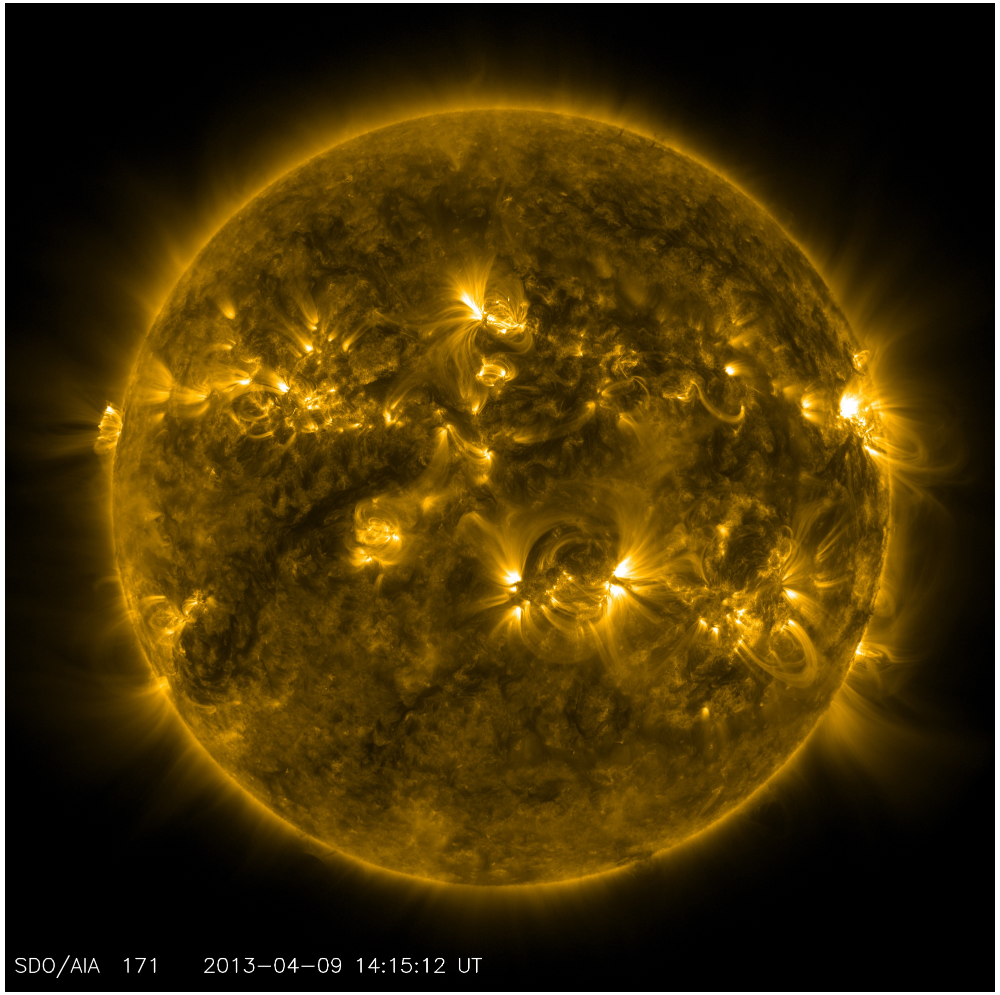
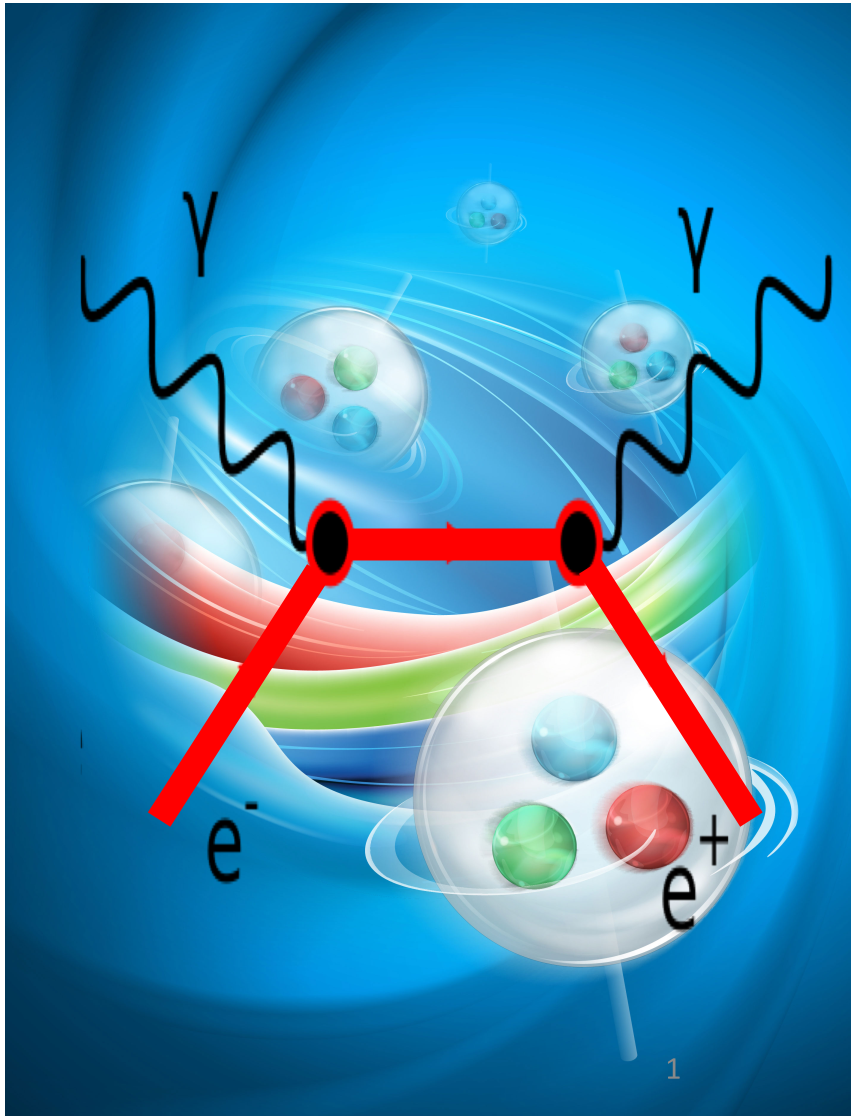
Probe strong magnetic field in QGP with dielectrons from photon-photon collisions



Zhangbu Xu

arXiv:1806.02295 **PRL**
arXiv:1804.01813 **PLB**
arXiv:1705.01460 **PRC**



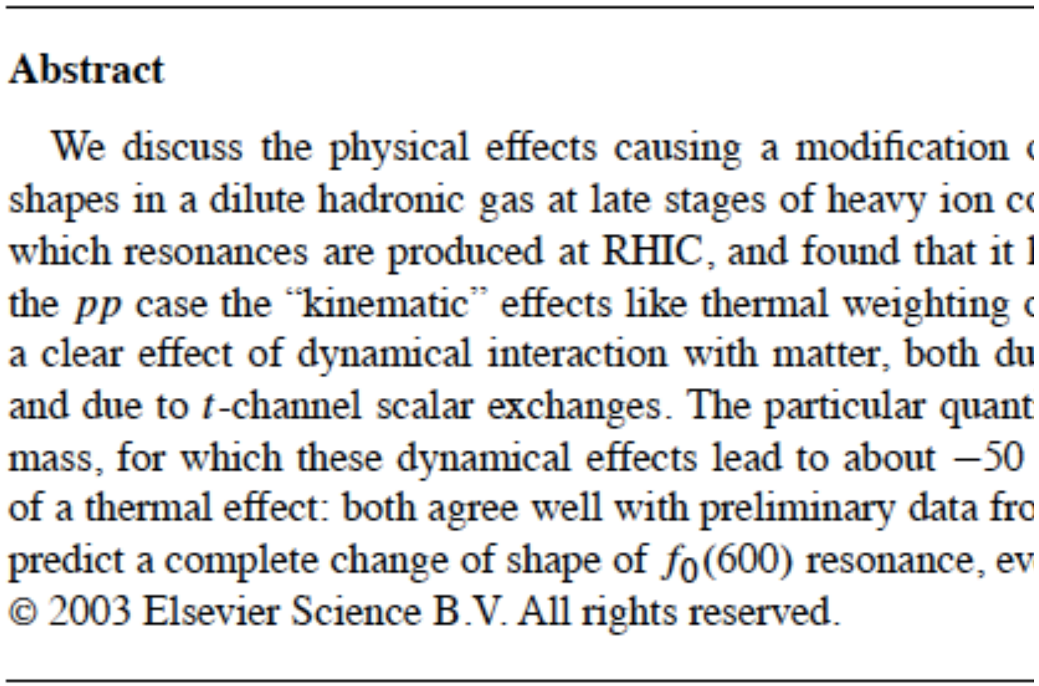
Matter-induced modification of resonances at RHIC freezeout

E.V. Shuryak *, G.E. Brown

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

Received 7 January 2003; accepted 24 January 2003

First Interaction, Final-stage effect



Abstract

We discuss the physical effects causing a modification
shapes in a dilute hadronic gas at late stages of heavy ion c
which resonances are produced at RHIC, and found that it
the *pp* case the "kinematic" effects like thermal weighting
a clear effect of dynamical interaction with matter, both du
and due to *t*-channel scalar exchanges. The particular quant
mass, for which these dynamical effects lead to about −50
of a thermal effect: both agree well with preliminary data fro
predict a complete change of shape of $f_0(600)$ resonance, ev

E.V. Shuryak, G.E. Brown / Nuclear Physics A 717 (2003) 322–335 323

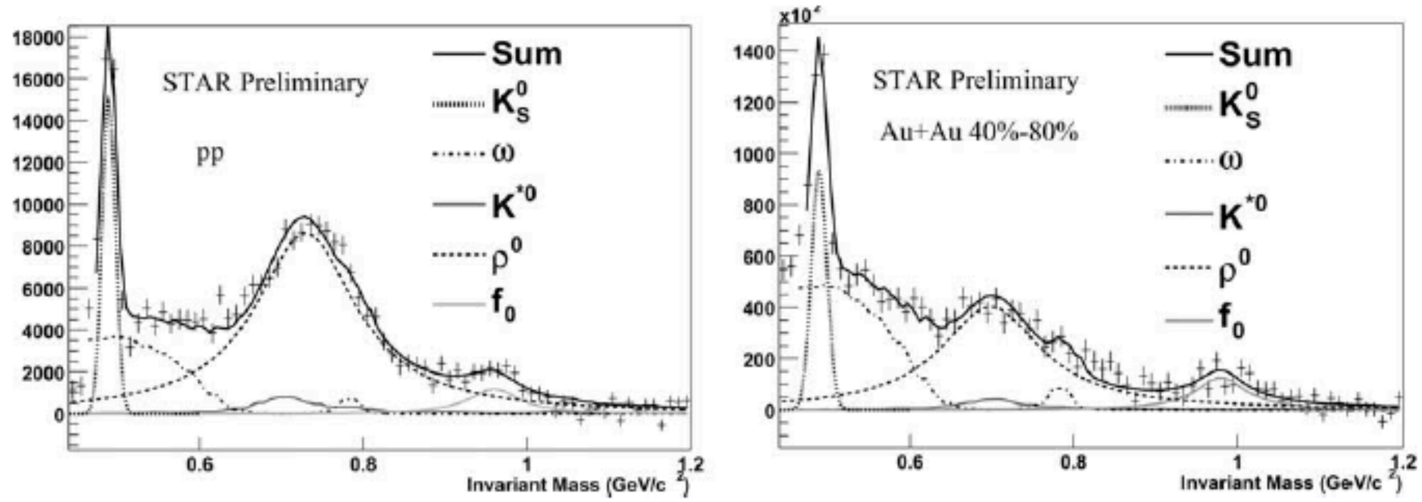
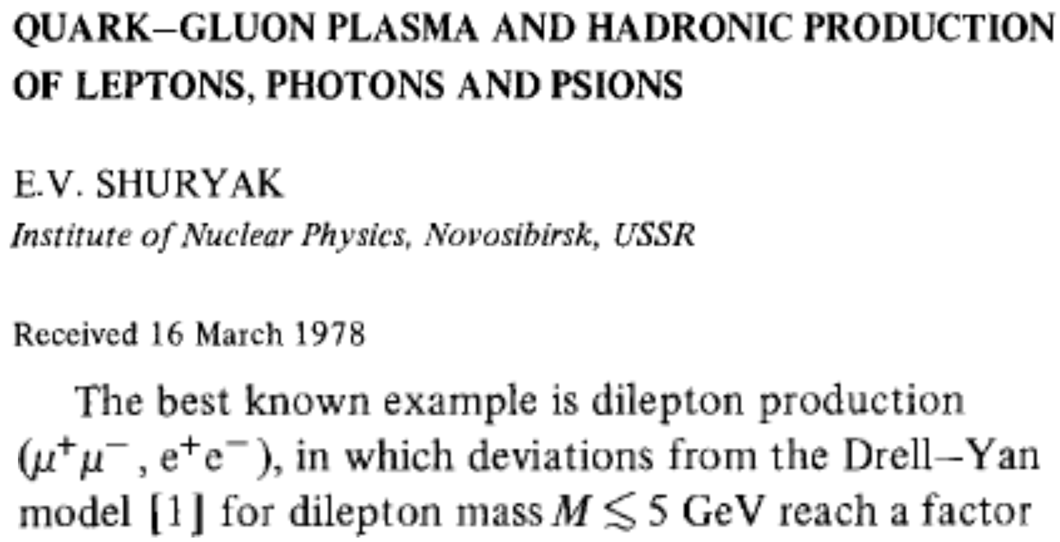


Fig. 1. The invariant mass distributions in *pp* and mid-central AuAu of the $\pi^+\pi^-$ system, with a transverse momentum cut $0.2 < p_t < 0.9$ GeV. The lines indicate contribution of particular resonances according to some model we do not discuss in this work.

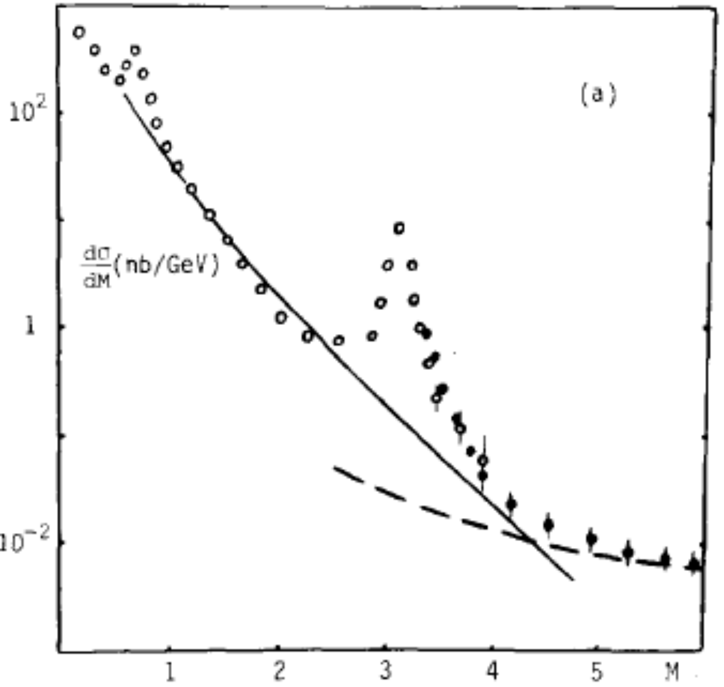


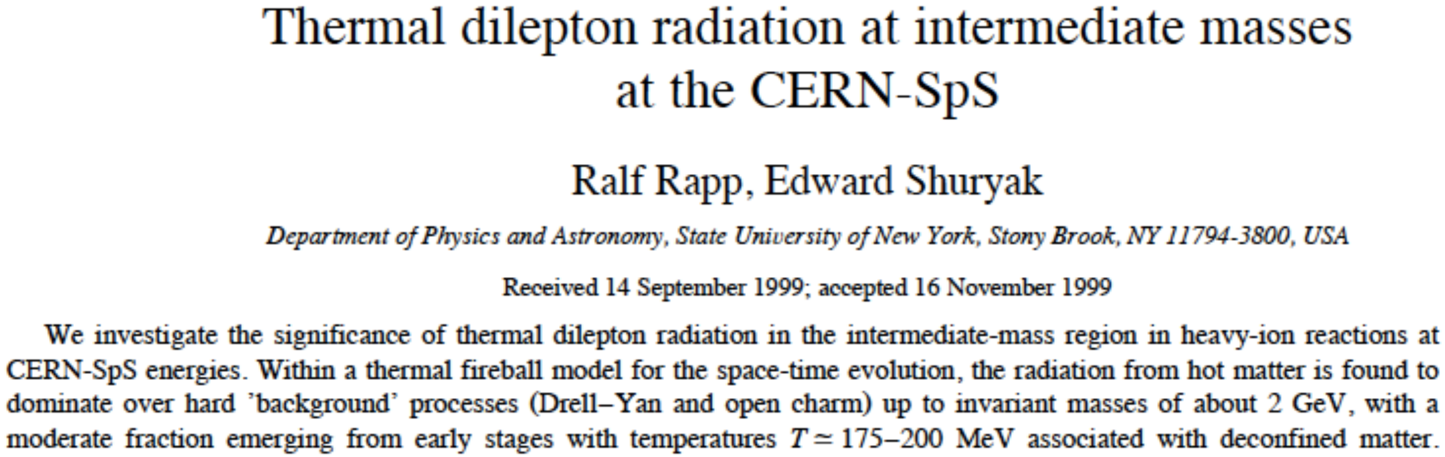
QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS

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





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

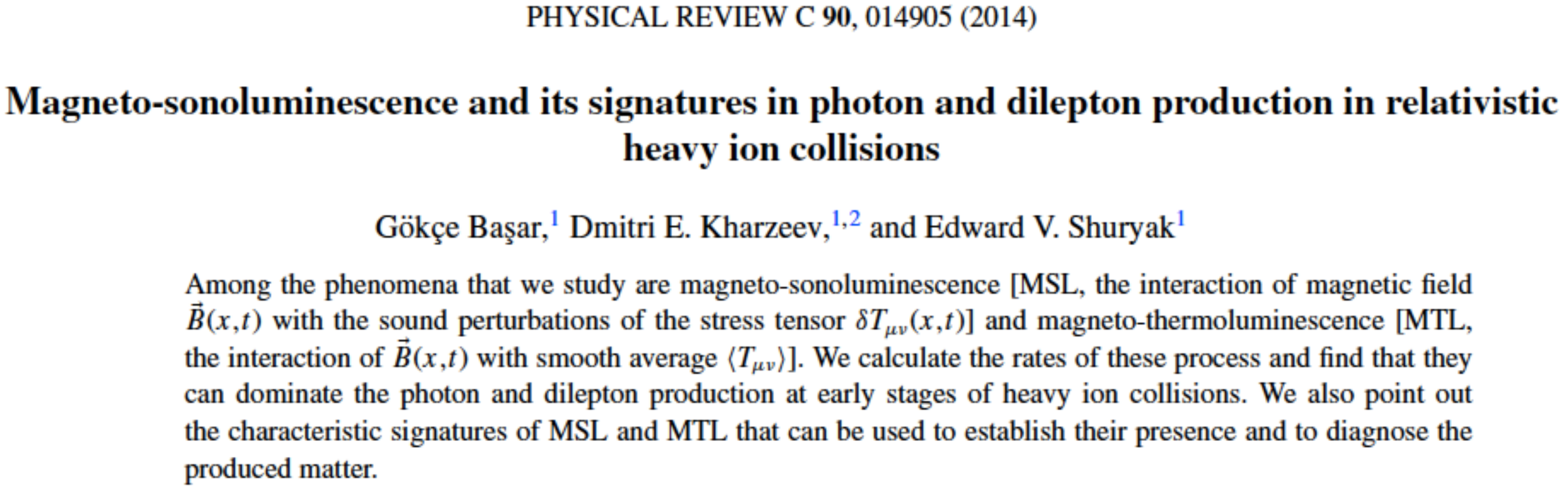
Received 14 September 1999; accepted 16 November 1999

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)

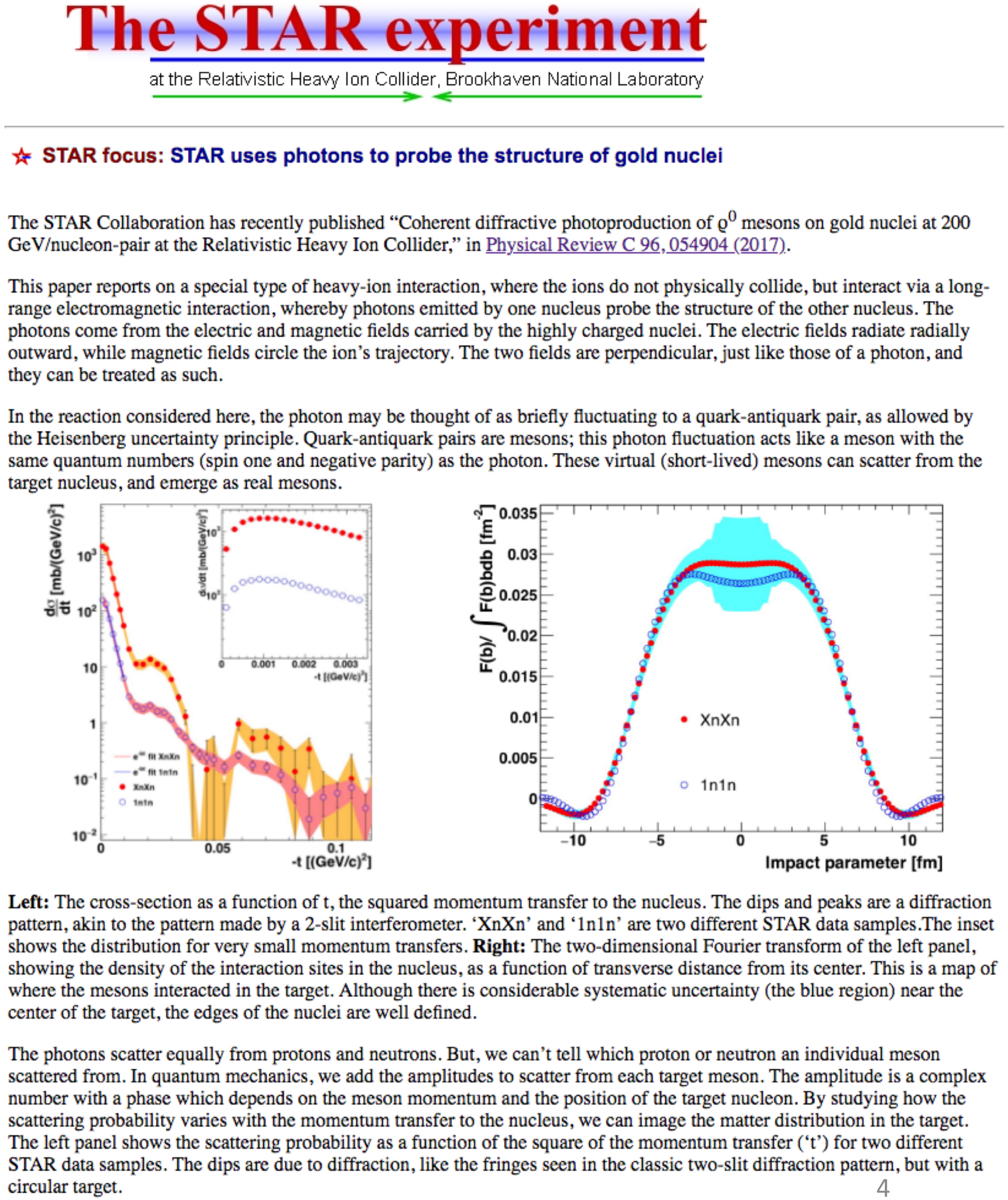
Magneto-sonoluminescence and its signatures in photon and dilepton production in relativistic heavy ion collisions

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.

Outline

- From Ultra-peripheral to hadronic peripheral collisions
- Magnetic field in QGP
- How STAR measures e^+e^- from photon-photon collisions?
- Results and Interpretations
- Conductivity of QCD magnetohydrodynamics
- Future Perspectives



The STAR experiment

at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory

★ **STAR focus: STAR uses photons to probe the structure of gold nuclei**

The STAR Collaboration has recently published "Coherent diffractive photoproduction of ρ^0 mesons on gold nuclei at 200 GeV/nucleon-pair at the Relativistic Heavy Ion Collider," in Physical Review C 96, 054904 (2017).

This paper reports on a special type of heavy-ion interaction, where the ions do not physically collide, but interact via a long-range electromagnetic interaction, whereby photons emitted by one nucleus probe the structure of the other nucleus. The photons come from the electric and magnetic fields carried by the highly charged nuclei. The electric fields radiate radially outward, while magnetic fields circle the ion's trajectory. The two fields are perpendicular, just like those of a photon, and they can be treated as such.

In the reaction considered here, the photon may be thought of as briefly fluctuating to a quark-antiquark pair, as allowed by the Heisenberg uncertainty principle. Quark-antiquark pairs are mesons; this photon fluctuation acts like a meson with the same quantum numbers (spin one and negative parity) as the photon. These virtual (short-lived) mesons can scatter from the target nucleus, and emerge as real mesons.

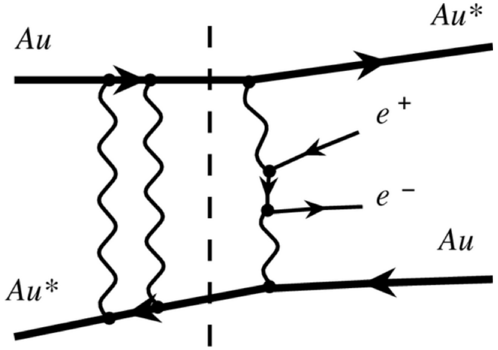
Left: The cross-section as a function of t, the squared momentum transfer to the nucleus. The dips and peaks are a diffraction pattern, akin to the pattern made by a 2-slit interferometer. 'XnXn' and '1n1n' are two different STAR data samples.The inset shows the distribution for very small momentum transfers. **Right:** The two-dimensional Fourier transform of the left panel, showing the density of the interaction sites in the nucleus, as a function of transverse distance from its center. This is a map of where the mesons interacted in the target. Although there is considerable systematic uncertainty (the blue region) near the center of the target, the edges of the nuclei are well defined.

The photons scatter equally from protons and neutrons. But, we can't tell which proton or neutron an individual meson scattered from. In quantum mechanics, we add the amplitudes to scatter from each target meson. The amplitude is a complex number with a phase which depends on the meson momentum and the position of the target nucleon. By studying how the scattering probability varies with the momentum transfer to the nucleus, we can image the matter distribution in the target. The left panel shows the scattering probability as a function of the square of the momentum transfer ('t') for two different STAR data samples. The dips are due to diffraction, like the fringes seen in the classic two-slit diffraction pattern, but with a circular target.

STAR has a long history of using photons from Ultra-peripheral collisions at RHIC

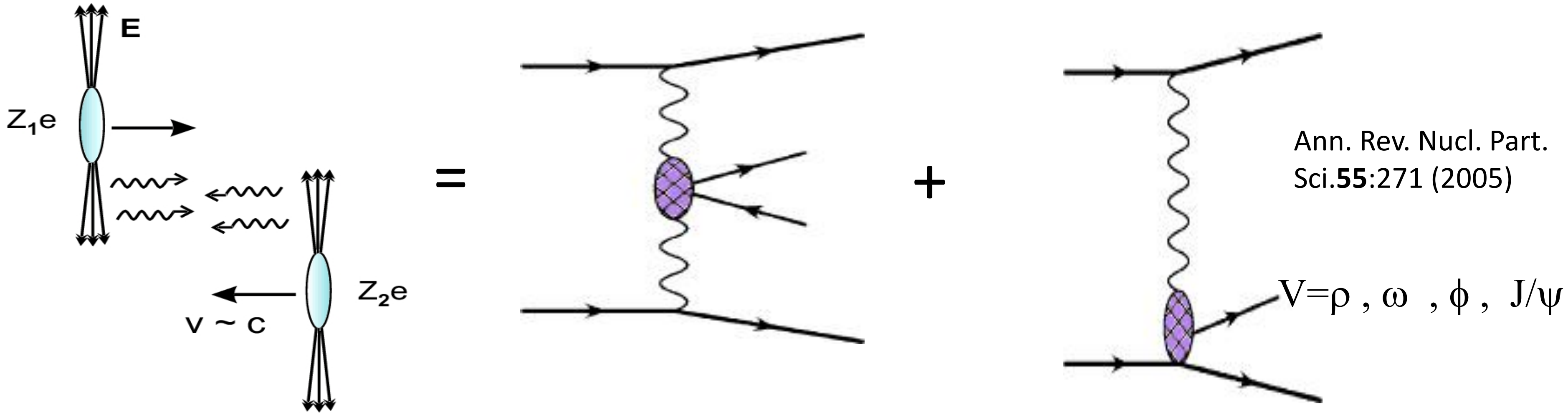
Photon-Pameron Interaction (vector-meson dominant)

- **Coherent diffractive photoproduction of rho0 mesons on gold nuclei at 200 GeV/nucleon-pair at the Relativistic Heavy Ion Collider**
  Phys. Rev. C **96** (2017) 54904
  e-Print Archives (1702.07705)
- **rho^{0} Photoproduction in AuAu Collisions at $\sqrt{s_{NN}}$=62.4 GeV with STAR**
  Phys. Rev. C **85** (2012) 14910
  e-Print Archives (arXiv:1107.4630)
- **Observation of pi^+pi^-pi^+pi^- photoproduction in ultraperipheral heavy-ion collisions at sqrt(s_NN) = 200 GeV at the STAR detector**
  Phys. Rev. C **81** (2010) 44901
  e-Print Archives (0912.0604)
- **Observation of Two-source Interference in the Photoproduction Reaction $Au Au \rightarrow Au Au \rho^0$**
  Phys. Rev. Lett. **102** (2009) 112301
  e-Print Archives (0812.1063)
- **ρ^0 Photoproduction in Ultra-Peripheral Relativistic Heavy Ion Collisions with STAR**
  Phys. Rev. C **77** (2008) 34910
  e-Print Archives (0712.3320)
- **Coherent Rho-zero Production in Ultra-Peripheral Heavy Ion Collisions**
  Phys. Rev. Lett. **89** (2002) 272302
  e-Print Archives (nucl-ex/0206004)
- **Production of e+e- Pairs Accompanied by Nuclear Dissociation in Ultra-Peripheral Heavy Ion Collision**
  Phys. Rev. C **70** (2004) 031902(R)
  e-Print Archives (nucl-ex/0404012)



photon-photon collisions

Photon interactions in A+A



Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

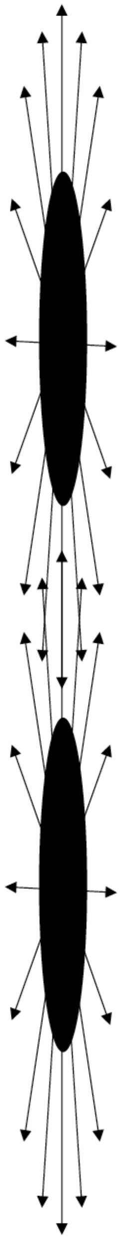
Electromagnetic interaction

Photon-photon interactions

Photon-nucleus interactions

- This large flux of quasi-real photons makes a hadron collider also a photon collider!
  - ✓ Photon-nucleus interactions: Vector meson
  - ✓ Photon-photon interactions: dileptons …
- Conventionally believed to be only exist in ultra-peripheral collisions (UPC) to keep “coherent”!

Ultra-peripheral vs Peripheral collisions

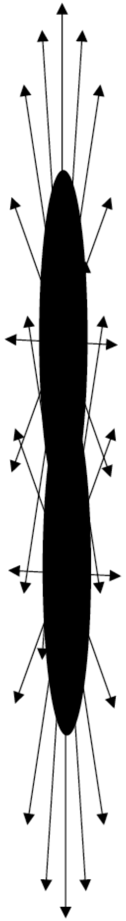


The process can be factorized into two parts:
A semi-classical part: the photon flux induced by the heavy ions
A quantum part: the description of the interaction of the two photons

$$\sigma(A + A \rightarrow A + A + X) = \int dk_1 dk_2 \frac{n(k_1)}{k_1} \frac{n(k_2)}{k_2} \sigma[\gamma\gamma \rightarrow X(W)]$$

The determination of photon flux: equivalent photon approximation
The cross section for continuum lepton pairs: the Breit – Wheeler formula

$$\sigma_{\gamma\gamma} = \frac{4\pi\alpha^2}{W^2}\left[\left(2 + \frac{8M^2}{W^2} - \frac{16M^4}{W^4}\right)\ln\frac{W + \sqrt{W^2 - 4M^2}}{2M} - \sqrt{1 - \frac{4M^2}{W^2}}\left(1 + \frac{4M^2}{W^2}\right)\right]$$



Transverse momentum spectra in UPC

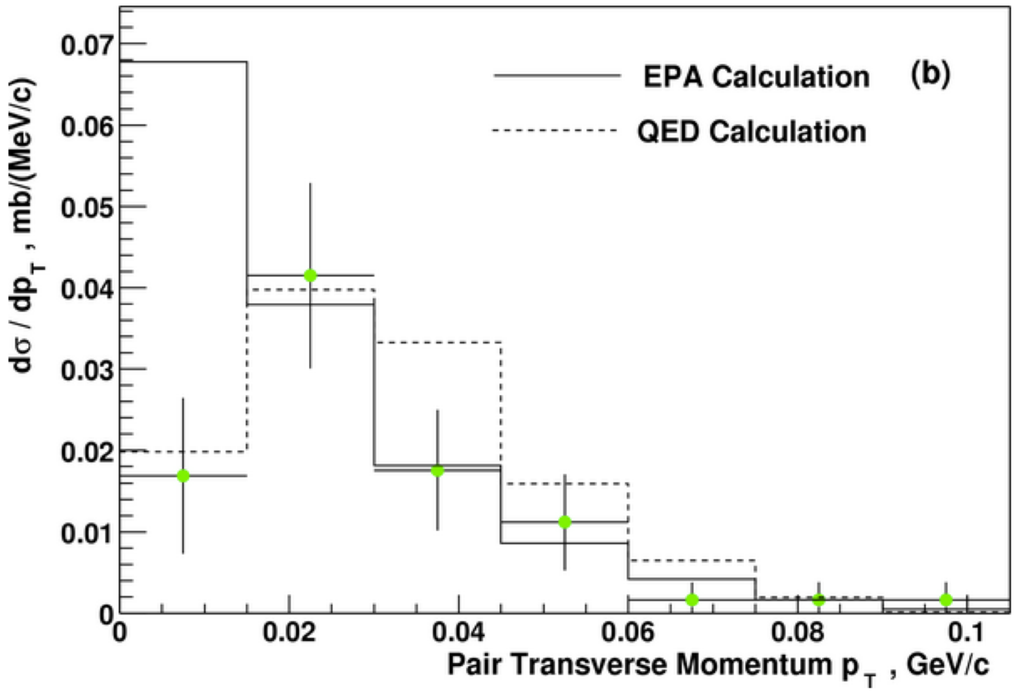
The photon k_T spectrum for fixed k:

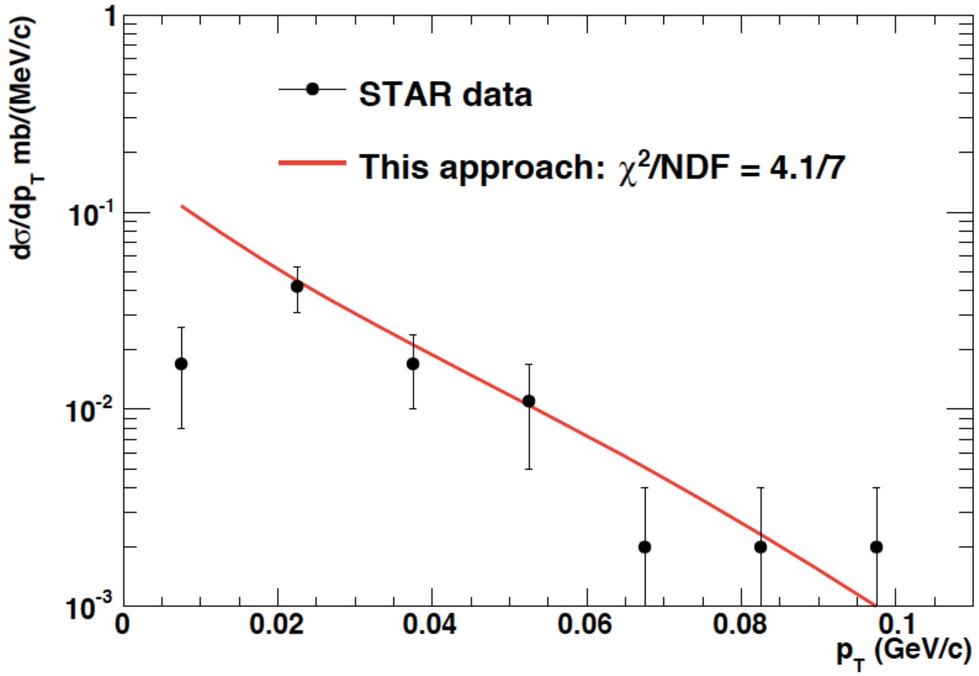
$$\frac{dN}{dk_\perp} = \frac{2Z^2\alpha F^2(k_\perp^2 + k^2/\gamma^2)k_\perp^3}{\pi[k_\perp^2 + k^2/\gamma^2]^2}$$

Point-like charge Z:

$$n(\omega; b) \approx \frac{Z^2\alpha}{2\pi}\frac{1}{\gamma b}e^{-2\omega b/\gamma}$$

The final-state e^+e^- p_T is the vector sum of the two photon.



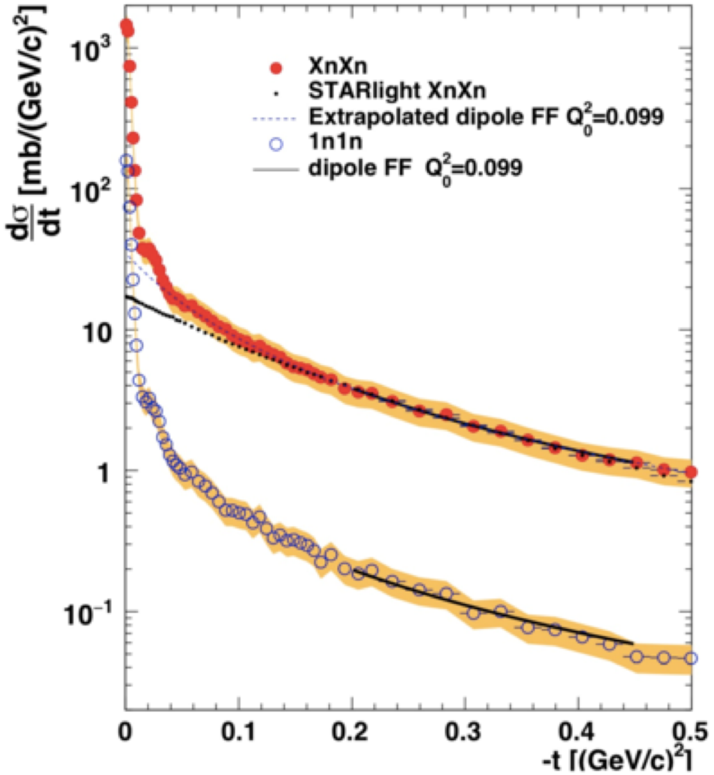


Phys. Rev. C **70** (2004) 031902(R)
e-Print Archives (nucl-ex/0404012)

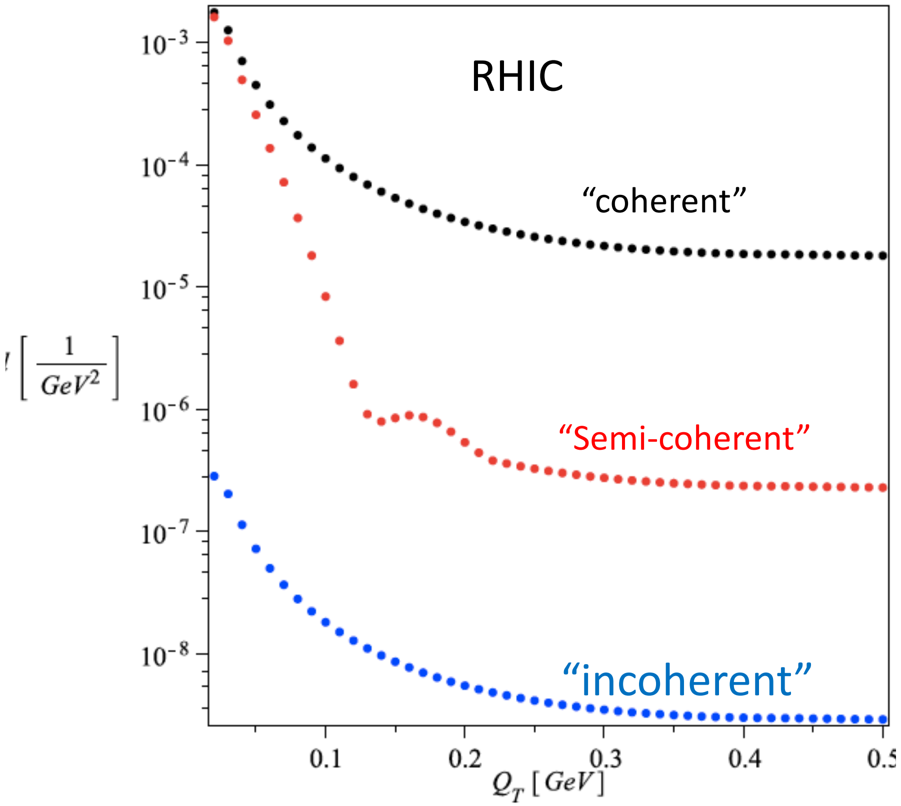
Phys.Lett. B781 (2018) 182-186

”Coherent” Interactions

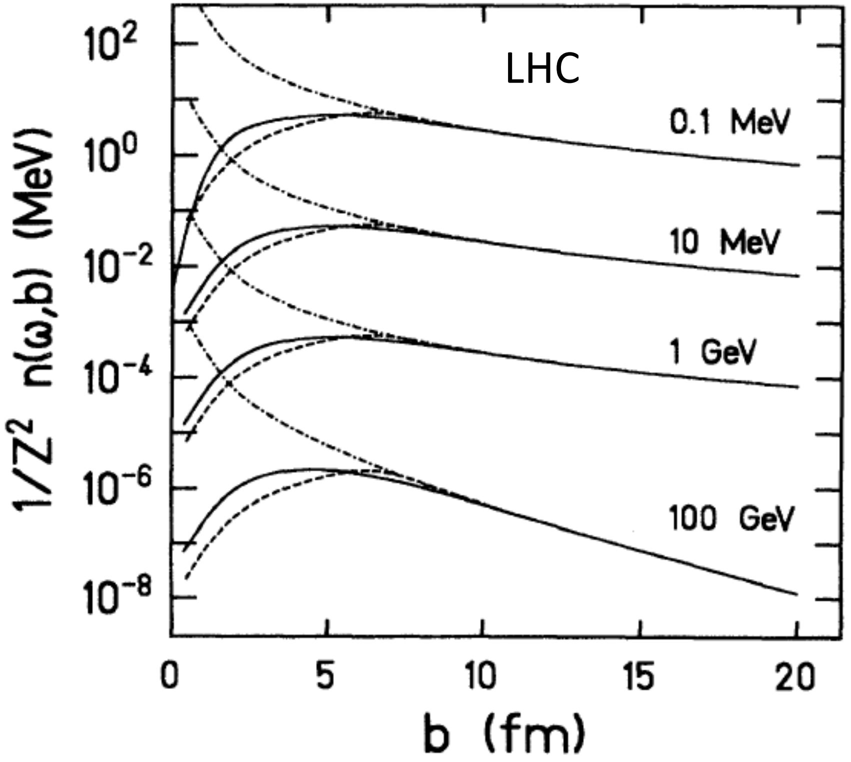
STAR PRC 96 (2017)



P. Staig, E. Shuryak, 1005.3531 unpublished



M. Vidovic, et al., PRC 47 (1993)

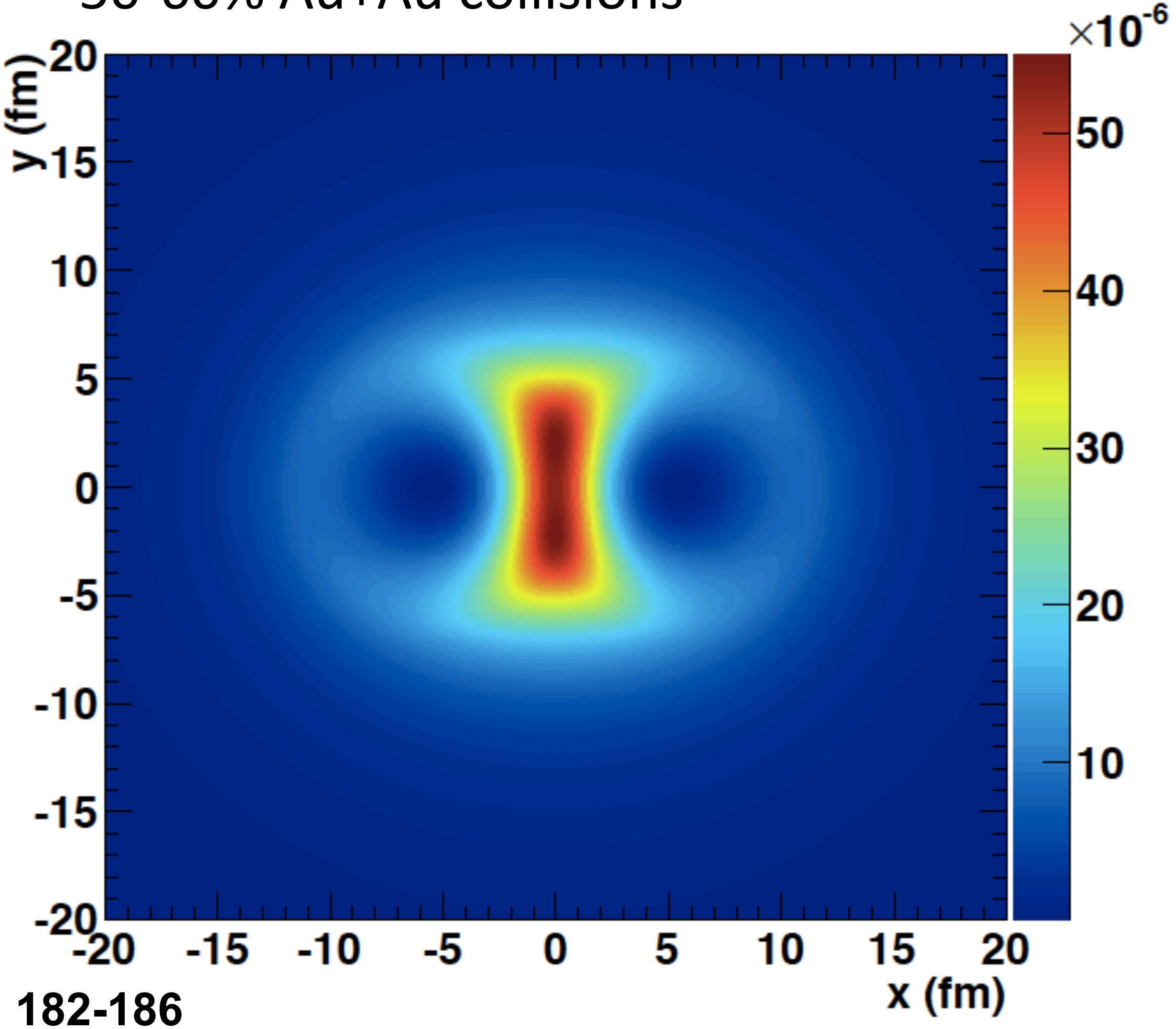


Traditional Coherent diffractive photoproduction:
Coherent dominates at low t,
Incoherent dominates at high t,
Diffractive pattern =
a Fourier transf. of nuclear size

Photon-photon collisions:
“coherent” dominates at all scale,
photon distribution does NOT depend on nuclear size (r>R),
cross-section dominates at $E_{1,2}/\gamma$, pt~=10s MeV
NOT sensitive to nuclear size

Spatial distribution of photon collisions

Example of e^+e^- pair spatial distribution,
50-60% Au+Au collisions



Phys.Lett. B781 (2018) 182-186

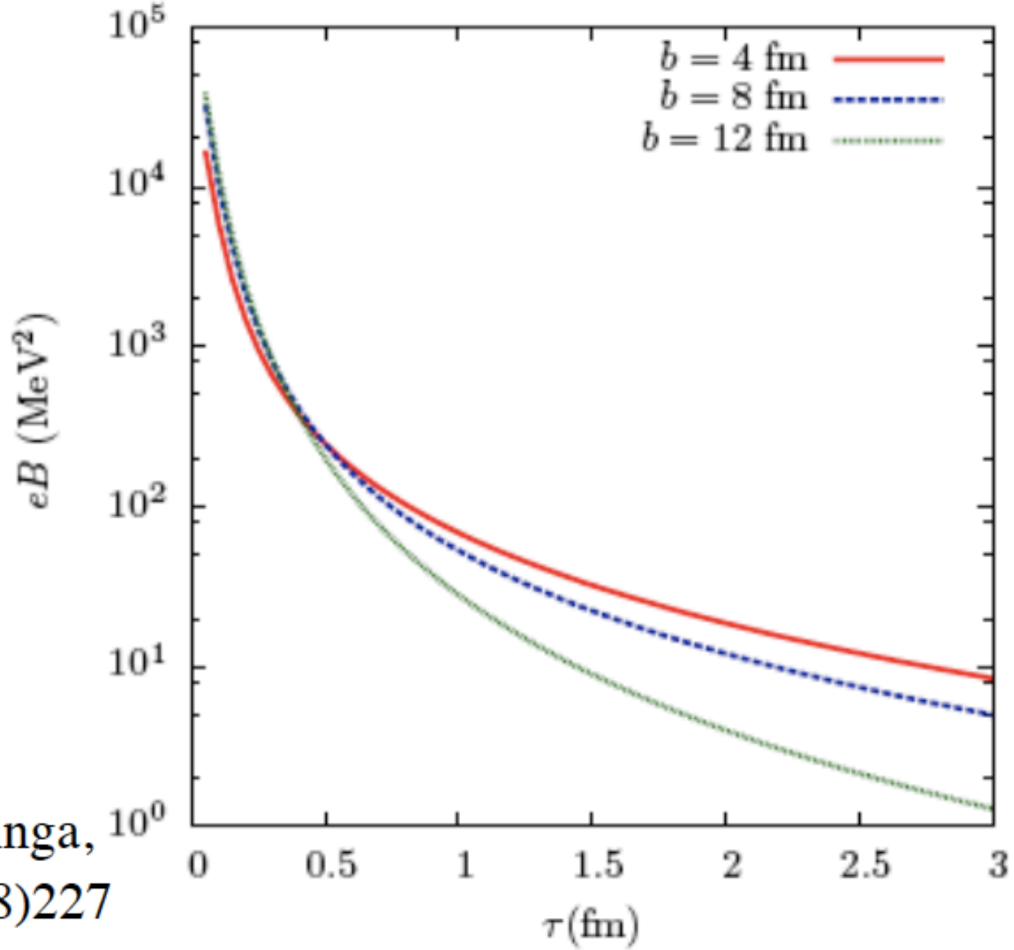
Heavy ion collisions as a source of the strongest magnetic fields available in the Laboratory

Also:

V. Skokov,

V. Toneev,

A. Illarionov…



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

CME & Magnetic Field

A required set of Extraordinary Phenomena:

QCD Topological Charge

+ Chiral Symmetry Restoration

+ Strong Magnetic Field

Observable:

Chirally restored quarks separated along magnetic field

Two other Extraordinary phenomena to make this possible (QCD topology reflects in charge separation)

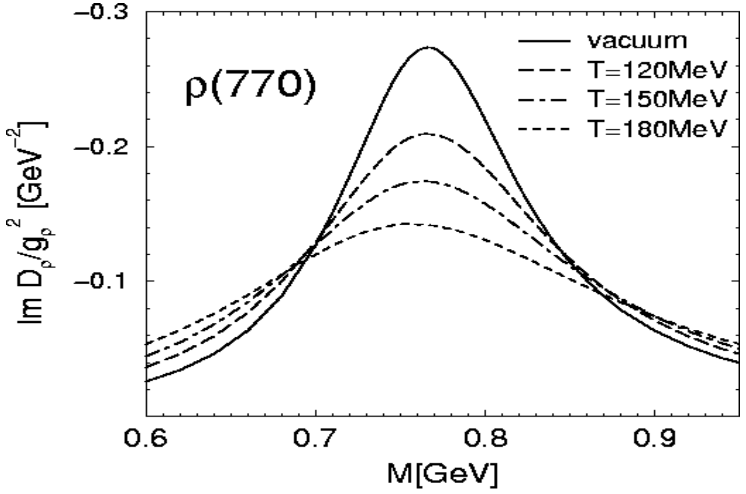
- Chiral Symmetry Restoration
  - low-mass dilepton excess (change of vector meson ρ spectral function)
- Strong Magnetic Field
  - Global Hyperon Polarization
  - Coherent photo-production of J/Ψ and low-mass dilepton in non-central A+A collisions

Disentangle and assess necessary conditions

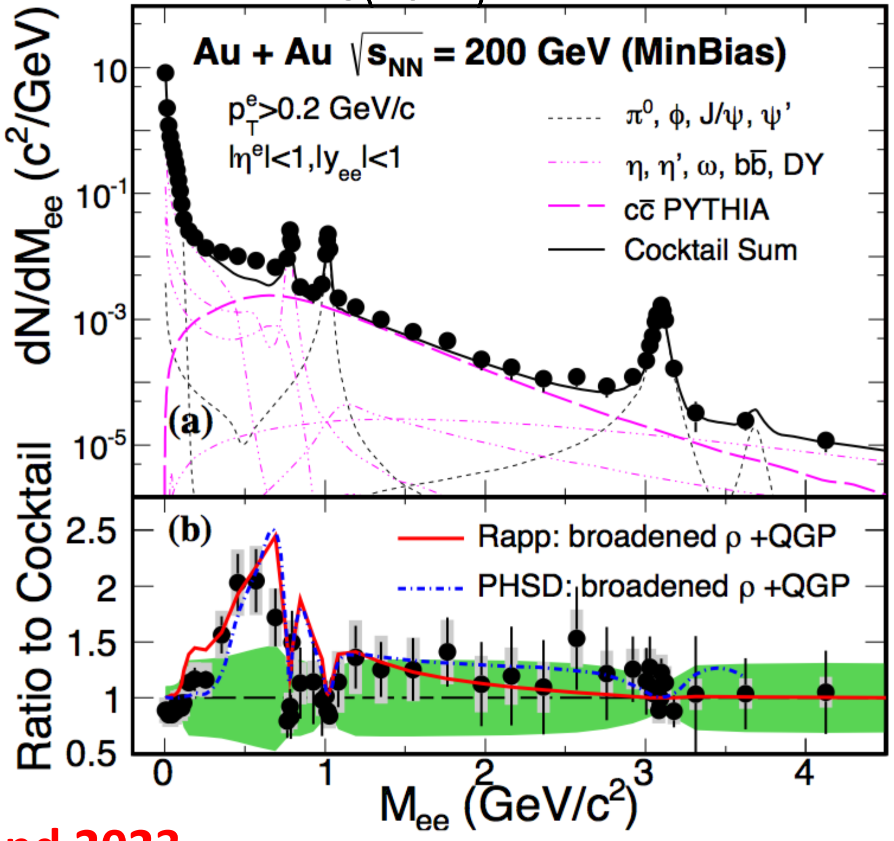
Zhangbu Xu, Moriond Conference, Italy, March 2017

QCD phase transition is a chiral phase transition

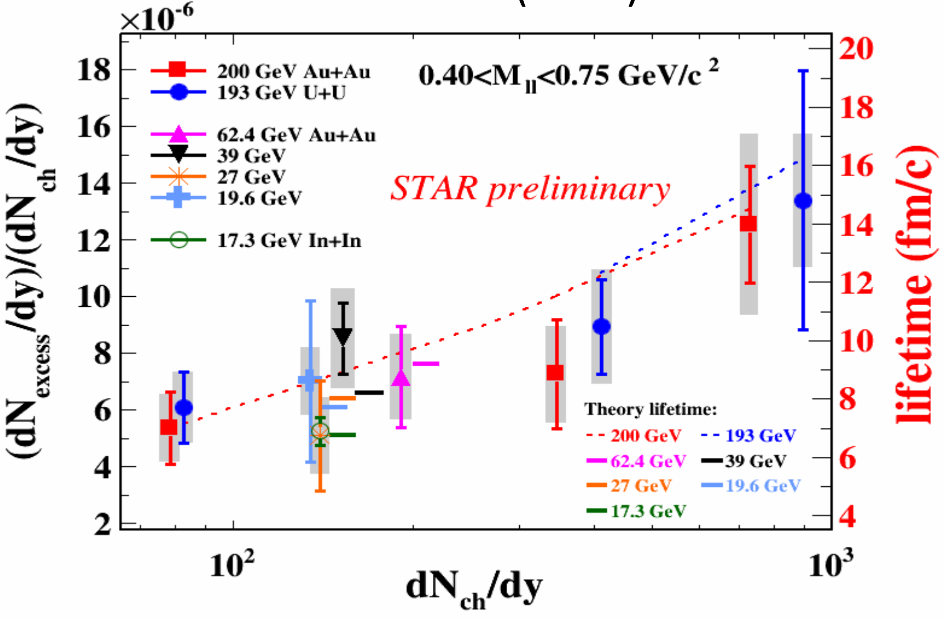
Golden probe of chiral symmetry restoration:
change vector meson ($\rho \rightarrow e^+e^-$) spectral function
STAR data (RHIC and SPS):
Consistent with continuous QGP radiation and
broadening of vector meson in-medium



PRL113(2014)

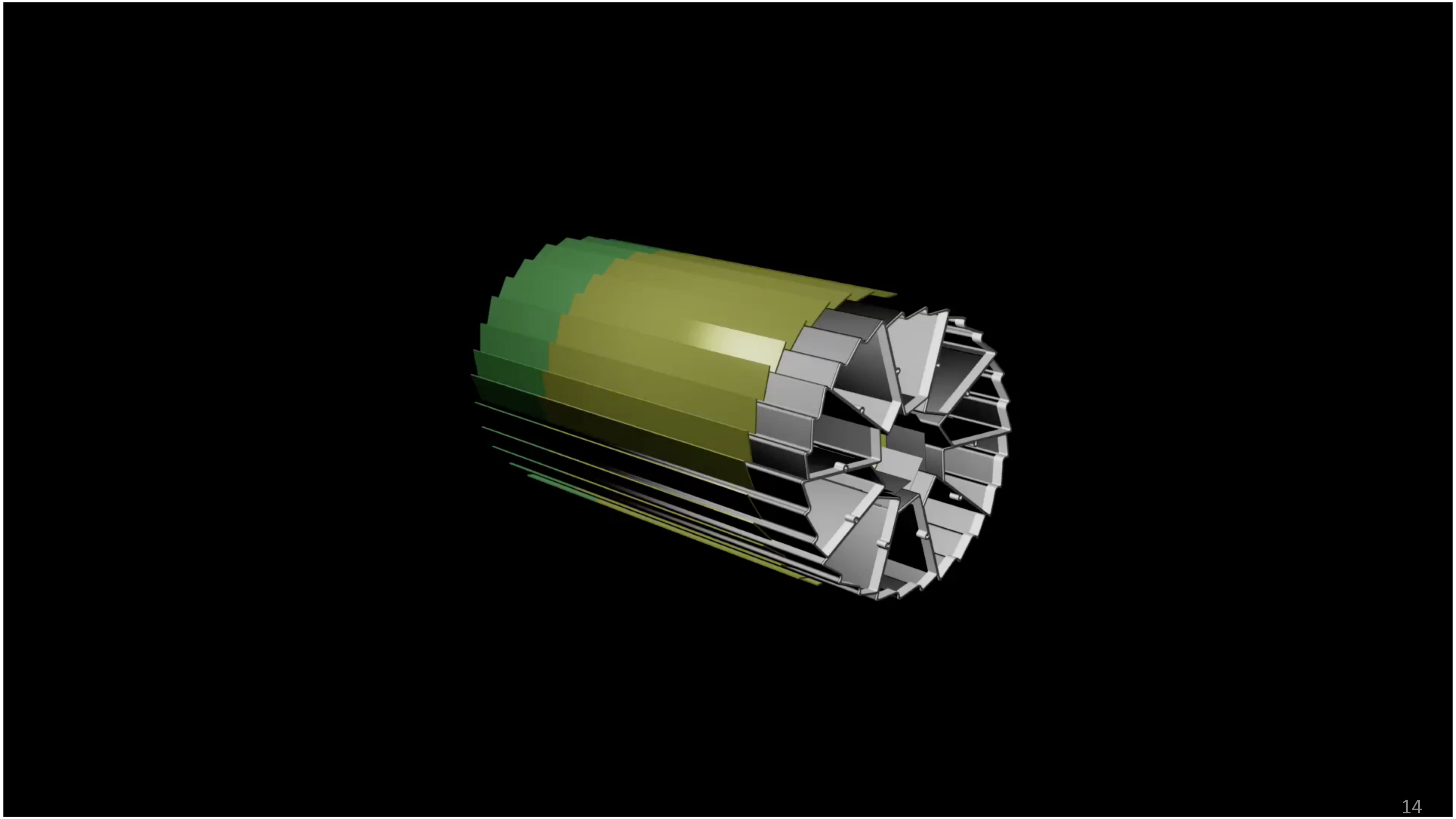


PLB750(2015)



IMR: BESII and 2023

STAR Detector used for dielectron analysis



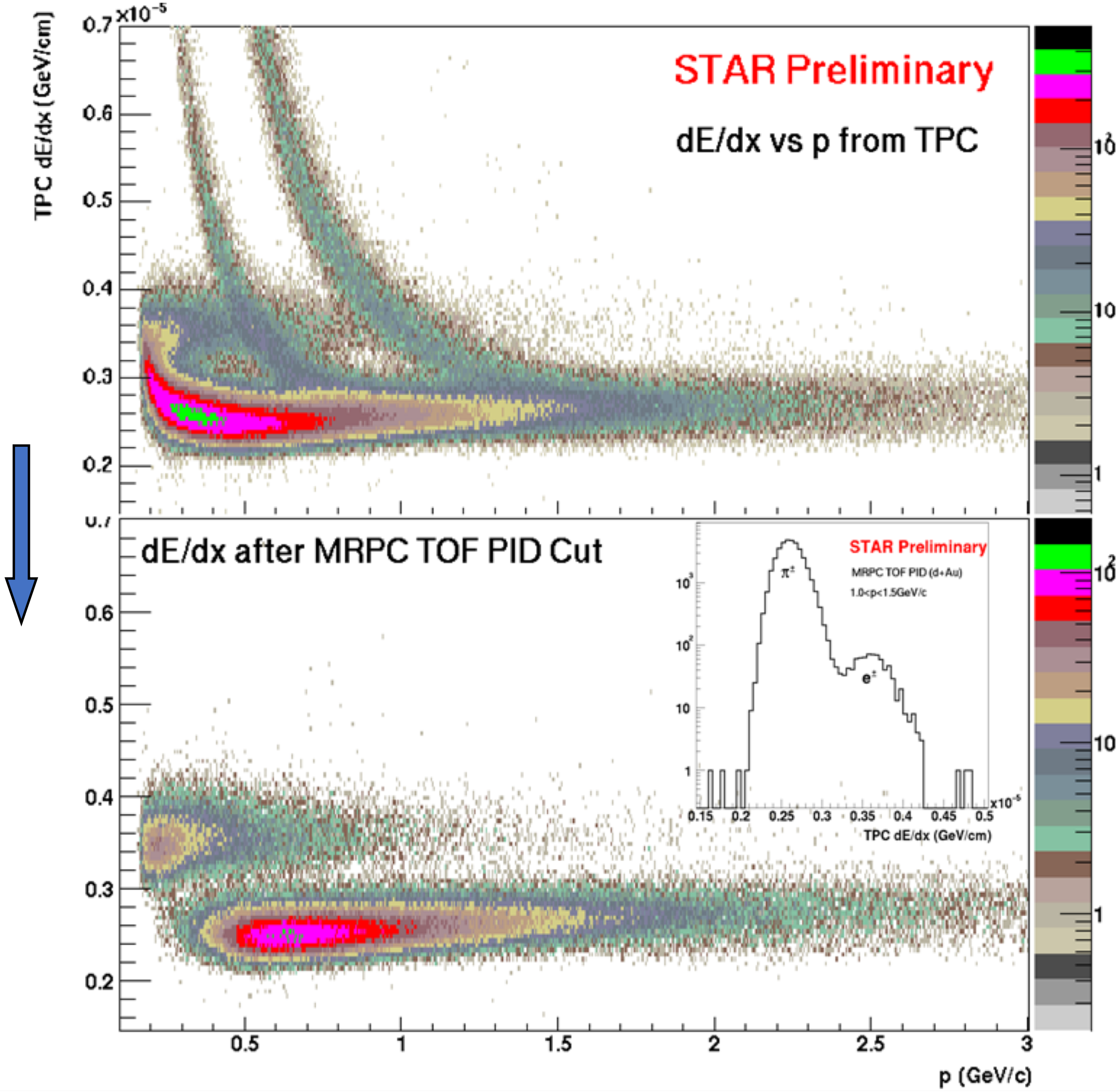
Electron Identification

TPC dE/dx: large hadron background

EMC: p_T>~2.0 GeV/c

A prototype TOF tray (TOFr) in 2003

|1/β-1|<0.03



Not able to do without TOF!

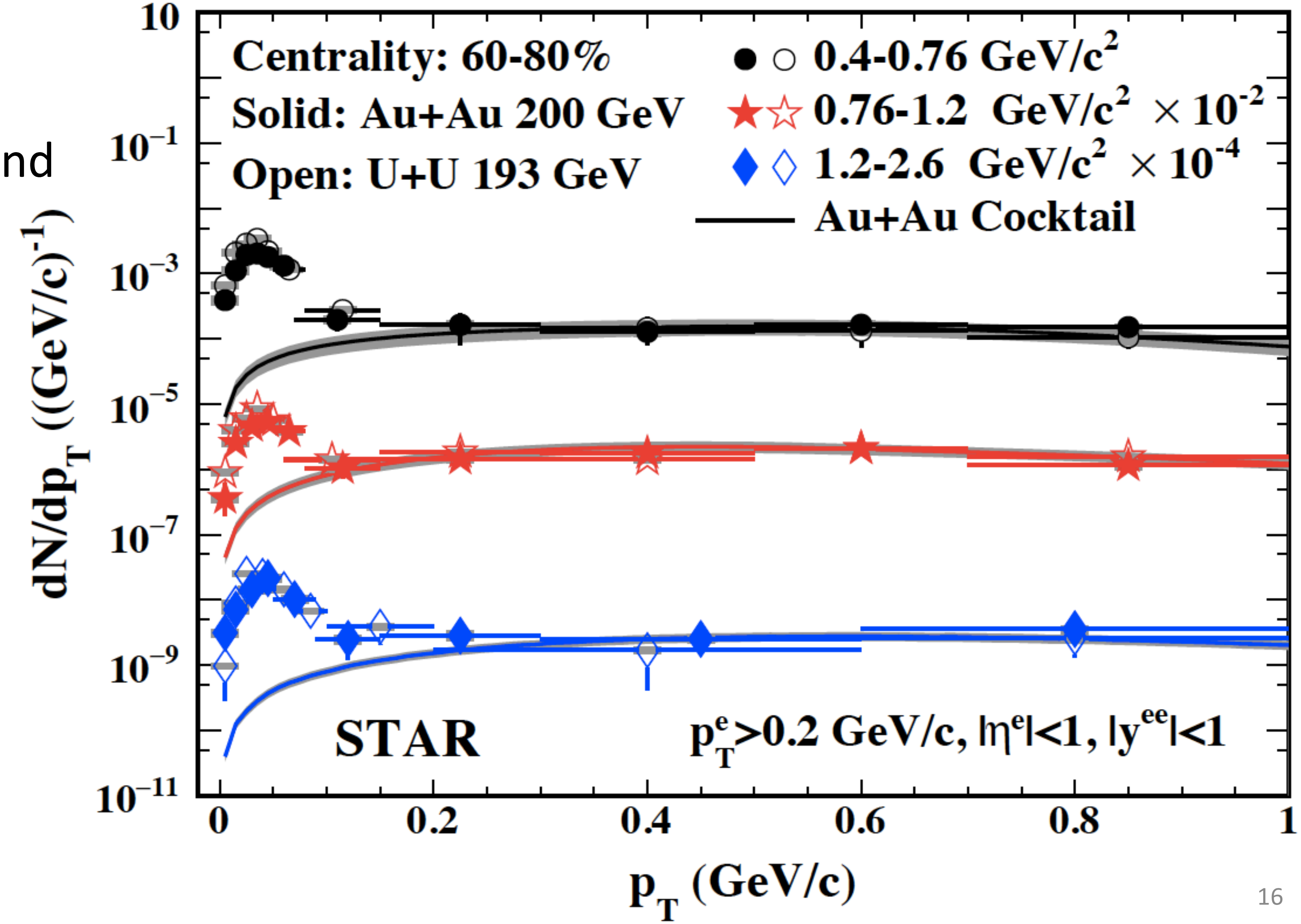
Nucl-ex/0505026, M. Shao et al.
X. Dong PHD Thesis (USTC 2005)

Characteristics of photon collisions

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

Hadronic production:
$\langle p_T \rangle$~=500MeV/c

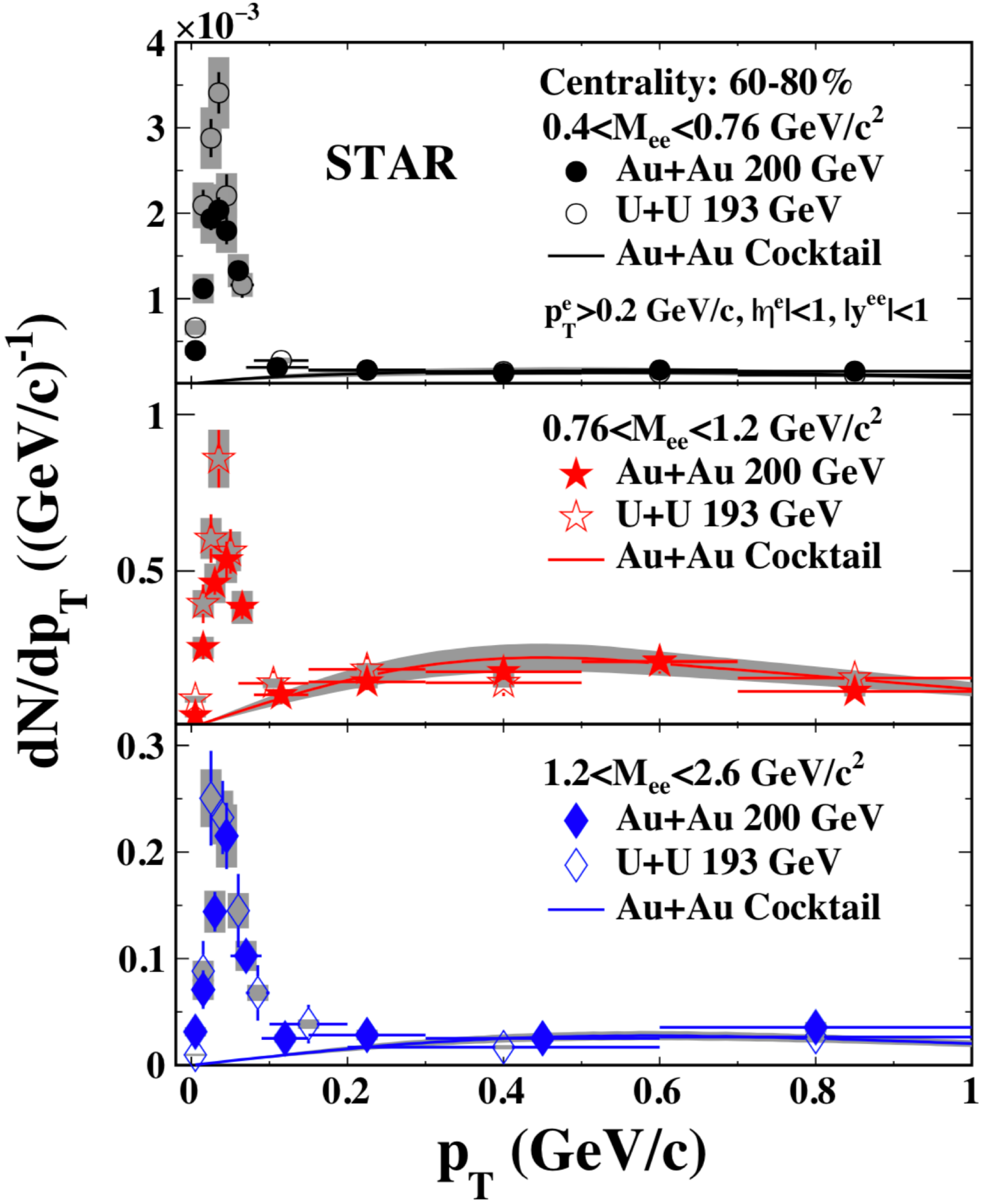
Datasets:
Au+Au 2010+2011
U+U 2012



Good Signal over background

Linear Scale

Signal-to-background ratio is about 17:1



Invariant mass distributions

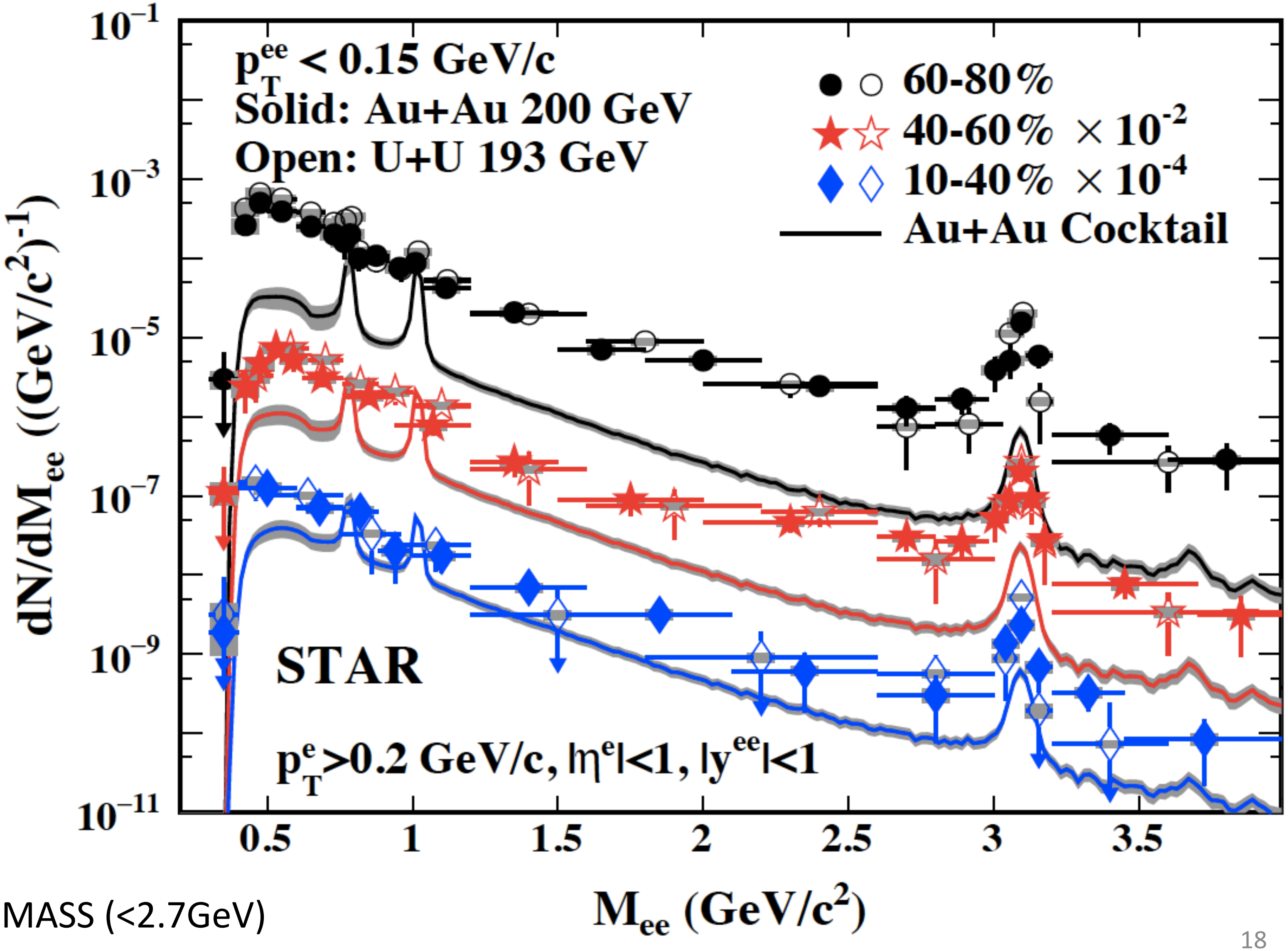
Photon collisions:
Continuous in invariant mass

Photoproduction:
Vector Meson Dominant

Invariant mass distributions show combination of both

High mass (VMD):
photoproduction of J/Psi

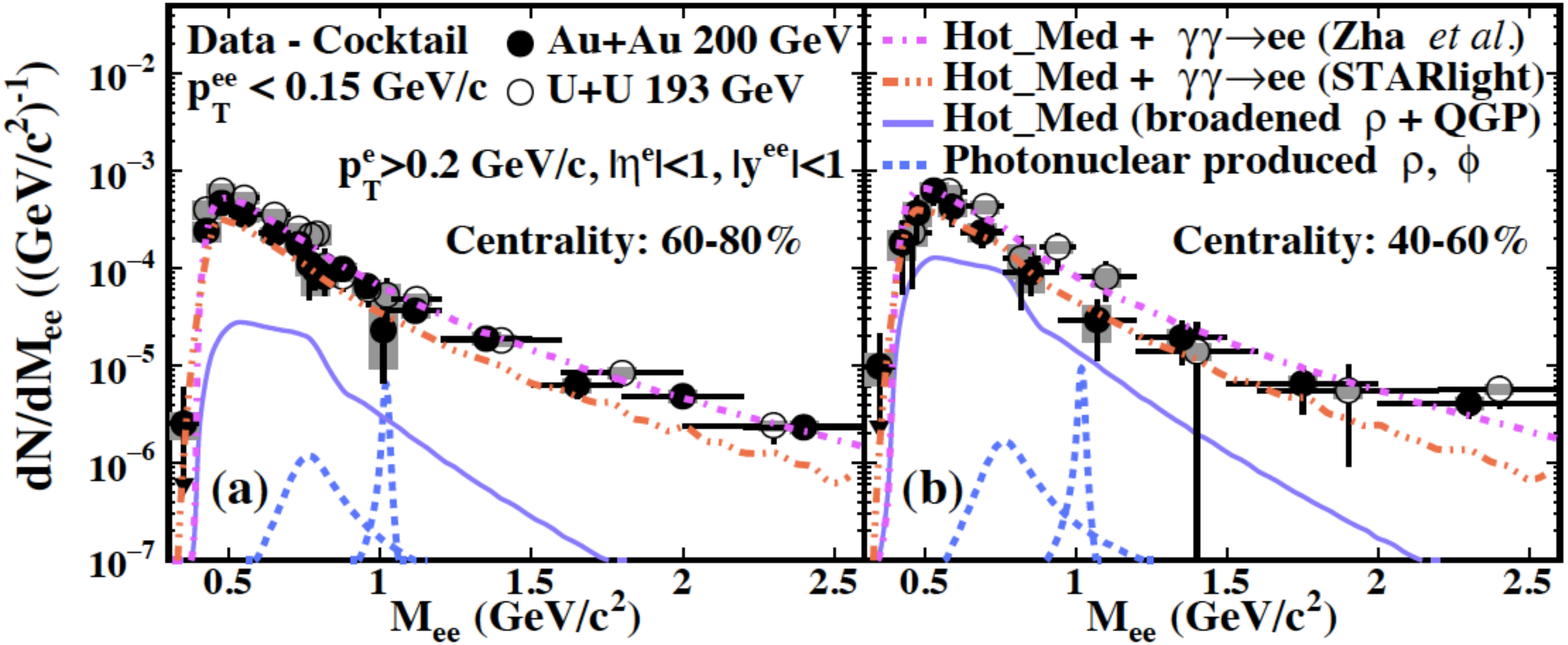
Low-mass:
photon collisions



FOCUS ON LOW MASS (<2.7GeV)

Contributions from different sources

Hadronic cocktail subtracted:
Smooth continuous invariant mass spectra



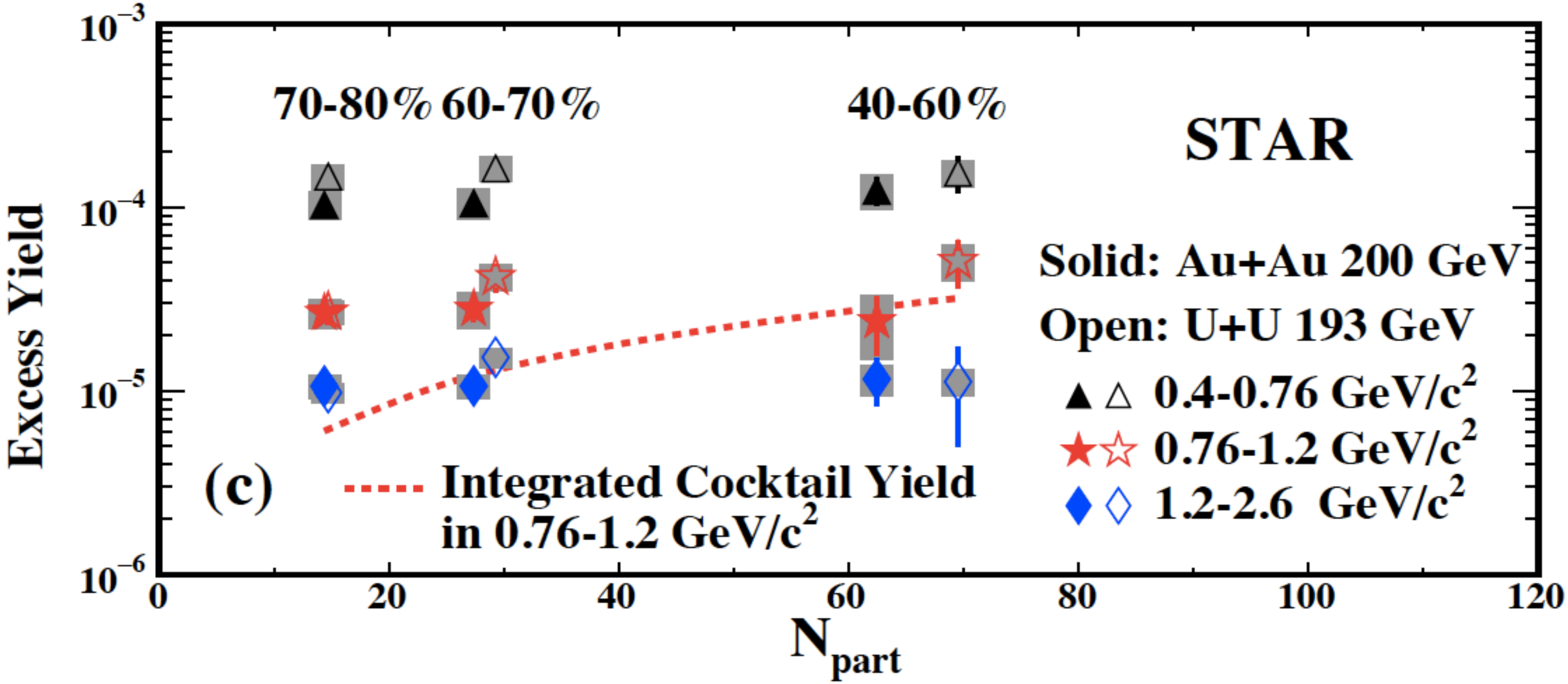
Residual:

- Photon collisions + photonuclear production + rho medium broadening + QGP radiation
- Model can describe the yields well
- Data dominated by photon collisions

Woods-Saxon match data on yields

STARlight underpredicts x2 yields

Yields in centrality and species



- Photon collision: Relatively independent of centrality
- hadronic yields increase rapidly with Npart
- U+U > Au+Au (40% higher)

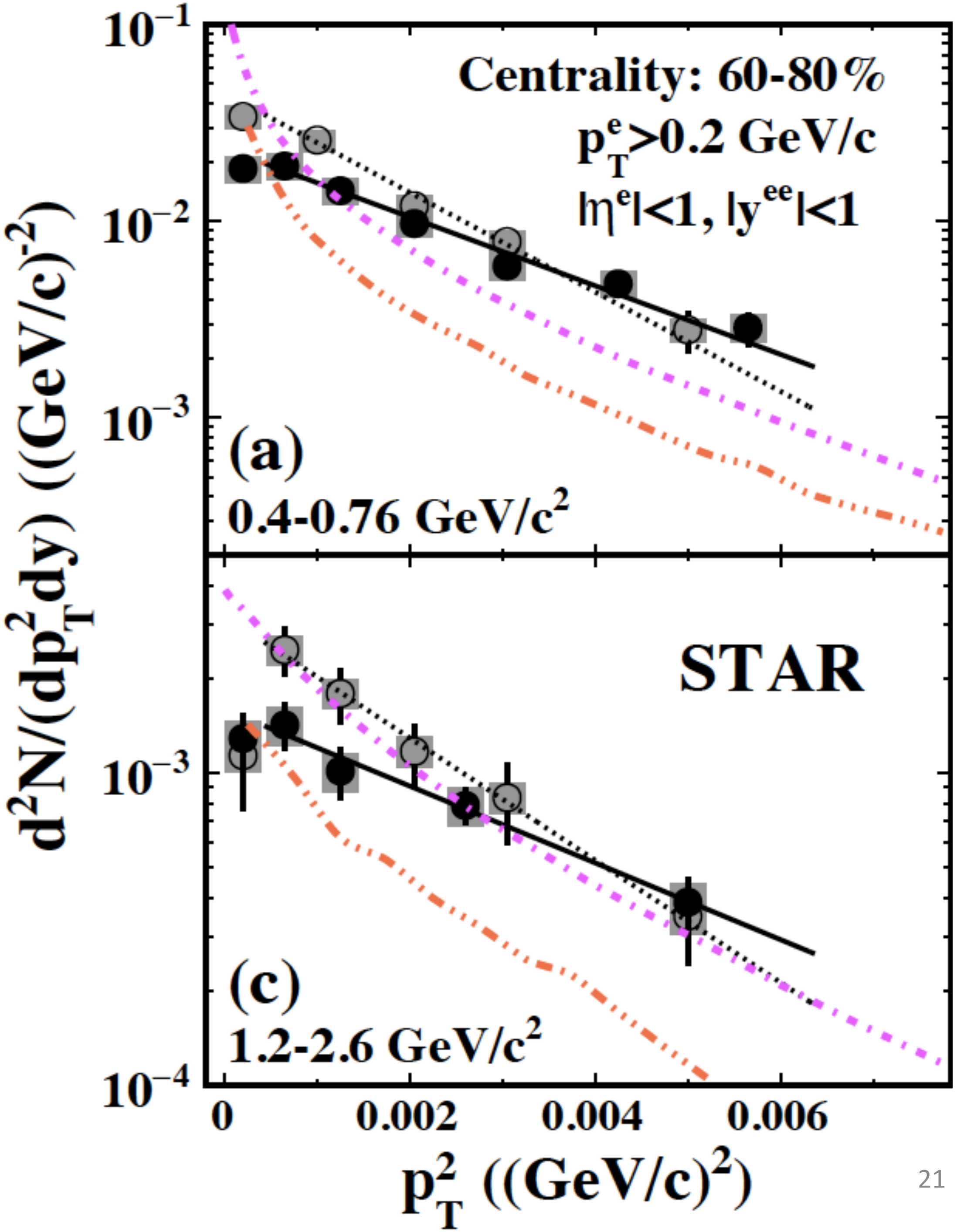
p_T^2 Spectra

Spectra is exponential in (-t) or Guassian in p_T: $\exp(-p_T^2/\sigma_t^2)$

U+U yield higher than Au+Au

Spectra broader than models

Au+Au p_T broader than U+U



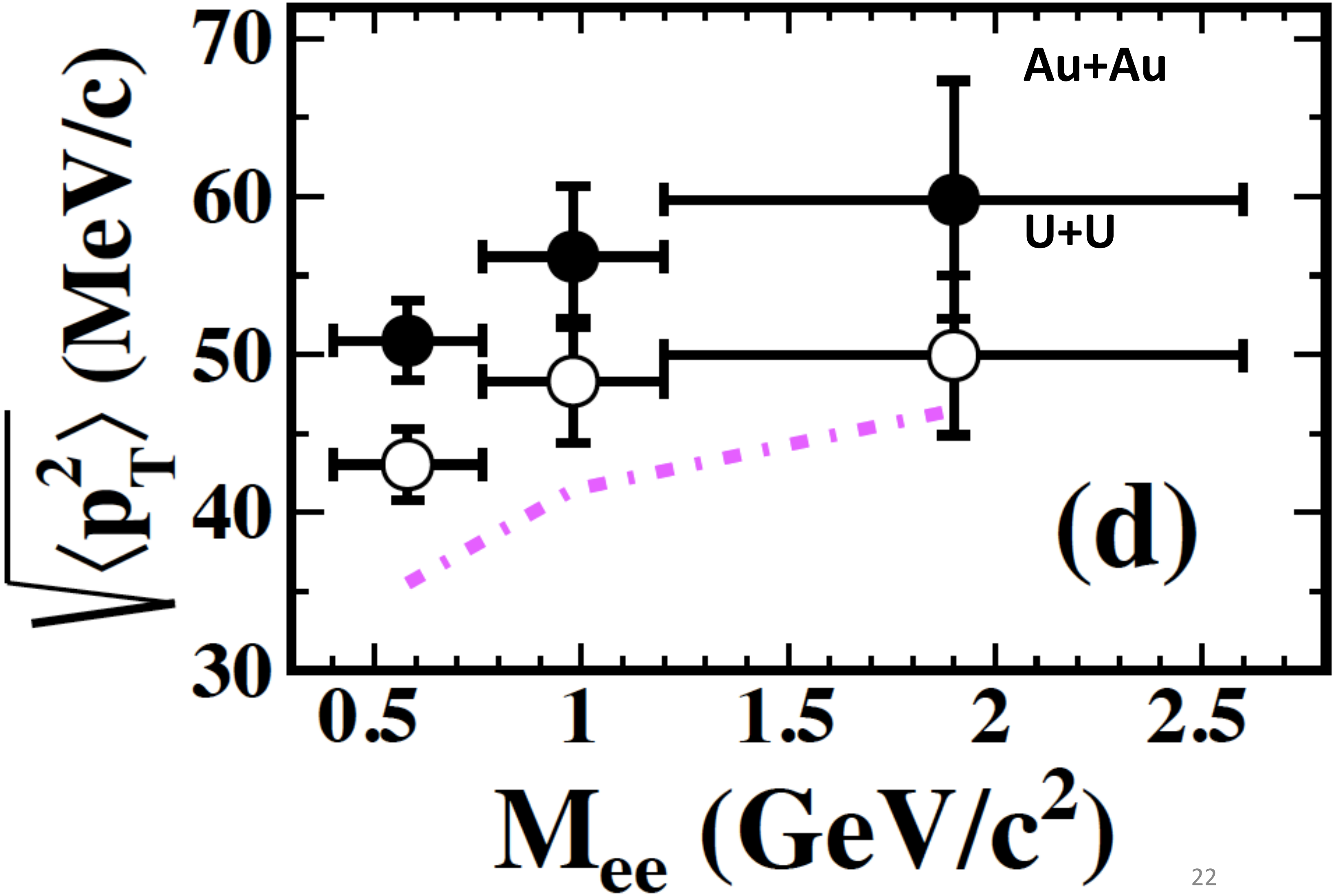
p_T broadening

Two Issues:

p_T spread (σ_t) > Model additional broadening of 40MeV

Au+Au > U+U

Why "broadening": Gaussian in p_T



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

Also:
V. Skokov,
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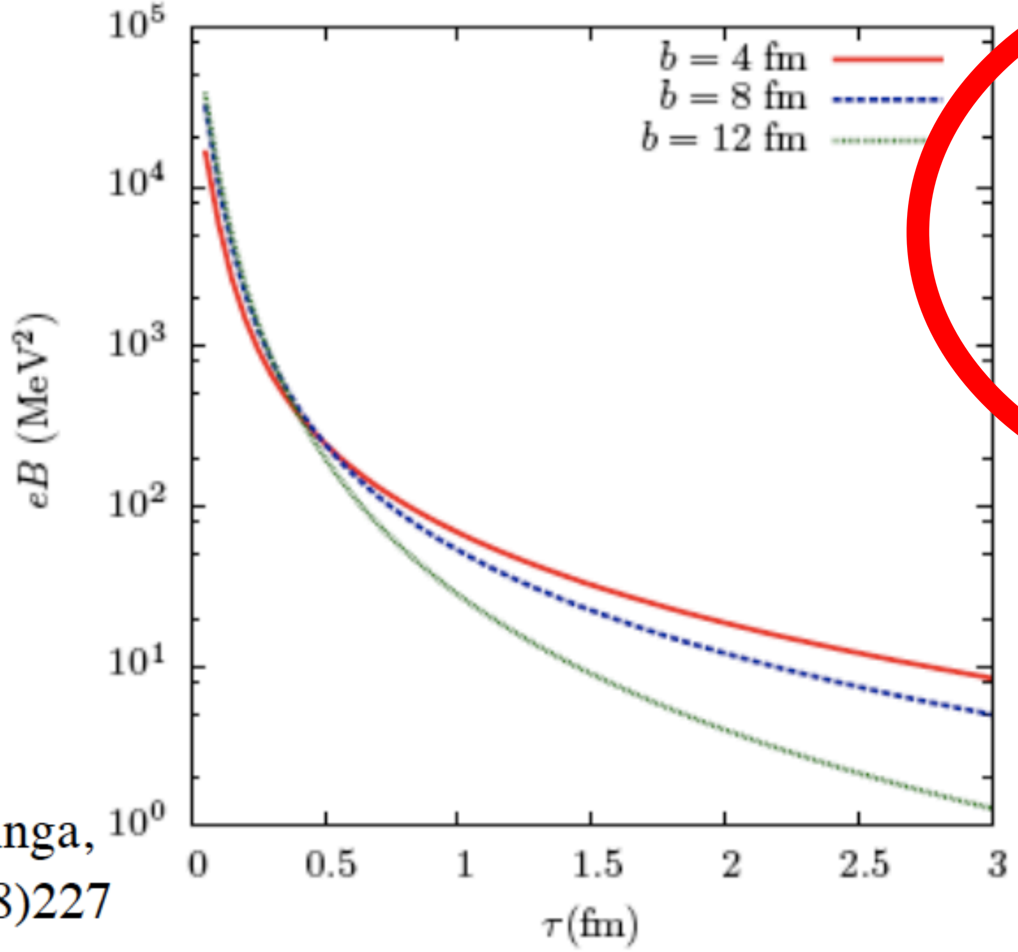


In a conducting plasma, Faraday induction can make the field long-lived:
K.Tuchin, arXiv:1006.3051

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

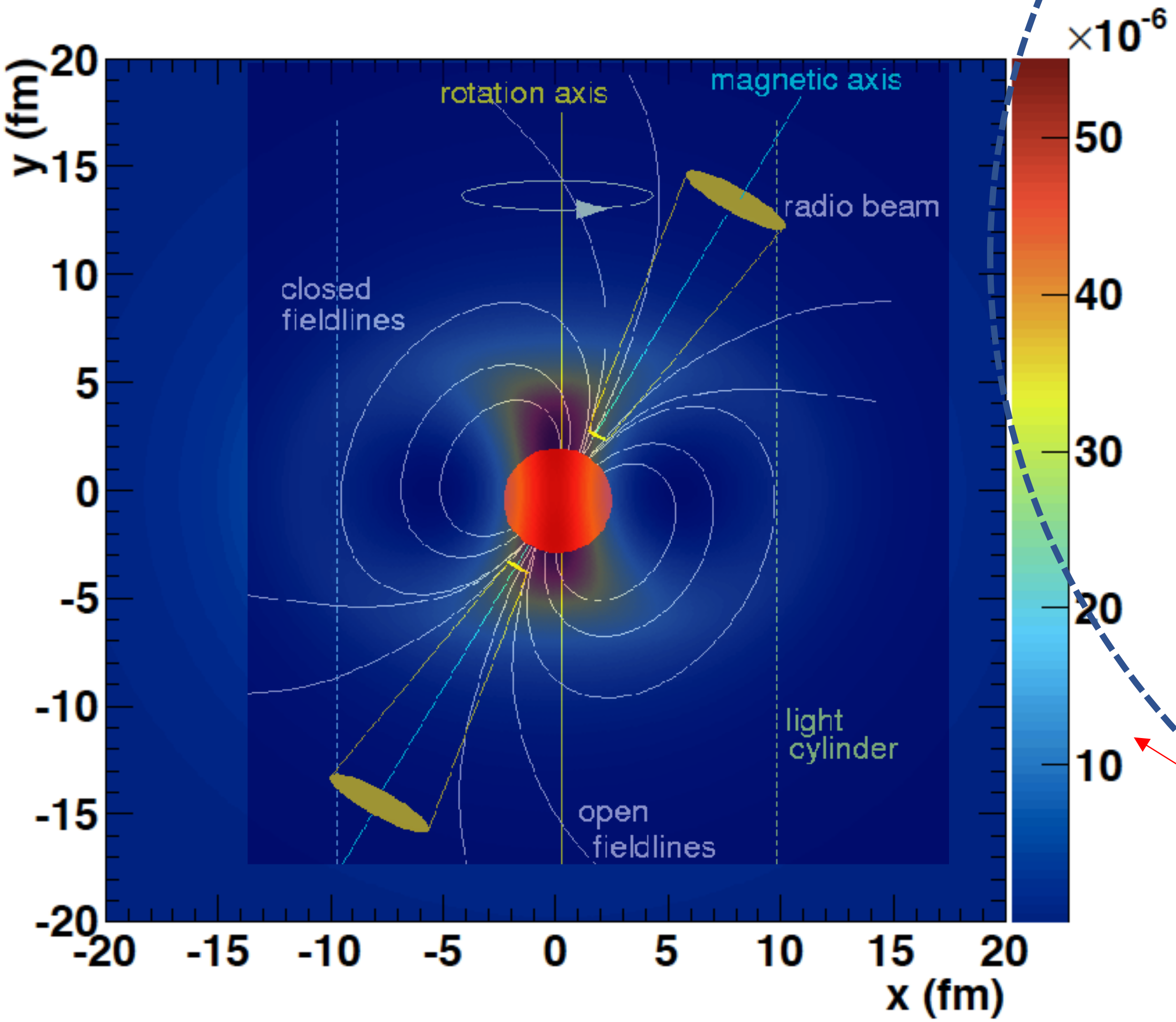
DK, McLerran, Warringa,
Nucl Phys A803(2008)227

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 ($Y_0 = 5.4$).

D. Kharzeev

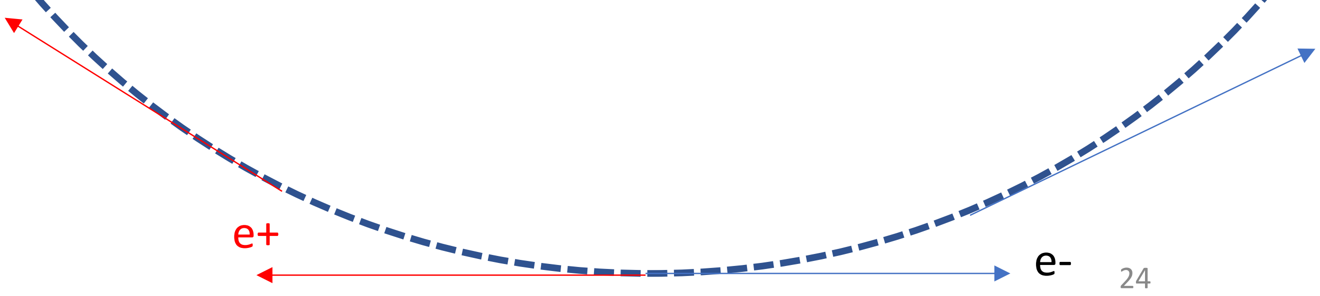
QUARK MATTER
ANNECY 2011

Impact of magnetic field on e^+e^- p_T spectra



🡐 Example of e+e- pair spacial distribution,

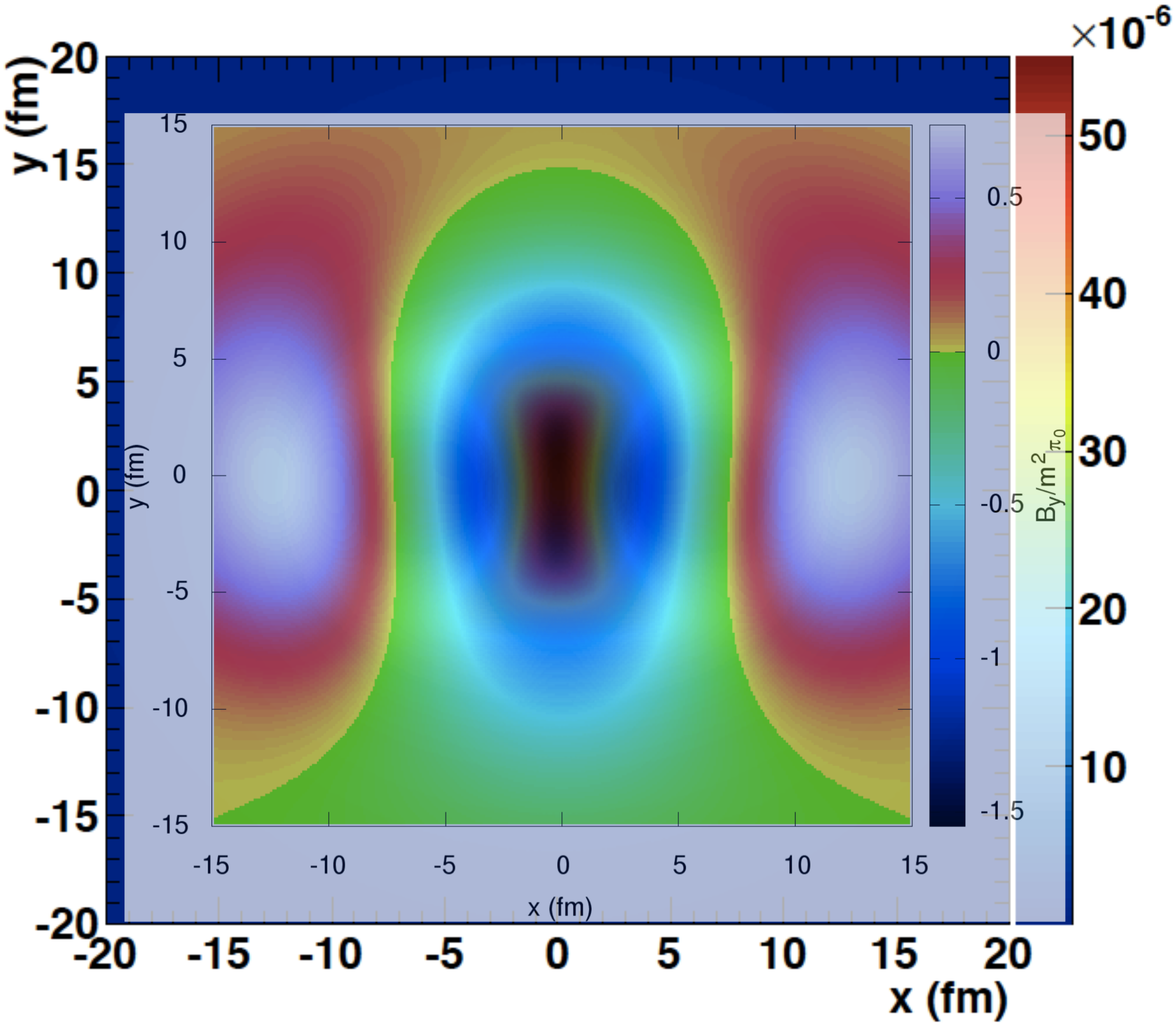
Assume uniform magnetic field along y-axis,
Calculate 10^{14}T and 1fm time (equivalent to the pair travels for 1fm in distance):
the deflection of the spectra is 2*e*L0*B



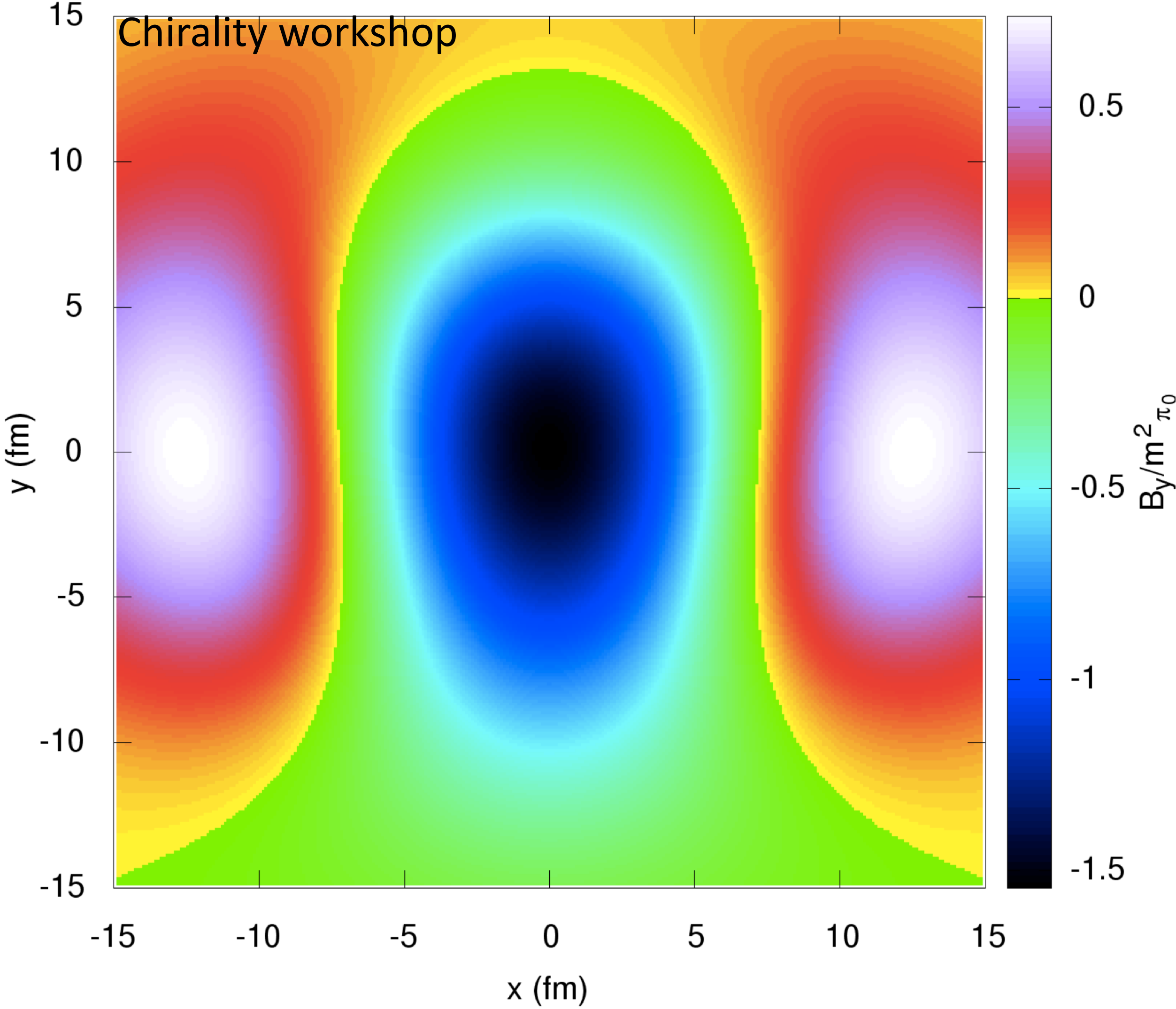
Spatial distribution of photon collisions

Example of e^+e^- pair spatial distribution,
50-60% Au+Au collisions

Conductivities of the medium
b=8fm, τ=0.4fm, σ= 5.8MeV, σ_χ= 1.5MeV



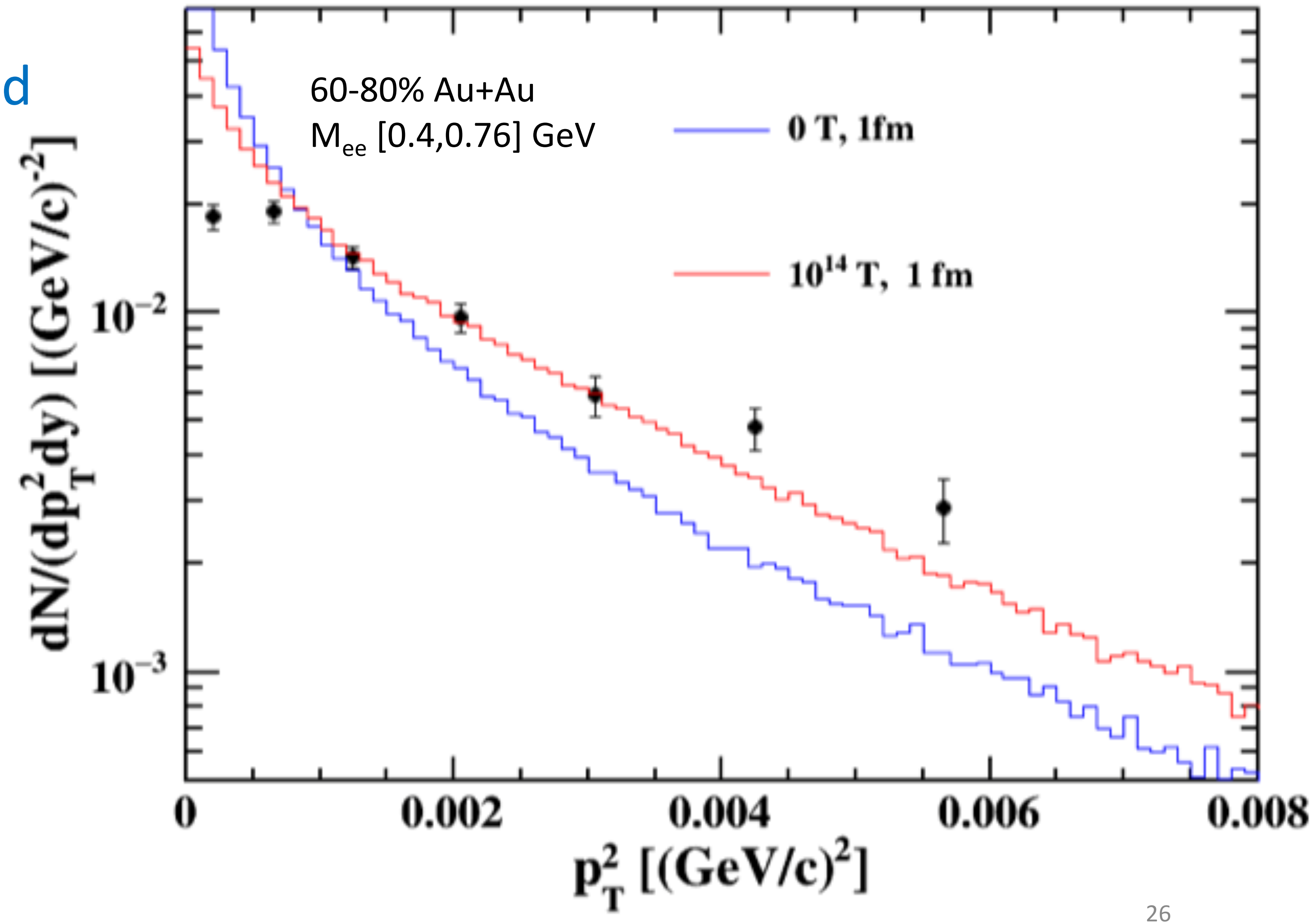
G. Inghirami et al., arXiv: 1609.03042,
Chirality workshop

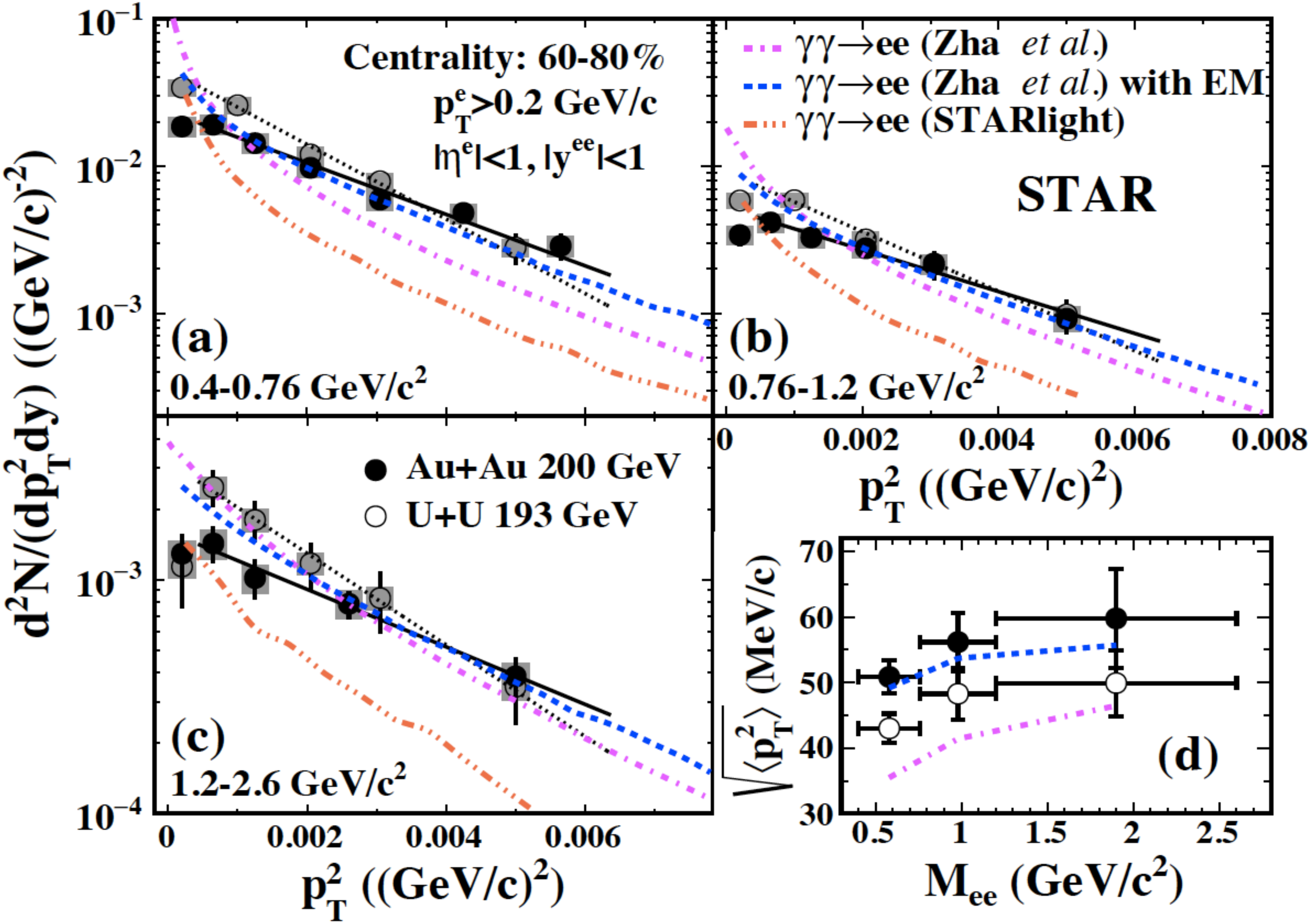


Measured p_T^2 spectra compared to models

BLUE curve is without B field

Red is with B field of 10^{14}T and 1fm
(time, traversing distance)





Yields

Au+Au<U+U

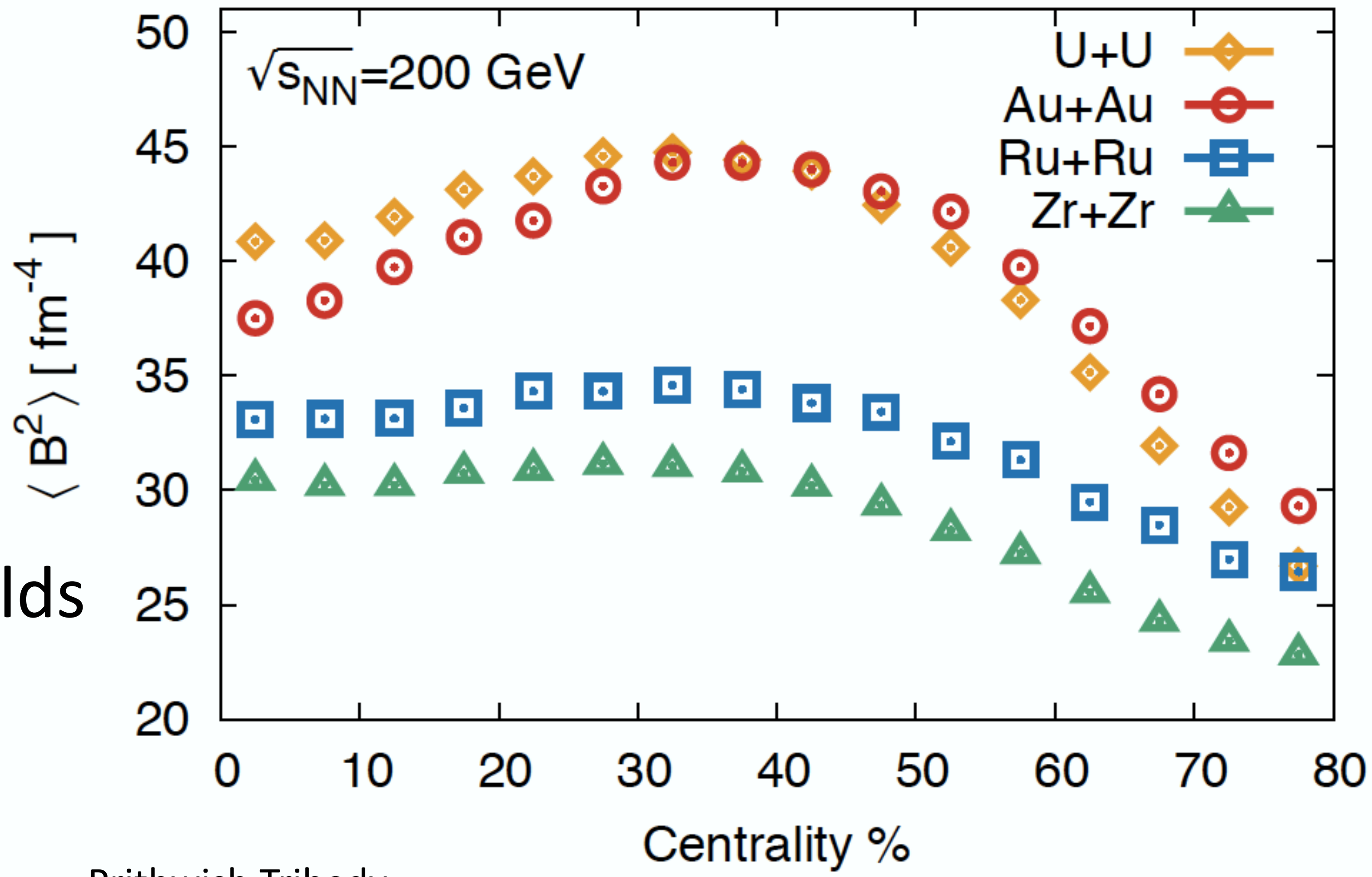
σ_t: $\langle p_T^2 \rangle$

Au+Au>U+U

Resolving U+U vs Au+Au puzzle

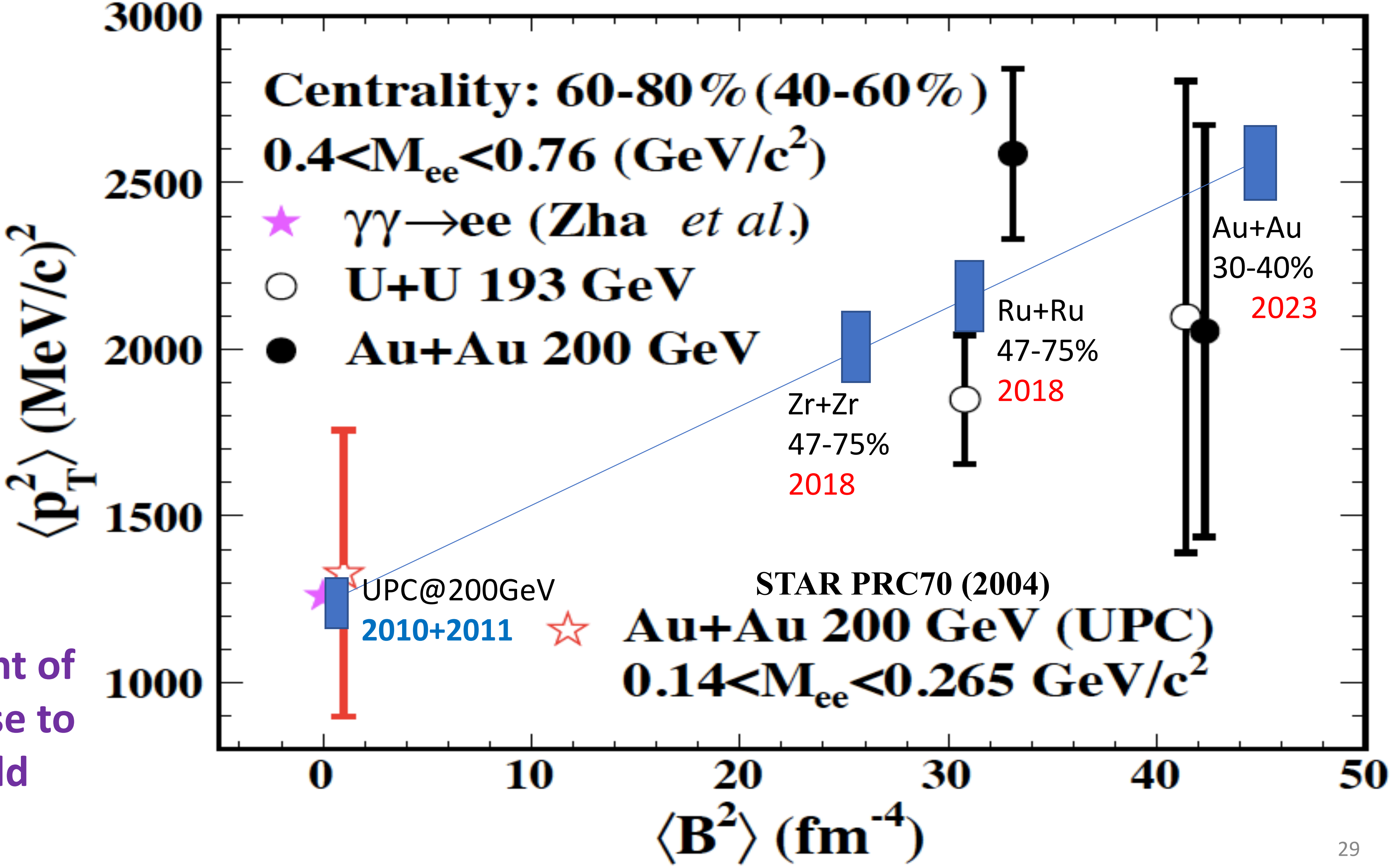
Peripheral U+U larger Z
More photon flux,
But more spread-out
weaker field at center
➔

- Higher dielectron yields
- Lower $<p_T^2>$



Prithwish Tribedy

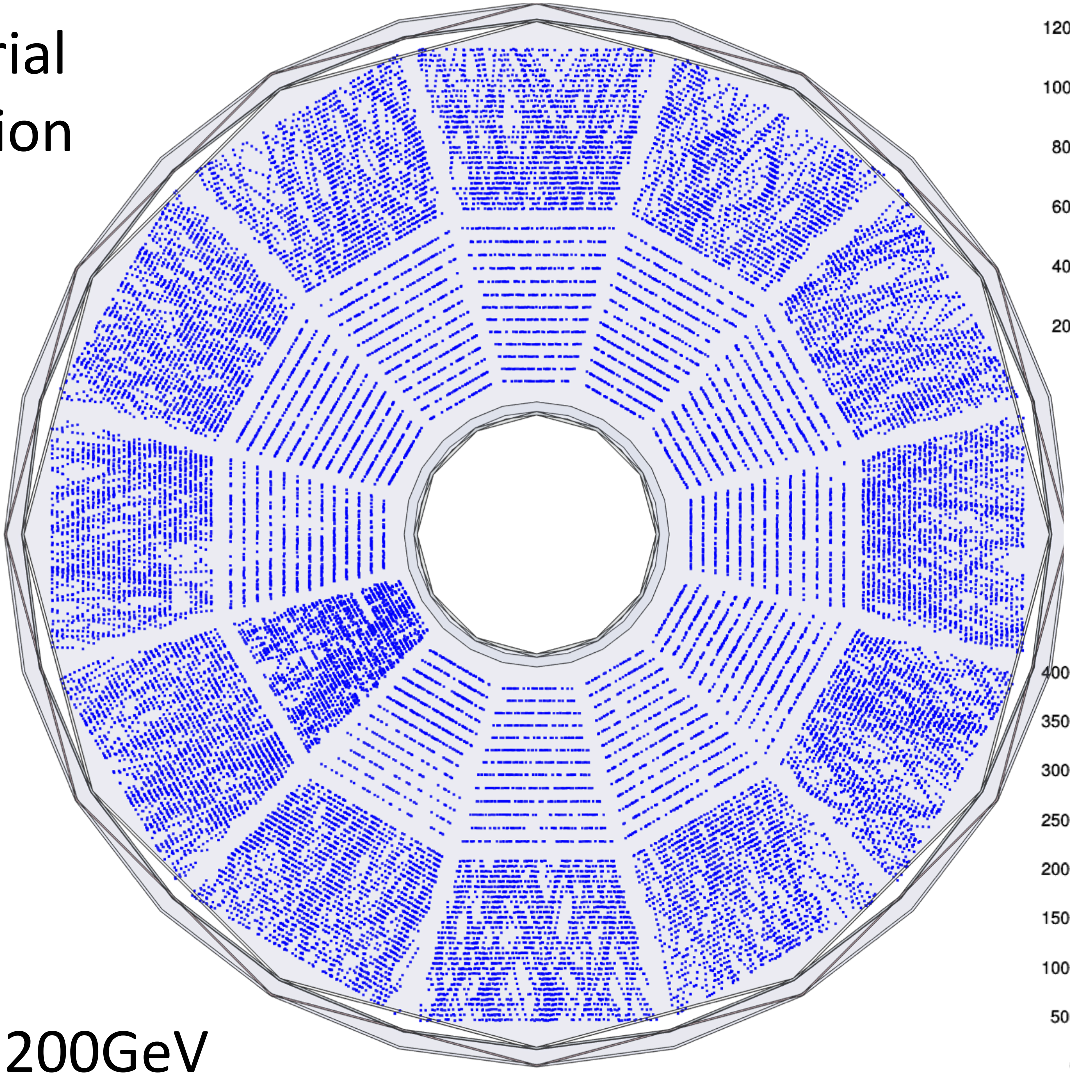
Projections and Predictions

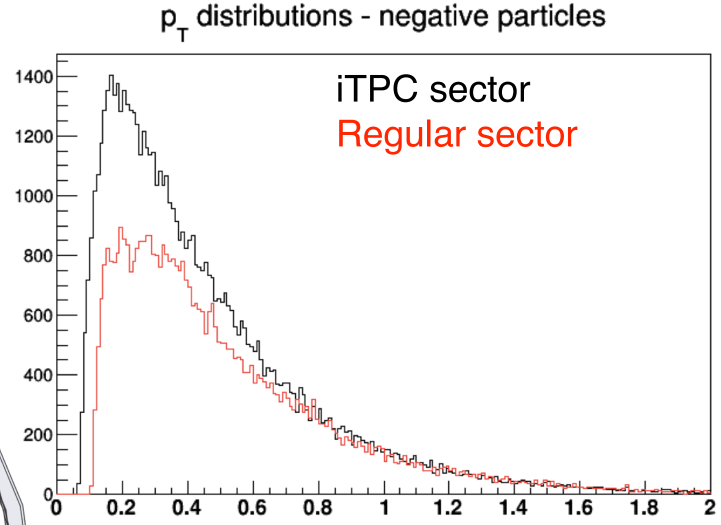


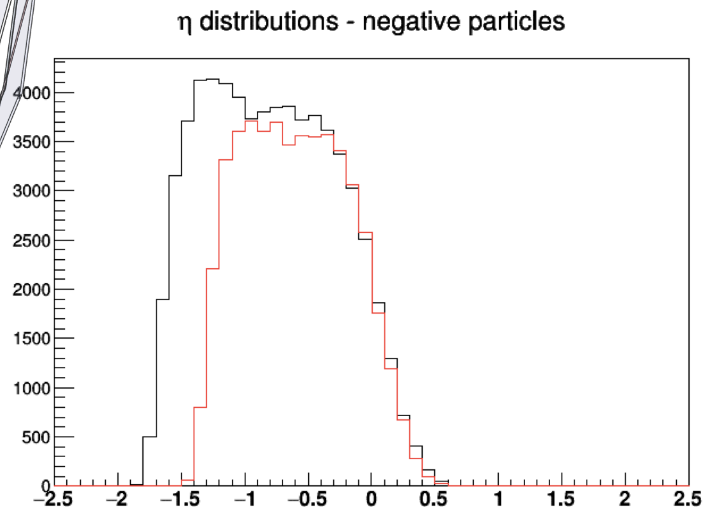
Quantitative Measurement of QGP response to magnetic field

Why 2023 and STAR@RHIC?

- Require low detector material
  - background from γ conversion
  - run14-16 not usable
  - 2010+2011 Au+Au @ 200
- Require excellent electron identification
  - TPC dE/dx and TOF
- Low-momentum electrons
- Require large acceptance
- Heavy-Ion Collisions with various species at the right energies:
  - $Z^4\gamma^2$
- Au+Au middle-centrality at 200GeV



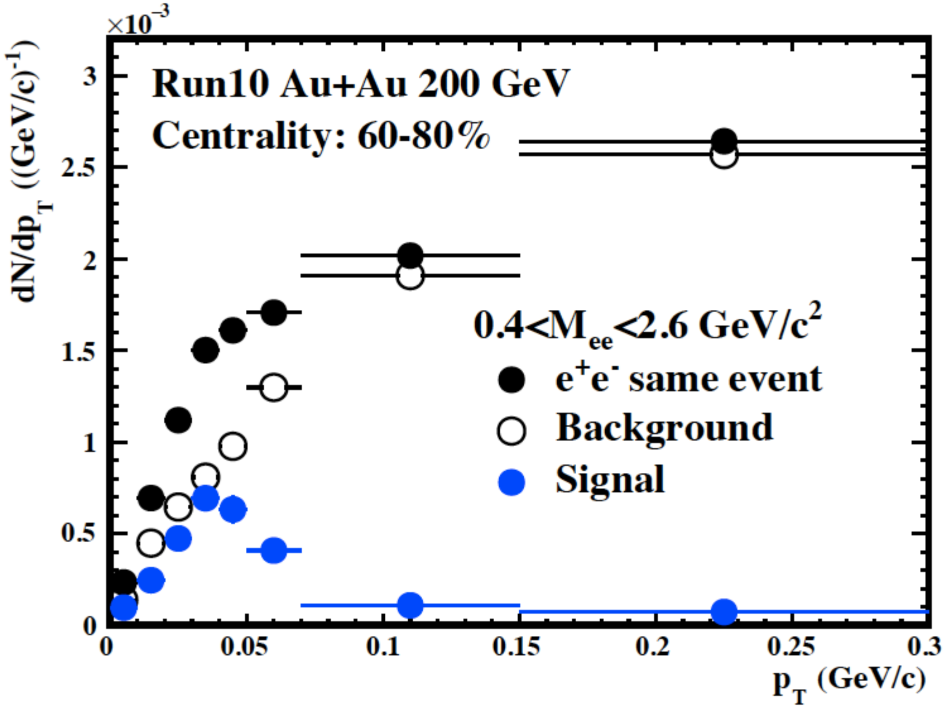


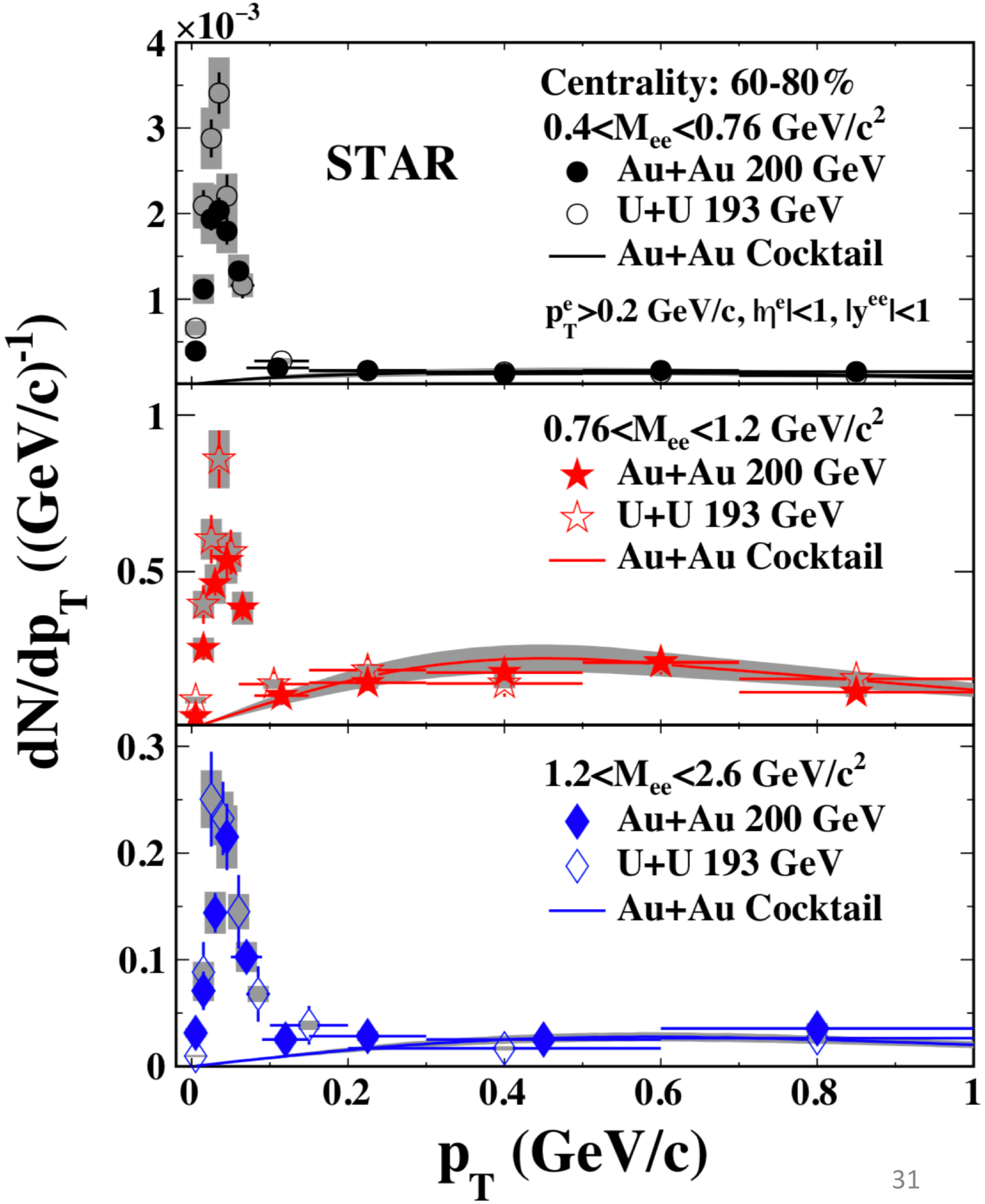


Combinatorial background could be show-stopper

Linear Scale

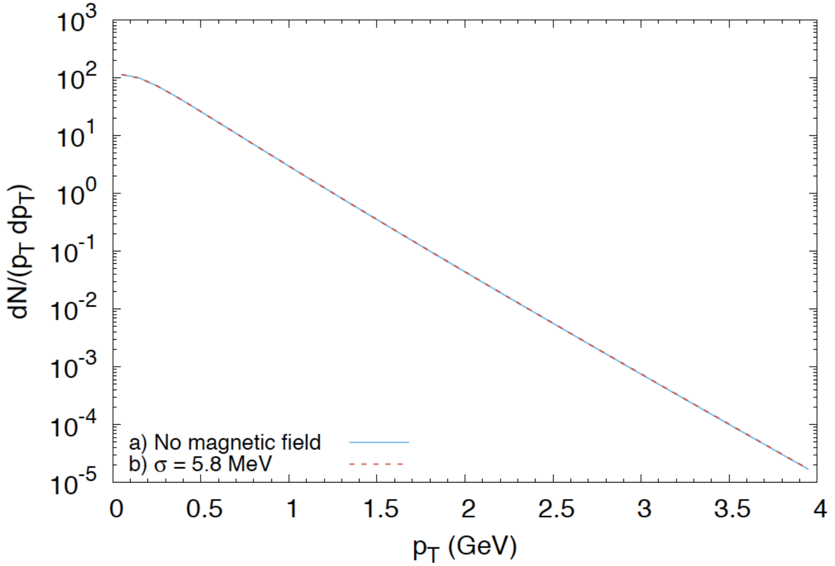
- Combinatorial background is low at this range with STAR at 0.3% material budget
  one layer of Silicon Tracker ~=1%
- After background subtraction,
  Signal-to-background ratio is about 17:1



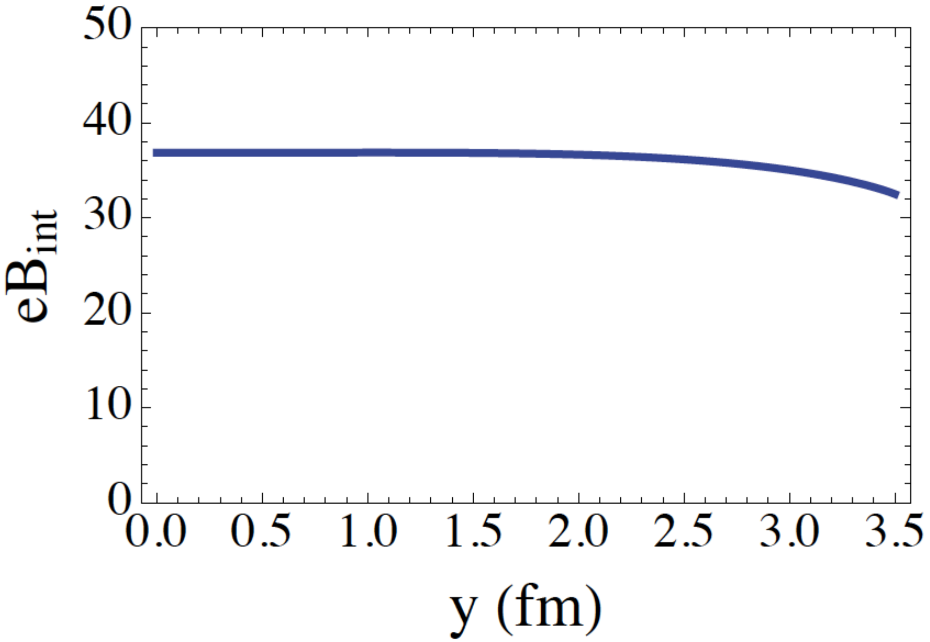


Why not other measurements?

- B field effect is at the level of 50MeV on momentum
- Most of hadrons $<p_T>$~=500MeV – 1GeV
  2% effect
  - Light hadron (pion+-: v1 difference)
  - Charm v1
  - Lambda and anti-Lambda polarization difference



G. Inghirami et al., arXiv: 1609.03042



Asakawa, Majumder, Mueller, arXiv:1003.2436

Why dielectrons from photon collisions perfect probe of Magnetic field in QGP?

- From beginning to the end, ONLY Electromagnetic processes are involved
- Dielectron pairs are created from initial-state photon flux (virtuality m~=0.5-1GeV, 0.2-0.5fm, not too late)
- Magnetic field in Vacuum is “normalized” by the UPC collisions
- Well-defined initial photon-photon cross section independent of QCD
- EM force is long range (electrons can get kicked even outside of QGP)
- Spectra peaks at p_T=30-50MeV, right magnitude to be very sensitive to magnetic field
- Clean probe with unique characteristics

D. Kharzeev, RHIC/AGS Users Meeting, June, 2015

Perspective

Outline

1. Hydrodynamics:

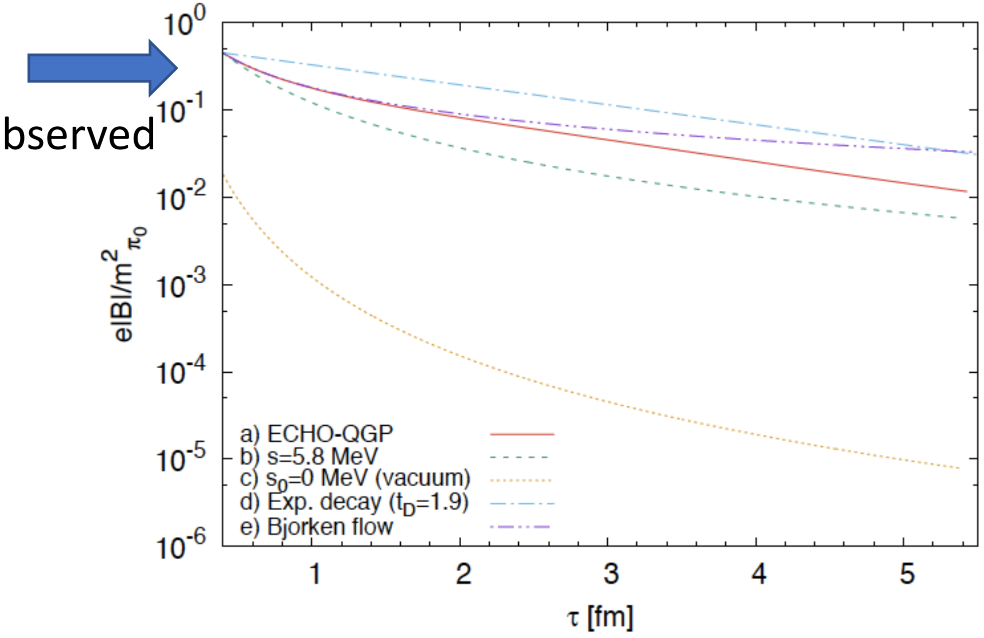
   the low-energy Theory of Everything

2. The XXI century hydrodynamics motivated by RHIC:

   a) quantum bounds on "conventional" transport coefficients
   b) new transport phenomena of entirely quantum origin

3. The future of hydrodynamics and BNL experiments

Quantum Fluid:
Highest temperature
Lowest viscosity/s
Most Vortical fluid
GOOD/best conductor?



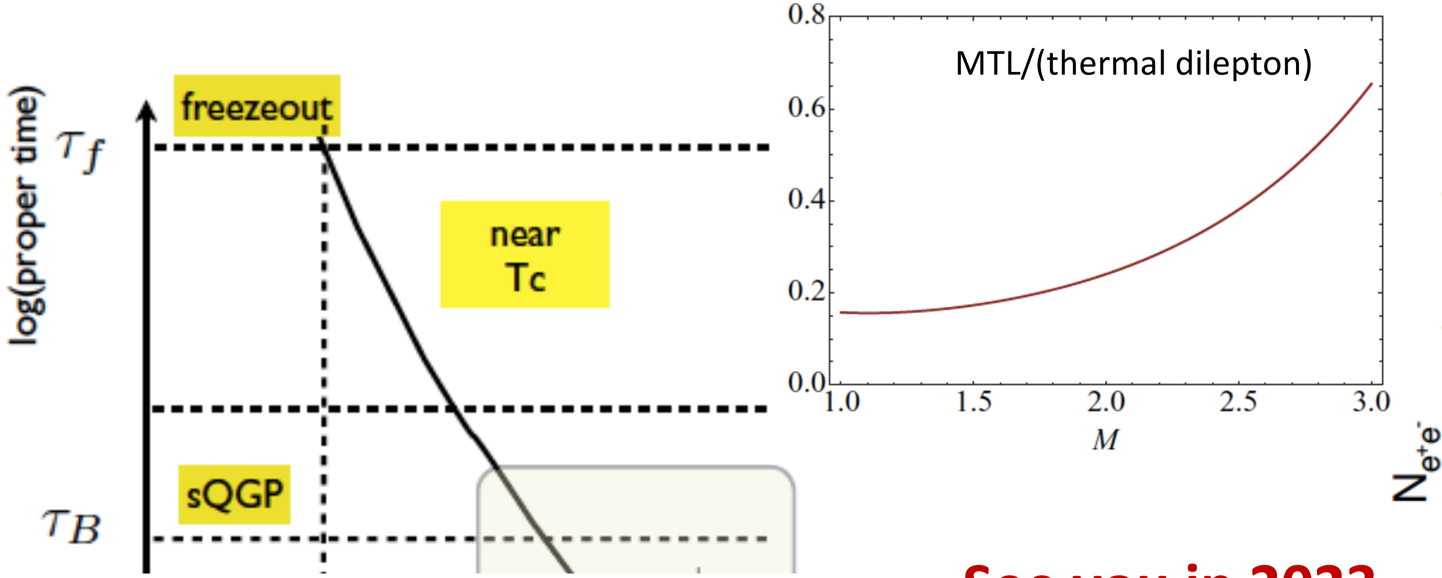
Level observed

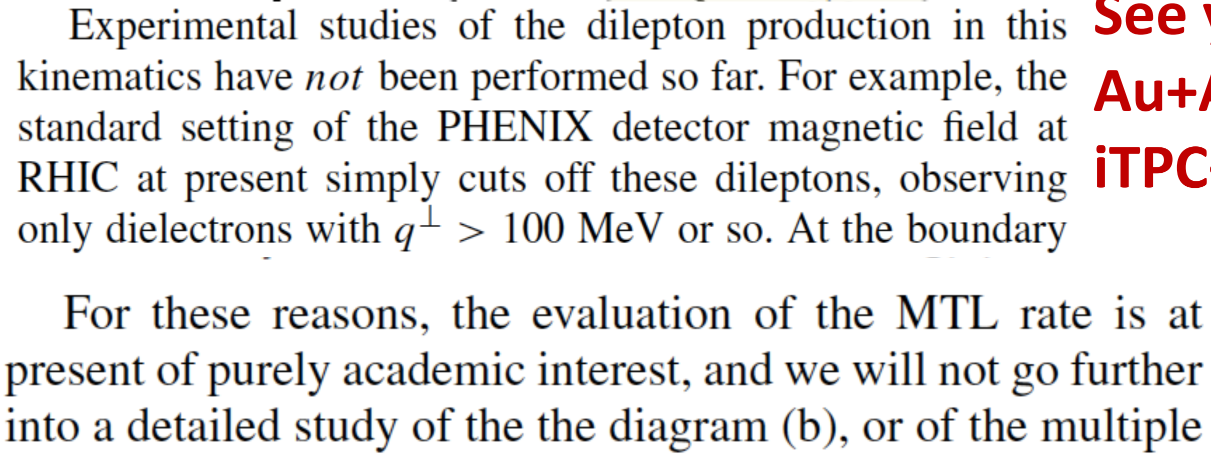
G. Inghirami et al., arXiv: 1609.03042

Radical Ideas, crazy experiments?

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

BAŞAR, KHARZEEV, AND SHURYAK



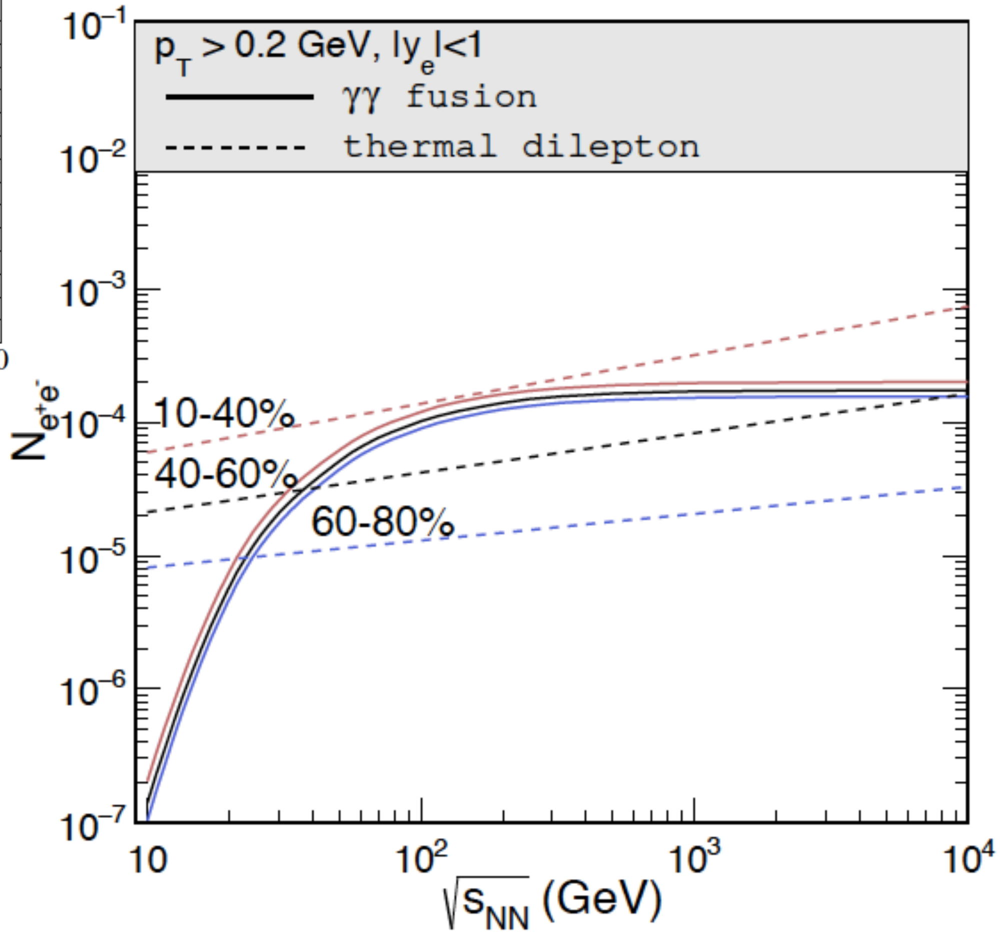


Experimental studies of the dilepton production in this kinematics have *not* been performed so far. For example, the standard setting of the PHENIX detector magnetic field at RHIC at present simply cuts off these dileptons, observing only dielectrons with $q^{\perp} > 100$ MeV or so. At the boundary

For these reasons, the evaluation of the MTL rate is at present of purely academic interest, and we will not go further into a detailed study of the the diagram (b), or of the multiple

See you in 2023
Au+Au
iTPC+EPD+eTOF

arXiv:1809.07049
Klusek-Gawenda, Rapp, Schaefer, Szczurek



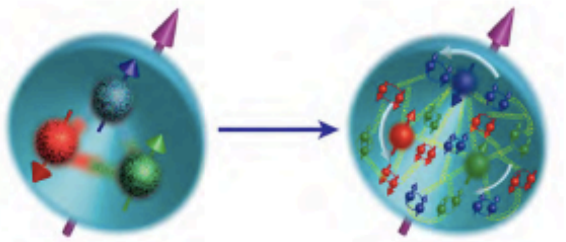
2021+: Science case

Unique program addressing fundamental questions in QCD - strongly endorsed by PAC

Exploits mid-rapidity upgrades from BES-II and new forward detectors

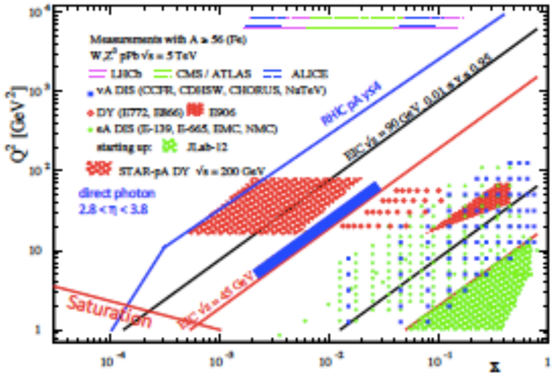
pp

- 3-dim. characterization of proton in momentum and spatial coordinates



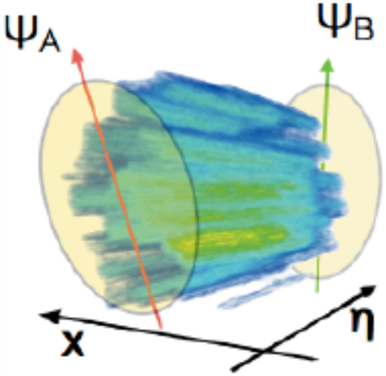
p+A

- Nature of initial state and hadronization in nuclear collisions
- Onset and A-dependence of saturation


pA@RHIC: unique kinematics

A+A

- Longitudinal medium characterization
- Precision flow measurements via long range correlations
- QGP response to B field via low-p_T dielectrons
- Rapidity dependence of Global Polarization

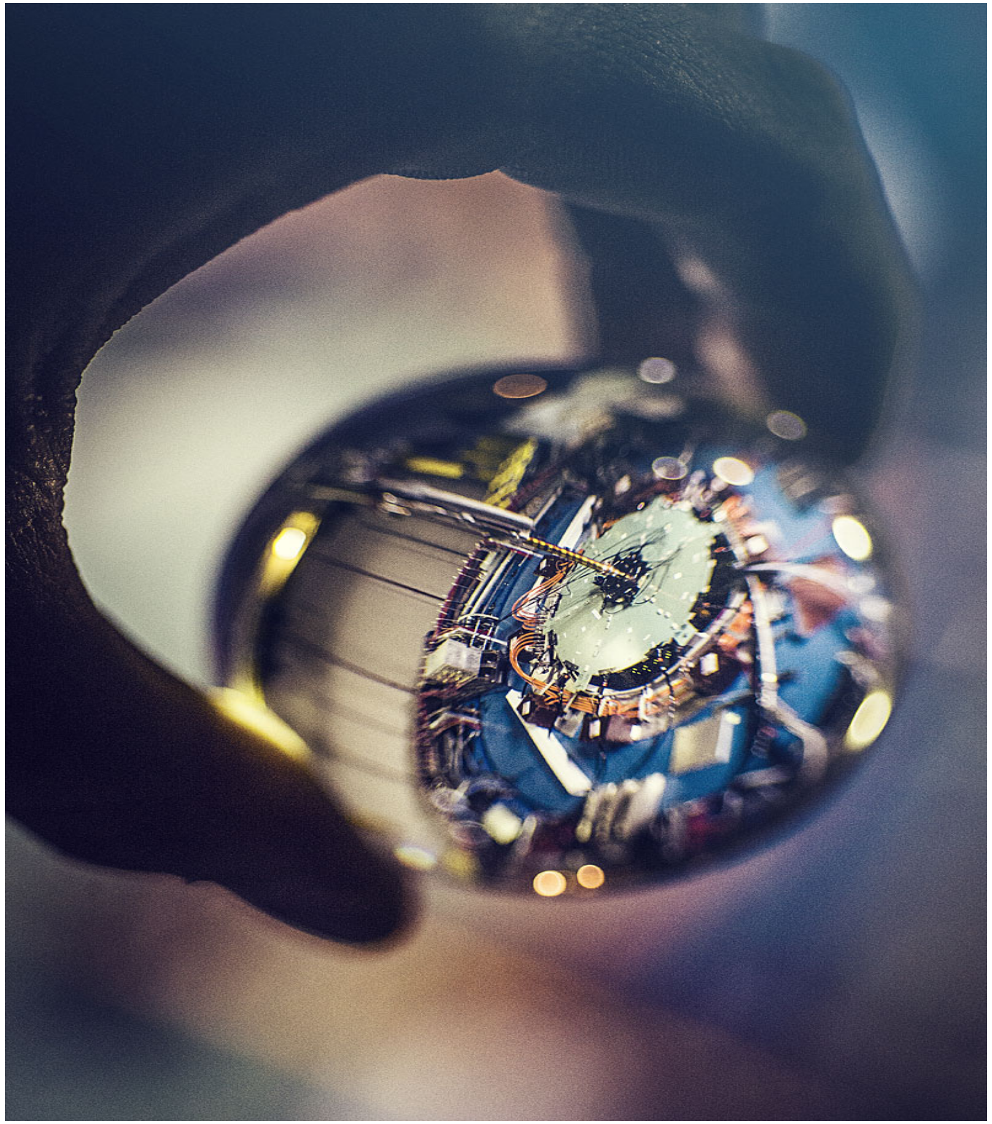


Essential input to RHIC's cold and hot QCD programs and realizing the scientific promise of the EIC

Solenoidal Tracker at RHIC

Artistic rusty representation of past and present

Crystal Ball prediction of future (literately)



Still an indispensable discovery detector

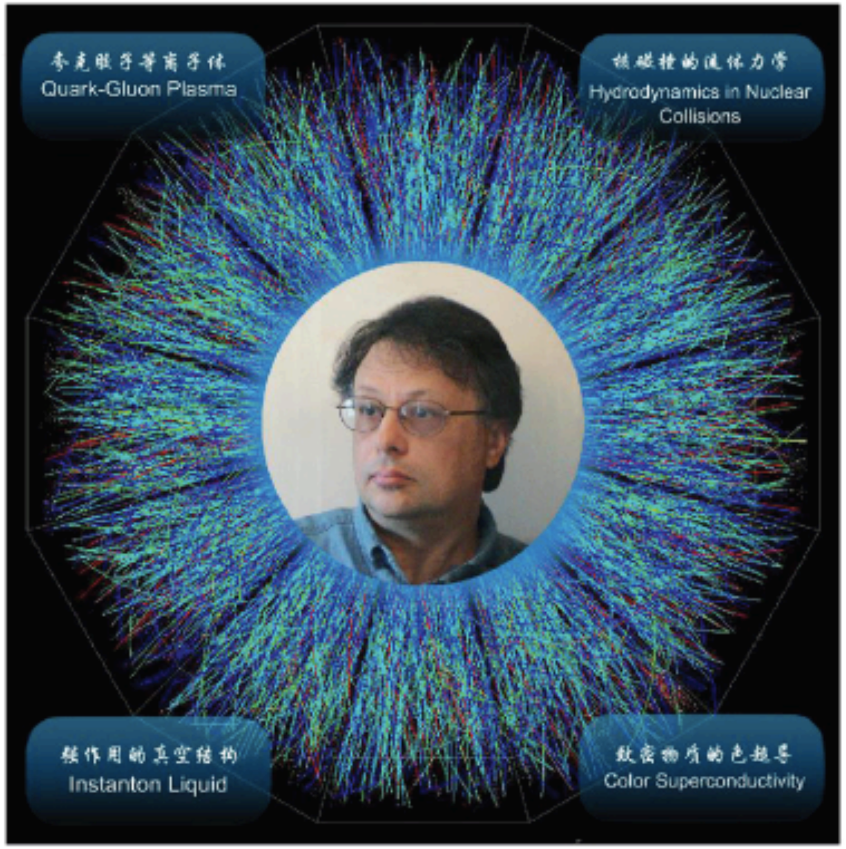
Volume 78B, number 1 PHYSICS LETTERS 11 Spetember 1797

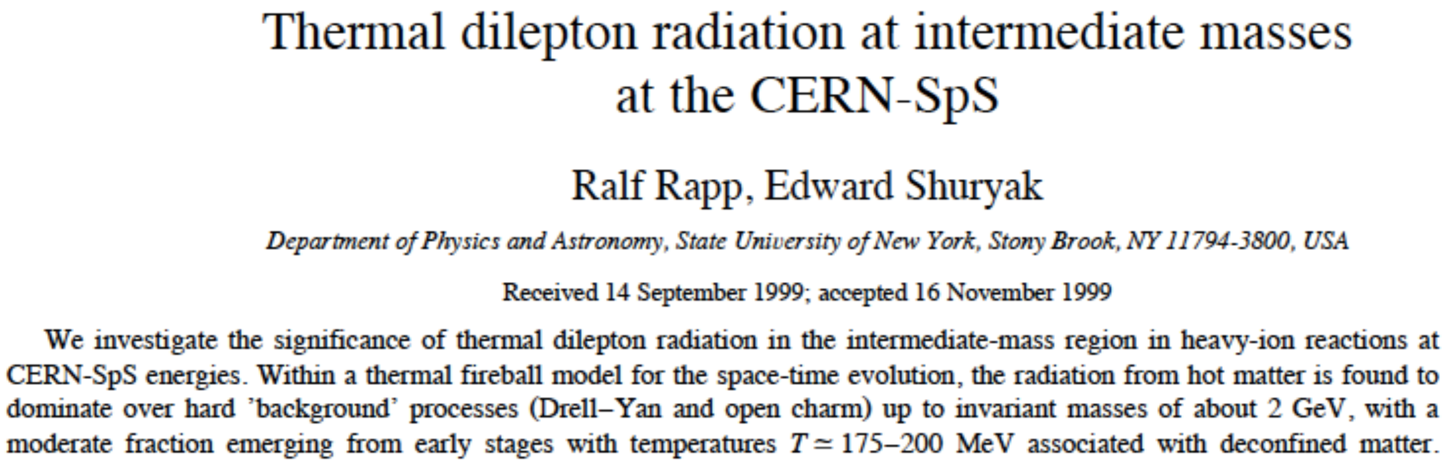
QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS

E.V. SHURYAK
Institute of Nuclear Physics, Novosibirsk, USSR

Received 16 March 1978

QCD calculations of the production rate in a quark–gluon plasma and account of the space–time picture of hadronic collisions lead to estimates of the dilepton mass spectrum, $p_\perp$ distributions of $e^\pm$, $\mu^\pm$, γ, $\pi^\pm$, production cross sections of charm and psions.





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

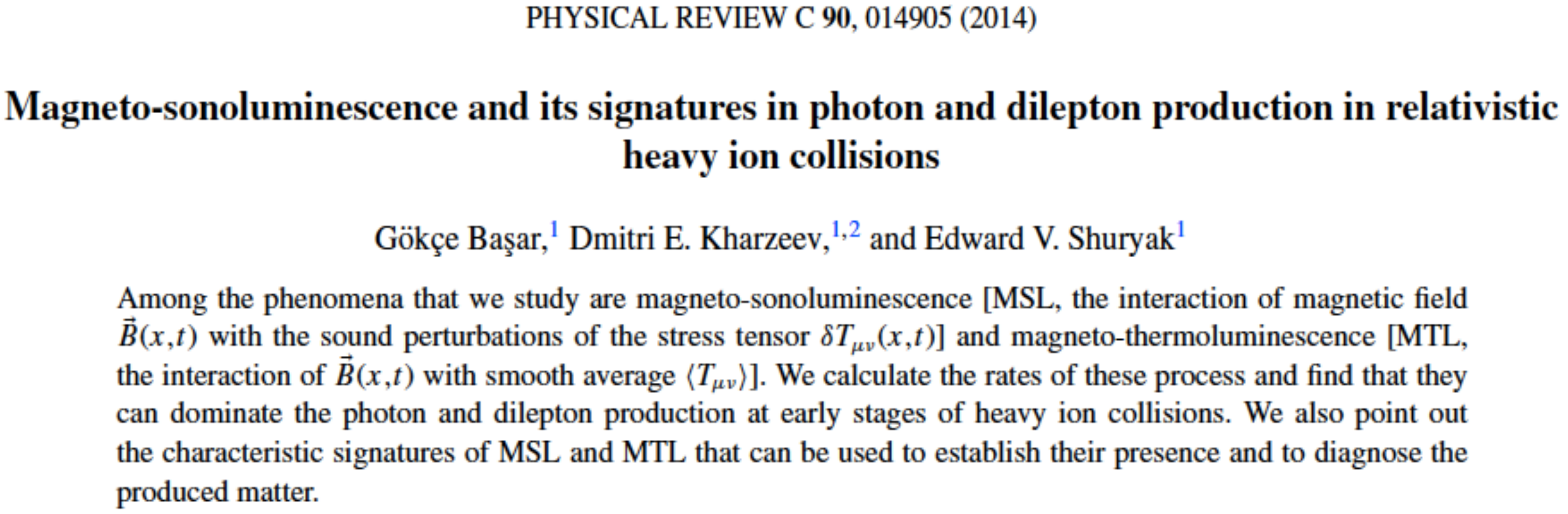
Received 14 September 1999; accepted 16 November 1999

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.

backup

Higher order QED correction

G. Baur et al. Phys. Report 364 (2002) 359
arXiv:0112211

(f) May be different in UPC and peripheral

Low invariant mass (~<1GeV), large formation time middle rapidity

$$\gamma + \gamma \to e^+ + e^- + \gamma .$$

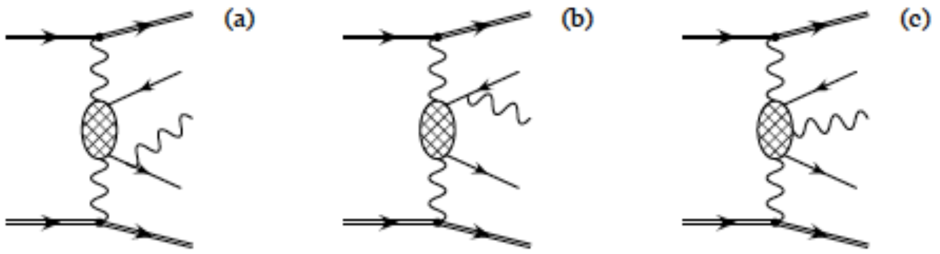


Fig. 34. Emission of a bremsstrahlung photon from pairs produced electromagnetically. Process (a) and (b) are dominant in the infrared regime. For the calculation either the IR approximation together with a full calculation of the pair production was used or a full calculation of all three diagrams together with photon spectra from double equivalent photon approximation (DEPA). Similar diagrams, where the photon line is attached to the ions are generally small due to the heavy mass of the ions. They are neglected here.

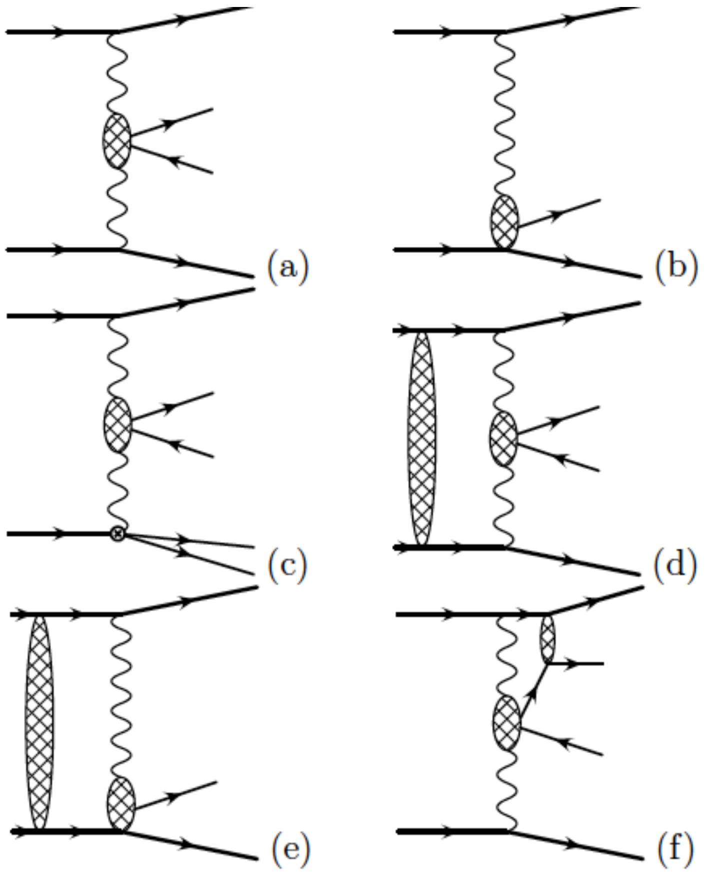


Fig. 3. In the collision of either leptons with hadrons or hadrons with hadrons photon-photon (a) and photon-hadron collisions (b) can be studied. The principal diagrams are shown schematically here. In the collisions of hadrons additional effects need to be taken into account: inelastic photon emission processes (c), "initial state interaction" (d) and (e), as well as final state interaction (f).