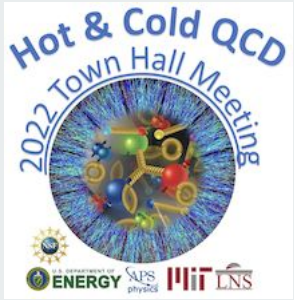
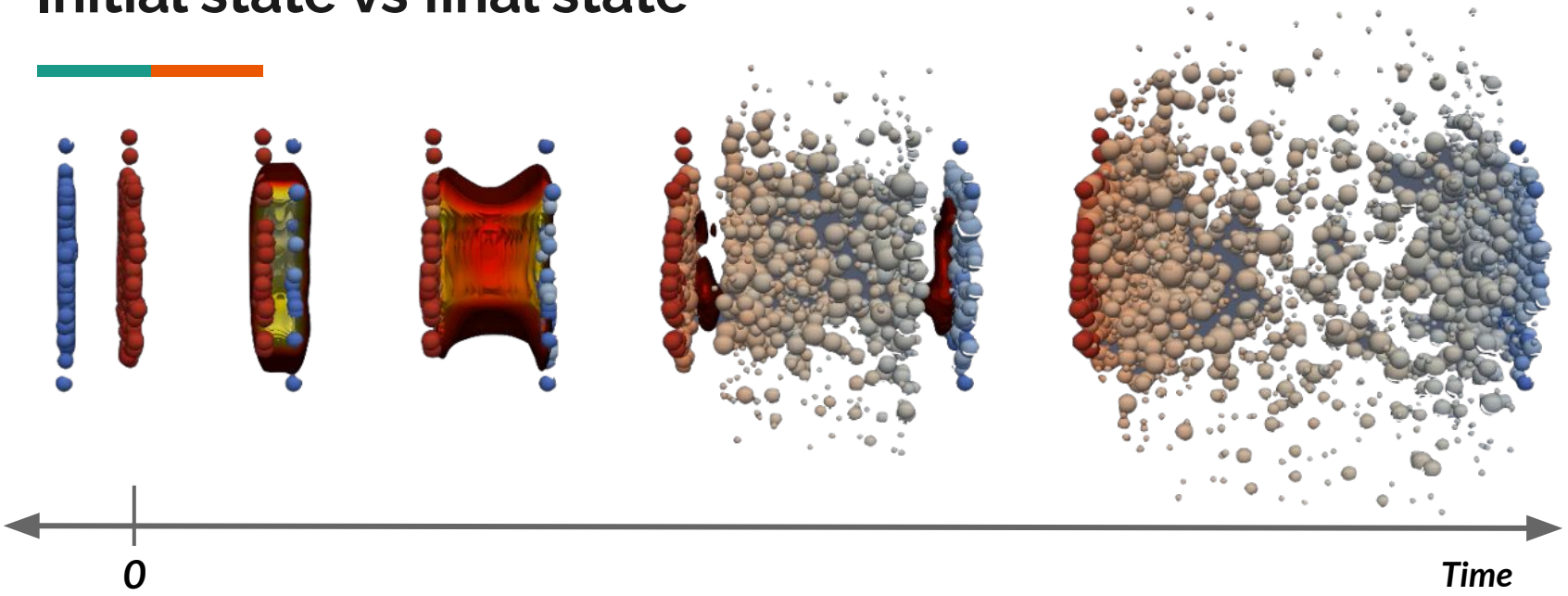
Photon-induced interactions as a probe of the initial-state of heavy nuclei –

Shining light on the *past* from the *future*

Kong Tu
BNL
09.24.2022



Initial state vs final state



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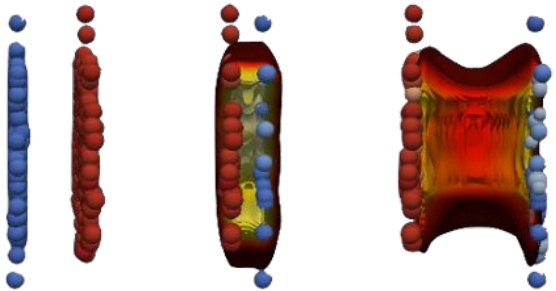
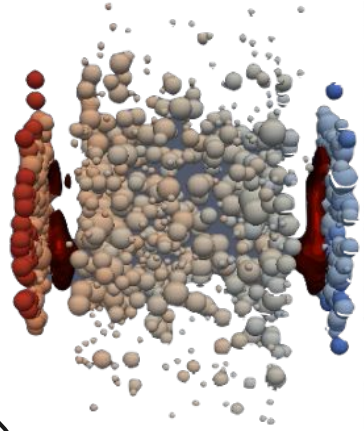
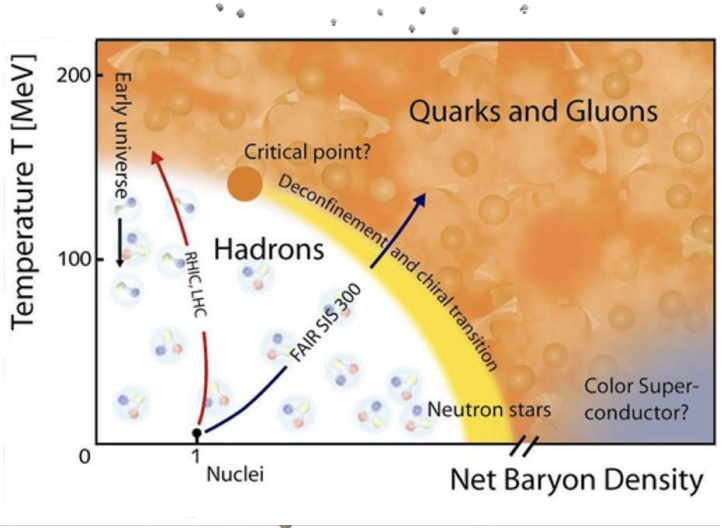






Many observables are subject to initial-state effects, if not all.

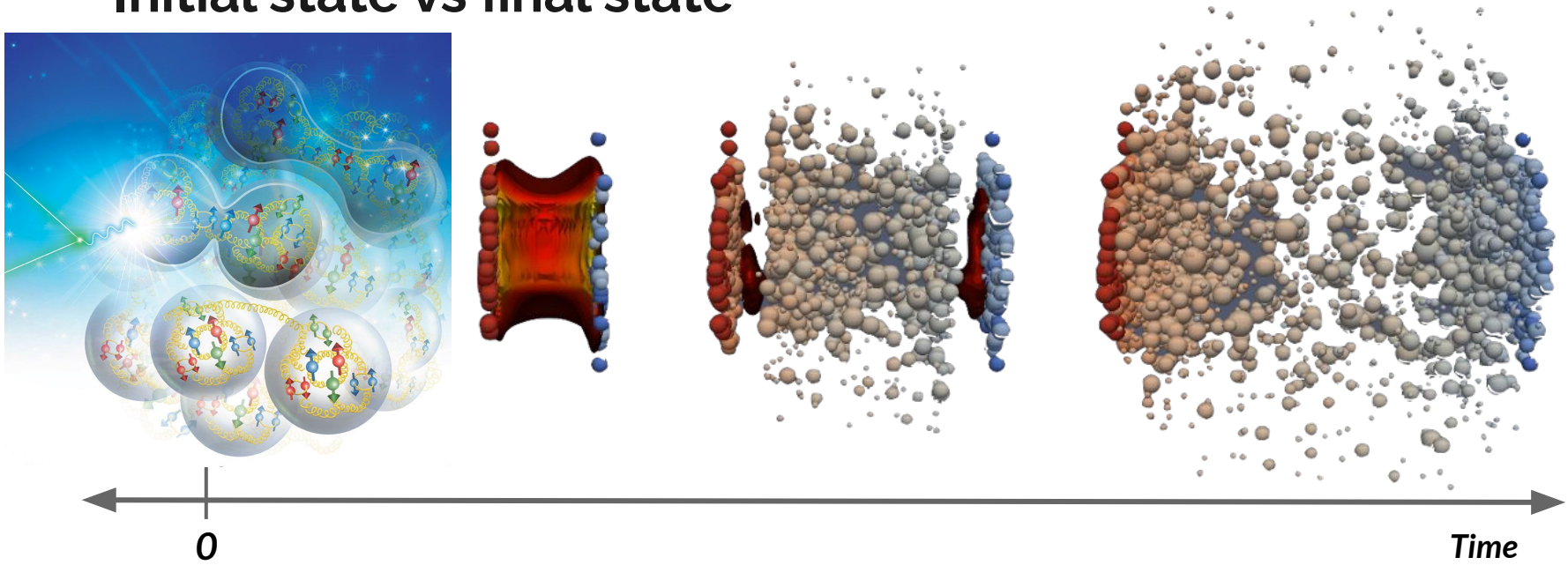
0

Time

Strongly interacting QGP

Many discoveries and understanding of the hot QCD medium, e.g., perfect fluid, vorticity, jet quenching, sequential melting of quarkonia…

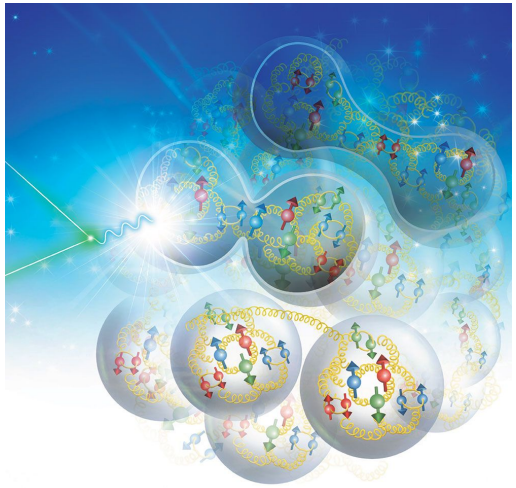
Initial state vs final state



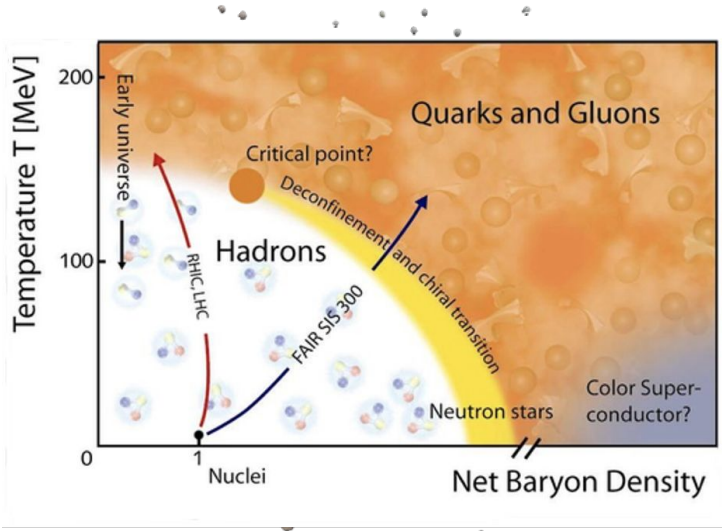
Initial-state of nucleon and nucleus

- High parton density phenomena.
- Parton density/structure, modification, spin, etc.
- Hadronization

Initial state vs final state



Understanding the initial-state of heavy-ion is a necessary key to understand the full QCD evolution and the QGP.



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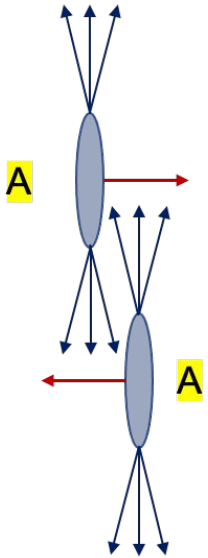
Strongly interacting QGP

Many discoveries and understanding of the hot QCD medium, e.g., perfect fluid, vorticity, jet quenching, sequential melting of quarkonia…

Photon as a probe of the initial state (IS)

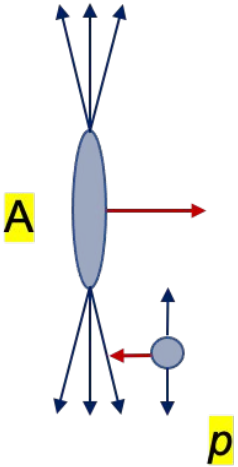
The entire *future* Electron-Ion Collider (EIC) program is based on photons: both quasi-real and virtual photon probes.



What can we learn on our way to the EIC ?

Ultra-Peripheral Collisions (UPCs) in AA, p(d)A, and pp collisions at RHIC and at the LHC.

1. **Exclusive** processes, e.g., Vector-Meson;
2. **Semi-inclusive** processes, e.g., Jets;
3. **Inclusive** particle photoproduction;
4. more…

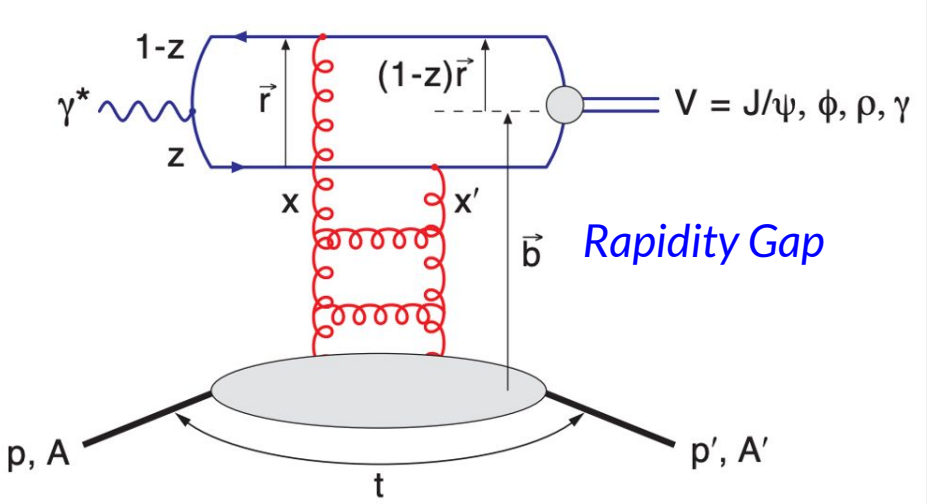


See an overview talk later by S. Klein on UPCs.

Exclusive Vector-Meson in UPCs

1) Exclusive Vector Meson as a probe to the Initial state

One particle *tells* a lot



Identical process in UPC and the EIC (except the photon p_T)

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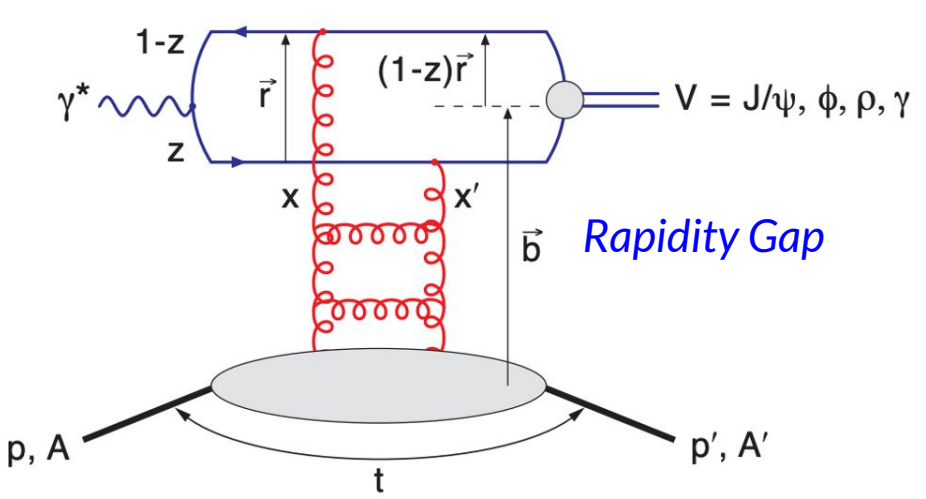
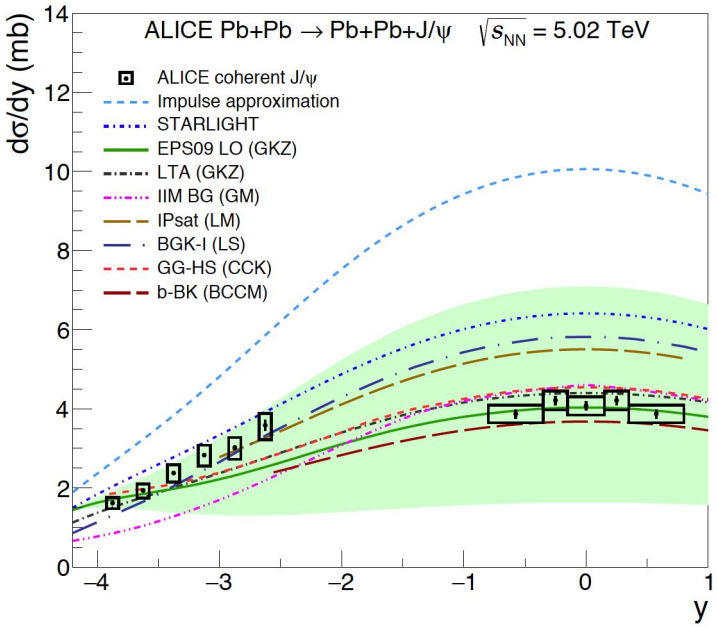


Identical process in UPC and the EIC (except the photon p_T)

Why exclusive VM?

- PDF: sensitive to the parton density, e.g., the gluon density $xG(x,Q^2)$.
- Gluon saturation and nuclear shadowing.
- Tomography - gluon spatial distribution
- Generalized Parton Distribution (GPD) of proton (polarized beam)
- Gluonic “binding”, Short-Range Nuclear Correlation in light ion;
- (sub)threshold production. Origin of mass, gravitational FF, D-term, etc.

(nuclear) Parton density at high energy



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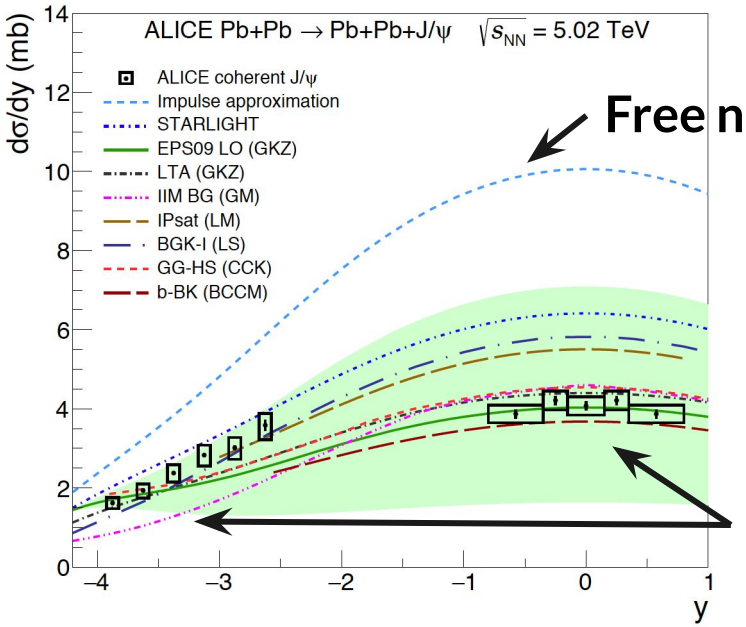
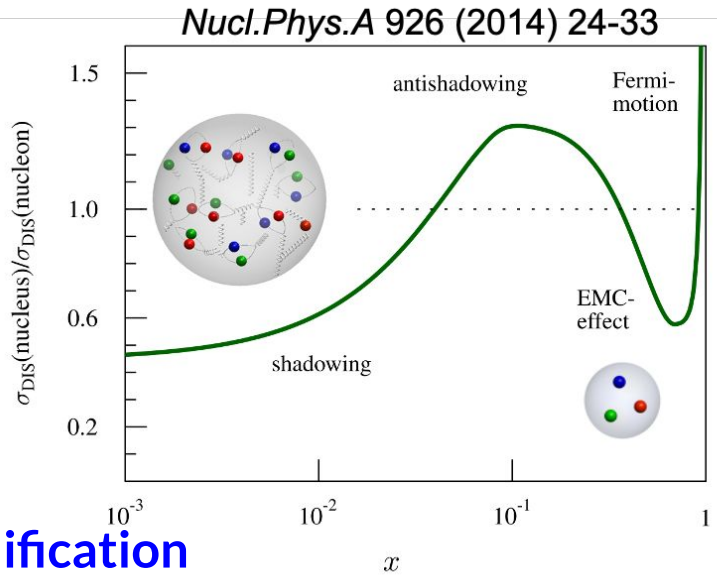


Free nucleon

Nuclear modification



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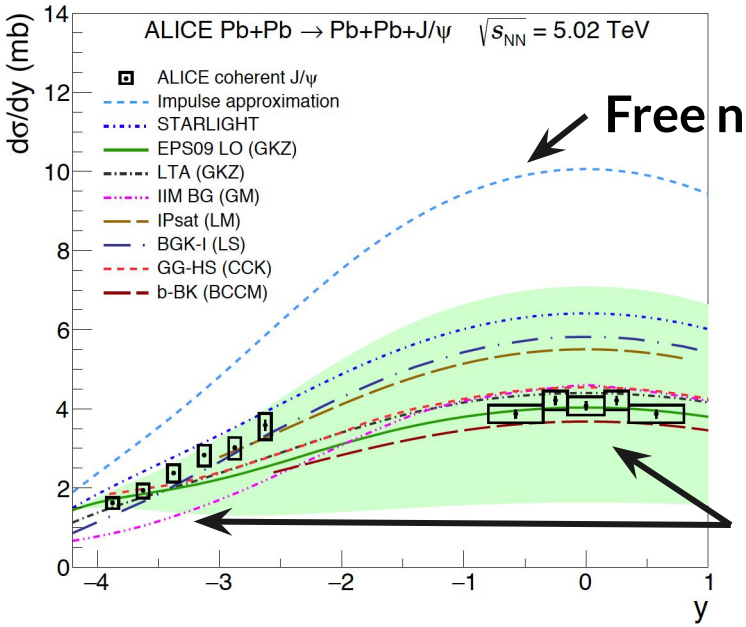


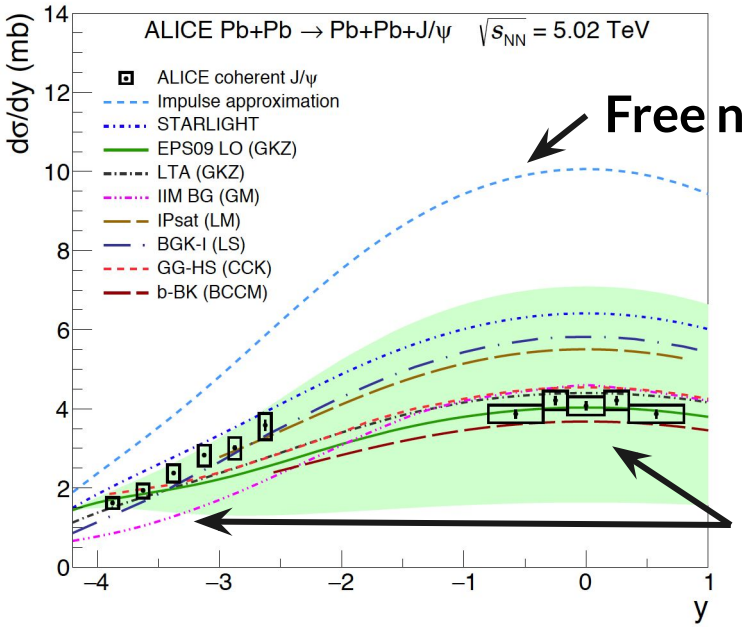
Free nucleon

Nuclear modification

Physics impact

- Observation of large suppression in **J/ψ** cross section in heavy nucleus
- Parton modification at high energy. Important constraints to nPDF.

(nuclear) Parton density at high energy



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Pocket formula of UPC:

$$x_{parton} = M_J^2/W^2 = M_J^2/2E_N M_J \exp(-y)$$

$y=0 \Leftrightarrow x_{parton} = 0.6\times10^{-3}$

$y=\mp4 \Leftrightarrow x_{parton} = 1.12\times10^{-5}$ OR $x_{parton} = 0.033$

(nuclear) Parton density at high energy

Remarks - two open questions (ambiguities)

1. (***Theory***) Underlying physics mechanism - saturation or shadowing?
2. (***Experiment***) Photon energy ambiguity - small- mixing with large-x.

(nuclear) Parton density at high energy

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1. (***Theory***) Underlying physics mechanism - saturation or shadowing?
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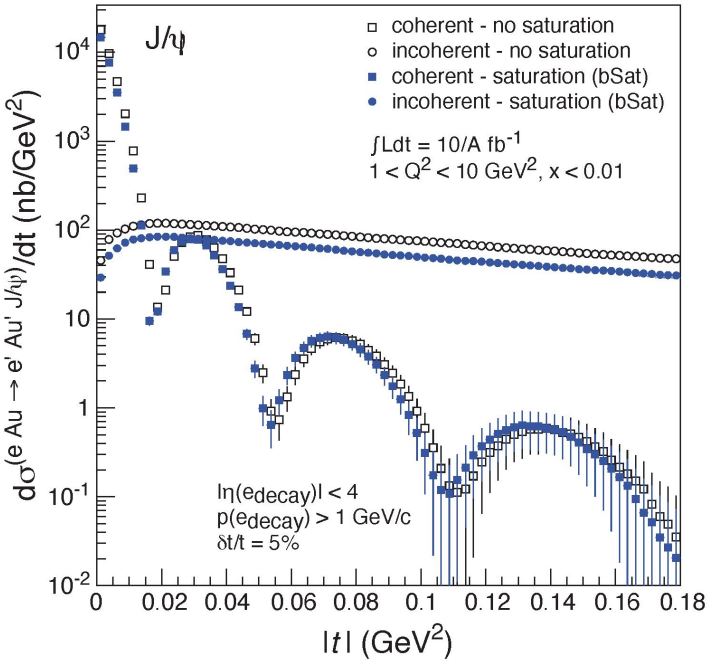
Micro-recommendations:

1. ***Theory*** comparisons: where both are absent (light ions or *large-x*) to both are present (heavy ions or small-x), and ***unique observables.***
2. ***Experimentally*** resolve the photon ambiguity using ZDC topology classes (*Eur. Phys. J C (2014) 74:2942*) → **Reach ~ 100 times lower in x for free!**

See some of these discussions at one dedicated photon physics workshop in 2021

Tomography - gluon spatial distribution

One of the golden EIC measurements



[Toll, Ullrich (2012), EIC WP]

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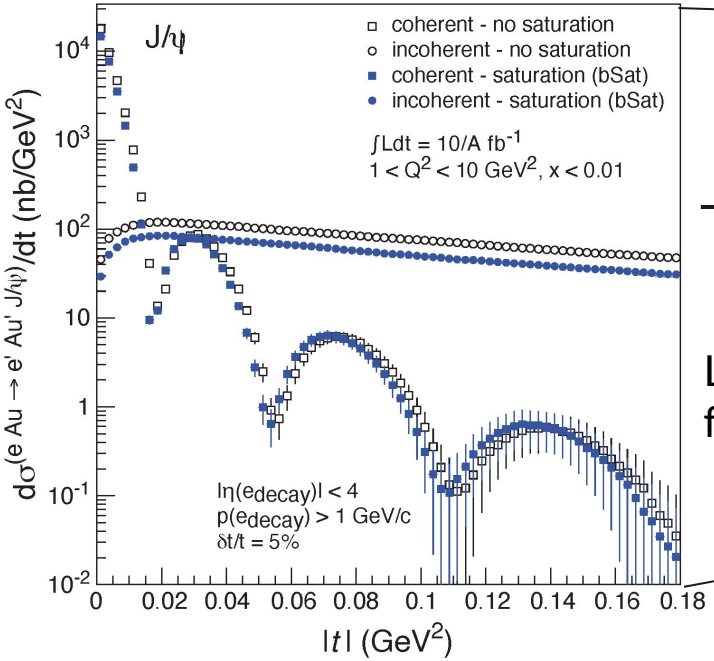
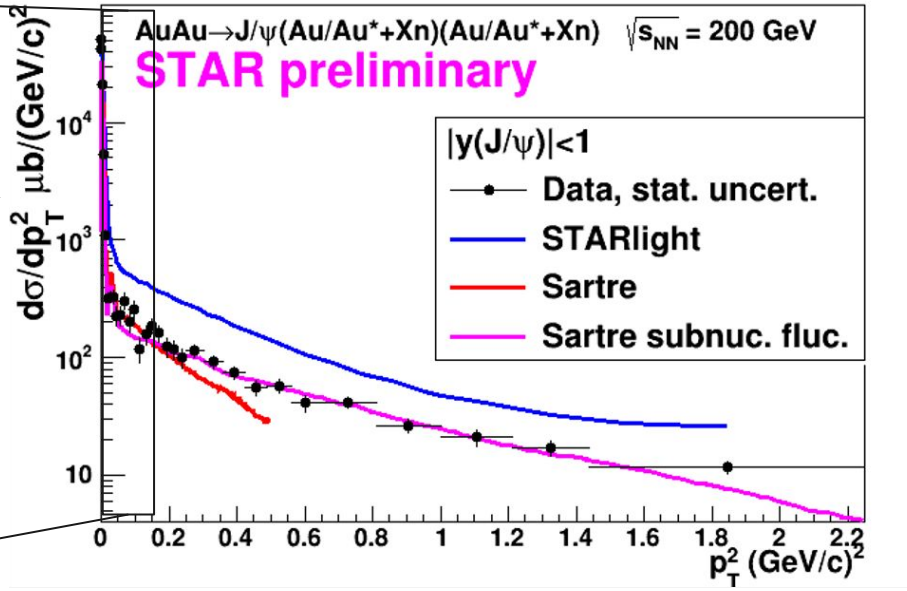


Little EIC from UPC



[Toll, Ullrich (2012), EIC WP]

Opportunity & Challenge: incoherent!

Tomography - gluon spatial distribution

One of the golden EIC measurements

Remarks - challenges and opportunities

- Similar measurements (and challenges) of ρ^0 in UPC have been done.
  [See S. Klein's talk on UPC]
- UPC has ***informed us*** the physics process, including theoretical and experimental challenges. [see K. Tu's talk at DIS 2022 for experimental aspect at the EIC]

Tomography - gluon spatial distribution

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Micro-recommendations:

- EIC is a must in order to see coherent diffractive pattern, if it exists.
- **New way** of gluon tomography via angular dependence of VM decays.
  [see S. Klein's talk and P. Tribedy's talk on RHIC highlights]
- **Understand incoherent production up to high *t*.**
  [e.g., nucleon shape/Qs fluctuations (Mantysaari, Schenke), dipole fluctuations (Guzey, Strikman, et. al.)]

A challenging measurement - ϕ photoproduction

Status:

- There's no UPC **ϕ** photoproduction has been measured.
  ϕ→ KK where K is very soft, ~ 100 MeV.
- **Physics need**: the Q2 dependence is extremely important for Saturation.
- Even at the EIC, the EPIC detector will have 1.7-2T B field and **ϕ** photoproduction is mostly out of acceptance.

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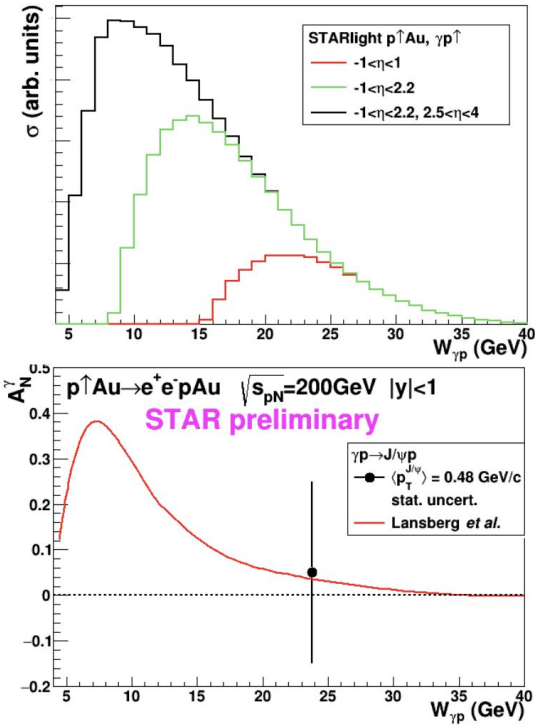
Micro-recommendations:

LHC/RHIC	EPIC EIC	EPIC/2nd IR
$0 < Q^2 < 0.1$	$1 < Q^2 < 100$	$0.1 < Q^2 < 1.0$
(LHC Run 3, RHIC Run23,25)	(White Paper requirement)	(challenging, need studies)

[See T. Ullrich's talk on EIC's 2nd detector] *time*

Other directions and open questions

(W. Schmidke, STAR Collaboration)



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  → **gluon orbital angular momentum**

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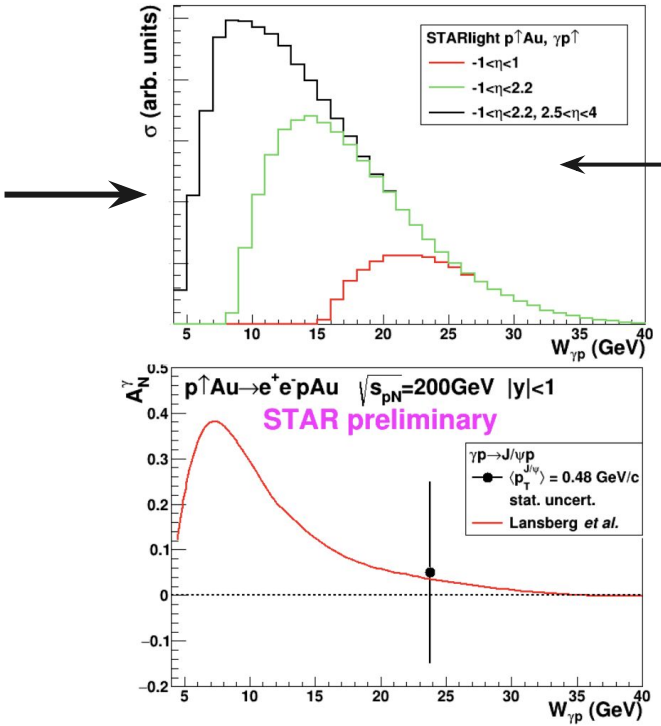

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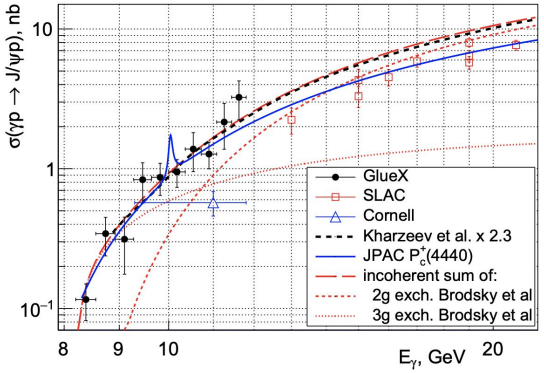
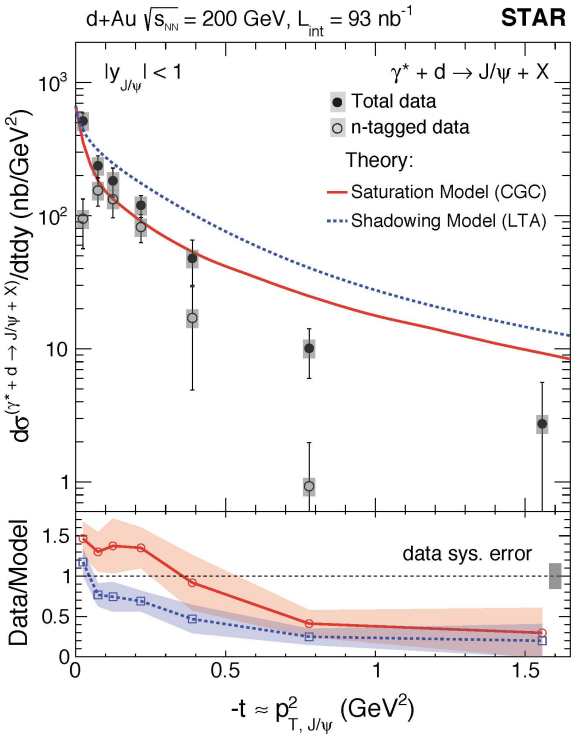
- STAR forward upgrade
  → **push to the J/ψ threshold**



JLab experiments meet RHIC

Origin of mass?
Gravitational FF?

Other directions and open questions



Phys.Rev.Lett. 128 (2022) 12, 122303

- pAu at RHIC is a unique system with polarized target (photon-proton)
  → **gluon orbital angular momentum**
- STAR forward upgrade
  → **push to the J/ψ threshold**
- STAR had **light ions, e.g., deuteron**, and provided important baselines for tagging at the EIC and model constraints.
  Direct connection to JLab physics.

Other directions and open questions

Remarks:

- Many great measurements should be/can be done.
- Connections to a broader field in nuclear and spin physics community.
  [e.g., JLab experiments, see Y. Hatta's talk, see S. Joosten's talk]

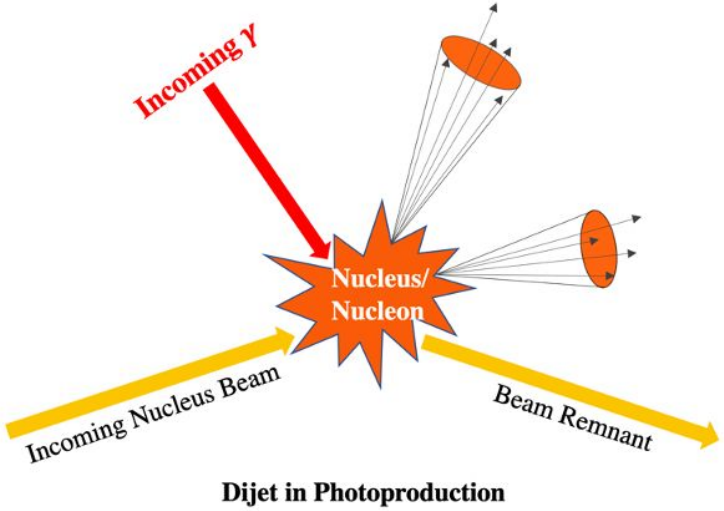
Micro-recommendations:

- STAR Forward upgrade and RHIC Run 24 (pp and **pAu**) with polarization are essential.
  [See E. Aschenauer's talk on Cold QCD at RHIC]

Semi-inclusive/jets in UPCs

Rich physics in (di)jet photoproduction

HERA ep, LHC/RHIC UPC, and the future EIC



Dijet in Photoproduction

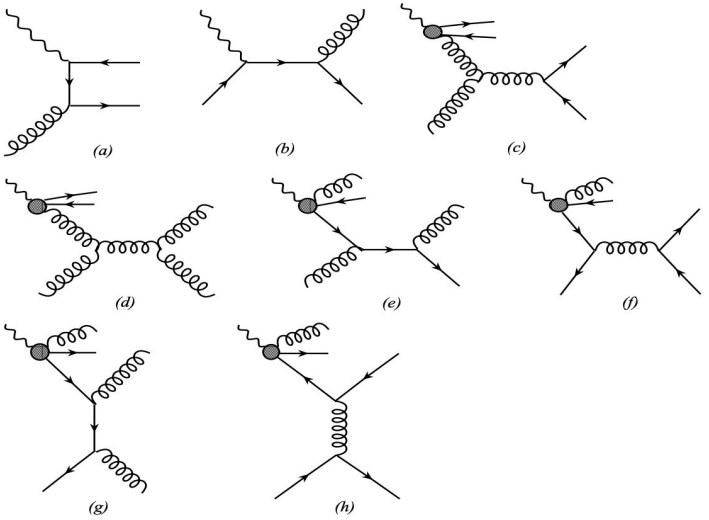
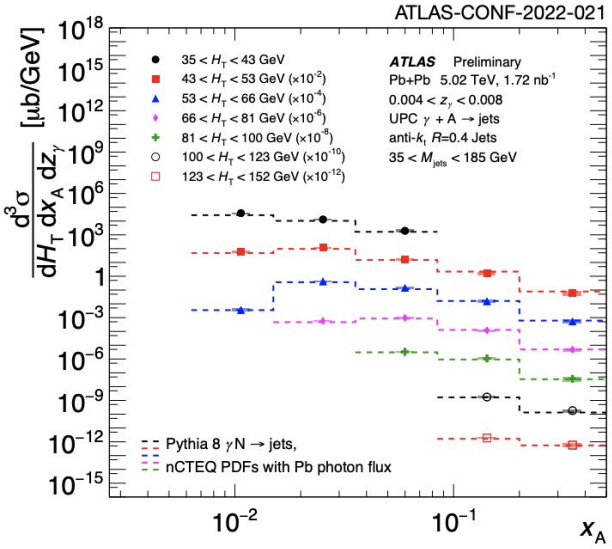
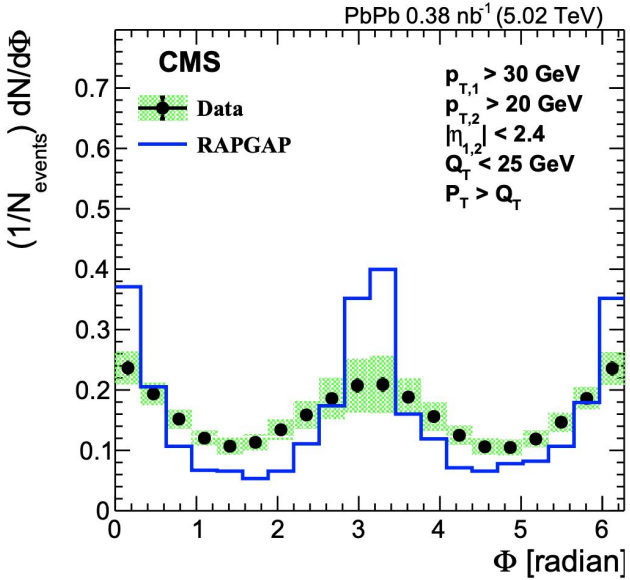


FIG. 1. Feynman diagrams for dijet photoproduction from direct, (a) and (b), and resolved photons, (c)-(h). Only a sample of the resolved diagrams are shown. Crossed diagrams are not shown.

Sensitive to both Photon and Proton/Nucleus structure and many more physics

Inclusive and diffractive dijet photoproduction





Nothing at RHIC (yet)

- **nPDFs**
- **Linearly polarized gluons:** small in UPC, unless it's a heavy quark! [Phys.Rev.C 99 (2019) 1, 015204]
- **Gluon Wigner distribution** [Phys. Rev. D 96, 034009 (2017), Phys. Rev. Lett. 116, 202301 (2016)]
- **Soft gluon radiation** [PRC 99, 015204 (2019), Phys. Rev. D 104, 054037 (2021)]

Single jet and dijet in UPC

Remarks:

- Very few data available and none exists at RHIC
- Closely related to the EIC jet and hadronization physics
  - (one of) the best training ground for young scientists for EIC physics.

Micro-recommendations:

- We need to measure **single jet** photoproduction at RHIC and the LHC
- We need to measure **dijet** photoproduction, esp. at RHIC.

Inclusive particles in UPCs

- *Origin of collectivity* in small system, UPC AA and pA.
- PID spectra and baryon junction in UPC AA.
- Entanglement entropy in photoproduction in proton and nucleus.

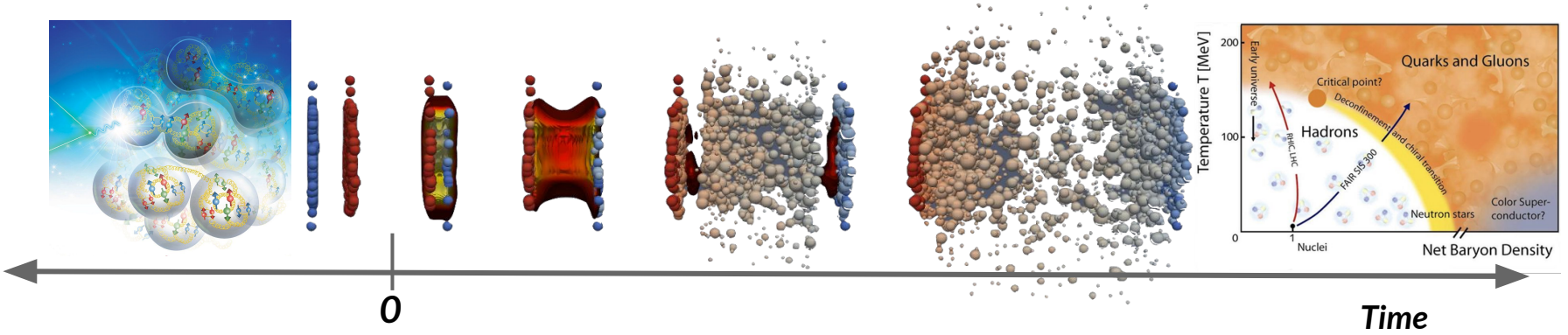
[see P. Tribedy's talk for some RHIC insights]

Summary

UPC in HIC = a mini EIC
w. real photons

- Exclusive processes, e.g., VM;
- Semi-inclusive/jets processes;
- Inclusive particle photoproduction.

UPC is one of the most important tools to study the initial-state of heavy ion collisions.



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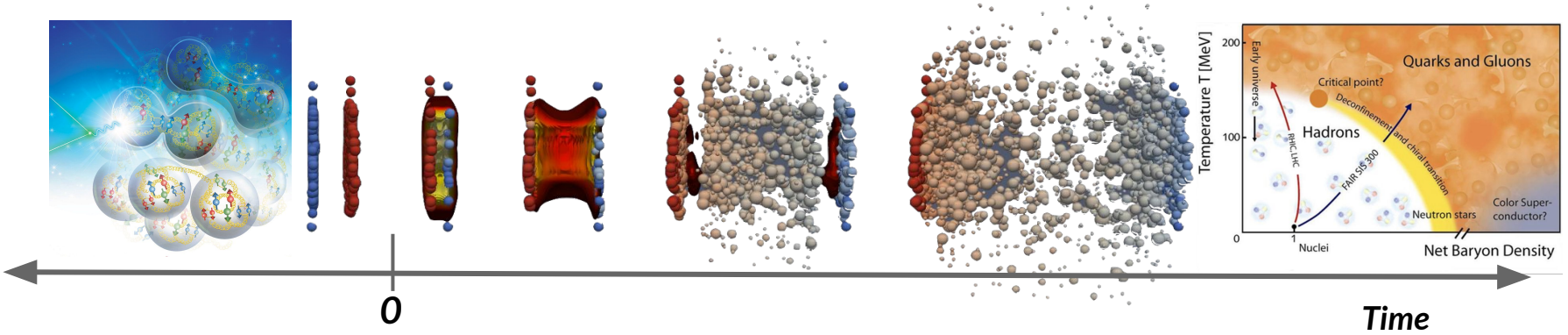

Mini-recommendations:

- Continued/Increased supports in the US for UPC, incl. person-power, data taking/analyses, etc. **Both LHC and RHIC.**
- Training the next-generation for EIC science with UPC. **Two birds, one stone!**

Acknowledgement

Great thanks to experts in UPC and EIC community for their inputs, supports, and comments.

Jarda Adam, Elke Aschenauer, Mark Baker, Daniel Brandenburg, Sasha Bylinkin, Wan Chang, Xiaoxuan Chu, Ben Gilbert, Vadim Guzey, Alex Jentsch, Dmitri Kharzeev, Krzysztof Kutak, Spencer Klein, Tuomas Lappi, Wei Li, Jiazhao Lin, Hekki Mantysaari, Michael Murray, Brian Page, Bjoern Schenke, Bill Schmidke, Mark Strikman, Peter Steinberg, Daniel Takaki, Kemal Tezgin, Prithwish Tribedy, Topias Toll, Thomas Ullrich, Raju Venugapalan, Christian Weiss, Zhangbu Xu, Zaochen Ye, Zhengqiao Zhang, and many more…

“The distinction between past, present, and future is only a stubbornly persistent illusion.”

Albert Einstein

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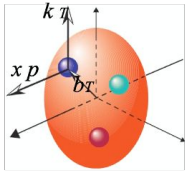
Well… at least the Long Range Plan is not. Let’s plan them, and plan them well!

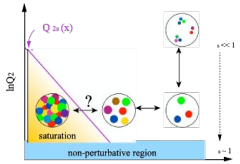
BACKUP

Photon as a probe of the initial state (IS)

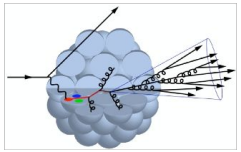
The entire *future* Electron-Ion Collider (EIC) program is based on photons: <u>both quasi-real and virtual photon probes.</u>



Tomography

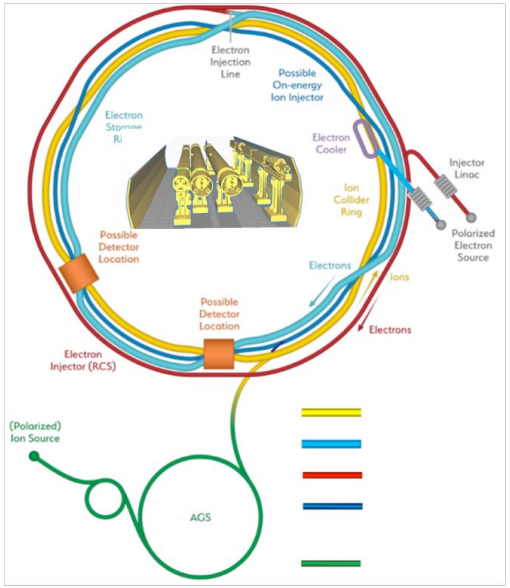


Saturation



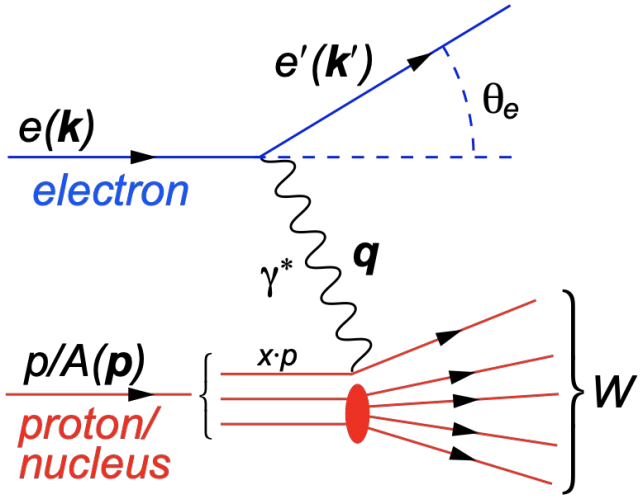
Hadronization

Spin



Sited at Brookhaven National Laboratory

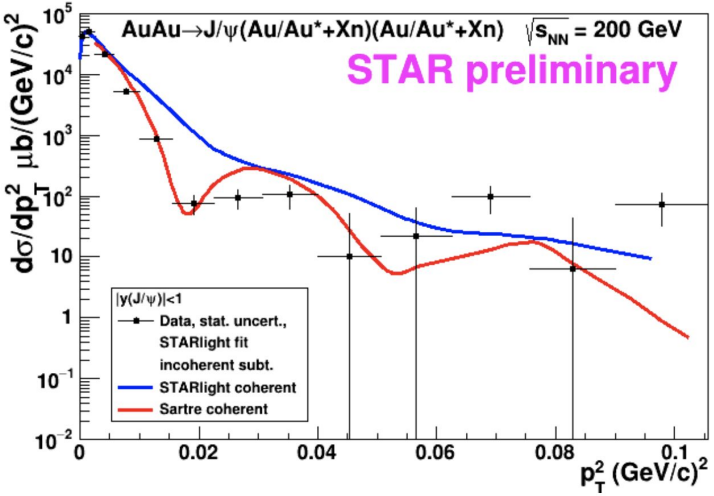
Electron-Ion Collider



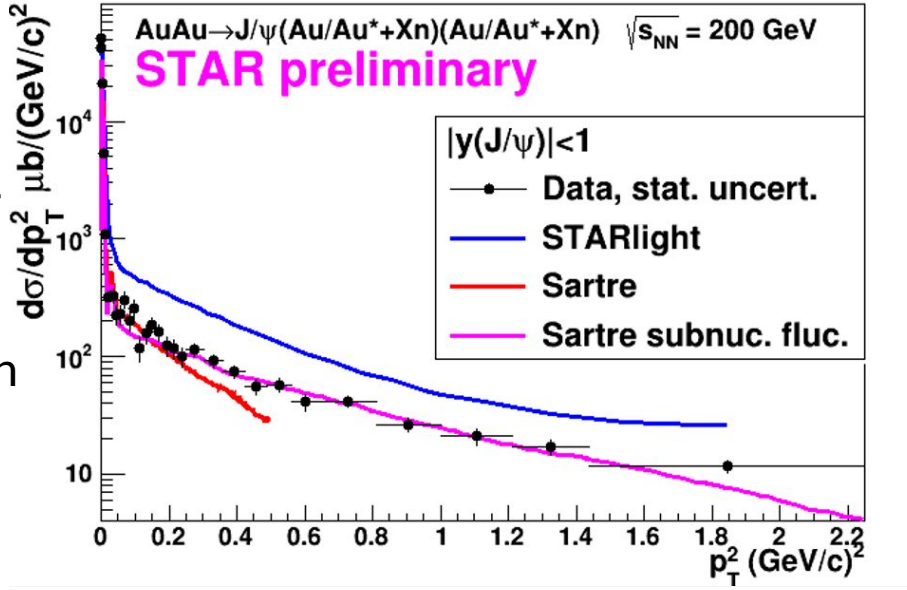
Tomography - gluon spatial distribution

One of the golden EIC measurements

Incoherent template from STARlight



Subtraction works?

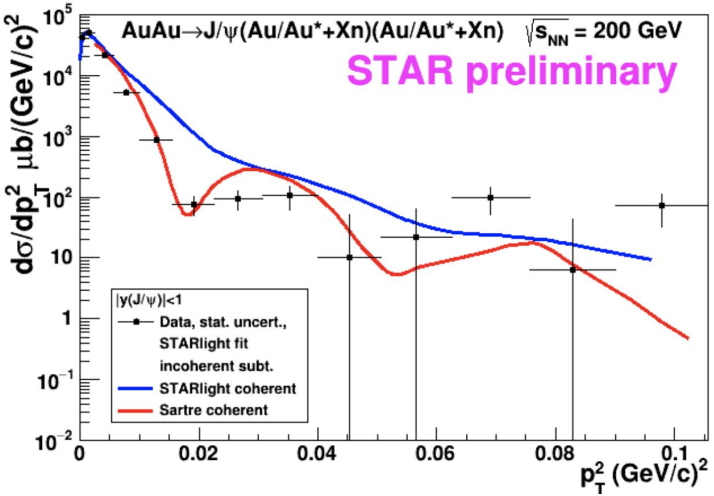


Challenge: incoherent background!

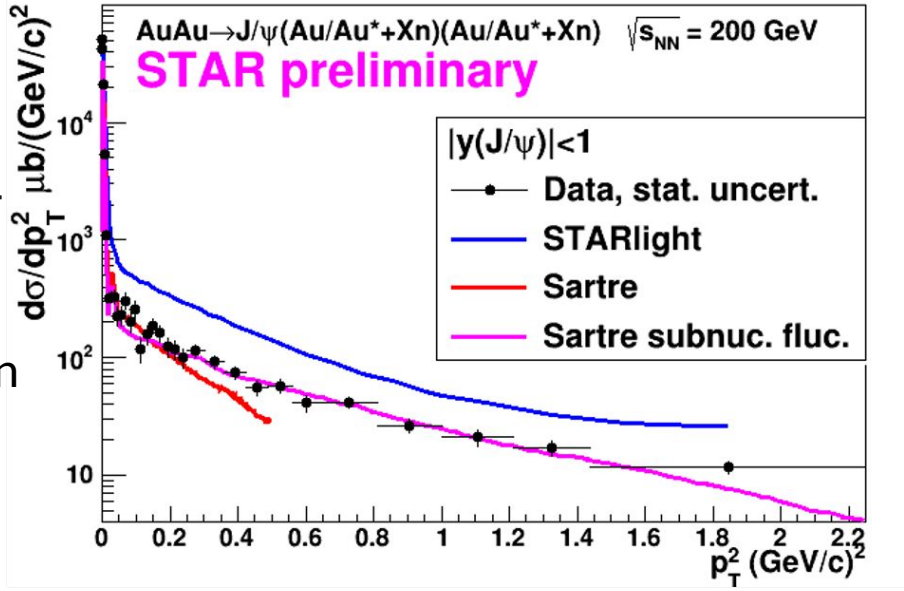
Tomography - gluon spatial distribution

One of the golden EIC measurements

Incoherent template from STARlight



Subtraction works?



Not really. **NEED the EIC**.

Large forward accept. to suppress the background

[Chang et. al. (2021) PRD 104 (2021) 11, 114030]

Challenge: incoherent background!

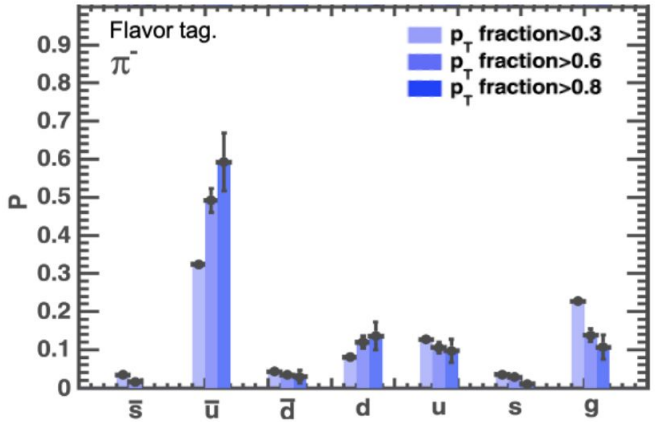
Inclusive single jet photoproduction

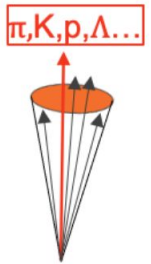
No UPC single jet photoproduction has been done.

Single jet photoproduction differential cross section in heavy nuclei at both RHIC & LHC:

- Experimental inputs to nPDFs, low to large x, high-order cal., different models
- **PID hadrons in jet** → Fragmentation:
  - Flavor tagging→ advantage of PID; test universality; path to EIC
  - Λ-polarization in jet. Polarizing FFs?. advantage in UPC → low energy
- Compare w. diffractive **J/ψ** in UPCs: saturation/shadowing [K.Tu work in progress]

[See X. Chu's talk on Saturation physics]





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