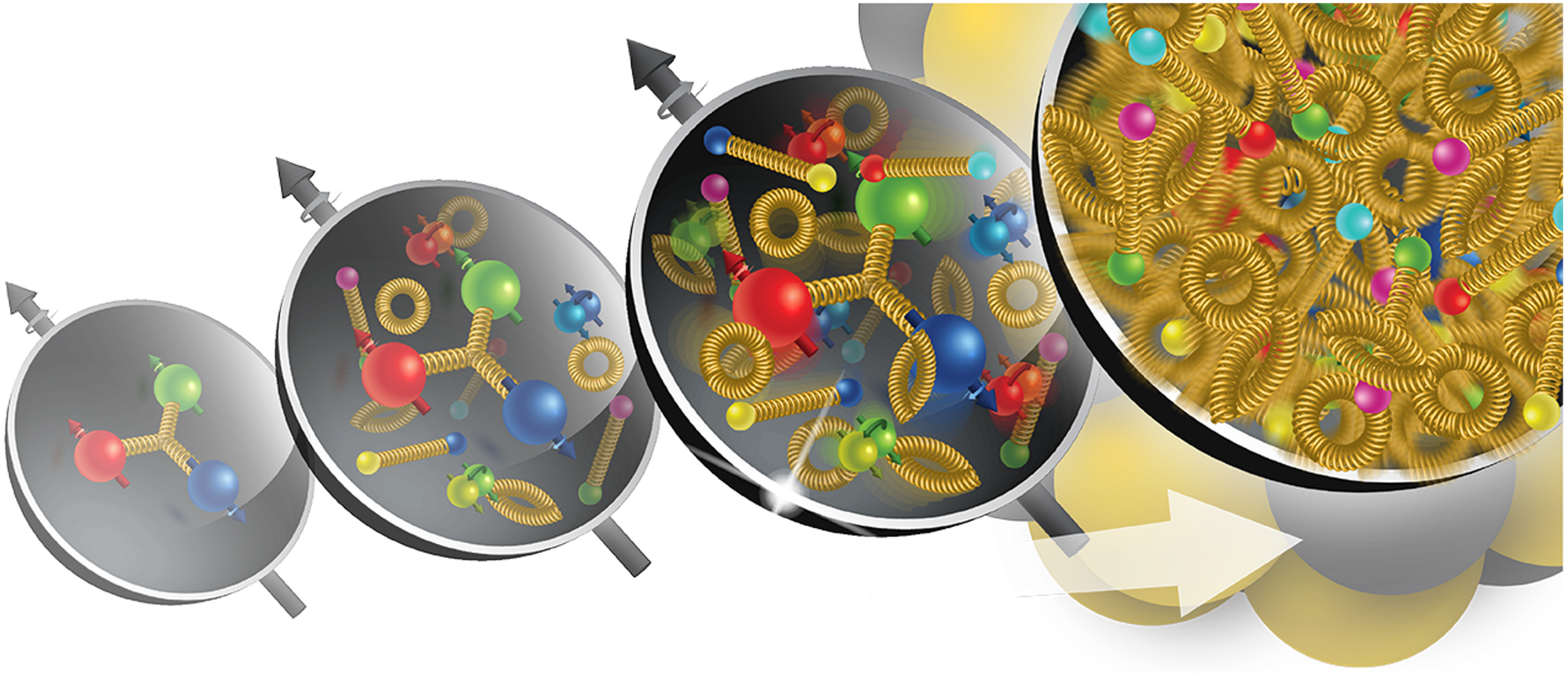
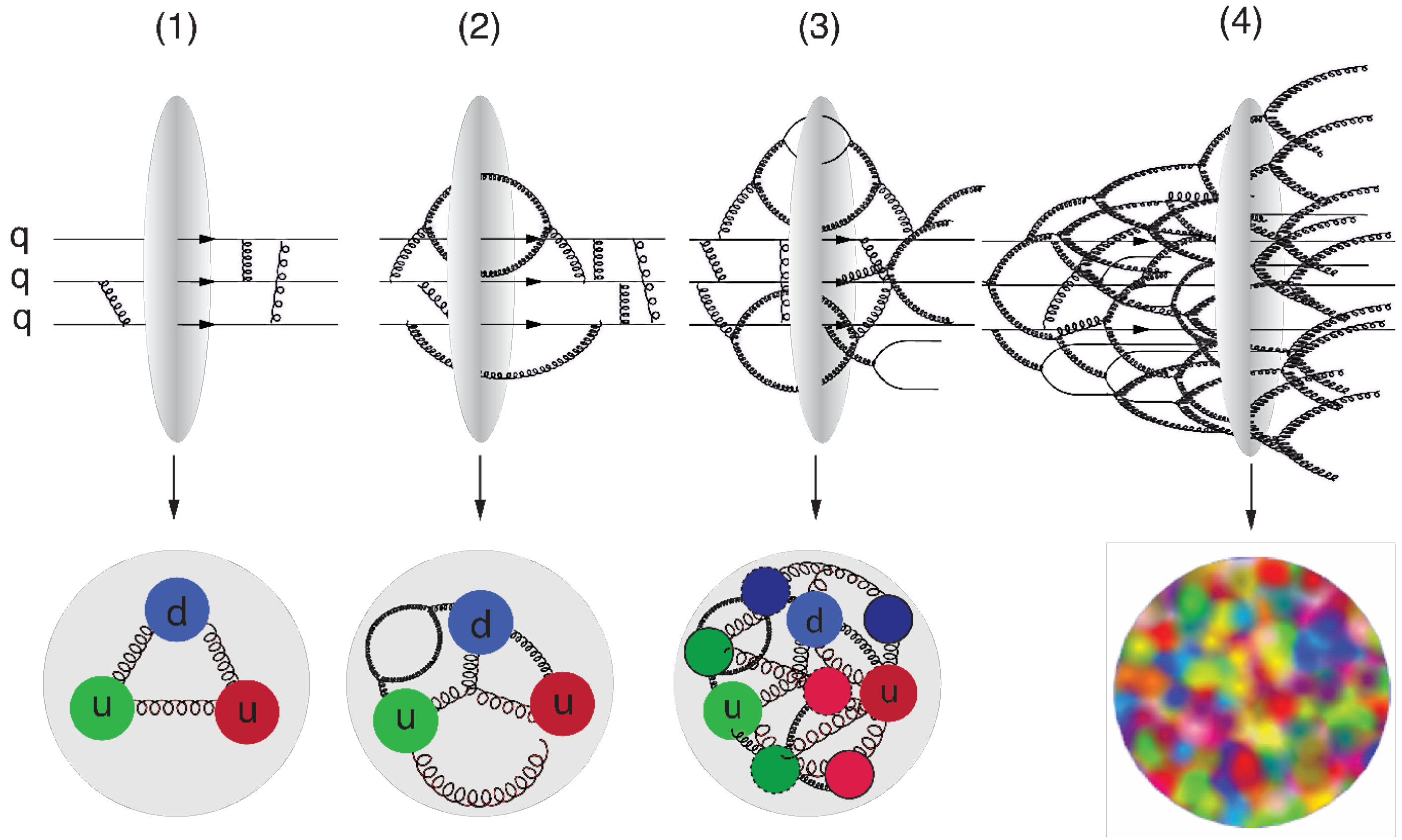
# Saturation phenomena at the EIC



*- Experimental Signatures*

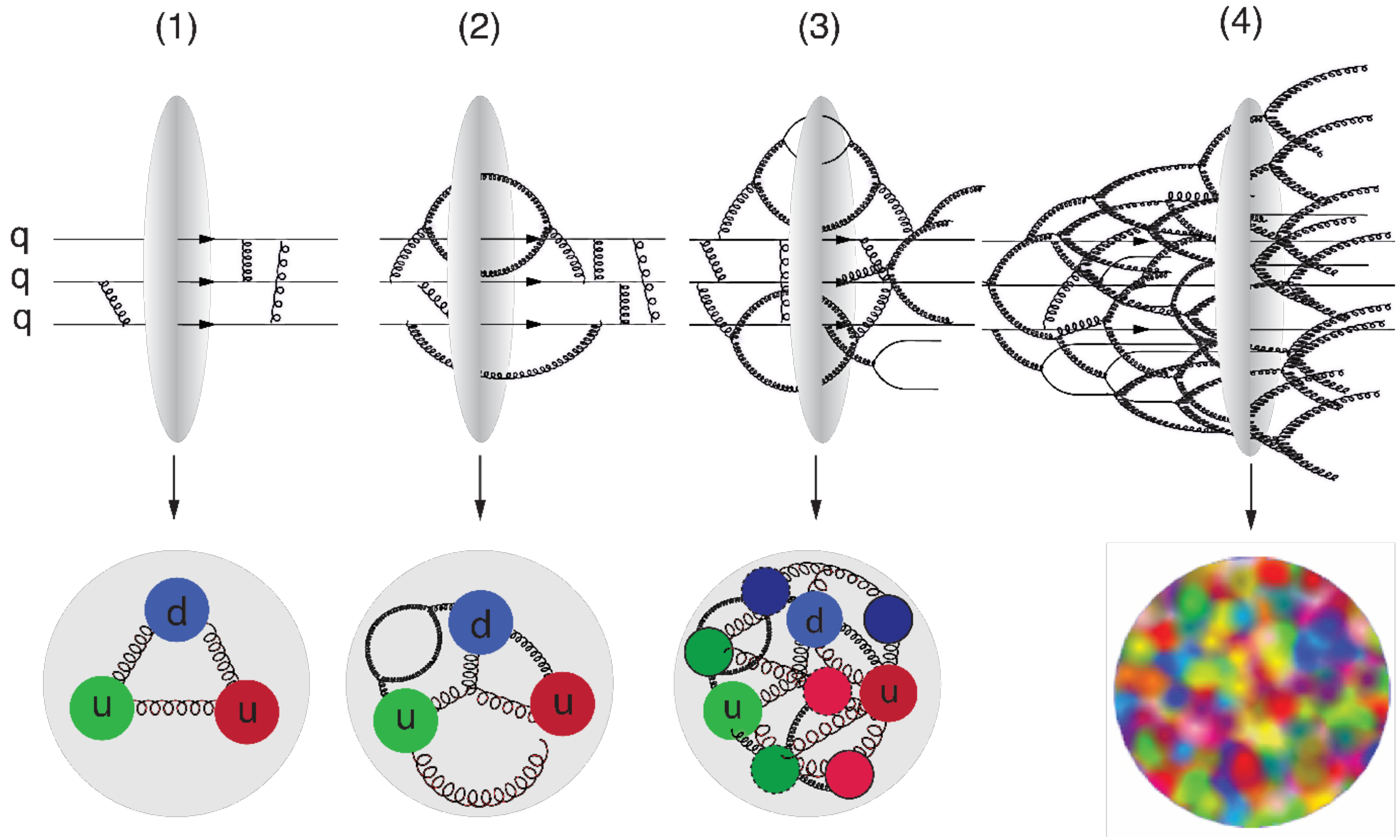
Kong Tu
BNL
06. 29. 2021

# Structure of nucleon




Proton from low to high energy – change of dynamics?

# Structure of nucleon – probed by DIS

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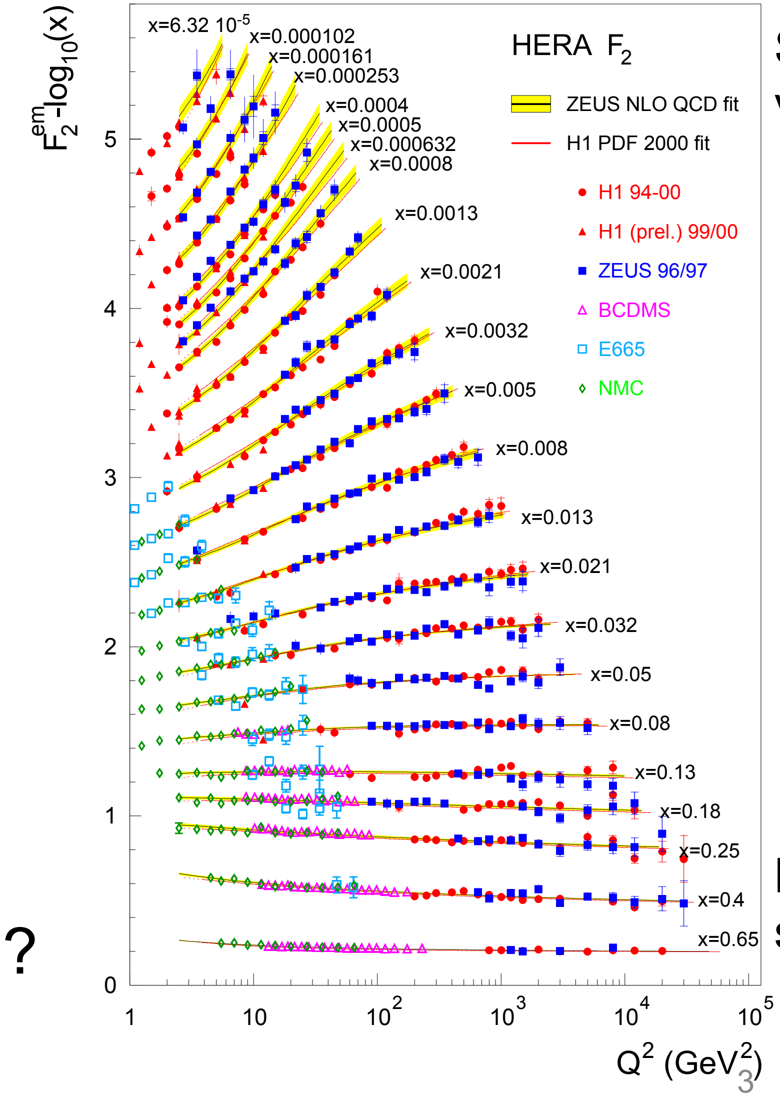
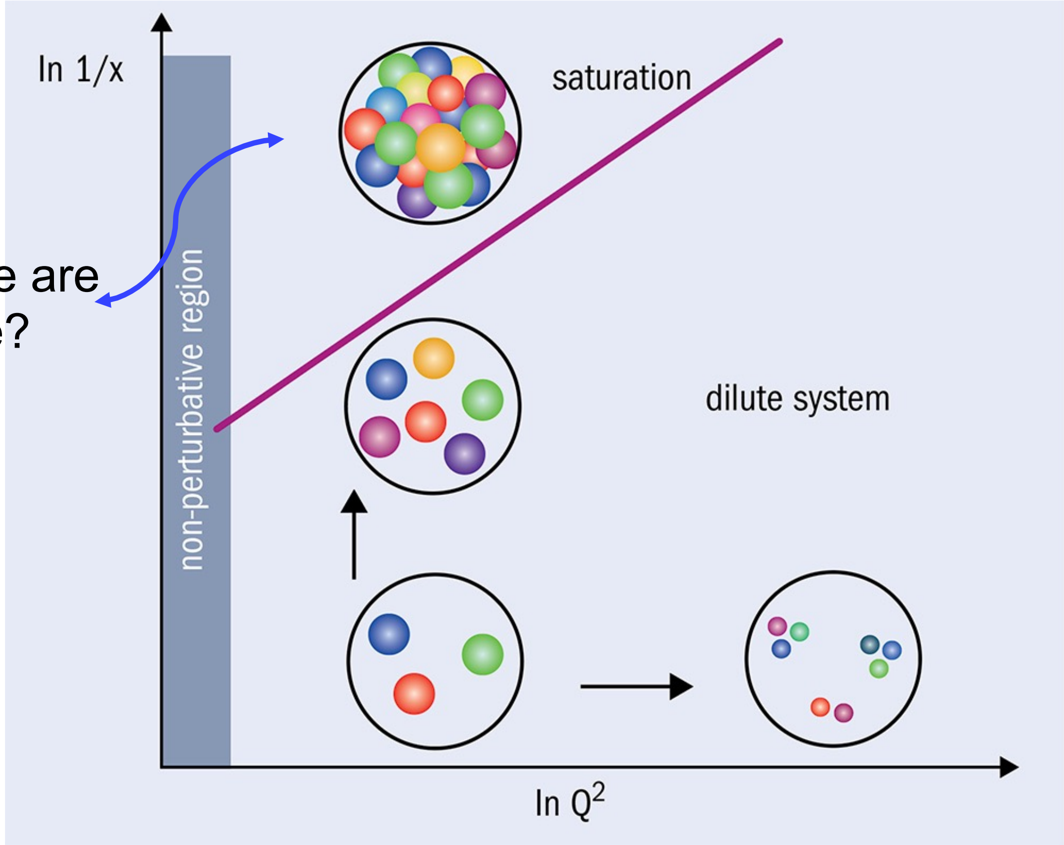



Scaling violation

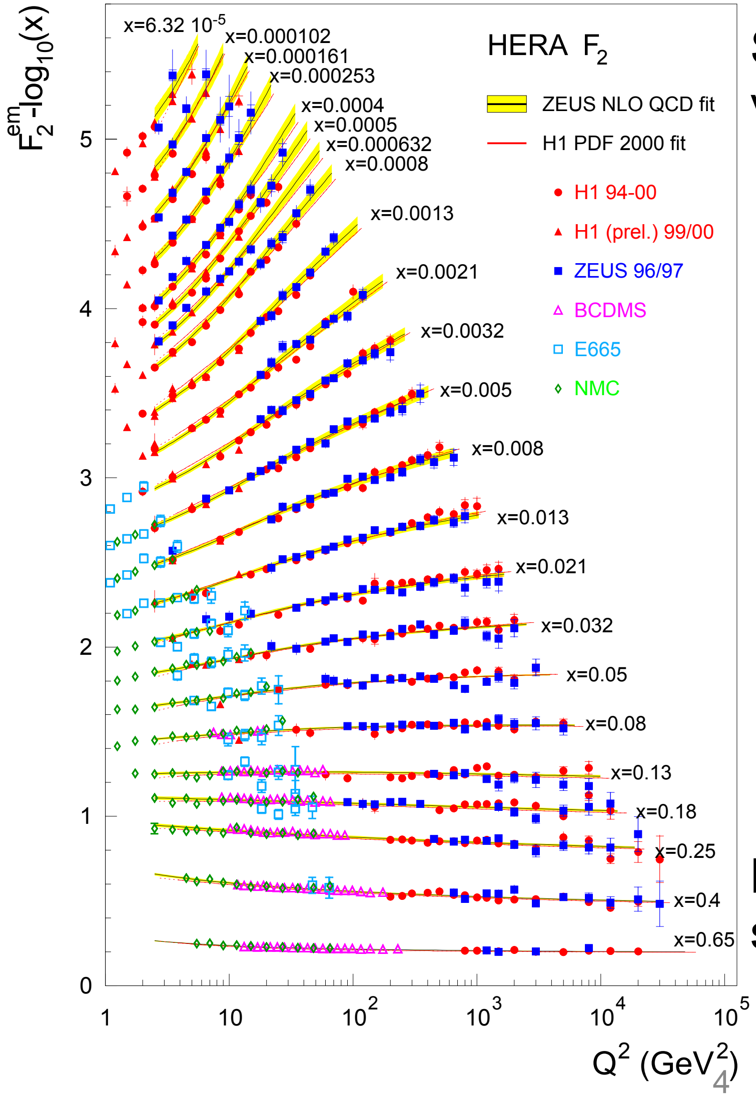
Bjorken scaling

# Structure of nucleon – probed by DIS

How to tell we are in this regime?




- **Where is the limit?**
- **What are the signatures of saturation?**

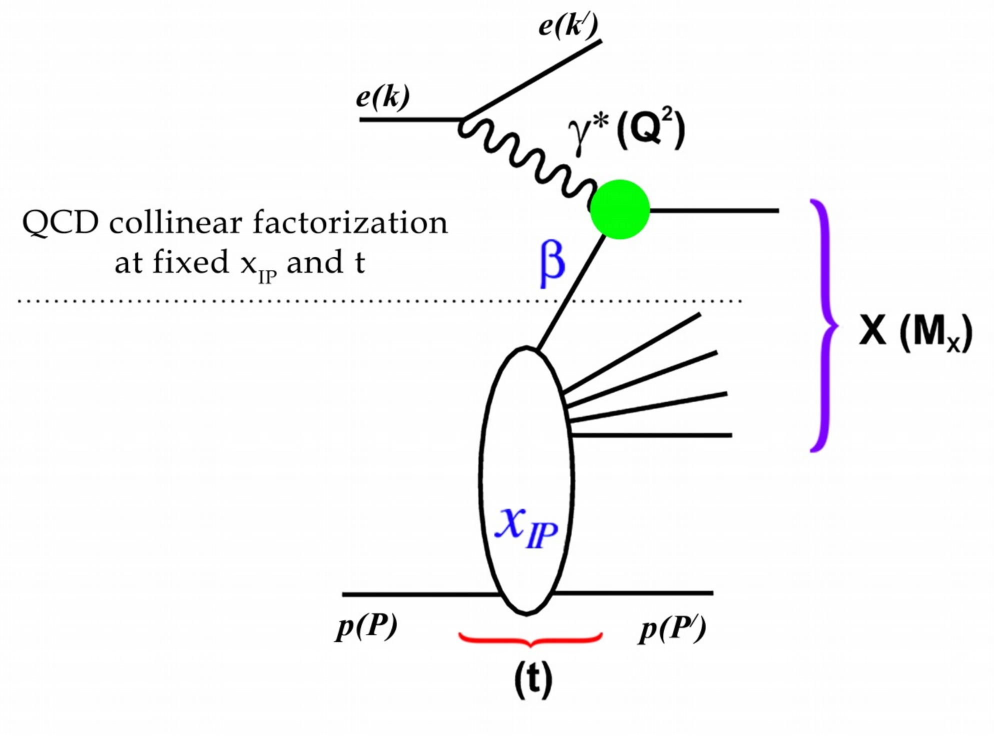



Scaling violation

Bjorken scaling

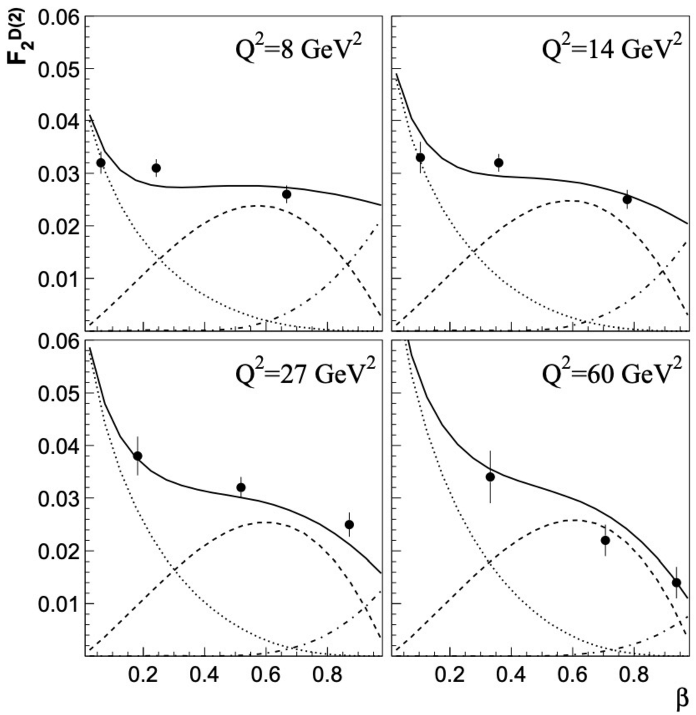
# Early signatures at HERA

- Saturation models successfully describe $F_2$ data at HERA – naturally describes high to low Q2 transitions.
- Diffractive cross section is more sensitive to saturation.[1]




[figure from Phys. Rev. D 99, 054007 (2019)]

ZEUS 1994

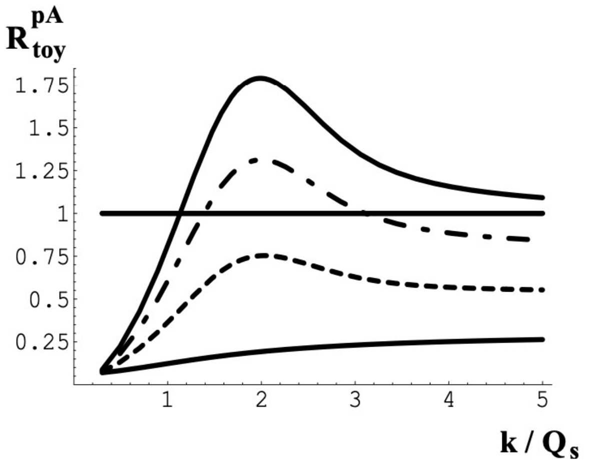



Overall normalization of the diffractive data is a direct result of saturation model without any fits.

1. K. Golec-Biernat and M. Wusthoff (1999)

# Signatures at RHIC

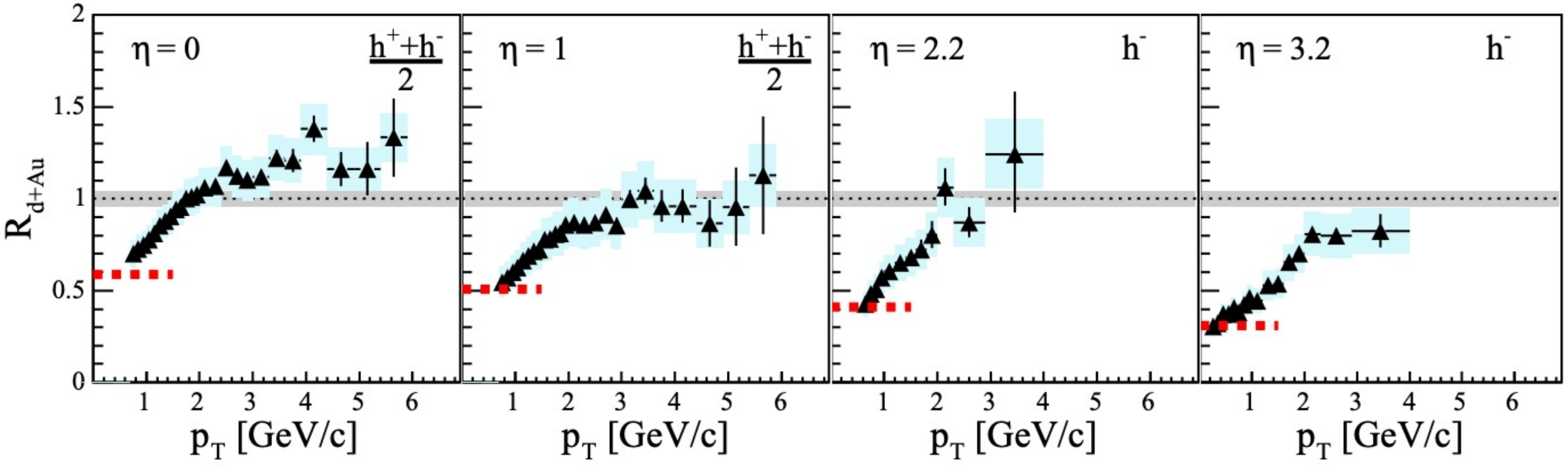
*Saturation model predictions*




Higher rapidity

(Prog.Part.Nucl.Phys.56:104-231,2006)

Nuclear modification factor, measured at BRAHMS, RHIC in dAu collisions



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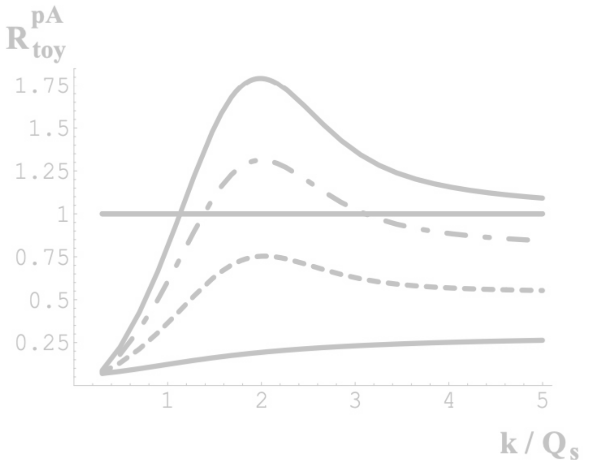


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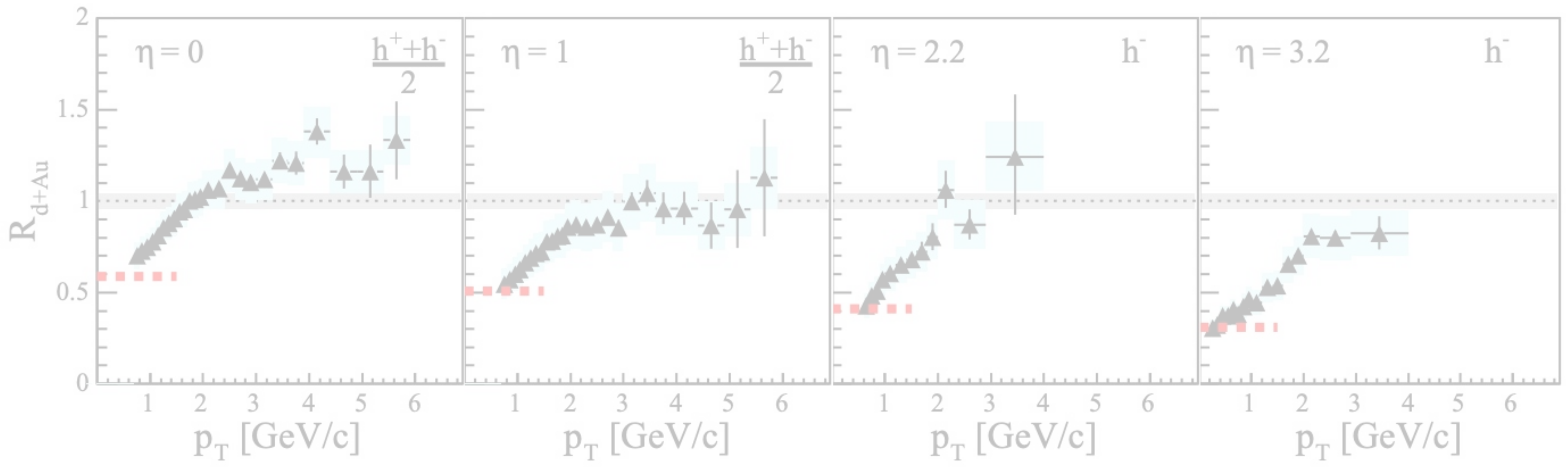
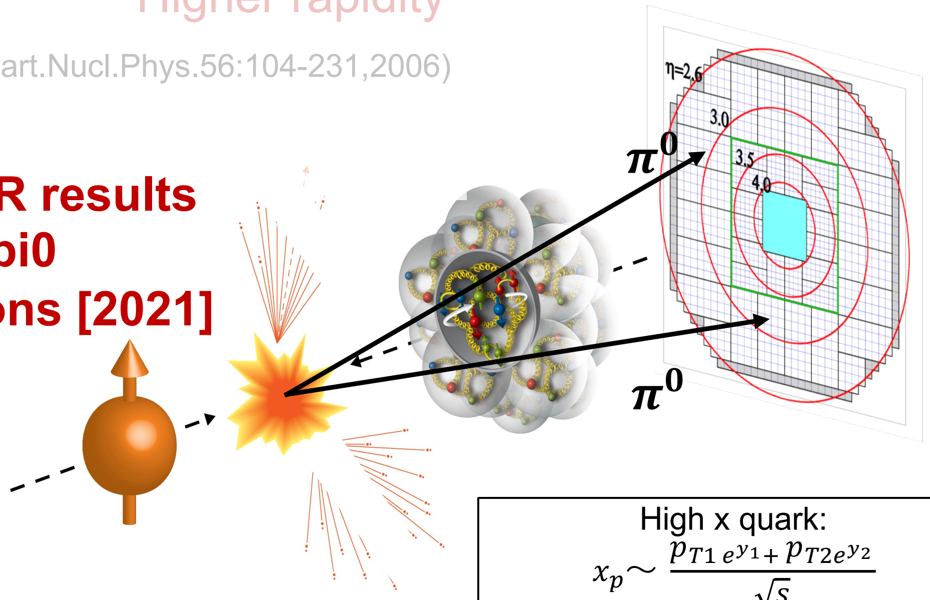
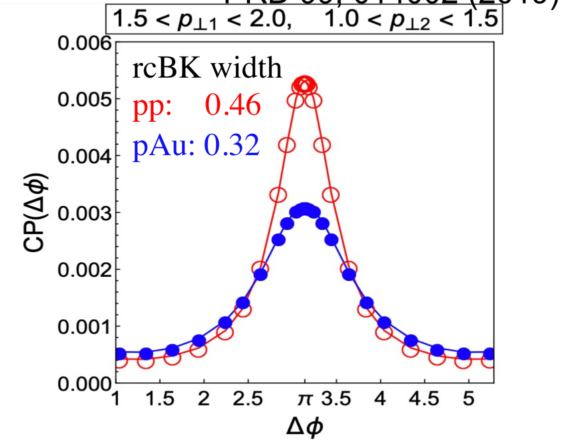
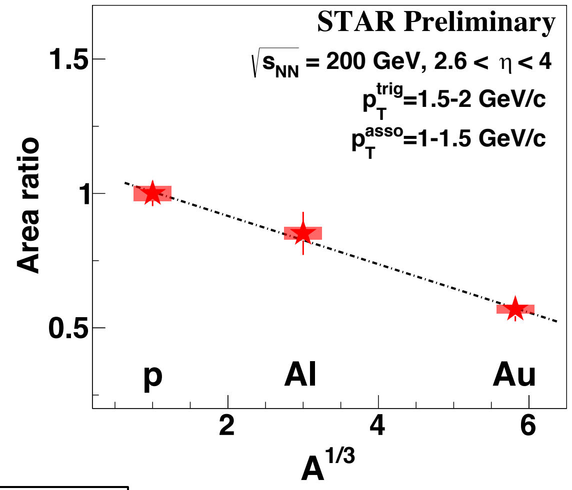



**New STAR results using di-pi0 correlations [2021]**




PRD 99, 014002 (2019)



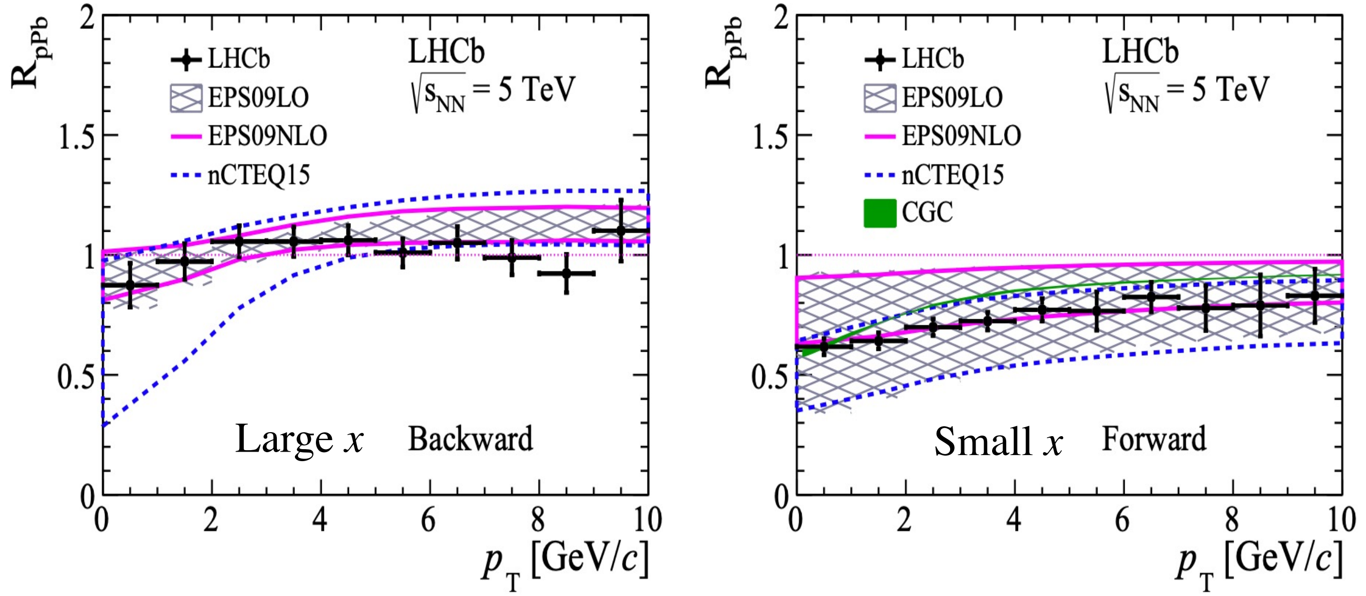

High x quark:
$$x_p \sim \frac{p_{T1}\, e^{y_1} + p_{T2} e^{y_2}}{\sqrt{s}}$$

Low x gluon:
$$x_A \sim \frac{p_{T1}\, e^{-y_1} + p_{T2} e^{-y_2}}{\sqrt{s}}$$

# Signatures at the LHC

LHCb, JHEP 1710 (2017) 090

Forward $D^0$ production at LHCb – suppression in forward



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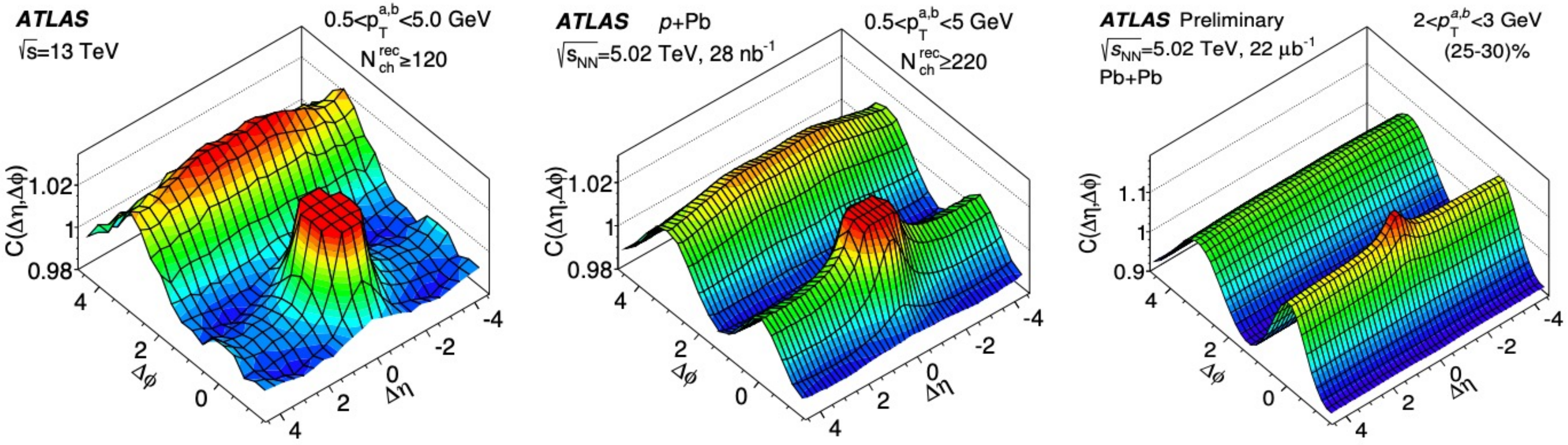
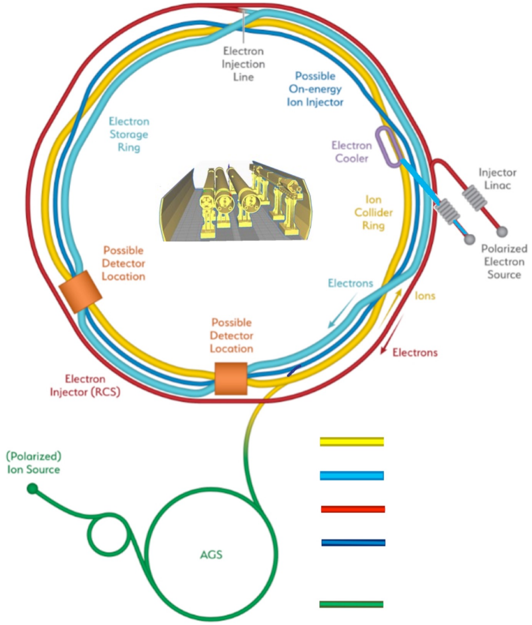


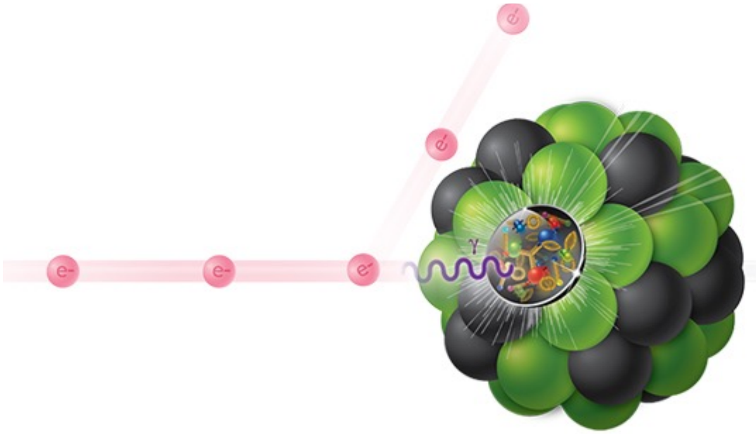

**Intensive investigations on the origin of collectivity and "ridge" in pp, pA, and AA collisions.**

*Saturation* plays an important role!

# How to nail it down experimentally?

- HERA, RHIC, and the LHC data showed promising hints of saturation phenomena, but not conclusive.
- A next-generation QCD machine - **EIC**

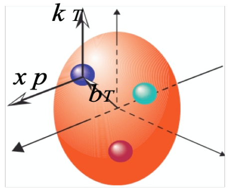


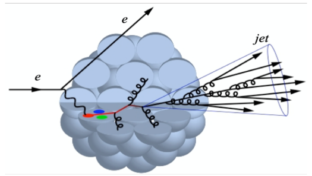
Sited at Brookhaven National Laboratory

**Electron-Ion Collider**

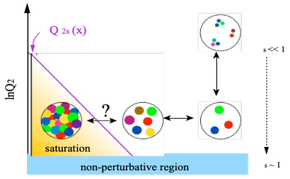
**Spin**



**Tomography**



**Hadronization**



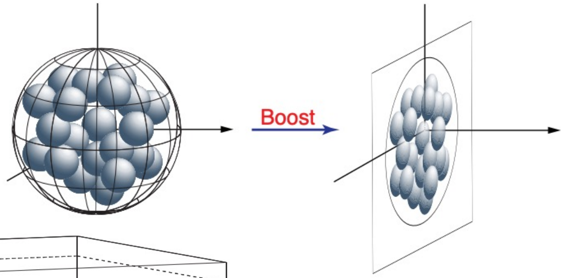

**Saturation**

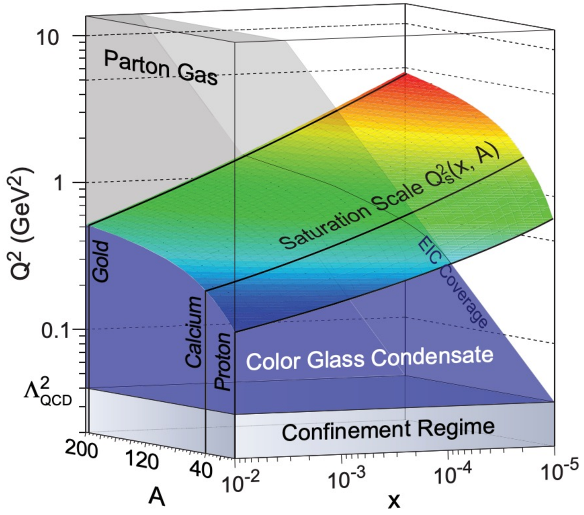
# What to look for at the EIC?

| | | |
|---|---|---|
| Structure functions | **$F_2$ & $F_L$** | Comparison with model |
| Inclusive diffraction with diff. gap | $\frac{\sigma_{\mathrm{diff}}}{\sigma_{\mathrm{tot}}}$ | Enhancement of diffraction in DIS |
| Di-hadron correlation (e.g., di-pi0) | **Back-to-back $\Delta\phi$** | Broadening and suppression A/p |
| Diffractive VM in eA | $d\sigma/dt$ | Saturation dynamics and gluon imaging |

(EIC white paper)

Nuclear "Oomph" factor




Nucleus at (the same) high energy is the cheapest way to go to saturation regime

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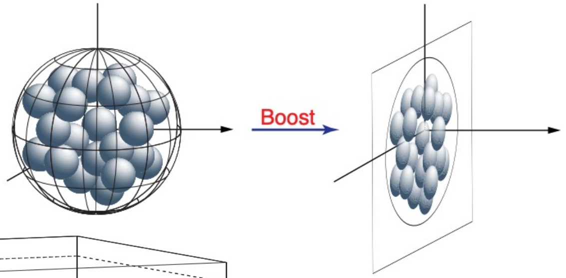


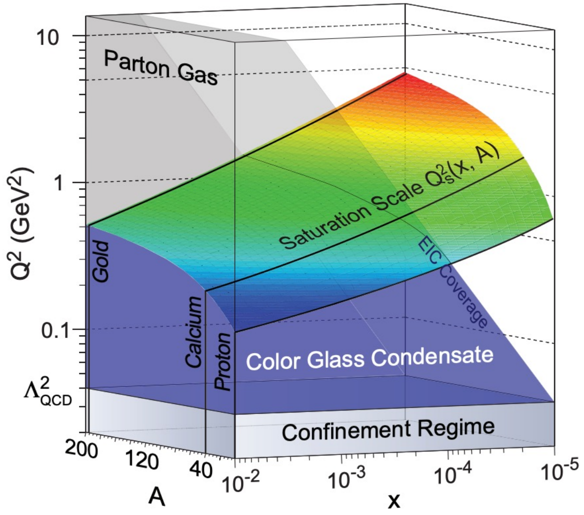


Nucleus at (the same) high energy is the cheapest way to go to saturation regime

(EIC white paper)

***Extraordinary discovery requires extraordinary evidences***

- All experimental signatures need to point to the same direction!

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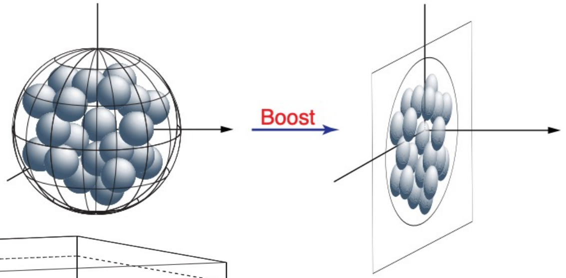


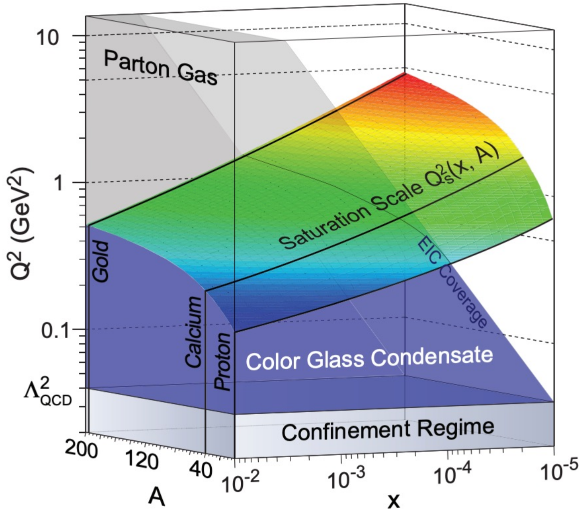


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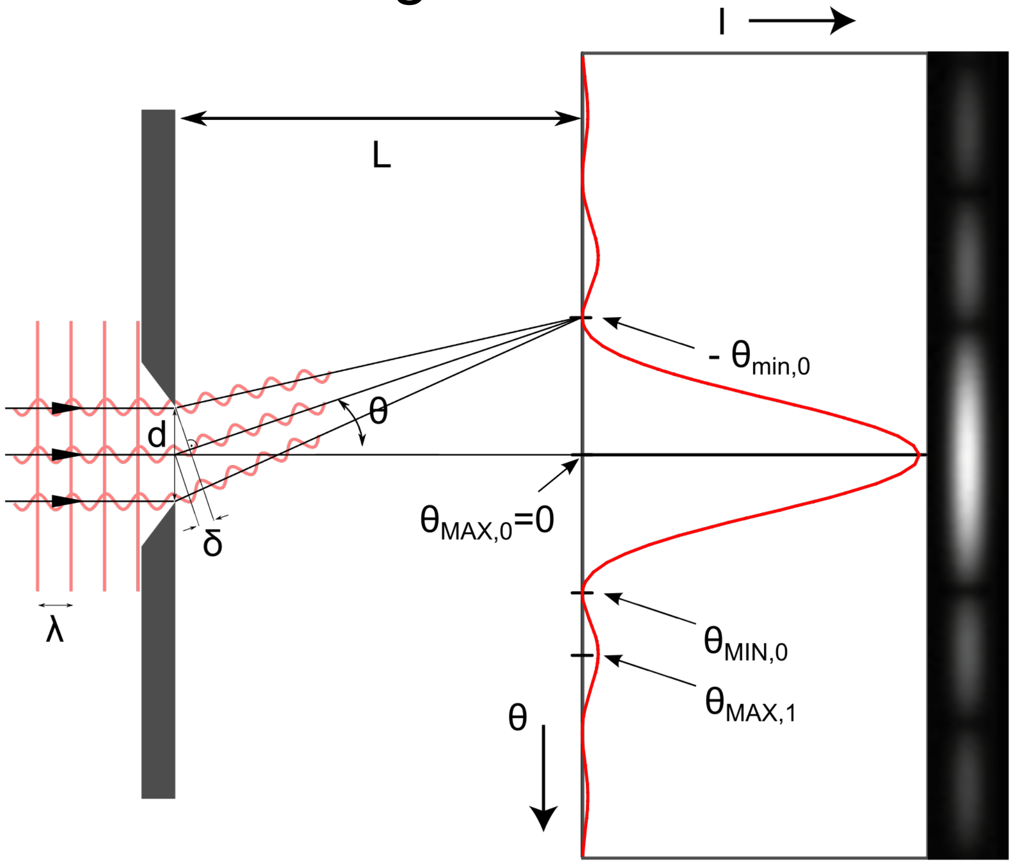
# Diffractive VM at the EIC

Single-slit diffraction




(College physics)

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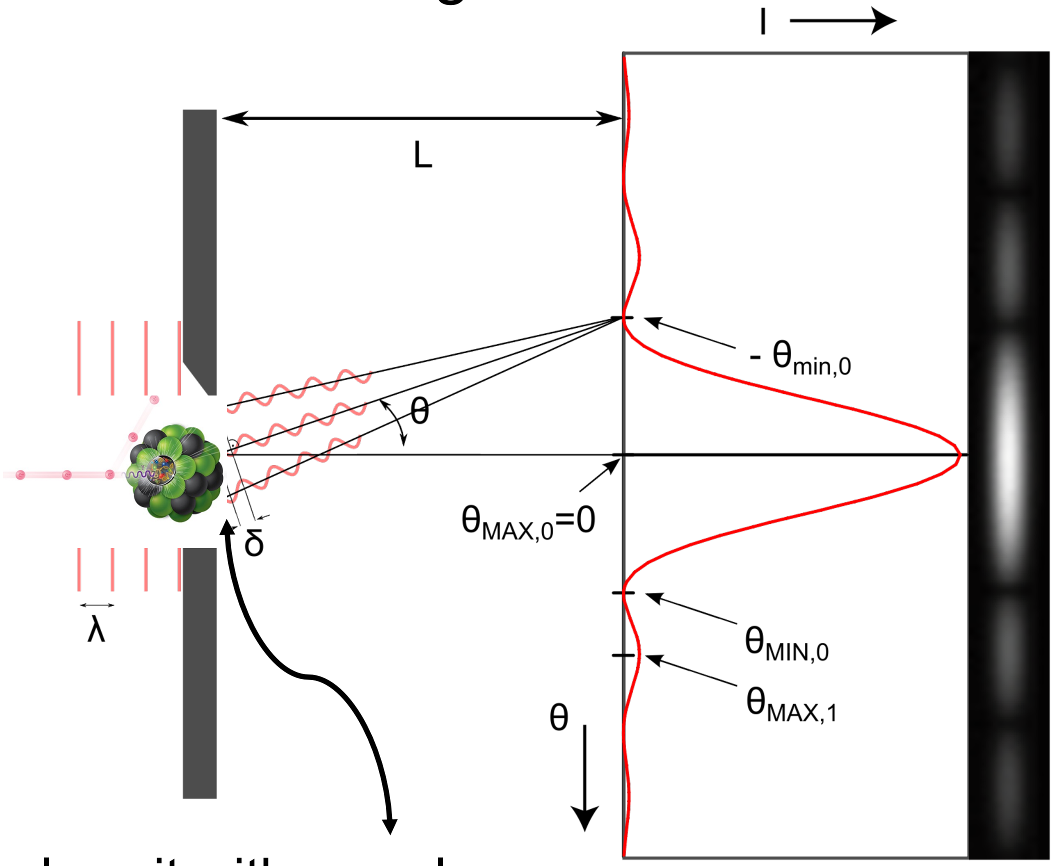
Single-slit diffraction

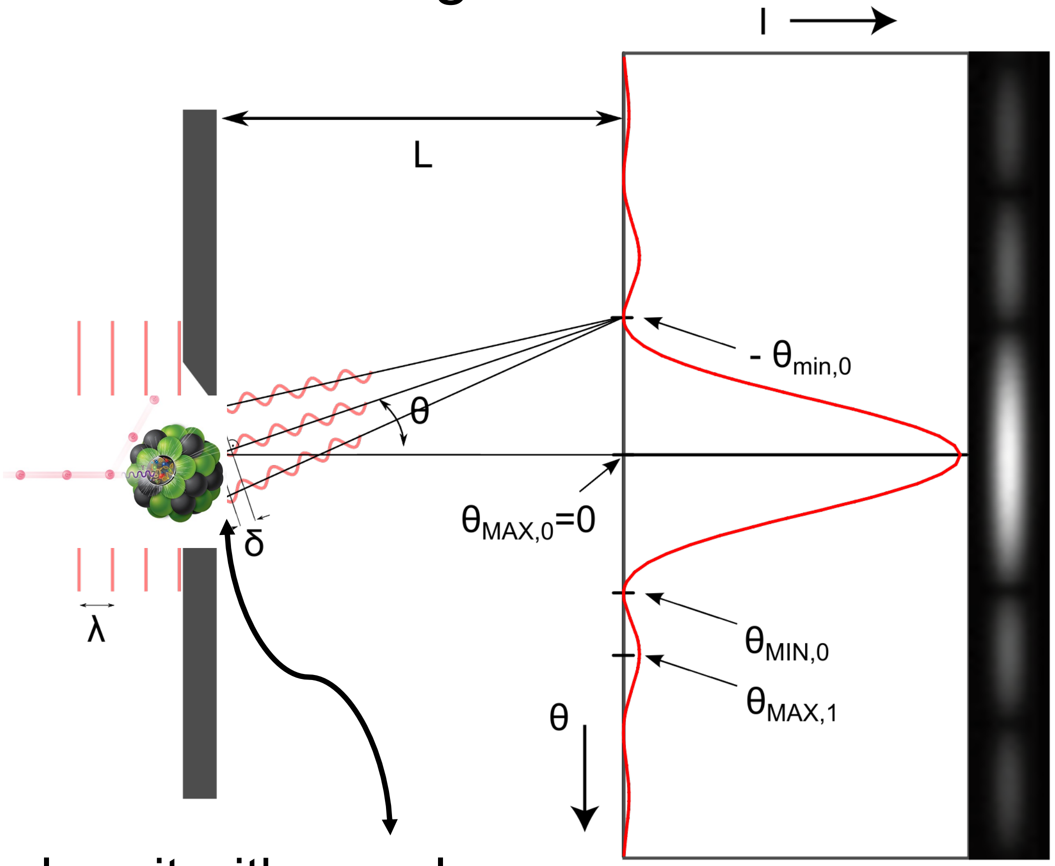



replace it with a nucleus

(EIC physics)

# Diffractive VM at the EIC

Single-slit diffraction

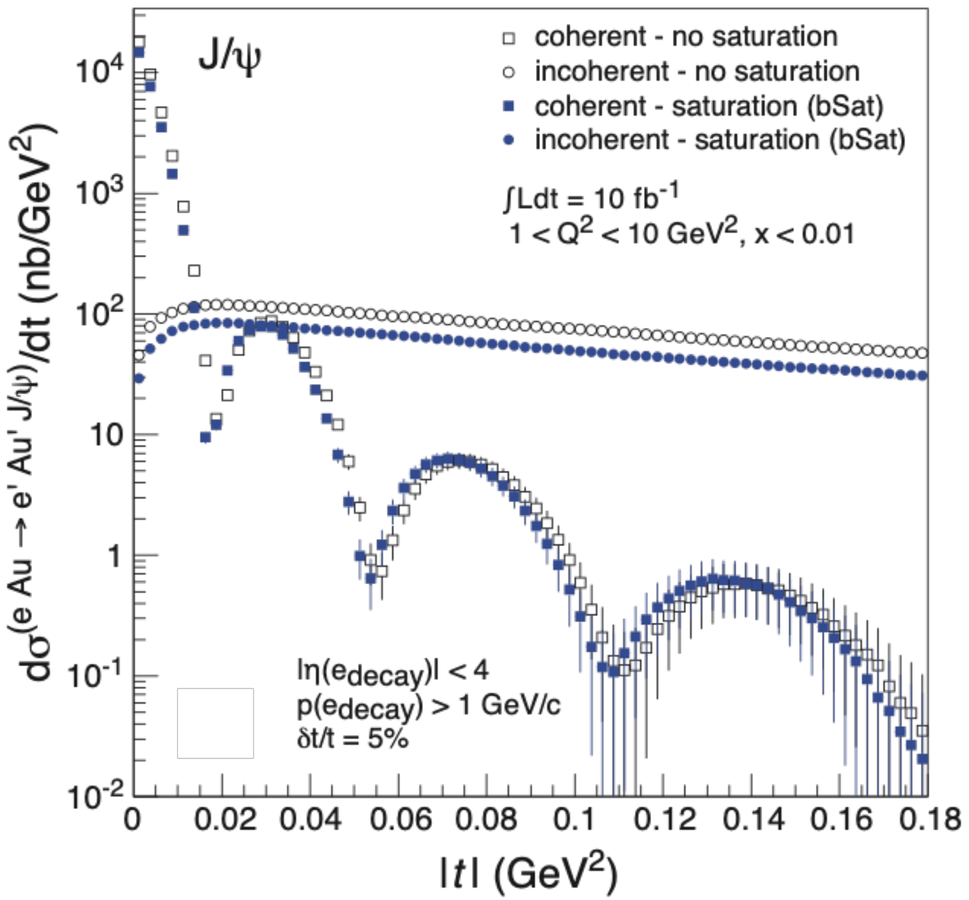



replace it with a nucleus

(EIC physics)

Phys.Rev.C 87 (2013) 2, 024913

**e+Au → e' + J/ψ + Au'**

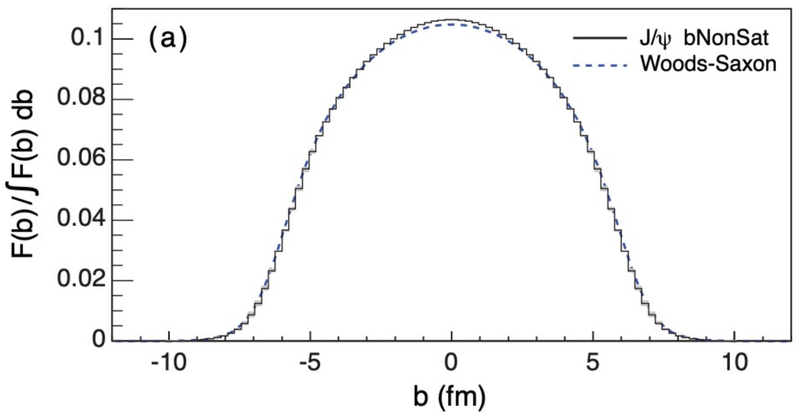



(momentum transfer –*t* distribution)

# Diffractive VM at the EIC

$$F(b) \sim \frac{1}{2\pi} \int_0^{\infty} d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

***- t*** distribution is a Fourier transformation of the source distribution ~ gluons $\boldsymbol{b_T}$




Gluon imaging

*Phys.Rev.C* 87 (2013) 2, 024913

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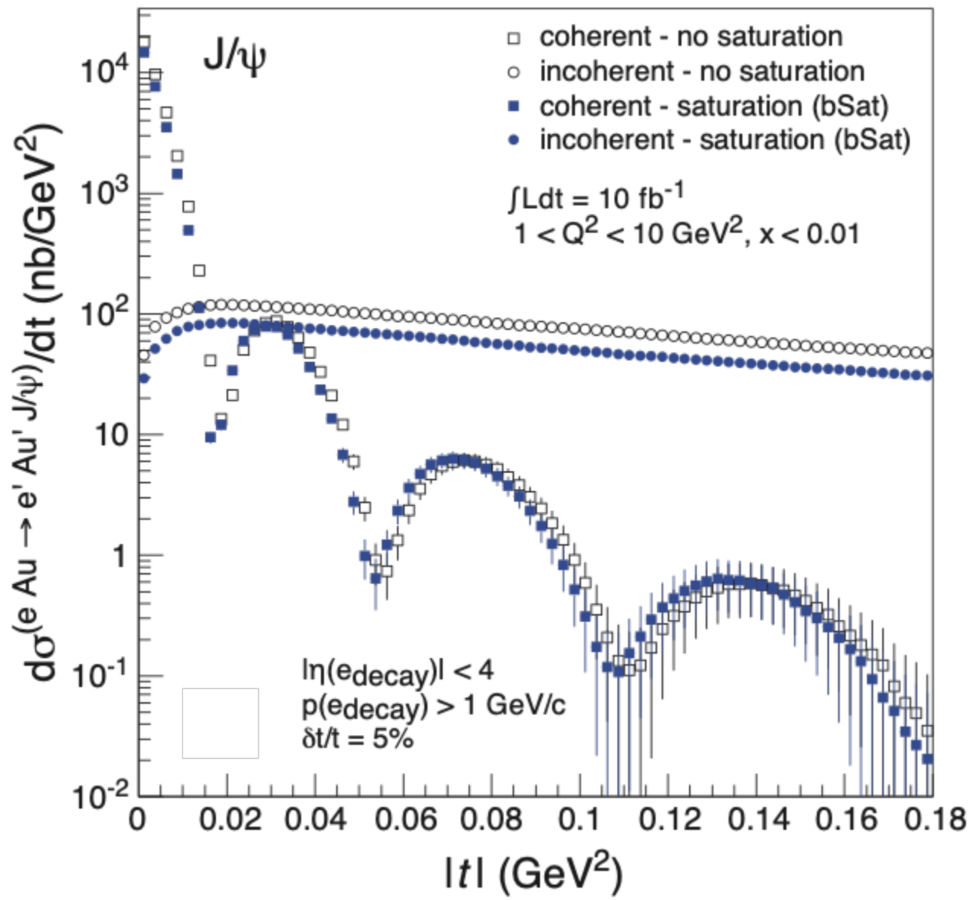


(momentum transfer ***–t*** distribution)

# Diffractive VM at the EIC

$$F(b) \sim \frac{1}{2\pi}\int_0^\infty d\Delta\, \Delta\, J_0(\Delta b)\sqrt{\frac{d\sigma}{dt}}$$

**Where is Saturation?**

*- t* distribution is a Fourier transformation of the source distribution ~ gluons $b_T$




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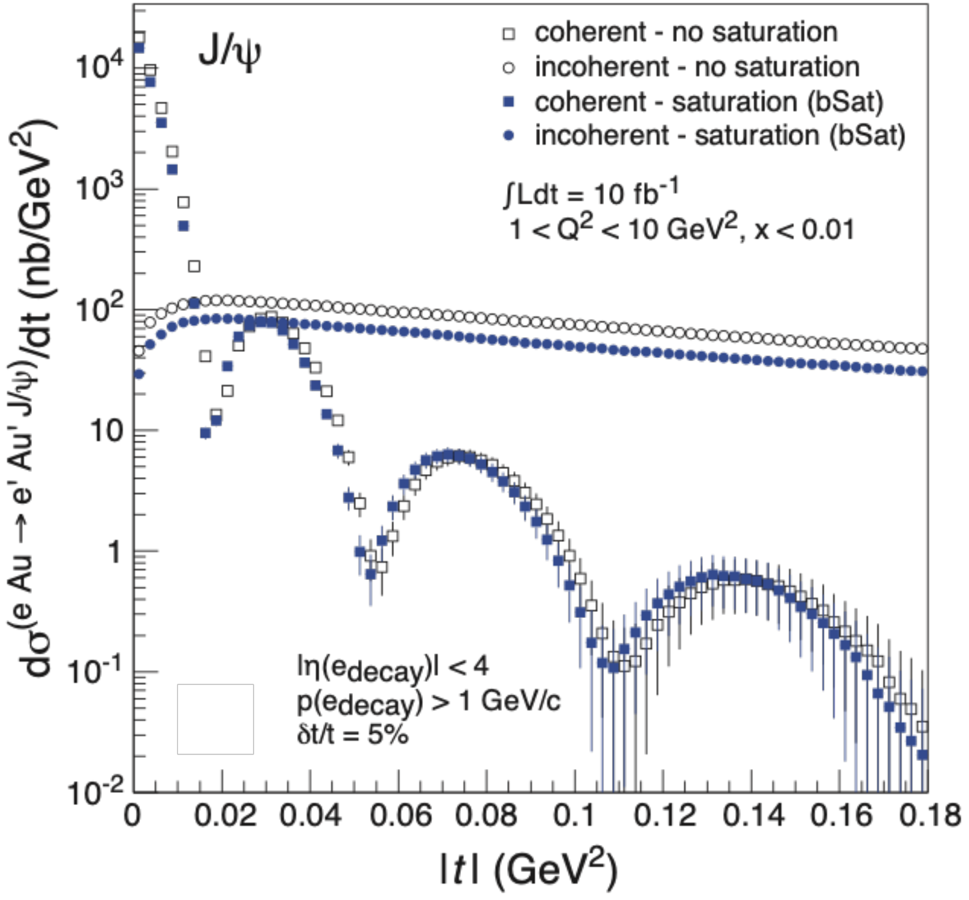


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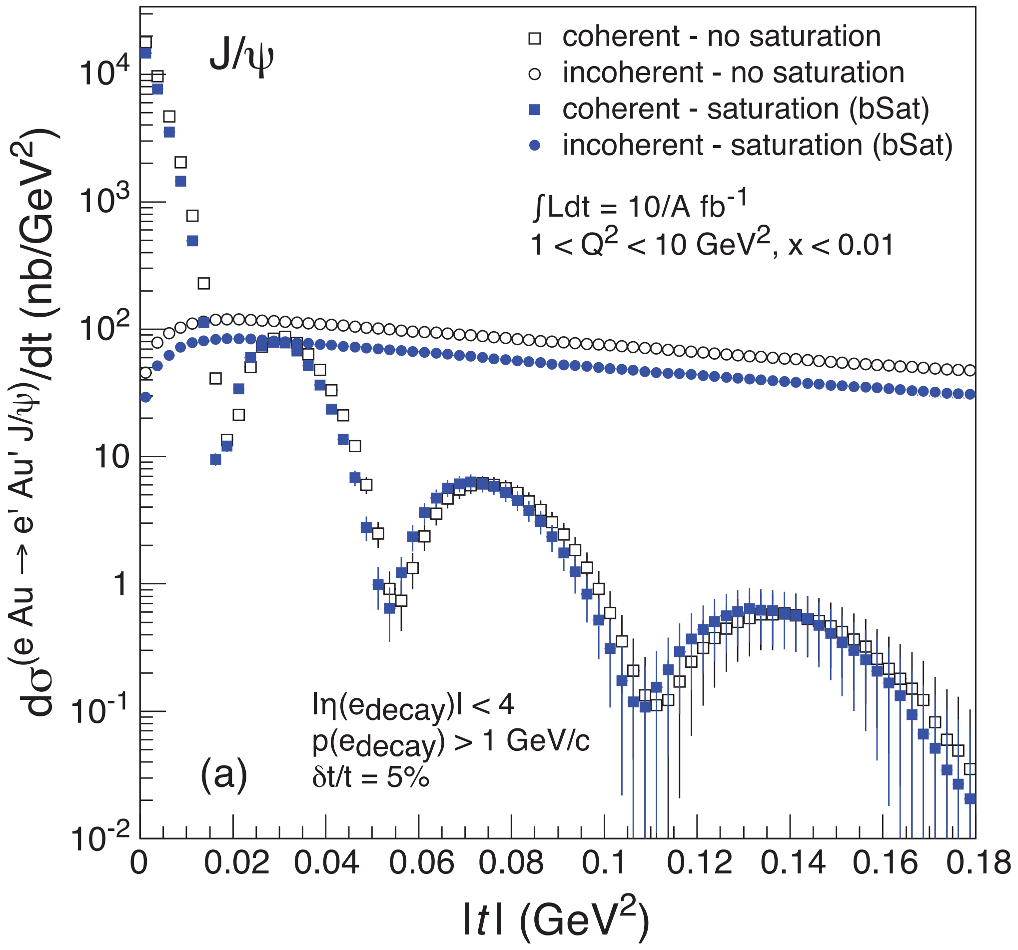
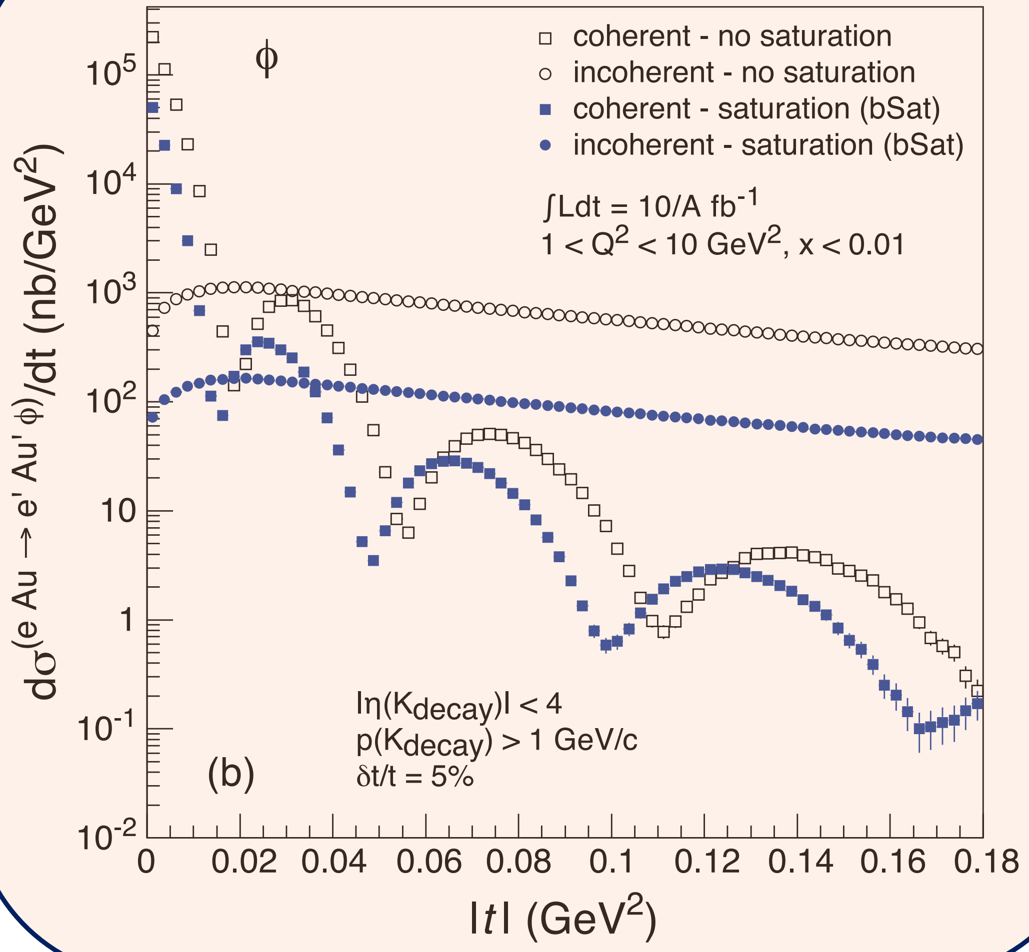
*Phys.Rev.C* 87 (2013) 2, 024913



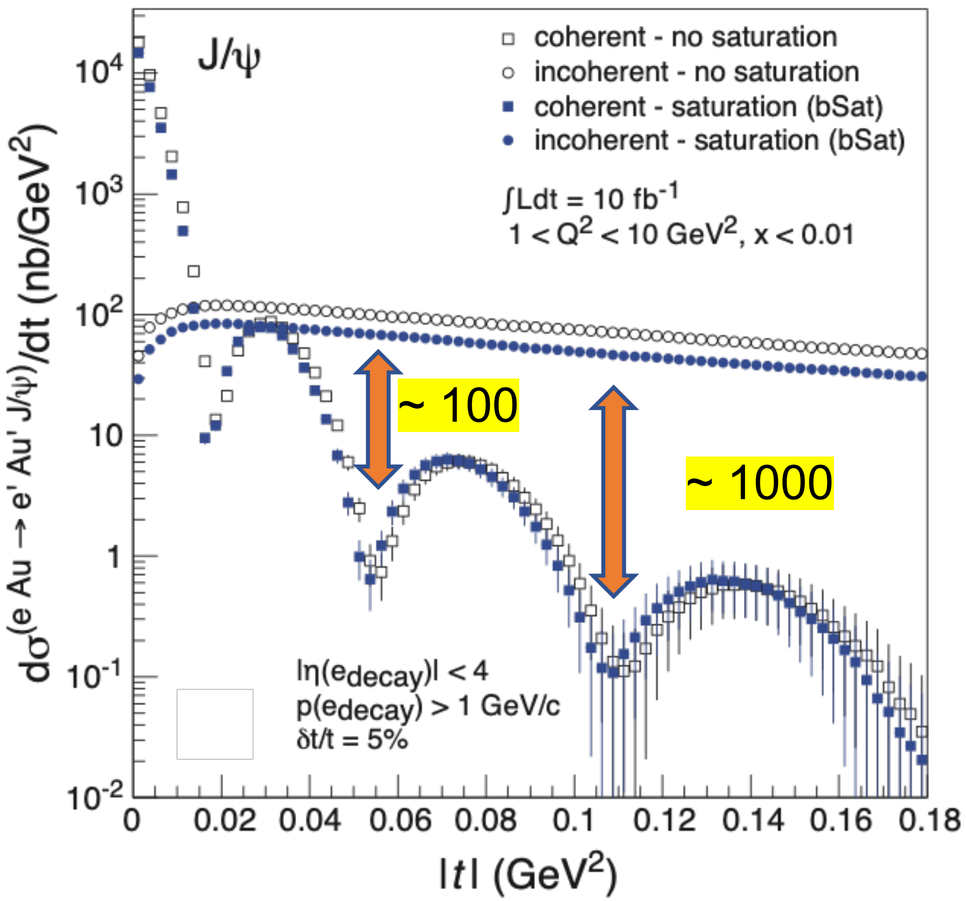




Dipole size $r_T$ is larger for phi meson – more saturation “seen” by the probe

# Challenges to coherent VM production

*Phys.Rev.C* 87 (2013) 2, 024913

**e+Au → e' + J/ψ + Au'**

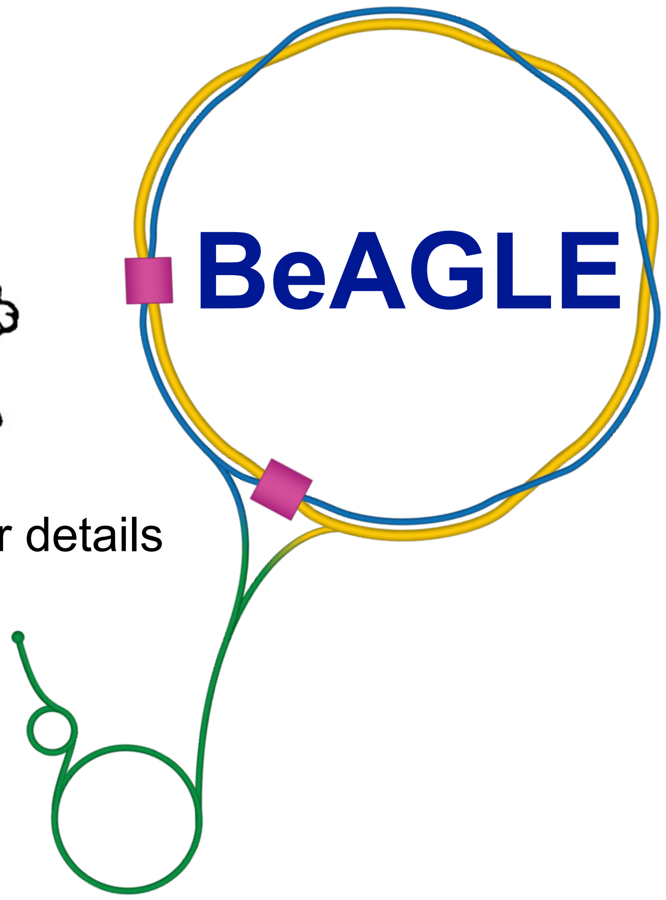



- Distinguish coherent and incoherent production as a function of ***t***.
- Reduction power needs up to ~ 1000 times
- This challenge was not "realized" until quantitative study was performed.

(combine model and detector/IR simulations)

# Incoherent VM: e+Pb → e' + J/ψ + X

BeAGLE – a general-purpose eA MC event generator




Click here for details

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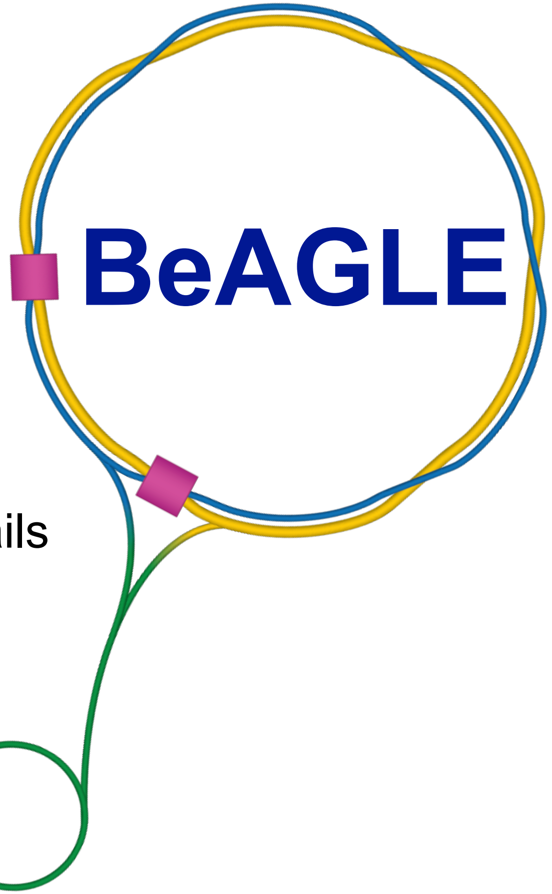


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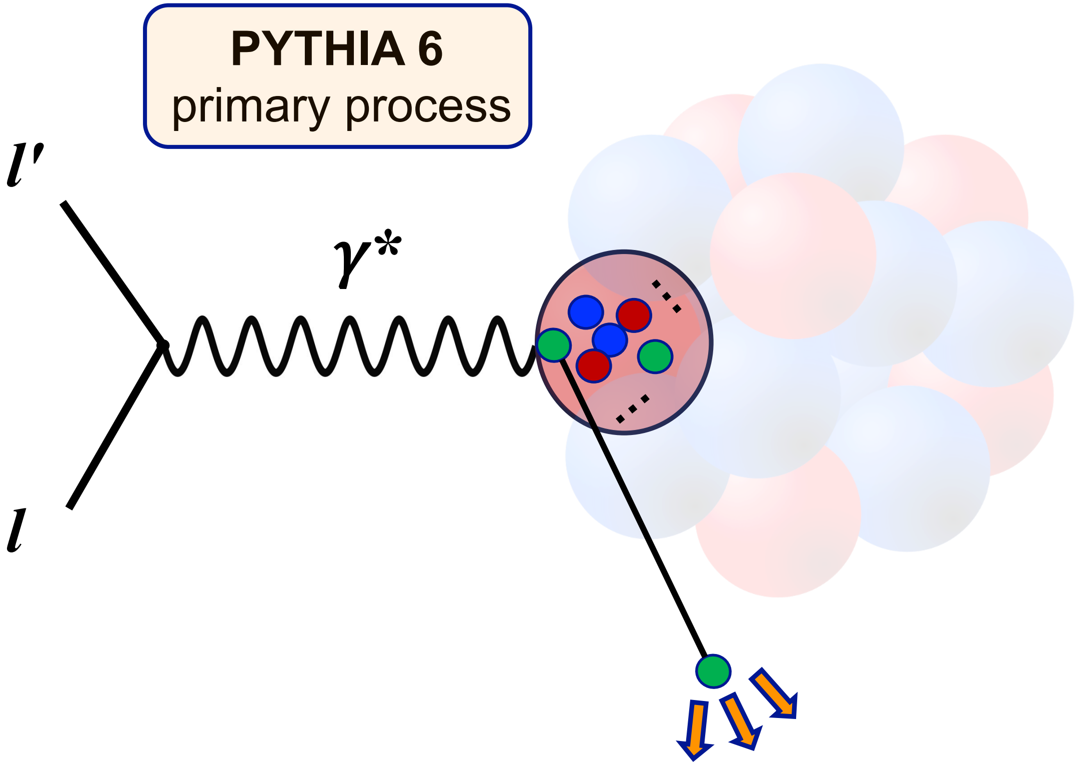

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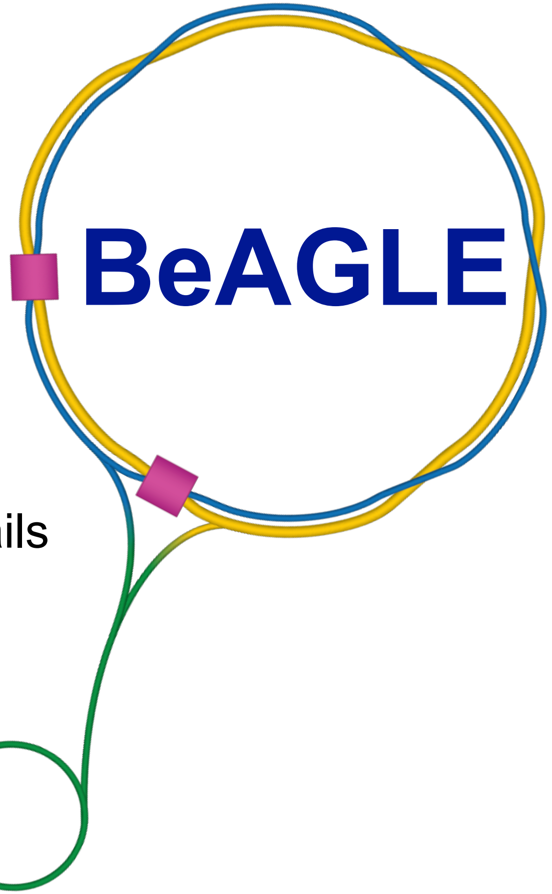


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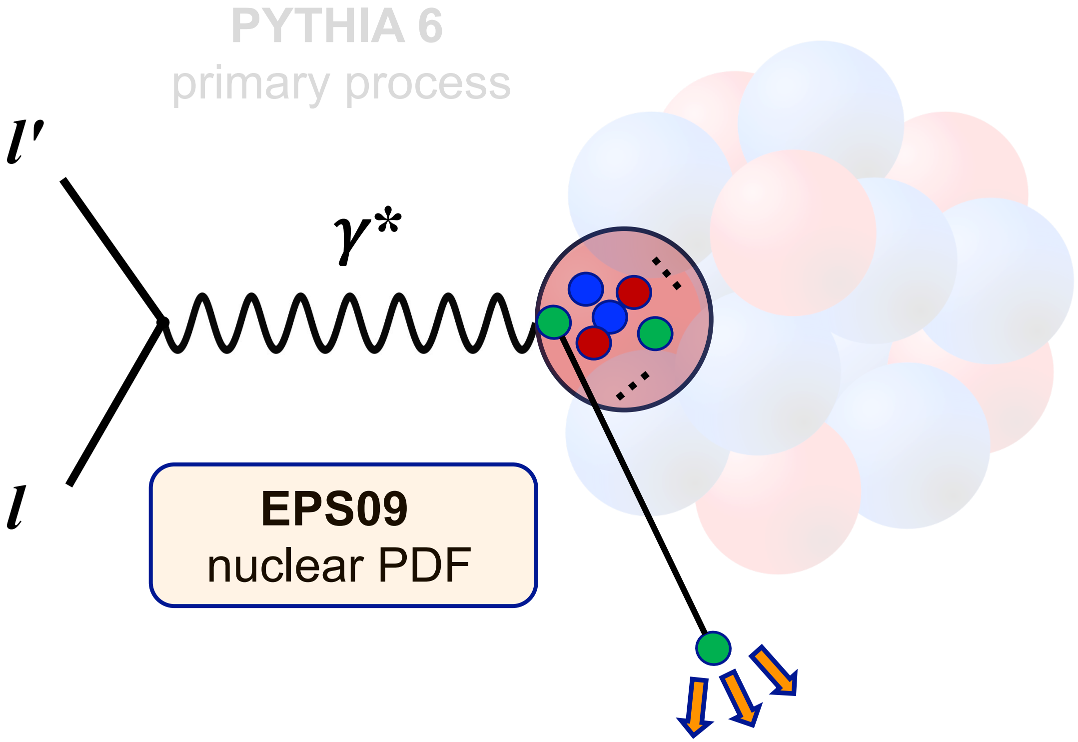

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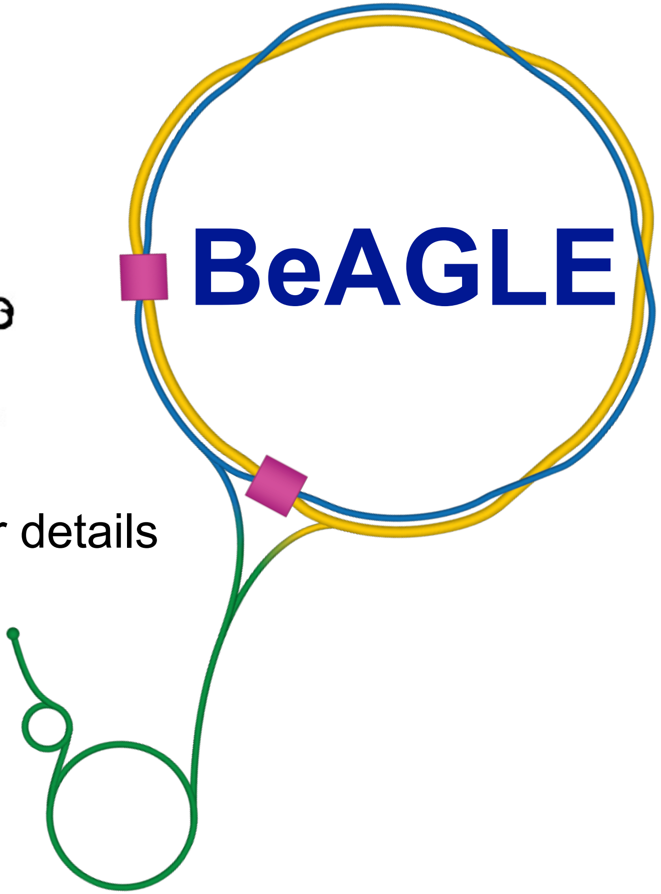


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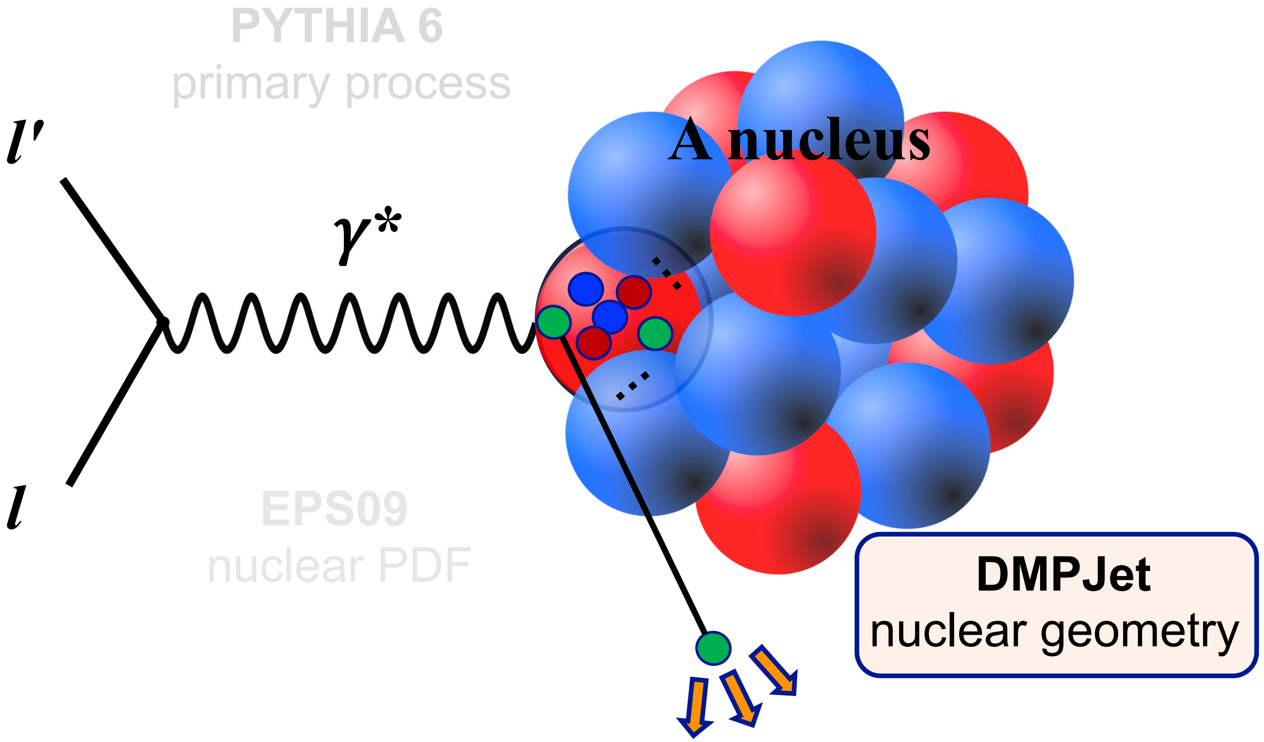

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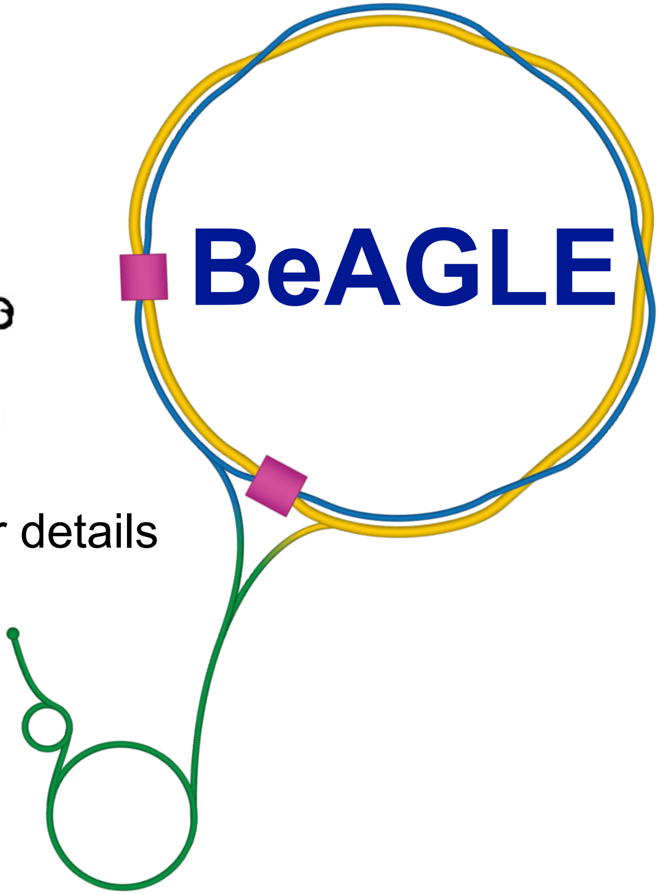


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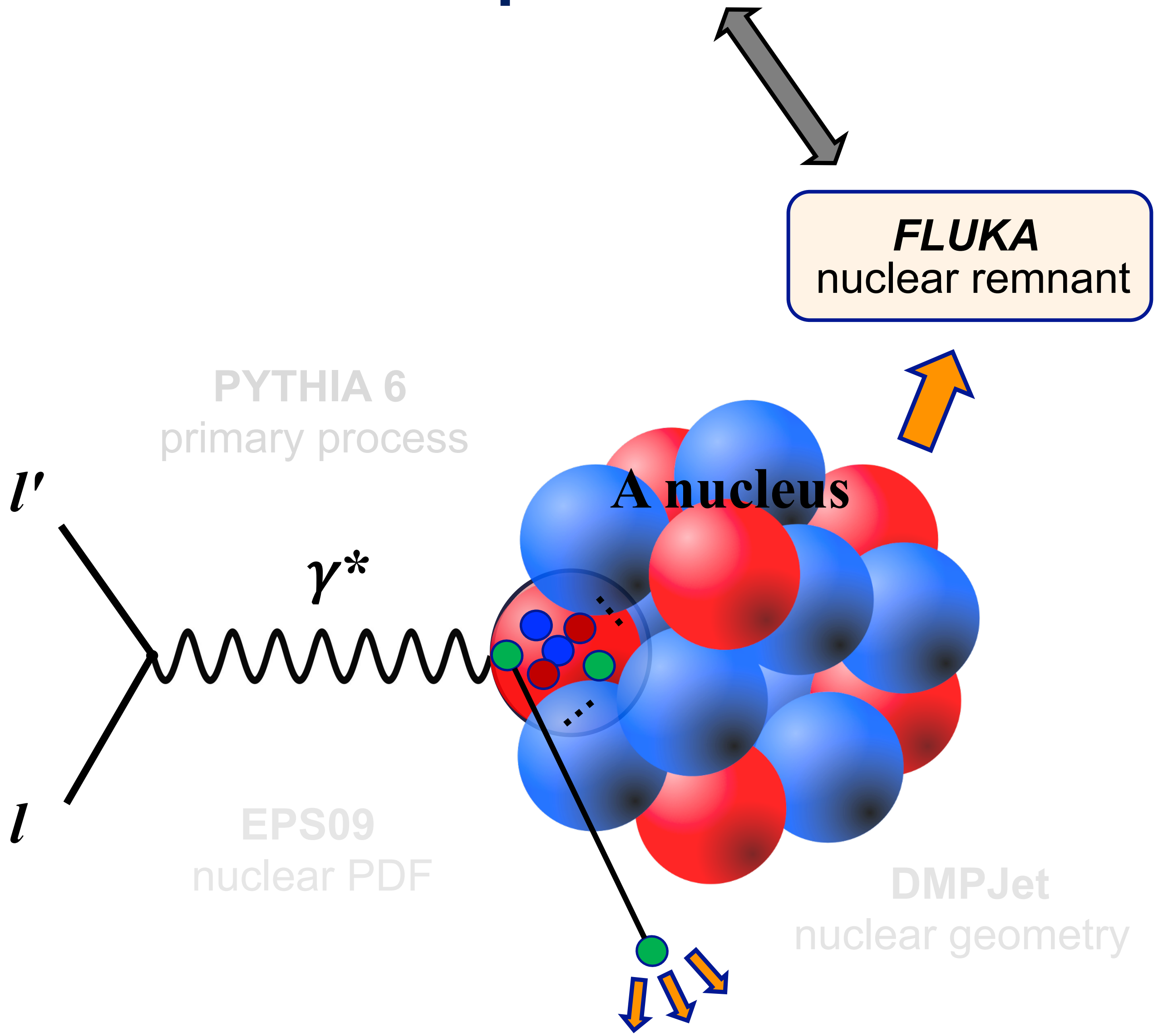
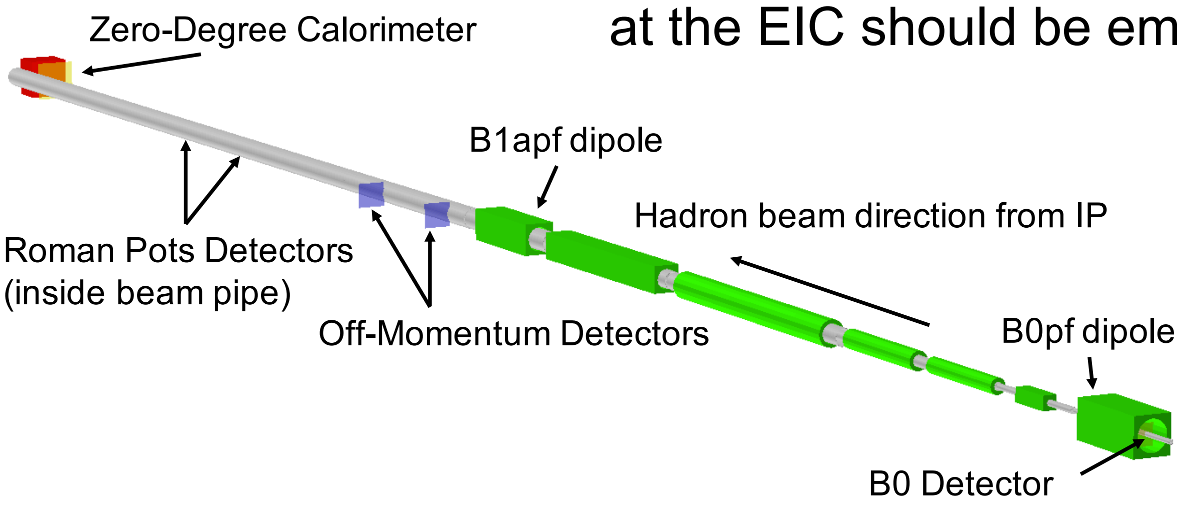
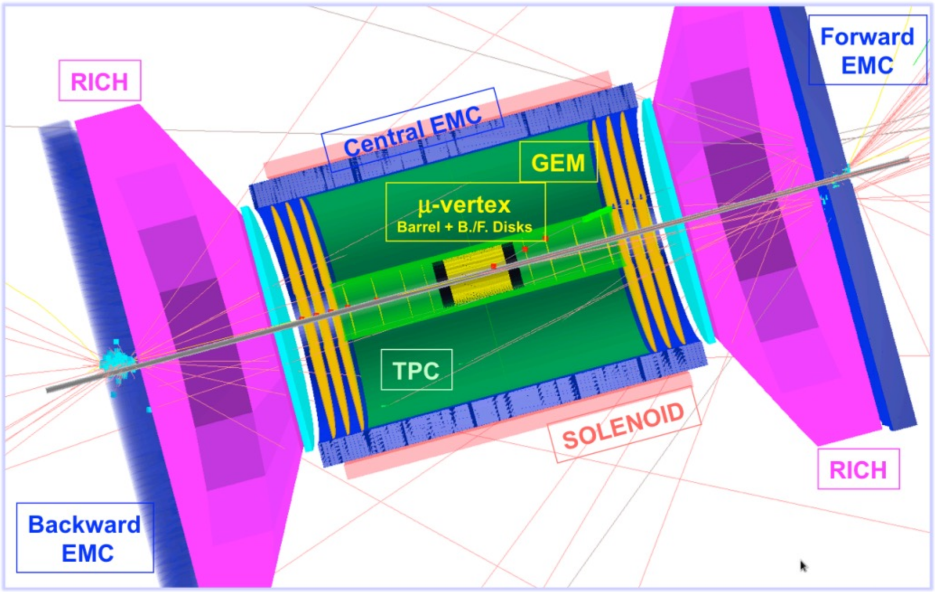


# Incoherent vetoing in ePb @ EIC




Basic idea is ~ far forward region at the EIC should be empty!

Main detector




(e' + J/ψ only)

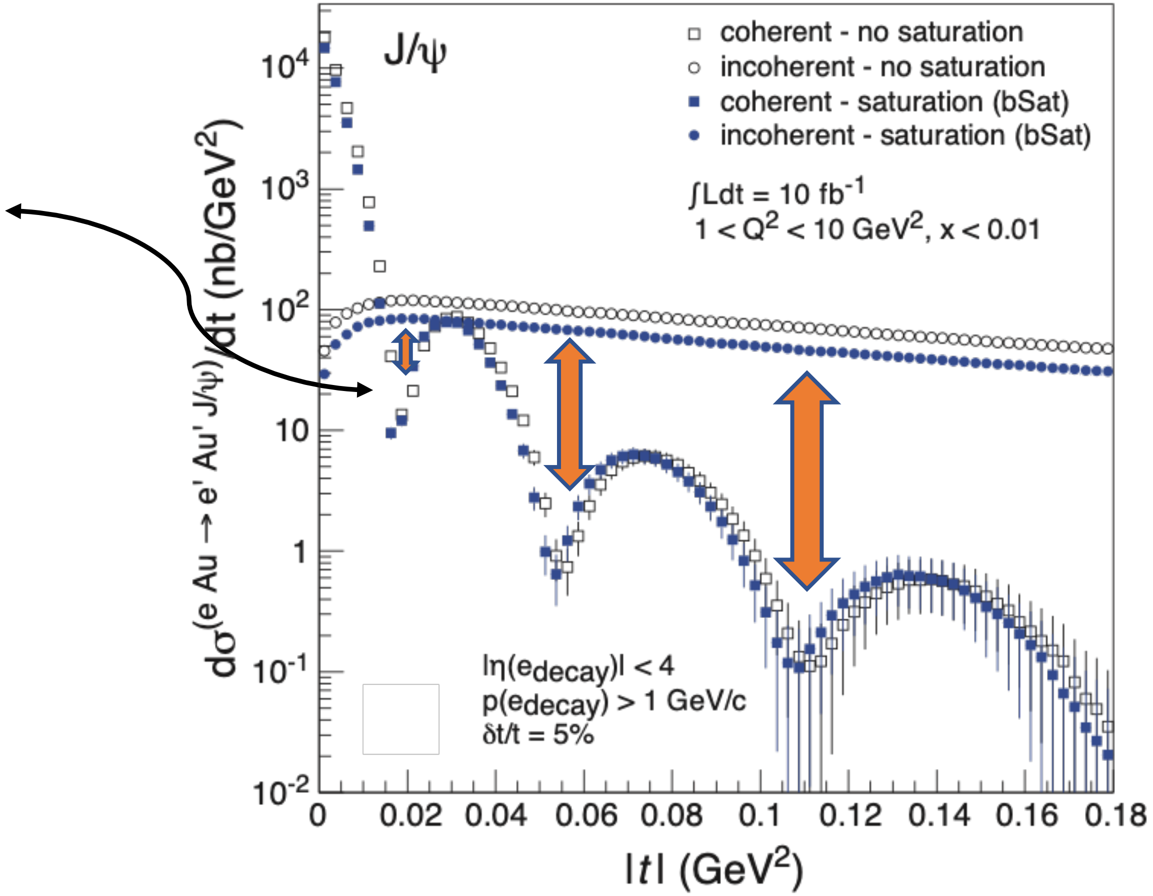
**General veto procedures:**

- Veto events with particles/activities in main detector to ensure exclusivity. (except for e' and J/psi);
- No particles, e.g., protons, neutrons, photons detected in far-forward detectors.

# Veto by steps

**Goal is to reach the 3 min. position:**

1st , 2nd , and 3rd min. are minimums of the diffractive pattern from coherent distribution. Model is based on *Satre*.



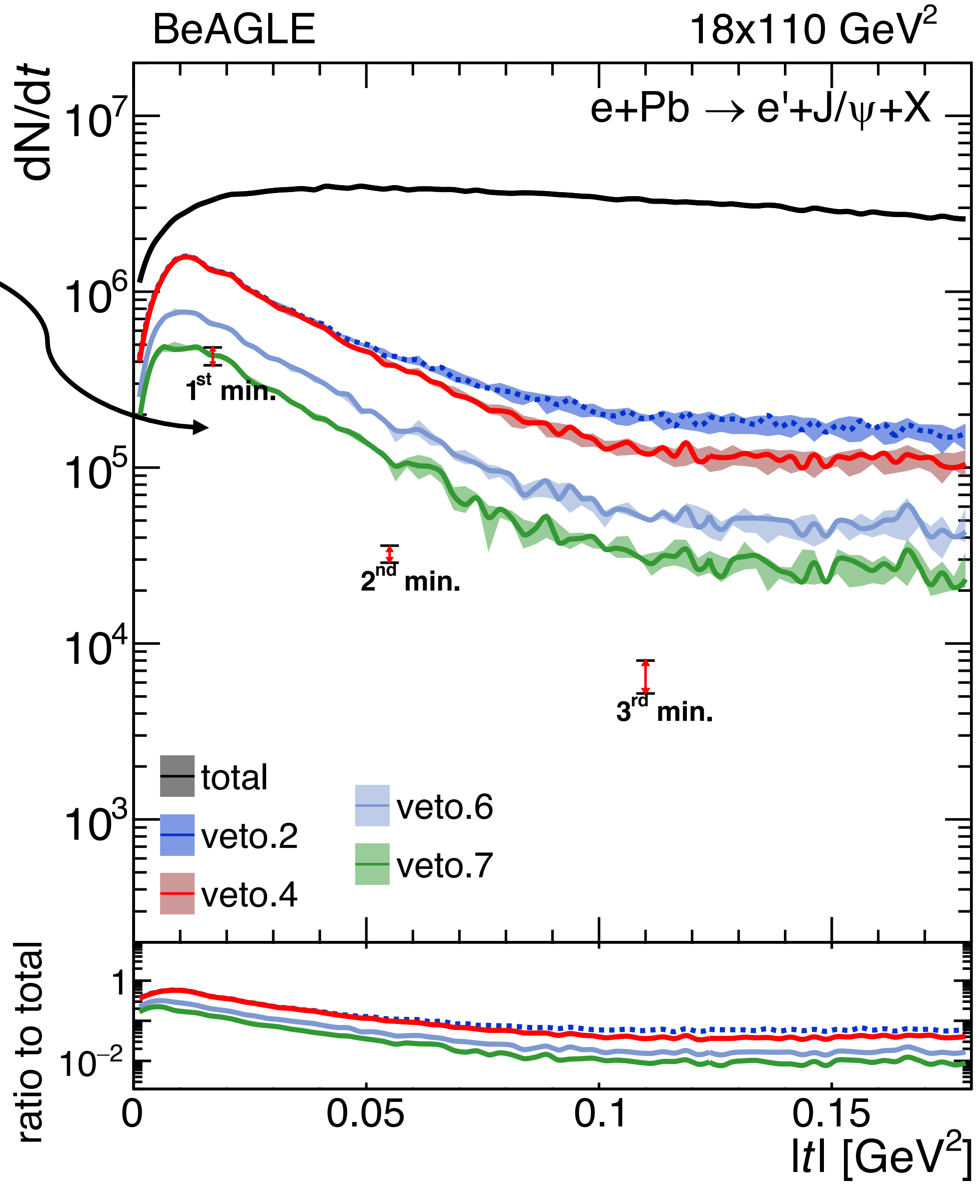
# Veto by steps

(Manuscript in preparation –BNL BeAGLE Team)

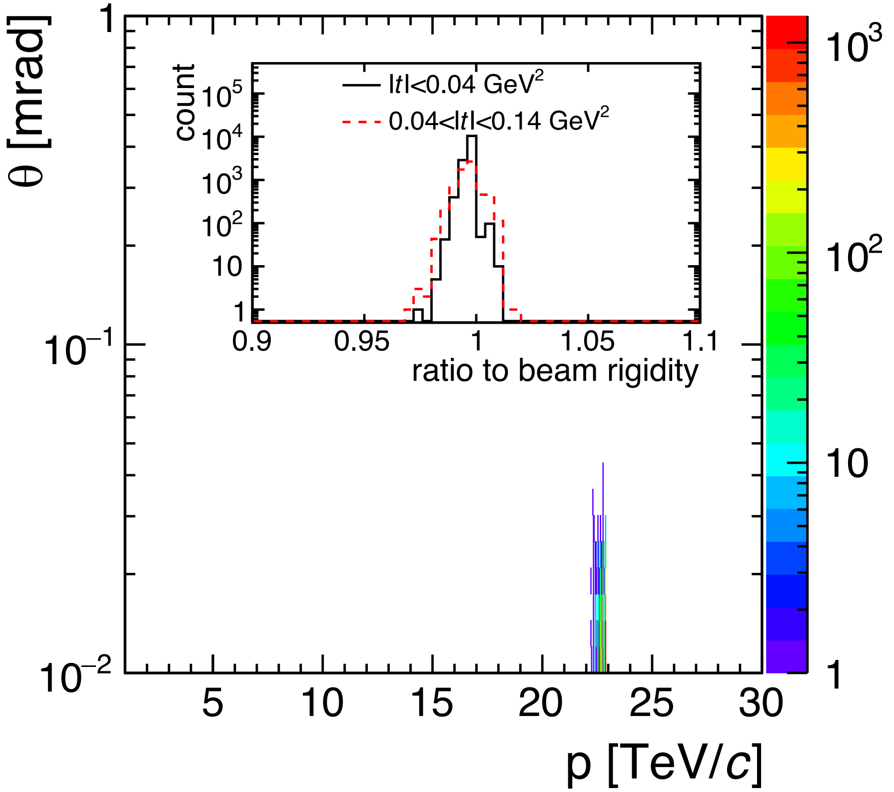
**Goal is to reach the 3 min. position:**

1st , 2nd , and 3rd min. are minimums of the diffractive pattern from coherent distribution. Model is based on *Satre*.

- Veto 1. No activity in main detector
- Veto 2. + No neutron in ZDC
- Veto 3. + No proton in Roman Pots
- Veto 4. + No proton in OMD
- Veto 5. + No proton in B0
- Veto 6. + No photon in B0
- Veto 7. + No photon in ZDC

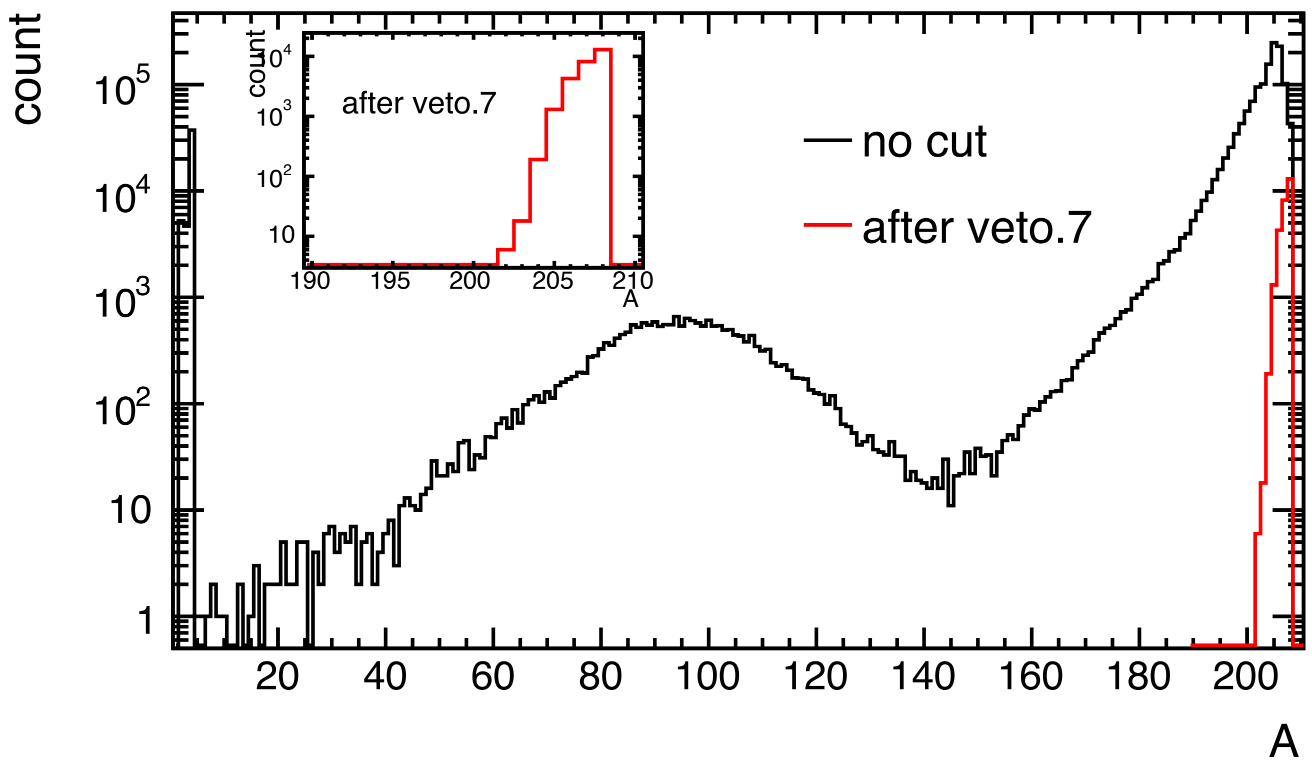


# Residues




Beam remnant scattering angle vs momentum

Details see Talk by W. Chang at DIS 2021

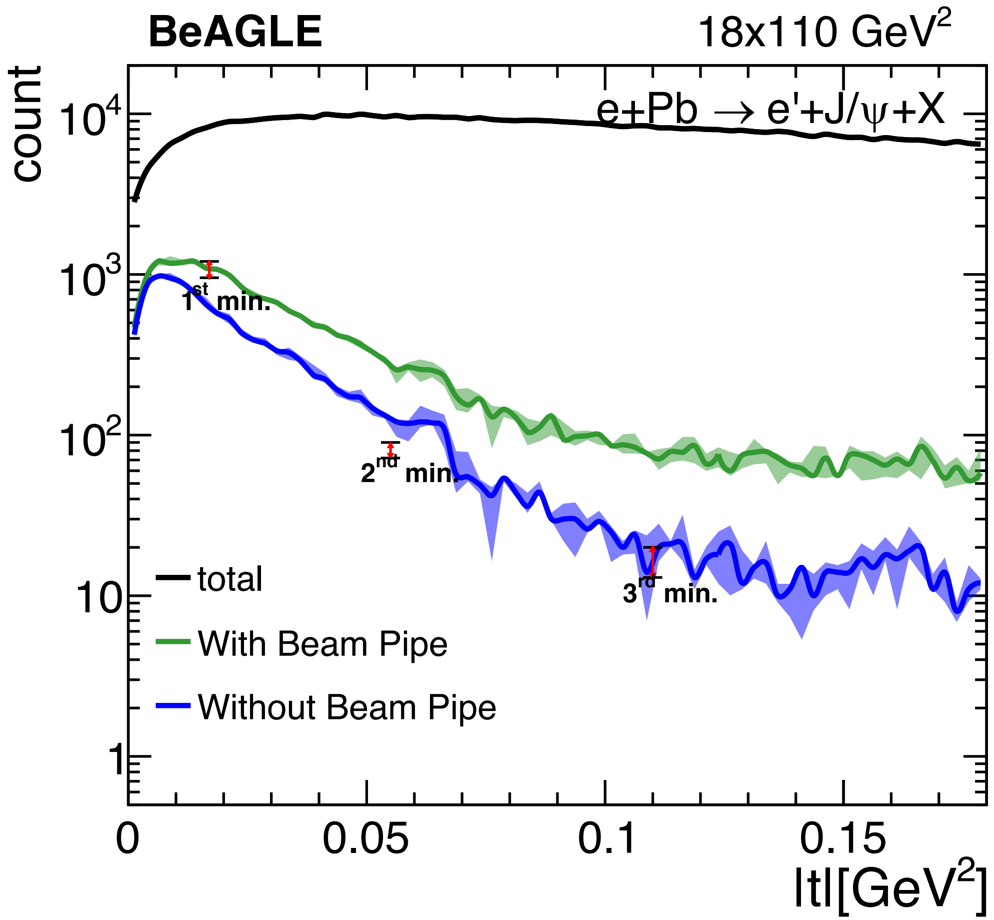



Dominated by A, A-1, A-2… systems, very close to beam rigidity

# Impact of beam pipes

**Stay tuned for the paper!**

| Survived Event Ratio | | | | |
|---|---|---|---|---|
| Material | Without beam pipe | Beryllium | Aluminum | Stainless Steel |
| Total events | 100 % | 100 % | 100% | 100% |
| veto.1 | 86.9% | 86.9% | 86.9% | 86.9 % |
| veto.2 | 5.81% | 9.73% | 9.89% | 17.15% |
| veto.3 | 5.81% | 9.73 % | 9.89% | 17.15% |
| veto.4 | 5.06% | 8.73% | 8.87% | 15.61% |
| veto.5 | 4.38% | 6.20% | 5.94% | 10.04% |
| veto.6 | 2.22% | 3.28% | 3.17% | 5.58% |
| veto.7 | 1.02% | 2.04% | 2.46% | 5.48% |

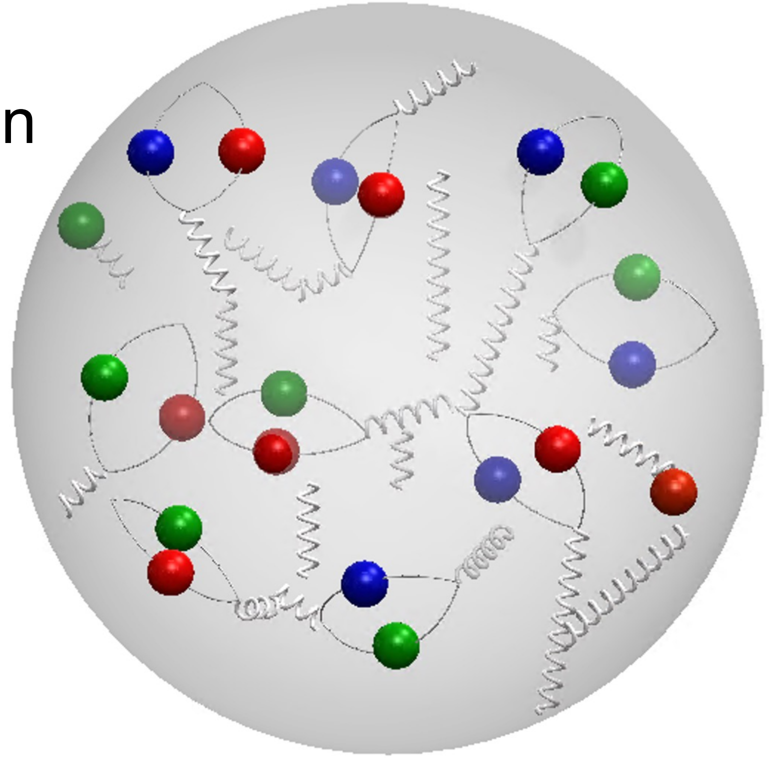



- Without a beam pipe is NOT possible.
- The question is how close can we get to the ideal case?
- New ideas about a secondary focus or other nucleus… are being actively investigated in the EIC community now.

# A new look at *Saturation* – *entanglement*

$$\rho_{tot} = |\Psi\rangle\langle\Psi|$$

Proton



At high energy, all partons are *quantum entangled*.

# A new look at *Saturation – entanglement*

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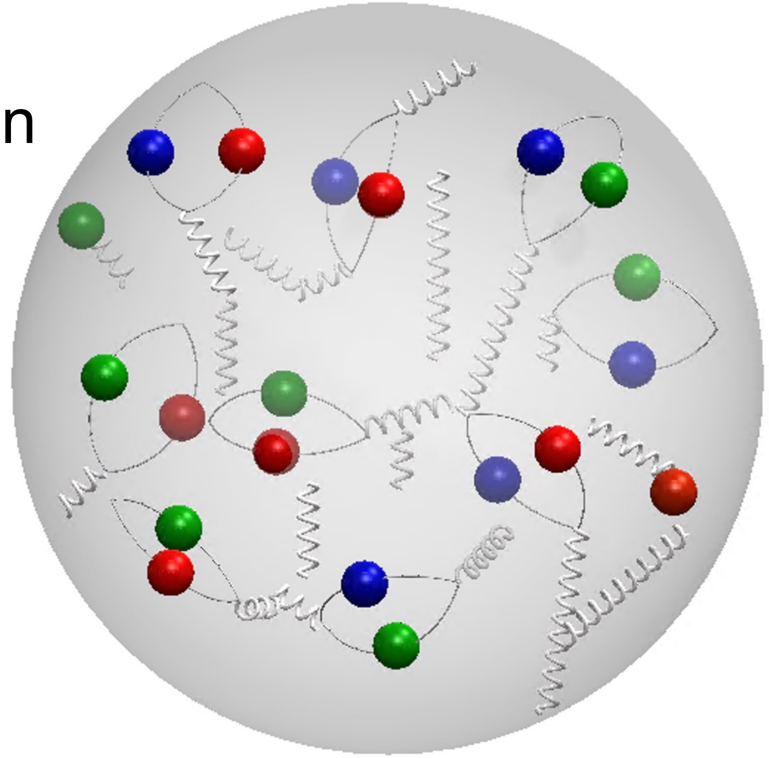

At high energy, all partons are *quantum entangled*.

If we do DIS:

(Kharzeev & Levin 2017)

$$S_A = \ln\left[xG(x, Q^2)\right]$$

gluon entropy for low x

EE in 1+1d CFT?

$$S_{\rm EE} = \frac{c}{3}\ln\left(\frac{L}{\epsilon}\right)$$

***c*** is central charge, ***L*** is the length of region ***A***, $\epsilon$ is resolution scale of the measurement

(see *Int.J.Quant.Inf. 4 (2006) 429*)

# A new look at *Saturation – entanglement*

The idea is that the Entanglement Entropy (EE) in DIS is found to be in a similar form of EE of 1+1D CFT, where ***c*** has an upper bound of 1.

$$xG(x) \leq \text{const}\ \frac{1}{x^{1/3}}.$$

A natural description of *saturation* at high energy. The proton is at the *maximally entangled states*.

(Kharzeev & Levin 2017)

$$S_A = \ln\left[xG(x, Q^2)\right]$$

gluon entropy for low x

EE in 1+1d CFT?

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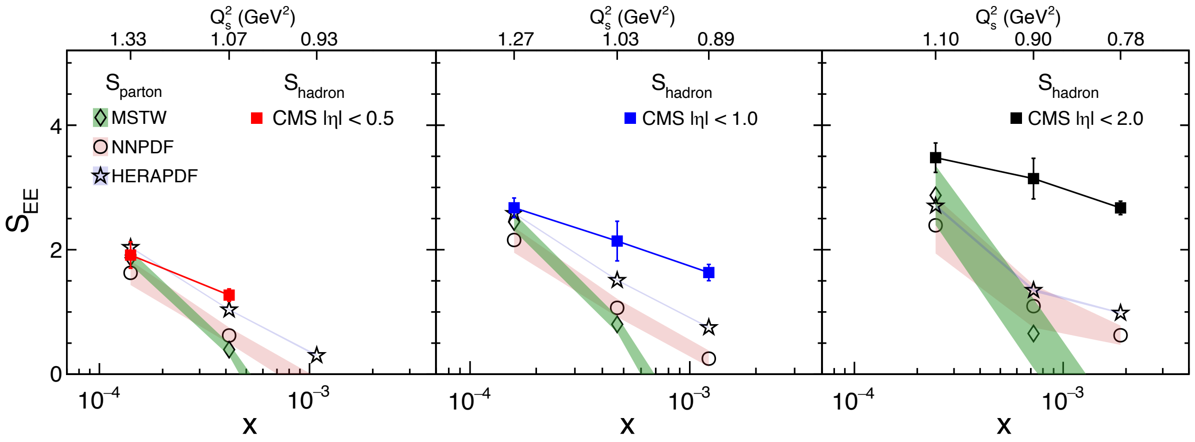
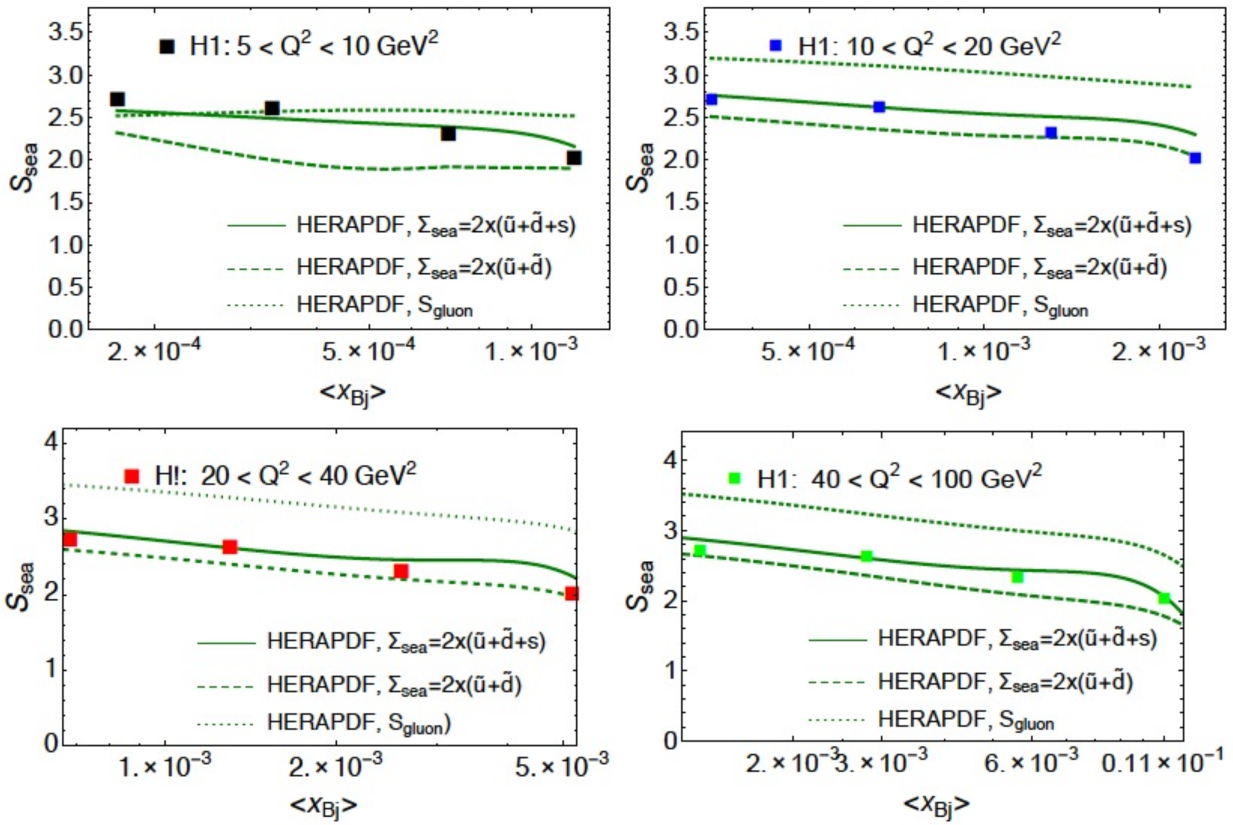
# Hints of entanglement in pp and ep DIS

Phys. Rev. Lett. 124, 062001 (2020)
(**ZT**, Kharzeev, Ullrich)




pp collisions at the LHC

ep DIS at H1

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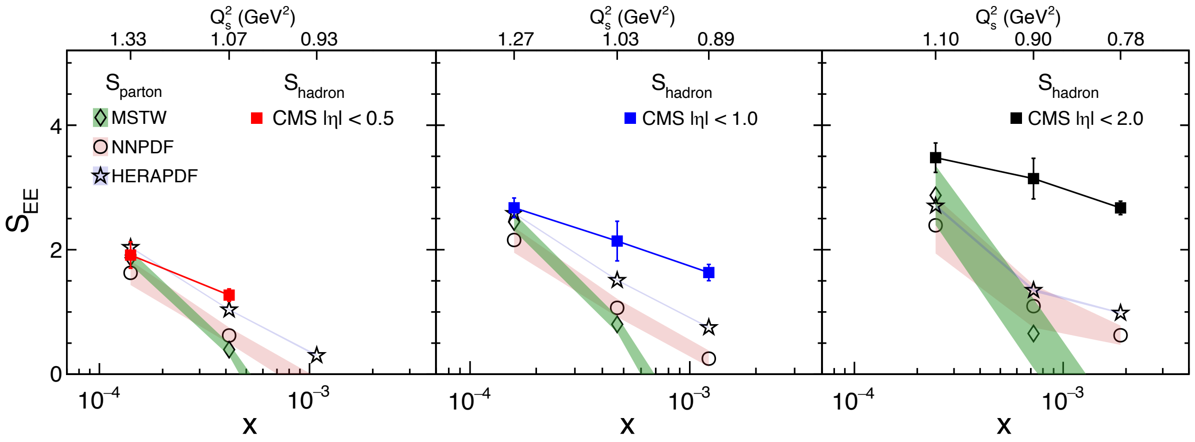
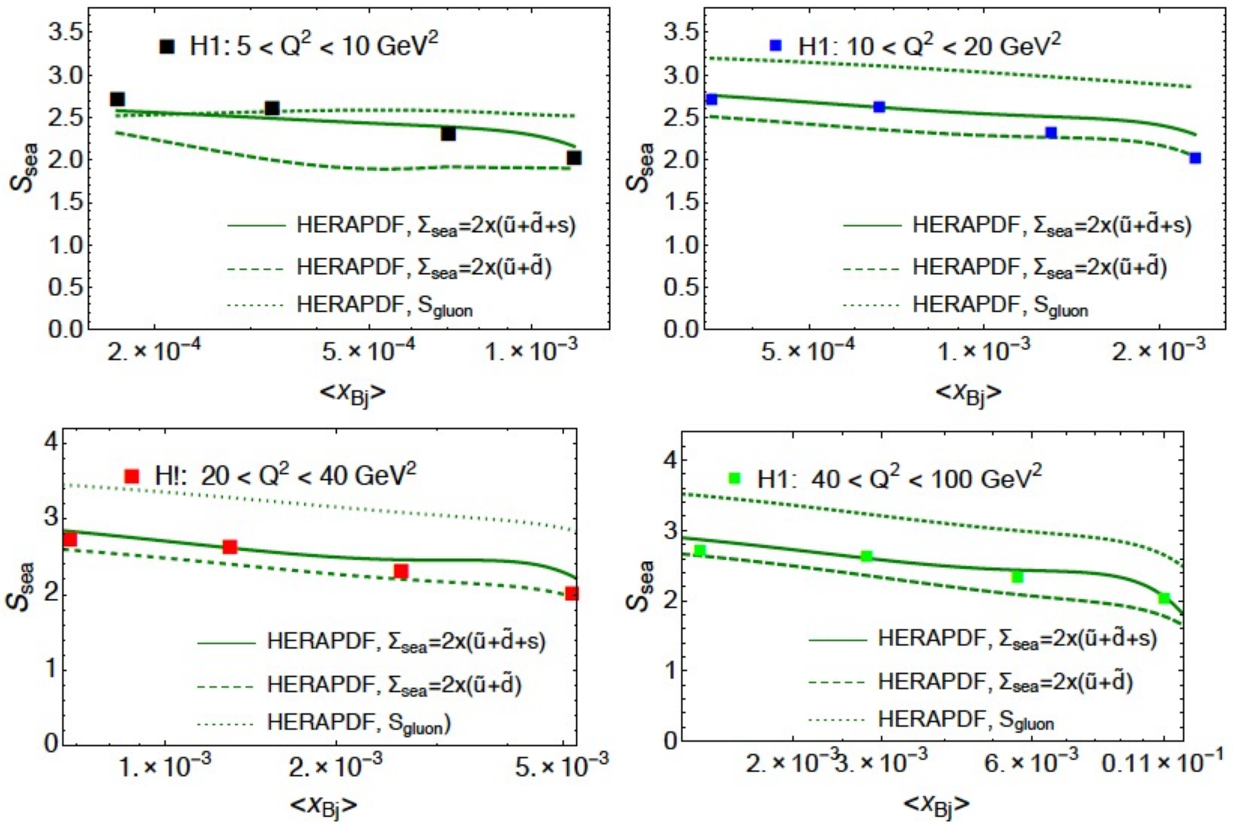



pp collisions at the LHC

**More definitive measurements at the EIC using eA collisions**

ep DIS at H1

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# Summary

- *Saturation* at the EIC – one of the pillars of the EIC program
- It is indispensable in our foundation of understanding the nucleon and nuclear structure.

- ***Extraordinary discovery requires extraordinary evidences***
  - Inclusive $F_{2,}$ $F_L$
  - Di-hadron correlations
  - Diffractions.
  - Collectivity in small systems
  - Entanglement?
  - …