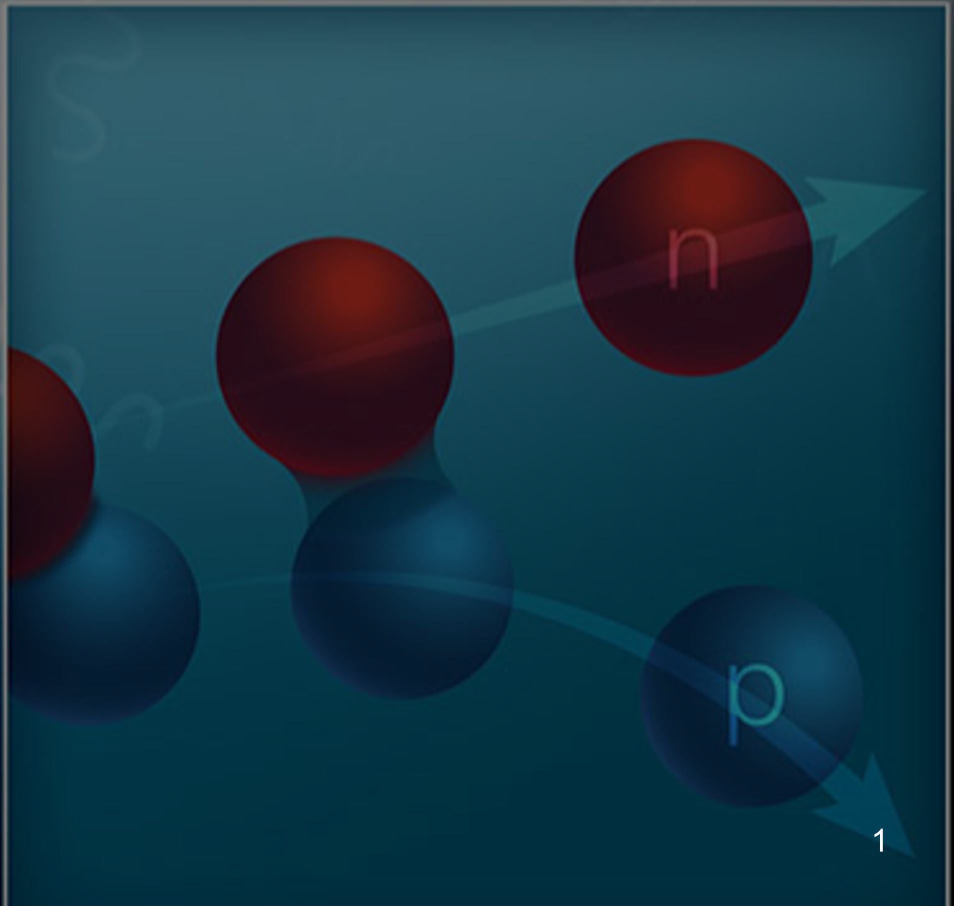
Ultra-Peripheral Collisions at RHIC and future opportunities

Kong Tu
BNL
05.23.2022



Almost exactly 10 years ago, I asked M. Murray:

"What is the most exciting physics in your research?"

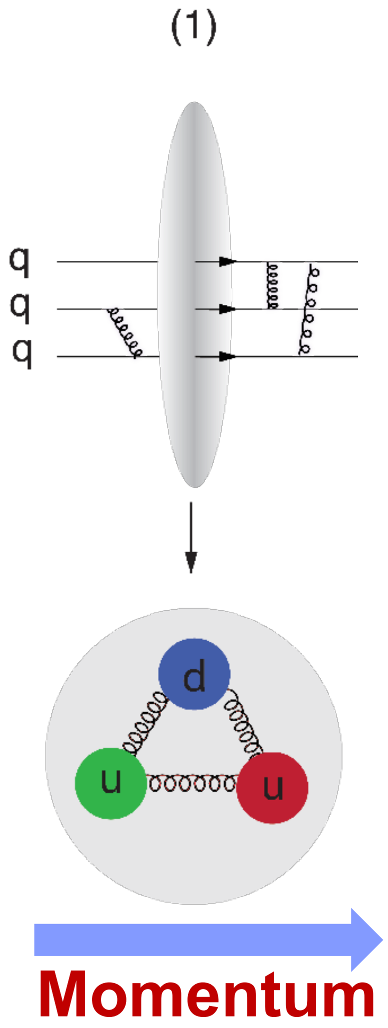
He said,

"*Ah ha… The proton is so complex and so fascinating…*" and went on for about an hour.

July 4th , 2012 Building 40, CERN

What’s inside of a nucleon?

What's inside of a nucleon?



an ``*observer*`` in the lab

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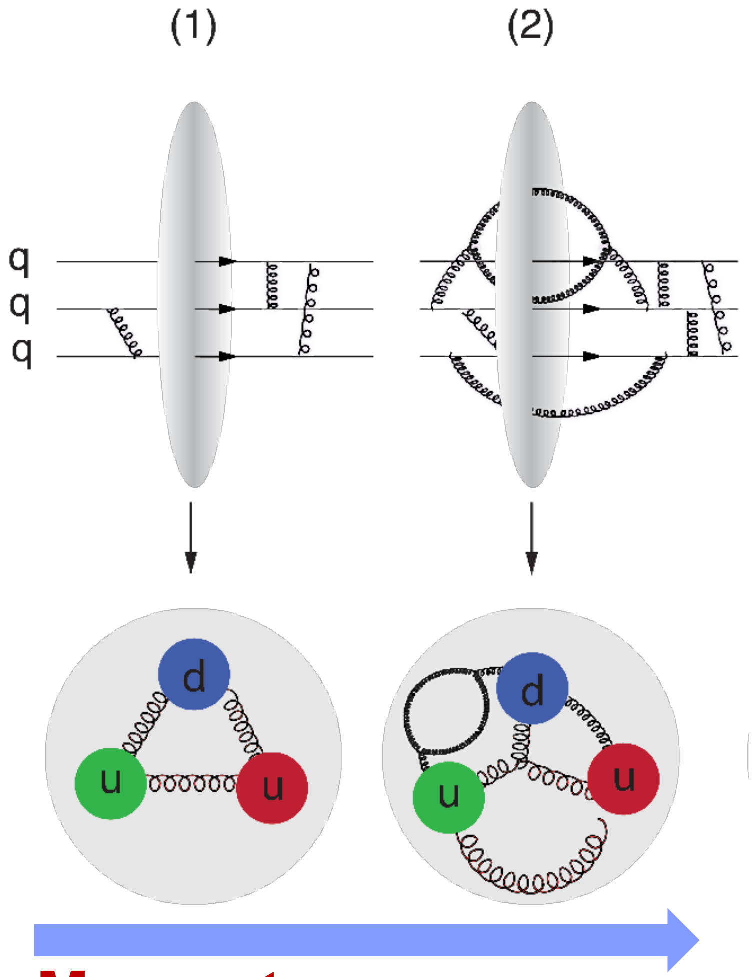

Momentum

an ``*observer*`` in the lab

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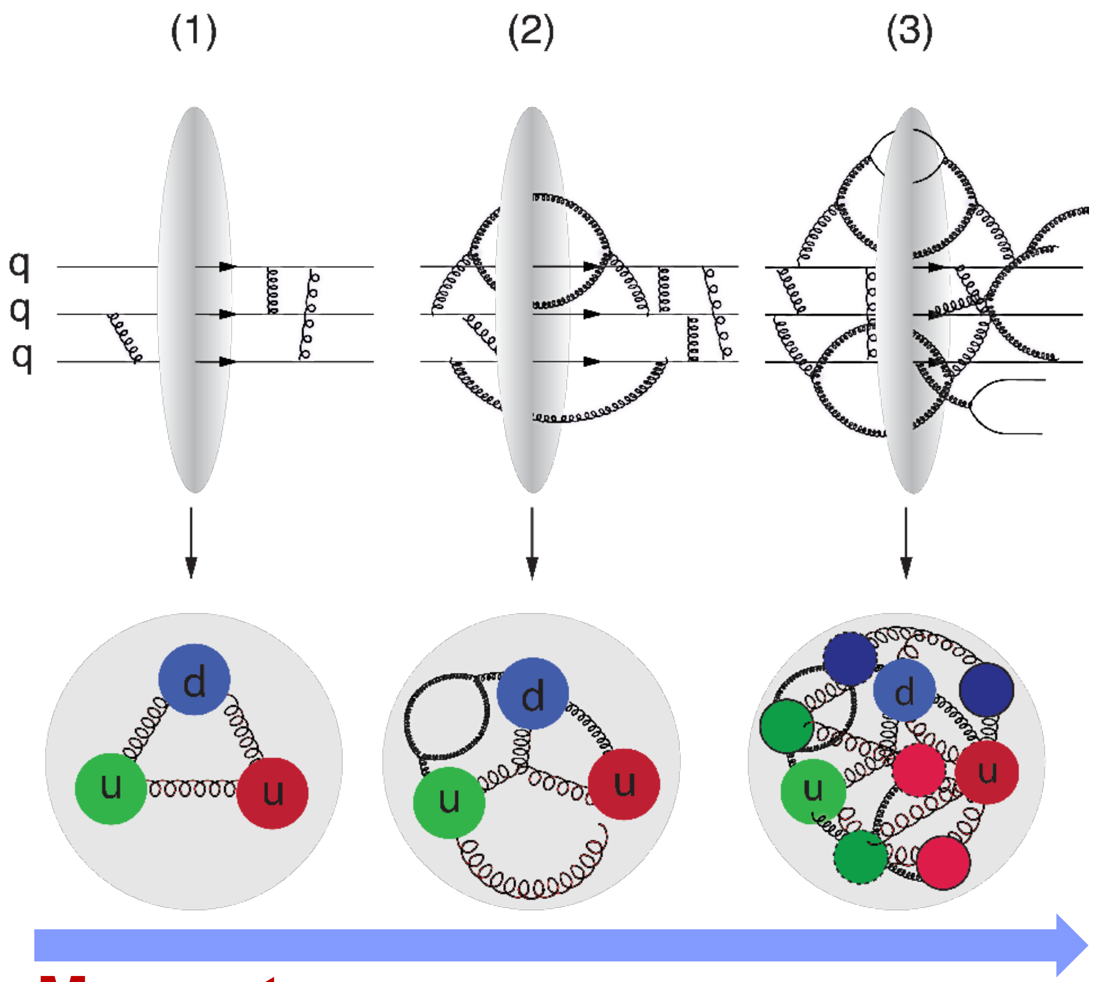
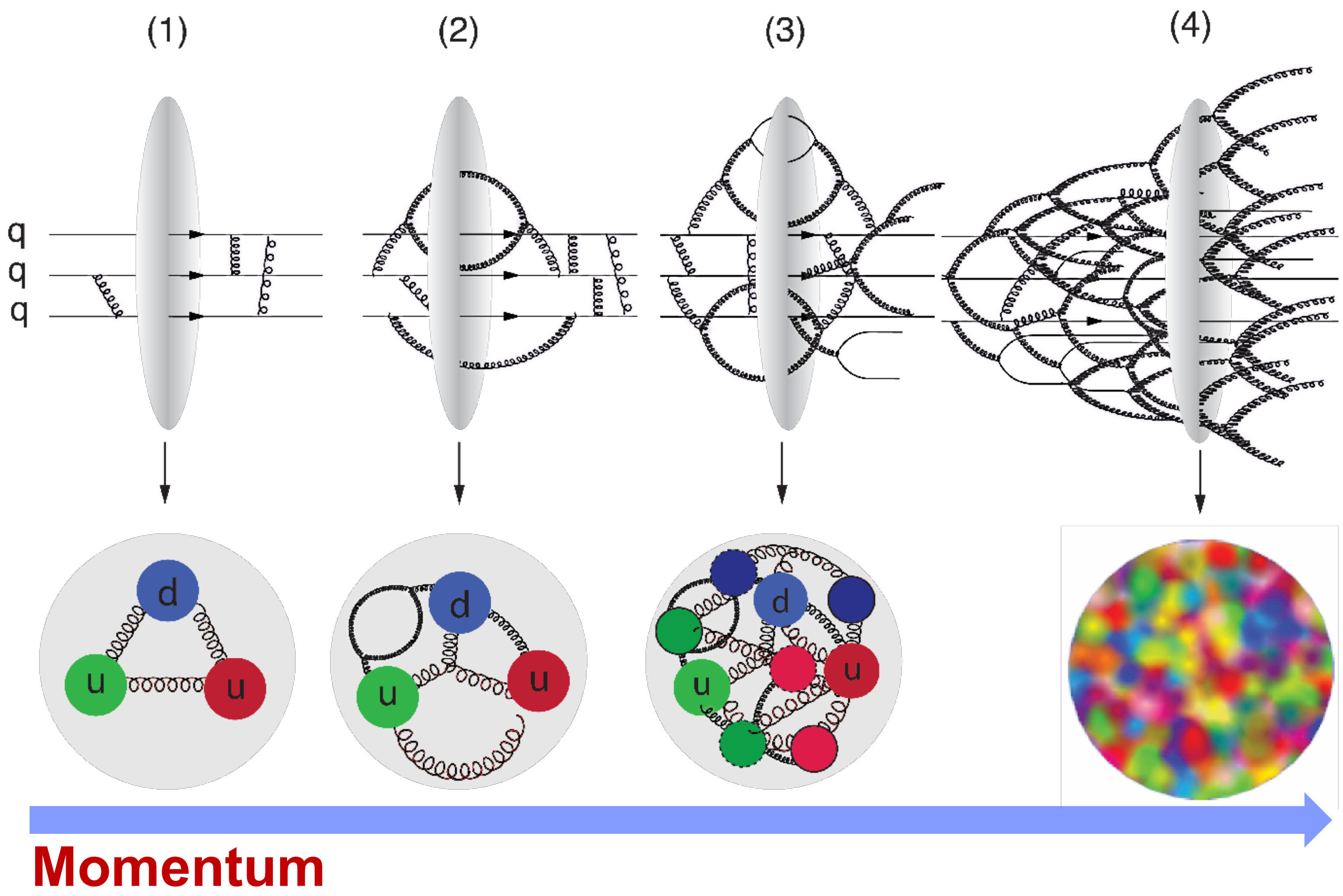


Momentum

Lorentz time dilation

What's inside of a nucleon?



an ``*observer*`` in the lab

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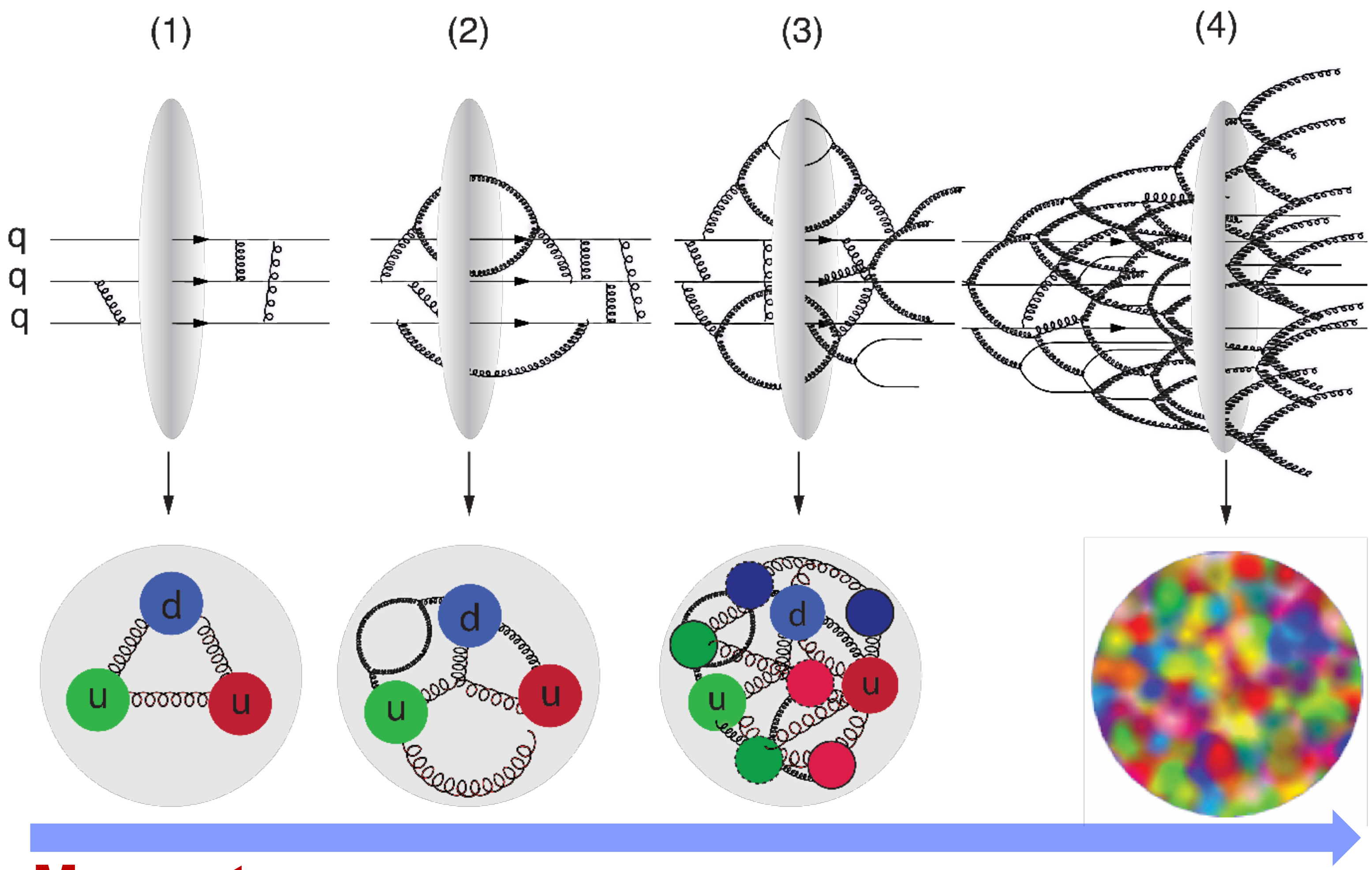


Momentum

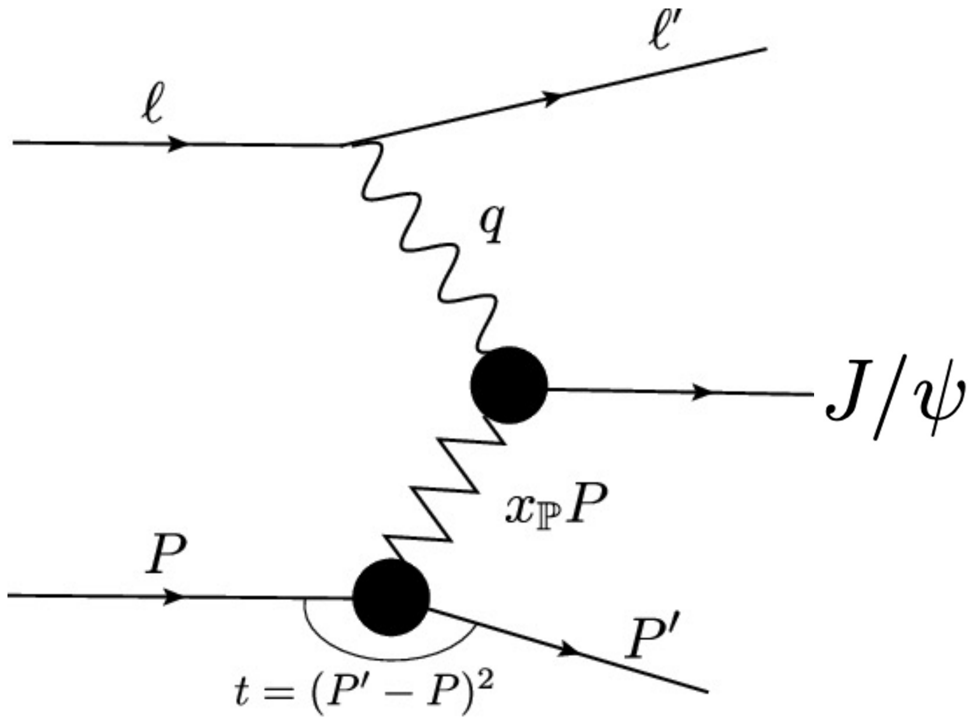
an ``*observer*`` in the lab

Pop quiz - where was the gluon discovered?

Petra ring
Answer:

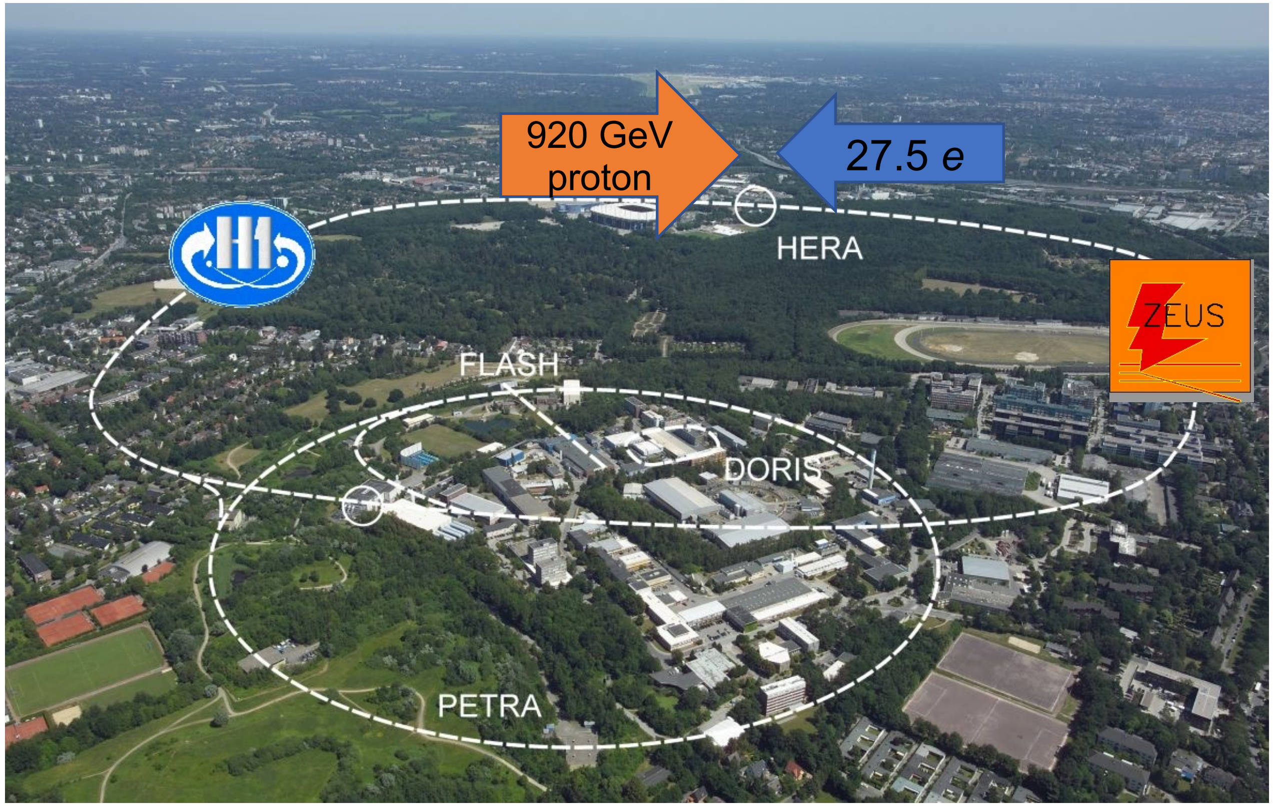
HERA – ep collider

Diffractive Vector-Meson (VM)



A sensitive process to gluons

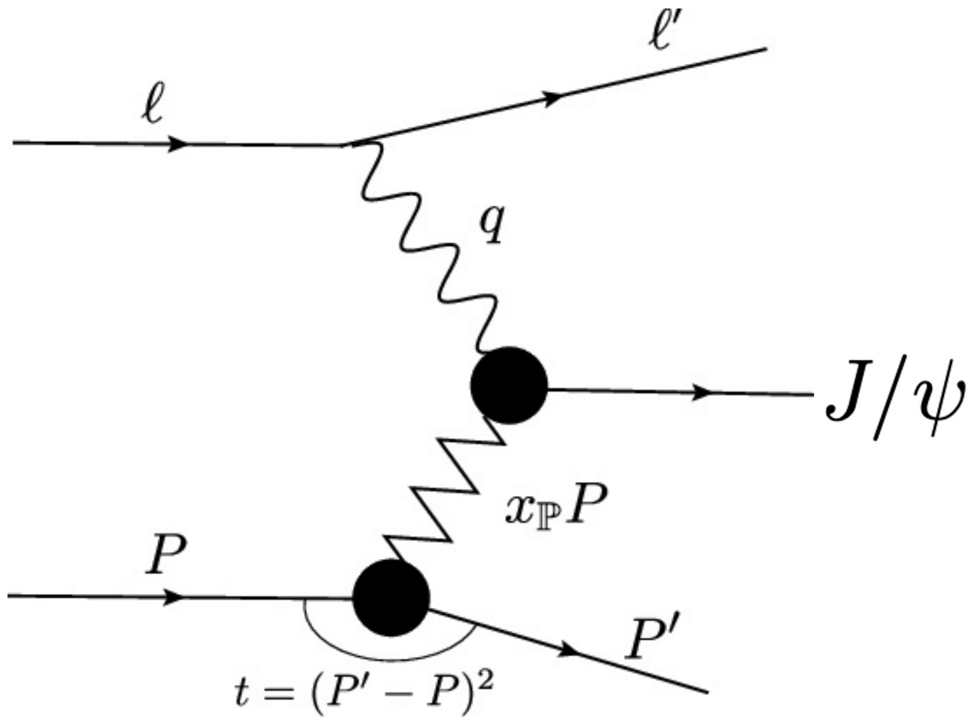
DESY, Hamburg, Germany



(HERA - 6.3 km in circumference)

HERA – ep collider

Diffractive Vector-Meson (VM)



A sensitive process to gluons

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- Exclusive probes with little bkg.
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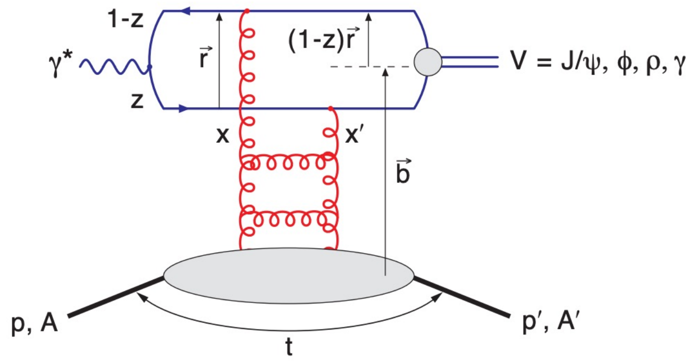
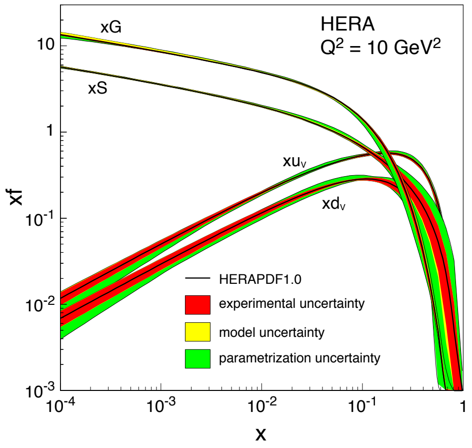
- Cross sections are sensitive to: i) gluon density and ii) its spatial distribution.

LO dipole picture





HERA – ep collider

1 **H1 and ZEUS publications about VM at HERA**

H1 Topic	Journal	ZEUS Topic	Journal
Exclusive $\pi^+\pi^-$ and ρ^0 in PHP	Eur.Phys.J.C80 (2020), 1189	$R(\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)})$ in DIS	Nucl. Phys. B 909 (2016) 934
Exclusive ρ^0 with Leading n in PHP	Eur.Phys.J.C76 (2016) 1, 41	Exclusive Electroproduction of 2π	Eur.Phys.J. C 72 (2012) 1869
Elastic and p-diss J/ψ in PHP	Eur.Phys.J.C73 (2013) 2466	$\Upsilon(1S)$ in PHP (t-dependence)	Phys.Lett. B 708 (2012) 14
Diffractive ρ^0 and ϕ in DIS	JHEP05 (2010) 032	P-dissociative J/ψ in PHP at large t	JHEP 05 (2010) 085
Diffractive PHP of ρ^0 with large t	Phys.Lett.B 638 (2006) 422	Exclusive PHP of Υ Mesons	Phys. Lett. B 680 (2009) 4
Elastic J/ψ in PHP and DIS	Eur.Phys.J.C46 (2006) 585	Exclusive ρ^0 in DIS	PMC Physics A 1, 6
Diffractive PHP of J/ψ with large t	Phys Lett B568 (2003) 205	Exclusive ϕ in DIS	Nucl. Phys. B 718 (2005) 3
Diffractive PHP of $\psi(2S)$	Phys.Lett.B541 (2002) 251	Exclusive J/ψ in DIS	Nucl. Phys. B 695 (2004) 3
Helicity structure of ρ^0 in DIS	Phys.Lett.B539 (2002) 25	P-dissociative VM in PHP at large t	Eur. Phys. J. C 26 (2003) 389
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Quasi-elastic $(z > 0.95)$ $\psi(2S)$ in PHP	Phys.Lett.B421 (1998) 385	Spin-Density ME of Exclusive ρ^0 in DIS	Eur. Phys. J. C 12 (2000) 393
P-diss. ρ^0 and Elastic ϕ in DIS	Z.Phys.C75 (1997) 607	Exclusive ρ^0 and J/ψ in DIS	Eur. Phys. J. C 6 (1999) 603
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		Elastic ω in PHP	Z. Phys. C 73 (1996) 73
		$\gamma^* p \to \phi p$ in DIS	Phys. Lett. B 380 (1996) 220
		Elastic ϕ in PHP	Phys. Lett. B 377 (1996) 259
		Elastic ρ^0 in PHP	Z. Phys. C 69 (1995) 39
		Exclusive ρ^0 in DIS	Phys. Lett. B 356 (1995) 601

Measured are: $\rho, \rho', \omega, \phi, J/\psi, \psi(2S), \Upsilon$ in EL and PD channels and for $0 < Q^2 < 100\,\mathrm{GeV}^2$
More that 5000 references; a couple of new "preliminary" results and ongoing analyses. ⇒
Too much to cover in one talk.

See a summary talk by S. Levonian

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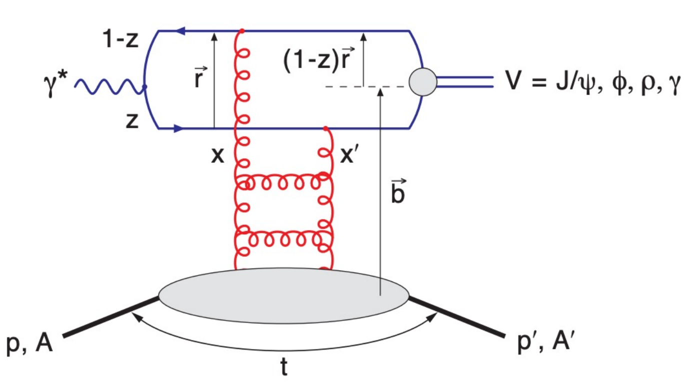
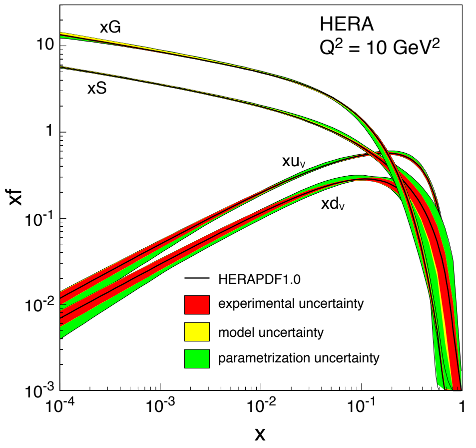
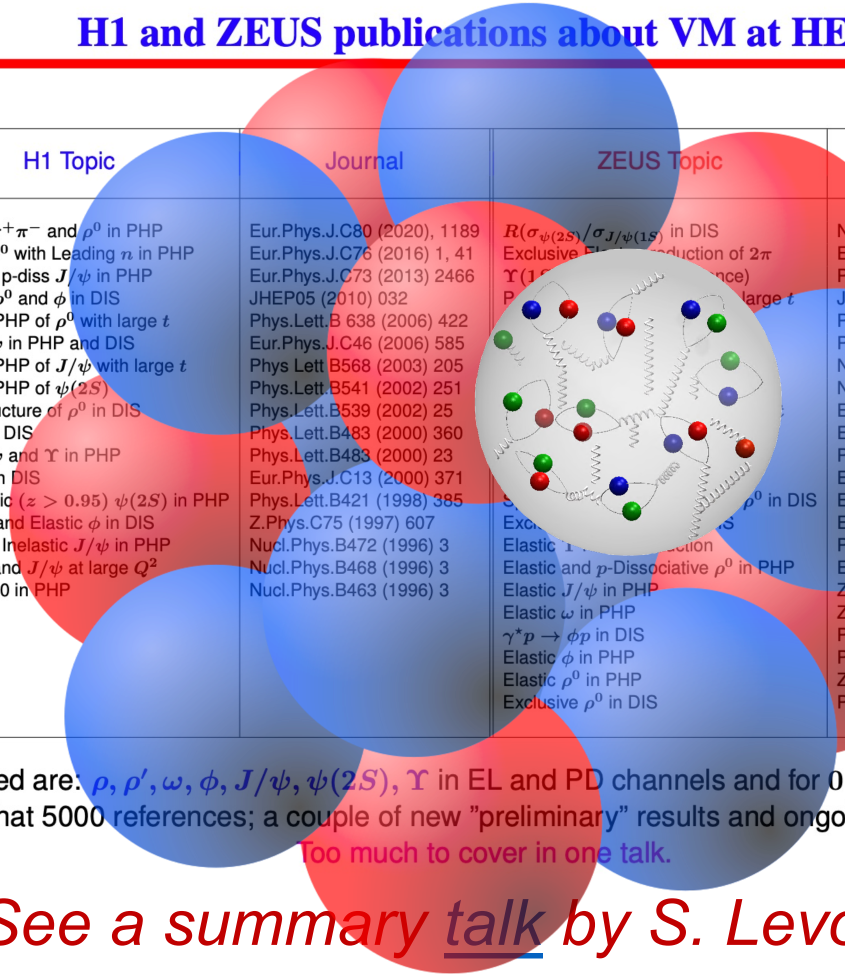




HERA – ep collider



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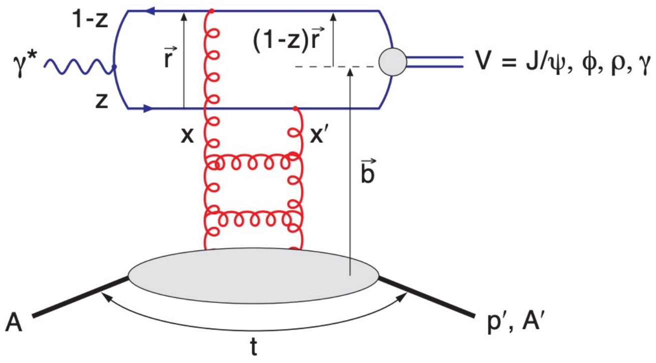
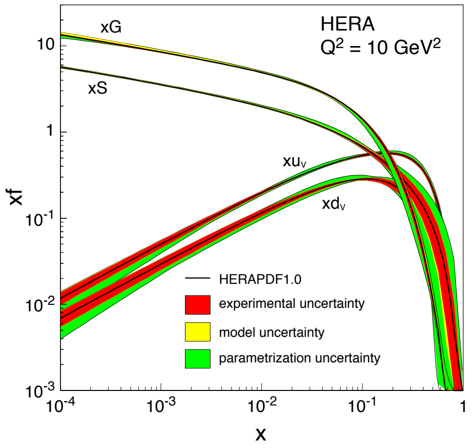
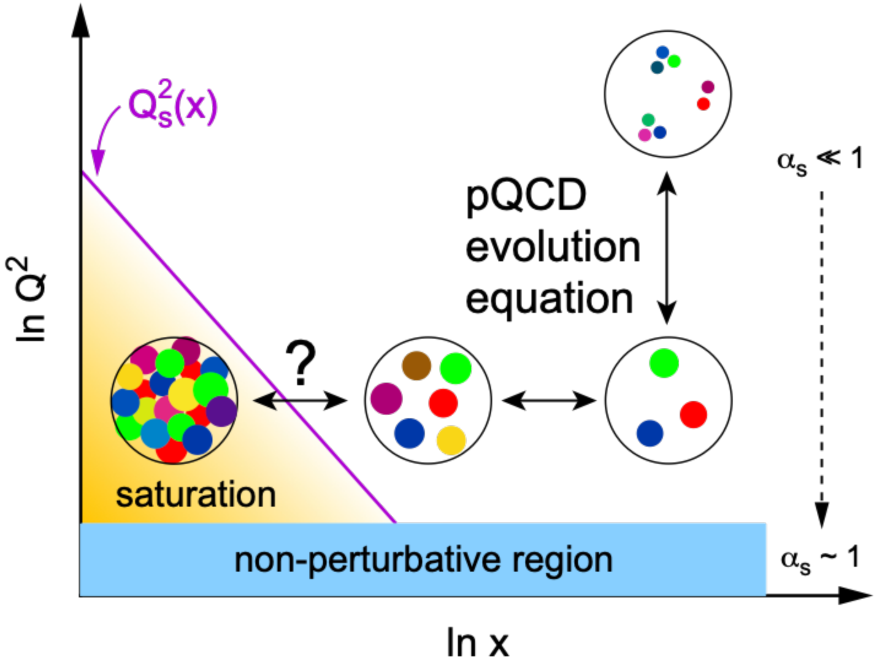




A big question: What happens going from a free nucleon to a nucleus?

One question, two perspectives

Color Glass Condensate (CGC)
Dipole-target scattering with small-x evolution equation + saturation scale Q_s



Gluon saturation

One question, two perspectives

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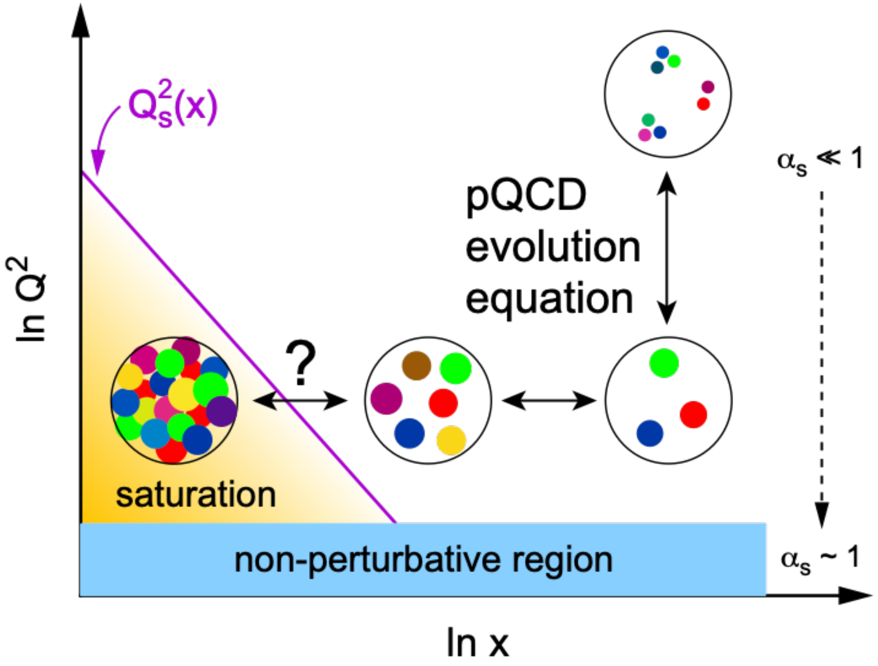
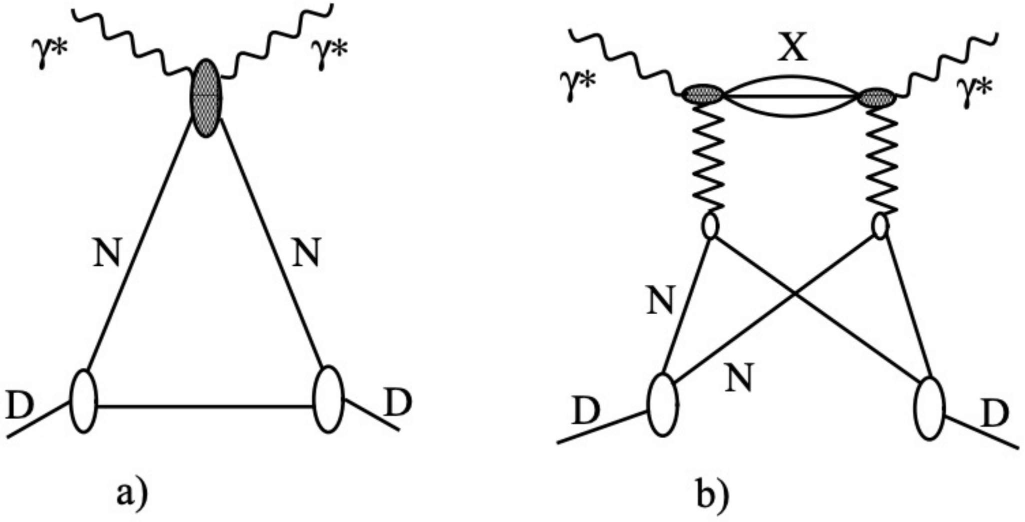


Gluon saturation

Leading Twist Approximation (LTA)
Combination of Gribov-Glauber theory, QCD factorization, and HERA diffractive data



L. Frankfrut,, V. Guzey, M. Strikman (Physics Reports 512 (2012) 255-393)

Nuclear shadowing

One question, two perspectives

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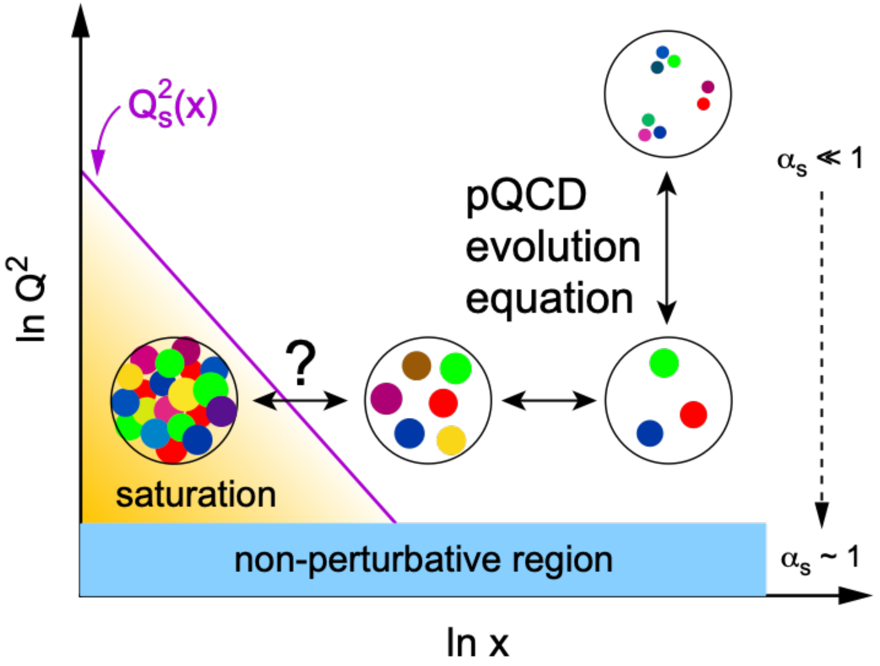

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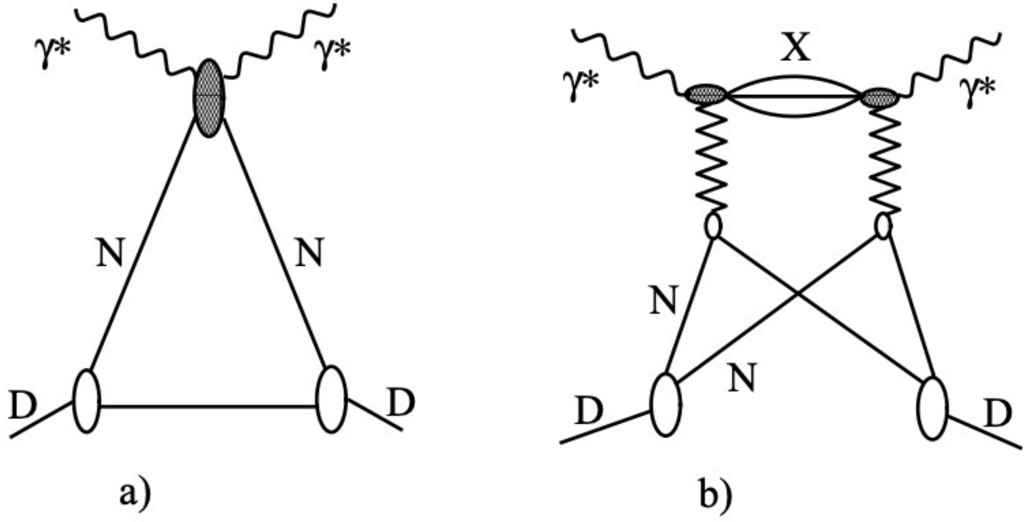

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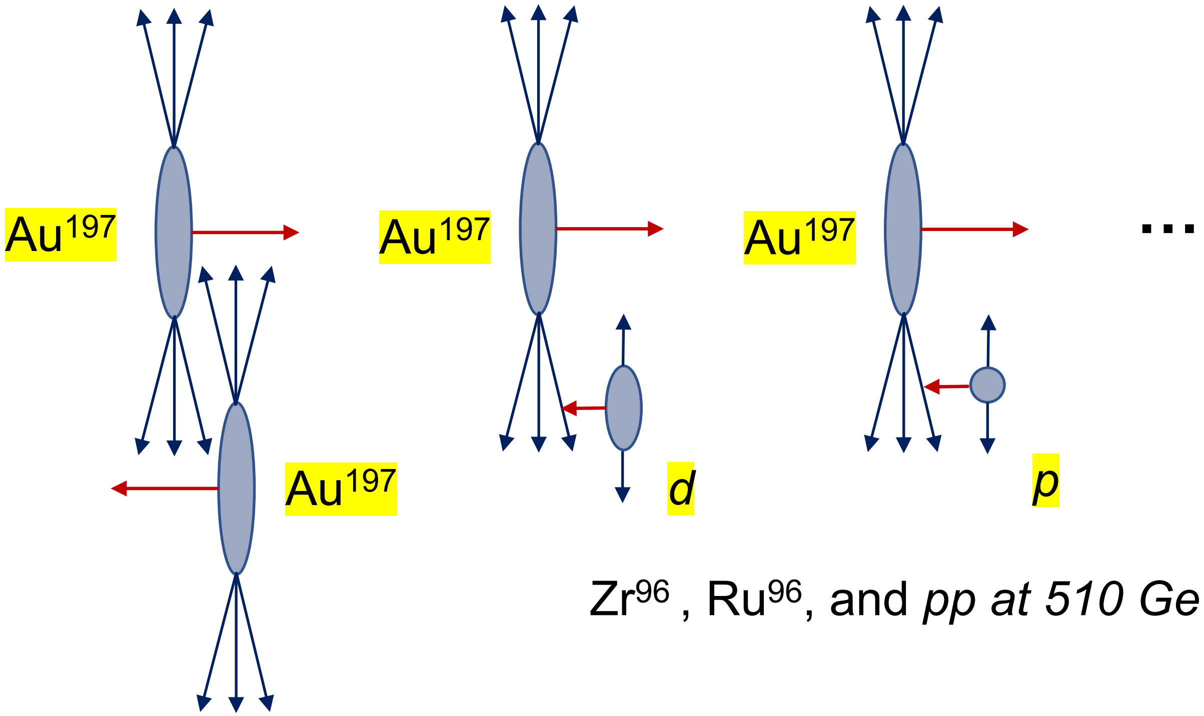
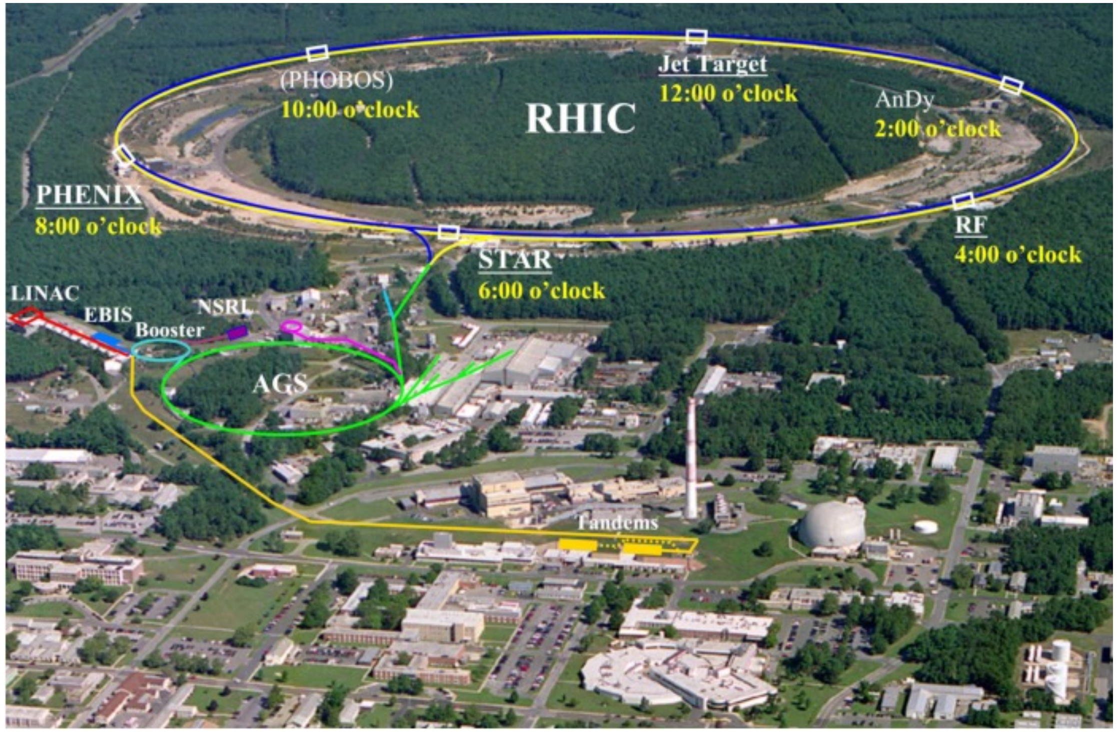
Nuclear shadowing

More different or more similar?

How to study the high-energy gluon dynamics



Zr[96] , Ru[96], and *pp at 510 GeV*



Ultra-Peripheral Collisions Program

Top RHIC energy of AuAu = 200 GeV

A very versatile program with different species, energy, and polarization.
Sensitive to a wide range of initial-state physics

Two approaches

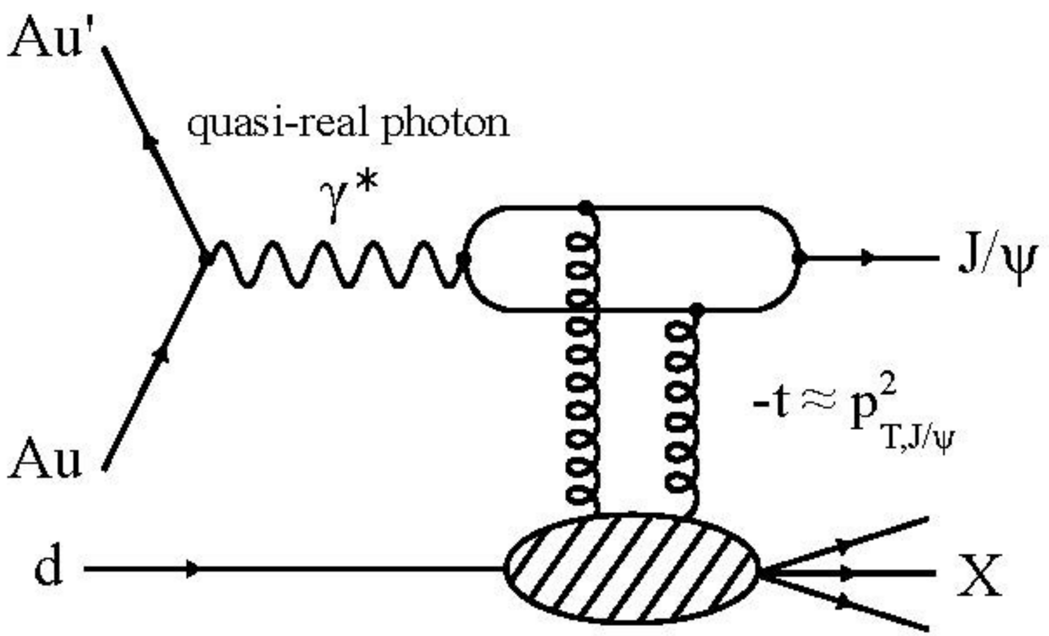
Experimental approaches for understanding the problem

1) Go to a simple nuclear system that (certainly) has neither *Saturation* nor *Shadowing* effect. Two models should converge.

2) Go to the largest nuclear system that has most *Saturation* and/or *Shadowing* effect but find an observable that separates them the most.

We learn from 1) similarities and 2) differences

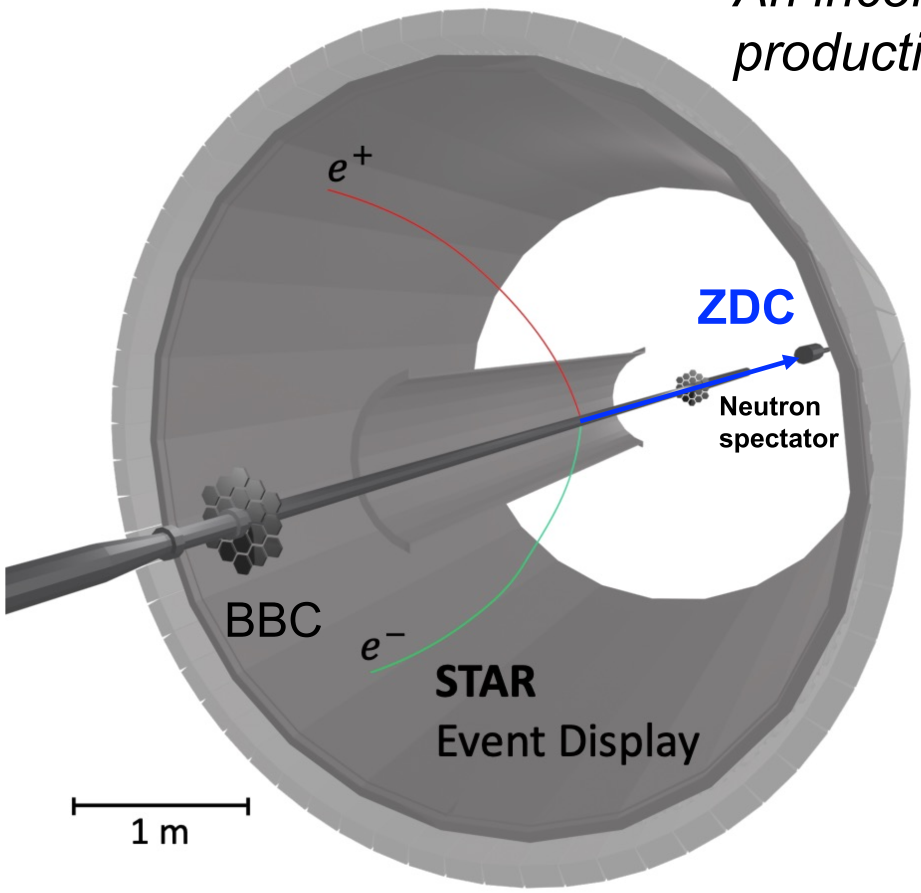
Approach 1). UPC J/ψ in deuteron



Trigger:

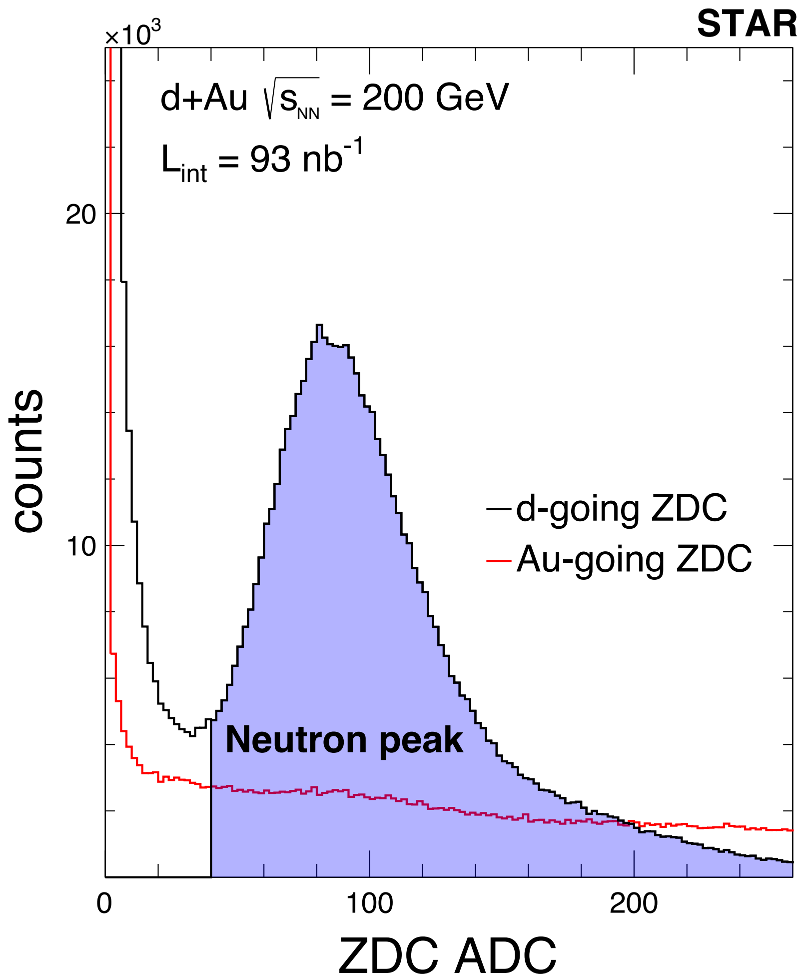
1. No ZDC requirement (this is important).
2. Back-to-back calorimeter tower trigger (BEMC).
3. Low event activity (multiplicities, BBC, etc..)

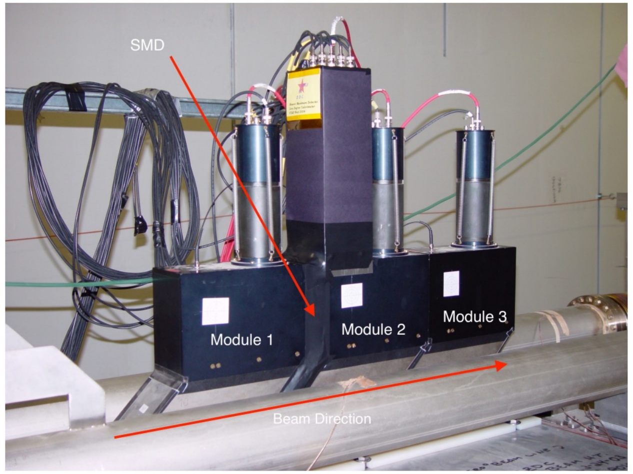
An incoherent J/ψ production event!



Using ZDC to detect nuclear breakup – tagging forward nucleon in exclusive events.

Approach 1). UPC J/ψ in deuteron





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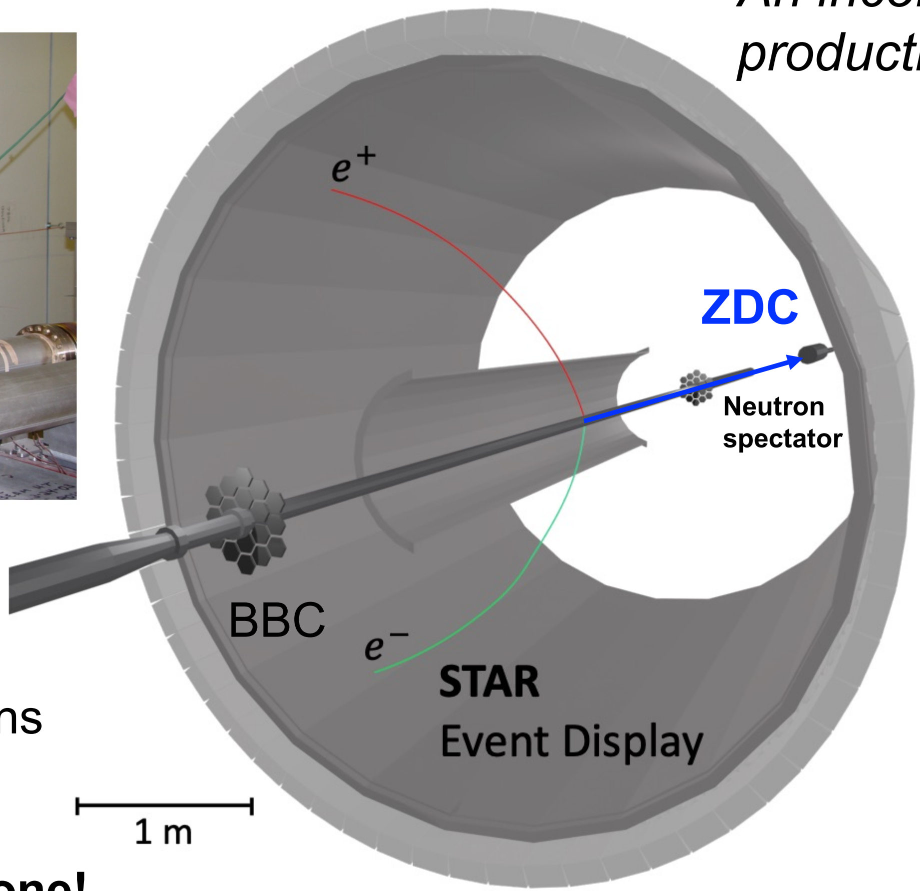


ZDC resolution can only separate up to 3-4 neutrons with large uncertainty.

Deuteron, there is only one!

Using ZDC to detect nuclear breakup – tagging forward nucleon in exclusive events.

No neutron from gold
→ photon-gold collisions very rare!

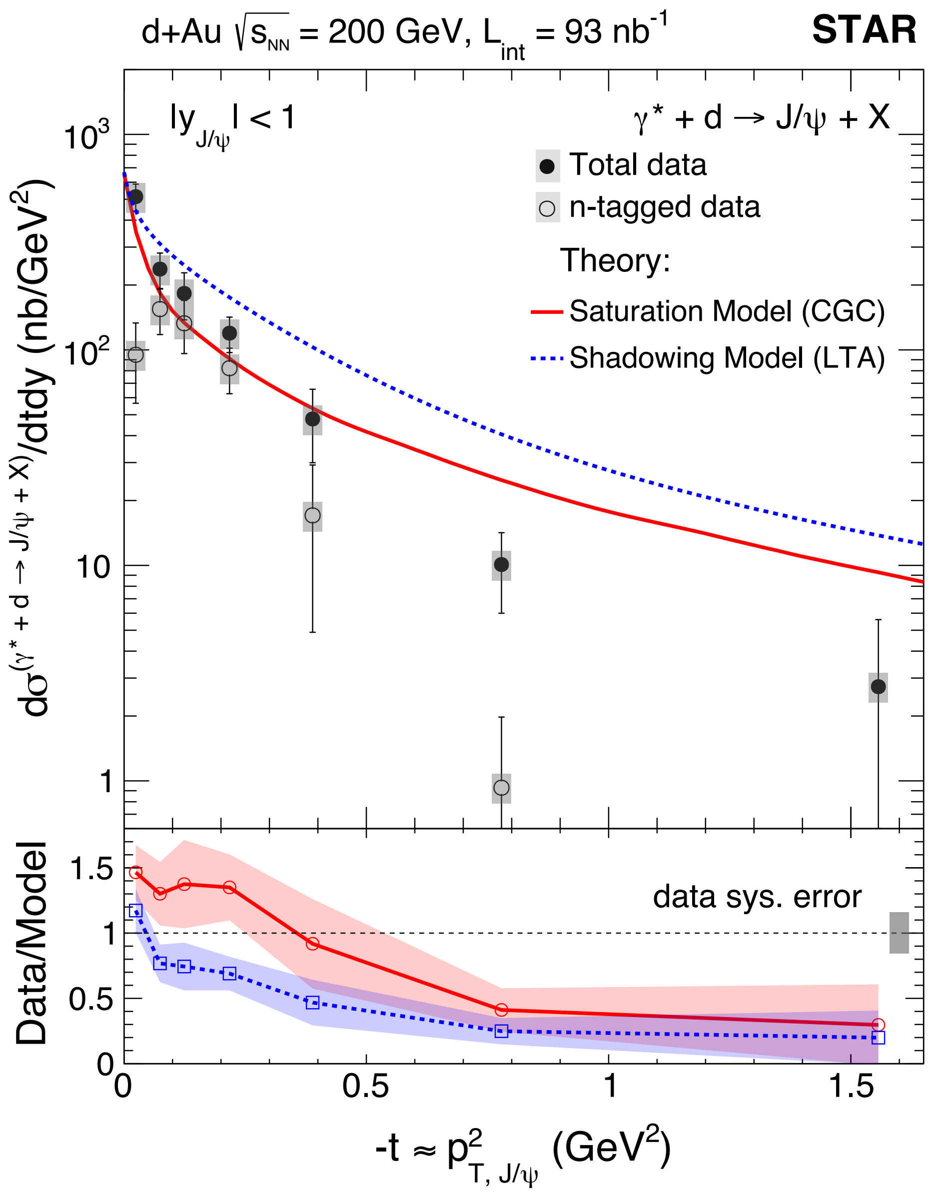
Results

- ✓ Correcting the photon flux from gold nucleus, reporting γd cross section.
- ✓ **Neutron-tagged data at low *-t*, expectation of incoherent deuteron breakup.**
- ✓ High *-t* is limited by ZDC acceptance. This shows the importance of the ZDC acceptance.

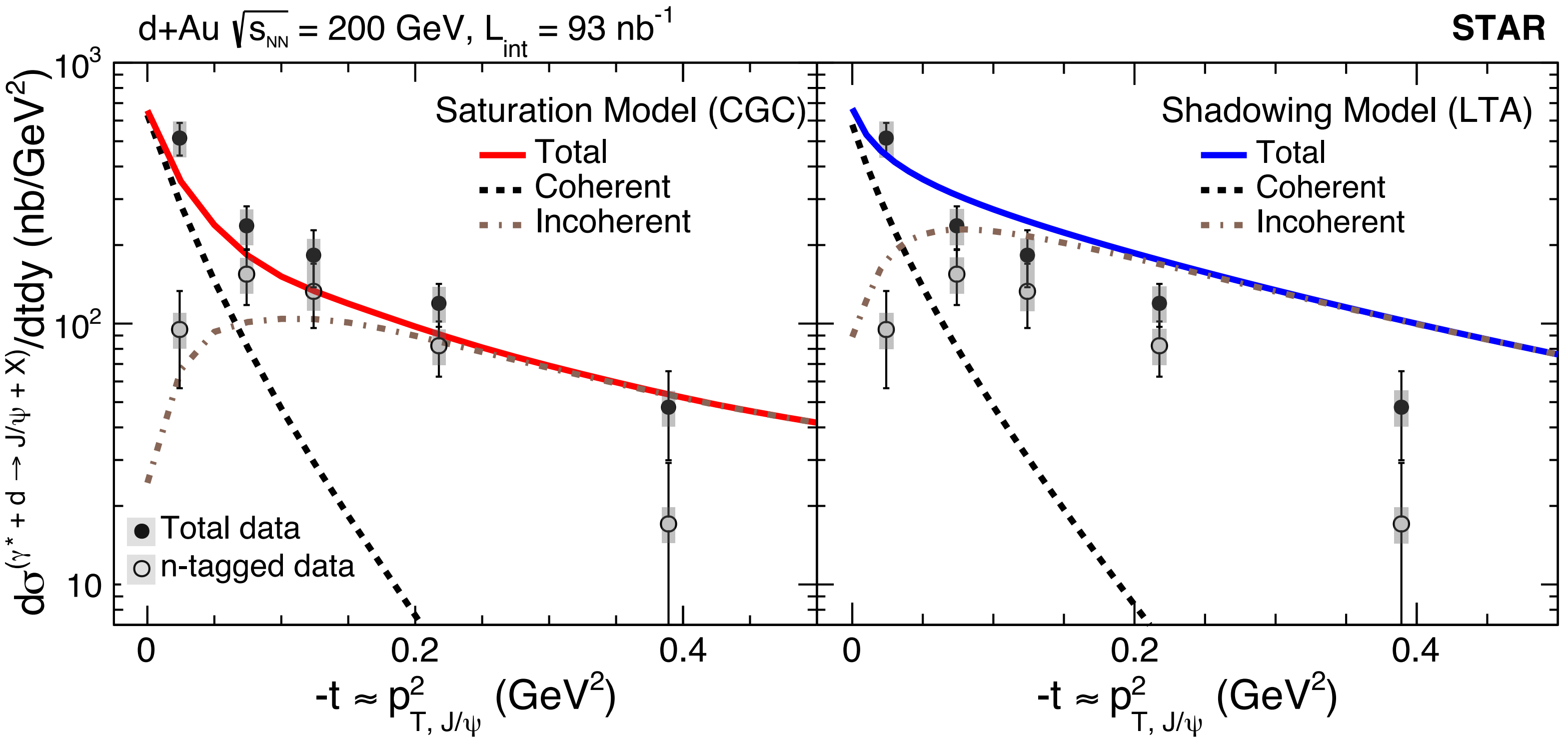
Model data comparison

- ✓ A good baseline system to test the CGC and LTA.
- ✓ Saturation model describes the data slightly better → Favors nucleon fluctuations in the CGC

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



Deuteron breakup



A breakdown view

Incoherent is the key!

- CGC and LTA uses the same ***d*** wavefunction – AV18, with nucleon/cross section fluctuations.

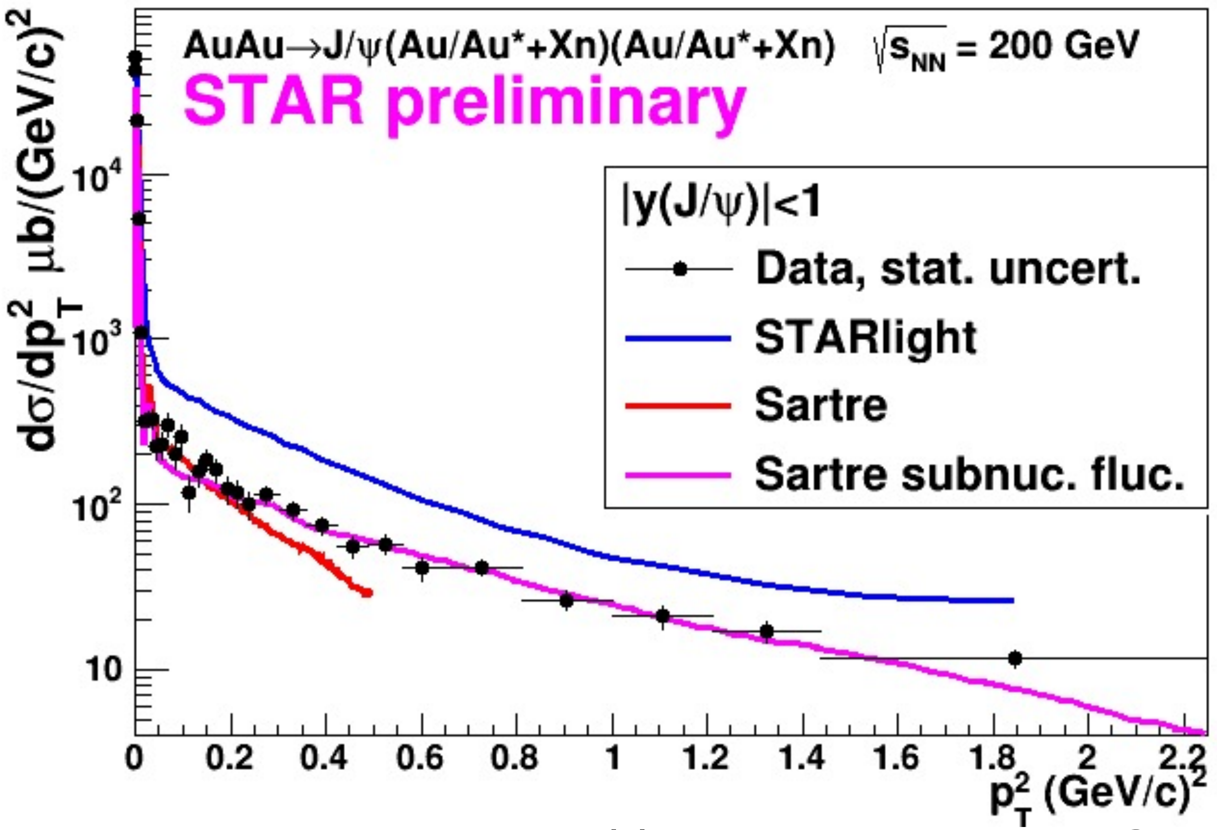
✓ **CGC has a smaller χ^2/dof**

A standing issue: why the two models differ by a lot?

Approach ~~2~~ 1.5). UPC J/ψ in gold

UPC J/ψ in AuAu at 200 GeV

- Kinematics: $W_{\gamma N}$ ~ 17-25 GeV, x ~ 0.01-0.03. Complementary to LHC
- Observation: distinctive coherent peak with long incoherent tail*.
- Sartre (saturation) with hot-spot fluctuations describe the data well.
- Shadowing? Will be available soon.

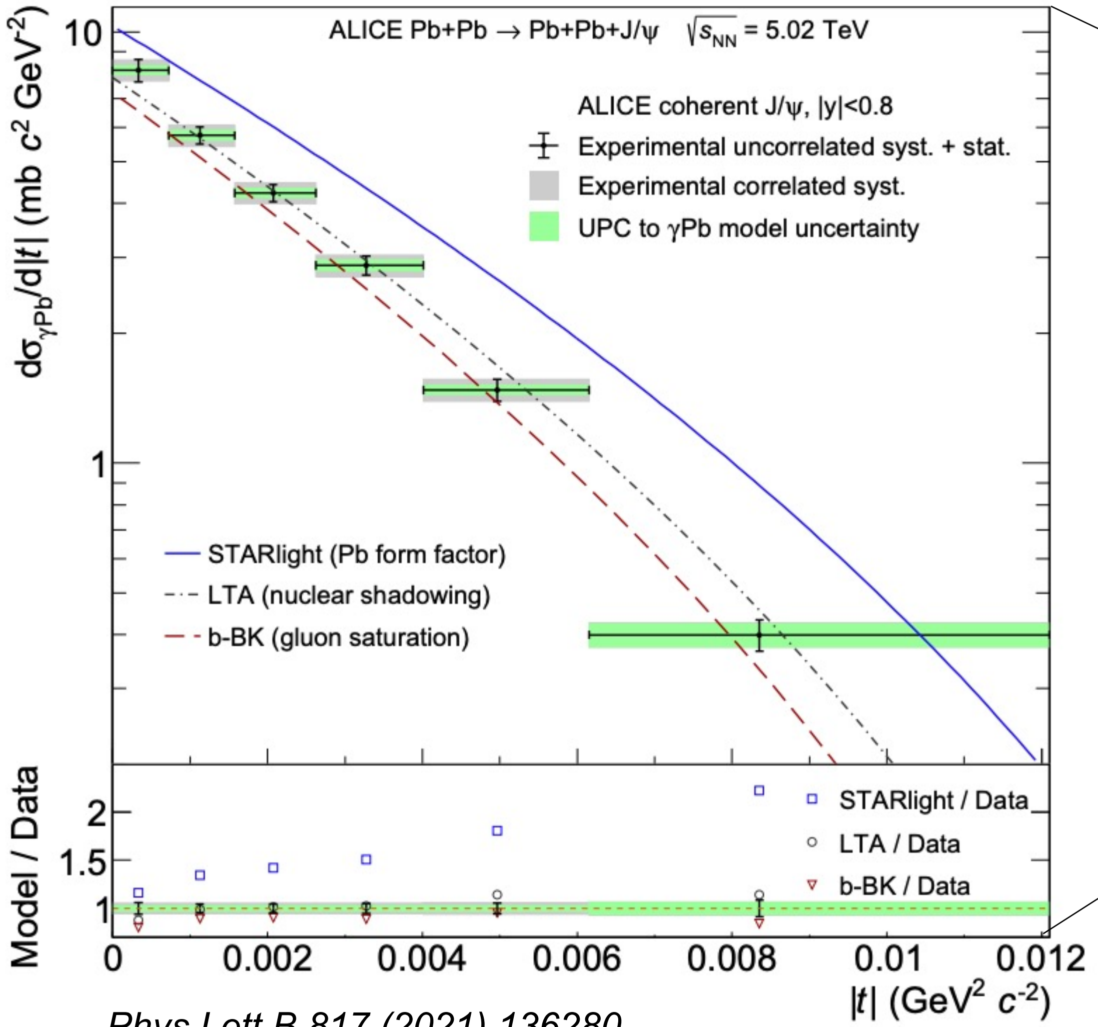


Measured incoherent |t| distribution up to 2 GeV^2

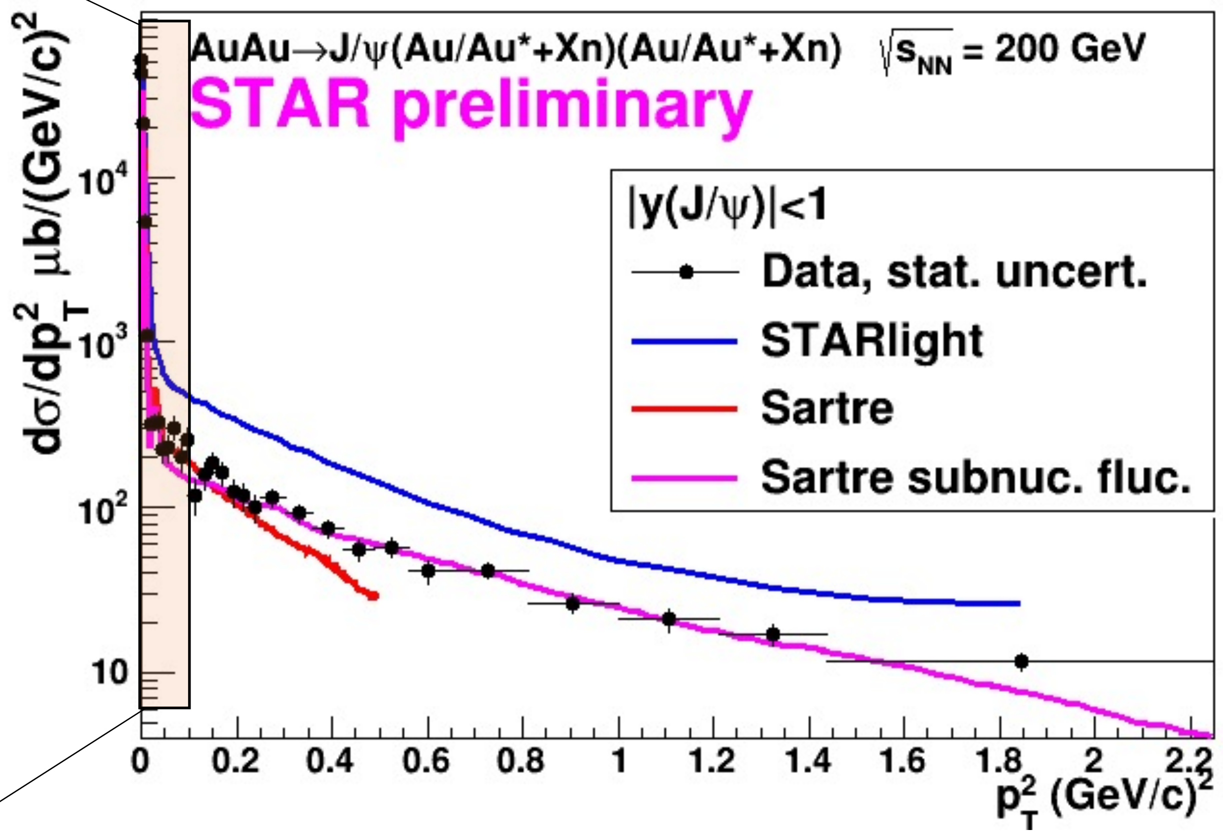
* the incoherent can be a much larger problem in heavy nucleus

Approach ~~2~~ 1.5). UPC J/ψ in gold

(Recap the ALICE result at 5 TeV PbPb)



Phys.Lett.B 817 (2021) 136280

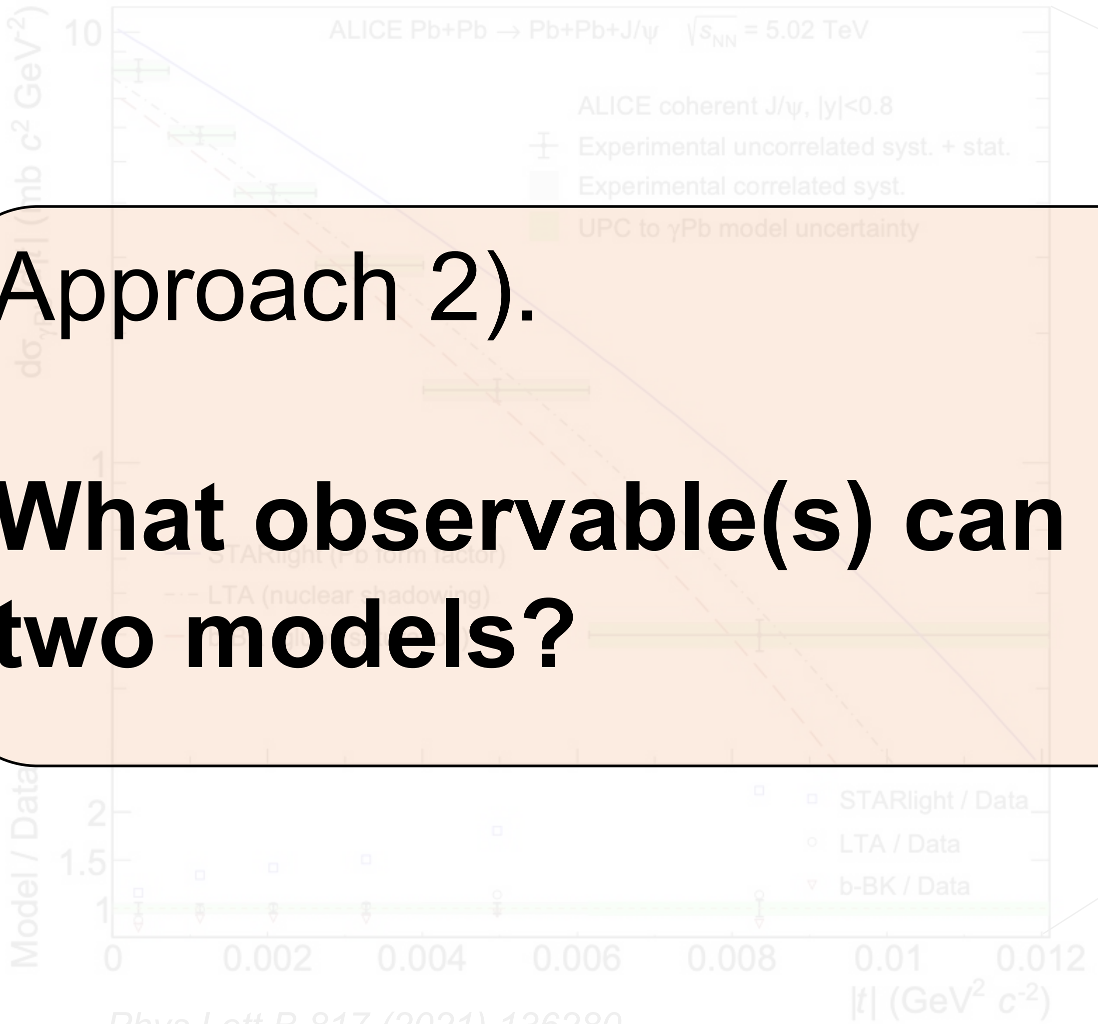


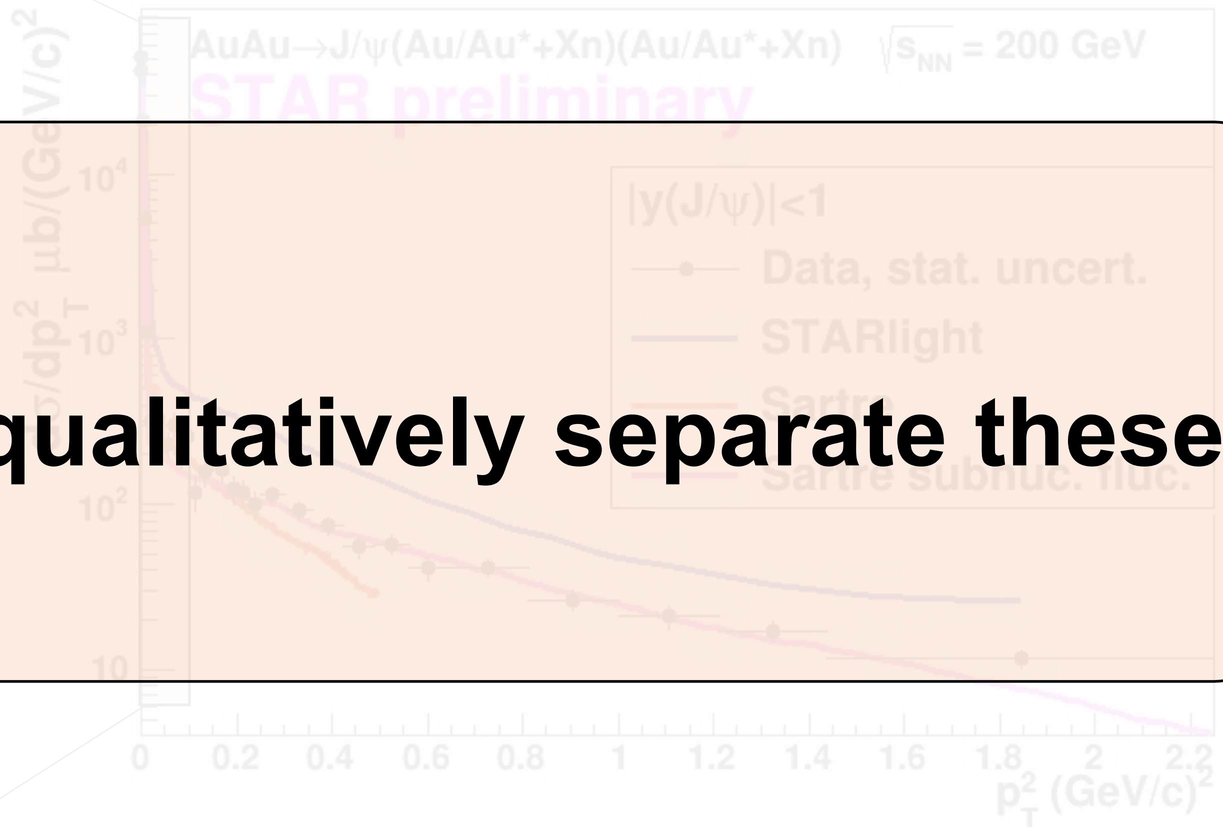
Both models capture the core physics

Separating coherent and incoherent - a big experimental challenge (See S. Klein's talk at EIC)

Approach ~~2~~ 1.5). UPC J/ψ in gold

(Recap the ALICE result at 5 TeV PbPb)





Approach 2).

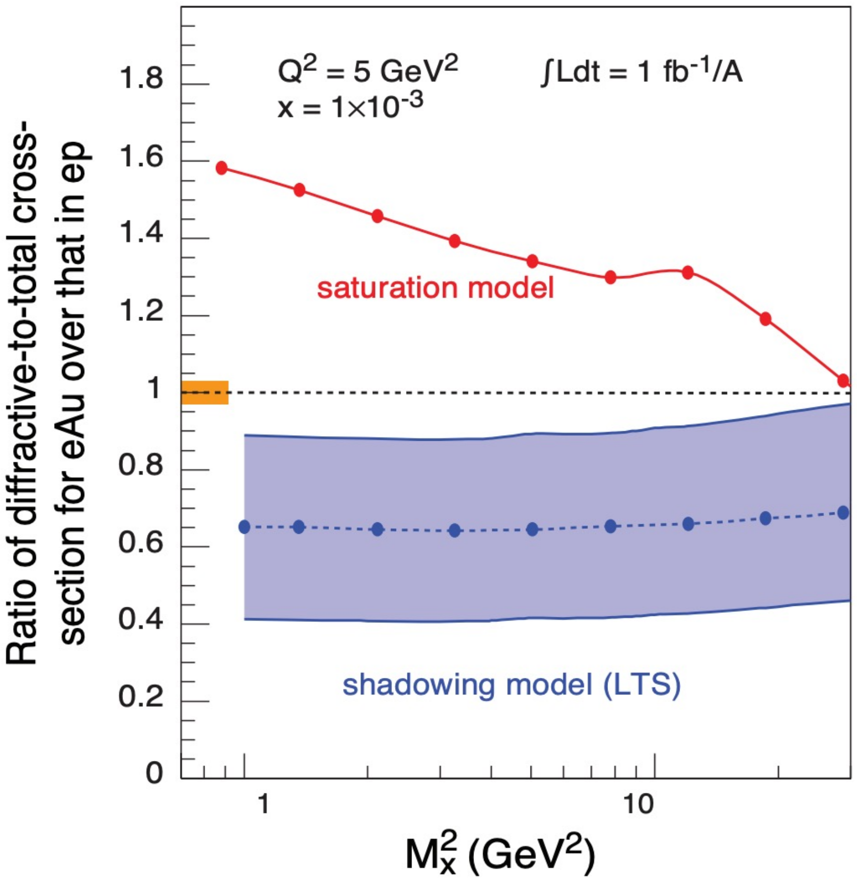
What observable(s) can qualitatively separate these two models?

Phys.Lett.B 817 (2021) 136280

Both models capture the core physics

Double ratio – an ultimate test?

EIC White Paper



DIS measurement

1. Saturation model:

$$\left[\frac{d\sigma_{\rm diff}/dM_x^2}{\sigma_{\rm tot}}\right]_{\rm eAu} > \left[\frac{d\sigma_{\rm diff}/dM_x^2}{\sigma_{\rm tot}}\right]_{\rm ep}$$

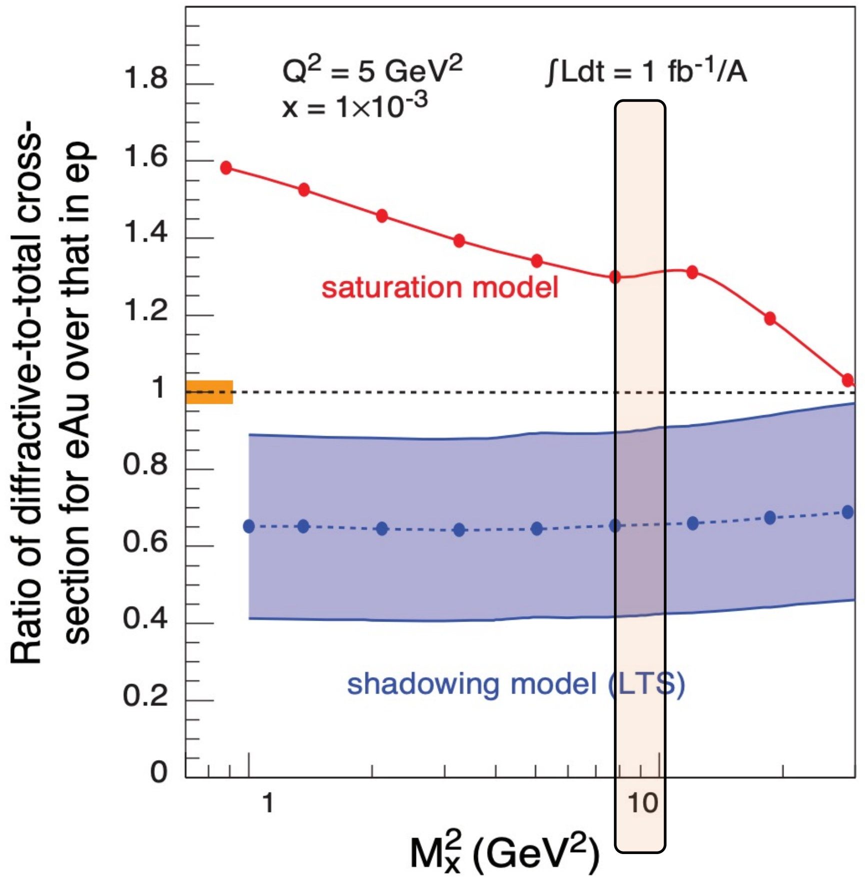
2. Shadowing model:

$$\left[\frac{d\sigma_{\rm diff}/dM_x^2}{\sigma_{\rm tot}}\right]_{\rm eAu} < \left[\frac{d\sigma_{\rm diff}/dM_x^2}{\sigma_{\rm tot}}\right]_{\rm ep}$$

Q^2 provides a hard scale → clear different expectation from the two models

Double ratio – an ultimate test?

EIC White Paper



A slice of phase space in M_x in photoproduction limit

Saturation

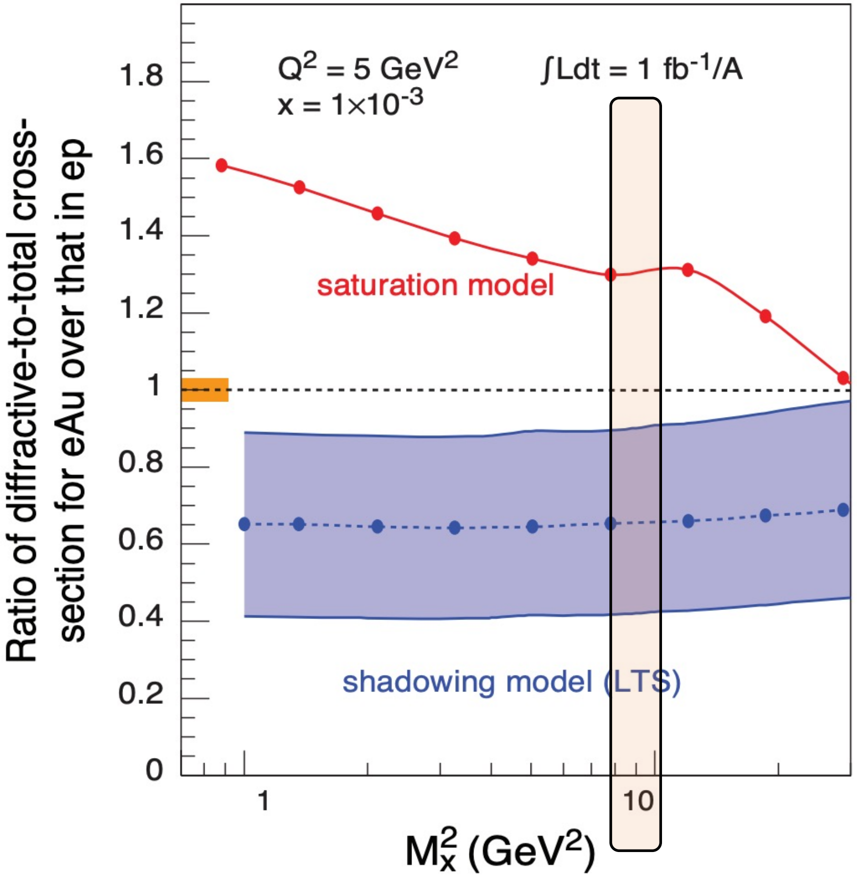
vs

Shadowing

Where is the hard scale?
Provided by J/ψ, e.g., charm quarks

Double ratio – an ultimate test?

EIC White Paper → **RHIC Upcoming runs 2023-2025**



A slice of phase space in M_x in photoproduction limit

Saturation

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Shadowing

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UPC photoprodution (photo-nucleus collisions)

Au+Au vs *p*+Au

$$\frac{\sigma^{\text{exclusive}}_{J/\psi} / \sigma^{\text{inclusive}}_{J/\psi}\Big|_{\text{Au}}}{\sigma^{\text{exclusive}}_{J/\psi} / \sigma^{\text{inclusive}}_{J/\psi}\Big|_{\text{p}}}$$

Model simulations in progress [ZT, 2022]

A potential ***qualitative*** different prediction for this double ratio!

Summary

- UPC VM program at RHIC has been extremely interesting towards understanding the nuclear gluonic structure – from light to heavy nucleus.
- **One big question, two perspectives (gluon saturation vs nuclear shadowing)**
  - Theoretical understandings are *greatly* needed towards incoherent production, nuclear breakups, and *cross validation/comparison among models*, etc.
  - Experimental approach needs to be more definitive and differentiative, e.g., double ratio of VM (J/psi) production.
- Many other physics and details were not shown, e.g., |t| distribution (a big topic), polarized proton target, etc.
- **Upcoming RHIC runs 2023-2025 (*p*+*p*, *p*+Au, and Au+Au) are exciting!**