Separating coherent and incoherent photoproduction at an Electron-Ion Collider: Comparing lead, gold and silver beams

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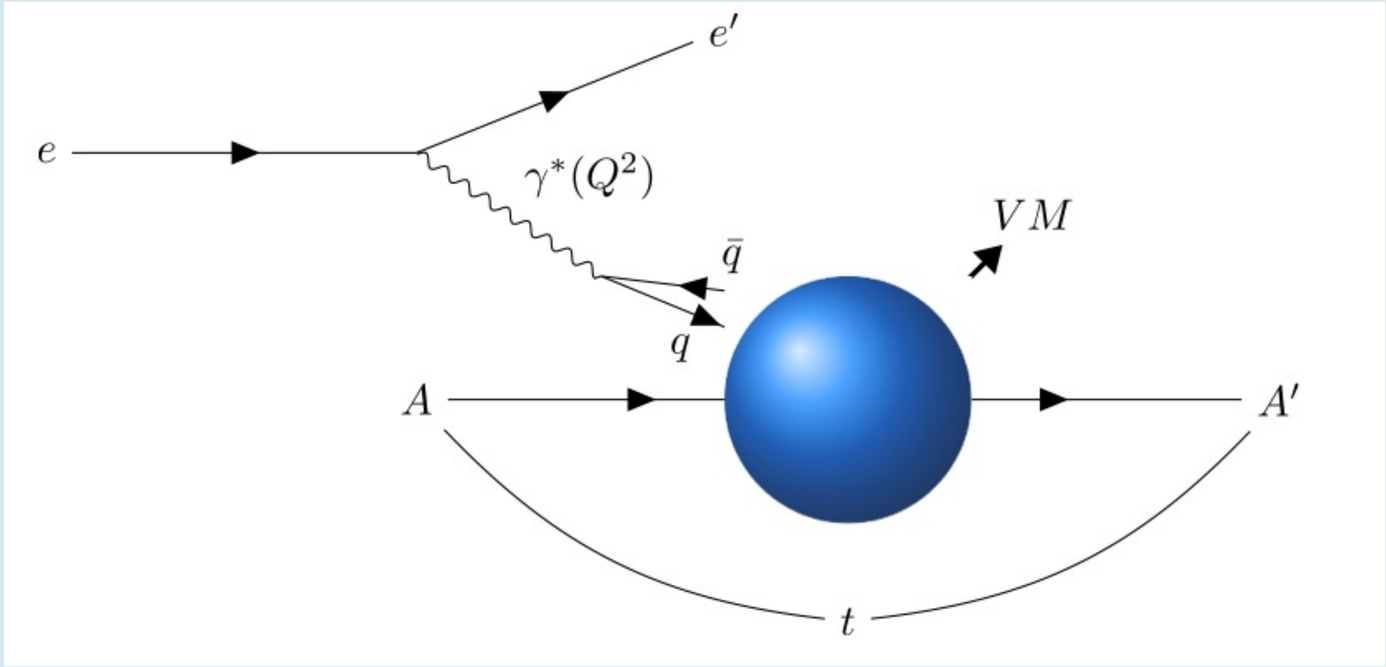
Vector meson production at the EIC

- Diffractive vector meson production provides access to gluon distribution.
  - Coherent production -> transverse gluon distribution
  - In Good-Walker, incoherent production -> fluctuations
- t_{min} is very small -> energy transfer can be very small
  - Nuclear shell model structure matters



M. Kessler *et al*., Phys. Lett. B **879,** 140585 (2026)

Good-Walker

- In VM production, coherent events measure average gluon configurations, and incoherent events are sensitive to fluctuations

$$\frac{\mathrm{d}\sigma_{\mathrm{coh}}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\langle A(K,\Omega)\rangle\right|^2$$

Average amplitudes (Ω)

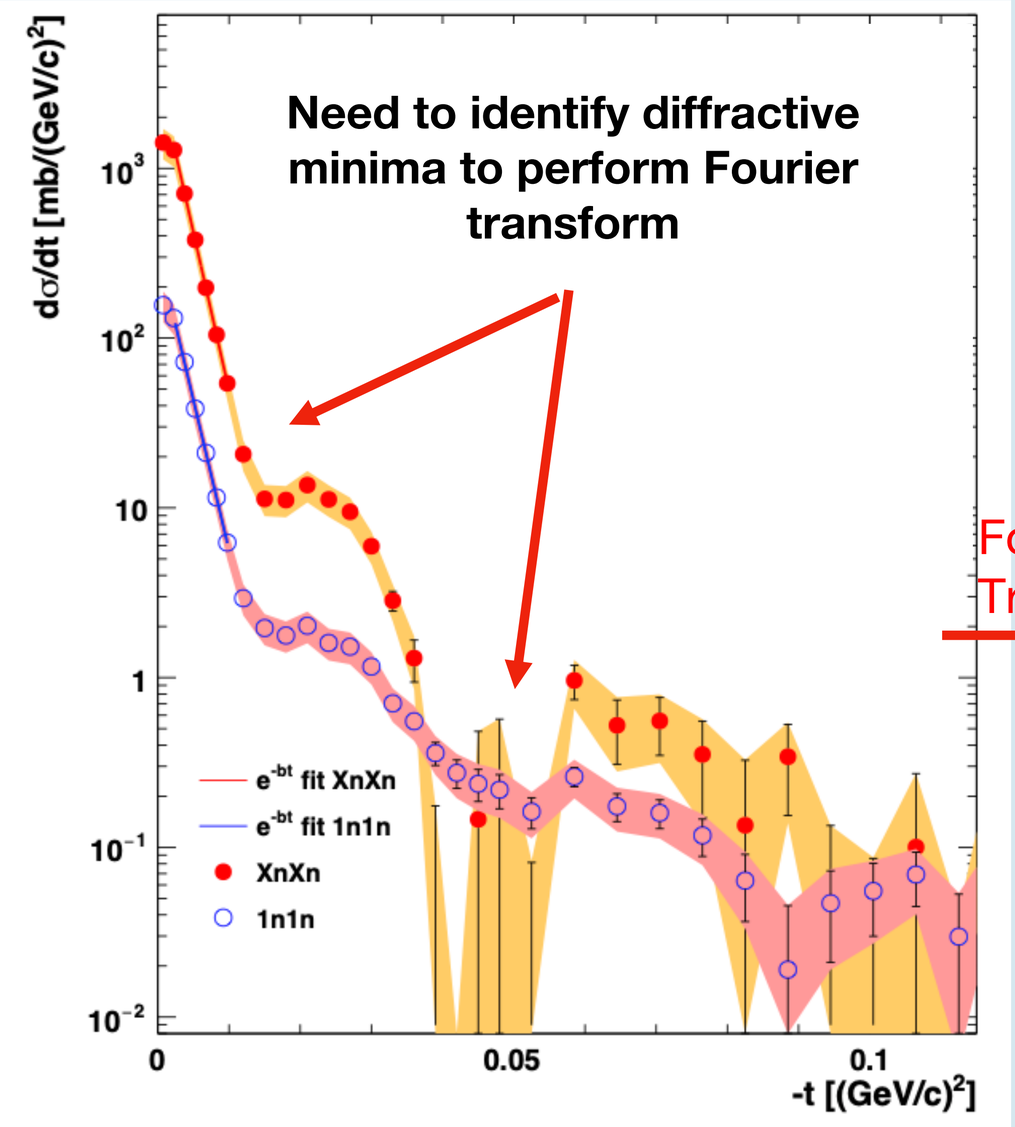
- Incoherent interactions are sensitive to event-by-event fluctuations

$$\frac{\mathrm{d}\sigma_{\mathrm{inc}}}{\mathrm{d}t} = \frac{1}{16\pi}\left(\left\langle\left|A(K,\Omega)\right|^2\right\rangle - \left|\left\langle A(K,\Omega)\right\rangle\right|^2\right)$$

Square of sums minus sum of squares -> fluctuations

- It is critical to separate coherent and incoherent interactions
- Incoherent interaction include nuclear excitations which may decay by proton, neutron or photon decay. Energy limits the accessible excitations.
- The photons are trickiest. The photon energy spectra emitted in nuclear de-excitation are governed bythe isotope's nuclear shell structure

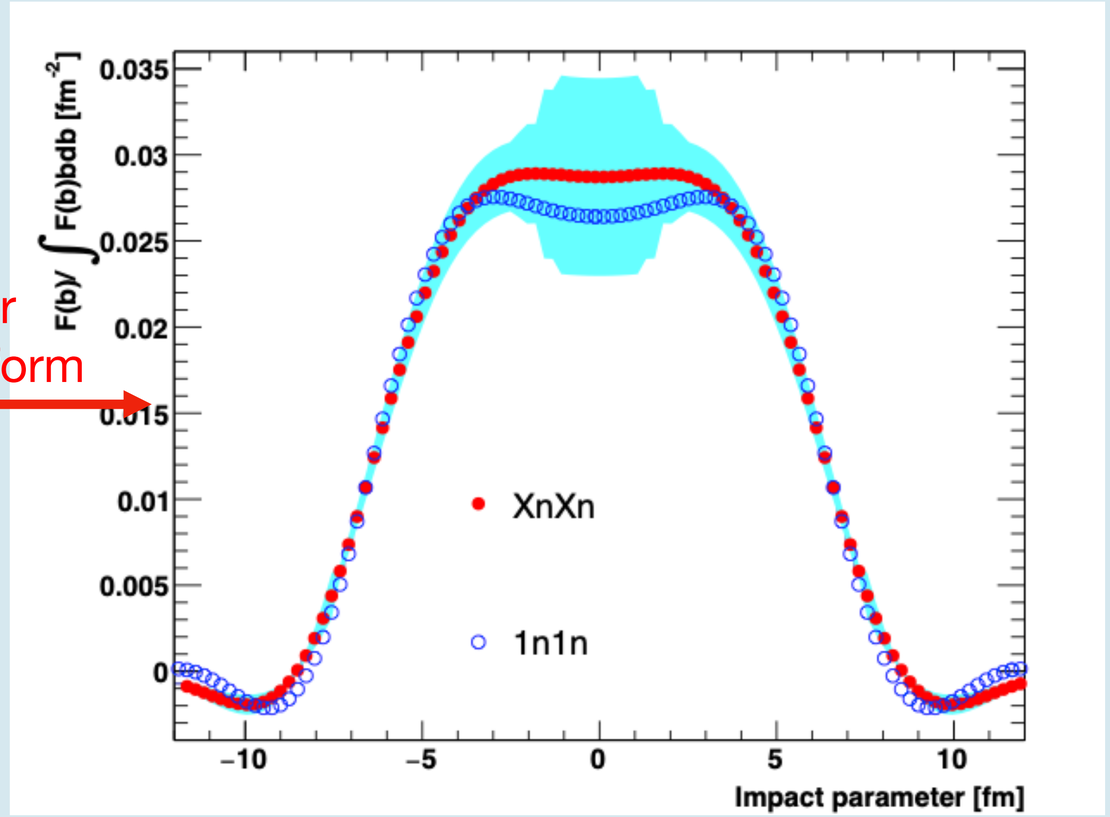
Coherent production



$$F(b) \propto \frac{1}{2\pi} \int_0^\infty dp_T\, p_T\, J_0(b p_T) \overset{*}{\sqrt{\frac{d\sigma}{dt}}}$$

* Flip sign of square root when crossing each diffractive minimum

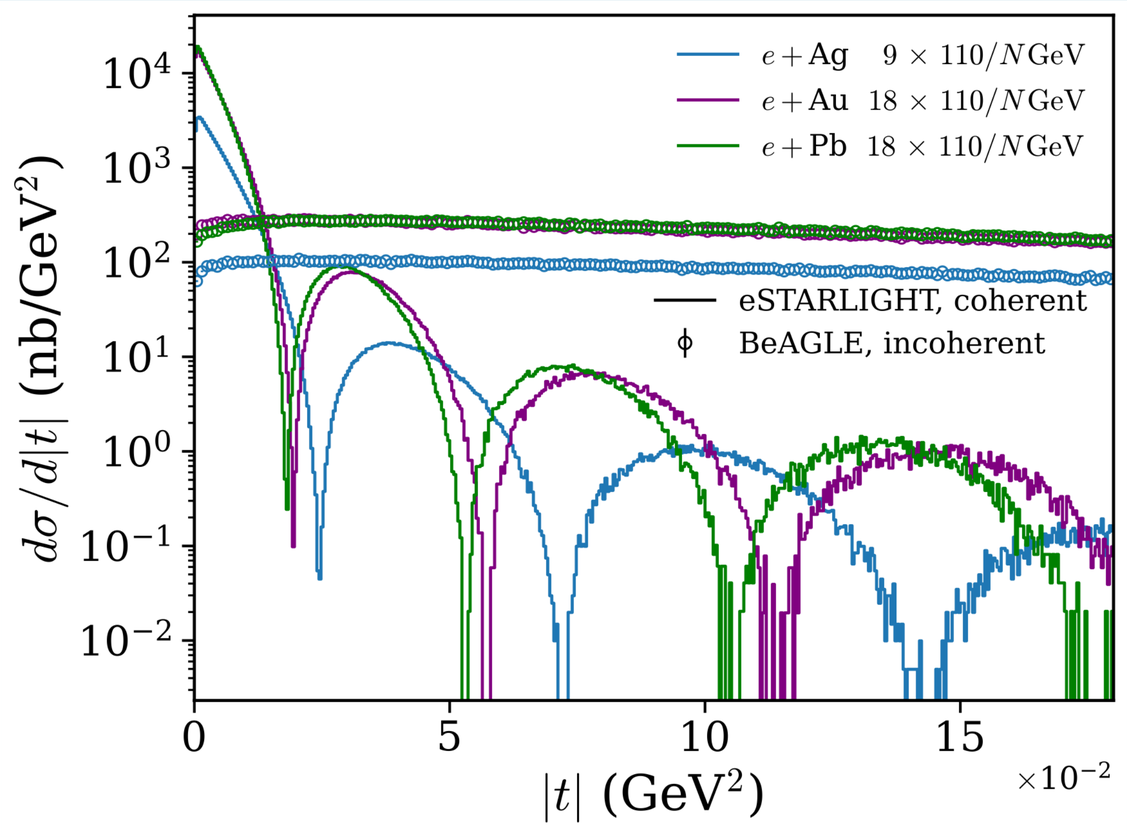
Fourier Transform



STAR Collaboration, Phys. Rev. C **96**, 0549054 (2017).

Incoherent production

- Incoherent events are when the nucleus does not remain in the ground state
- One model: photon interactions with single nucleons
  - In tension with idea behind Good-Walker, but implemented in BeAGLE
- Need to be able to separate between coherent and incoherent



BeAGLE and eSTARlight simulations

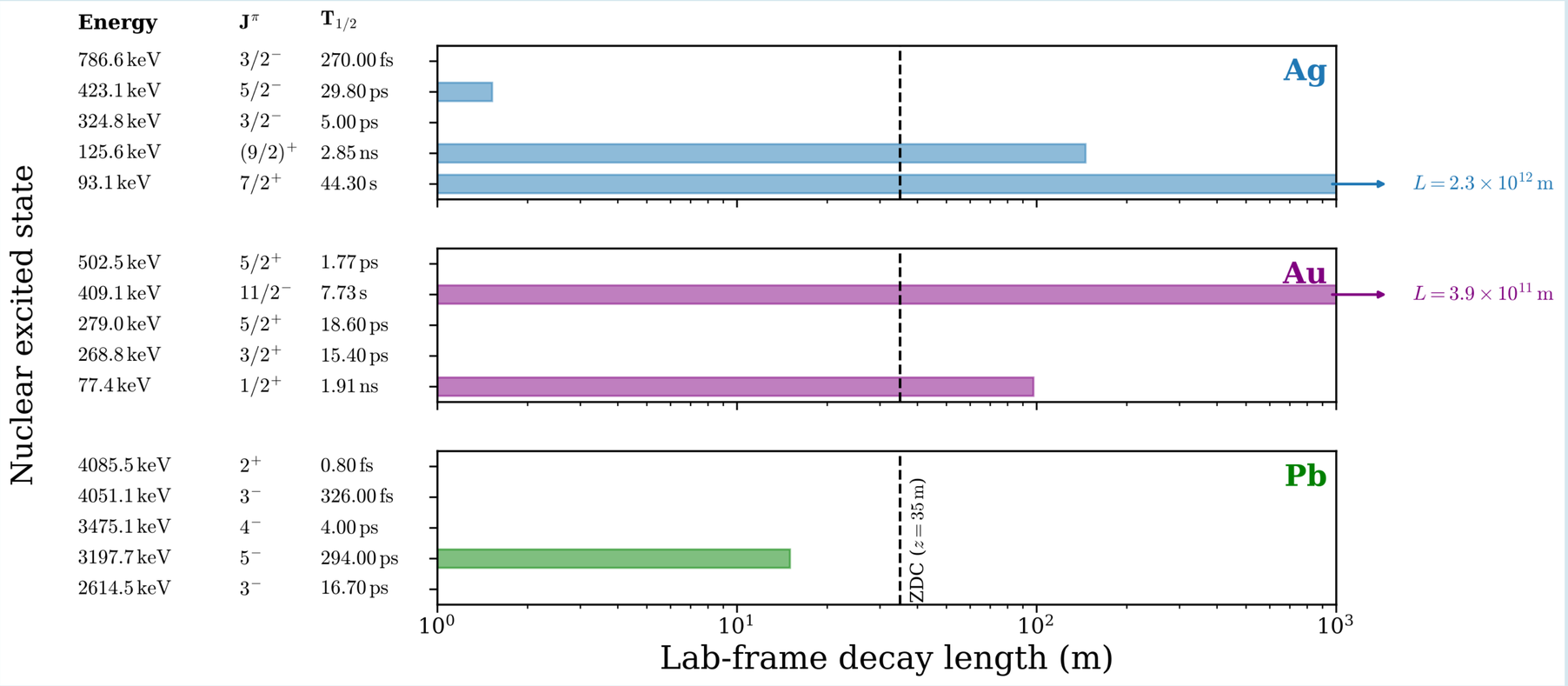
Choice of nuclear target species

- EIC early running: Ag beams. Later, a heavy ion, tentatively Au
  - Silver isotope is unspecified. We use Ag-107 because it is slightly more abundant than Ag-109, and has been used for EIC injector experiments. Our conclusions would be similar with Ag-109
- RHIC uses Au, CERN uses Pb
  - Usually seen as equivalent, with similar density profile and shadowing.
- Different shell structure. How does this affect studies at EIC?



“Initial commissioning will use beams of medium-mass ions, such as Ag, at the energy of 115 GeV, to ensure technical stability during the commissioning period”

Comparing nuclear targets

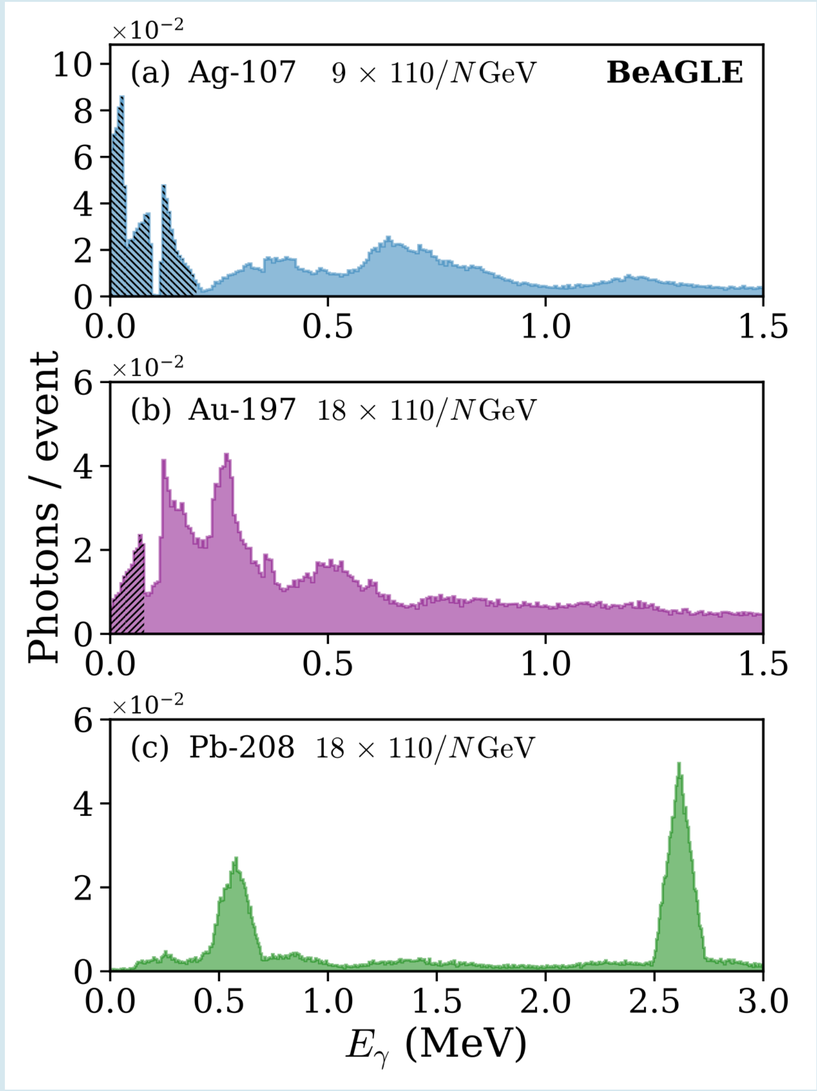


- First excited states Ag-107 **(93 KeV)** and Au-197 **(77 KeV)** are much lower energy than Pb-208 **(2.6 MeV)**

- Ag-107 and Au-197 have states that are long enough lived that they would decay outside of the planned ePIC acceptance. Not the case for Pb-208

BeAGLE

- We study incoherent J/Ψ photoproduction with these three different targets using BeAGLE ($1 < Q^2 < 10$ GeV^2)
  - Au and Pb **18×110 GeV**
  - Ag **9×110 GeV**, consistent with early running expectations
- **Right**: spectrum of de-excitation photons from BeAGLE when no neutrons or protons are emitted
- **Shaded region**: long lived photons*

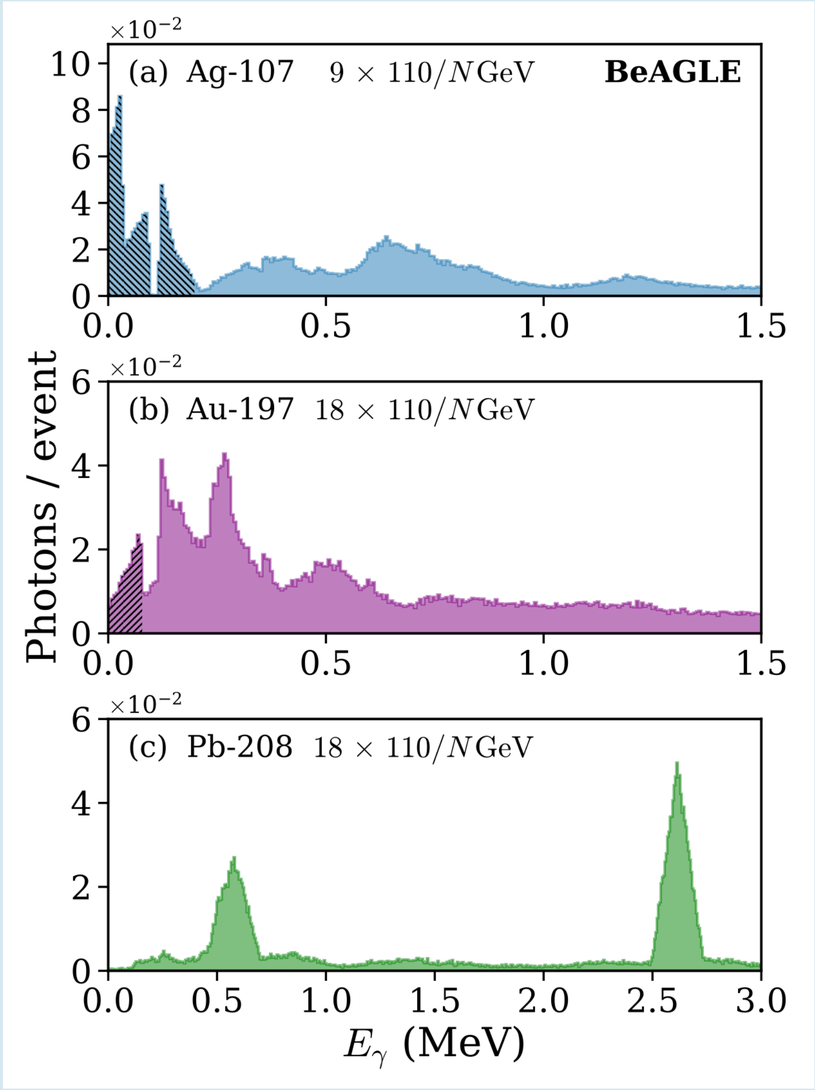


BeAGLE

- **PYTHIA-6**: initial partonic interaction
- **DPMJET**: intranuclear cascade
- **FLUKA**: evaporation, fission and γ de-excitation. Source of the photons studied here
- Vector meson kinematics are generated first, determining the energy transfer to the nucleus. This energy transfer is continuous, and does not match the shell-model levels.

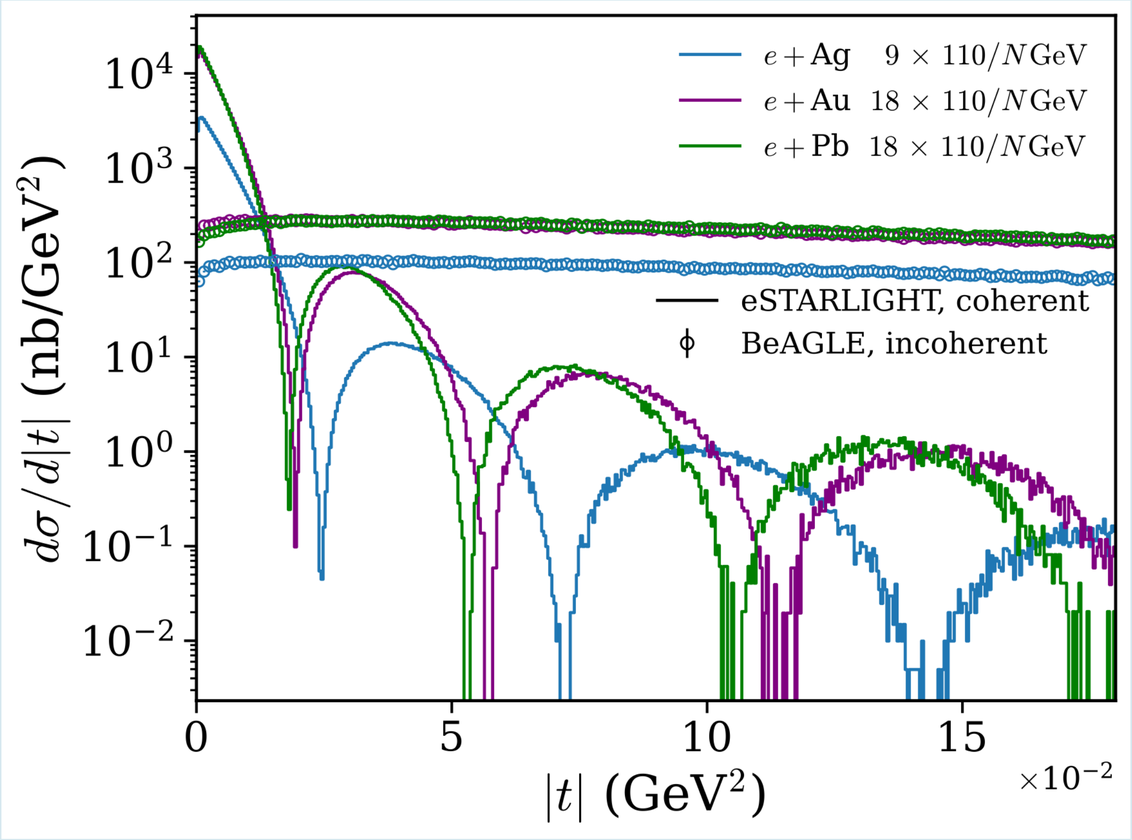
FLUKA

- FLUKA handles the nuclear de-excitations that we study here, and has a couple issues pertinent to our study:
  - 1. If the excitation energy is below the first excited state, it emits an ‘artificial’ photon
  - 2. When the excitation energy is above the first excited state, it first emits an ‘artificial’ photon to get to the nearest discrete energy level



Coherent and incoherent cross sections

- Coherent from eSTARLIGHT for same energy and Q^2
- Diffractive minima move according to ion size.
- Coherent $\frac{d\sigma}{d|t|}|_{|t|=0}$ scales as A^2 (modulo the energy dependence)
- Magnitude of incoherent cross sections also depends on ion size



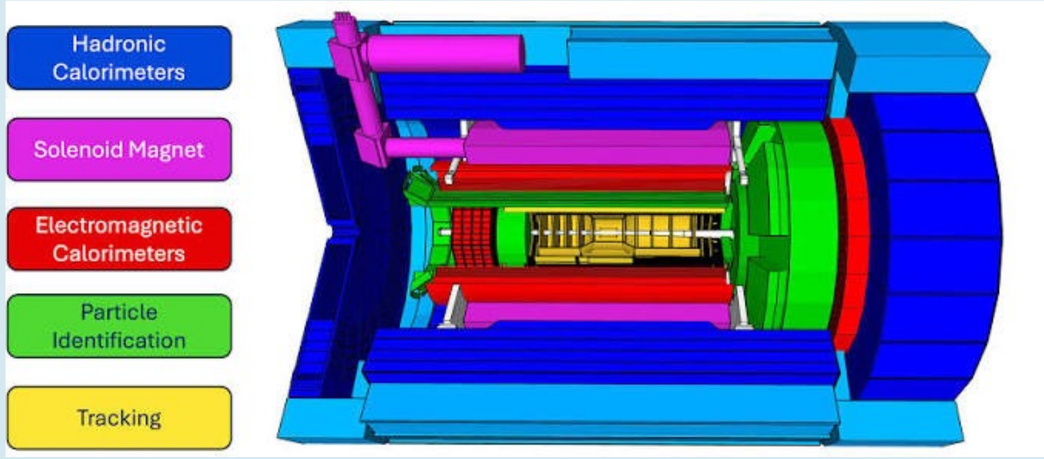
Lead vs. gold/silver

- Lead has a much higher first excited energy than gold/silver
  - 2.6 MeV vs. 77 keV/93 keV
- There are values of ***t*** that are kinematically allowed for gold/silver targets, but which are impossible with lead targets. This will manifest itself as a difference in incoherent cross sections at very low |t|.
  - This difference comes from the shell model, but in Good-Walker it would be attributed to fluctuations in nucleon positions or gluonic hot spots.

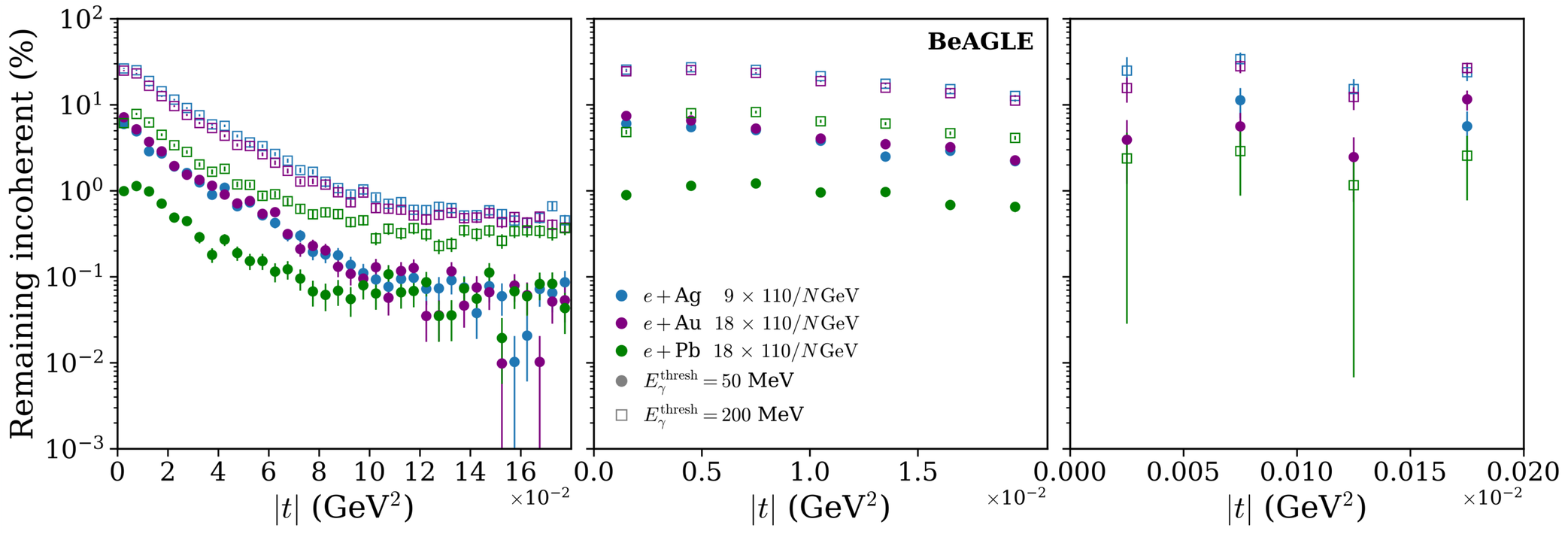
Vetoing incoherent events

- We use the following requirements to veto incoherent events, based on a simple model of the ePIC detector:
- Same as: Chang et al., Phys. Rev. D **104**, 114030 (2021)with the added requirement of a minimum photon energy in the B0
- Maybe an optimistic acceptance, no kinematic smearing or detector resolution
- We consider two photon thresholds in the B0 and ZDC: **50 and 200 MeV**

- a J/ψ and the scattered electron in the central detector ($p_{\mathrm{T}} > 100$ MeV, $|\eta| < 4$);
- a neutron in the ZDC ($\theta < 5.5$ mrad);
- a proton in the Roman pots ($\theta < 5$ mrad, $0.6 < p/p_{\mathrm{beam}} < 1.0$);
- a proton in the off-momentum detectors ($\theta < 5$ mrad, $0.3 < p/p_{\mathrm{beam}} < 0.6$);
- a charged track in B0 ($5\,\mathrm{mrad} < \theta < 22$ mrad);
- a photon in the B0 ($5\,\mathrm{mrad} < \theta < 22$ mrad, with laboratory energy above a threshold $E_{\gamma}^{\mathrm{thresh}}$);
- a photon in the ZDC ($\theta < 5$ mrad) with laboratory energy above a threshold $E_{\gamma}^{\mathrm{thresh}}$.

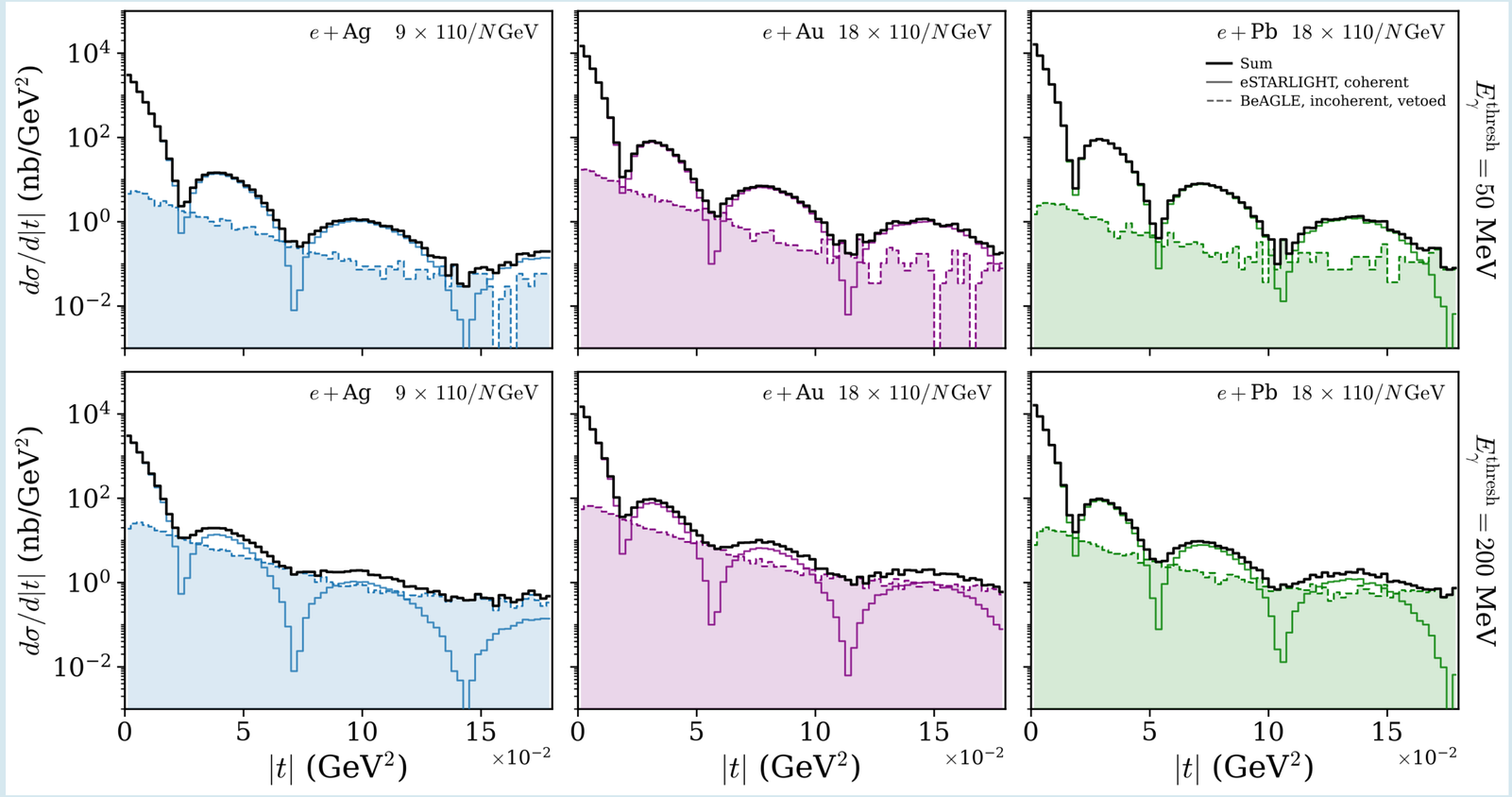


Veto efficiencies of each species



- Pb-208 has the lowest fraction of events surviving the veto
- It is easier to detect the higher energy and short-lived photons that are coming from Pb-208.
- Because of the higher energy level of its first excited state, Pb also has more events affected by the FLUKA artificial photon cut

Estimation of contaminated cross sections



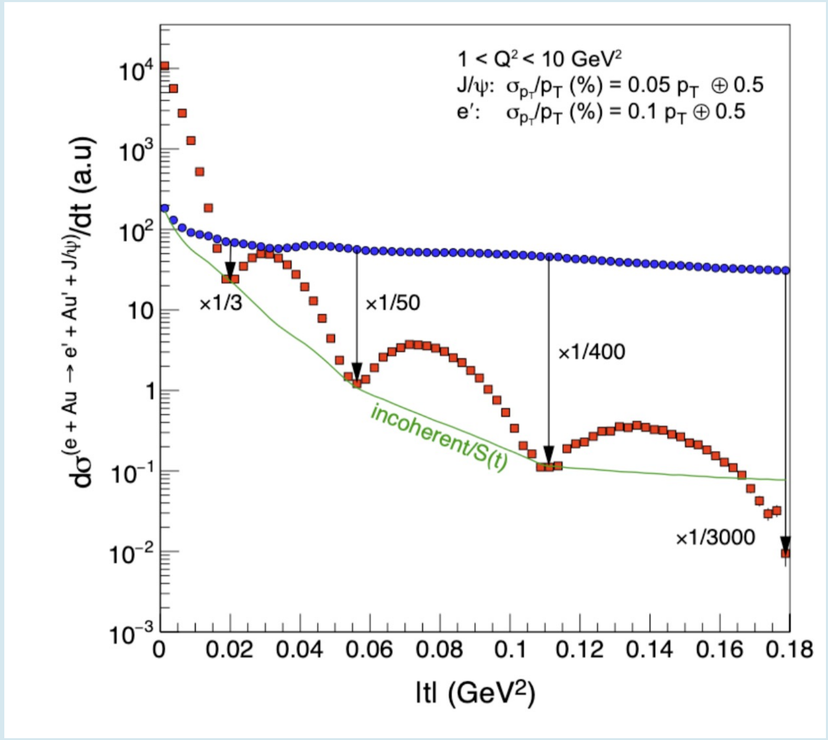
- **Above:** sum of coherent + non-vetoed incoherent events
- Less contamination with Pb at both thresholds
- 50 MeV threshold is far better

Caveats

- Known sources of uncertainty in the models we used:
  - The location, width, and magnitude of the diffractive minima differ when comparing different e+A event generators (eg. eSTARLIGHT and Sar*t*re)
  - These minima widen significantly once detector resolution is included
  - BeAGLE/FLUKA quantize the nuclear levels, but some photons are non-physical
  - More uncertainties about how Pomeron exchange and the subsequent nucleon recoil leads to nuclear breakup.
- At the EIC can compare Pb and Au, and hopefully learn enough to reduce the systematic errors. One could also do studies with exclusive ρ at Jefferson Lab, using a high-purity germanium detector near the target to see the de-excitation photons accompanying ρ production (J/ψ rate is low there)

1:400 requirement

- Diffractive minima must be well located because of the sign-flip in the Fourier Transform
- EIC Yellow Report set a detector requirement of a coherent to incoherent ratio of about 1:400 at the third diffractive minimum, but the exact origin is not very clear.
- The dip depth depends on the calculation and on detector resolution, so the requirement does too. A model-independent and resolution-independent requirement would be better.
- This 'requirement' is not met, in our calculation or in Chang et al. Our predictions are more pessimistic than Chang et al., because of our treatment of long-lived states and FLUKA artificial photons.



*E. Aschenauer et al., Physical Review D **111**, 072013 (2025).*

Summary

- We have compared how the ePIC detector veto's incoherent J/ψ electroproduction events from Ag-107, Au-197 and Pb-208 targets for VM production at the EIC. In addition to looking at photon energies, we have also considered the effects of long-lived nuclear states.
- Nuclear shell structure limits the kinematics of incoherent events. Lead has a higher first excitation energy, and there are values of ***t*** where incoherent photoproduction is possible for gold, but not for lead, independent of any fluctuations.
  - Photons from lead are higher energy, so they can be detected more efficiently.
- A 50 MeV photon energy threshold performs much better than 200 MeV
- Current calculations have large systematic uncertainties. Simulation code that correctly accounts for the shell model structure and long-lived states should be high priority.
- Species-dependent effects will still be a significant uncertainty when the EIC takes data, although studies at Jlab could provide useful data.

Please take a look at arXiv: 2609.31862 for more details.