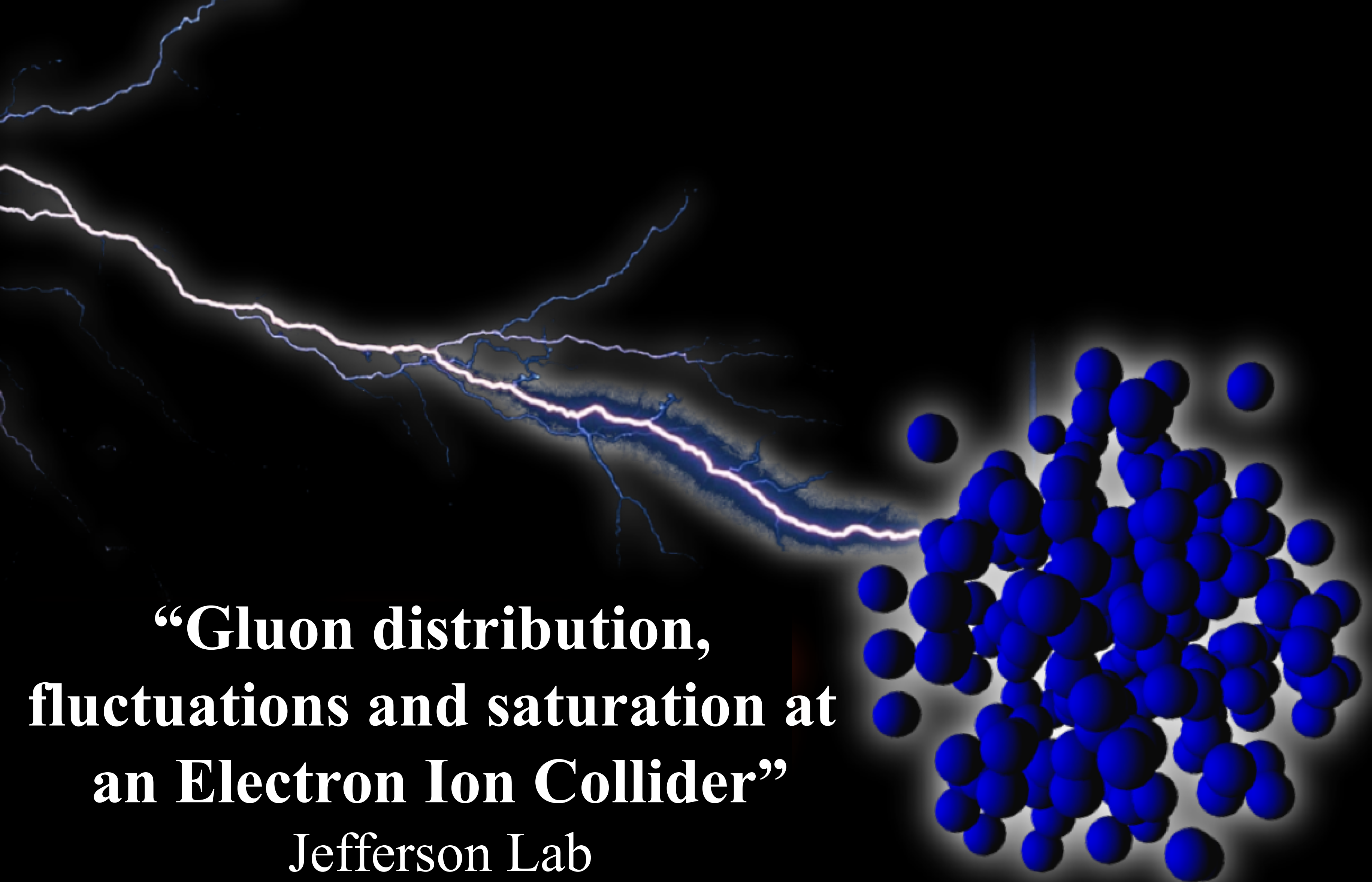


“Gluon distribution, fluctuations and saturation at an Electron Ion Collider”

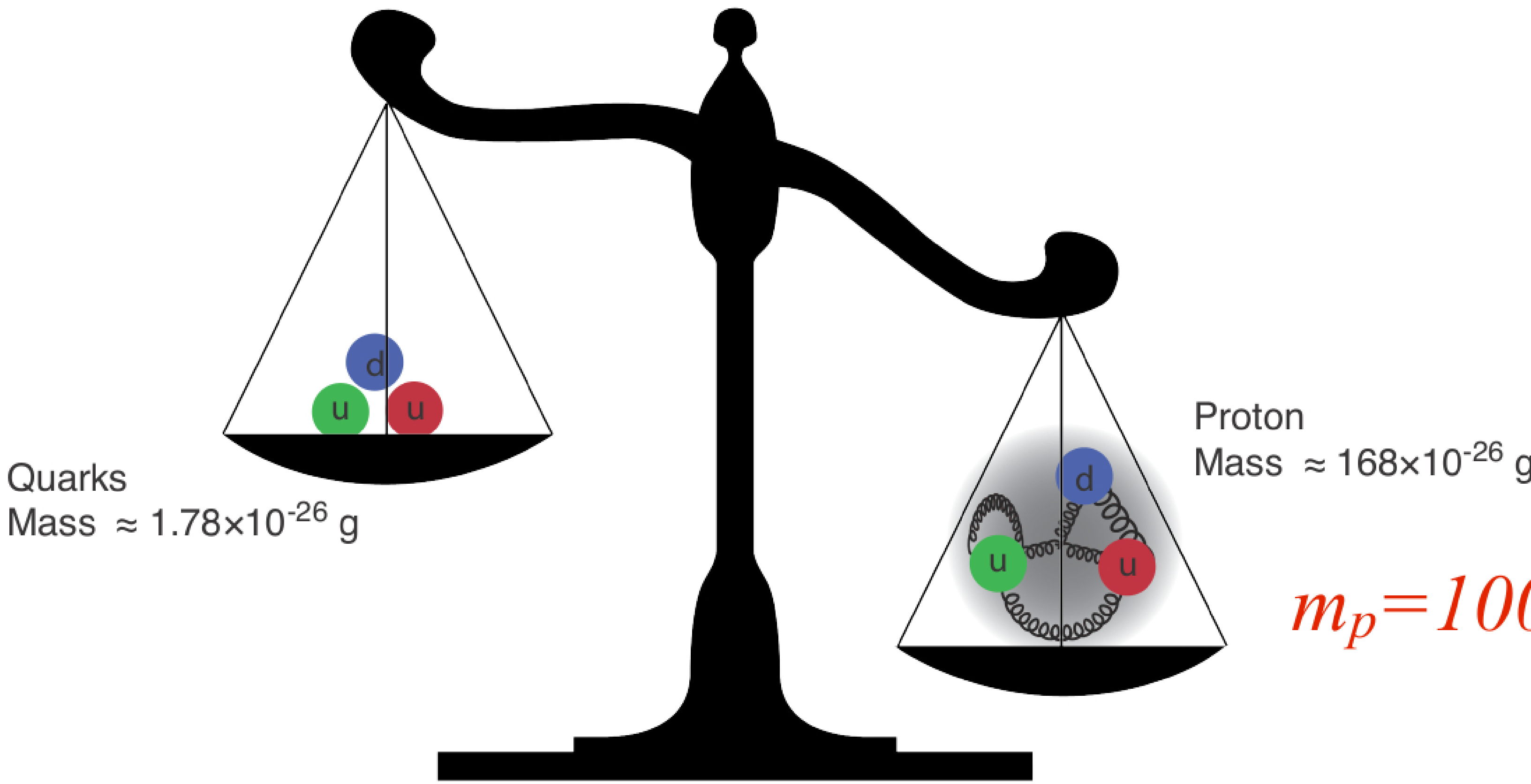
Jefferson Lab

June 16, 2017

Tobias Toll

Shiv Nadar University

The Hadron Mass Puzzle



$$m_p = 100 \sum m_q$$

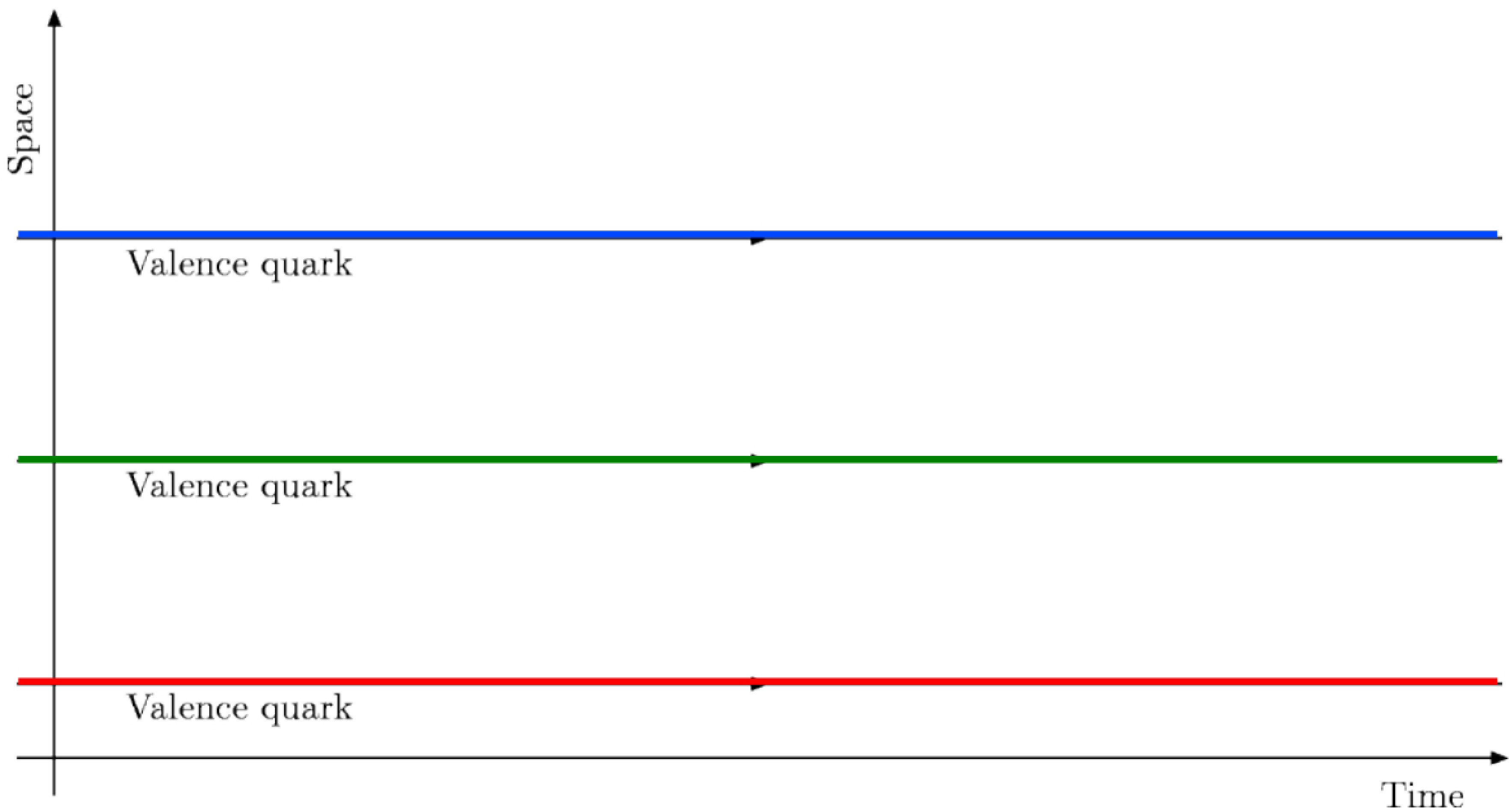
Quarks carry only ~1% of proton mass

Answer can come only from Quantum Chromodynamics

Gluons make up 98% of the visible mass of the universe!

Our Understanding of a Proton

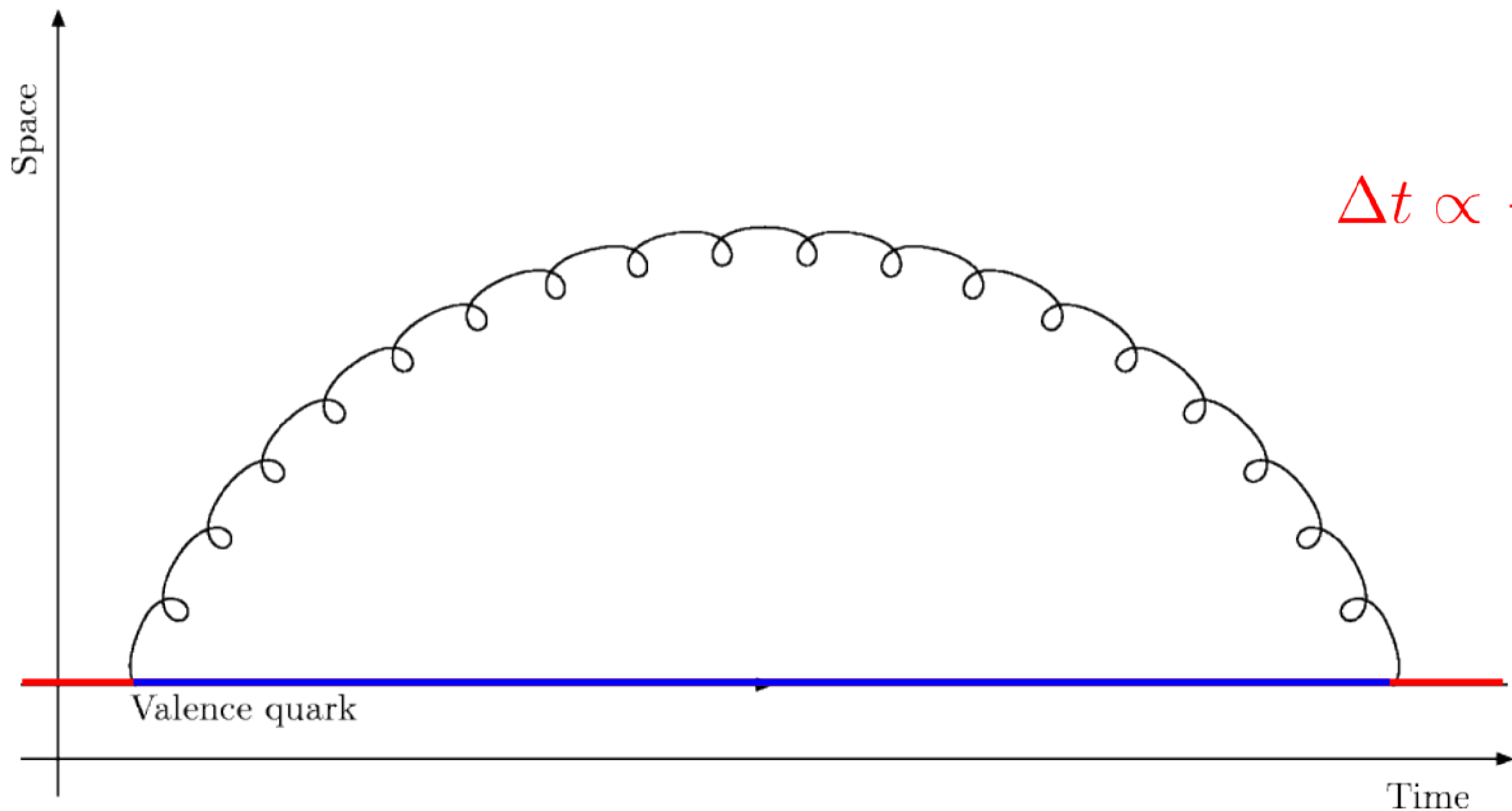
$x \approx 0.33$



Our Understanding of a Proton

$x \approx 0.17$

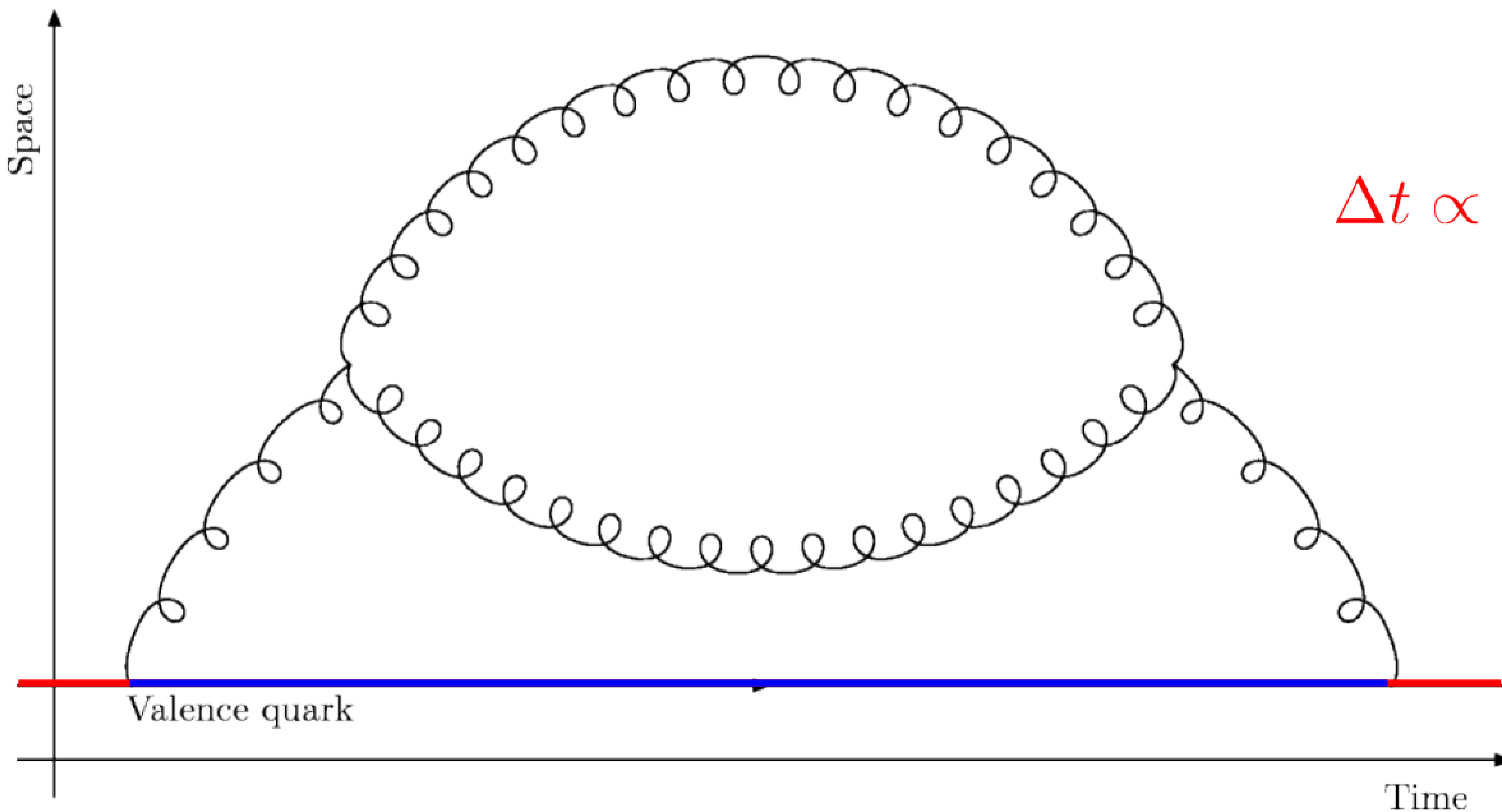
$\Delta t \propto \frac{1}{V}$



Our Understanding of a Proton

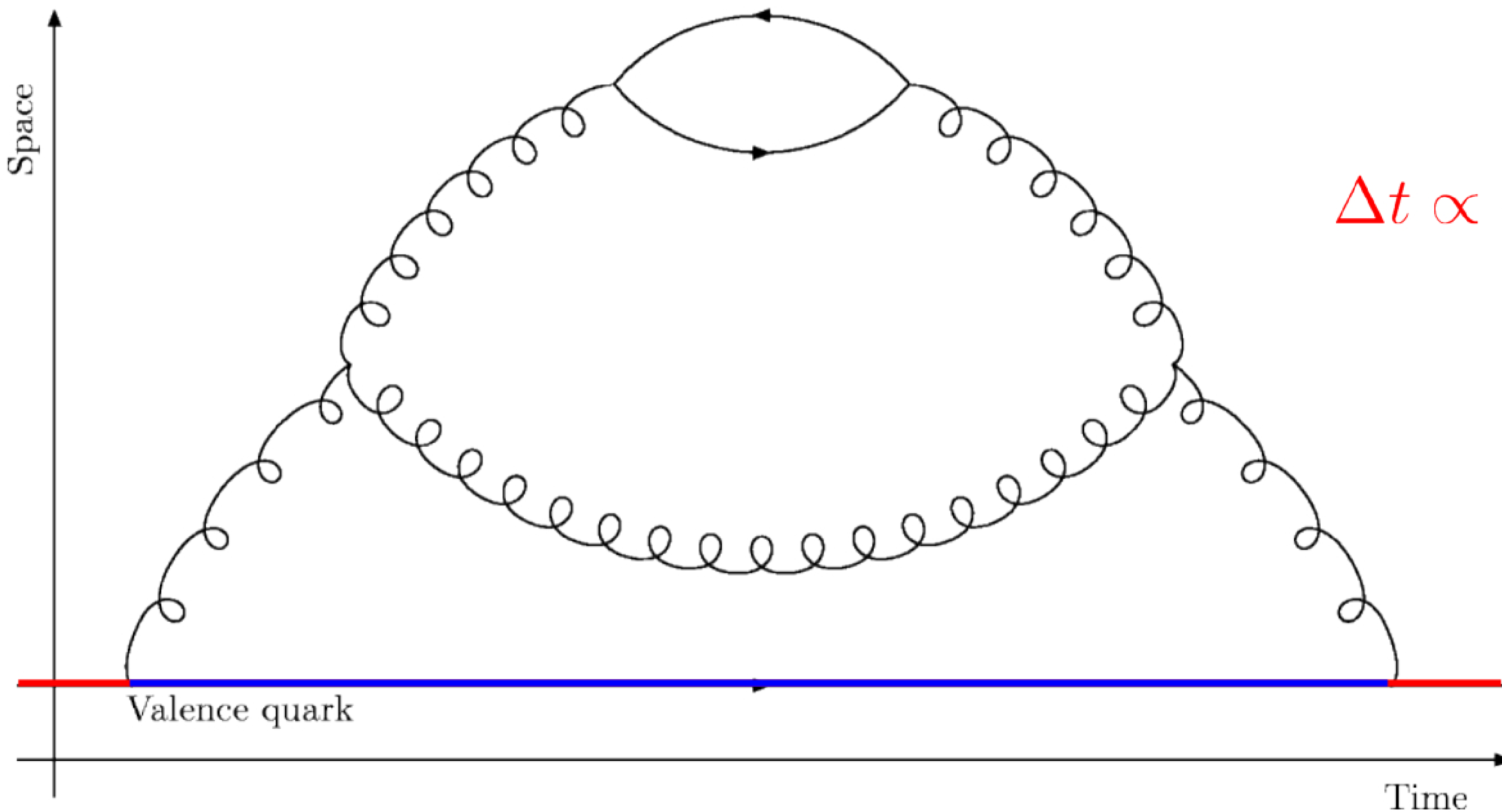
$x \approx 0.11$

$\Delta t \propto \frac{1}{V}$



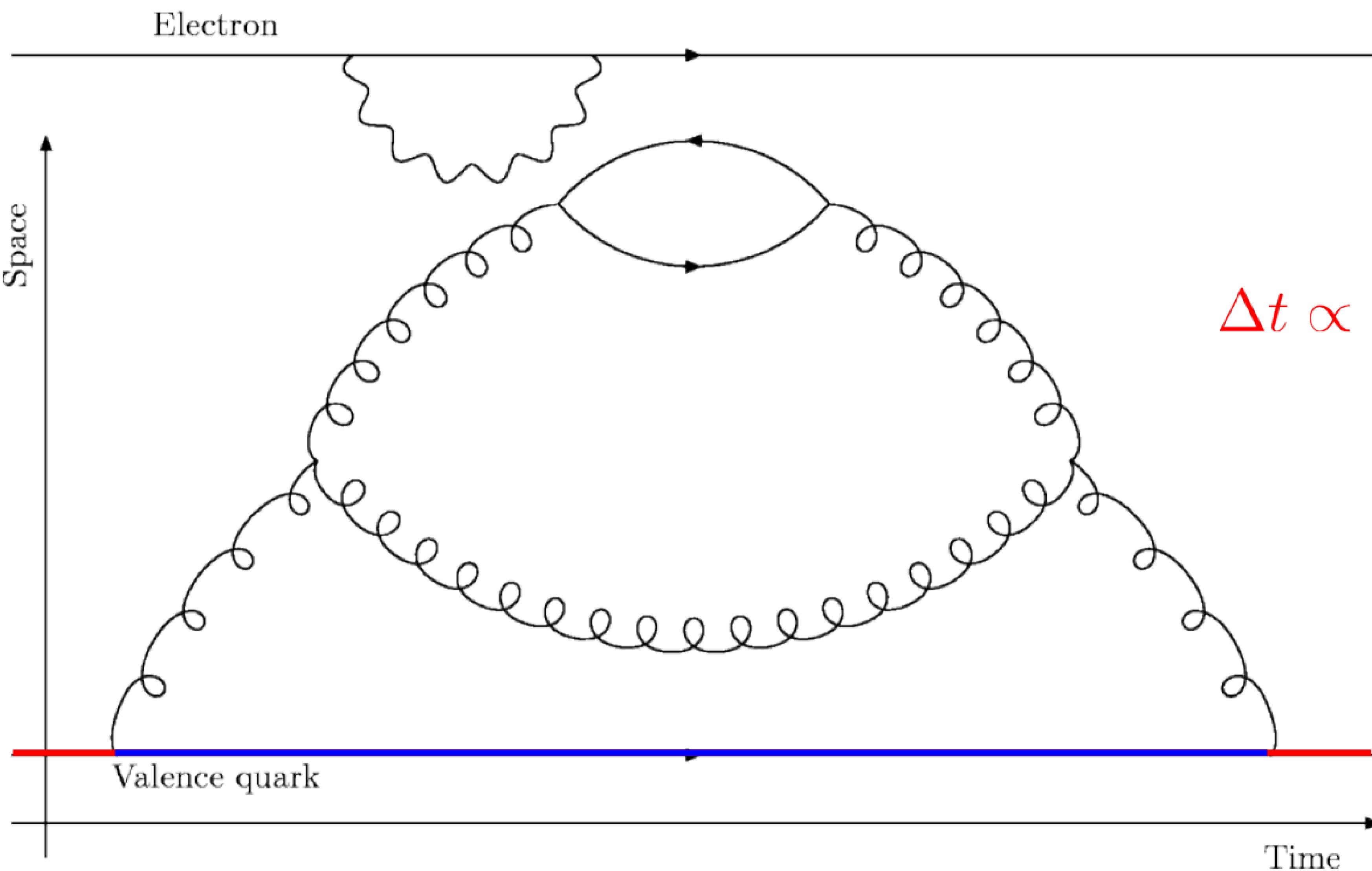
Our Understanding of a Proton

$x \approx 0.08$



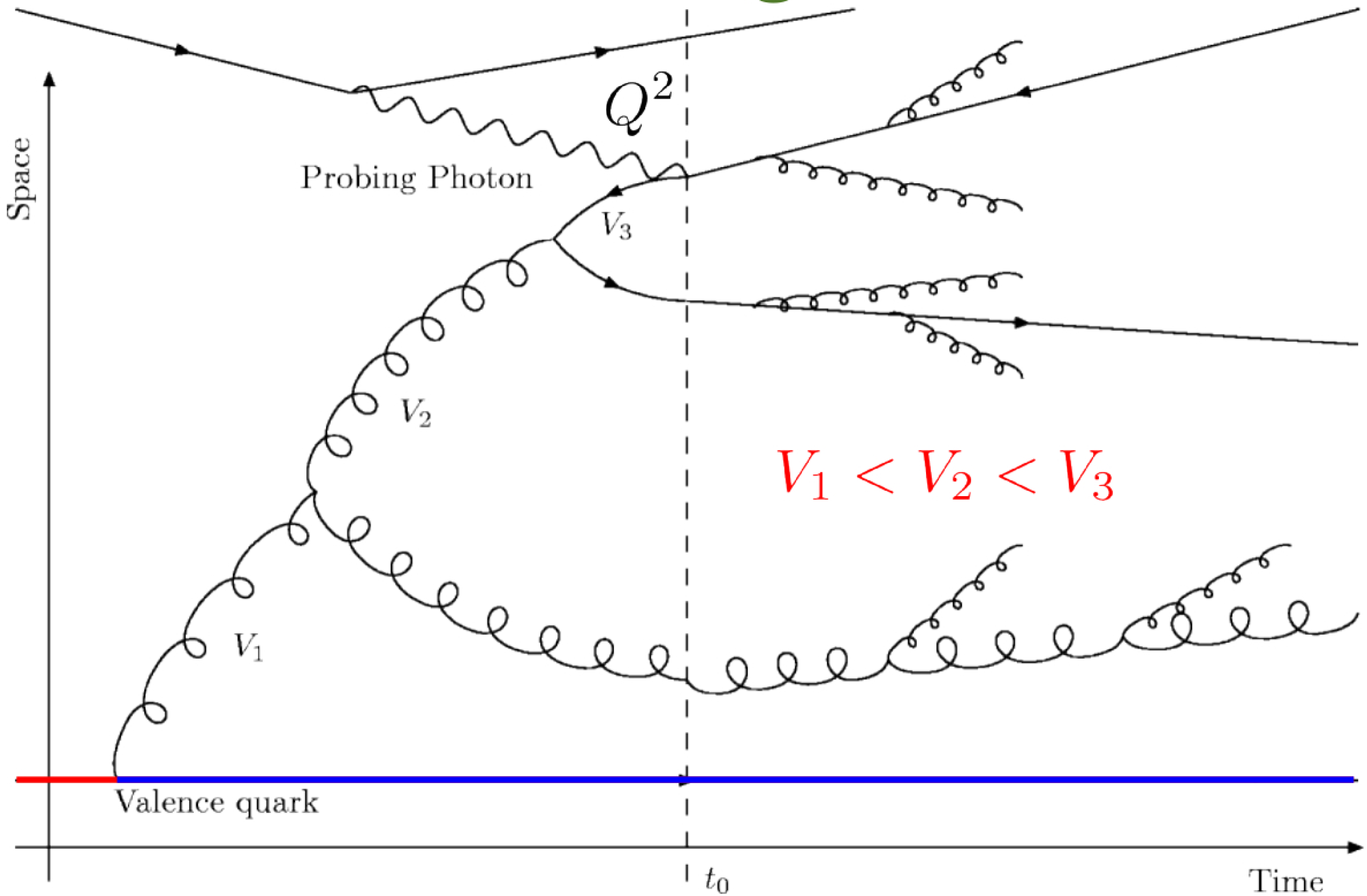
$\Delta t \propto \frac{1}{V}$

Our Understanding of a Proton



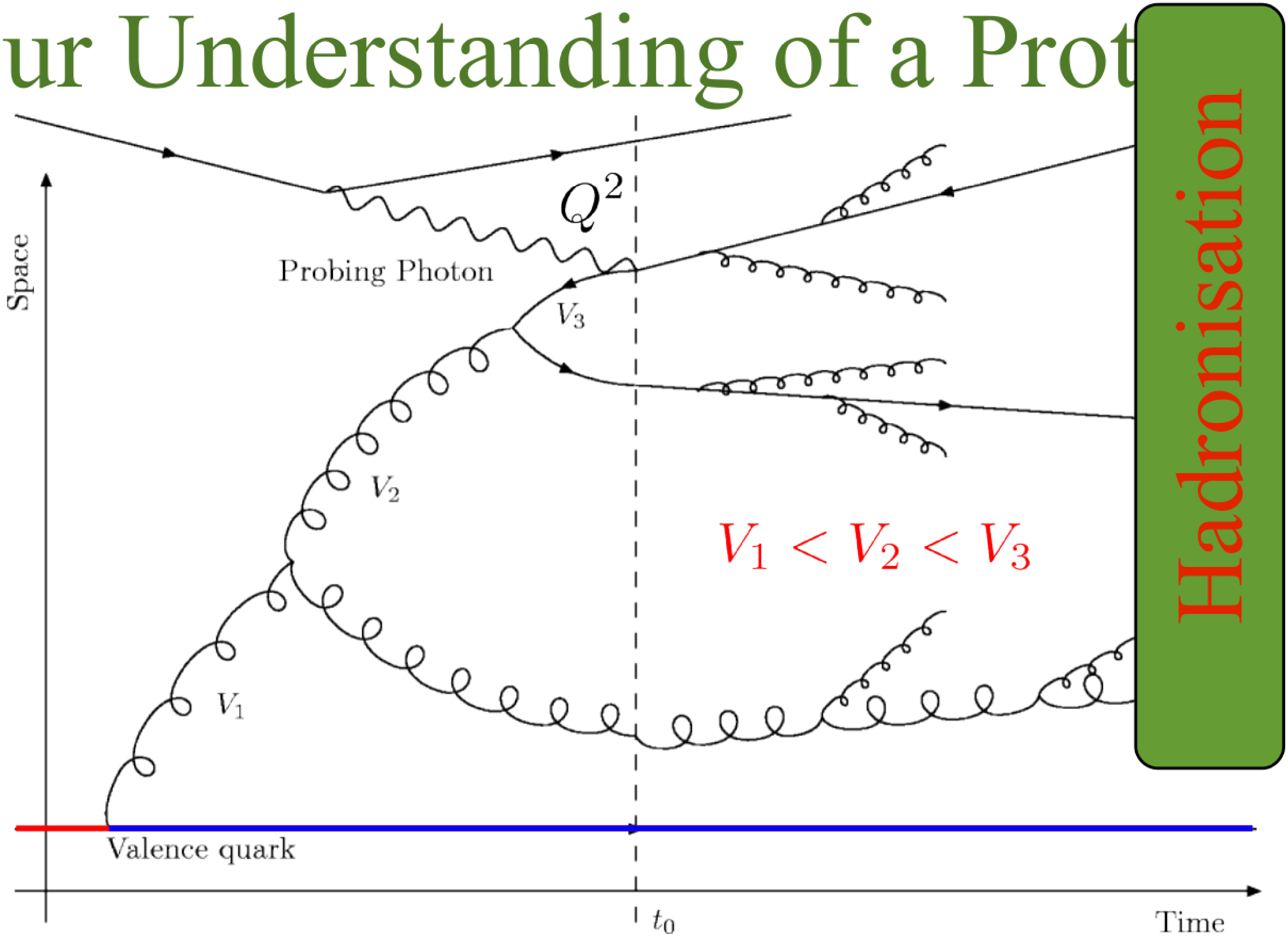
$$\Delta t \propto \frac{1}{V}$$

Our Understanding of a Proton



D*okshitzer* **G***ribov* **L***ipatov* **A***ltarelli* **P***arisi* **DGLAP**

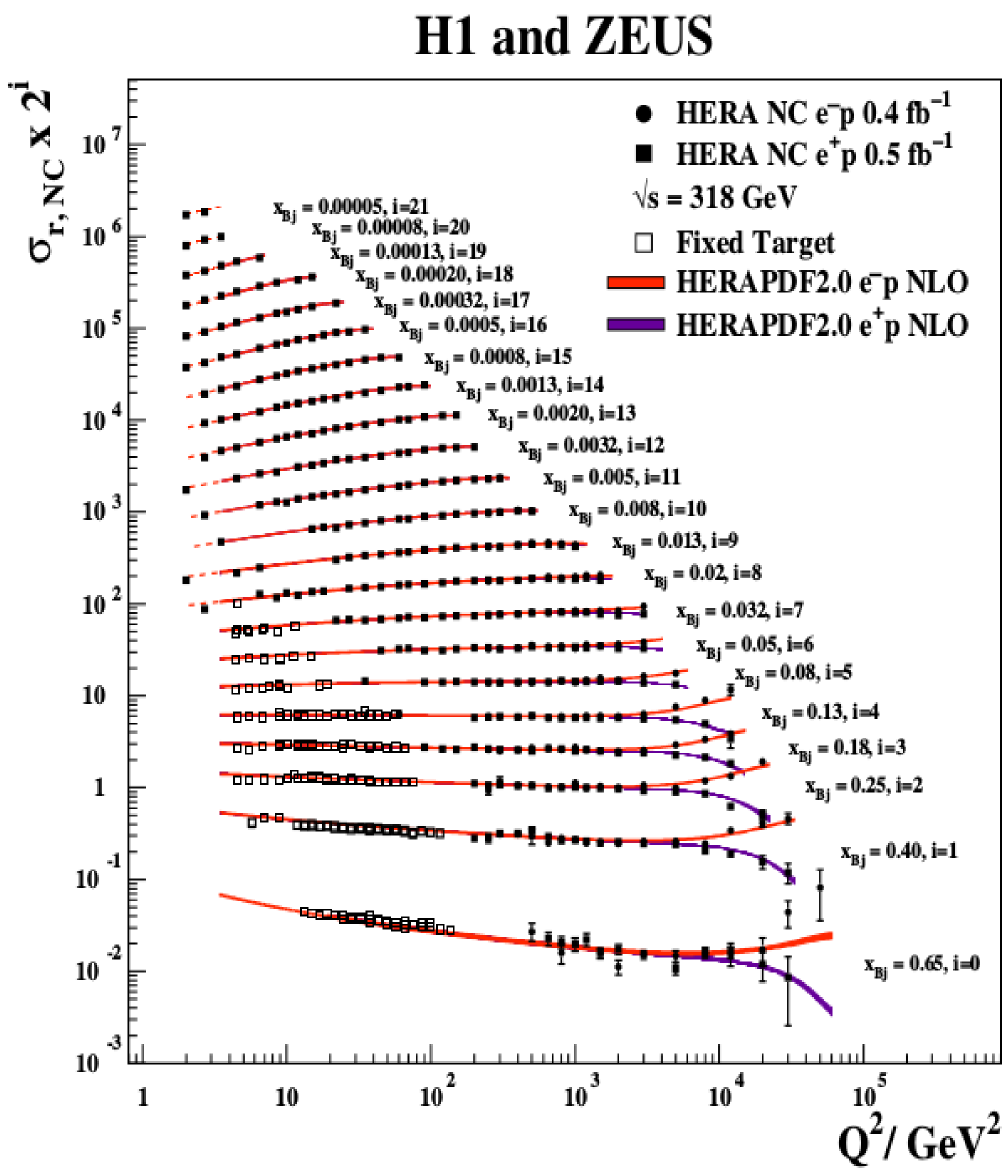
Our Understanding of a Prot

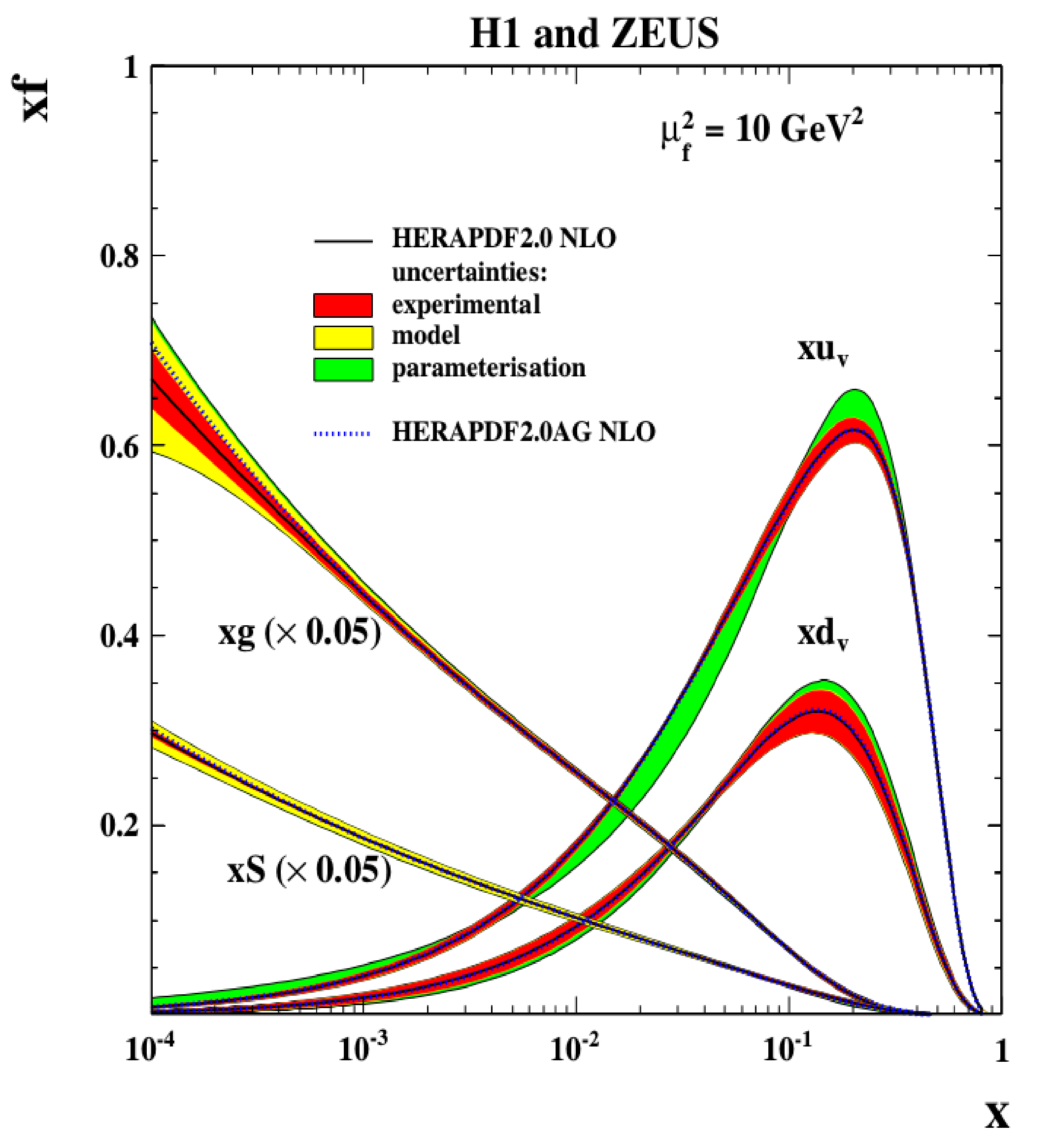


D*okshitzer* ***G****ribov* ***L****ipatov* ***A****ltarelli* ***P****arisi* **DGLAP**

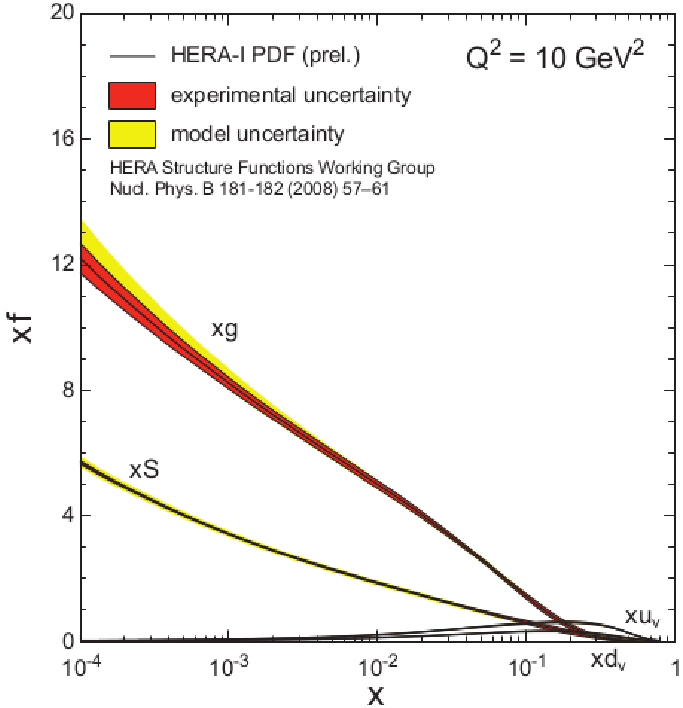
DGLAP in e+p collisions at HERA

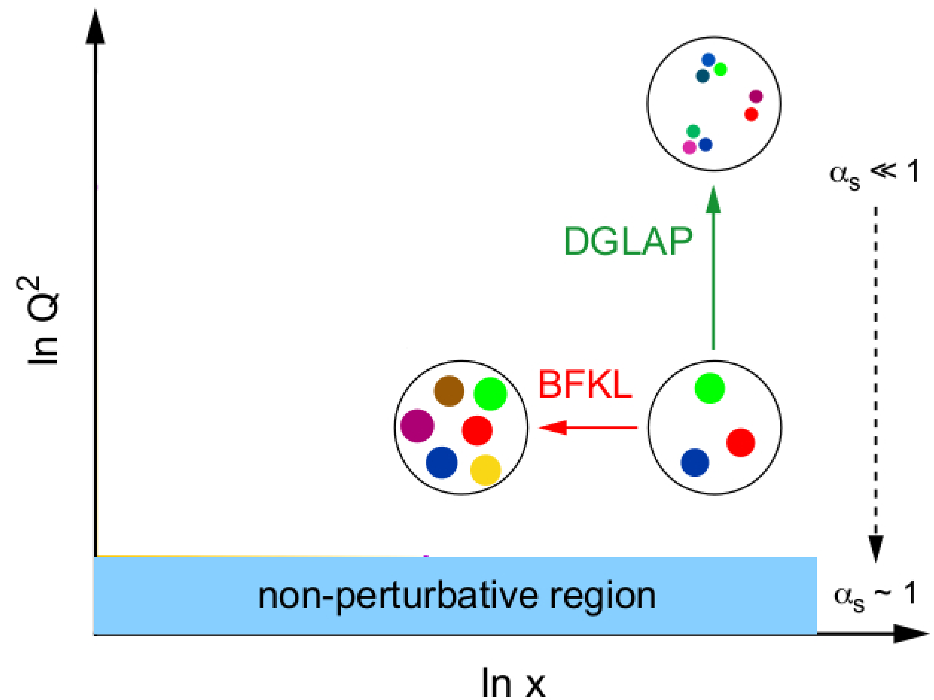
$$\sigma_r(x,Q^2) = F_2(x,Q^2) - \frac{y^2}{Y^+}F_L(x,Q^2)$$





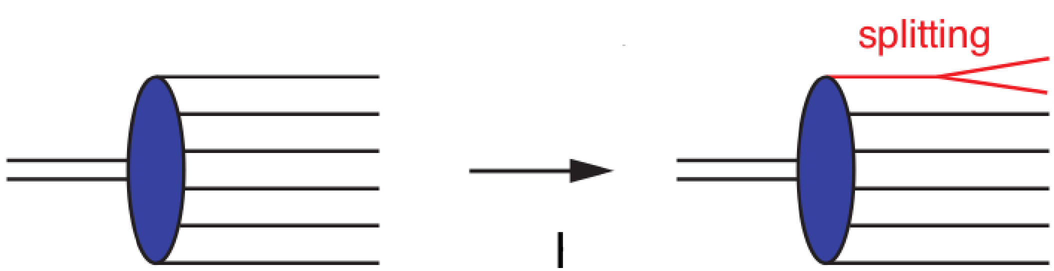
The small-x Puzzle



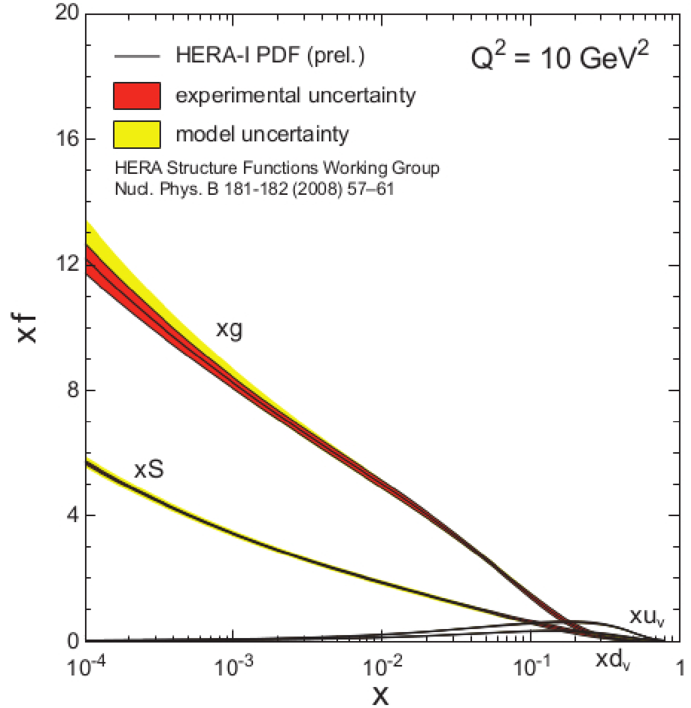


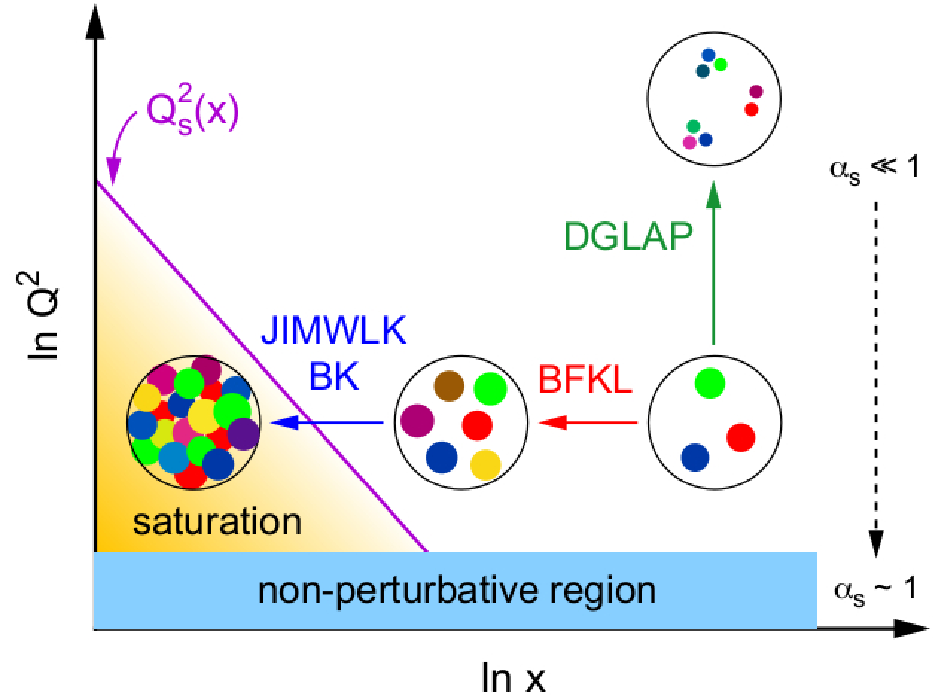
- Gluons dominate the PDFs at small- to intermediate-x ($x < 0.1$)

➡ Rapid rise in gluons described naturally by linear DGLAP evolution equations

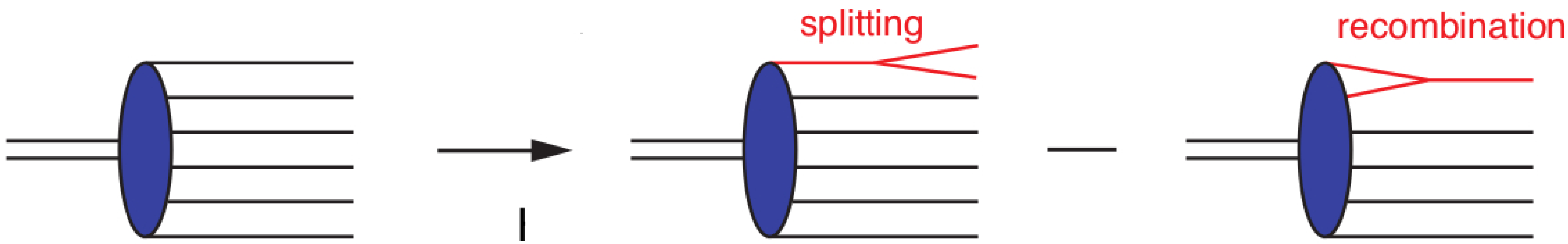


The small-x Puzzle

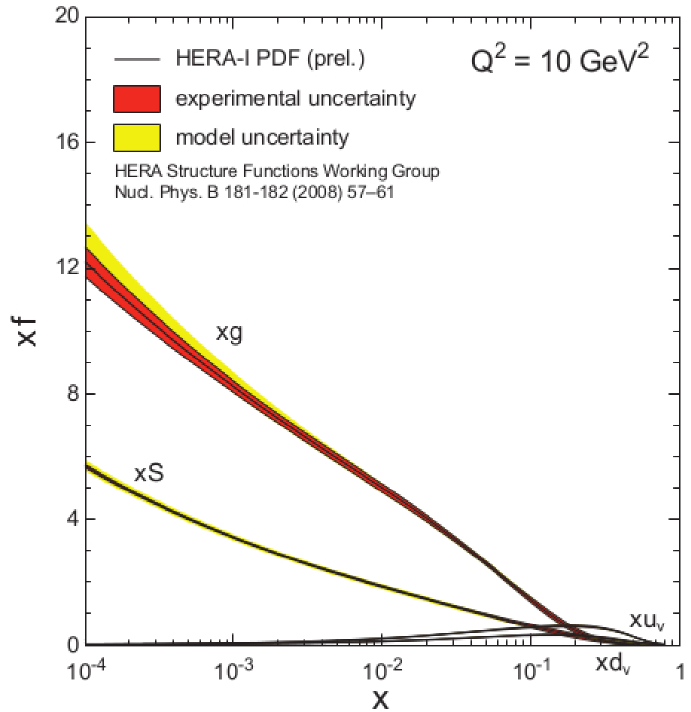


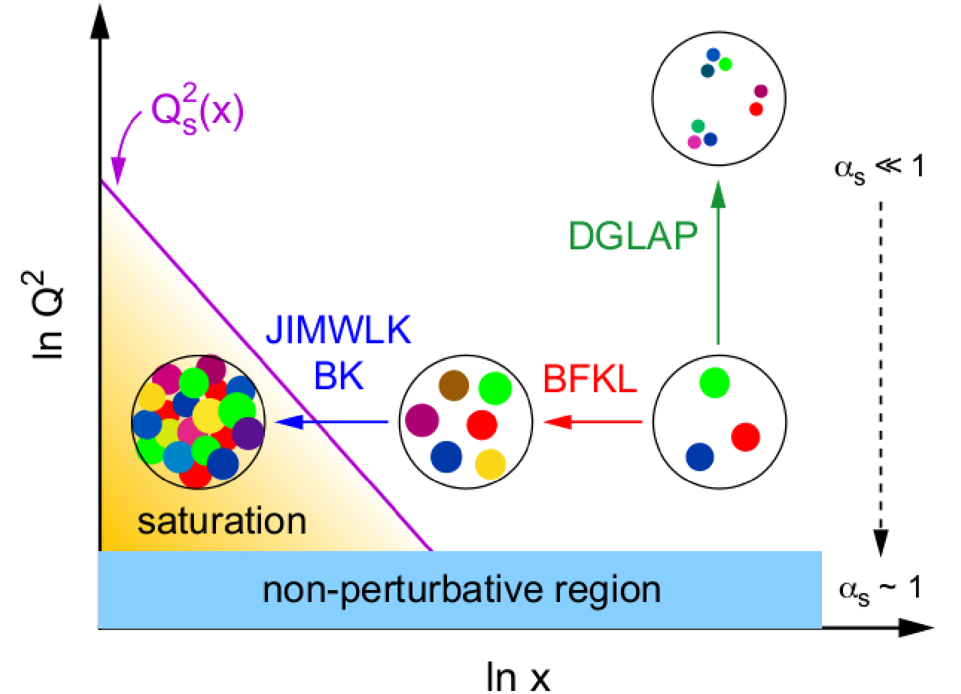


- Gluons dominate the PDFs at small- to intermediate-x ($x < 0.1$)
  - ➡ Rapid rise in gluons described naturally by linear DGLAP evolution equations
  - ➡ This rise cannot increase forever - gluon cross-section>proton cross-section!
    - non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a **saturation** of gluons, characterised by the saturation scale $Q^2{}_S(x)$



The small-*x* Puzzle



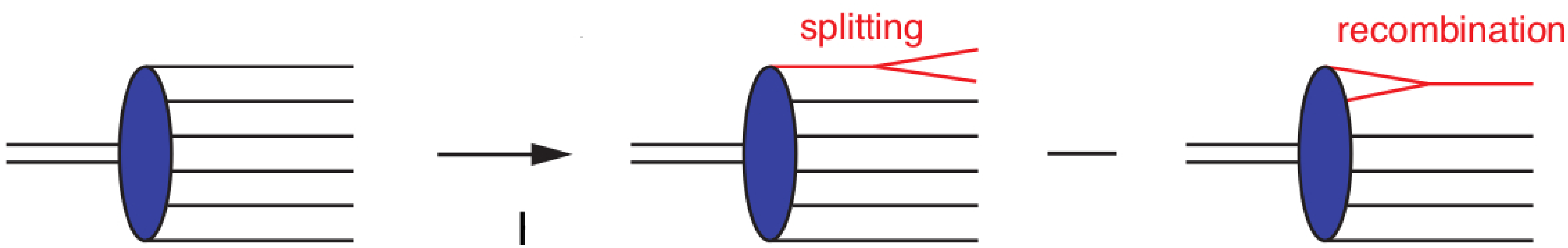


- Gluons dominate the PDFs at small- to intermediate-*x* ($x < 0.1$)

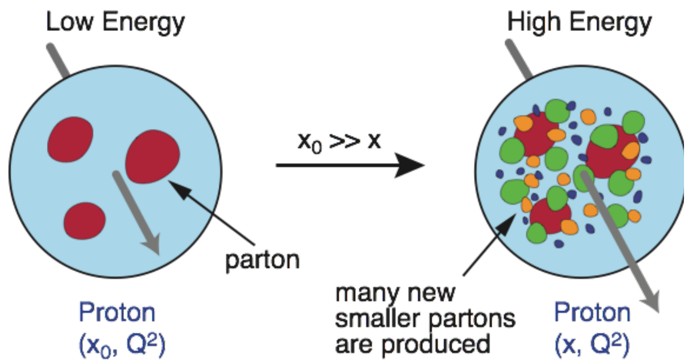
➡ Rapid rise in gluons described naturally by linear DGLAP evolution equations

Saturation in the gluon density is not observed in the gluon distribution at HERA, too high *x*

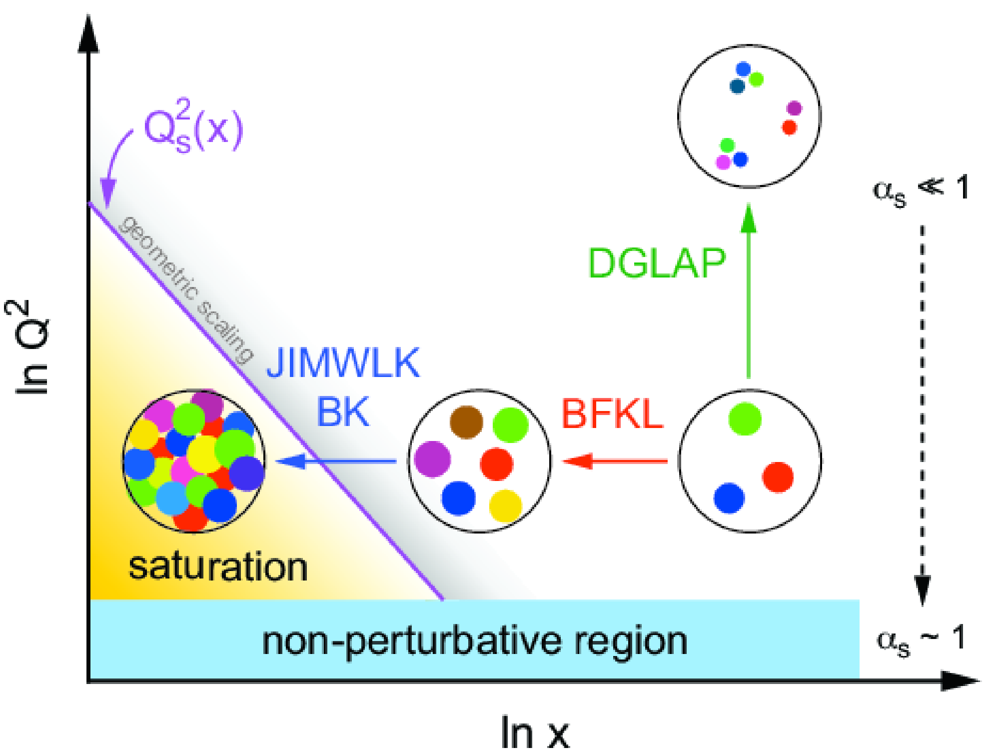
lead to a **saturation** of gluons, characterised by the saturation scale $Q^2_s(x)$



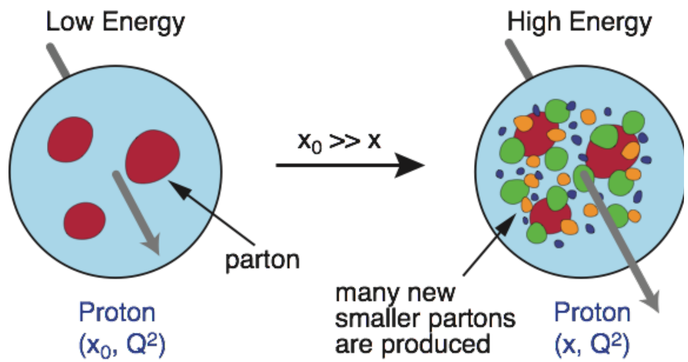
Saturation at EIC

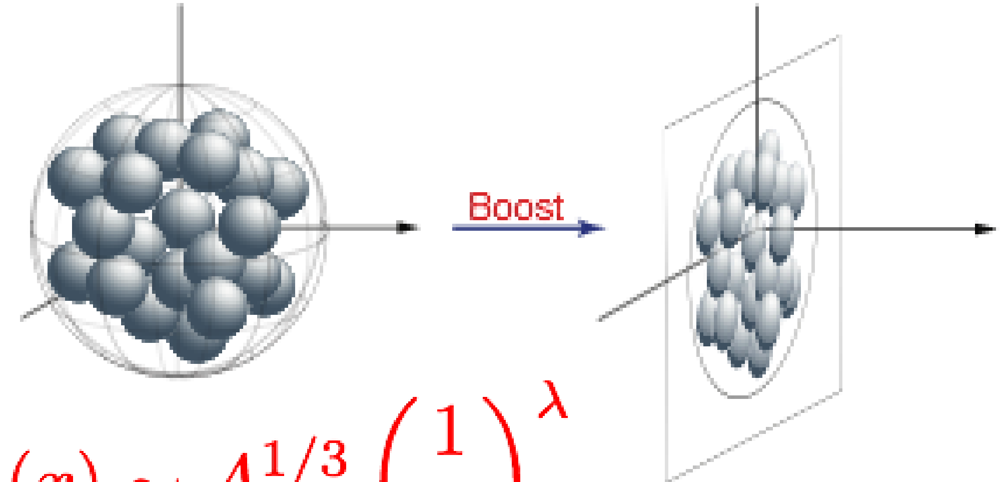


$$Q_s^2(x) \sim \left(\frac{1}{x}\right)^{\lambda}$$

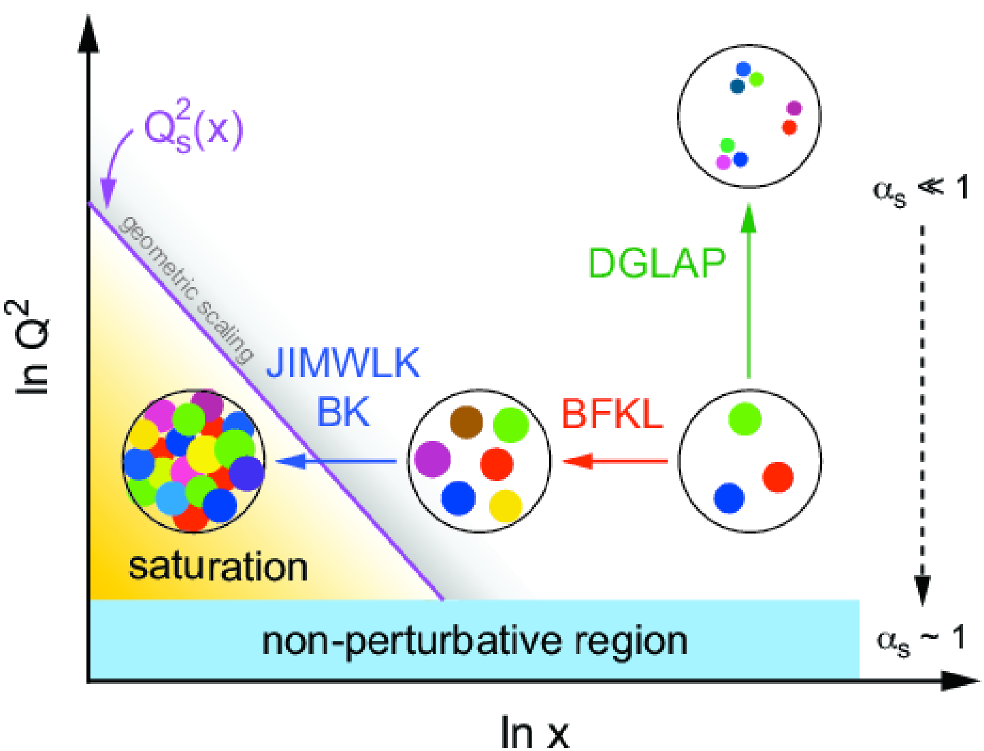


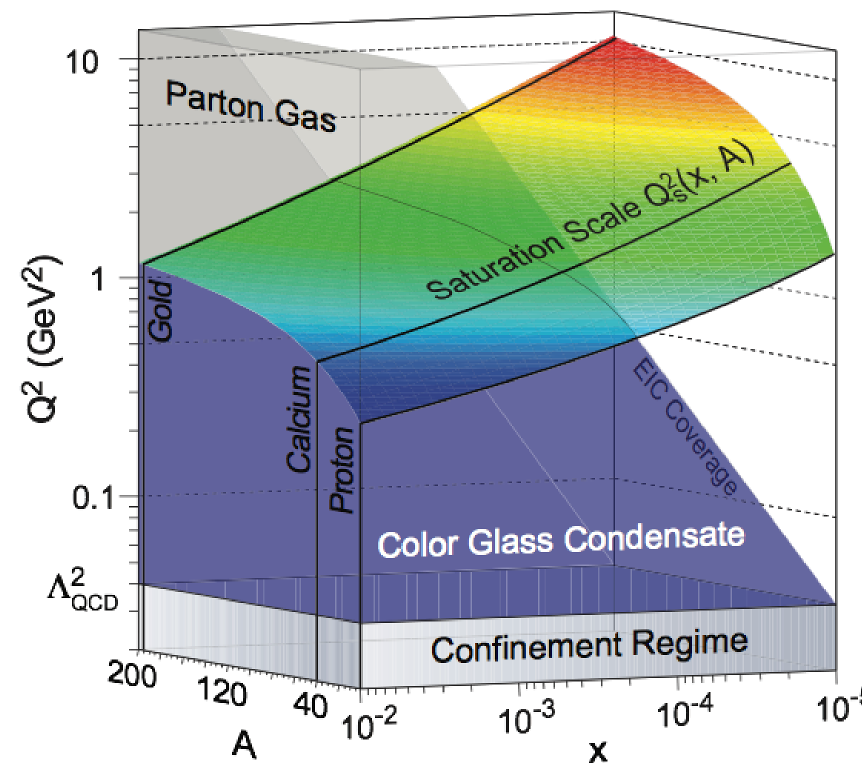
Saturation at EIC





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

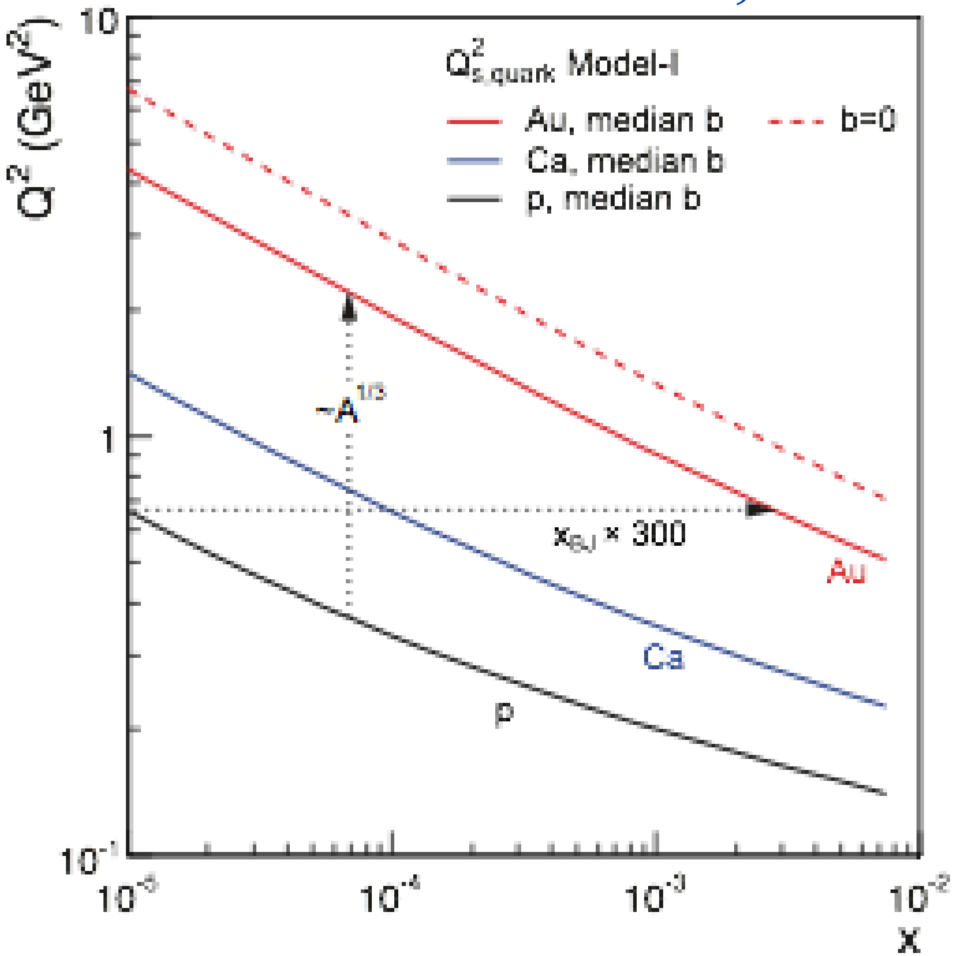


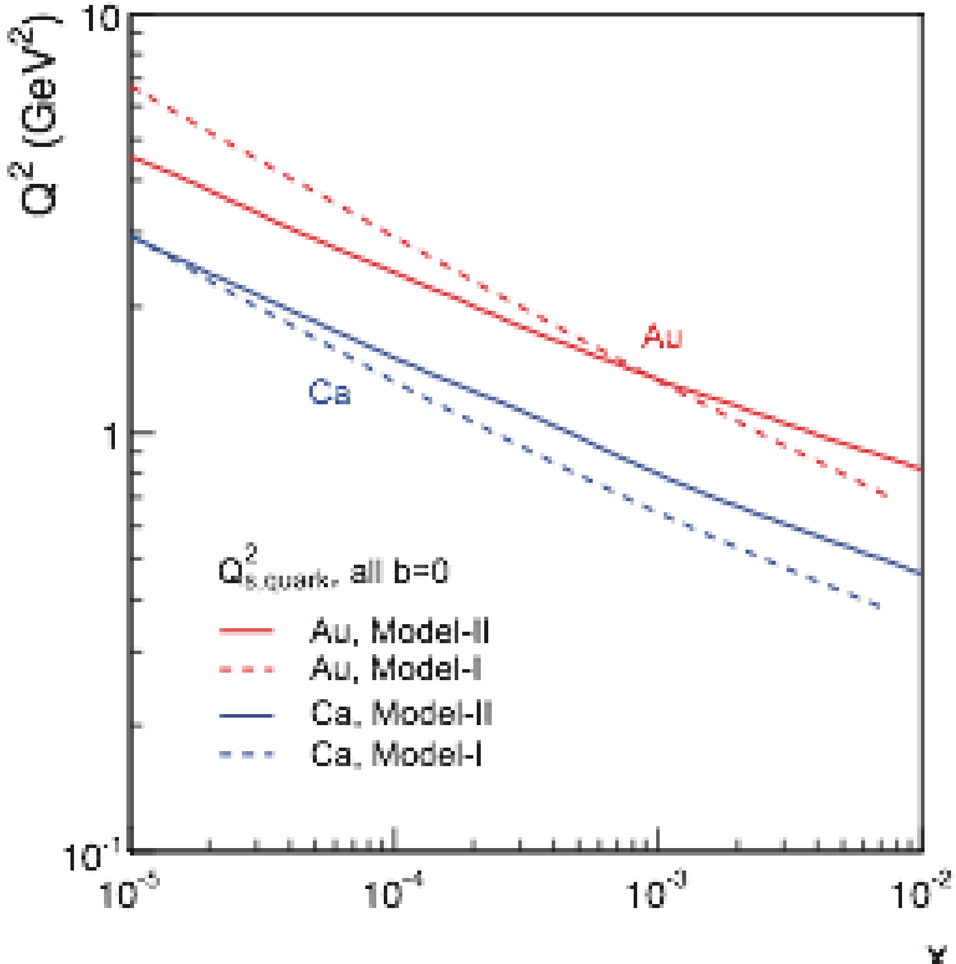


Saturation at EIC

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

Gold: A=197, x 197 times smaller!





Model-I: bSat, Model-II: rcBK

Saturation at EIC

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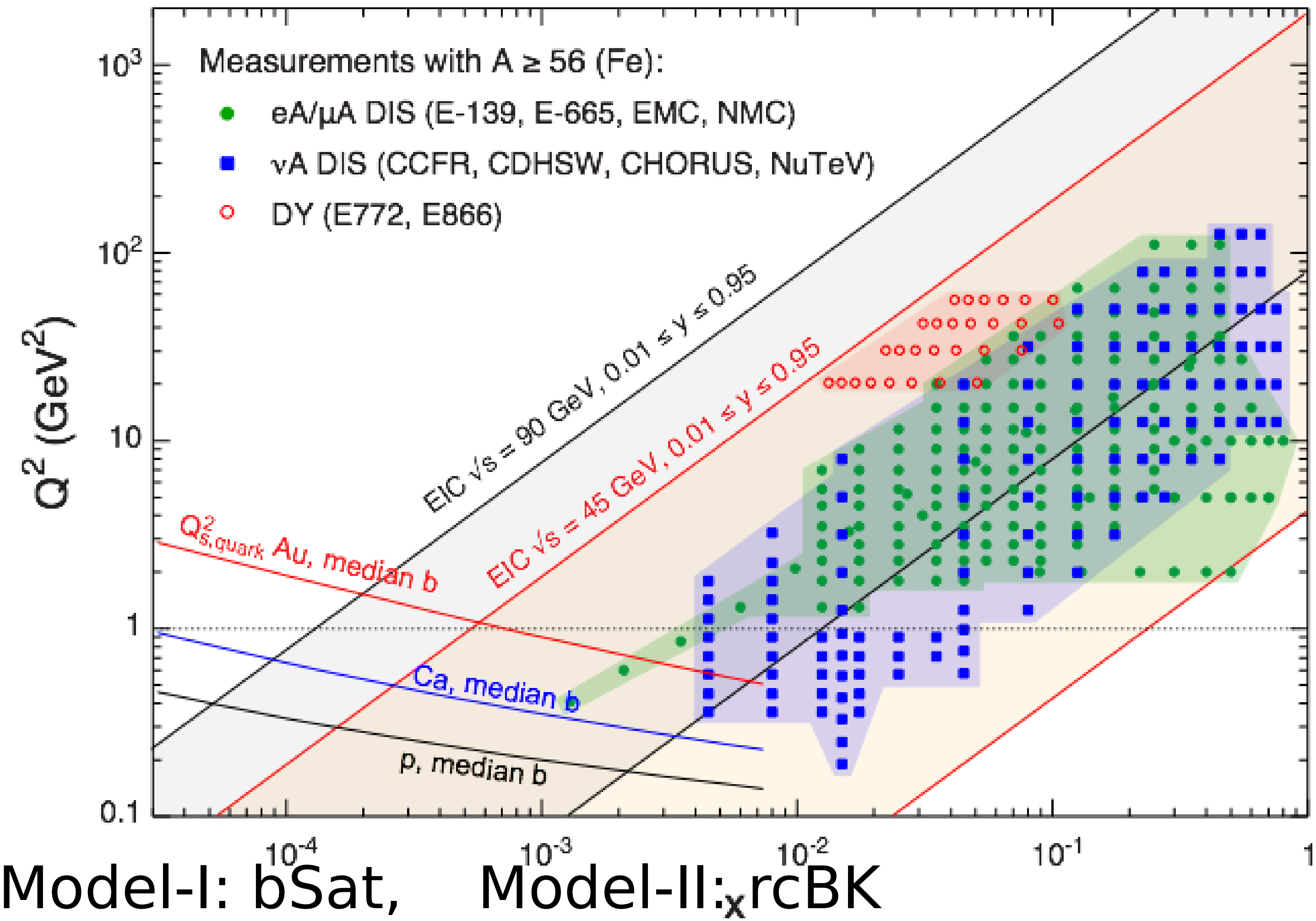
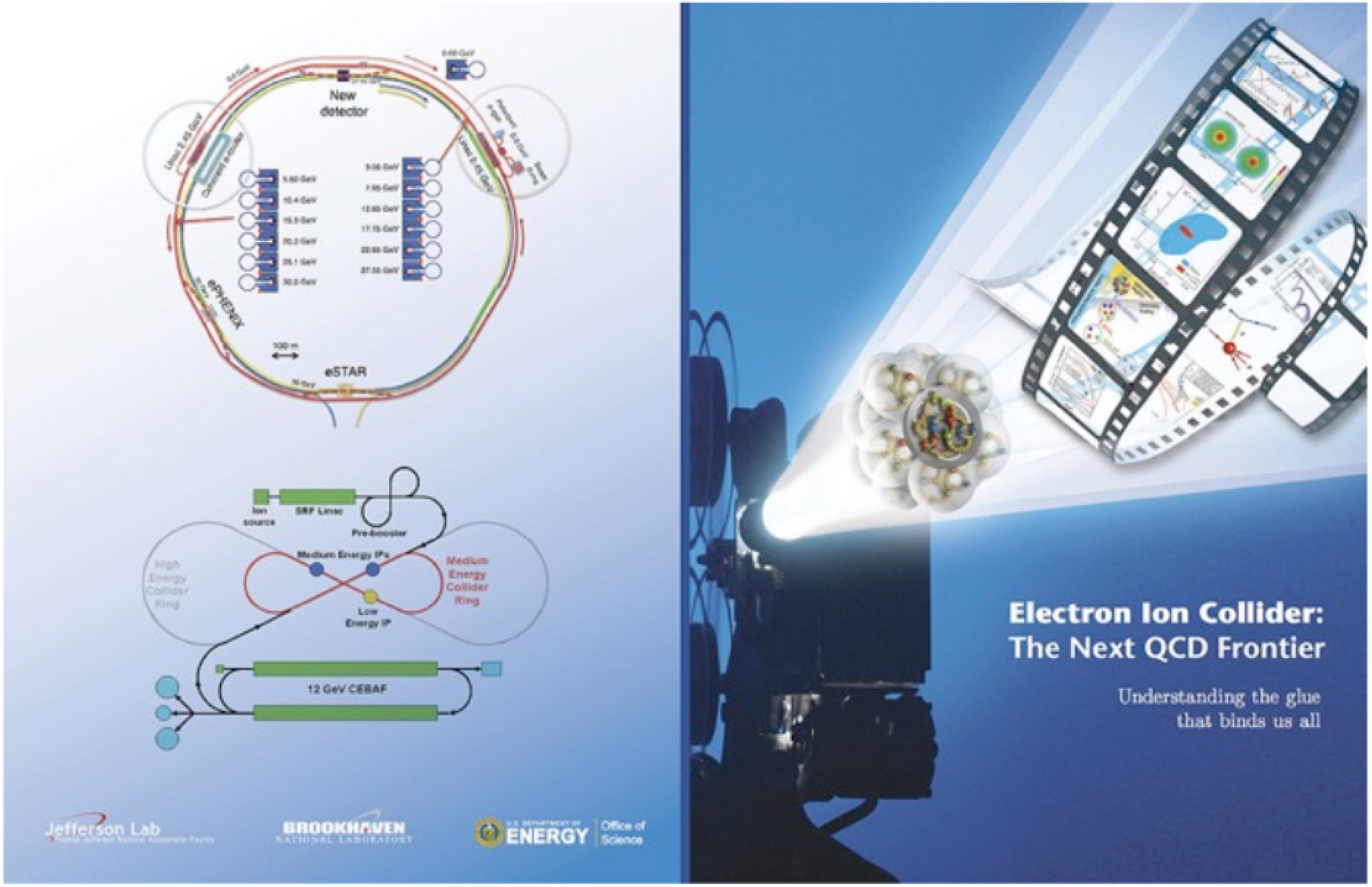


Model-I: bSat,   Model-II: rcBK

The EIC Physics Programme

Eur.Phys.J. A52 (2016) no.9, 268



arXiv:1212.1701

Physics of Strong Colour Fields

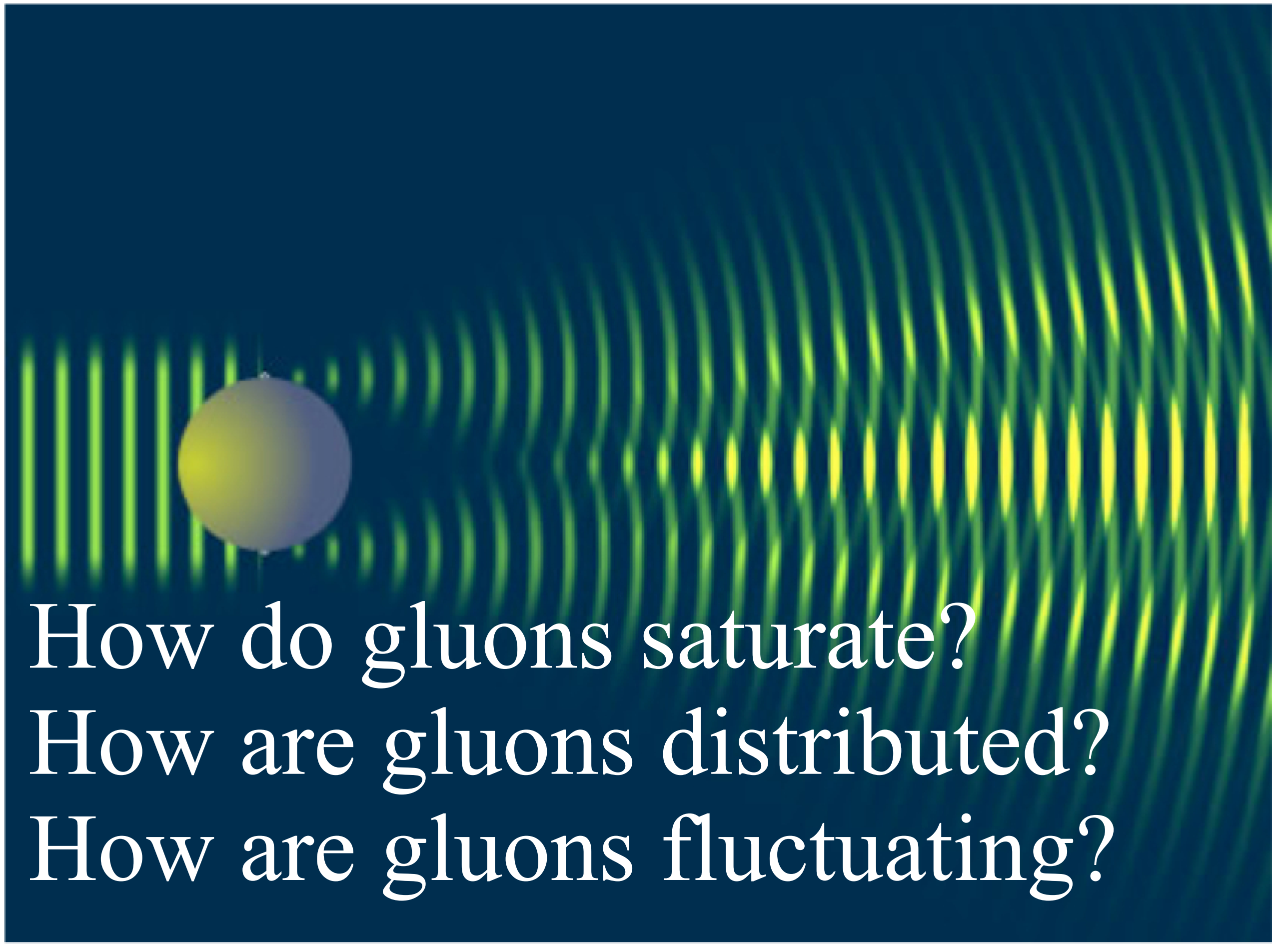
Spin Physics

3D Imaging

Hadronisation

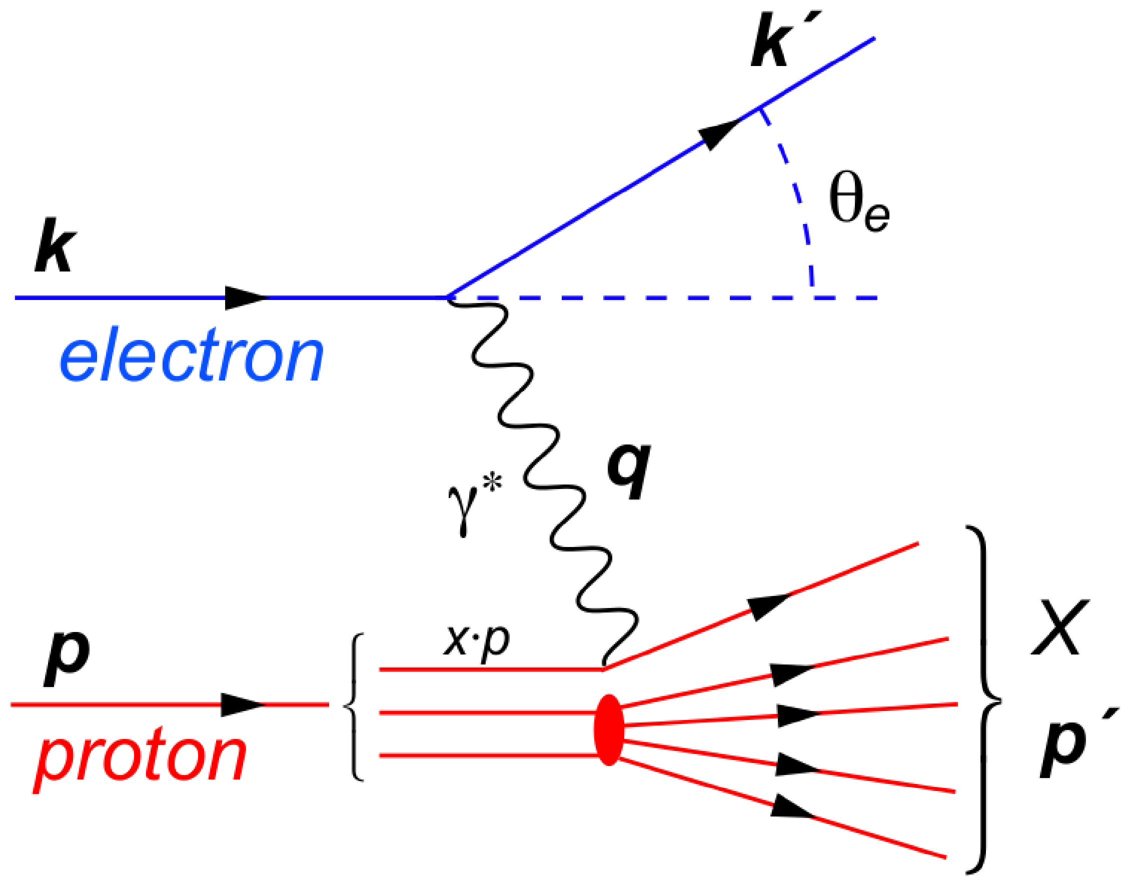
Electroweak

Key Measurements:
Diffractive Processes in eA



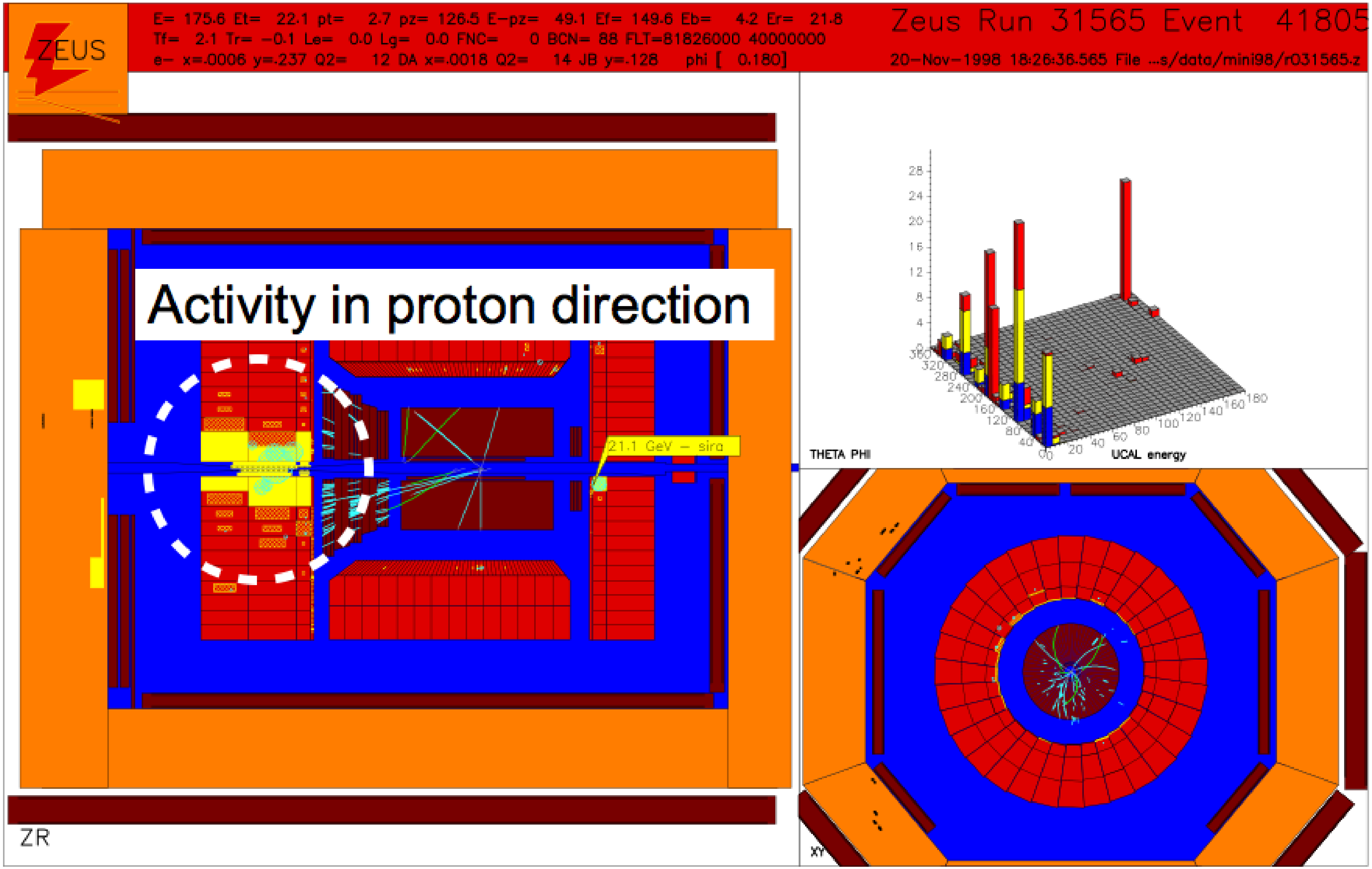
In Nuclei and Protons

Deep Inelastic Scattering
ep and *e*A

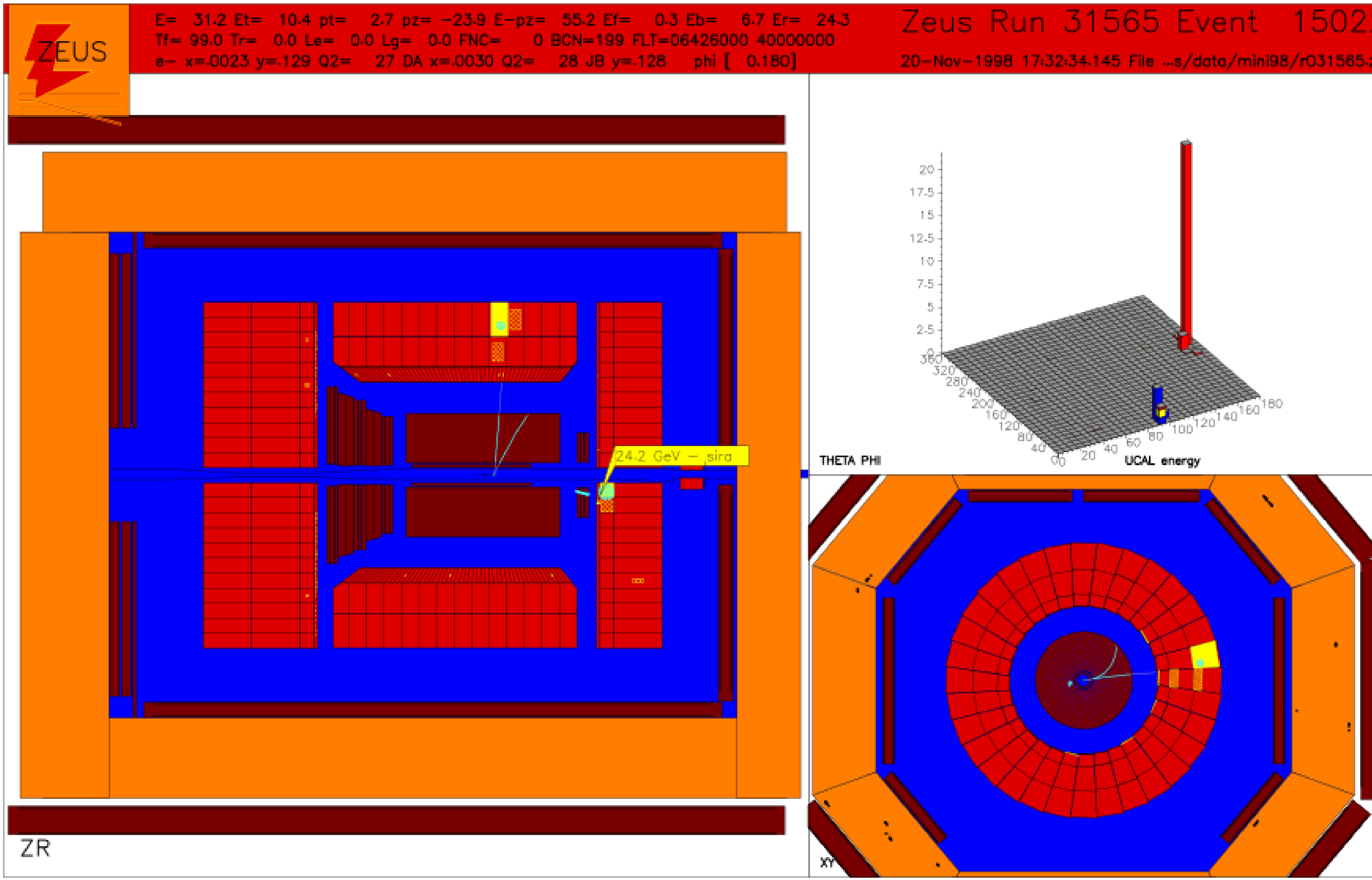


Theoretical view

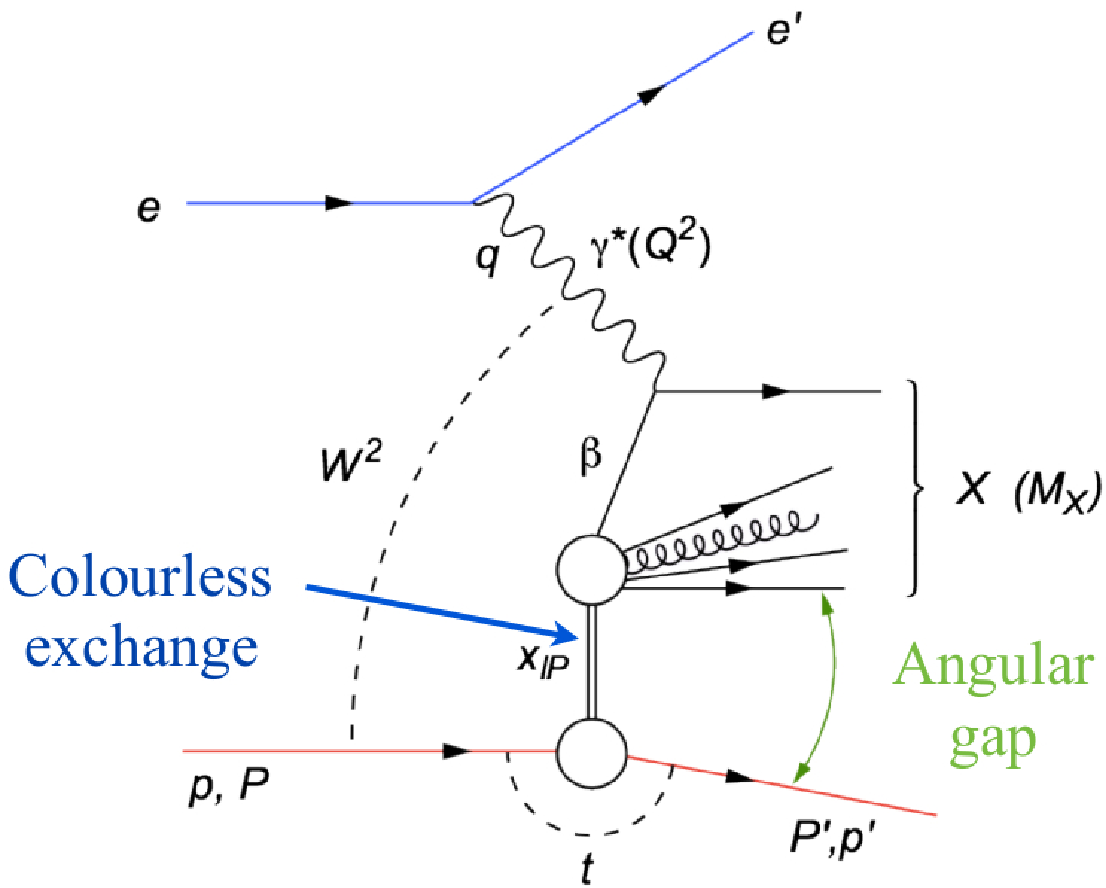
DIS *ep* and *eA*


E= 175.6 Et= 22.1 pt= 2.7 pz= 126.5 E−pz= 49.1 Ef= 149.6 Eb= 4.2 Er= 21.8
Tf= 2.1 Tr= −0.1 Le= 0.0 Lg= 0.0 FNC= 0 BCN= 88 FLT=81826000 40000000
e− x=.0006 y=.237 Q2= 12 DA x=.0018 Q2= 14 JB y=.128 phi [0.180]
Zeus Run 31565 Event 41805
20−Nov−1998 18:26:36.565 File ...s/data/mini98/r031565.z
ZEUS
Activity in proton direction
21.1 GeV − sira
ZR
THETA PHI
UCAL energy
XY

diffraction *ep* and *eA*



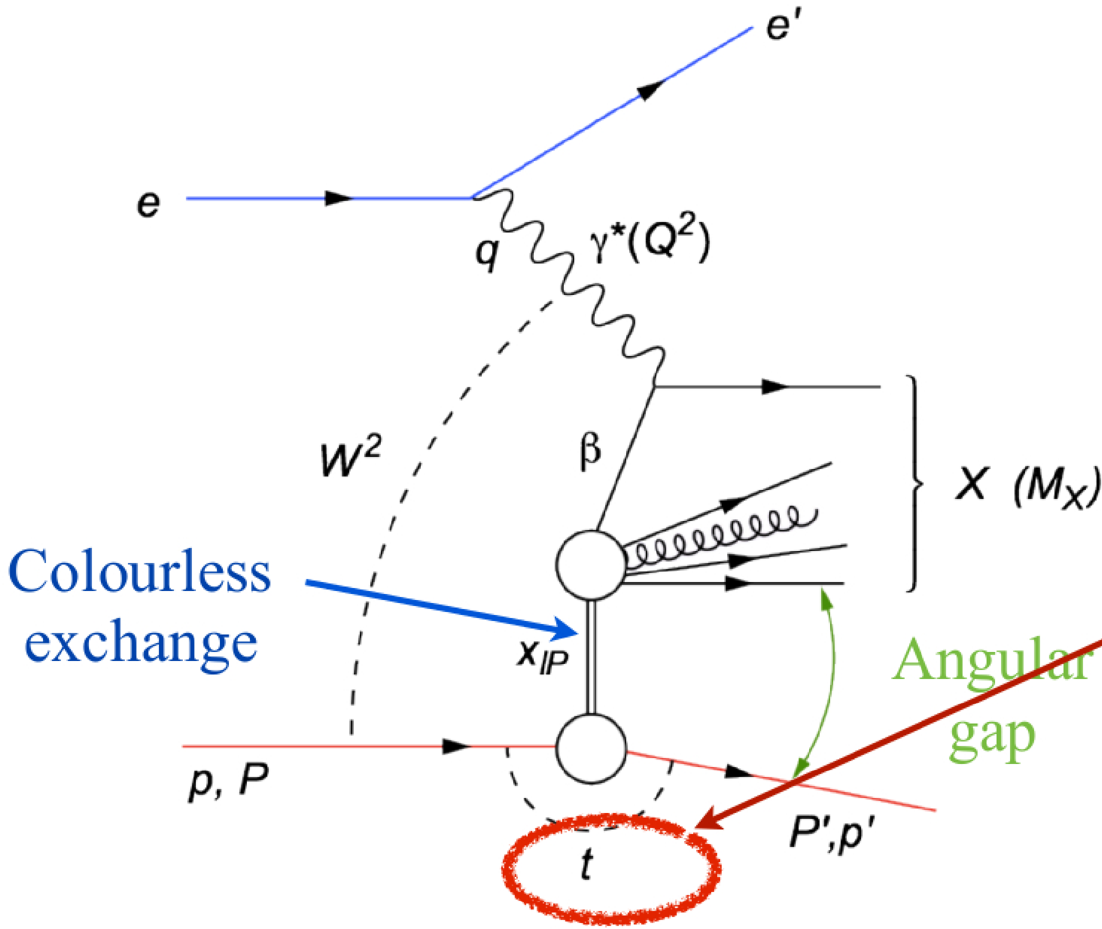
Diffraction *ep* and *eA*



HERA:
Proton collides with electron at CMS energy ~300m_p.
In ~15% of measured collisions proton stays intact!

EIC *e*+A:
Ion predicted to stay intact in 25%-40% of events w. saturation!

Diffraction *ep* and *eA*



Another kinematic handle

$$t = (p - p')^2$$

HERA:

Proton collides with electron at CMS energy ~300m_p.
In ~15% of measured collisions proton stays intact!

EIC *e*+A:

Ion predicted to stay intact in 25%-40% of events w. saturation!

how to measure $t=(P_A-P_A')^2$

need to measure $P_{A'}$

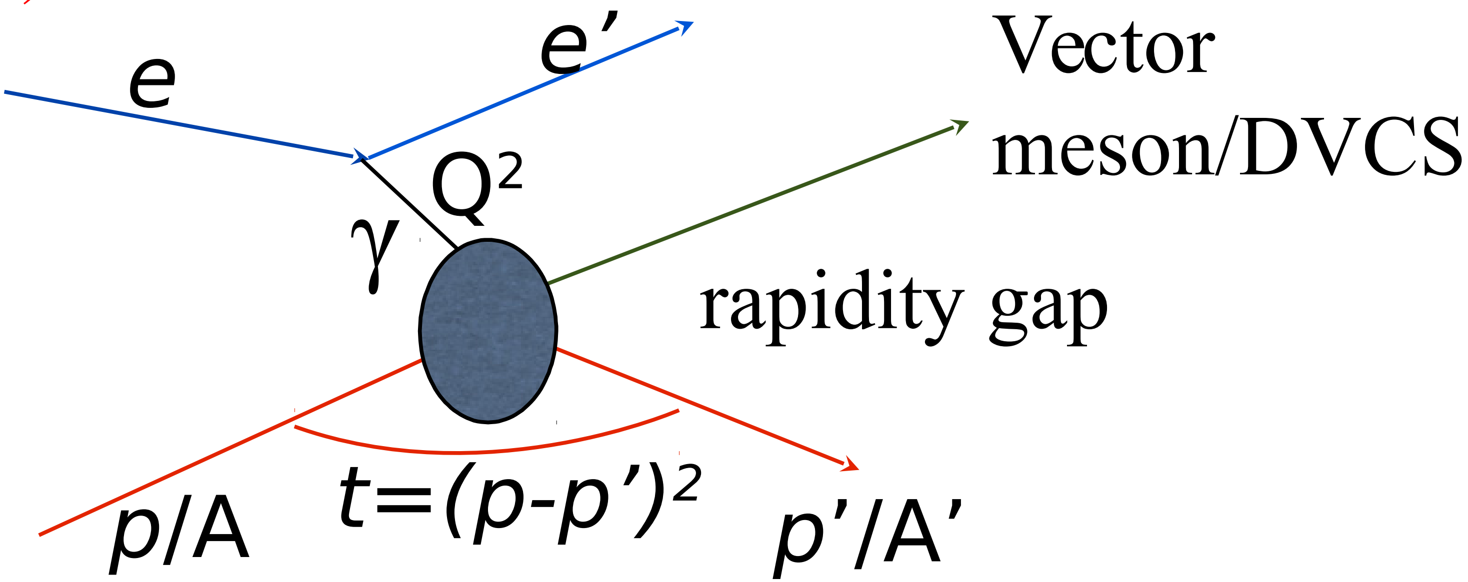
coherent case: A' disappears down beam pipe

incoherent case: cannot measure all beam remnants

only possibility: Exclusive diffraction

$e+A \rightarrow e'+VM+A'$

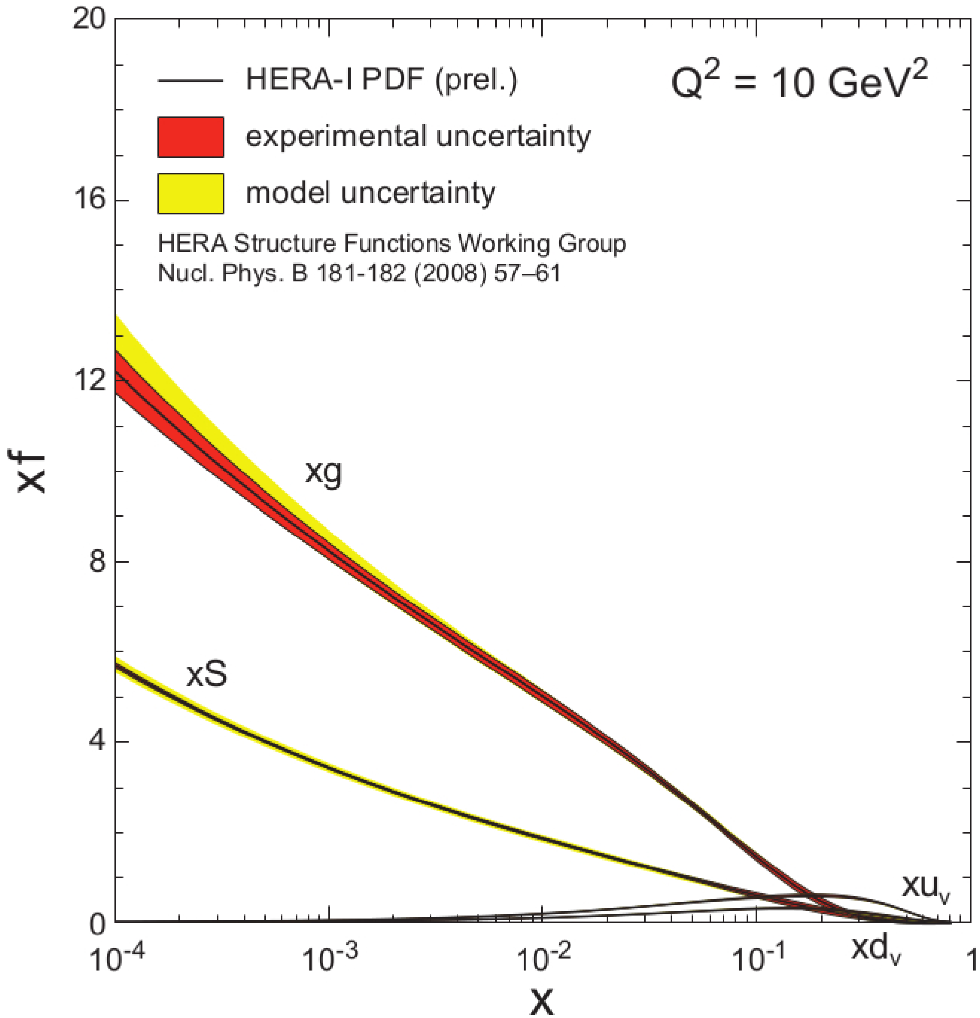
$t=(P_{VM}+P_{e'}-P_e)^2$

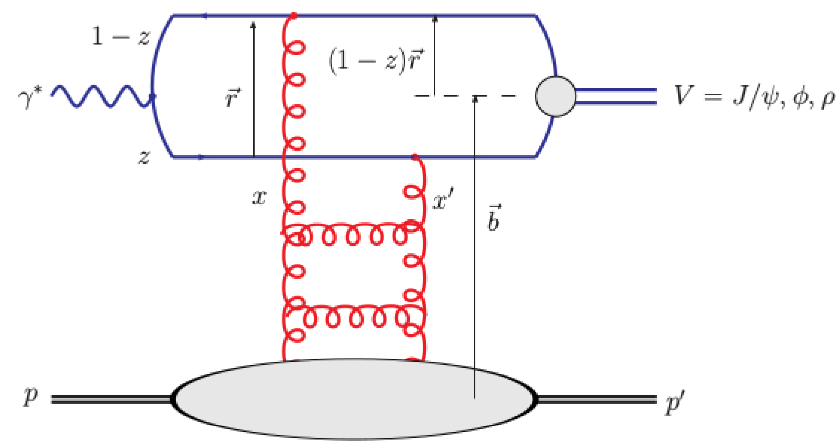


Why diffraction is so great

Diffraction sensitive to gluon momentum distributions^2:

$$\sigma \propto g(x,Q^2)^2$$





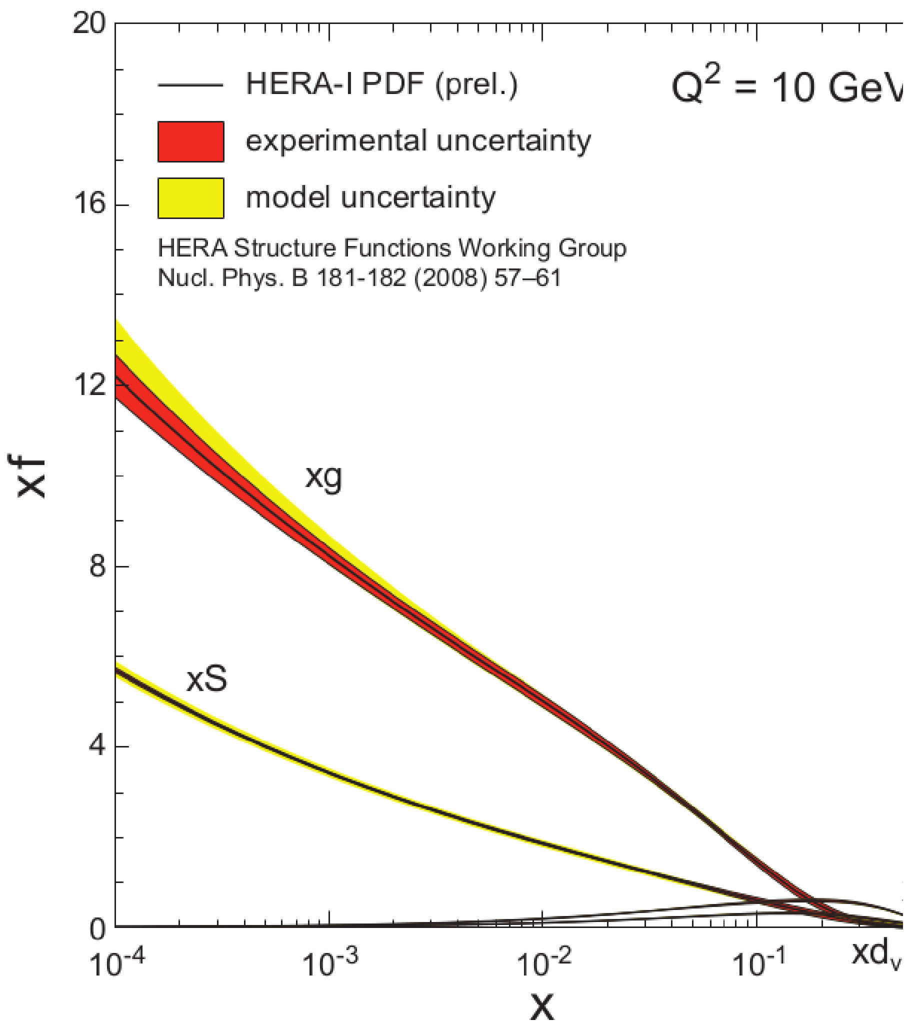
The colourless exchange can be understood as two gluons screening eachother's colour

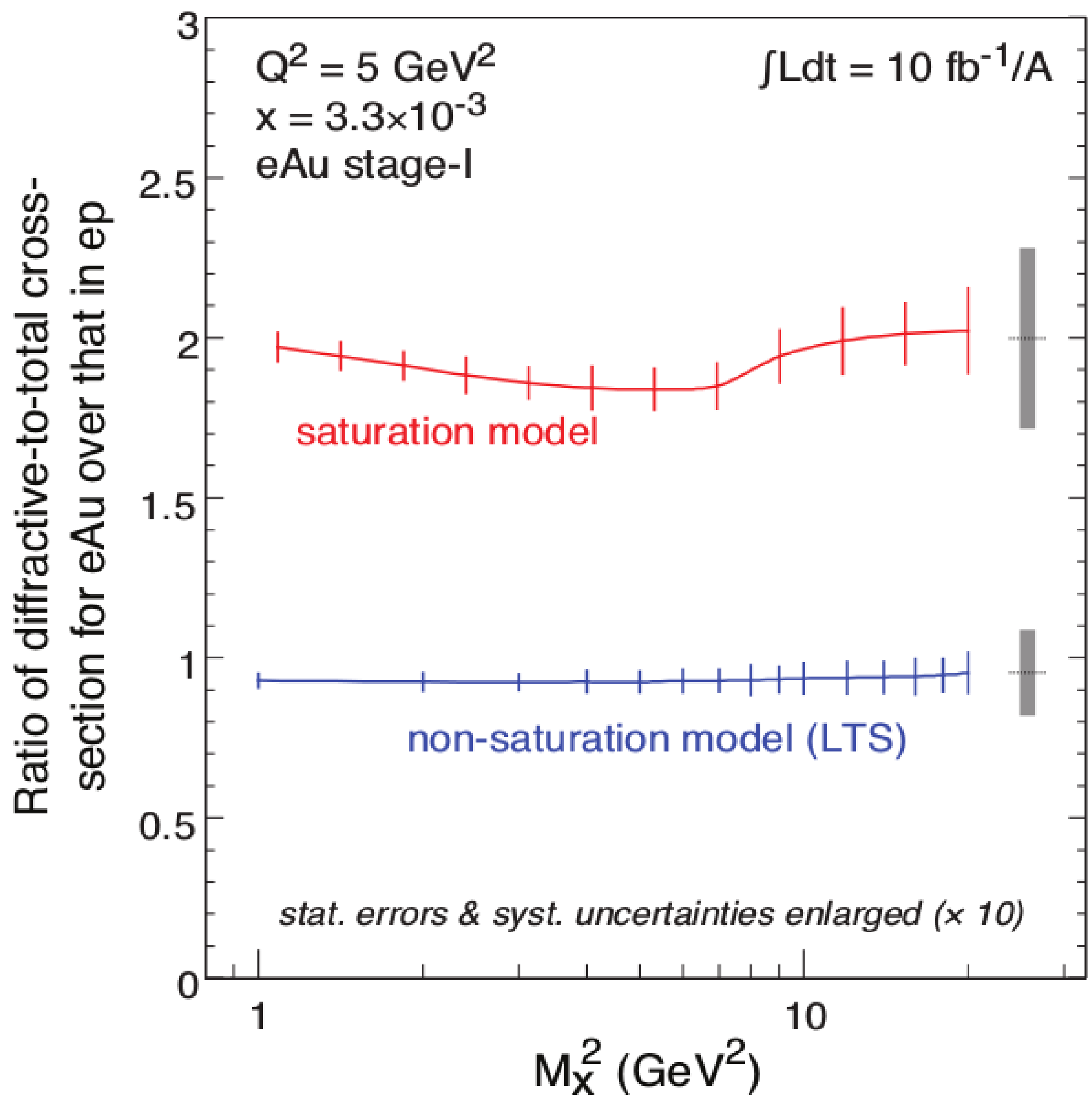
Sensitive to how the gluon distribution saturates at small x

Why diffraction is so great

Diffraction sensitive to gluon momentum distributions²:

$$\sigma \propto g(x,Q^2)^2$$





Why diffraction is so great

Sensitive to spatial gluon distributions

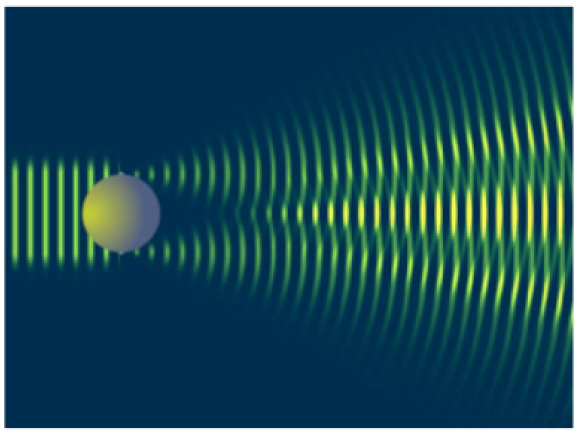
Light scattering elastically off a circular screen of radius R

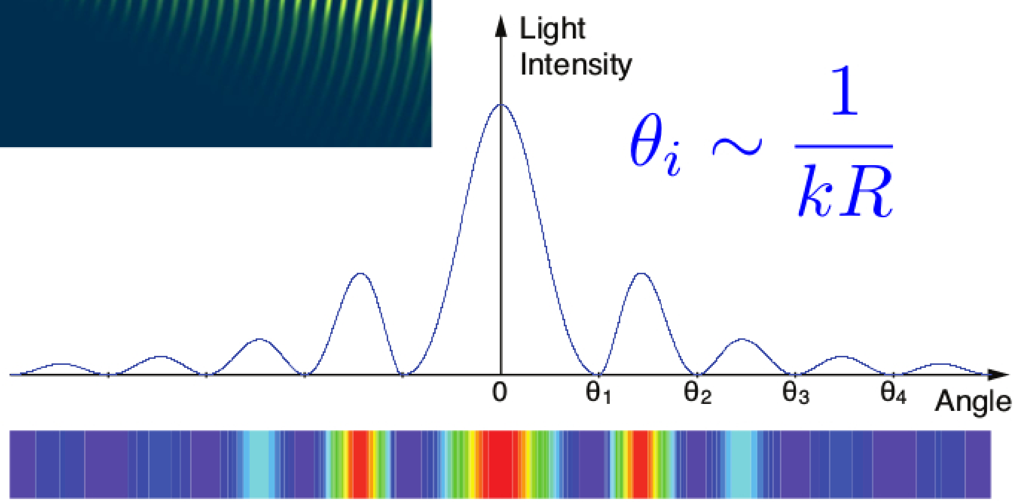
a projectile scattering off a nucleus of radius R

-not a ‘black disk’, edge effects

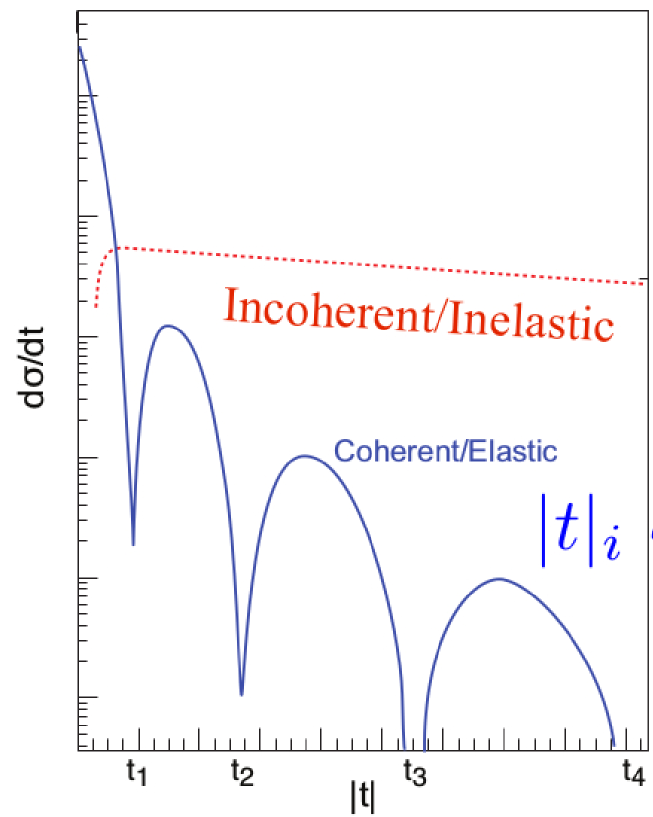
-inelastic scattering

t: Fourier conjugate to ion shape



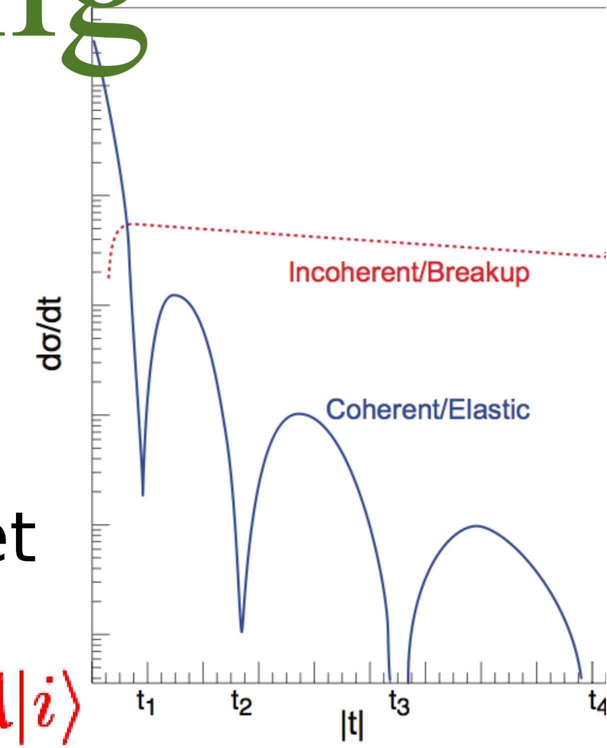


$$\theta_i \sim \frac{1}{kR}$$



$$|t|_i \sim \frac{1}{R^2}$$

Incoherent Scattering



Good, Walker:

nucleus dissociates ($f \neq i$):

$$\sigma_{\text{incoherent}} \propto \sum_{f \neq i} \langle i|\mathcal{A}|f\rangle^{\dagger} \langle f|\mathcal{A}|i\rangle$$

complete set

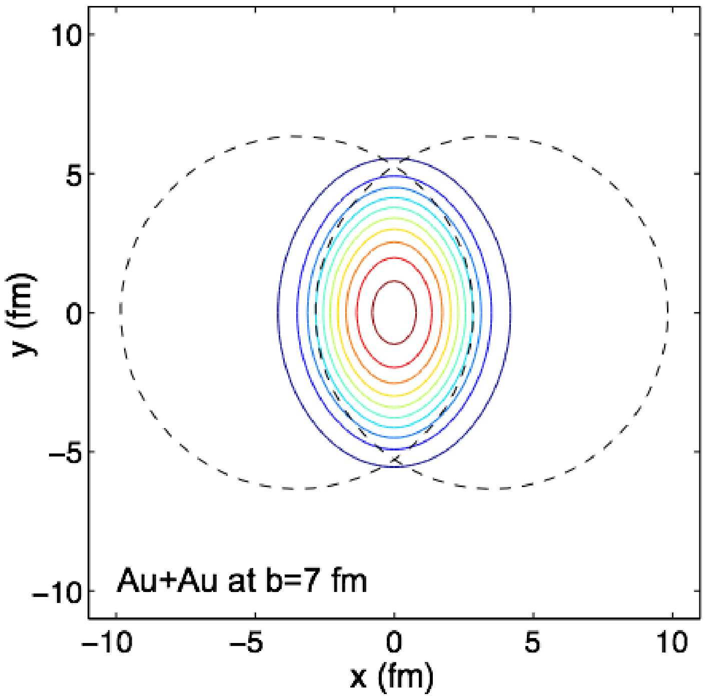
$$= \sum_{f} \langle i|\mathcal{A}\underbrace{|f\rangle^{\dagger} \langle f|}\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^{\dagger} \langle i|\mathcal{A}|i\rangle$$

$$= \langle i\,||\mathcal{A}|^2|\,i\rangle - |\langle i|\mathcal{A}|i\rangle|^2 = \left\langle |\mathcal{A}|^2 \right\rangle - |\langle \mathcal{A}\rangle|^2$$

the incoherent CS is the variance of the amplitude!!

$$\frac{d\sigma_{\text{total}}}{dt} = \frac{1}{16\pi}\left\langle |\mathcal{A}|^2 \right\rangle \qquad \frac{d\sigma_{\text{coherent}}}{dt} = \frac{1}{16\pi}|\langle \mathcal{A}\rangle|^2$$

Eccentricity and the spatial distribution



$$\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)] + \ldots$$

$$v_2 = \langle \cos[2(\varphi - \psi_R)] \rangle$$

Sensitive to early interactions and pressure gradients

Ideal hydrodynamics, $v_2 \propto$ spatial eccentricity ε: $\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$

v_2/ε versus particle density is sensitive test if system approaches ideal hydrodynamic

$$\frac{v_2}{\epsilon} = \frac{h}{1 + B/(\frac{1}{S}\frac{dN}{dy})}$$

S transverse area, h hydro limit of v_2/ε and

$B \propto \eta/s$ Shear Viscosity/Entropy Density

Bhalerao, Blaizot, Borghini and Ollitrault, Phys. Lett. B 627 (2005) 49

Luzum and Romatschke, Phys. Rev. C 78, 034915

Eccentricity and the spatial distribution

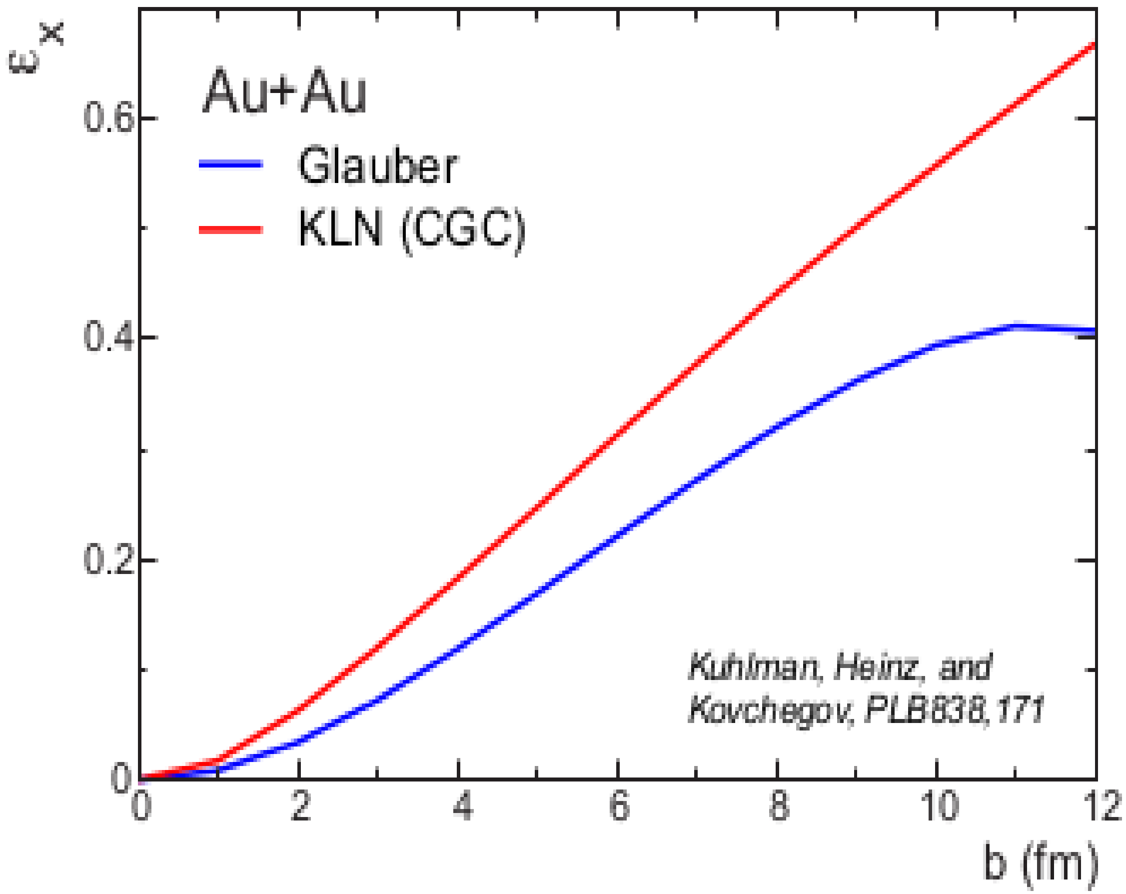
The question is what is ε?

RHIC & LHC: low-p_T realm driven almost entirely by glue

⇒ spatial distribution of glue in nuclei?

Two methods for ε:

- Glauber (non-saturated)?
- CGC (saturated)?



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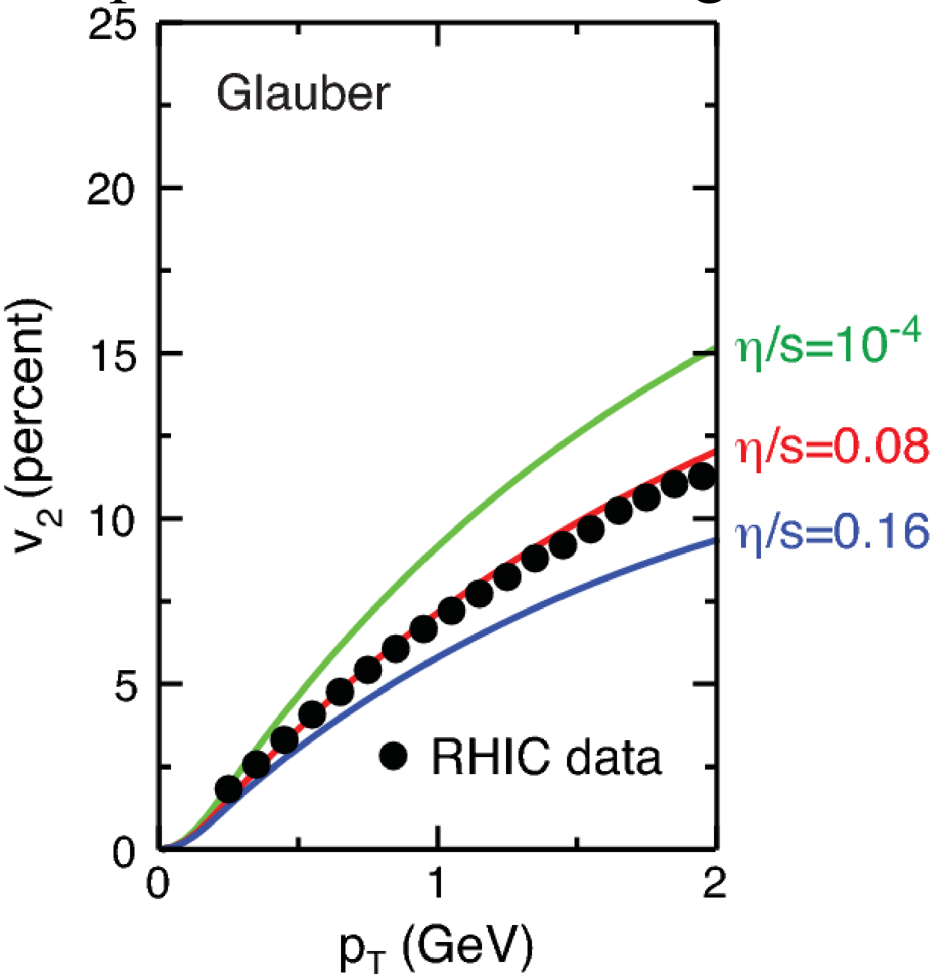
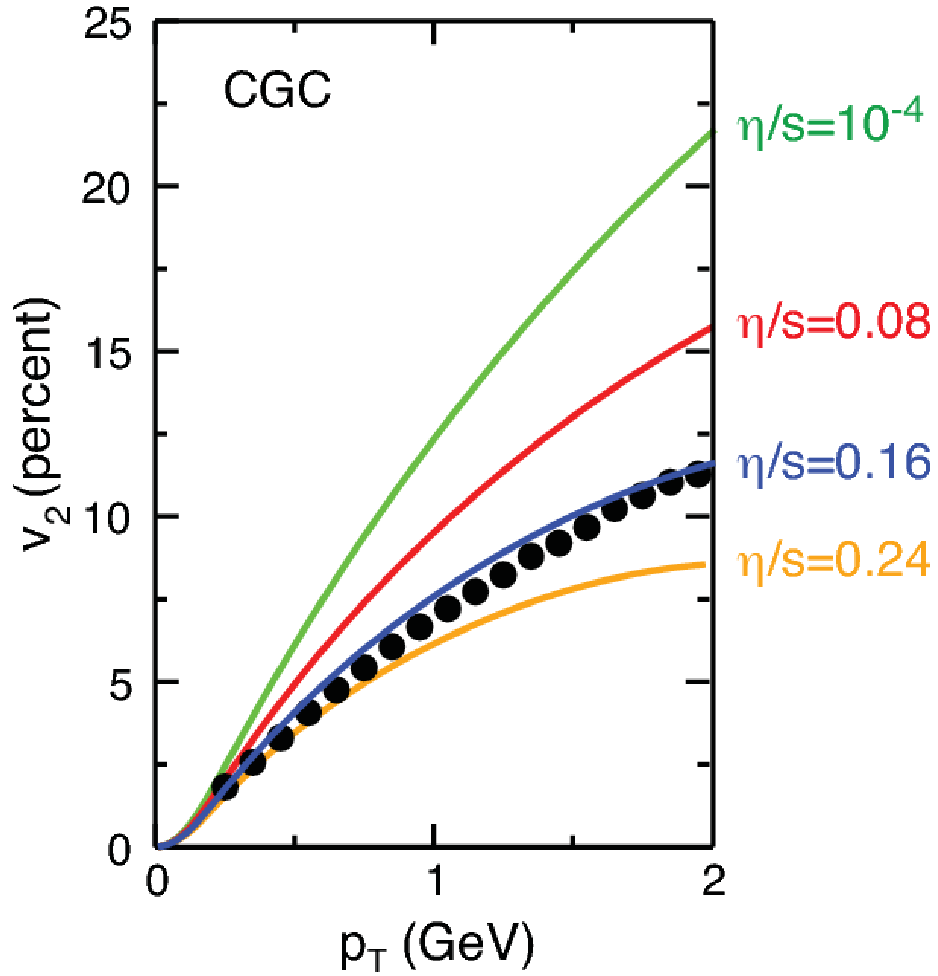
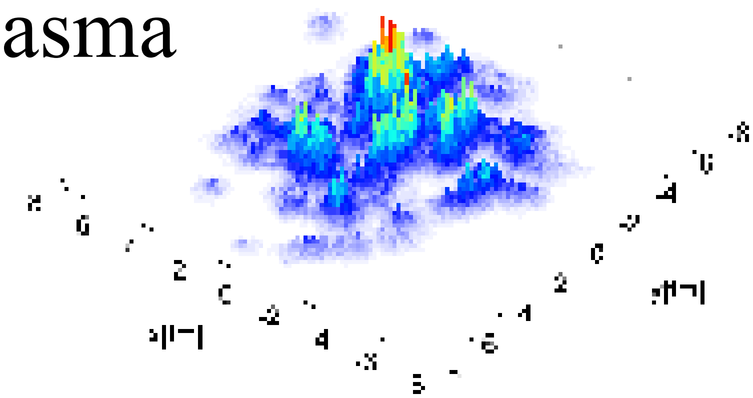




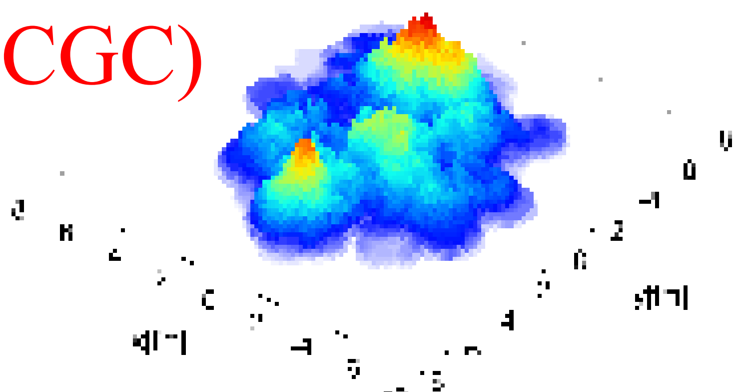
Schenke, Tribedy, Venugopalan arXiv:1202.6646

Fluctuations

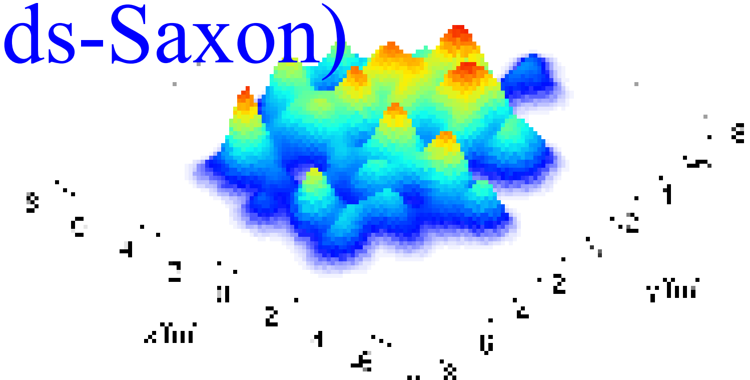
IP-Glasma

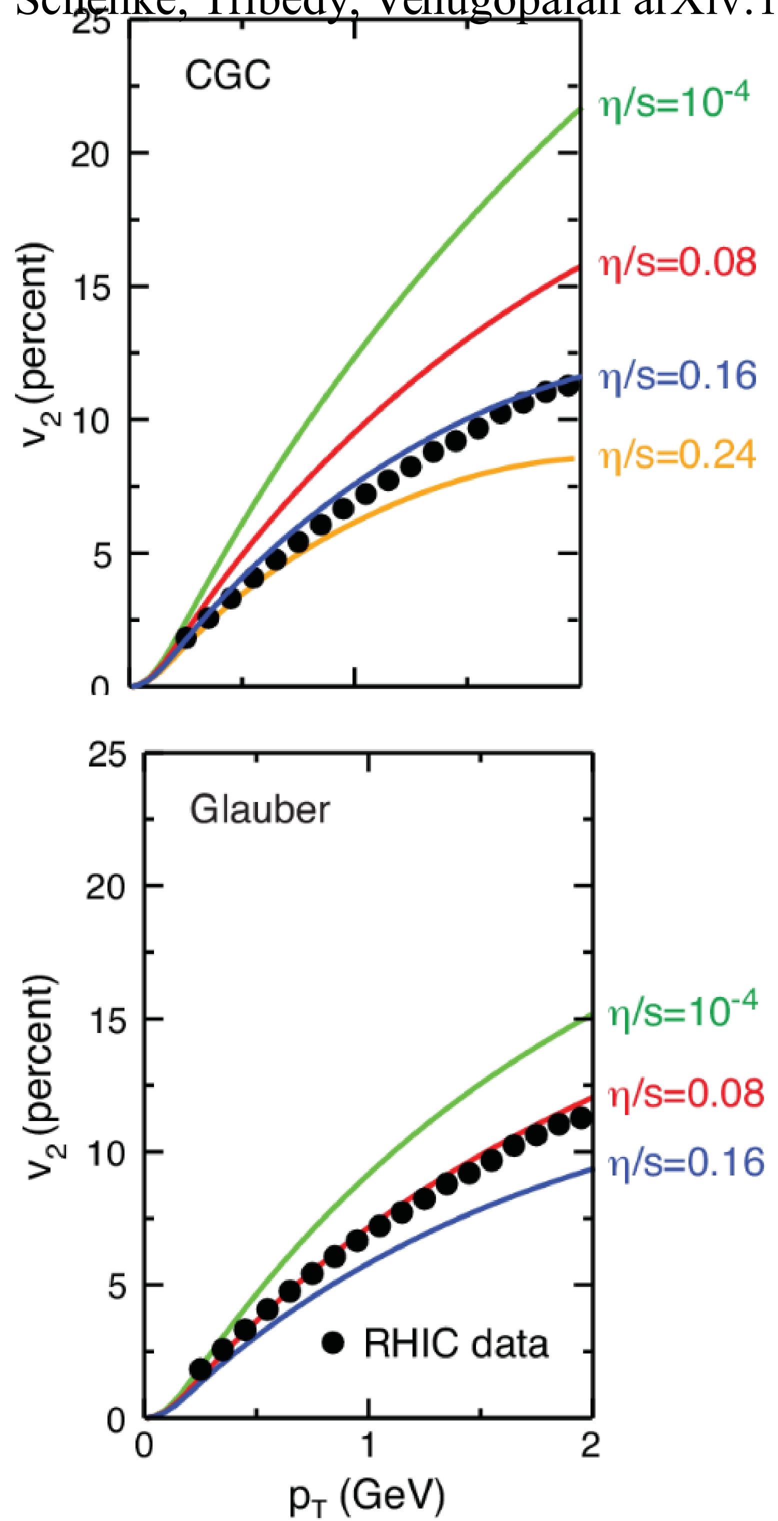


KLN(CGC)



Glauber
(Woods-Saxon)



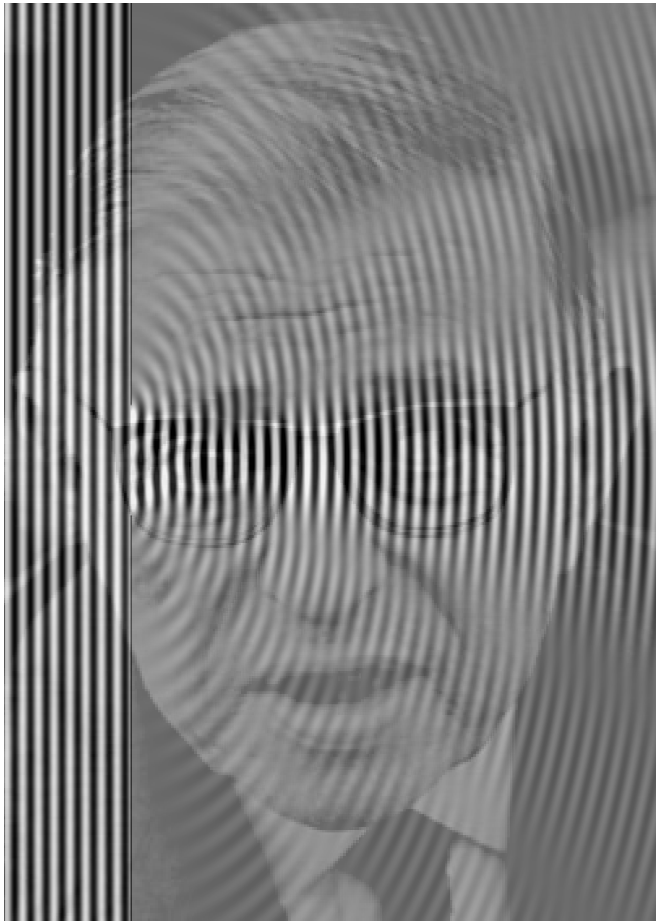


EIC predictions:

Physics Event Generator

Sar*t*re

Exclusive Diffractive Vector Meson and DVCS production in *ep and e*A



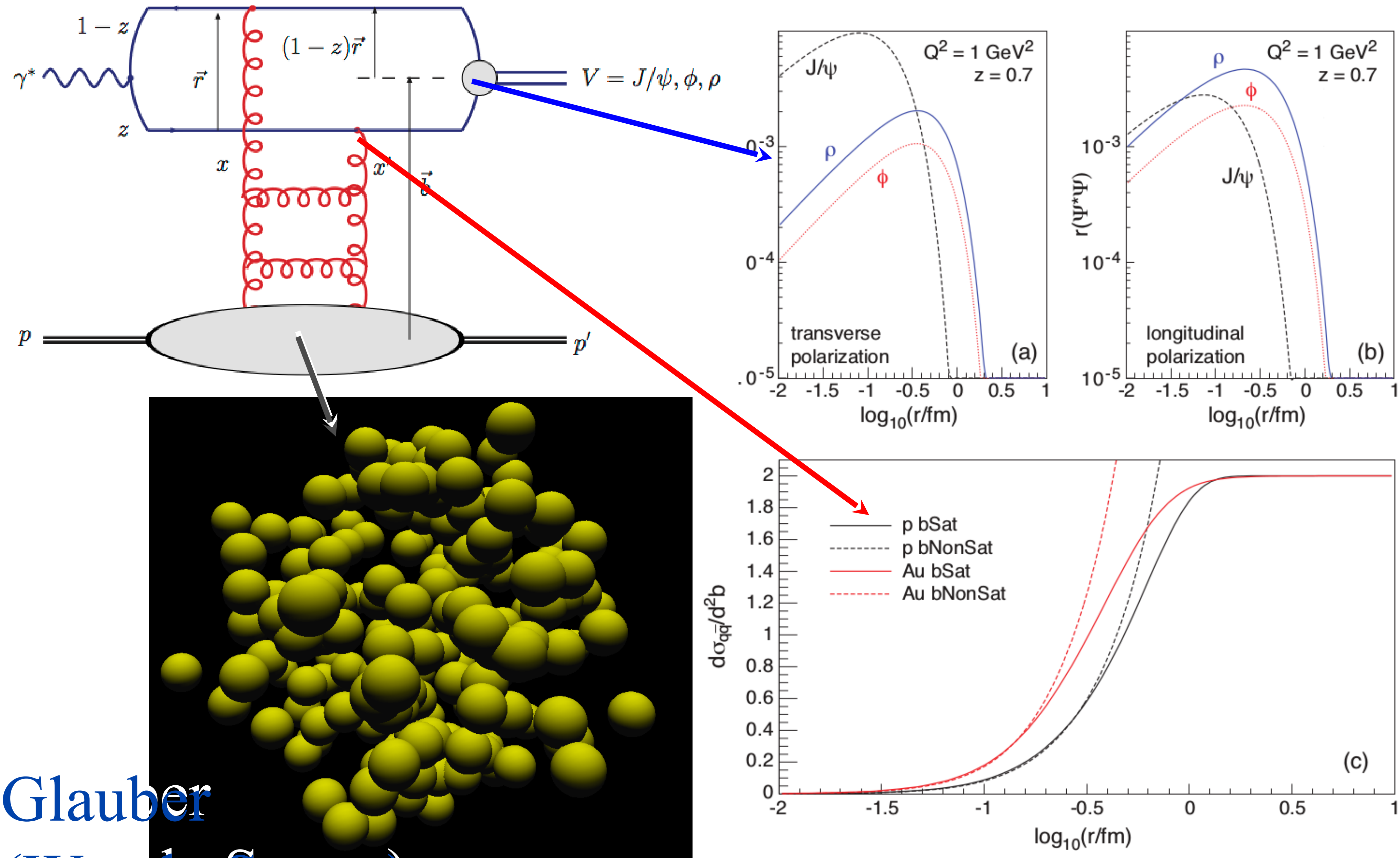
TT and T. Ullrich,
Exclusive diffractive processes in electron-ion collisions

Phys. Rev. C 87, 024913 (2013)
arXiv:1211.3048

TT and T. Ullrich,
The dipole model Monte Carlo generator Sartre 1

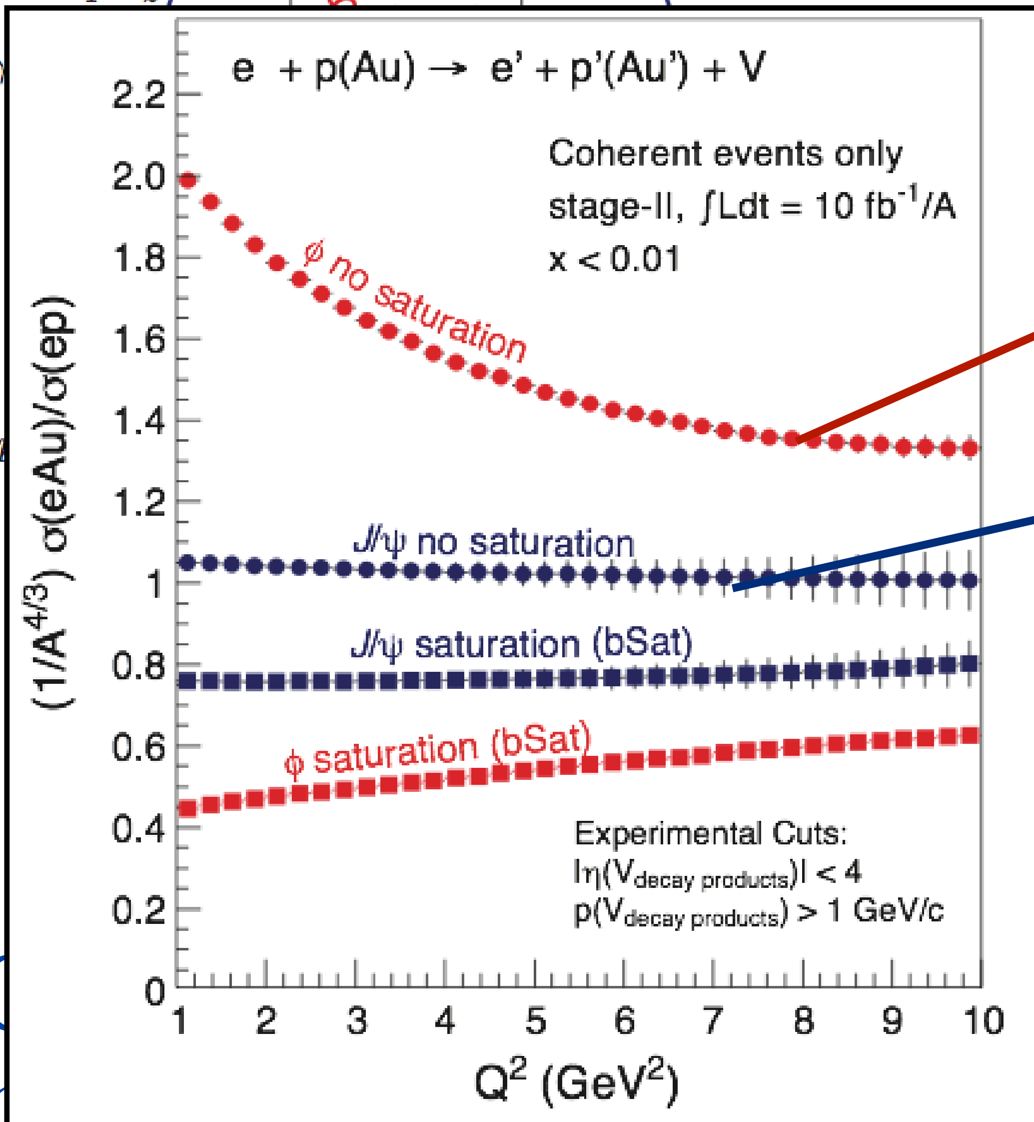
Comput.Phys.Commun. 185 (2014) 1835-1853
arXiv:1307.8059

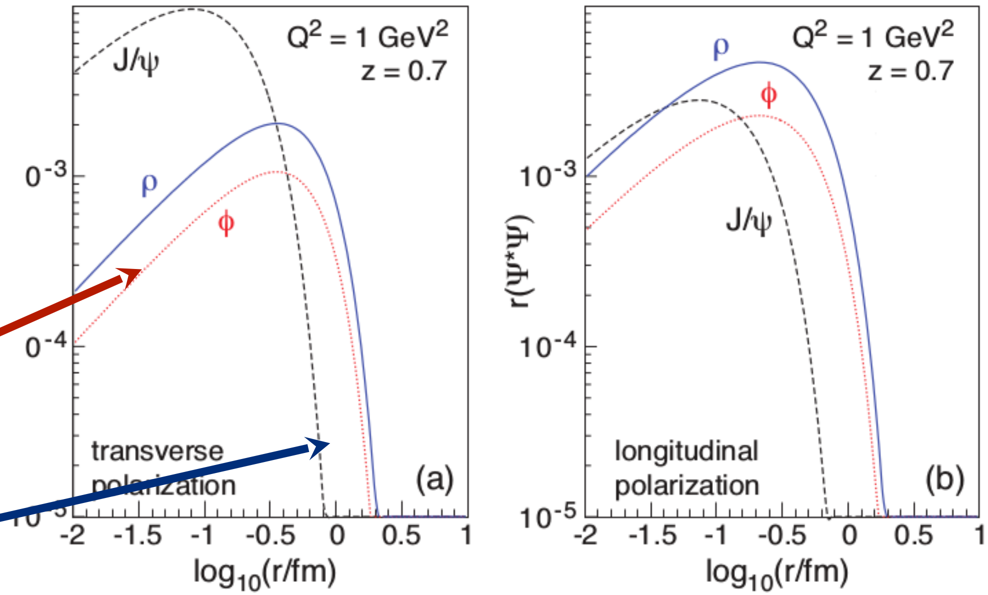
Sar*t*re dipole model with glauber bSat and bNonSat

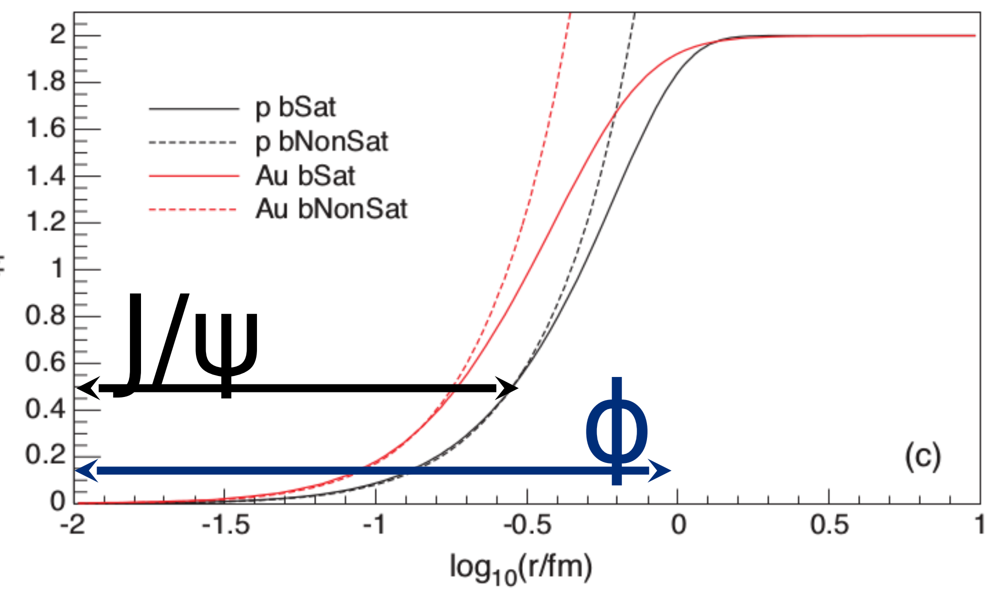


Glauber
(Woods-Saxon)

Sartre dipole model with glauber bSat and bNonSat



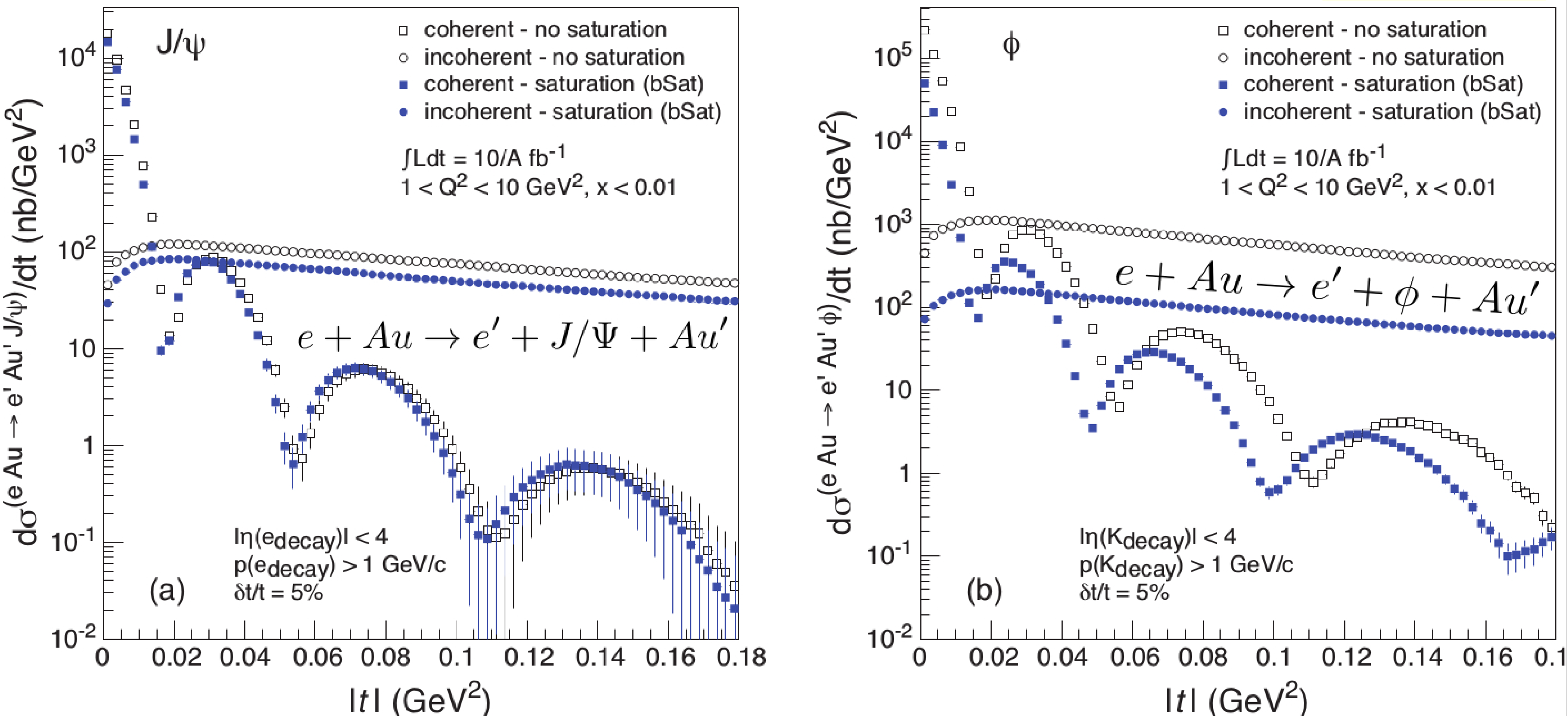




(Woods-
Saxon)

EIC predictions: exclusive diffraction

T.T. & Thomas Ullrich
PRC 87 (2013) 024913

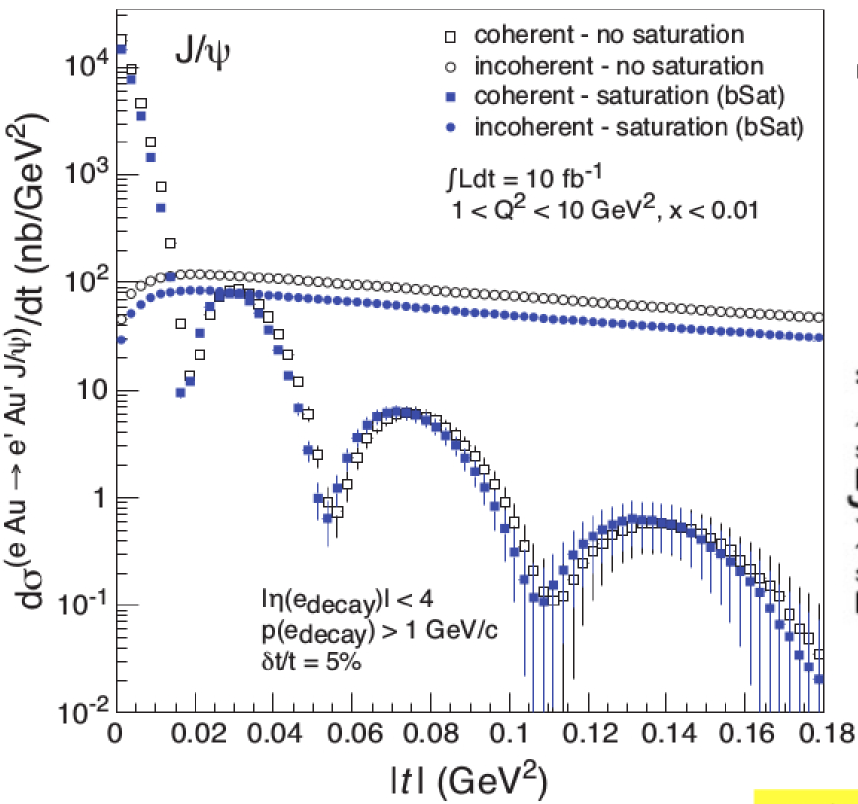


Can constrain models a lot with a few months of running!

First 4 dips obtainable.

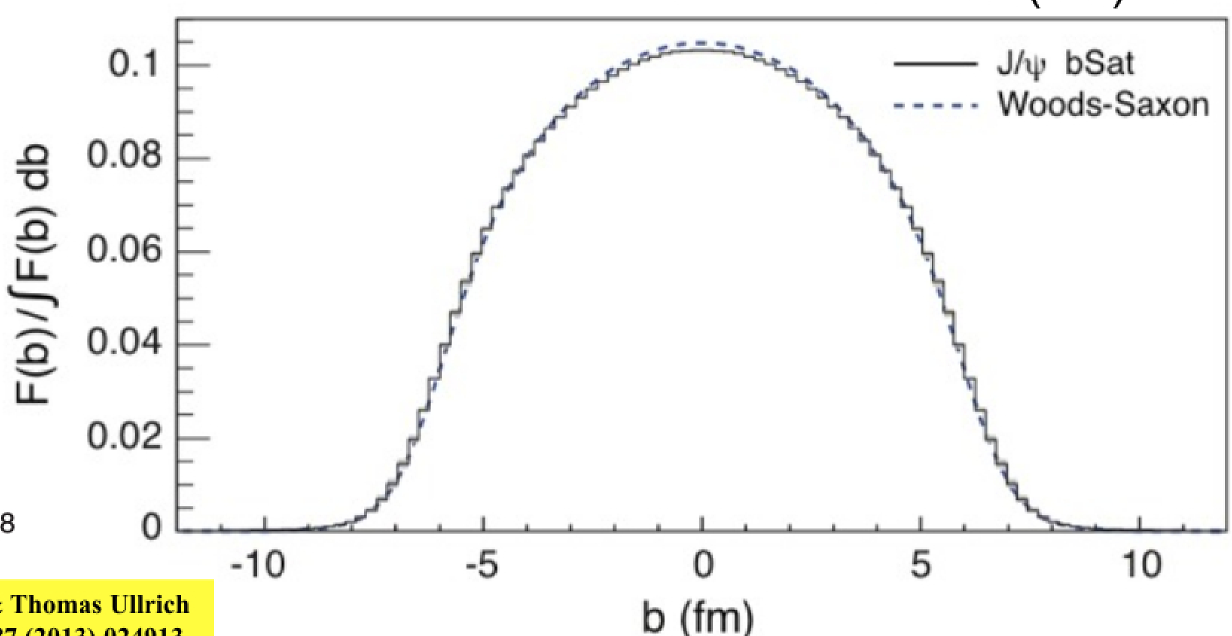
Probing the spatial gluon distribution at EIC

Momentum transfer t conjugate to transverse coordinate b



$$F(b) \propto \int \mathrm{d}\Delta \Delta J_0(\Delta b) \sqrt{\frac{\mathrm{d}\sigma}{\mathrm{d}t}}$$

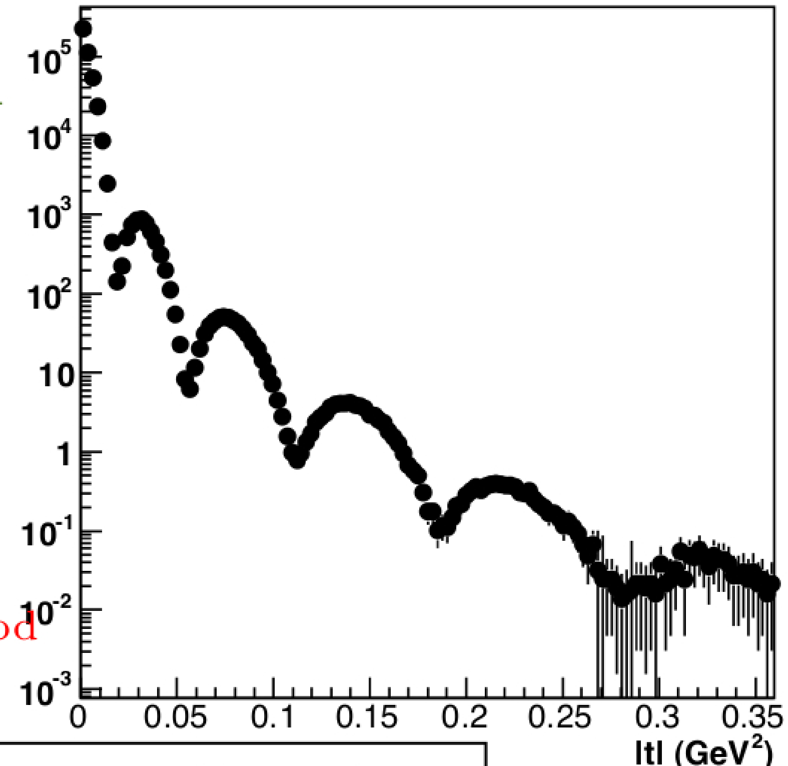
$t = \Delta^2/(1-x) \approx \Delta^2$



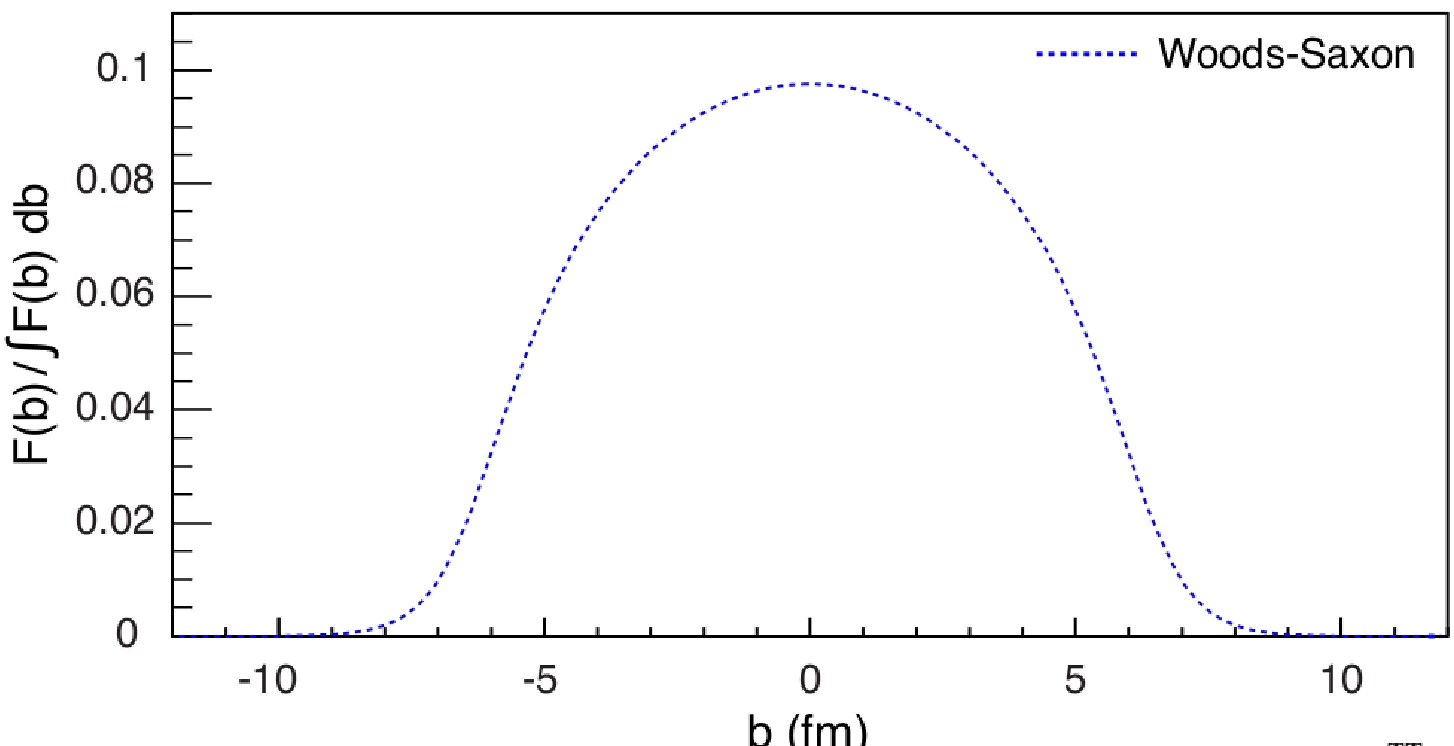
T.T. & Thomas Ullrich
PRC 87 (2013) 024913

EIC will be able to retrieve the spatial gluon distribution with high precision.

Probing the spatial gluon distribution at EIC

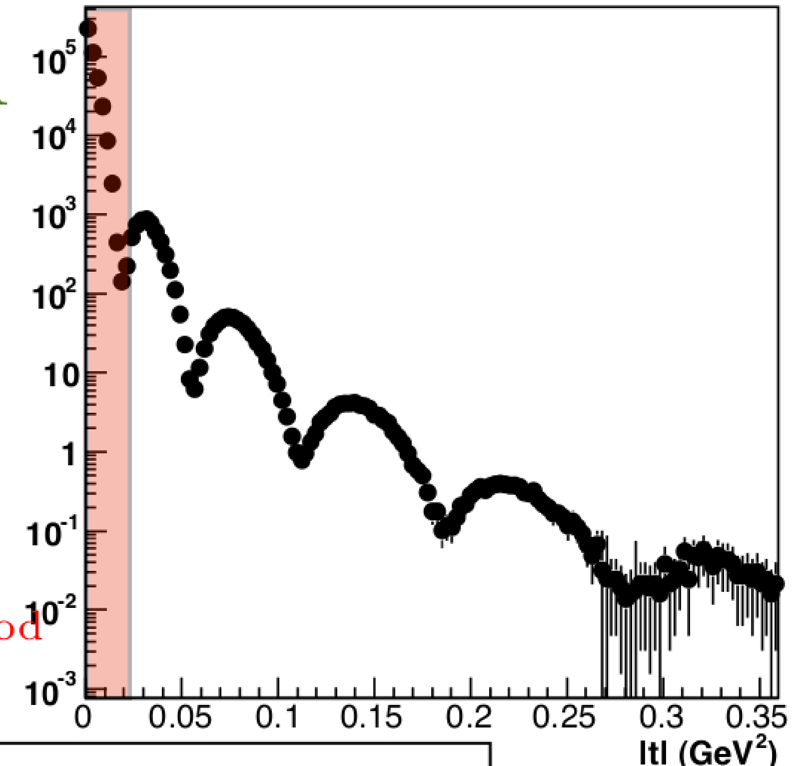


$$F(b) = \frac{1}{2\pi}\int_0^\infty \mathrm{d}\Delta\Delta J_0(\Delta b)\sqrt{\frac{\mathrm{d}\sigma_{\mathrm{coherent}}}{\mathrm{d}t}(\Delta)}\bigg|_{\mathrm{mod}}$$



TT and T. Ullrich,
Phys. Rev. C 87, 024913 (2013)
arXiv:1211.3048

Probing the spatial gluon distribution at EIC



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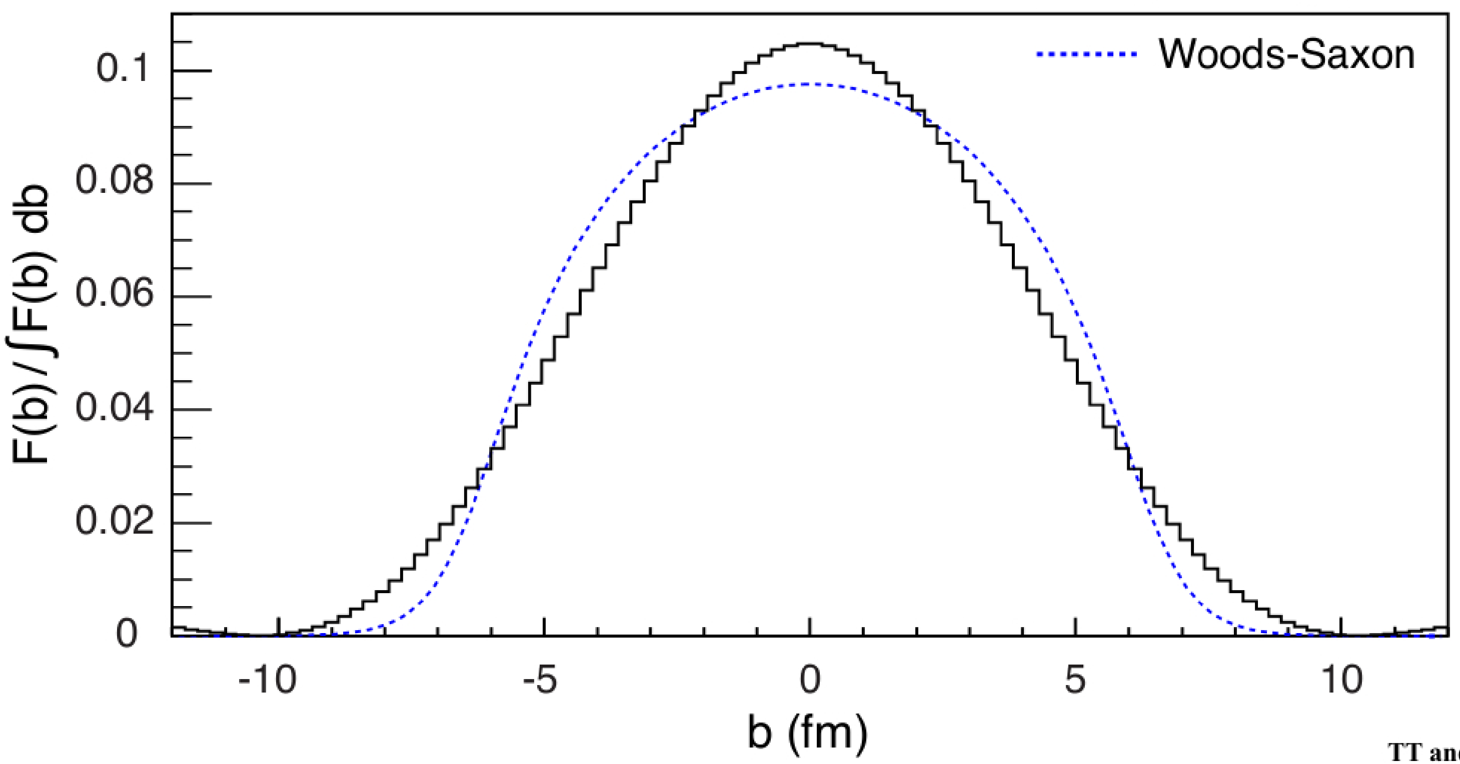

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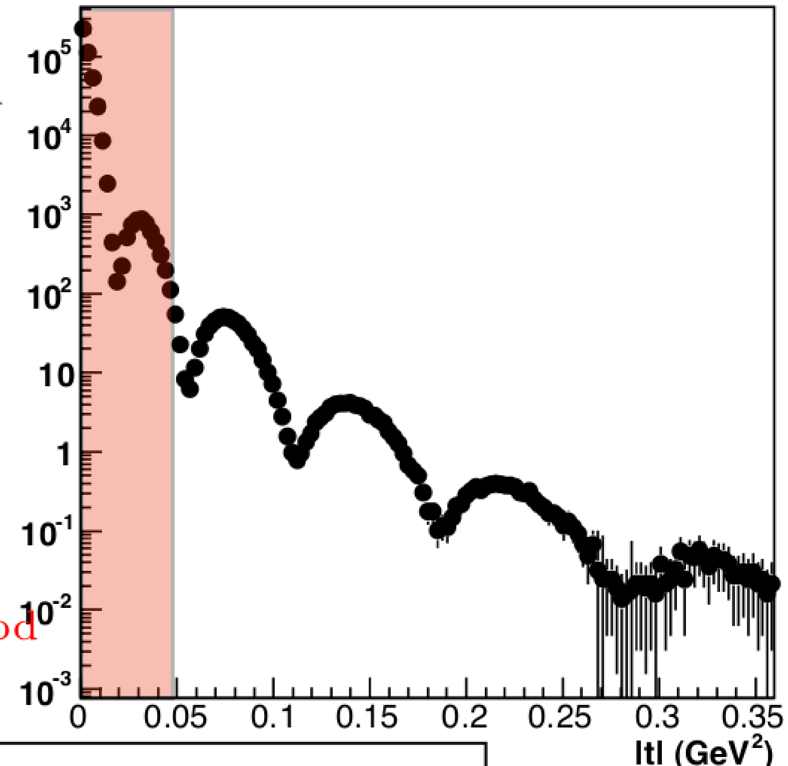

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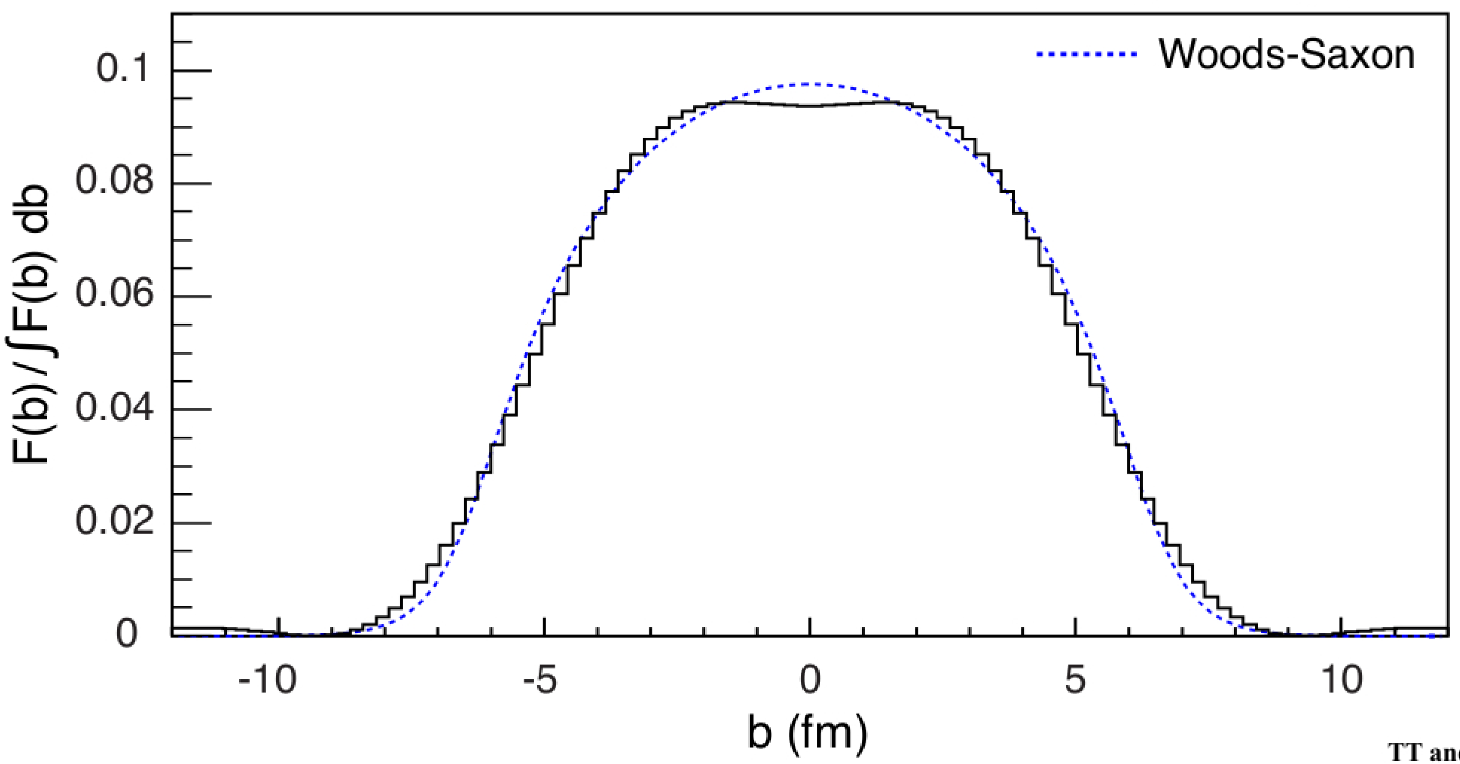

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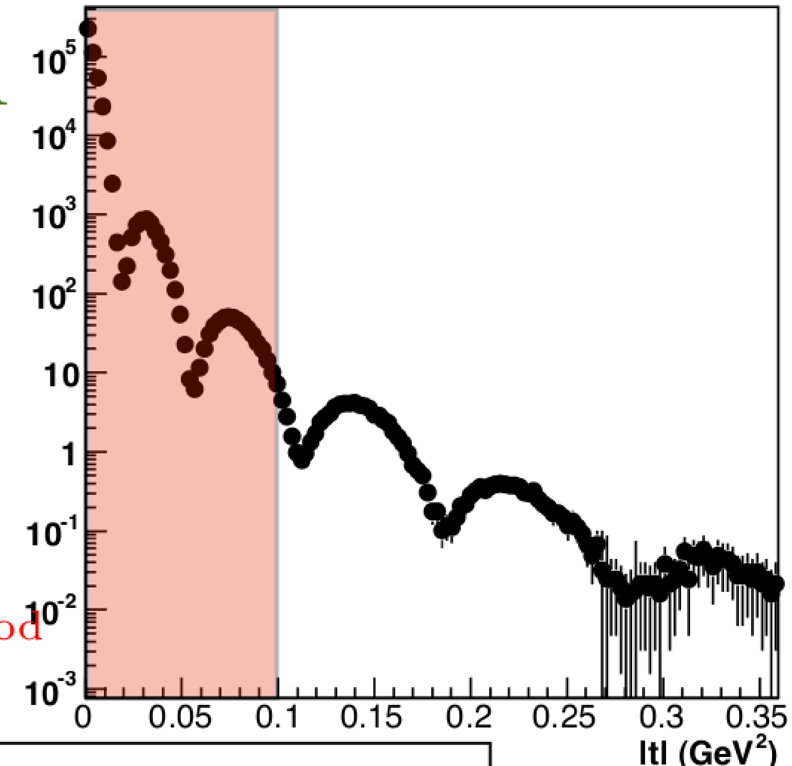

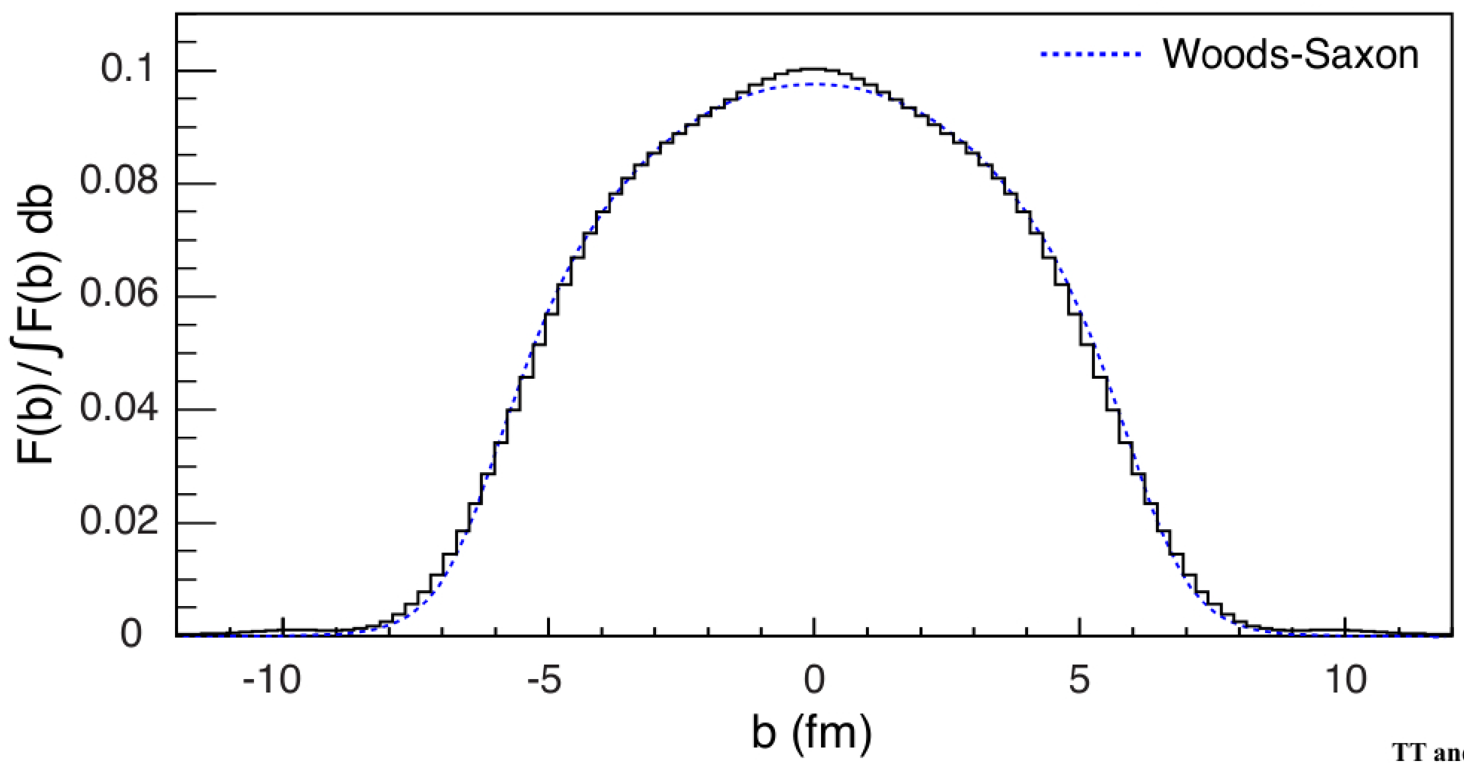

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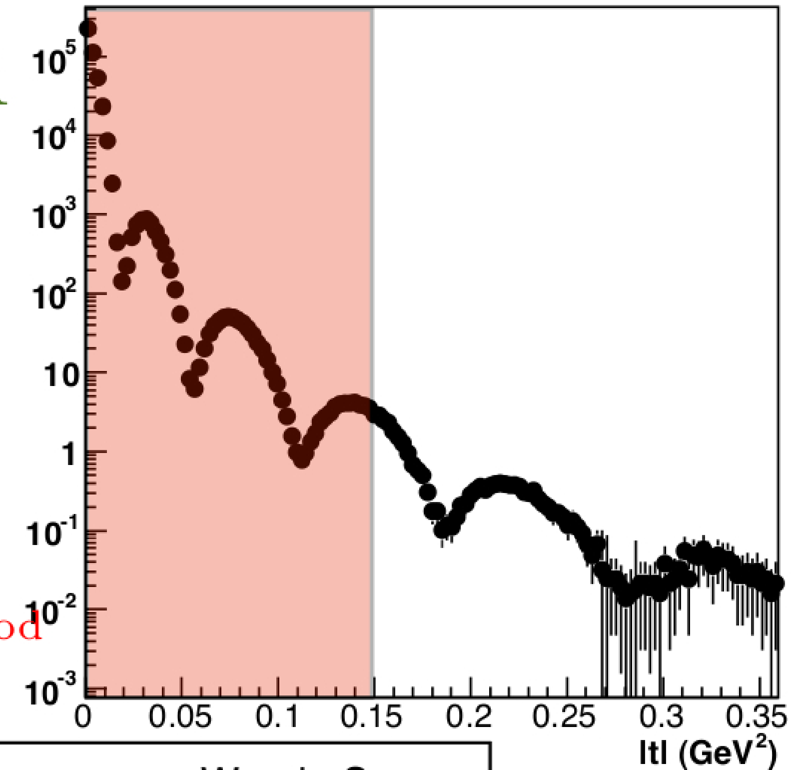

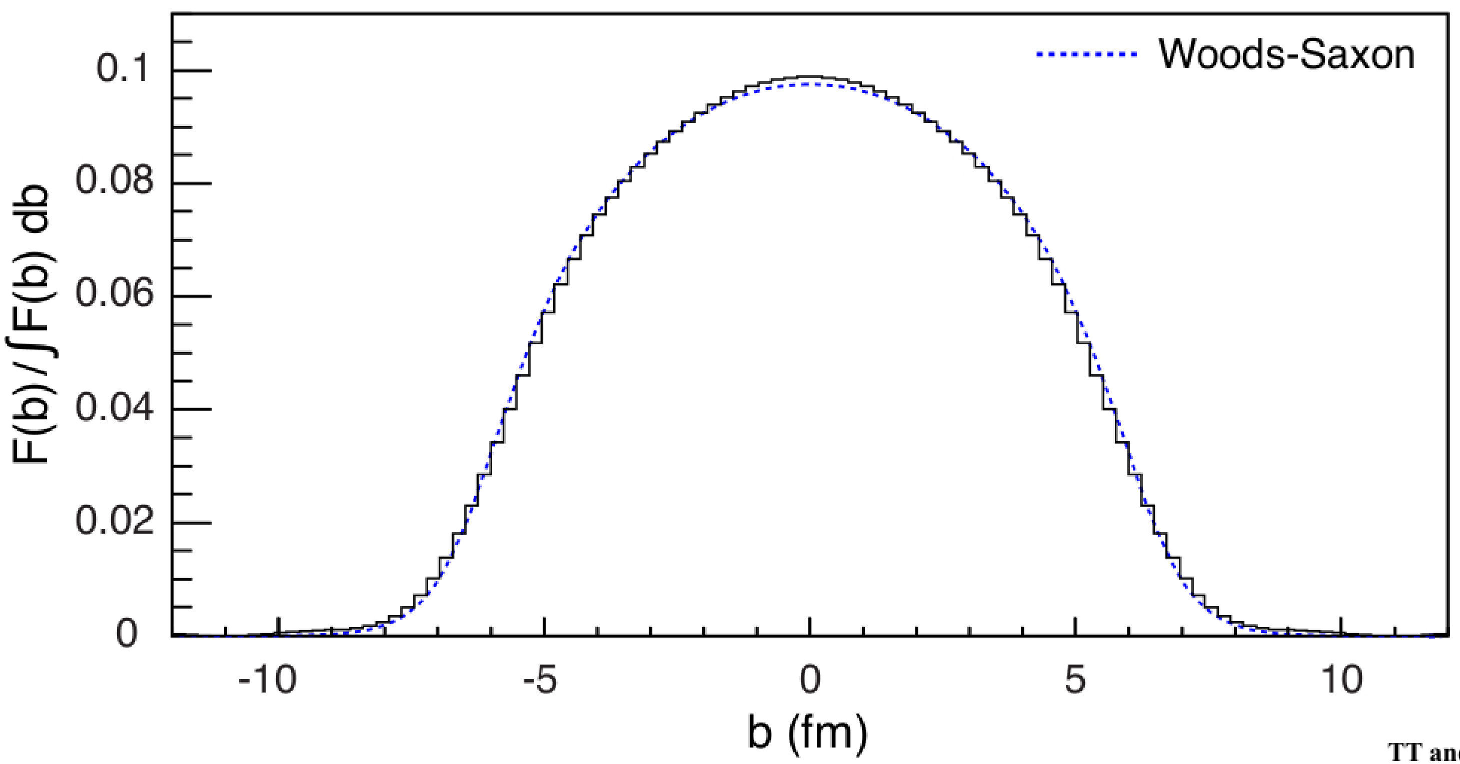

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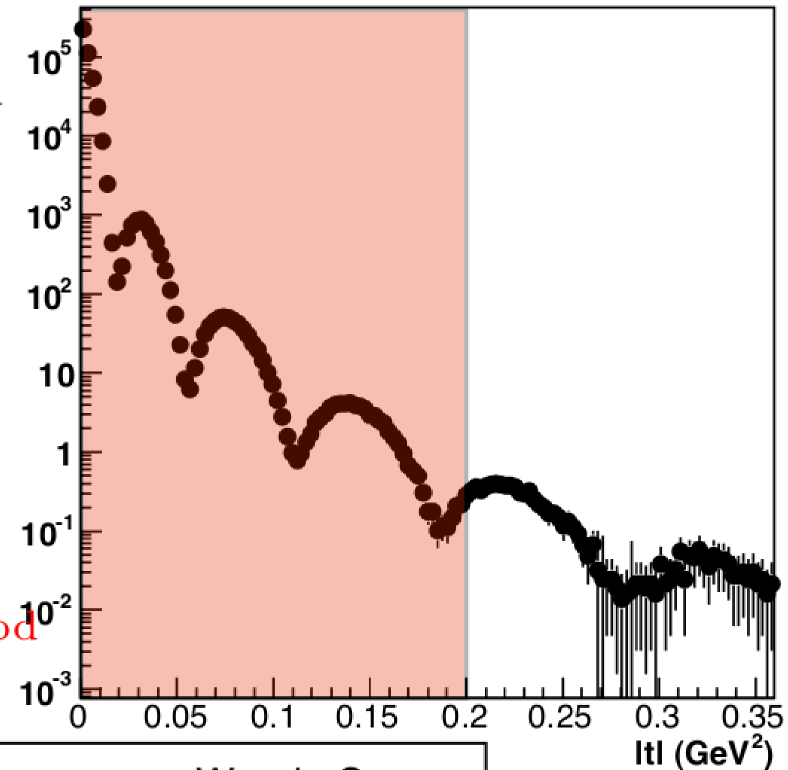

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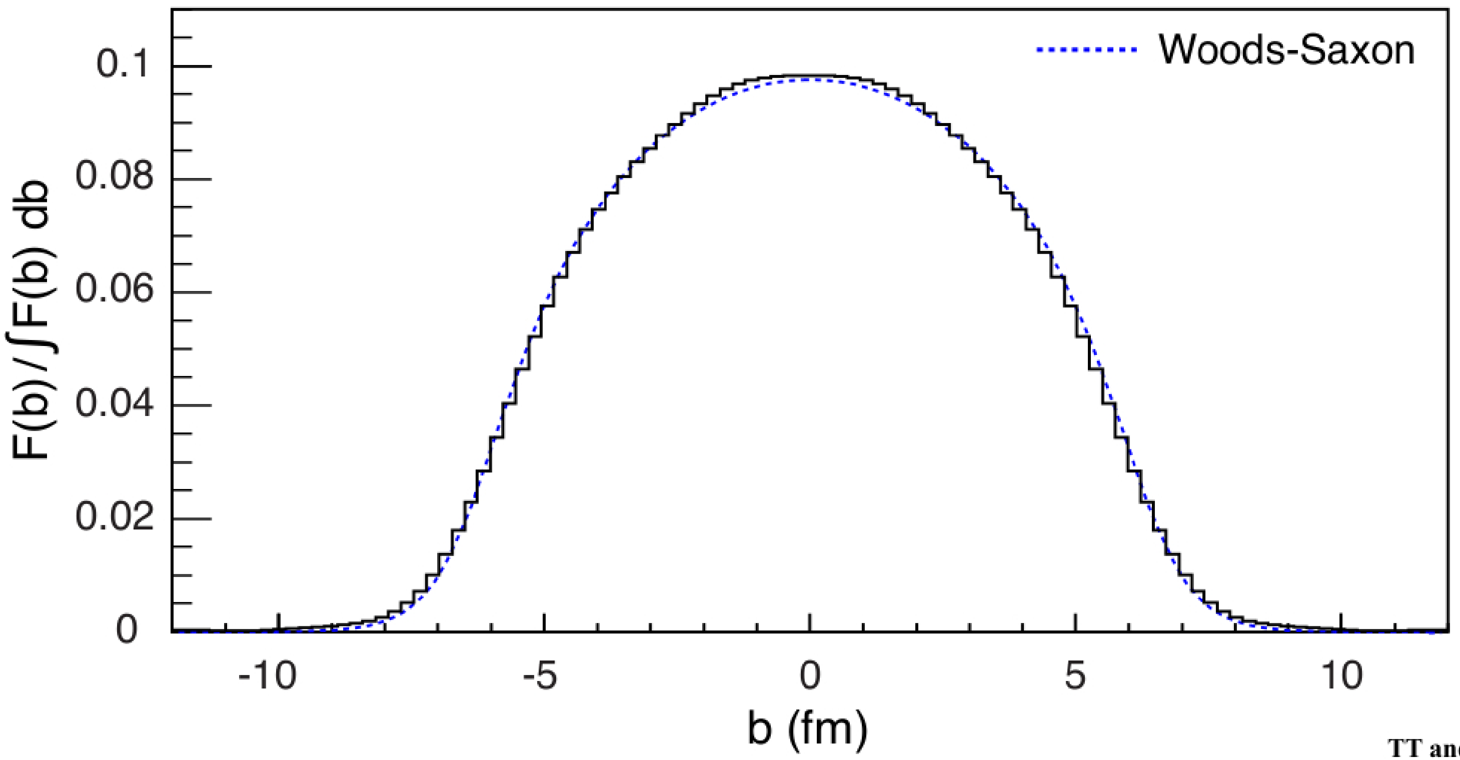

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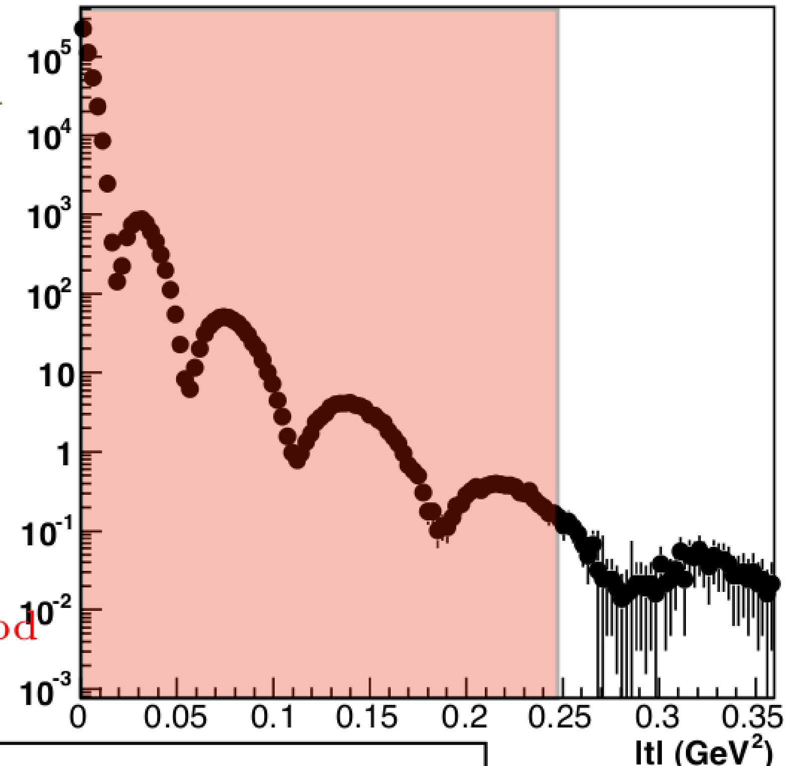

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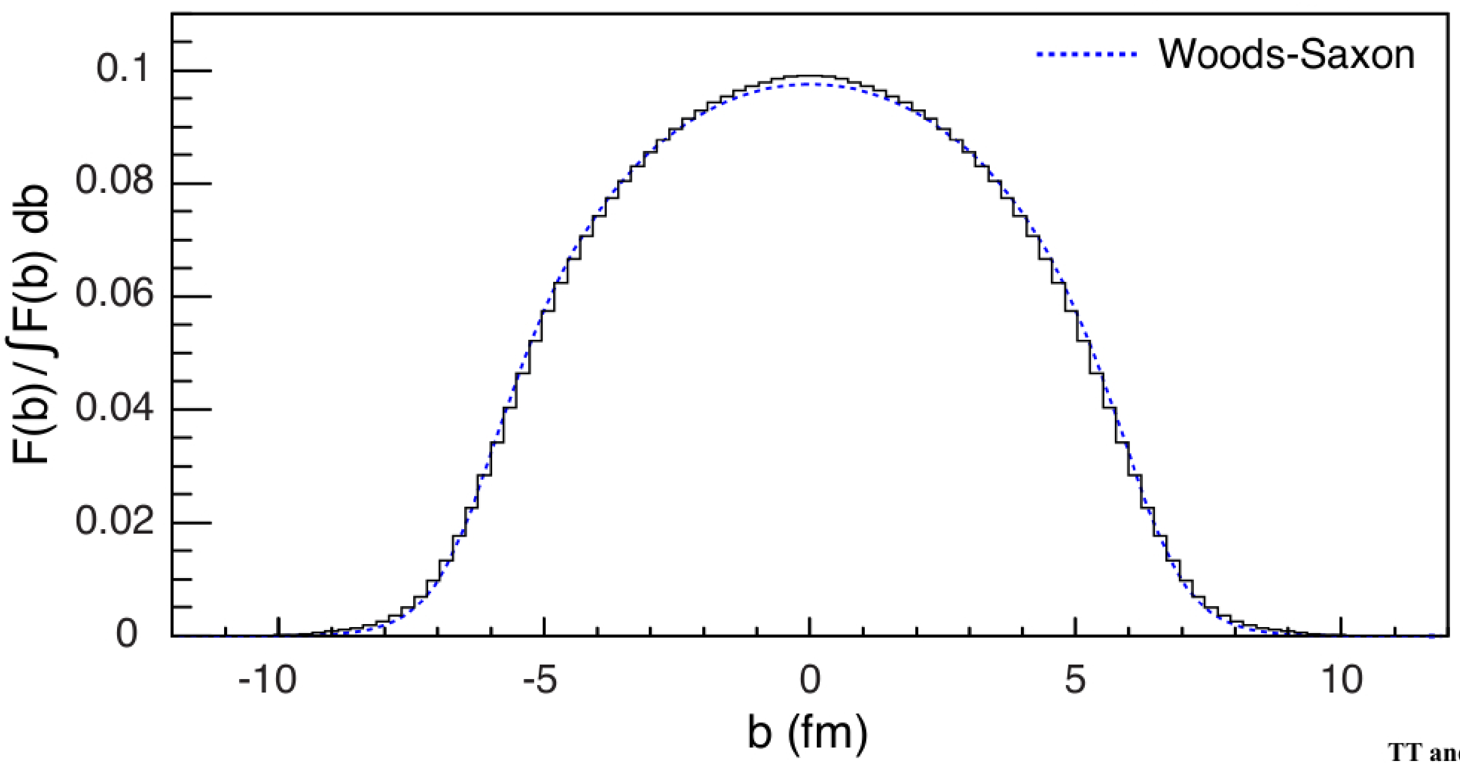

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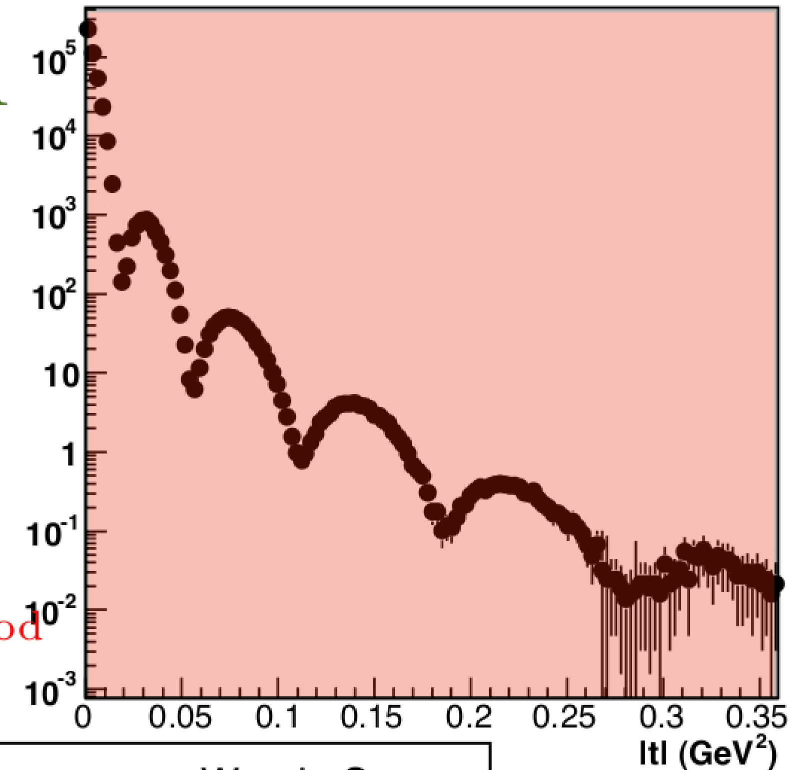

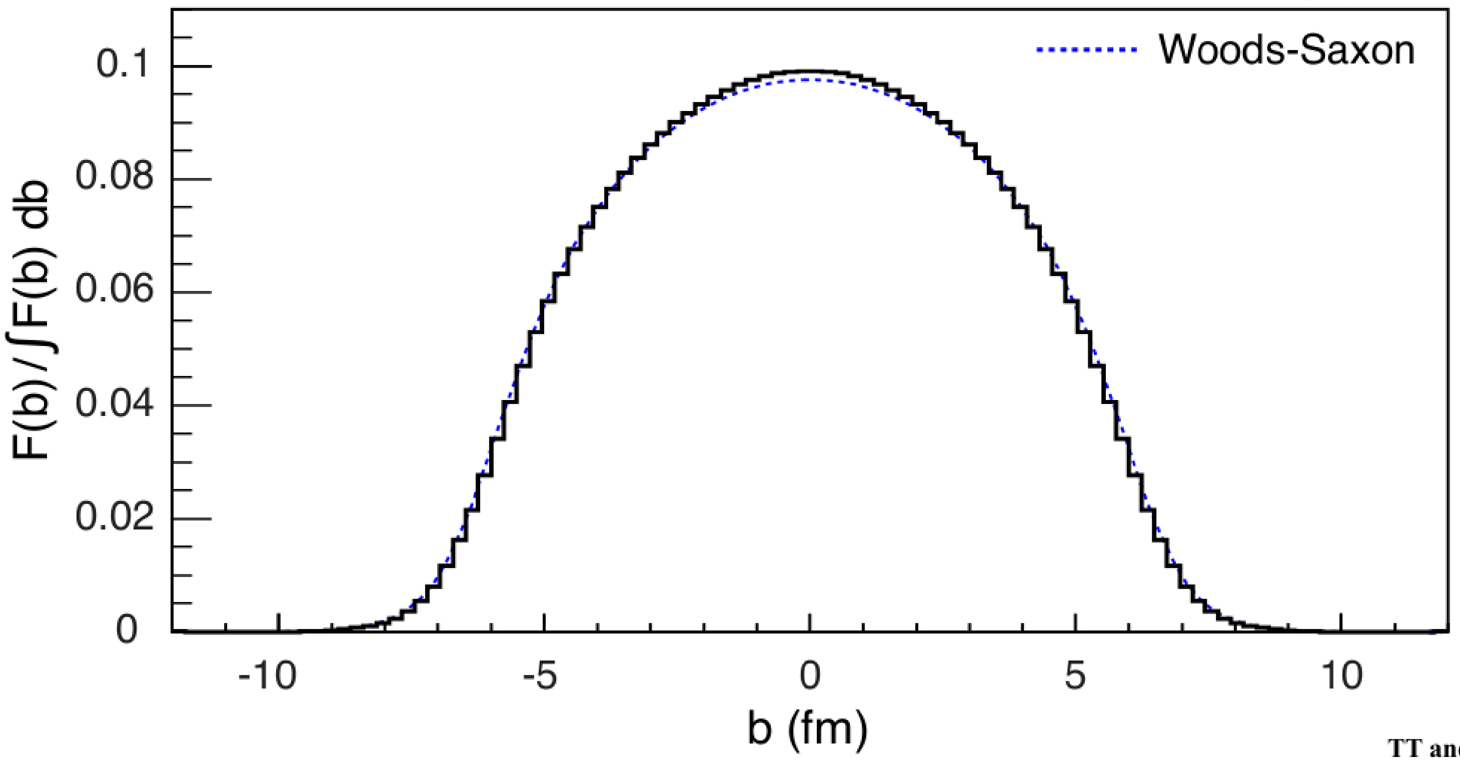

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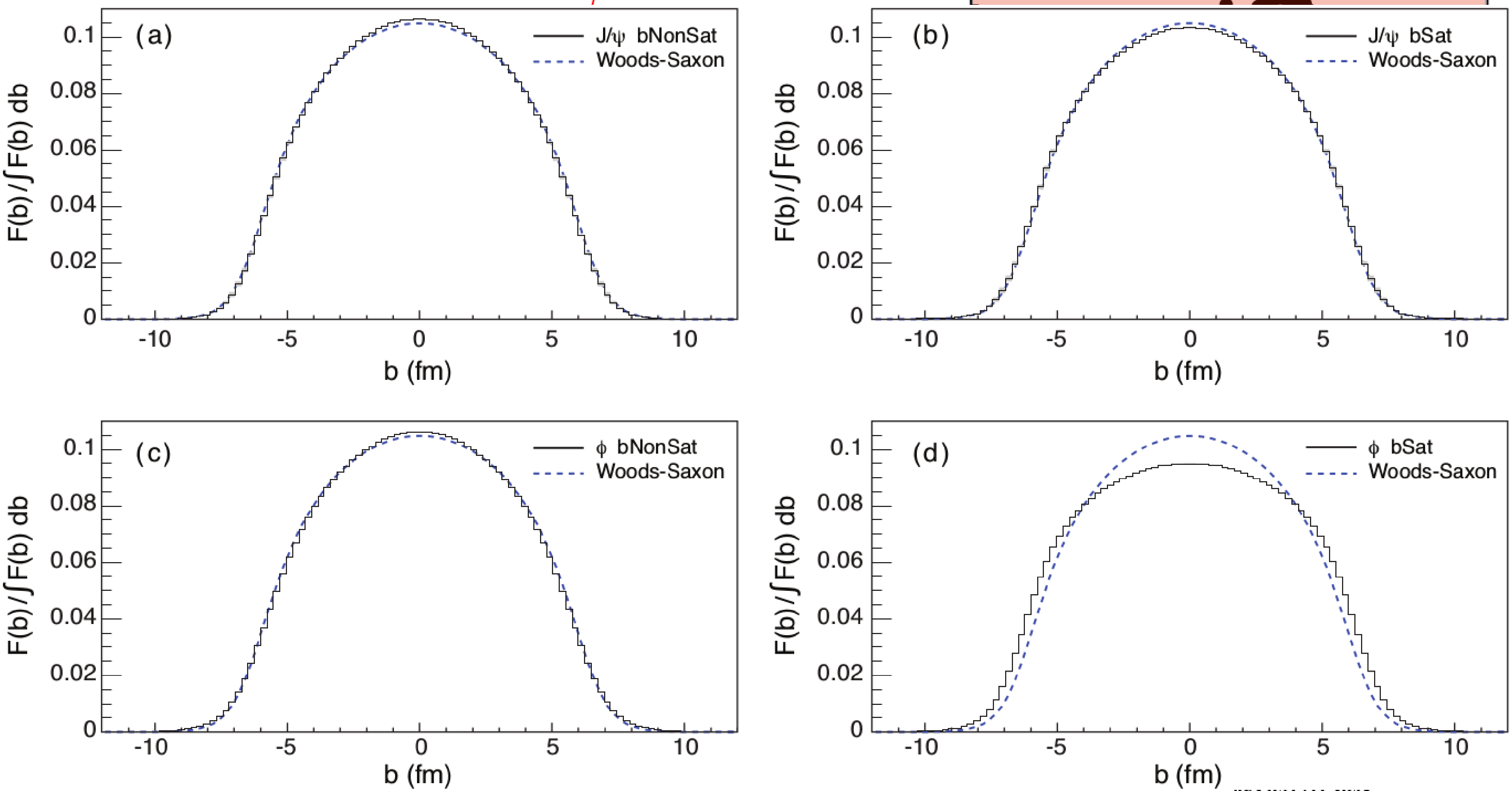
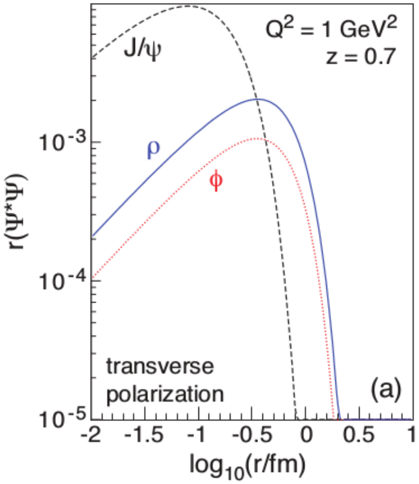
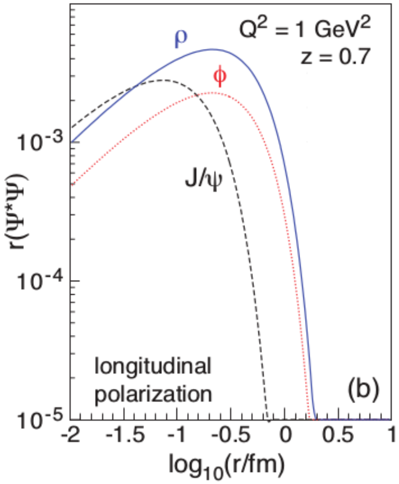
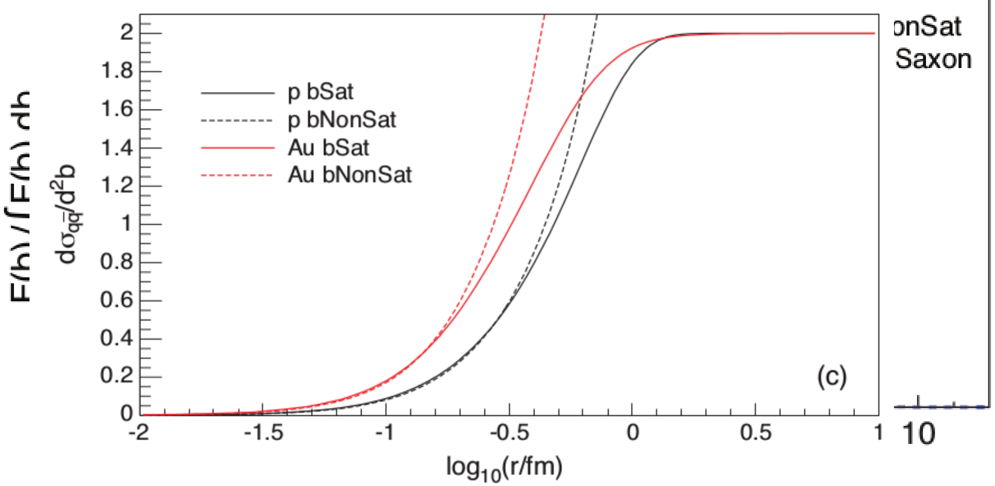


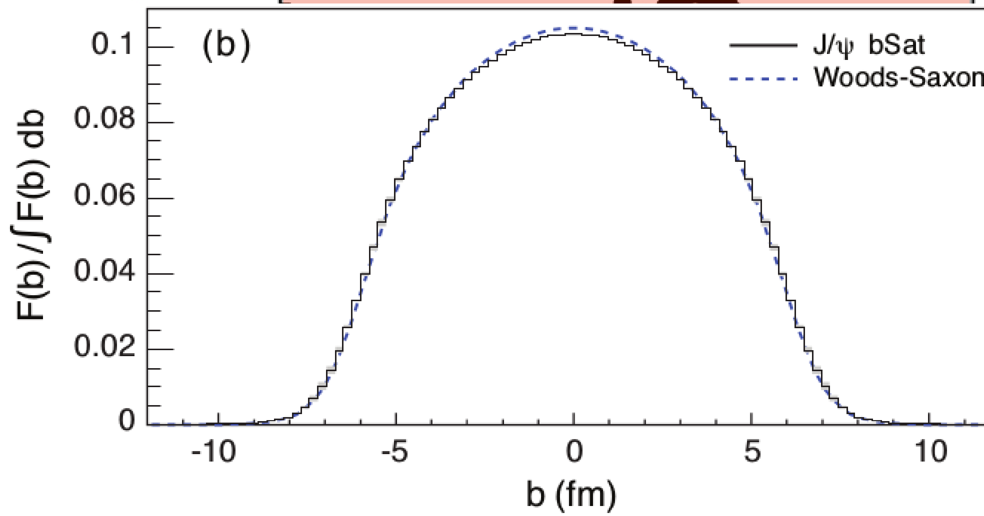
arXiv:1211.3048

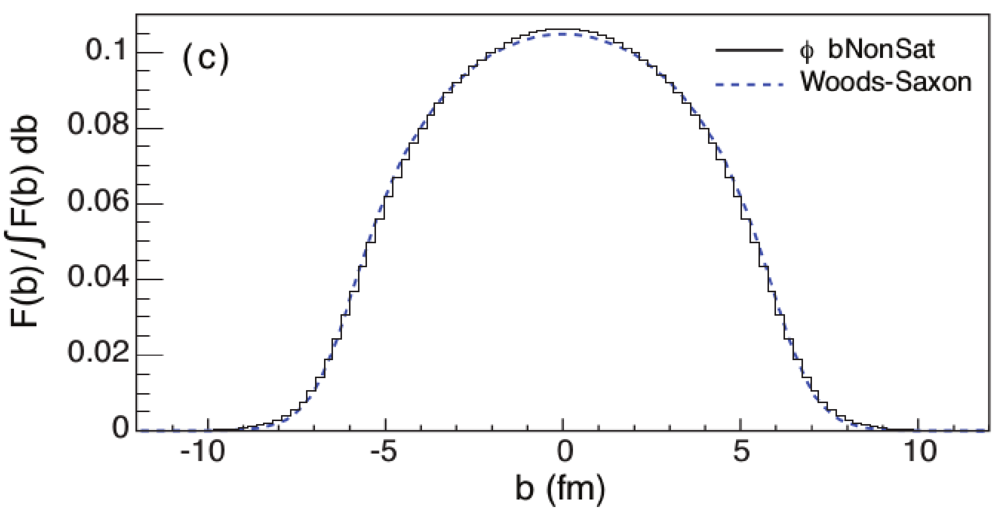
P l gluon EIC

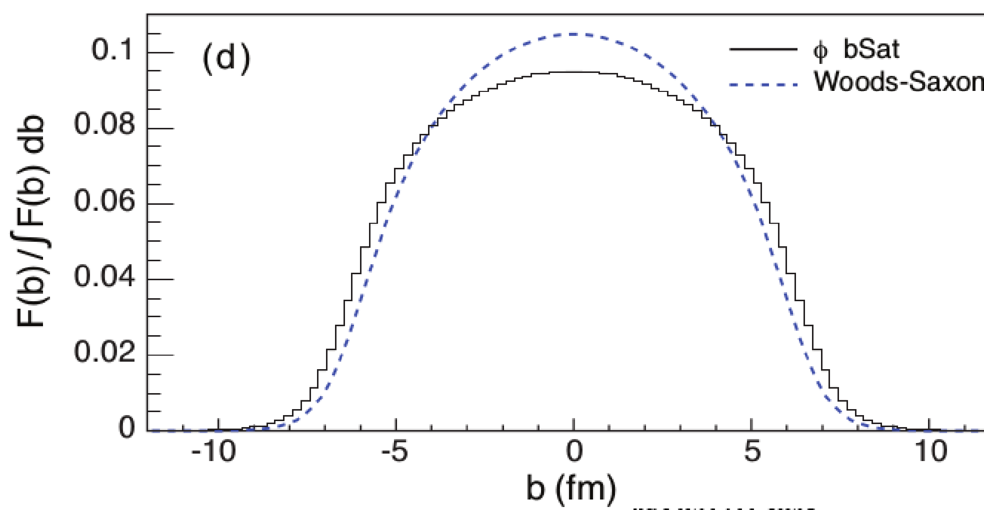






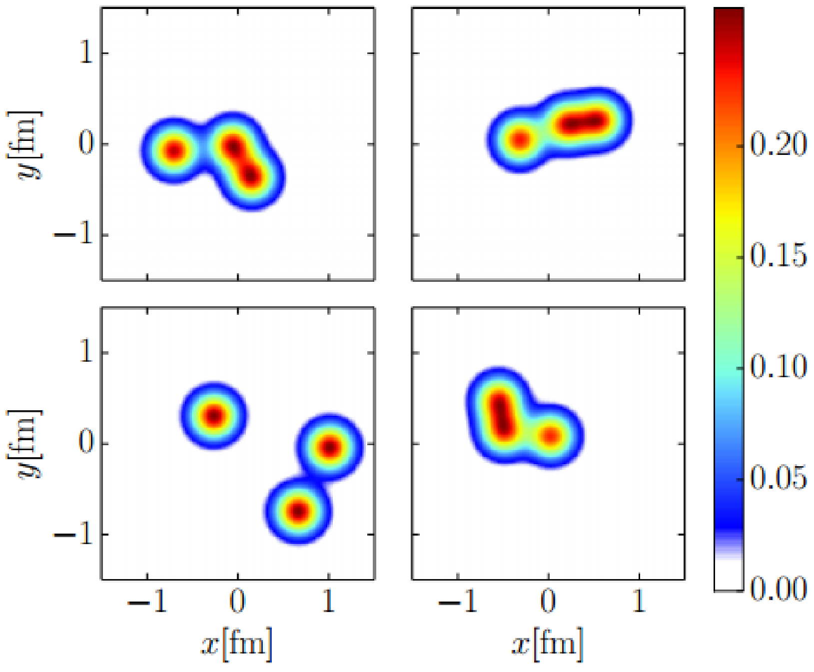




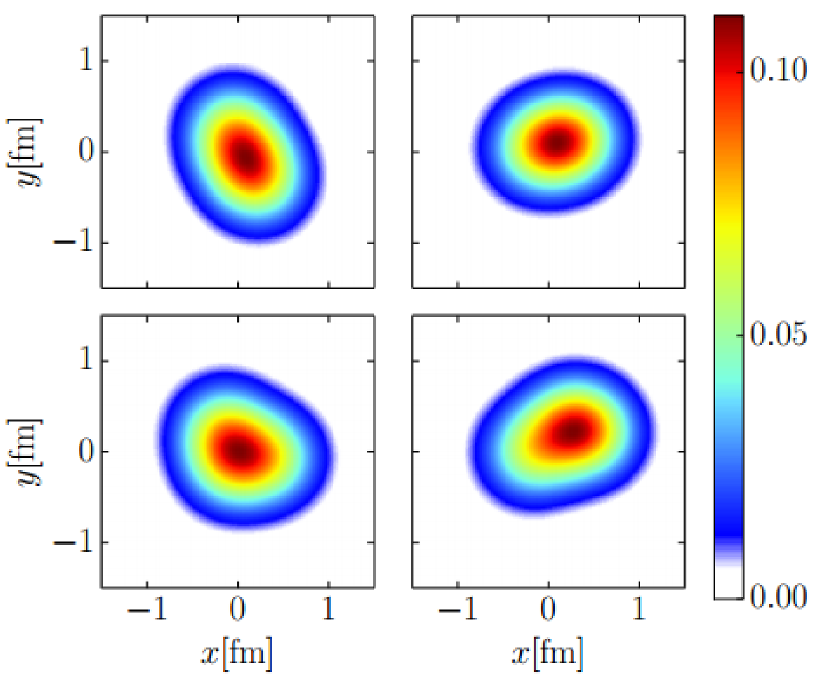


arXiv:1211.3048

Recent work on Fluctuations



(a) $B_{qc} = 3.3\ \mathrm{GeV}^{-2}, B_q = 0.7\ \mathrm{GeV}^{-2}$



(b) $B_{qc} = 1.0\ \mathrm{GeV}^{-2}, B_q = 3.0\ \mathrm{GeV}^{-2}$

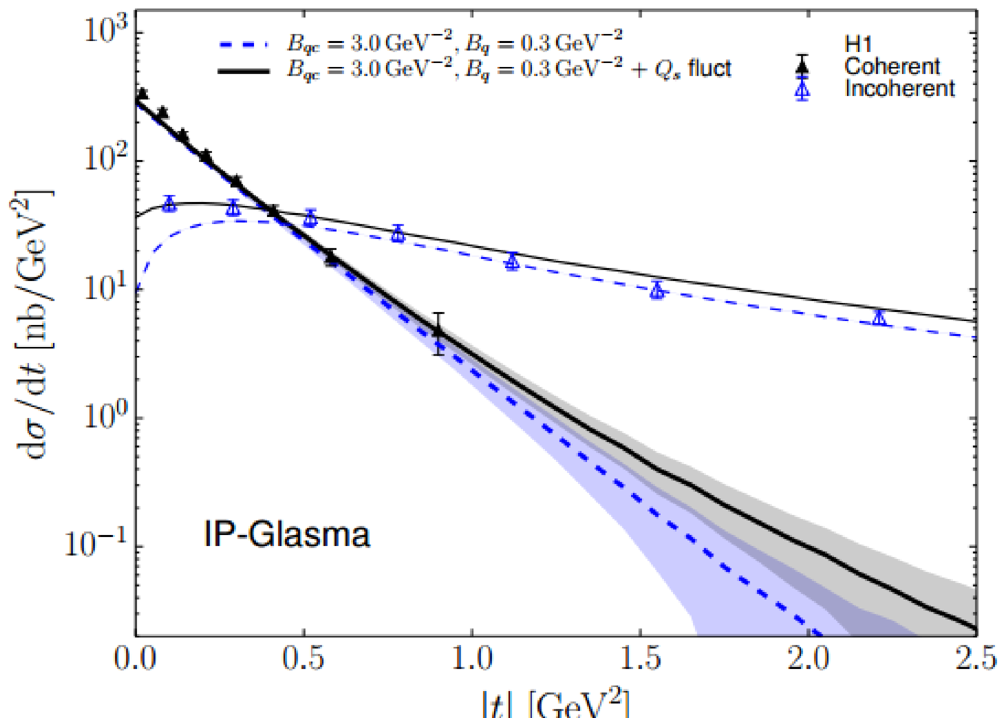
Two different fluctuations:

Around low scale partons

+ Saturation Scale

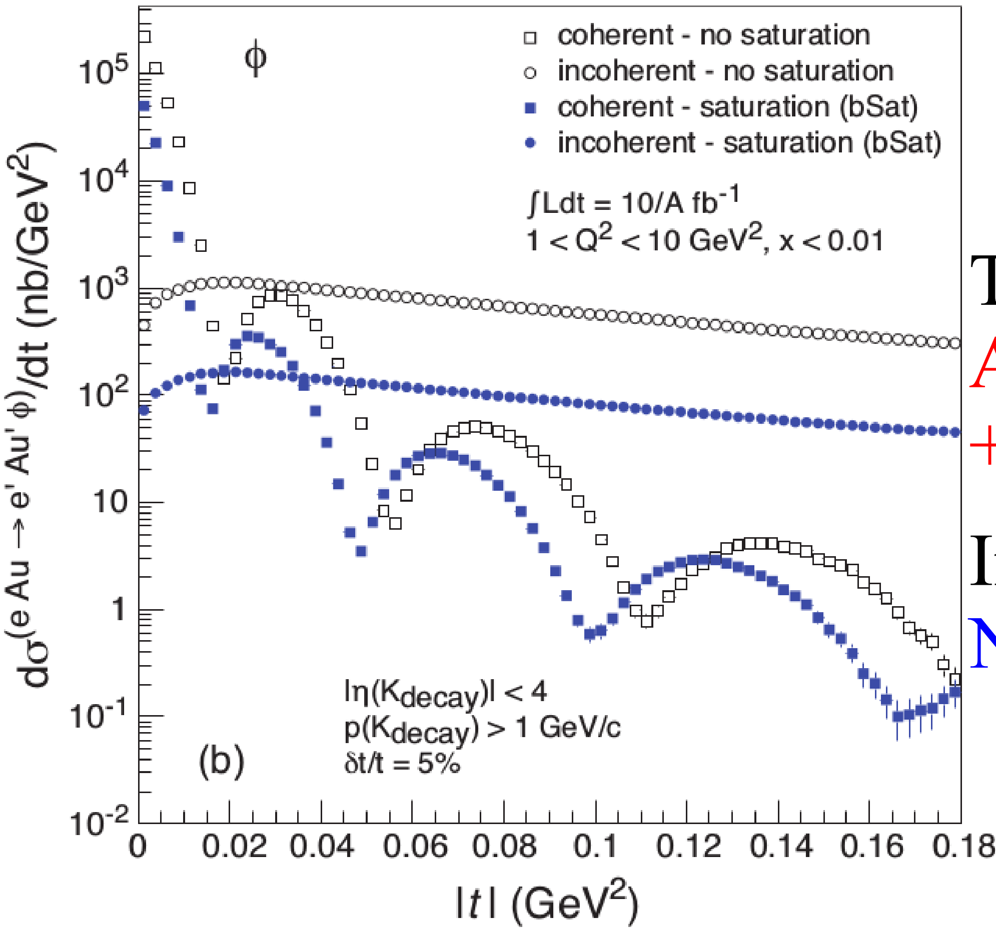
In Nuclei:

Nucleon Configuration Fluctuations



Heikki Mäntysaari, Björn Schenke (Brookhaven Natl. Lab.)Phys.Rev. D94 (2016) no.3, 034042

Recent work on Fluctuations



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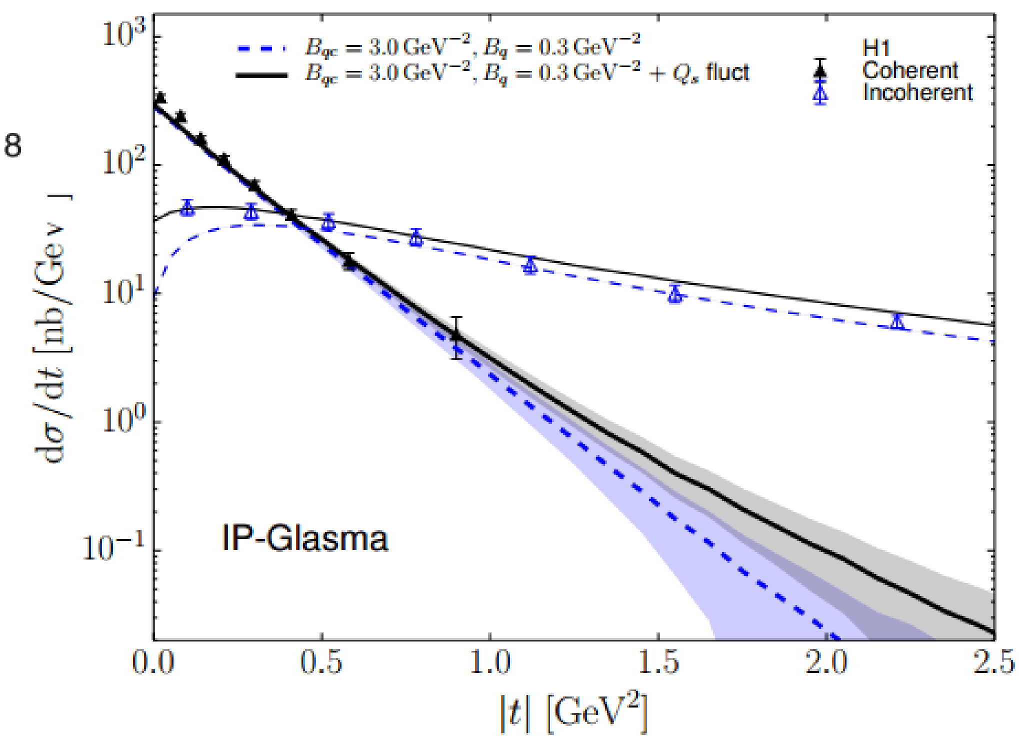

Heikki Mäntysaari, Björn Schenke (Brookhaven Natl. Lab.)Phys.Rev. D94 (2016) no.3, 034042

Ongoing Work: **Inclusive Diffraction** Investigating the Proton Size & Shape in the Dipole Model

Making a new fit for the dipole model parameters to combined HERA data for:

Inclusive DIS

Inclusive Diffraction

F_2 charm

Sar*t*re 2: Inclusive and Exclusive Diffraction

Ultraperipheral Collisions with Sartre

At first glance, change the photon flux of the electron:

$$\frac{\mathrm{d}^2 N^e_{\gamma,T}}{\mathrm{d}Q^2 \mathrm{d}W^2} = \frac{\alpha_{\mathrm{EM}}(1-y)}{2\pi Q^2 s y} \cdot \left(1 + (1-y)^2 - 2(1-y)\frac{Q^2_{\mathrm{min}}}{Q^2}\right)$$

into that of a proton or ion:

$$\frac{\mathrm{d}^2 N^A_{\gamma,T}}{\mathrm{d}Q^2 \mathrm{d}W^2} = \frac{\alpha_{\mathrm{EM}} Z^2 Q^2}{\pi E_\gamma} \left(\frac{F(Q^2 + E_\gamma^2/\gamma^2_{\mathrm{Lorentz}})}{Q^2 + E_\gamma^2/\gamma^2_{\mathrm{Lorentz}}}\right)^2 \frac{\mathrm{d}E_\gamma}{\mathrm{d}W^2}$$

$$F^{(p)}(Q^2) = \frac{1}{\left(1 + Q^2/0.71\ \mathrm{GeV}^2\right)^2} \qquad F^{(A)}(Q^2) = \frac{4\pi\rho_0}{AQ^3} \frac{\sin(QR) - qR\cos(QR)}{1 + a^2_{\mathrm{Yukawa}} Q^2}$$

Ongoing work: Sar*t*re can soon be used for UPC at RHIC and LHC

Summary

The EIC will profoundly impact our understanding of QCD, with its high energy, its polarised beams, its versatility in accelerating different nuclear species, and its high luminosity.

***ep*:** Precision studies of PDFs, TMDs, and GPDs will lead to the most comprehensive picture of the nucleon ever: its flavor, spin, **spatial and momentum structure and parton fluctuations**

***e*A**: Unprecedented study of matter in a new regime where physics is not described by "ordinary" QCD: non-linear QCD (**saturation**) effects, **properties of gluon distribution (momentum and space)**, in nucleons and nuclei, as well as their **fluctuations** due to different effects.
Only way to measure nuclear initial state.

Sar*t*re: Simulates exclusive diffractive ep and eA, as well as UPC in pA and AA.

Sartre 2 will be an event generator for **inclusive** diffractive DIS as well.

This physics is tied to a future high energy polarised Electron Ion Collider and cannot be done without it.