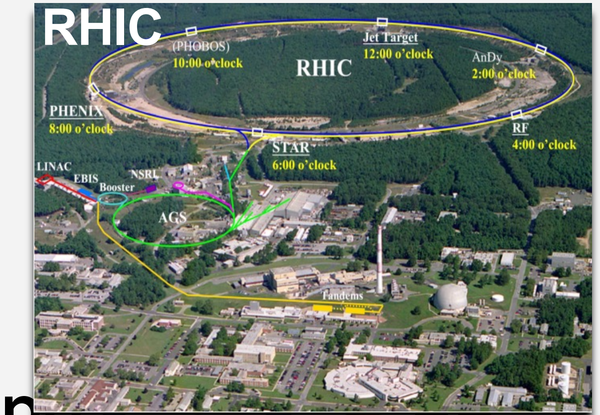
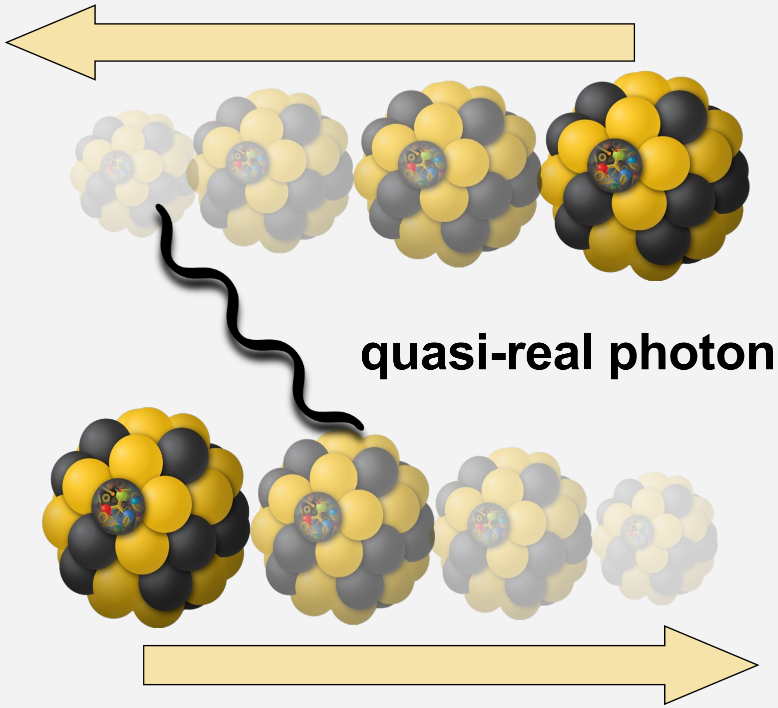
Ultra-Peripheral Collisions as a probe of gluon saturation

- Kong Tu, BNL

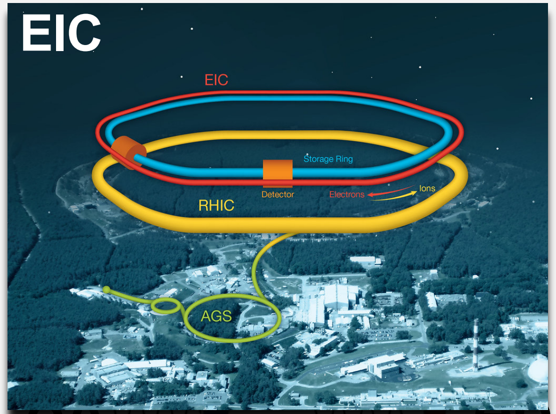
pp & pA & AA machines



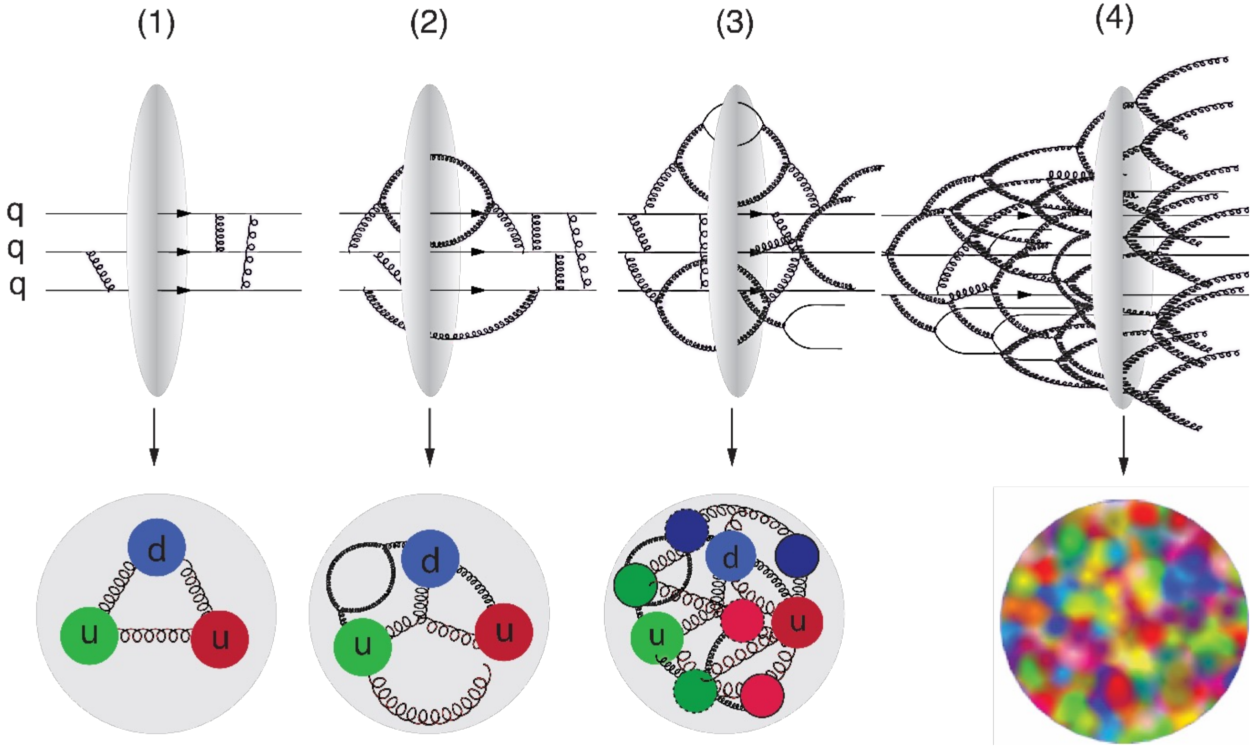


quasi-real photon

ep & eA machines



Two ways to reach saturation experimentally

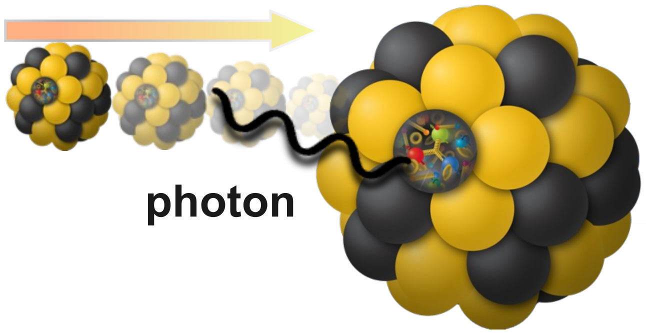


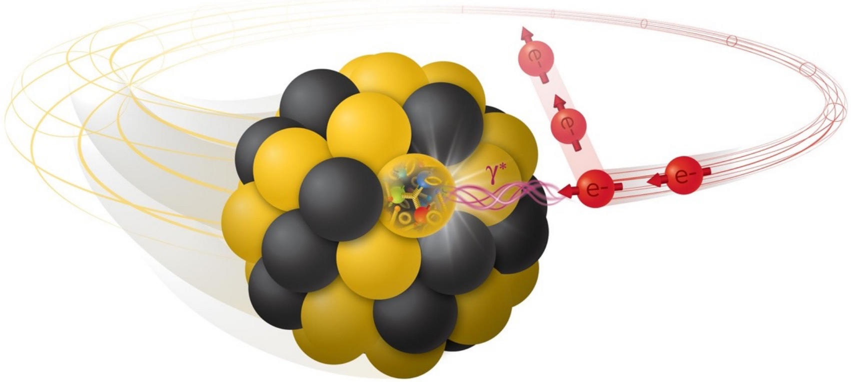
a) higher energy (1/x)
b) higher nuclear density (A)

$$Q_s^2 \sim \left(\frac{A}{x}\right)^{1/3}$$

Simply speaking, saturation is a nonlinear gluon dynamics that *gluon splitting ~ gluon recombination*.

Complementarity: UPC and EIC

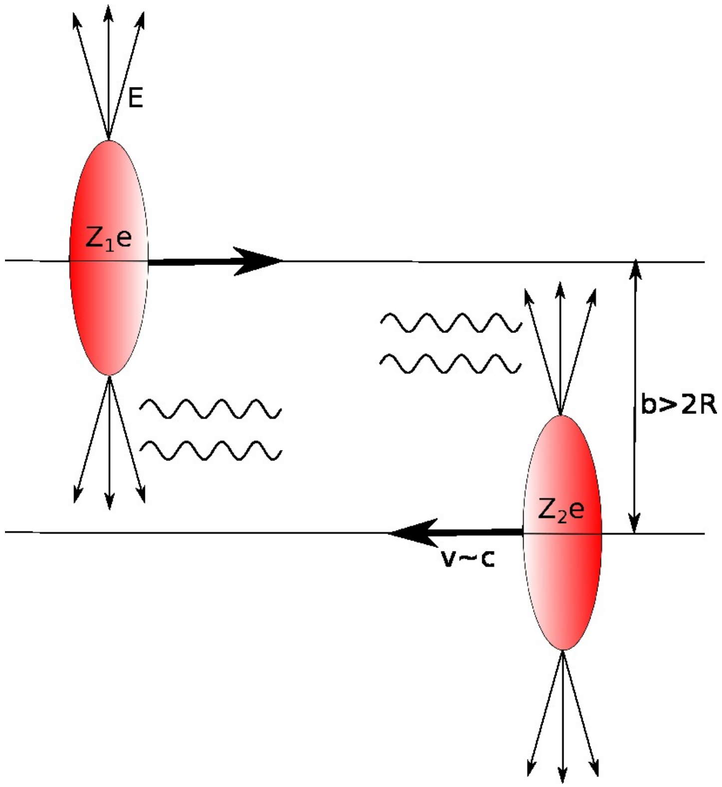




UPC RHIC & LHC	**EIC**
Photoproduction only (real photons)	Electroproduction (virtual photons)
Mass or p_T – hard scales	Q^2 – an independent hard scale
CM energy, W ~ [4, 400-1000] GeV, x ~ 10^{-5} -10^{-1}	CM energy, W ~ [9, 86] GeV, x ~ 10^{-4} -10^{-2}
mostly Pb^{208}, Au^{197}.	Deuterium to Uranium
Limited far-forward coverage for breakup products	Large far-forward coverage, esp. for nuclear breakup.

Naively, UPCs is an "easier" option to probe saturation.

UPCs kinematics & challenges



- $Z\alpha_{EM} \sim \mathcal{O}(1)$, overcomes the weak coupling by **large photon flux**;

Three challenges:

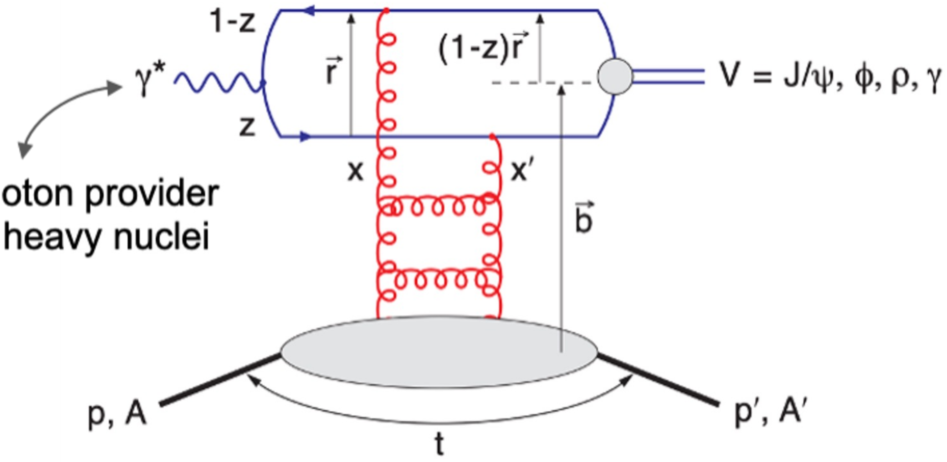
a) Impact parameter b > $2R_A$, but cannot be controlled event-by-event;
How to know its photon-induced interactions?

b) Kinematics is unknown, unless inferred by the final-states:
what is the C.o.M energy (e.g., W)?

c) Photon energy is ambiguous in AA UPCs:
who is the photon emitter?

Vector Meson photoproduction sensitive to $xG(x,Q^2)$

- One that ticks all the boxes…



Photon provider
→ heavy nuclei

Vector Meson photoproduction sensitive to $xG(x,Q^2)$

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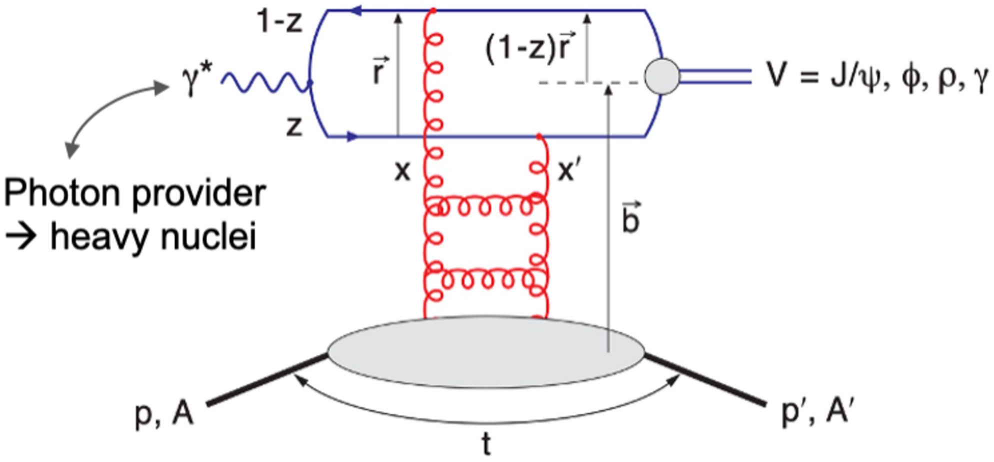

Photon provider
→ heavy nuclei

UPC VMs measurement:

- Large rapidity gap and only 1 VM in central rapidity.
- *t* is approximated by: $t \sim (\mathbf{k}_{T,photon} + \mathbf{p}_{T,VM})^2 \sim (\mathbf{p}_{T,VM})^2$, photon $\langle k_T \rangle$ is 30-40 MeV
- W is determined by exclusivity: $W^2 = 2E_N M_{VM} \mathrm{Exp}(-y)$

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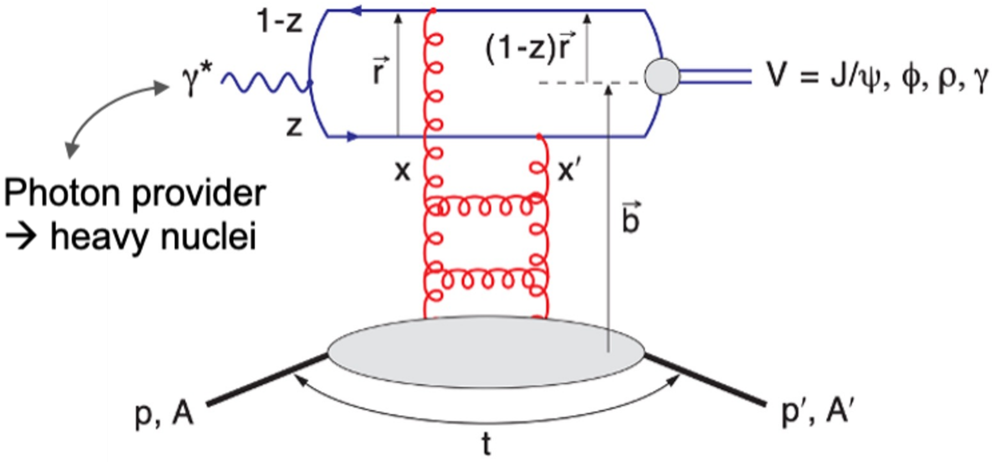

Coherent (target stays intact)	**Incoherent (target breaks up)**
Average gluon density*	Event-by-event gluon density fluctuations*
Momentum transfer (*t*) and transverse spatial position (*b*) are Fourier transforms of each other;	

* known as the Good-Walker Paradigm

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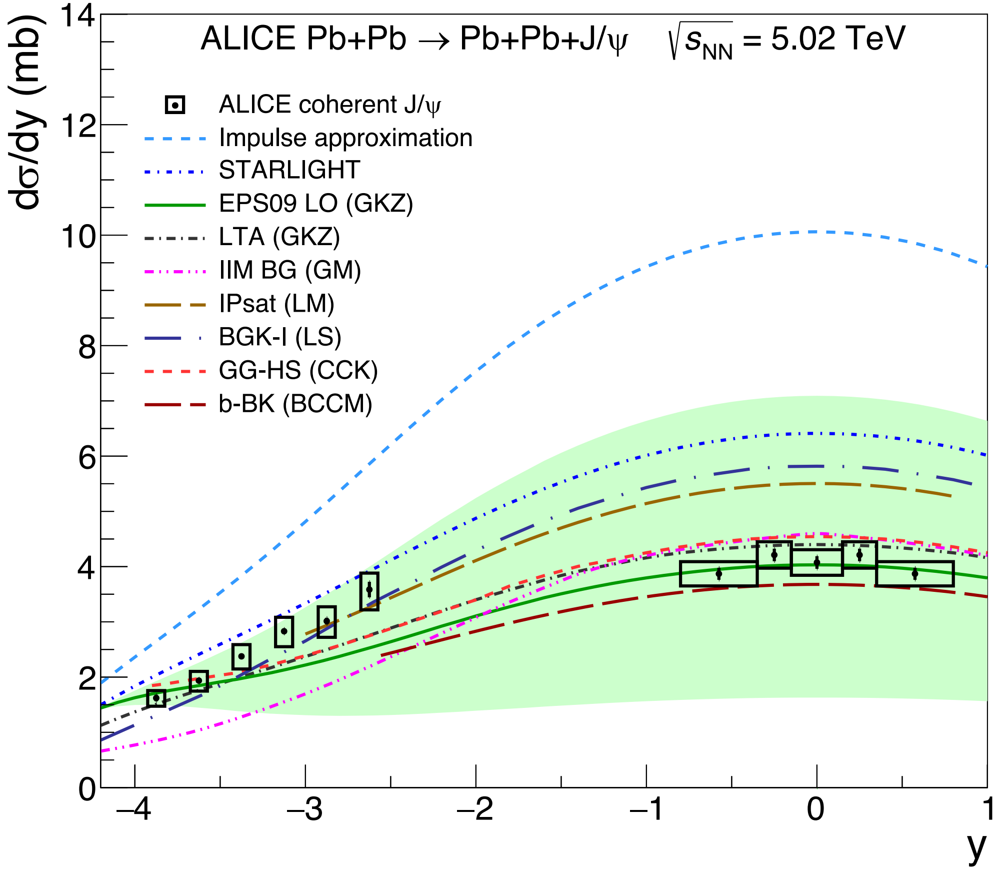
Large suppression has been found in AA UPCs w.r.t free nucleon (~ Impulse approximation)

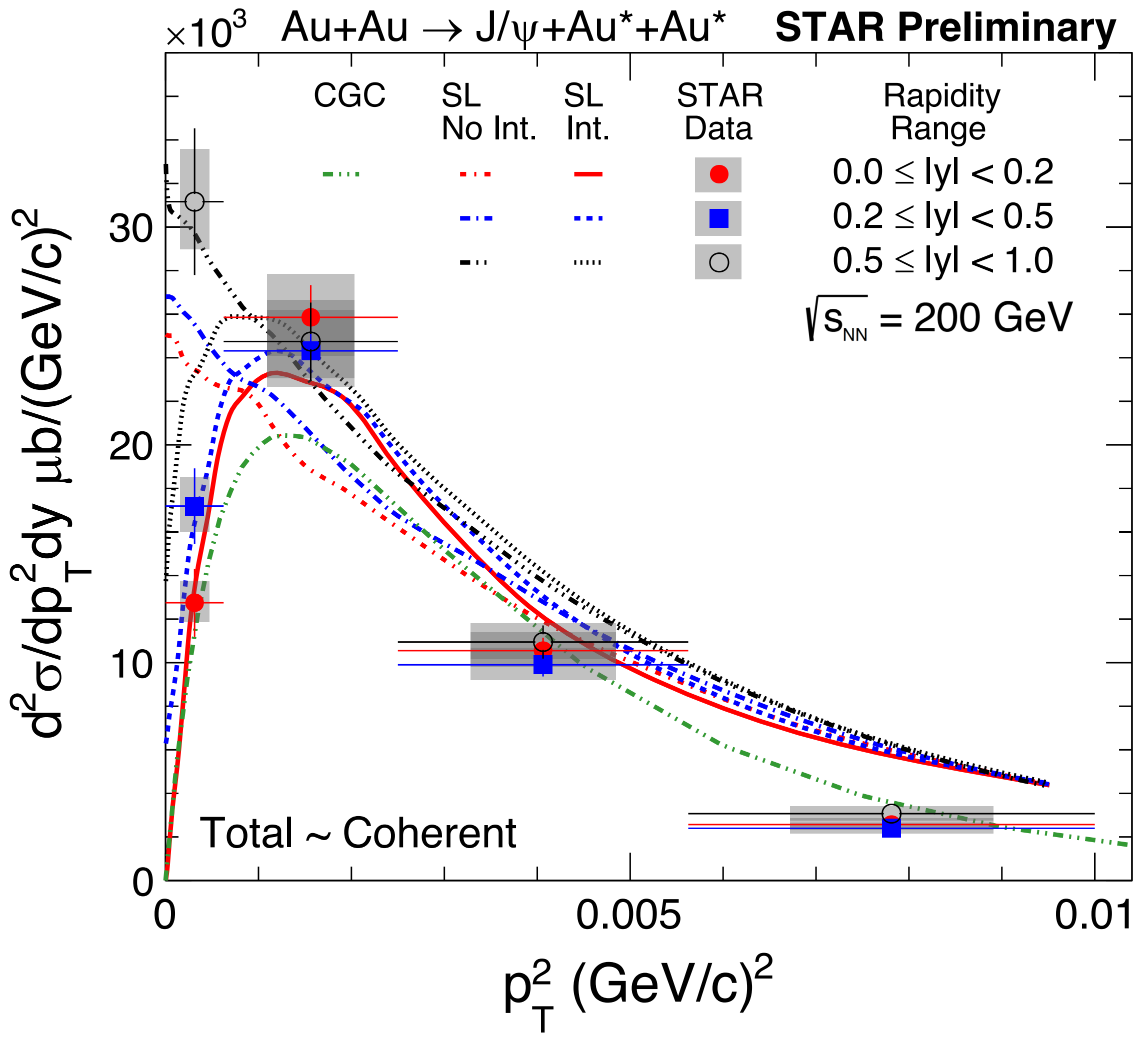


- **Saturation** models vs **Shadowing** models, none of them can describe both forward and midrapidity data simultaneously.

- **Challenge c) was not addressed:** Photon energy ambiguity.

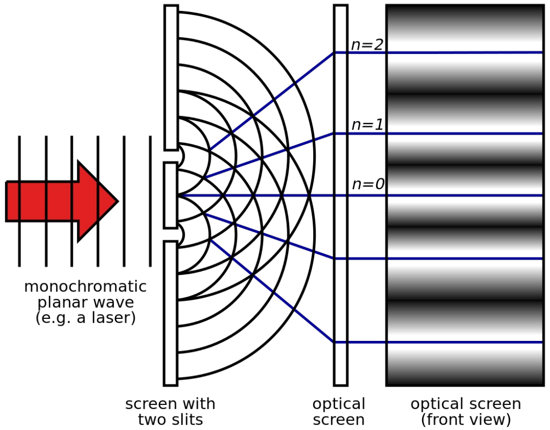
$$W^2 = 2E_N M_{VM} \mathrm{Exp}(-y).$$

Proof of ambiguity: two-source interference



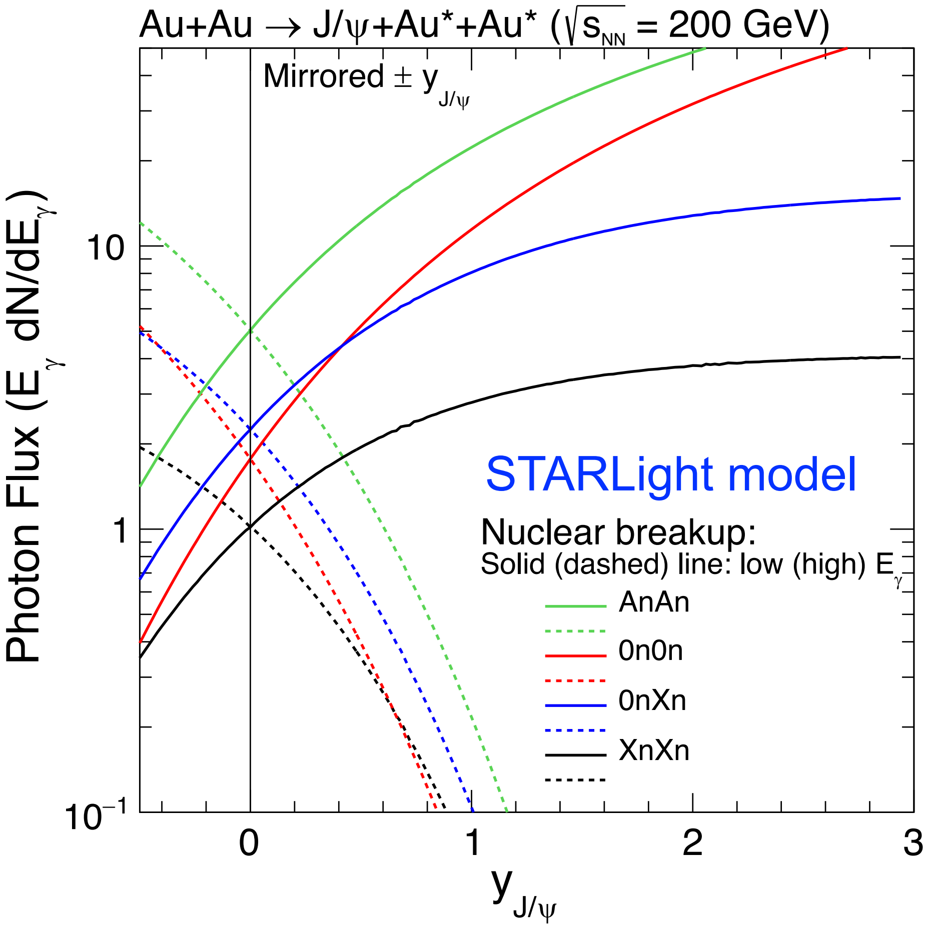
Reference to CGC: *Phys. Rev. D* 106 (2022) 7, 074019

Rapidity dependence is consistent with theory/model; interference effect is stronger if photon energies are similar.



First observed w. ρ^0 in 2008 by STAR (Phys.Rev.Lett.102:112301,2009)

Ambiguity at a closer look



- If VM at rapidity $y \neq 0$, there is a high energy photon (k_1) candidate and a low energy photon (k_2) one;
- Different photon energies correspond to different flux factors (~number of photons)
- Different neutron emissions associate with different flux factors and **assumed to be independent of coherent process.**

Neutron classes:
- **0n0n:** no neutron on either side
- **0nXn:** >=1 neutron on one side
- **XnXn:** >=1 neutron on both sides

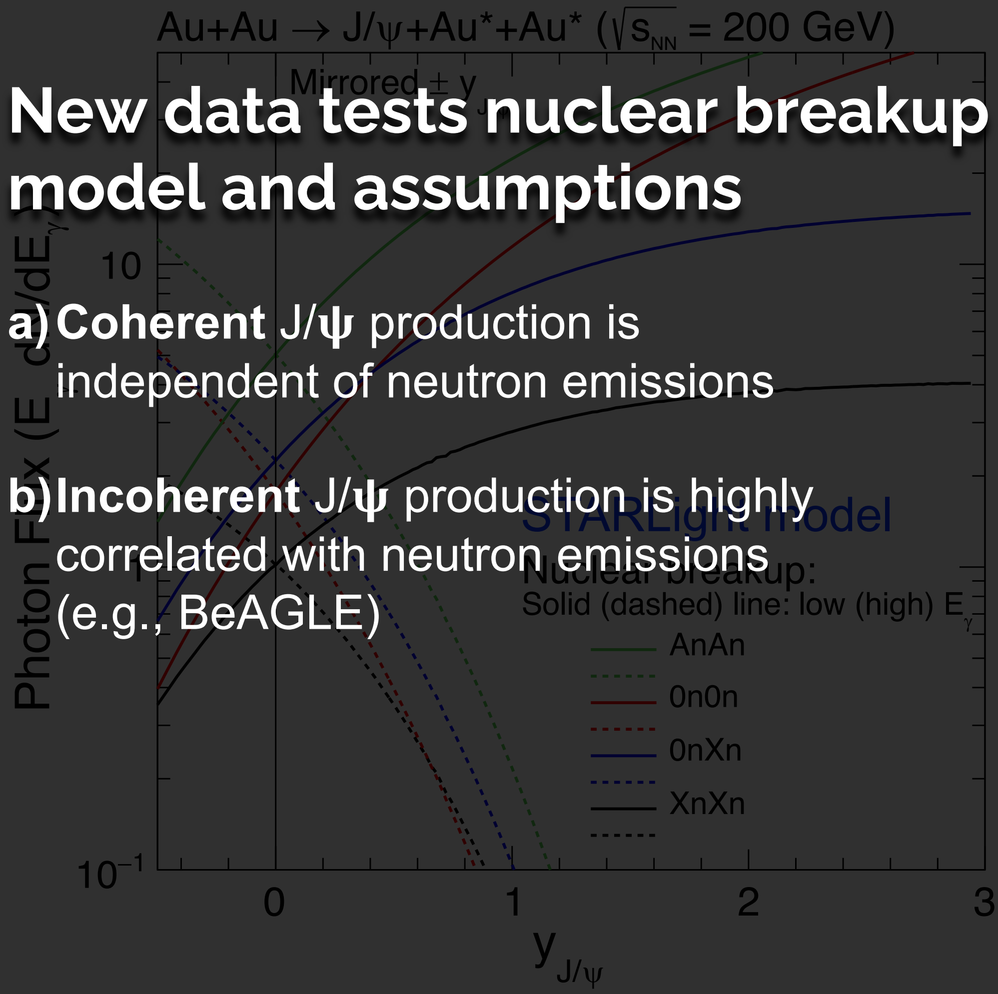
Ambiguity at a closer lo

New

New data tests nuclear breakup model and assumptions

a) **Coherent** J/ψ production is independent of neutron emissions

b) **Incoherent** J/ψ production is highly correlated with neutron emissions (e.g., BeAGLE)



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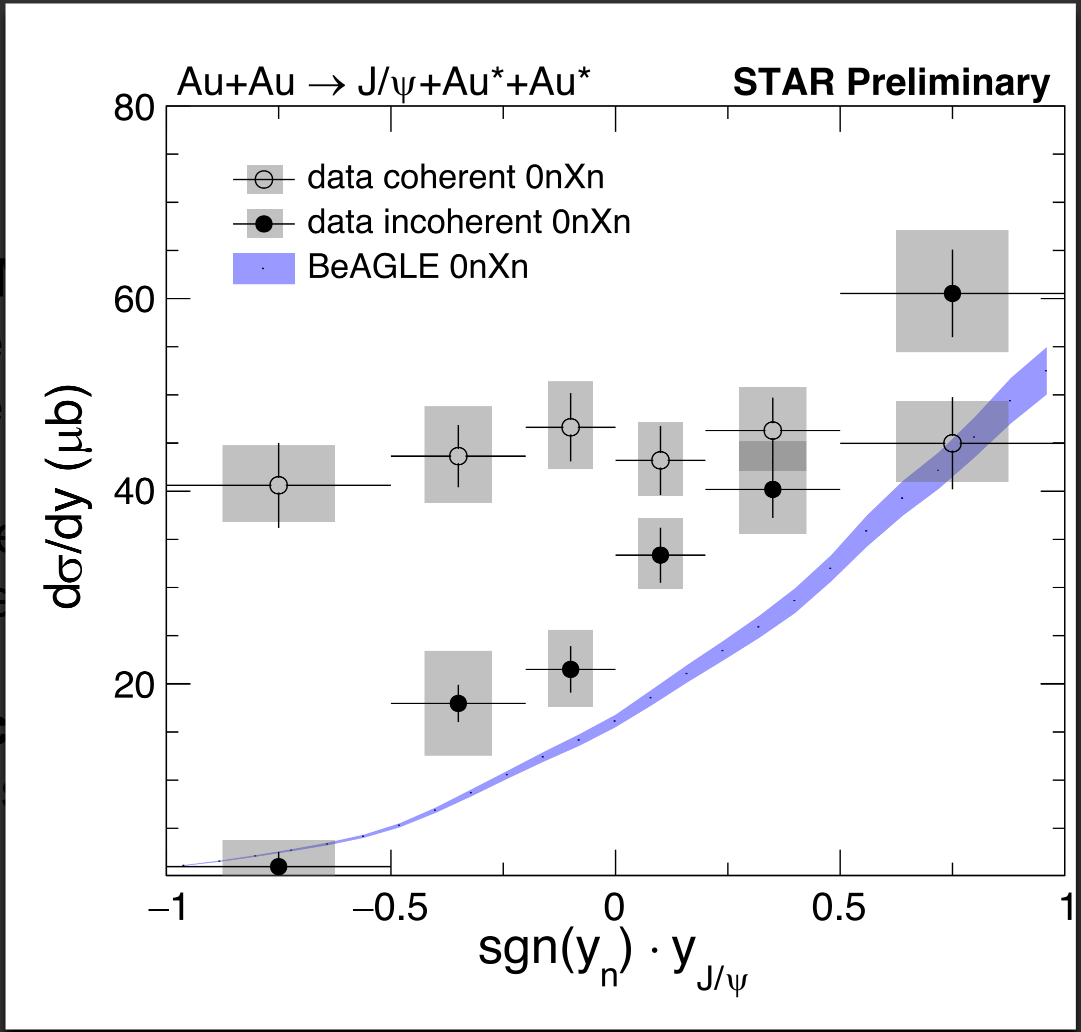


- **XnXn:** >=1 neutron on both sides

Reference to BeAGLE: *Phys. Rev. D* 106 (2022) 1, 012007

Neutron emission helps resolve the two-way ambiguity

$$
\begin{aligned}
d\sigma^{AnBn}/dy &= \Phi^{AnBn}_{T.\gamma}(k_1)\,\sigma_{\gamma^*+\mathrm{Au}\to\mathrm{J}/\psi+\mathrm{Au}}(k_1) \\
&\quad +\Phi^{AnBn}_{T.\gamma}(k_2)\,\sigma_{\gamma^*+\mathrm{Au}\to\mathrm{J}/\psi+\mathrm{Au}}(k_2)
\end{aligned}
$$

Measurements (slide 6)

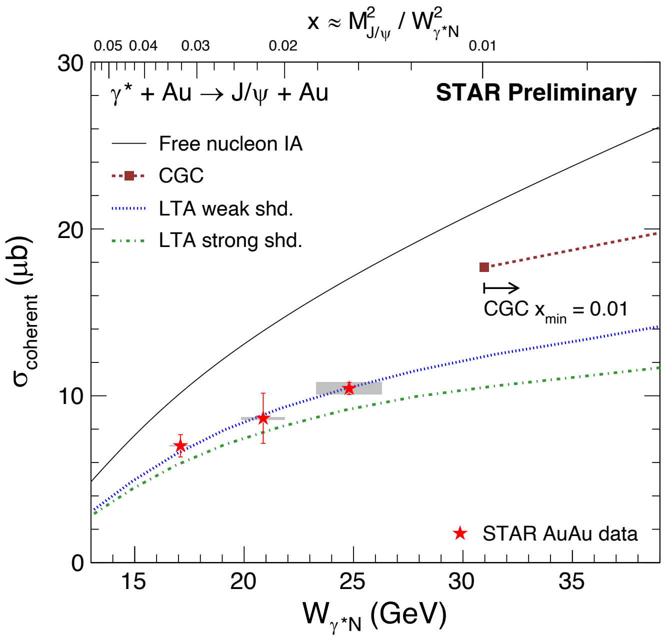
Photon fluxes (slide 8)

Unknowns

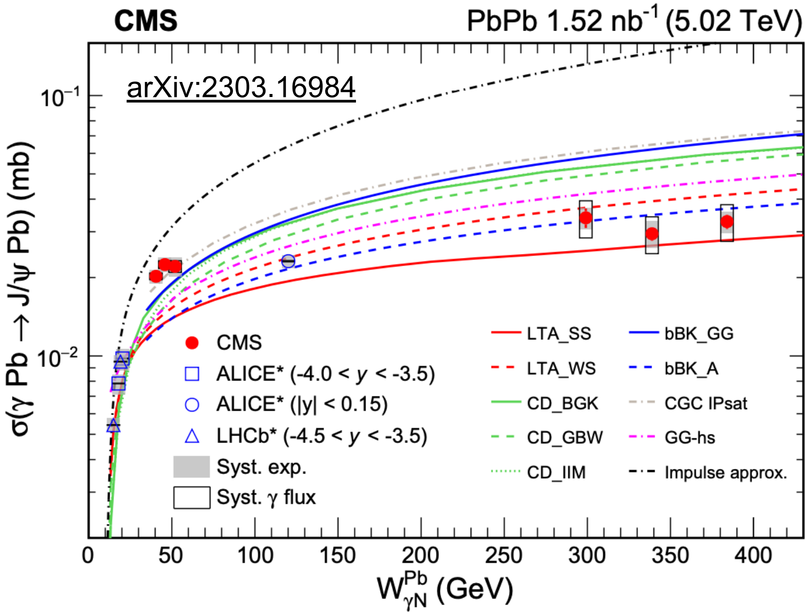
Eur. Phys. J C (2014) 74:2942

Need to measure differential cross section in *y* and in neutron emission classes; **at least 2 equations to solve 2 unknowns.**

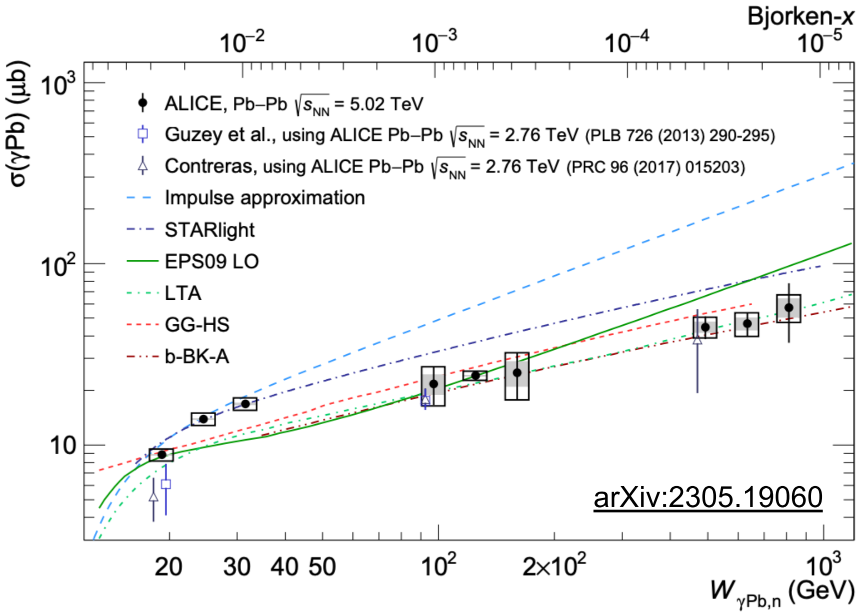
Coherent J/ψ cross section vs energy W: Smoking gun for saturation starting at x ~$10^{-2.5}$?



STAR



CMS



ALICE

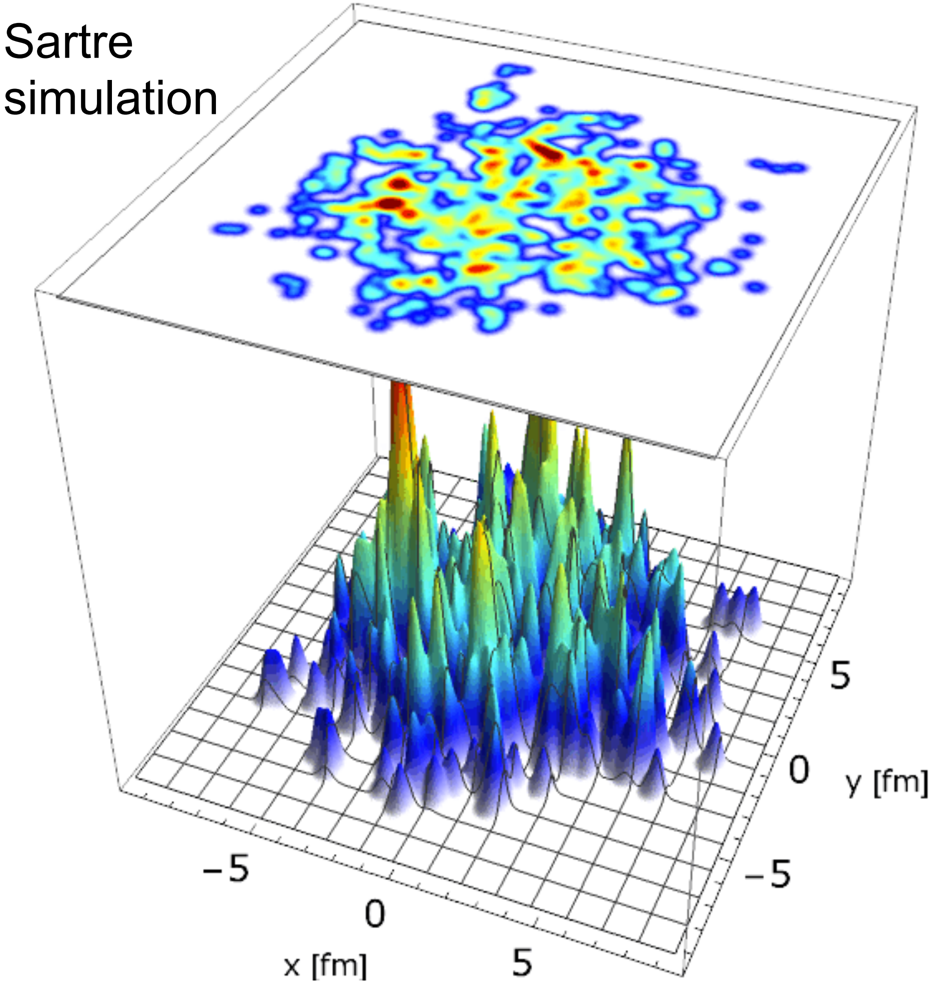
Data are compatible to each other, and still none of the models can describe the W dependence.

CGC saturation calculation does not have enough suppression.

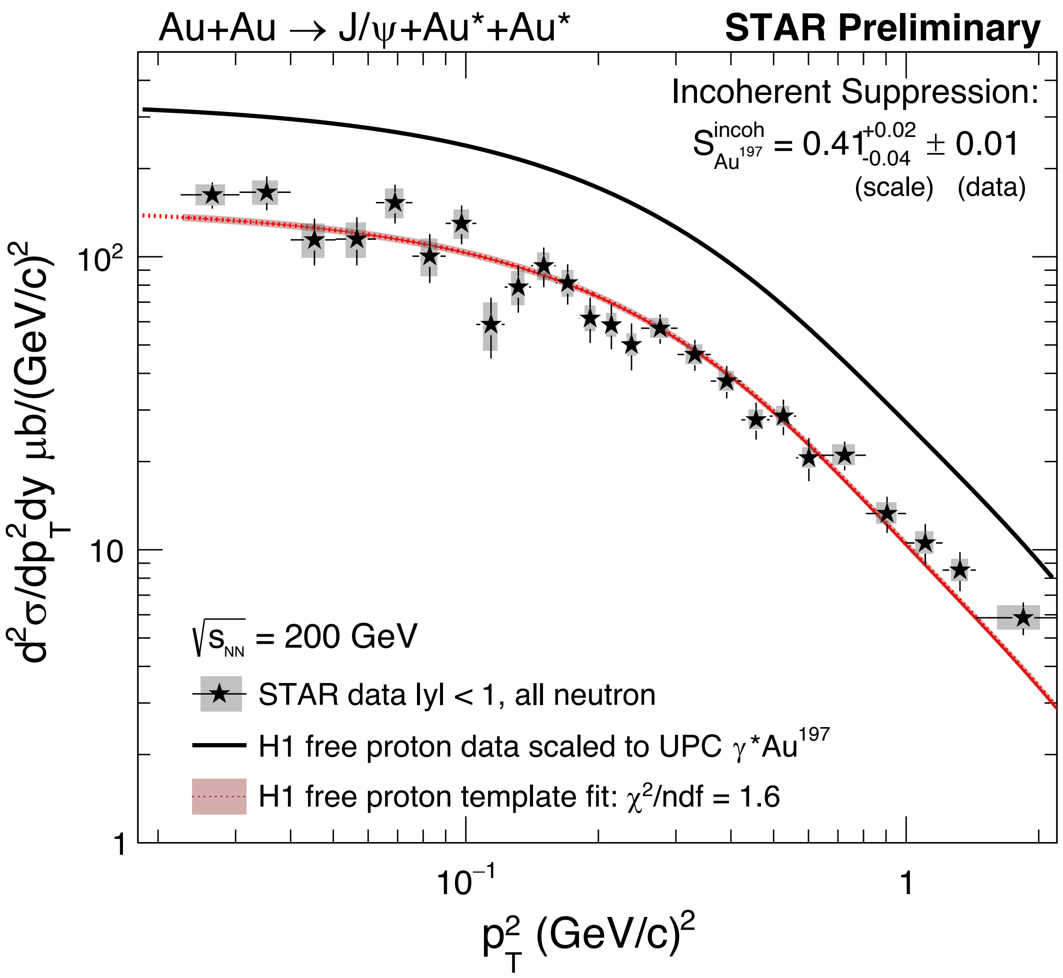
Incoherent J/ψ cross section vs p_T^2

New

Sartre simulation



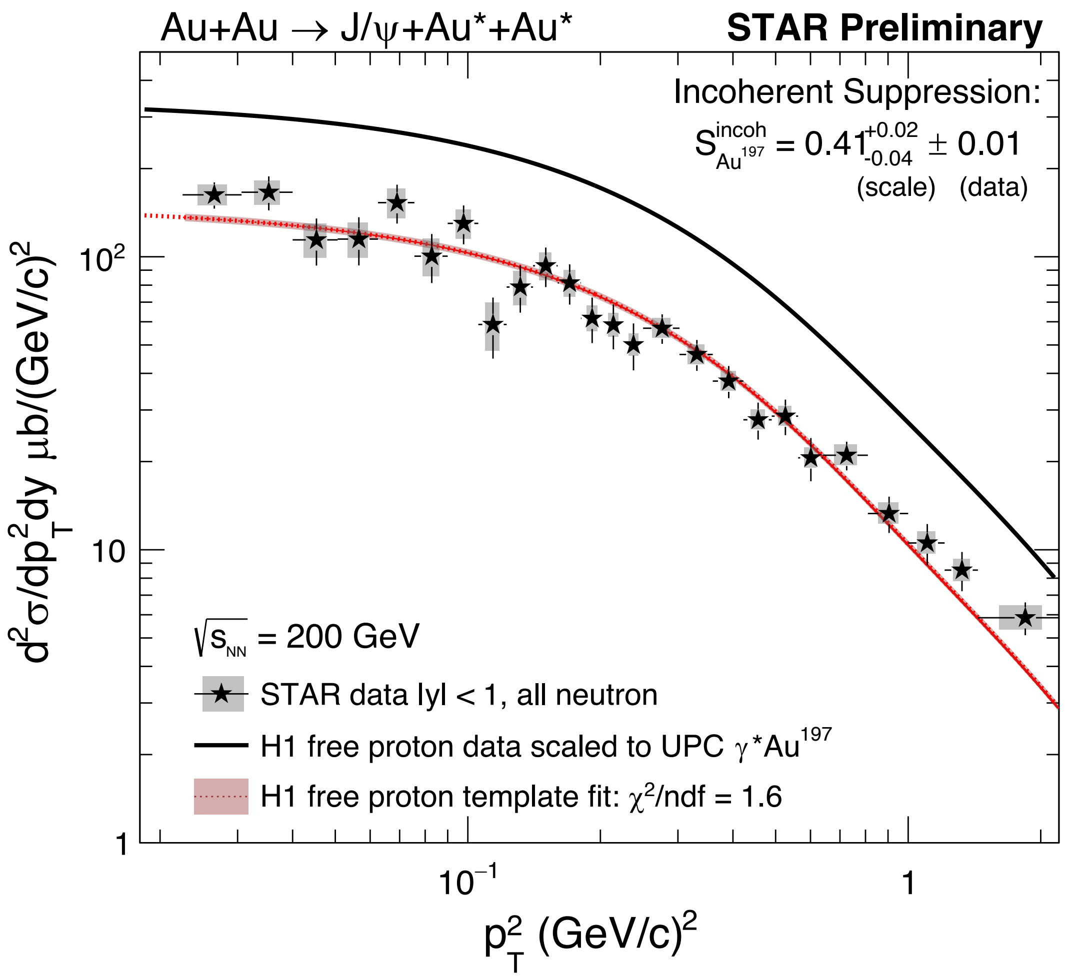
[made by A. Kumar (IIT, Delhi)]



Incoherent J/ψ cross section vs p_T^2

New

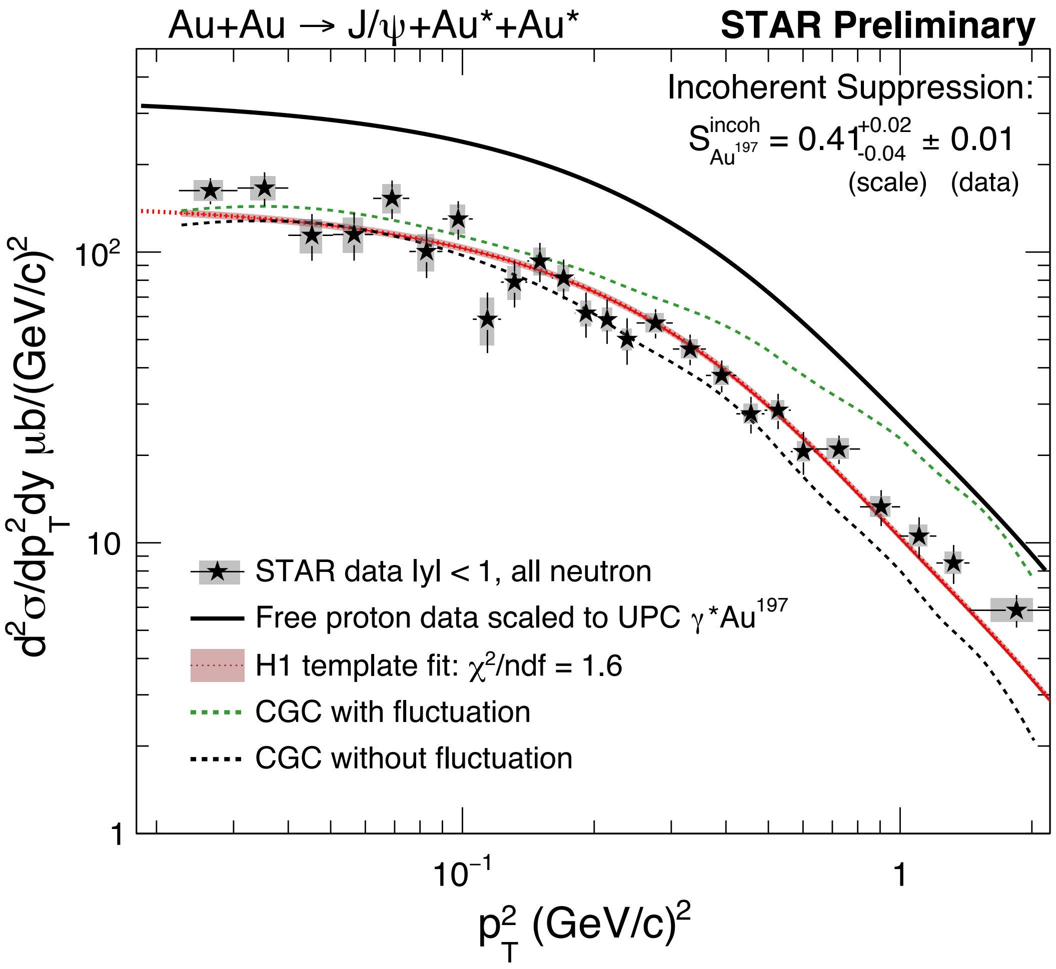
- Compared to the H1 data with free proton. **The suppression factor ~ is 40%.** Stronger than that for coherent production.
- Models have found that the H1 data supports **sub-nucleonic fluctuation**. *[Phys. Rev. Lett. 117 (2016) 5, 052301]*
- STAR data shows the bound nucleon has a similar shape in p_T^2 as the free proton, indicating **similar sub-nucleonic fluctuation in heavy nuclei.** *[Phys. Rev. D 106 (2022) 7, 074019]*



Incoherent J/ψ cross section vs p_T^2

New

- Direct comparisons to the fluctuation models do not give a clear answer.
- **The shape seems to be supported more by the one without fluctuation.**



Incoherent J/ψ cross sectio

ALICE new data (arXiv:2305.06169) is perfectly compatible with STAR's in terms of shape.

ALICE claimed the data supported scenario with fluctuation.

- Compared to the H1 data with free proton. **The suppression factor ~ is 40%.** Stronger than that for coherent production.

[illegible] supports [illegible] **nucleonic fluctuation**.
[Phys. Rev. Lett. 117 (2016) 5, 052301]

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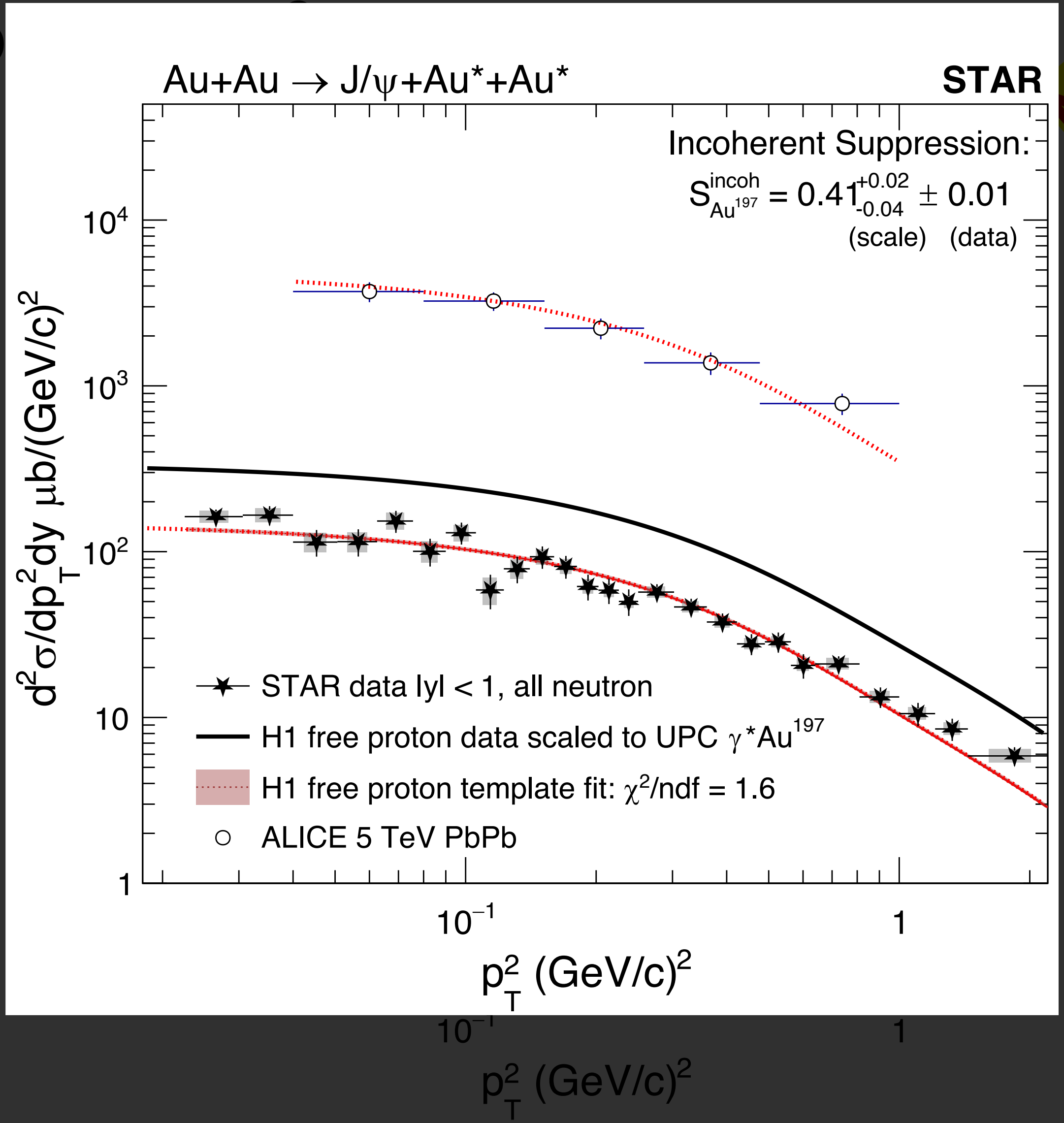


New

A new idea in UPCs: double ratio w. qualitative difference

$$R_{\mathrm{DEI}} = \frac{\left.\left(\sigma_{\mathrm{VM}}^{\mathrm{diffractive/exclusive}} \;/\; \sigma_{\mathrm{jet/high-p_T}}^{\mathrm{inclusive}}\right)\right|_{\mathrm{Au,Pb}}}{\left.\left(\sigma_{\mathrm{VM}}^{\mathrm{diffractive/exclusive}} \;/\; \sigma_{\mathrm{jet/high-p_T}}^{\mathrm{inclusive}}\right)\right|_{\mathrm{proton}}}$$

2-gluon exchange vs 1-gluon exchange

Shadowing models predict
$R_{DEI} < 1$

Saturation models predict
$R_{DEI} > 1$

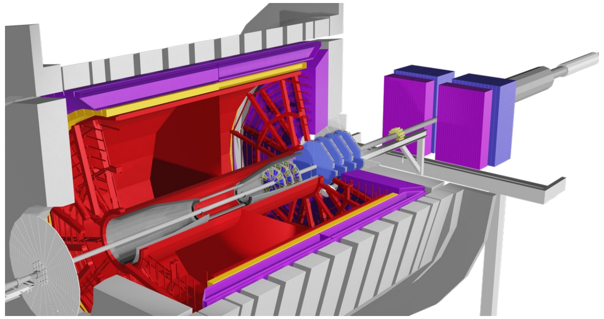
RHIC expects **$R_{DEI} < 1$**

LHC?

Energy (GeV)

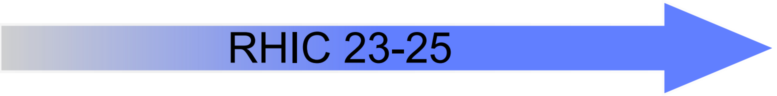
Ongoing theory study for saturation (see talk by B. Sun tomorrow)

Future UPCs opportunities



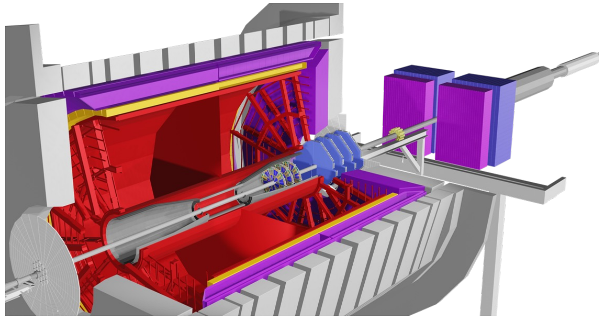
Since 2022, STAR has forward detectors (**$2.5 < \eta < 4.0$**):

- J/ψ coherent and incoherent production with **high precision**. Lower W towards a few GeV, and high t to better understand fluctuation.
- **ϕ photoproduction.**
- **Photoproduction of jets.**
- **New observables.**



2023 2025 2029 2034+

Future UPCs opportunities



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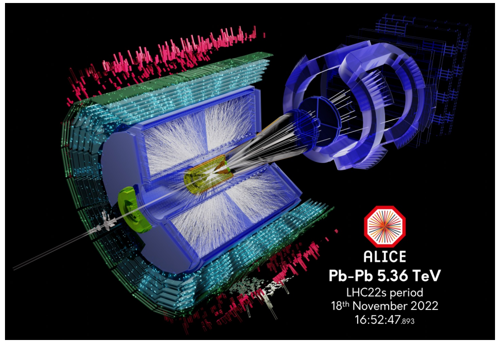
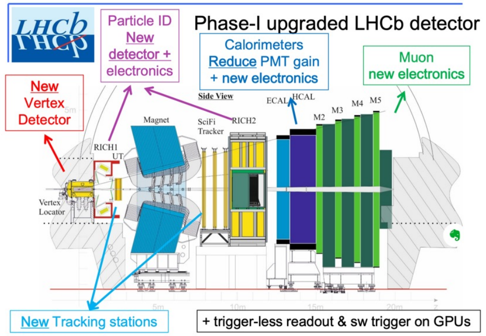
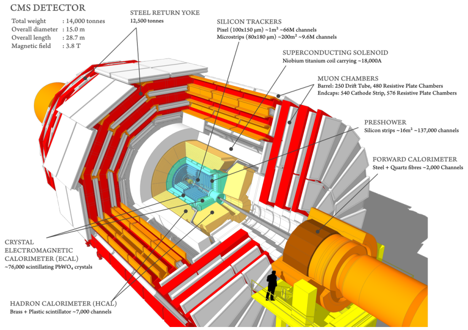
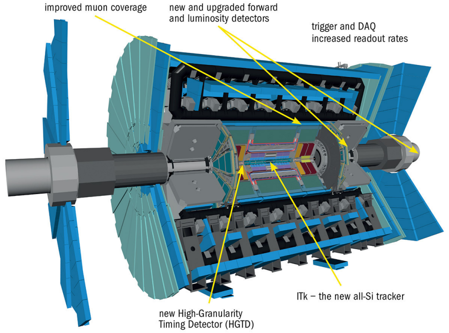






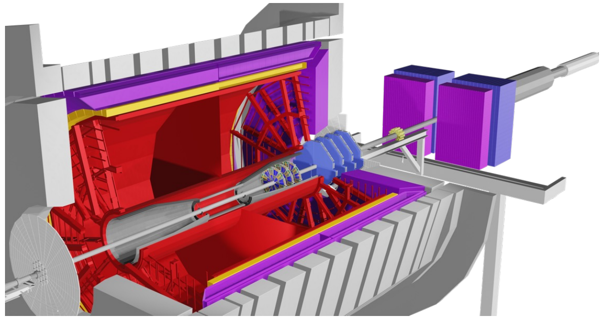


All LHC experiments will have significant upgrades in Run 3 & 4 (e.g., wide acceptances, ALICE FoCal, etc.). **Lower-x reach!**

RHIC 23-25 & LHC Run 3 LHC Run 4

2023 2025 2029 2034+

Future UPCs opportunities



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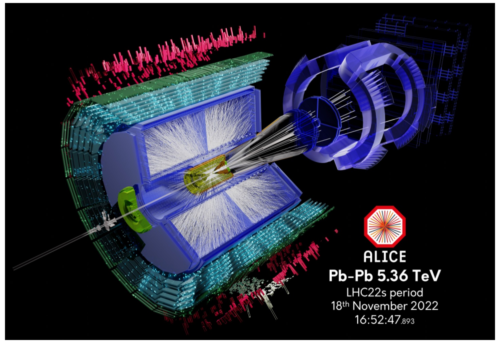

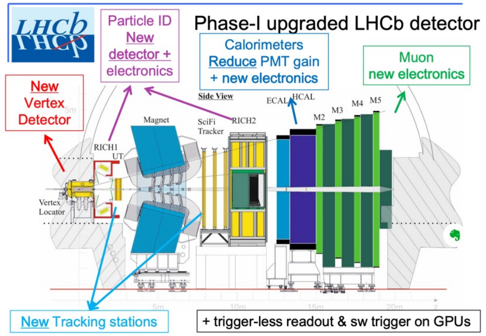

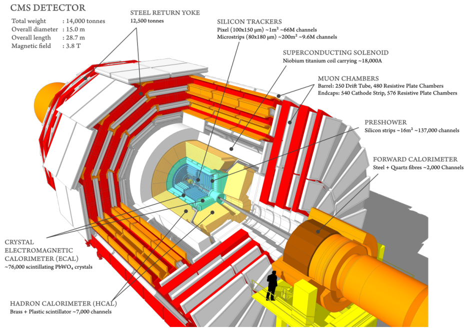

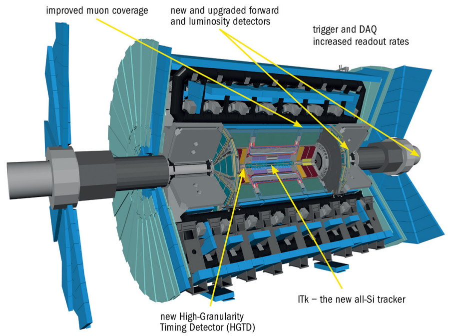

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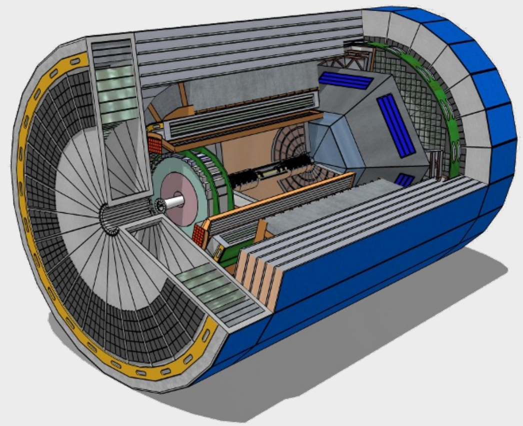
EIC era

The ePIC detector and possible a 2nd detector: the ultimate machine for understanding saturation quantitatively with a wide variety of observables.



RHIC 23-25 & LHC Run 3

LHC Run 4

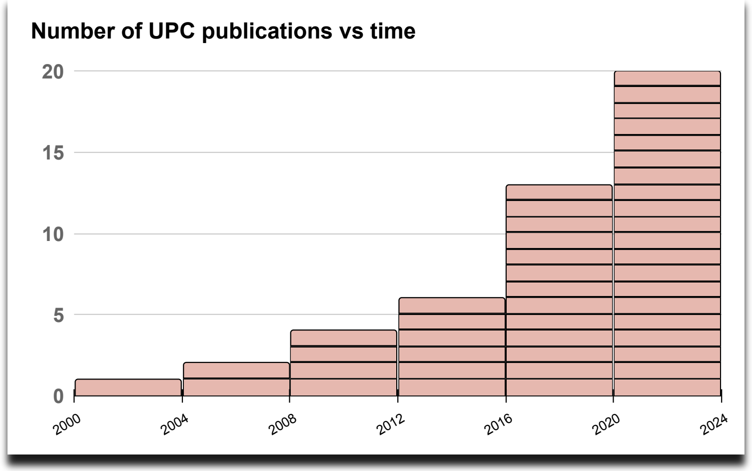
2023

2025

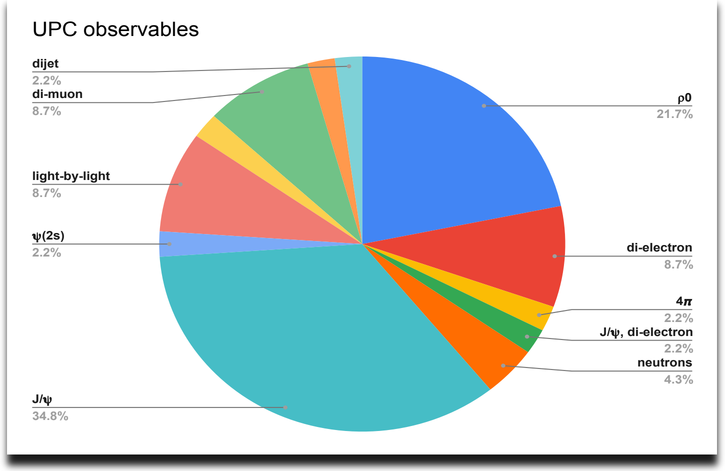
2029

2034+

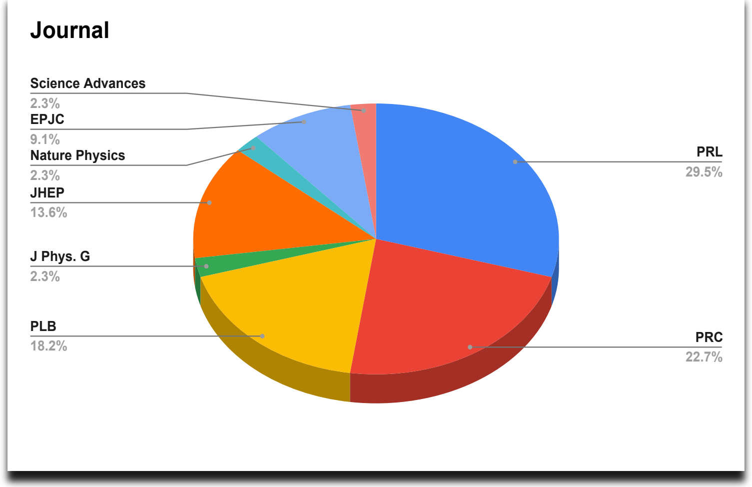
UPCs studies in the past 2 decades



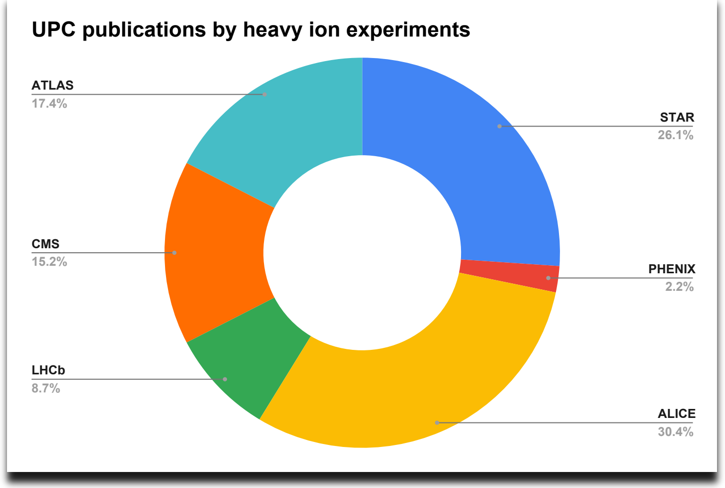
Number of UPC publications vs time



UPC observables



Journal



UPC publications by heavy ion experiments

Note:
Only experimental publications (I counted 46) with at least one beam is nucleus.

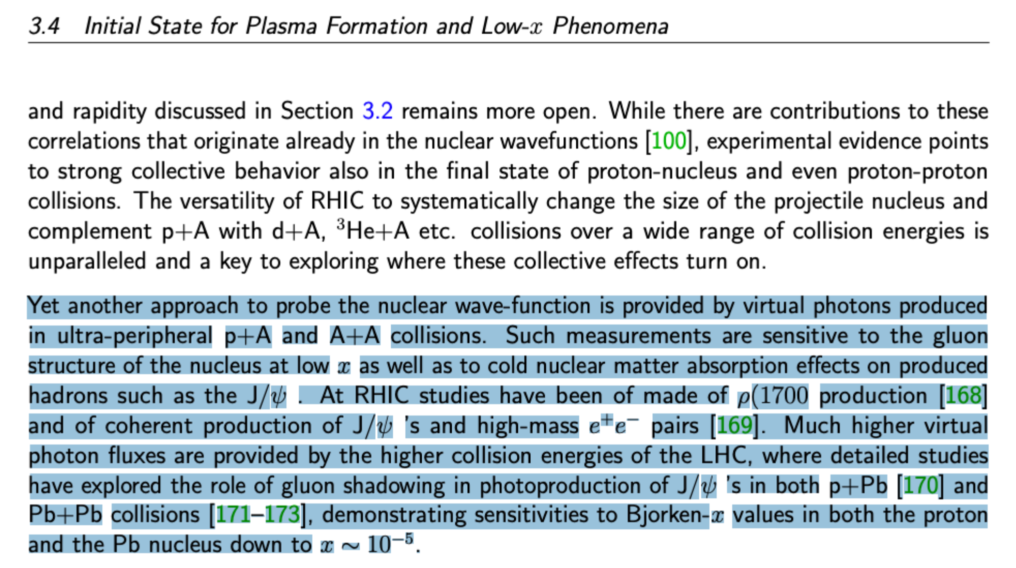
Hot QCD White Paper (2023)

UPCs studies in the past 2

Number of UPC publications vs time

Journal

Hot QCD White Paper (2015)

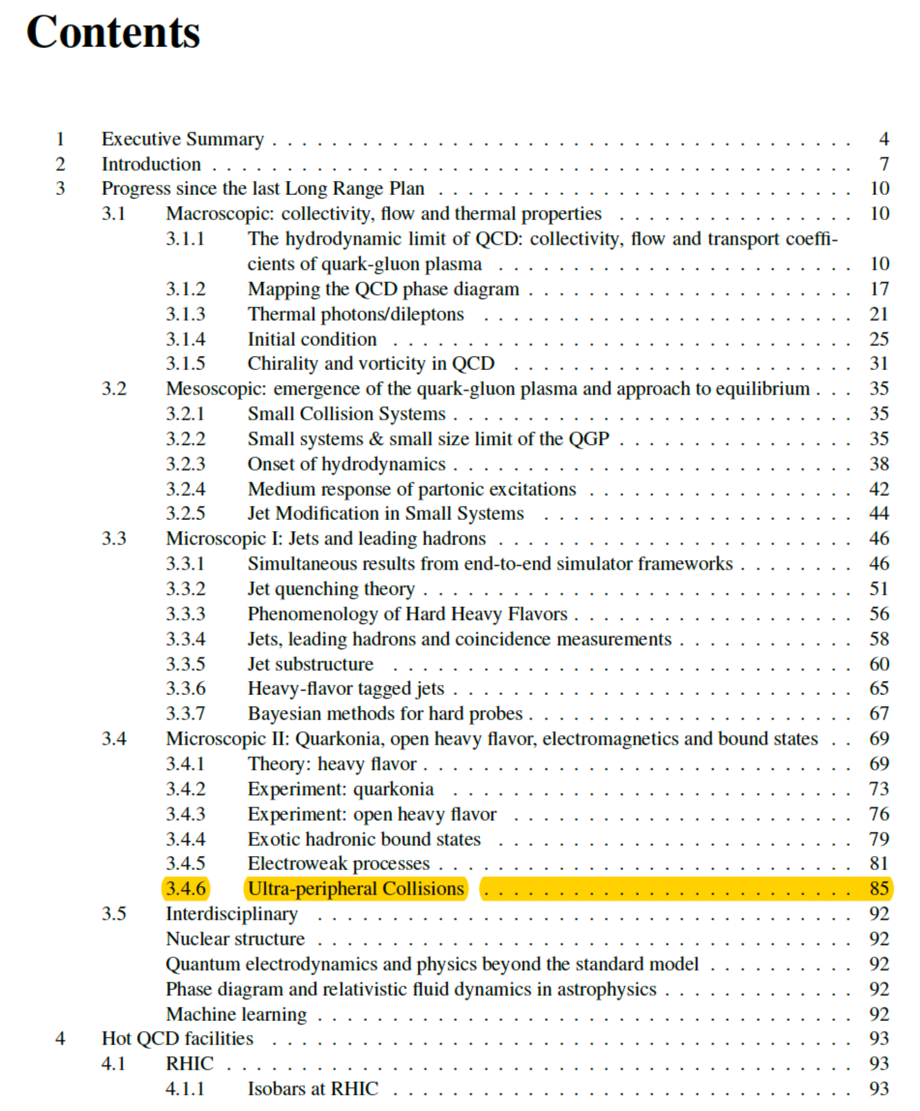


3.4 Initial State for Plasma Formation and Low-x Phenomena

and rapidity discussed in Section 3.2 remains more open. While there are contributions to these correlations that originate already in the nuclear wavefunctions [100], experimental evidence points to strong collective behavior also in the final state of proton-nucleus and even proton-proton collisions. The versatility of RHIC to systematically change the size of the projectile nucleus and complement p+A with d+A, ^{3}He+A etc. collisions over a wide range of collision energies is unparalleled and a key to exploring where these collective effects turn on.

Yet another approach to probe the nuclear wave-function is provided by virtual photons produced in ultra-peripheral p+A and A+A collisions. Such measurements are sensitive to the gluon structure of the nucleus at low x as well as to cold nuclear matter absorption effects on produced hadrons such as the J/ψ . At RHIC studies have been of made of $\rho(1700$ production [168] and of coherent production of J/ψ 's and high-mass e^+e^- pairs [169]. Much higher virtual photon fluxes are provided by the higher collision energies of the LHC, where detailed studies have explored the role of gluon shadowing in photoproduction of J/ψ 's in both p+Pb [170] and Pb+Pb collisions [171–173], demonstrating sensitivities to Bjorken-x values in both the proton and the Pb nucleus down to $x \sim 10^{-5}$.

Only 1 paragraph on UPCs



Contents

~ 10 pages on UPCs

Summary

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  - LHC UPC J/ψ data has been found significantly suppressed relative to the free nucleon.
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  - Incoherent J/ψ production is found to be **more suppressed than that in coherent,** and **similar level of fluctuation** as in free nucleon.
- LHC and RHIC UPCs program are complementary, covering a **wide energy reach**.

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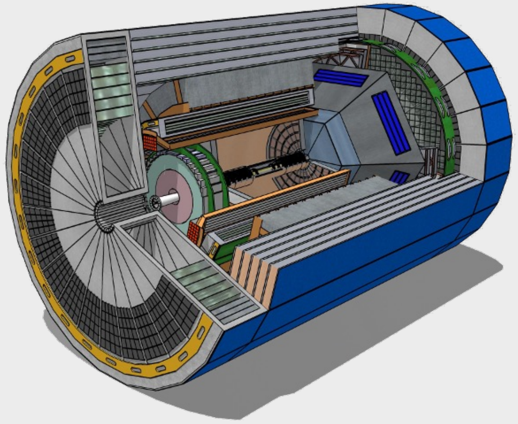

Special thanks to:

CGC: Heikki Mäntysaari, Farid Salazar, Björn Schenke
Sartre: Tobias Toll, Arjun Kumar
Nuclear shadowing: Vadim Guzey, Mark Strikman, Mikhail Zhalov
NLO pQCD: Topi Löytäinen et al.
Saturation observables: Brian Sun, Y. Kovchegov

For discussions and inputs.

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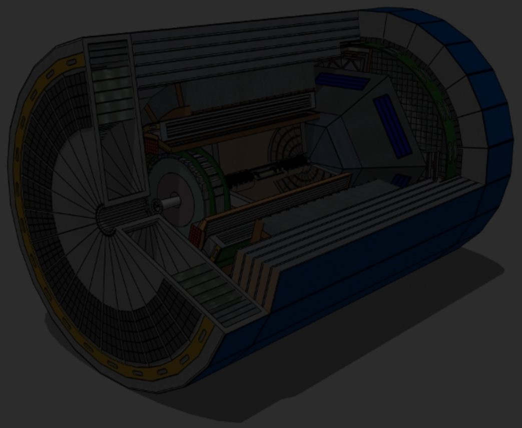
- LHC and RHIC UPCs program are complementary, covering **wide energy reach**.

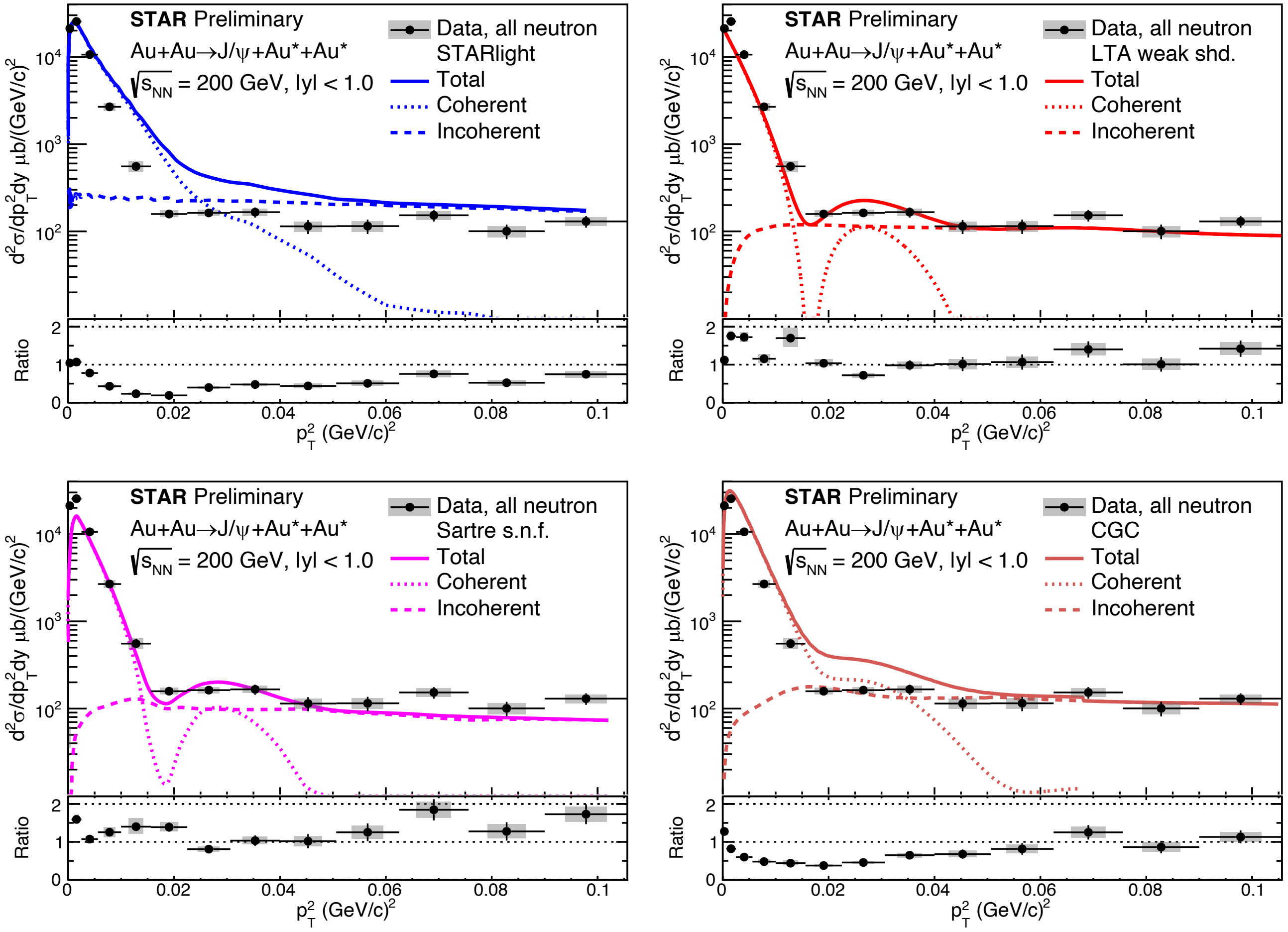
EIC era

The ePIC detector and possible a 2nd detector: the ultimate machine for understanding saturation quantitatively with a wide variety of observables.



Backup

A full picture: coherent + incoherent



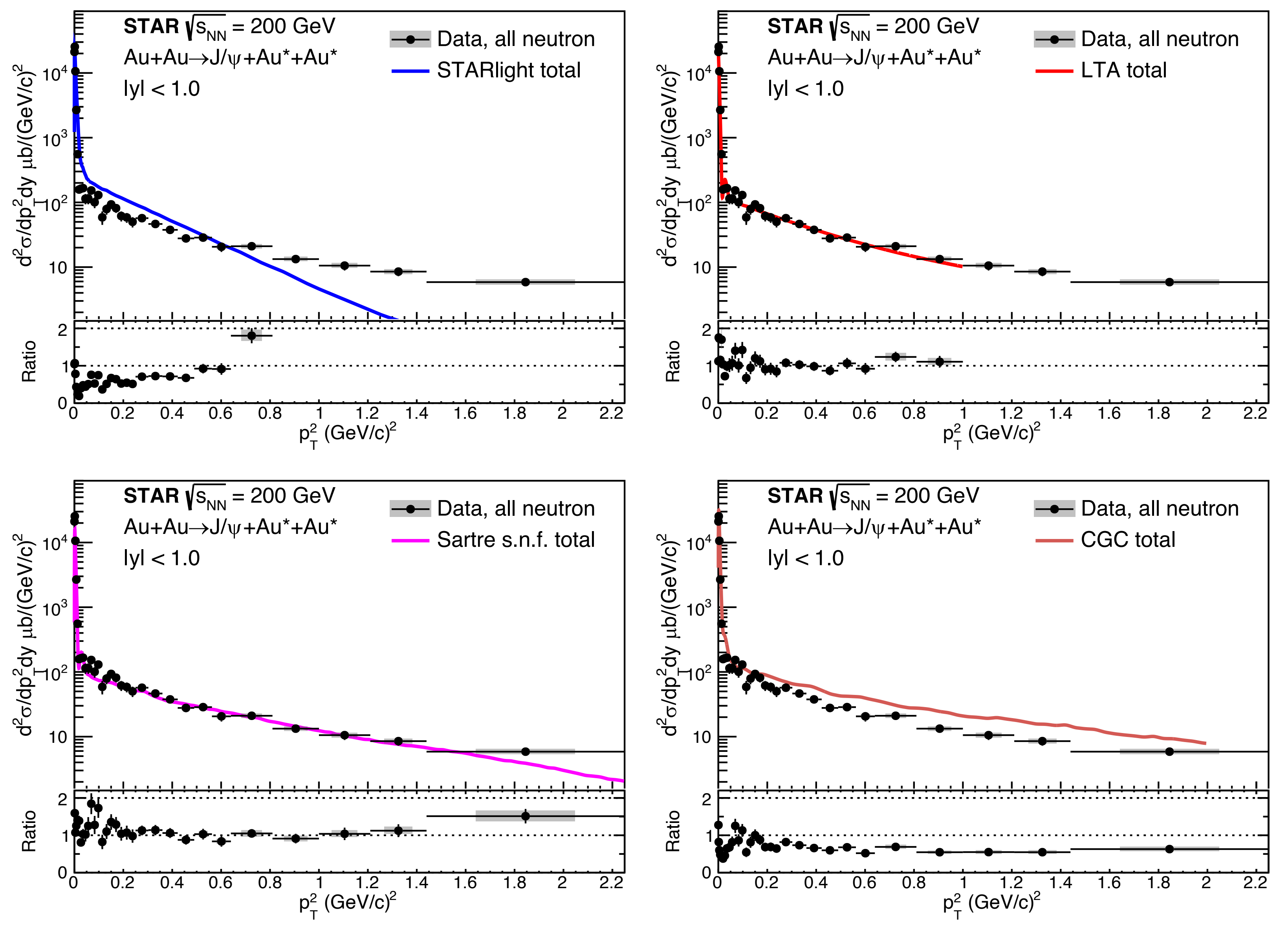
- ❖ STAR data compared with four theory/MC models.
- ❖ Sartre with sub-nucleonic fluctuation (s.n.f) & CGC are similar models but different by a normalization factor ~ 0.65.
- ❖ **Question to theorists: Why?**

Reference to CGC: Phys. Rev. D 106 (2022) 7, 074019
Reference to LTA: arXiv:2303.12052

A full picture:

Full momentum region

STAR data is important to understand



NLO calculation

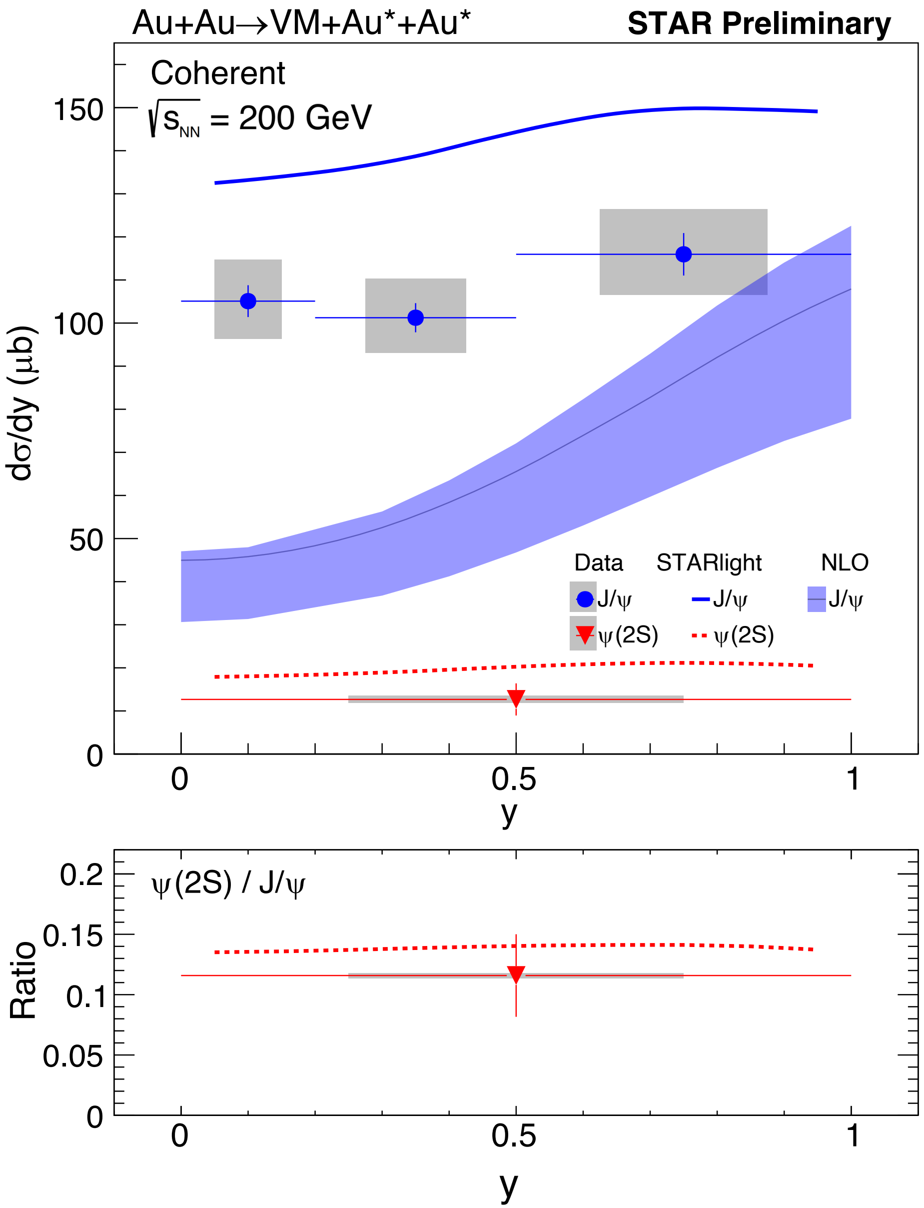
Next-to-Leading Order (NLO) pQCD calculation, constrained **by the LHC data**

EPPS21 + scale at 2.39 GeV.
Only scale uncertainty shown.

Could not describe the STAR data at y = 0.

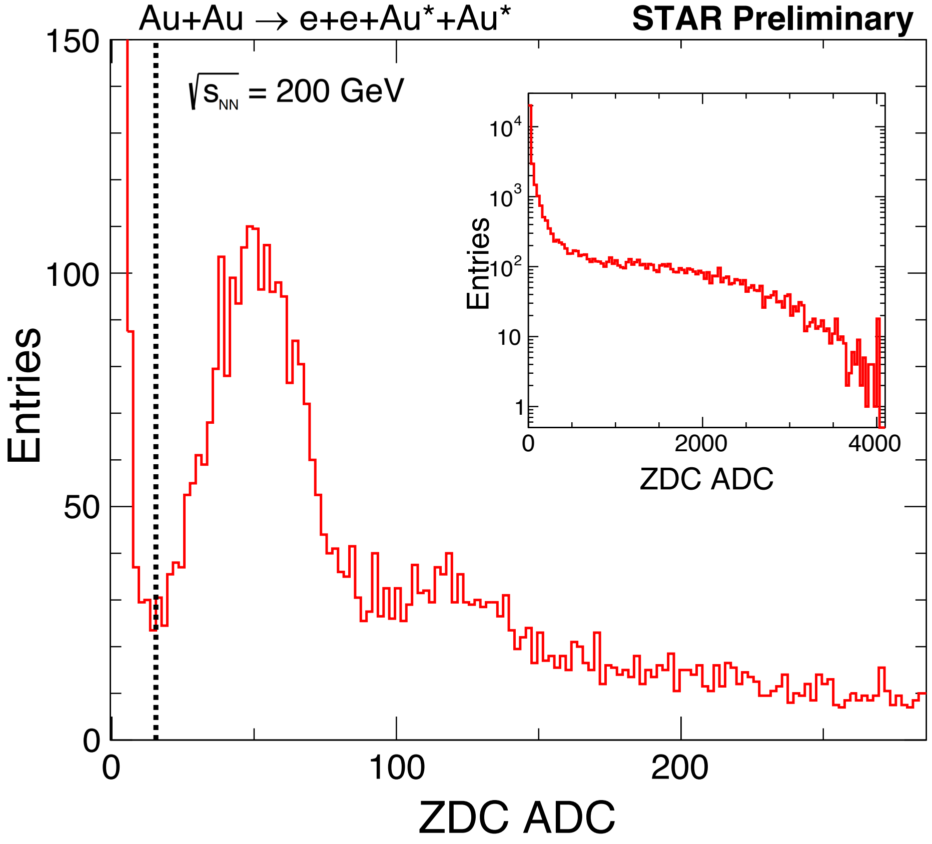
Reference to NLO pQCD calculation:

a) arXiv:2210.16048
b) Phys. Rev. C 106 (2022) 3, 035202



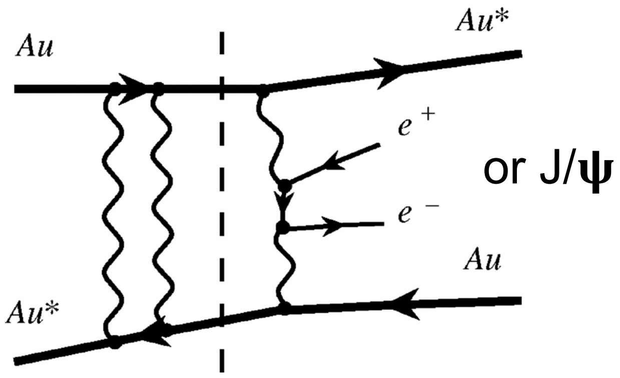
New

Neutron emissions in UPCs



Neutron classes:

- **0n0n:** no neutron on either side
- **0nXn:** >=1 neutron on one side
- **XnXn:** >=1 neutron on both sides



UPCs have large contributions from QED Coulomb excitations

List of UPC experimental papers at RHIC &LHC

200 GeV	Au+Au	2002	ρ0	PRL	STAR	https://arxiv.org/abs/nucl-ex/0206004
200 GeV	Au+Au	2004	di-electron	PRC	STAR	https://arxiv.org/abs/nucl-ex/0404012
200 GeV	Au+Au	2007	ρ0	PRC	STAR	https://arxiv.org/abs/0712.3320
200 GeV	Au+Au	2008	ρ0	PRL	STAR	https://arxiv.org/abs/0812.1063
200 GeV	Au+Au	2009	4π	PRC	STAR	https://arxiv.org/abs/0912.0604
200 GeV	Au+Au	2009	J/ψ, di-electron	PLB	PHENIX	https://arxiv.org/abs/0903.2041
62.4 GeV	Au+Au	2011	ρ0	PRC	STAR	https://arxiv.org/abs/1107.4630
2760 GeV	Pb+Pb	2012	neutrons	PRL	ALICE	https://arxiv.org/abs/1203.2436v3
2760 GeV	Pb+Pb	2012	J/ψ	PLB	ALICE	https://arxiv.org/abs/1209.3715v3
7000 GeV	p+p	2013	J/ψ	J Phys. G	LHCb	https://arxiv.org/abs/1301.7084
5020 GeV	p+Pb	2014	J/ψ	PRL	ALICE	https://arxiv.org/abs/1406.7819v2
5020 GeV	Pb+Pb	2015	ρ0	JHEP	ALICE	https://arxiv.org/abs/1503.09177v2
5020 GeV	Pb+Pb	2015	ψ(2s)	PLB	ALICE	https://arxiv.org/abs/1508.05076v2
2760 GeV	Pb+Pb	2016	J/ψ	PLB	CMS	https://arxiv.org/abs/1605.06966
200 GeV	Au+Au	2017	ρ0	PRC	STAR	https://arxiv.org/abs/1702.07705
5020 GeV	Pb+Pb	2017	light-by-light	Nature Physics	ATLAS	https://arxiv.org/abs/1702.01625
200 GeV	Au+Au & U+U	2018	di-electron	PRL	STAR	https://arxiv.org/abs/1806.02295
5020 GeV	p+Pb	2018	Υ	EPJC	CMS	https://arxiv.org/abs/1809.11080
5020 GeV	Pb+Pb	2018	light-by-light	PLB	CMS	https://arxiv.org/abs/1810.04602
5020 GeV	p+Pb	2018	J/ψ	EPJC	ALICE	https://arxiv.org/abs/1809.03235v2
5020 GeV	Pb+Pb	2018	di-muon	PRL	ATLAS	https://arxiv.org/abs/1806.08708
200 GeV	Au+Au & U+U	2019	J/ψ	PRL	STAR	https://arxiv.org/abs/1904.11658
200 GeV	Au+Au	2019	di-electron	PRL	STAR	https://arxiv.org/abs/1910.12400
5020 GeV	Pb+Pb	2019	ρ0	EPJC	CMS	https://arxiv.org/abs/1902.01339
5020 GeV	Pb+Pb	2019	J/ψ	PLB	ALICE	https://arxiv.org/abs/1904.06272v2
5020 GeV	Pb+Pb	2019	light-by-light	PRL	ATLAS	https://arxiv.org/abs/1904.03536
5020 GeV	Pb+Pb	2020	di-muon	PRL	CMS	https://arxiv.org/abs/2011.05239
5020 GeV	Pb+Pb	2020	ρ0	JHEP	ALICE	https://arxiv.org/abs/2002.10897v2
5020 GeV	Pb+Pb	2020	light-by-light	JHEP	ATLAS	https://arxiv.org/abs/2008.05355
5020 GeV	Pb+Pb	2020	di-muon	PRC	ATLAS	https://arxiv.org/abs/2011.12211
200 GeV	d+Au	2021	J/ψ	PRL	STAR	https://arxiv.org/abs/2109.07625
5020 GeV	Pb+Pb	2021	J/ψ	JHEP	LHCb	https://arxiv.org/abs/2107.03223
5020 GeV	Pb+Pb	2021	J/ψ	JHEP	LHCb	https://arxiv.org/abs/2108.02681
5440 GeV	Xe+Xe	2021	ρ0	PLB	ALICE	https://arxiv.org/abs/2101.02581v2
5020 GeV	Pb+Pb	2021	J/ψ	EPJC	ALICE	https://arxiv.org/abs/2101.04577v2
5020 GeV	Pb+Pb	2021	J/ψ	PLB	ALICE	https://arxiv.org/abs/2101.04623v2
5020 GeV	Pb+Pb	2021	inclusive	PRC	ATLAS	https://arxiv.org/abs/2101.10771
200 GeV	Au+Au	2022	ρ0	Science Advances	STAR	https://arxiv.org/abs/2204.01625
5020 GeV	Pb+Pb	2022	dijet	PRL	CMS	https://arxiv.org/abs/2205.00045
5020 GeV	Pb+Pb	2022	J/ψ	PRC	LHCb	https://arxiv.org/abs/2206.08221
5020 GeV	Pb+Pb	2022	neutrons	PRC	ALICE	https://arxiv.org/abs/2209.04250v1
5020 GeV	Pb+Pb	2022	di-muon	PRC	ATLAS	https://arxiv.org/abs/2206.12594
5020 GeV	Pb+Pb	2022	di-electron	JHEP	ATLAS	https://arxiv.org/abs/2207.12781
5021 GeV	Pb+Pb	2023	J/ψ	PRL	CMS	https://arxiv.org/abs/2303.16984
5022 GeV	Pb+Pb	2023	J/ψ	PRL	ALICE	https://arxiv.org/abs/2305.06169
5023 GeV	Pb+Pb	2023	J/ψ	JHEP	ALICE	https://arxiv.org/abs/2305.19060v1