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Nuclear Imaging Through Coherent Exclusive Vector Meson Production

Exclusive/Diffractive/Tagging PWG

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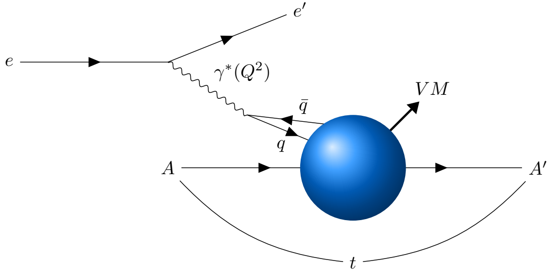
Center for Nuclear Research

Introduction

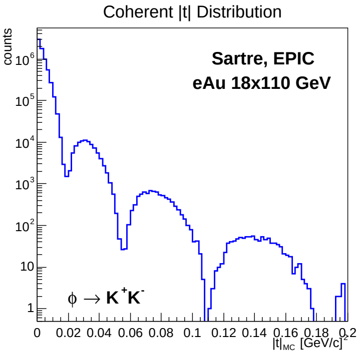
Critical measurement: exclusive vector meson (VM) production in scattering

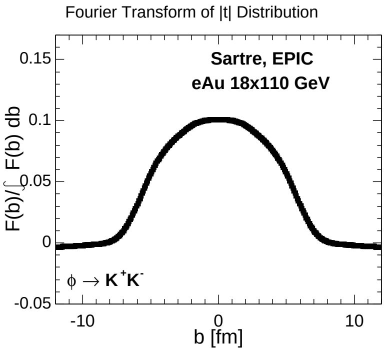
- Probe to gluon density $\rightarrow$ precisely see structure $\rightarrow$ saturation
- Deflection of VM measures spatial distribution of gluons



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

Goal





What does this diffractive pattern tell us?

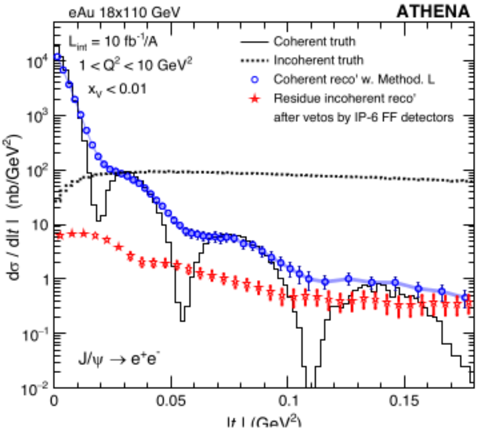
- Height of peak $\propto$ gluon density
- Larger nucleus $\rightarrow$ closer first minimum: $\Delta t \propto 1/R^2$

What does the transform tell us?

- Central peak is core of nucleus where gluon density is highest
- Indicates how sharply gluon density drops off near nuclear edge

Challenges

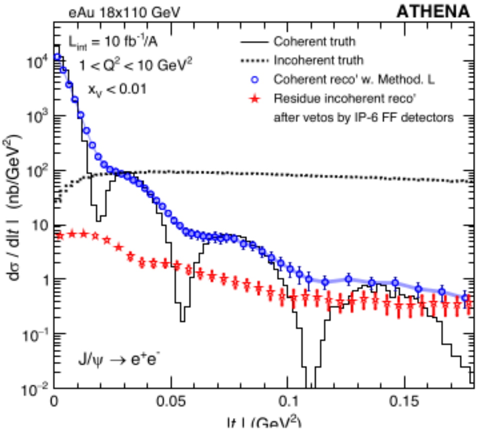
Measurements of the t distribution encounter 2 primary challenges:



- **Limited resolution in measuring t**
  - Peaks and valleys washed out
  - Mainly momentum resolution of outgoing electron (blue circles)
    - Scattered very far backward → emerges at small angle
    - Tiny angular error → large p_T error

Challenges

Measurements of the t distribution encounter 2 primary challenges:



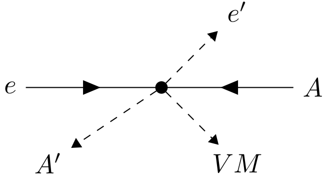
- **Overwhelming incoherent background**
  - Black dashed curve
  - Detector can suppress some incoherent production (red stars)

Methods for Extracting t

- Reconstruct t from exclusive VM production

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

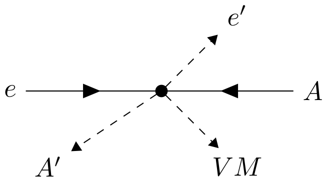
- To access t: need complete final state
  - Cannot measure $P_{A'}$
    - For heavy nuclei $\rightarrow$ stays within beam envelope
    - Tiny momentum change + tiny angular deflection



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

$$\begin{aligned} e + A &\rightarrow e' + A' + VM \\ P_{A'} &= P_e + P_A - P_{e'} - P_{VM} \end{aligned}$$

Methods for Extracting t



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

$$\boxed{e + A \rightarrow e' + A' + VM}$$

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

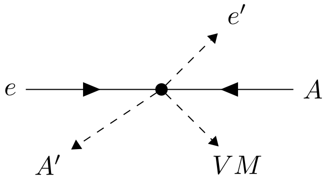
- **Method E** (exact, MC): delivers true t

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

  - **Con:** Subtract large incoming/outgoing momenta to get longitudinal component of t $\rightarrow$ small error/inaccuracy has large effect on t

$$\frac{\sigma_t}{t} = \frac{(t_{\text{measured}} - t_{\text{true}})}{t_{\text{true}}}$$

Methods for Extracting t



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

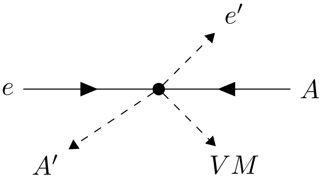
$$e + A \rightarrow e' + A' + VM$$

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

- **Method A** (approximate): Assume small scatting angle ($P_{A_{//}} \approx P_{A'_{//}}$) and incoming e/ion along beamline ($p_T = psin\theta \approx 0$)

$$t = \left[\mathbf{p}_T(e') + \mathbf{p}_T(VM)\right]^2$$

  - Used extensively at HERA
  - **Con:** underestimates true t, valid only for small t and small Q^2



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

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

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

- **Method L**: corrects $P_{A'}$ using true invariant mass

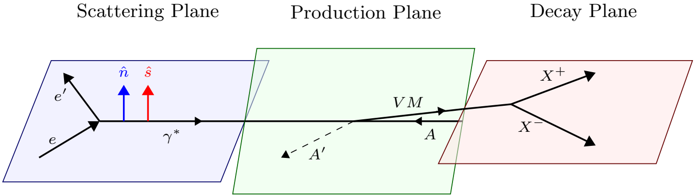
$$P_{A'}^{\mathrm{corr}} = [p_{x,A'}, p_{y,A'}, (p_{A'}^{+} - p_{A'}^{-})/2, (p_{A'}^{+} + p_{A'}^{-})/2]$$

$$t_{\mathrm{corr}} = (P_A - P_{A'}^{\mathrm{corr}})^2$$

  - Improvement to method A
  - **Con:** Only applies to coherent events

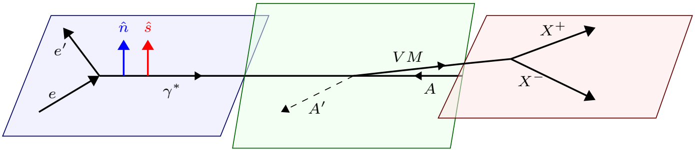
Projection Technique

Measure *projection of* $|t|_{\hat{n}}$ along the normal direction ($\hat{n}$) of the electron scattering plane



- Eliminate momentum resolution contribution from the outgoing electron
- Only need to measure the electron directions, *not their momenta*

Our Method



Method E:

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

Method L:

$$t_{\text{corr}} = (P_A - P_{A'}^{\text{corr}})^2$$

Define $\hat{n}$:

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

Projected t_{corr}

$$t_{\hat{n}} = [(P_{VM} + P_{e'}^{\text{corr}} - P_e) \cdot \hat{n}]^2$$
$$= (P_{VM} \cdot \hat{n} + P_{e'} \cdot \hat{n} - P_e \cdot \hat{n})^2$$
$$t_{\hat{n}} = (P_{VM} \cdot \hat{n})^2$$

$$\boxed{t = (t_x, t_{\hat{n}}, t_z, t_E)}$$

How it Works

Want to work with transverse plane

Decompose t:

$$t = t_\perp + t_{//}$$
$$t_\perp = t_x + t_y$$
$$= q_x^2 + q_y^2$$
$$t_\perp = q_\perp^2$$

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

$$q_x = q_\perp \sin(\theta)$$
$$q_y = q_\perp \cos(\theta)$$
$$\theta_{\mathrm{max}} = \tan^{-1}\left(\frac{q_x}{q_y}\right)$$

Define $q_x = \sqrt{|t_x|}$ to be in $\hat{x} = \hat{n} \times \hat{p}_e$ direction

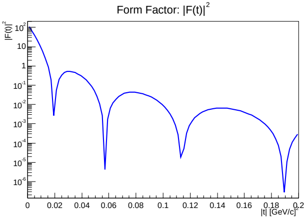
- Cut wedge of angle θ_{max} from $\hat{n}$-direction ($q_y \rightarrow$ projected VM)
- Eliminates most of the q_x component (e' direction)

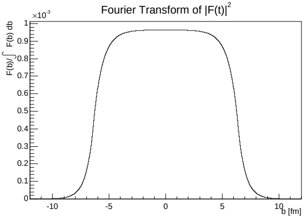
The Model

Form Factor:

$$F(q=\sqrt{t}) = \frac{4\pi\rho_0}{Aq^3}\left[\sin(qR_A) - qR_A\cos(qR_A)\right]\left(\frac{1}{1+a^2q^2}\right)$$

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





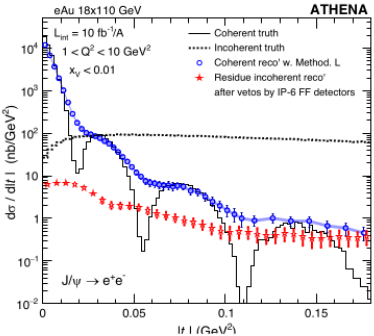
Fourier-Bessel Transformation:

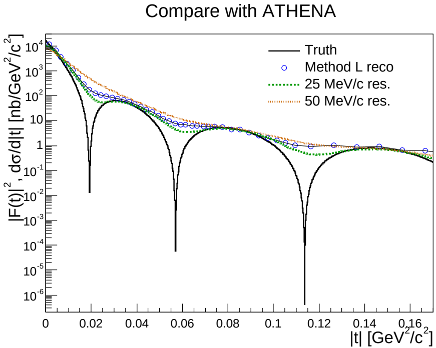
$$\tilde{F}(b) = \frac{(2\pi)^{3/2}}{\sqrt{b}}\int_0^\infty \sqrt{F(q)}J_{1/2}(bq)q^{3/2}dq$$

Add Smearing

Convolute with Gaussian

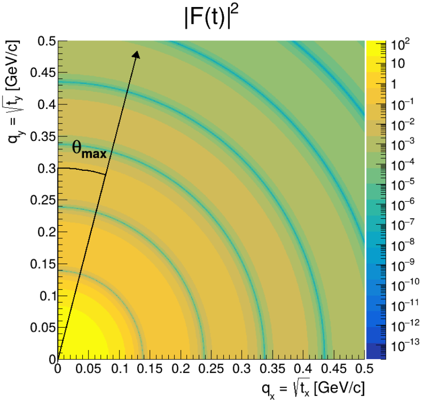
$$|F(q_{x'}, q_y)|^2 = \int |F(q_x, q_y)|^2 e^{\frac{-(q_x - q_{x'})^2}{(2\sigma^2)}} dq_x$$



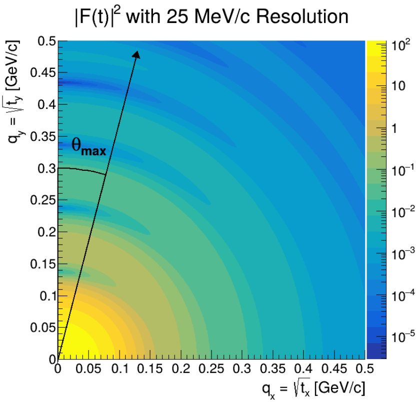


Results use 25 MeV

2D Distributions



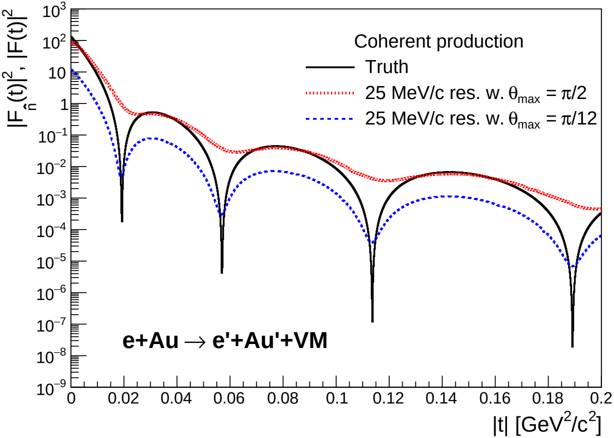
Truth Distribution



Distribution with Resolution

Model Results

- Using the projected VM momentum and a $\pi/12$ wedge cut

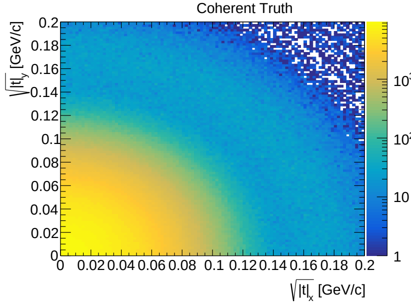


- We see a significant improvement!
- **Con:** loss of statistics

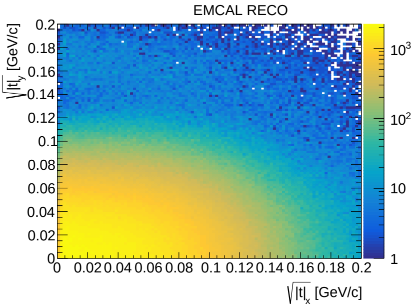
Simulation

- Sartre simulation for diffractive phi production
  - eAu 18x110 GeV
  - $\phi \rightarrow K^+K^-$

2D transverse plane after running through simulation

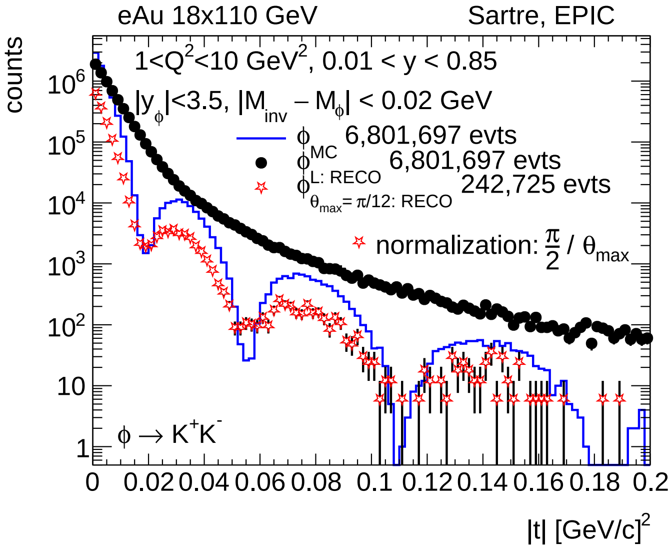


Nice concentric circles



Smeared out $\rightarrow$ more elliptical

Results



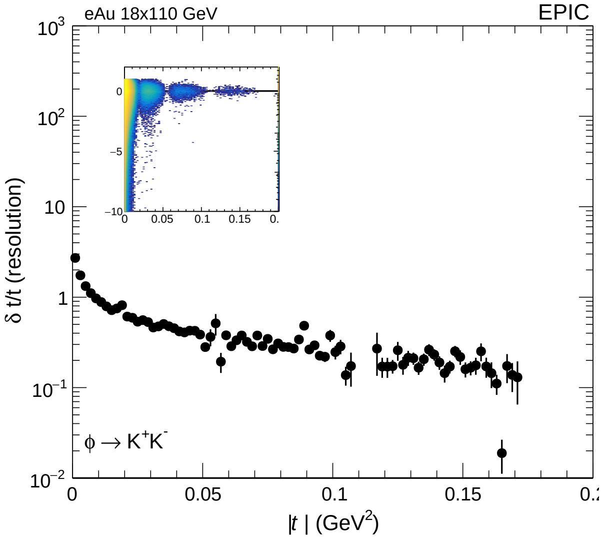
eAu 18x110 GeV
Sartre, EPIC
$1<Q^2<10$ GeV^2, $0.01 < y < 0.85$
$|y_\phi|<3.5$, $|M_{inv} - M_\phi| < 0.02$ GeV
ϕ_{MC} 6,801,697 evts
$\phi_{L: RECO}$ 6,801,697 evts
$\phi_{\theta_{max}=\pi/12: RECO}$ 242,725 evts
normalization: $\frac{\pi}{2} / \theta_{max}$
$\phi \rightarrow K^+K^-$
counts
$|t|$ [GeV/c]^2

Summary

- New technique shows promising results
  - Projection ($|t_{\hat{n}}|$)
  - Wedge cut (θ_{max})
- To do:
  - Add BeAGLE simulation to analysis
  - Separate coherent and incoherent events
  - Continue with correcting
  - Transformation

Backup Slides

$|t|$ resolution



Method A Derivation

Start with method E: Conservation of 4-momenta

$$\begin{aligned} P_e + P_A &= P_{e'} + P_{A'} + P_{\mathrm{VM}} \\ P_{A'} &= P_e + P_A - P_{e'} - P_{\mathrm{VM}} \\ t &= (P_A - P_{A'})^2 \end{aligned}$$

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

Assume small scatting angle for incoming/outgoing ion: $P_{A_{//}} \approx P_{A'_{//}}$

$$\begin{aligned} t &= [p_T(A) + p_{//}(A) - p_T(A') + p_{//}(A')]^2 \\ &= [p_T(A) - p_T(A')]^2 \end{aligned}$$

Assume incoming e/ion traveling along beamline: $p_T = p \sin\theta \approx 0$

$$t = [p_T(A) - p_T(e) - p_T(A) + p_T(e') + p_T(VM)]^2$$

$$\boxed{t = [p_T(e') + p_T(VM)]^2}$$

Method L Derivation

Lightcone variables:

$$\begin{aligned} p_{\pm} &= p_E \pm p_z \\ p^2 &= p_+ p_- - p_T^2 = m^2 \end{aligned} \tag{1}$$

Correct outgoing ion: $P_{A'} = (p_x, p_y, p_z, p_E)$

$$\begin{aligned} p_+ &= p_E + p_z \\ p_- &= p_E - p_z \\ p_+ &= (m^2 + p_T^2)/p_- \\ p_- &= (m^2 + p_T^2)/p_+ \end{aligned} \tag{2}$$

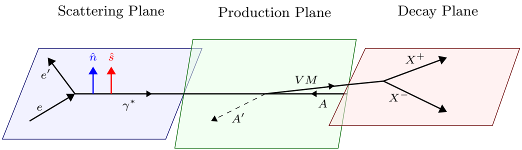
$$\boxed{P_{A'}^{\mathrm{corr}} = [p_x, p_y, (p_+ - p_-)/2, (p_- + p_+)/2]}$$

Future Plan

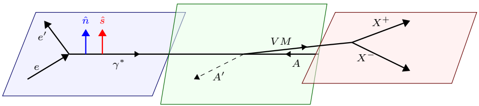
- Utilize transversely polarized e^- beams
  - *e^- spin is perpendicular to its momentum*
- Exploit decay pattern of VM wrt $\hat{n}$
  - Determine the *fraction of coherently produced VMs*

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

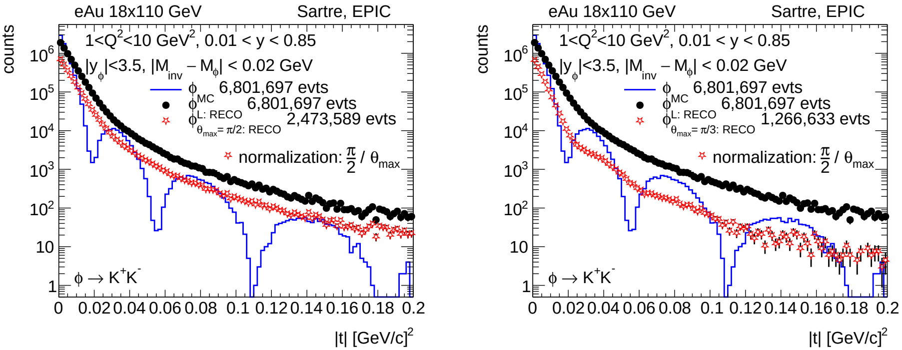
Incoherent Events

- 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 with different θ_{max}



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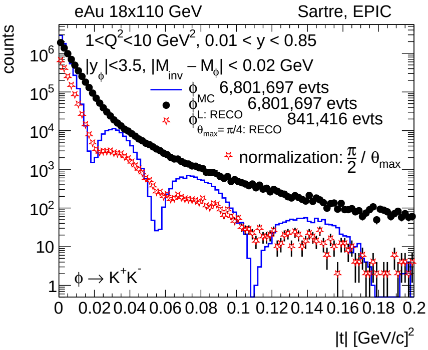

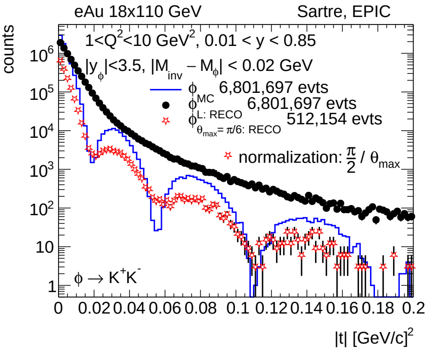

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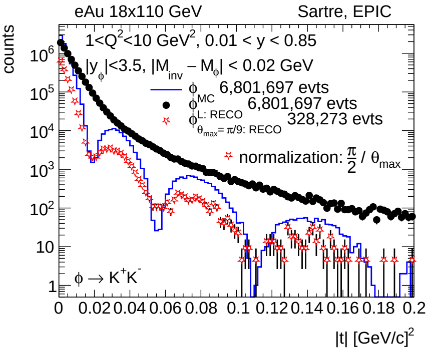

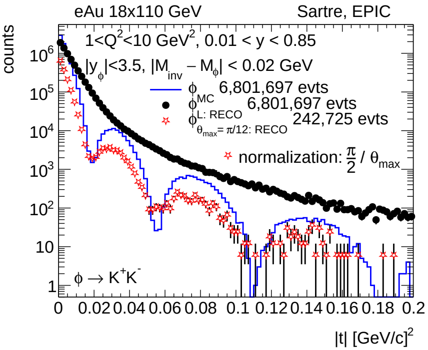

More plots with different θ_{max}