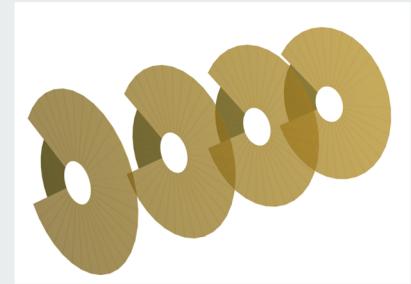
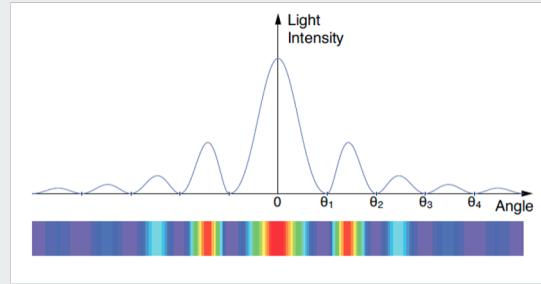
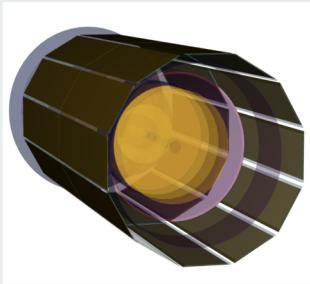
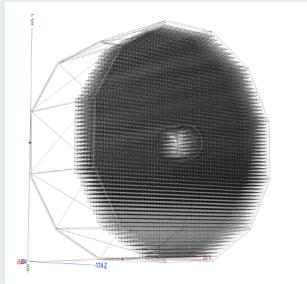


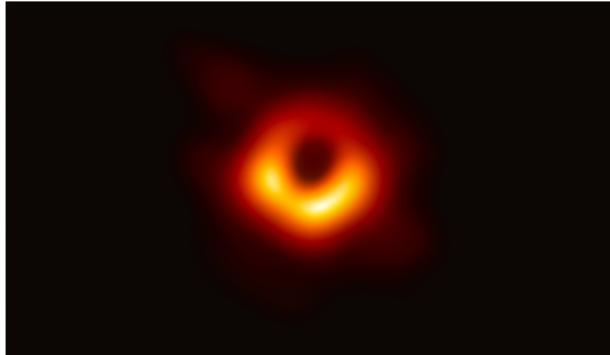
Exclusive Vector-Meson in eA collisions at the EIC



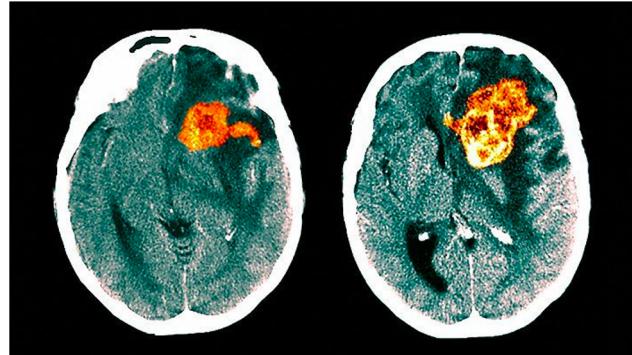
Kong Tu
BNL
Dec 20, 2022

Seeing is believing - the power of *imaging*

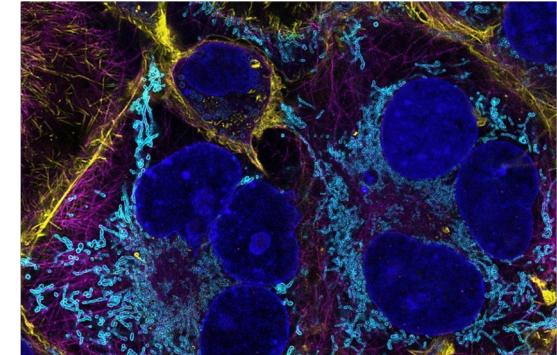
38 billion km ($\sim 10^{12}$ m)



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



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



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

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

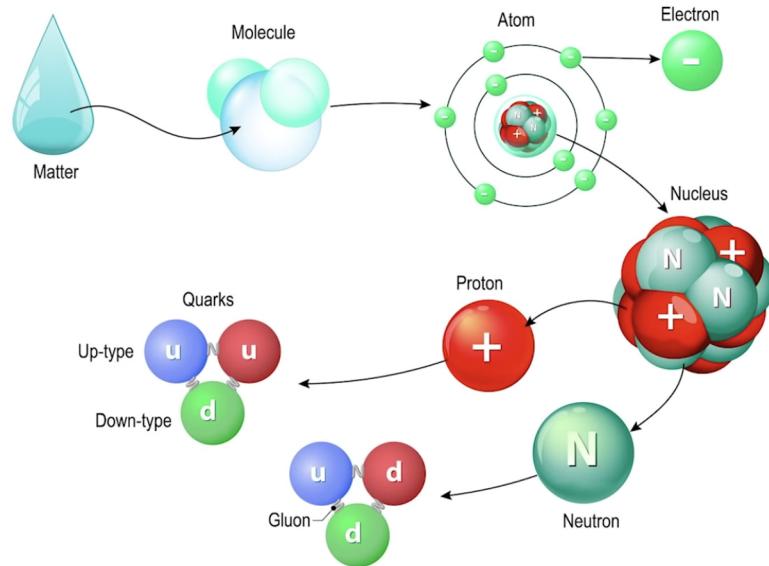
3D images of myelin - the
insulation coating our nerve fibres

Astronomical scale

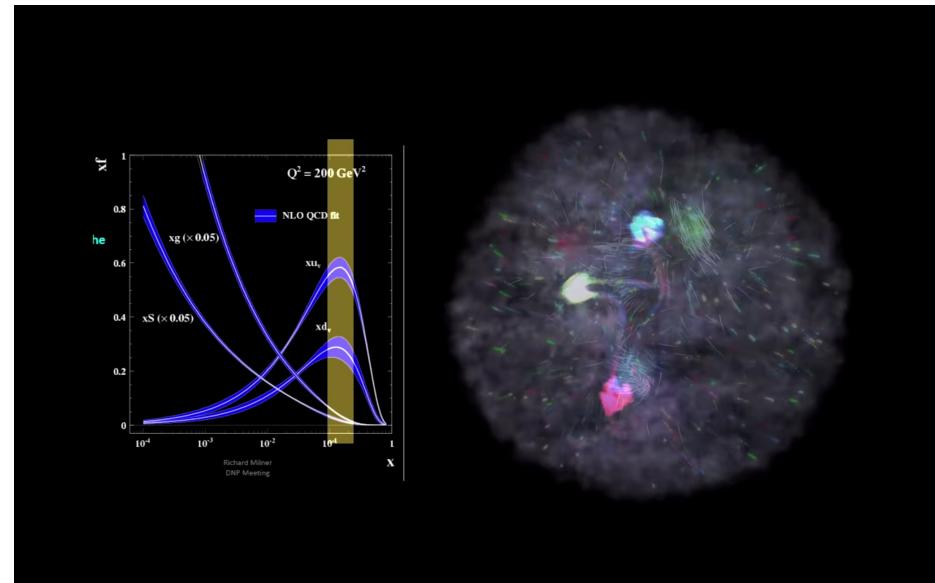
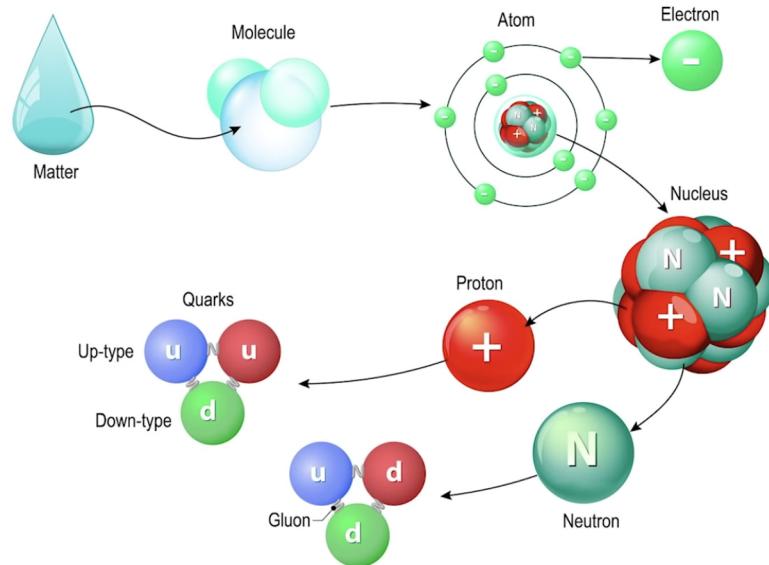
microscopic scale

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

Going even smaller - building block of visible matter

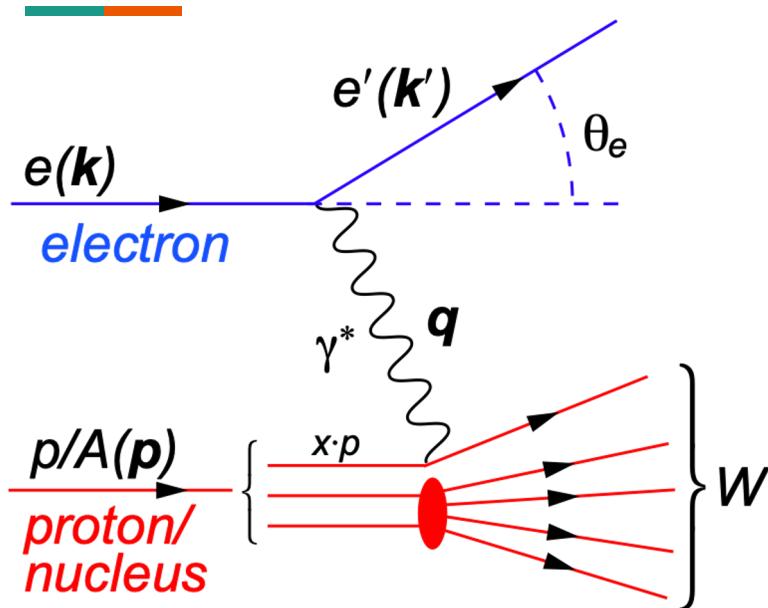


Going even smaller - building block of visible matter

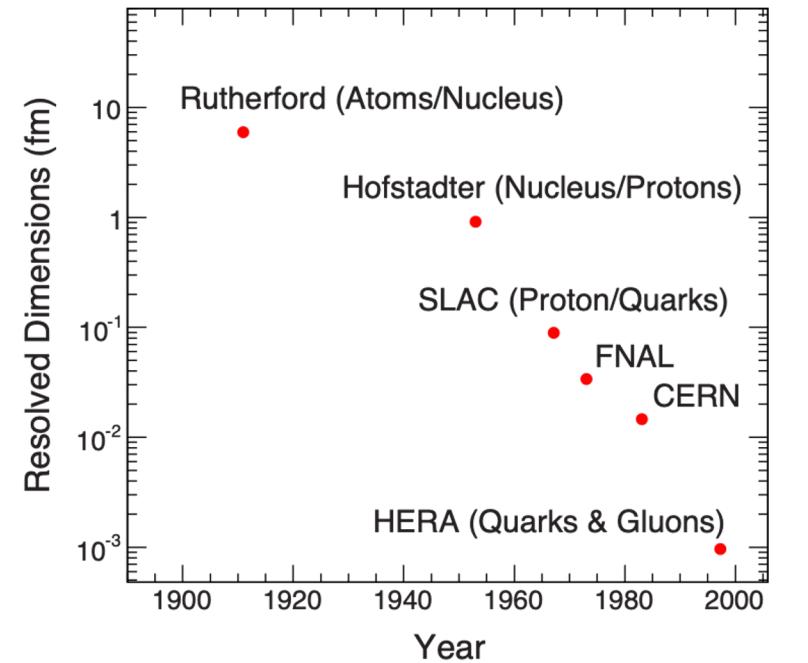


Visualize the proton! (<https://news.mit.edu/2022/visualizing-proton-through-animation-film-0425>)

Femtoscope - deep inelastic scattering (DIS)



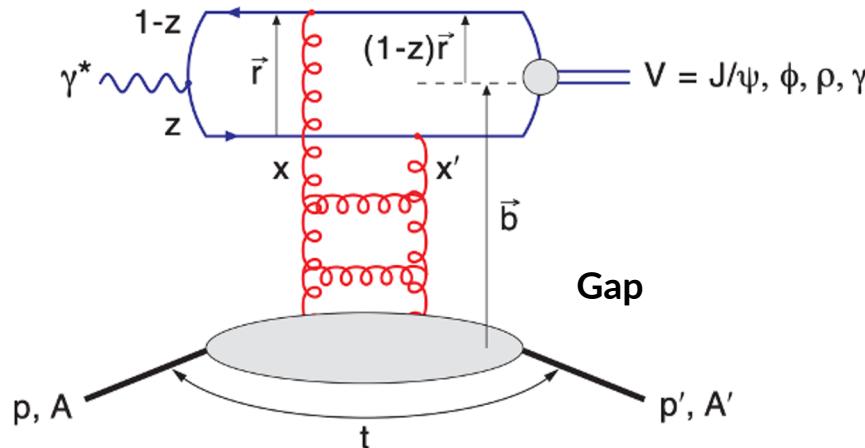
1. Resolution $\sim Q^2 = -q^2$
2. Momentum fraction $\sim x_{bj} = \frac{Q^2}{2Pq}$



$\sim 10^{-3} - 1$ femtometer (10^{-15} m)

Exclusive and diffractive vector meson production

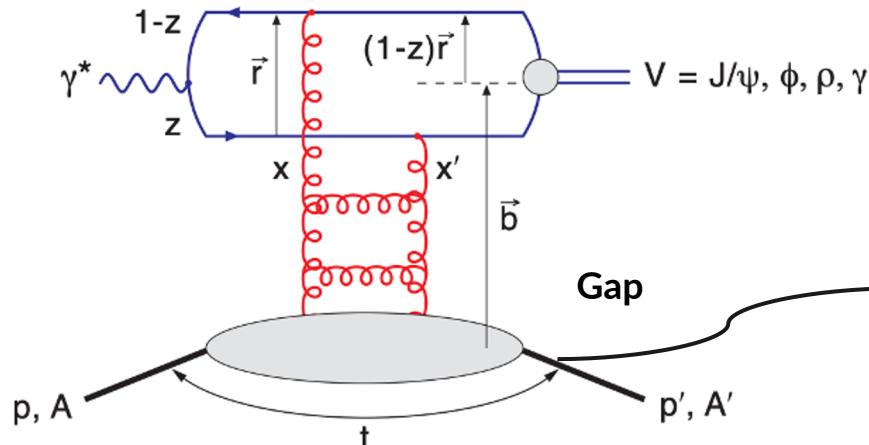
- A sensitive probe to the **gluon density**, spatial distributions, and their fluctuations.



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

Exclusive and diffractive vector meson production

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



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

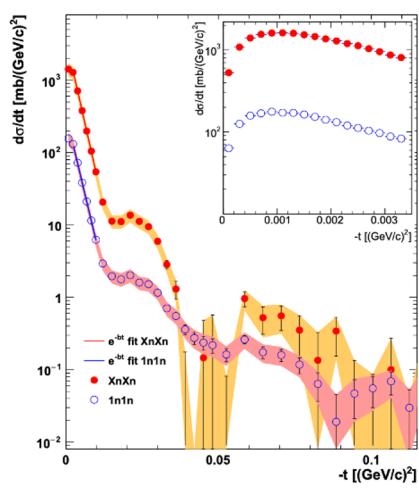
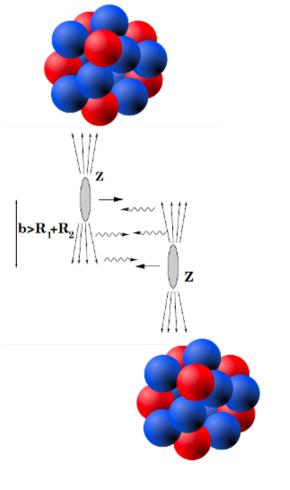
Momentum (t) and position (b) are conjugate variable, and can be related by Fourier Transform:

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

See details in T. Toll and A. Kumar's talk

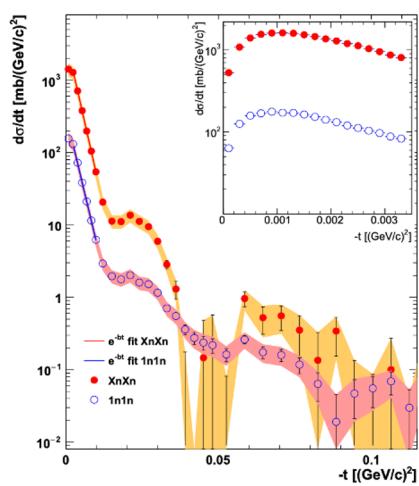
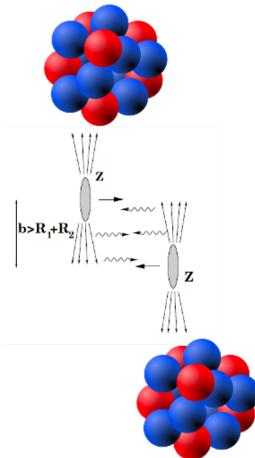
Current status - what do we know about heavy nuclei?

- Gluon spatial distribution in nuclei only has been measured with p^0 in Ultra-Peripheral Collisions;
- Uncertainty is large at high $-t$, scale is soft ($Q^2+M^2 < 1$), many questions remained!

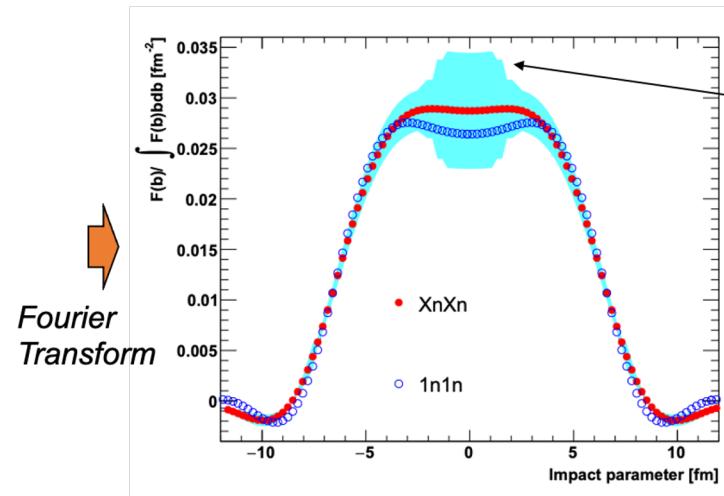


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Fourier
Transform



Large error at
small b came
from high $-t$

Important first result of proof-of-principle, but not good enough!

Why is it so difficult?

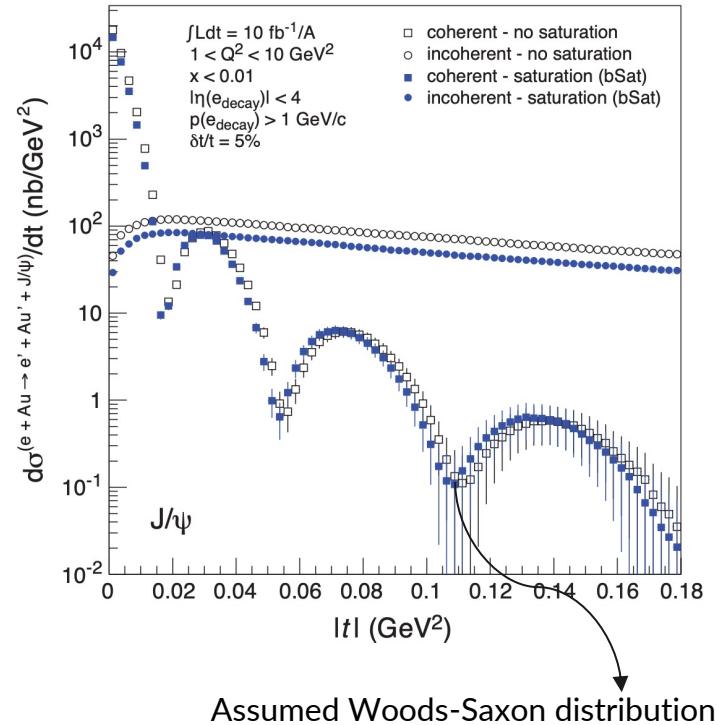
Why is it so difficult?

Two major challenges:

Challenge 1 - Excellent momentum resolution to resolve the structure of the coherent diffractive peaks/dips.

Challenge 2 - Incoherent background dominates most of the $-t$ regime. How to veto/suppress this background?

(EIC White Paper; Tolls & Ullrich)



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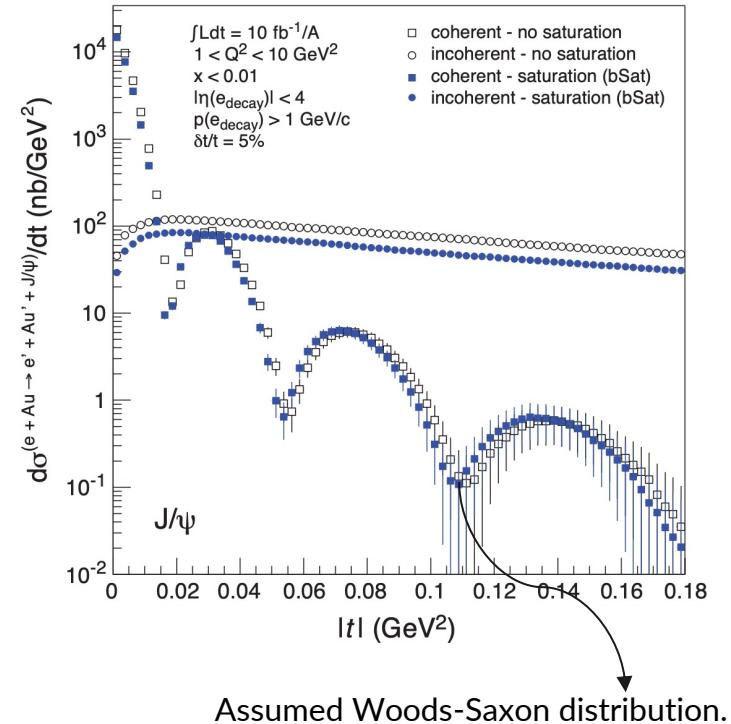
Challenge 1 - Excellent momentum resolution to resolve the structure of the coherent diffractive peaks/dips.

Challenge 2 - Incoherent background dominates most of the $-t$ regime. How to veto/suppress this background?

How well do we understand these challenges?

- Resolution. What effect dominant in resolution?
- Incoherent background. What kind of final states?

(EIC White Paper; Tolls & Ullrich)



Momentum transfer and resolution – the 3 particles

Challenge 1

- $e + Au \rightarrow e' + J/\psi (e^+e^-)^* + Au'$
- $e + Au \rightarrow e' + \phi(K^+K^-) + Au'$
- ...

$$-t = -(p_{A'} - p_A)^2 = -(p_e - p_{e'} - p_{VM})^2$$



Only 3 particles are in the detector.

* Can be dimuons

Momentum transfer and resolution – the 3 particles

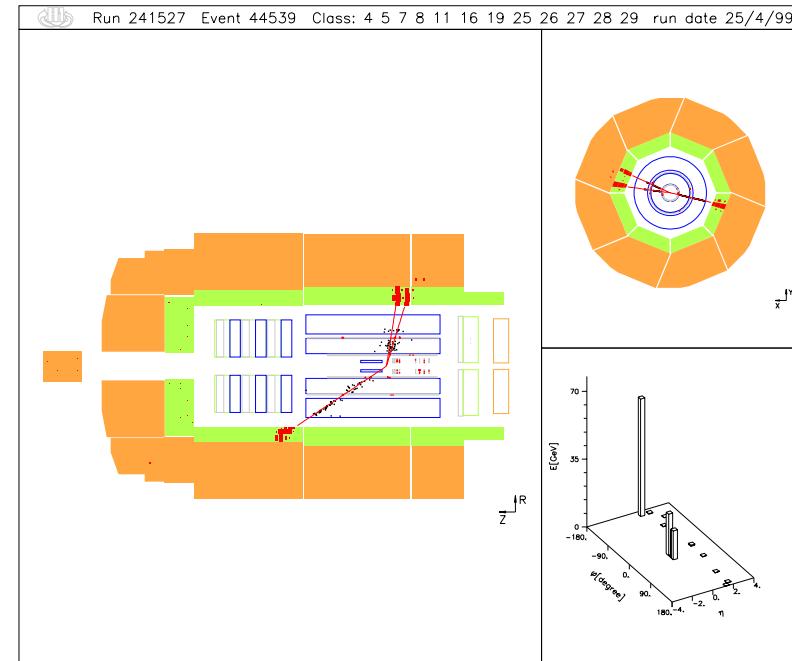
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Only 3 particles are in the detector.

H1 event display $e + p \rightarrow e' + e^+e^- + p'$



* Can be dimuons

Momentum transfer and resolution – the 3 particles

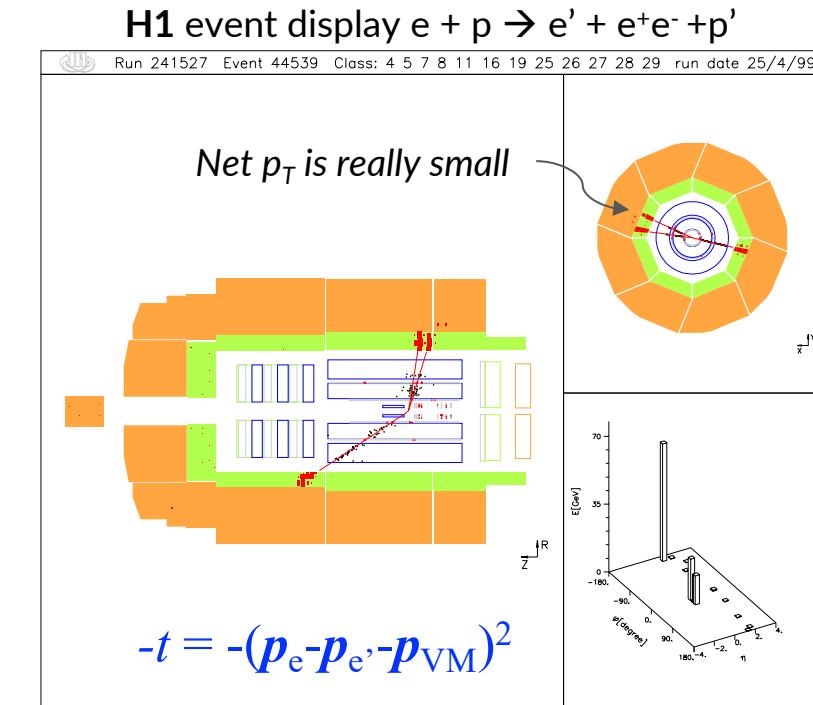
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Only 3 particles are in the detector.

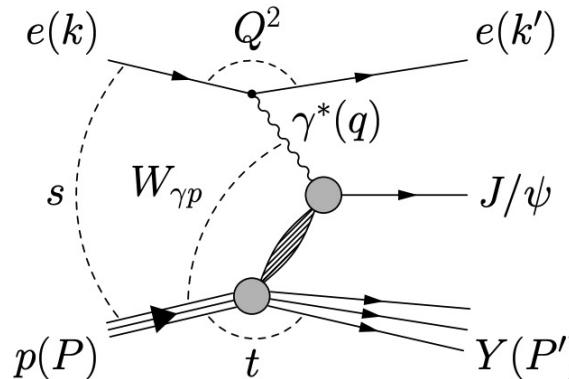
Momentum resolution is determined by how well we reconstruct them.



* Can be dimuons

Incoherent background

Challenge 2

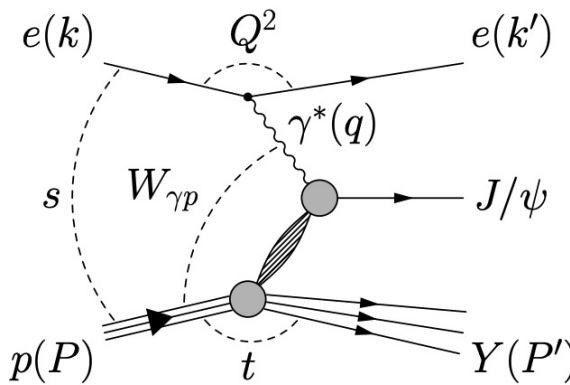


Good-Walker paradigm:

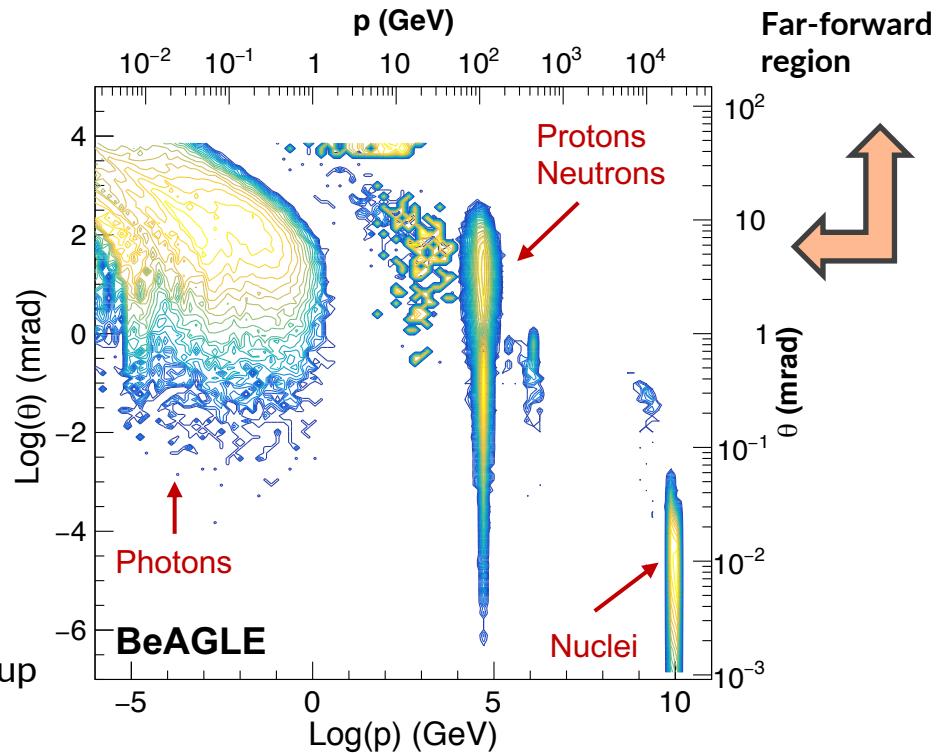
Incoherent process probes the fluctuation of nuclear configuration, and the nucleus breaks up

Incoherent background

Challenge 2

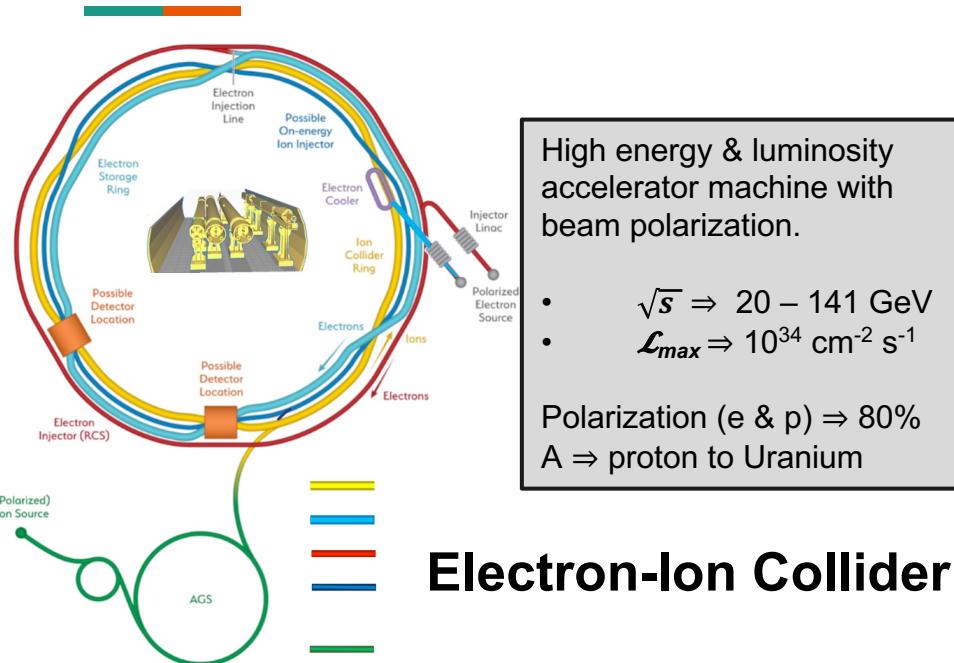


Good-Walker paradigm:
Incoherent process probes the fluctuation of nuclear configuration, and the nucleus breaks up



Next generation QCD machine and detector

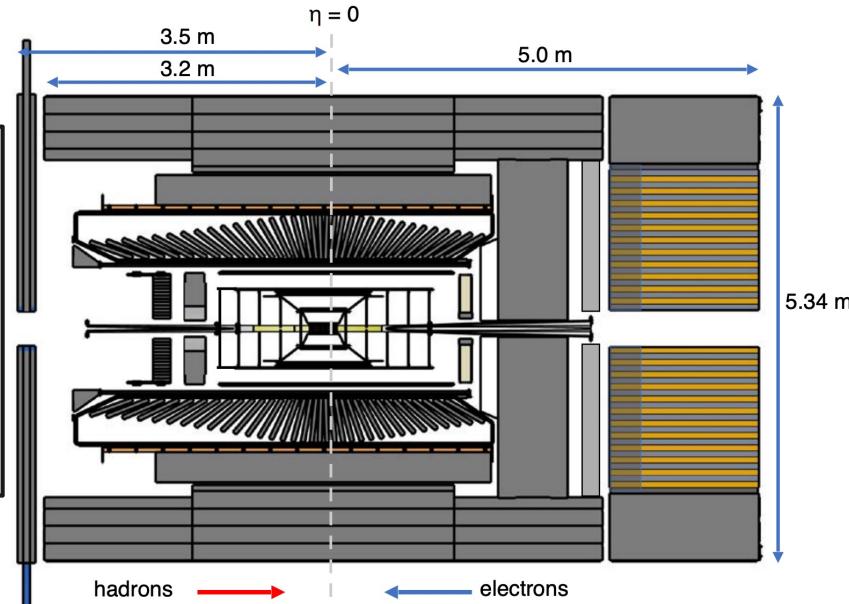
See E. Aschenauer's talk



High energy & luminosity accelerator machine with beam polarization.

- $\sqrt{s} \Rightarrow 20 - 141 \text{ GeV}$
- $\mathcal{L}_{max} \Rightarrow 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Polarization (e & p) $\Rightarrow 80\%$
 $A \Rightarrow \text{proton to Uranium}$

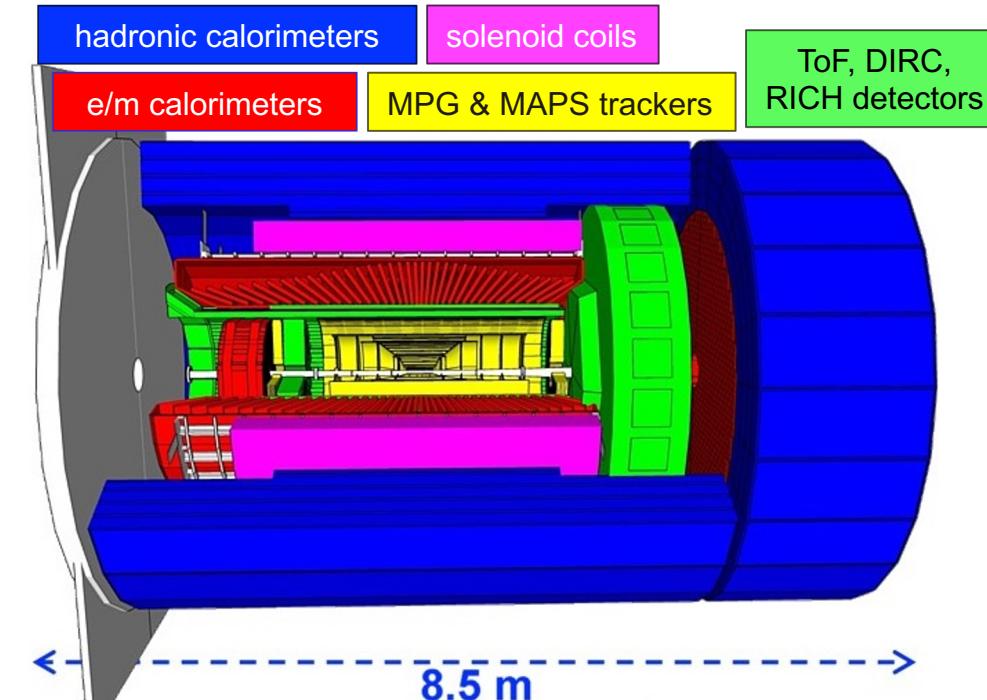


Sited at Brookhaven National Laboratory

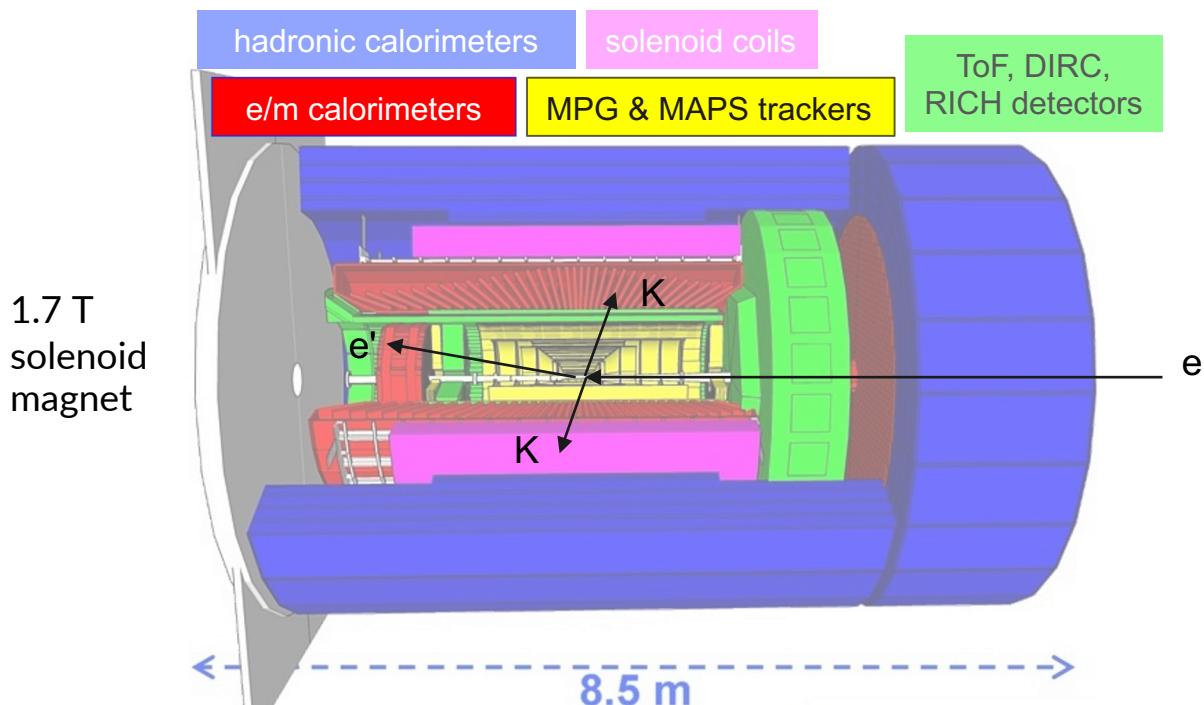
EPIC Detector@IP6 (currently the STAR hall)

What detectors do we need?

1.7 T
solenoid
magnet

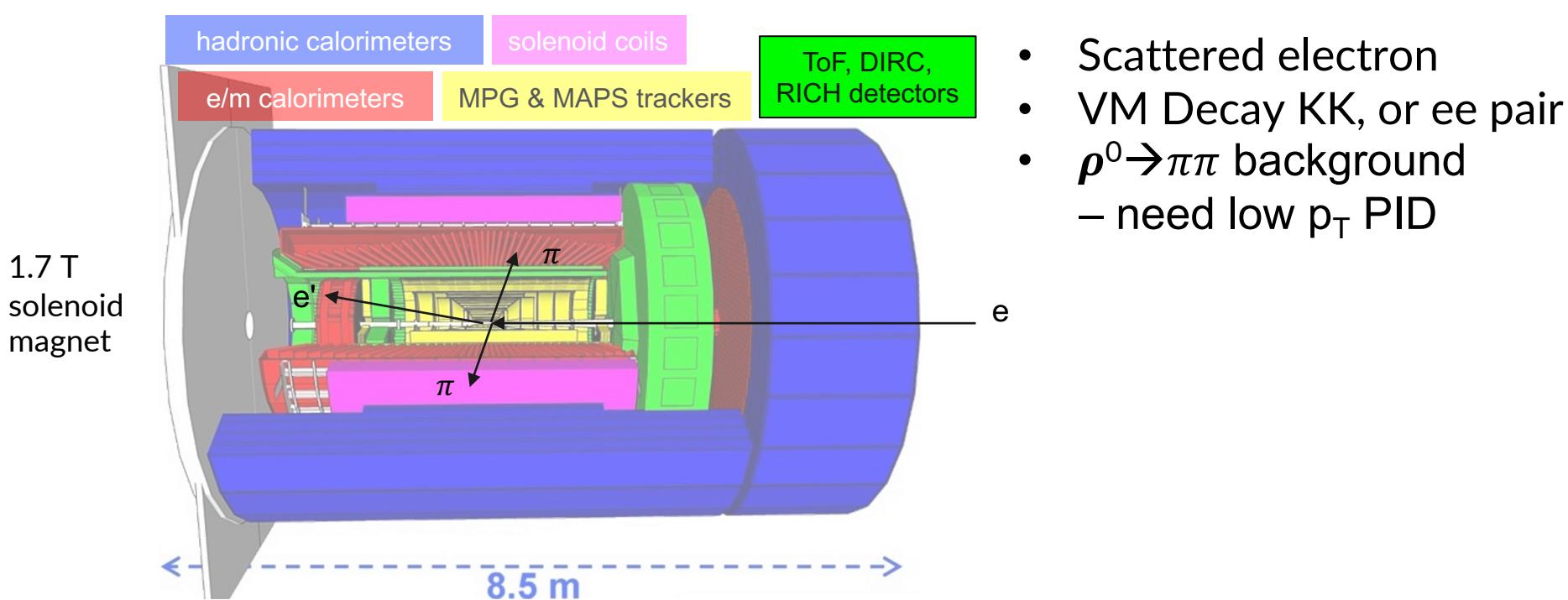


What detectors do we need?



- Scattered electron
- VM Decay KK, or ee pair

What detectors do we need?



What detectors do we need?

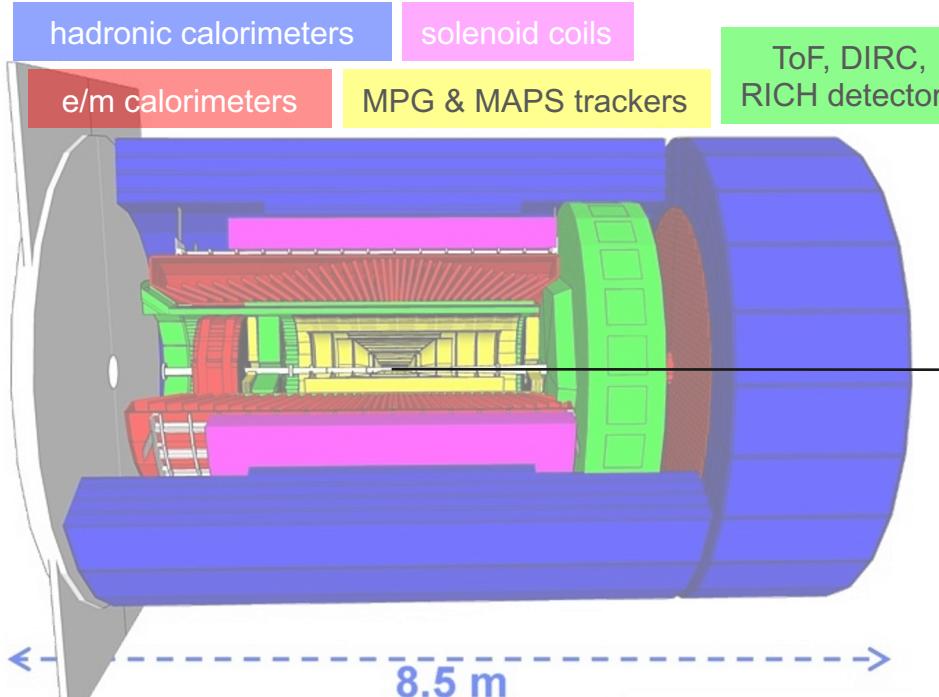
hadronic calorimeters
e/m calorimeters

solenoid coils

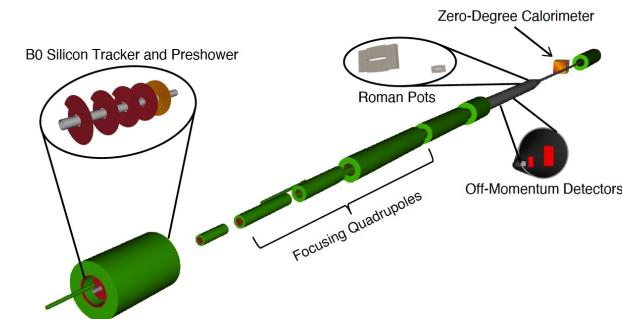
MPG & MAPS trackers

ToF, DIRC,
RICH detectors

1.7 T
solenoid
magnet

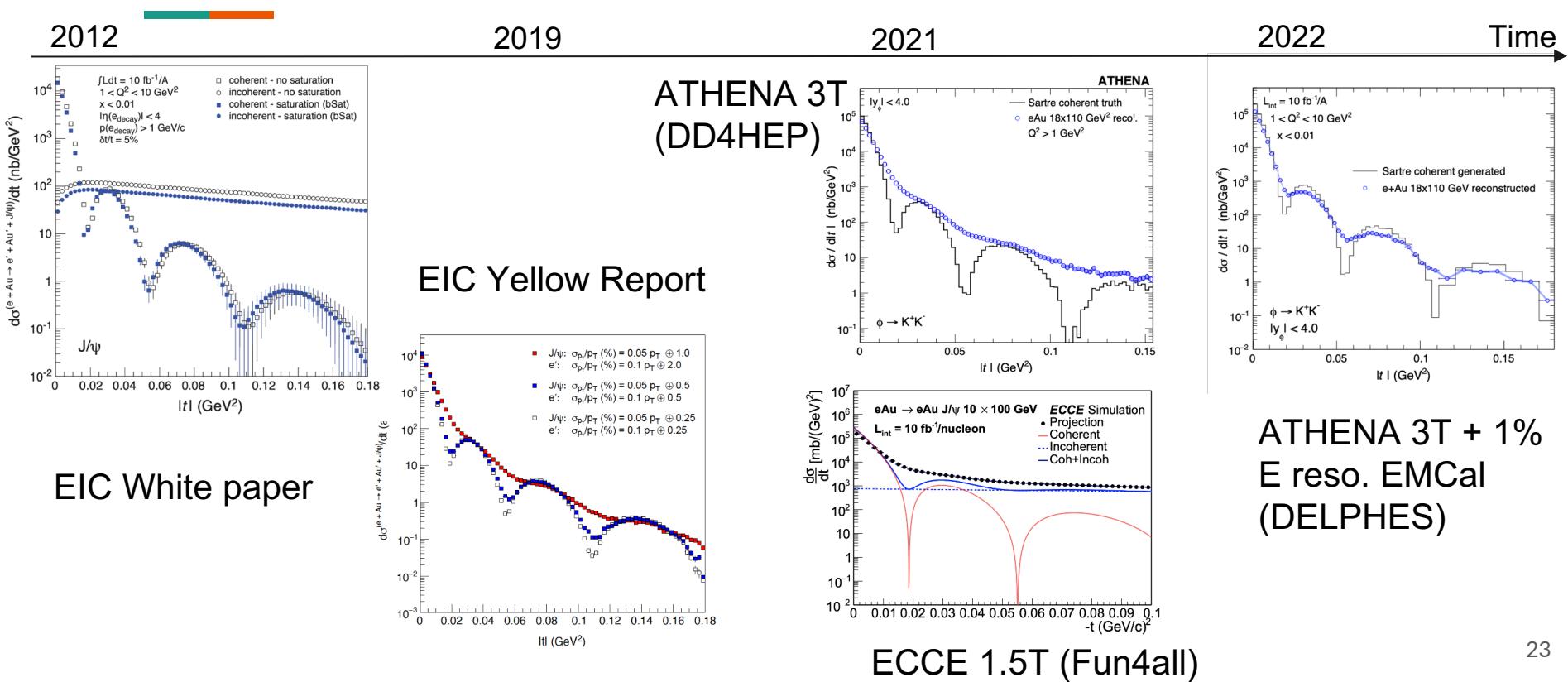


- Scattered electron
- VM Decay KK, or ee pair



Far-forward detectors:
- to make sure we don't see anything for coherent process!

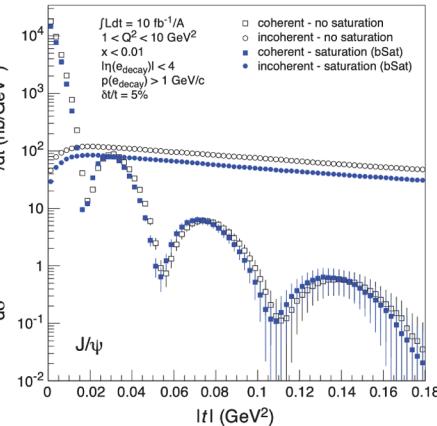
Diffractive VM timeline



Diffractive VM timeline

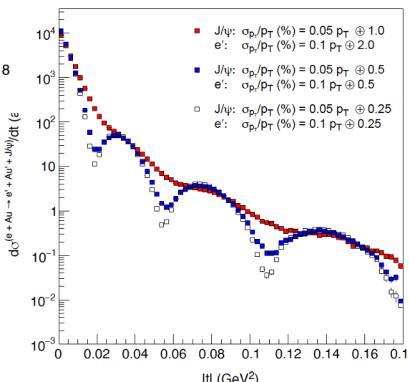
intense debate mostly caused by software differences

2012



2019

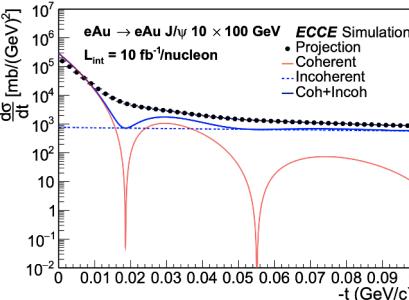
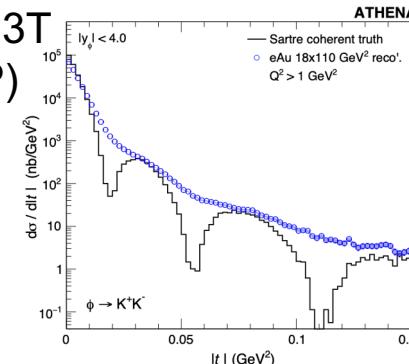
EIC Yellow Report



EIC White paper

2021

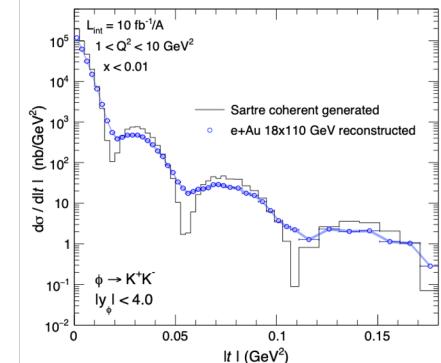
ATHENA 3T (DD4HEP)



ECCE 1.5T (Fun4all)

2022

Time

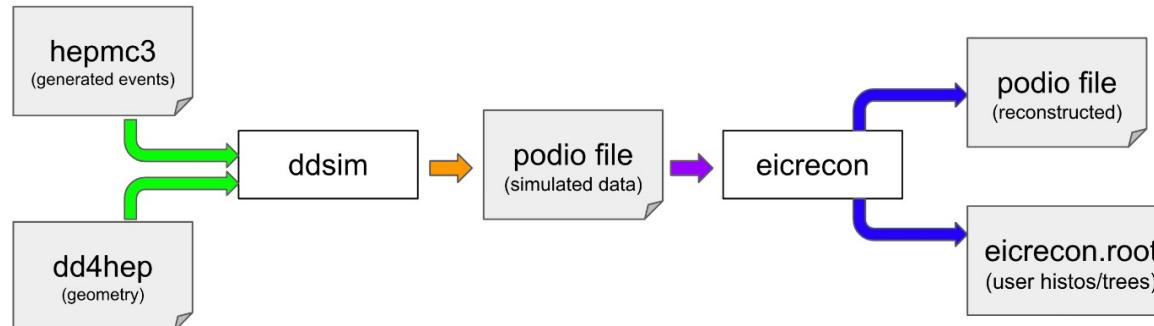


ATHENA 3T + 1%
E reso. EMCal
(DELPHES)

Modern software and simulation

See M. Diefenthaler's talk

-
- 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!

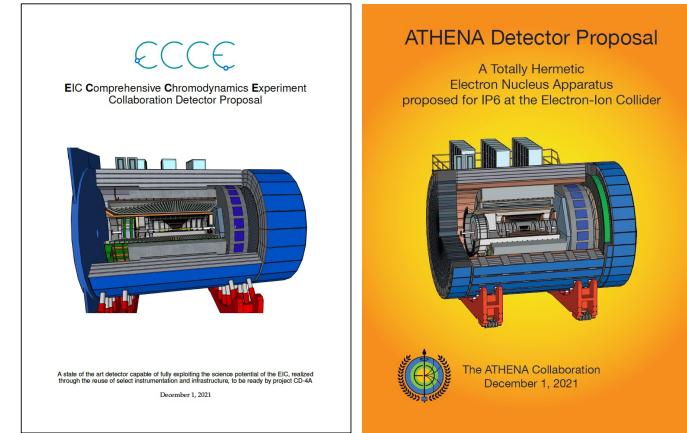


(We are constantly recruiting for software enthusiasts😊)

As of Dec 2022

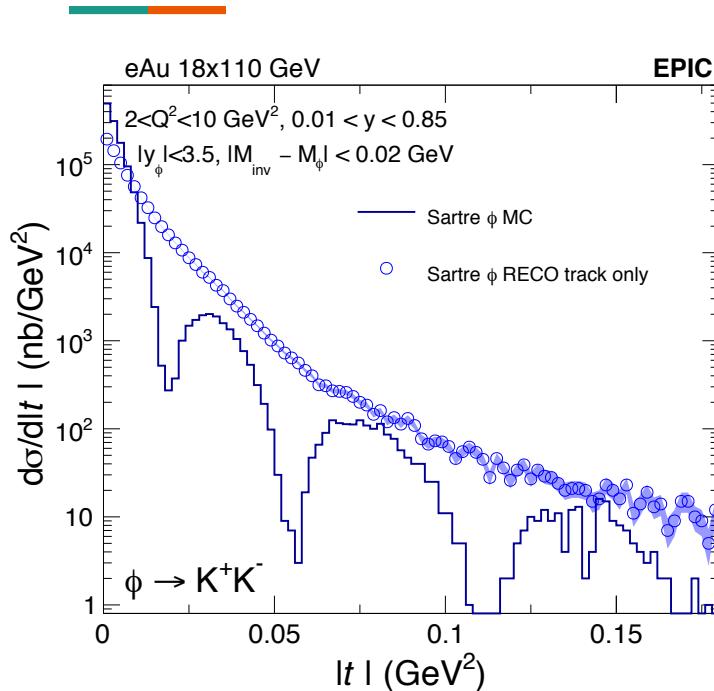
EPIC detector:

- New magnet - 1.7T
- Two configurations (arches vs brycecanyon)
 - mRICH vs pfRICH;
 - SciGlass vs Imaging
- Tracking (5 layers, has been a lot of optimization)
- Same Endcap ECal, PbWO₄
- New single-stack software program (DD4Hep, edm4eic, EICrecon, PODIO, etc)



All results shown later are from new simulation framework

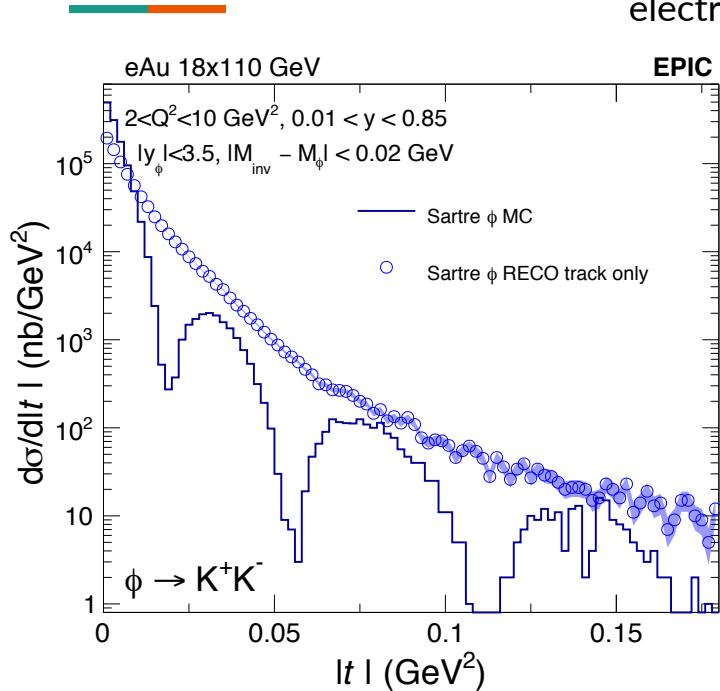
Results I



Legend details:

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

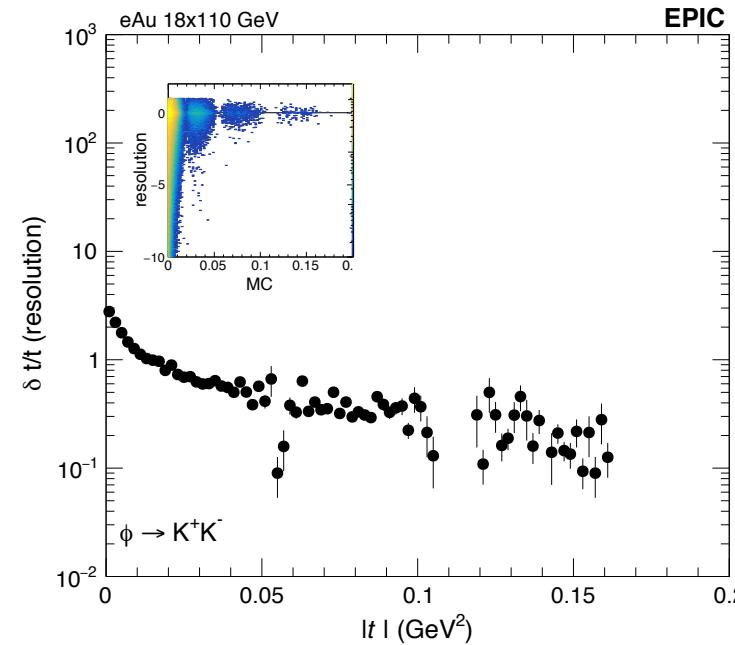
Results I



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

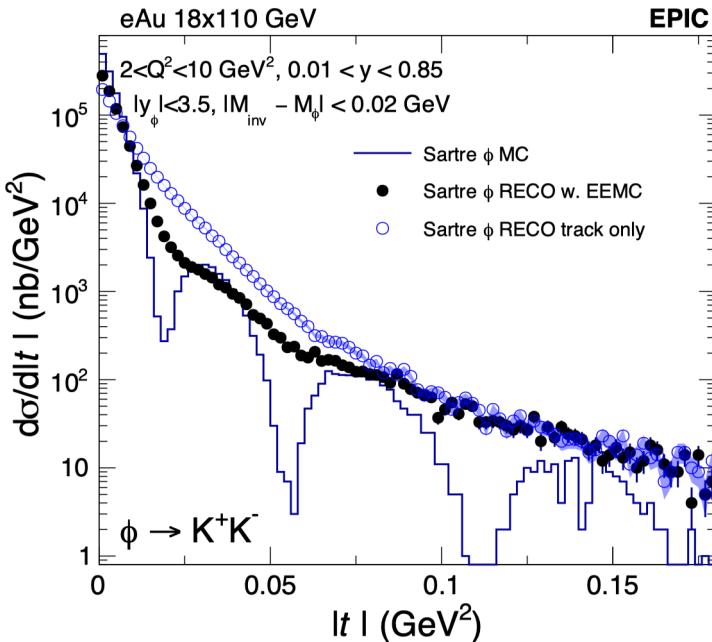
Legend details:

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



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

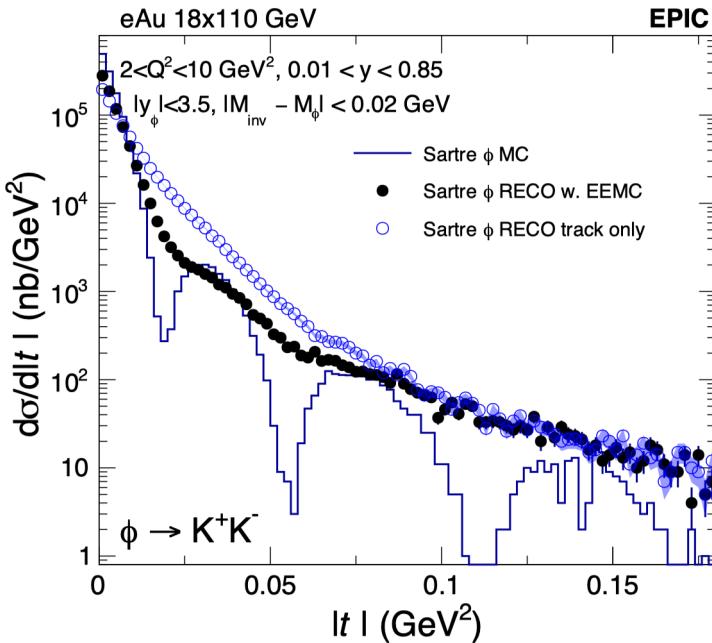
Results II



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

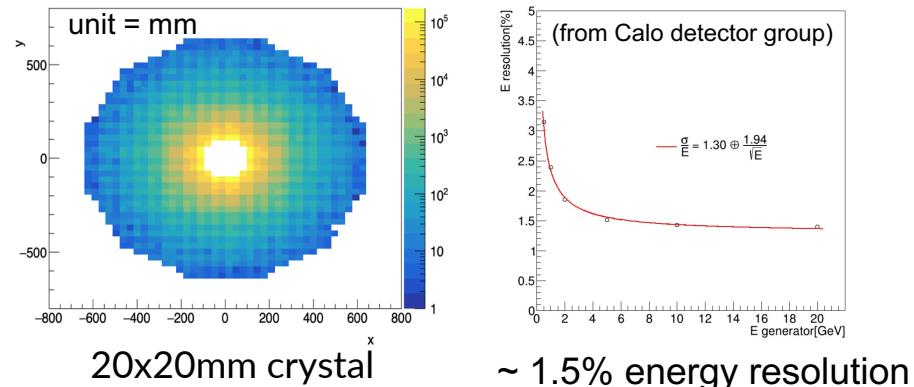
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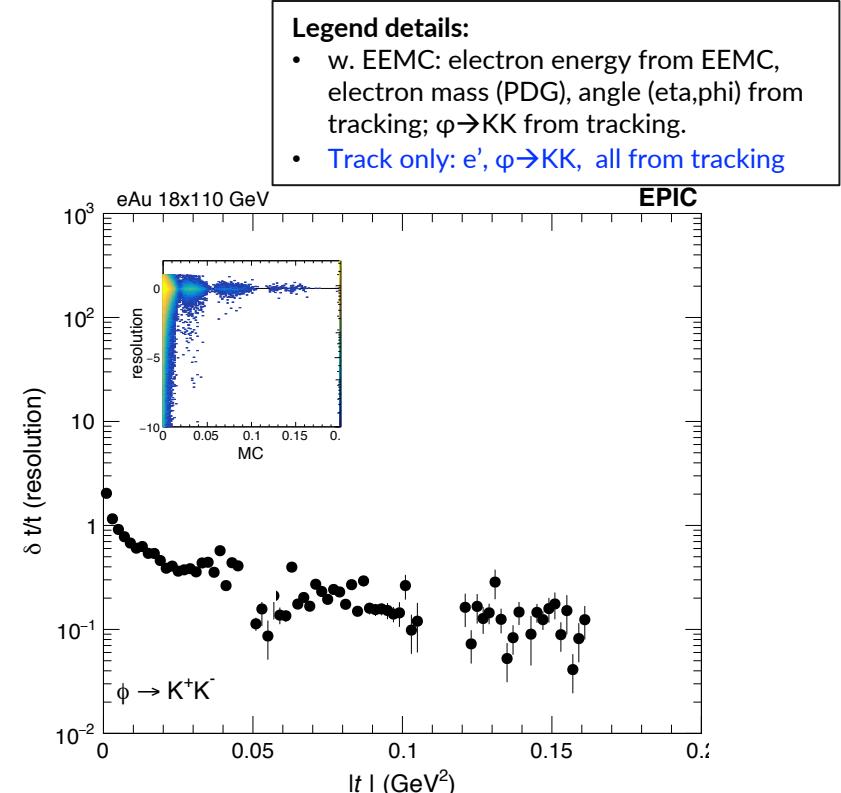
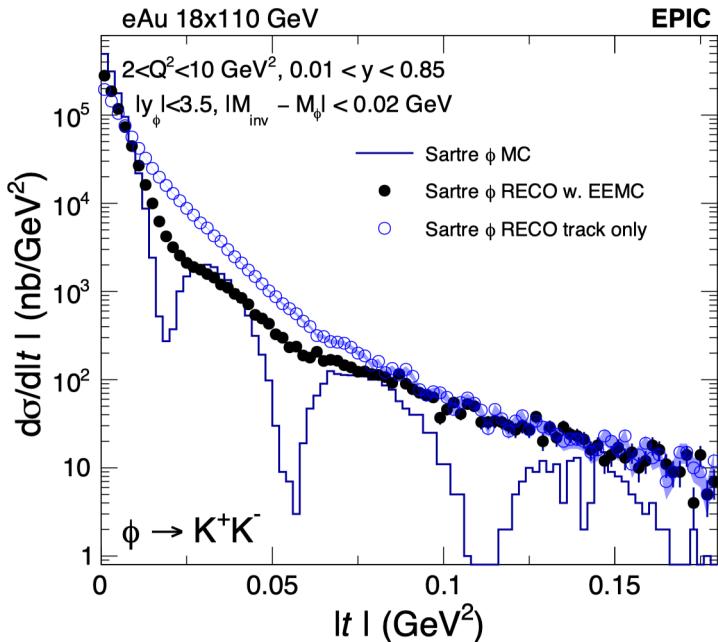
1. Electron energy from EEMC



2. Assume electron mass (PDG)

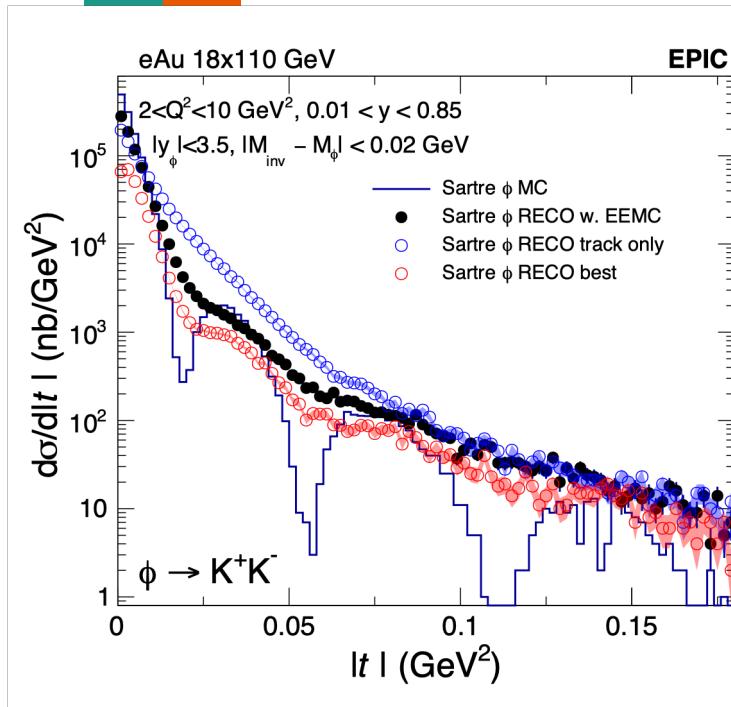
3. Angle (position) from tracking
(better resolution than from cluster position)

Results II



Some huge improvements have been seen with the EEMC

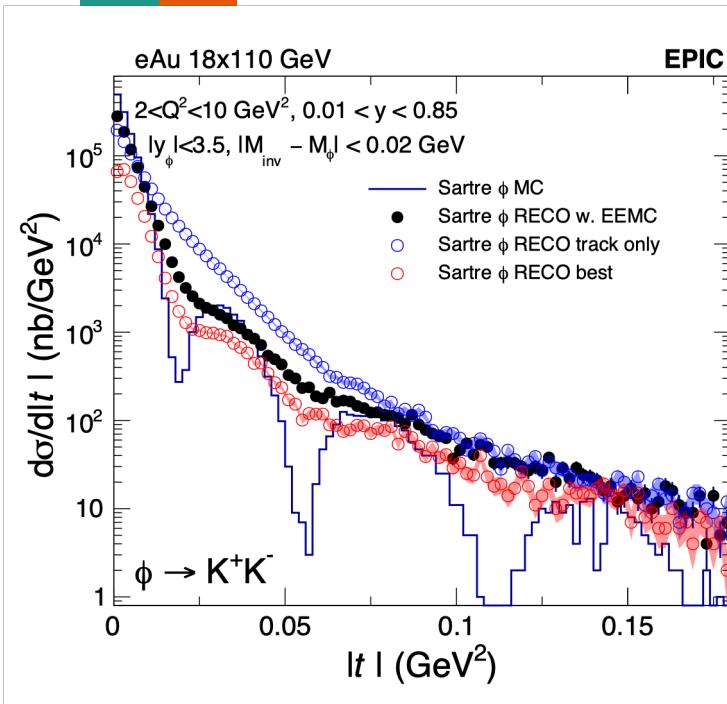
Results III



Legend details:

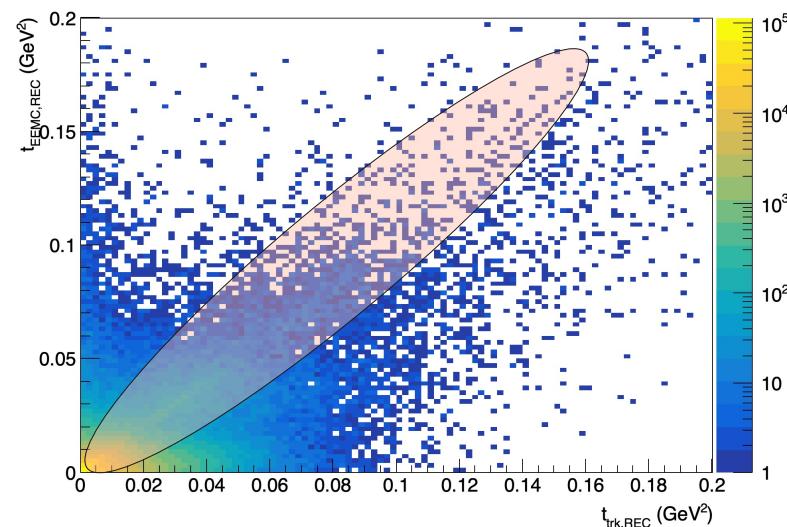
- w. EEMC: electron energy from EEMC, electron mass (PDG), angle (eta,phi) from tracking; $\phi \rightarrow KK$ from tracking.
- Track only: $e', \phi \rightarrow KK$, all from tracking
- Best: average of the above 2 E-by-E.

Results III



Legend details:

- w. EEMC: electron energy from EEMC, electron mass (PDG), angle (eta,phi) from tracking; $\phi \rightarrow KK$ from tracking.
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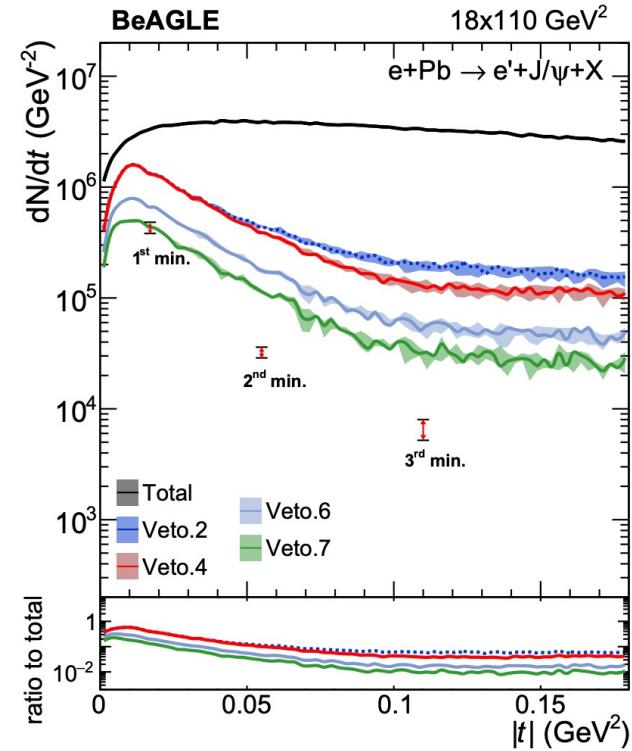
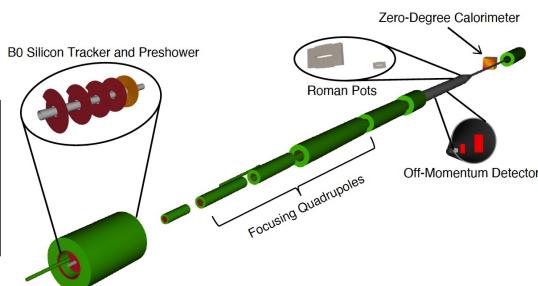
Improvements from *algorithm*:

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

Incoherent background suppressions

- No neutrons in ZDC (veto 2)
- No proton in any forward detectors (veto 3-5)
- No photon > 50 MeV in B0 or ZDC (veto 6-7)
- Minima (1st min. 2nd min. 3rd min.) assumed
only 5% $|t|$ resolution assumed.

Vetoing all of them is impossible. The question is how much is needed.

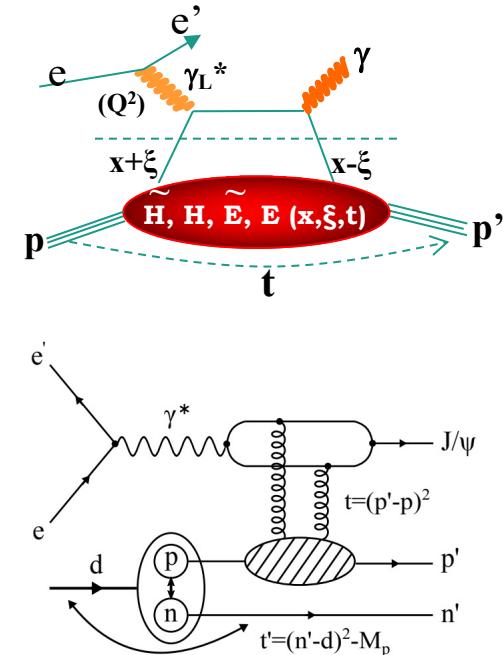


Simulating this in EPIC full simulation is urgently needed!

Phys. Rev. D 104, 114030

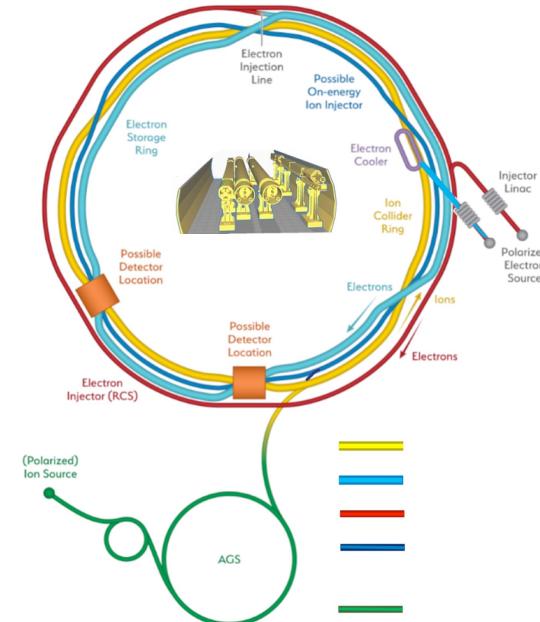
Other (imaging) exclusive processes

- High precision imaging at EIC at low and high x in ep,
Golden channel: DVCS;
 - Need far-forward proton (RP) detection.
 - Barrel EMCAL to detect photon (or suppress pi0 decays)
- High precision imaging on free neutron: DVCS in eD with spectator tagging.
- Exclusive J/psi (or VM) on light nuclei with spectator tagging.
[Phys.Lett.B 811 (2020) 135877]
- Many other programs: meson structures, TCS, backward u-channel production, Upsilon, J/psi near-threshold in ep, etc.



Summary

- EIC science has been established ~10-15 years ago, now it's time to build the detector!
- The Exclusive program, e.g., vector-meson, is one of the pillars of EIC science.
 - Connects to other fields/communities, from Jlab to the LHC (e.g., the UPC);
 - Stringent requirements on the detectors;
 - Drives the Far-forward detector system design and integration;
- EPIC experiment at the EIC is on its full speed towards TDR and on the right track.



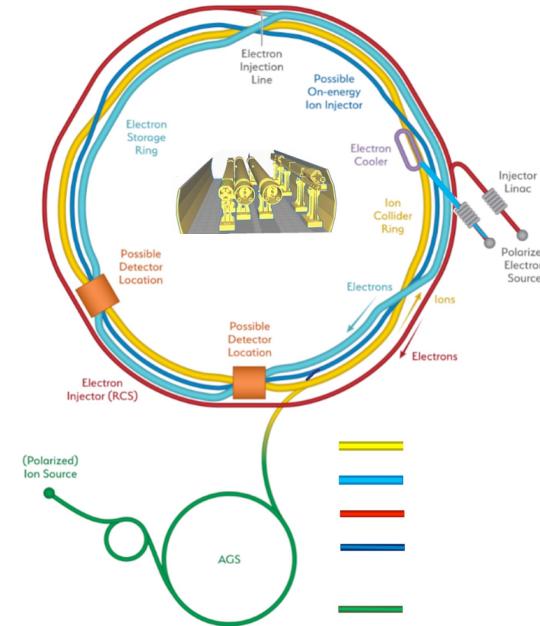
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Looking forward to seeing new collaborators from India

THANK YOU!



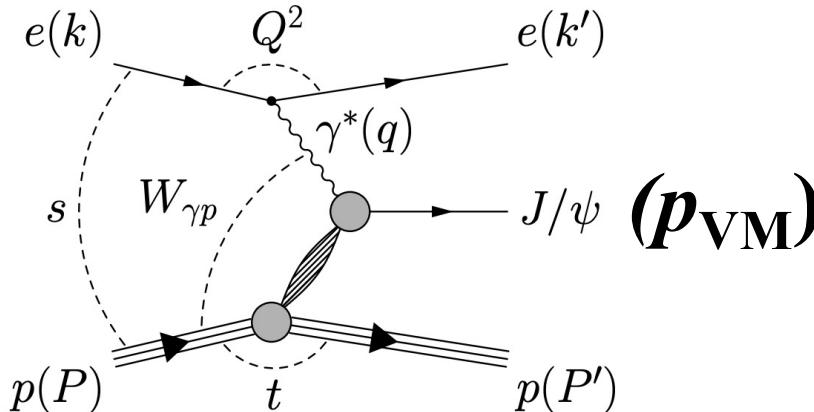
Looking forward to seeing new collaborators from India

Backup



Experimental methods

- Method Exact (E):
- Method Approximate (A) (UPCs)
- Improved Method E: **Method L**



$$-t = -(p_e - p_{e'} - \mathbf{p}_{\text{VM}})^2 = -(\mathbf{p}_A - \mathbf{p}_A')^2$$

$$-t = (p_{T,e'} + p_{T,\text{VM}})^2$$

$$-t = -(\mathbf{p}_{A',\text{corr}} - \mathbf{p}_A)^2,$$

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

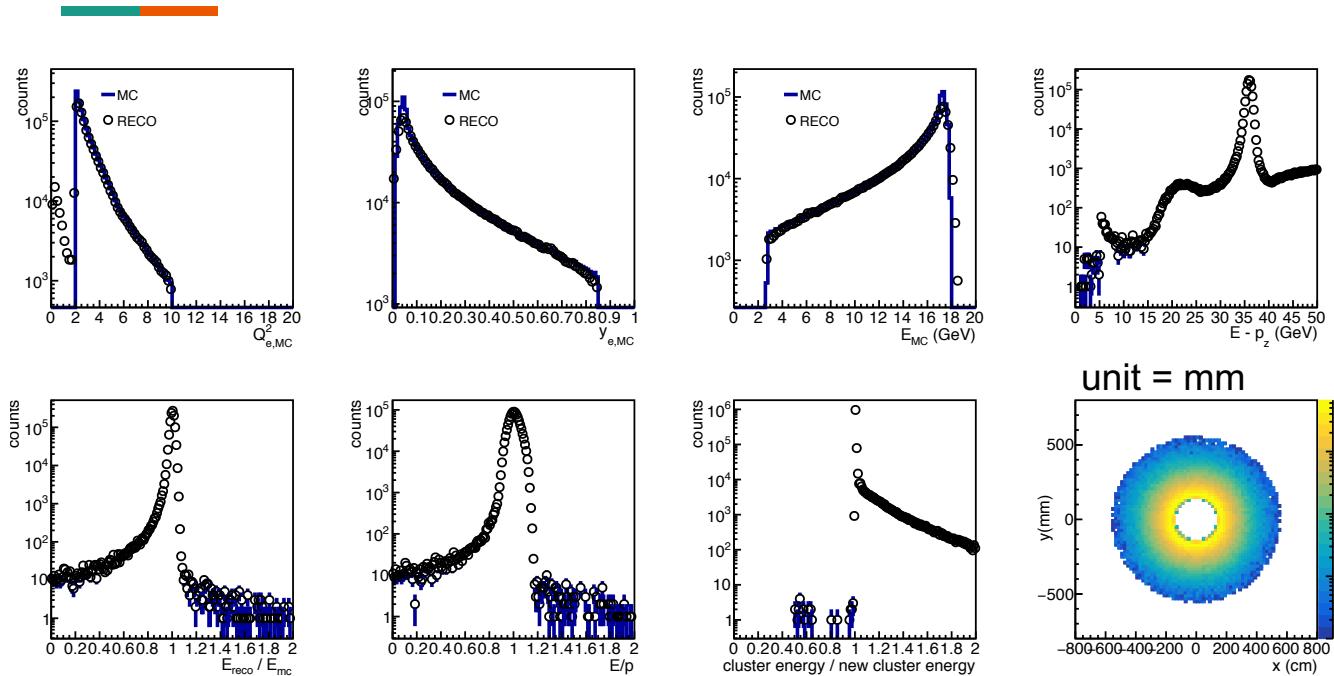
Best method concluded from the EIC Yellow Report – **Method L**

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

New event and track selections

- $2 < Q^2 < 10 \text{ GeV}^2, 0.01 < y < 0.85$
- Good electron selections:
 - Leading cluster (new algorithm).
 - Energy calibration is $\sim 4.5\%$
 - Select $150 \text{ mm} < \text{clusterRadius} < 550 \text{ mm}$
 - Electron track (leading p_T , charge < 0 , !association to K^-)
 - $0.8 < E/p < 1.18$
- DIS event selection:
 - $27 < E - P_z < 40 \text{ GeV}$
- φ phase space:
 - daughter K $|\text{pseudorapidity}| < 3.0$;
 - Within 0.02 GeV of φ mass.
- Method L on t reco.

DIS control plot ($Q^2 > 2$, $0.01 < y < 0.85$)



- Much improved! Acceptance selection is important; Q^2 at 1 is too small.