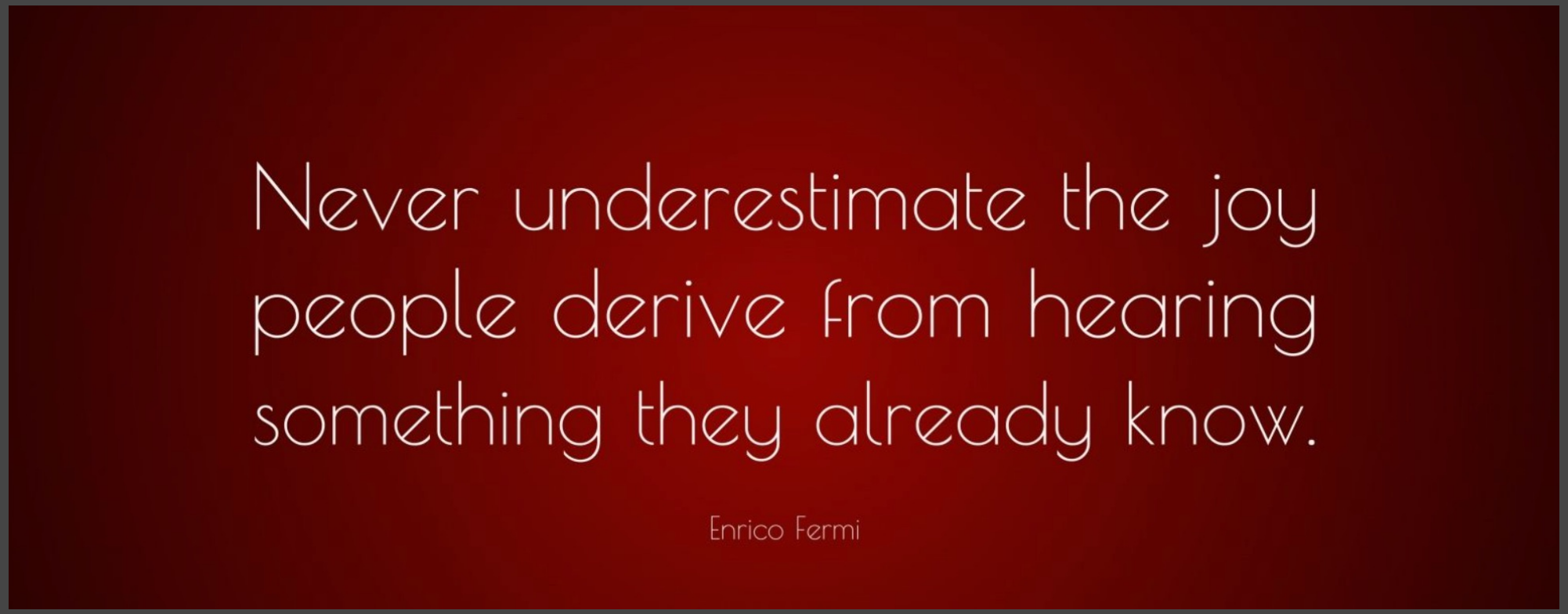
Parton structure and fluctuations in inclusive & exclusive reactions

Imaging the visible matter that binds us

Kong Tu
BNL

Last day of a 5-week workshop…

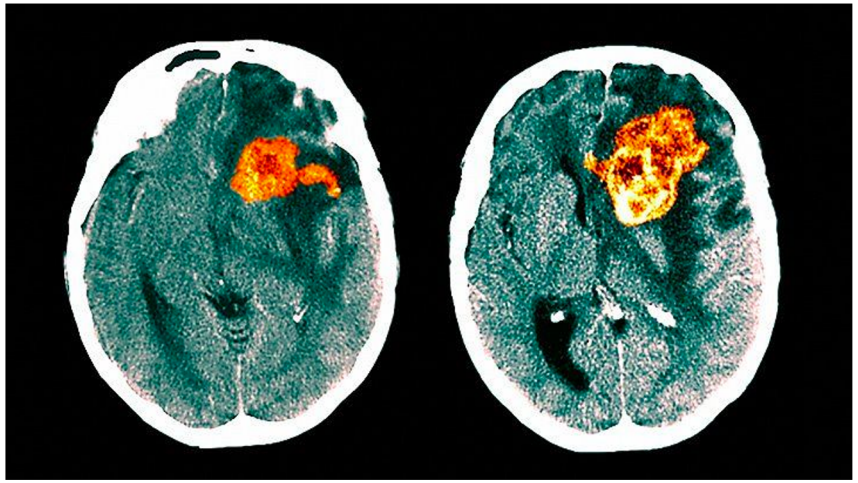


Seeing is believing

38 billion km (~10^{12}m)

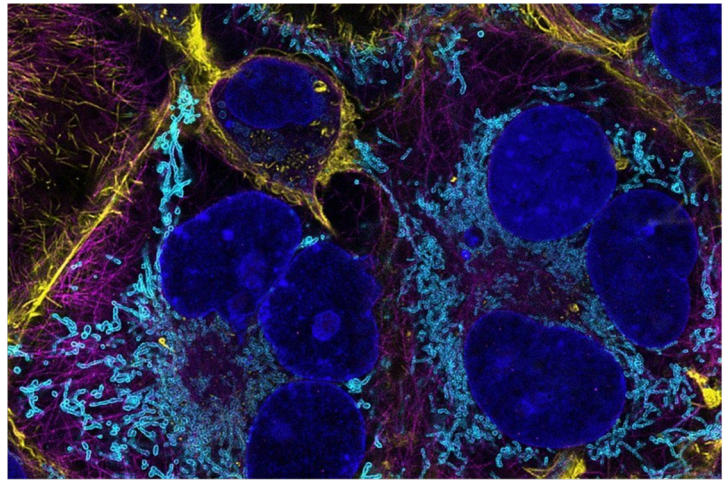
First-ever image of a black hole - *Event Horizon Telescope*

a few centimeter (~10^{-2} m)



CT scan sequence of a patient with a *glioblastoma*.

10-100 nanometer (~10^{-9} m)

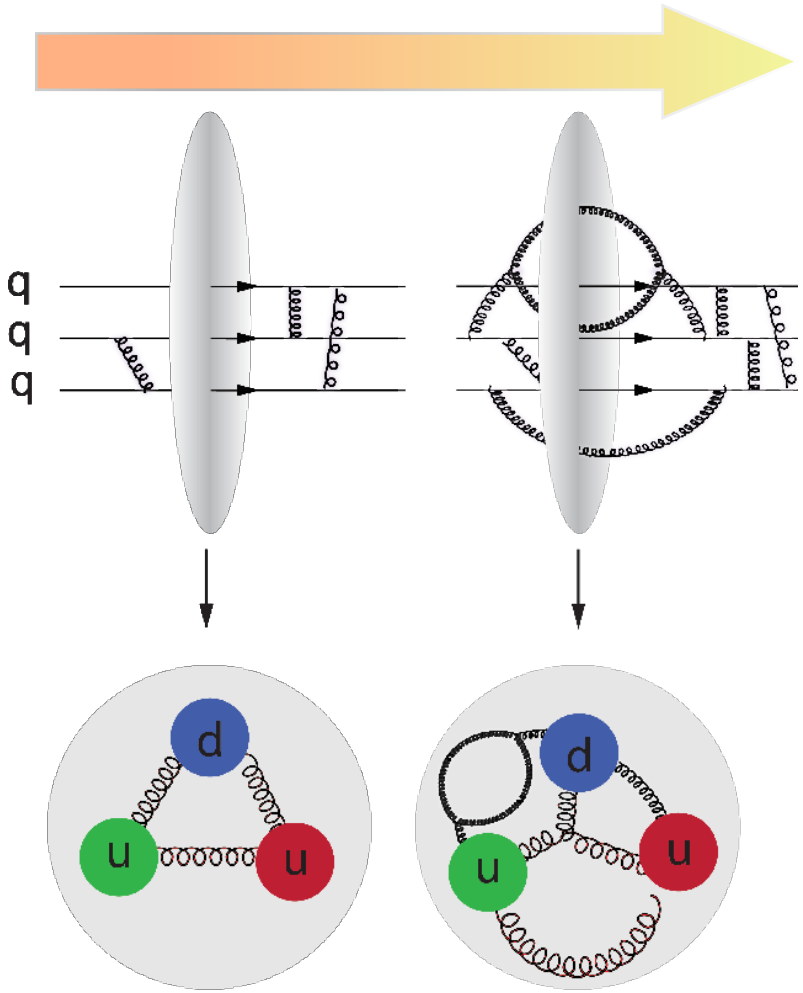


3D images of myelin - the insulation coating our nerve fibres

Astronomical scale → microscopic scale

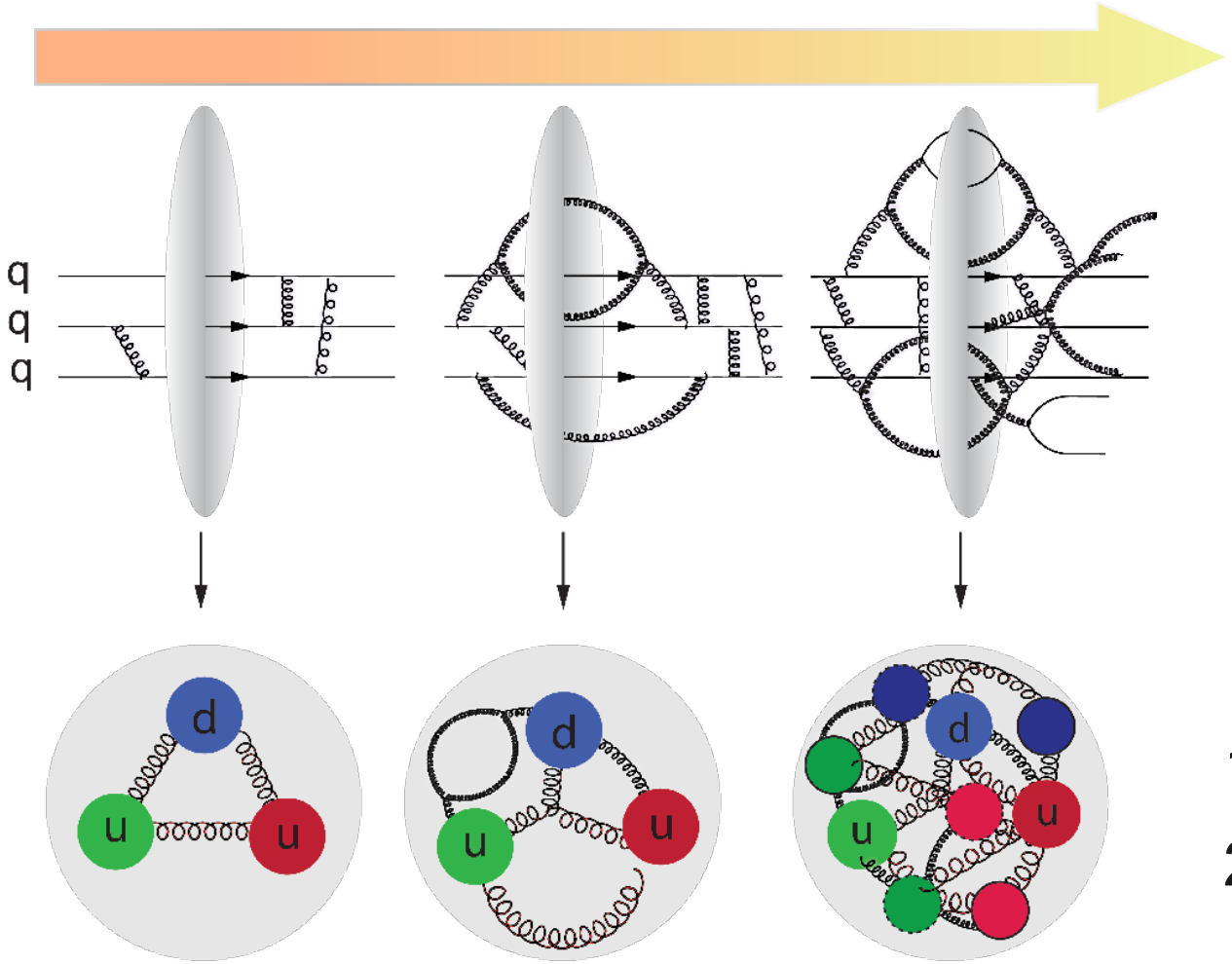
One of the most convincing scientific methods to understand our nature!

How to SEE the partons

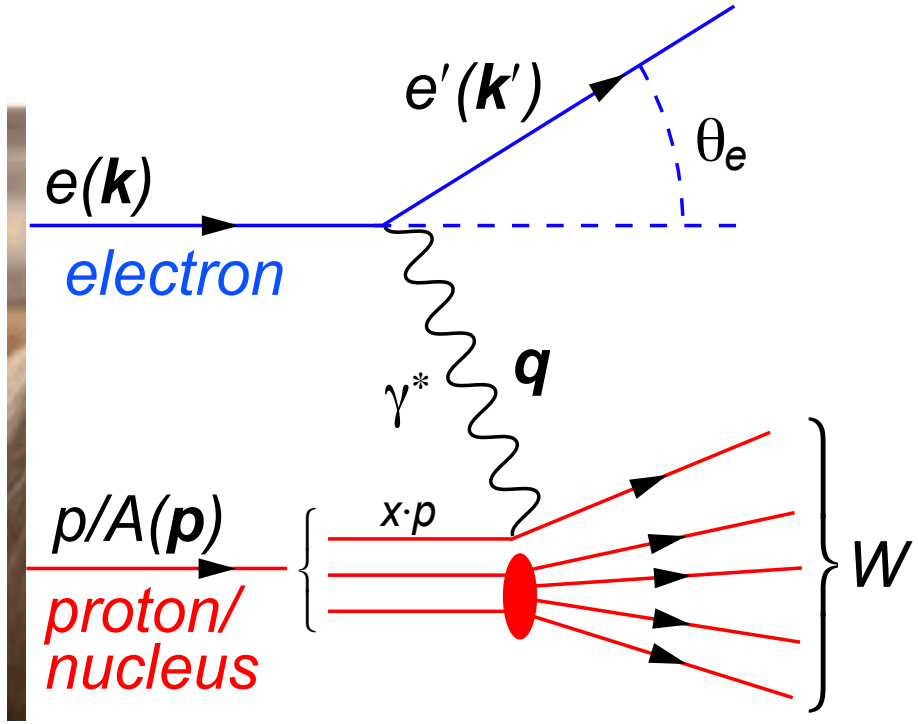


Speed or momentum

How to SEE the partons



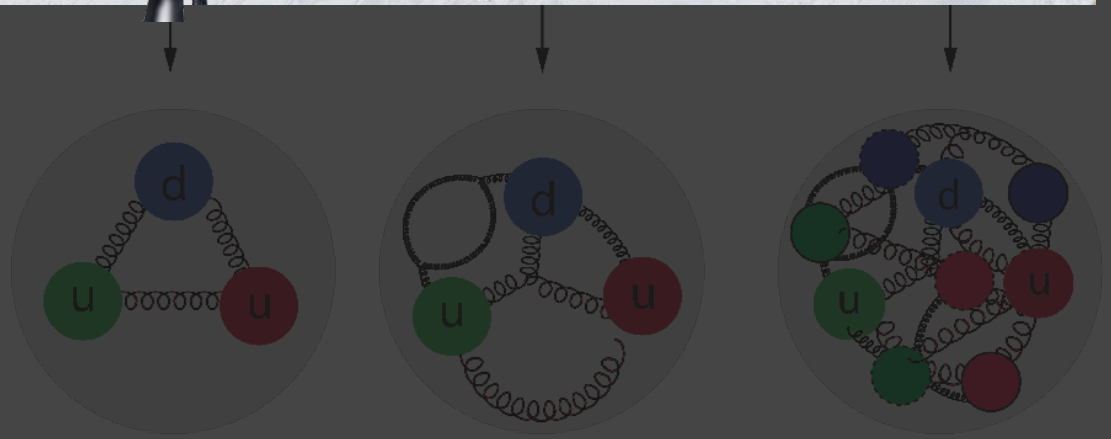
Deep Inelastic Scattering

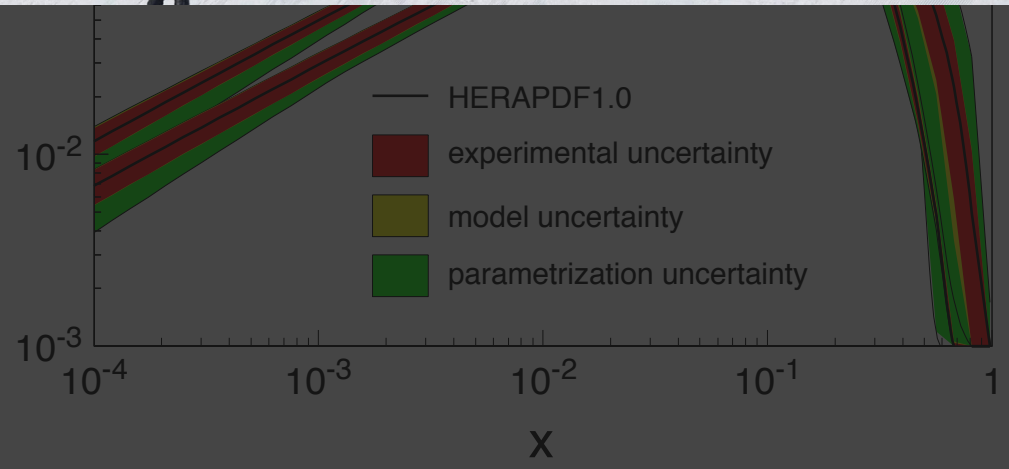


1. Resolution ~ $Q^2 = -q^2$
2. Momentum fraction ~ $x_{\mathrm{bj}} = \dfrac{Q^2}{2Pq}$

Lorentz time dilation

How to SEE the partons

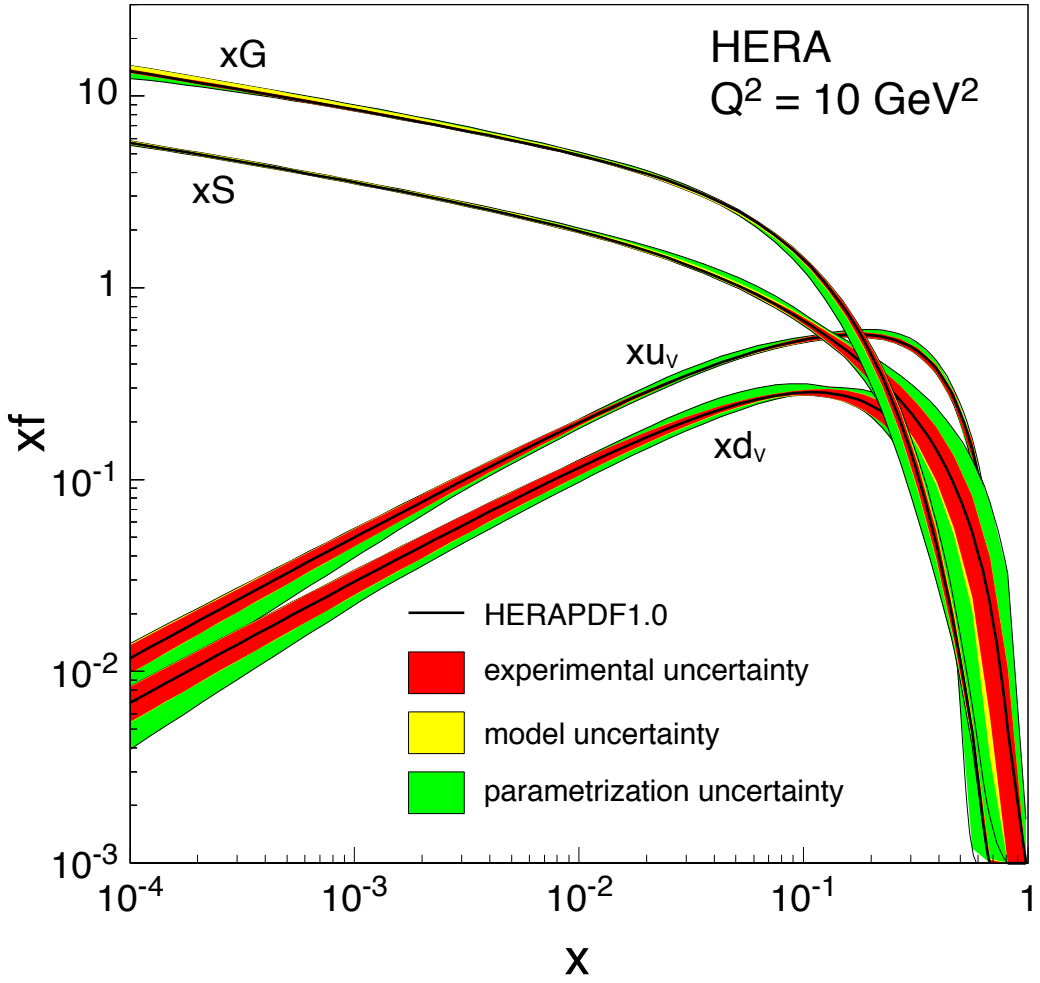




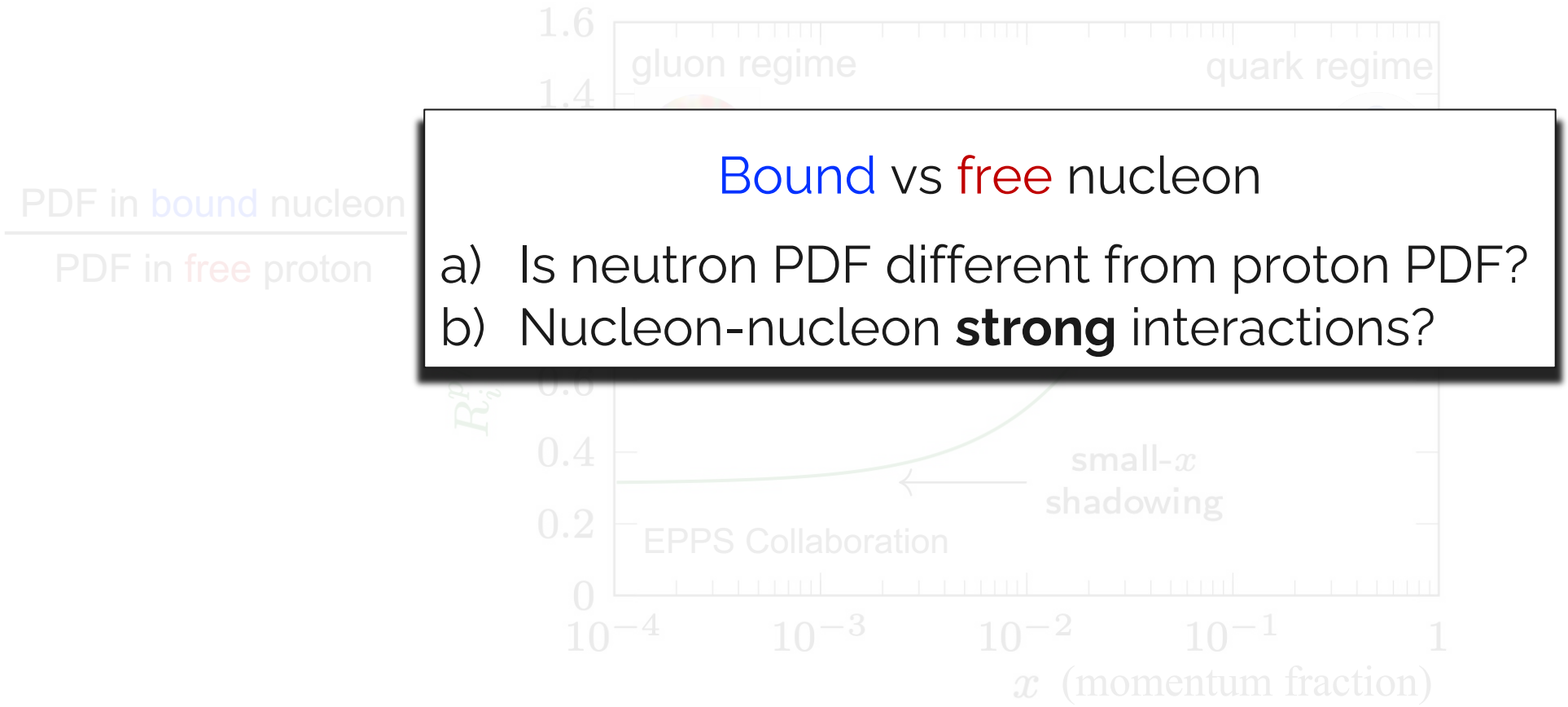
How to SEE the partons

HERA's precise data on free proton
What about nuclei?

Parton Distribution Functions (PDFs)



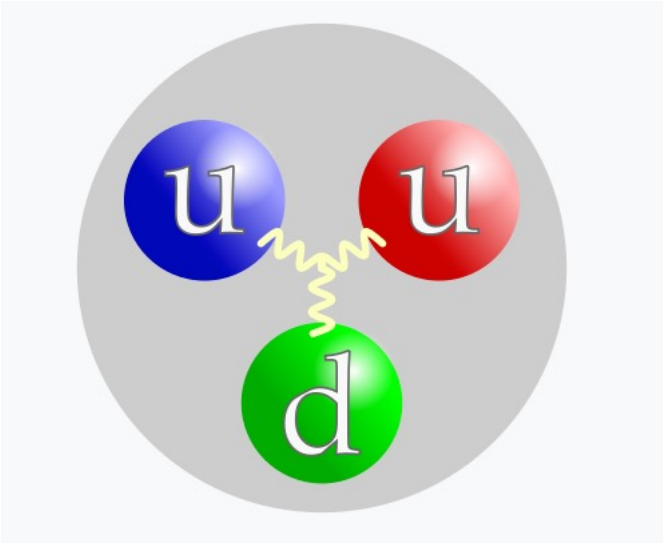
Parton structure in heavy nuclei



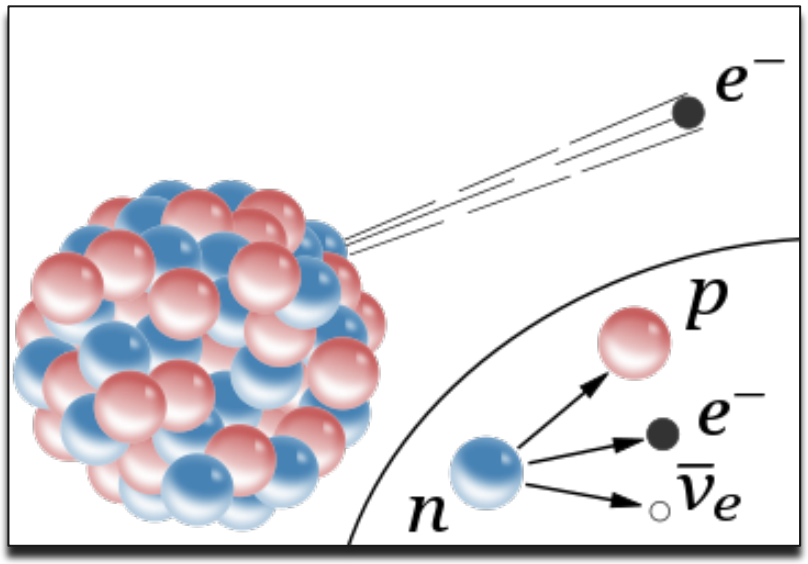
Bound vs free nucleon

a) Is neutron PDF different from proton PDF?
b) Nucleon-nucleon **strong** interactions?

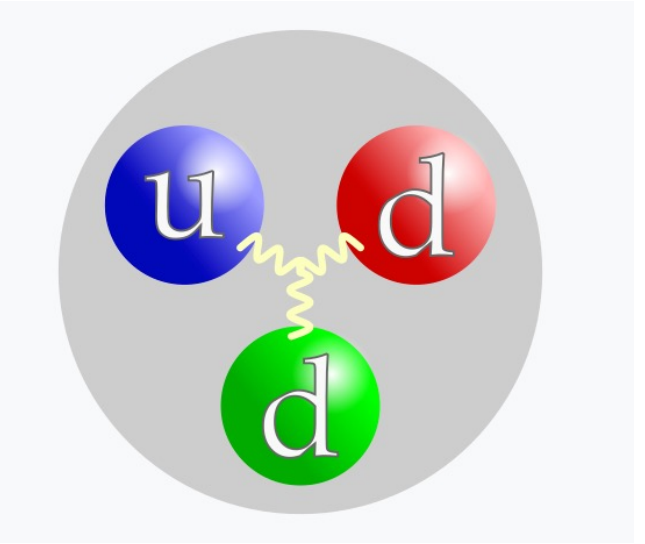
Neutron structure is difficult to measure



Proton **1e^-**
0.93827 GeV/c^2



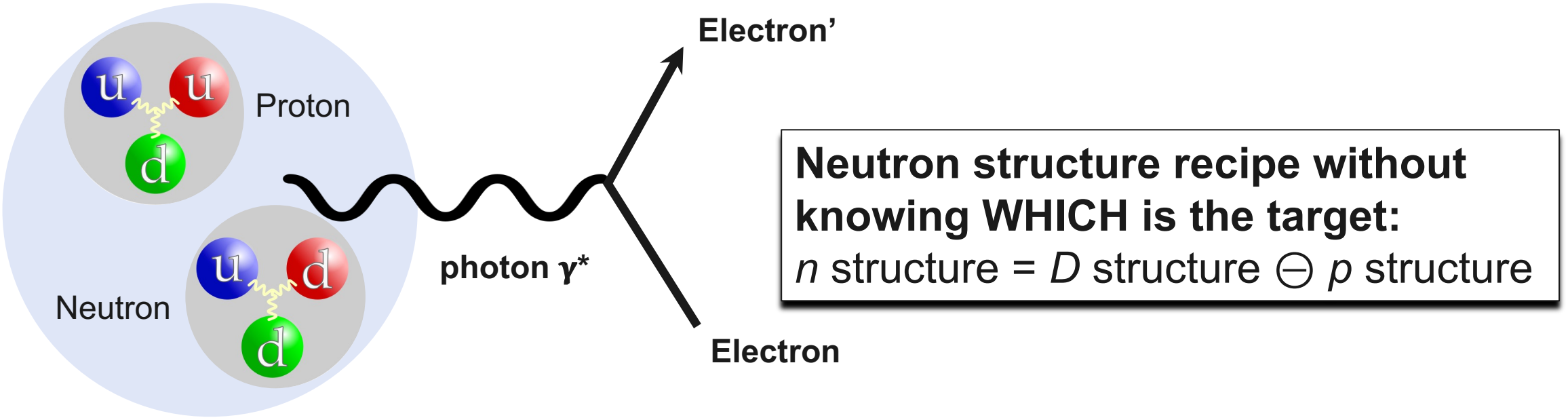
Beta decay
lifetime ~ 10 mins



Neutron **0e^-**
0.93957 GeV/c^2

How to study partonic structure of neutron?

Deuteron ~ proton + neutron

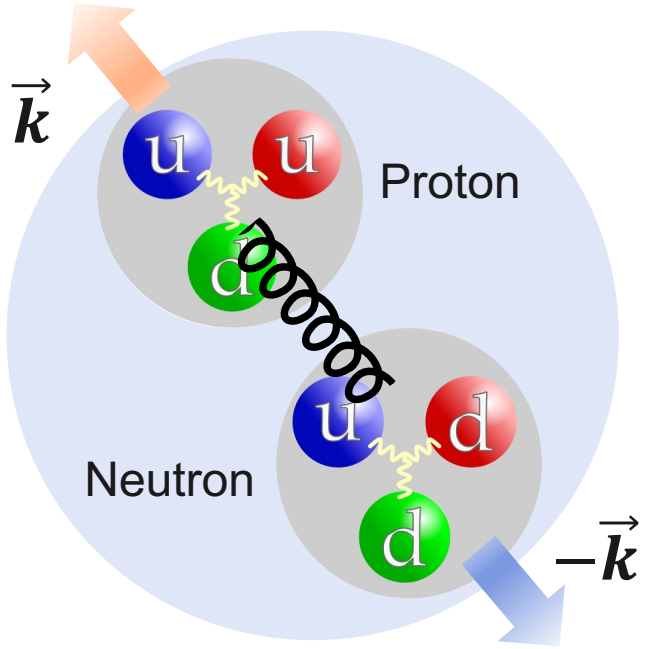


Neutron structure recipe without knowing WHICH is the target:
n structure = *D* structure ⊖ *p* structure

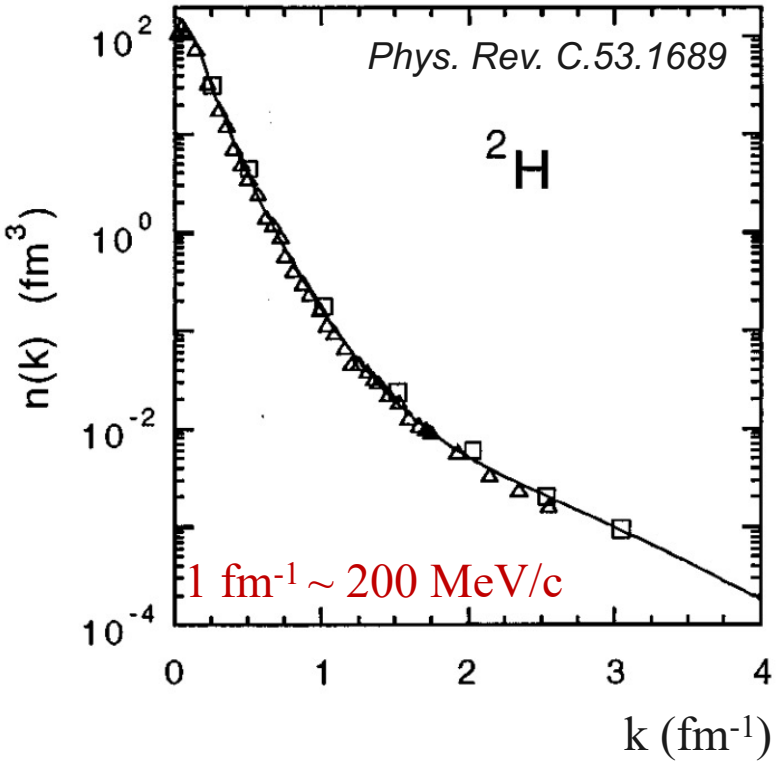
Deuteron
1.8756 GeV/c^2

What about proton-neutron interaction?

Deuteron ~ proton + neutron



Deuteron
1.8756 GeV/c²

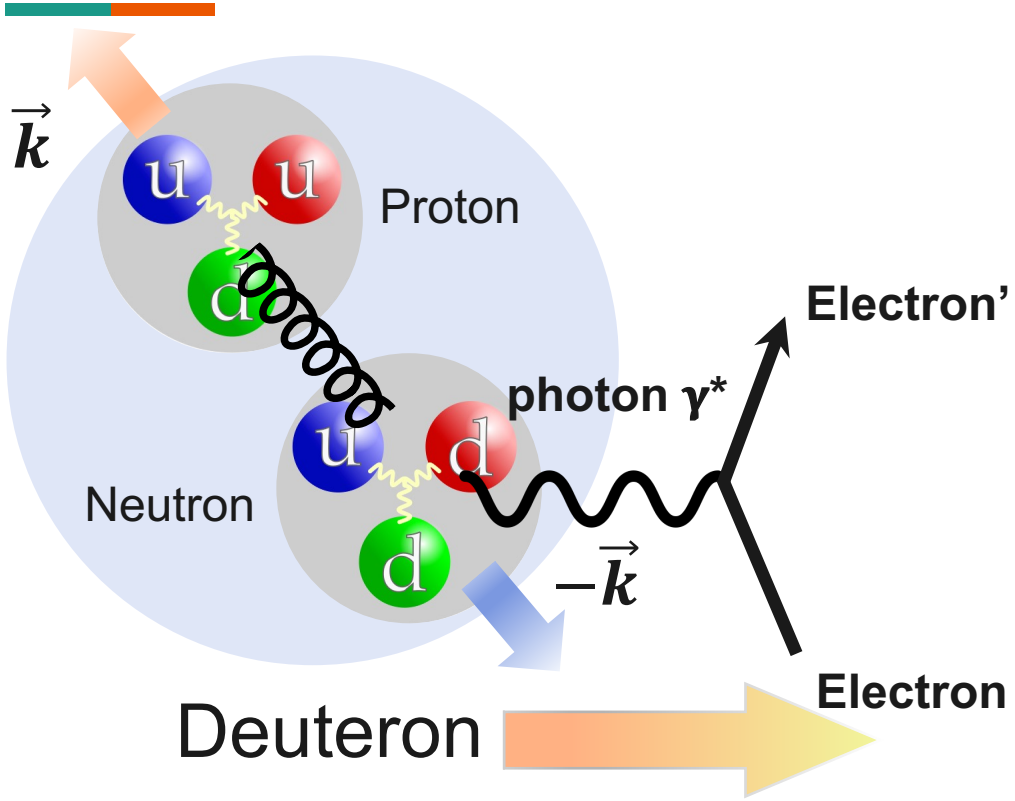


Neutron is not free

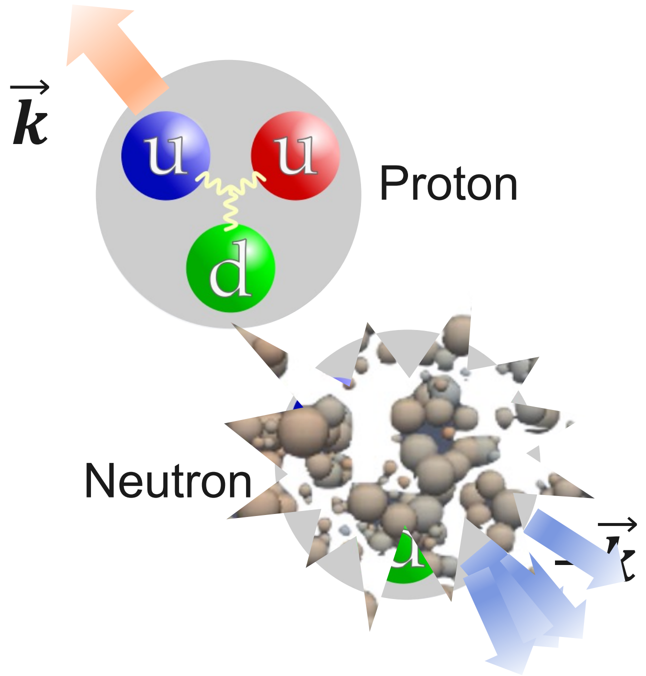
~~**Neutron structure Recipe:**~~
~~*n* structure = *D* structure ⊖ *p* structure~~

How to get to free neutron?

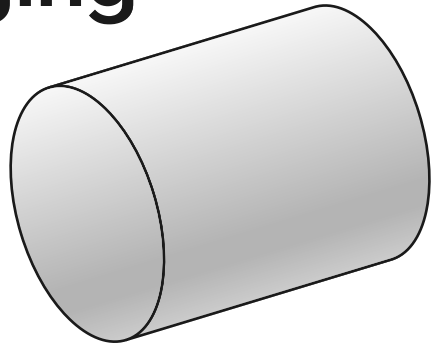
Game changer – EIC provides forward tagging



Game changer – EIC provides forward tagging

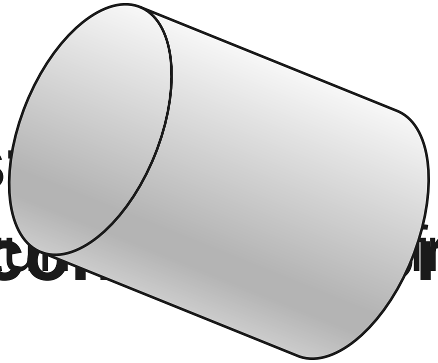


Spectator



Proton detector

Reconstruct momentum **p** + Lorentz Boost
= internal nucleon momemtum $\vec{\mathbf{k}}$



Active nucleon breaks up
But was with momentum $-\vec{\mathbf{k}}$

The beauty of collider kinematics:
Boost the detector measurement of zero momentum frame!

Fully recons…
initial-state co… in

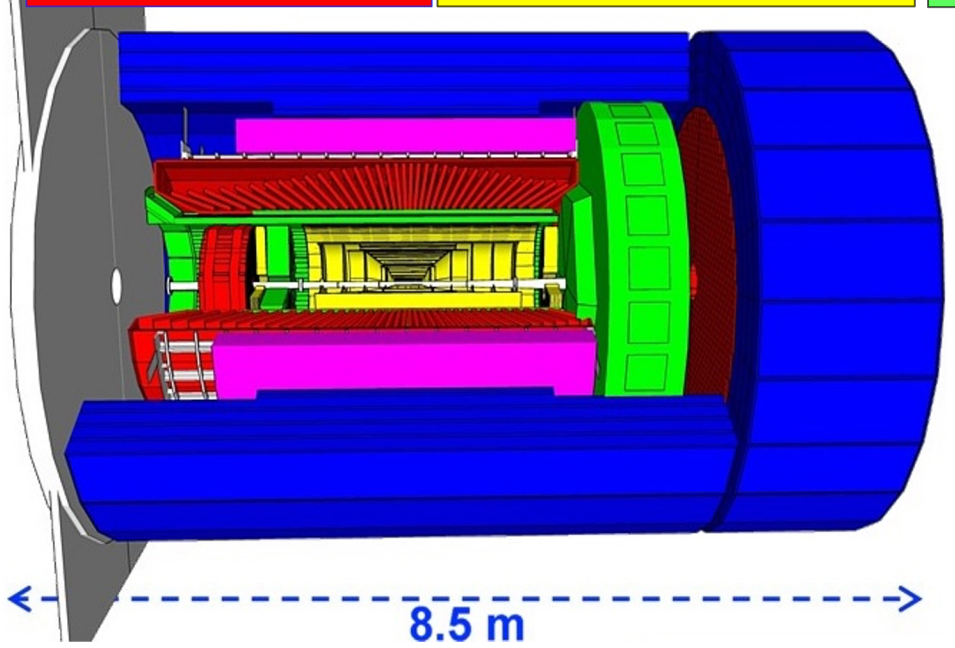
Neutron detector

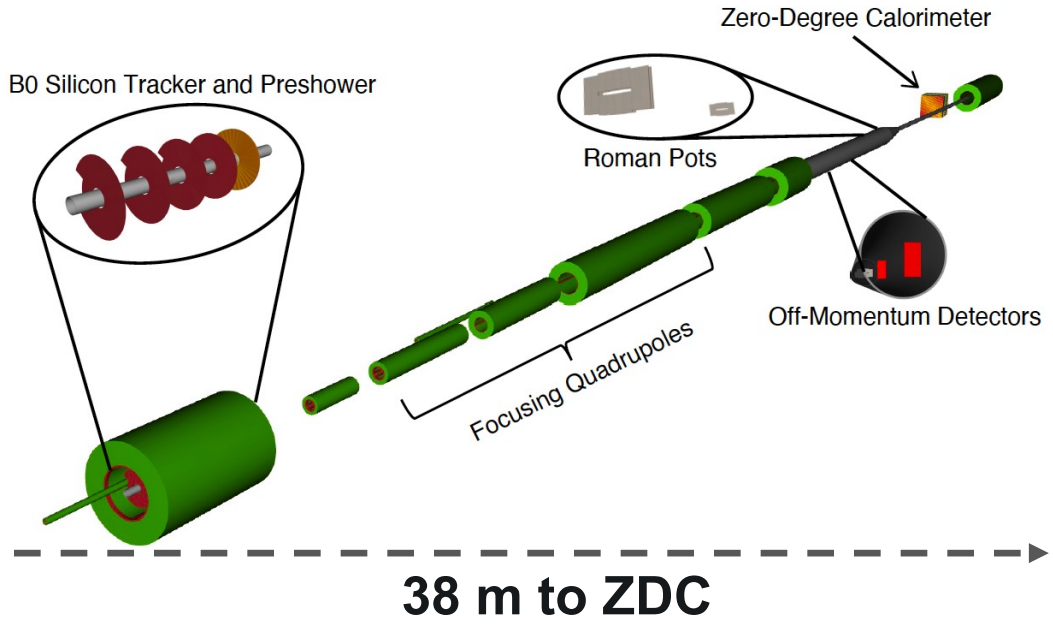
Measuring free neutron structure at EIC

hadronic calorimeters | solenoid coils | e/m calorimeters | MPG & MAPS trackers | ToF, DIRC, RICH detectors

EIC Far-Forward detector – indispensable to the **tagging** program

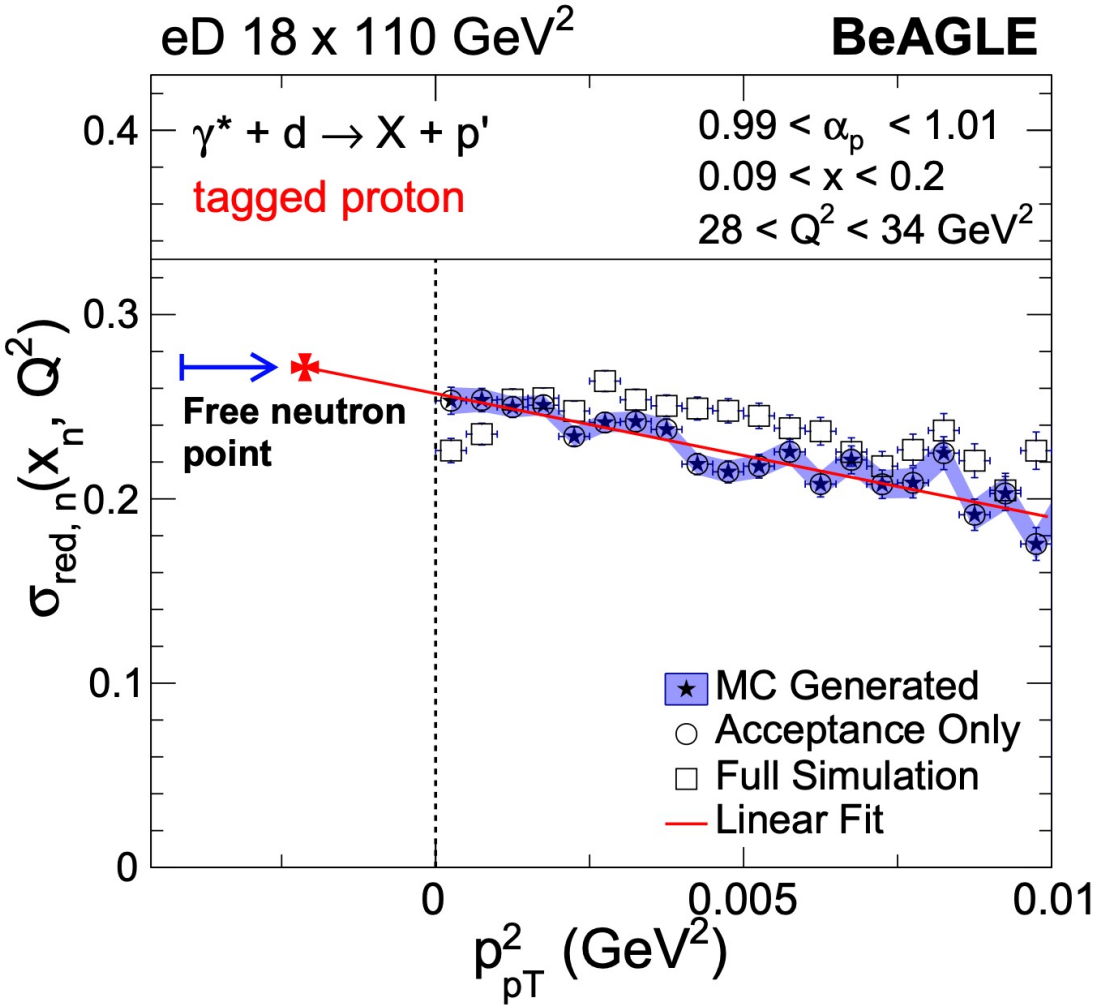
1.7 T solenoid magnet

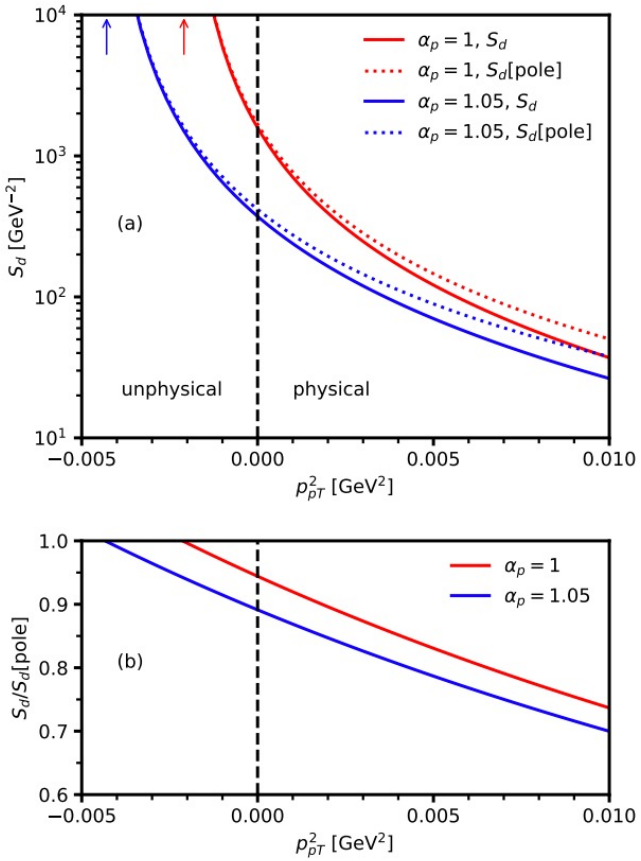


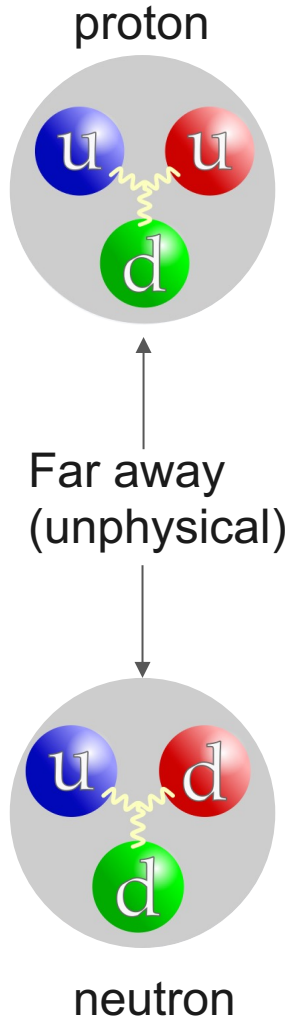


electron → **proton or nucleus**

Measuring free neutron structure at EIC

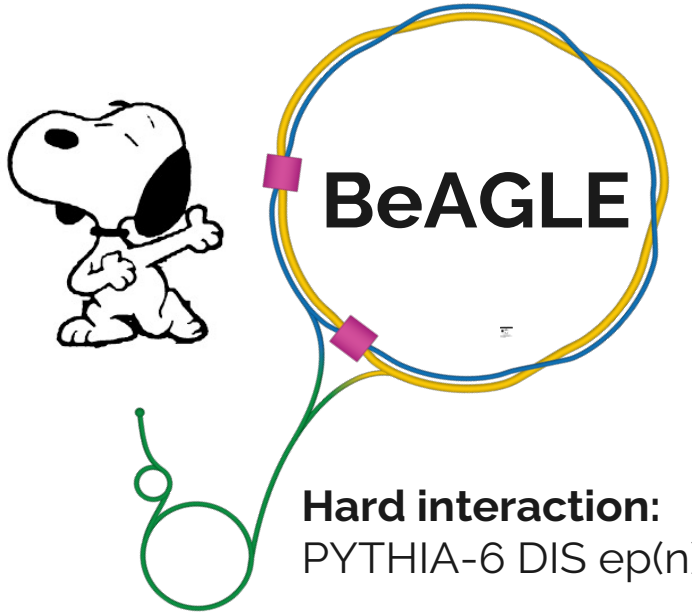






Measuring free neutron structure at EIC

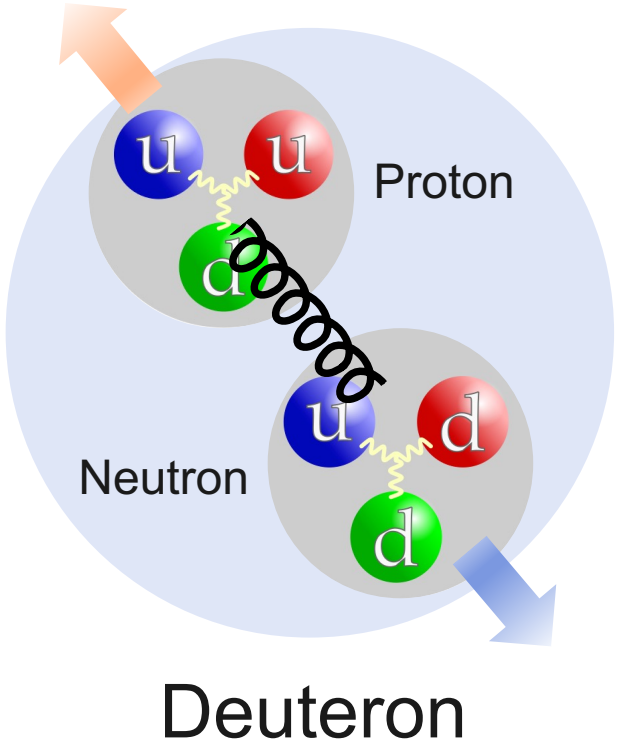
General-purpose eA DIS MC generator
https://eic.github.io/software/beagle.html

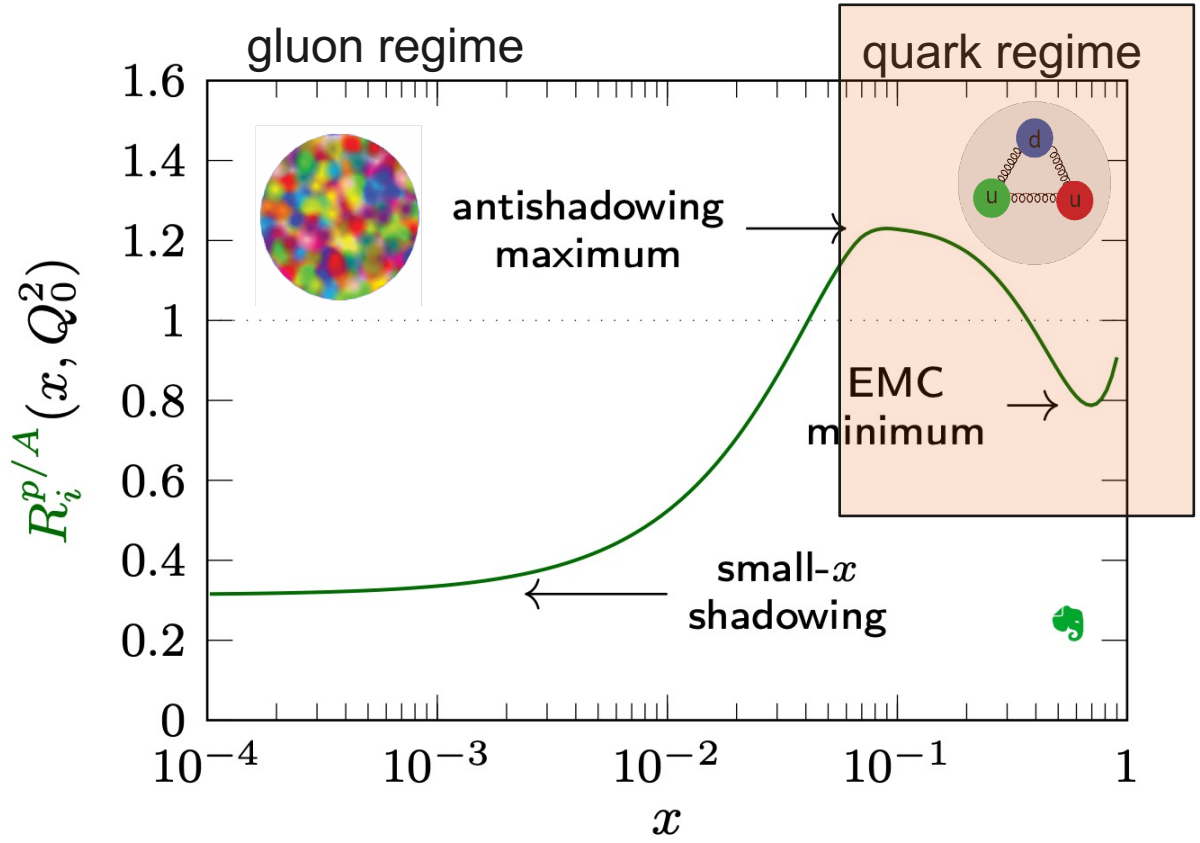


Hard interaction:
PYTHIA-6 DIS ep(n) + nPDFs

Recent comprehensive overview of BeAGLE,
(Phys. Rev. D 106 (2022) 1, 012007)
co-PIs: M. Baker, **ZT***

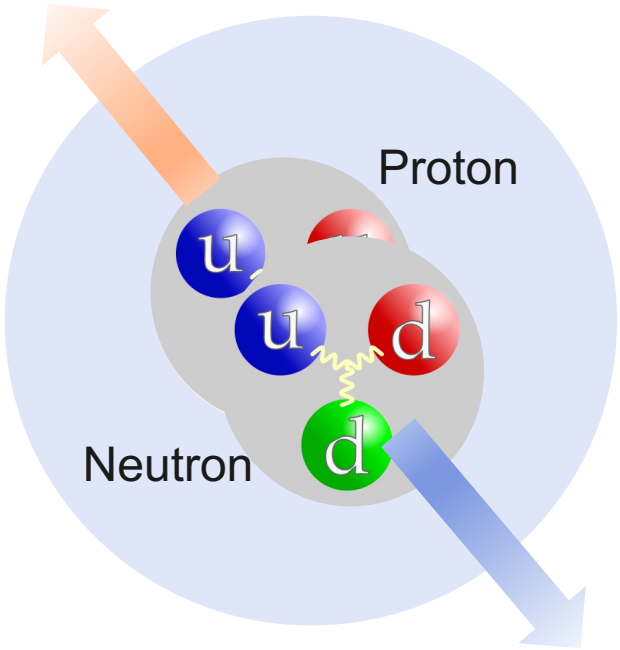
Two sides of the same coin: Strong NN interaction





Does nucleon internal momentum correlate with the quark modification?

Universality?

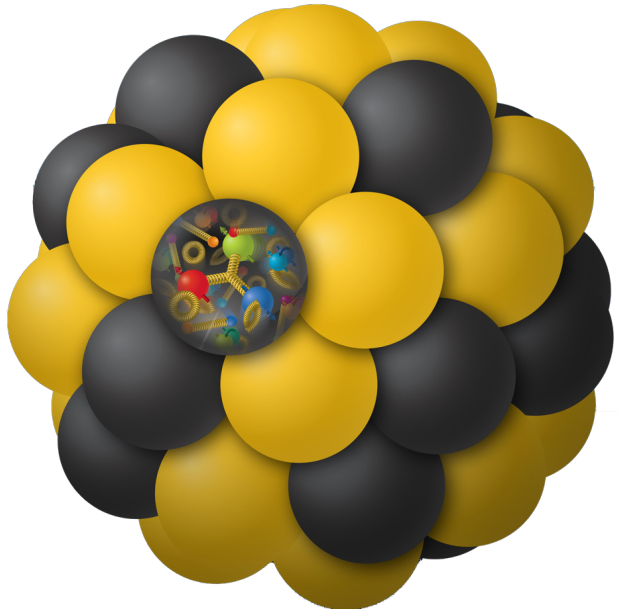


Deuteron
(high *p*-*n* momentum)

Universality

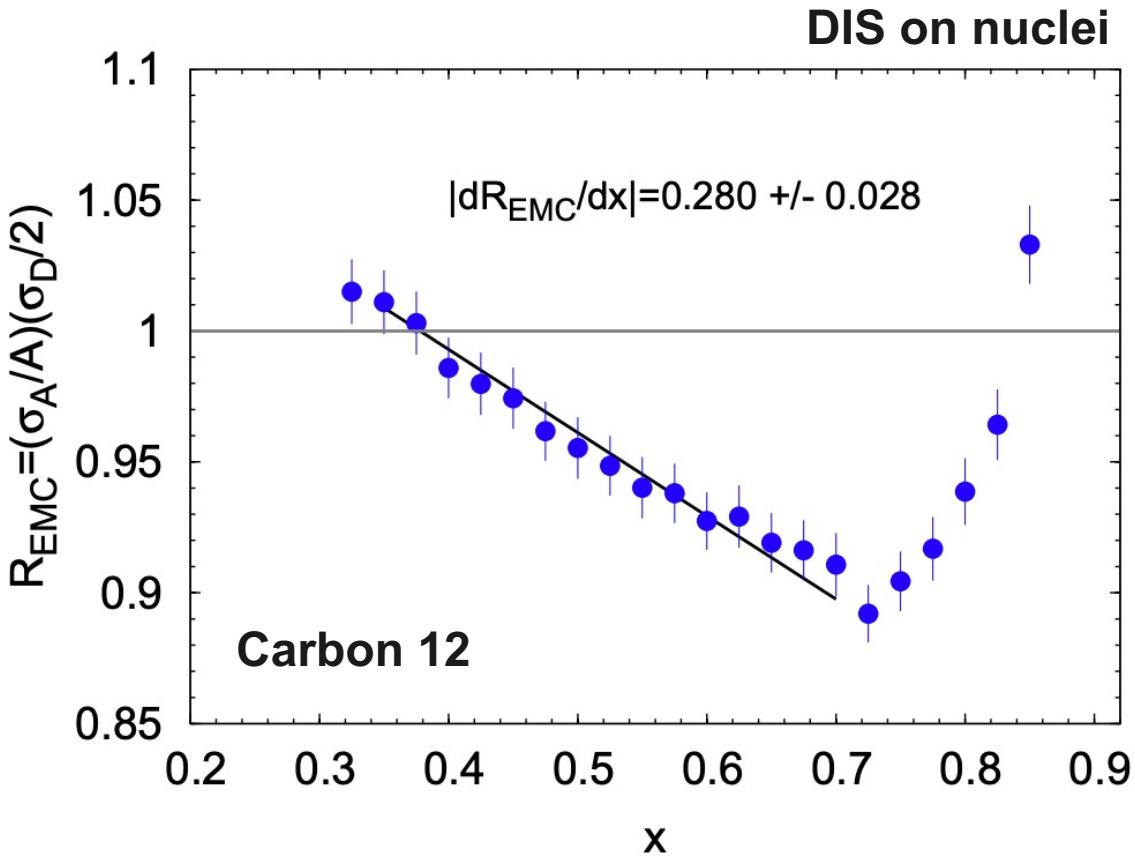
EIC may solve the
40-year EMC puzzle
via **forward tagging**

?
≅



Heavy nuclei
(higher nuclear density)

A reminder – the EMC effect

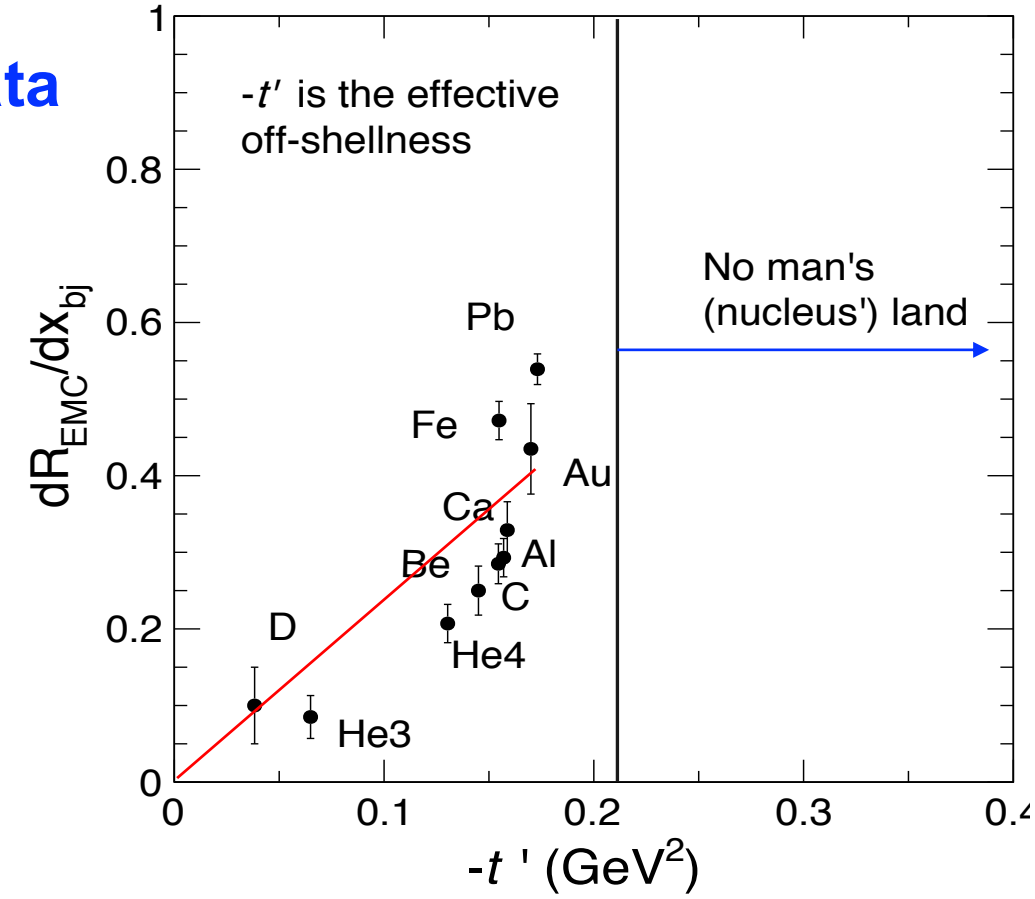


Terminology:

The so-called “EMC slope” parameter gets larger when **A** increases

Hypothesis: nucleon virtuality effect

Data

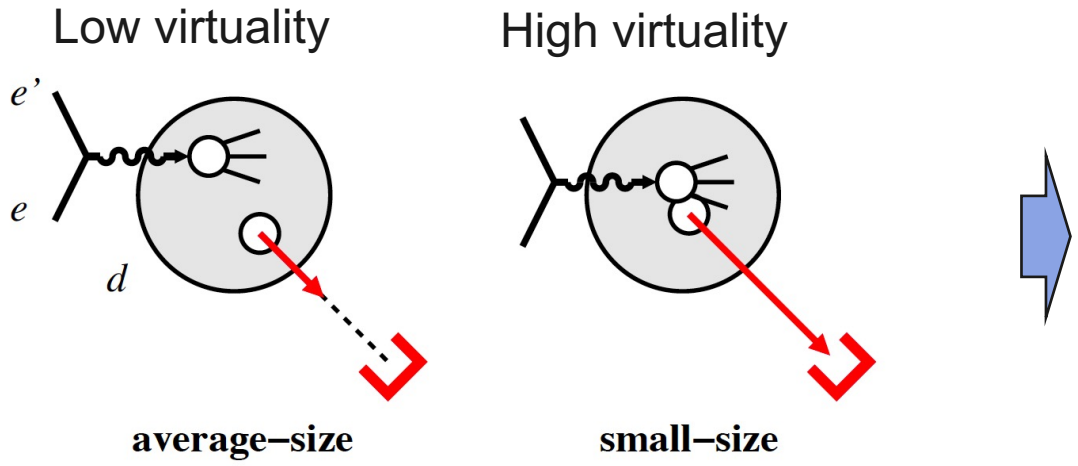


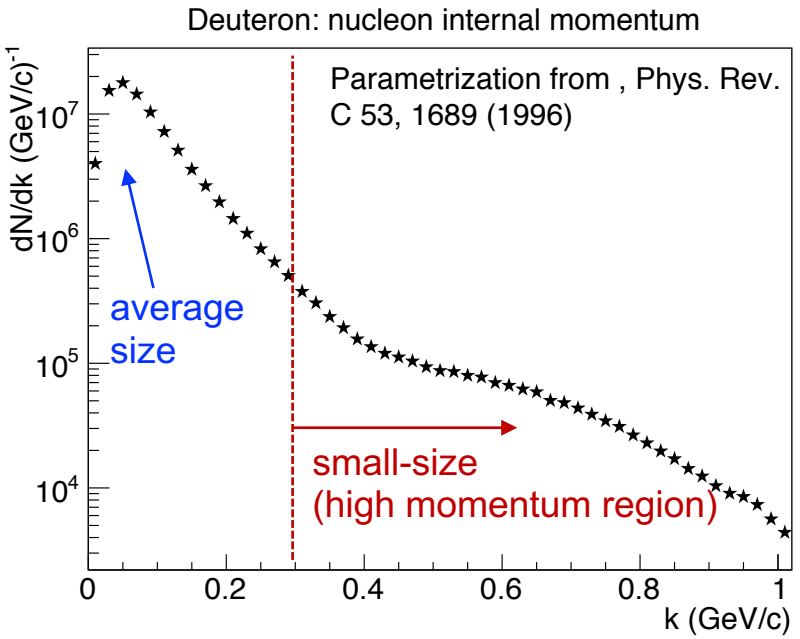
Model

- dR_{EMC}/dx_{bj} is the EMC slope;
- $-t' \sim \nu_{NR}$ is the active nucleon virtuality based on model calculations (*Phys.Rev.C76 055206,2007*)
- If the virtuality is indeed the cause, can the EMC effect be reproducible without changing the system, but rather only varying *–t'*?

Minimal parametrization (linear)
Linear offshell dependence on the EMC effect.
(Frankfurt, Strikman, Weiss)

Virtuality or off-shellness in deuteron

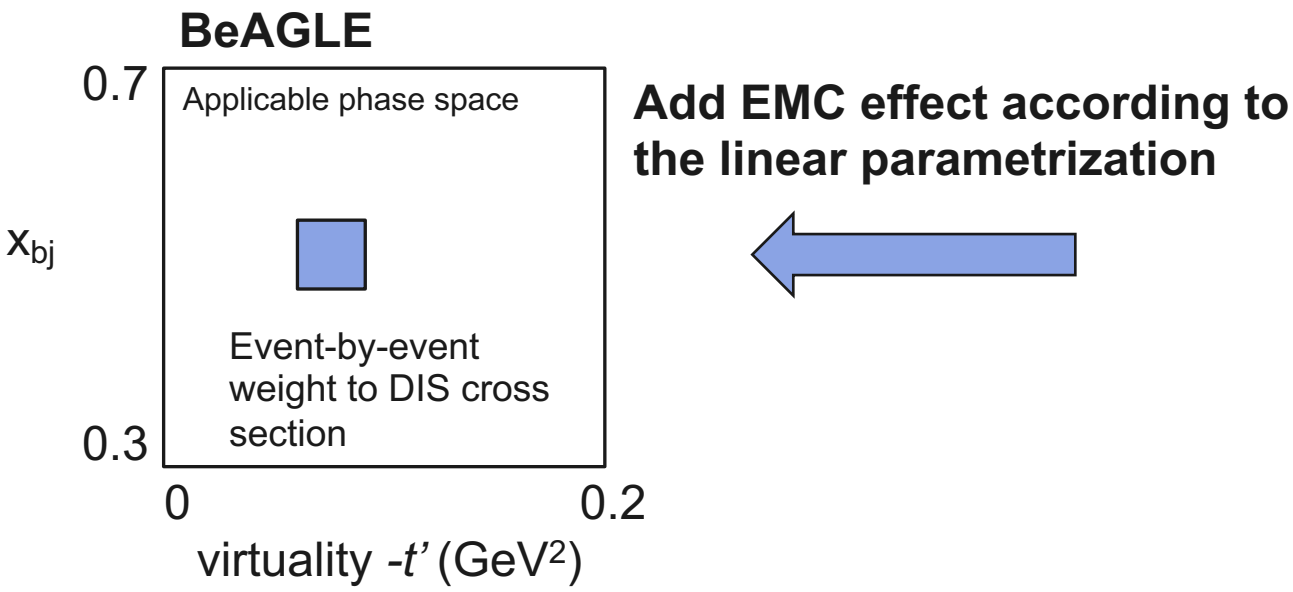




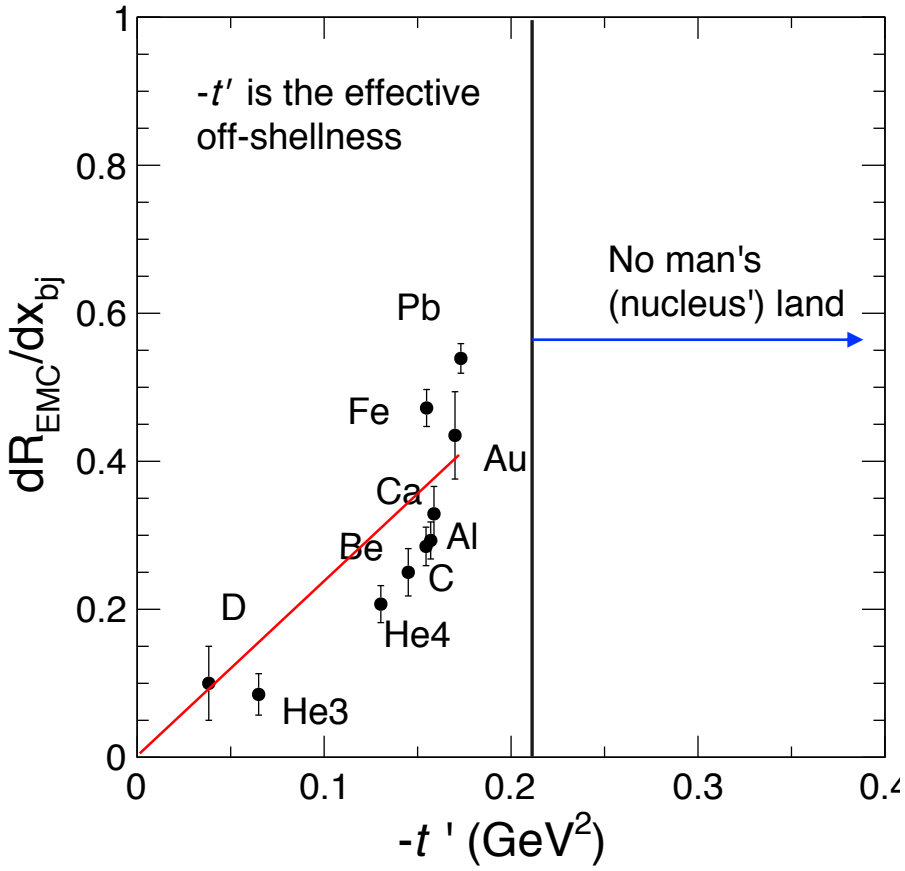
Tagged DIS Process: e + d → e' + X + p' or n'

$-t^2 = M_N^2 - \left(p_d - p_p\right)^2$ virtuality/off-shellness in deuteron

BeAGLE – implementing EMC effect



Add EMC effect according to the linear parametrization



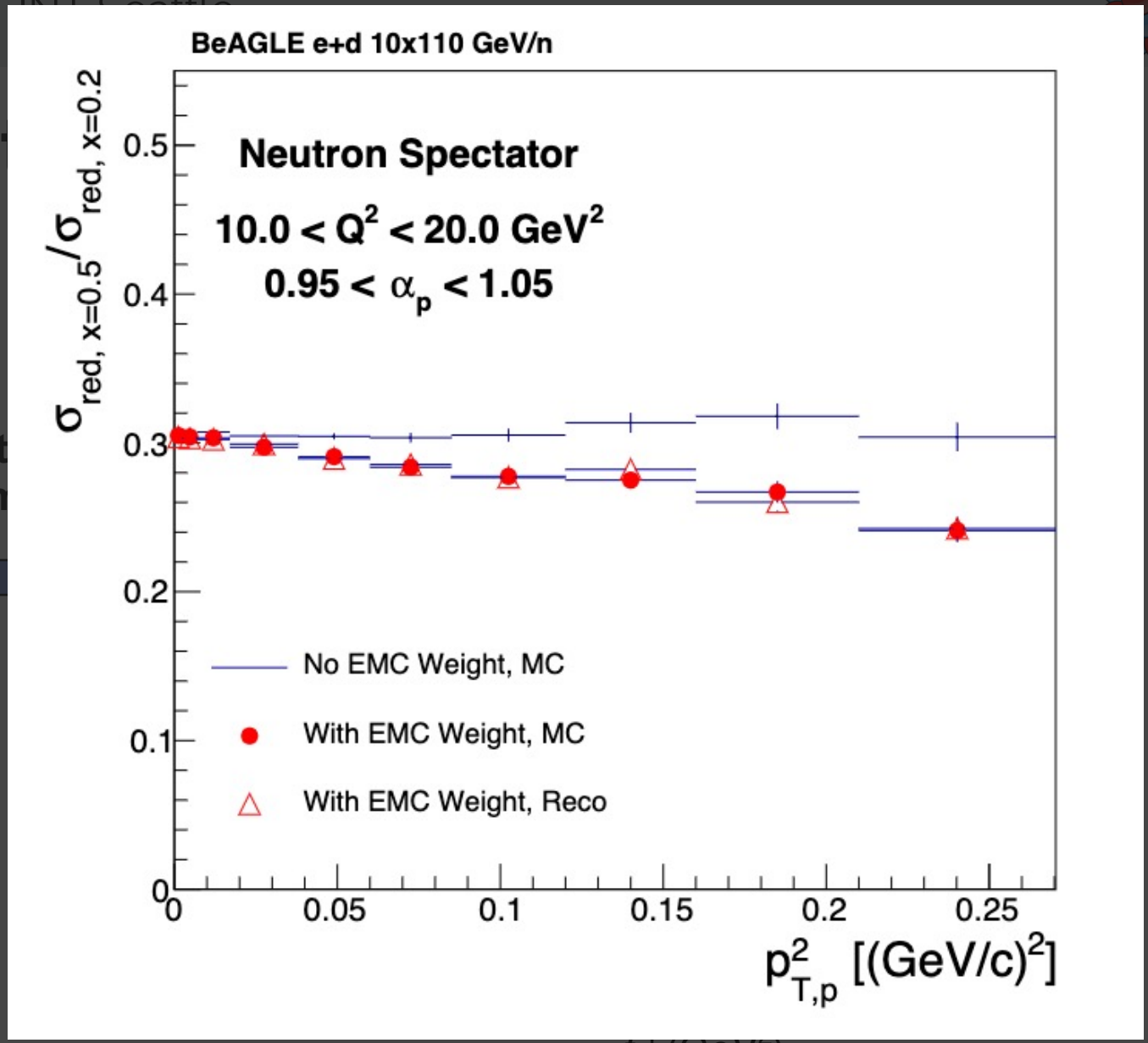
- Only apply to $0.3 < x_{bj} < 0.7$
- Q^2 independent
- Weight = F_2 (bound)/ F_2 (free)

BeAGLE – implement

Strong nuclear suppression seen in deuteron with high p_T breakup

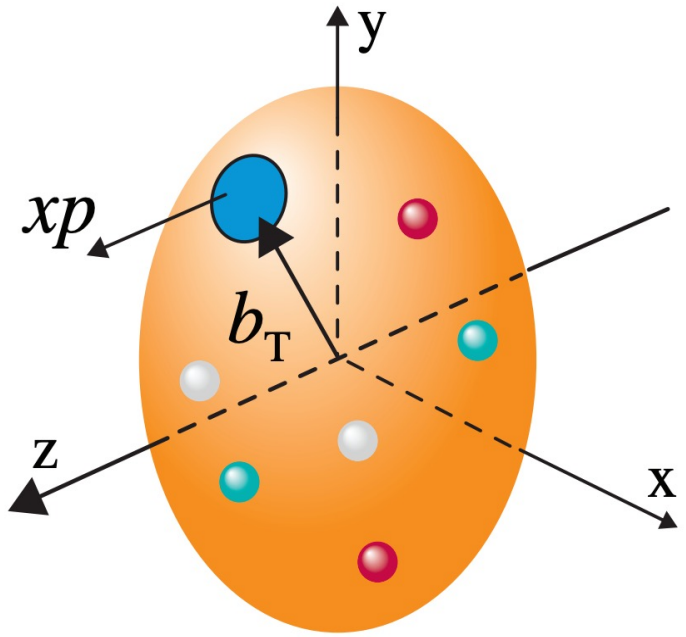
Far-Forward Detectors at EIC is indispensable

- Only apply to $0.3 < x_{bj} < 0.7$
- Q^2 independent
- Weight = F_2 (bound)/ F_2 (free)



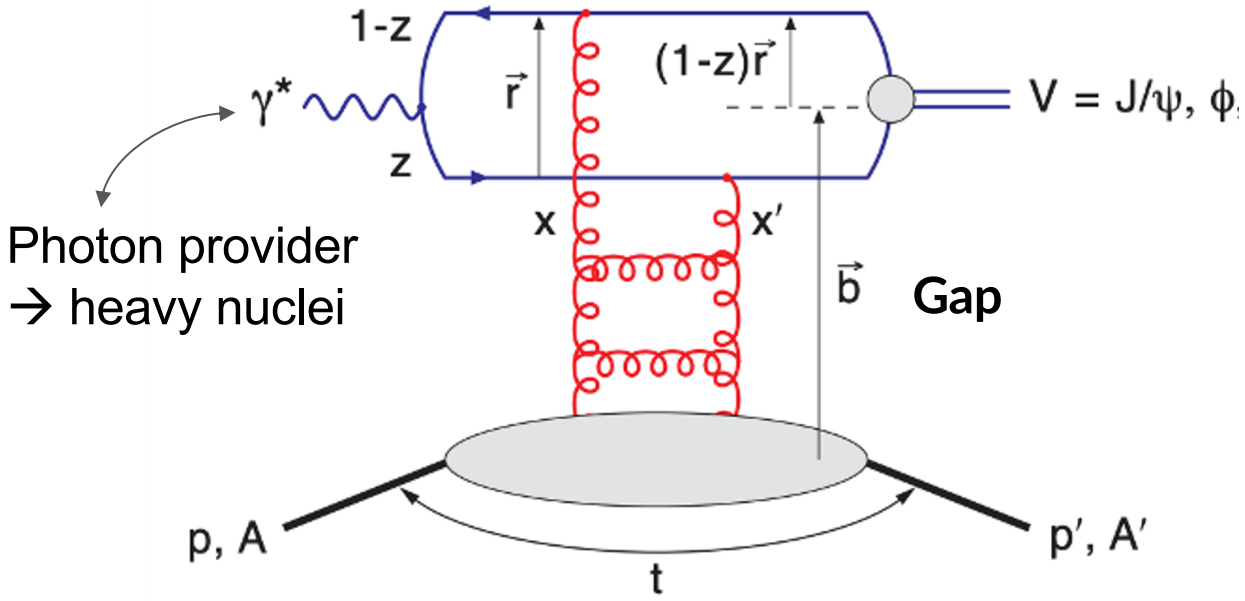
A. Jentsch, M. Strikman, **ZT**, C. Weiss (In preparation)

Parton 3D structure at the EIC



3D structure b_T

Vector Meson (J/ψ) exclusive production



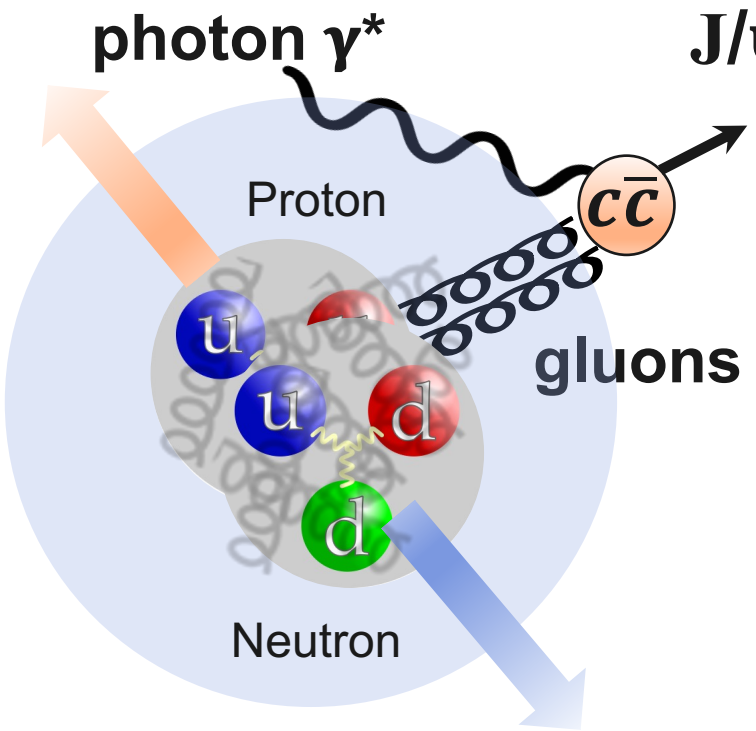
$$\sigma_{J/\psi} \sim [xg(x, Q^2)]^2$$

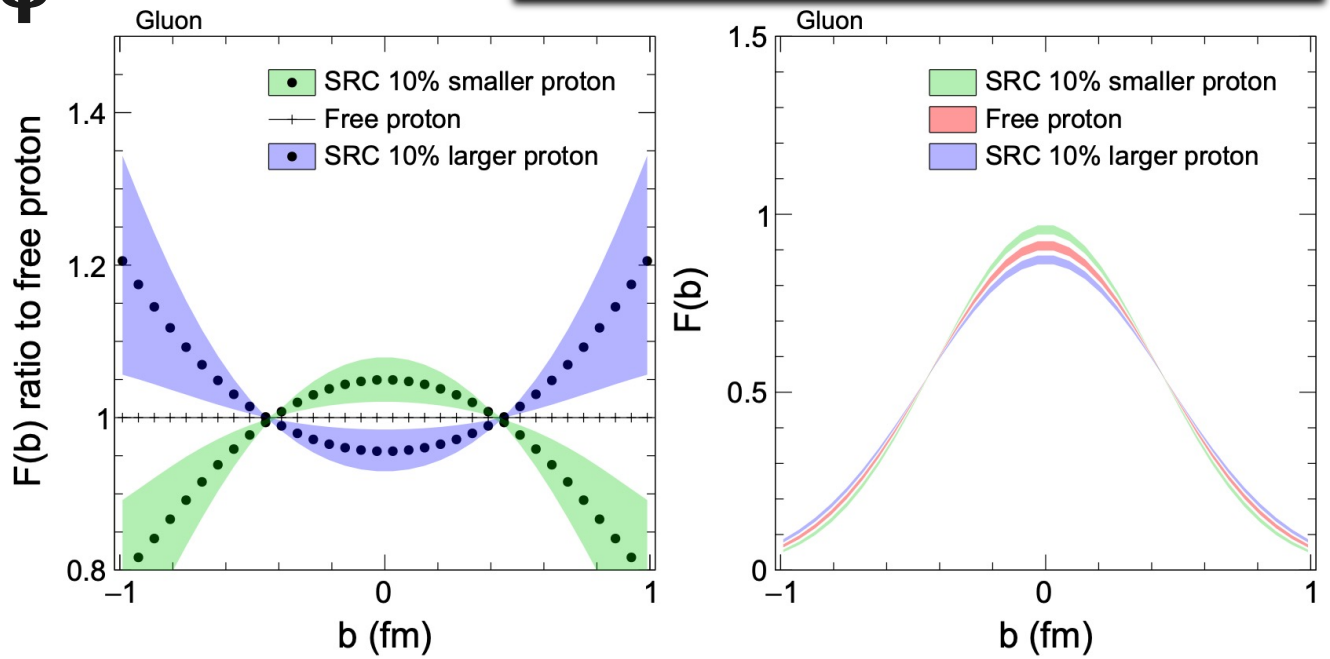
Coherent (target stays intact)	**Incoherent (target breaks up)**
Average nuclear parton density	Event-by-Event parton density fluctuations
Momentum transfer (t) and transverse spatial position (b) are Fourier transform to each other;	

A sensitive probe to the gluon density, spatial distributions, and their fluctuations.

Strong NN interaction at low-x

(**ZT**, M. Baker, A. Jentsch et al)
Phys. Lett. B 811 (2020) 135877

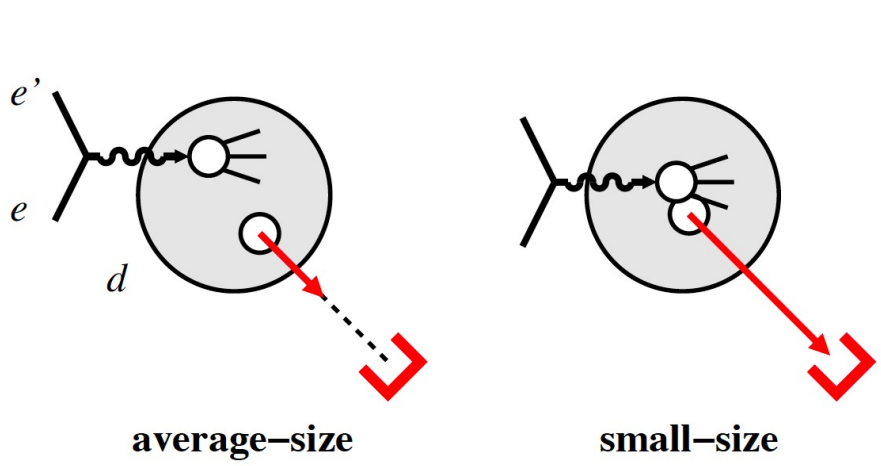


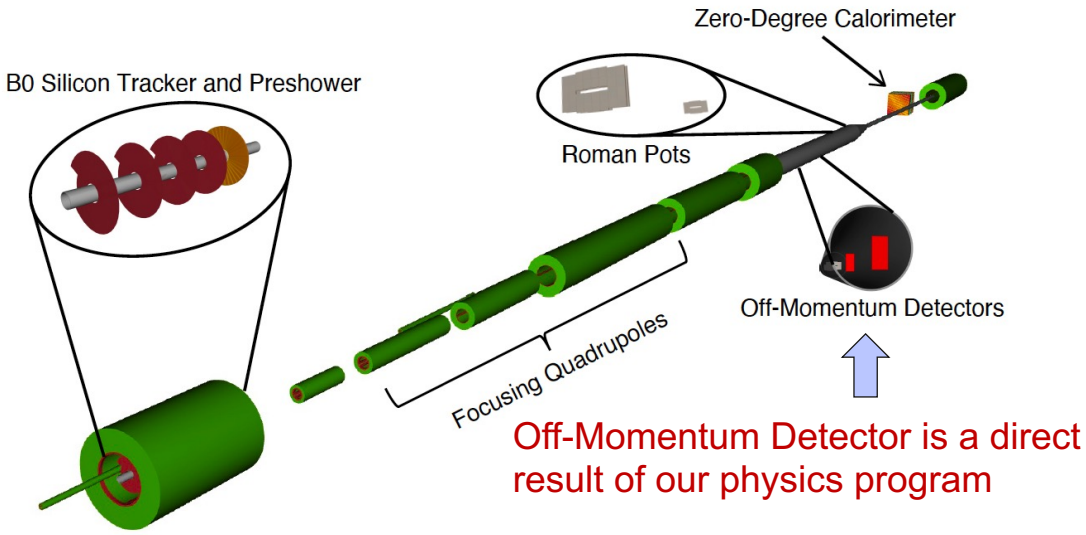


Deuteron
(high *p-n* momentum)

Gluonic radius: get squeezed or stretched?
nucleonic d.o.f → partonic d.o.f

New EIC tagging program established





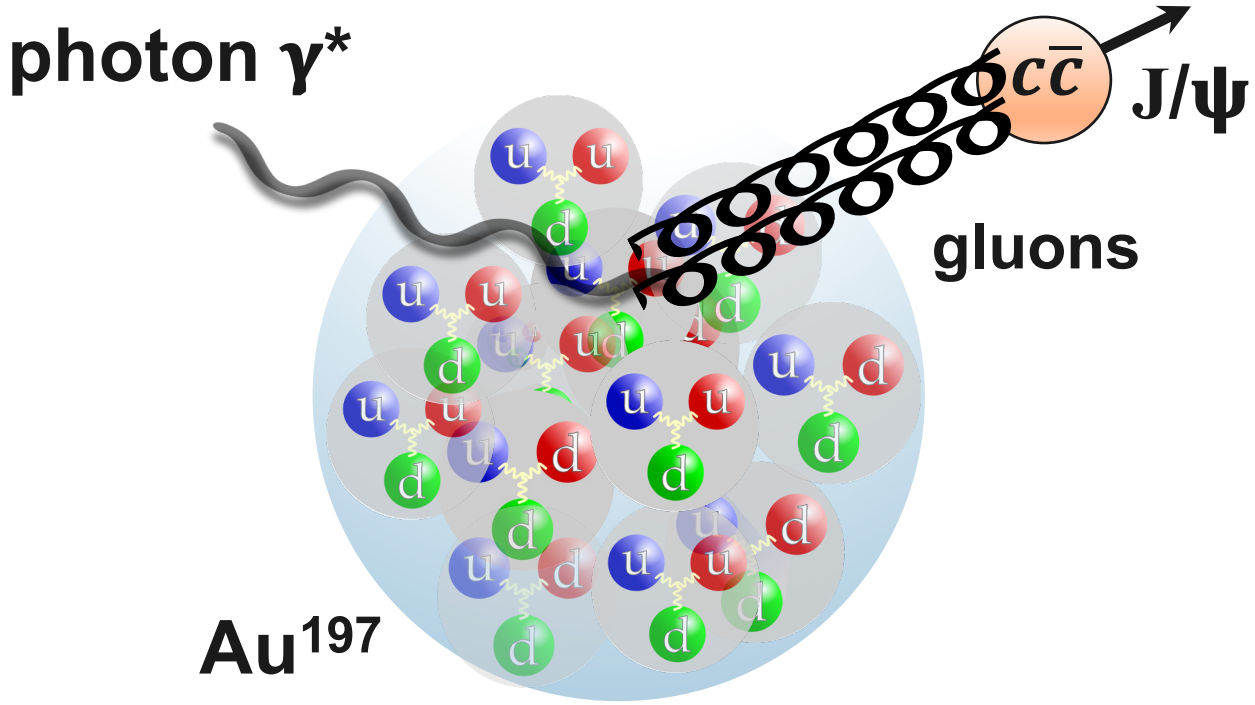
Deuteron spectator tagging program

- Free neutron structure
- EMC effect for quark modification
- Gluon modification

New projects (theory + experiment)

- Deeply Virtual Compton Scattering
- Polarized deuteron for spin
- Other light-ions

3D gluon structure of heavy nuclei

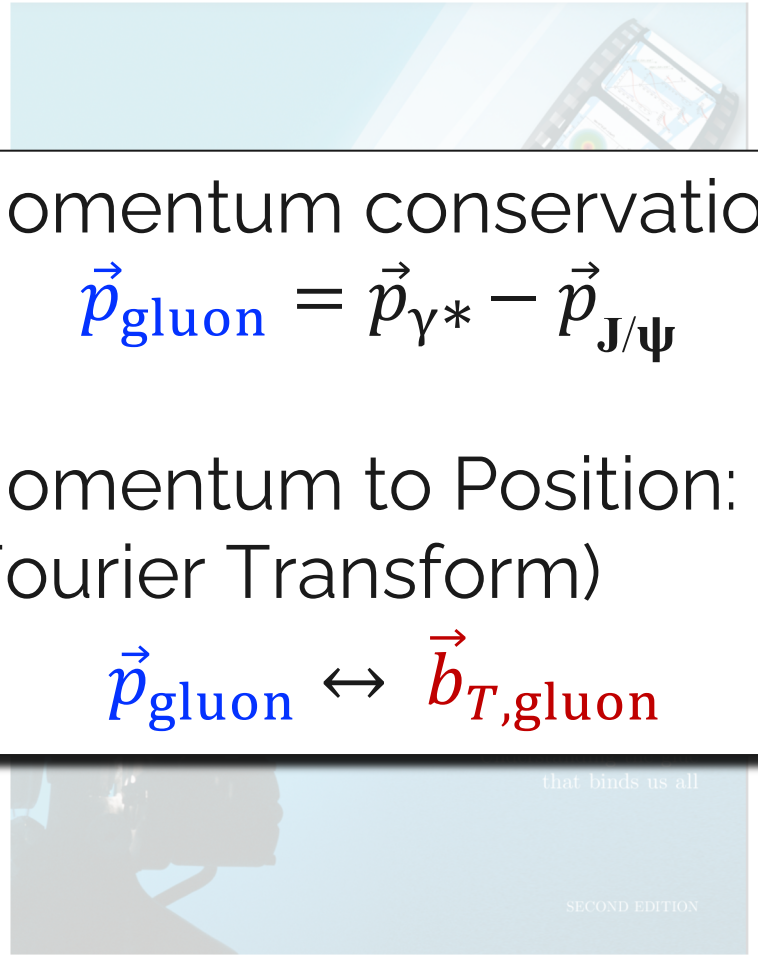


Momentum conservation:

$$\vec{p}_{\text{gluon}} = \vec{p}_{\gamma*} - \vec{p}_{\text{J/}\psi}$$

Momentum to Position:
(Fourier Transform)

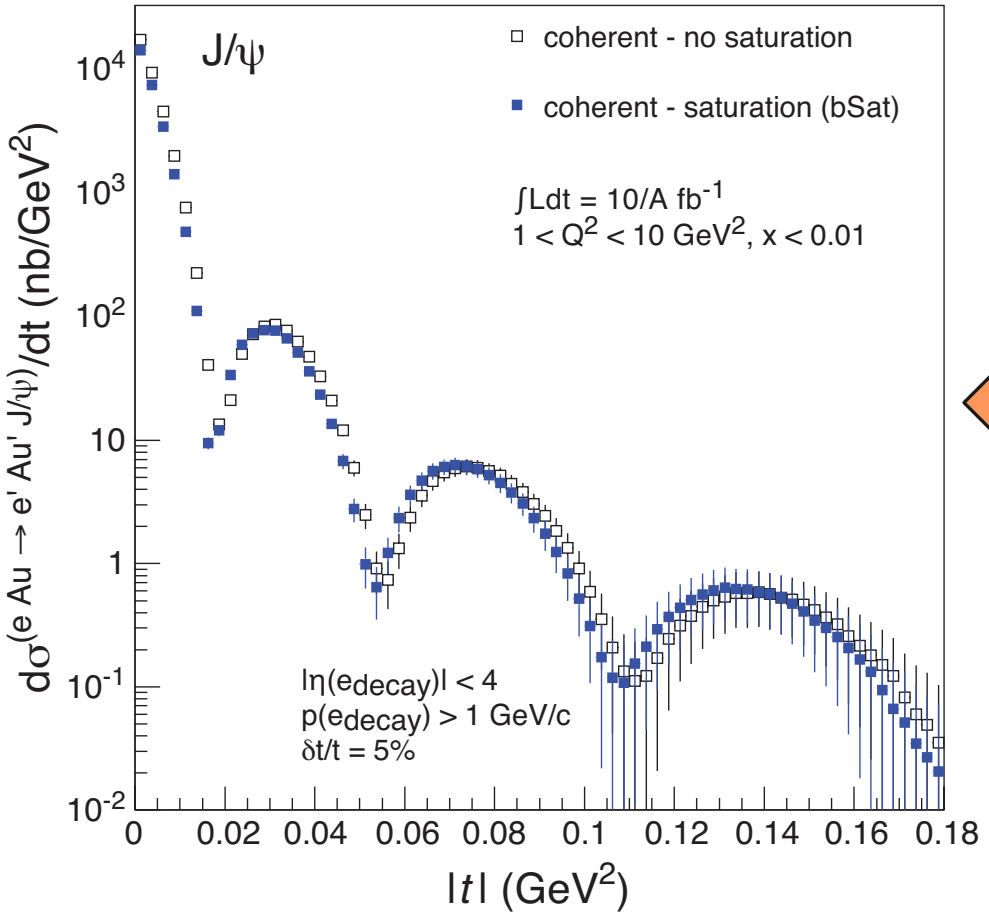
$$\vec{p}_{\text{gluon}} \leftrightarrow \vec{b}_{T,\text{gluon}}$$



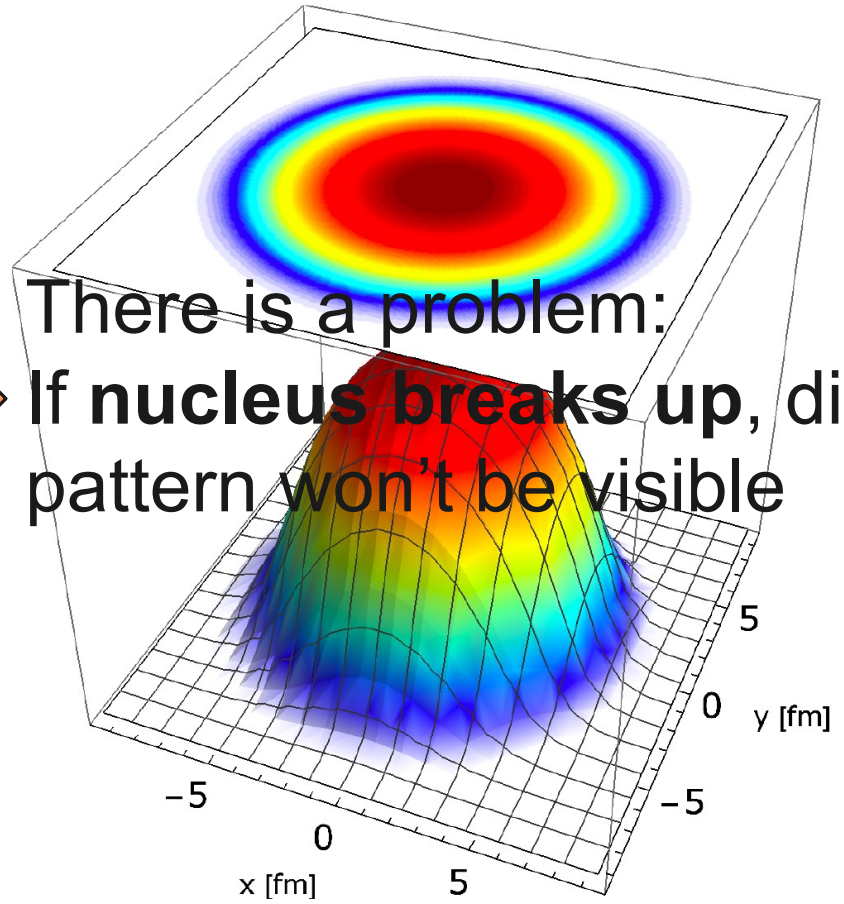
"It's a **Golden** Channel" - EIC white paper

Gluon spatial distribution at the EIC

Toll & Ullrich (2012)



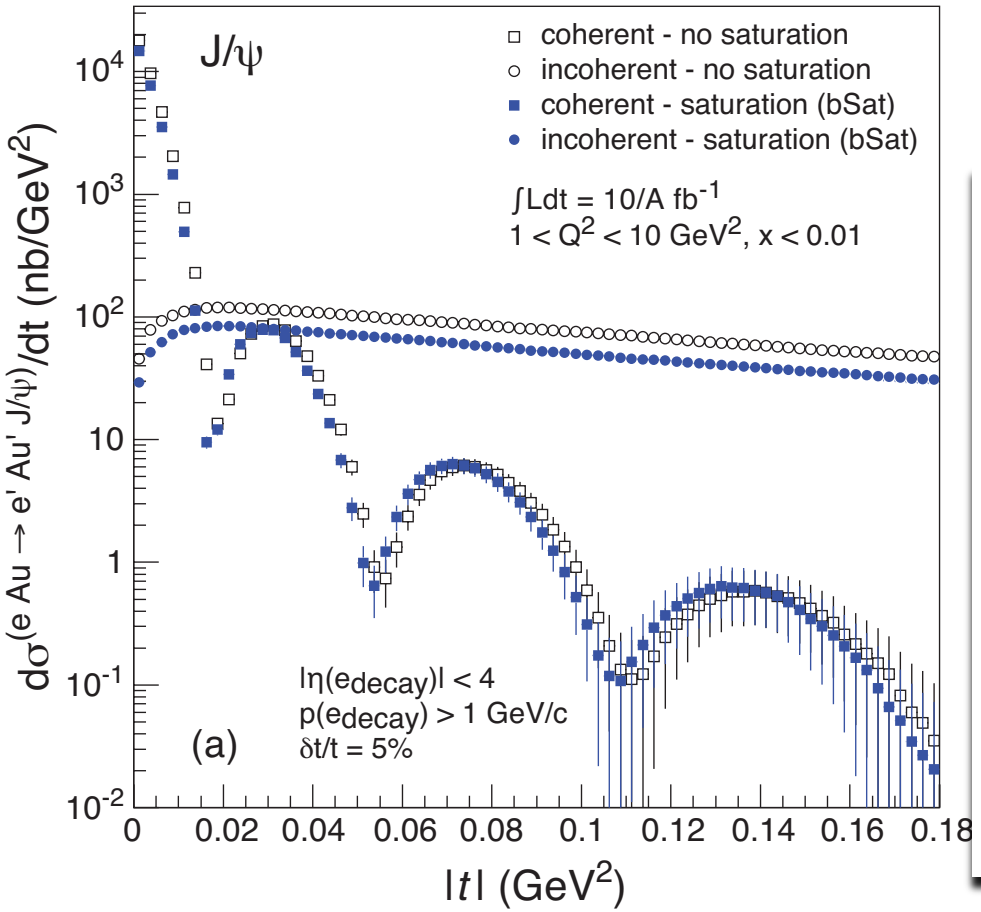
Gluon spatial distribution



There is a problem:
If **nucleus breaks up**, diffractive pattern won't be visible

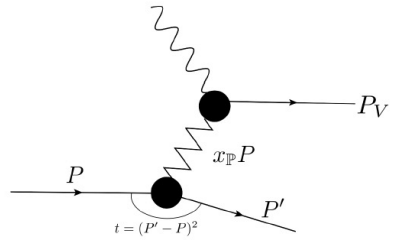
Gluon spatial distribution at the EIC

Toll & Ullrich (2012)



(See B. Schenke's talk)

Diffractive vector meson production



- Coherent diffraction: Target stays intact

$$\frac{d\sigma^{\gamma^* p \to Vp}}{dt} = \frac{1}{16\pi}\left|\left\langle A^{\gamma^* p \to Vp}\left(x_P, Q^2, \vec{\Delta}\right)\right\rangle\right|^2$$

sensitive to the average size of the target

- Incoherent diffraction: Target breaks up

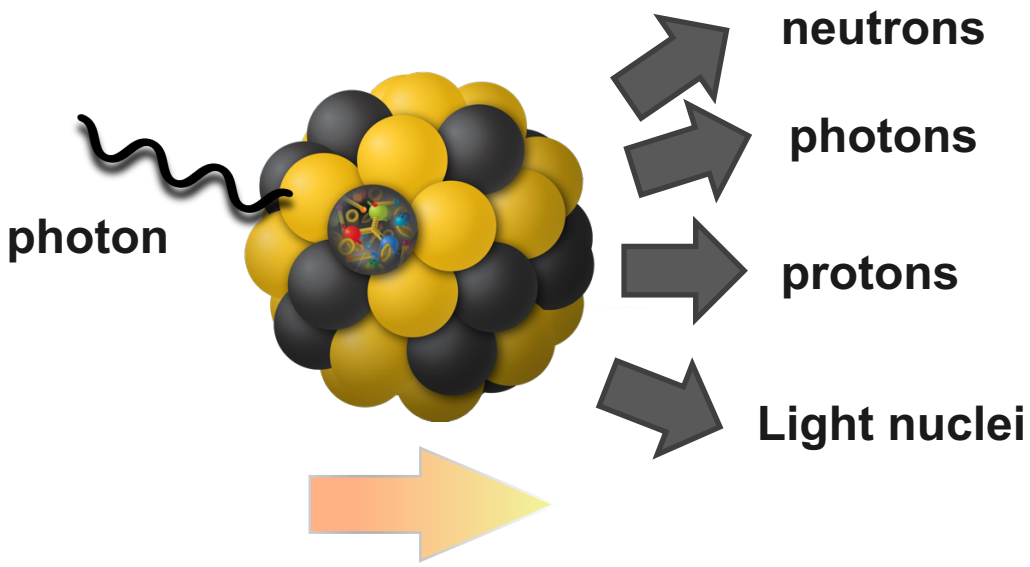
$$\frac{d\sigma^{\gamma^* p \to Vp^*}}{dt} = \frac{1}{16\pi}\left(\left\langle\left|A^{\gamma^* p \to Vp}\left(x_P, Q^2, \vec{\Delta}\right)\right|^2\right\rangle - \left|\left\langle A^{\gamma^* p \to Vp}\left(x_P, Q^2, \vec{\Delta}\right)\right\rangle\right|^2\right)$$

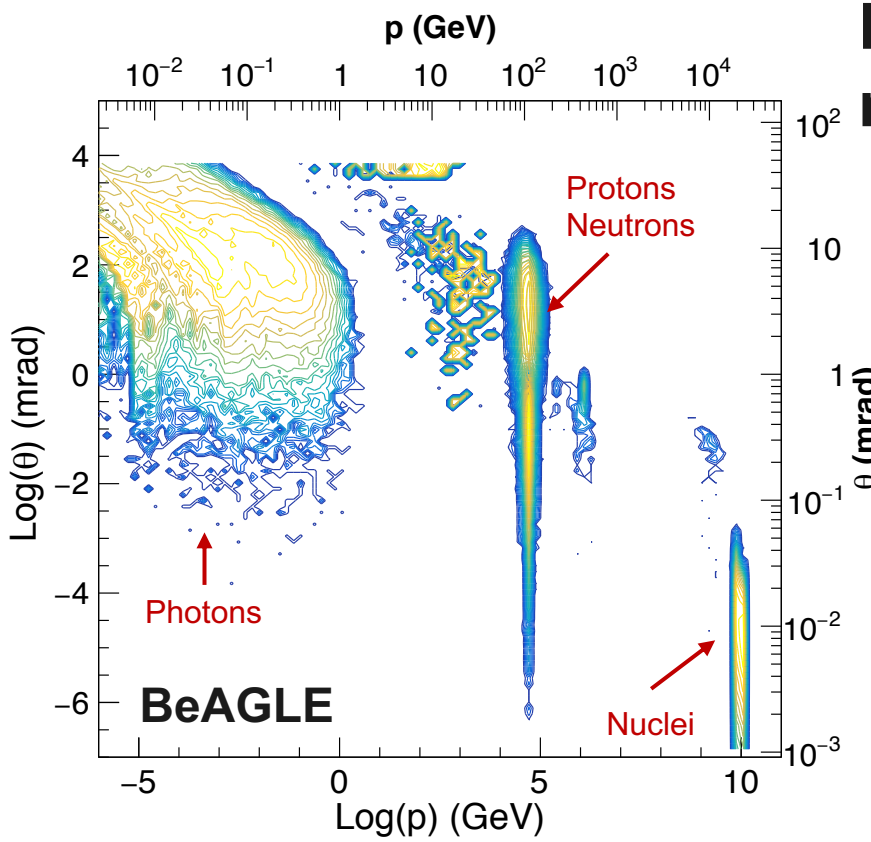
sensitive to fluctuations (including geometric ones)

M. L. Good and W. D. Walker, Phys. Rev. 120 (1960) 1857
H. I. Miettinen and J. Pumplin, Phys. Rev. D18 (1978) 1696
Y. V. Kovchegov and L. D. McLerran, Phys. Rev. D60 (1999) 054025
A. Kovner and U. A. Wiedemann, Phys. Rev. D64 (2001) 114002

9

Nuclear breakups



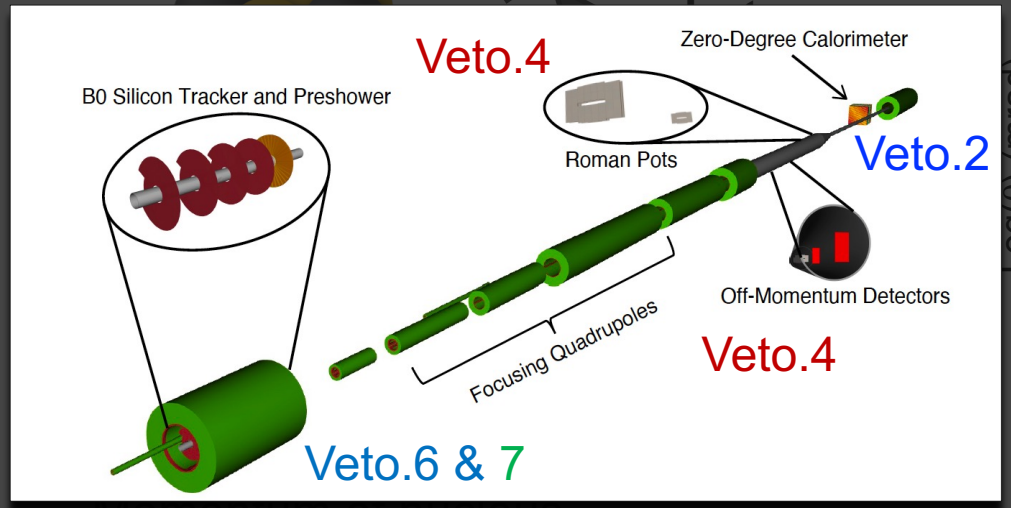


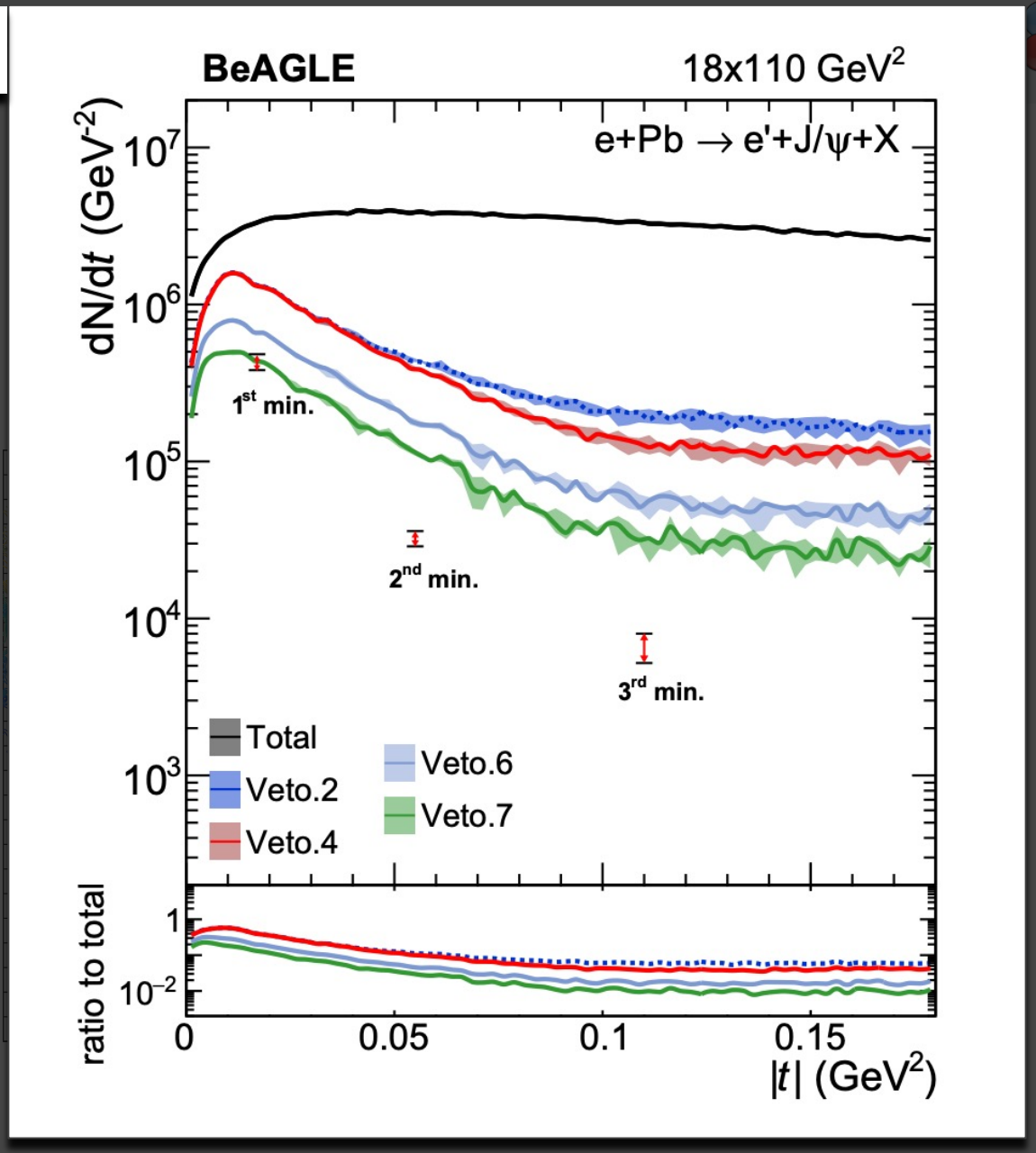
Far-forward region

Incoherent background study

Nuclear breakup

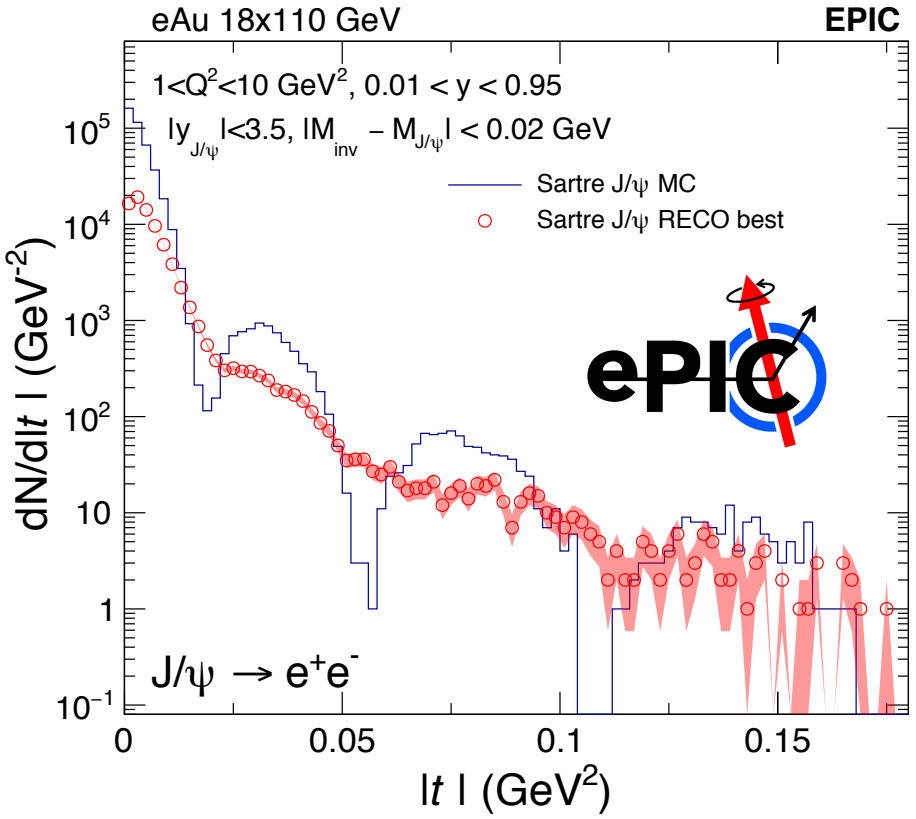
Veto breakups are based on Far-Forward Detectors at EIC



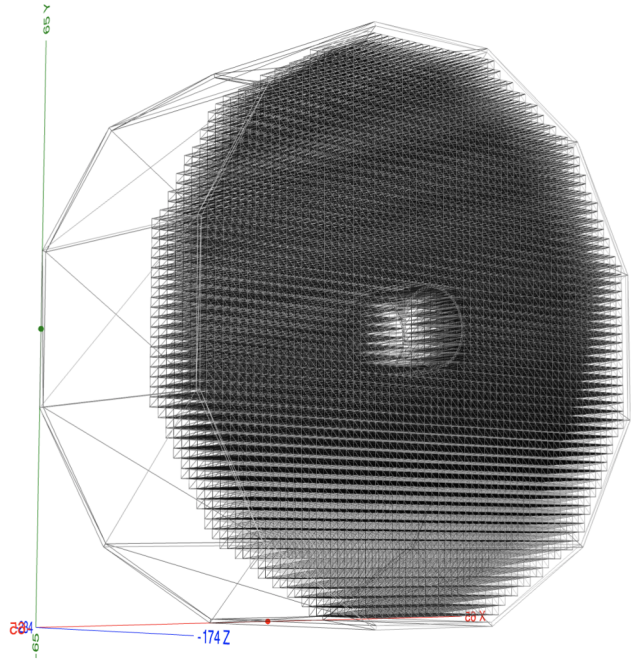


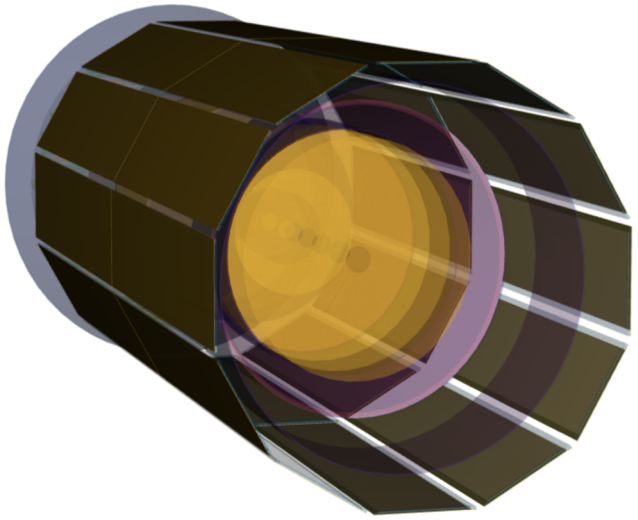
(Phys. Rev. D 104 (2021) 11, 114030)

EIC full simulation in ePIC



Momentum reconstruction with EEMC + Tracker





$$-t = -(p_e - p_{e'} - p_{VM})^2 = -(p_{A'} - p_A)^2$$

Measurement of |t| precisely requires excellent det. resolution

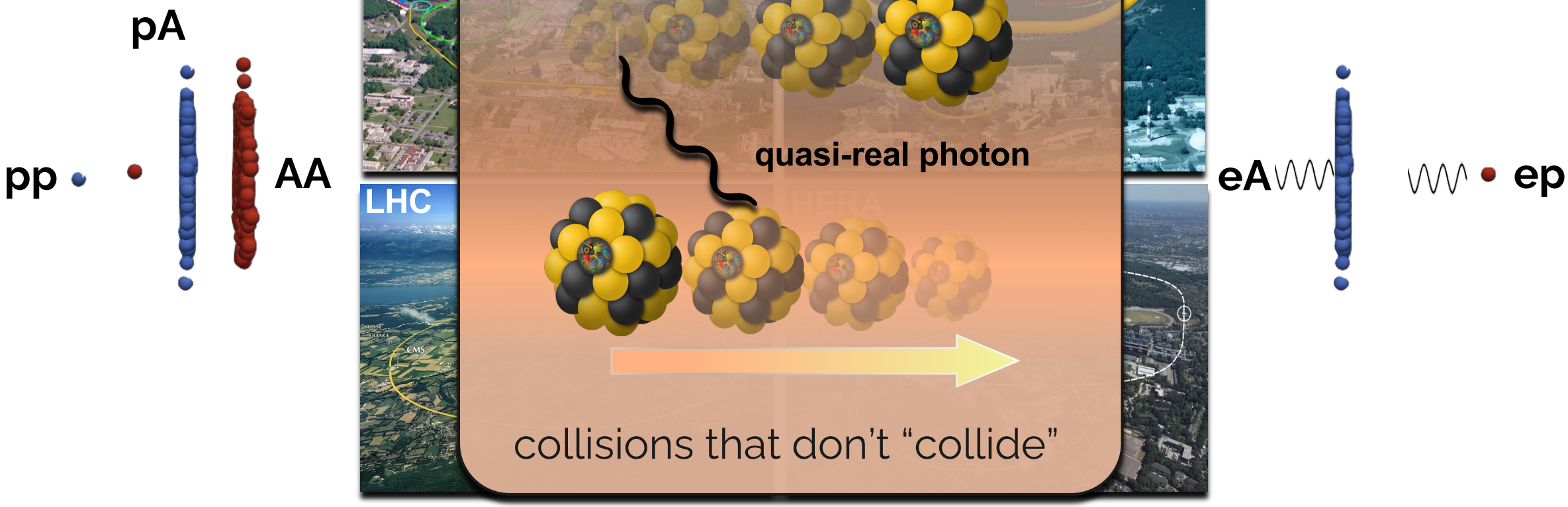
What can we learn about
Parton structure & fluctuation before the EIC ?

QCD Machines

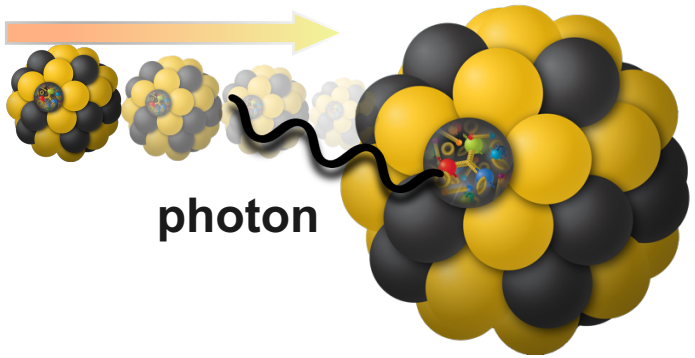
pp & pA & AA machines

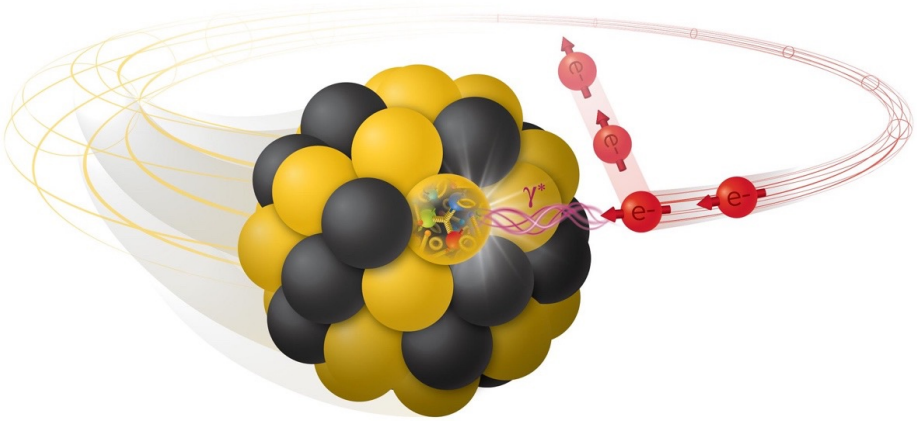
Ultraperipheral collisions (UPCs)

ep & eA machines



Complementarity: UPC and EIC





UPC RHIC & LHC

Photoproduction only (real photons)

Mass or p_T – hard scales

CM energy, W ~ [4, 400-1000] GeV, x ~ 10^{-5} -10^{-1}

mostly Pb^{208}, Au^{197}.

Limited far-forward coverage for breakup products

EIC

Electroproduction (virtual photons)

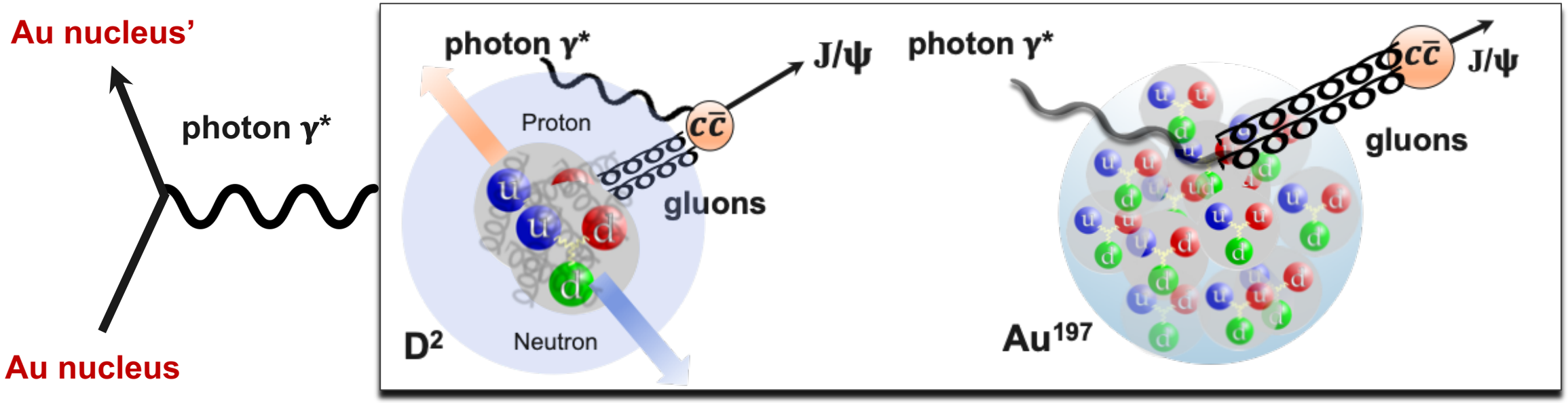
Q^2 – an independent hard scale

CM energy, W ~ [9, 86] GeV, x ~ 10^{-4} -10^{-2}

Deuterium to Uranium

Large far-forward coverage, esp. for nuclear breakup.

Can we preview EIC physics via UPCs?



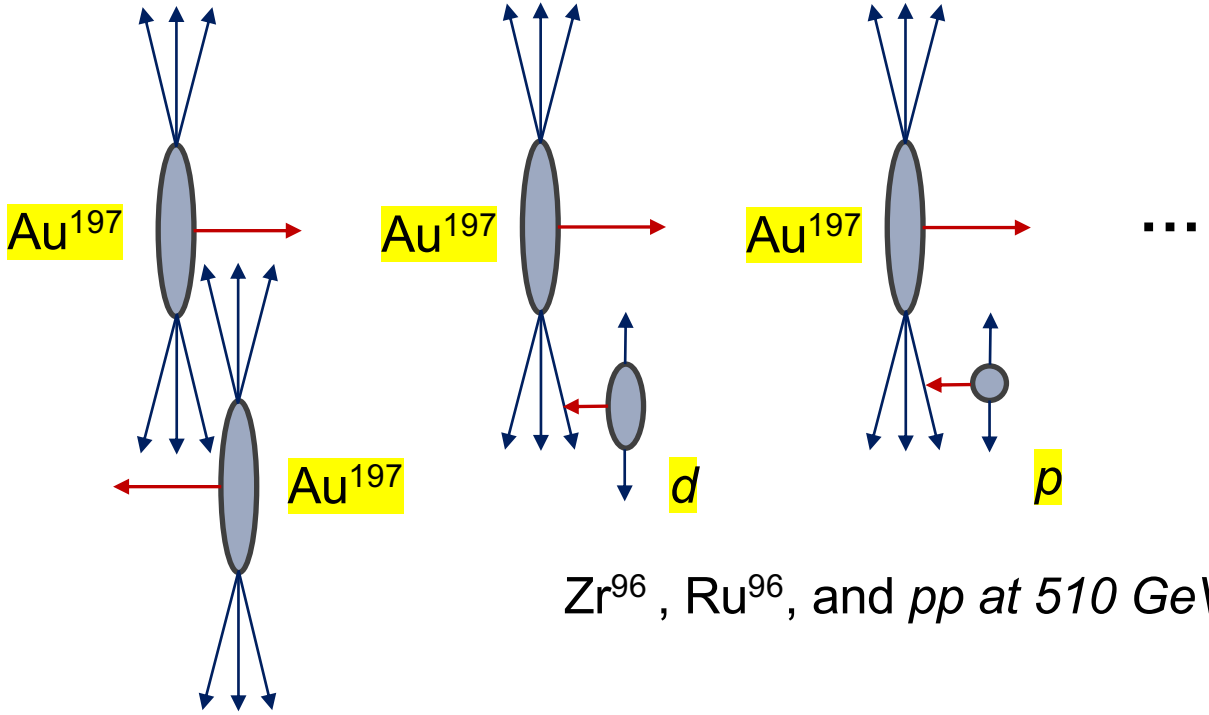
Preview in UPCs

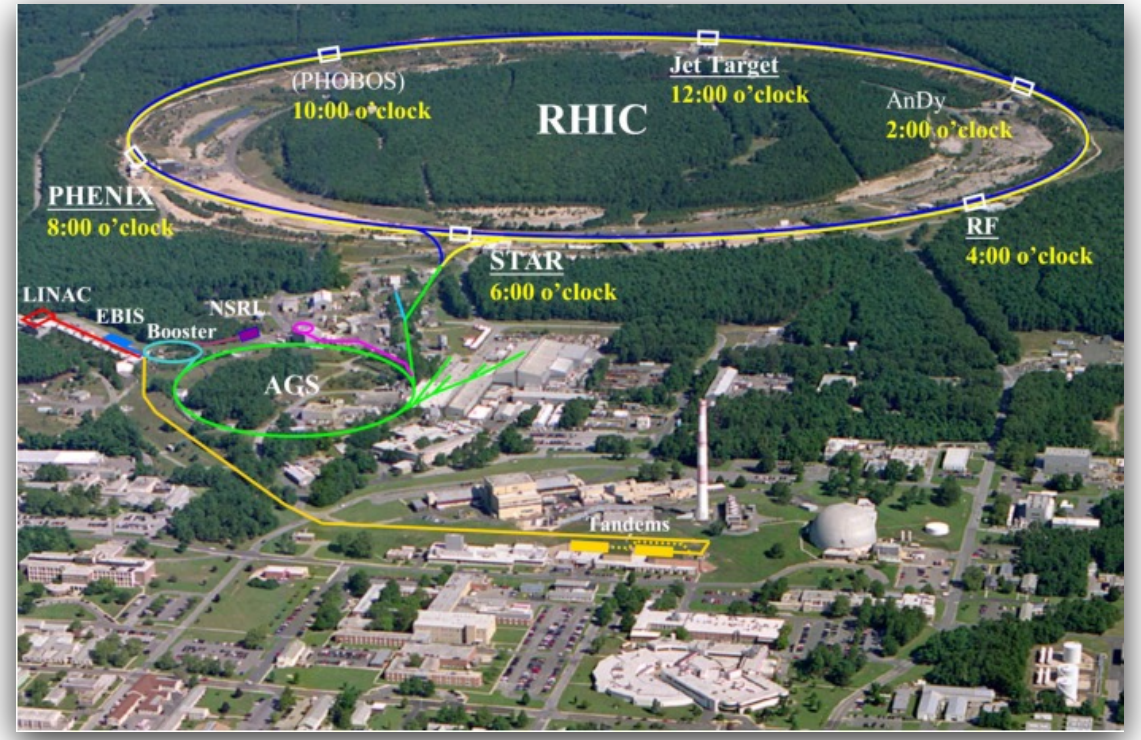
EIC new tagging program

EIC Golden channel

By replacing the photon provider!

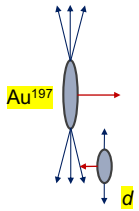
UPCs at RHIC-STAR



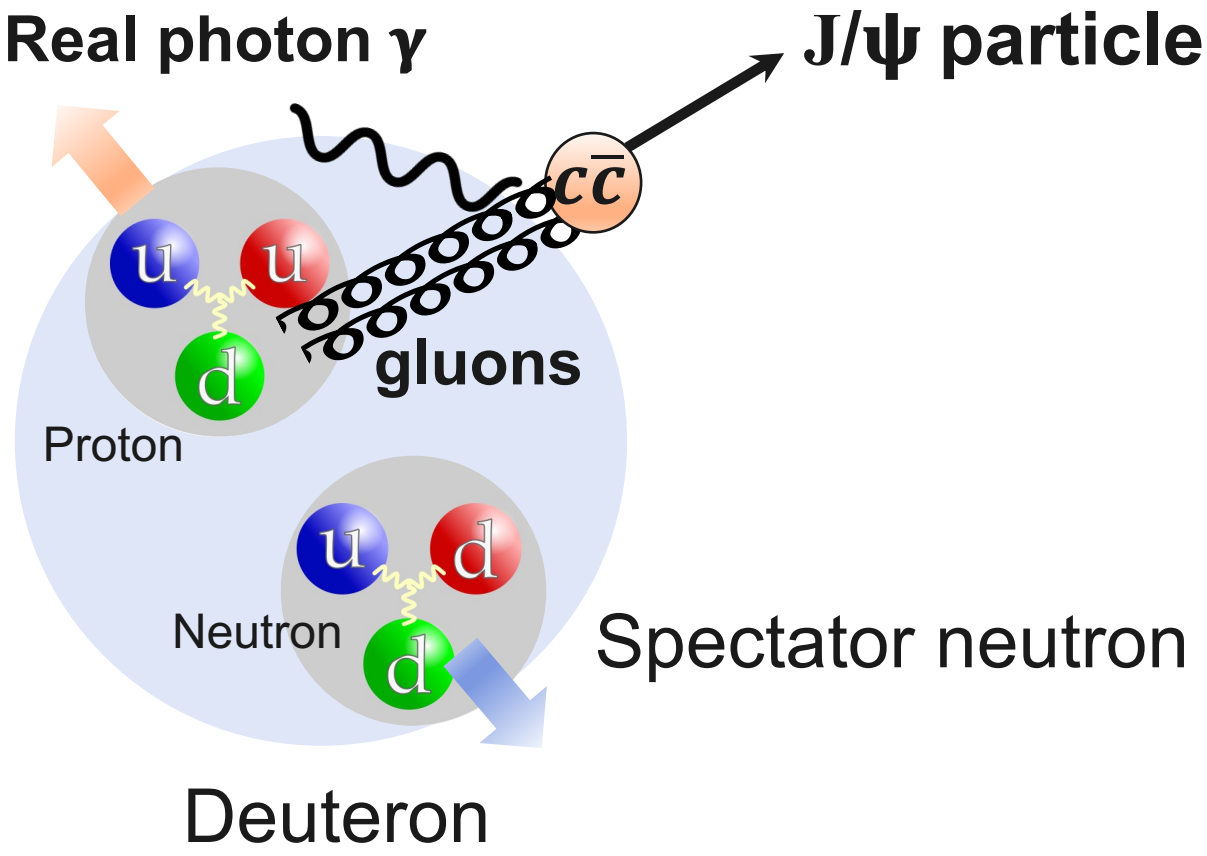


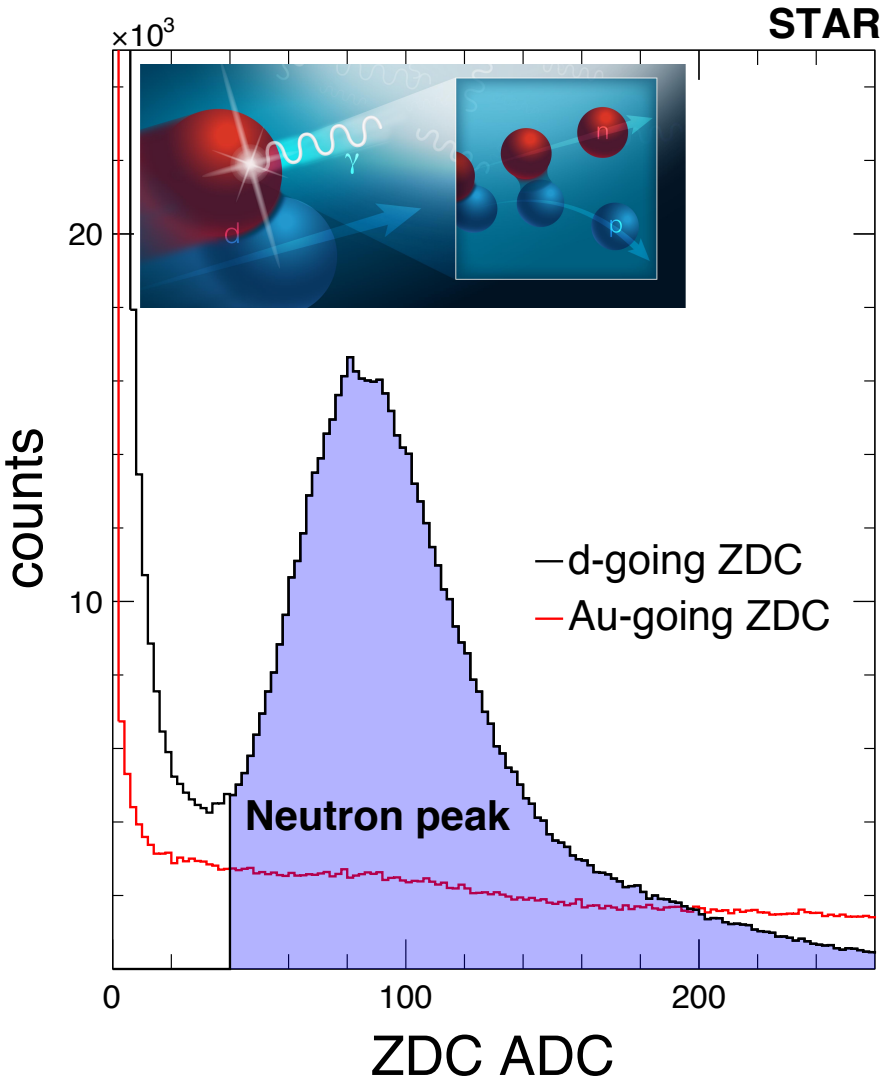
Zr^{96} , Ru^{96}, and *pp at 510 GeV*

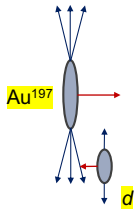
A versatile program with different species, energy, and polarization.
Sensitive to a wide range of **EIC physics**



First deuteron-gold UPC J/ψ & tagging



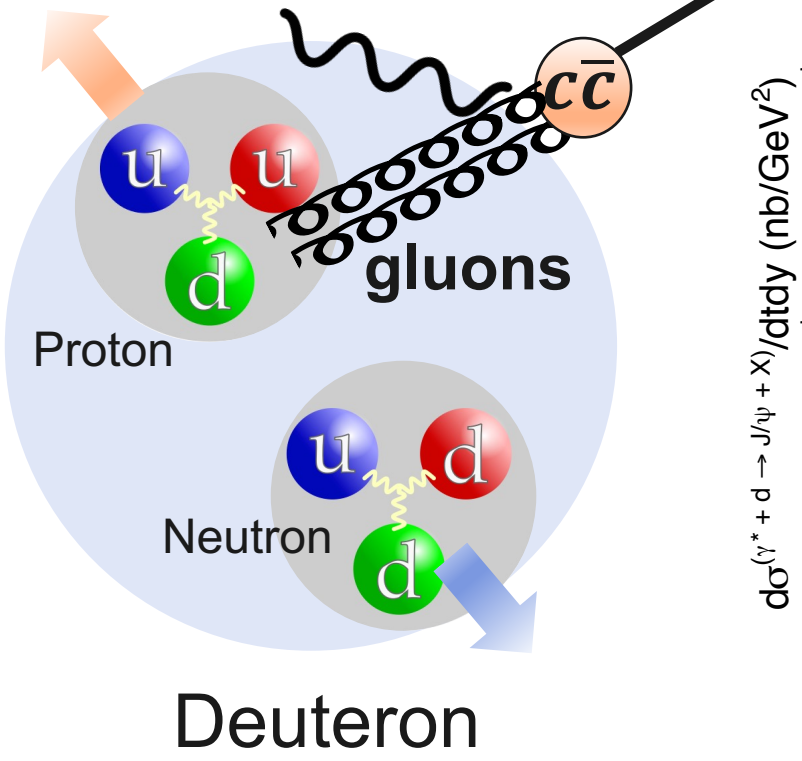


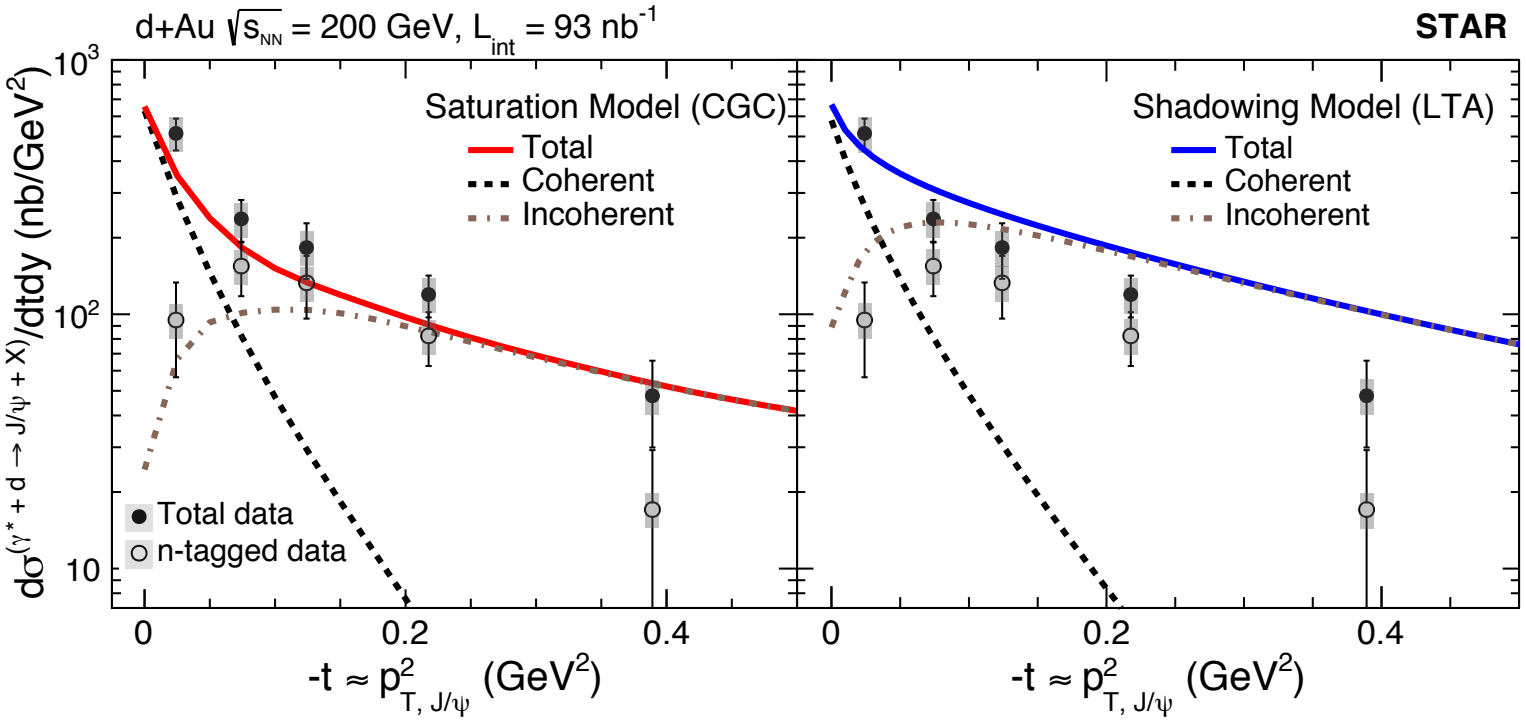


First deuteron-gold UPC J/ψ & tagging

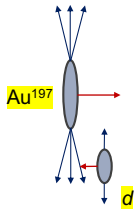
Real photon γ

J/ψ particle





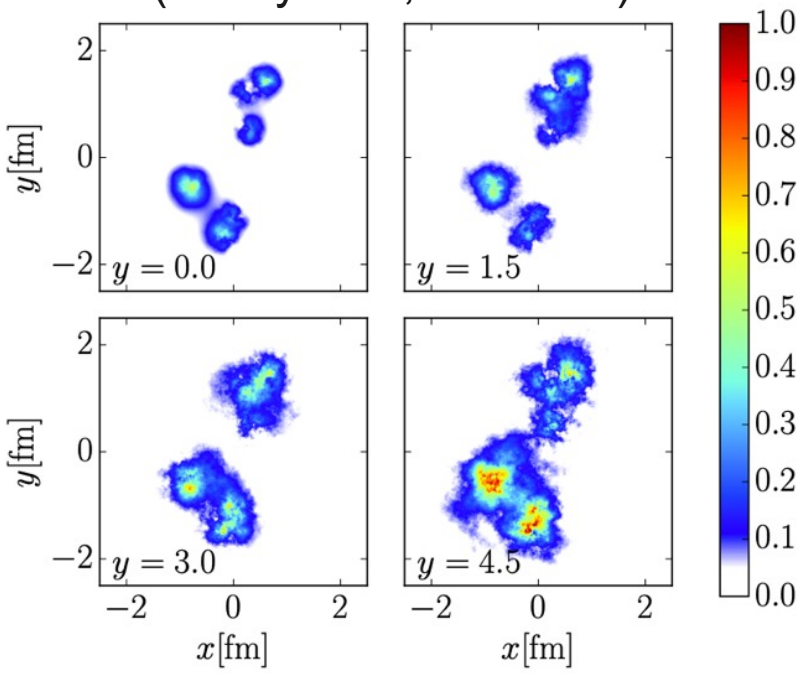
PRL 128 (2022) 12, 122303

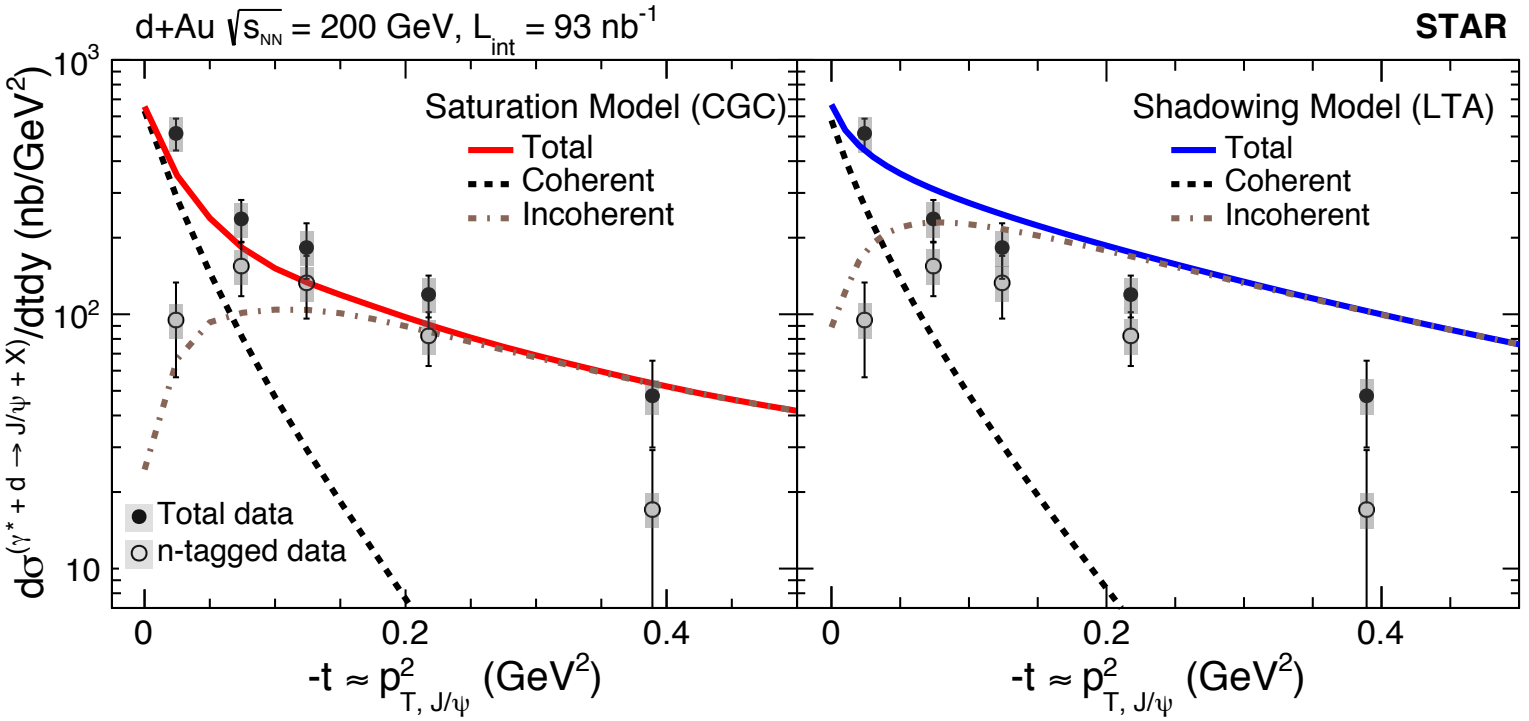


First deuteron-gold UPC J/ψ & tagging

enables **incoherent** data

(Mäntysaari, Schenke)



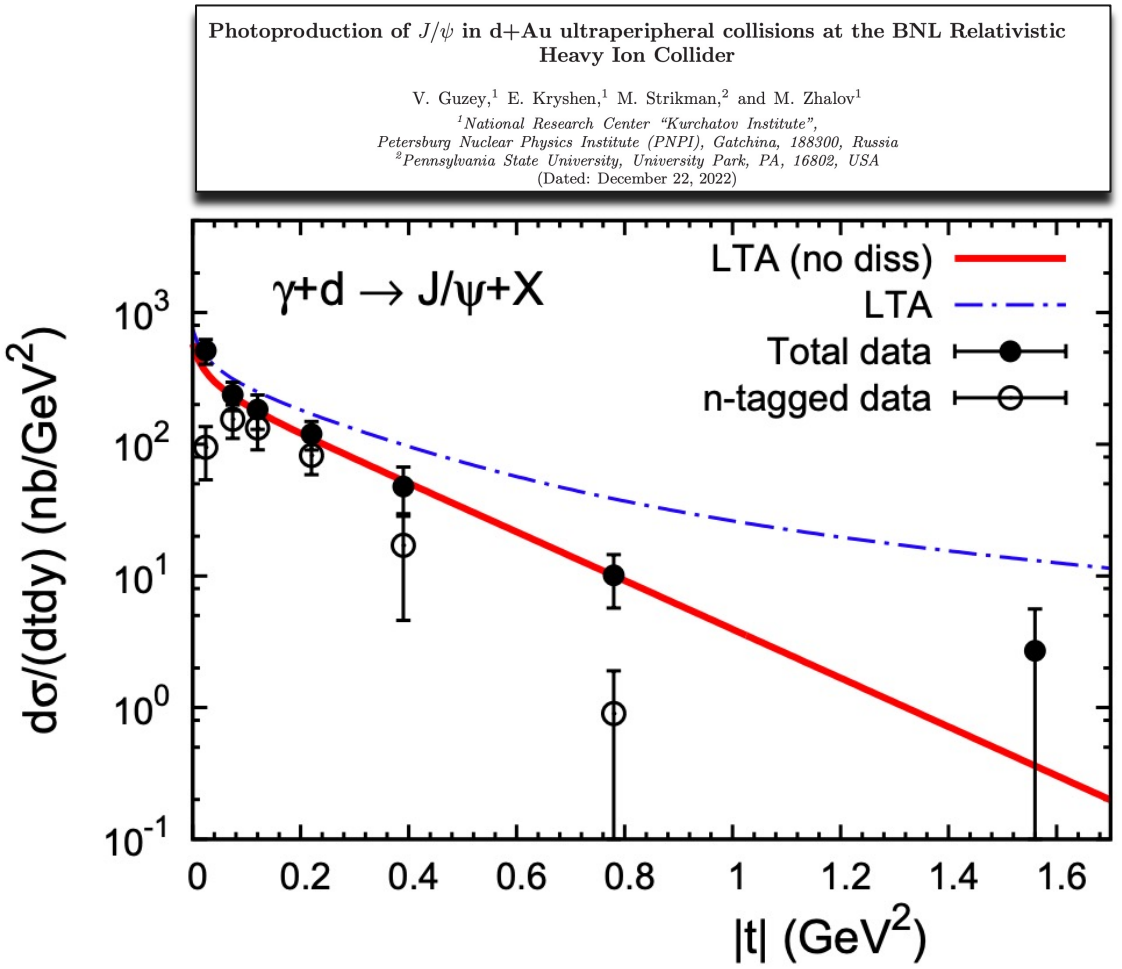


Supporting gluon density fluctuation

PRL 128 (2022) 12, 122303

Shadowing model revisited

If nucleon dissociation is off, LTA can describe STAR data well



Remark on dAu UPC data

Deuteron is a model calibrator:
At x ~ 0.01, neither **saturation** nor **shadowing** is strong.

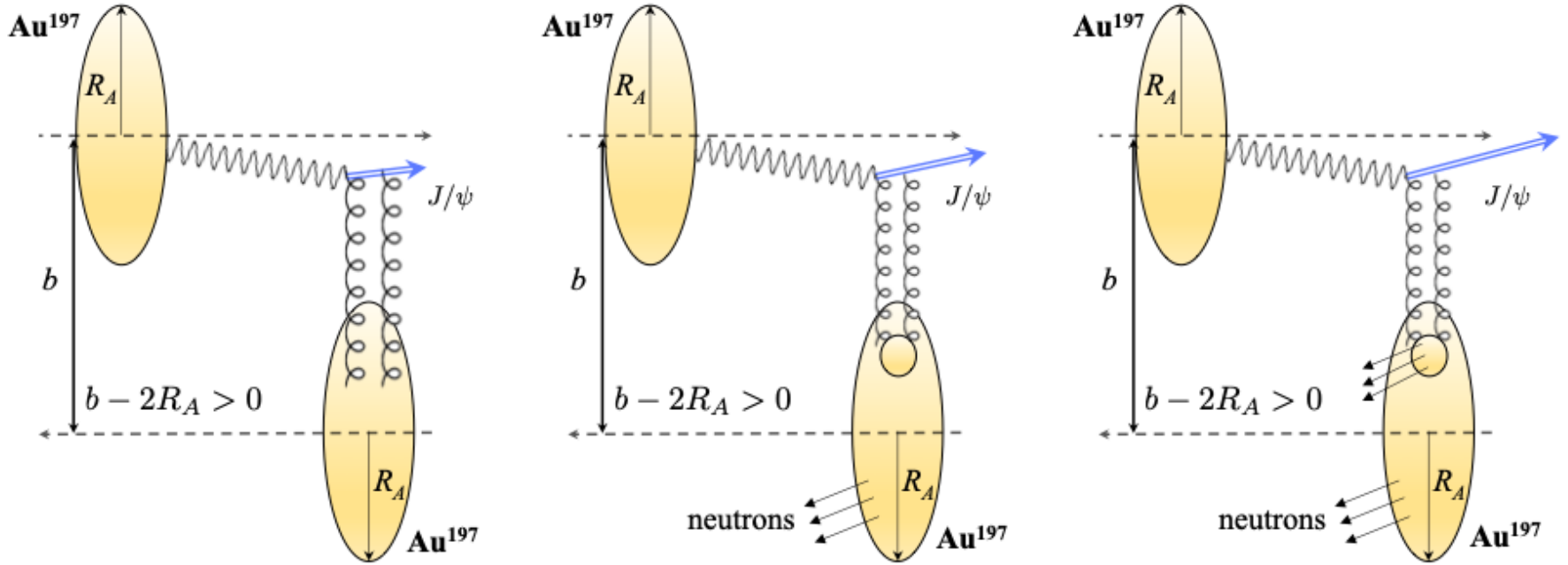
Deuteron incoherent breakup:

a) Saturation model suggests strong sub-nucleonic shape or density fluctuation – driven by nucleon dissociation.

b) Shadowing model suggests to have NO nucleon dissociation.

These two explanations can't be right at the same time

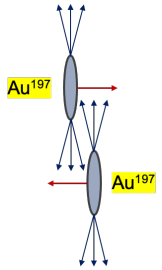
AuAu UPCs



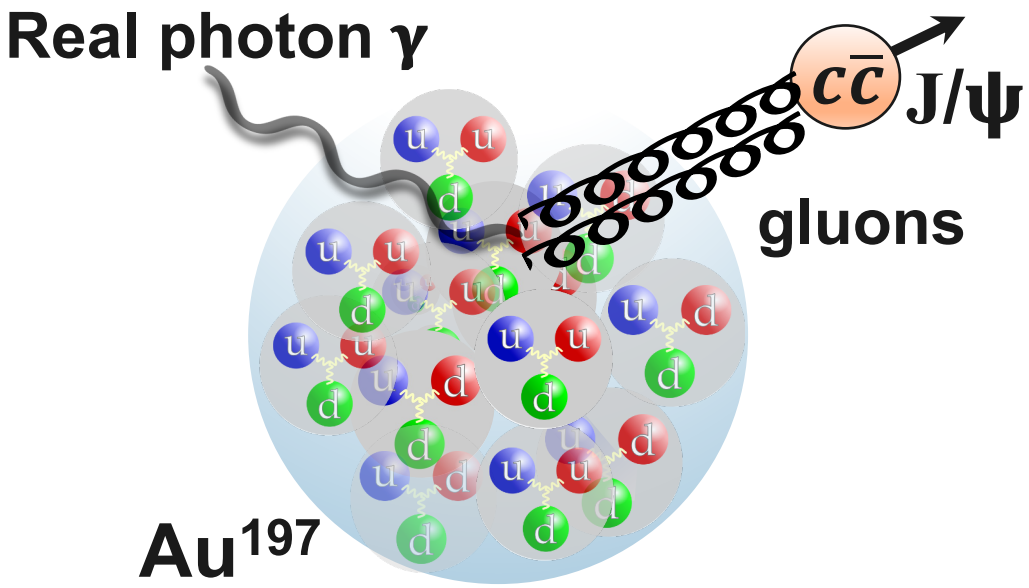
(a) Coherent with nucleus stays intact

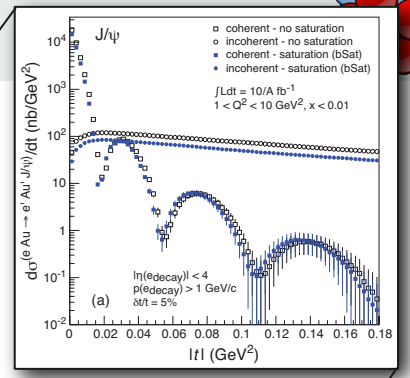
(b) Incoherent with elastic nucleon

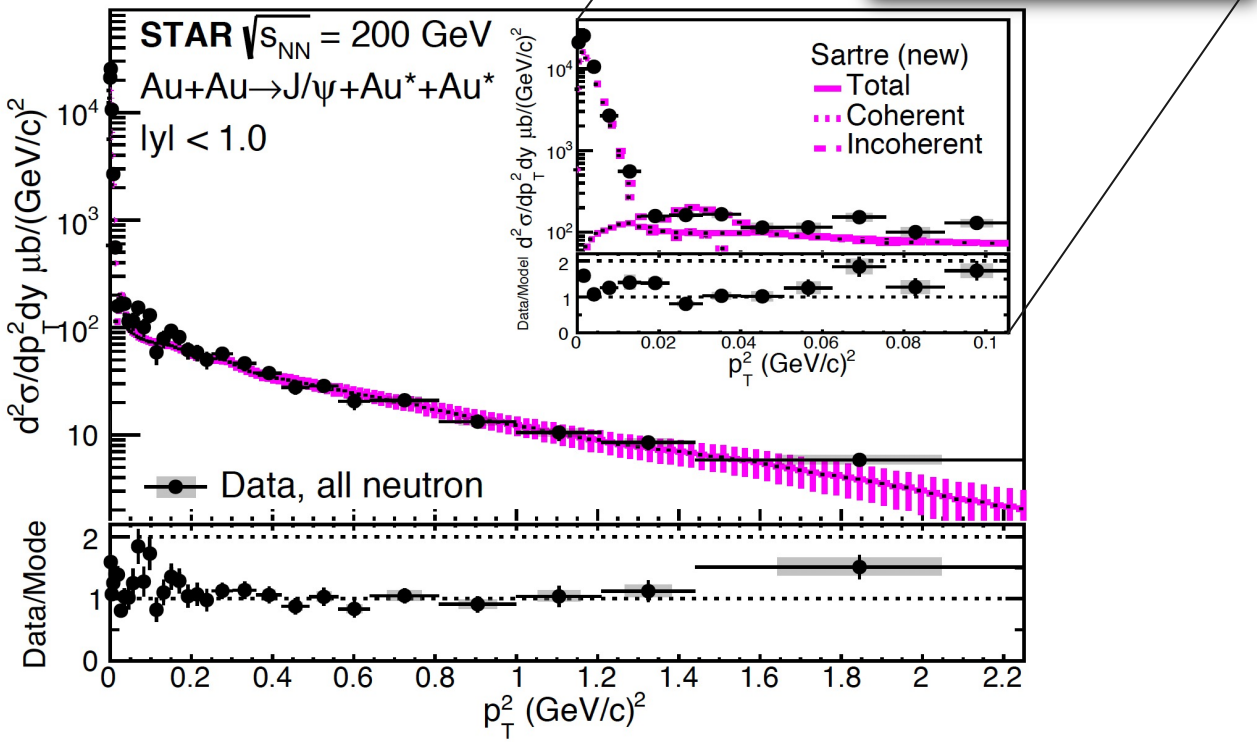
(c) Incoherent with nucleon dissociative



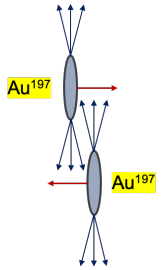
Imaging 3D gluon structure via AuAu UPCs



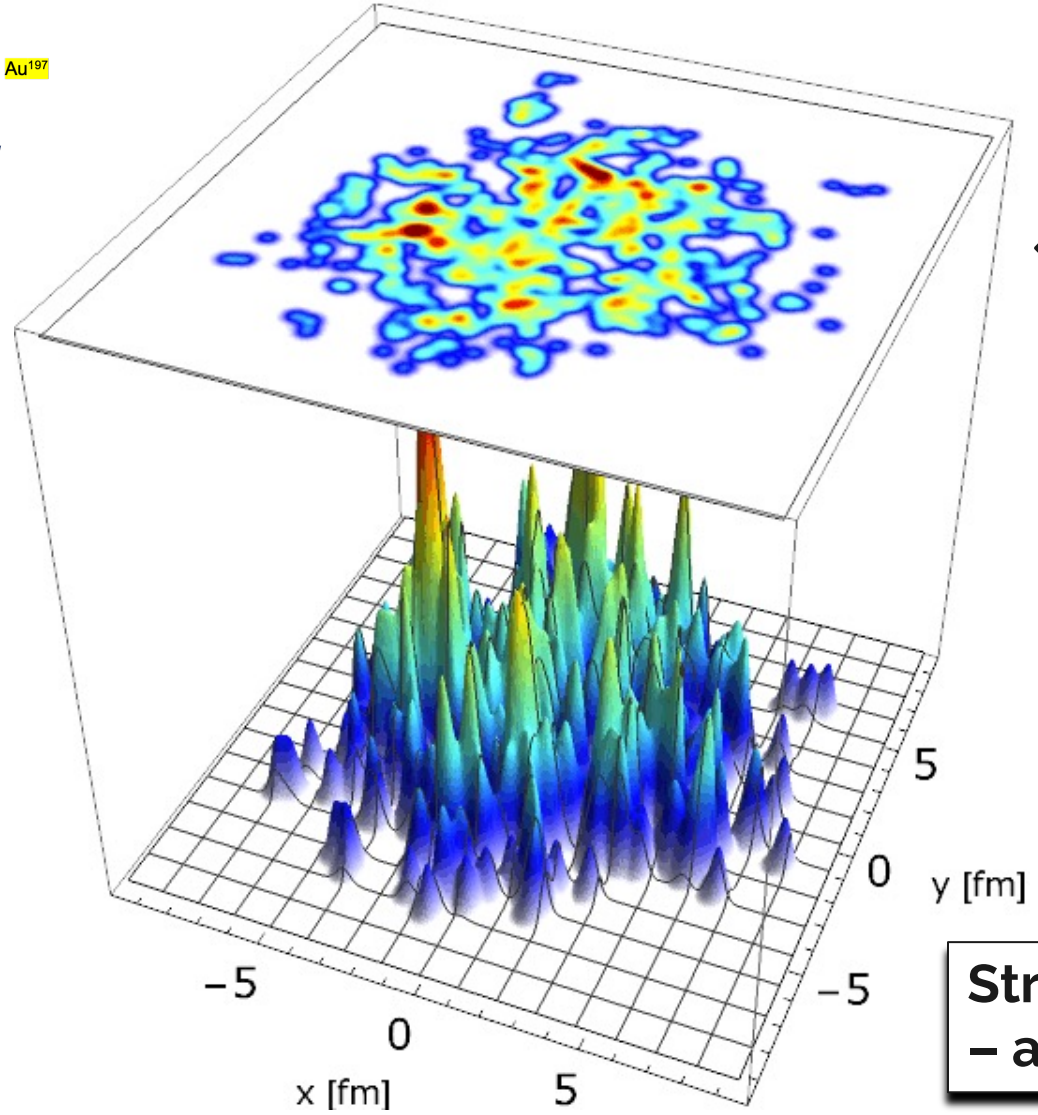


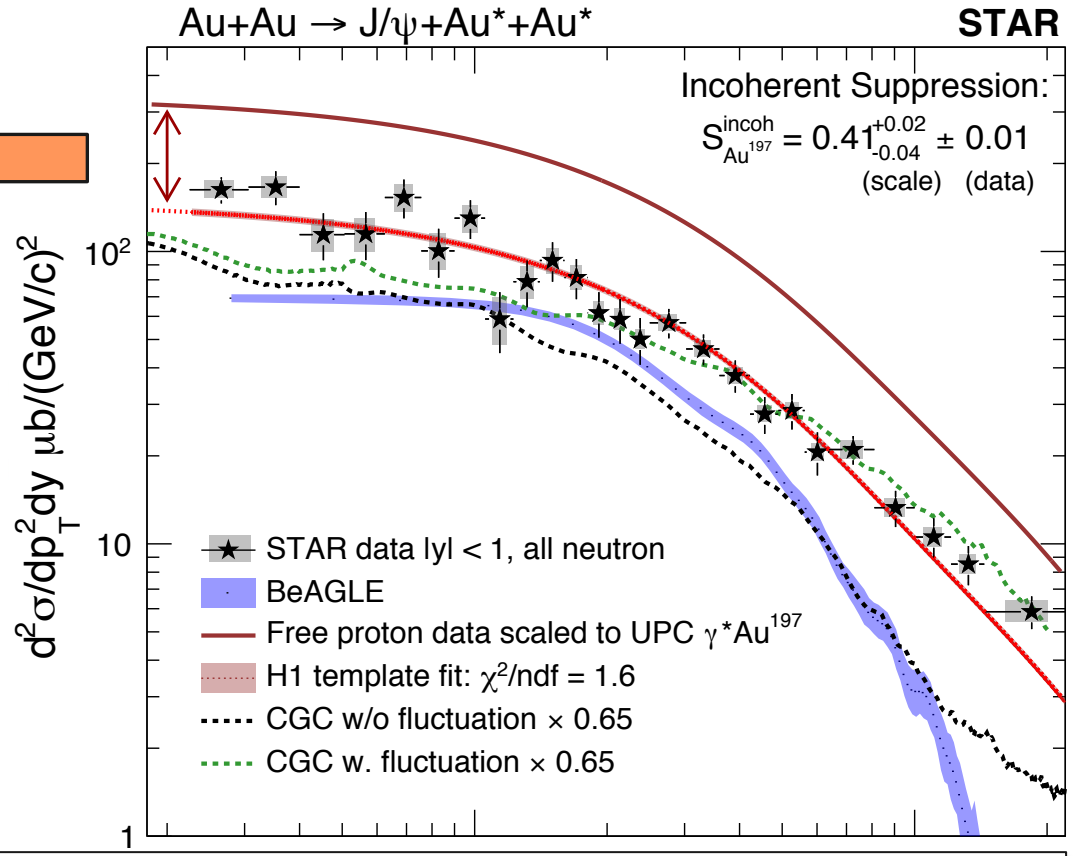


As expected, incoherent events dominate high momentum regime



Incoherent production = fluctuation

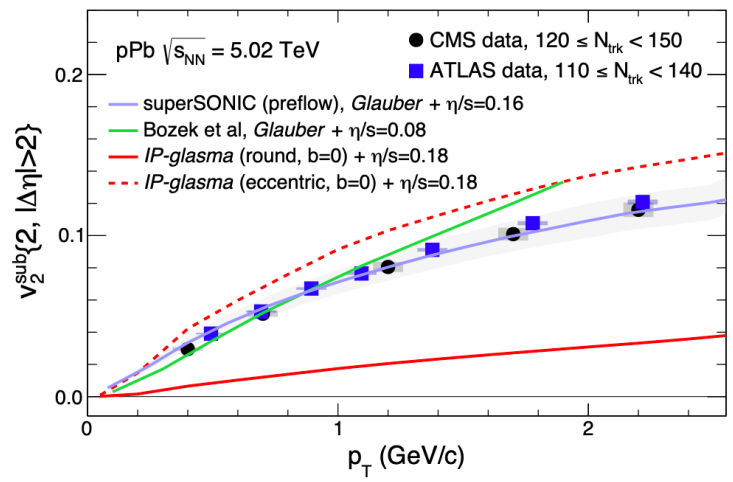




Strong evidence for gluon density fluctuation – an important input to HI hadronic collisions.

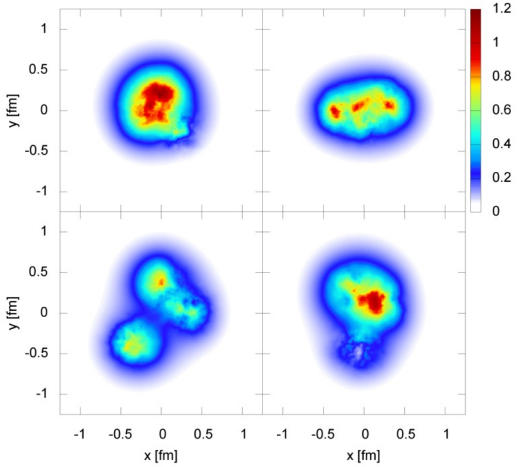
Remark: fluctuation plays an important role

Round proton
vs fluctuating proton



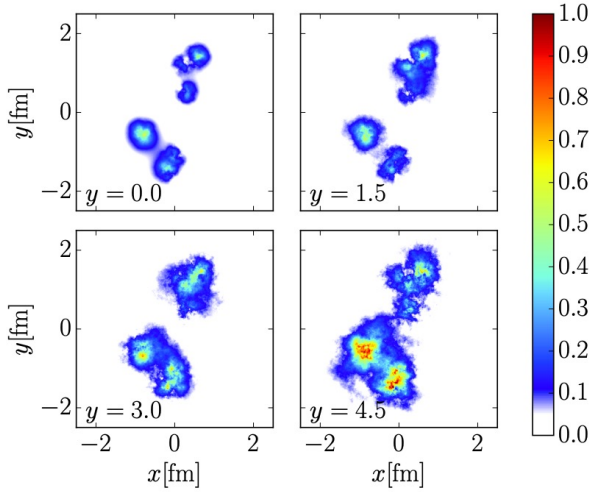
pPb v_2 → fluctuations

Phys. Rev. Lett. 117
(2016) 5, 052301



proton

Phys. Rev. C 101
(2020) 1, 015203



deuteron

. . .

Density fluctuation was a big step forward in understanding the HI flow data

Many more new data from STAR, but wait for DIS 2023

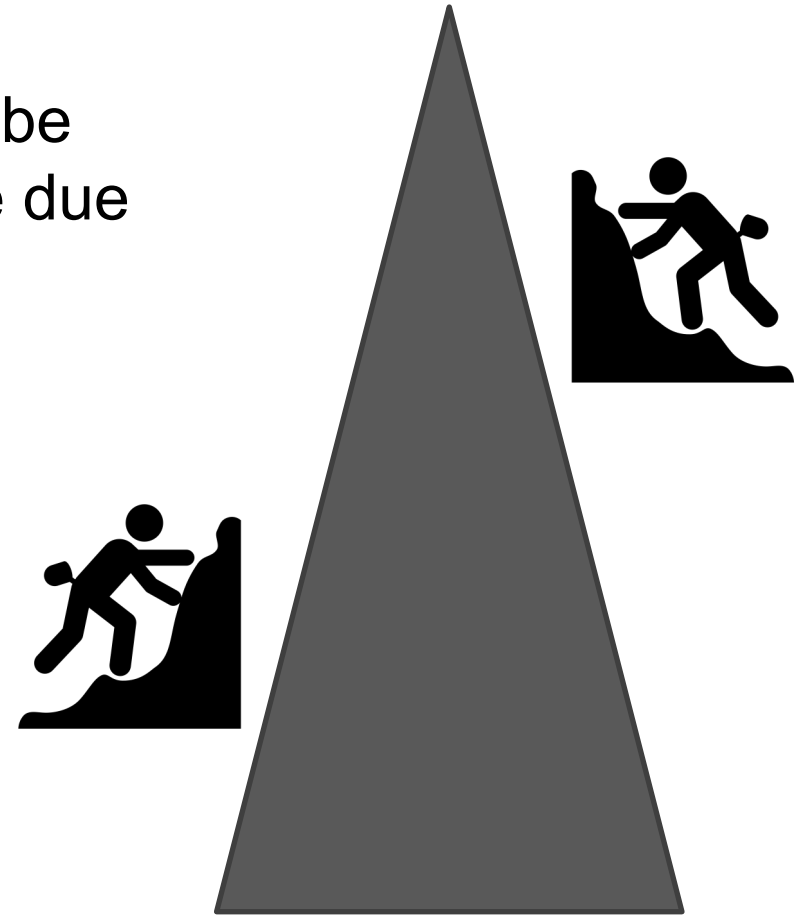
- Shine new lights to parton structure in heavy nuclei;
- Comparisons with many models and NLO;
- and more…

Climbing the same mountain from different sides

A different route to the top? Entanglement in proton

Proton is an entangled system – in fact, this might be the best example of an entangled system in nature due to QCD **confinement**.

$$|p\rangle = |qqq\rangle \otimes |ggg\rangle \otimes |qgqq..\rangle \otimes ...$$



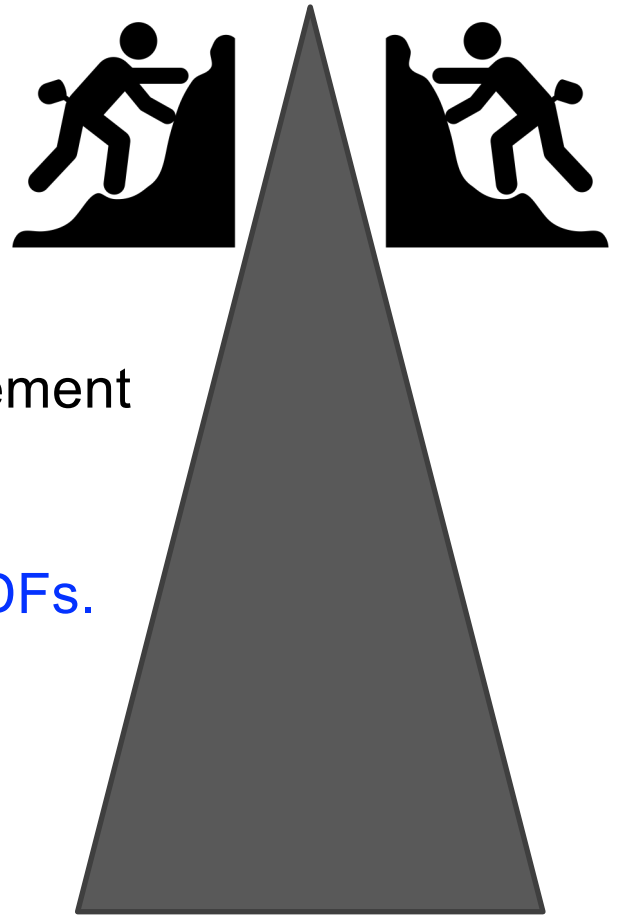
Maximally entangled ≅ Saturation?

***Entanglement* implications:**

i) Thermalization in pp collisions. [Baker & Kharzeev];

ii) Proton is in a *maximally entangled* state at low-x. Entanglement Entropy (EE) is related to $xg(x,Q^2)$. [Kharzeev & Levin]

iii) At low-Q^2, EE applies to non-perturbative regime unlike PDFs.



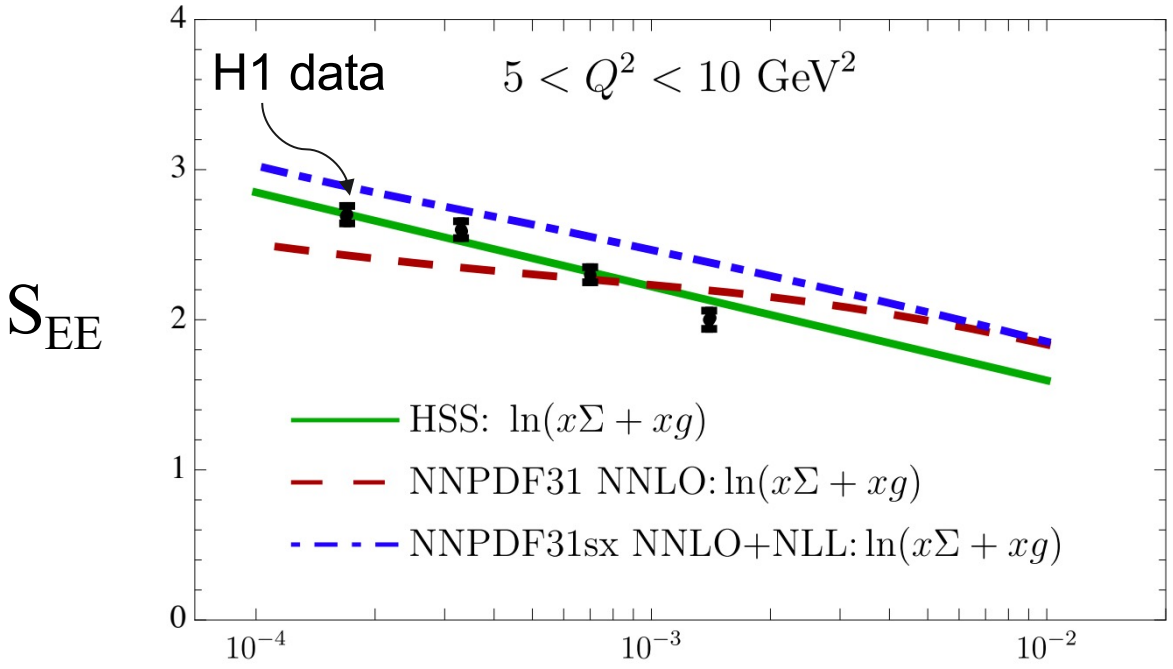
maximally entangled
$S_{EE} = \ln[xg(x,Q^2)]$

$\cong$

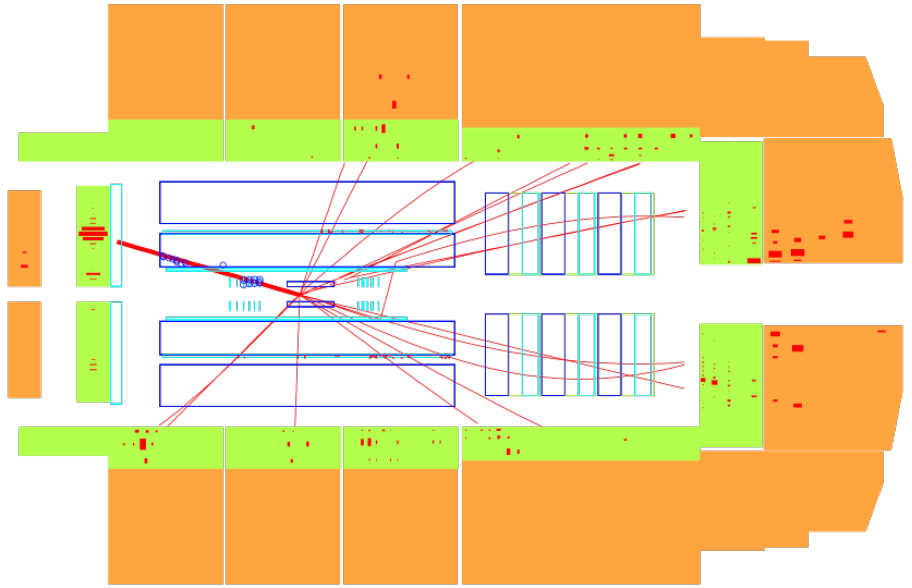
Gluon saturation?
$xg(x,Q^2)$

Observation of maximally entangled proton

Hentschinski, Kutak (2021)



H1 @HERA ep 27x920 GeV DIS



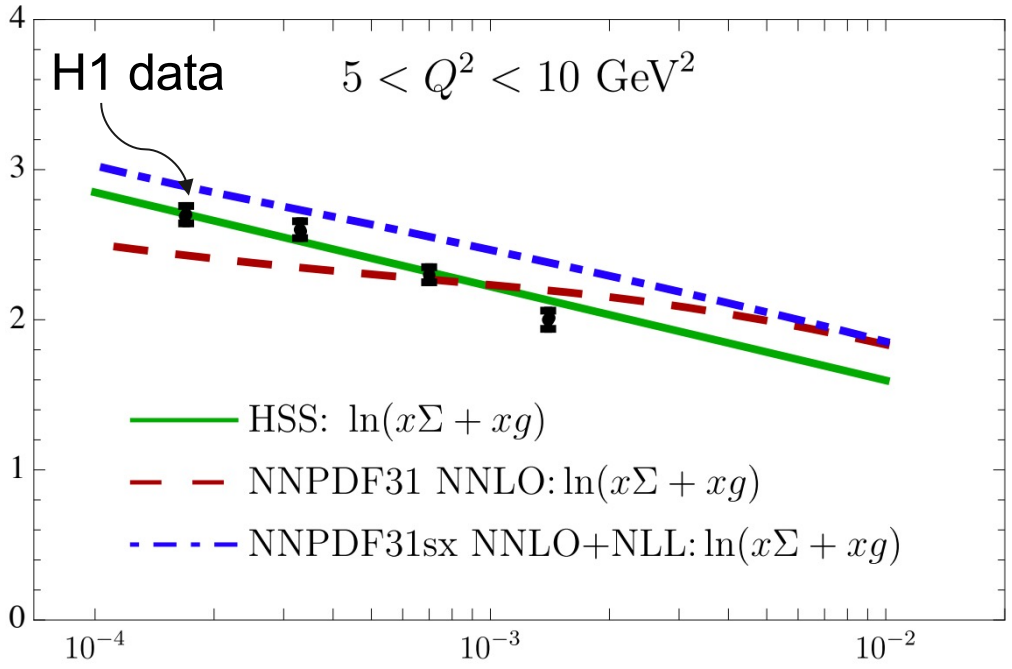
I joined H1 experiment 12 years after it was shutdown

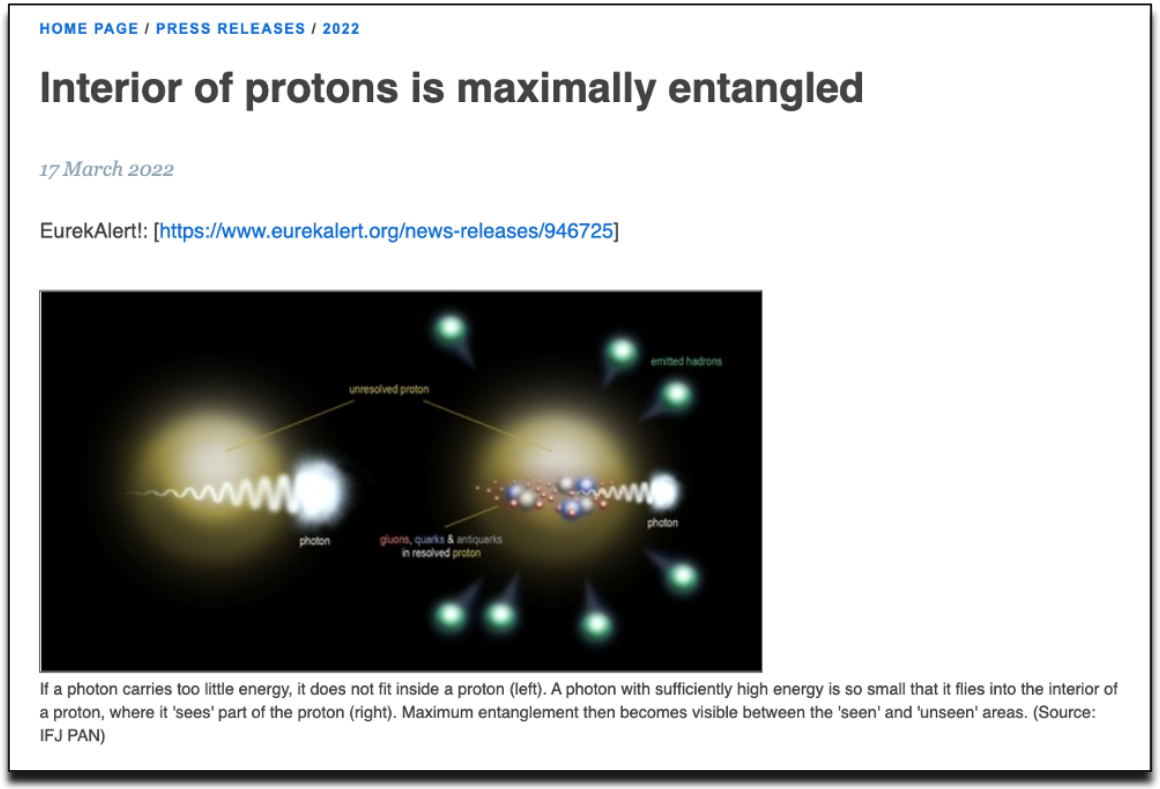
ep Deep Inelastic Scattering data at ~ 320 GeV showed indication of maximally entangled proton

Observation of maximally entangled proton

Hentschinski, Kutak (2021)

S_{EE}

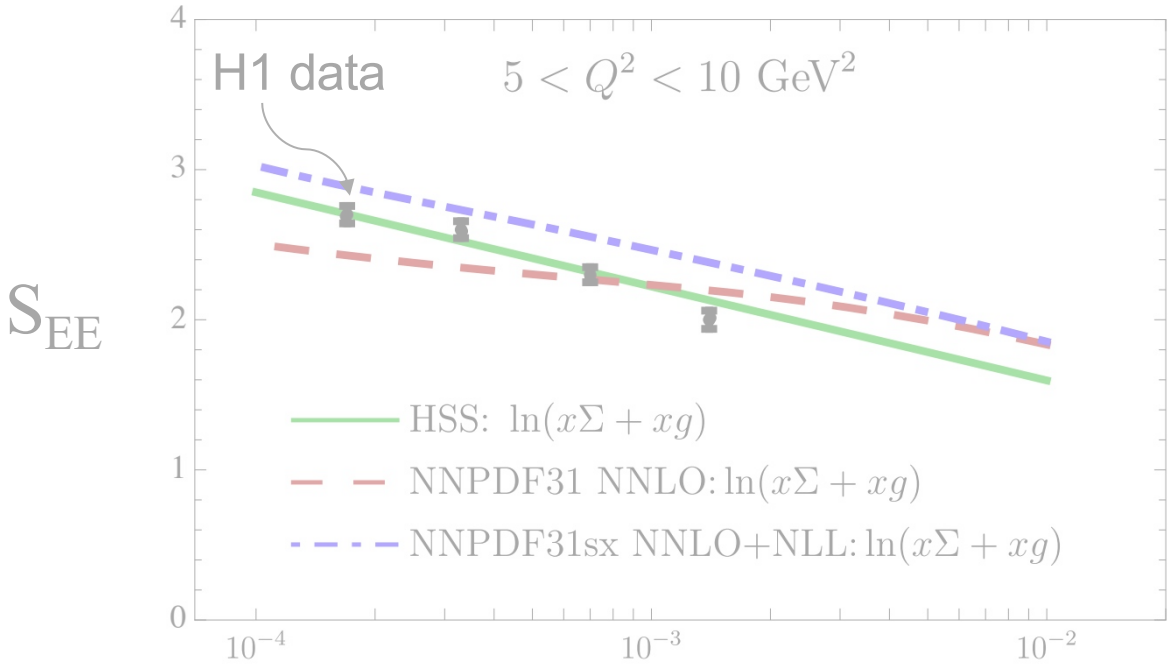




ep Deep Inelastic Scattering data at ~ 320 GeV showed indication of maximally entangled proton

Observation of maximally entangled proton

Hentschinski, Kutak (2021)



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Interior of protons is maximally entangled

Further reading

- **Science News Article**
  [https://www.sciencenews.org/article/experiment-hints-quantum-entanglement-inside-protons]
- **ZT***, Kharzeev, Ullrich (2020)
  [Phys. Rev. Lett. 124, 062001]
- H1 Collaboration (2021)
  [Eur. Phys. J. C (2021) 81: 212]
- M. Hentschinski, K. Kutak
  [Eur.Phys.J.C 82 (2022) 2, 111]

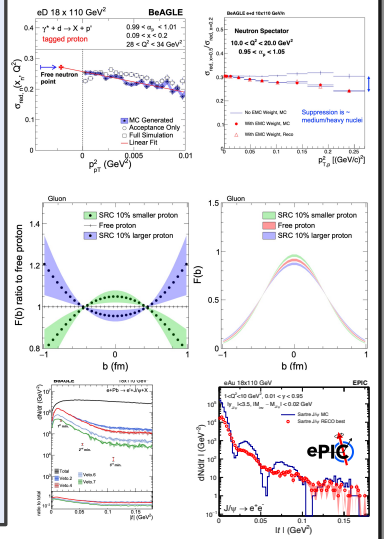
ep Deep Inelastic Scattering data at ~ 320 GeV showed indication of maximally entangled proton

Summary – parton structure & fluctuation

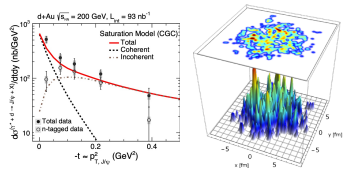
Established a new EIC program enabled by **forward tagging** – Deuteron

- Unique measurement of "two sides of the same coin"- **free vs bound nucleon**;
- **Gluon tomography** of nucleon.

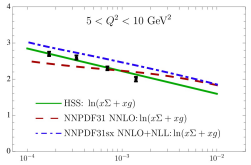
Established experimental program to realize the EIC **Golden Channel.**

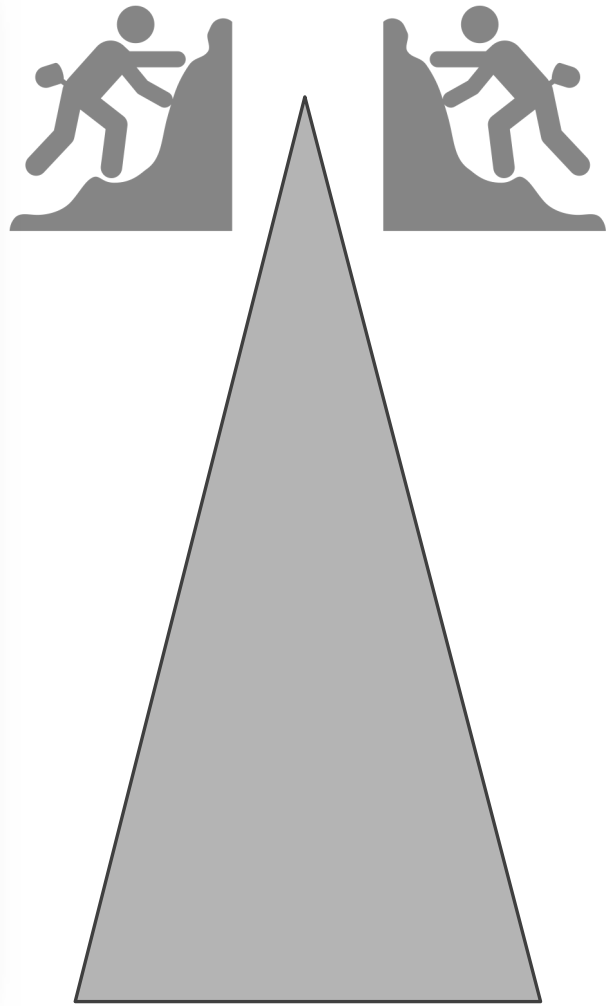


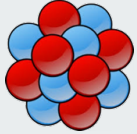
UPC in heavy-ion program (dAu, AuAu, …)
– a complementary program to EIC science



DIS at HERA – entanglement entropy
- A new way to describe parton structure



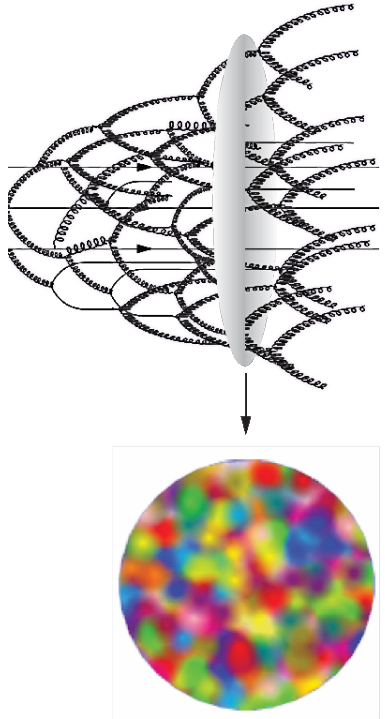




Backup

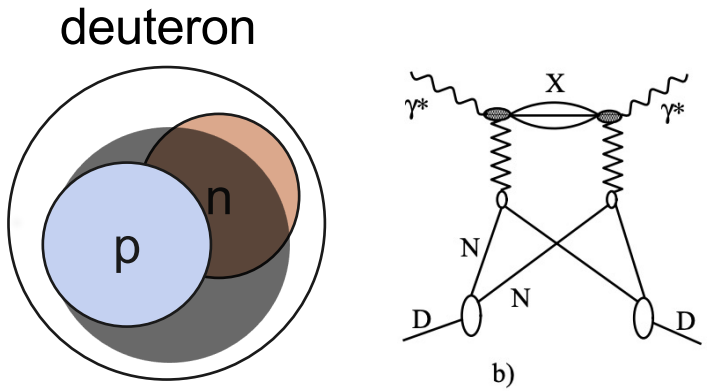
A reminder – Saturation vs (nuclear) Shadowing

1. Saturation model (CGC)



First-principle tells us gluon density $xg(x,Q^2)$ cannot be infinite!

2. Shadowing model (LTA)



$xg(x,Q^2)$ is not changed, but effectively suppressed in nuclei from interference.

In nuclei, saturation effect is stronger; in proton, no shadowing effect

Reconstruction method of $-t$

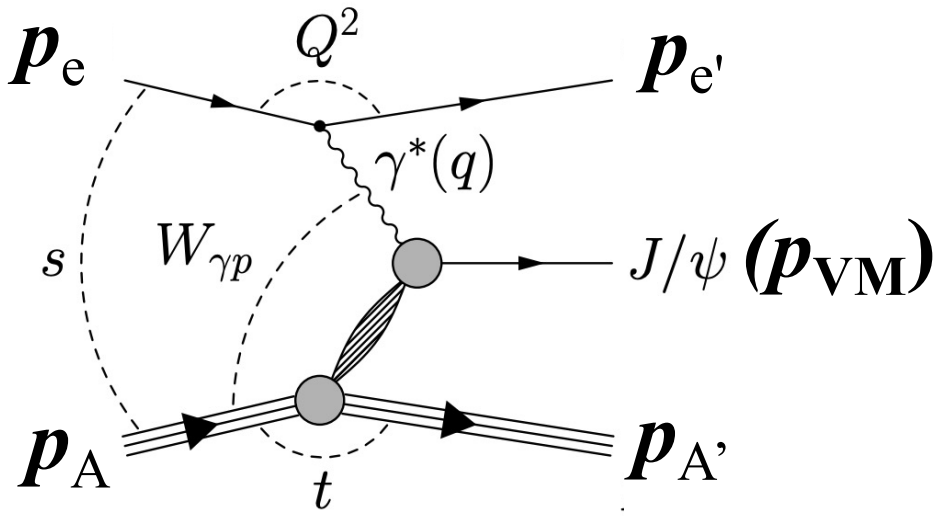
- Method Exact (E):
- Method Approximate (A) (UPCs)
- Improved Method E: Method L

$$-t = -(\boldsymbol{p}_e - \boldsymbol{p}_{e'} - \boldsymbol{p}_{VM})^2 = -(\boldsymbol{p}_{A'} - \boldsymbol{p}_A)^2$$

$$-t = (\vec{p}_{T,e'} + \vec{p}_{T,VM})^2$$

$$-t = -(\boldsymbol{p}_{A',corr} - \boldsymbol{p}_A)^2,$$

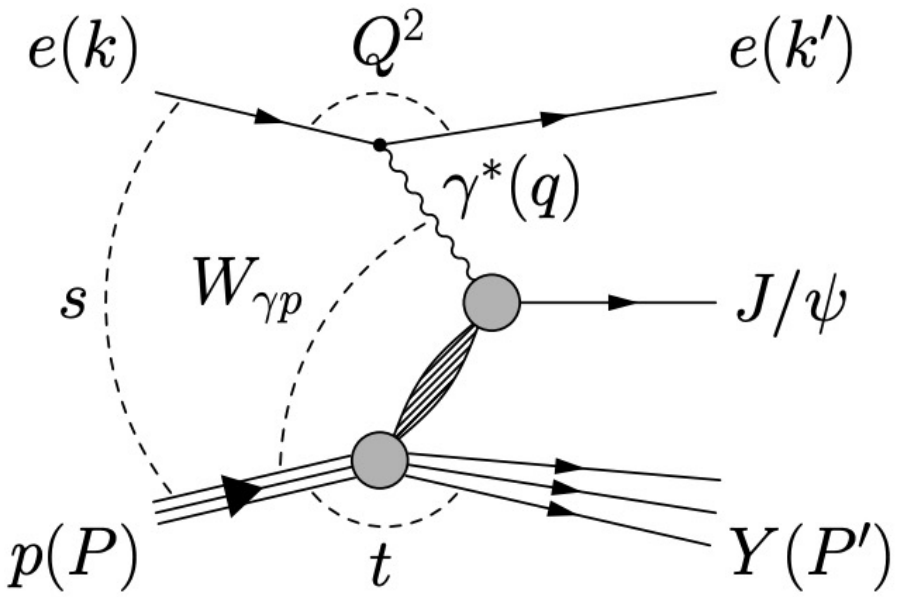
where $\boldsymbol{p}_{A',corr}$ is constrained by exclusive reaction.



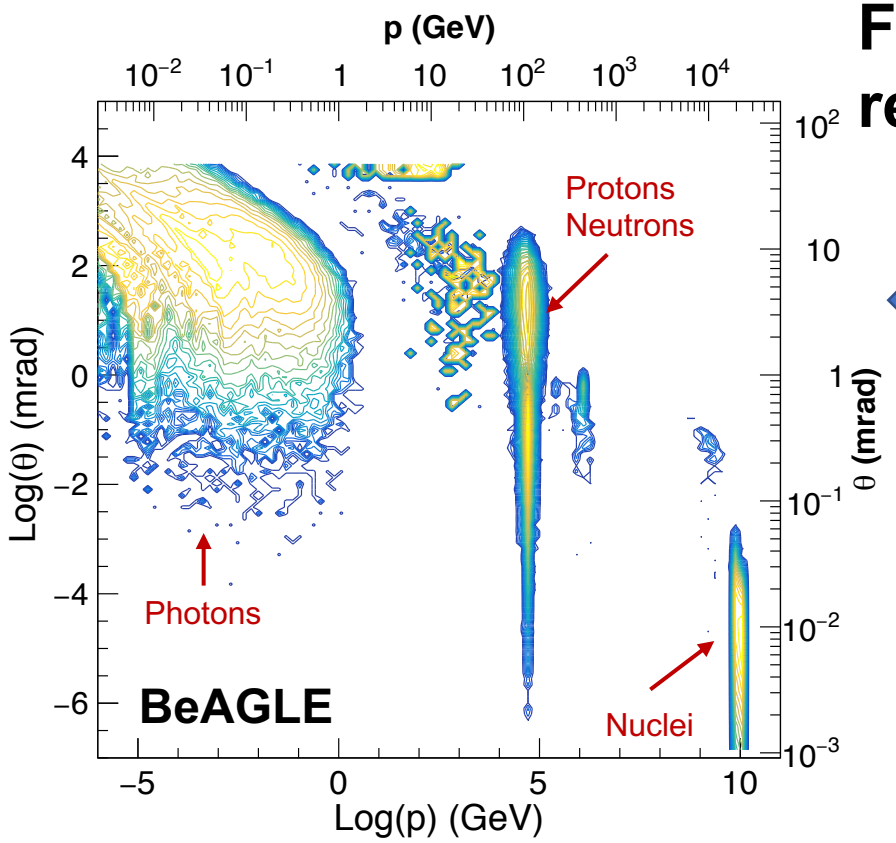
Best method concluded from the EIC Yellow Report – **Method L**

- Insensitive to beam effects, e.g., angular divergence and momentum spread.
- More precise than Method A for electroproduction

Incoherent background



Proton or nucleus dissociation



Far-forward region

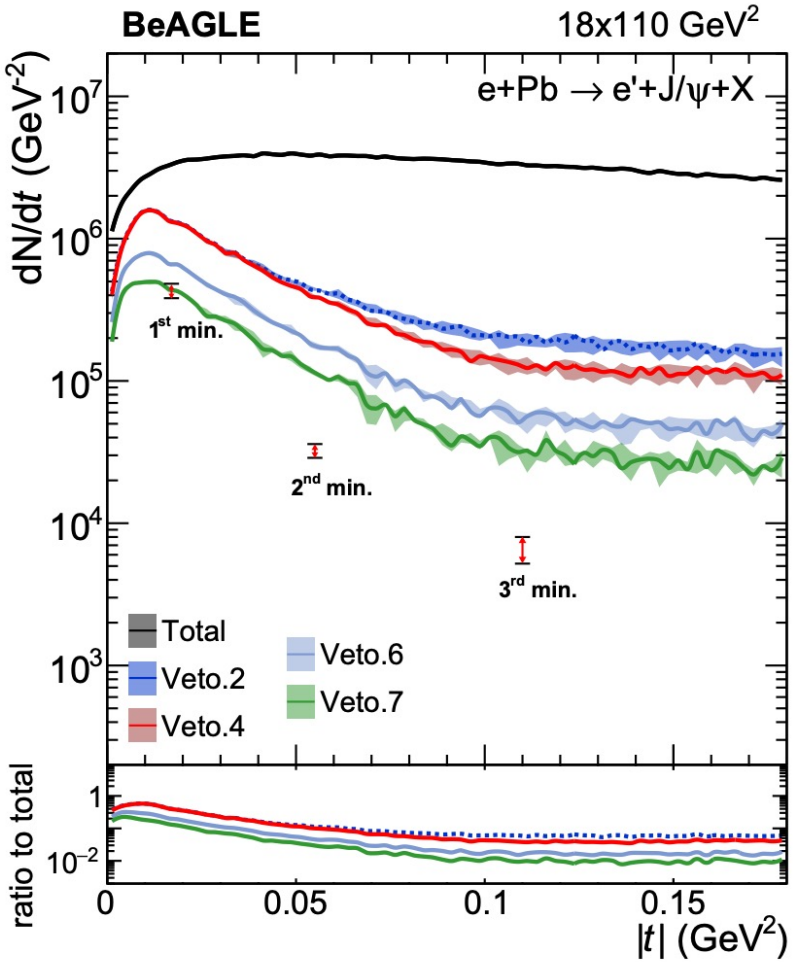
- *Incoherent itself is a great interest*, but it is the major background to the coherent case.
- Far-forward region is busy! Many breakup particles, e.g., protons, neutrons, photons, and nuclei
- BeAGLE – general-purpose eA MC, see https://eic.github.io/software/beagle.html

Performance of background suppressions

- No neutrons in ZDC (veto 2)
- No proton in any forward detectors (veto 3-5)
- No photon > 50 MeV in B0 or ZDC (veto 6-7)
- Minima (1st min. 2nd min. 3rd min.) are from *Sartre* MC generator (slide 4-5). Only 5% resolution assumed.

➢Vetoing all of them is impossible. The question is how much is needed.

➢This result was used in ATHENA proposal



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Result – ATHENA Tracker only

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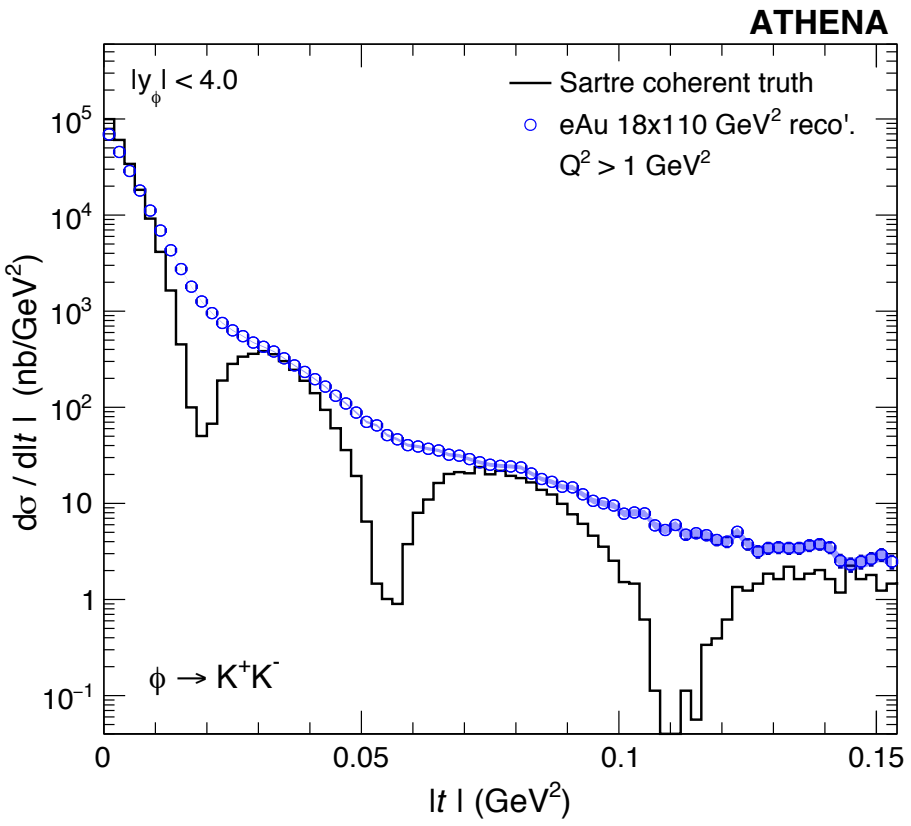

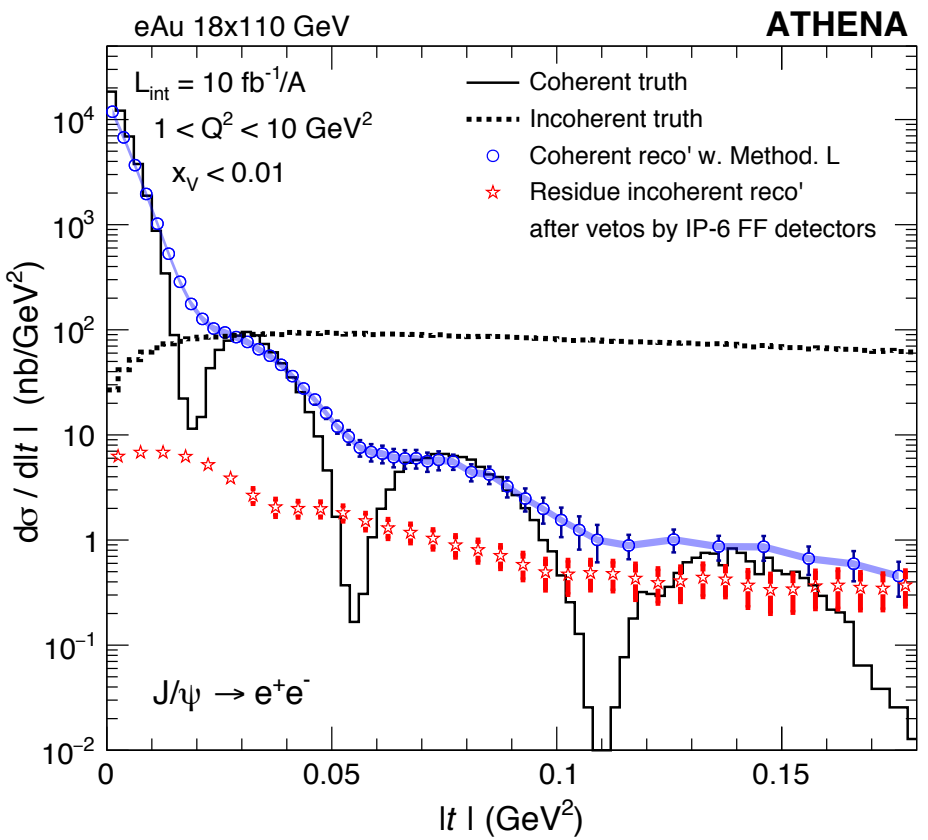

J/ψ

- Challenge 1: Incoherent background, but it only becomes an issue at high *–t;*
- Challenge 2: *Momentum resolution is not enough. Bottleneck - p_T resolution of the scattered electron.*