Interference of Vector Mesons in Peripheral and Ultraperipheral Collisions

Daniel Torres Valladares

Midsummer School in QCD

Saariselkä, 1 July, 2024

Supported by

U.S. DEPARTMENT OF ENERGY

RICE UNIVERSITY

Agenda

- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
    - Photon Equivalent Method
    - Vector Meson Dominance Model
    - Photonuclear production
    - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

Agenda

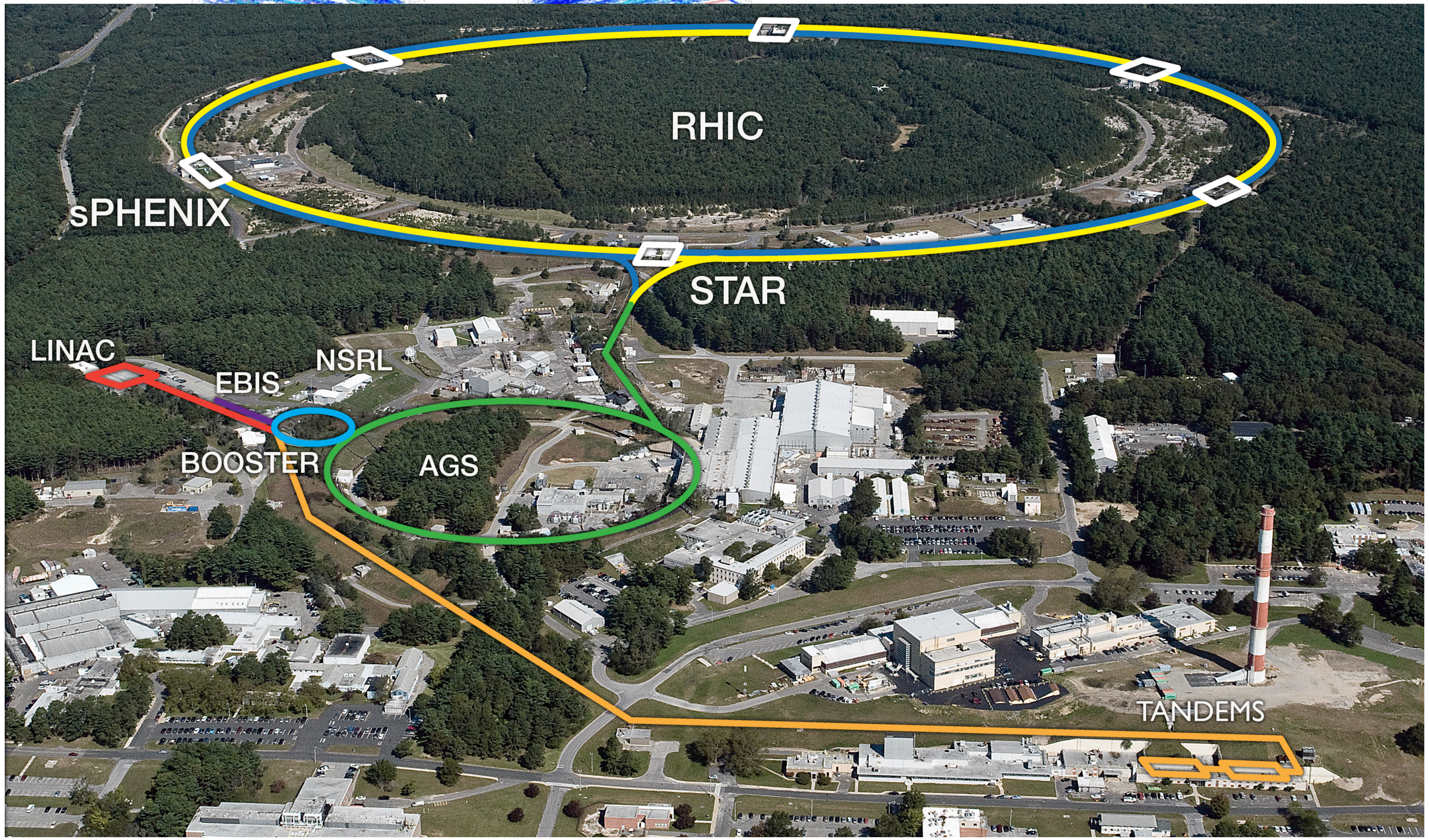
- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
  - Photon Equivalent Method
  - Vector Meson Dominance Model
  - Photonuclear production
  - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

The STAR Experiment

Experiment overview

- The Solenoidal Tracker at RHIC (STAR) experiment is one of the experiments located in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory.

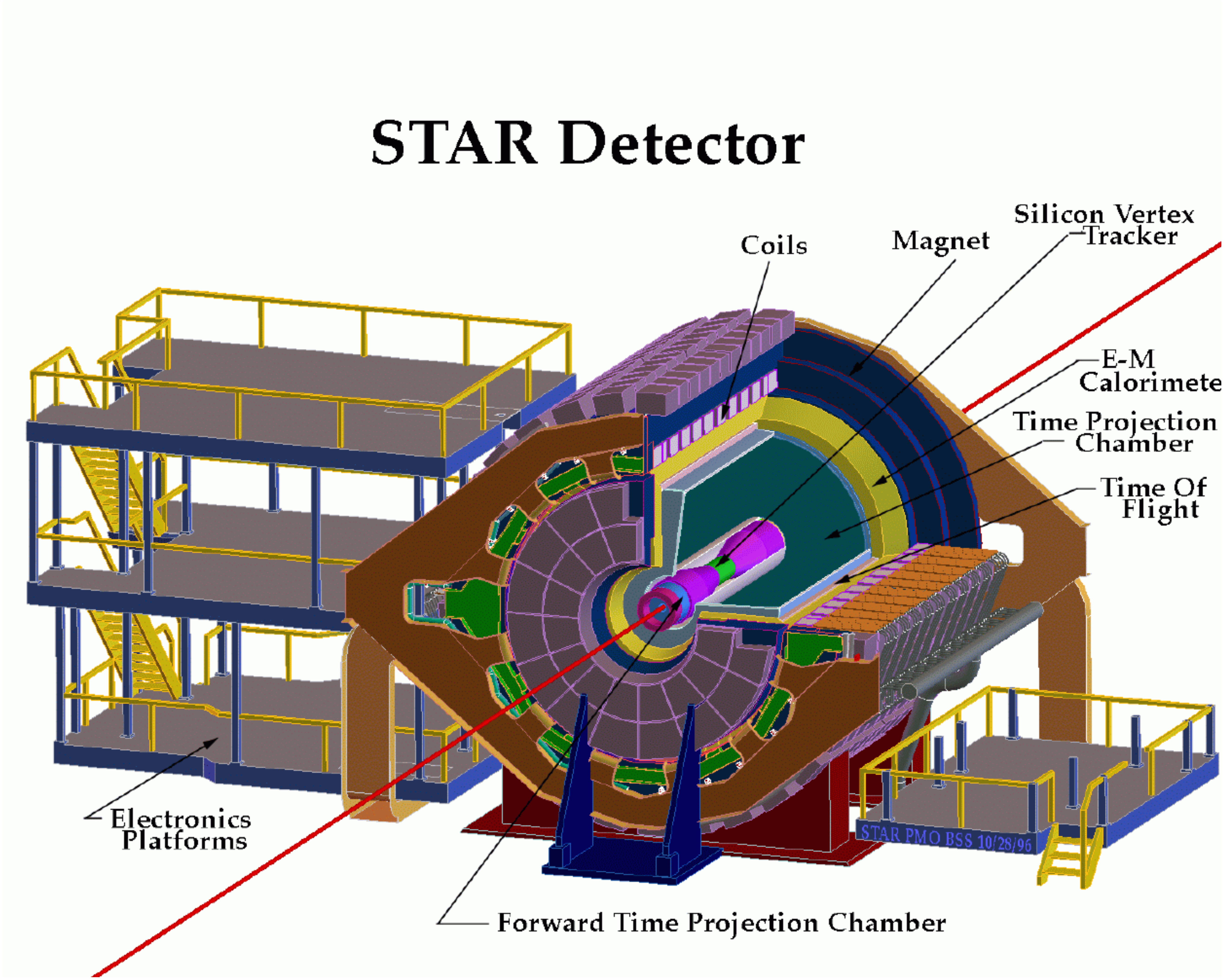
- STAR's goal is to study the fundamental properties of matter in similar conditions to those of the early Universe (microseconds after the Big Bang).



Retrieved from: https://www.flickr.com/photos/brookhavenlab/albums/72157613690851651/

The STAR Experiment

Detector overview



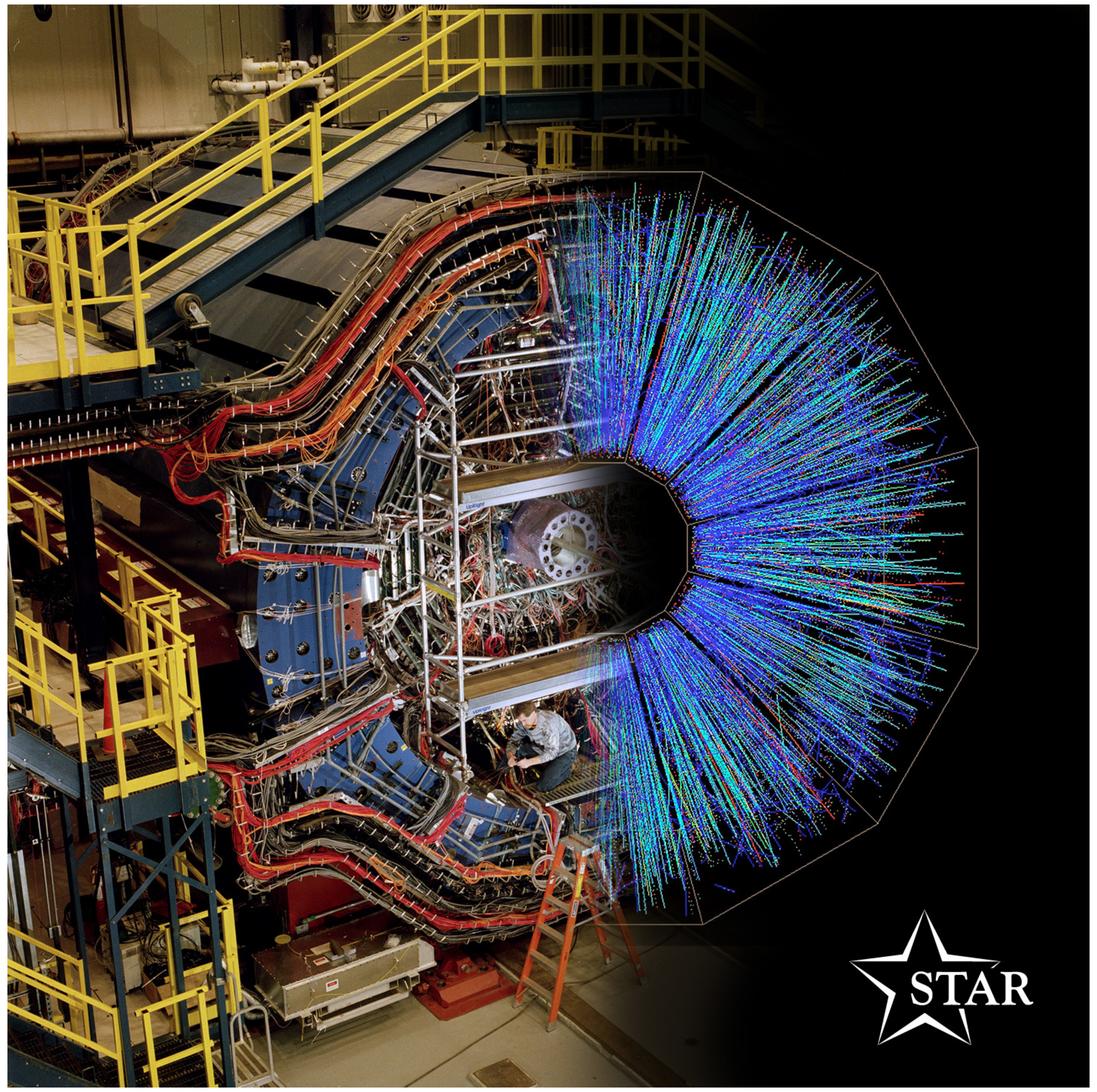
Retrieved from: https://www.flickr.com/photos/brookhavenlab/albums/72157613690851651/

- Time Projection Chamber (TPC)
- Time Of Flight (TOF)
- Vertex Position Detector (VPD)
- EM Calorimeter
- + other trigger detectors

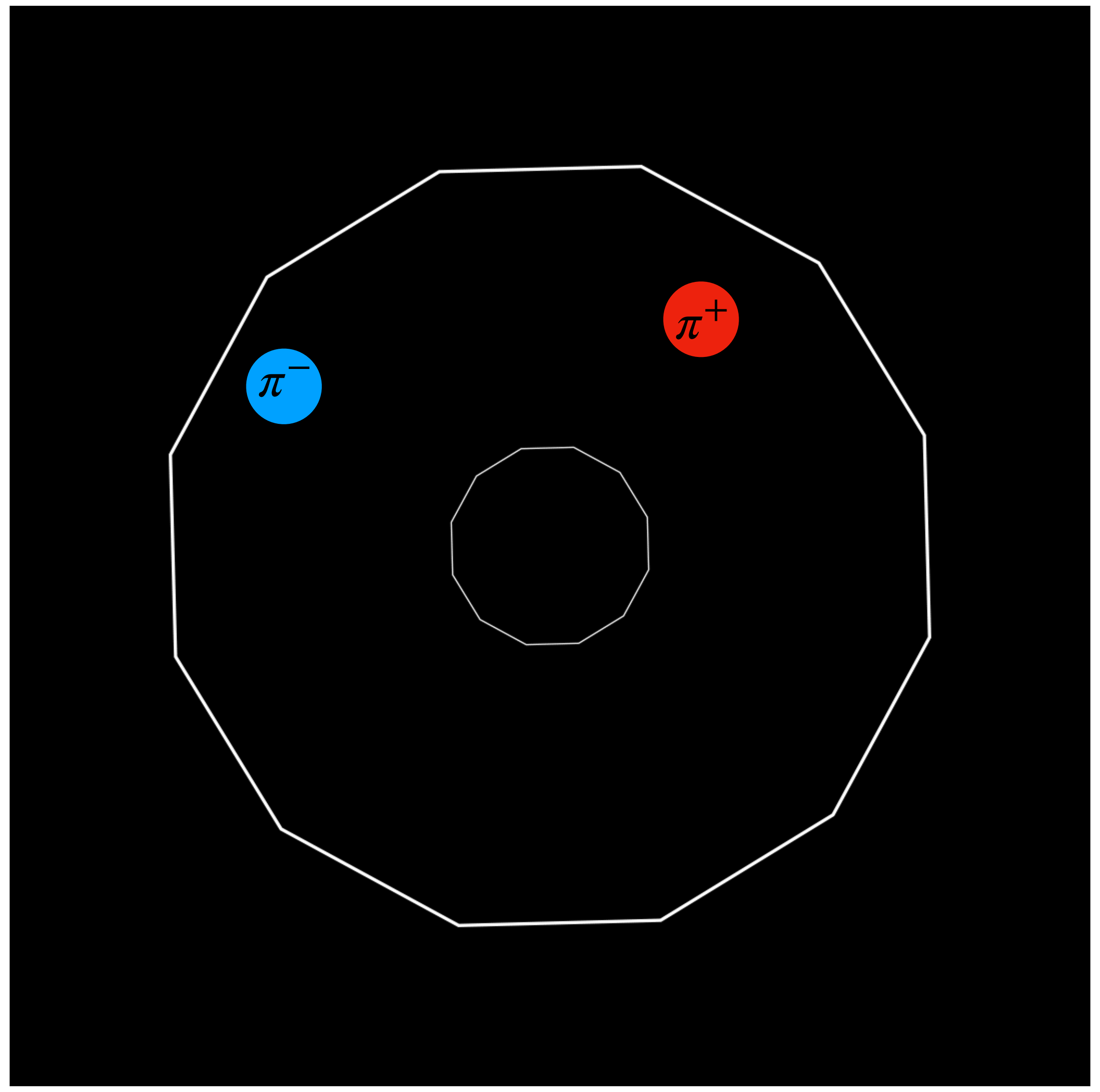
The STAR Experiment

The Time Projection Chamber (TPC)

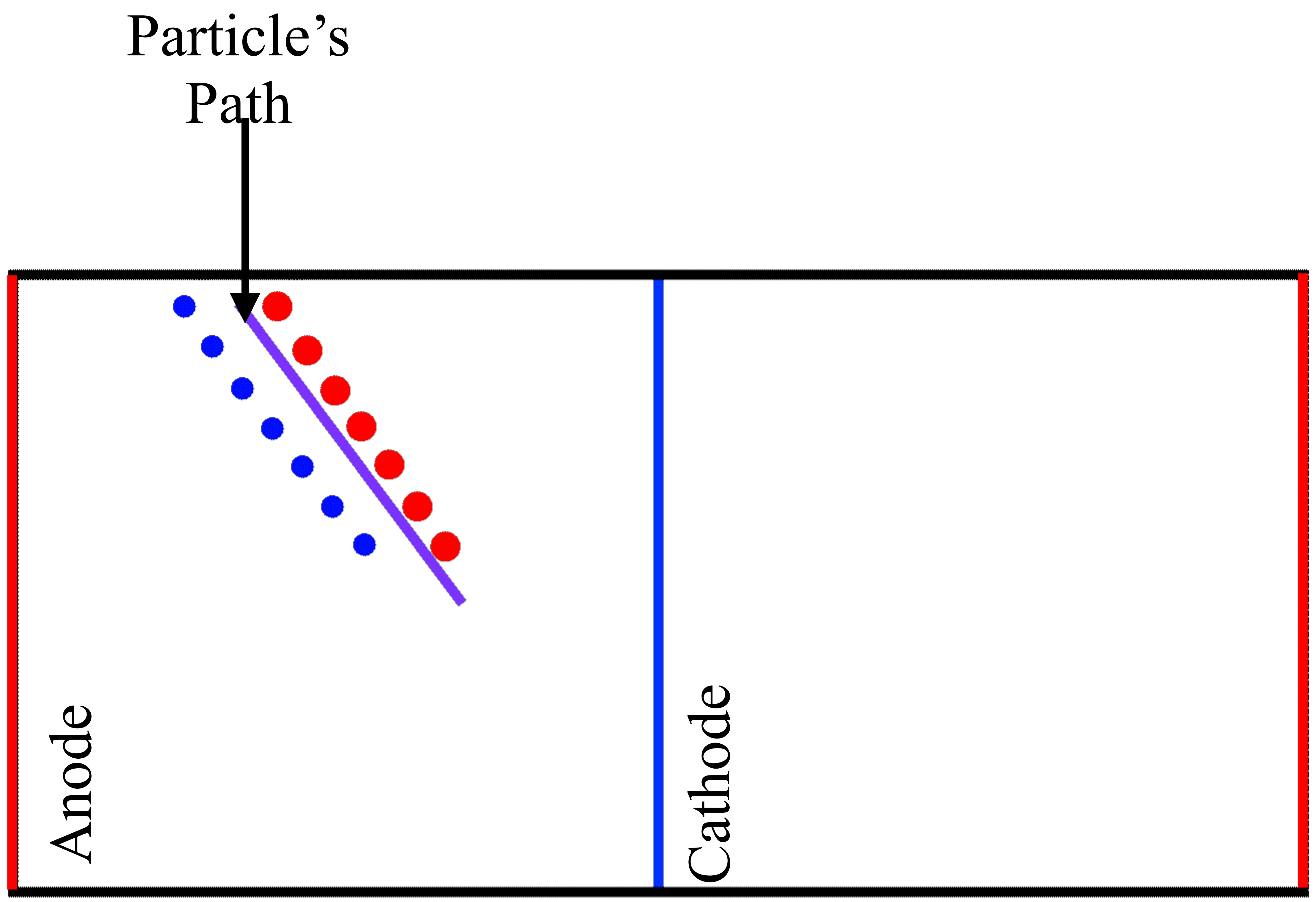
The TPC gives a 3D reconstruction of the particle's path through the chamber. For particle Identification.



Retrieved from: https://www.flickr.com/photos/brookhavenlab/albums/72157613690851651/



Transversal View



Logitudinal View

TPC provides: Charge (Q), Energy Loss (dE/dx), Momentum (p), track length (s), Vertex position (V_x, V_y, V_z).

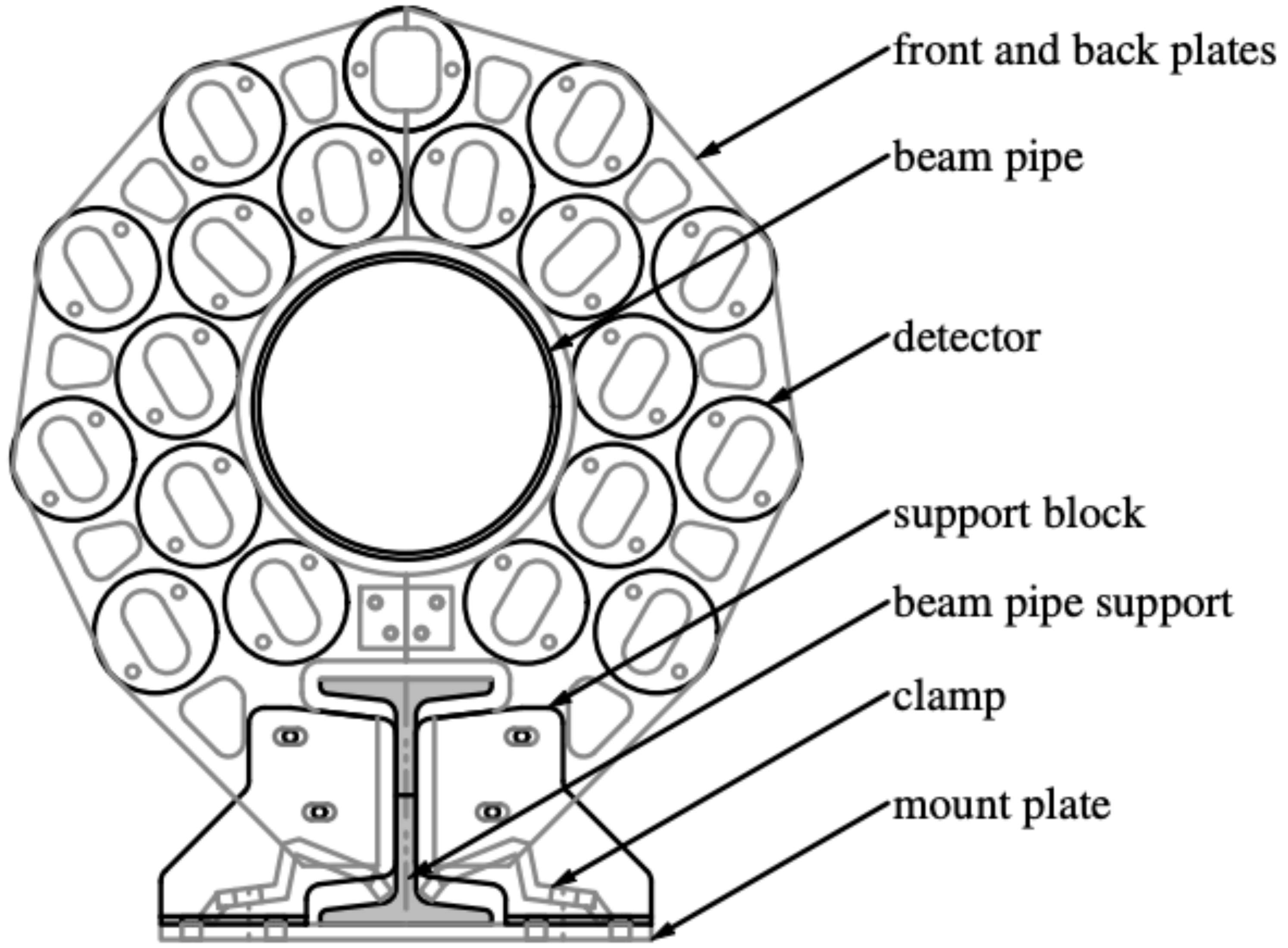
The STAR Experiment

Time of Flight (TOF) and Vertex Position Detector (VPD)

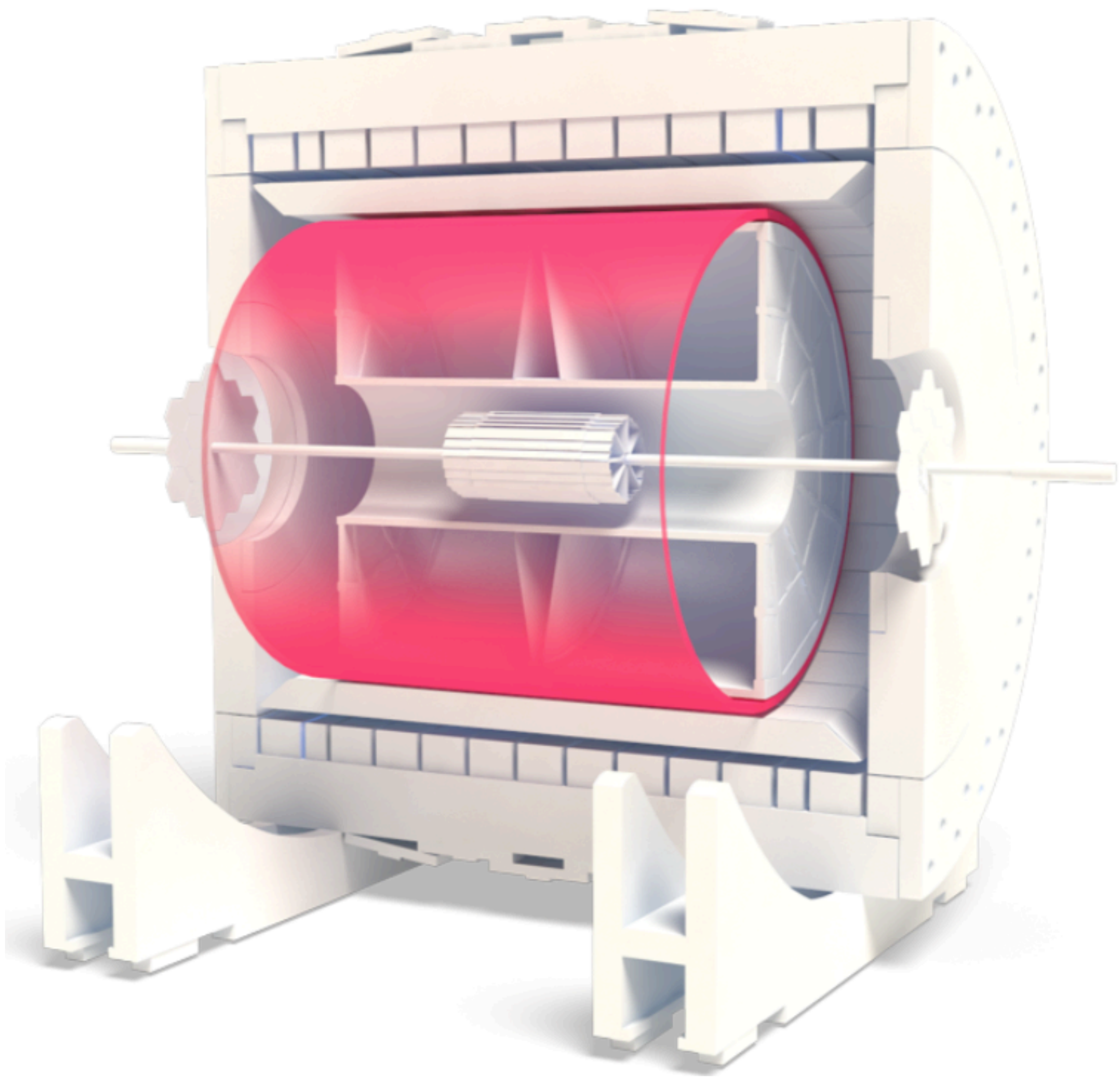
This two detector together provide the Total time of flight of a particle.

VPD: Start time

TOF: End time



Retrieved from: arXiv:1403.6855



Retrieved from: https://nsww.org/projects/bnl/star/sub-systems.php

Agenda

- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
  - Photon Equivalent Method
  - Vector Meson Dominance Model
  - Photonuclear production
  - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

Particle Identification (PiD)

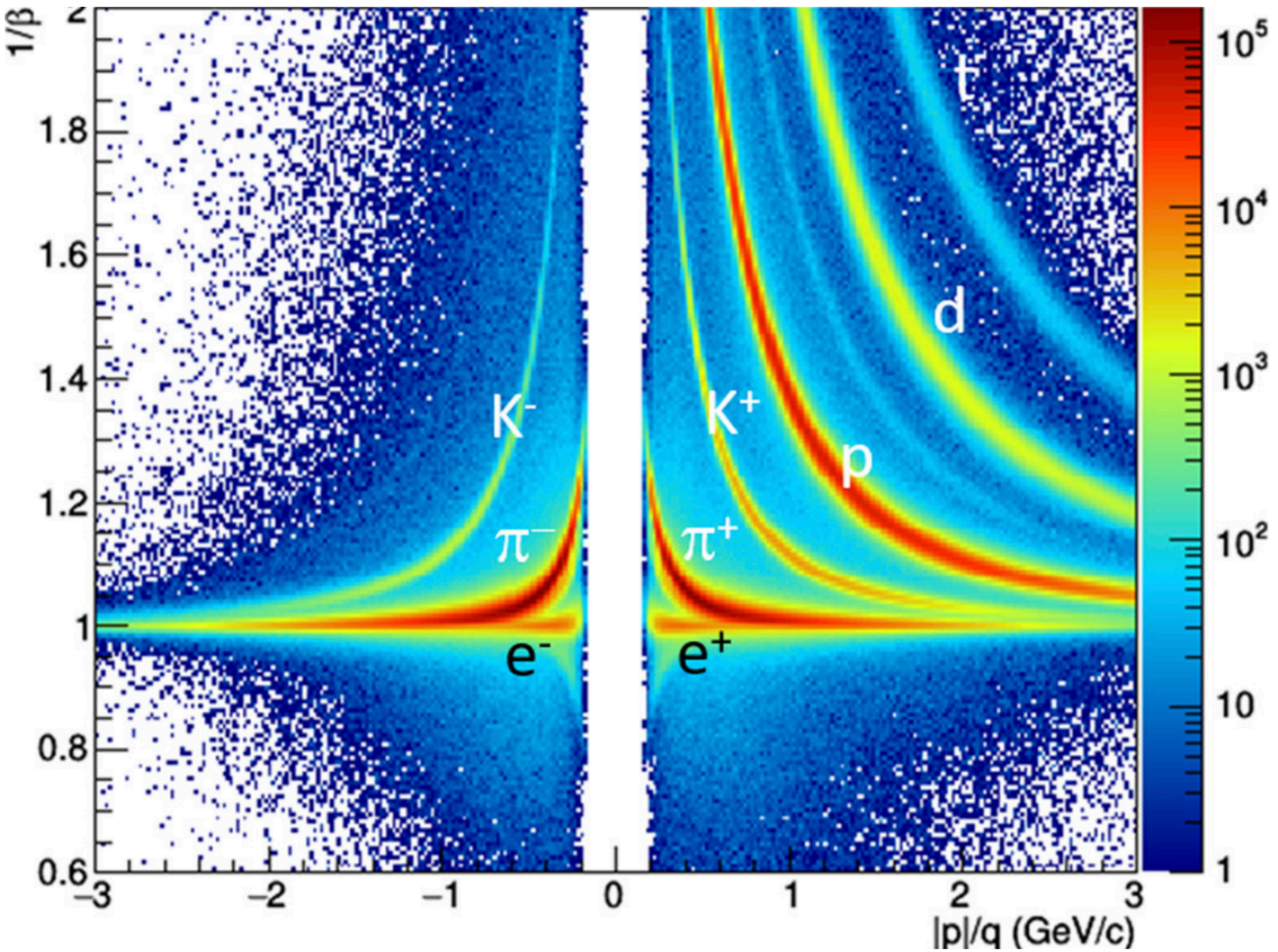
Obtaining the mass and charge

To identify a particle we basically need two observables:

- Invariant Mass
- Charge

All PiD uses the momentum relation $p = \gamma m v$ to get information about the mass of the particle.

$$\frac{1}{\beta} = \sqrt{1 + \frac{m^2c^2}{p^2}}$$



M. S. Abdallah *et al.* (STAR Collaboration) Phys. Rev. C **103**, 034908

Particle Identification (PiD)

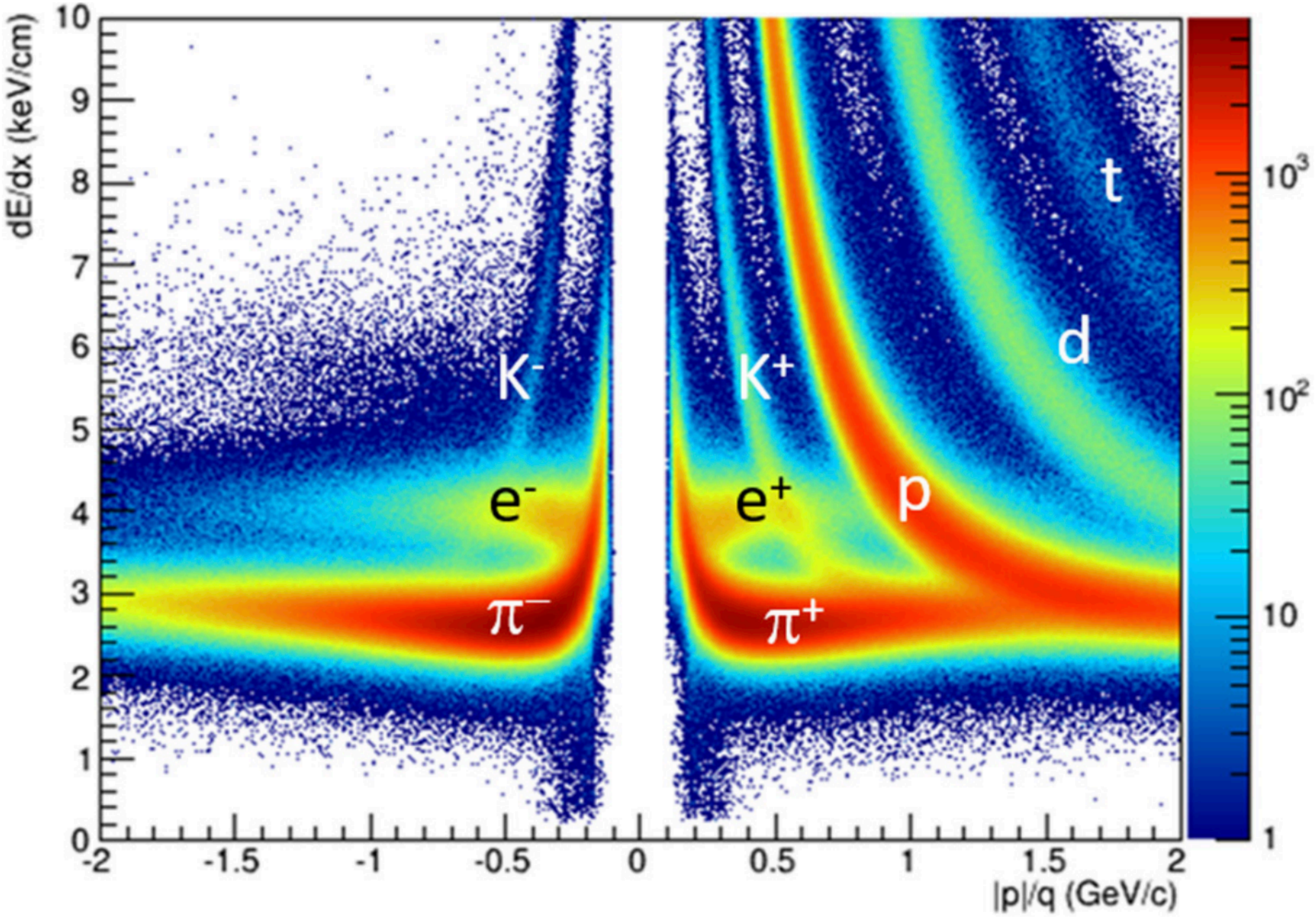
Energy Loss (dE/dx)

We also use the energy loss of the particle as it moves through the medium.

The energy loss of the particle as it moves through the medium (dE/dx). Depends of the Mass of incident particle according to the Bethe-Block Equation.

$$\left(\frac{dE}{dx}\right) = -Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_ec^2\beta^2\gamma^2T_{\text{max}}}{I^2}\right) - \beta^2 - \frac{\delta}{2}\right]$$

$$T_{\text{max}} = \frac{2m_ec^2\beta^2\gamma^2}{1 + 2\gamma\frac{m_e}{M} + \left(\frac{m_e}{M}\right)^2}$$



M. S. Abdallah *et al.* (STAR Collaboration) Phys. Rev. C **103**, 034908

Agenda

- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
    - Photon Equivalent Method
    - Vector Meson Dominance Model
    - Photonuclear production
    - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

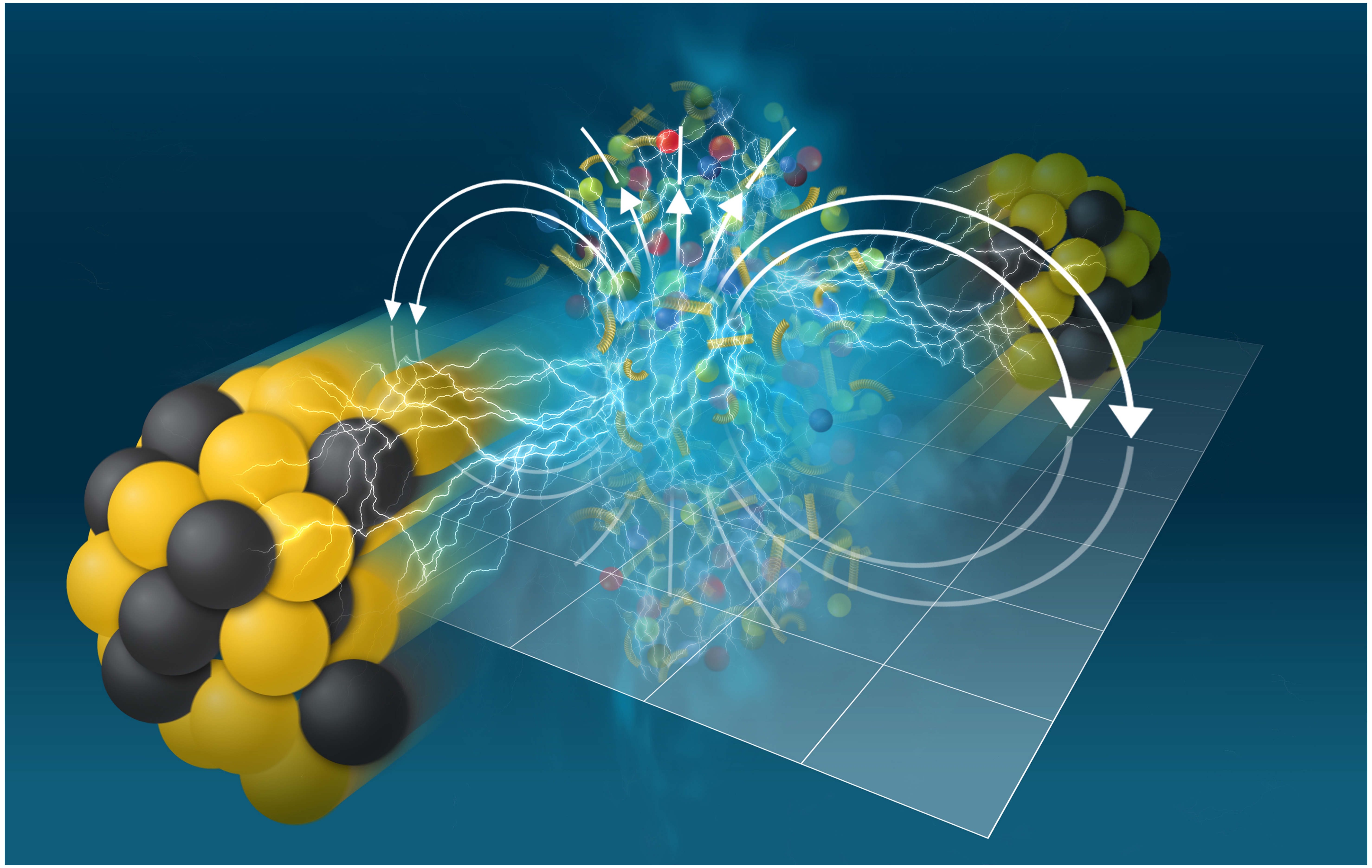
Physics Motivation

Understanding the fundamental forces

Observe the interaction of hadronic matter with strong electromagnetic fields.

Studying how photons scatter inside the nucleus could provide insights of the nuclear internal structure.

We want to test QED in a strong interacting media.



Retrieved from: https://www.flickr.com/photos/brookhavenlab/albums/72157613690851651/

Agenda

- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
  - Photon Equivalent Method
  - Vector Meson Dominance Model
  - Photonuclear production
  - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

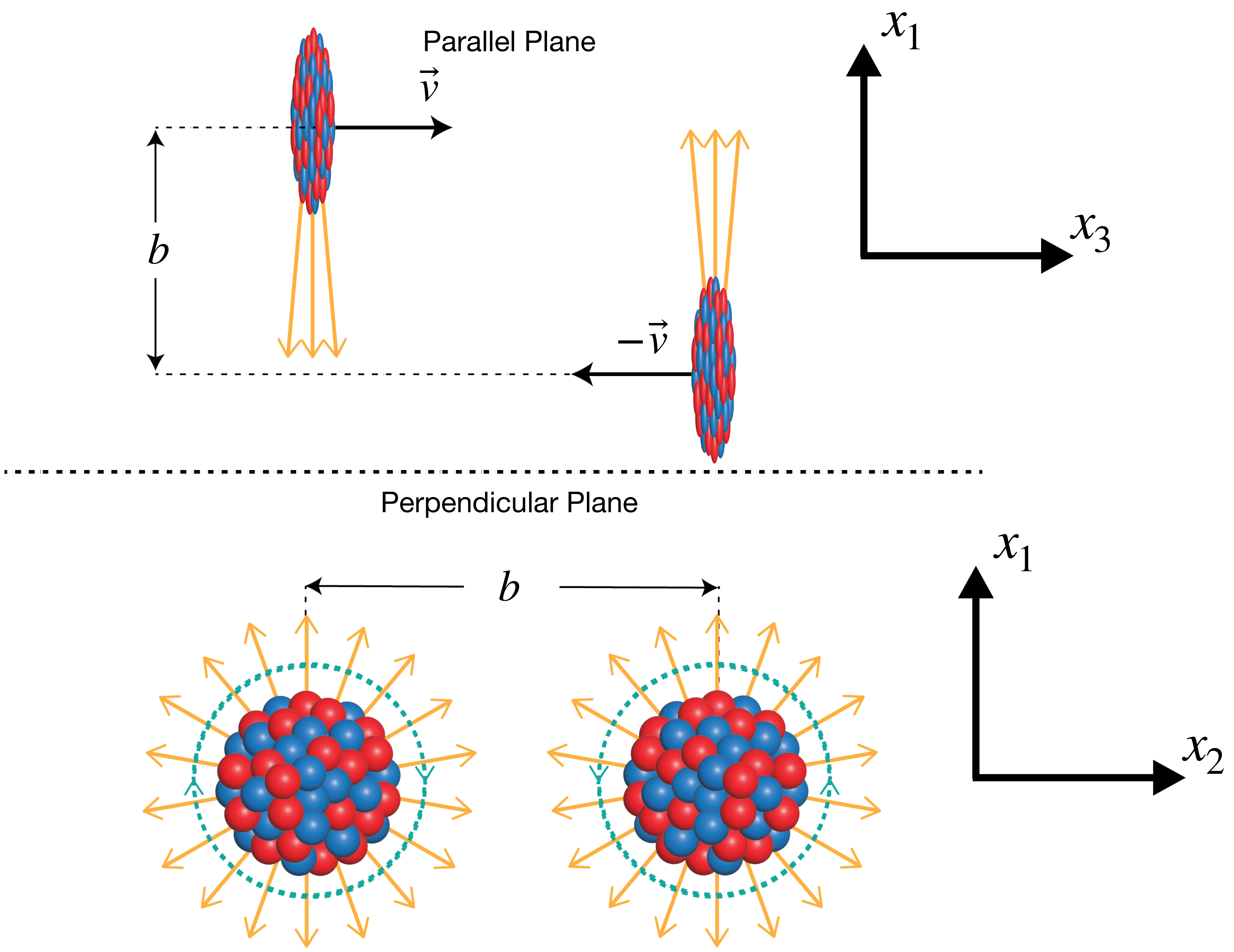
Ultra Peripheral Collisions (UPC)

What is UPC?

UPC is a type of ‘collision’ were there is no hadron-hadron interaction.

The nuclei center are farther away from $2(R_A + R_B)$ missing each other. However, they are close enough so that they can still interact through their electromagnetic (EM) fields.

UPCs are the perfect playground to analyze the interactions of hadronic matter with strong EM fields.



Agenda

- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
    - Photon Equivalent Method
    - Vector Meson Dominance Model
    - Photonuclear production
    - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

Equivalent photon method

EM fields as a pulse of radiation

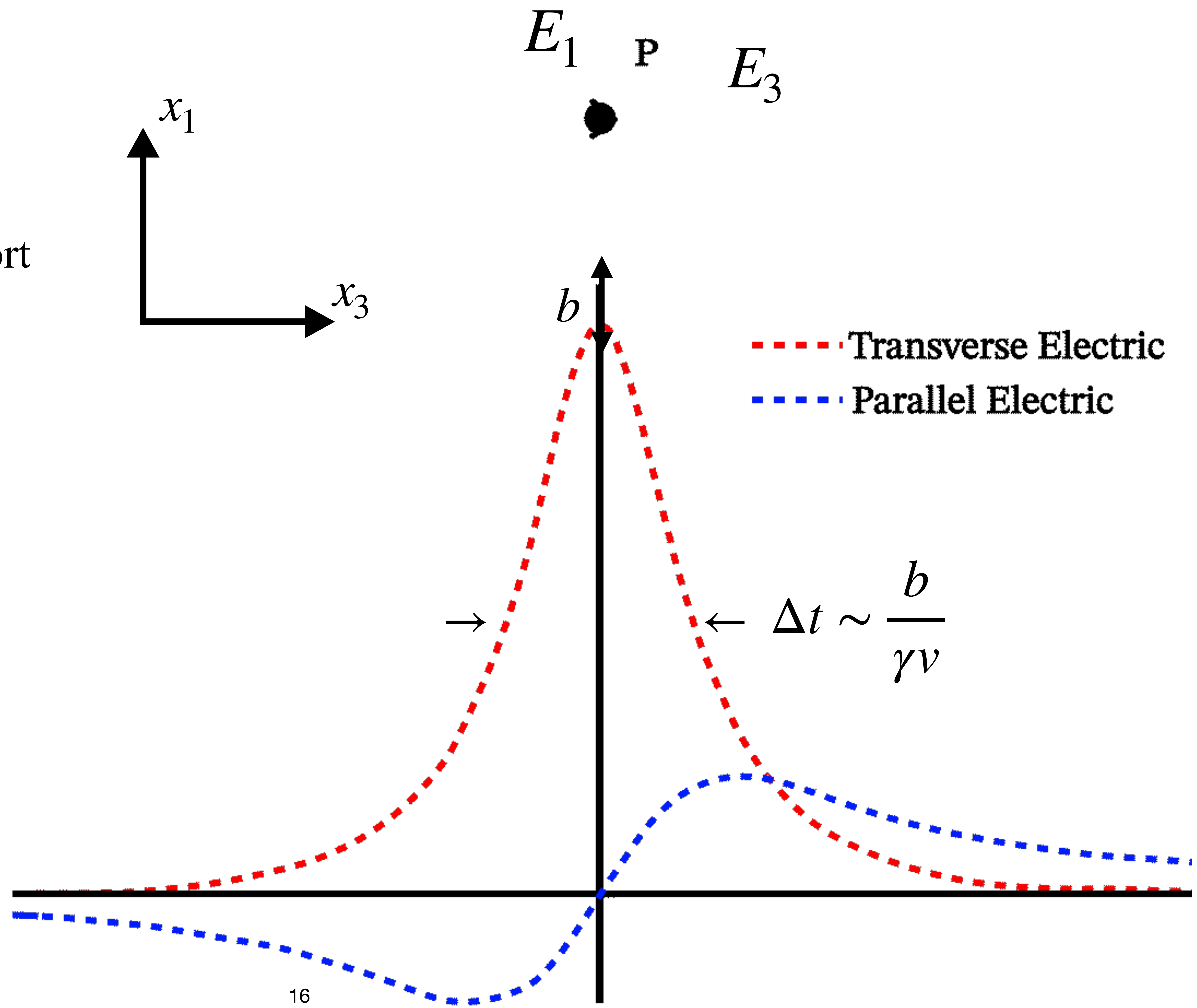
Relativistic heavy ions produce a short but strong pulse of electromagnetic radiation.

The electric and magnetic field observed by the target particle

$$E_1 = \frac{\gamma q b}{(b^2 + \gamma^2 v^2 t^2)^{3/2}}$$

$$B_2 = \beta E_1$$

$$E_3 = \frac{\gamma q v t}{(b^2 + \gamma^2 v^2 t^2)^{3/2}}$$



Jackson (1998, p. 520)

Equivalent photon method

The Energy per unit frequency is given by

$$\frac{dI}{d\omega} = 2\pi \int_{b_{min}}^{\infty} \left[\frac{c}{2\pi} |E_1(\omega)|^2 \right] bdb$$

Where $b_{min} \sim 2R$, so

We due to the interaction length we can define a

$$\omega_{max} \sim \frac{1}{\Delta t} = \frac{\gamma v}{b_{min}}$$

$$\lambda_{min} = \frac{c}{\omega_{max}}$$

In the low frequency range $\omega \ll \gamma v / b_{min} = \omega_{max}$, which is the range of interest for coherent production, the energy per unit frequency reduces to

$$\frac{dI}{d\omega}(\omega) \approx \frac{2q^2}{\pi c \beta^2} \left[\ln\left(\frac{1.123\gamma v}{\omega b_{min}} \right) - \frac{\beta^2}{2} \right]$$

The number of of virtual photons $N(\hbar\omega)$

$$\frac{dI}{d\omega}(\omega)d\omega = \hbar\omega n(\hbar\omega)d(\hbar\omega)$$

$$n(\hbar\omega) \approx \frac{2q^2}{\pi \hbar^2 \omega c \beta^2} \left[\ln\left(\frac{1.123\gamma v}{\omega b_{min}} \right) - \frac{\beta^2}{2} \right]$$

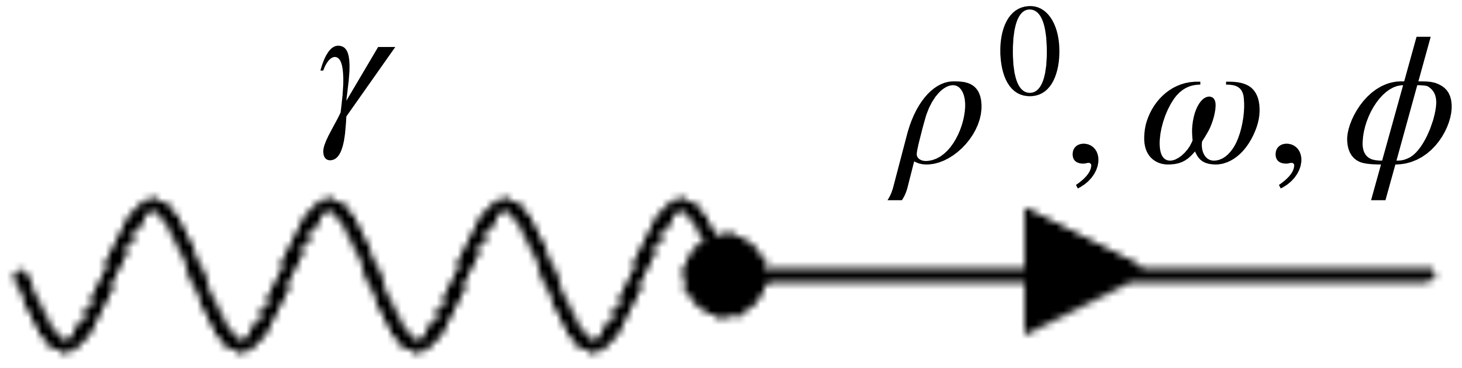
Jackson (1998, p. 520)

Agenda

- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
  - Photon Equivalent Method
  - Vector Meson Dominance Model
  - Photonuclear production
  - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

Vector Meson Dominance Model (VDM)

Vector Meson Dominance Model (VDM) can is an effective description where vector mesons are the relevant degrees of freedom for describing low-energy photon-hadron interactions.



$$\mathscr{L}_{V\gamma} = -M_V^2 \frac{e}{g} A_\mu \left[\frac{\rho^\mu}{\sqrt{2}} + \frac{\omega^\mu}{3\sqrt{3}} - \frac{\phi^\mu}{3} \right]$$

The Key Points of VDM are:

- **Photon-Meson Conversion**: The photon is assumed to convert into a vector meson with the same quantum numbers.
- **Hadrons Interaction**: The vector meson then interacts with hadrons. This simplifies the description of photon-hadron interactions because the meson-hadron interaction is typically easier to model.

J. M. Dias et al 2018 Chinese Phys. C 42 043106

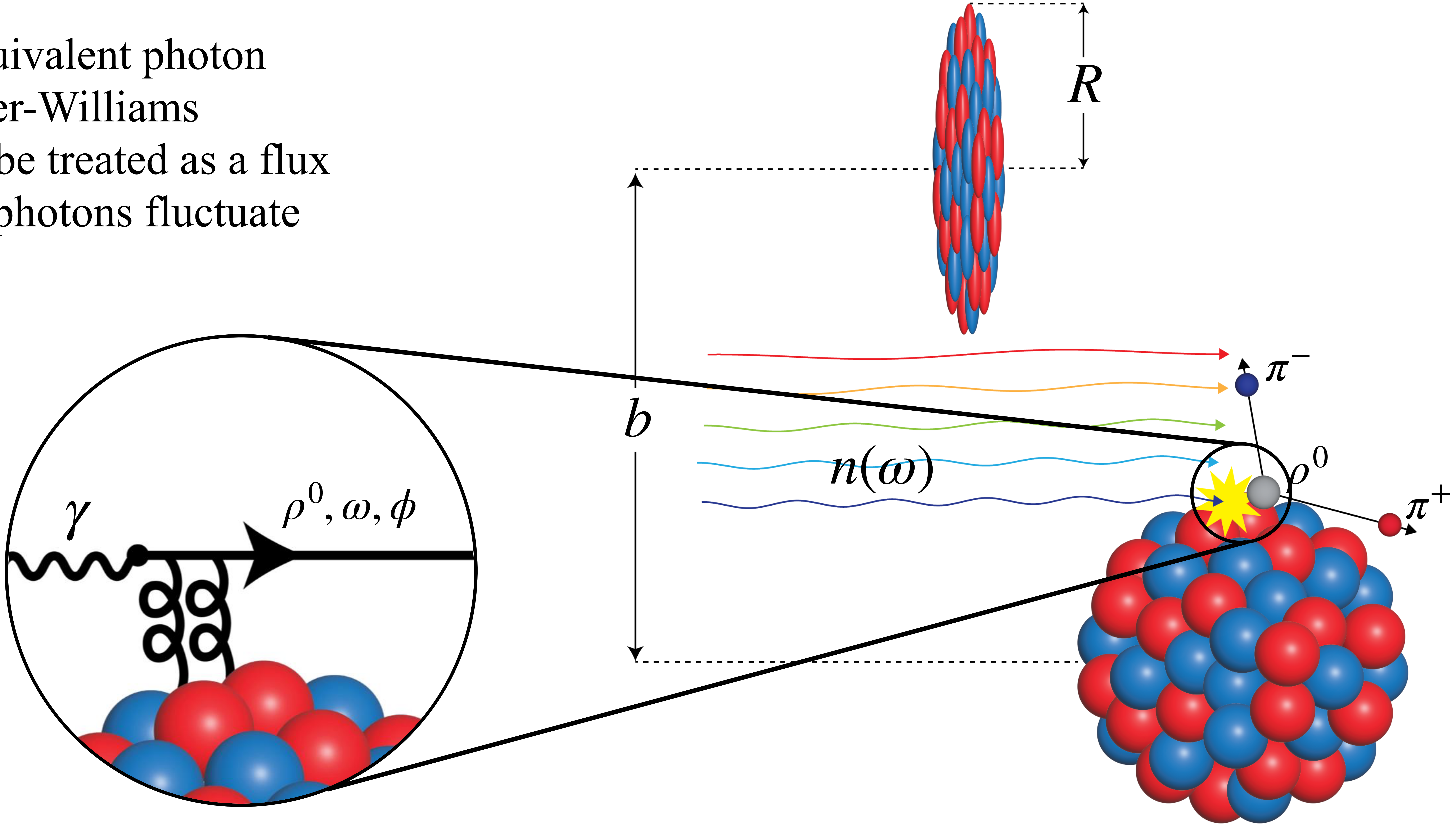
Agenda

- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
    - Photon Equivalent Method
    - Vector Meson Dominance Model
    - Photonuclear production
    - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

Photonuclear production in UPC

Then, according to the equivalent photon approximation (Weizsäcker-Williams method) those pulses can be treated as a flux of photons. Those virtual photons fluctuate to virtual vector mesons.

Finally, this virtual mesons can scatter with the target nucleus to produce a real vector meson.



UPC sketch of two identical nuclei in the reference frame of the target nucleus.

Agenda

- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
    - Photon Equivalent Method
    - Vector Meson Dominance Model
    - Photonuclear production
    - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

Interference effect in the Matrix element

The big picture

Process 1 has a matrix element

$$\mathscr{M}_1 \sim \left\langle A_1, A_2, M \,|\, \mathscr{H}_{int} \,|\, A_1, A_2 \right\rangle$$

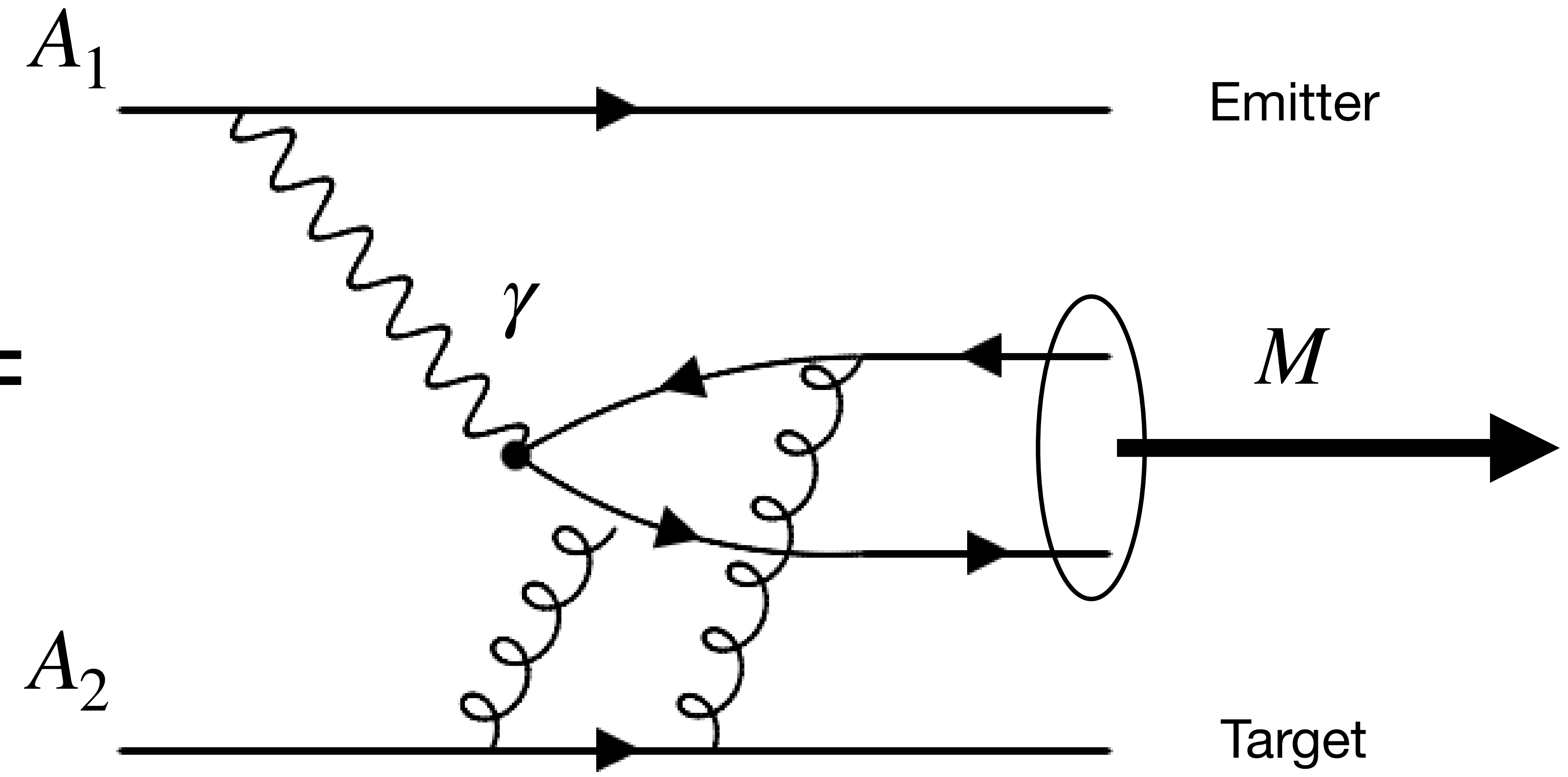
Process 2 is the parity transformation of $\mathscr{M}_1$

$$\mathscr{M}_1 \xrightarrow{\hat{P}} \mathscr{M}_2 \sim t_{A_1}^2 t_{A_2}^2 t_M \left\langle A_1, A_2, M \,|\, \mathscr{H}_{int} \,|\, A_1, A_2 \right\rangle e^{i\vec{b}\cdot\vec{p}_\perp}$$

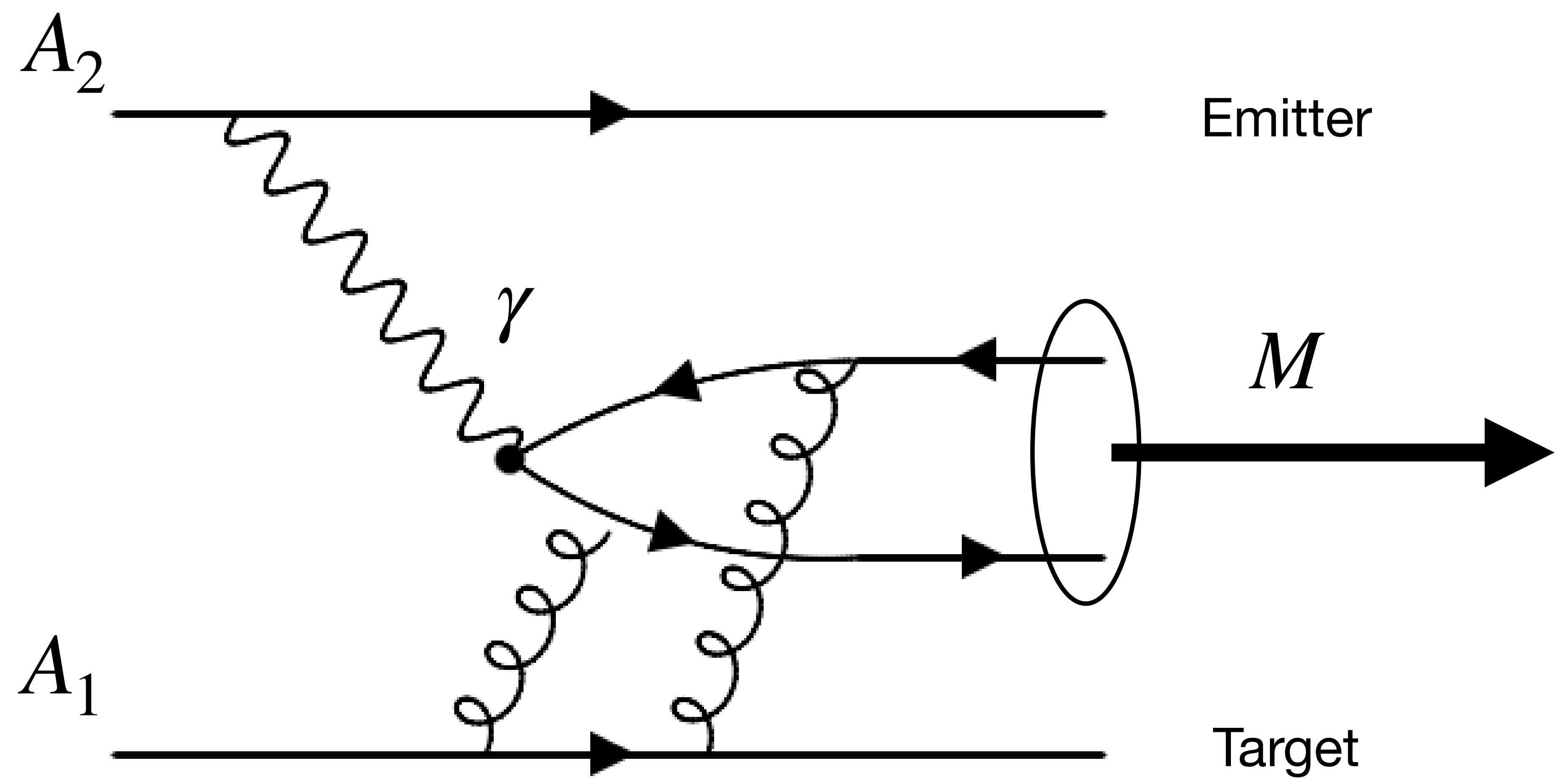
Thus, if particle M has a negative intrinsic parity ($t_M = -1$), then

$$\mathscr{M} = \mathscr{M}_1 + \mathscr{M}_2 = \mathscr{M}_1 \left(1 - e^{i\vec{b}\cdot\vec{p}_\perp}\right)$$

$\mathscr{M}_1 =$



$\mathscr{M}_2 =$



Klein, S. R., & Nystrand, J. (2000). Phys. Rev. Lett., 84, 2330.

Agenda

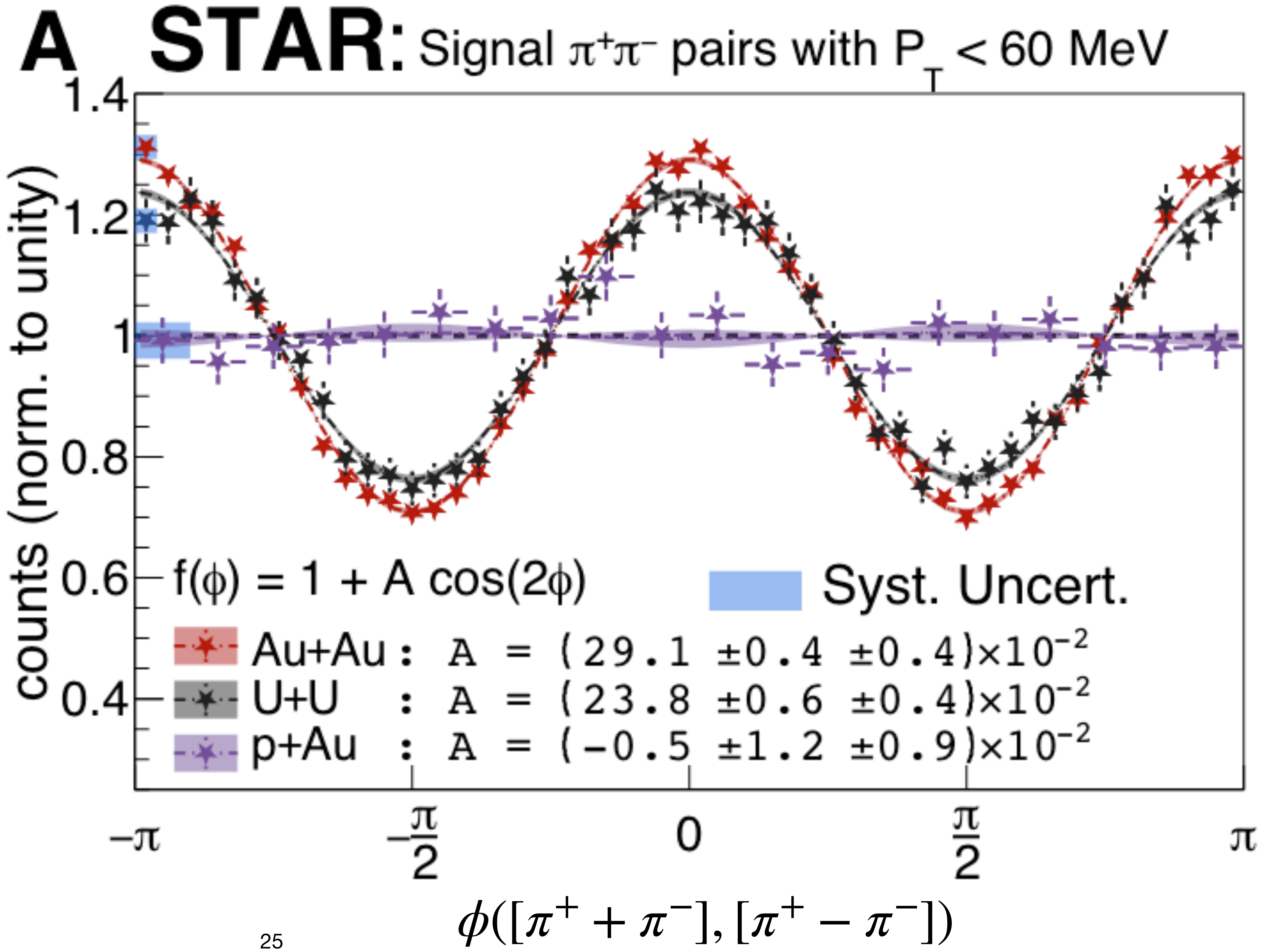
- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
  - Photon Equivalent Method
  - Vector Meson Dominance Model
  - Photonuclear production
  - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

UPC Results

J. D. Brandenburg 2023 Science Advances 9 BNL-223867-2023-JAAM

What can we observe in this plot?

- There are strong modulation in identical ion collisions.
- The differences in Au+Au and U+U are attributed to nuclear geometry.
- p+Au serves to demonstrate that as we break the symmetry of the collision the interference pattern is reduced.



Agenda

- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
    - Photon Equivalent Method
    - Vector Meson Dominance Model
    - Photonuclear production
    - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

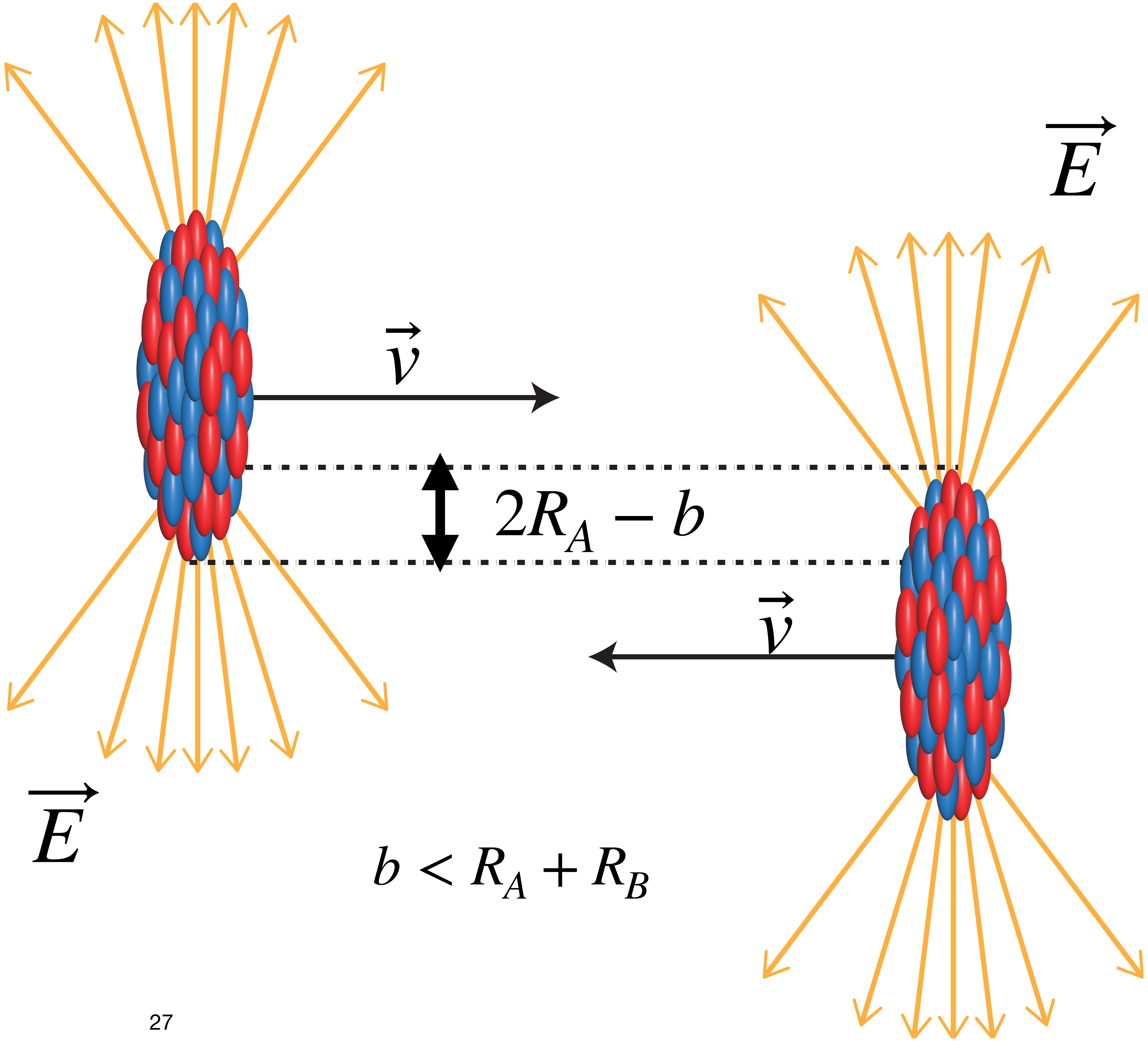
Moving from UPC to Peripheral Collisions

Relevance:

- Increase the virtuality of photons
- Study the effects of the impact parameter
- Study how the hadronic medium affect the interference patterns observed in UPC.

Challenges:

- Smaller signal/background ratio



Agenda

- What is the STAR Experiment
- Particle Identification
- Research Motivation
- Ultra Peripheral Collisions in Heavy Ions
- Theoretical Frame Work
    - Photon Equivalent Method
    - Vector Meson Dominance Model
    - Photonuclear production
    - Interference effect due to a parity asymmetry
- UPC results
- From UPC to Peripheral Collisions
- Summary and Future Work

Summary and Future work

- UPC are able to enhance electromagnetic fields due to their big Lorentz factors ($\gamma \sim 200, \beta \approx 1$).
- This electromagnetic fields could be treat as a flux of photons that interact with hadronic matter.
- In UPC we have observed the production of vector mesons due to the interaction of photons with hadronic matter.
- We want to study the same phenomena seen in UPC but in less peripheral events, to observe hadronic matter and geometric effects.

Thank you!