Imaging Nuclei Through Exclusive Vector Meson Production

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BNL Nuclear Physics Seminar

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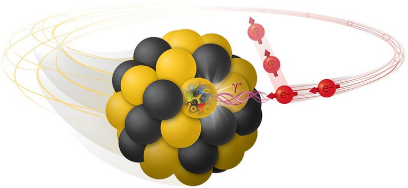
Outline

1. Introduction
2. Measuring Momentum the Transfer Distribution
3. Toy Model
4. ePIC Simulation
5. Dominate Background Sources
6. Incoherent Suppression
7. AI Model
8. Summary

electron-Proton/Ion Collider (ePIC)

Major goals of the EIC

- 3D structure of nuclei
- **Gluon saturation**
- Origin of proton spin
- Quark and gluon confinement

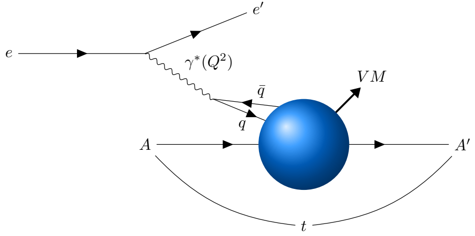


- Highly integrated into beamline
  - Detect particles at **small angles**
- Central detector + Far-forward systems
  - Allows us to **reconstruct exclusive and diffractive physics**

Motivation

Critical Measurement:
Exclusive Vector Meson (VM) Production

- Probe to gluon density → precisely see structure → **saturation**
- Deflection of VM measures **spatial distribution** of gluons

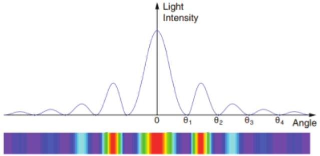


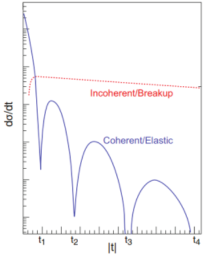
- Distribution of momentum transfer (t):
  - Fourier conjugate to impact parameter
  - Reflects the spatial profile
- **Gluon imaging**

Saturation models predict at EIC **more than 20% of the cross-section will be diffractive**

EIC YR: https://doi.org/10.1016/j.nuclphysa.2022.122447

Diffractive eA Events



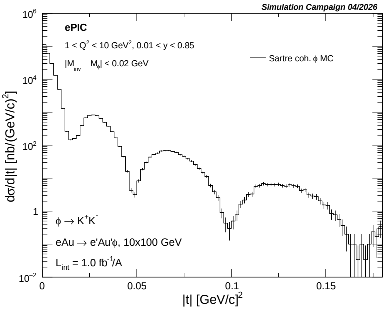


EIC WP: 10.1140/epja/i2016-16268-9

- **Diffractive pattern in optics:** light intensity on a screen behind a circular object
- **Diffractive VM production:** expected differential cross-section

- Analogous Fourier transformation
- Enables **spatial imaging of nucleus**
- We observe:
  - **Coherent production** → nucleus *remains intact*
  - **Incoherent production** → target *nucleus breaks up*

Goal: Diffractive Pattern



What does diffractive pattern tell us?

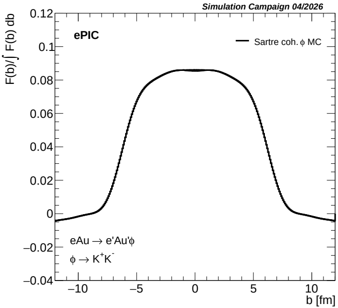
- First peak $\propto$ gluon density^2
- First minima $\propto 1/R^2$
- Larger nucleus $\rightarrow$ **closer first minimum**
- **Gluon saturation** $\rightarrow$ shifts first minimum, stronger diffractive oscillations

Form Factor:

$$\frac{d\sigma}{dt}(\gamma^* A \rightarrow VA) \sim g(x, Q^2)^2$$

xg: gluon distribution

Goal: Transformation



What does the transform tell us?

- Peak → gluon density is highest
- Smooth dist: **sharp diffractive peaks** in $|t|$ dist → **heavy nuclei**
- Sharp features: smaller/ more irregular gluon structure → protons
- **Gluon saturation** → flatter, larger radius

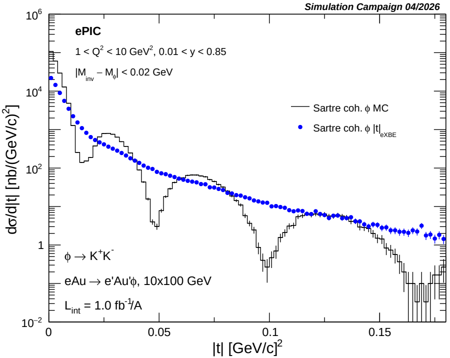
Fourier-Bessel Transformation:

$$\tilde{F}(b) \propto \frac{1}{2\pi} \int_0^\infty d\Delta_T \Delta_T J_0(b\Delta_T) \sqrt{\frac{d\sigma}{d|t|}}$$

b : impact parameter, Δ_T : transverse momentum, J_0 : Bessel function of the first kind

Challenges

Measurements of the $|t|$ distribution encounter **2 primary challenges:**



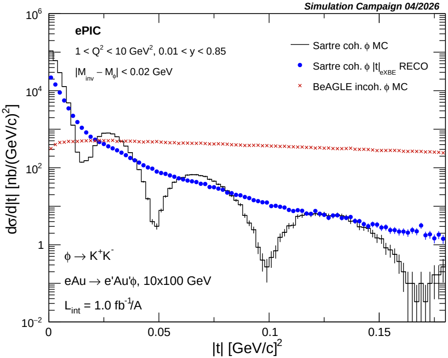
1. **Limited resolution in measuring $|t|$:**
   - Peaks and valleys washed out
   - **Mainly momentum resolution of e'**
     - Scattered very far backward $\rightarrow$ emerges at small angle
     - Tiny angular error $\rightarrow$ **large p_T error**

Best method of $|t|$ reconstruction $\rightarrow |t|_{\mathrm{eXBE}}$ **(blue circles)**

EIC YR: https://doi.org/10.1016/j.nuclphysa.2022.122447

Challenges

Measurements of the $|t|$ distribution encounter **2 primary challenges:**



1. **Overwhelming incoherent background:**
   - **Red x's**
   - Detector **cannot** suppress all incoherent production

Outline

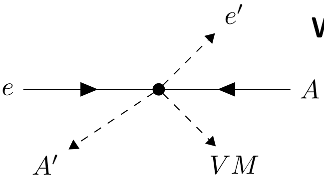
Extracting $|t|$

Reconstruct from exclusive VM production

$$|t| = (P_A - P_{A'})^2$$

To access $|t|$: **need complete final state**

- **Cannot measure $P_{A'}$**
  - For heavy nuclei $\rightarrow$ stays within beam envelope
  - Tiny momentum change + tiny angular deflection

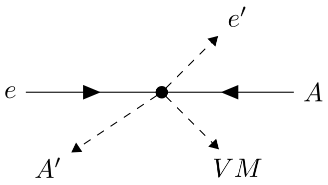


We know 4-momenta of e, A, e', and VM

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

$$P_{A'} = P_e + P_A - P_{e'} - P_{VM}$$

Different Methods



$$|t| = (P_A - P_{A'})^2$$

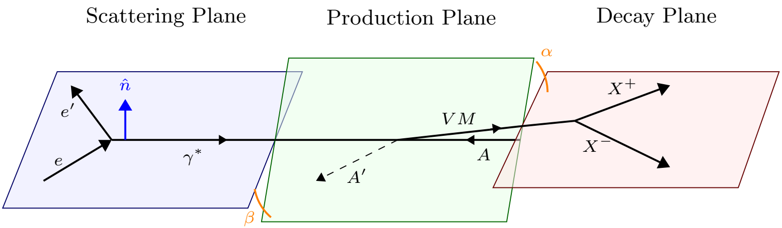
$$e + A \to e' + A' + VM$$

$$P_{A'} = P_e + P_A - P_{e'} - P_{VM}$$

- $|t|_{\mathrm{BABE}}$ (method E): $|t| = (P_{VM} + P_{e'} - P_e)^2$
  - Small error/inaccuracy has large effect on $|t| \to \frac{\sigma_t}{t}$
  - Beam momentum spread
- $|t|_{\mathrm{eX}}$ (method A): $|t| = [\mathbf{p}_T(e') + \mathbf{p}_T(VM)]^2$
  - Underestimates true t, valid only for small $|t|$ and small Q^2
- $|t|_{\mathrm{eXBE}}$ (method L): $|t| = (P_A - P_{A'}^{\mathrm{corr}})^2$
  - Only applies to coherent events

EIC YR: https://doi.org/10.1016/j.nuclphysa.2022.122447

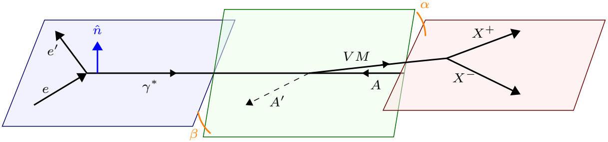
Projected-$|t|$ Method



- Measure **$|t|$ component along normal direction ($\hat{n}$)** of electron scattering plane
- **$|t|_{\hat{n}}$ unaffected by momentum resolution** $\rightarrow$ eliminate momentum resolution contribution from scattered electron

M. Kesler, A. I. Sheikh, et. al., 10.1016/j.physletb.2026.140585

Define Normal Direction



Calculate $\hat{n}$:

$$\hat{n} = \hat{p}_e \times \hat{p}_{e'}$$

$|t|_{\text{eXBE}}$:

$$|t| = (P_A - P_{A'}^{\text{corr}})^2$$

$|t|_{\text{BABE}}$:

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

$$|t|_{\hat{n}} = [(P_{VM} + P_{e'} - P_e) \cdot \hat{n}]^2$$

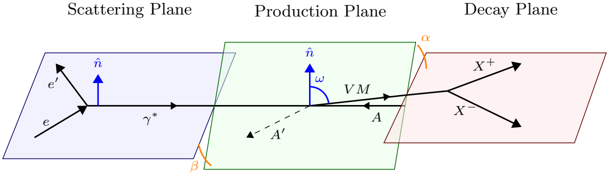
$$\boldsymbol{|t|_{\hat{n}} = (P_{VM} \cdot \hat{n})^2}$$

$$|t| = (|t|_x, \boldsymbol{|t|_{\hat{n}}}, |t|_z, |t|_E)$$

Wedge Cut

$$|t| = (|t|_x, \color{red}{|t|_{\hat{n}}}, |t|_z, |t|_E)$$

Want phase space where $|t|_{\hat{n}}$ dominates



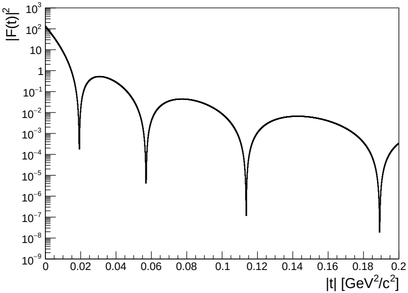
- Define $\Delta_x = \sqrt{|t_x|}$ to be in ***e′* direction ($\hat{x} = \hat{n} \times \hat{p}_e$)**
- Cut wedge of angle $\omega_{\max}$ from **$\hat{n}$ direction ($\Delta_y = \sqrt{|t|_{\hat{n}}}$)**

Parameterize $\Delta_\perp = \pm\sqrt{|t_\perp|}$:

$$\Delta_x = \Delta_\perp \sin(\omega)$$
$$\Delta_y = \Delta_\perp \cos(\omega)$$
$$\omega_{\max} = \tan^{-1}\left(\frac{\Delta_x}{\Delta_y}\right)$$

Outline

Model Simulations



- Use F(t) to **model diffractive pattern**

$$\frac{d\sigma}{d|t|} \propto |F(t)|^2$$

- Convolution of hard sphere with Yukawa potential

Form Factor:

$$F(\Delta = \sqrt{|t|}) = \frac{4\pi\rho_0}{A\Delta^3}\left[\sin(R_\mathrm{A}\Delta) - R_\mathrm{A}\Delta\cos(R_\mathrm{A}\Delta)\right]\left(\frac{1}{1+a^2\Delta^2}\right)$$

ρ_o: nuclear density, A: atomic number, R_A: nuclear radius, Δ: $= \sqrt{|t|}$, a: range of Yukawa potential

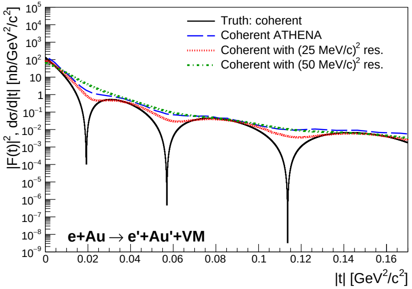
M. Lomnitz & S. Klein, https://doi.org/10.1103/PhysRevC.99.015203

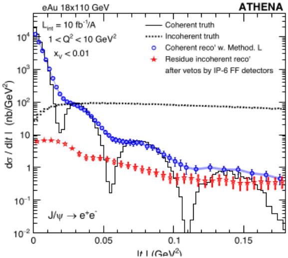
Model Detector Resolution

Guassian Smearing:

$$F'(\Delta) = \int F(\Delta) e^{\frac{-(\Delta_x - \Delta'_x)}{2\sigma^2}} d\Delta'_x$$

σ: resolution



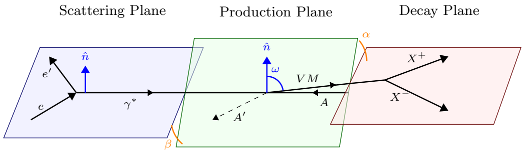


Z. Tu, https://doi.org/10.5281/zenodo.7074220

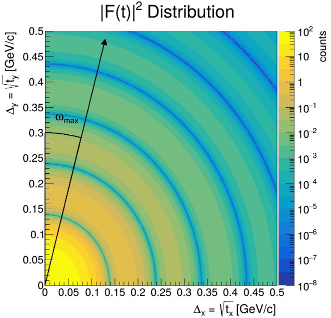
- Compare detector resolution
- We used **25 MeV^2/c^2** to smear distribution

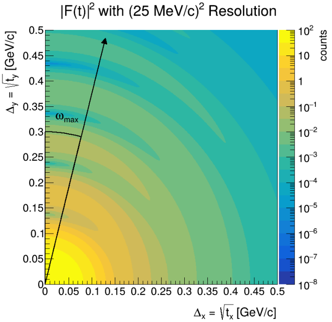
Projection Plus Wedge Cut

Want phase space where $|t|_{\hat{n}}$ dominates

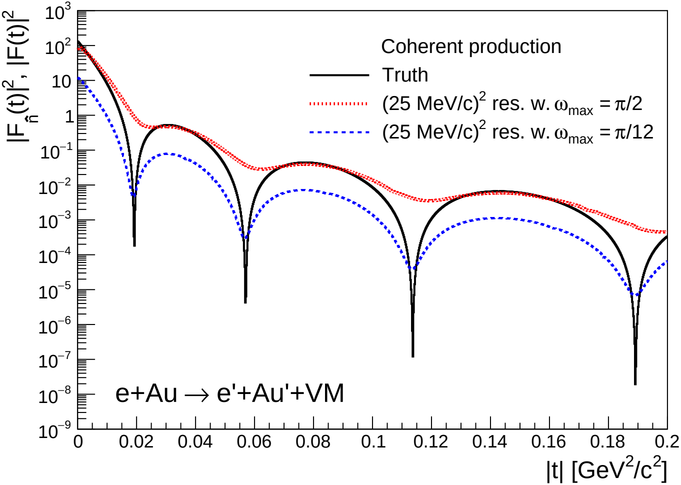


- Eliminates most of ***e′* direction(Δ_x)**
- Capture more of diffractive pattern





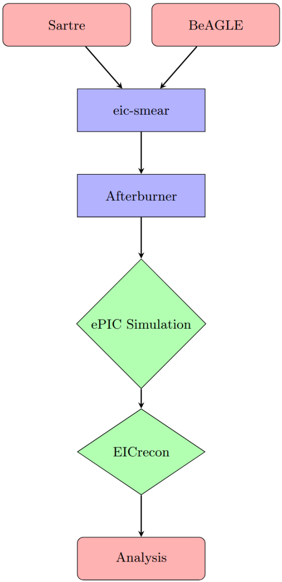
Model Results



Ability to resolve the minima!

Outline

Event Generators: eAu 10x100 GeV



Sartre1.39-1

T. Toll & T. Ullrich, https://sartre.hepforge.org/

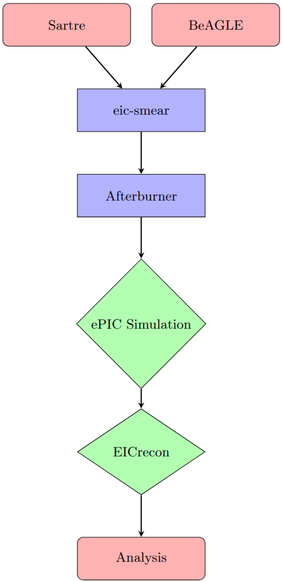
- Event generator for exclusive diffractive VM production
- Saturated, CraterLake 26.04.1:
  - **Coherent exclusive ϕ and ρ production**

BeAGLE1.03.02-1

E. Aschenaue, M. Baker, et. al., https://eic.github.io/software/beagle.html

- General purpose eA Monte-Carlo generator
- CraterLake 26.04.1:
  - **Incoherent ϕ production and DIS**

Preparing for Analysis



eic-smear

T. Burton, M. Savastio, et. al., https://github.com/eic/eic-smear

- **Adds detector smearing**
- Builds and writes events to ROOT file

Afterburner

EIC Collab., https://github.com/eic/afterburner

- **Adds beam crossing angle and beam effects**
- Converts HepMC file

ePIC Simulation & EICrecon

ePIC Collab., https://github.com/eic/epic

- Simulate hits, detector geometry, and **generates data**
- **Reconstructs data** for analysis

Code Logic: Build Clean Exclusive Events

Implement e' Finder ePIC Collab., https://github.com/eic/snippets/blob/main/ElectronID/ElectronID.hh

- $0.8 < E/p < 1.2$
- Isolation energy > 0.9 GeV

Build HFS:

- $\phi \to K^+K^-$
- Veto if **HFS > 2** or if **!kaons**

Build DIS Kinematics:

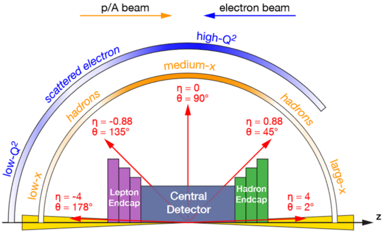
- $15 < E - p_z < 25$ GeV
- $1 < Q^2 < 10$ GeV$^2/c^2$
- $0.01 < y < 0.85$

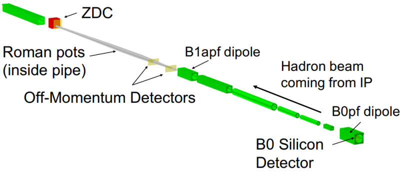
Remove incoherent events:

- Veto **OMD, RP, or ZDC**

Calculate $|t|$:

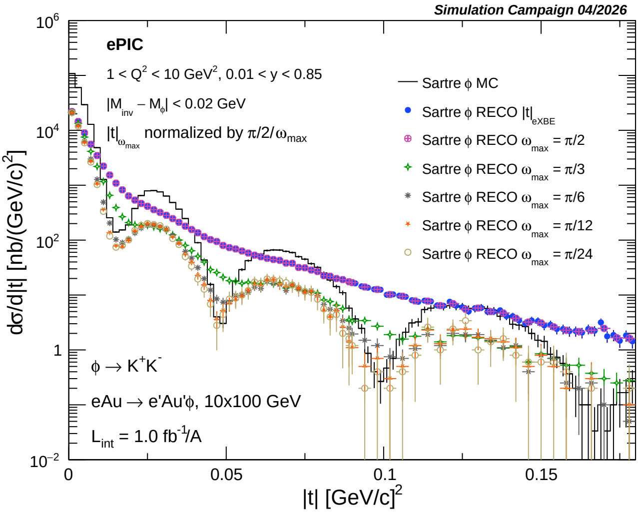
- **Extract $|t|$ from ϕ kinematics**



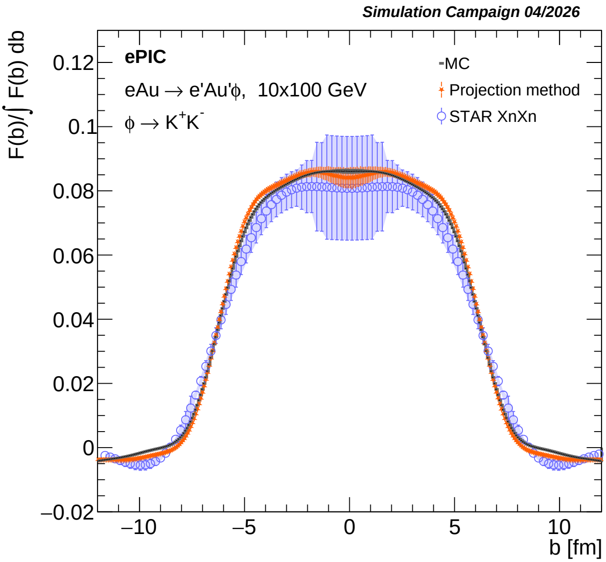


EIC YR: https://doi.org/10.1016/j.nuclphysa.2022.122447

Different ω_{max} Cuts



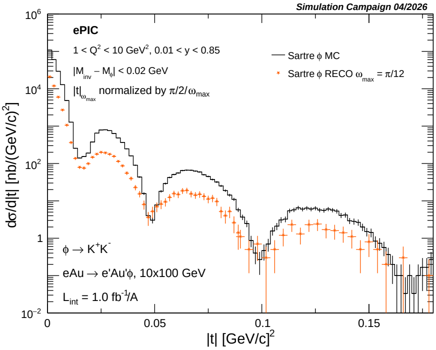
- $|t|_{eX} \rightleftharpoons |t|_{\omega=\pi/2}$
- Increase $\omega_{\max}$:
  - Increase **ability to resolve dips**
  - Lose statistics
- **Will use $\omega_{\max} = \pi/12$ for rest of results**

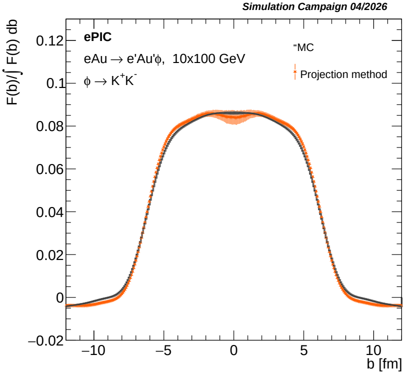


- Small errors in minima = large errors in density
- Need **precise location of minima**
- Smaller $|b|$ determined by larger $|t|$

STAR Collaboration, 10.1103/PhysRevC.96.054904

Final Results of Projected-$|t|$ Method



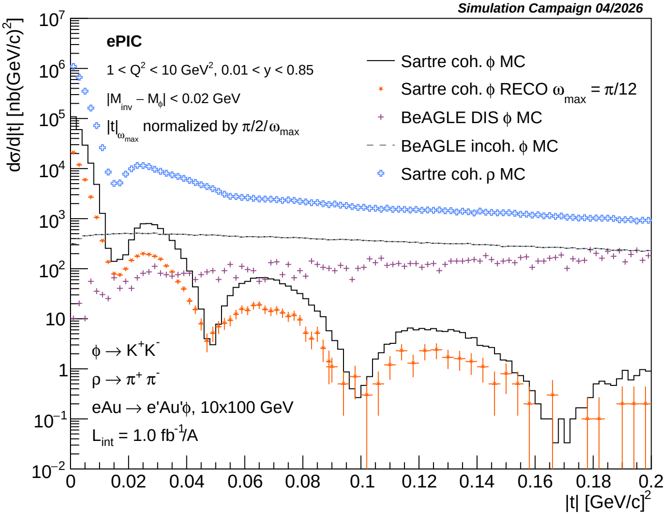


Significant **improvement** in both distributions!

M. Kesler, A. I. Sheikh, et. al., https://doi.org/10.5281/zenodo.19439688

Outline

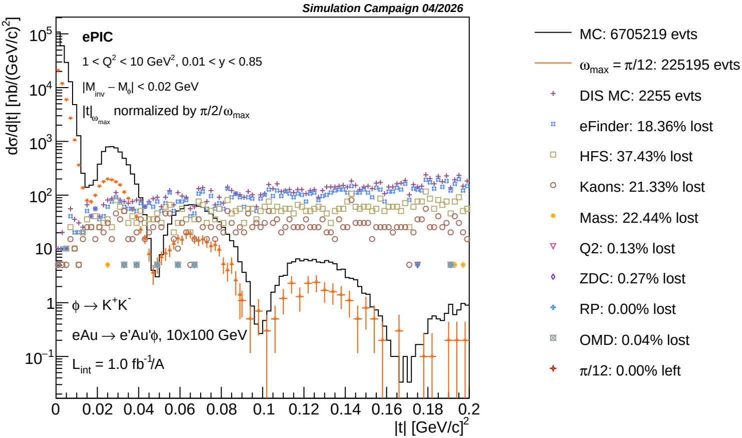
Background Contributions



1. DIS background
2. Incoherent production
3. ρ contamination

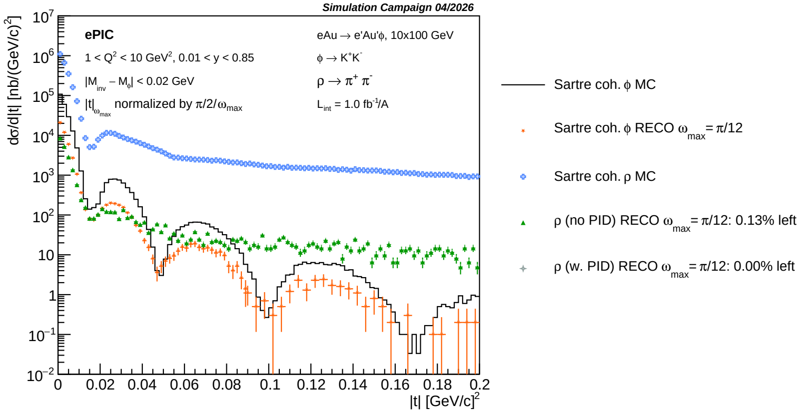
Note: will implement more sources of uncertainty in future

DIS Background



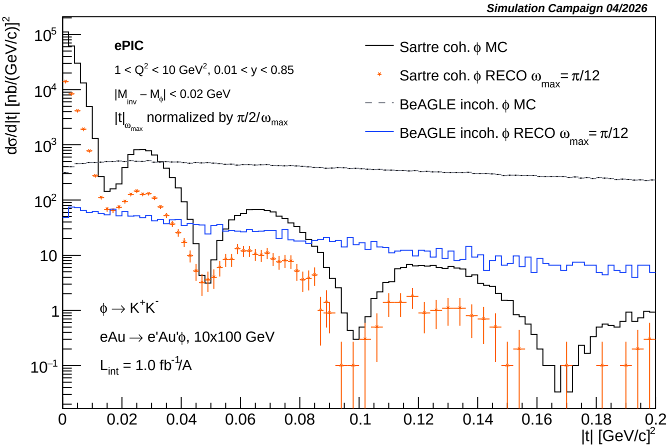
- **Distribution is dominated** by DIS background contributions
- Applying all vetoes and cuts **removes DIS background**

ρ Contamination



- VM **daughters can be misidentified**
- Applying PID **removes ρ contribution**

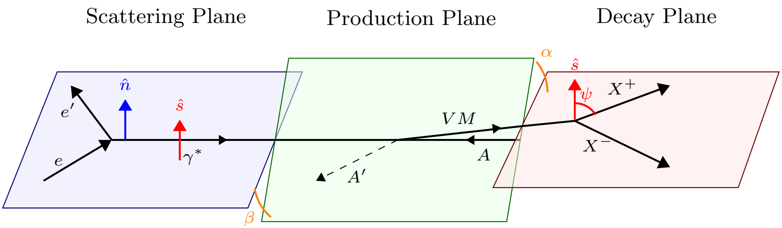
Incoherent Production



- **Dominate source of background**
- Detector can suppress some
- Can **only resolve first minima**

Outline

Measure decay angle of VM wrt electron beam polarization



- **Difference in spin transfer** between coherent & incoherent
- VM **azimuthal decay patterns** should also **differ**
- ψ measured relative to spin axis $\rightarrow$ **longitudinal or transverse polarization**

Coherent Processes

- In ep → **photon polarization** almost fully **transferred to VM**

  K. Schilling, P. Seyboth, G. Wolf, https://doi.org/10.1016/0550-3213(70)90070-2

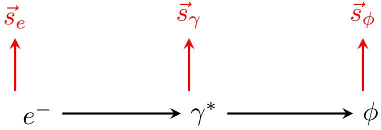
- Correlation between VM **momentum & impact parameter**

  H1 Collab., https://doi.org/10.1007/JHEP05(2010)032

- In UPCs → VM spin aligned with photons polarization

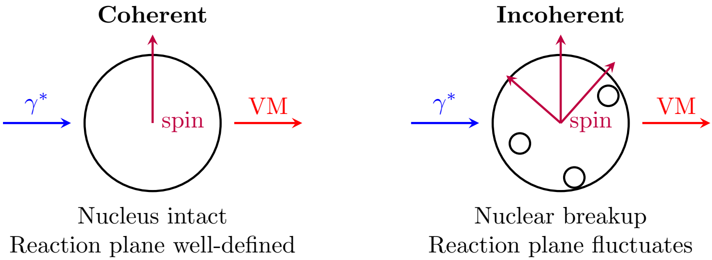
  ALICE Collab., https://doi.org/10.1016/j.physletb.2024.139017

- Alignment results in **azimuthal modulation in daughter emission** wrt VM momentum



Spin transfer through spin-0 Pomeron

Incoherent Processes



- **Little azimuthal modulation has been observed**
- **Correlation** between polarized photon and VM spin **not fully preserved**
- **Can be experimentally tested:**
  - In UPCs: measure spin alignment of incoherently produced VMs wrt reaction plane
  - In eA: measure polarization of a nonexclusive process at a given $|t|$

Separating Coherent From Incoherent Production

Goal:

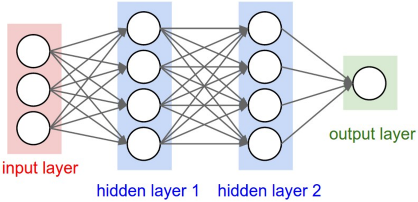
Take advantage of **differences in** degree of **spin alignment**
$\rightarrow$ method holds for transverse or longitudinal polarization

Next Steps:

- No spin in simulation files
- Need to **put in by hand**
- Calculate angle (ψ) between $\hat{s}$ and $\hat{K}$
- **Compare distributions** from coherent and incoherent processes

Outline

Multilayer Perceptron (MLP)



- Deep learning artificial NN
- 3 or more layers
- Can **learn non-linear patterns in data**
- Feedforward NN

Goal

- Give model (supervised learning):
  - $|t|_{\mathrm{MC}}$
  - Kinematics from eA collisions
- **Train it to recover the $|t|$ distribution**

AI Deconvolution

- Model **learns relationship between $|t|_{\mathrm{MC}}$ and kinematic variables**
- $|t|_{\mathrm{MC}}$ provides correct mapping

$$\boxed{|t|_{\mathrm{MC}} \Rightarrow f(Q^2_{\mathrm{RECO}}, x_{\mathrm{RECO}}, y_{\mathrm{RECO}}, \ldots)}$$

- Promising **results without the wedge cut**

Next Steps:

- Compare model e' resolution with ePIC
- Continue hyperparameter tuning and optimizing model

Outline

Summary

New technique shows considerable enhancement:

- Projected-$|t|$ method able to **resolve much more of diffractive pattern**
- Proves a **more precise transformation**
- Allows us to study onset of saturation

Currently Working On:

- **Incoherent Suppression**
  - Relies on polarization transfer
  - Looking for **any finite difference in correlations** between coherent and incoherent processes
  - Statistically separate the two components
- **ML**
  - Compare with ePIC analysis
- **Saturation**
  - Compare saturated and unsaturated distributions

Backup Slides

Gluon Saturation in Early Running of ePIC/EIC

- Establishing the non-linear QCD regime is identified as **one of most critical EIC goals**
- Diffractive cross-sections very sensitive to onset of non-linear dynamics in QCD $\sigma \propto xg(x, Q^2)^2$

Species	Beam energy (GeV)	Integrated luminosity (fb^{-1})	Electron-beam polarization	Hadron-beam polarization
e+Ag	9×115	1.0	NO	N/A
e+D	9×130	1.5	LONG	NO
$e + p$	9×130	1.0	LONG	TRANS and/or LONG
$e + p$	9×275	2.5	LONG	TRANS and/or LONG
e+Au	9×100	1.0	LONG	N/A
$e+{}^3$He	9×166	1.5	LONG	TRANS and/or LONG

"An early measurement of coherent diffraction in eA collisions at the EIC would provide the first unambiguous evidence for gluon saturation" - YR

https://doi.org/10.1016/j.nuclphysa.2022.122447

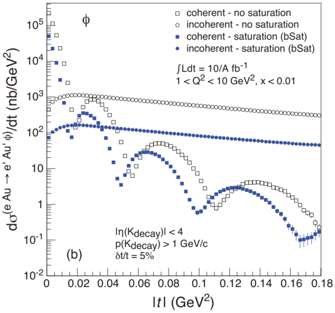
How Can We Tell?

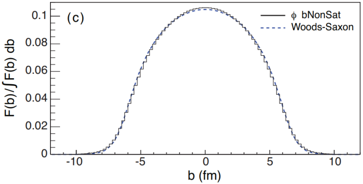
Compare:

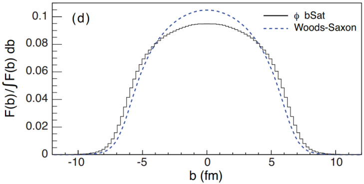
- $|t|$ distributions
- Density distributions

Looking for:

→ Shift in minima
→ Stronger oscillations
→ Flatter, larger radius







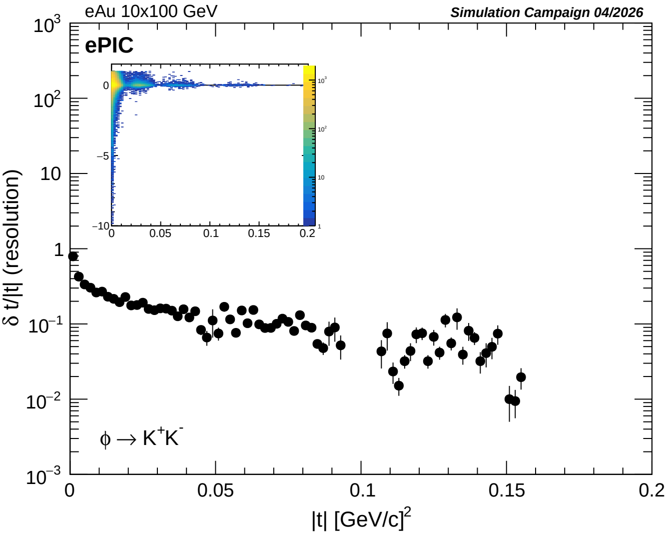
Toll and Ullrich arXiv:1211.3048

The Onset of Saturation

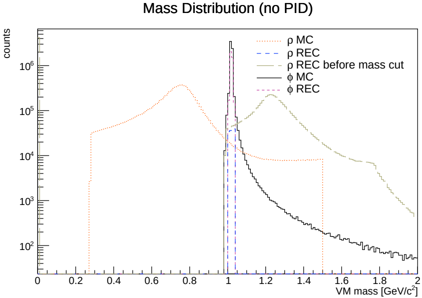
Next Steps:

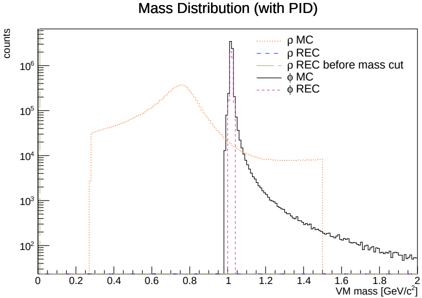
- Generate Sartre non-saturated files (bNonSat)
  - Currently I've been working with saturated simulations (bSat)
  - Coming soon $\rightarrow$ **files already processed and submitted for ρ and ϕ**
  - Hopefully ready for August campaign

$|t|$ resolution



ρ Mass





Adding PID eliminates all ρ contamination (blue dashed curve and green long dashed curve)