第十三届全国粒子物理学术会议

RHIC上电磁探针研究进展与实验计划

杨 驰

山东大学

Outline

- Introduction
- Search for Breit-Wheeler pair production
- Summary of the results on EM probes
- Recent detector upgrades
- Future plan
- Summary

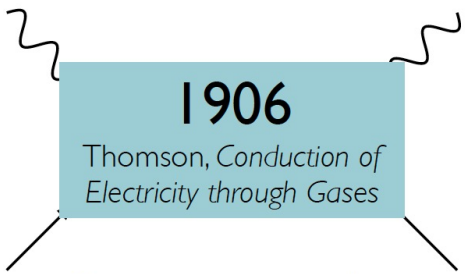
Electromagnetic Probes in HICs

Dileptons and real photons —— ideal electromagnetic probes

- Suffer no strong interaction
- Produced at all stages of the system evolution
- Bring production information to final state
- Can probe temperature of the system during its hottest phases
- **Sensitive to electromagnetic fields**

Fundamental Interactions: Light & Matter

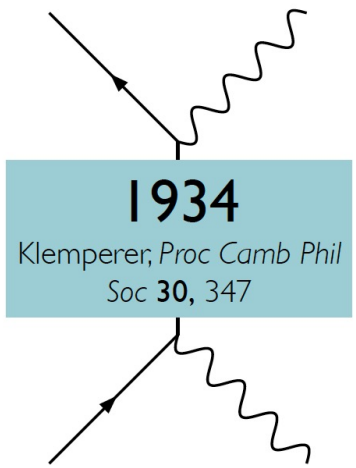
Plots from O. Pike



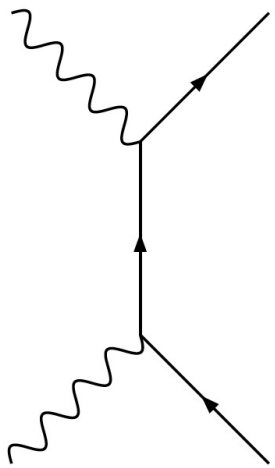
Compton scattering

Photoelectric effect

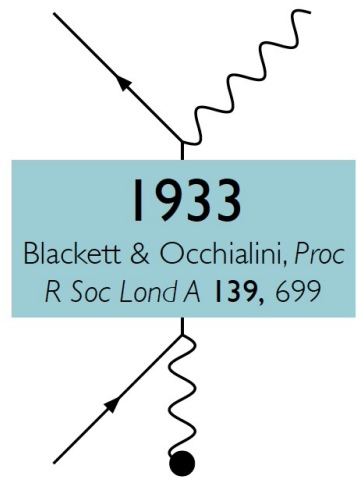
Bremsstrahlung



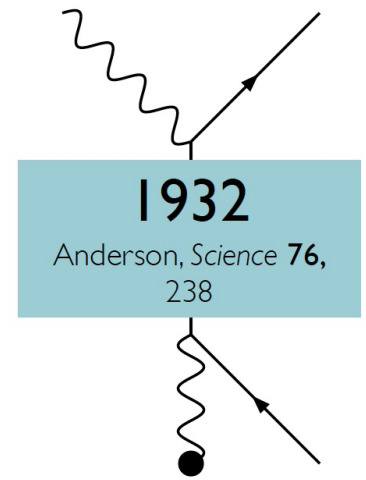
Dirac annihilation



Breit-Wheeler pair production



Single photon annihilation



Bethe-Heitler pair production

Phys. Rev. 46, 1087 (1934)

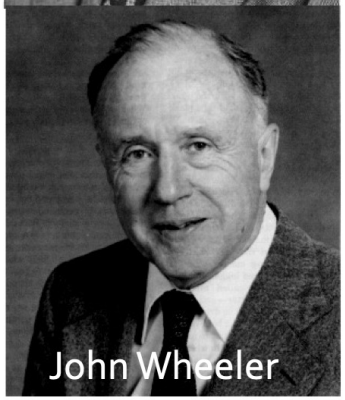
Why is the Breit-Wheeler Process So Elusive?

DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME 46

Collision of Two Light Quanta

G. BREIT* AND JOHN A. WHEELER,** *Department of Physics, New York University*

(Received October 23, 1934)



As has been reported at the Washington meeting, pair production due to collisions of cosmic rays with the temperature radiation of interstellar space is much too small to be of any interest. We do not give the explicit calculations, since the result is due to the orders of magnitude rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ-rays meeting each other on account of the smallness of σ and the insufficiently large available densities 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 of nucleii available in unit volume of ordinary materials, increases the effect to observable amounts. Analyzing the field of the nucleus into quanta by a procedure similar to that of v. Weizsäcker,[4] he finds that if one quantum $h\nu$

Second Series *November 15, 1930* *Vol. 36, No. 10*

THE
PHYSICAL REVIEW

SCATTERING OF HARD γ-RAYS

BY C. Y. CHAO*
NORMAN BRIDGE LABORATORY OF PHYSICS, CALIFORNIA INSTITUTE OF TECHNOLOGY

(Received October 13, 1930)

Breit and Wheeler mentioned it was hard, and they even introduced field generated by heavy ion.

赵忠尧先生1930年实际首次观察到正负电子对的湮灭辐射

Search for Breit-Wheeler Pair Production

Beam + Laser	Gamma-ray (100 GeV)	Optical laser photon (eV)
Beam + Beam	Gamma-ray (MeV)	Gamma-ray (MeV)
Beam + Target	Gamma-ray (GeV)	Thermal x-ray field (100 eV)

As numerous 100+ petawatt lasers facilities are planned or being built world-wide, a detailed understanding of strong field Quantum Electrodynamics has become more important than ever.

Recently proposed experiments for achieving the Breit-Wheeler process:
Nature Photonics **8**, 434–436 (2014)
Nature Communications **7**, Article number: 13686 (2016)
Communications Physics **1**, Article number: 93 (2018)

National Ignition Facility (USA)

Long-pulse: 2 MJ in 192 beams

LLNL

Laser Megajoule (France)

Long-pulse: 1.4 MJ in 176 beams

P. Labeguerie / CEA

SLAC E-144 experiment:
first sign of positron production in light-by-light scattering

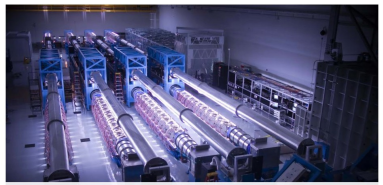
Burke et al., Phys.Rev. Lett. 79, 1626 (1997)
Hu & Müller, Phys.Rev. Lett. 107, 090402 (2010)

Orion Laser (UK)

Long-pulse: 5 kJ in 10 beams

© British Crown Owned Copyright / AWE

OMEGA EP (USA)



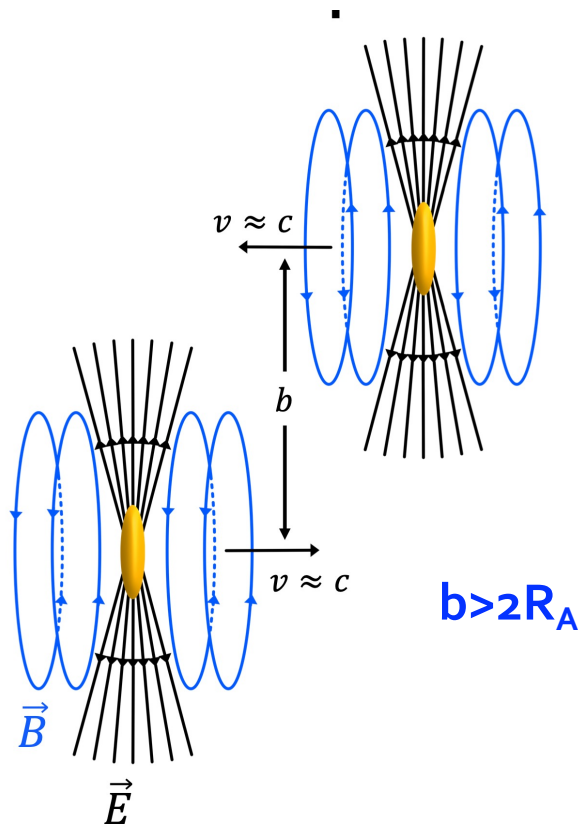
Long-pulse: 40 kJ in 60 beams

University of Rochester

Ultra-Peripheral Collisions Provide Opportunities

Main challenges in detection:

- **Peak of the same order of that in Compton scattering and Dirac annihilation.**
- **Center-of-mass energy > $2m_e$**
- **High photon density need.**



Test QED under extreme conditions

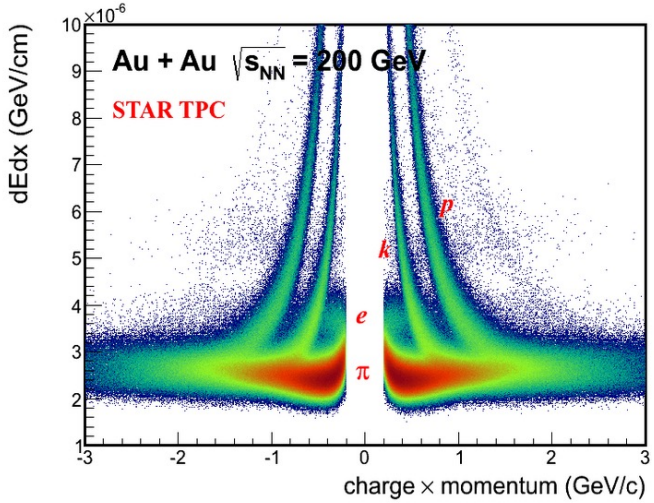
$b>2R_A$

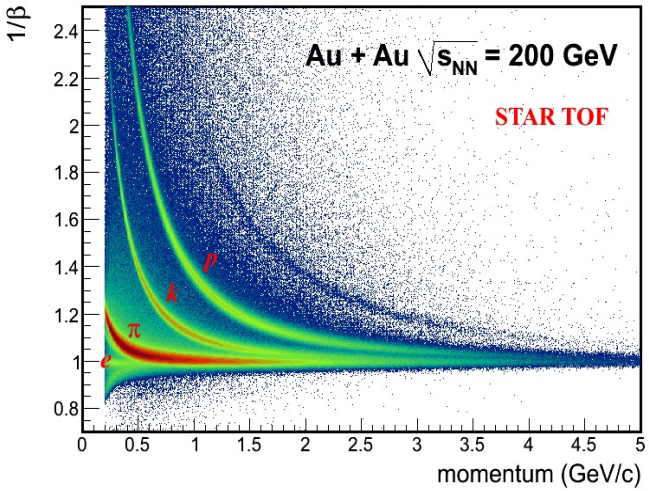
UPC of heavy ions solve the central challenges:

- Highly Lorentz contracted EM field, quantized as a flux of quasi-real photons
- $|B|\sim10^{14\text{-}16}$T
- High photon density: $Z\alpha \sim 1$
- $Z^4\sim40{,}000{,}000$ times higher yield than collisions of single charged particle pairs
- Clean background, no hadronic collisions

Particle Identification

In HHICs

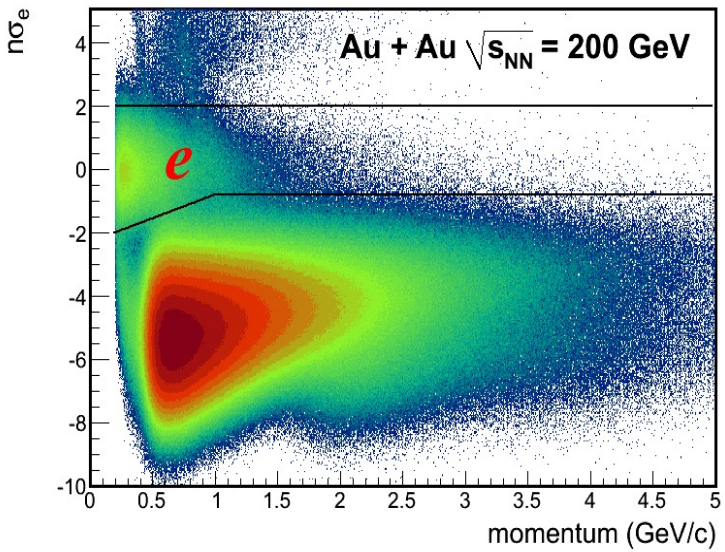




Chinese STAR group contribute to the eID/muID:

- **TPC: FDU+SDU+SINAP**
- **TOF: FDU+SINAP+THU+USTC**
- **MTD: THU+USTC**

Require β close to speed of light



Electron identification: TPC+TOF

Phys. Rev. Lett. 94, 062301 (2005)

Muon identification: TPC or TPC+MTD

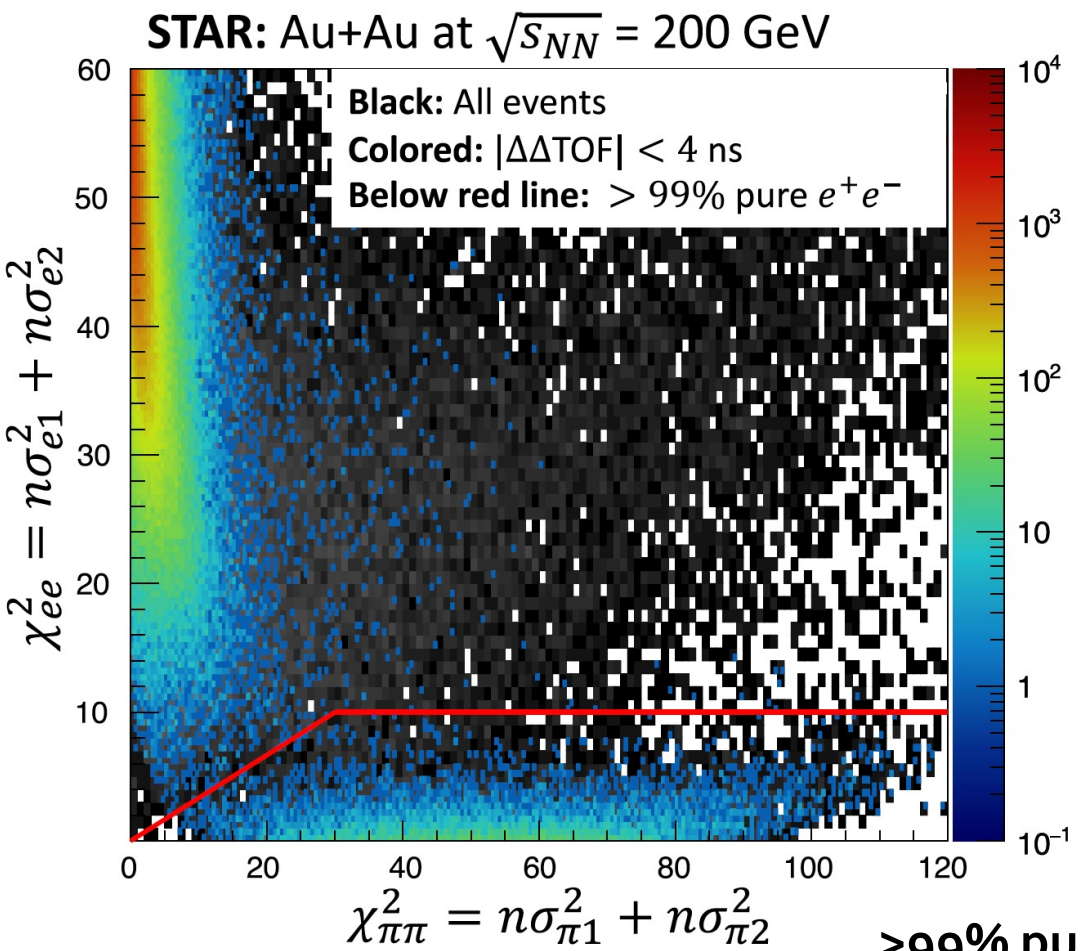
J.D.Brandenburg, Nucl. Phys. A 982, 192 (2019)
T.C.Huang, et.al., NIM.A 833, 88-93 (2016)

Particle Identification

Chinese STAR group contribute to the eID/muID:

- **TPC: FDU+SDU+SINAP**
- **TOF: FDU+SINAP+THU+USTC**
- **MTD: THU+USTC**

In UPCs

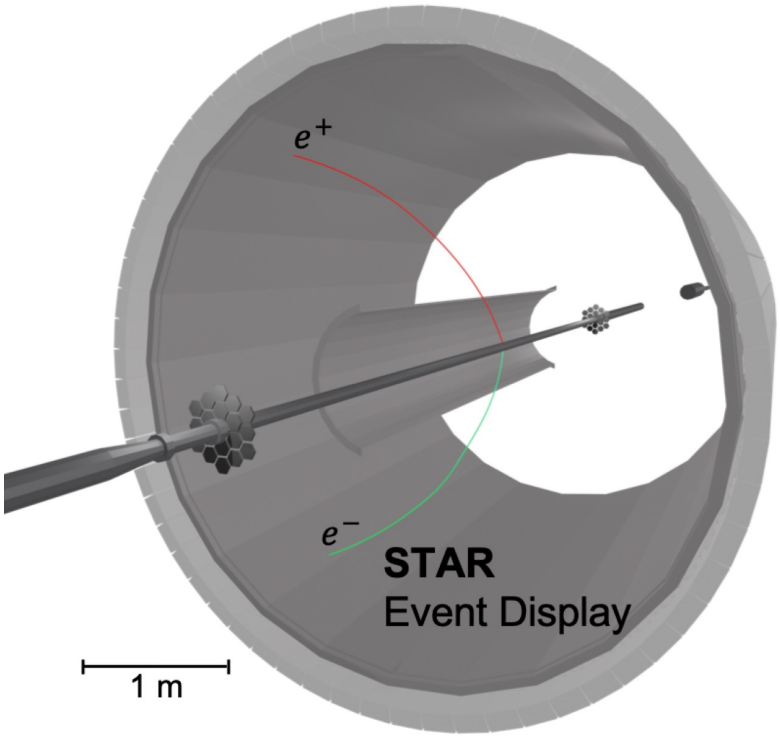


>99% purity of the dielectron pair

Search for Breit-Wheeler Process at RHIC-STAR

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

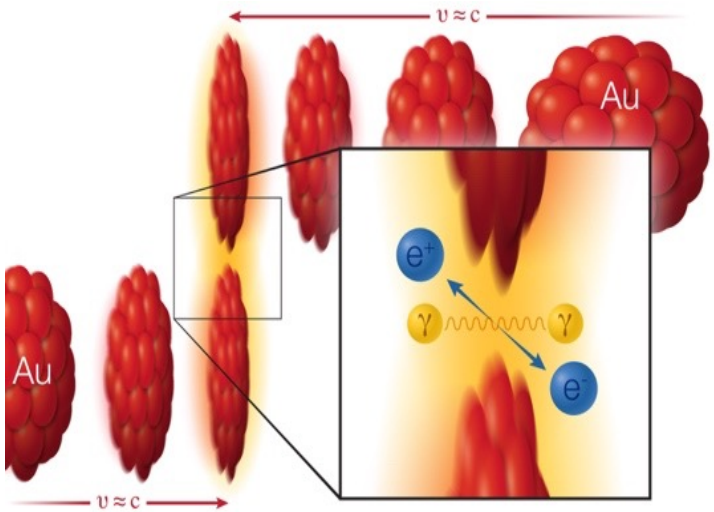
1. Observe 6085 exclusive e^+e^- pairs from data collected in 2010 at STAR.



2. No vector meson contribution visible

3. Energy spectrum

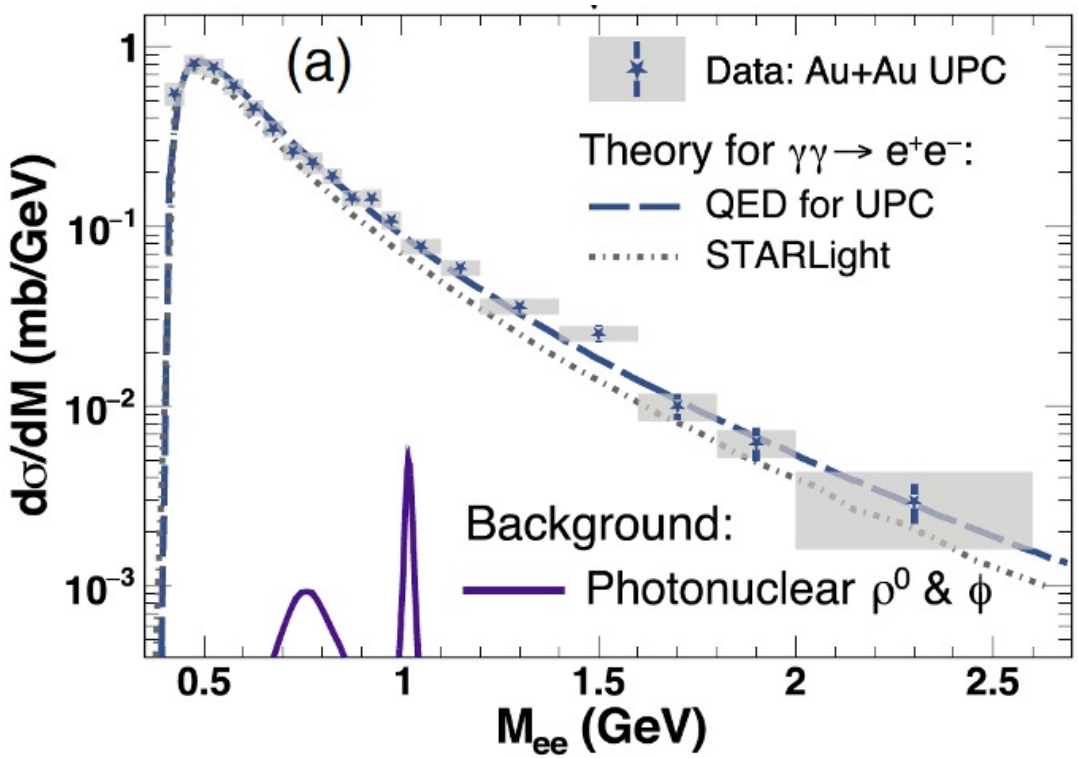
4. Photon transverse polarization & spatial distribution



https://www.bnl.gov/newsroom/news.php?a=119023

Cross-Section in STAR Acceptance

STAR: Au+Au at $\sqrt{s_{NN}}$ = 200 GeV, $|y^{ee}| < 1$, $P_{\perp} < 0.1$ GeV, $P_T^e > 0.2$ GeV, $|\eta^e| < 1$



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

- **No vector meson production**
- **Pure QED 2->2 scattering**

S.R. Klein, et.al, Compt.Phys. Commun.212, 258 (2017)
W.Zha, et.al, Phys.Lett.B 800, 135089 (2020)
C.Li, et.al, Phys.Rev. D 101, 034015 (2020)

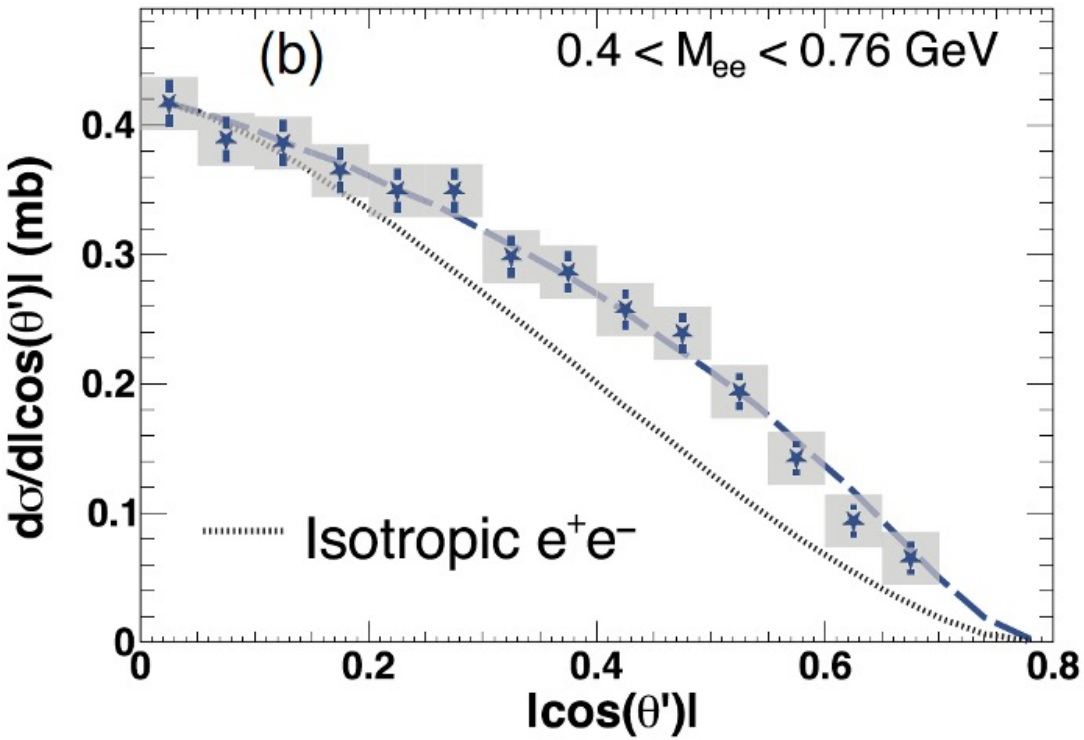
$\sigma(\gamma\gamma \to e^+e^-)$ **in STAR Acceptance:**
0.261 ± 0.004(stat.) ± 0.013(sys.) ± 0.034(scale) mb

STARLight: 0.22mb
Generalized EPA: 0.26mb
QED: 0.26mb

Measured cross-section consist with various theory calculations within ± 1σ

Polar Angle of the e⁺ Momentum and the Beam Axis

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



θ': angle of the e⁺ momentum w.r.t the beam axis in the pair rest frame

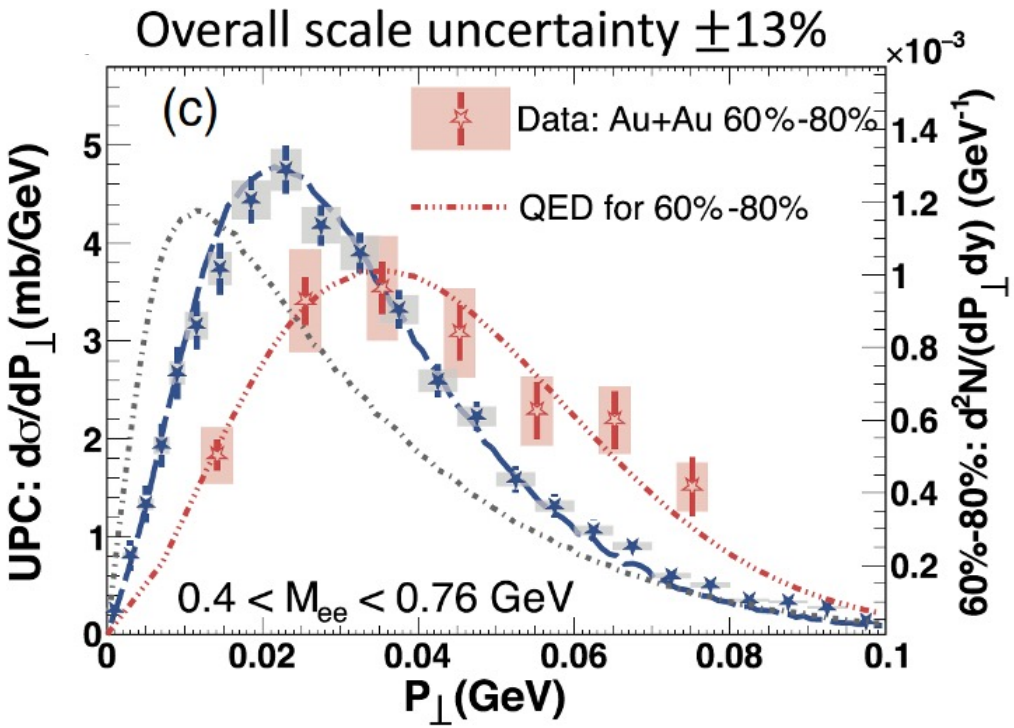
- **Breit-Wheeler process exhibits an enhancement toward a small polar angle**
- **Highly virtual photon interactions should have an isotropic distribution**

$\gamma\gamma \rightarrow e^+e^-$ **: Individual e⁺/e⁻ preferentially aligned along beam direction**

S. Brodsky, T. Kinoshita and H. Terazawa, Phys. Rev. D 4, 1532 (1971)

e^+e^- Pair Transverse Momentum Distribution

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



60%-80%: Phys. Rev. Lett. 121, 132301 (2018)

	Ultraperipheral				Peripheral	
	Measured	QED	SC	SL	Measured	QED
$\sqrt{\langle P_\perp^2 \rangle}$ (MeV)	38.1 ± 0.9	37.6	35.4	35.9	50.9 ± 2.5	48.5

- **Peak at very low p_T**
- **Impact parameter dependence**

Polarized Photon-Photon Collisions

Gluons are highly linearly polarized.

Metz & 周剑, 2011

CGC is highly linearly polarized state.

QCD:	QED:	
$gg \to q\bar{q}$	$\gamma\gamma \to l^+l^-$	• By direct analogy, in extreme QED fields, the linear photon polarization distribution can be measured via $\cos(2\Delta\phi)$ and $\cos(4\Delta\phi)$ modulations
$\Delta\phi = \phi^{q\bar{q}} - \phi^q$	$\Delta\phi = \phi^{ll} - \phi^l$	

The same analysis applies to the QED case.

Azimuthal Modulations Predicted for Real Photon

Idea generated from a local discussion at SDU between experiment group and theory group.

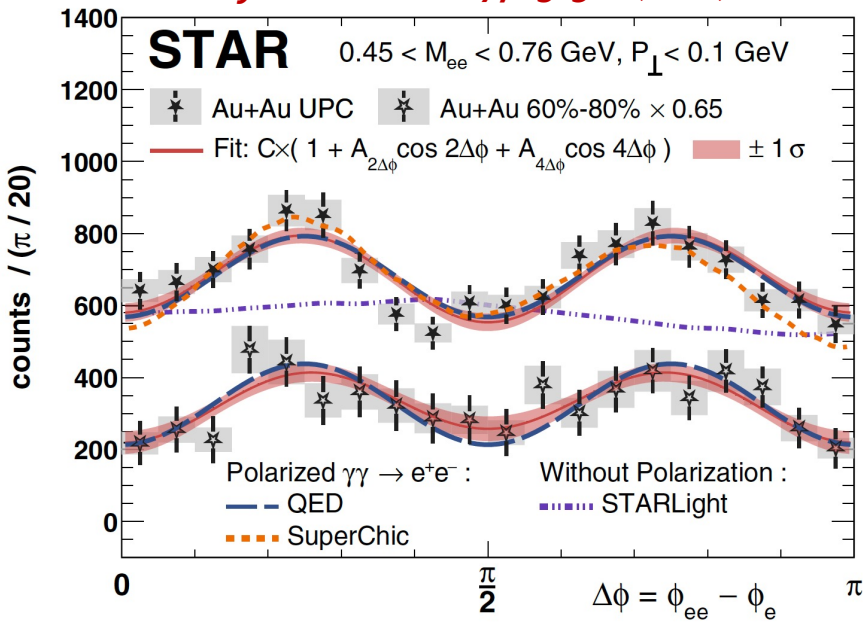
Phys.Lett. B 795, 576 (2019)
Phys.Rev. D 101, 034015 (2020)

周剑

周雅瑾

李聪

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



	Ultraperipheral				Peripheral	
	Measured	QED	SC	SL	Measured	QED
$\lvert A_{4\Delta\phi}\rvert$ (%)	16.8 ± 2.5	16.5	19	0	27 ± 6	34.5
$\lvert A_{2\Delta\phi}\rvert$ (%)	2.0 ± 2.4	0	5	5	6 ± 6	0

Results at STAR are well consistent with the theory prediction.

Link to Vacuum Birefringence

W. Heisenberg and H. Euler, Z. Phys. 98, 714 (1936)

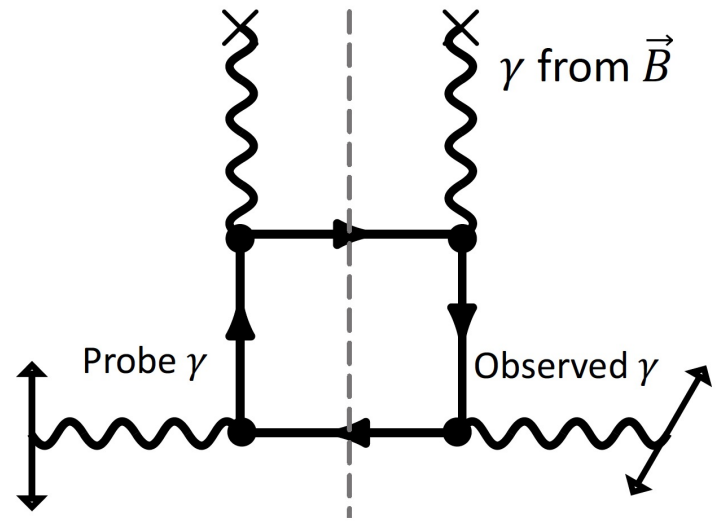
Vacuum birefringence:

predicted in 1936 by Heisenberg & Euler.

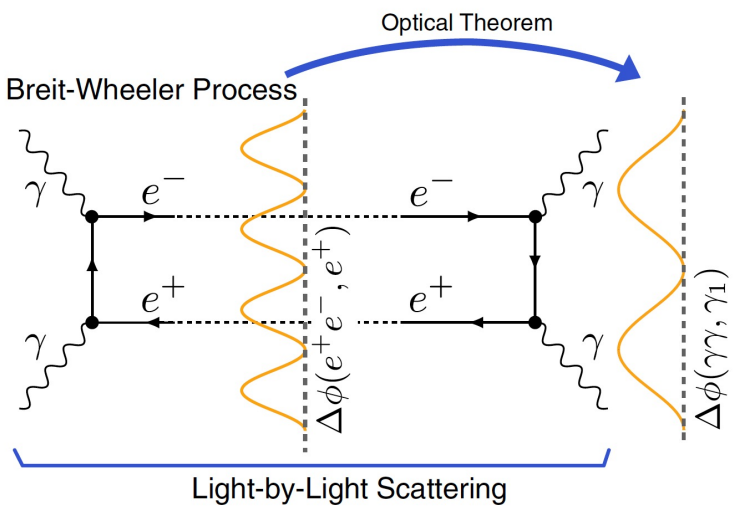
EM field polarizes the vacuum in the absence of a medium.

Photon refract in magnetic field due to relative polarization angle.

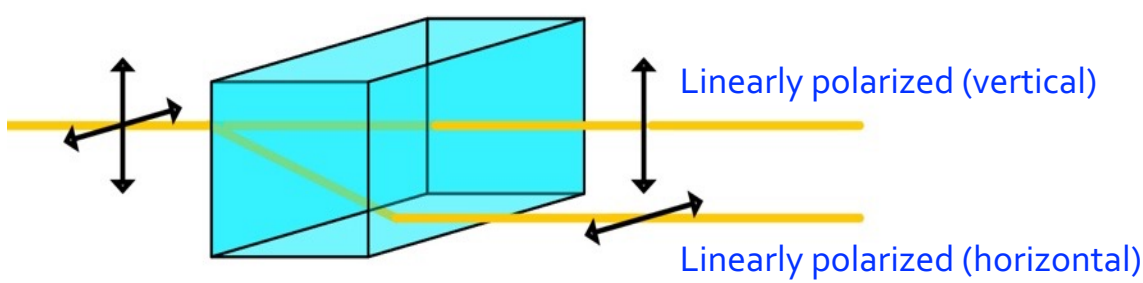
Feynman Diagram for Vacuum Birefringence



$Real(n)$ = transmission process $\gamma\gamma \to \gamma\gamma$
$Imag(n)$ = absorption process $\gamma\gamma \to e^+e^-$ (diagram cut)



QED vacuum + Extreme Magnetic field

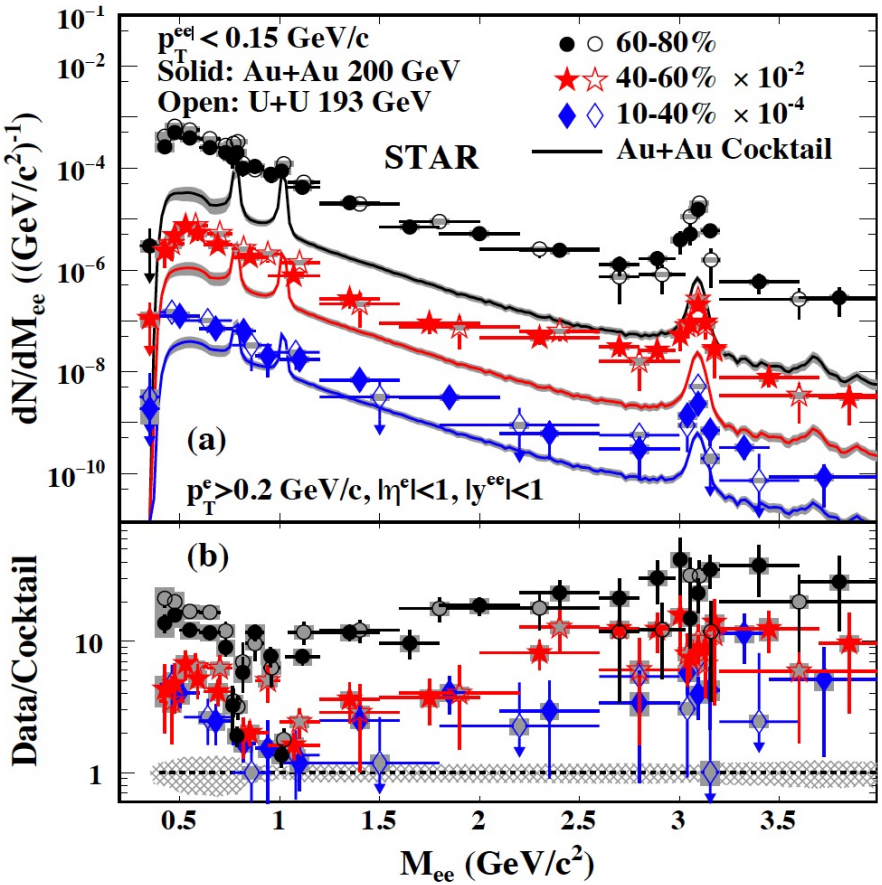


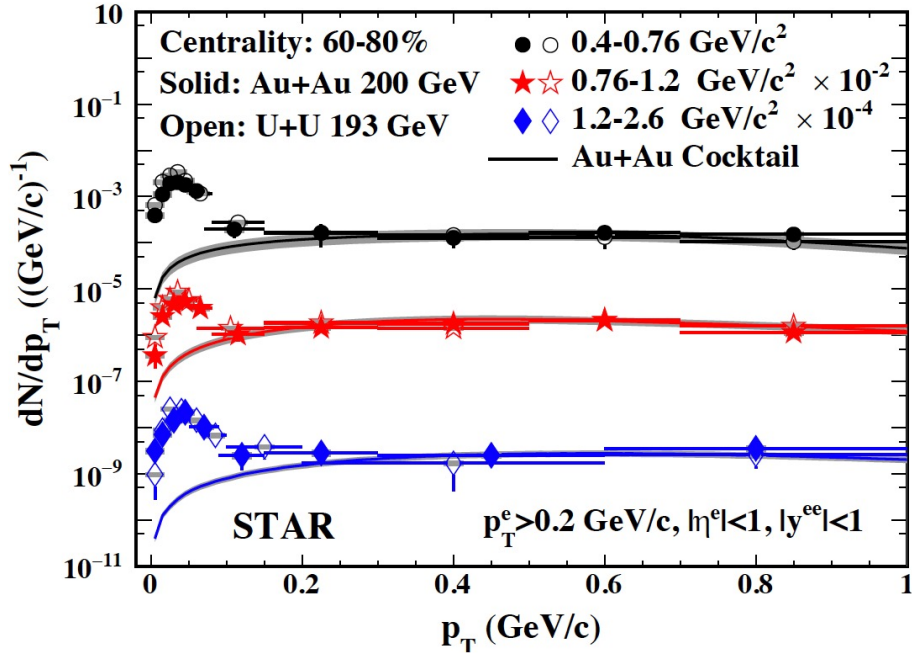
Maybe more closely related to the vacuum dichroism?

K. Hattori, H. Taya, and S. Yoshida, JHEP 01,93 (2021)

Coherent Low p_T e^+e^- in Au+Au and U+U

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





Dimuon channel: Jian Zhou's talk at 11:30 Tue.

- Significant enhancement
- Excesses concentrate below $p_T \approx 0.15$ GeV/c
- Data are consistent with hadronic expectation when $p_T > 0.15$ GeV/c
- Coherent photon-photon and photon-nucleon interactions in HHIC

We Proceed as We Planned

Chi Yang, ISMD2019 talk, Santa Fe

In UPC

- Provide baseline
- Exclusive and clean e^+e^- detection
- Individual e should be preferentially aligned longitudinally and the azimuthal angle between the e^+e^- pair momentum and the individual e momenta should display modulations

In HHIC

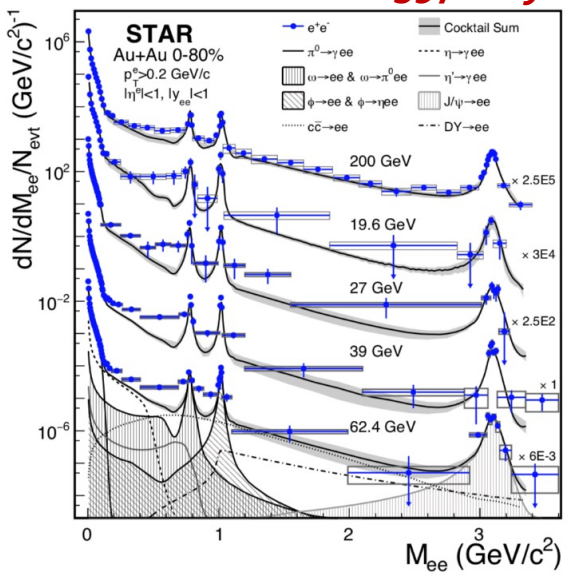
- Study extreme magnetic field and potential medium effect
- A+A centralities and different species *(A+B, STAR isobaric data)*
- Kinematics WRT B-field (reaction plane), mass, p_T, longitudinal alignment

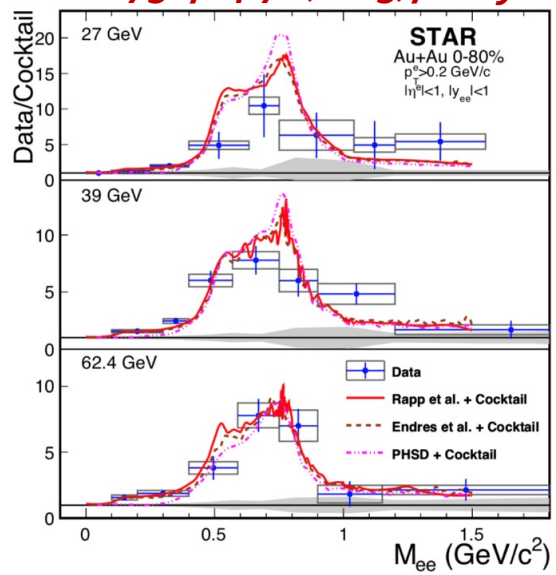
The energy spectrum and angular distribution provide the information needed to map the spatial extent of the intense electromagnetic fields produced by ultra-relativistic heavy nuclei for the first time.

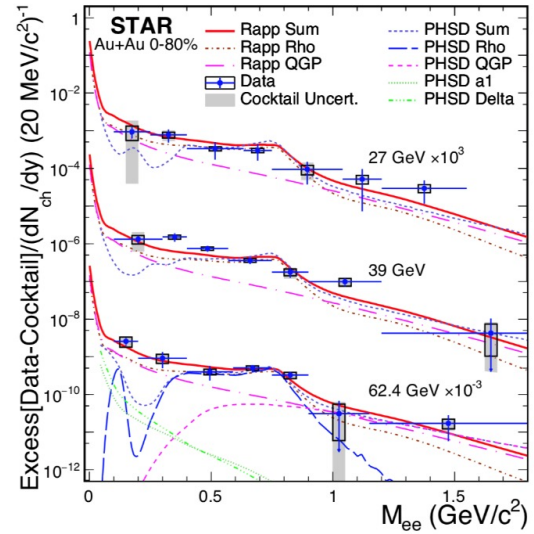
Can be compared to different models (*Q. Y. Shou, Y. G. Ma, P. Sorensen, A. H. Tang, F. Videbæk, and H. Wang, Phys.Lett. B 749, 215 (2015)*) which incorporate the charge distribution with a Lorentz boost.

Dielectron in Beam Energy Scan Phase I

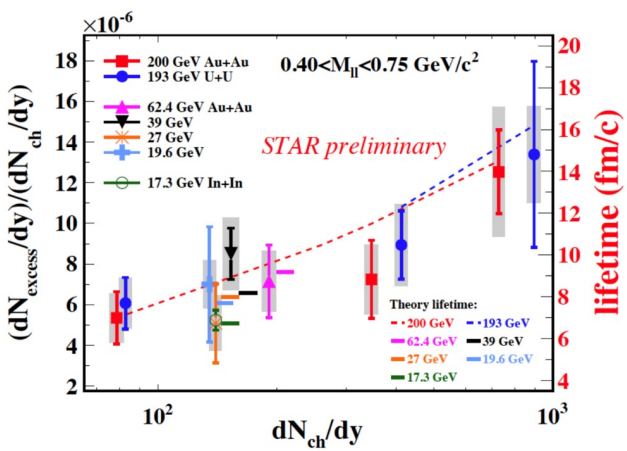
arXiv:1810.10159; Phys. Lett. B 750,64-71(2015); Phys. Rev. Lett. 113,022301 (2014)



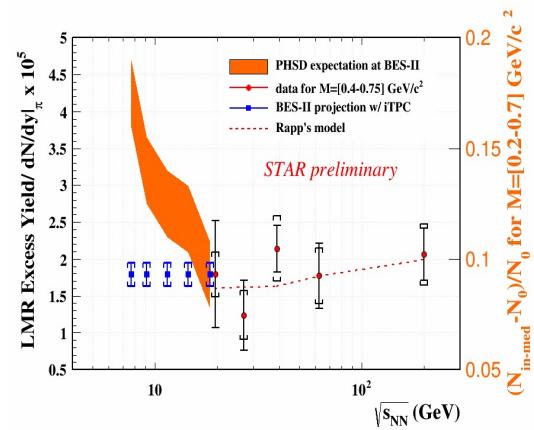




- Low mass excesses are consistent with ρ broadening scenario from RHIC top energy down to 19.6GeV



Low-mass e^+e^- emission is effected by T, total baryon density, lifetime



Total baryon density increases

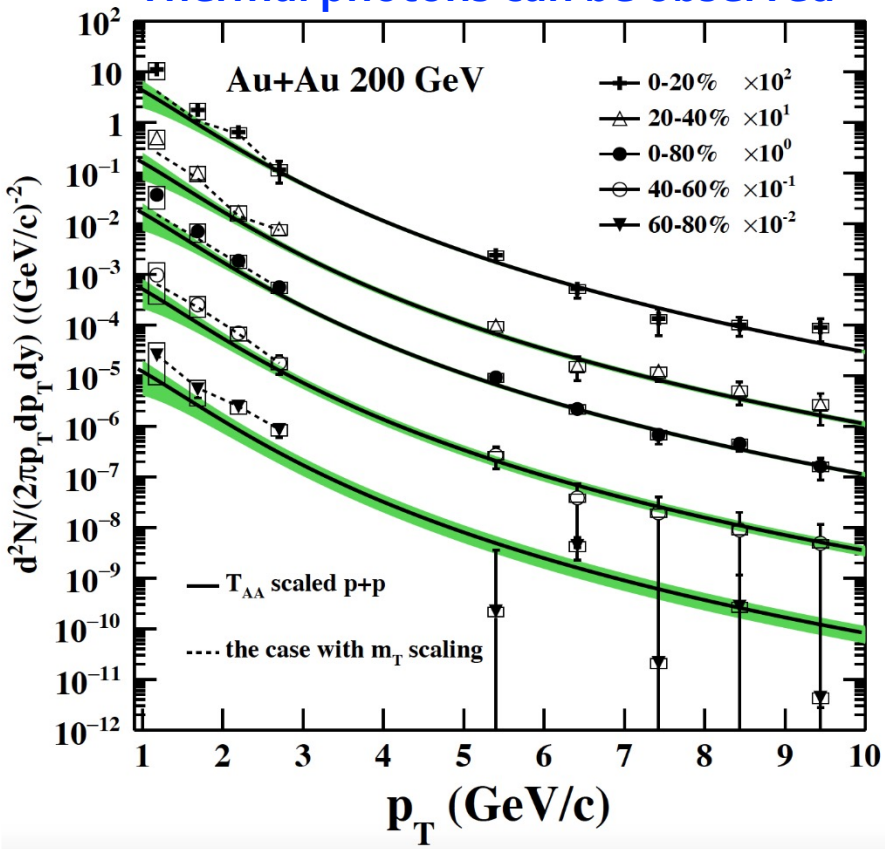
Constant total baryon density

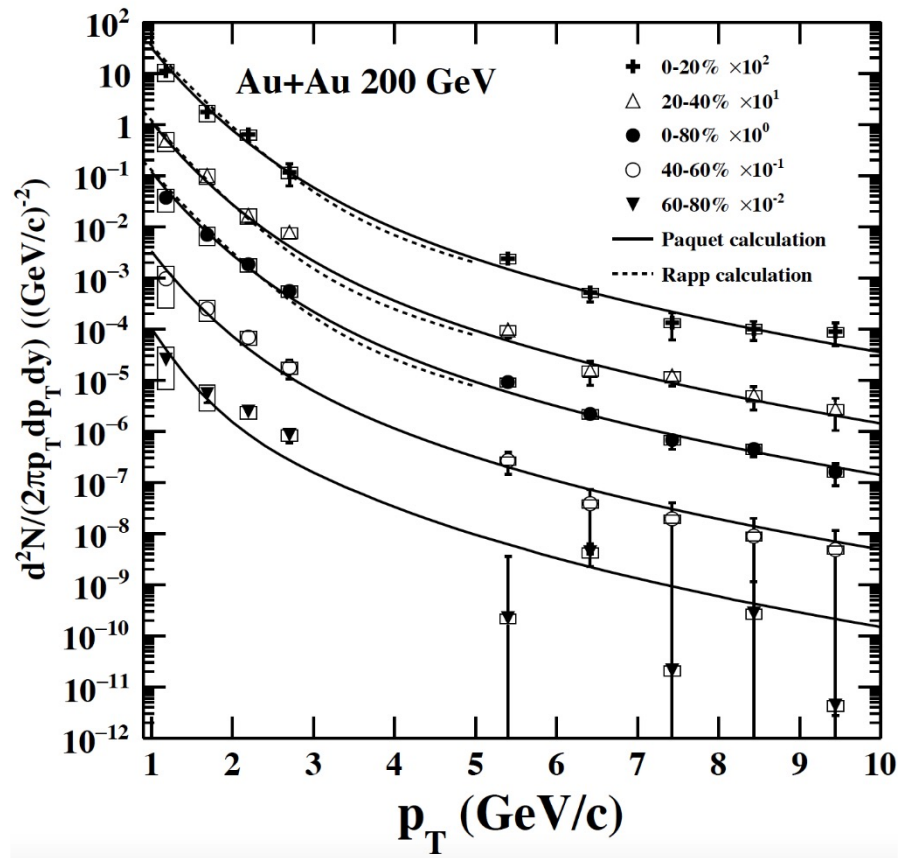
- Emission rate is dominant in the T_c region
- More clear pictures of the excess versus lifetime and total baryon density in BES-II

Direct Virtual Photon at RHIC Top Energy

Phys.Lett. B 770, 451-458 (2017)

Thermal photons can be observed





Model calculations:

- Consistent with the yield within uncertainties except some bins in 60-80%
- Simultaneously describe both dielectron and direct virtual photon yields

Summary of Dielectron and Direct Photons at STAR

One decade passed, on dileptons and direct photons as EM probes:

3 PRL(200GeV A+A Dielectron, Low pT Peripherial Dielectron, Breit-Wheeler Process)
2 PLB(19.6GeV A+A Dielectron, 200GeV A+A Direct Photon)
3 PRC(200GeV p+p Dielectron, 200GeV A+A, Dielectron v_2)

Achieved:

- ✓ *Rho broadening observed*
- ✓ *Possible IMR excess observed*
- ✓ *Thermal photon observed*
- ✓ *Photon-photon interaction in HHICs*
- ✓ *Breit-Wheeler pair production in UPCs*

Target/Focus:

chiral symmetry restoration

QGP thermal radiation

medium temperature

QGP in extreme EM field

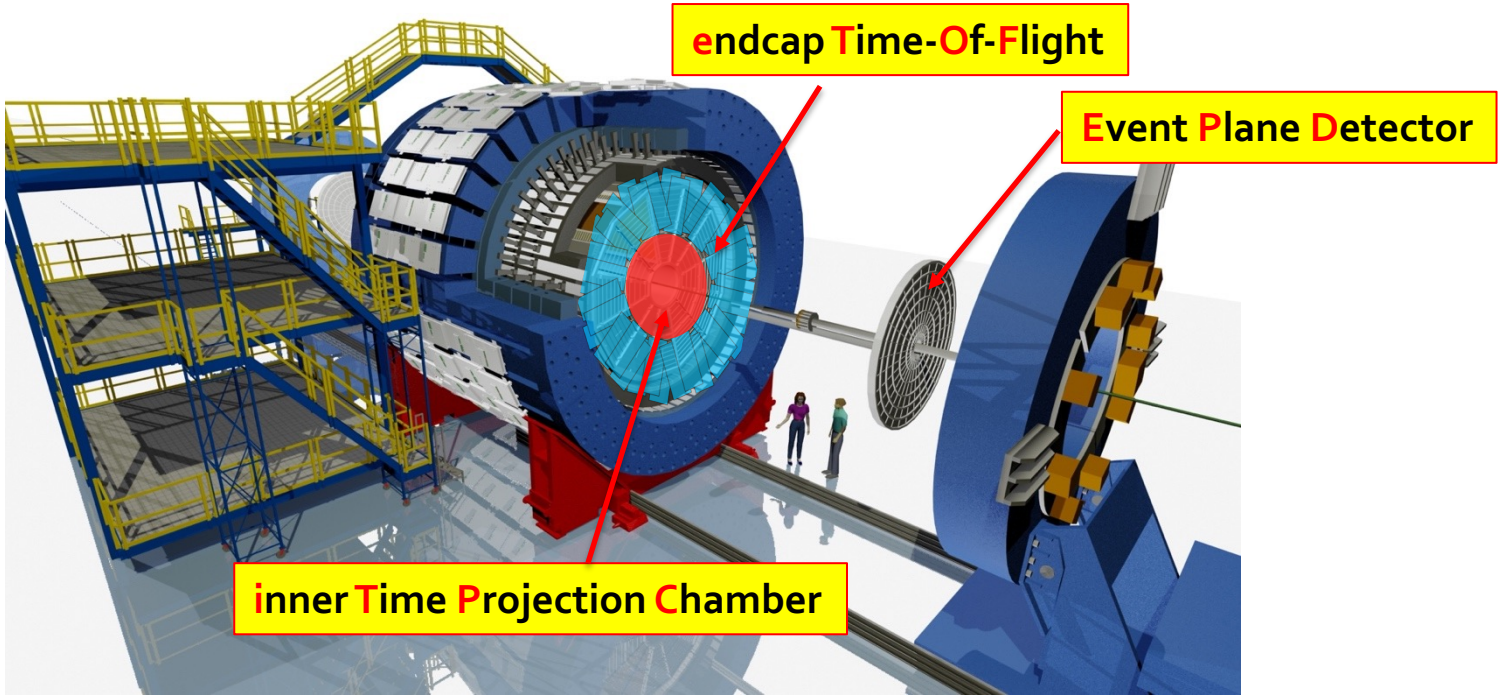
QED under extreme EM field

Main challenges: Low S/B, Hadron spectrum, Statistics, PID

Our TOF and MTD enables analysis at STAR with the lepton channels.

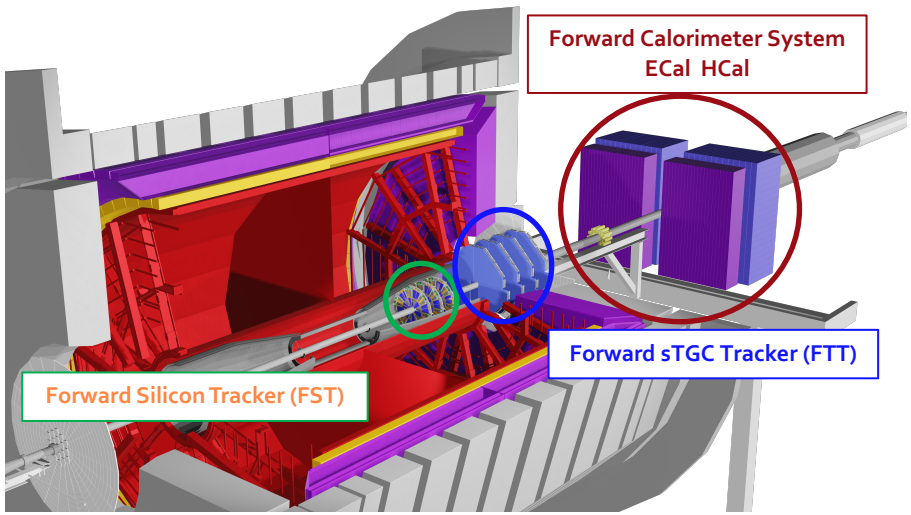
Excellent STAR detectors push us moving forward!

Detector Upgrades for Beam Energy Scan Phase II at RHIC



iTPC upgrade	EPD upgrade	eTOF upgrade
Continuous pad rows Replace all inner TPC sectors	Replace Beam Beam Counter	Add CBM TOF modules and electronics (FAIR Phase 0)
$\|\eta\|<1.5$ (was 1.0)	$2.1<\|\eta\|<5.1$	$-1.6<\eta<-1.1$
p_T >60 MeV/c (was 150MeV/c)	Better trigger & b/g reduction	Extend forward PID capability
Better dE/dx resolution Better momentum resolution	Greatly improved Event Plane info (esp. 1st-order EP)	Allows higher energy range of Fixed Target program
Fully operational in 2019	Fully operational in 2018	Fully operational in 2019

New Detectors at STAR Forward Rapidity



Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

FCS: 7 m from the IP

ECal: reuse PHENIX SHASHLYK 1496 Ch.

- Lateral tower Size 5.5 x 5.5 x 33 cm³ （18X_0 ）

HCal: Fe/Sc (20mm/3 mm) sandwich 520 Ch.

- Lateral tower size 10 x 10 cm², ~ 4.5λ

✓ in close collaboration with EIC R&D

Preshower:

- Existing EPD, with additional splitter

FST, 3 Silicon disks: at 146, 160, and 173 cm from IP

Built on successful experience with STAR IST

- Single-sided double-metal mini-strip sensors
  - ✓ Granularity: fine in f and coarse in R
  - ✓ Si from Hamamatsu
- Frontend chips: APV25-S1 → IST all in hand
- Reuse IST DAQ system and cooling system

FTT, 4 sTGC disks: at 307, 325, 343 and 361 cm from IP

- location inside Magnet pole tip opening
  - ✓ inhomogeneous magnetic field
- 4 quadrants double sided sTGC → 1 disk
  - ✓ sTGC technique developed by ATLAS
- Position resolution: ~200 um
- Readout: based on VMM-chips

STAR note 0648：https://drupal.star.bnl.gov/STAR/starnotes/public/sno648

Forward sTGC Tracker, fSTAR

From 2018 till now:

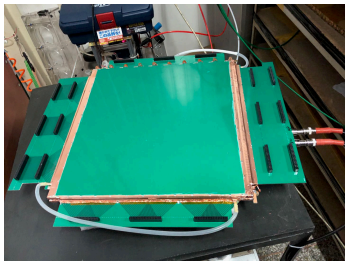
- ✓ Three versions of module prototypes
- ✓ Three versions of electronics prototype
- ✓ 25 modules in mass production

Integrations & DAQ: **BNL**

Commissioning & software: **BNL, SDU**

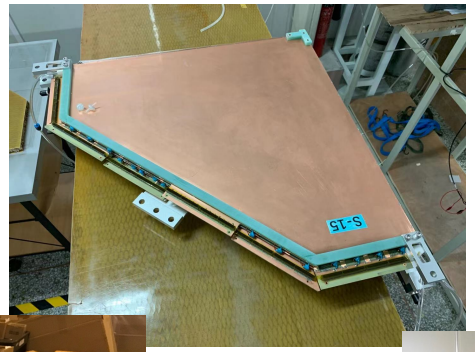
Detector	Produced	Shipped	Installed
1st prototype	Oct.2018	Jan.2019	Jun.2019
2nd prototype	Jan.2019	Jul.2020	May 2021
3rd prototype	Oct.2020	N/A	N/A
Final modules	*May 2021*	*Jun.2021*	*Sep.2021*

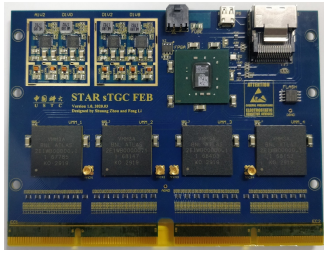
30 x 30 cm² prototype

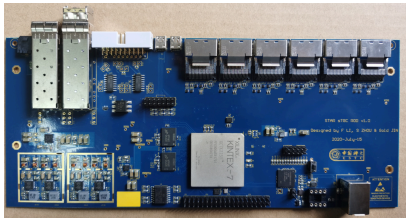


60 x 60 cm² prototype

55 x 55 cm² pentagon

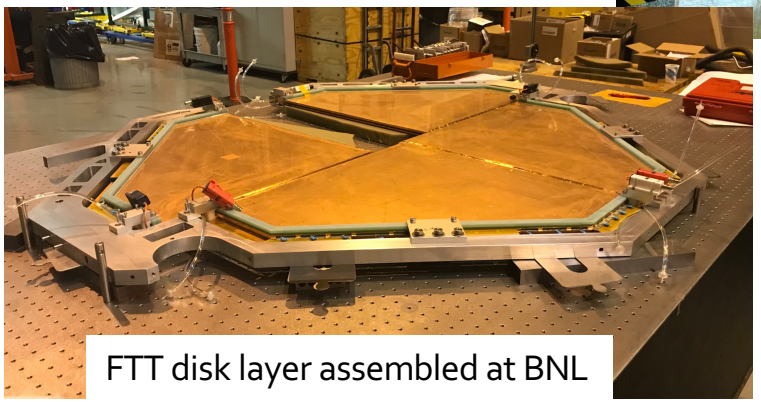






Module Production: **SDU**

Electronics: **USTC**



FTT disk layer assembled at BNL

Joint test at SDU in Sep.2020.

Organizational Structure in STAR Forward Upgrade

sTGC

- Brookhaven National Laboratory
- Shandong University
- University of Science and Technology of China

Silicon

- UIC University of Illinois at Chicago
- Shandong University
- Indiana University
- Brookhaven National Laboratory
- National Cheng Kung University

ECal

- Kentucky
- Valparaiso University
- Abilene Christian University

HCal

- UCLA
- Texas A&M University
- Indiana University
- Valparaiso University
- Rutgers
- Abilene Christian University
- Ohio State

DAQ

- Brookhaven National Laboratory
- Indiana University
- Kentucky
- UCLA
- Texas A&M University

Software

- Brookhaven National Laboratory
- UIC University of Illinois at Chicago
- Indiana University
- Texas A&M University
- Shandong University

Integration

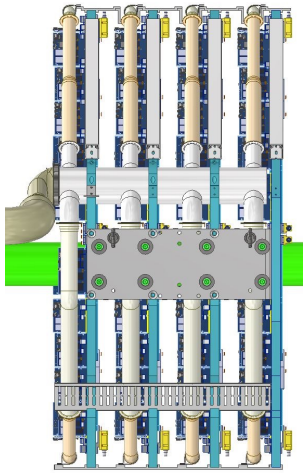
- Brookhaven National Laboratory

Calibration

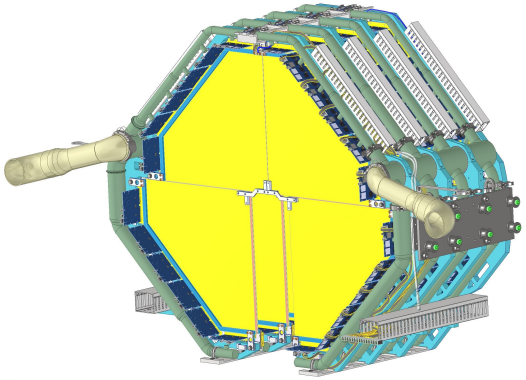
- UC Riverside
- Temple University

Slow Controls

- Valparaiso University
- Abilene Christian University
- Creighton University



Efficient and professional collaborating within STAR collaboration!



The Physics at RHIC beyond 2021+

Opportunities in RHIC 2021+ on dileptons and photons

Mid-rapidity -1.5<η<1.5 | **Forward-rapidity 2.8< η <4.2**

A+A

Beam:

Full Energy (200 GeV) Au+Au

Physics Topics:

a deep look into the properties of the QGP:

- **γ & e+e- pairs**
- **Chiral symmetry restoration**
- **Temperature and lifetime of hot, dense medium**
- Lower momentum π, K, p spectra
- Hypertriton Lifetime Measurement
- **Precision measurements of direct photon yields and v_n**

p+A, p+p

Beam:

500 GeV: p+p

200 GeV: p+p and p+A

Physics Topics:

Improve statistical precision:

- TMD measurements, i.e. Collins, Sivers, …
- Access s & Ds through Kaons in jets
- Measurement of GPD E_g through UPC J/Ψ
- First access to Wigner functions through di-jets in UPC
- Gluon and quark vacuum fragmentation
- Gluon and quark fragmentation in nuclear medium
- Nuclear dependence of Collins FF

A+A

Beam:

Full Energy AuAu (2023/25)

Physics Topics:

- Temperature dependence of viscosity through flow harmonics up to η ~4
- Longitudinal decorrelation up to η ~4
- Strong rapidity dependence in Global Lambda Polarization

p+A, p+p

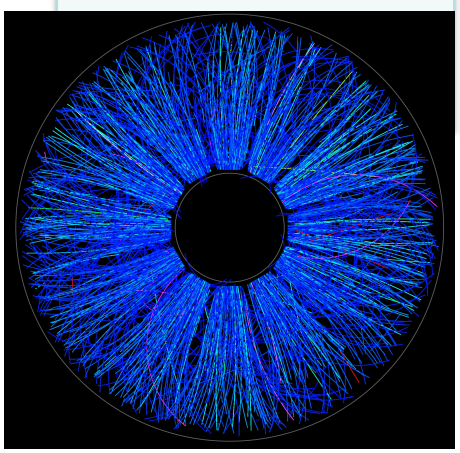
Beam:

500 GeV: p+p

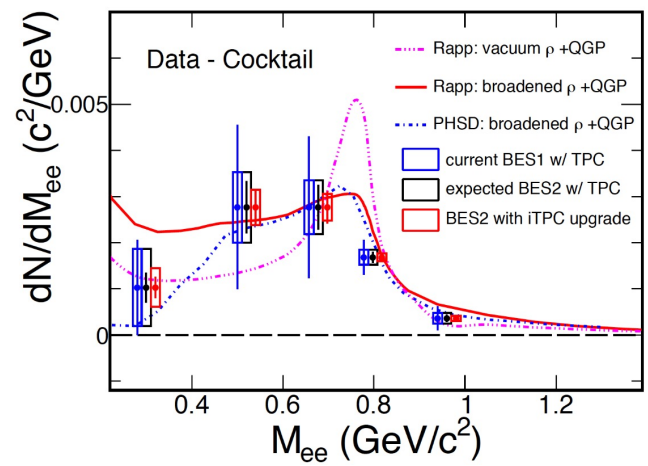
200 GeV: p+p and p+A

Physics Topics:

- TMD measurements at high x
  - o transversity → tensor charge
  - o Sivers through DY, direct γ and tagged jets
- Gluon PDFs for nuclei
- ➢ **R_{pA} for direct photons** & DY, and hadrons
- Test of Saturation predictions through di-hadrons, γ -Jets, di-jets



2019 Event Display : Au+Au 19.6 GeV
Full tracking with all iTPC sectors



Uncertainty projection w. iTPC

Current and Future Opportunities on EM Probes at RHIC

Au+Au 54 GeV and Au+Au 27 GeV data collected in Run 17

-- Smaller heavy flavor semi-leptonic decay in IMR

BNL, RICE, SDU, USTC

Isobaric collision data collected in Run 18

-- Same A, different Z – similar hadronic interaction, different initial magnetic field

BES-II in Run 19， Run 20 and Run 21

Need man power

-- Different total baryon densities, scan in high total baryon density region. Connect with NICA-MPD EM probes research

Beyond 2021+

-- Mid-rapidity: e^+e^- measurement at μ_B~0

Link to chiral symmetry restoration

-- Precise ρ spectra

Thermal radiation from QGP

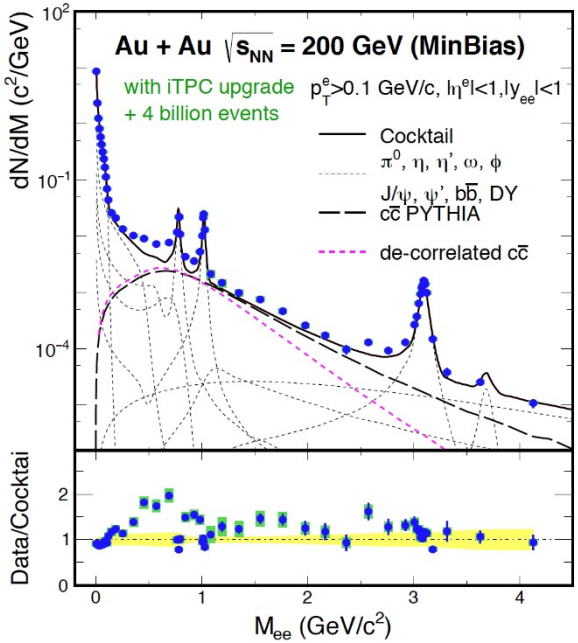
-- IMR slope

Direct virtual photon at RHIC top energy

-- Thermal photon slope

Photon-photon collisions

-- EM field



Uncertainty prediction with iTPC + 4 billion events

From RHIC to EIC

Current and future plans at RHIC provide opportunities in:

✓ **Detector R&D with techniques potentially used in EIC**

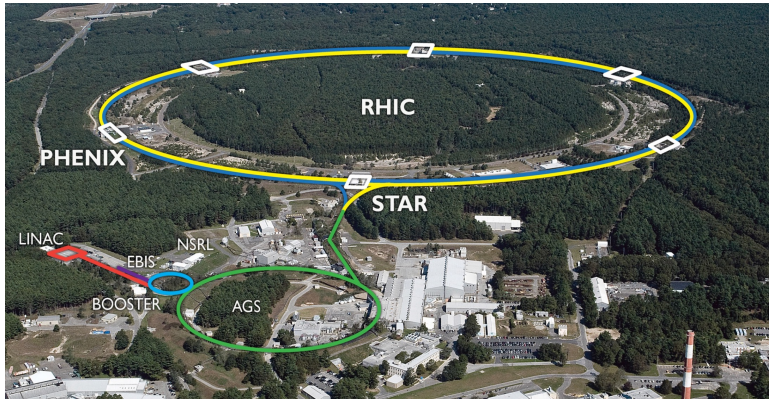
- HCal+SiPM readout same as EIC-fHCal (joint STAR EIC R&D)
- Silicon technique for EIC tracker
- sTGC technique for EIC trigger/tracker

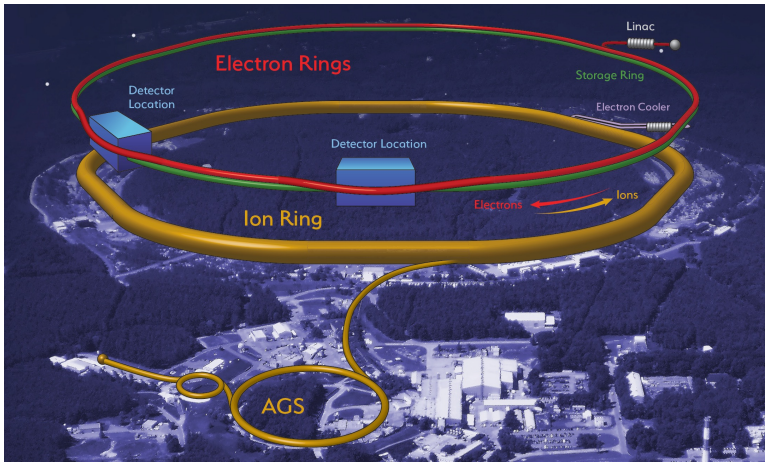
✓ **Help to realize the scientific promise of the EIC**

- Inform the physics program
- Quantify experimental requirements
- **Especially on photon-nucleus interaction**

✓ **Train the young talents especially on detector R&Ds for EIC**

- Several tens of the graduate/undergraduate students working on fSTAR





Summary I

- **Plenty of important results have been achieved from RHIC-STAR based on electromagnetic probes from the passed decade.**

- **Recent research extend the study on EM probes to fundamental QED process. The photoproduction study is crucial for the understanding of various topics:**
  - ✓ Initial EM field in HICs
  - ✓ QED under extreme EM field
  - ✓ QGP under extreme EM field
  - ✓ Interdisciplinary with astronomy, laser physics, quantum magnetohydrodinamics, …

Summary II

- Chinese STAR group have made and are making crucial and significant contributions to most of the key sub-systems at STAR.
- These sub-systems support our physics program precisely!