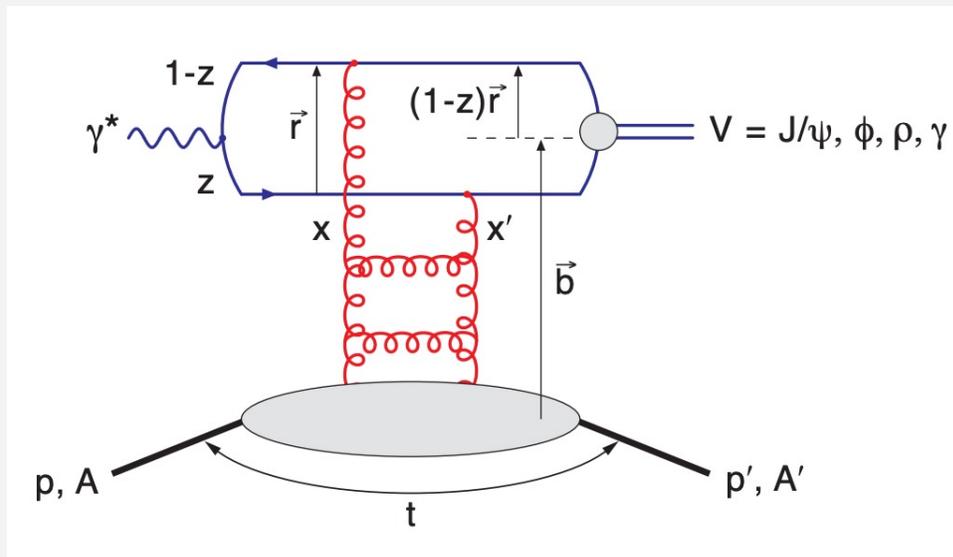


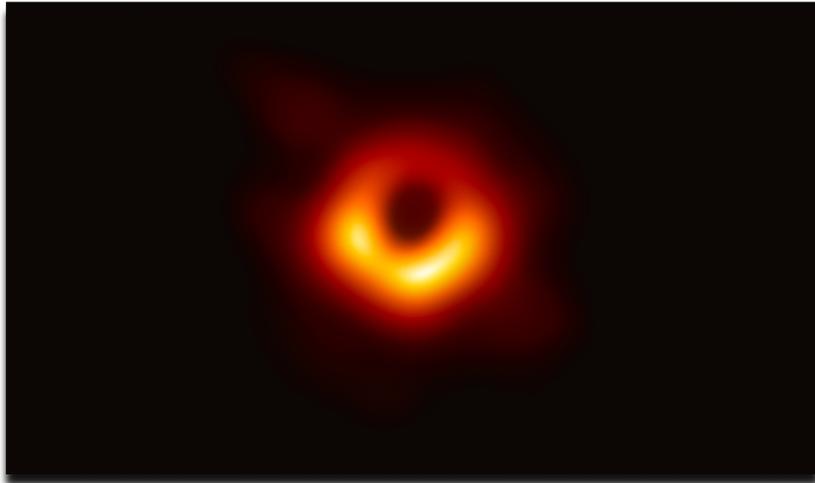
Measuring the spatial gluons distribution in nuclei with ePIC at the EIC



Kong Tu (BNL)
for the ePIC Collaboration

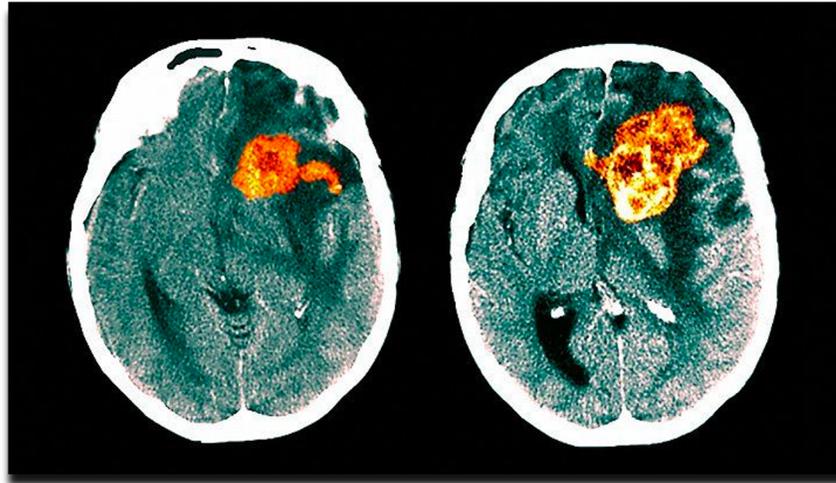
Seeing is believing - the power of *imaging*

38 billion km ($\sim 10^{12}$ m)



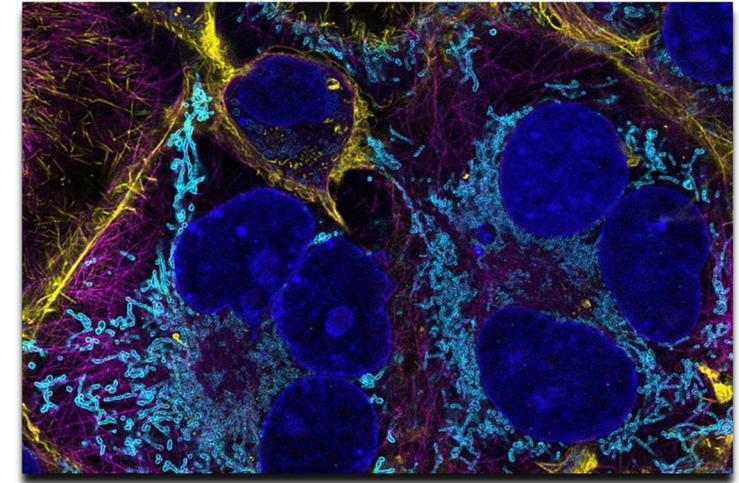
First-ever image of a black hole -
Event Horizon Telescope

a few centimeter ($\sim 10^{-2}$ m)



CT scan sequence of a patient
with a *glioblastoma*.

10-100 nanometer ($\sim 10^{-9}$ m)



3D images of myelin - the
insulation coating our nerve fibres

Astronomical scale

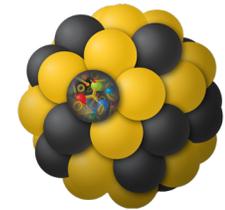
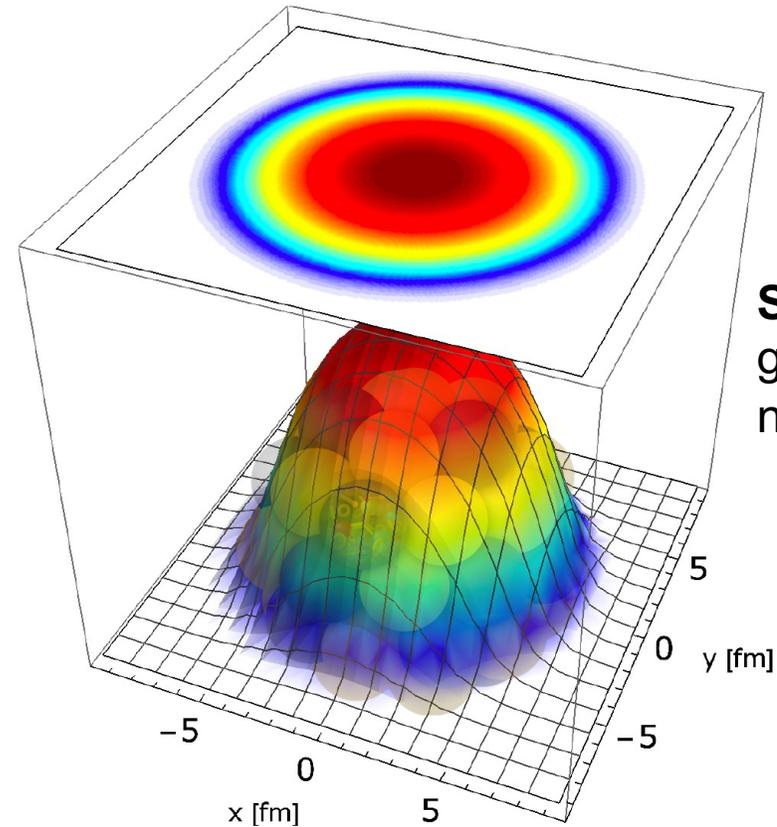
microscopic scale

Imaging: one of the most convincing scientific methods to understand our nature!

Gluon spatial distribution of heavy nuclei

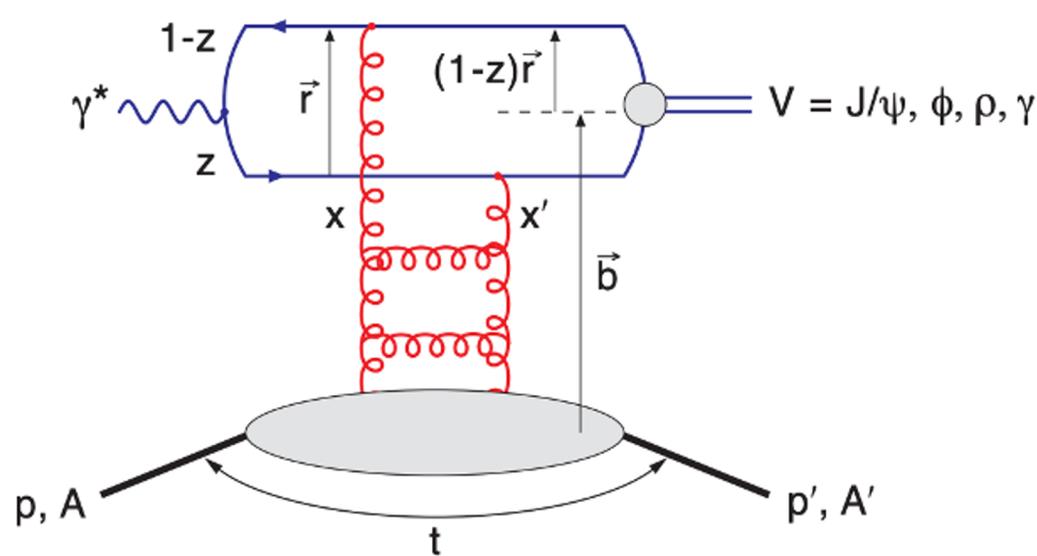
Understanding how the **gluons are distributed in nuclei** will significantly advance our understanding:

- Nuclear `binding` in high energy where gluons are dominated.
- Probing gluon **saturation dynamics** in terms of gluon spatial distribution.
- Nuclear matter radius vs charge radius.



Sartre model:
gluon density profile in gold nucleus (made by A. Kumar)

Exclusive and diffractive vector meson production



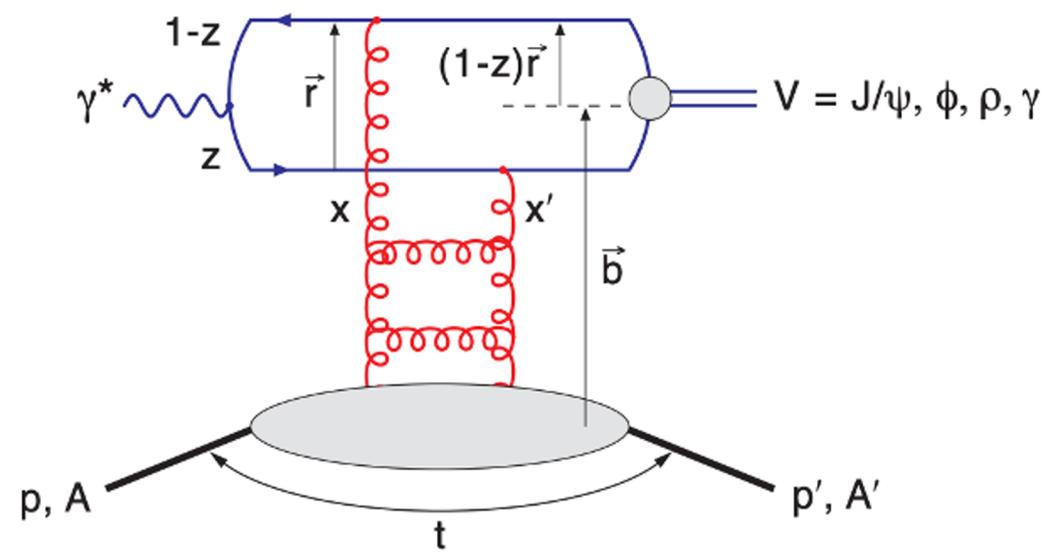
At NLO, things may look differently [arXiv:2203.11613]

Momentum (t) and position (b) are conjugate variable, and can be related by Fourier Transform:

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

$$\Delta = \sqrt{-t}$$

Exclusive and diffractive vector meson production



At NLO, things may look differently [arXiv:2203.11613]

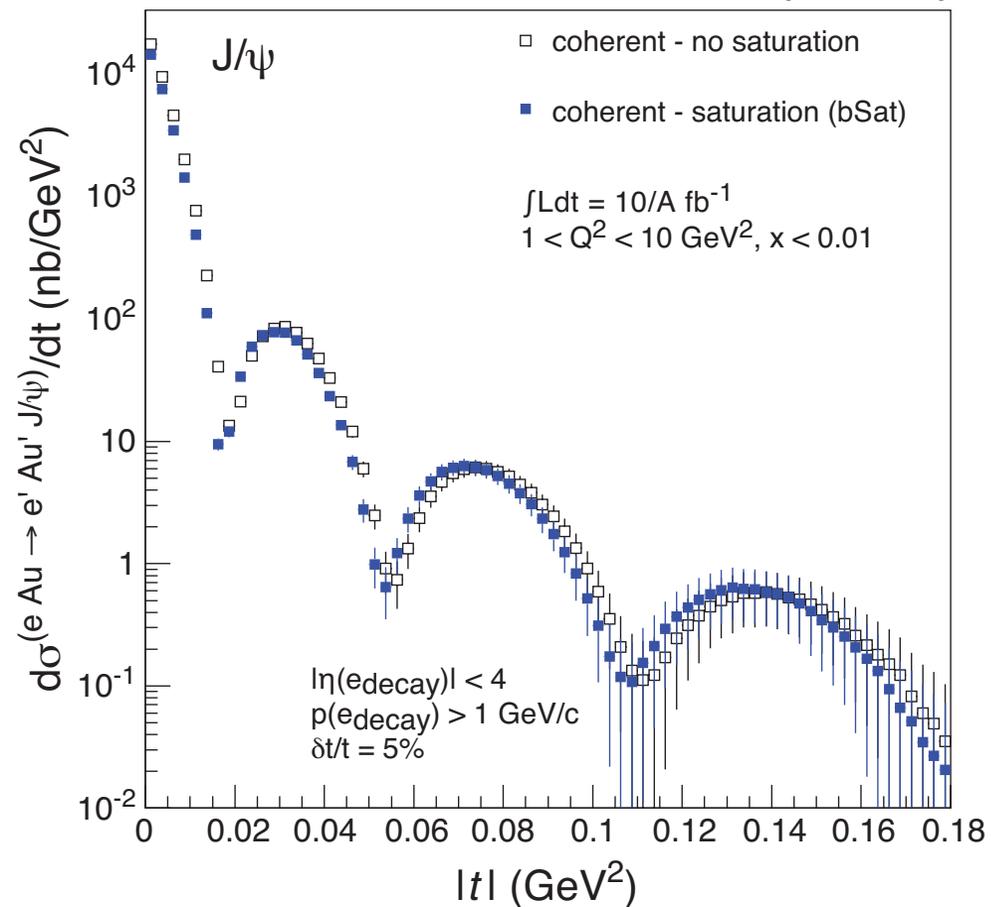
See talk later from STAR UPCs on incoherent process (Mar 30, 2023, 2:40 PM)

Coherent (target stays intact)	Incoherent (target breaks up)
Average nuclear parton density	Event-by-Event parton density fluctuations
Momentum transfer (t) and transverse spatial position (b) are Fourier transforms of each other;	

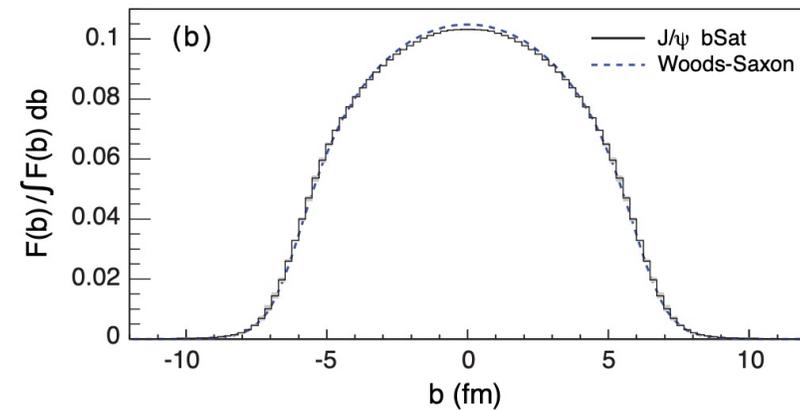
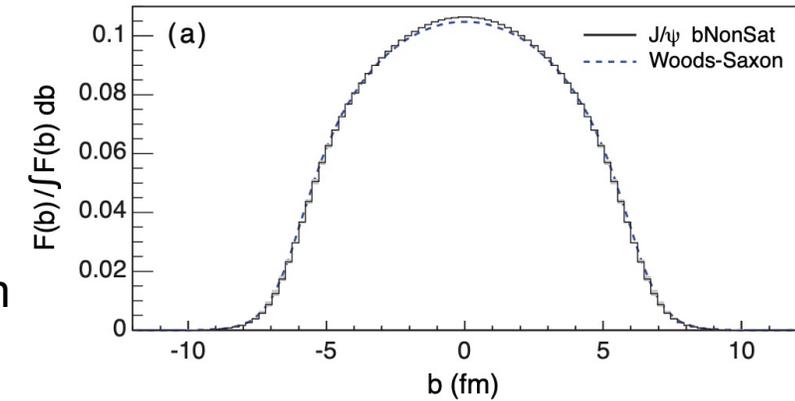
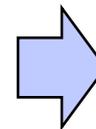
A sensitive probe to the **gluon** density, spatial distributions, and their fluctuations.

EIC White Paper: golden channel

EIC WP, Toll & Ullrich (2012)

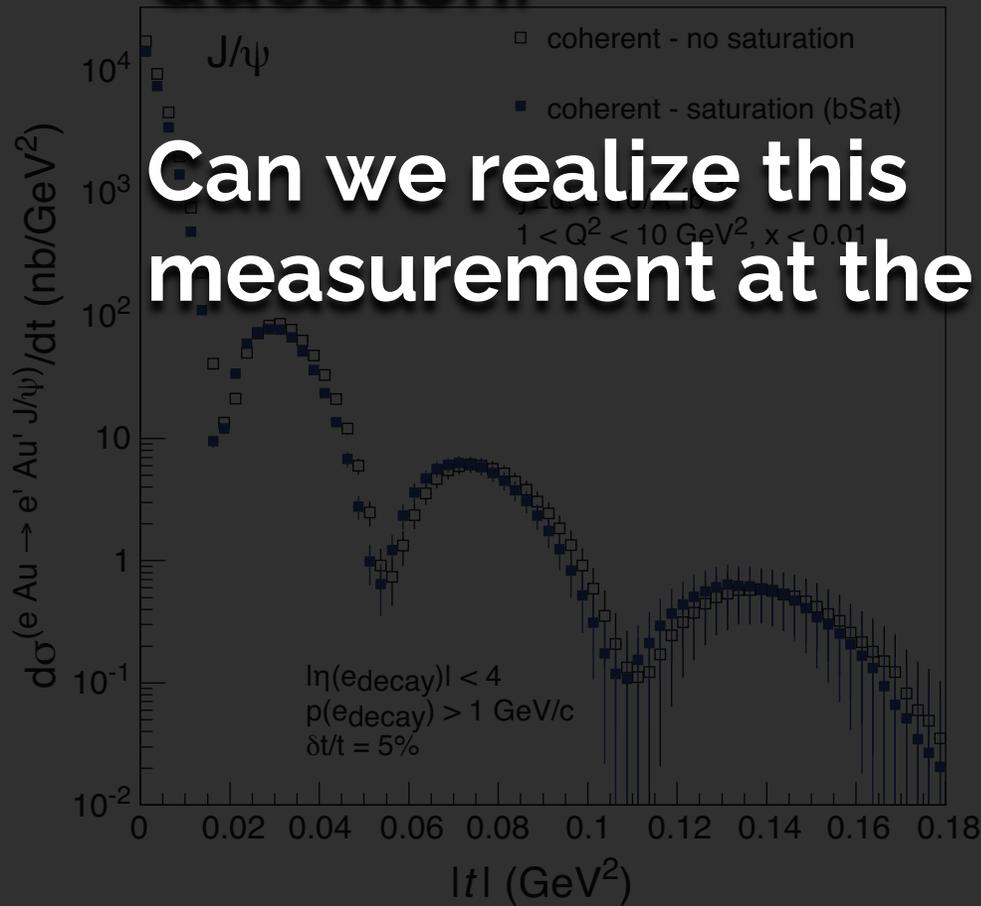


Fourier Transform

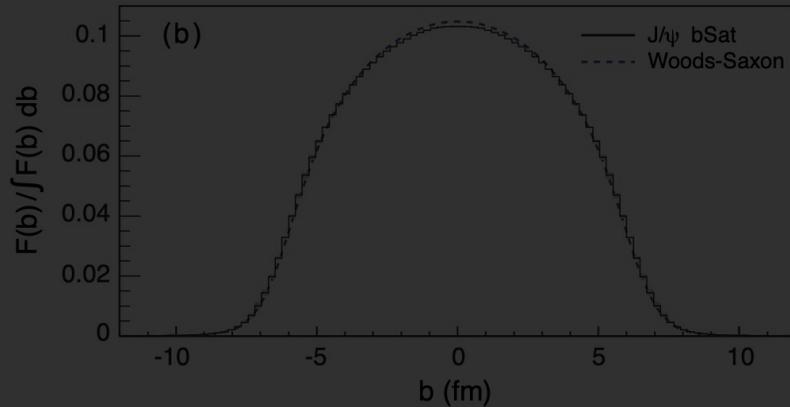
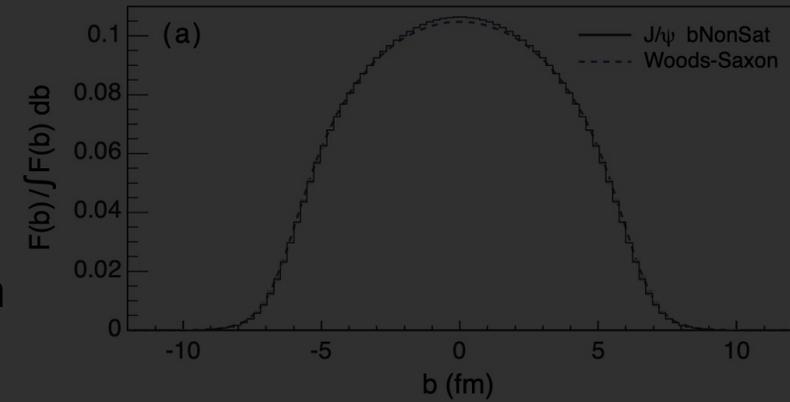


EIC White Paper: golden channel

Question: **Can we realize this measurement at the EIC?**



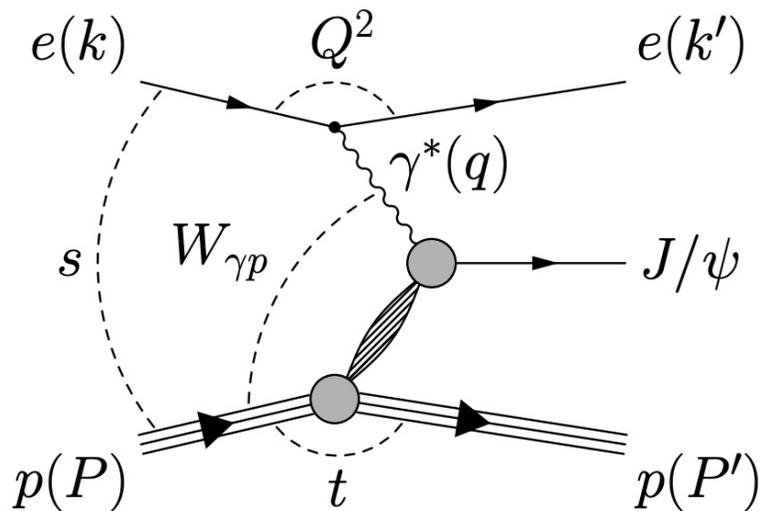
Fourier Transform



Reconstruction method of $-t$

- Method Exact (E): $-t = -(\mathbf{p}_e - \mathbf{p}_{e'} - \mathbf{p}_{VM})^2 = -(\mathbf{p}_{A'} - \mathbf{p}_A)^2$
- Method Approximate (A) (UPCs) $-t = (p_{T,e'} + p_{T,VM})^2$
- Method with **exclusivity corrected** (L): $-t = -(\mathbf{p}_{A',\text{corr}} - \mathbf{p}_A)^2,$

where $\mathbf{p}_{A',\text{corr}}$ is constrained by exclusive reaction.



Best method concluded from the EIC Yellow Report* is with **exclusivity corrected**:

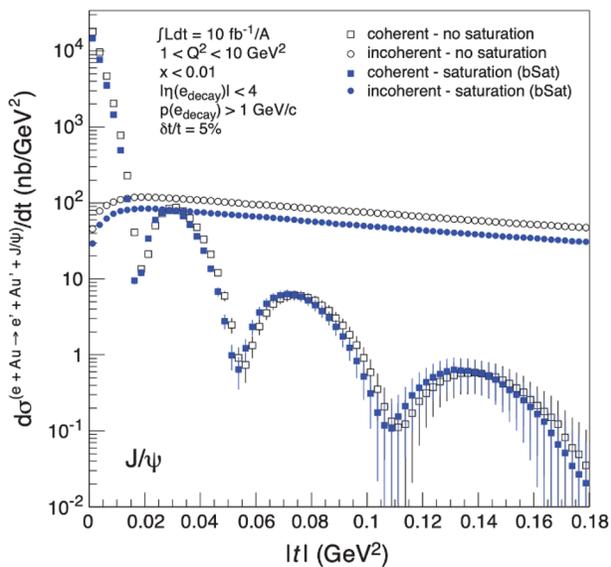
- Insensitive to beam effects, e.g., angular divergence and momentum spread.
- More precise than Method A for electroproduction

* also known as **Method L** in the Yellow Report

Diffractive VM timeline

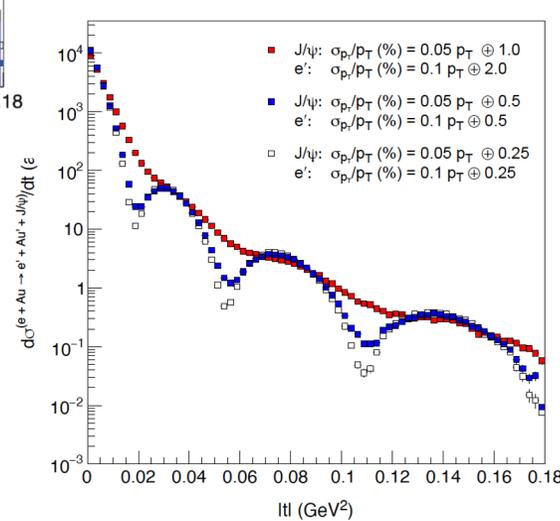
2012 2019 2021 2022 Time

intense debate; some were caused by software differences

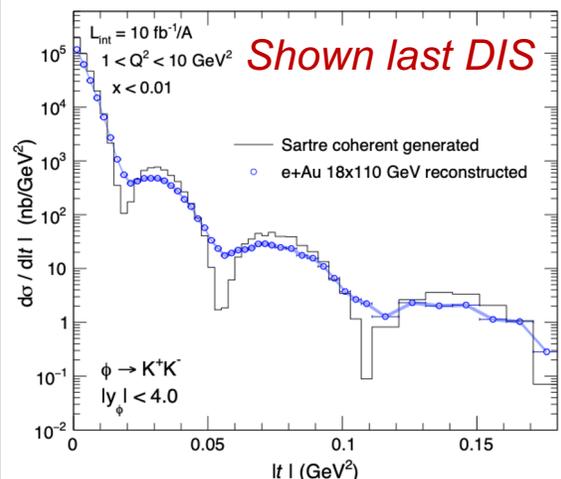
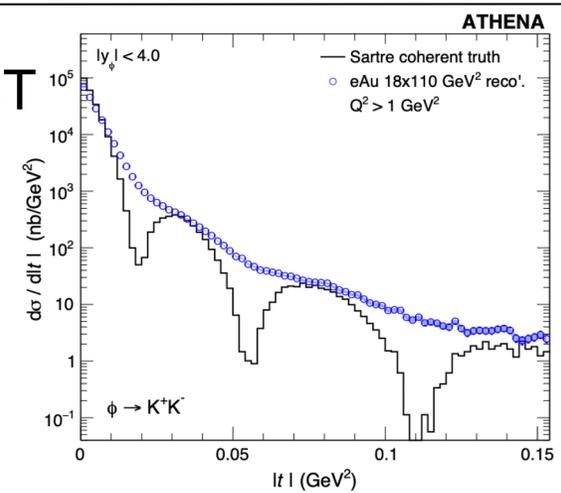


EIC White paper

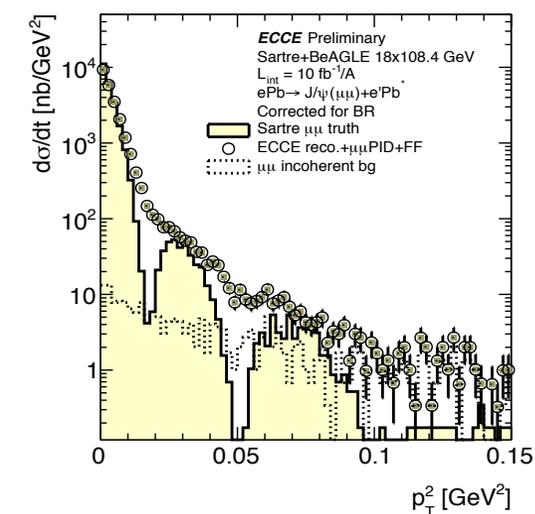
EIC Yellow Report



ATHENA 3T (DD4HEP)

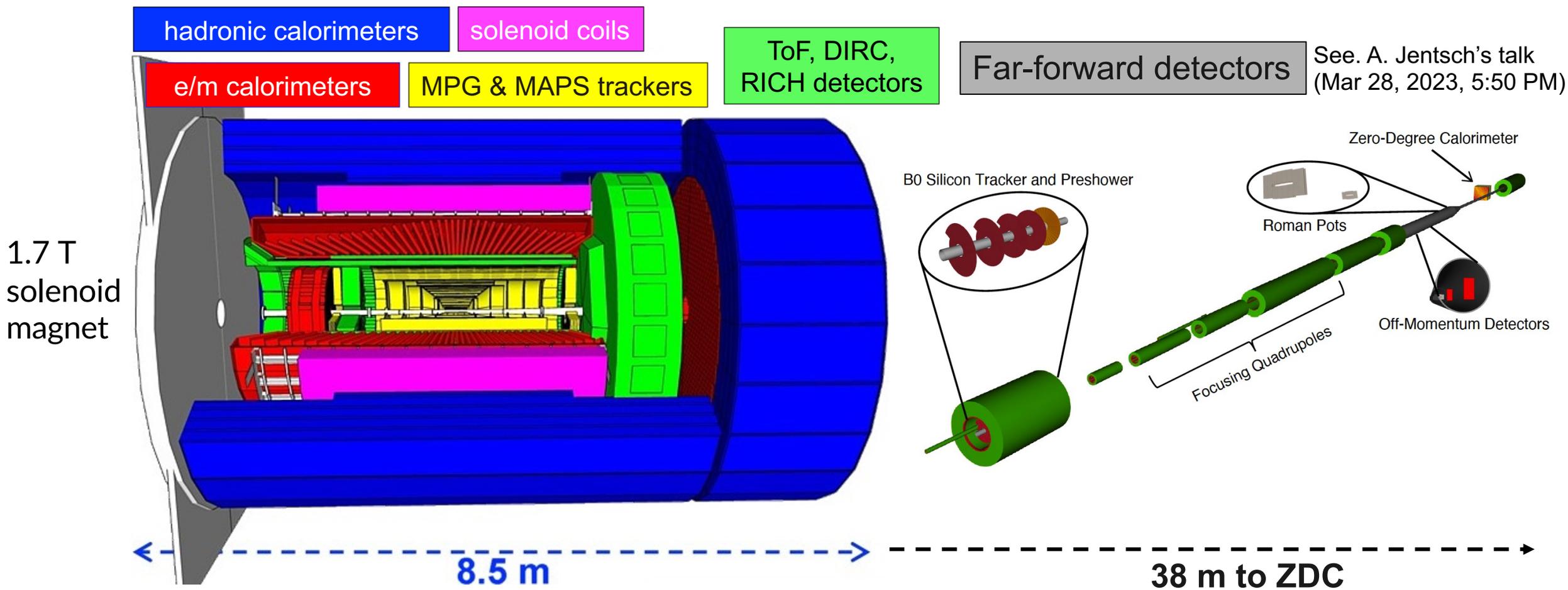


ATHENA 3T + 1% E reso. EMCal (DELPHESES)



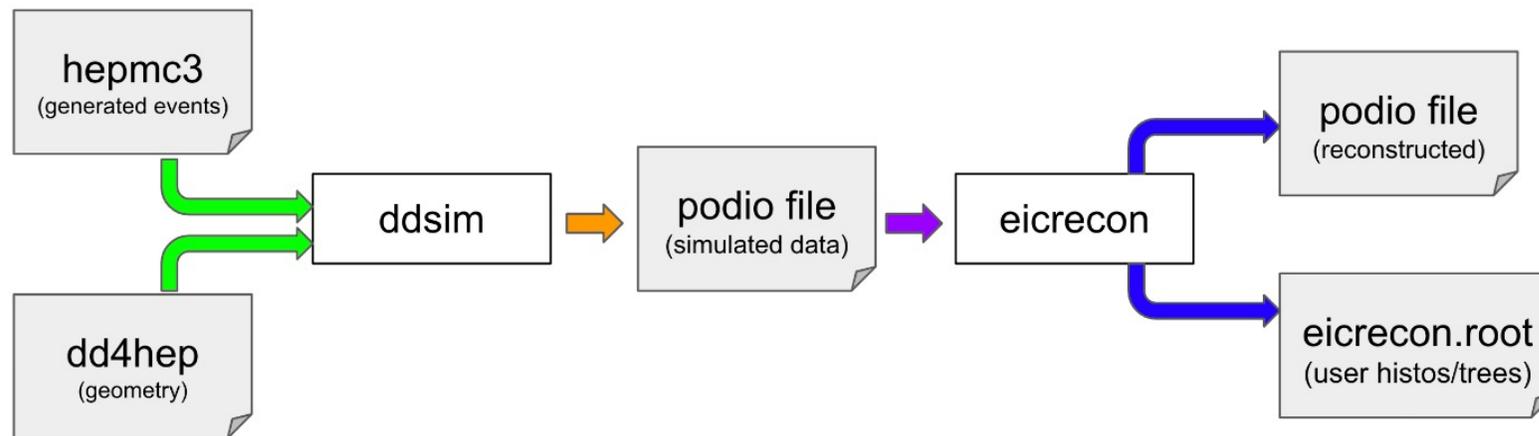
ECCE 1.5T +EMCal (Fun4all)

ePIC experiment at the EIC



Modern software and simulation

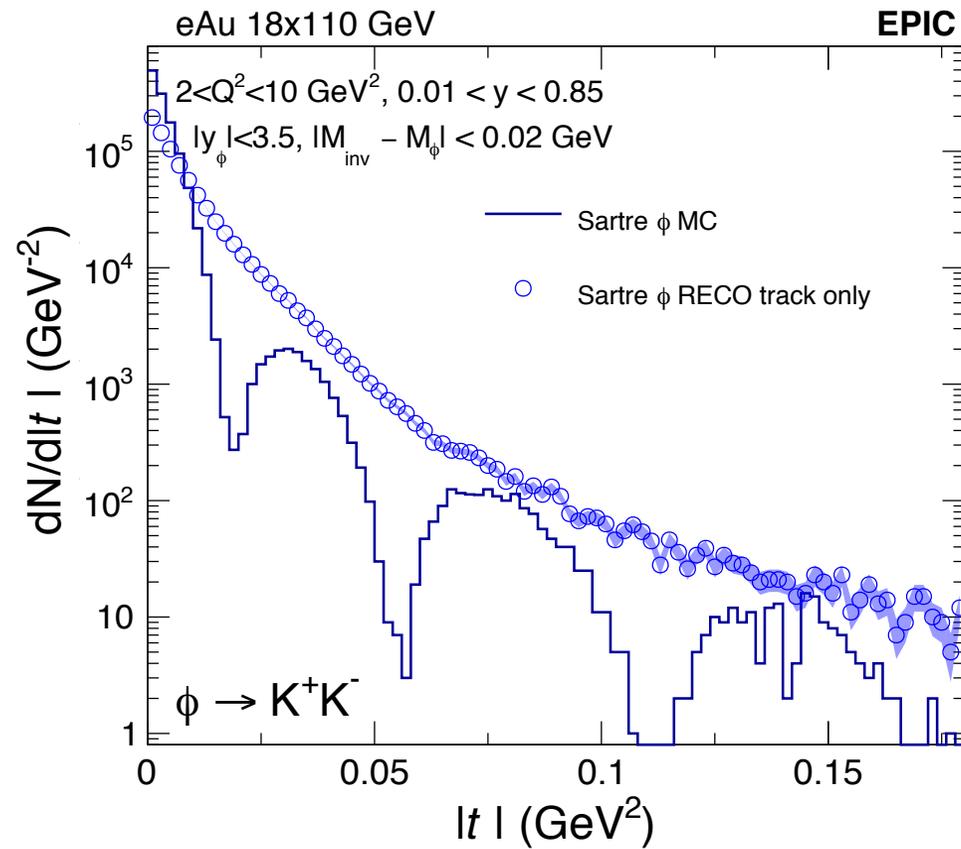
- dd4hep detector geometry description (see EPIC detector, <https://github.com/eic/epic>)
- ddsim for simulation/digitization
- edm4eic data structure defined with podio and edm4hep (<https://github.com/eic/EDM4eic>)
- EICrecon reconstruction framework based on JANA (<https://github.com/eic/EICrecon>)
- Reconstructed output → Ready for physics!



(We are constantly recruiting for software enthusiasts 😊)

Results I

Legend details:
• Track only: e' , $\phi \rightarrow KK$, all from tracking

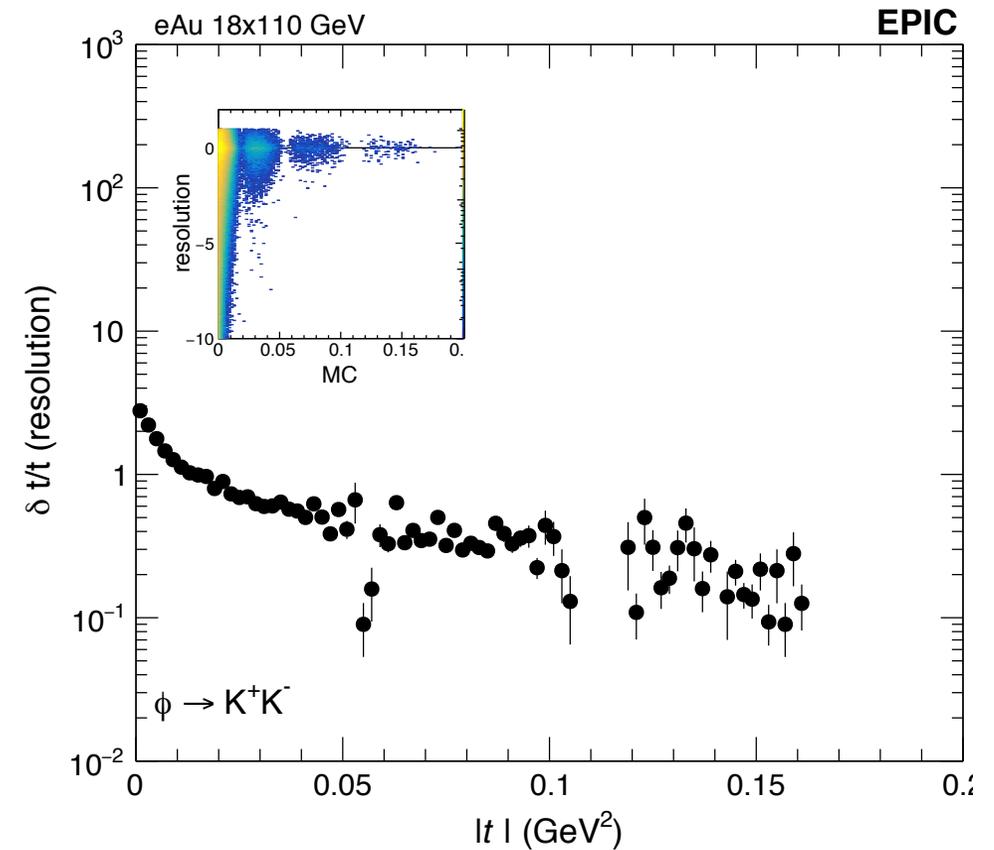
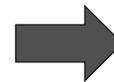
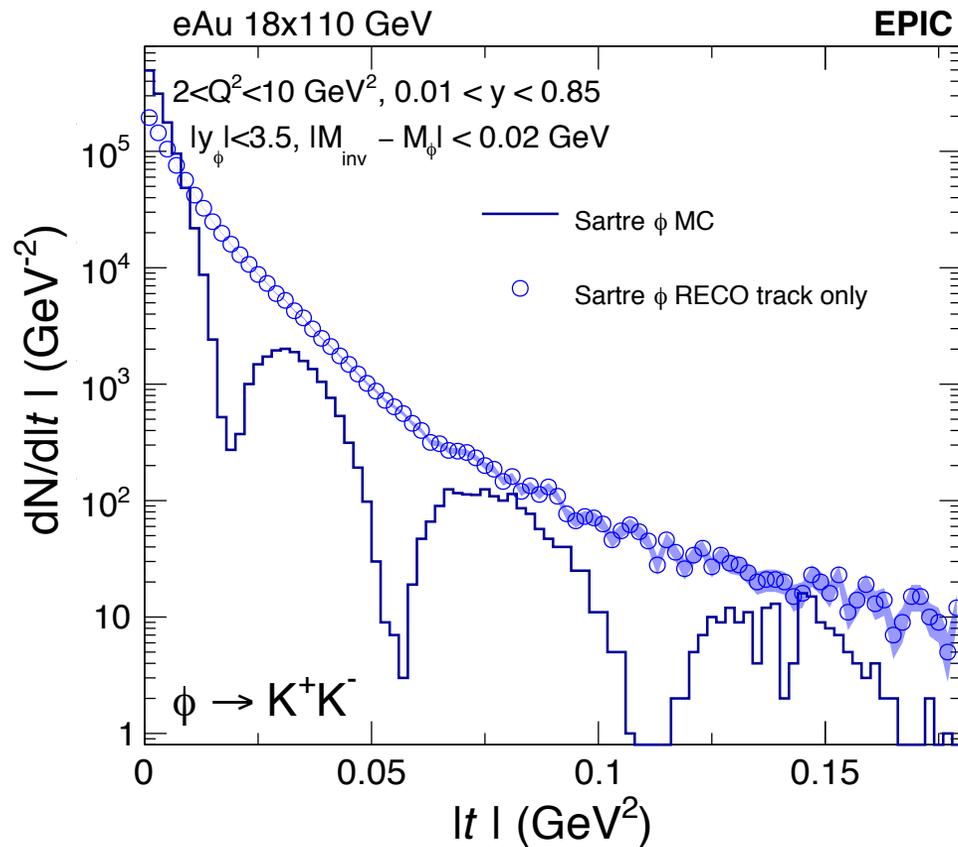


Results I

Legend details:

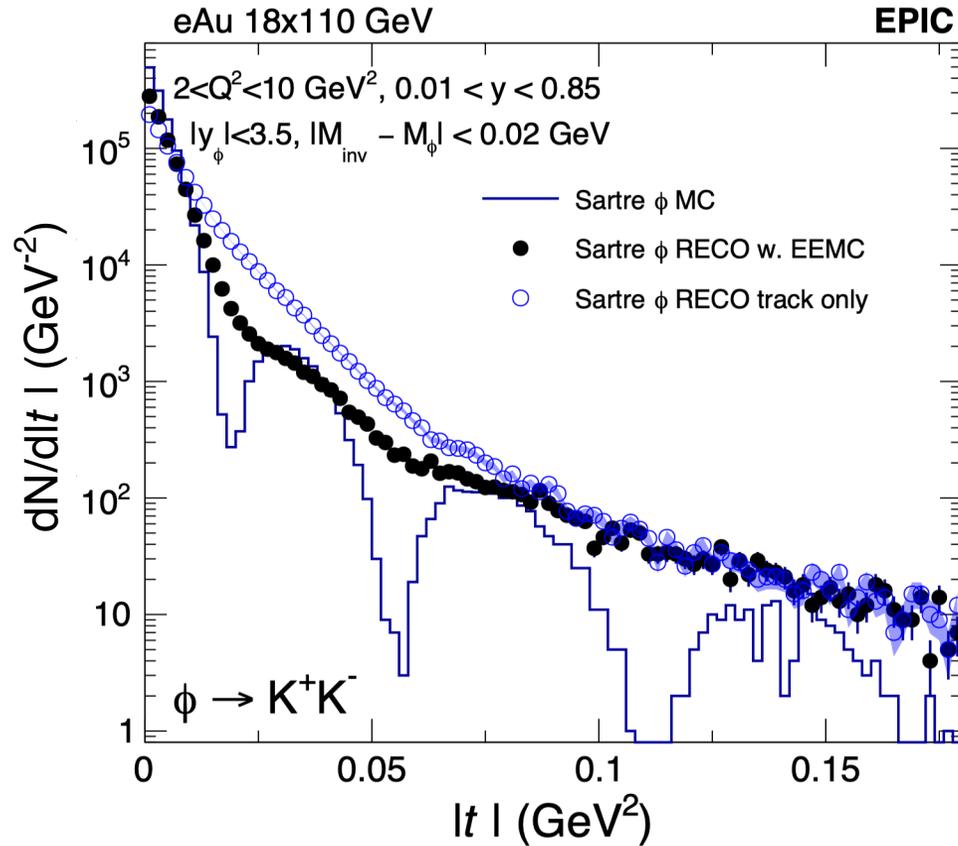
- Track only: e' , $\phi \rightarrow KK$, all from tracking

p (p_T) resolution of the scattered electron in this region $\sim 4\%$



Tracking p resolution directly impact the $|t|$ resolution; even 3T field cannot do it, let alone 1.7T

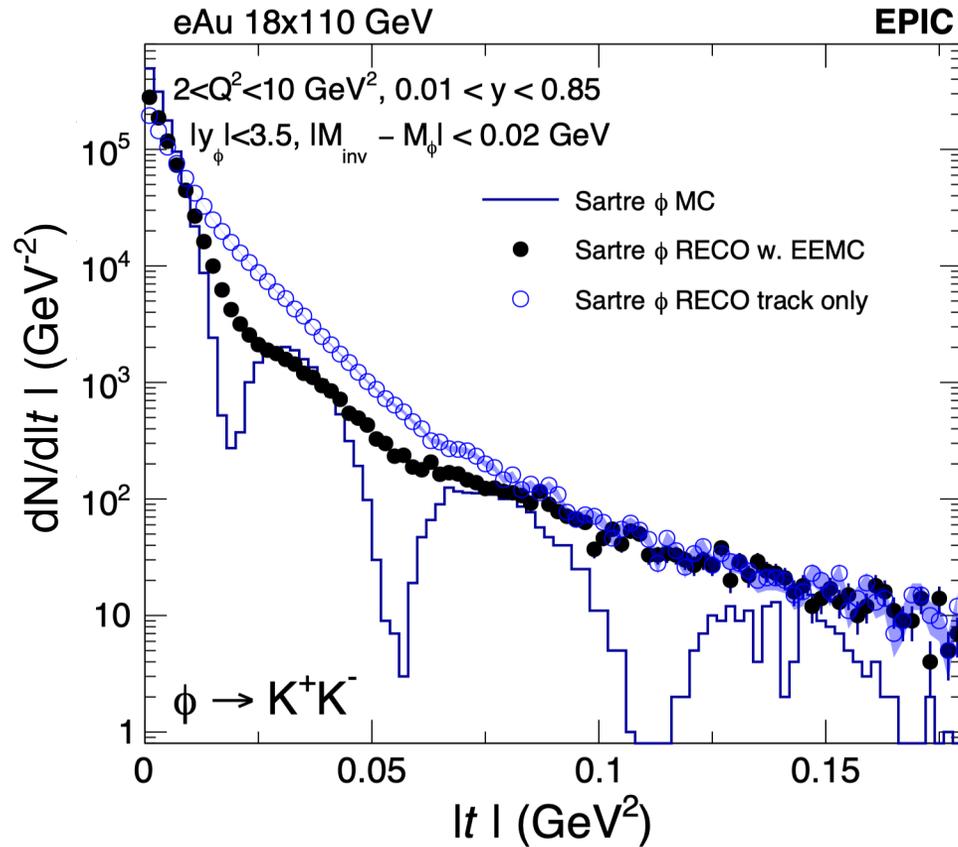
Results II



Legend details:

- w. EEMC: electron energy from EEMC, electron mass (PDG), angle (eta,phi) from tracking; $\phi \rightarrow KK$ from tracking.
- Track only: e' , $\phi \rightarrow KK$, all from tracking

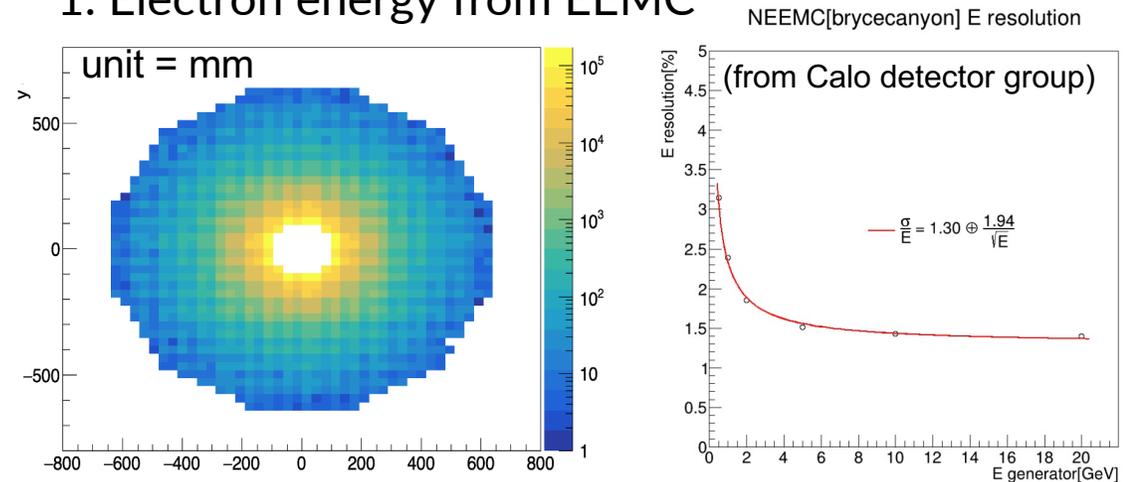
Results II



Legend details:

- w. EEMC: electron energy from EEMC, electron mass (PDG), angle (eta,phi) from tracking; $\phi \rightarrow KK$ from tracking.
- Track only: e' , $\phi \rightarrow KK$, all from tracking

1. Electron energy from EEMC



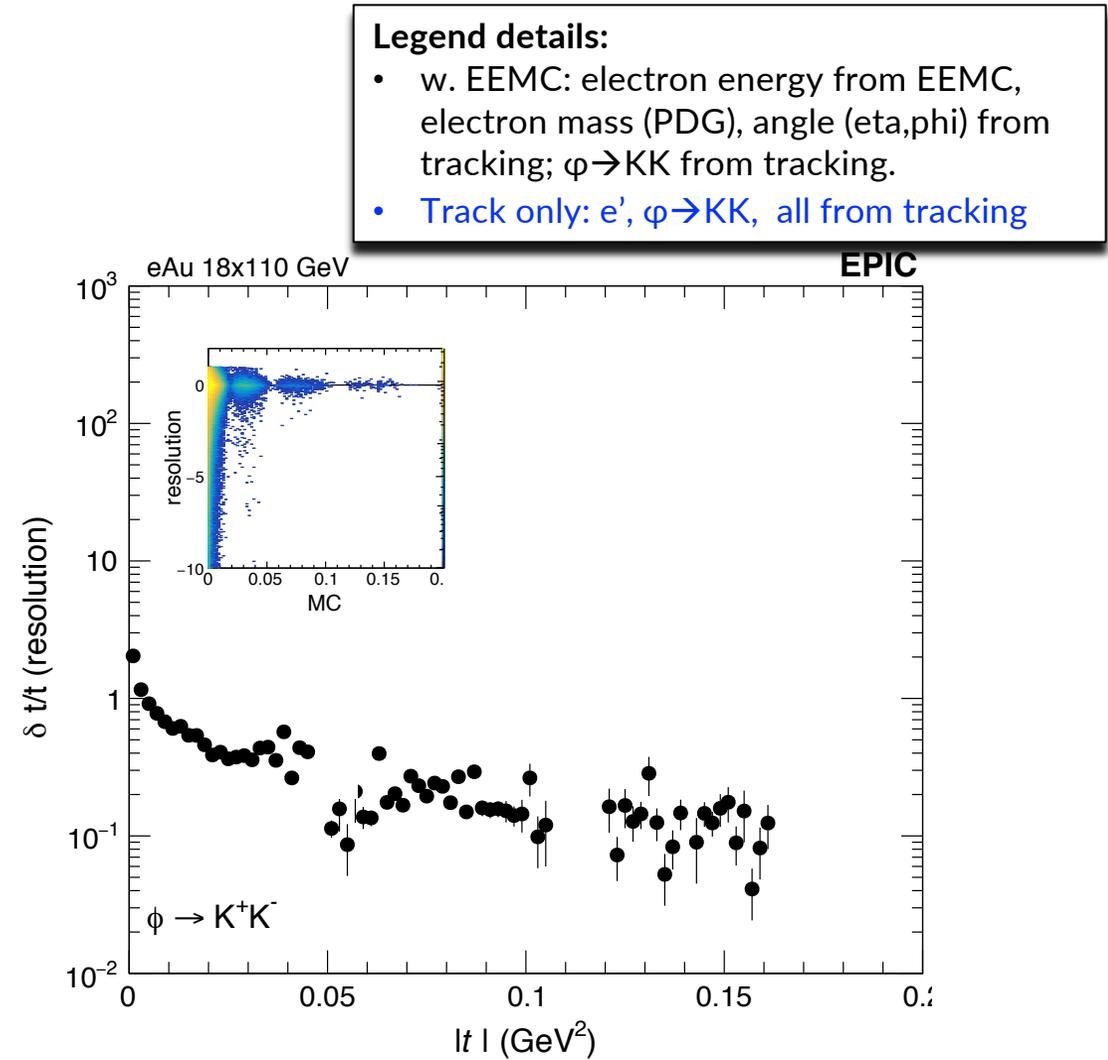
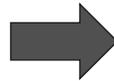
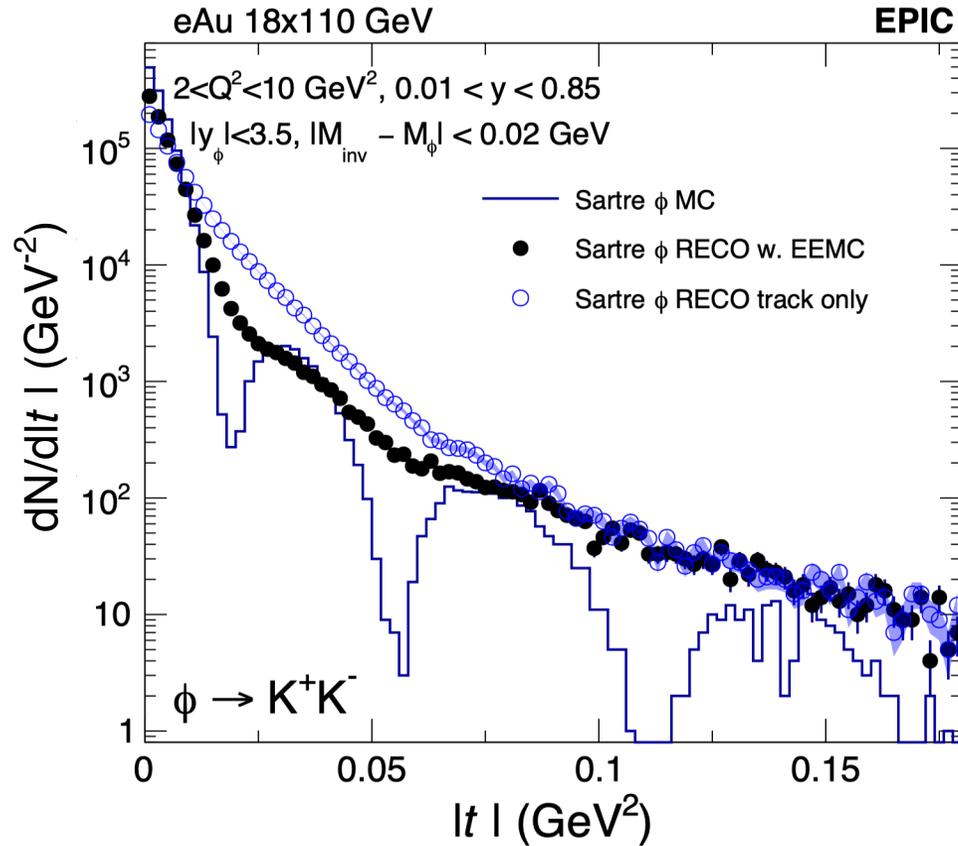
20x20mm crystal

~ 1.5% energy resolution

2. Assume electron mass (PDG)

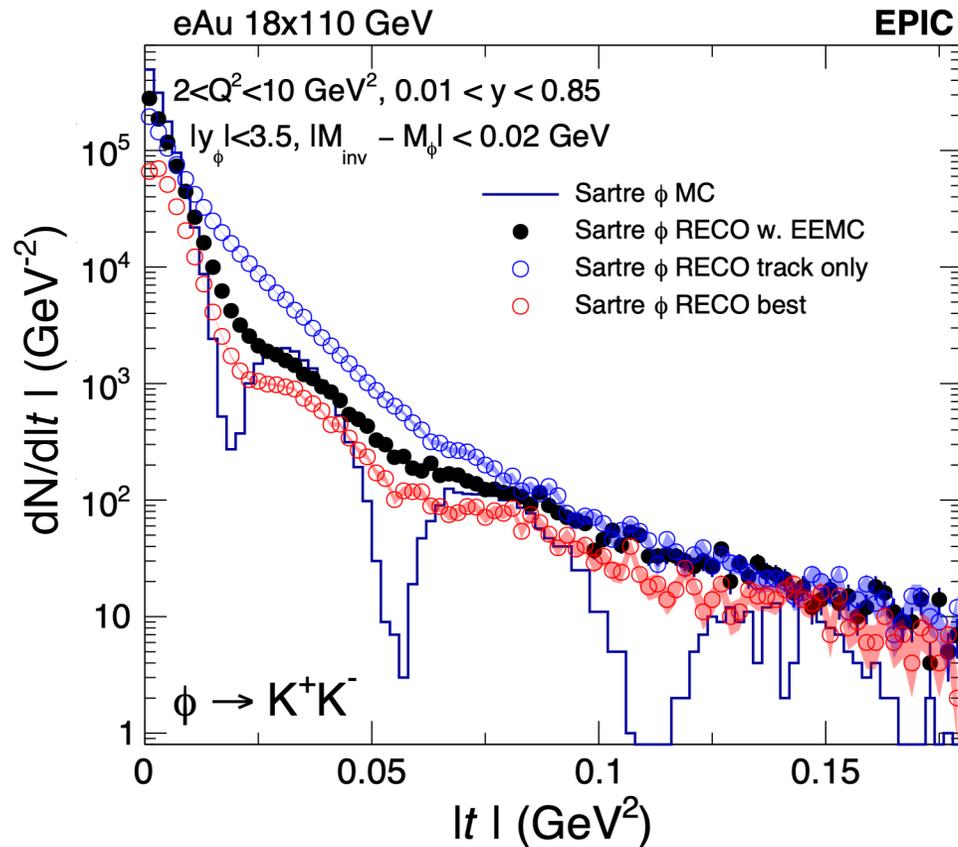
3. Angle (position) from tracking
 (better resolution than from cluster position)

Results II



Some huge improvements have been seen with the EEMC

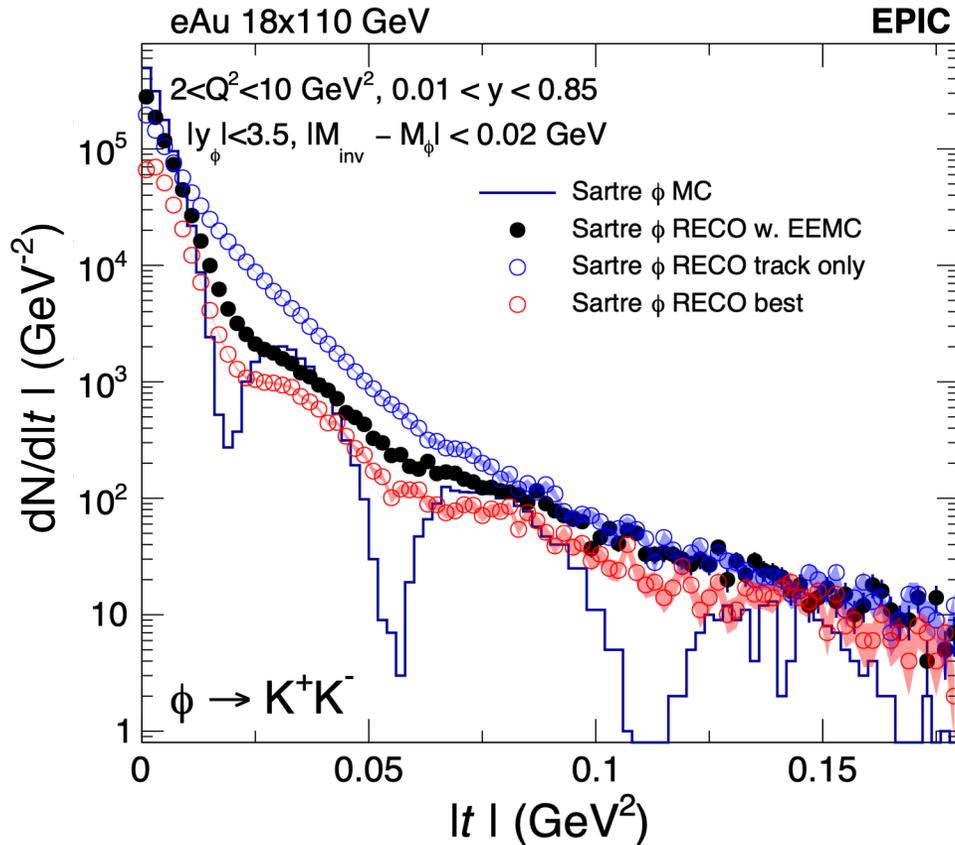
Results III



Legend details:

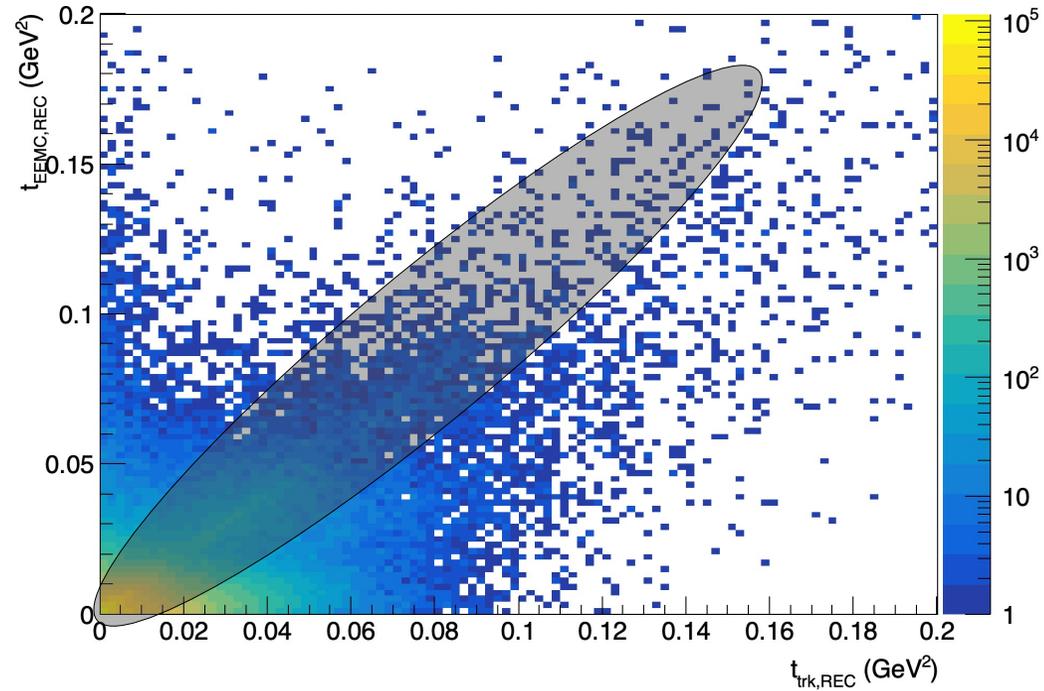
- w. EEMC: electron energy from EEMC, electron mass (PDG), angle (eta,phi) from tracking; $\phi \rightarrow KK$ from tracking.
- Track only: e' , $\phi \rightarrow KK$, all from tracking
- Best: average of the above 2 E-by-E.

Results III



Legend details:

- w. EEMC: electron energy from EEMC, electron mass (PDG), angle (eta,phi) from tracking; $\phi \rightarrow KK$ from tracking.
- Track only: e' , $\phi \rightarrow KK$, all from tracking
- Best: average of the above 2 E-by-E.



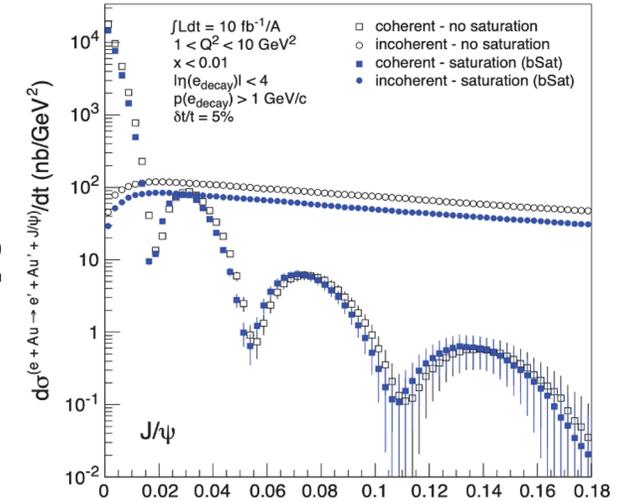
Improvements from *algorithm*:

- The two methods can be used together to further improve the $|t|$ resolution.

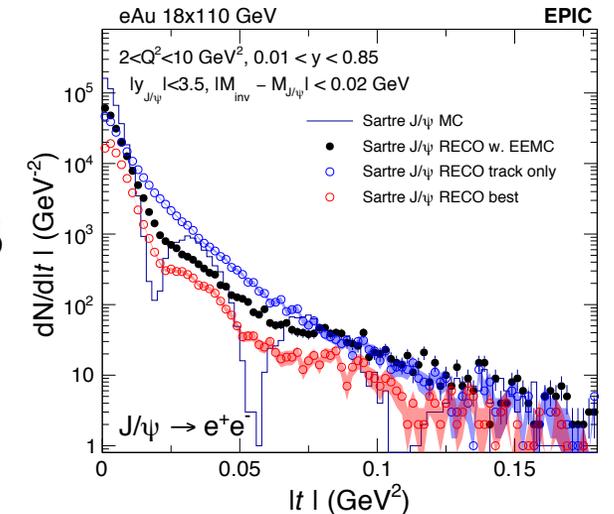
Summary - a dream came true

- Diffractive Vector-Meson is a powerful experimental tool to study the nucleon and nuclear structure, e.g., **gluon spatial distributions**.
- From 2022 DIS to 2023 DIS:
 - **We achieved:** First full **ePIC simulation** in an **unified and modern software framework**.
 - **Next in ePIC:** Incoherent background, where the nucleus breaks up. Veto on far-forward particles.
- Will be further **optimizing** the algorithm and detector performance – full speed towards the TDR.

2012



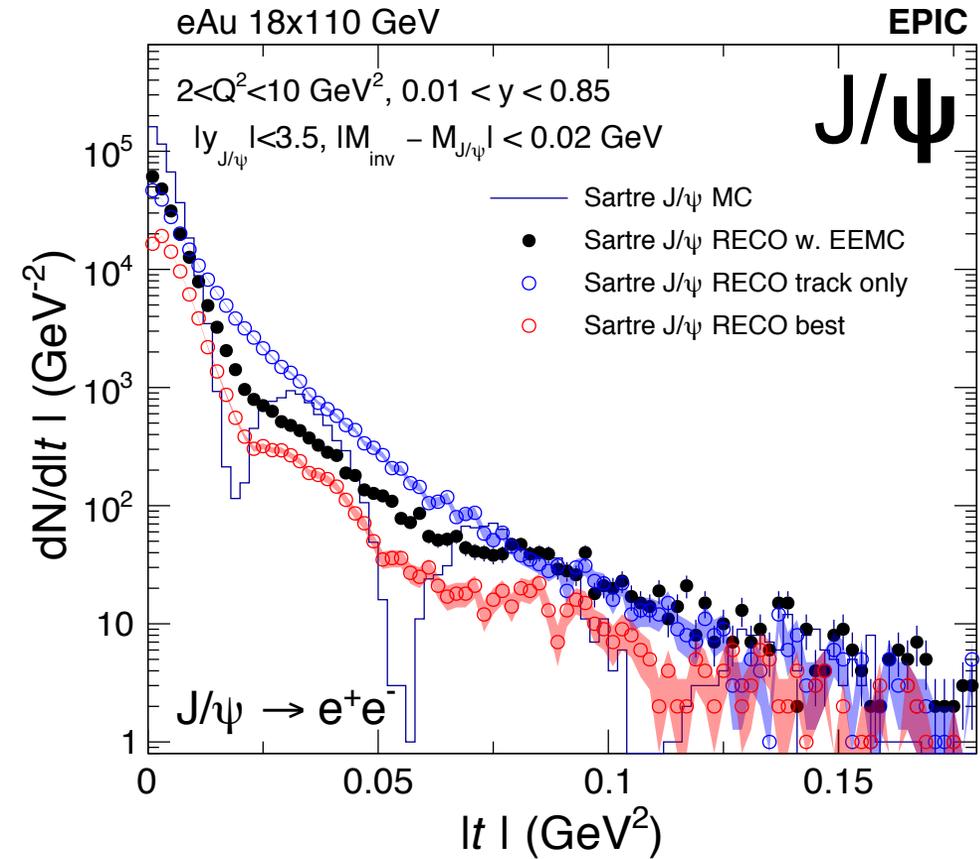
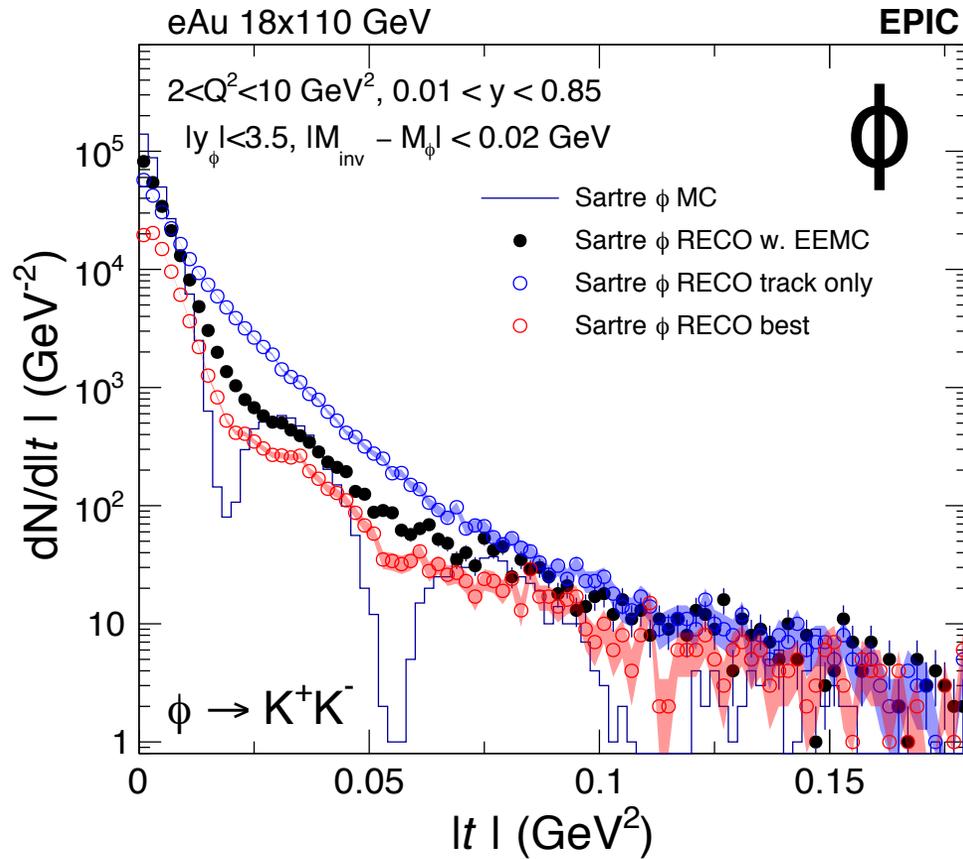
2023





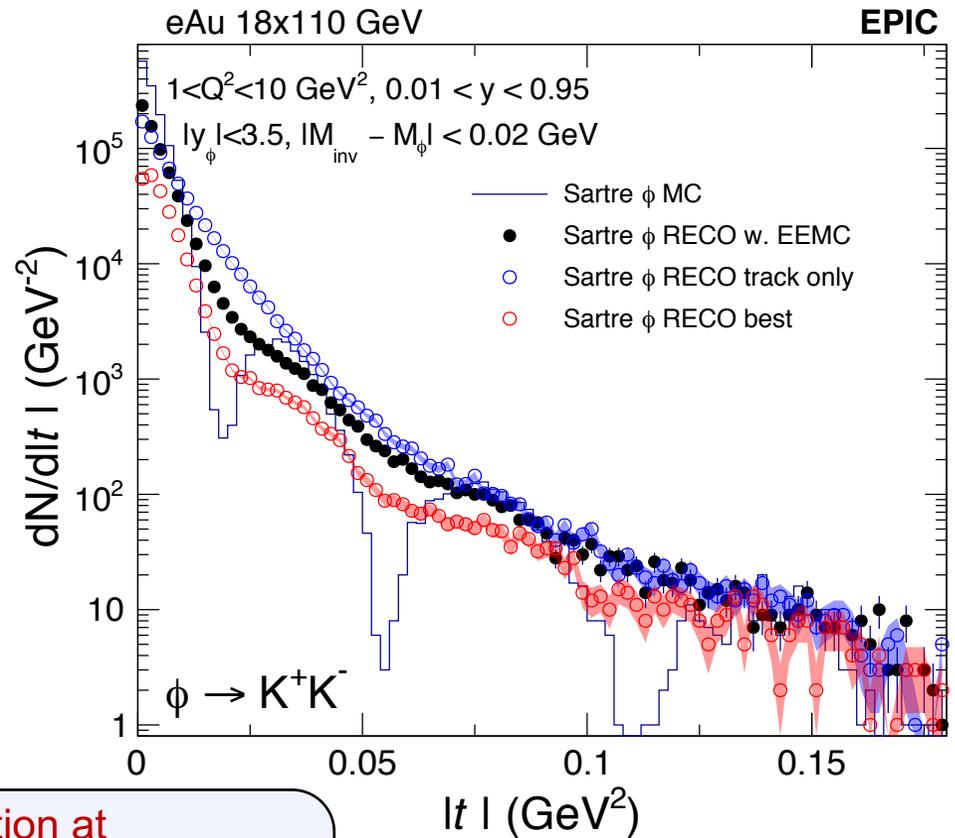
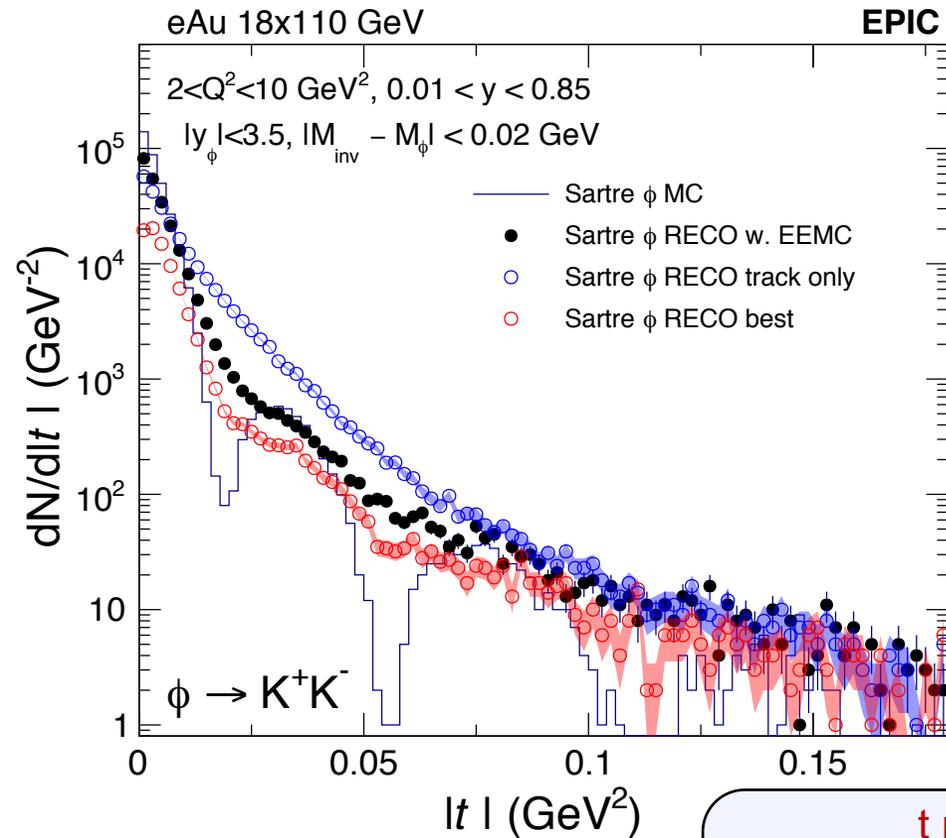
Backup

ϕ vs J/ψ



Similar performance for ϕ and J/ψ particle. Bottle neck is scattered electron

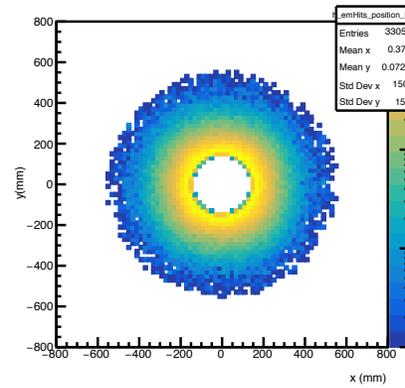
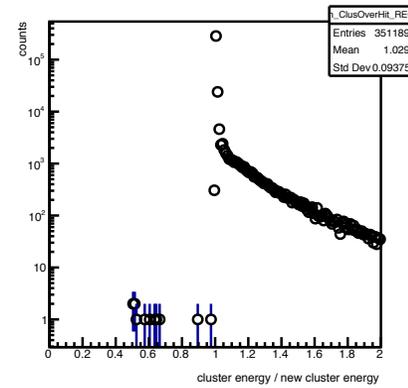
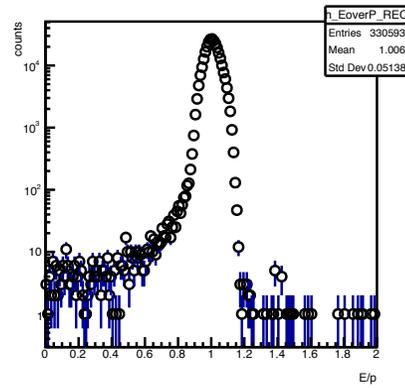
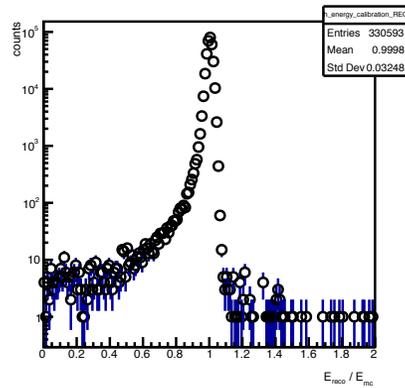
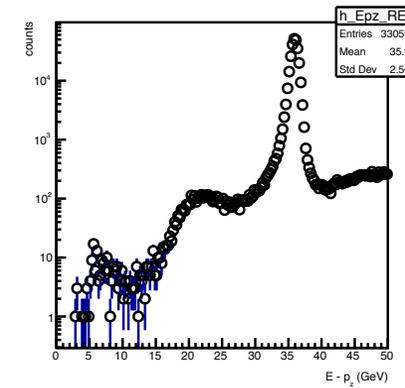
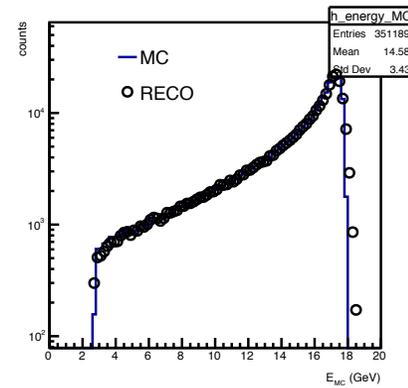
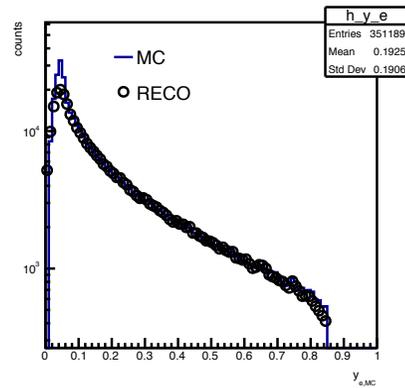
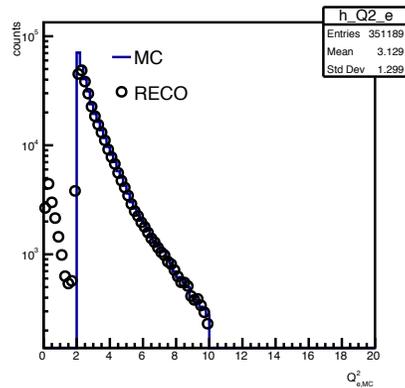
$Q^2 > 2$ vs $Q^2 > 1$ GeV²



	t resolution at		
	1 st dip	2 nd dip	3 rd dip
$Q^2 > 2$	37.33%	10.79%	4.28%
$Q^2 > 1$	45.05%	15.19%	3.54%



DIS control $Q^2 > 2 \text{ GeV}^2$





DIS control $Q^2 > 1 \text{ GeV}^2$

