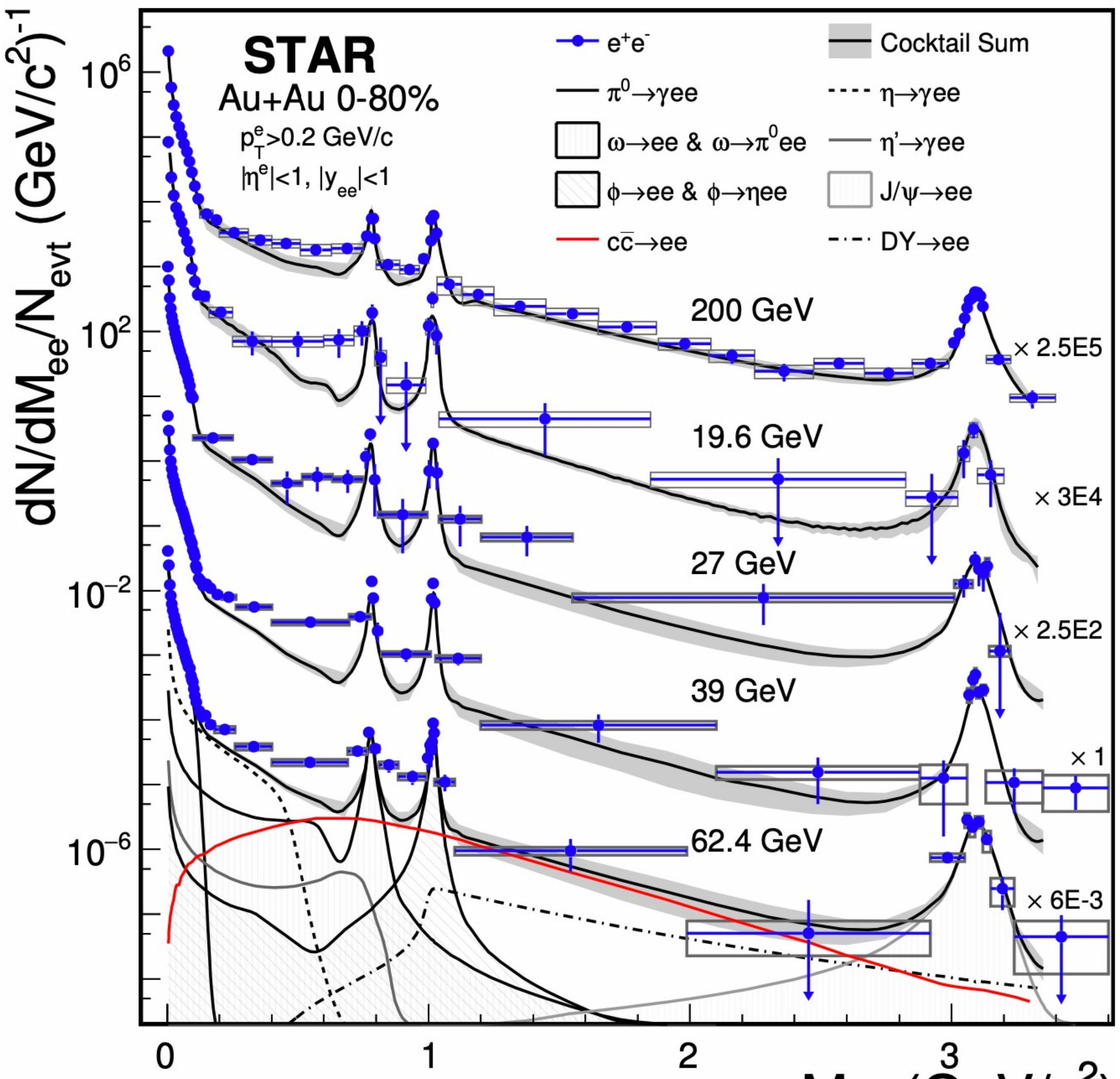
PHENIX, PRC 93(2016)



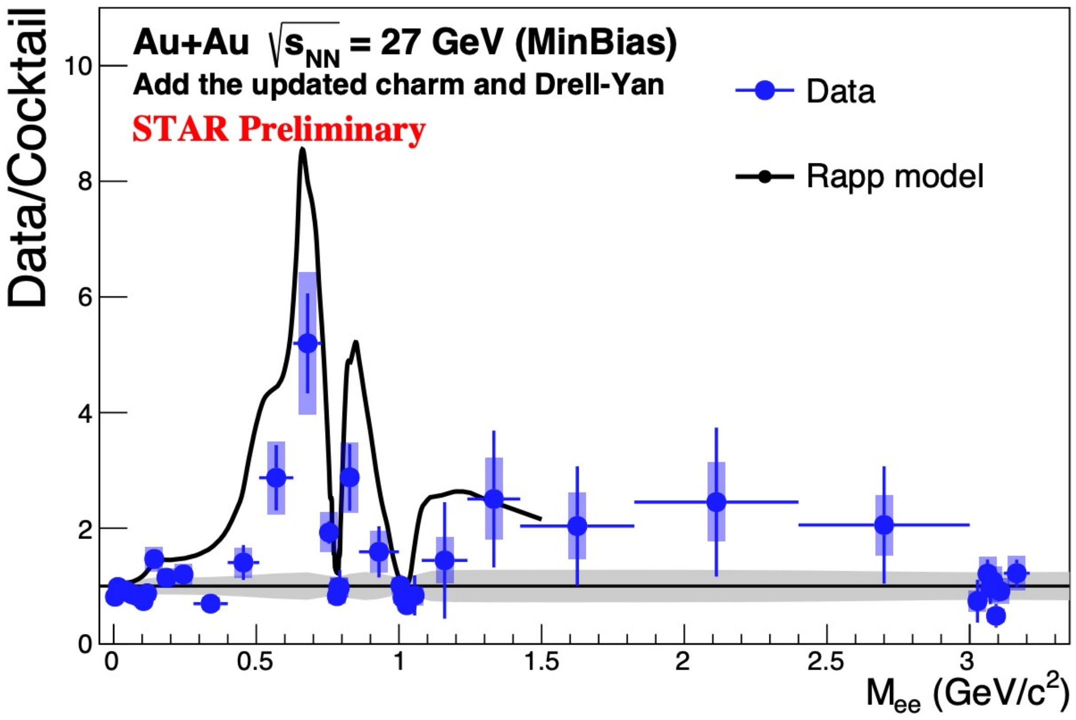
PLB750(2015), PRL 113 (2014)



Scanning through the phase diagram



Zaochen Ye (STAR), Hard Probes 2020



- LMR ($M_{ee} < M_{\phi}$): in-medium modifications linked to the chiral symmetry restoration
- IMR ($M_{\phi} < M_{ee} < M_{J/\psi}$): excess from thermal radiation → medium temperature

Empirical fitting with thermal factor

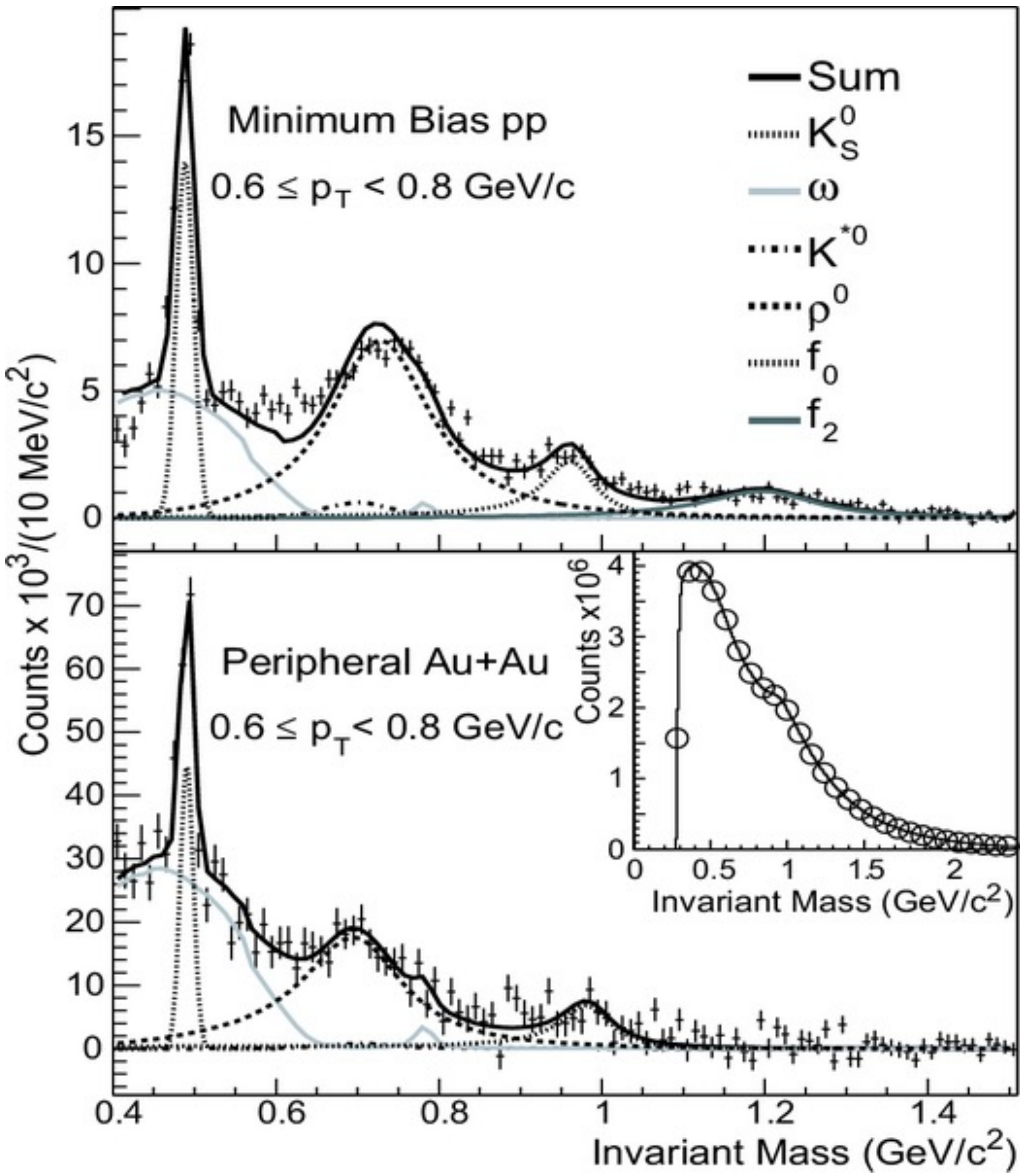
STAR, PRL 2004

- ρ hadronic decay channel
  fit with Breit-Wigner function
  and a phase-space factor:

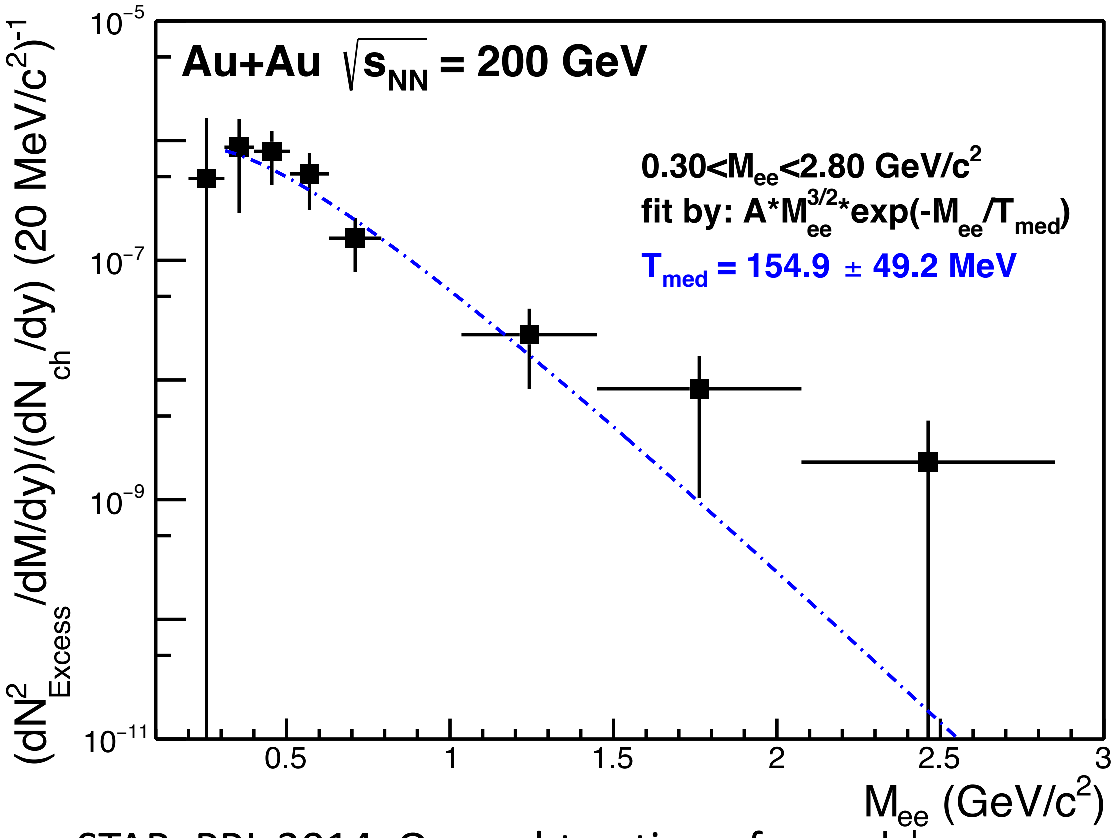
  BW*PS

- PS=M*exp(-M/T)

R. Rapp, NPA (2003)
Shuryak, Brown, NPA 2003
Kolb, Prokash, PRC 2003
PBM

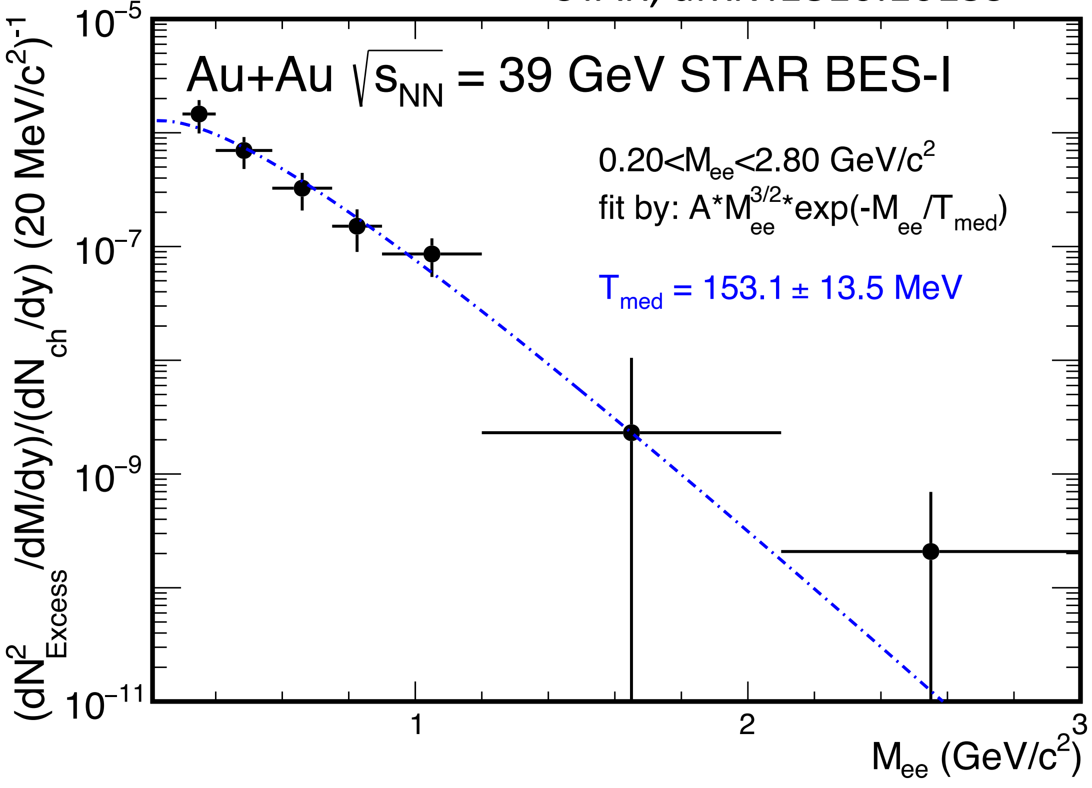


LMR dielectrons as thermometer



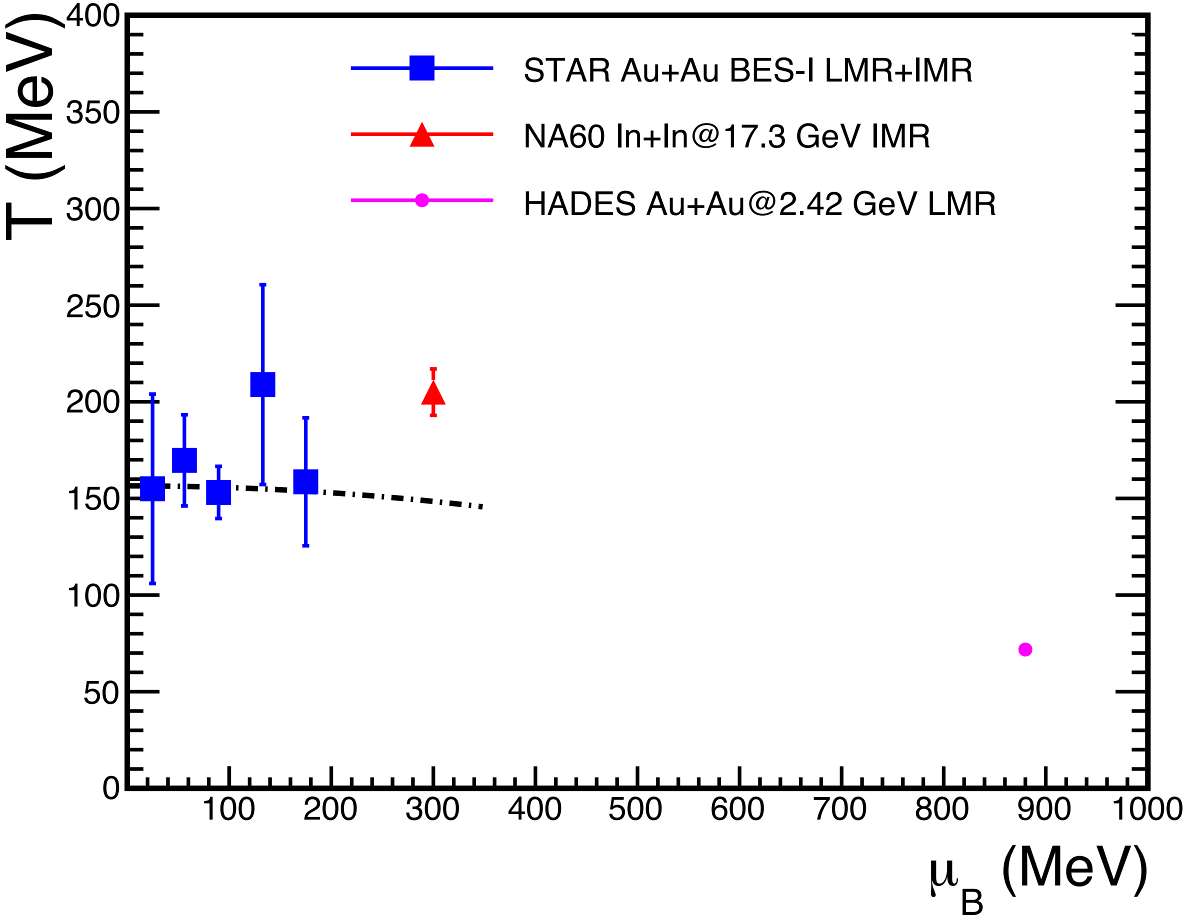
STAR, PRL 2014, Oversubtraction of ω and ϕ

STAR, arxiv:1810.10159

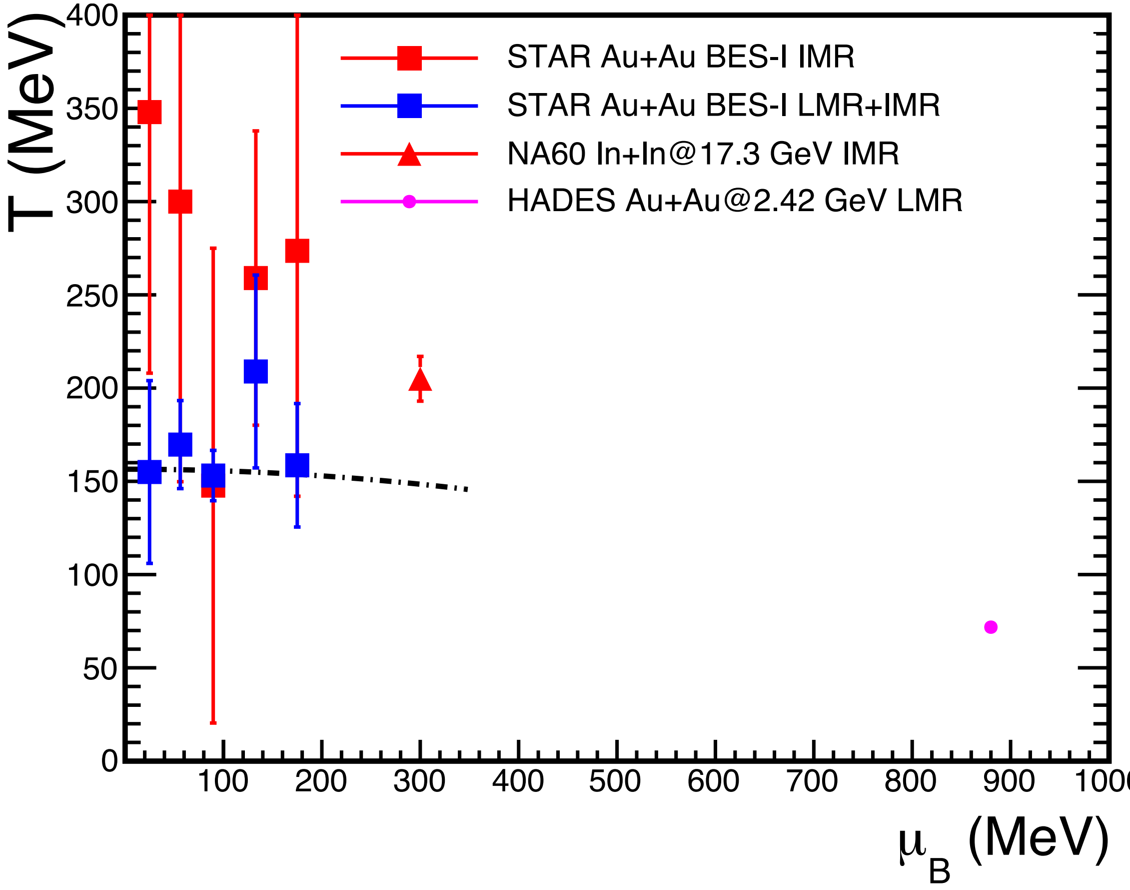


When temperature is high enough and rho broadening to the extent of becoming part of the effective thermal radiation;
LMR is a measure of average thermal temperature;
Do we also empirically achieve Chiral Symmetry Restoration?

True Temperature without Blue Shift



Zaochen Ye (RICE)



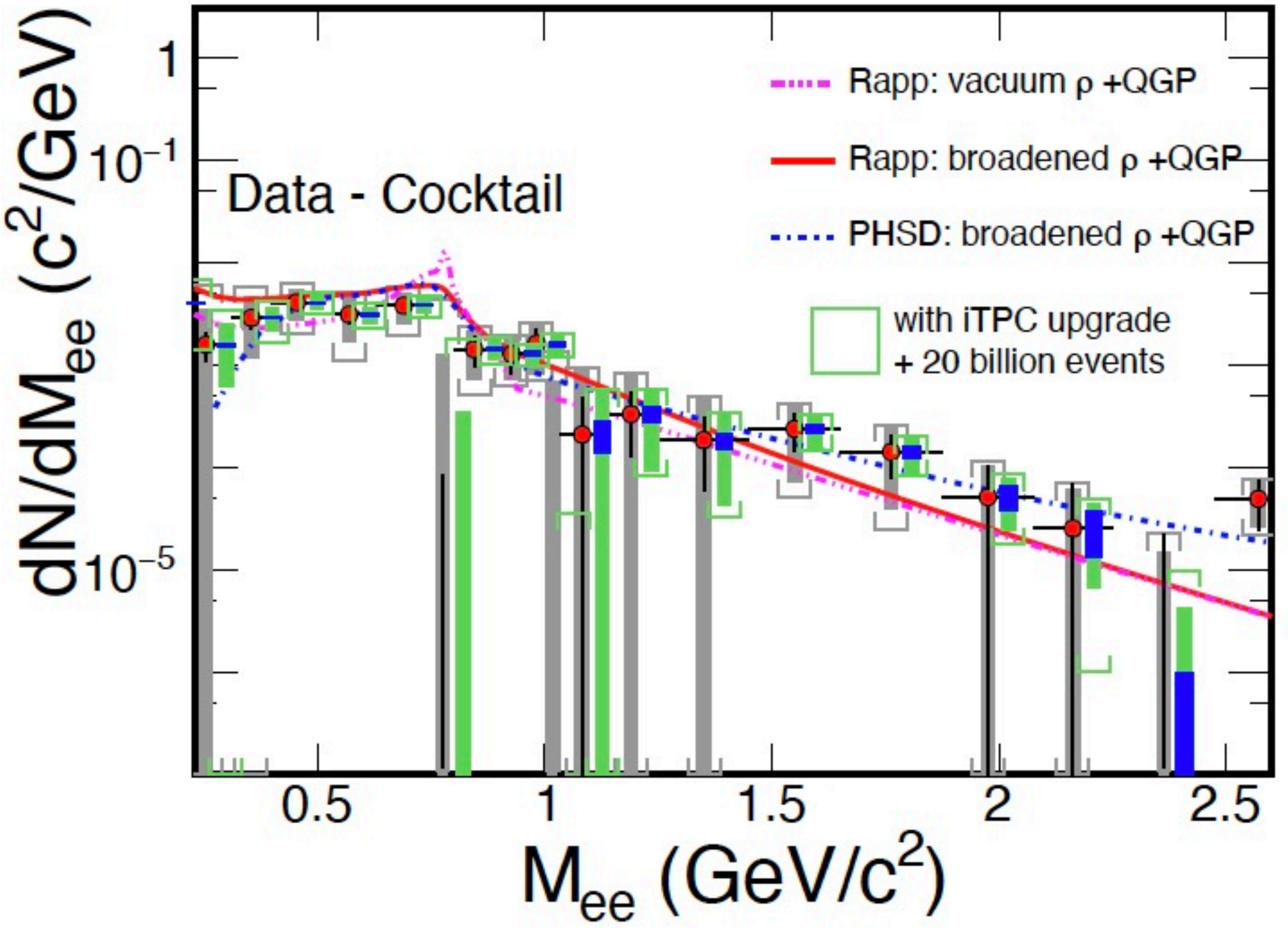
Measure LMR with thermal factor, temperature consistently around phase transition
It is a measure of average temperature (early temperature has to be higher).
IMR systematically above LMR temperature with large uncertainty
BES-II (x10 events) + 2023-2025, reduce errors by x3

Jana Guenther, (LQCD curve)
https://arxiv.org/pdf/2010.15503.pdf

Perspectives from STAR on LMR+IMR

- New and preliminary results from high statistics 27 (2018) and 54GeV (2017)
- BESII datasets with FXT 100M—1B events per energy x10 more data
- High statistics 200GeV in 2023-2025 with low detector material and iTPC upgrade

STAR BUR 2023-25



Heavy ion collisions as a source of the strongest magnetic fields available in the Laboratory

Also:
V. Skokov,
V. Toneev,
A. Illarionov...

NOT just about CME

DK, McLerran, Warringa,
Nucl Phys A803(2008)227

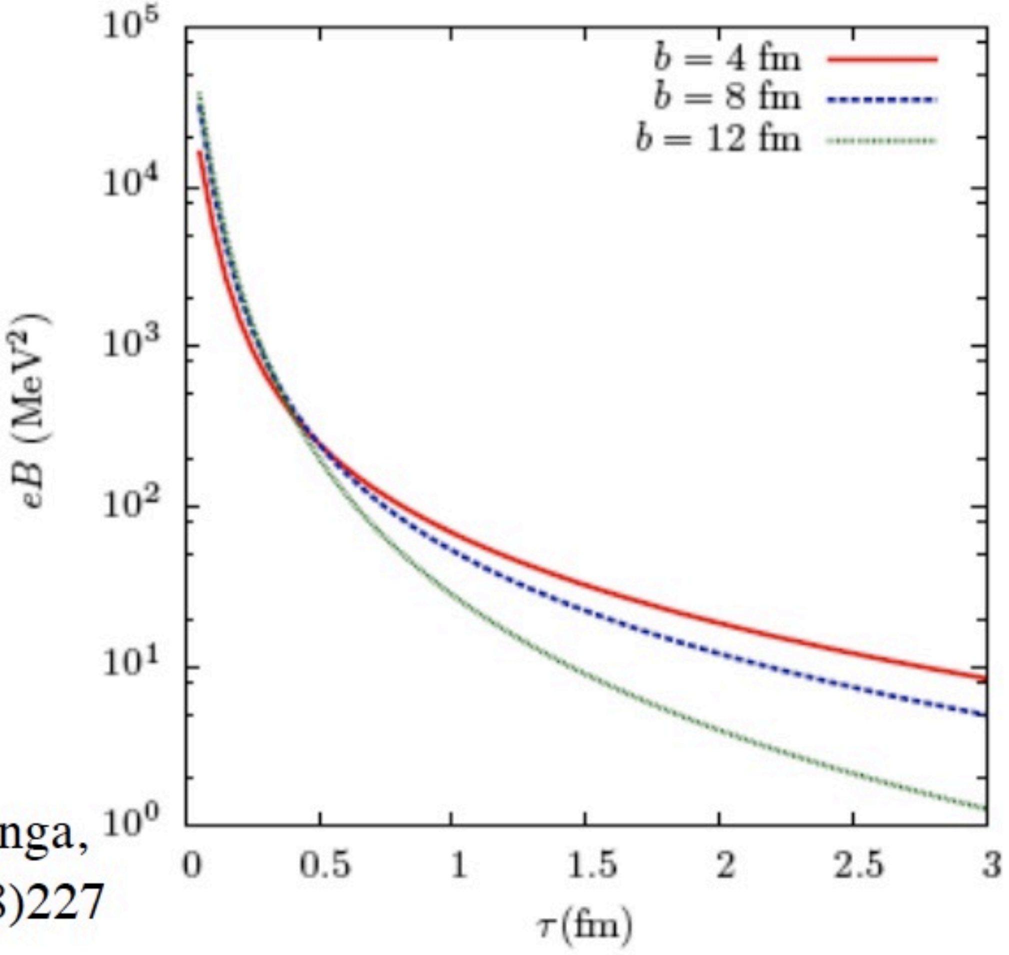


Fig. A.2. Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).

In a conducting plasma, Faraday induction can make the field long-lived:
K.Tuchin, arXiv:1006.3051

NB: magnetic flux is conserved in MHD! - expect the effect at LHC

D. Kharzeev

QUARK MATTER ANNECY 2011

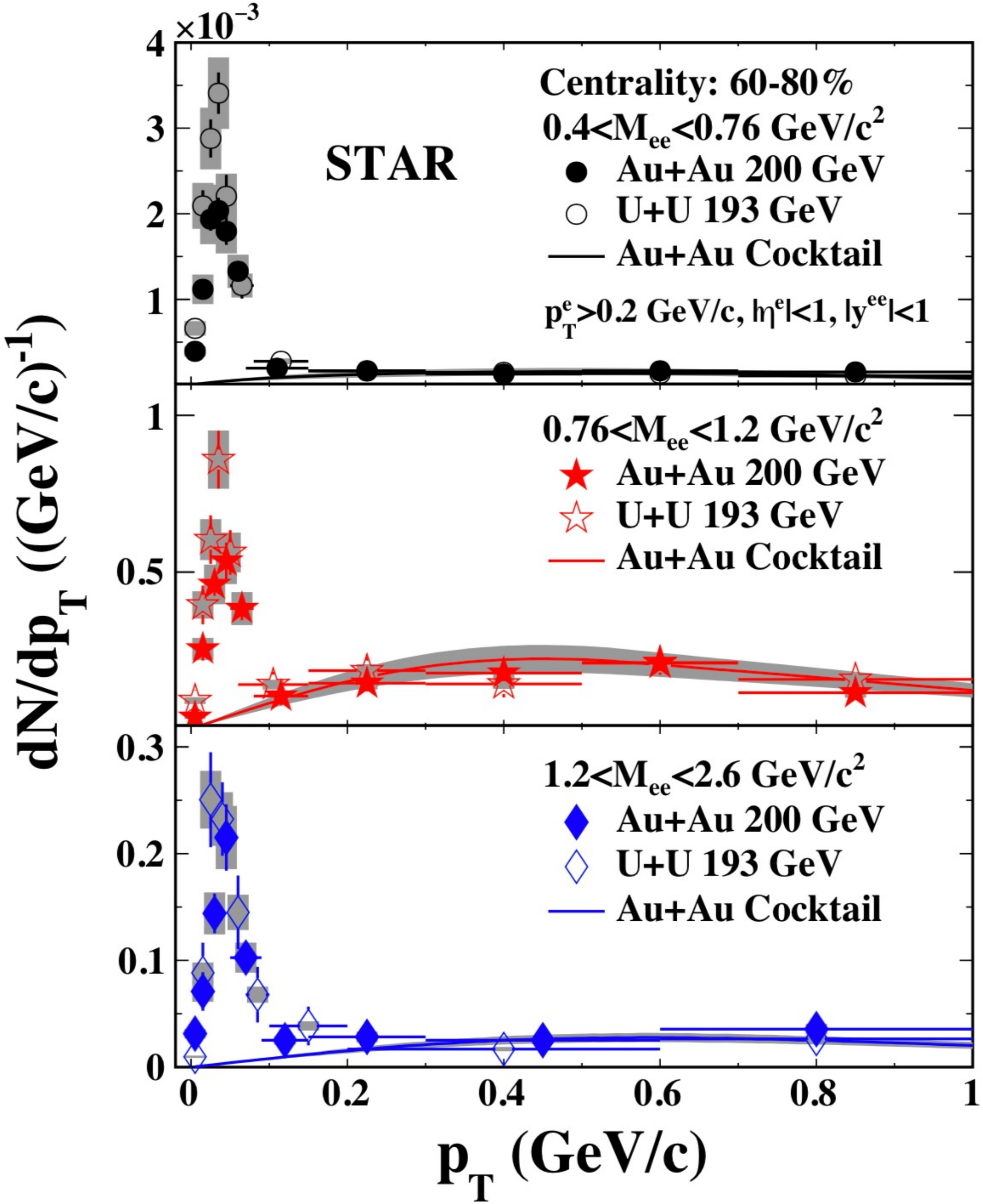
Characteristics of photon collisions

Photon-interactions:
Peak at low p_T ~= 30MeV
Prominent above background

Hadronic production:
$<p_T>$~=500MeV/c

Datasets:
Au+Au 2010+2011
U+U 2012

Linear Scale
Signal-to-background ratio is about 17:1



Old Question with new spin

ATLAS data: PRL 121 (2018) 212301

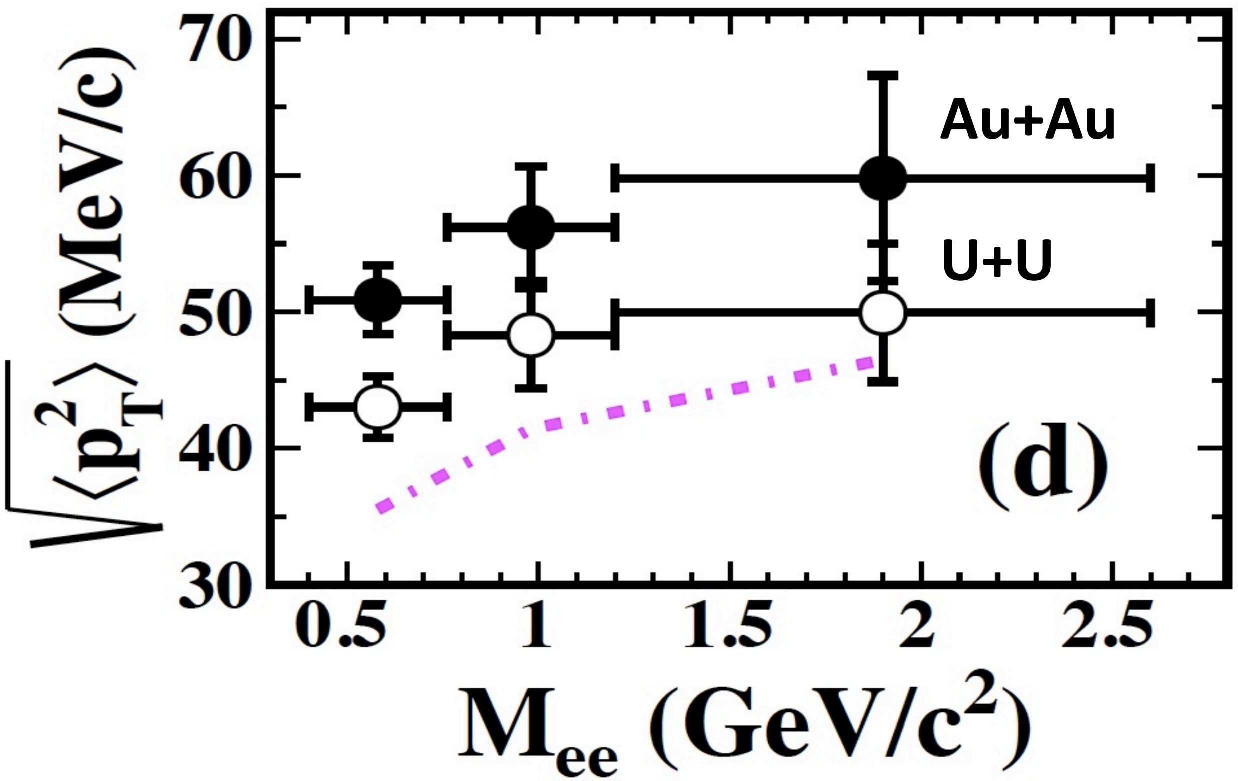
PHYSICAL REVIEW LETTERS 121, 132301 (2018)

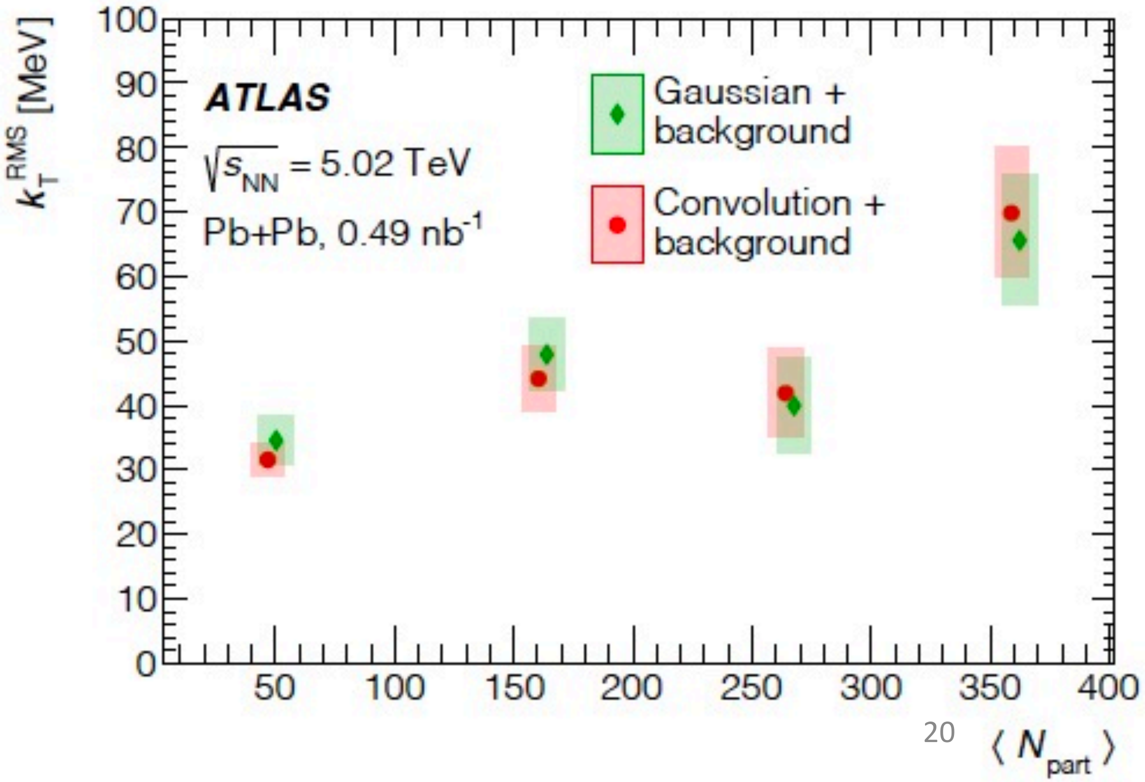
(Received 6 June 2018; revised manuscript received 30 August 2018; published 25 September 2018)

We report first measurements of e^+e^- pair production in the mass region $0.4 < M_{ee} < 2.6$ GeV/c^2 at low transverse momentum ($p_T < 0.15$ GeV/c) in noncentral Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and U + U collisions at $\sqrt{s_{NN}} = 193$ GeV. Significant enhancement factors, expressed as ratios of data over known hadronic contributions, are observed in the 40%–80% centrality of these collisions. The excess yields peak distinctly at low p_T with a width ($\sqrt{\langle p_T^2 \rangle}$) between 40 and 60 MeV/$c$. The absolute cross section of the excess depends weakly on centrality, while those from a theoretical model calculation incorporating an in-medium broadened ρ spectral function and radiation from a quark gluon plasma or hadronic cocktail contributions increase dramatically with an increasing number of participant nucleons. Model calculations of photon-photon interactions generated by the initial projectile and target nuclei describe the observed excess yields but fail to reproduce the p_T^2 distributions.

DOI: 10.1103/PhysRevLett.121.132301

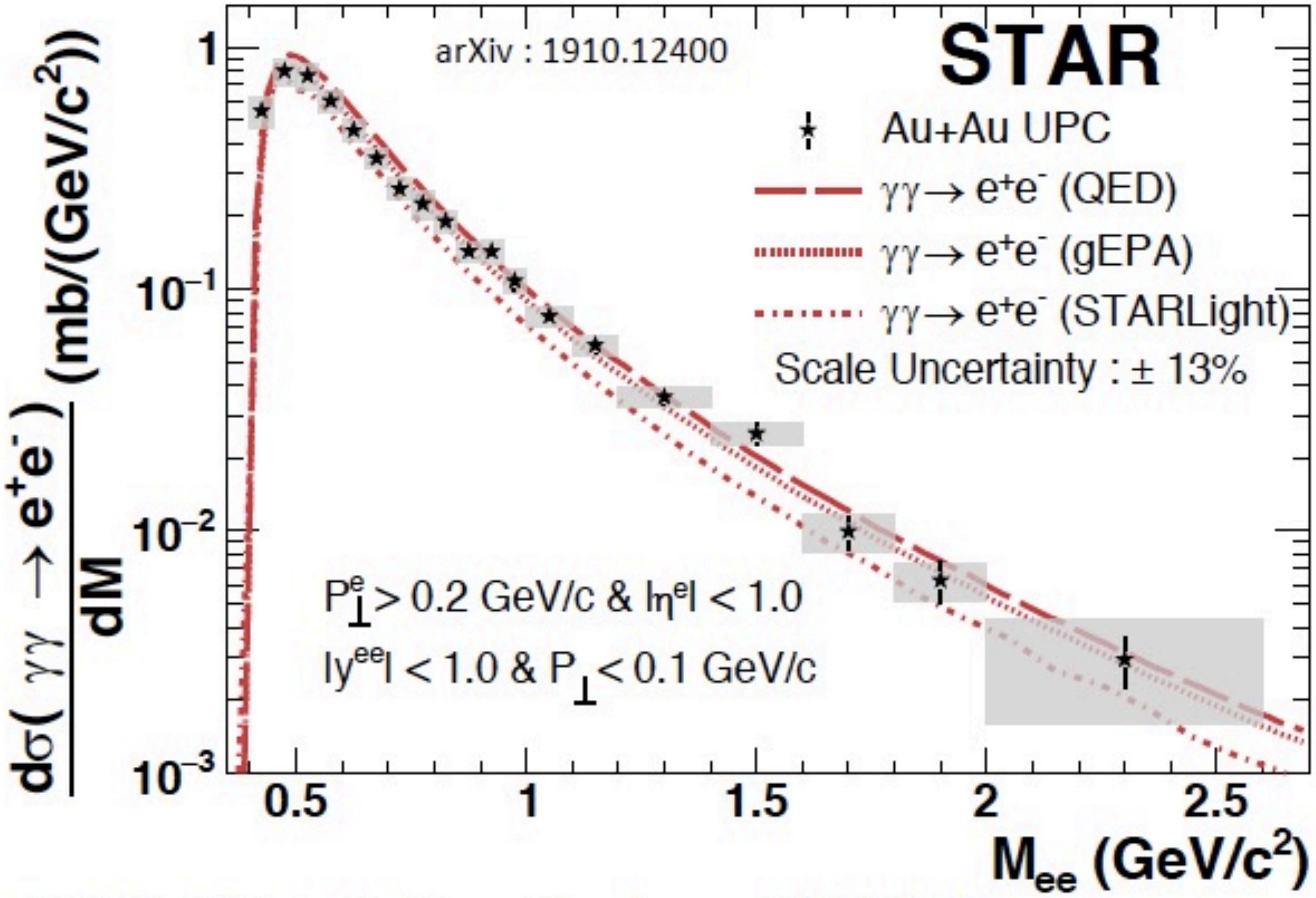
This Letter presents a measurement of $\gamma\gamma \to \mu^+\mu^-$ production in Pb+Pb collisions recorded by the ATLAS detector at the Large Hadron Collider at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with an integrated luminosity of 0.49 nb^{-1}. The azimuthal angle and transverse momentum correlations between the muons are measured as a function of collision centrality. The muon pairs are produced from $\gamma\gamma$ through the interaction of the large electromagnetic fields of the nuclei. The contribution from background sources of muon pairs is removed using a template fit method. In peripheral collisions, the muons exhibit a strong back-to-back correlation consistent with previous measurements of muon pair production in ultra-peripheral collisions. The angular correlations are observed to broaden significantly in central collisions. The modifications are qualitatively consistent with rescattering of the muons while passing through the hot matter produced in the collision.





Total $\gamma\gamma \rightarrow e^+e^-$ cross-section in STAR Acceptance

STAR, PRL 127 (2021)



STARLight: S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258
gEPA & QED : W. Zha, J.D.B., Z. Tang, Z. Xu arXiv:1812.02820 [nucl-th]

Pure QED $2 \rightarrow 2$ scattering :

$$d\sigma/dM \propto E^{-4} \approx M^{-4}$$

No vector meson production
→ Forbidden for real photons with helicity ± 1 (i.e. 0 is forbidden)

$\sigma(\gamma\gamma \rightarrow e^+e^-)$ in STAR Acceptance:

Data : 0.261$\pm$0.004 (stat.) $\pm$ 0.013 (sys.) $\pm$ 0.034 (scale) mb

STARLight	gEPA	QED
0.22 mb	0.26 mb	0.29 mb

Measurement of total cross section agrees with theory calculations at $\pm 1\sigma$ level

Photon TMD in UPC

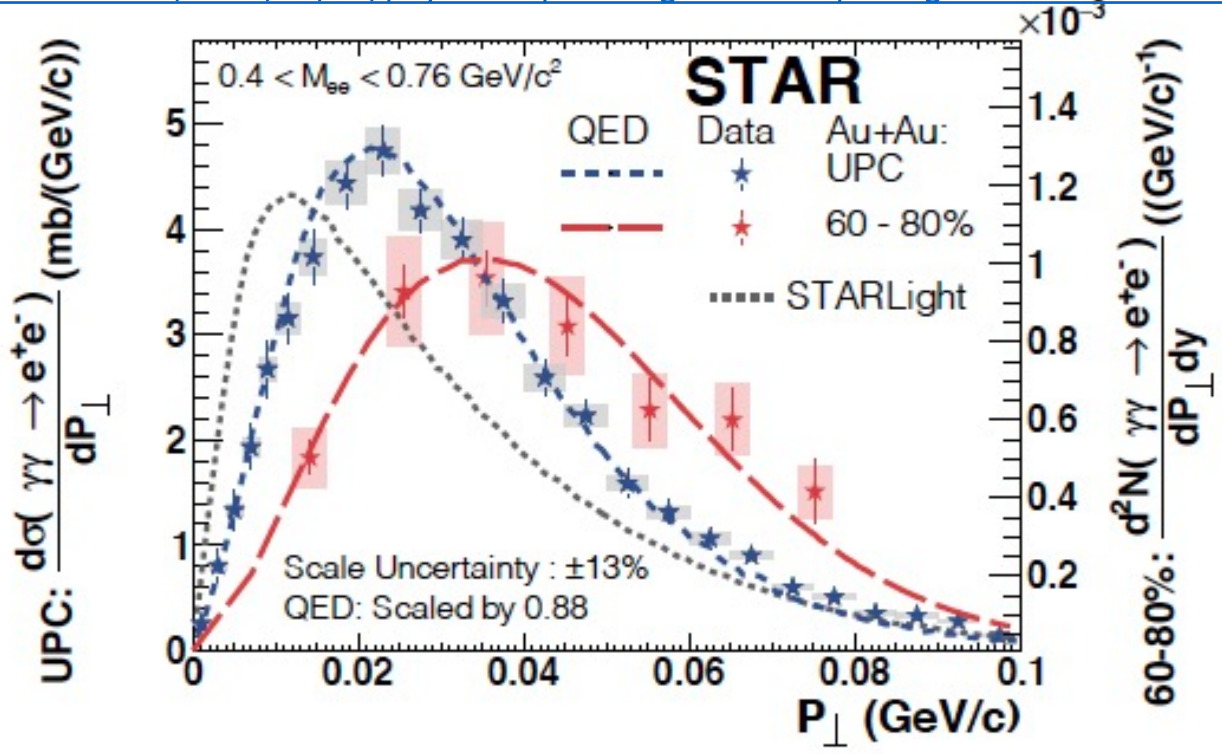
CMS Abstract: "This observation demonstrates the transverse momentum and energy of photons emitted from relativistic ions have impact parameter dependence. These results constrain precision modeling of initial photon-induced interactions in ultra-peripheral collisions. They also provide a controllable baseline to search for possible final-state effects on lepton pairs resulting from the production of quark-gluon plasma in hadronic heavy ion collisions."

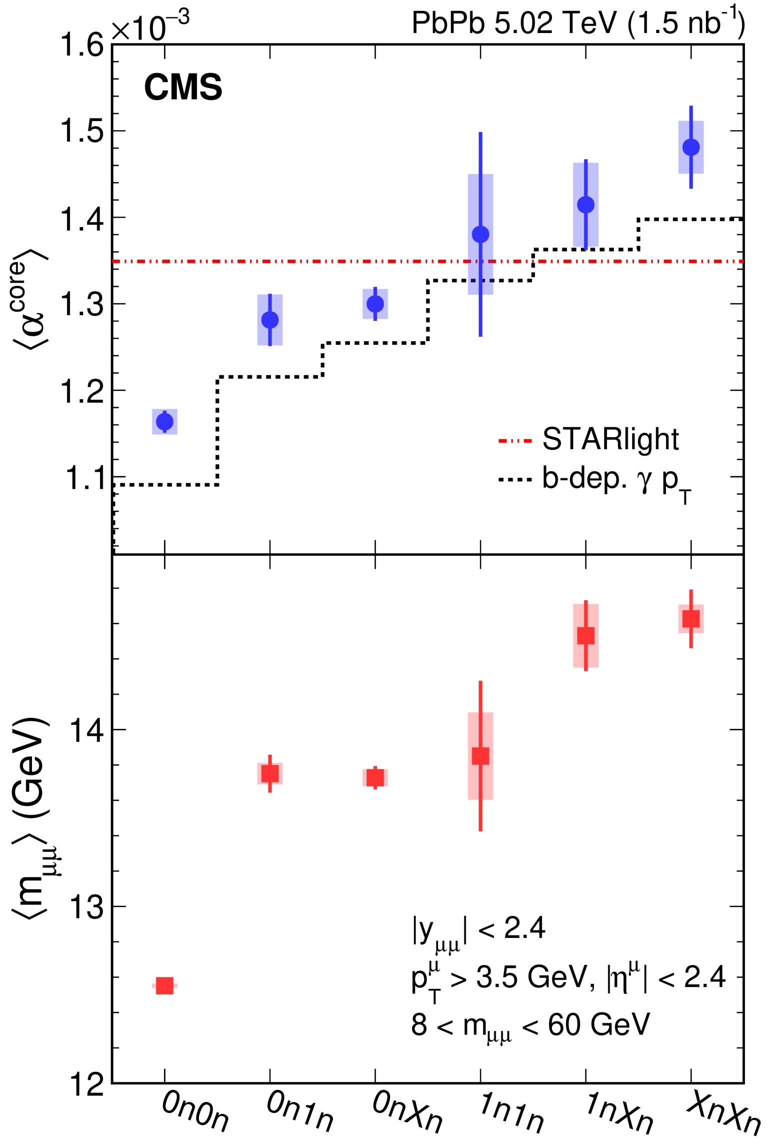
https://news.rice.edu/2021/09/20/physicists-probe-light-smashups-to-guide-future-research-2/

50. STAR Collaboration, J., Adam *et al.* Probing Extreme Electromagnetic Fields with the Breit-Wheeler Process. (2019). https://arxiv.org/abs/1910.12400.

51. ATLAS Collaboration. Measurement of non-exclusive dimuon pairs produced via $\gamma\gamma$ scattering in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector. ATLAS-CONF-2019-051. (2019). https://inspirehep.net/literature/1762955.

52. CMS Collaboration,. Observation of forward neutron multiplicity dependence of dimuon acoplanarity in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV CMS-PAS-HIN-19-014. (2020). https://inspirehep.net/literature/1798862.

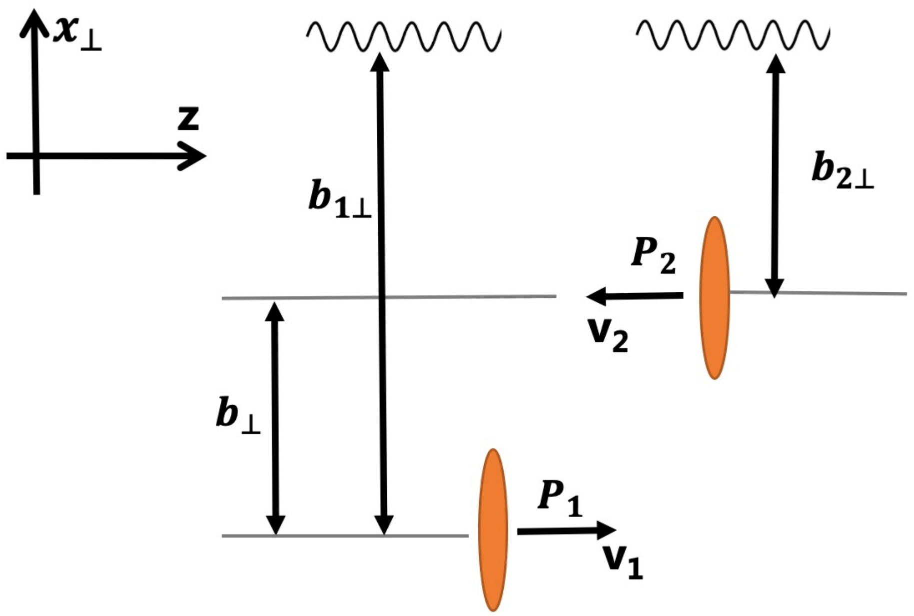


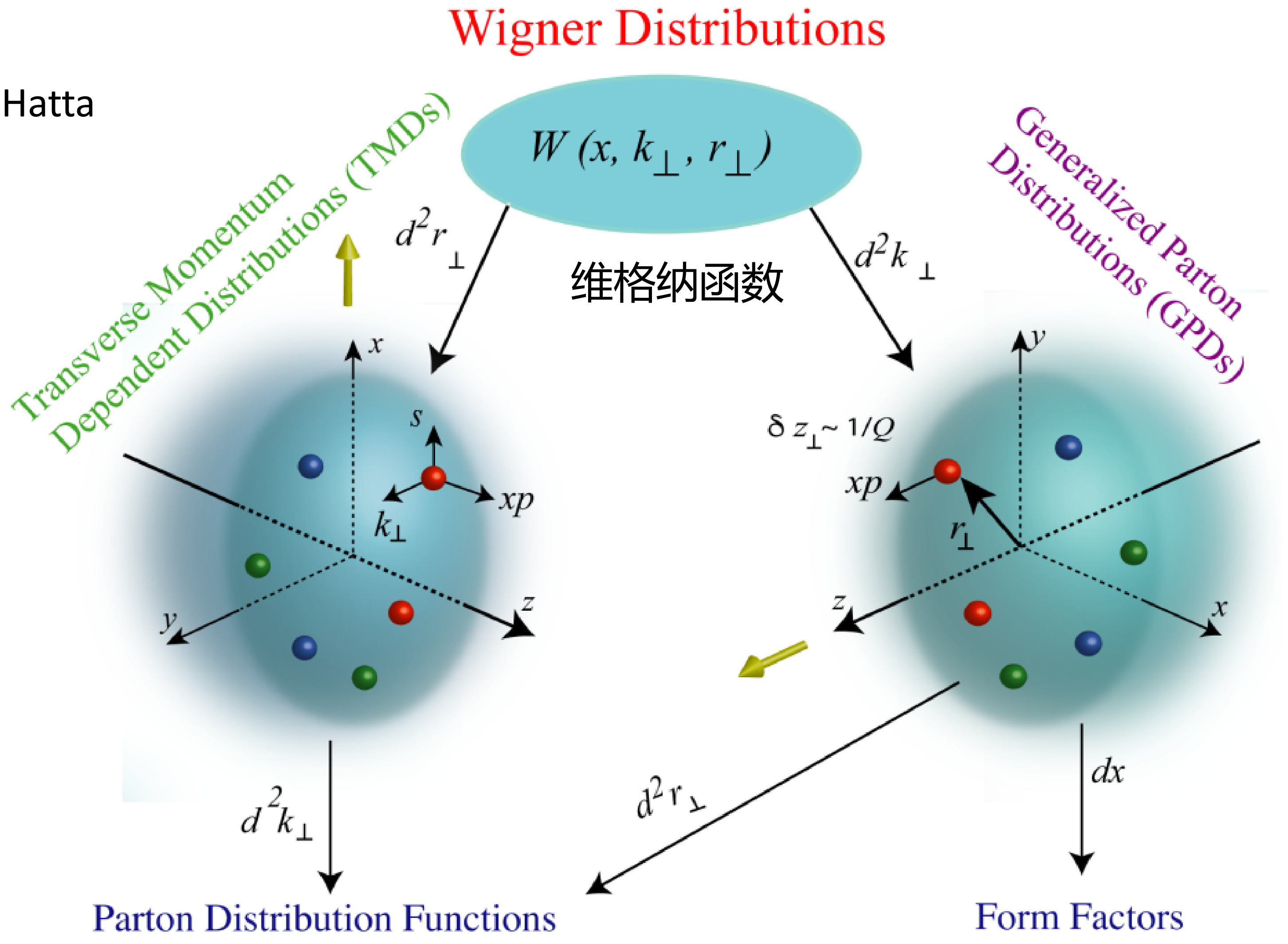


Quite a few techniques used in QCD can be used in strong-field QED as well

Y. Hatta

Understanding the QED is also important for quantitative extraction of the photoproduction

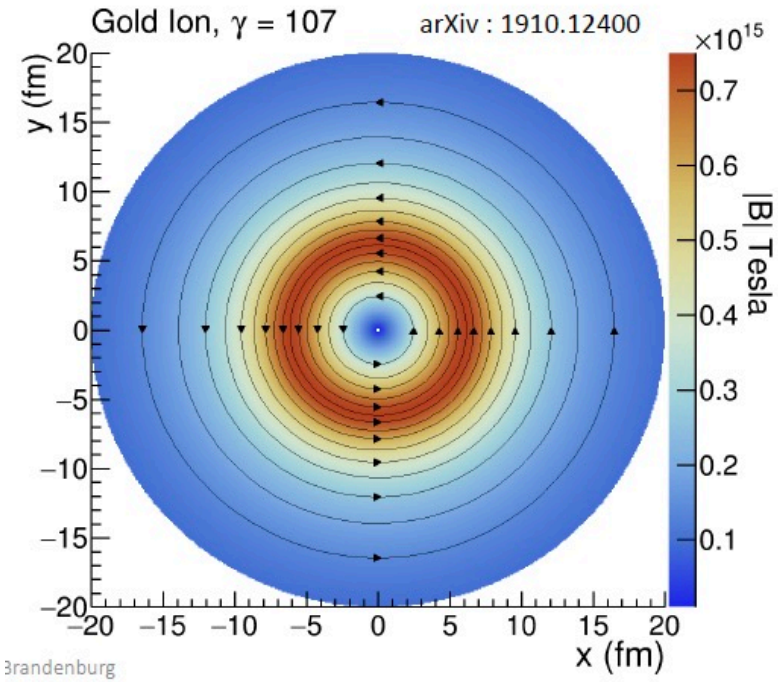




Wang/Pu/Wang, PRD, https://arxiv.org/pdf/2106.05462.pdf

Observables of photon linear polarization

- Magnetic field generated by the heavy-ions are circular around the nucleus
- Photons are linearly polarized along the transverse radial direction
- There is a significant momentum-space correlation of photon field



Birefringence of the QED Vacuum

[1] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)
QED calculation: arxiv : 1911.00237

Recently realized, $\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0$ leads to $\cos(n\Delta\phi)$ modulations in polarized $\gamma\gamma \to e^+e^-$ [1]

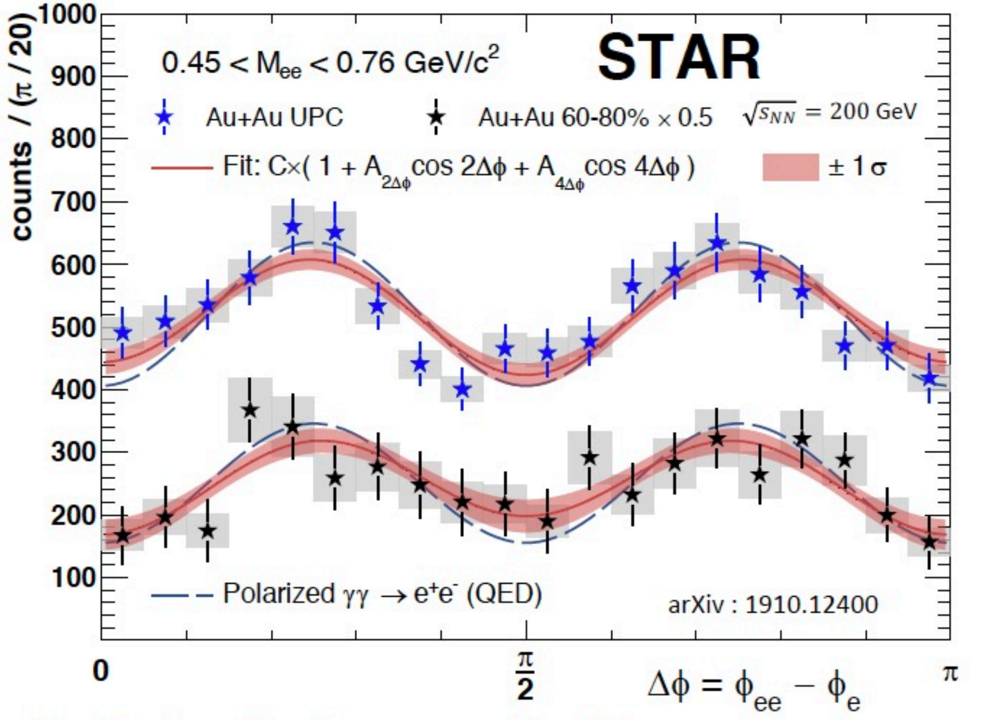
$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)] \approx \Delta\phi[(e^+ + e^-), e^+]$$

Ultra-Peripheral

Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	16.8 ± 2.5	16	18.8 / 16

Peripheral (60–80%)

Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	27 ± 6	34	10.2 / 17



→ **First Earth-based observation (6.7σ level) of vacuum birefringence**

11/05/19 Daniel Brandenburg 13

- **Necessary for observed cos(2phi) in rho photoproduction**

2.2 Dileptons as a probe in heavy ion collisions:

The comprehensive understanding of pure electromagnetic lepton pair production is not only important for probing extreme electromagnetic fields, but also interesting for studying the EM properties of QGP. For example, the significant pair transverse momentum $q_\perp$ broadening effect at different impact parameters found by the STAR[49,50], ATLAS[54] and CMS[52] collaborations has triggered quite an amount of theoretical efforts aimed at understanding if this effect results from the initial QED field strength, or is caused by the final state medium effect. The detailed comparison between theory/model calculations and experimental data appears to be in favor of the initial state effect[46,47,56,67,68], though there is some room left for the final state effect, such as the trapped magnetic field[69] and multiple EM scattering in QGP. Since such an impact-parameter sensitive observable is implicitly dependent on the photon Wigner distribution, it can serve as a clean testing ground for developing the QCD factorization formalism in terms of quark and gluon Wigner functions, which play a central role in exploring the 3D structure of nucleons/nuclei in the forthcoming EIC era. Another interesting development along this line is the prediction of a sizable v_4 anisotropic distribution with respect to the reaction plane [70] in lepton pair production in non-central heavy ion collisions. This EM v_4 anisotropy is purely generated by the initial EM field configuration, while the EM v_2 anisotropy is absent. This unique prediction, if confirmed from the experiments, shall provide a crucial handle on the production mechanism for dileptons in two photon processes in non-UPC collisions.

50. STAR Collaboration, J., Adam *et al.* Probing Extreme Electromagnetic Fields with the Breit-Wheeler Process. (2019). https://arxiv.org/abs/1910.12400.

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67. Zha, W., Ruan, L., Tang, Z., Xu, Z. & Yang, S. Coherent lepton pair production in hadronic heavy ion collisions. *Phys. Lett. B* **781**, 182–186, DOI: https://doi.org/10.1016/j.physletb.2018.04.006 (2018). https://arxiv.org/abs/1804.01813.

68. Zha, W., Brandenburg, J. D., Tang, Z. & Xu, Z. Initial transverse-momentum broadening of Breit-Wheeler process in relativistic heavy-ion collisions. *Phys. Lett. B* **800**, 135089, DOI: https://doi.org/10.1016/j.physletb.2019.135089 (2020). https://arxiv.org/abs/1812.02820.

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PRL 119, 250403 (2017) PHYSICAL REVIEW LETTERS week ending 22 DECEMBER 2017

High-Energy Vacuum Birefringence and Dichroism in an Ultrastrong Laser Field

Sergey Bragin, Sebastian Meuren,* Christoph H. Keitel, and Antonino Di Piazza
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany
(Received 6 July 2017; published 21 December 2017)

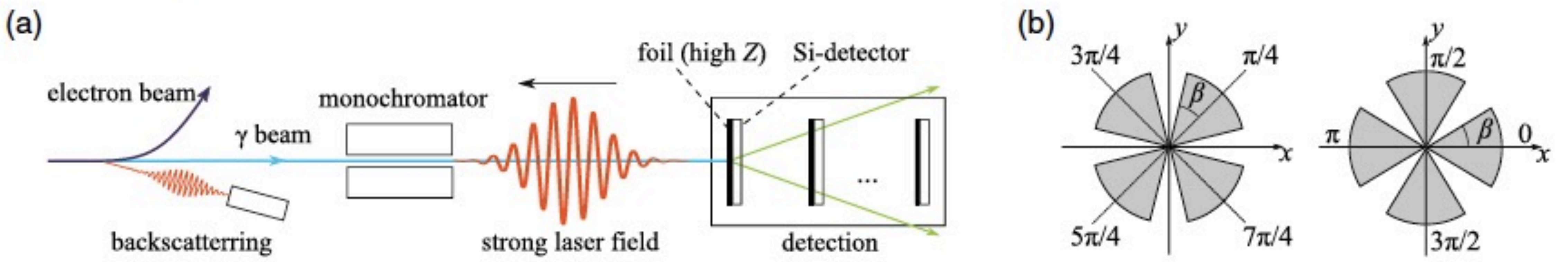


FIG. 3. (a) Experimental setup. Polarized highly energetic gamma photons (produced via Compton backscattering) propagate through a strong laser field, which induces vacuum birefringence and dichroism. Afterward, the gamma photons are converted into electron-positron pairs. From their azimuthal distribution, the polarization state is deduced. (b) Regions of the transverse plane (gray), which are used to define the observables R_B (left) and R_D (right) [see Eq. (13)].

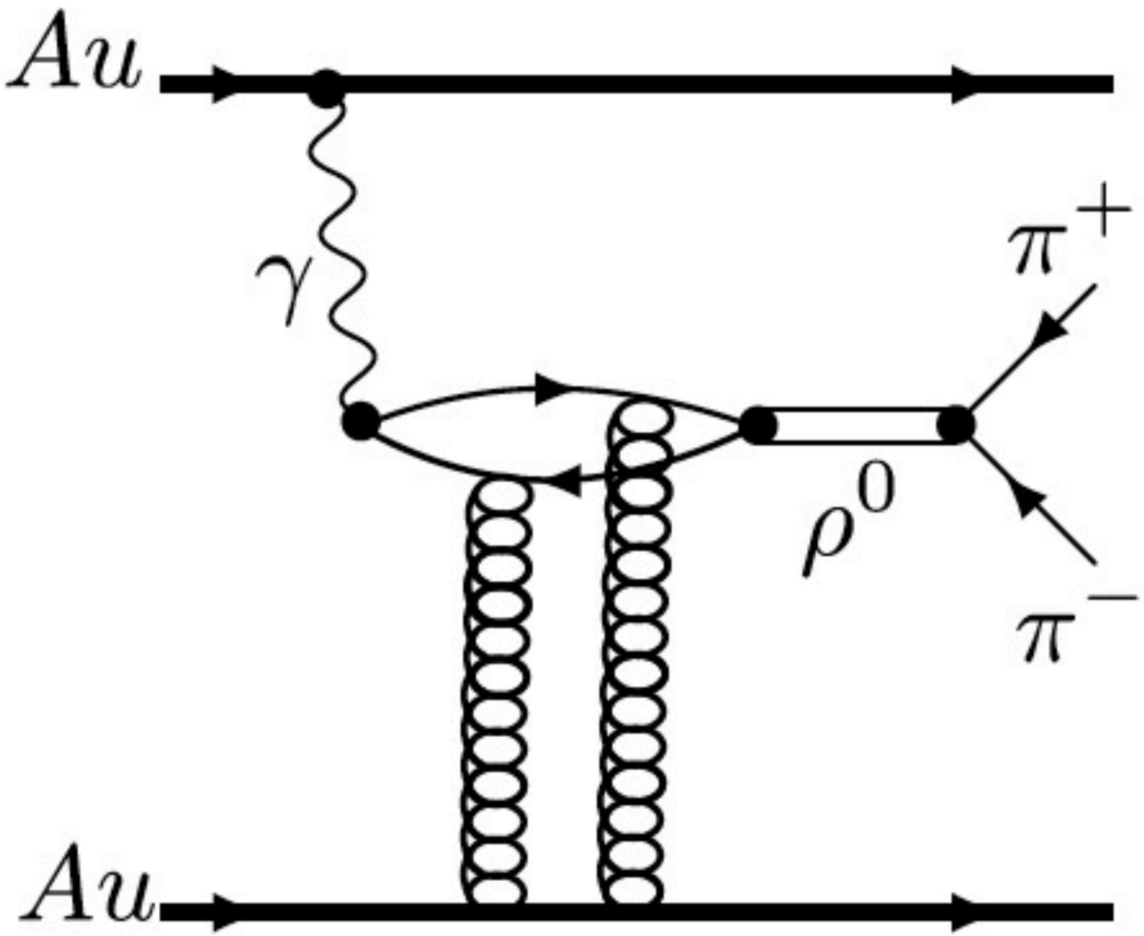
Will we be able to actually do something similar at LHC,RHIC and EIC at forward rapidity?

Linearly polarized photon-gluon collisions: diffractive photoproduction of ρ vector

Employ the same observable for $\rho^0 \to \pi^+\pi^-$ (and direct $\pi^+\pi^-$)

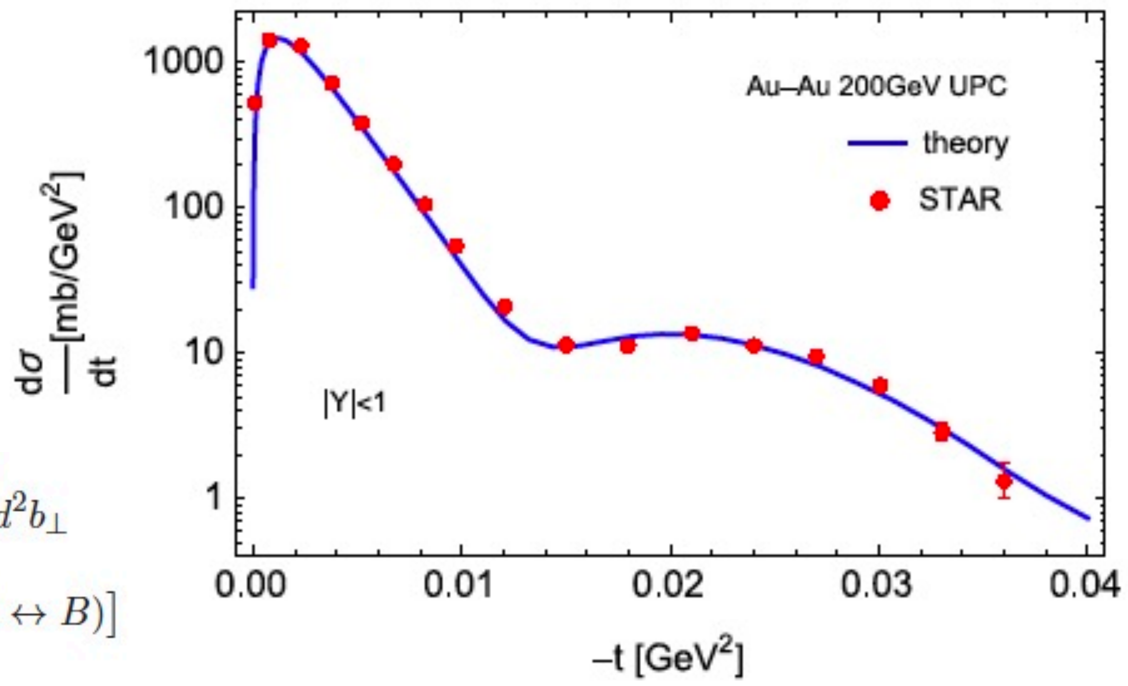
- **Use the <u>polarized</u> γ as a probe of the nucleus**
- Calculate coefficients $\langle \cos(n\Delta\phi) \rangle$

$$\Delta\phi = \Delta\phi[(\pi^+ + \pi^-), (\pi^+ - \pi^-)]$$



What new and necessary for quantitative Imaging?

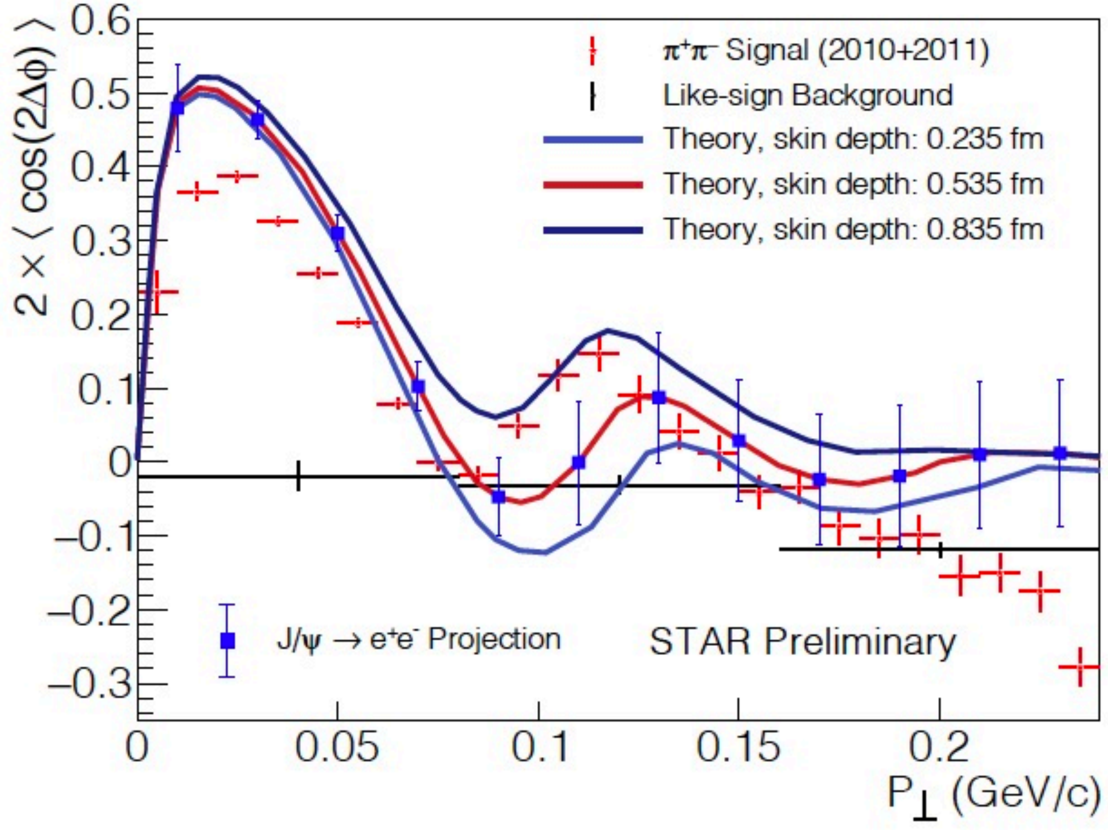
- Gluon Shadowing/saturation
- Transverse Momentum Distribution (TMD)
- Photons and Gluons are linearly polarized
- Interference

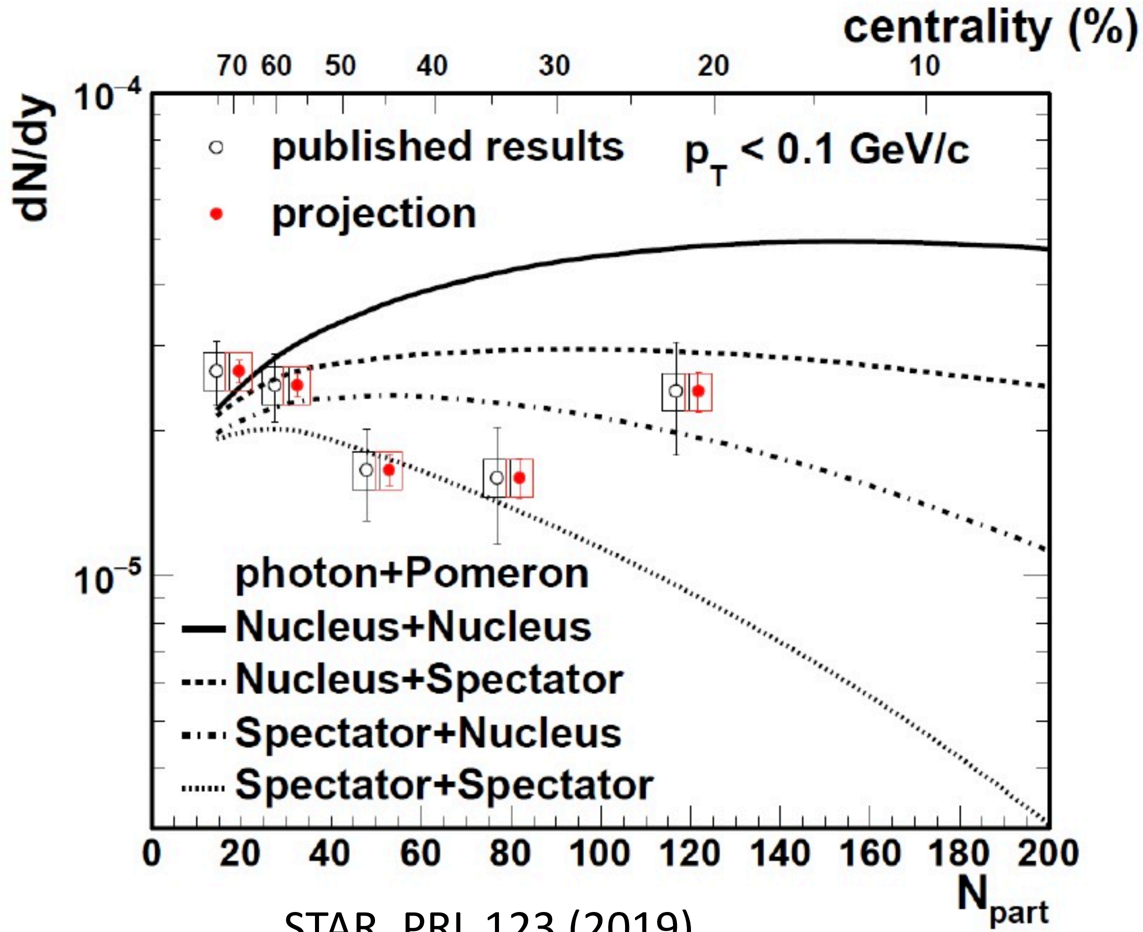


$$
\begin{aligned}
\frac{d\sigma}{d^2q_\perp dY\, d^2\tilde{b}_\perp} =& \frac{1}{(2\pi)^4}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp+\Delta_\perp-q_\perp)(\epsilon_\perp^{V*}\cdot\hat{k}_\perp)(\epsilon_\perp^{V}\cdot\hat{k}'_\perp)\Big\{\int d^2b_\perp \\
&\times e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\left[T_A(b_\perp)\mathcal{A}_{in}(Y,\Delta_\perp)\mathcal{A}^*_{in}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp)+(A\leftrightarrow B)\right] \\
&+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right] \\
&+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-\Delta_\perp)}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right] \\
&+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right] \\
&+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp-\Delta_\perp)}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right]\Big\}, \qquad (2.14)
\end{aligned}
$$

Xing, et al., JHEP, arXiv: 2006.06206

Photonuclear J/ψ with QGP





What is coherent?
Why diffractive process exist in violent A+A collisions?
Do quantum interference and EPR exist in this circumstance?
Do photonuclear J/Ψ experience QGP color screening?

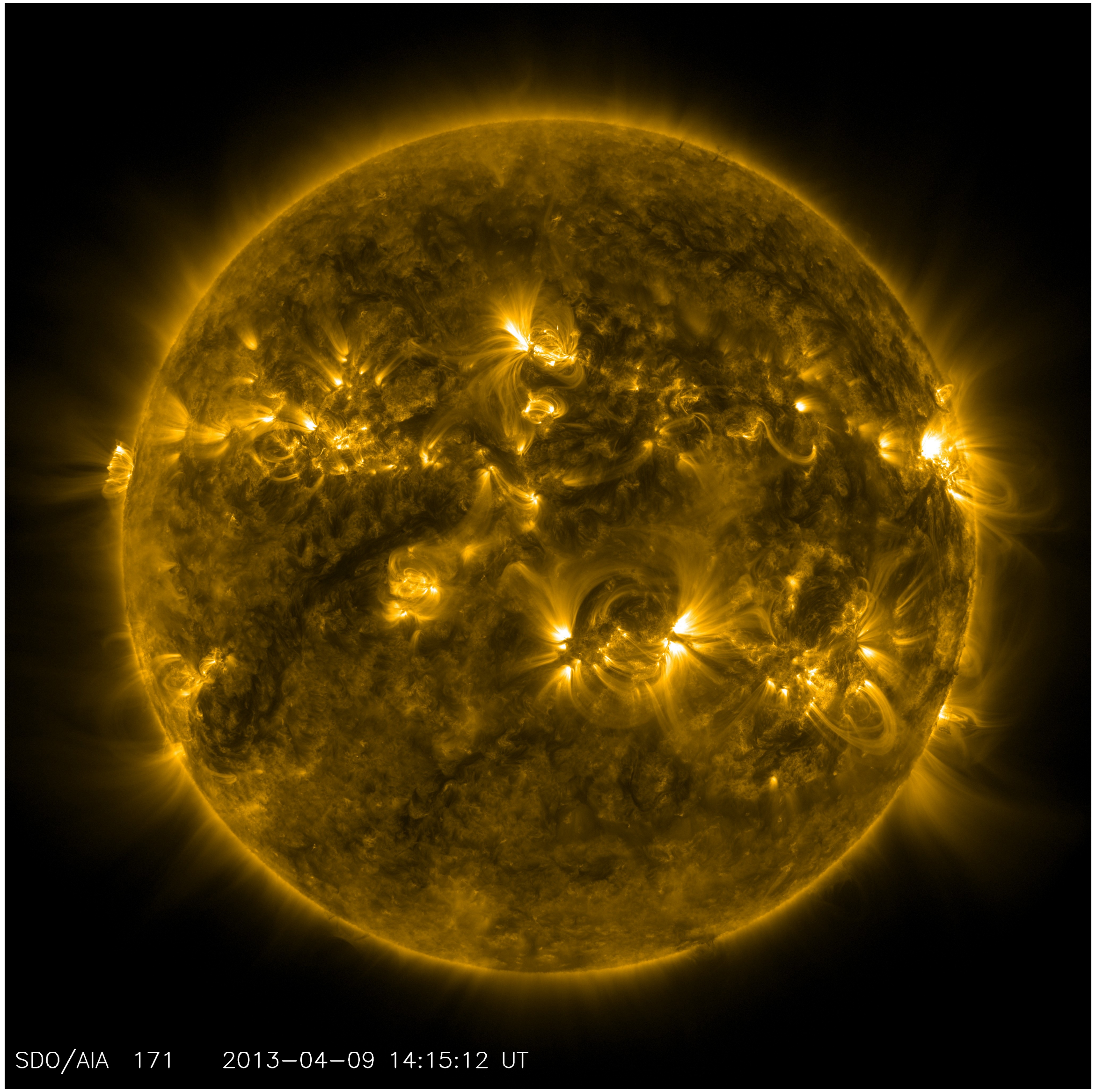
STAR, PRL 123 (2019)
STAR BUR 2023-25

ALICE: PRL 116 (2016) pioneered the work on J/ψ

Best example of magnetohydrodynamics: SUN

Magnetohydrodynamics (**MHD**) is the study of the magnetic properties and behavior of electrically conducting fluids. Examples of such magnetofluids include plasmas, liquid metals, salt water, and electrolytes. The word "magneto-hydrodynamics" is derived from *magneto-* meaning magnetic field, *hydro-*meaning water, and *dynamics* meaning movement. The field of MHD was initiated by Hannes Alfv, for which he received the Nobel Prize in Physics in 1970. The fundamental concept behind MHD is that magnetic fields can induce currents in a moving conductive fluid, which in turn polarizes the fluid and reciprocally changes the magnetic field itself. The set of equations that describe MHD are a combination of the Navier–Stokes equations of fluid dynamics and Maxwell's equations of electromagnetism. These differential equations must be solved simultaneously, either analytically or numerically.

Wikipedia



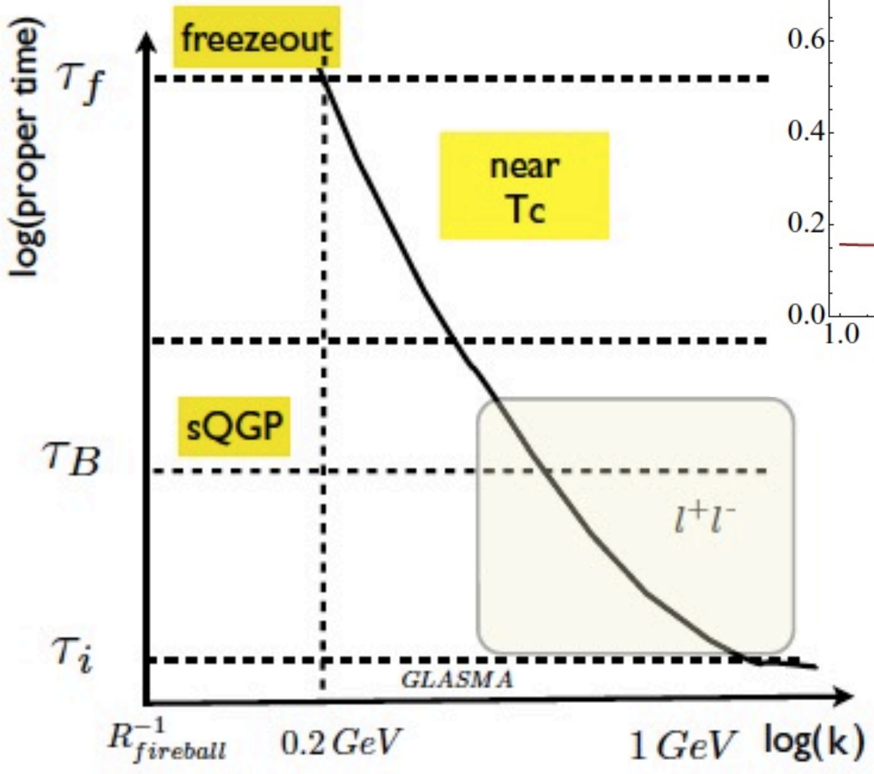
This image taken by the Solar Dynamics Observatory's Atmospheric Imaging Assembly (AIA) instrument at 171 Angstrom shows the current conditions of the quiet corona and upper transition region of the Sun.

Image Credit: NASA/SDO
Last Updated: Aug. 7, 2017
Editor: NASA Content Administrator

Radical Ideas, crazy experiments?

Magneto-(sono)thermoluminescence (∝ B*V)

BAŞAR, KHARZEEV, AND SHURYAK



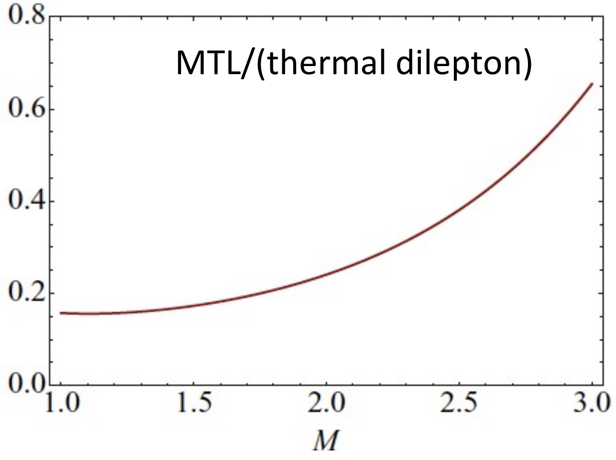
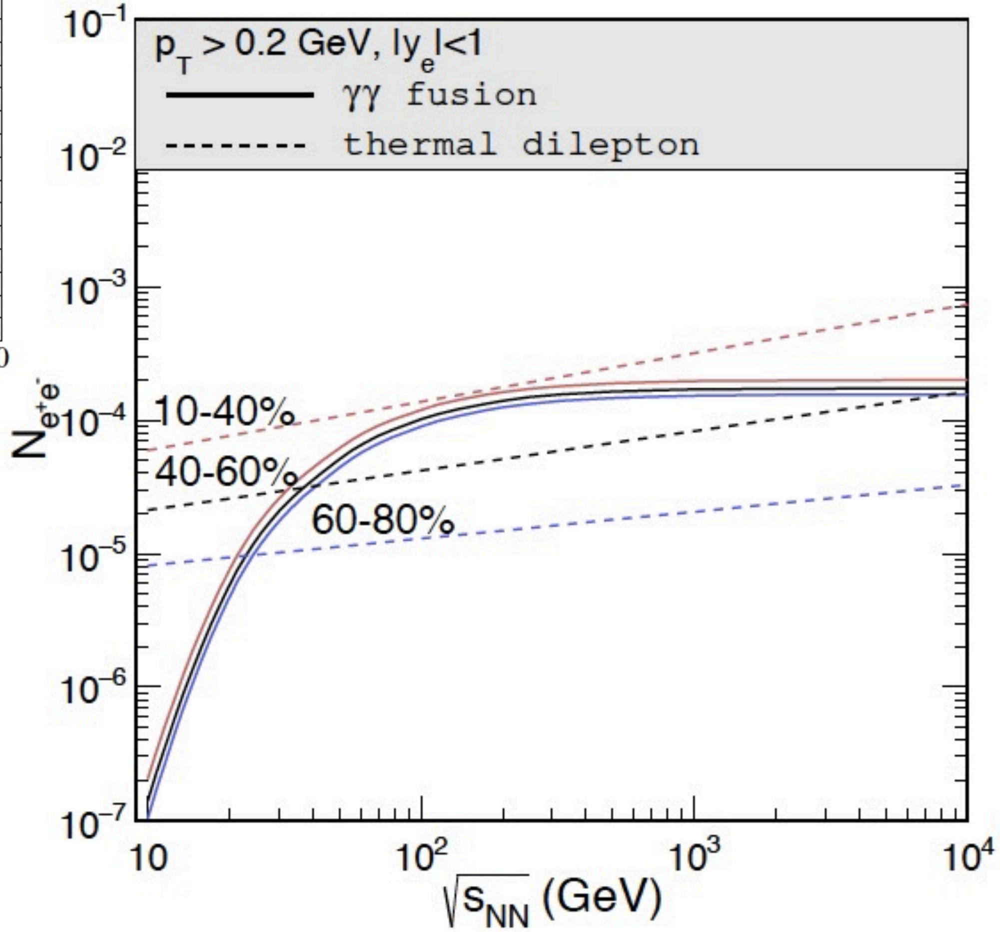


FIG. 5. (Color online) Schematic map of sounds, on a log-log plane of proper time versus the transverse momentum. For a description, see the text.

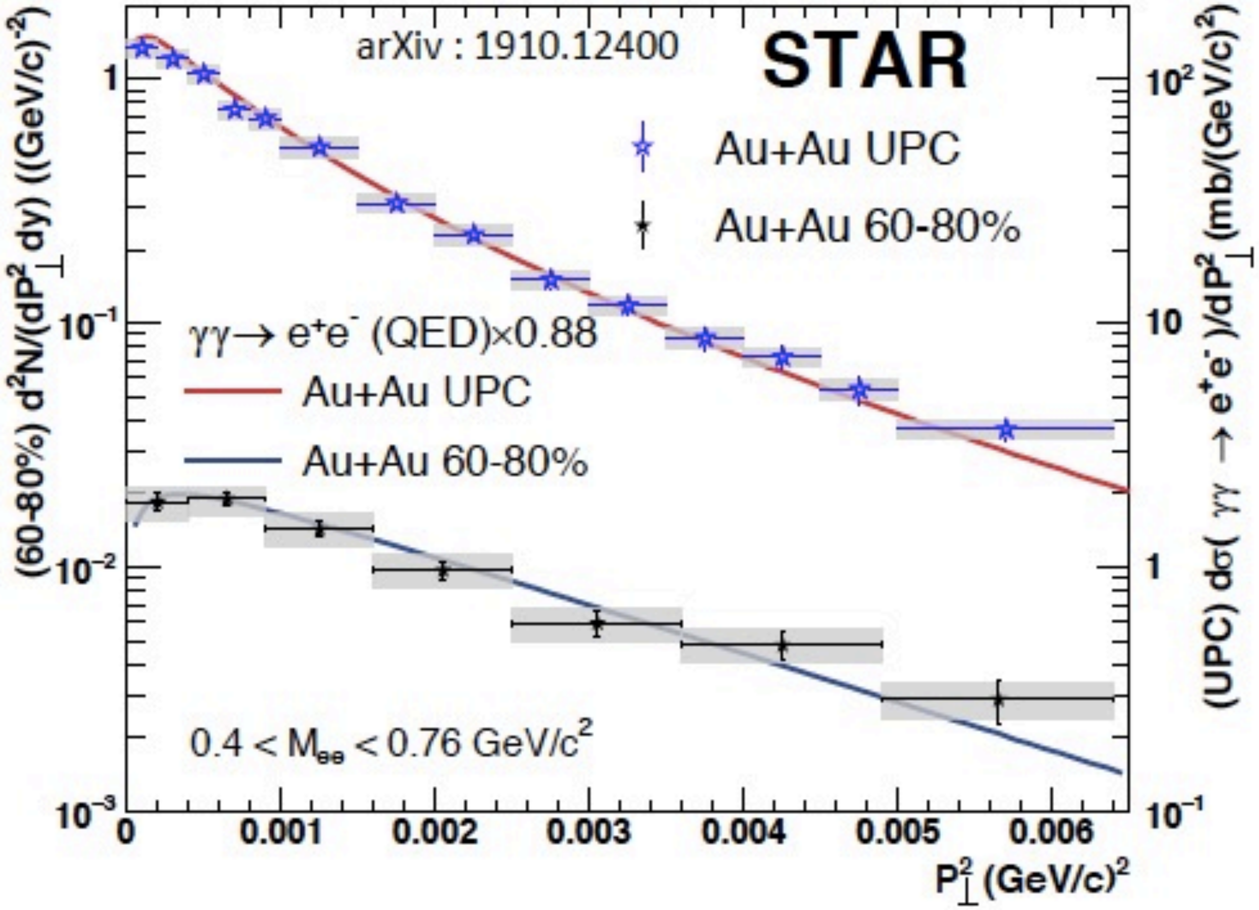
arXiv:1809.07049

Klusek-Gawenda, Rapp, Schaefer, Szczurek



$\gamma\gamma \to e^+e^-$: UPC vs. Peripheral

[1] STAR, Phys. Rev. Lett. 121 (2018) 132301
[2] S. R. Klein, et. al, Phys. Rev. Lett. 122, (2019), 132301
[3] ATLAS Phys. Rev. Lett. 121 (2018) , 212301



Characterize difference in spectra via $\sqrt{\langle P_\perp^2 \rangle}$

$\sqrt{\langle P_\perp^2 \rangle}$ (MeV/c)	UPC Au+Au	60-80% Au+Au
Measured	38.1 ± 0.9	50.9 ± 2.5
QED	37.6	48.5
b range (fm)	≈ 20	$\approx 11.5 - 13.5$

- Leading order QED calculation of $\gamma\gamma \to e^+e^-$ describes both spectra ($\pm 1\sigma$)
- Best fit for spectra in 60-80% collisions found for QED shape plus 14 ± 4 (stat.)± 4 (syst.) MeV/c broadening
- Proposed as a probe of trapped magnetic field or Coulomb scattering in QGP [1-3]

STAR observes 4.8σ difference between UPC and 60-80% Au+Au collisions

J.D. Brandenburg, et al, arXiv:2103.16623

Are there final-state QED effects?

Precision data with
QED theory comparisons:
Both on-going at LHC and RHIC

How about azimuthal anisotropy
relative to reaction plane?

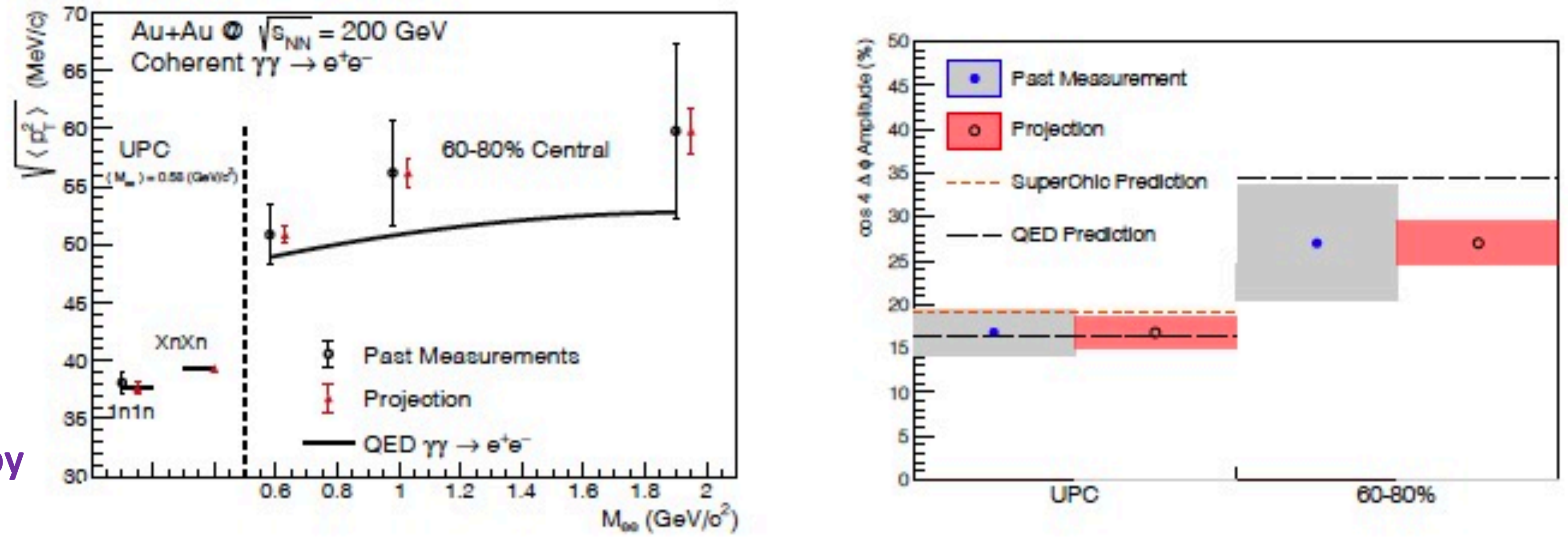


Figure 57: (Color online) Projections for measurements of the $\gamma\gamma \to e^+e^-$ process in peripheral and ultra-peripheral collisions. Left: The $\sqrt{\langle p_T^2 \rangle}$ of di-electron pairs within the fiducial acceptance as a function of pair mass, M_{ee}, for 60 – 80% central and ultra-peripheral Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Right: The projection of the $\cos 4\Delta\phi$ measurement for both peripheral (60 – 80%) and ultra-peripheral collisions.

STAR Beam Use Request (2023-2025):

https://drupal.star.bnl.gov/STAR/system/files/BUR2020_final.pdf

p_T broadening and azimuthal correlations of e^+e^- pairs sensitive to electro-magnetic (EM) field;
Impact parameter dependence of transverse momentum distribution of EM production is the key component to describe data.

Is there a sensitivity to final magnetic field in QGP?

Precise measurement of p_T broadening and angular correlation will tell at >3σ for each observable.

Conclusions

- Low-momentum J/Psi show large suppression over entire RHIC energies, future flow vn measurements would determine contributions from coalescence of charm quarks in QGP
- Dieletron LMR shows rho in-medium effect consistent with broadening model, and its Boltzmann phase-space factor is consistent with temperature at phase transition (no blue shift effect)
- New exciting opportunity of extracting temperature from IMR at RHIC
- Electromagnetic probes of new emerging phenomena in high-energy nuclear collisions. Coupling of strong QED and QCD fields are very interesting and exciting frontiers
- Just to name a few of QED/QCD:
  chiral symmetry restoration, chiral magnetic effect, Magnetohydrodynamics, Breit-Wheeler process, Vacuum Birefringence, spin interference and EPR
- RHIC is still very much in understanding and discovering these new phenomena

Measurement of e+e− Momentum and Angular Distributions fr... arized

Overview of attention for article published in Physical Review Letters, July 2021

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成大高能核物理實驗室 參與愛因斯坦著名公式驗證

PC Home, 08 Sep 2021

【大成報/記者于郁金/臺南報導】國立成功大學高能核物理實驗室參與位在美國布魯克海文國... ory，BNL)STAR 首次驗證從純能量(光子)產生正反物質對，這就是愛因斯坦最著名的質能互換公式：E...

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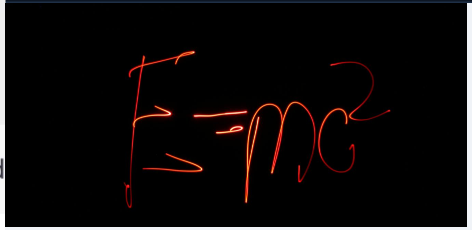
Equação de Einstein usada, pela primeira vez, para criar matéri...

ZAP, 20 Aug 2021

(dr) Brookhaven National Laboratory Detector STAR Com base numa das equações mai... a de físic...

Matter Has Been Created From Light For The First Time – Provin... gain

Wonderful Engineering, 18 Aug 2021



THE VANGUARD

The 5 Coolest Things On Earth This Week

Rebecca M. Oliver

August 24, 2021

Echoing Albert Einstein, scientists are creating matter from energy, building bridges from carbon and making vaccines from plants. This week's coolest things turn over a whole new leaf.

Let There Be Matter

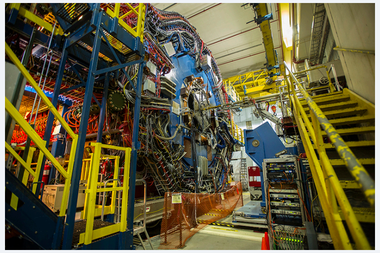


Image credit: Brookhaven National Laboratory. Top image credit: Getty Images.

What is it? Scientists at Brookhaven National Laboratory (BNL) demonstrated for the first time that pure light energy can produce matter and antimatter.

https://www.g... th-this-week-80