Initial-state physics program with UPCs at RHIC – BUR 2023-2025

1. Exclusive processes, e.g., Vector Meson.
2. Semi-inclusive/jets, e.g., dijets photoproduction
3. Inclusive processes, charged particle production

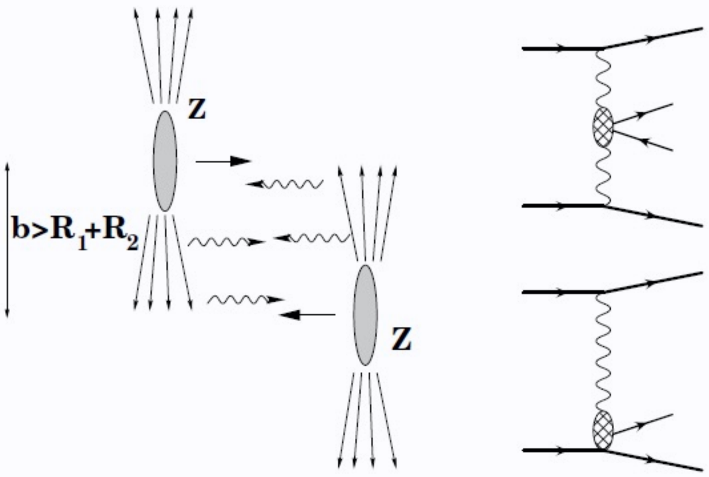
D. Brandenburg, X. Chu, W. Schmidke, Kong Tu, Z. Zhang

BNL

04.22.2022

UPC – a general approach to photoproductions

Exclusive processes

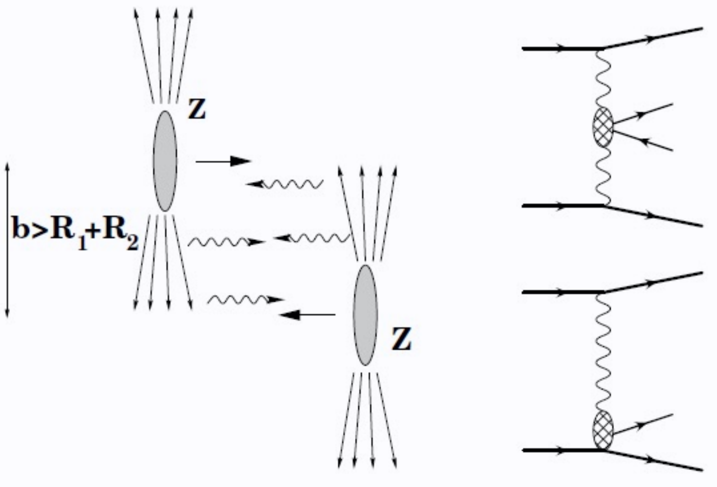


What we mostly focused on in the UPC physics – VM and dilepton

- Nuclear gluon density ~ *xG, low-x physics, saturation, shadowing, etc.*
- QED process

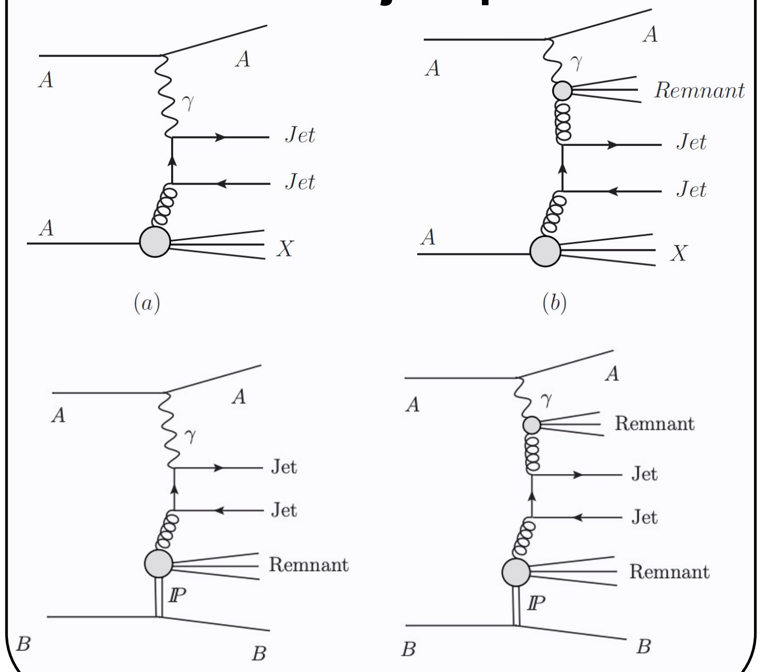
UPC – a general approach to photoproductions

Exclusive processes



What we mostly focused on in the UPC physics – VM and dilepton

Semi-inclusive/jets processes



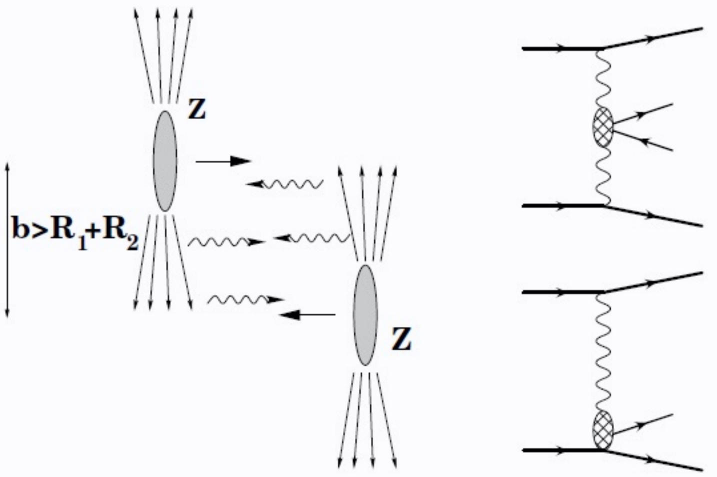
- Nuclear gluon density ~ *xG, low-x physics, saturation, shadowing, etc.*
- QED process

- nPDFs*, moderate-x at RHIC, anti-shadowing region!*
- QCD factorization breaking and diffractive nPDFs
- Photon structure.

UPC – a general approach to photoproductions

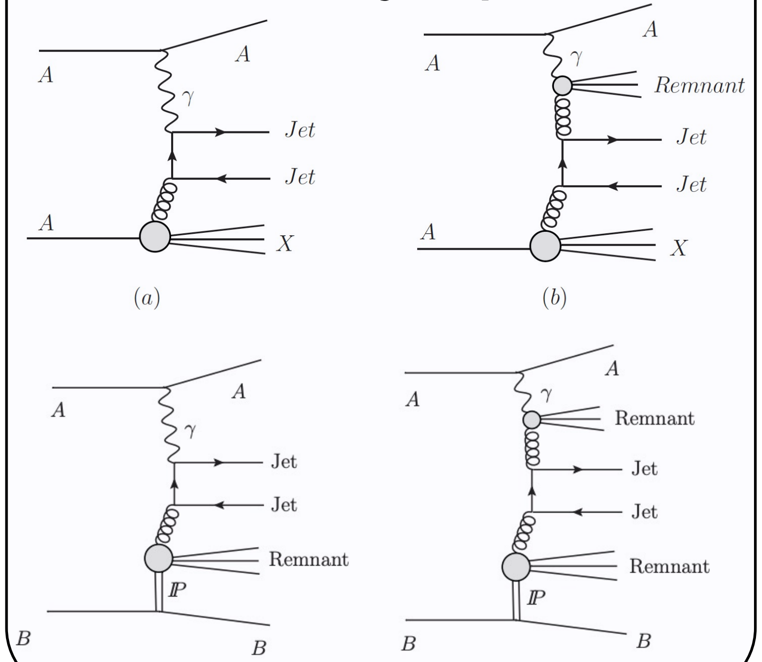
Submitted to PRD (April 15,2022)

Exclusive processes

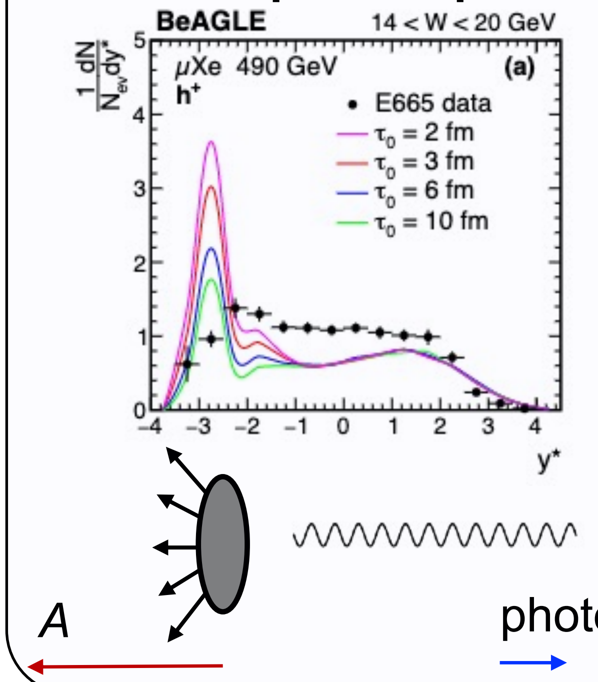


What we mostly focused on in the UPC physics – VM and dilepton

Semi-inclusive/jets processes



Inclusive particle production



- Nuclear gluon density ~ *xG, low-x physics, saturation, shadowing, etc.*
- QED process

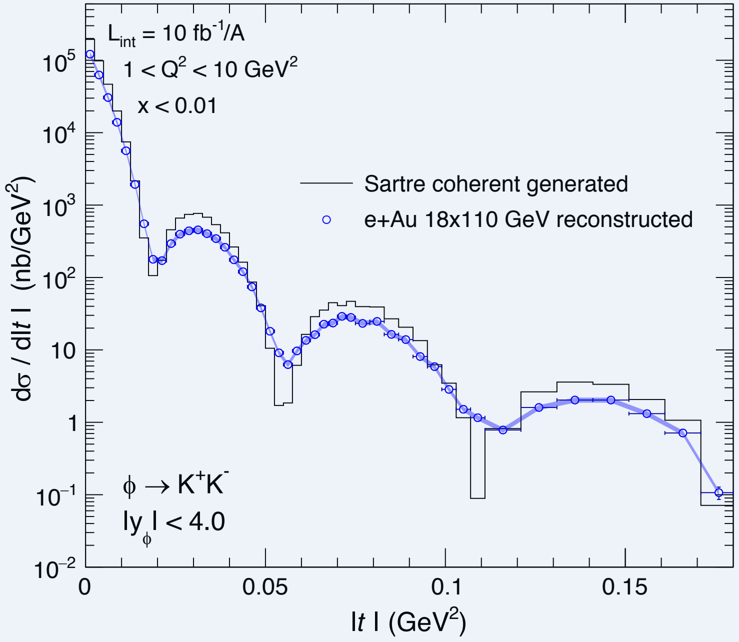
- nPDFs, *moderate-x at RHIC, anti-shadowing region!*
- QCD factorization breaking and diffractive nPDFs
- Photon structure.

- Inclusive – sensitive to target fragmentation in nucleus, Intra-Nuclear Cascade, etc.
- Baseline for saturation studies

Exclusive processes for STAR 2023+

- J/psi photoproduction with high precisions,
  - Wide rapidity coverage.
  - Neutron multiplicity classes to solve *photon ambiguity.*
  - Precise cross section measurement compared with pAu - direct observation of suppression and huge impact on models.
- J/psi photoproduction off proton with transverse polarization Run 2024 (already in BUR)
- φ meson photoproduction, first time opportunity and a now-or-never type of measurement! **Half-field running of STAR.**
  - **Extensive studies have shown** φ meson is the best to see saturation in UPC (Ullrich, Tobias)
- Dielectron from Breit-Wheeler process towards low mass. **Half-field running of STAR.**

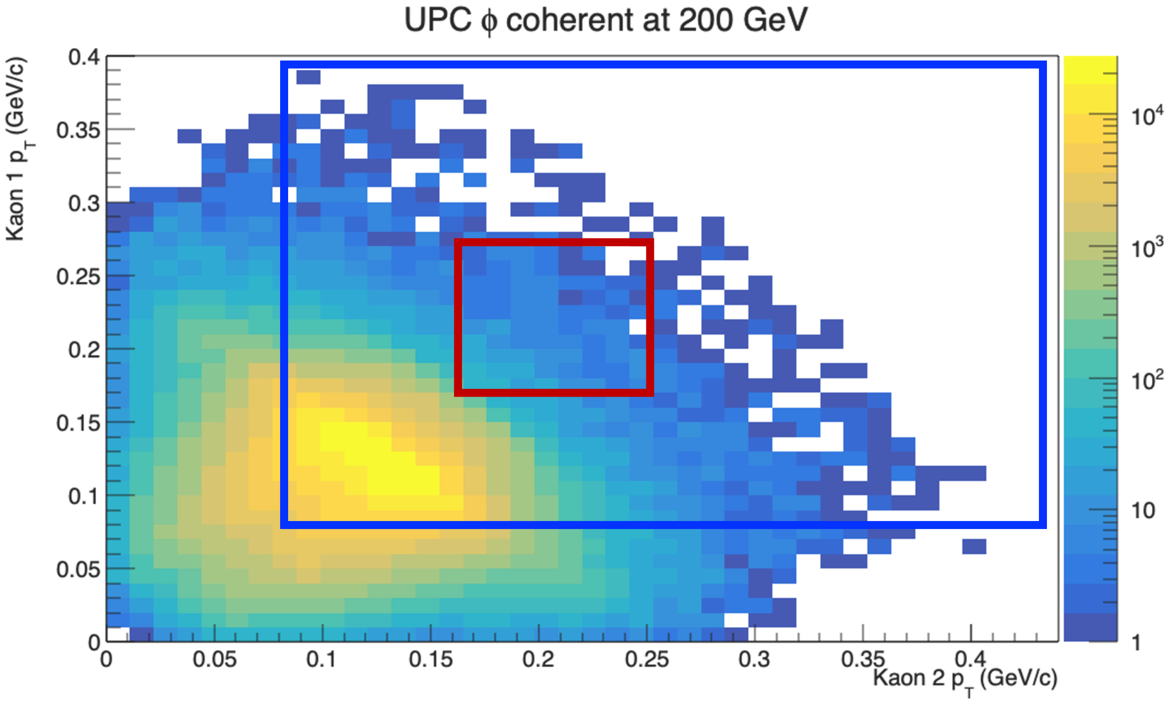
EIC Detector-1 Proposal (ATHENA)
One of the most important sciences at the EIC



Even at EIC, photoproduction of φ meson is difficult, if not impossible

φ meson

- Q^2 ~ 0 + coherent φ meson has very low p_T → very soft decays to the K^+K^-(~ 100 MeV/c)
- With full field at STAR (0.5T), the acceptance is very poor



STARlight simulations at 200 GeV AuAu

p_T acceptance with $\boxed{\text{full field}}$ and $\boxed{\text{half field.}}$

However, not every daughter can reach TOF (~ 2 meters) even with the half field

Total acceptance ~ 5.2% of all generated φ

Reference: Rho→ pi+pi-, total acceptance is ~ 17%

Running estimates

- Based on STARLight and UPC ρ^0 paper at STAR

VM	Acceptance to TOF-based UPC trigger	Cross section*	Luminosity	Raw yield (in STAR)
ρ^0	17%	40 mb	1 nb^{-1}	~400,000
φ	5.2%	1.5 mb	1 nb^{-1}	**~4500**

* Includes branching ratio to KK

→Scenario 1: 0.3 nb^{-1} ~ 1500 φ

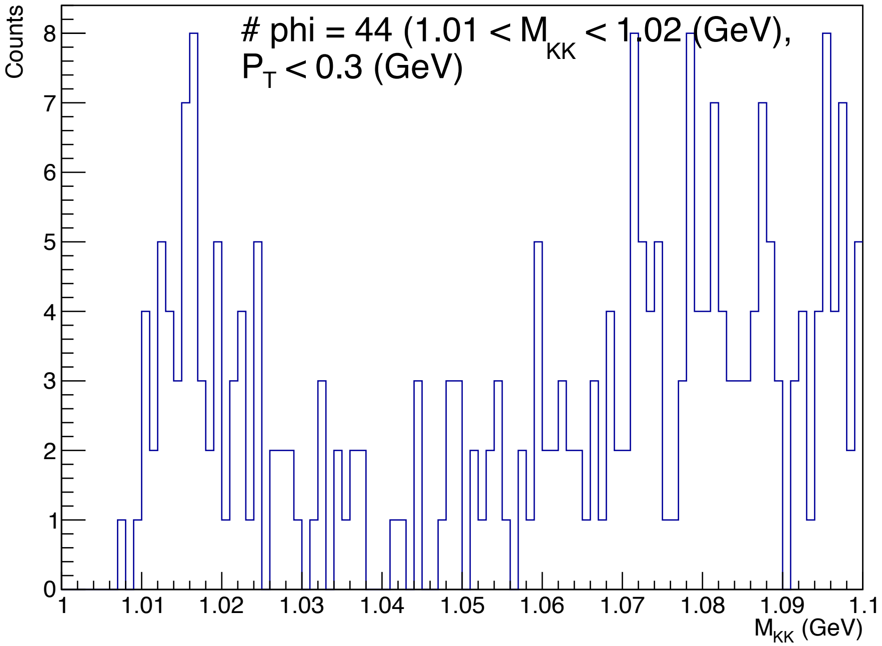
→Scenario 2: 1 nb^{-1} ~ 4500 φ

(1-2% of target luminosity for Run 2023 and/or 2025)

STAR might be the only place capable of doing it, now or never
Low costs with high returns!

A quick preview – UPC φ meson

Run19 Au+Au 200 GeV



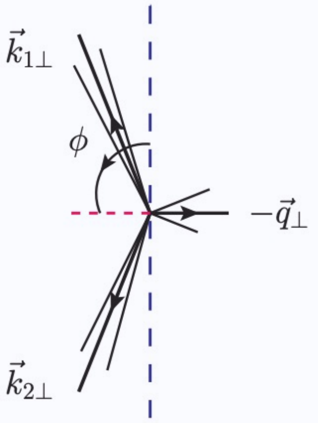
(Plot by Daniel. B)

Offline selections:
BBC VETO
gRefMult < 4
Primary Vertex with exactly 2 tracks

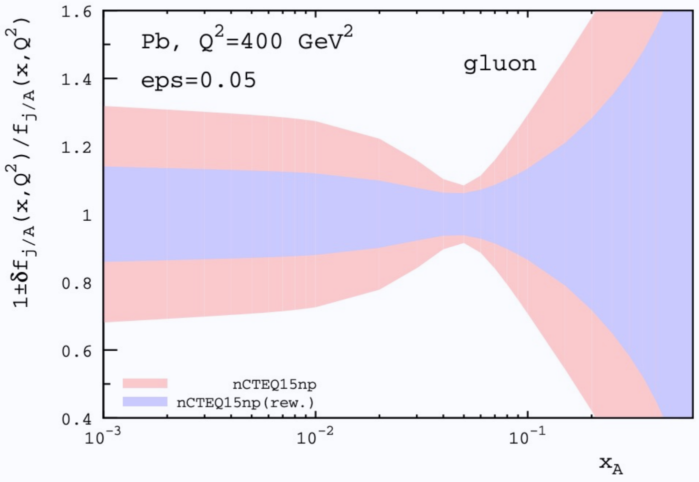
- Taken with only ZDC coincidence trigger in 2019, UPC φ meson is therefore included.
- 40 φ meson out of a total of 120M triggered events.
- With full field, the tracking with iTPC can go down to lower p_T , this proves the capability of STAR can make this measurement.
- However, with dedicated half-field running, we can be much more efficient, with cleaner events using TOF trigger, etc.

Dijets photoproduction for STAR 2023+

- Only preliminary dijet measurements done by ATLAS is available



Recent interest in azimuthal correlations



Guzey, Klasen, EPJ C 79 (2019) 5, 396

Use LHC dijet pseudo-data, Guzey, Klasen estimated the power for reducing gluon PDF

Kinematic reach down to $x_A \sim 10^3$

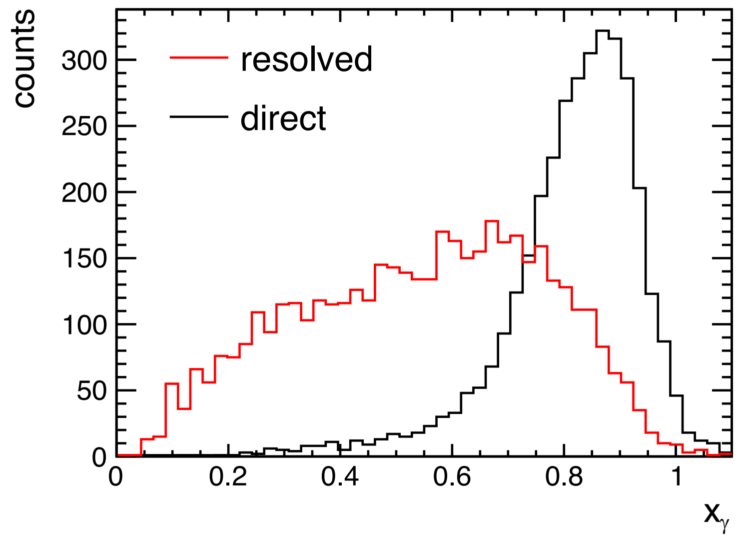
Dijets are also sensitive probe to saturation at the EIC, see talk 2 hours ago!
https://indico.bnl.gov/event/14946/

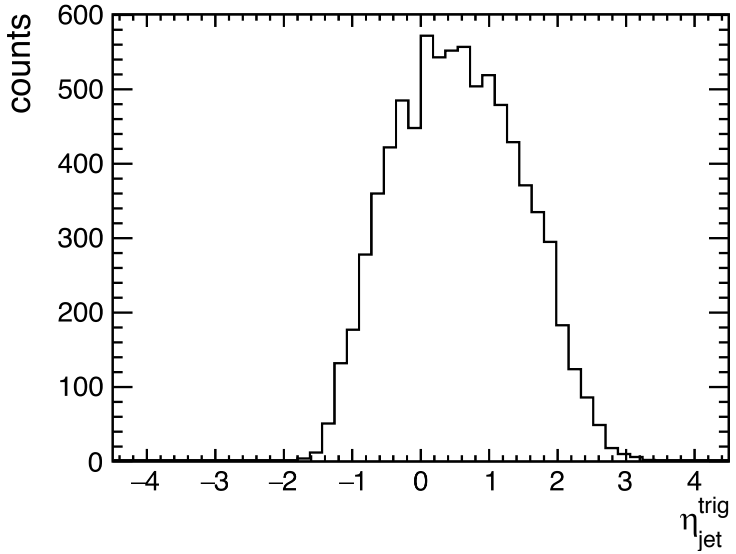
RHIC energy with dijets photoproduction can probe the anti-shadowing region, x ~ 0.1

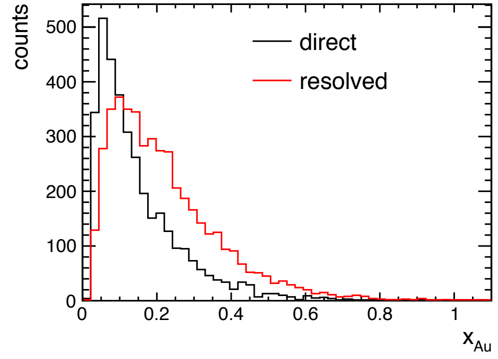
(Plots by Xiaoxuan Chu)

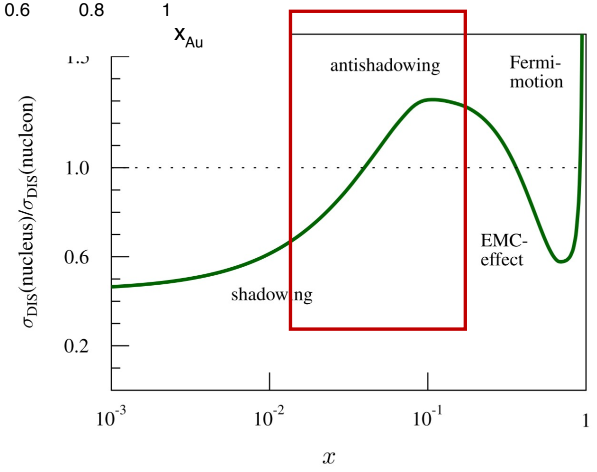
Inclusive dijets photoproduction in UPC.

UPC AuAu 200 GeV – new model from BeAGLE eAu 18x100 with UPC photon fluxes
(no existing model, we need to make our model…)









Leading jet p_T > 5 GeV, subleading p_T > 4.5 GeV

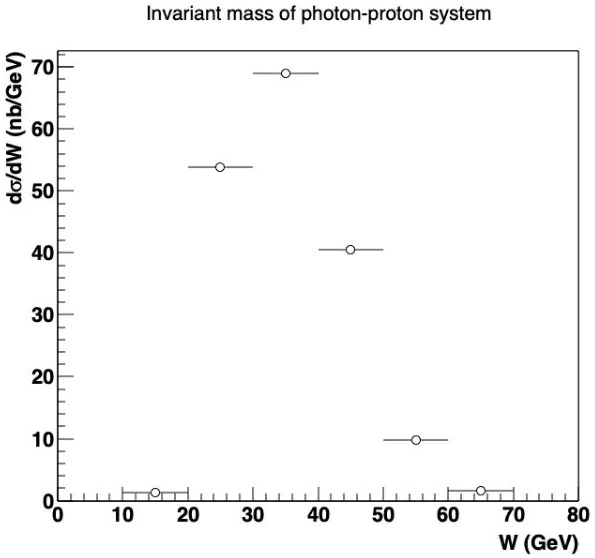
Complementary kinematics to the LHC, sensitive to the anti-shadowing regime, never done at RHIC before

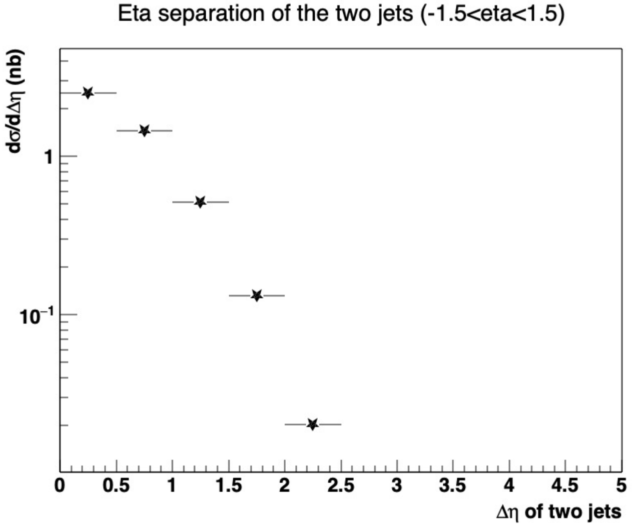
(Plots by Zhengqiao Zhang)

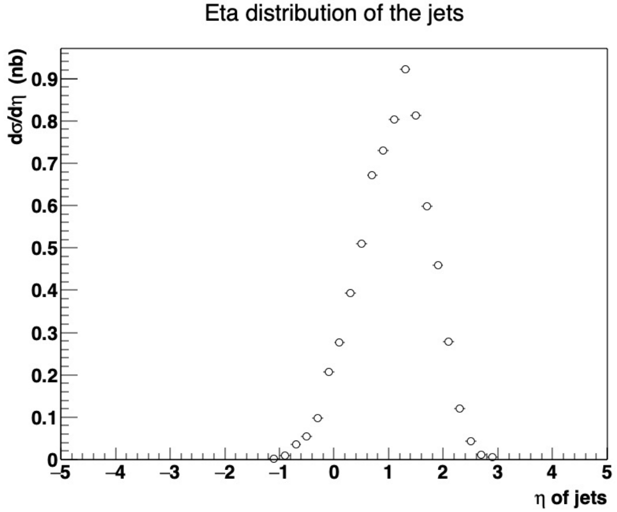
A quick simulation for pAu **diffractive** dijets PYTHIA 8

- Used Au photon flux and PYTHIA 8 generator. HardQCD processes.
- pAu 200 GeV, where photon emitted from Au nucleus, proton is the target.
- Leading jet p_T > 5 GeV, subleading jet p_T > 4 GeV
- STAR has a good acceptance of these events.
- We are still calculating how much events we can get, a very rough estimate is about 3k diffractive dijets events for Run 2024 pAu run.

(cross section is small for diffractive jets, rates will not be a problem)

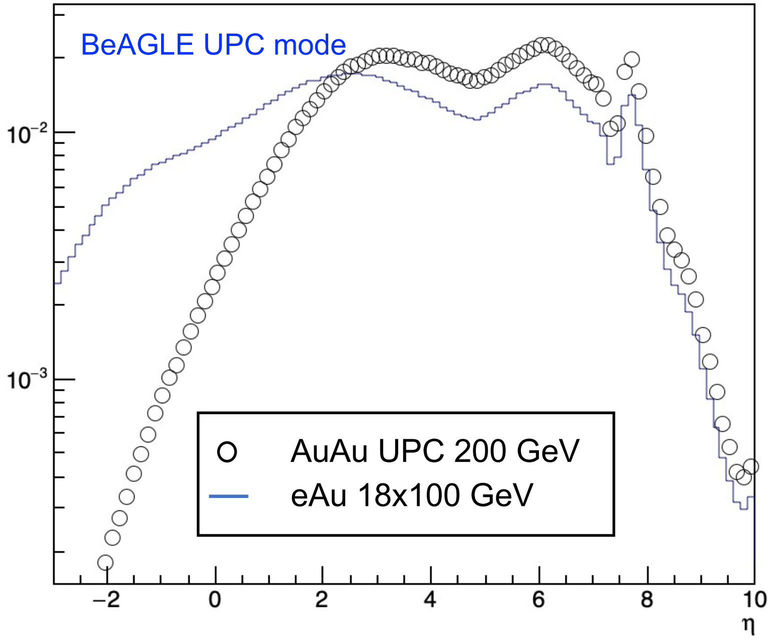






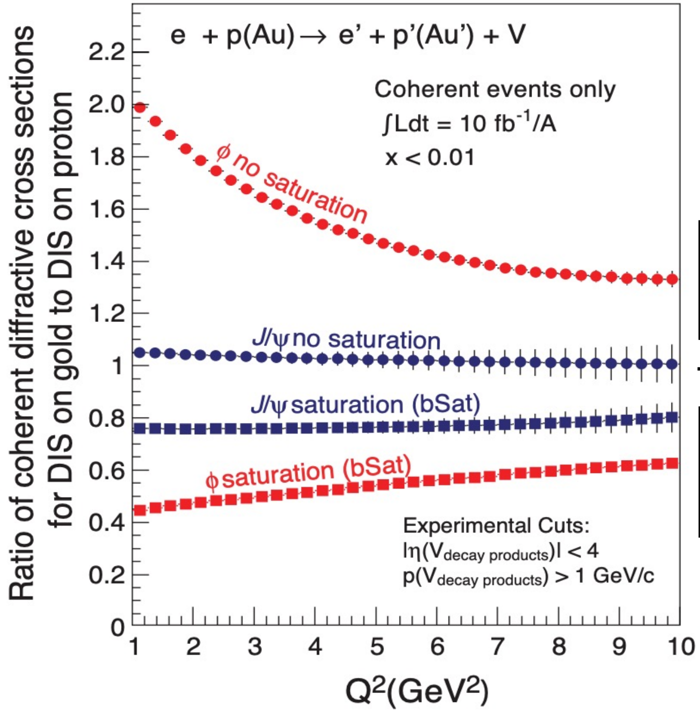
Inclusive process for STAR 2023+

- Inclusive processes are sensitive to fragmentation in nuclei, cold nuclear matter effect, intra-nuclear cascade (INC)
- Baryon stopping (N. Lewis et al)
- High multiplicity events for v_2



➢ Charged particle spectra

- Ultimate measurement of non-linear gluon dynamics at RHIC?



Double ratio

$$\frac{\left[\dfrac{\sigma_{J/\psi}(M_x^2=10)}{\sigma_{\rm inc}}\right]_{\rm Au}}{\left[\dfrac{\sigma_{J/\psi}(M_x^2=10)}{\sigma_{\rm inc}}\right]_{\rm p}}$$

➢ Photoproduction is at the regime with the **largest difference btw bsat and nonbsat**

➢ Qualitatively different to shadowing model!

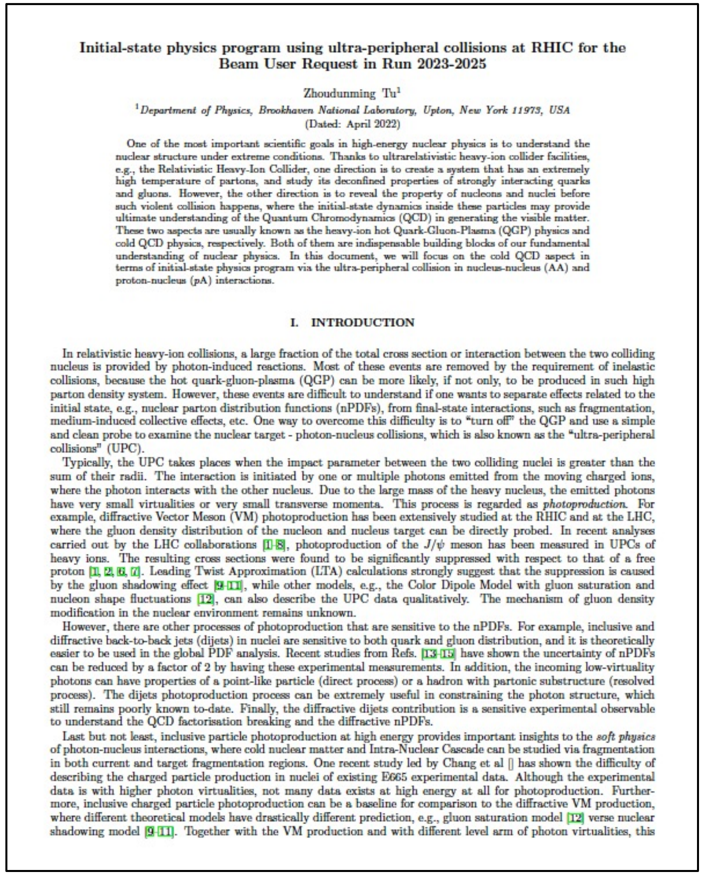
Summary

Draft document/write-up for Daniel. C

- Many physics opportunities of STAR Run 2023-2025 with UPC program – initial-state physics.

- Not only (1) VM production, but also (2) dijets photoproductions and (3) inclusive processes.

- RHIC energy and STAR forward upgrades have unique phase space and kinematics, and if with the half-field running, first-time φ meson photoproduction.



Initial-state physics program using ultra-peripheral collisions at RHIC for the Beam User Request in Run 2023-2025

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(Dated: April 2022)

One of the most important scientific goals in high-energy nuclear physics is to understand the nuclear structure under extreme conditions. Thanks to ultrarelativistic heavy-ion collider facilities, e.g., the Relativistic Heavy-Ion Collider, one direction is to create a system that has an extremely high temperature of partons, and study its deconfined properties of strongly interacting quarks and gluons. However, the other direction is to reveal the property of nucleons and nuclei before such violent collision happens, where the initial-state dynamics inside these particles may provide ultimate understanding of the Quantum Chromodynamics (QCD) in generating the visible matter. These two aspects are usually known as the heavy-ion hot Quark-Gluon-Plasma (QGP) physics and cold QCD physics, respectively. Both of them are indispensable building blocks of our fundamental understanding of nuclear physics. In this document, we will focus on the cold QCD aspect in terms of initial-state physics program via the ultra-peripheral collision in nucleus-nucleus (AA) and proton-nucleus (pA) interactions.

I. INTRODUCTION

In relativistic heavy-ion collisions, a large fraction of the total cross section or interaction between the two colliding nucleus is provided by photon-induced reactions. Most of these events are removed by the requirement of inelastic collisions, because the hot quark-gluon-plasma (QGP) can be more likely, if not only, to be produced in such high parton density system. However, these events are difficult to understand if one wants to separate effects related to the initial state, e.g., nuclear parton distribution functions (nPDFs), from final-state interactions, such as fragmentation, medium-induced collective effects, etc. One way to overcome this difficulty is to "turn off" the QGP and use a simple and clean probe to examine the nuclear target - photon-nucleus collisions, which is also known as the "ultra-peripheral collisions" (UPC).

Typically, the UPC takes places when the impact parameter between the two colliding nuclei is greater than the sum of their radii. The interaction is initiated by one or multiple photons emitted from the moving charged ions, where the photon interacts with the other nucleus. Due to the large mass of the heavy nucleus, the emitted photons have very small virtualities or very small transverse momenta. This process is regarded as *photoproduction*. For example, diffractive Vector Meson (VM) photoproduction has been extensively studied at the RHIC and at the LHC, where the gluon density distribution of the nucleon and nucleus target can be directly probed. In recent analyses carried out by the LHC collaborations [1-8], photoproduction of the J/ψ meson has been measured in UPCs of heavy ions. The resulting cross sections were found to be significantly suppressed with respect to that of a free proton [1, 2, 6, 7]. Leading Twist Approximation (LTA) calculations strongly suggest that the suppression is caused by the gluon shadowing effect [9-11], while other models, e.g., the Color Dipole Model with gluon saturation and nucleon shape fluctuations [12], can also describe the UPC data qualitatively. The mechanism of gluon density modification in the nuclear environment remains unknown.

However, there are other processes of photoproduction that are sensitive to the nPDFs. For example, inclusive and diffractive back-to-back jets (dijets) in nuclei are sensitive to both quark and gluon distribution, and it is theoretically easier to be used in the global PDF analysis. Recent studies from Refs. [13-15] have shown the uncertainty of nPDFs can be reduced by a factor of 2 by having these experimental measurements. In addition, the incoming low-virtuality photons can have properties of a point-like particle (direct process) or a hadron with partonic substructure (resolved process). The dijets photoproduction process can be extremely useful in constraining the photon structure, which still remains poorly known to-date. Finally, the diffractive dijets contribution is a sensitive experimental observable to understand the QCD factorisation breaking and the diffractive nPDFs.

Last but not least, inclusive particle photoproduction at high energy provides important insights to the *soft physics* of photon-nucleus interactions, where cold nuclear matter and Intra-Nuclear Cascade can be studied via fragmentation in both current and target fragmentation regions. One recent study led by Chang et al [] has shown the difficulty of describing the charged particle production in nuclei of existing E665 experimental data. Although the experimental data is with higher photon virtualities, not many data exists at high energy at all for photoproduction. Furthermore, inclusive charged particle photoproduction can be a baseline for comparison to the diffractive VM production, where different theoretical models have drastically different prediction, e.g., gluon saturation model [12] verse nuclear shadowing model [9-11]. Together with the VM production and with different level arm of photon virtualities, this

Writing ongoing…

These measurements make a smooth transition from RHIC to the EIC physics.