Gertrude Scharff-Goldhaber Prize 2023 presented to Xiaofeng Wang

- "I have been fascinated by physics since I was a young student, I wanted to understand the fundamental nature of matter and energy and the origin and evolution of the universe."
- Wang's study of the Breit-Wheeler process began in the autumn of 2019, under the supervision of Zhangbu Xu (BNL), Chi Yang (Shandong University), and James Daniel Brandenburg (Ohio State University).

Brookhaven National Laboratory

STAR

SHANDONG UNIVERSITY 1901

Energy Dependence of Breit-Wheeler Process in Heavy-Ion Collisions and Its Application to Nuclear Charge Radius Measurements

Xiaofeng Wang （王晓凤）

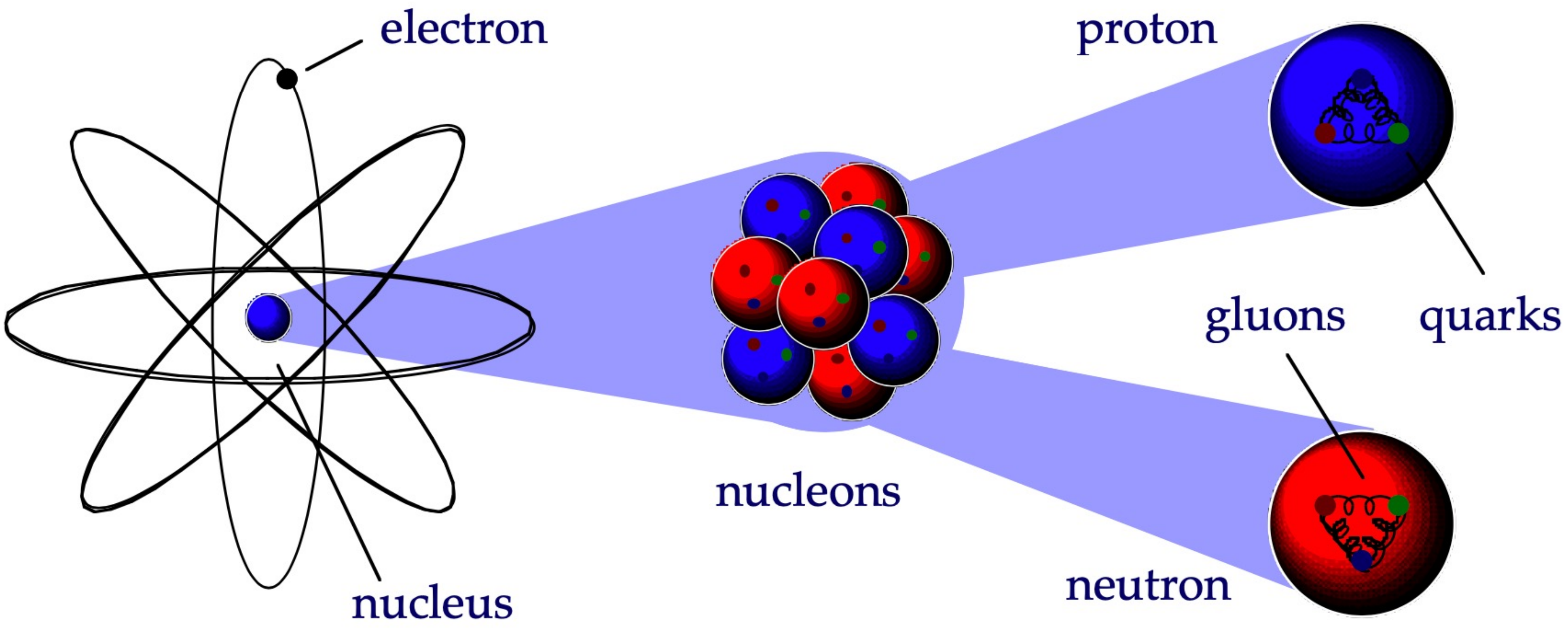
Scharff-Goldhaber Prize Ceremony

August 15, 2023

Outline

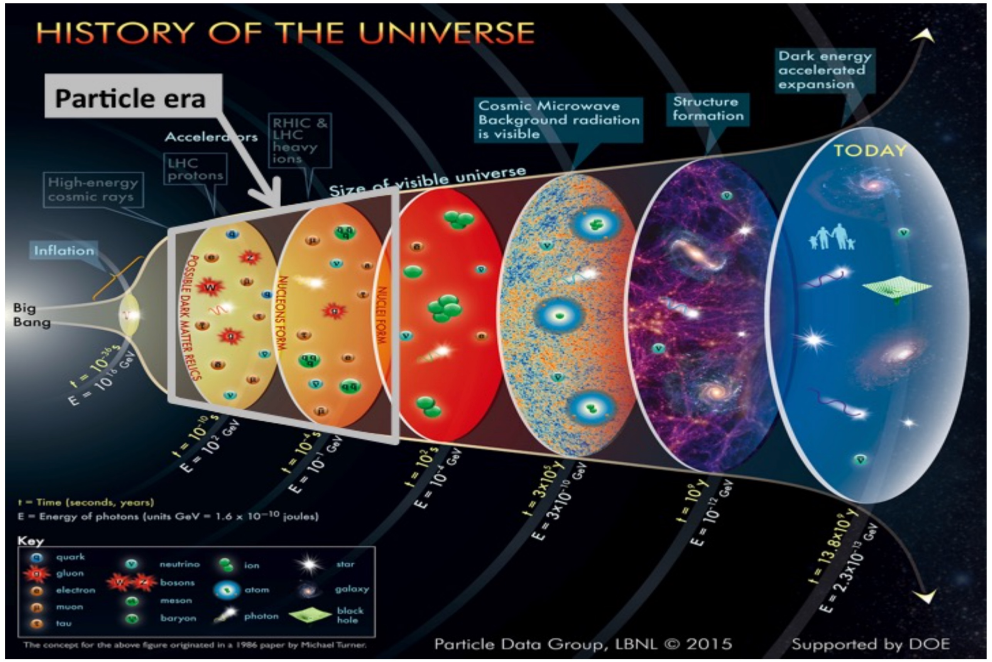
- ◆ Quark Gluon Plasma in Heavy Ion Collisions
- ◆ Breit-Wheeler Process in Heavy Ion Collisions
- ◆ Application of Breit-Wheeler Process
  - ✓ Study the properties of quark gluon plasma
  - ✓ Map the magnetic field
  - ✓ Constrain nuclear charge radii
- ◆ Summary and Perspective

Configuration of Atom



Quarks/gluons: confined in protons and neutrons through strong force

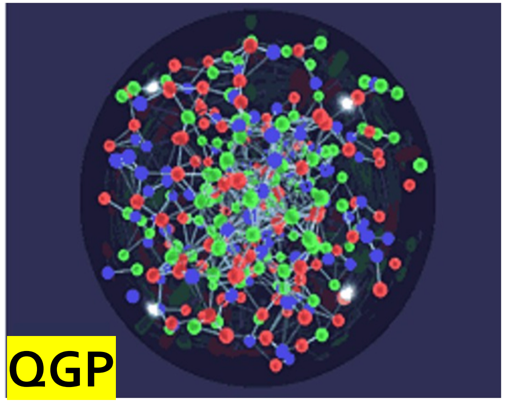
Quark Deconfinement



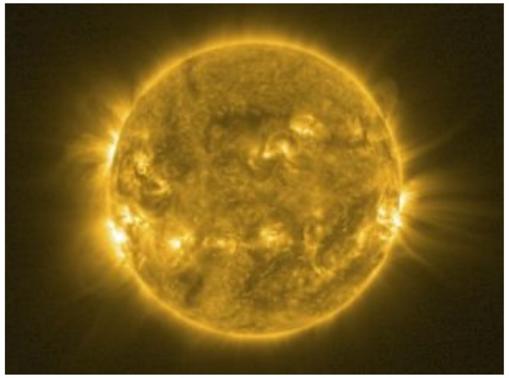
Quark-Gluon Plasma (QGP):

A new state of quark and gluon degrees of freedom

Is it possible to observe QGP in the laboratory?



Relativistic Heavy Ion Collisions: Heated to 10^{12} K !!



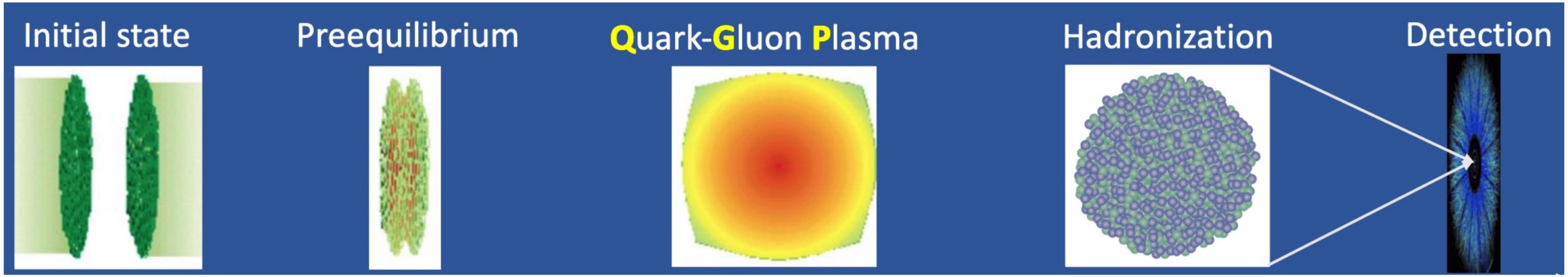
The core temperature of the sun: $2*10^7$K
(quarks are still confined in hadrons)

T. D. Lee (1926-)

the Nobel Prize in Physics in 1957

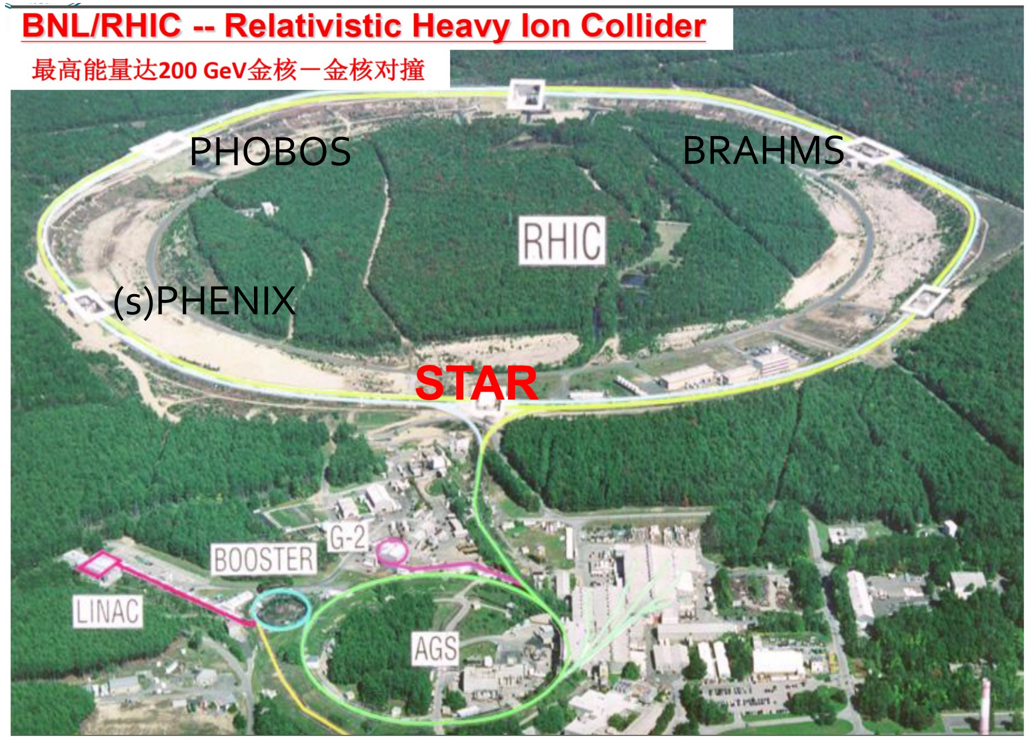
T. D. Lee and G. C. Wick, Phys. Rev. D 9, 2291 (1974).
Vacuum stability and vacuum excitation in a spin-0 field theory.

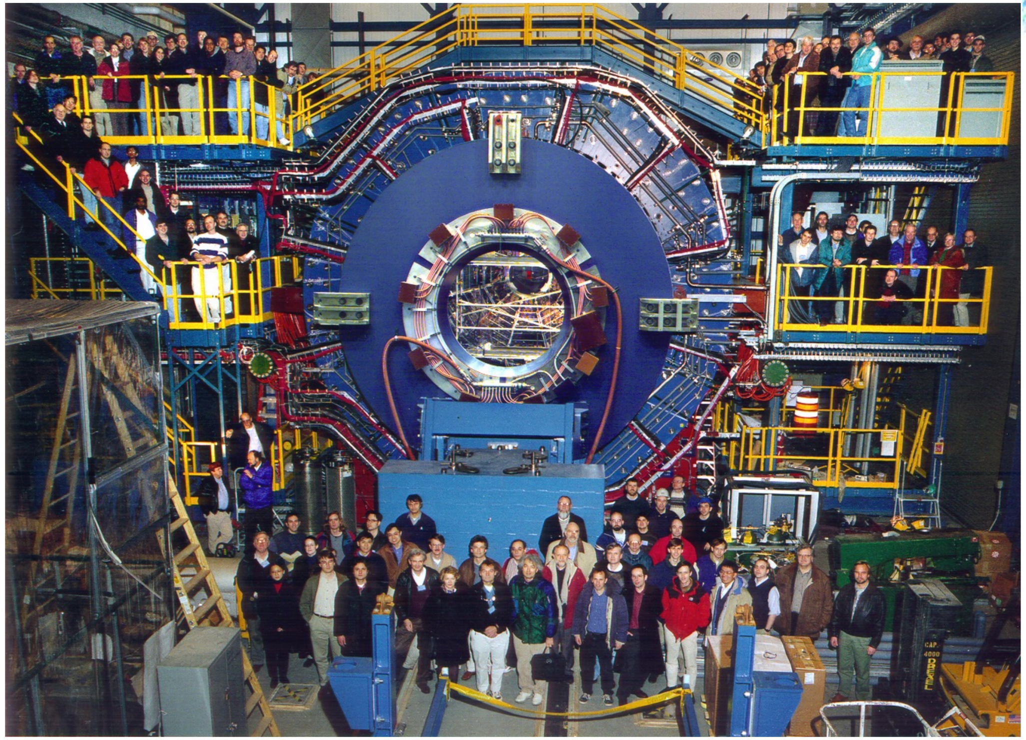
Hottest Temperature in the Lab: About 10^5 times hotter than the center of the Sun



QGP can be created in relativistic heavy ion collisions

Relativistic Heavy Ion Collider (RHIC) and STAR



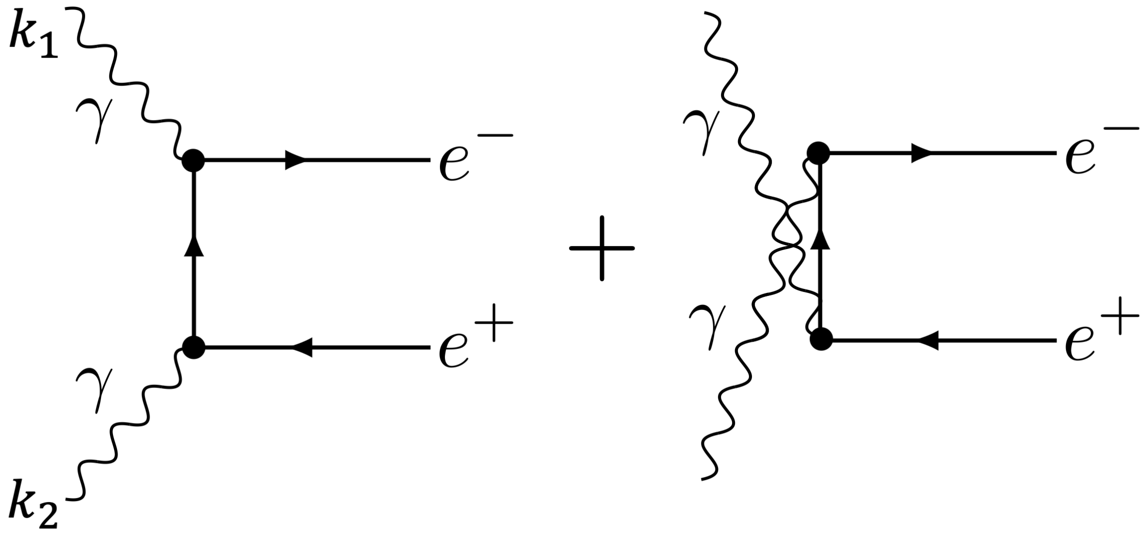


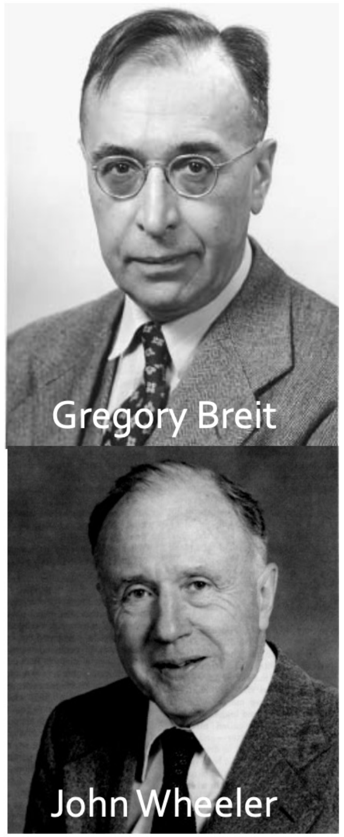
RHIC can create QGP

Solenoidal Tracker At RHIC (STAR) can measure the properties of QGP

Dielectron: No strong interaction → Ideal electromagnetic probe for probing QGP properties

The Breit-Wheeler Process : $\gamma\gamma \rightarrow e^+e^-$





◆**Breit-Wheeler process:**

converting **real** photon into e^+e^-

Breit & Wheeler, Phys. Rev. 46 (1934) 1087

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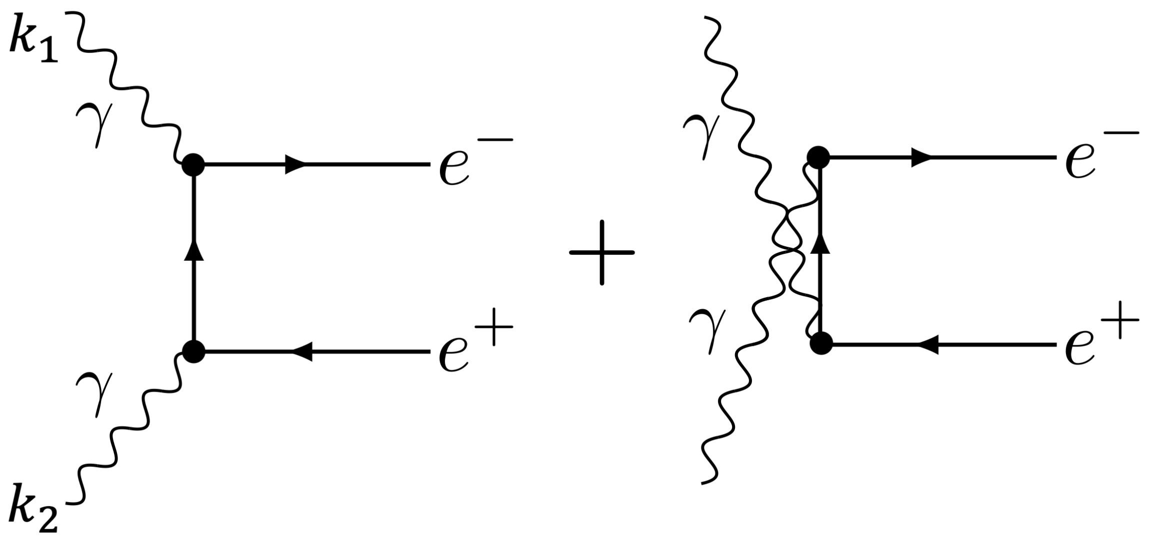
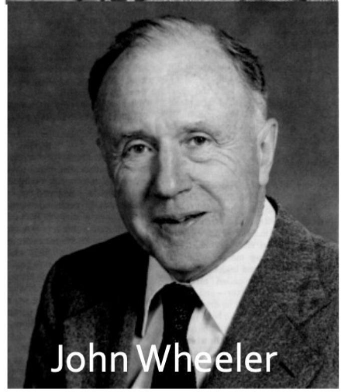


Hard to observe

- ☐ The cross section is small
- ☐ The insufficiently large available densities of photon



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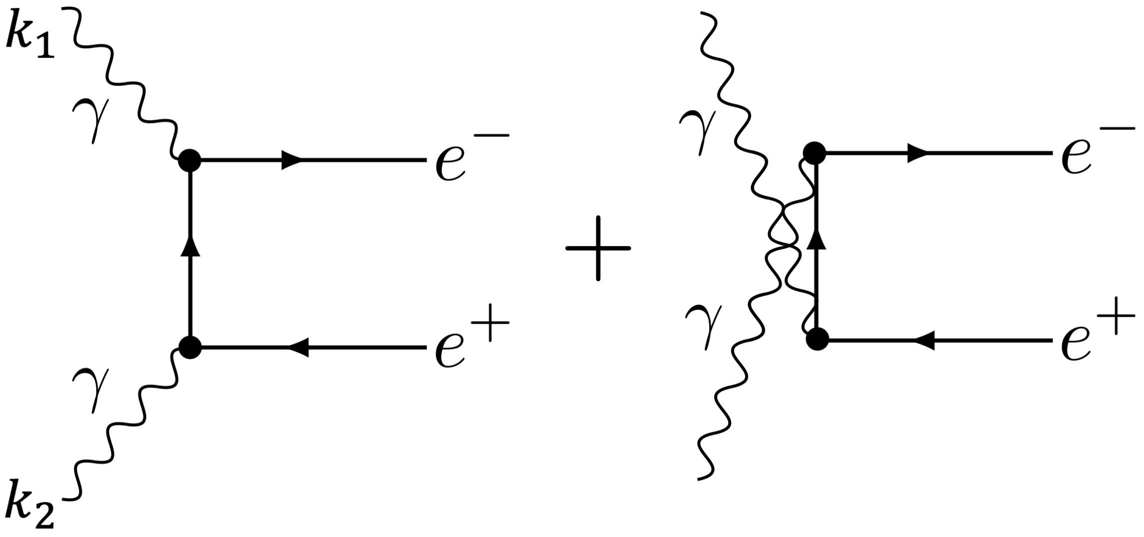

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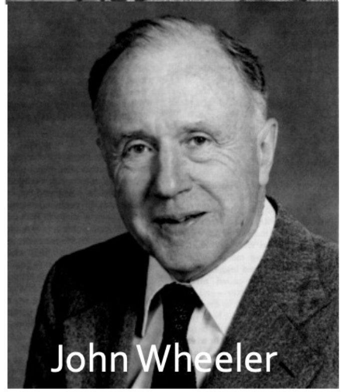


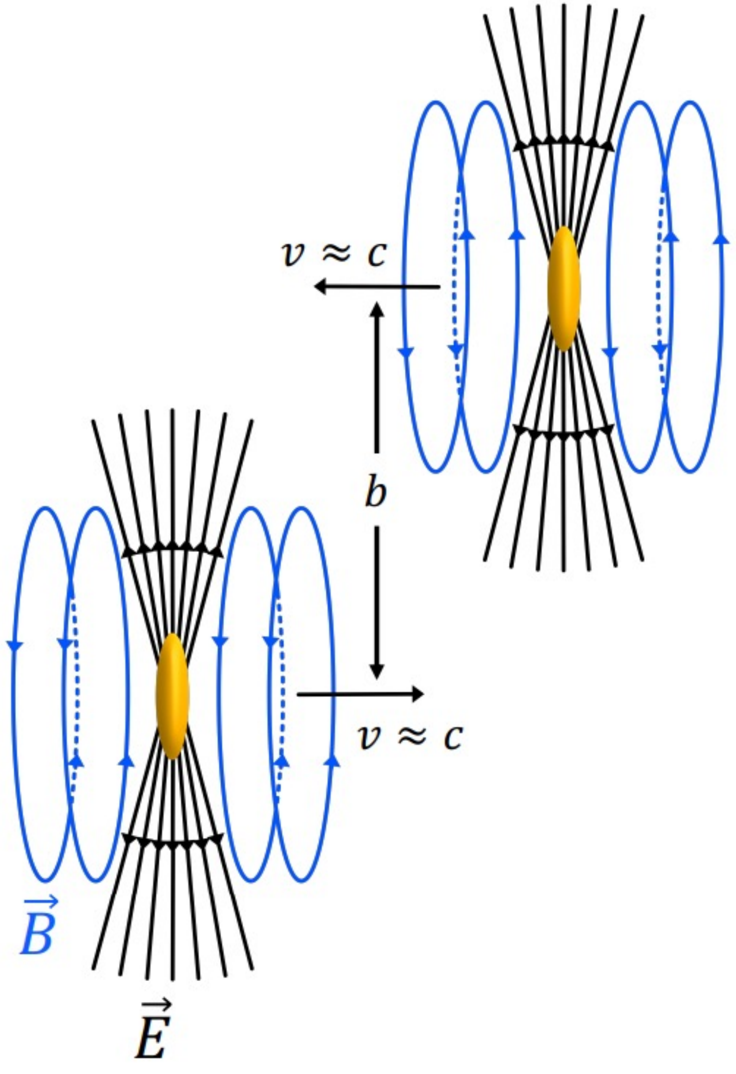
◆ **Breit-Wheeler process:**

converting **real** photon into $e^{+}e^{-}$

Breit & Wheeler, Phys. Rev. 46 (1934) 1087

of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number

Ultra-Peripheral Heavy Ion Collisions (UPCs)



- Highly Lorentz-contracted charged nuclei produce electromagnetic fields (EM)
- Equivalent Photon Approximation (EPA): EM fields → a flux of **quasi-real photons**

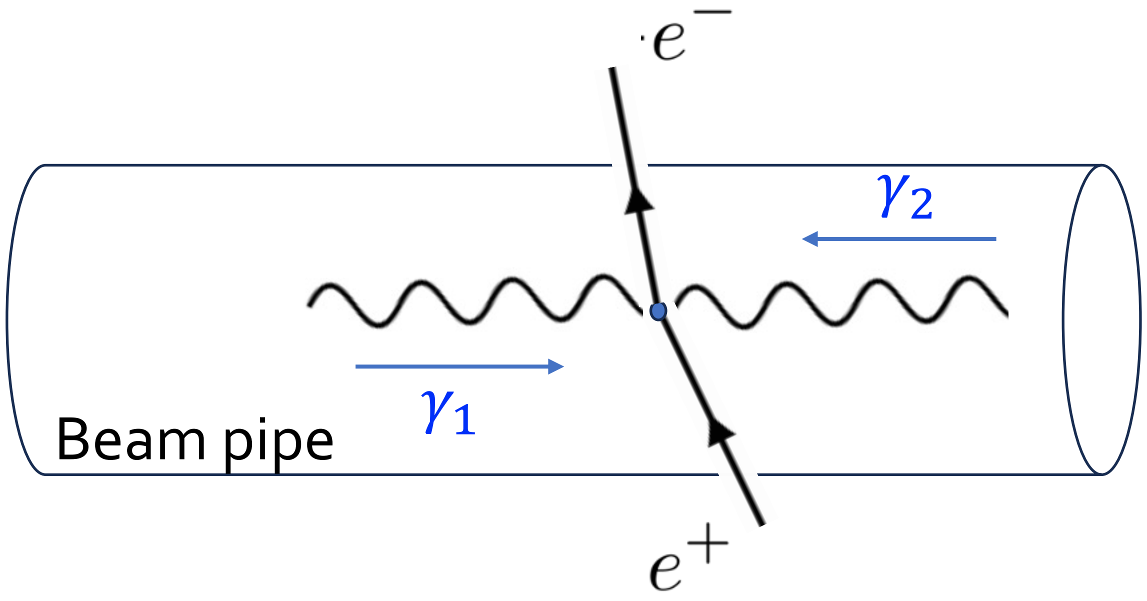
  Weizsäcker, C. F. v. Zeitschrift für Physik 88 (1934): 612
- High photon density from highly charged nuclei ($\propto Z^2$)
- Virtuality $Q^2 \lesssim (\hbar/R_A)^2$ in UPCs $\Longrightarrow$ **almost real**

  Ann.Rev.Nucl.Part.Sci. 55 (2005) 271-310
- Virtuality cancels at low photon transverse momentum

  Vidovic, M. and Greiner, M. and Best, C. Phys.Rev.C 47 (1993) 2308-2319

Breit-Wheeler Process Was Observed in UPCs at STAR

STAR, PRL 127 (2021) 052302



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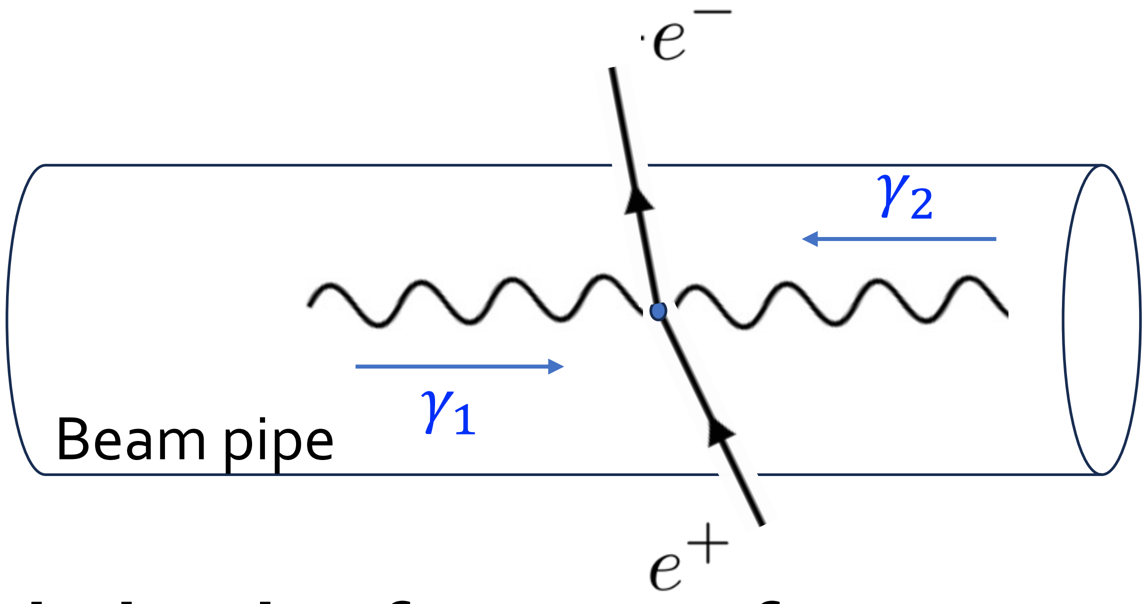

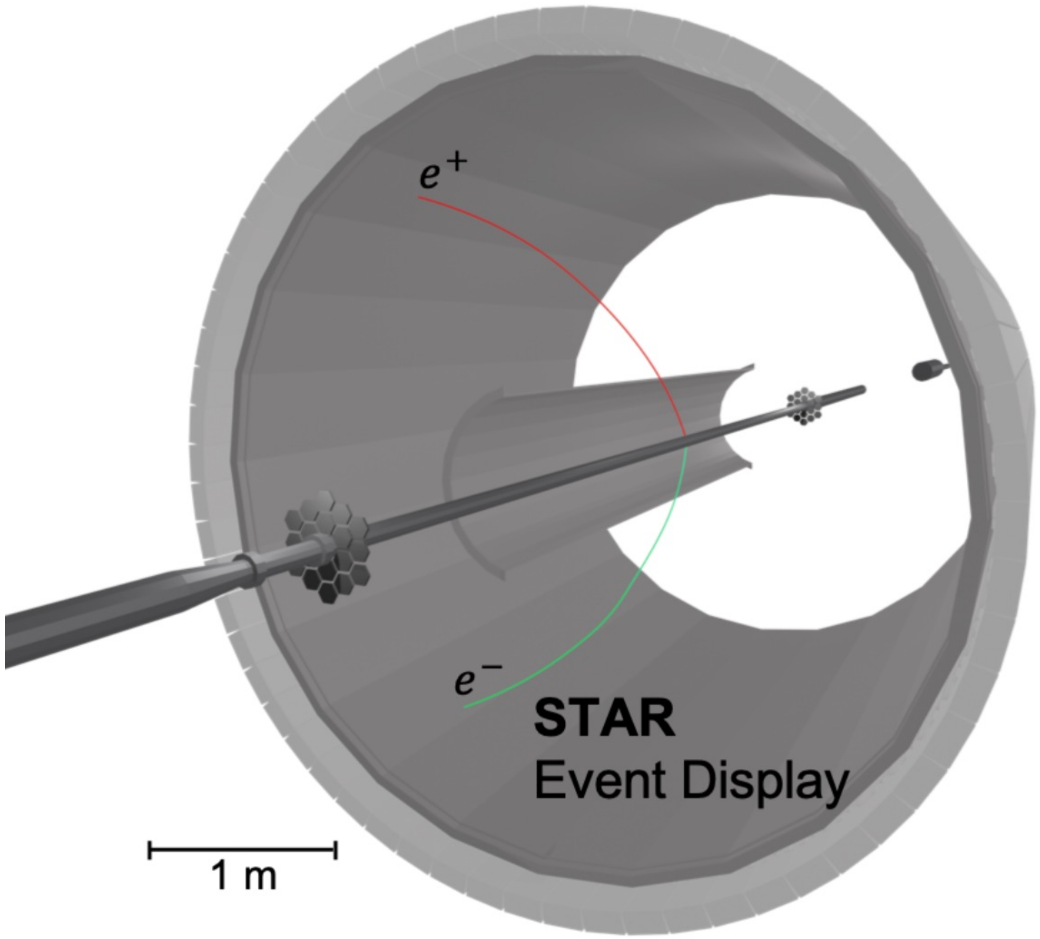

Distinctive features of BW process

- Exclusive production of e^+e^- pair

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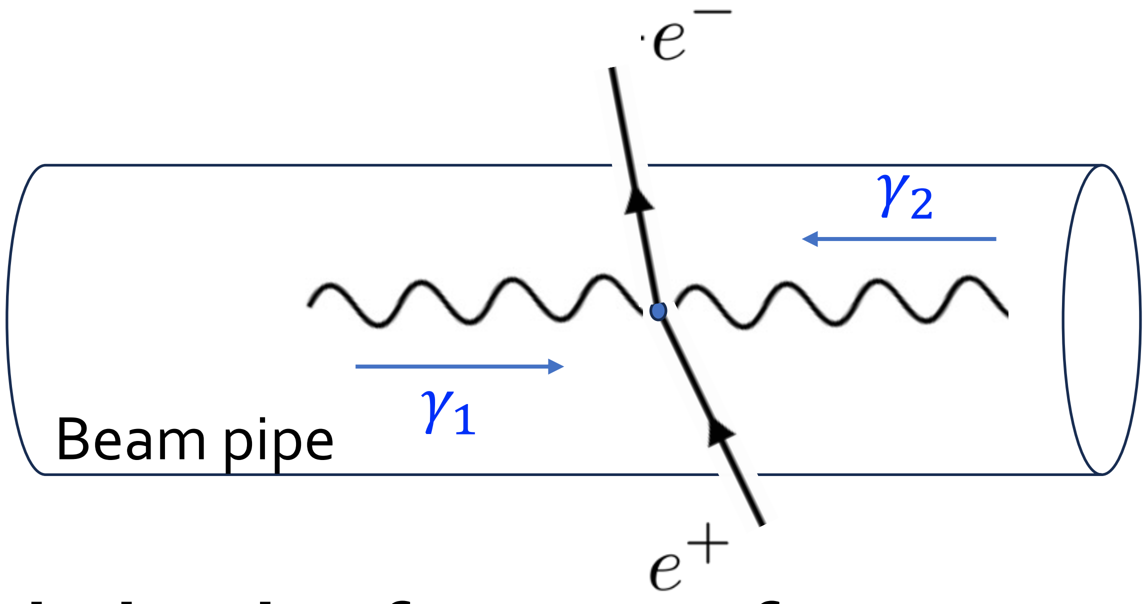
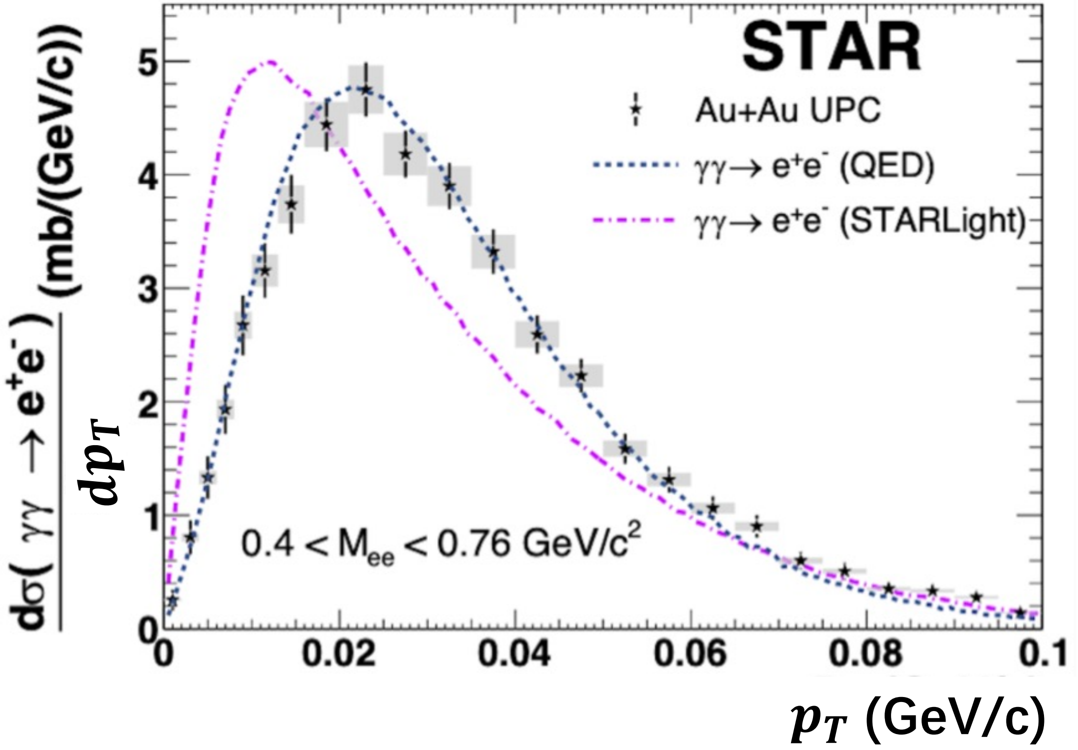


QED: Quantum ElectroDynamics



Distinctive features of BW process

- Exclusive production of e^+e^- pair
- **Concentrated at low transverse momentum(p_T)**
  - **Back to back in transverse plane**

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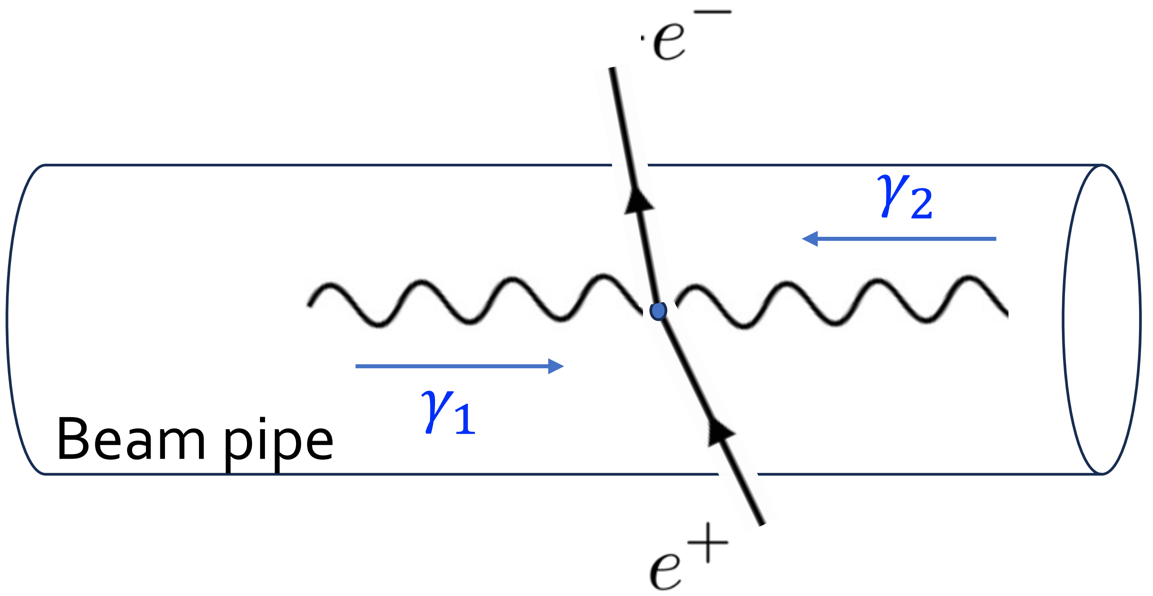
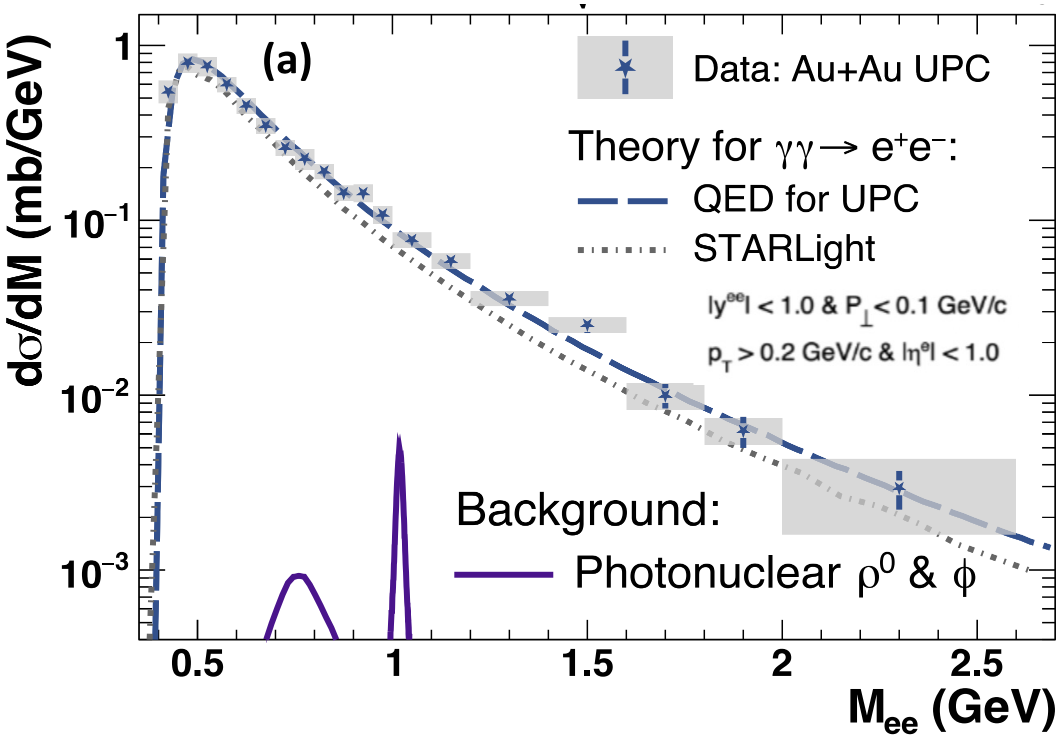
STAR, PRL 127 (2021) 052302



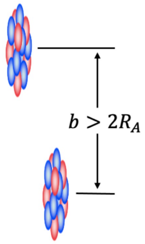
Einstein's mass-energy equation
$E^2 - p^2 = M^2, p\sim 0 \Longrightarrow E^2 = M^2$



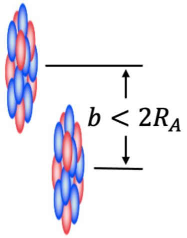
Distinctive features of BW process

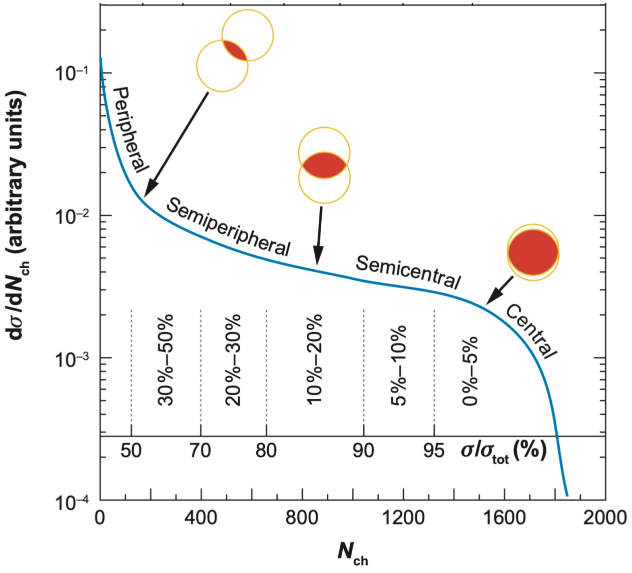
- Exclusive production of e^+e^- pair
- **Concentrated at low transverse momentum(p_T)**
  - **Back to back in transverse plane**
- Smooth invariant mass spectra
  - Quantum number conservation

Breit-Wheeler Process in Hadronic Heavy Ion Collisions (HHIC)



UPC ⟹ HHIC





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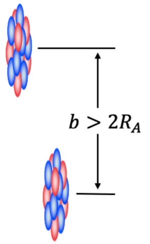
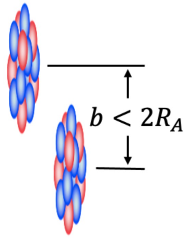
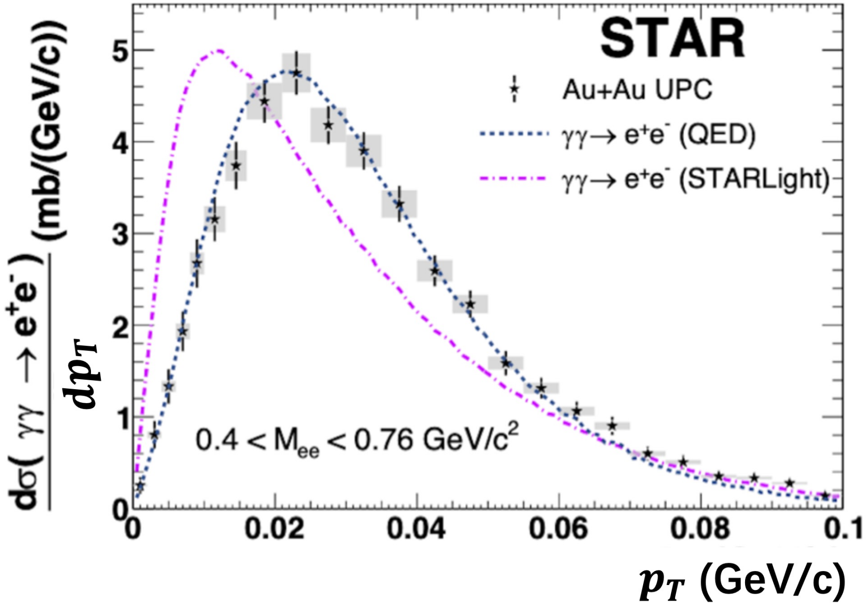


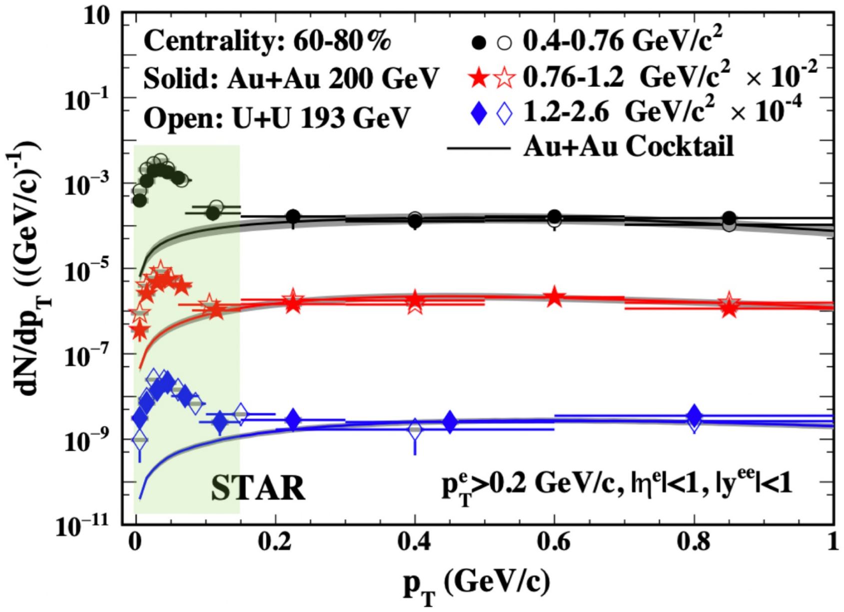
UPC

HHIC

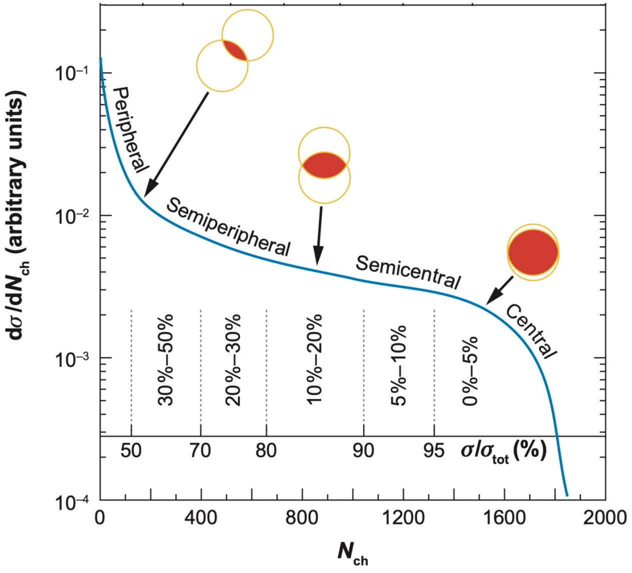




STAR: Phys.Rev.Lett. 127, 052302 (2021)



STAR: Phys.Rev.Lett. 121, 132301 (2018)



Photon-induced dielectrons as probes to study the properties of QGP in HHIC

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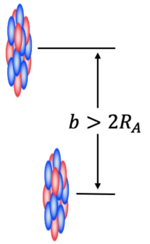

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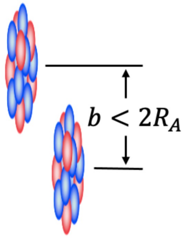

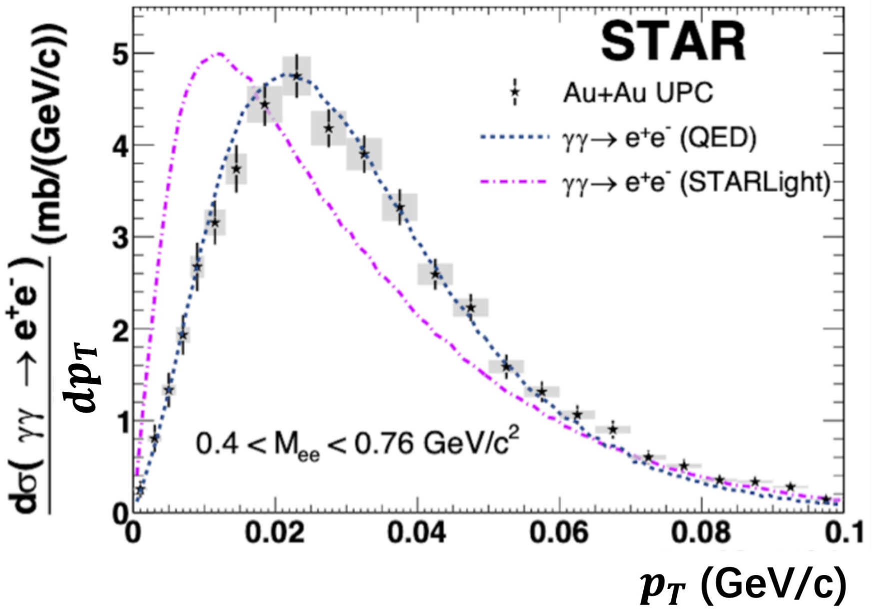

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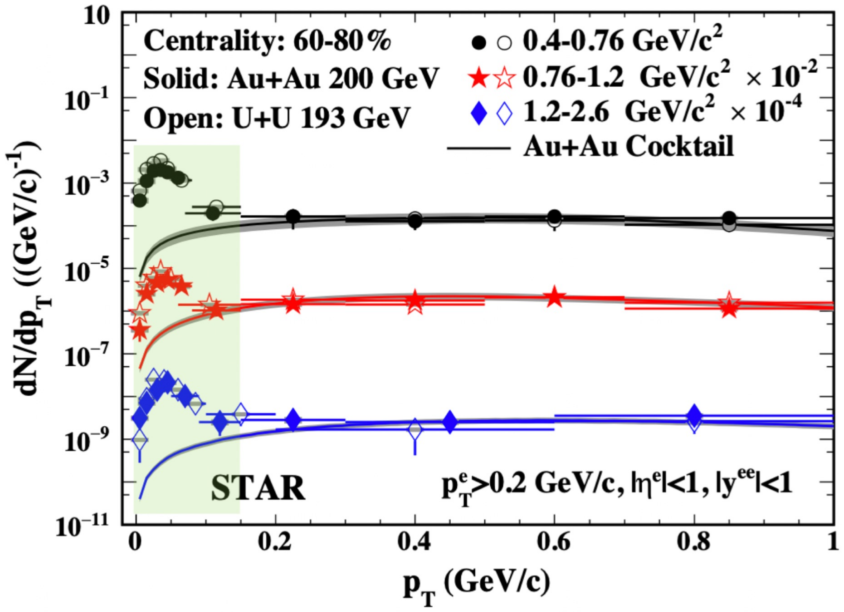

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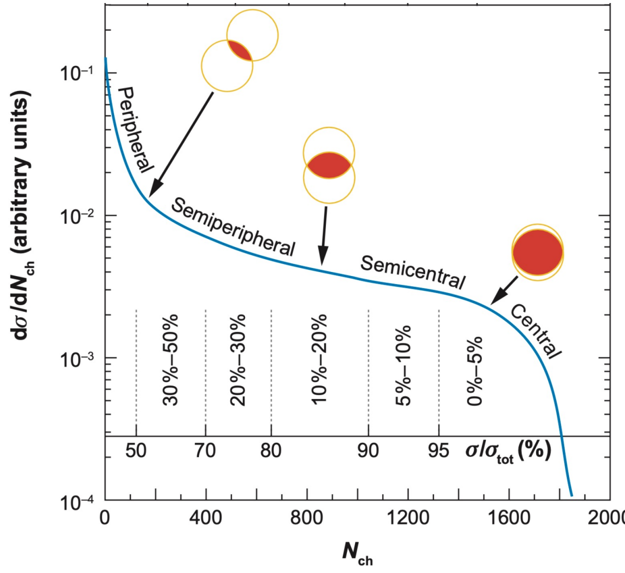

Data samples of 54 GeV and BES-I program

Energy	27 GeV	39 GeV	54 GeV	62 GeV
Used MB events	68M	132M	875M	62M

Photon-induced dielectrons as probes to study the properties of QGP in HHIC

Signal Extraction

Extracting the signal in signal/background is only 1%!

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methods

- Like sign (to remove combinational and correlated background)
- Mix event (to correct acceptance difference)
- Efficiency correction (for detector inefficiency and PID)
- Hadronic cocktail simulation to remove hadron contribution

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The first measurement of 80-100% centrality at STAR

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- No measurement of input (hadron p_T spectra, yield...)
- trigger bias in peripheral collisions

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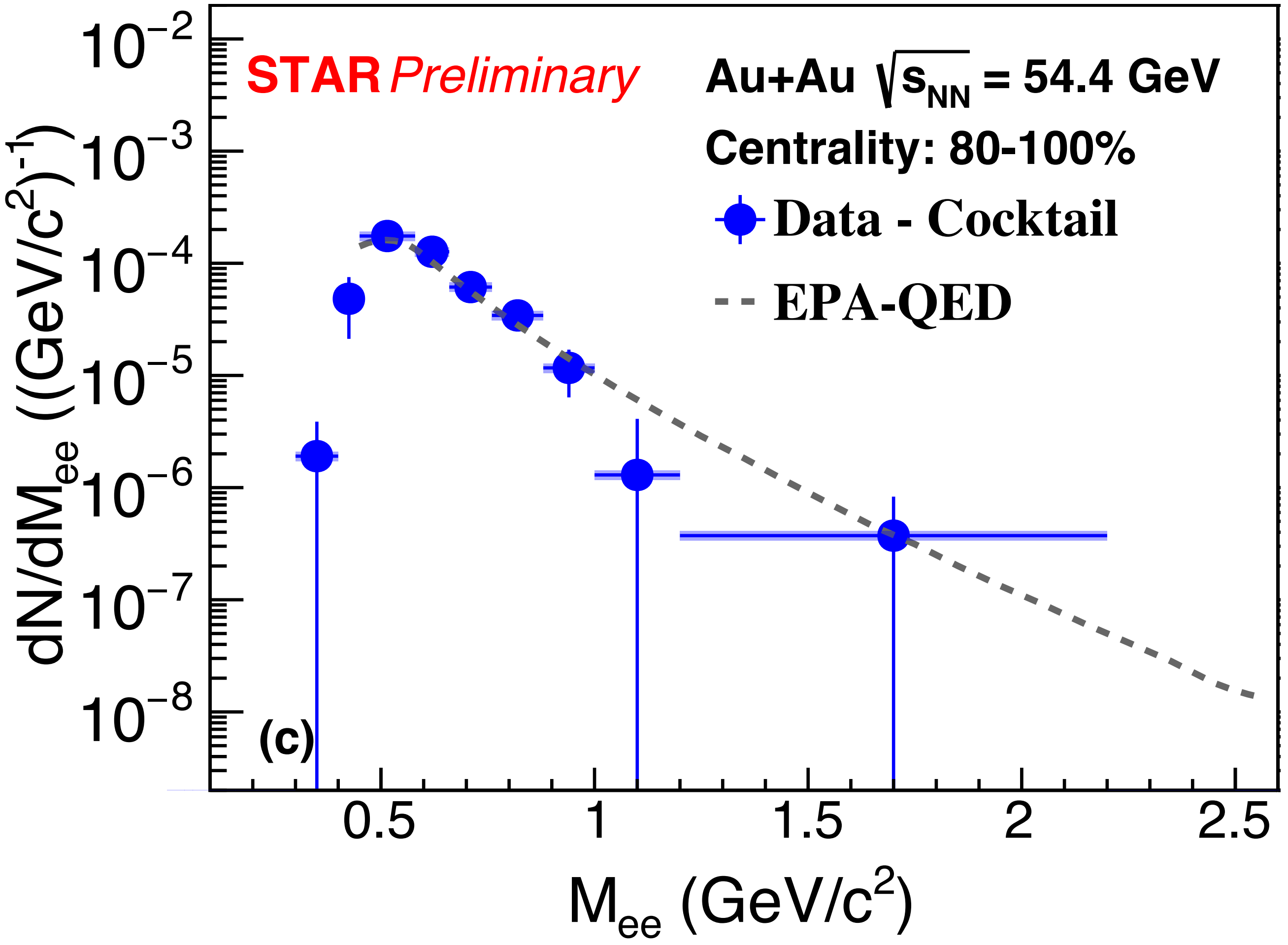
The first measurement of 80-100% centrality at STAR

- No measurement of input (hadron p_T spectra, yield…)
  - Tsallis Blast-Wave model
  - Two Component model and Glauber model
- trigger bias in peripheral collisions
  - Glauber model and QED prediction

methods

Invariant Mass Distribution at Low-p_T

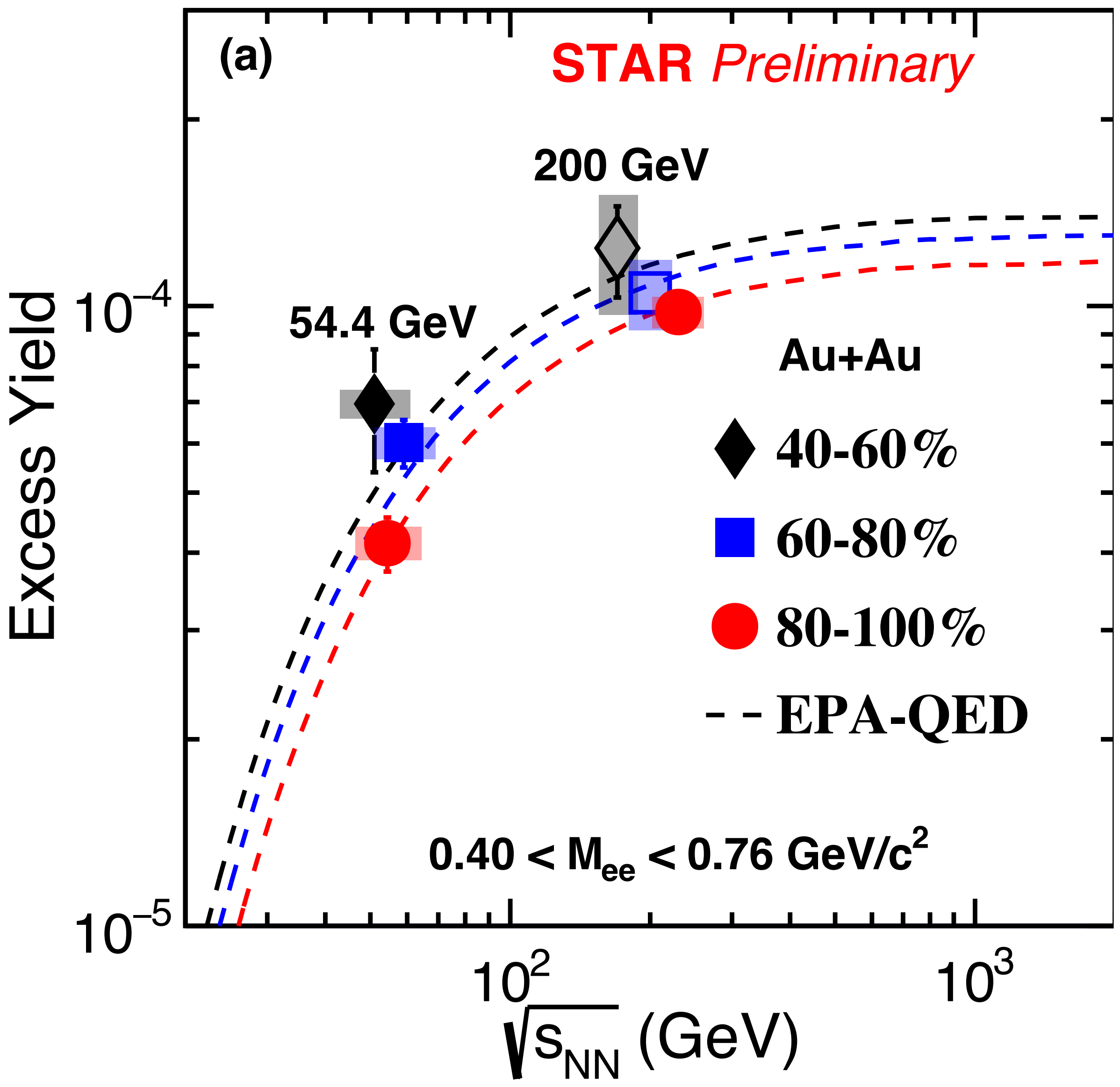


Excesses (Data - Cocktail) are extracted

No vector meson observed ($\gamma\gamma \nrightarrow$ vector meson)

Excesses are well described by lowest order EPA-QED predictions

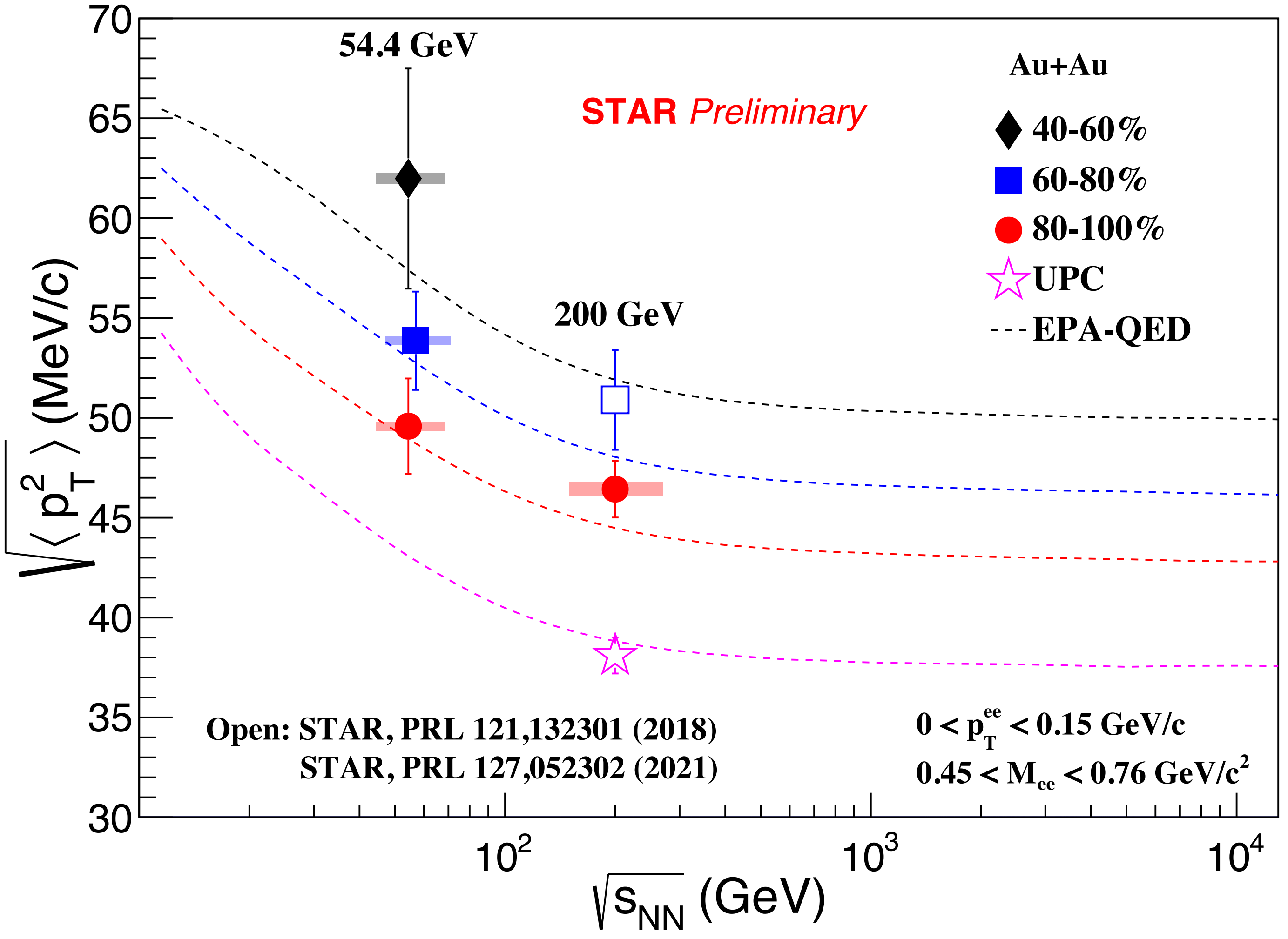
Energy Dependence of Excess Yield



Excess yield increase with beam energy

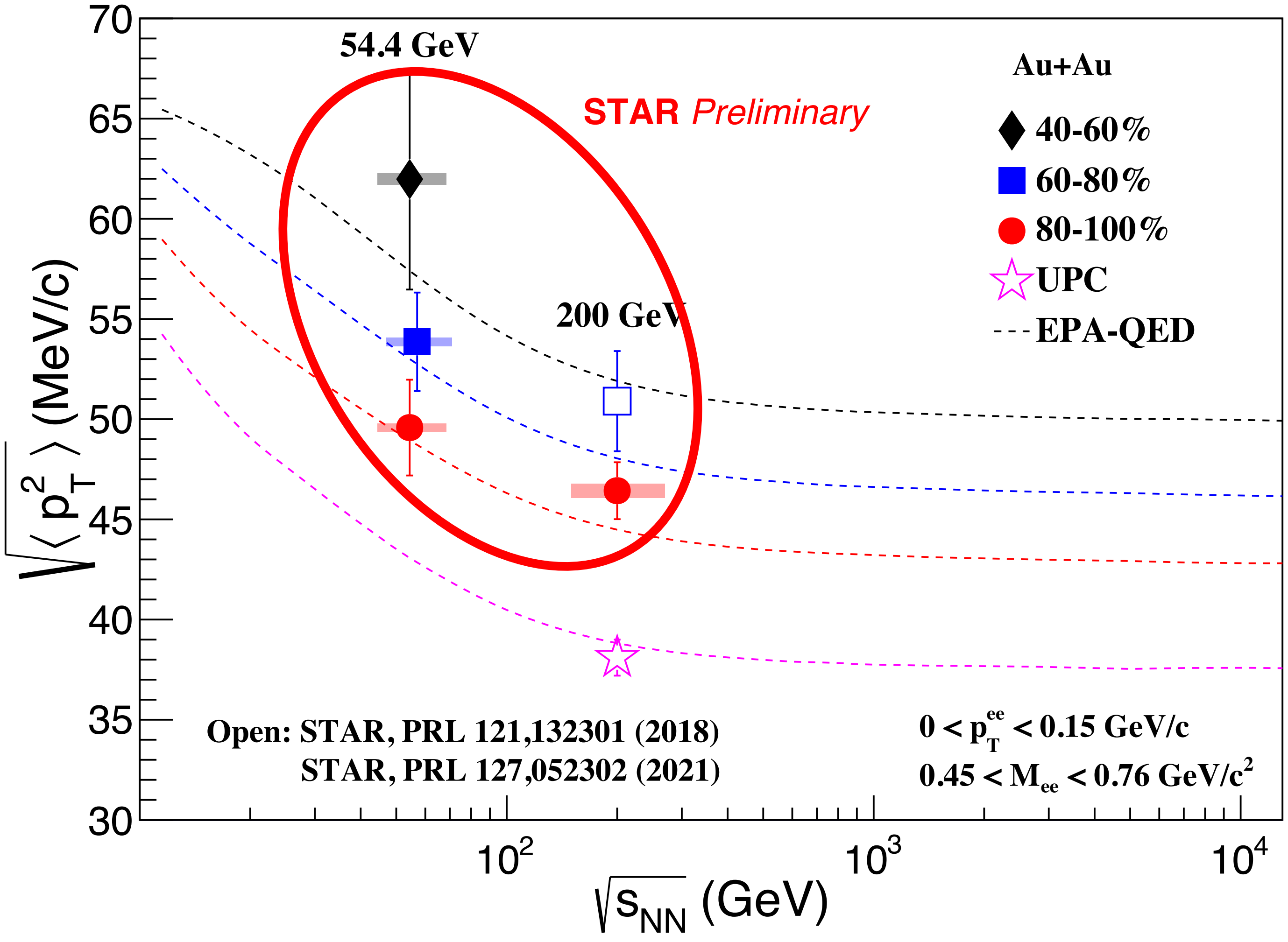
EPA-QED predicts similar energy dependence

Energy Dependence of $\sqrt{\langle p_T^2 \rangle}$



- The $\sqrt{\langle p_T^2 \rangle}$ of e^+e^- pairs decreases with increasing beam energy

Energy Dependence of $\sqrt{\langle p_T^2 \rangle}$

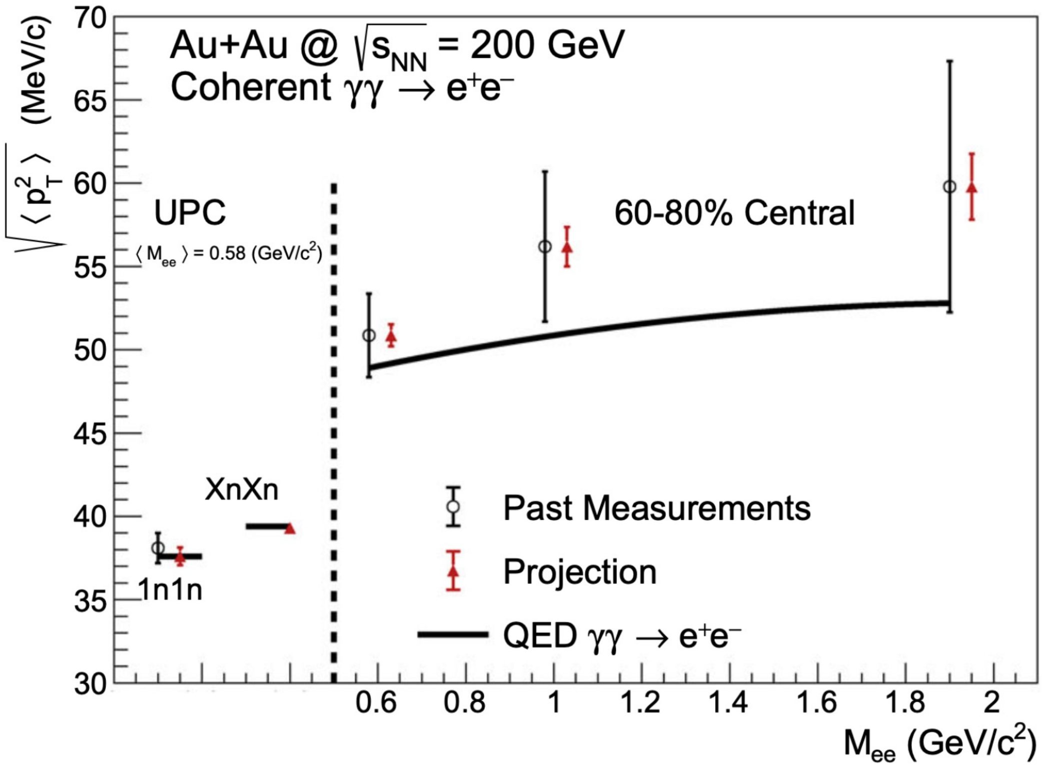


- The $\sqrt{\langle p_T^2 \rangle}$ of e^+e^- pairs decreases with increasing beam energy
- Indication of final state effect

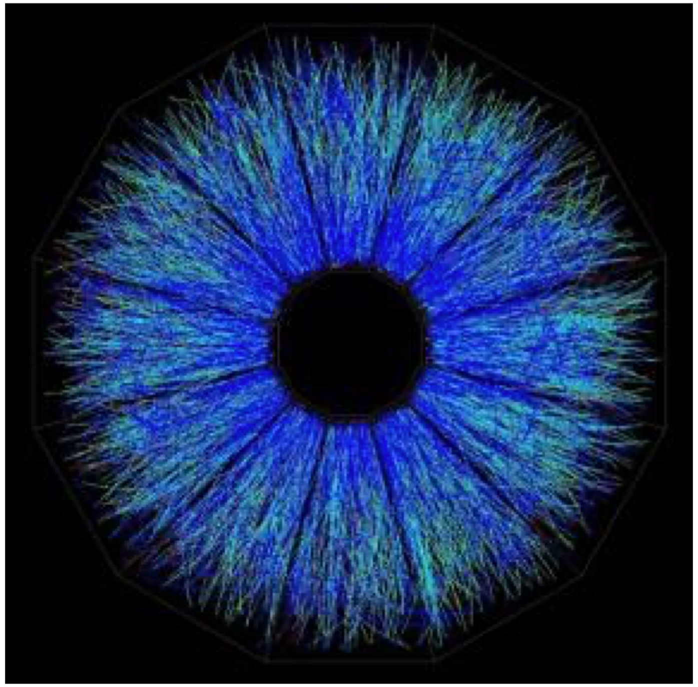
Are There Final-State QED Effect?

higher statistics

STAR collaboration Beam Use Requests for Run-23-25

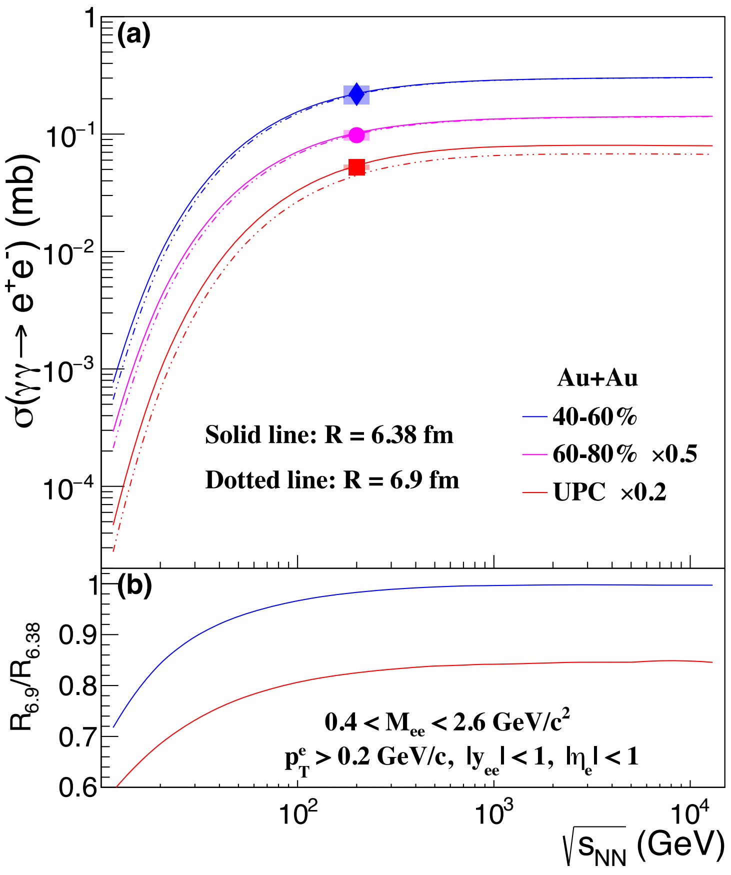


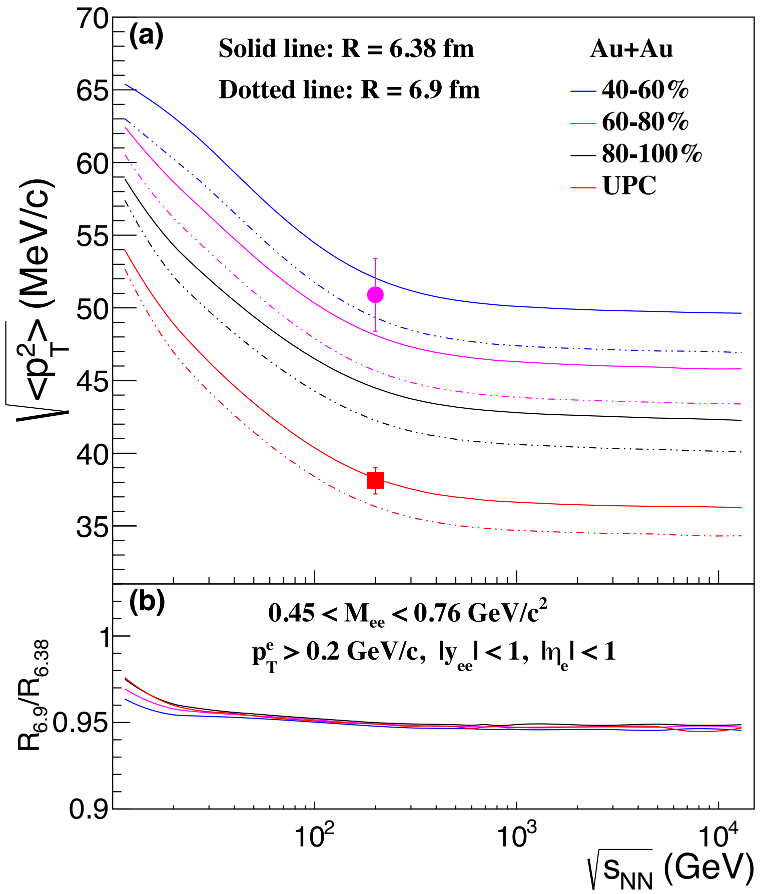
Upgrade of inner Time Projection Chamber



lower p_T, lower systematic uncertainty

Energy Dependence of Cross Section and $\sqrt{\langle p_T^2 \rangle}$





The kinematics of the Breit-Wheeler process are
sensitive to the details of the **nuclear charge distribution**

X. W, J.D. Brandenburg, L. Ruan, F. Shao, Z. Xu, C. Yang, and W. Zha. Phys. Rev. C 107, 044906 (2023)

Application: Mapping the Magnetic Field

R. D. Woods and D. S. Saxon, Phys. Rev. 95, 577–578 (1954)

Woods-Saxon: $$\rho_A(r) = \frac{\rho^0}{1 + \exp[(r - R)/d]}$$

R: charge radius, d: skin depth

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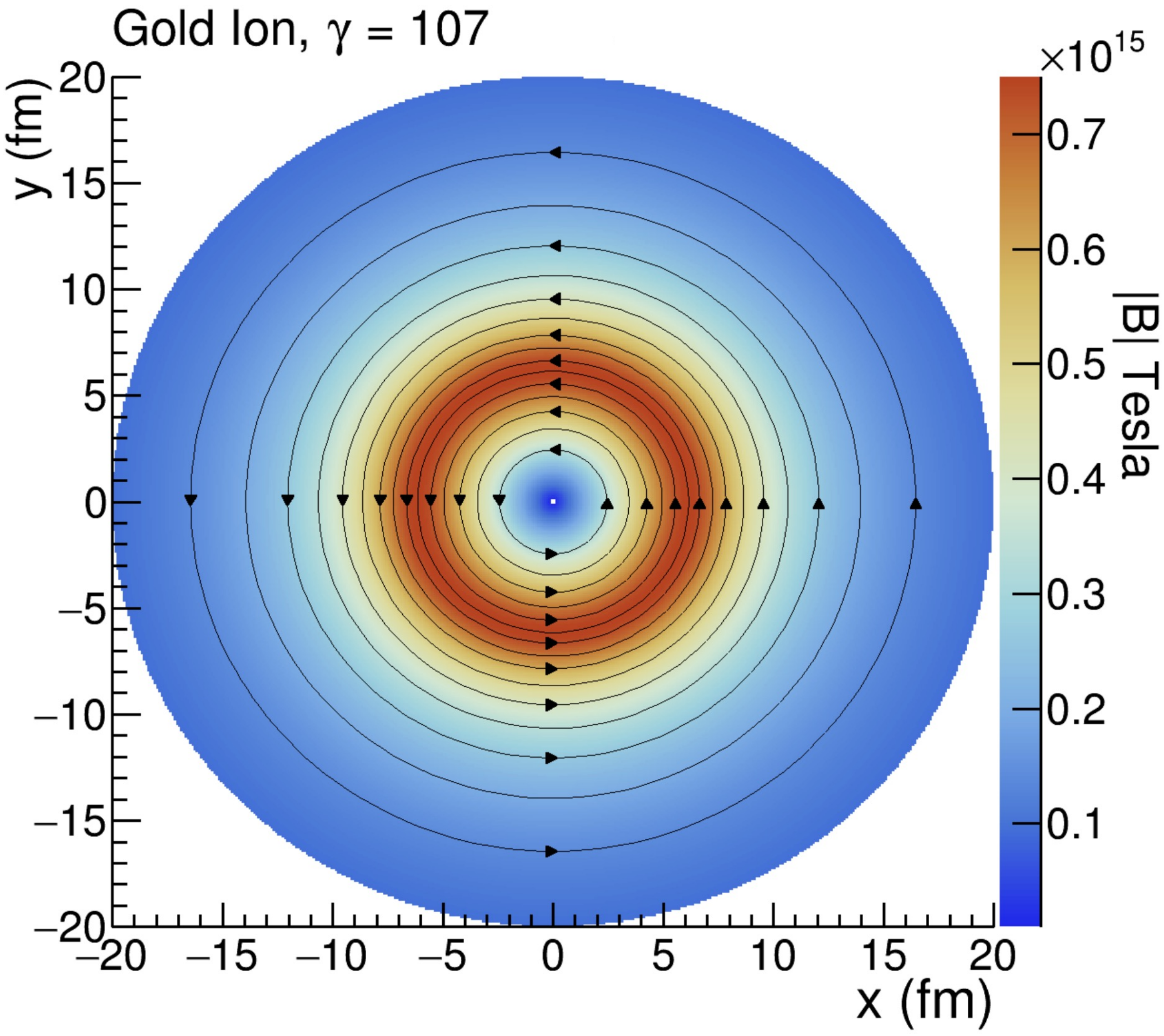
Nuclear charge distribution

↓ Biot-Savart Law

Magnetic field



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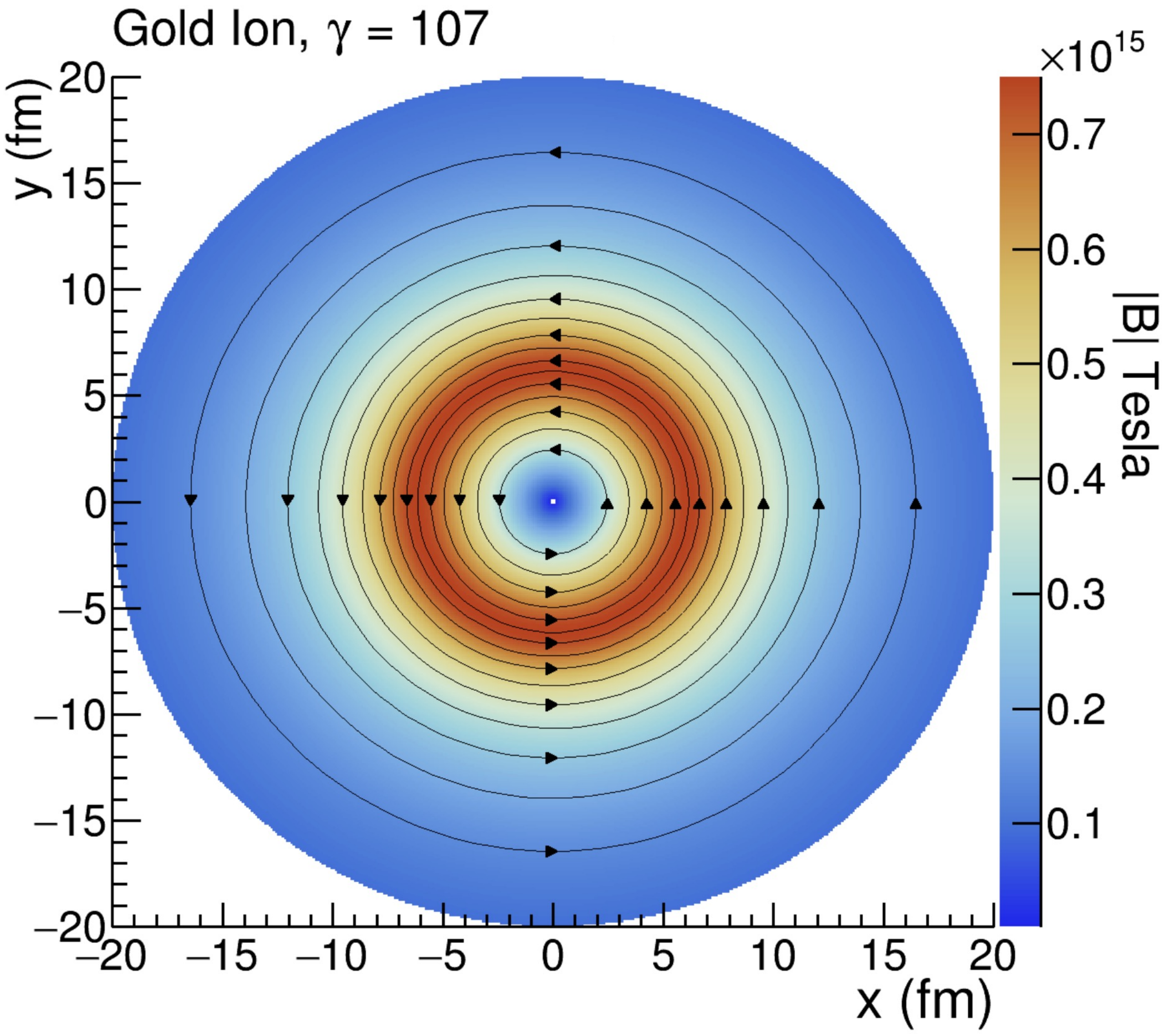
Magnetic field

↓ EPA

The kinematics of Breit-Wheeler process



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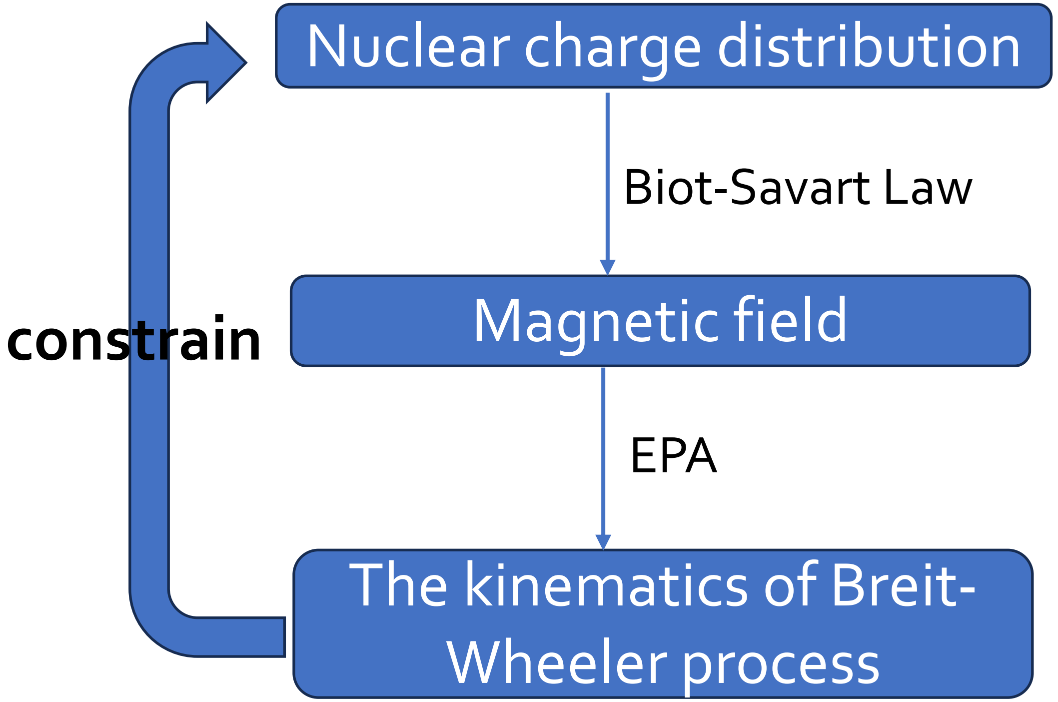
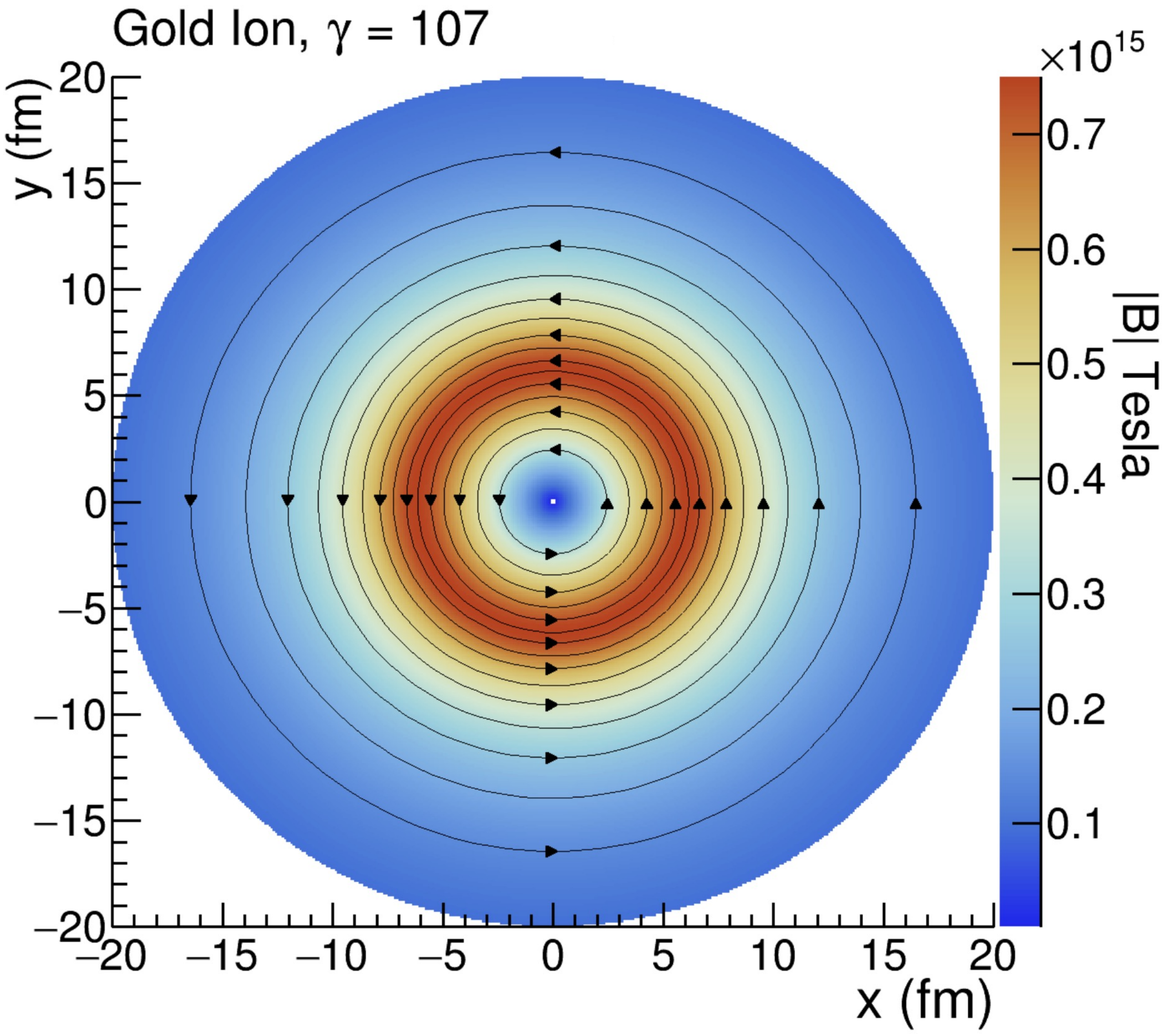
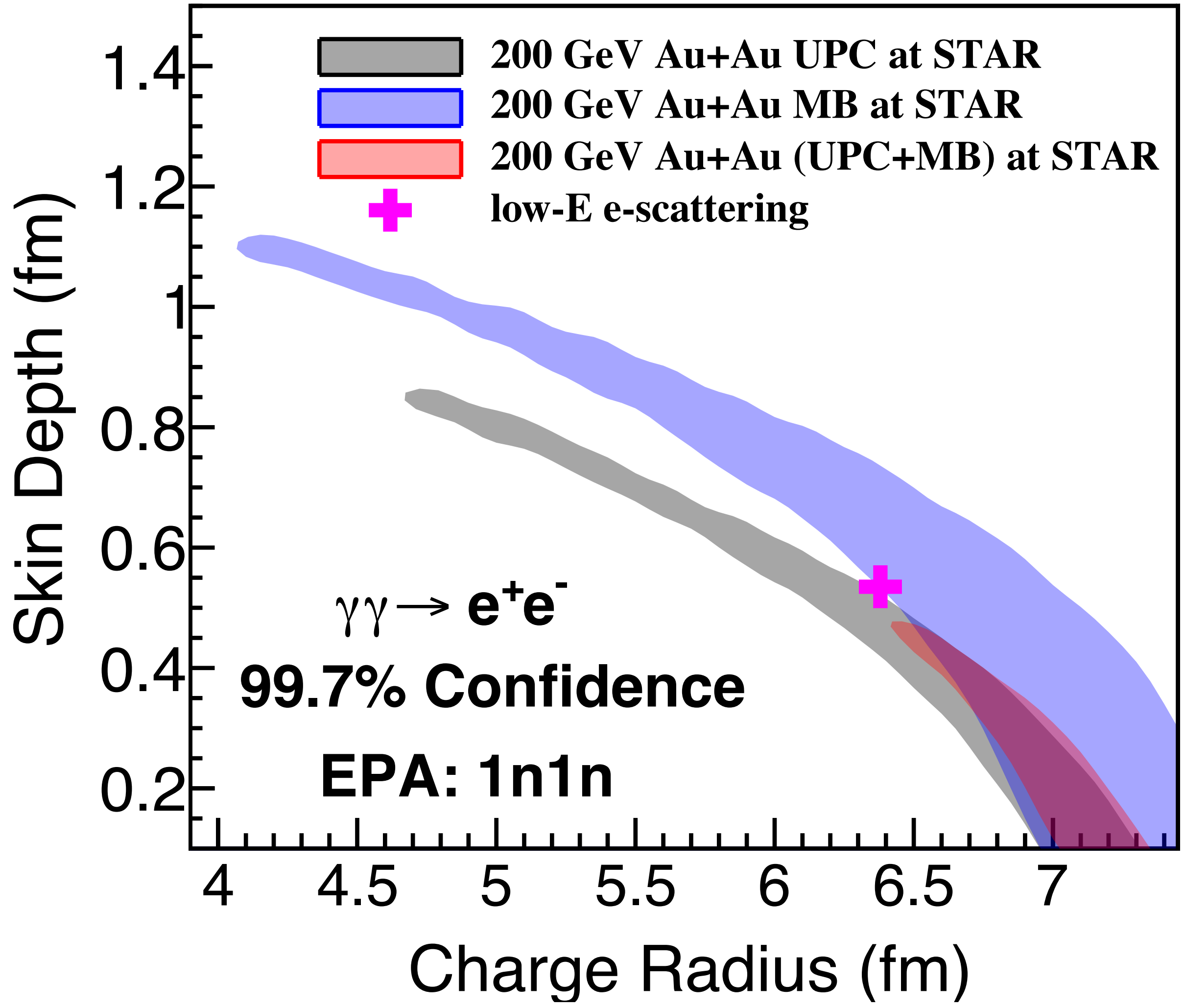




Application: Constrain Charge Distribution with Precision



RMS of radius, low-E e-scattering: 5.33 fm

	UPC	MB	UPC+MB
RMS	5.39+0.14-0.21	5.67+0.08-0.12	5.53+0.10-0.02

UPC consistent with nominal nuclear geometry

Peripheral collisions systematically larger

Indication of final state effect in HHIC

X. W, J.D. Brandenburg, L. Ruan, F. Shao, Z. Xu, C. Yang, and W. Zha. Phys. Rev. C 107, 044906 (2023)

Summary

- Breit-Wheeler process has been measured at STAR
  - ✓ **The kinematics** of the Breit-Wheeler process have beam energy dependences
  - ✓ $\sqrt{\langle p_T^2 \rangle}$ and nuclear charge radius: Indication of final state effect
- **Application:** Breit-Wheeler process can be used to **map the magnetic field** and **constrain nuclear charge distribution**

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- **Application:** Breit-Wheeler process can be used to **map the magnetic field** and **constrain nuclear charge distribution**

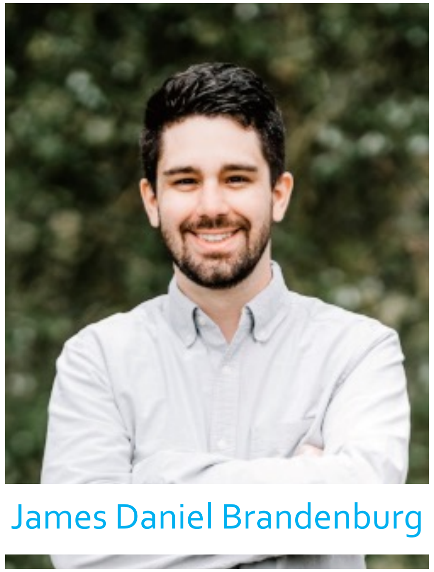
Perspective

- The high-statistics data produced by STAR from 2023 to 2025, can be used to search for the final state effect from QGP
- Recently, the LHC has also measured the dilepton production via photon fusion. We can use these results to measure the charge radius of the lead nucleus

Acknowledgement


Zhangbu Xu


Chi Yang

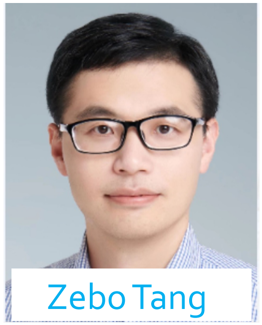

James Daniel Brandenburg


Fenglan Shao

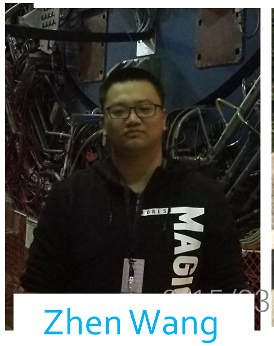

Lijuan Ruan

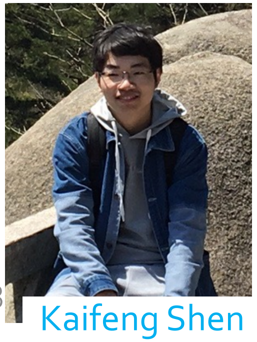

Shuai Yang


Wangmei Zha


Zebo Tang

SDU STAR Group


Zhen Wang


Kaifeng Shen

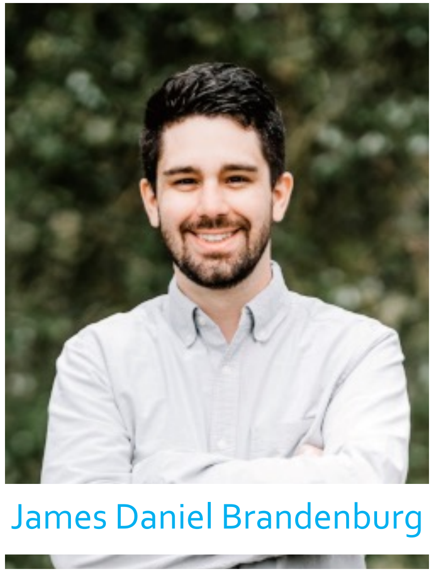

Jian Zhou


Xin Wu

Acknowledgement


Zhangbu Xu


Chi Yang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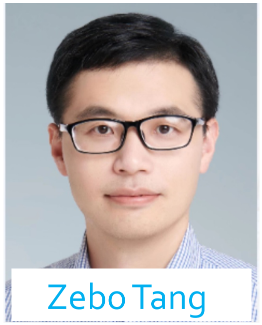
Zebo Tang

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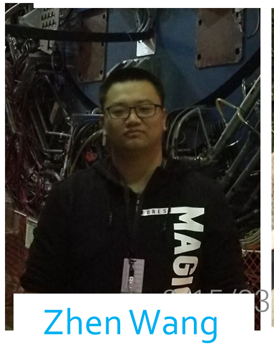
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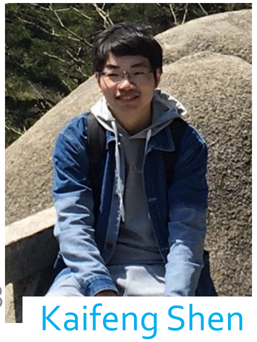
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Thanks for your attention!