Improving $|t|$ measurement through exclusive coherent VM production

Exclusive/Diffractive/Tagging PWG

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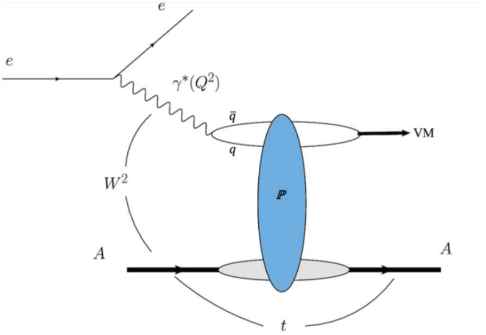
Motivation

Map out gluon structure in nuclei $\rightarrow$ gluon saturation

Critical measurement: exclusive VM production in scattering

- Measures spatial distribution of gluons
  - Probe to gluon density $\rightarrow$ precisely see structure

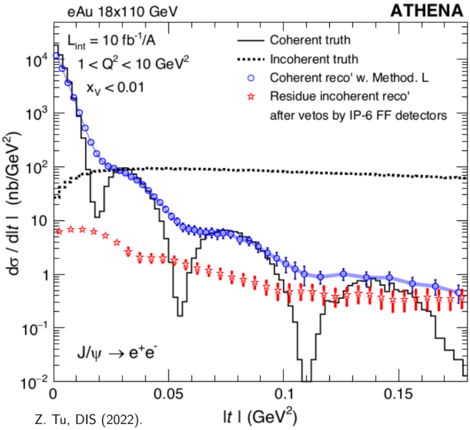


M. Krelina et al., NPA **989**, 187(2019)

- Distribution of nuclear momentum transfer ($|t|$) reflects the spatial distribution of gluons inside nucleus
  - $|t|$ conjugate to impact parameter
  - Fourier transform

Challenges

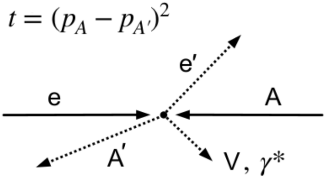
Measurements of the $|t|$ distribution encounter 2 primary challenges:



Z. Tu, DIS (2022).

1. **Limited resolution in measuring $|t|$**
   - Peaks and valleys washed out
   - Mainly momentum resolution of outgoing electron (blue circles)
2. **Overwhelming incoherent background**
   - Black dashed curve
   - Detector can suppress some incoherent production (red stars)

Extracting t: $e + A \rightarrow e' + A' + V$



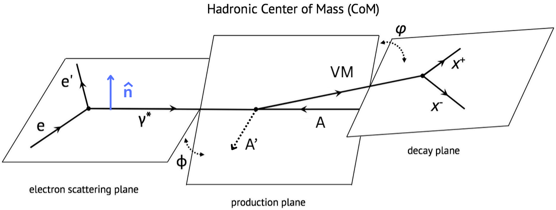
T. Ullrich, (2020).

- To access t: need complete final state
  - Cannot measure $p_{A'}$
- Know 4-momenta of e, A, e', and V
- Different methods to do this

- **Method E:** gives true $t = (\mathrm{p}_V + p_{e'} - p_e)^2$
  - **Cons:** Subtract large incoming/outgoing momenta to get longitudinal component of $t \rightarrow$ small error/inaccuracy has large effect on t
- **Method A:** ignores longitudinal momenta $t = [\mathbf{p}_T(e') + \mathbf{p}_T(V)]^2$
  - **Cons:** underestimates true t, valid only for small t and small Q^2
- **Method L:** improvement to Method E, corrects $p_{A'}$ and uses true invariant mass to compensate the smearing $t_{\mathrm{corr}} = |p_A - p_{A'}^{\mathrm{corr}}|^2$
  - **Cons:** only applies to coherent events

Reconstruct t from exclusive VM production

- Measure *projection of* $|t|$ along the normal direction ($\hat{n}$) of the electron scattering plane
  - Eliminate momentum resolution contribution from the outgoing e
  - **Potential issue:** loss of information on gluon structure



Decompose t:

$$t = -(p_{A'}^{\mathrm{corr}} - p_A)^2$$

$$t = t_\perp + t_\parallel \longrightarrow t_\perp = t_x + t_y$$

$$t_\perp = q_\perp^2 = q_x^2 + q_y^2$$

t in terms of q:

$$q_y = \pm\sqrt{|t_y|} = (p_V \cdot \hat{n})\hat{n}$$

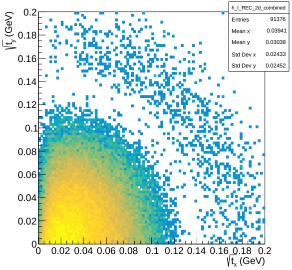
$$q_x = \pm\sqrt{|t_x|} = (-p_{A'}^{\mathrm{corr}} + p_A - p_y)(\hat{n} \times \hat{z})$$

Projection technique

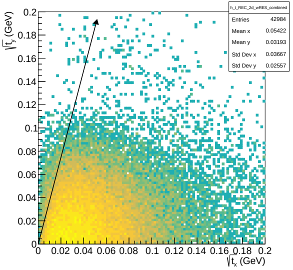
Parameterize $q_\perp = \pm\sqrt{|t_\perp|}$:

$$
\begin{aligned}
q_x &= q_\perp \sin(\theta) \\
q_y &= q_\perp \cos(\theta) \\
\theta &= \tan^{-1}\left(\frac{q_x}{q_y}\right)
\end{aligned}
$$

- Cut wedge of angle θ from the $\hat{n}$-direction (q_y)
- Eliminates most of the q_x component

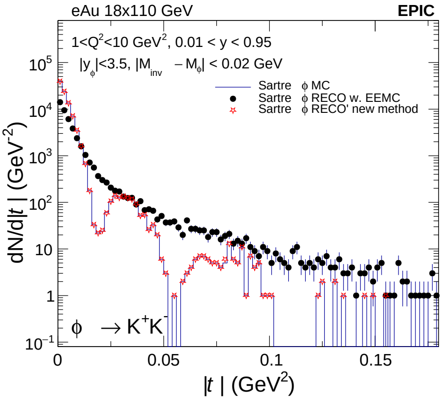


2D no resolution

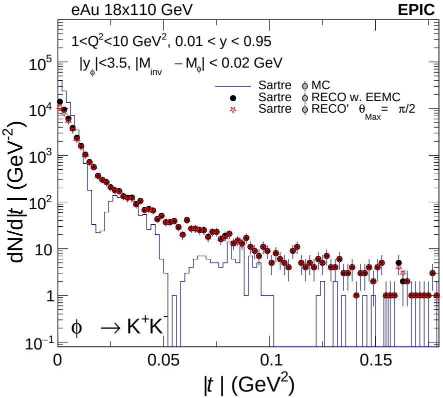


2D with resolution

Reproduce $|t|$ distribution

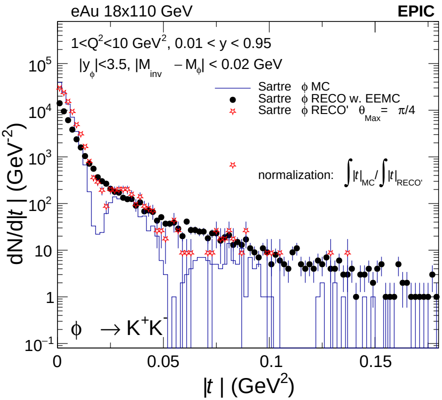


No cut, no resolution

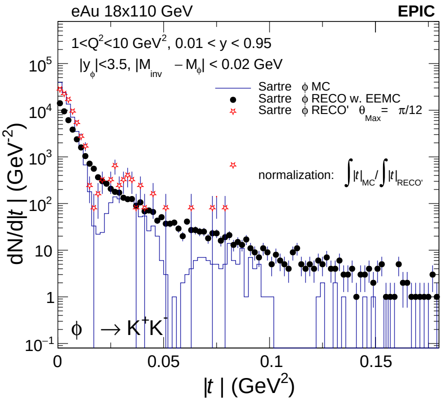


$\pi/2$ cut, with resolution

Result on $|t|$ distribution



$\pi/4$ cut, with resolution



$\pi/12$ cut, with resolution

- We see a significant improvement!

Next steps...

- Get more statistics
- Correcting
- Fourier Transform to spatial distribution
- Separate coherent and incoherent events
  - Determine the fraction of coherently produced VMs by utilizing the transversely polarized electron beams $\rightarrow$ spin projection

Link to poster: ▸ Link
Link to arxiv: ▸ Link

arXiv:2502.15596

Thank You :)

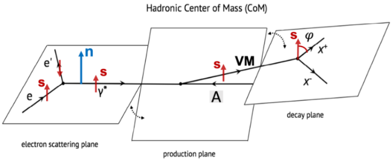
Backup Slides

Future Plan

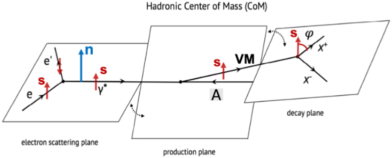
- Utilize transversely polarized e^- beams
  - *e^- spin is perpendicular to its momentum*
- Exploit decay pattern of VM wrt $\hat{n}$
  - Determine the *fraction of coherently produced VMs*

Coherent Events

- If e^- spin flips:
  - Spin of VM aligns with $\hat{n}$
  - Expect $\cos 2\phi$ modulation if we project momentum of VM decay daughter onto VM spin direction



Future Plan



- If e^- spin does not flip:
  - No preferred direction of VM spin
  - Expect a flat ϕ distribution

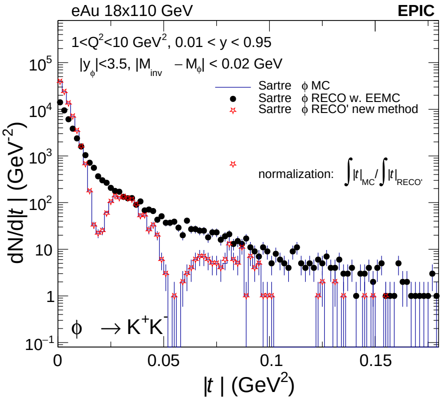
Incoherent Events

- VM spin expected to be random wrt $\hat{n}$

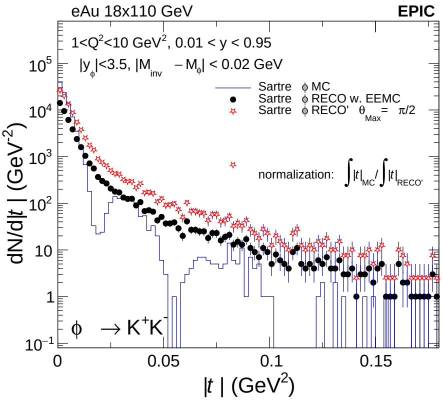
Result:

- Fraction of coherent events (case when e^- flips spin) is $< \cos 2\phi >$
- Assume probability for e^- to flip spin is C
- Fraction of total coherent events is given by $\frac{<\cos 2\phi>}{C}$
- Can then obtain $|t|_{\hat{n}}$ distributions for coherent VM production
  - Extract spatial distribution of gluons in nucleus

More plots

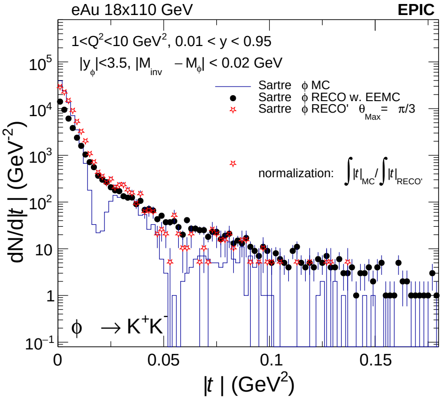


No cut, no resolution

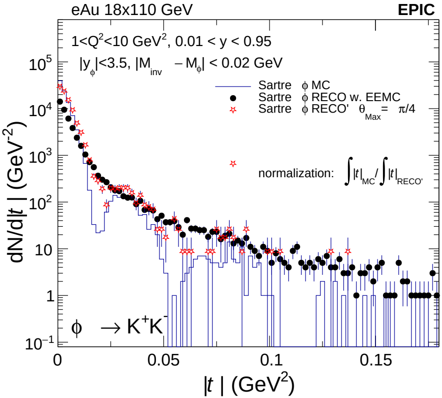


$\pi/2$ wedge cut, with resolution

More plots

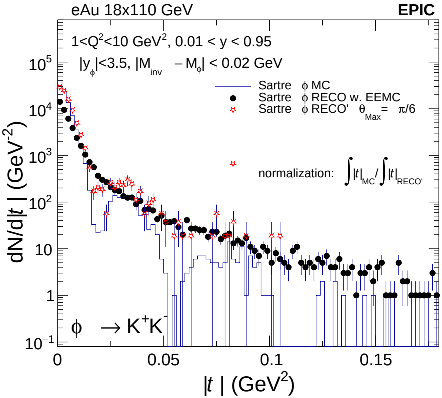


$\pi/3$ wedge cut, with resolution

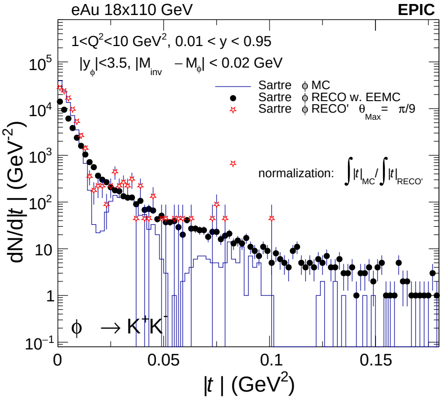


$\pi/4$ wedge cut, with resolution

More plots



$\pi/6$ wedge cut, with resolution

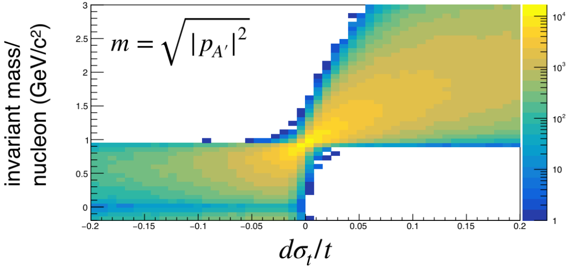


$\pi/9$ wedge cut, with resolution

Method L from T. Ullrich EIC WG meeting (2020)

- Calculate A' 4-momentum: $p_{A'} = p_A - (p_V + p_{e'} - p_e)$

method E



- Any smearing of the longitudinal momentum difference will change the invariant mass of the target

- For coherent events this essentially indicates the failure of method E due to beam and detector smearing effects or that the event was mischaracterized as coherent $\Longrightarrow$ Important analysis/cross-check tool

Method L from T. Ullrich EIC WG meeting (2020)

- How the method works
  - Calculate p of outgoing A': $p_{A'} = p_A - (p_V + p_{e'} - p_e)$
  - Express and correct the outgoing nucleus in light cone variables:
    - $p^+_{A'} = E_{A'} + p_{z,A'}$
    - $p^2_{T,A'} = p^2_{x,A'} + p^2_{y,A'}$
    - $p^-_{A'} = (M^2_A + p^2_{T,A'})/p^+_{A'}$ where $p^-_{A'}$ is now modified by using the true mass M^2_A.
  - The corrected 4-momentum of the outgoing nuclei is now

$$p^{\text{corr}}_{A'} = \left[p_{x,A'},\ p_{y,A'},\ (p^+_{A'} - p^-_{A'})/2,\ (p^+_{A'} + p^-_{A'})/2\right]$$

  - In short, you are using the true invariant mass of the nucleus to compensate the smearing in the larger component of the electron 4-momentum by modifying $E_{A'}$ and $p_{z,A'}$ simultaneously.
  - Now simply: $t_{\text{corr}} = \left| p_A - p^{\text{corr}}_{A'} \right|^2$