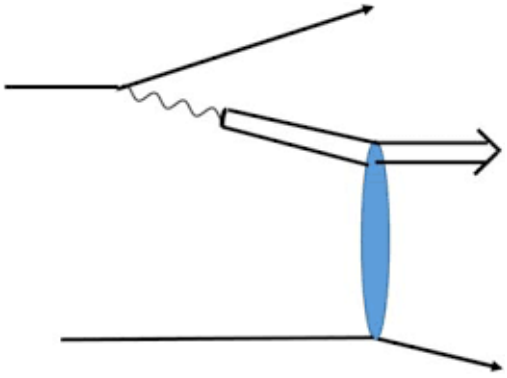
the eSTARlight Monte Carlo

Spencer Klein, LBNL

Presented at the "MC4EIC Workshop,
Nov. 16-18, 2022

- Photoproduction at UPCs and at an EIC
- Shape evolution in gold nuclei with Q^2
- The eSTARlight Monte Carlo
  - Current Status
  - Future plans
- Conclusions



eSTARlight

- Monte Carlo for photoproduction and electroproduction of vector mesons at an EIC
  - Here, photoproduction is $Q^2 < 1$ GeV^2, while electroproduction is $Q^2>1$ GeV^2
- An **experimentally-oriented** fast, **complete**, reasonably accurate model of vector meson production, not a sophisticated theoretical calculation
  - Experimental projections, detector simulations….
  - Electron (or positron) -> γ^* -> vector meson -> final state
  - Vector meson polarization and decay angular distribution
  - Based on data where possible, phenomenology elsewhere
    - *Some extrapolations required
- Easily extensible
- User interface similar to STARlight (for ultra-peripheral collisions), but underlying algorithms are very different

M. Lomnitz & S. Klein, Phys. Rev. **C99**, 015203 (2019)

Initial states

- Electron (or positron)
- Protons
- Light ions ($Z<7$) are modelled with a Gaussian distribution
- Heavy ions are modelled with a Woods-Saxon distribution
- For protons, lead, gold, zirconium, ruthenium, xenon or copper parameters are from electron scattering data
  - No neutron halo
- For other nuclei, radii are determined from simple formulae
- Nuclear properties are easy to change if desired
  - **Coming soon:** individual models for light nuclei
- Arbitrary beam energies…

Final states

- ρ, ω, φ, ρ' (i. e. ππππ), ρ + direct ππ, with interference
  - Simple states decayed in STARlight
  - Complex final states via PYTHIA interface
  - Easily extensible
    - **New:** ω -> π^+p-p0, w-> p0g
- Incoherent photonuclear interactions w/ DPMJET
  - Real photon approximation
- eSTARlight tracks outgoing electron & proton/nucleon
- eSTARlight outputs photon 4-vector
- **Relatively new:** eSTARlight output in HEPMC3 format

Electronuclear interactions

$$\sigma(e + X \to e + X + V.M.) = \int dQ^2 \int dE_\gamma \boxed{\frac{dN_\gamma(E_\gamma, Q^2)}{dE_\gamma dQ2}} \boxed{\sigma_{\gamma X}(W, Q^2)}$$

- Convolution of photon flux from electron with cross-section; both depend on Q^2
- Photon flux depends on virtuality

$$\frac{d^2N}{d(Q^2)dE_\gamma} = \frac{\alpha}{\pi}\frac{1}{E_\gamma|Q^2|}\left[1 - \frac{E_\gamma}{E_e} + \frac{1}{2}\left(\frac{E_\gamma}{E_e}\right)^2 - \left(1 - \frac{E_\gamma}{E_e}\right)\left|\frac{Q^2_{min}}{Q^2}\right|\right]$$

Cross-sections

- Parameterized from HERA data

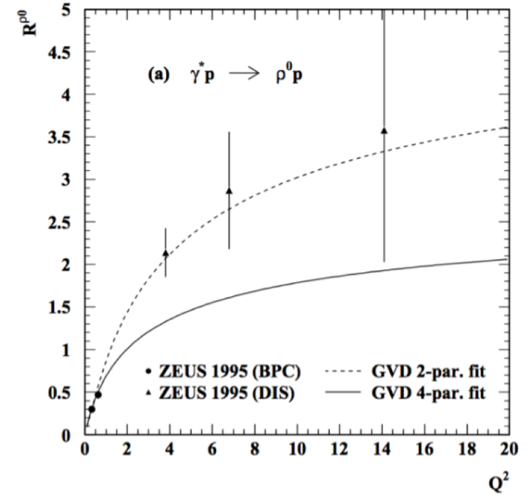
$$\sigma_{\gamma p} = \left(\frac{1}{1+Q^2/M_v^2}\right)^n \sigma_{\gamma p}(W) \qquad \sigma_{\gamma p}(W) = \sigma_P \cdot W^\epsilon + \sigma_M \cdot W^\eta$$

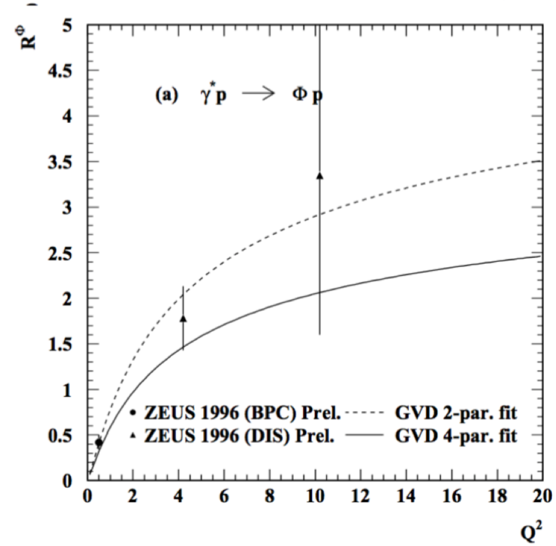
- $n=c_1+c_2(Q^2+M_V^2)$

Meson	c_1	c_2 $(10^{-2}\mathrm{GeV}^{-2})$
ρ	2.09 ± 0.10	0.73 ± 0.18
ϕ	2.15 ± 0.17	0.74 ± 0.46
J/ψ	2.36 ± 0.20	0.29 ± 0.43

- Pomeron & Reggeon (meson) exchange
  - Reggeon exchange matters at an EIC
- Q^2 dependence included via a power-law
  - Data on power n is not available for all mesons; we use the ‘closest’ meson
- $\sigma_{\gamma p}$ parameterized from HERA data
  - Pomeron exchange + Reggeon exchange
- More accurate parameterization used for heavy mesons, to better model near-threshold production

Vector meson decays





- Vector mesons retain the spin of the incident photon
- For Q^2 -> 0, s-channel helicity conservation means that the vector mesons are transversely polarized to the beam direction
  - As Q^2 rises, longitudinal polarization rises
- The Q^2 dependence of the transverse:longitudinal polarization ratio is not well known
- Parameterize HERA data in terms of spin-matrix elements:

$$R_v = \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - r_{00}^{04}}$$

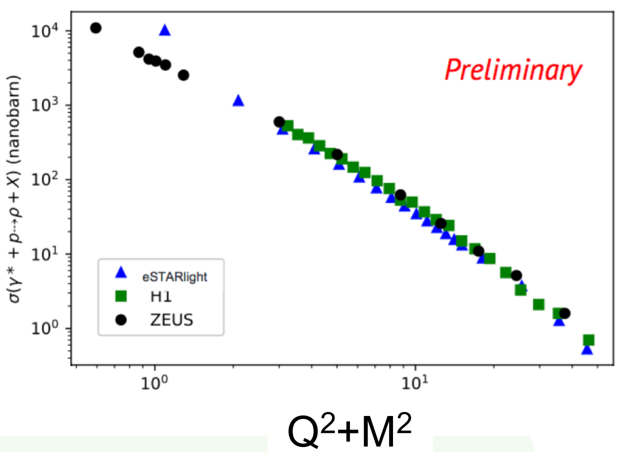
- Only known for some mesons; use most ‘similar’ meson where needed

Comparison with HERA data

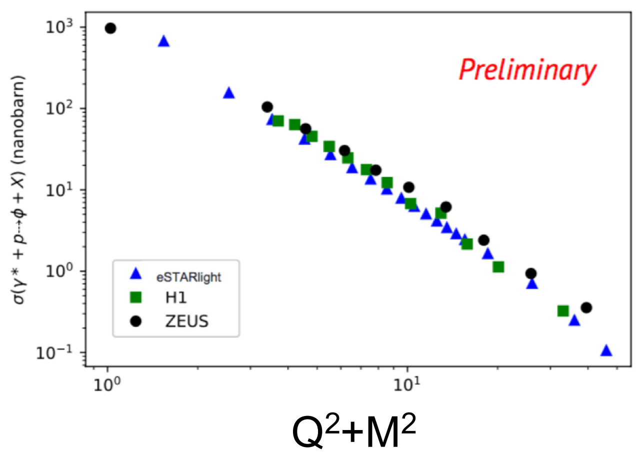
$$\sigma_{\gamma p} = \frac{\int dE_\gamma \int dQ^2 \frac{d^2N}{dE_\gamma d(Q^2)} \sigma_{\gamma p}(E_\gamma, Q^2)}{\int dE_\gamma \int dQ^2 \frac{d^2N}{dE_\gamma d(Q^2)}}$$

- HERA shows γ^*p cross-sections
  - Remove the photon flux from the eSTARlight calculations

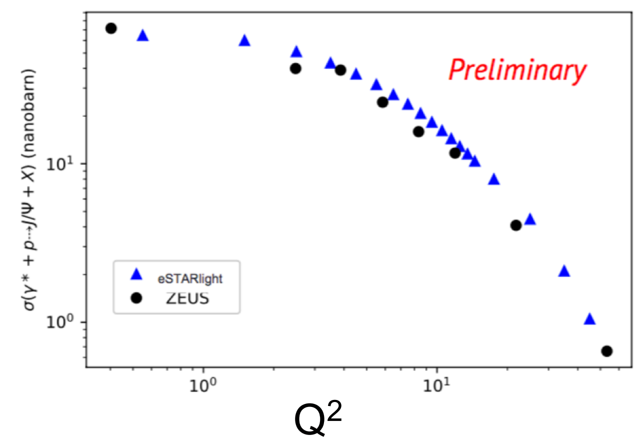
ρ

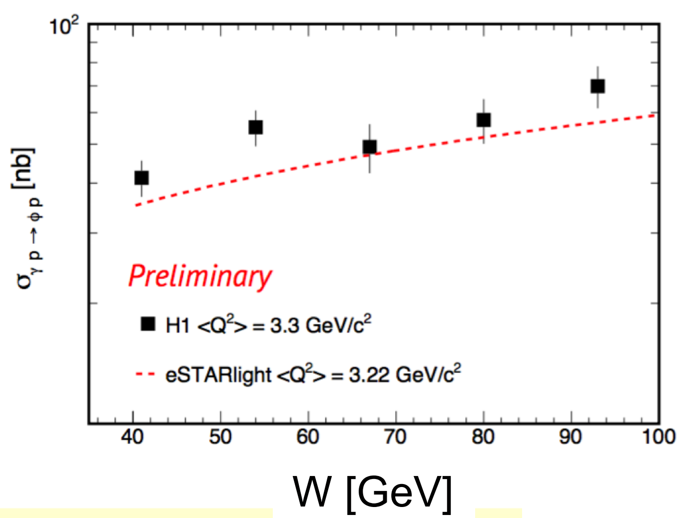


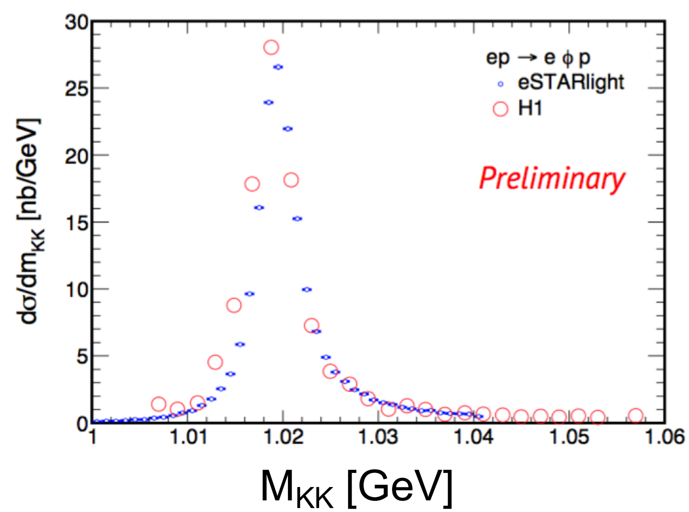
ϕ



J/ψ







From γp to γA

- With a quantum Glauber calculation, generalized vector meson dominance and the optical theorem:

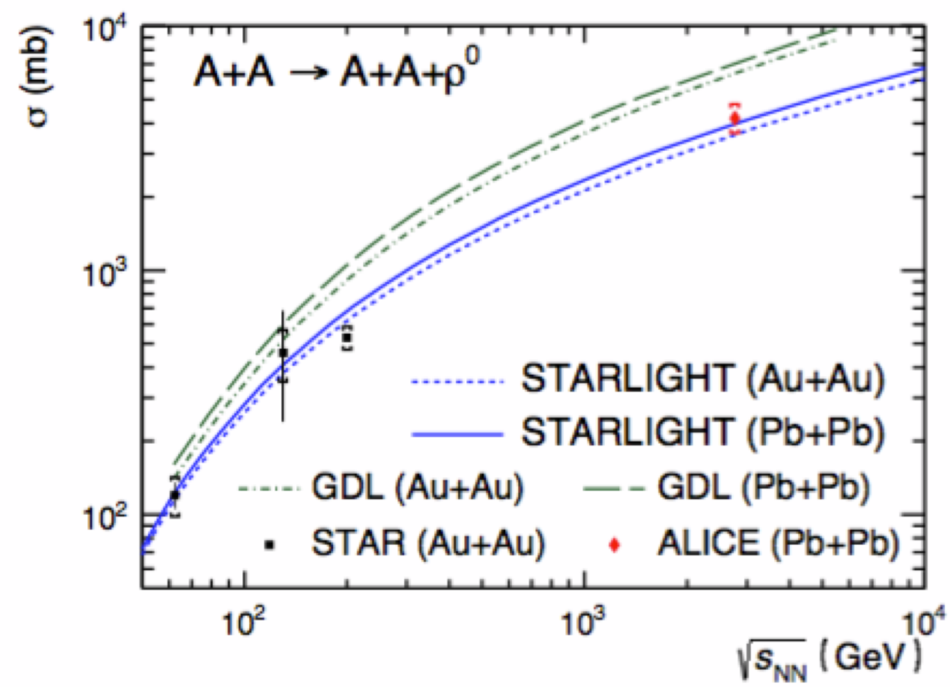
$$\sigma_{tot}(VA) = \int d^2b \left[2 \cdot \left(1 - e^{-\sigma_{tot}(Vp)T_{AA}(b)/2}\right)\right]$$

$$\sigma(\gamma A \to VA) = \frac{d\sigma(\gamma A \to VA}{dt}\bigg|_{t=0} \int_{t_{min}}^{\infty} dt |F(t)|^2$$

- For heavy mesons (small dipoles), $d\sigma/dt|_{t=0} \sim A^2$
- For the ρ^0 (smallish dipoles), $d\sigma/dt|_{t=0} \sim A^{4/3}$

Glauber calculations

- quantum Glauber calculation does not match STAR and ALICE UPC data; a classical Glauber does well.
  - Can add a correction for nuclear inelastic shadowing
  - eSTARlight currently allows classical Glauber as an option



ALICE, JHEP 1509, 095 (2015).
L. Frankfurt et al. Phys. Lett. **B752**, 51 (2018)

Rates at EICs

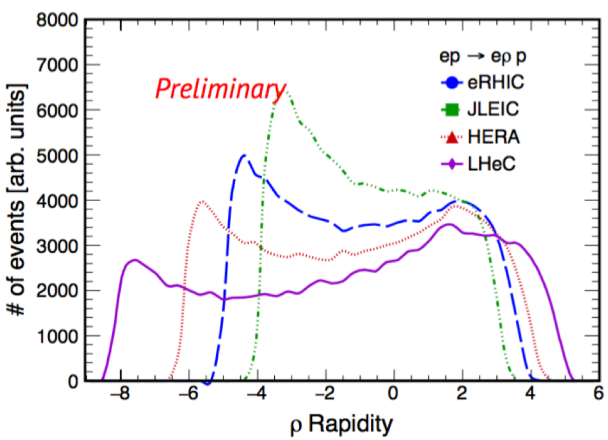
- Assumed integrated luminosity 10 fb^{-1}/A

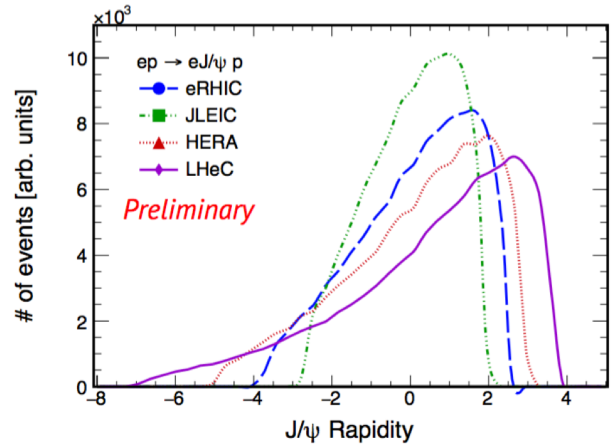
		Photo-production ($Q^2 < 1$ GeV^2)					Electro-production ($Q^2 > 1$ GeV^2)				
		ρ	ϕ	J/ψ	ψ'	Υ	ρ	ϕ	J/ψ	ψ'	Υ
eRHIC	ep	50 G	2.3 G	85 M	14 M	140 K	140 M	17 M	5.7 M	1.2 M	24 K
	eAu	44 G	2.8 G	100 M	16 M	60 K	37 M	5.6 M	3.9 M	960 K	10 K
JLEIC	ep	37 G	1.6 G	39 M	6.0 M	43 K	100 M	12 M	2.7 M	550 K	7.9 K
	ePb	28 G	1.6 G	28 M	3.9 M	-	22 M	3.2 M	1.2 M	250 K	-
LHeC	ep	100 G	5.6 G	470 M	78 M	1.2 M	260 M	37 M	29 M	6.3 M	180 K
	ePb	110 G	8.2 G	720 M	140 M	2.0 M	100 M	16 M	27 M	7.2 M	250 K

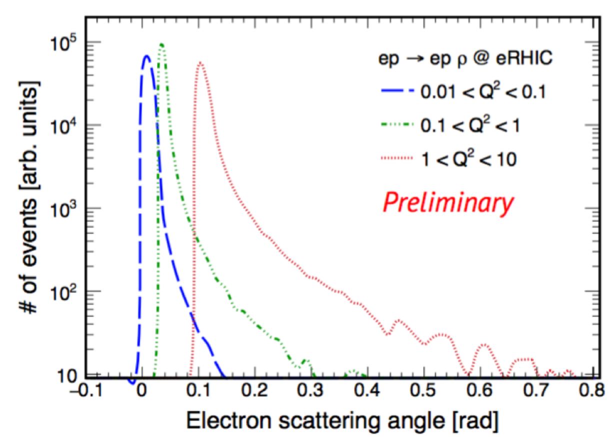
- Photoproduction
  - High rates (>10^9/year) for light mesons
  - Good rates (>10^6/year) for ccbar
  - Usable rates for Upsilon
- Electroproduction
  - Rates from ~<1% of photoproduction (light mesons), rising to 15% of photoproduction rates for the Upsilon

Rapidity and Angular distributions

- Vector meson production over a wide rapidity range
  - N. b. unscaled distributions here



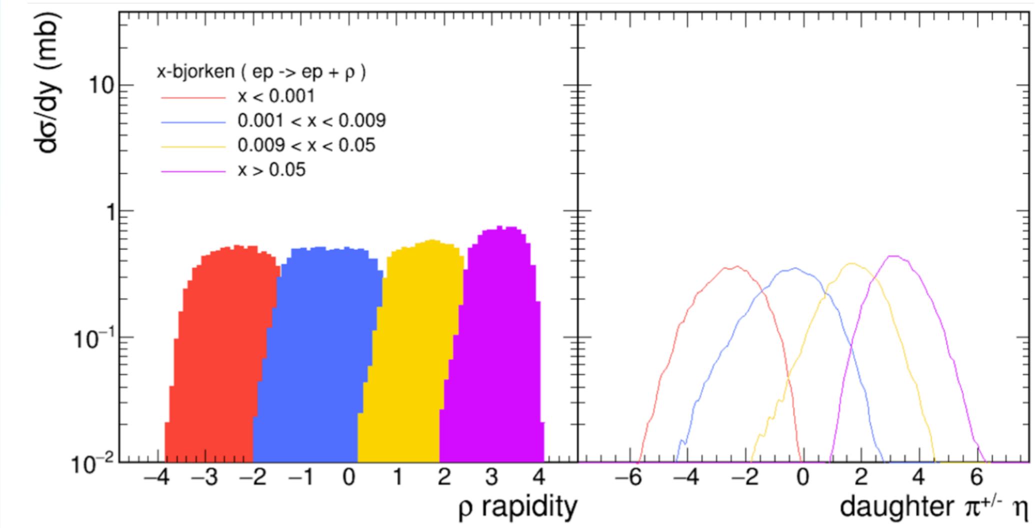




- ρ^0 'double peak' is due to Reggeon exchange (near threshold) and Pomeron exchange at large k/rapidity
- If pure Pomeron exchange is important need to go to large rapidity, or use ϕ or J/ψ, which are not produced via Reggeon exchange
- Electrons scattering angle is small (no surprise)

Photon energy/Bjorken-x vs. rapidity

- For photoproduction, k= $M_V/2$ ln(y)
  - Electroproduction shifts this slightly to the right



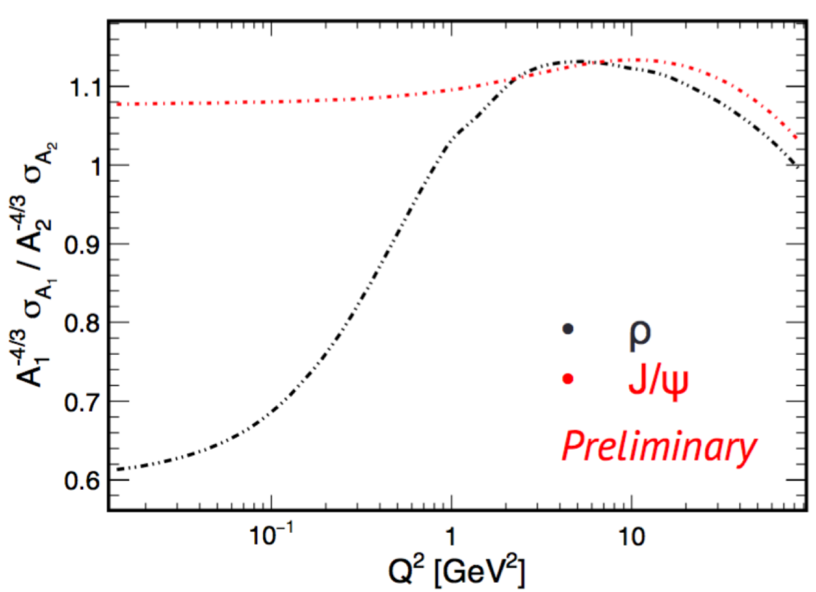
- Rapidity range widest for light mesons
  - Want to detect rho in range |y|<4
  - Pions extend to pseudorapidity $|\eta|<6$
  - Need correct polarization to get pseudorapidity range
- Shift threshold to mid-rapidity by lowering beam energy

J. Arrington et al., arXiv:2102.08337

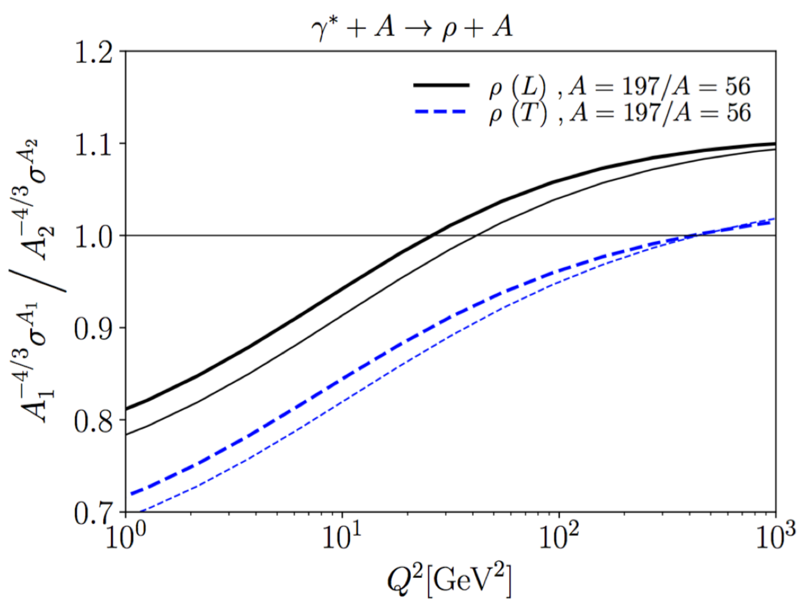
Cross-section vs. A & Q^2: shadowing

- Without shadowing (i. e. for small dipoles), the cross-section scales as $A^{4/3}$
  - A^2 for forward scattering cross-section, $A^{-2/3}$ for phase space
  - With shadowing, the growth in σ with A is smaller
- eSTARlight reproduces this well

eSTARlight



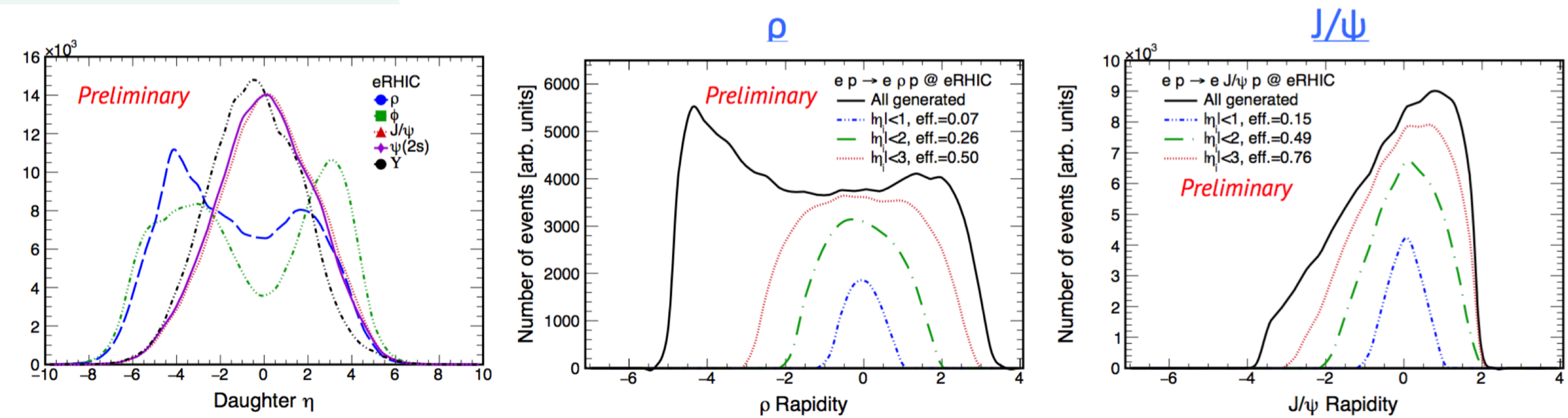
Mantysaari & Venugopalan



Phys.Lett. B781 (2018) 664-671

Final state particle distributions

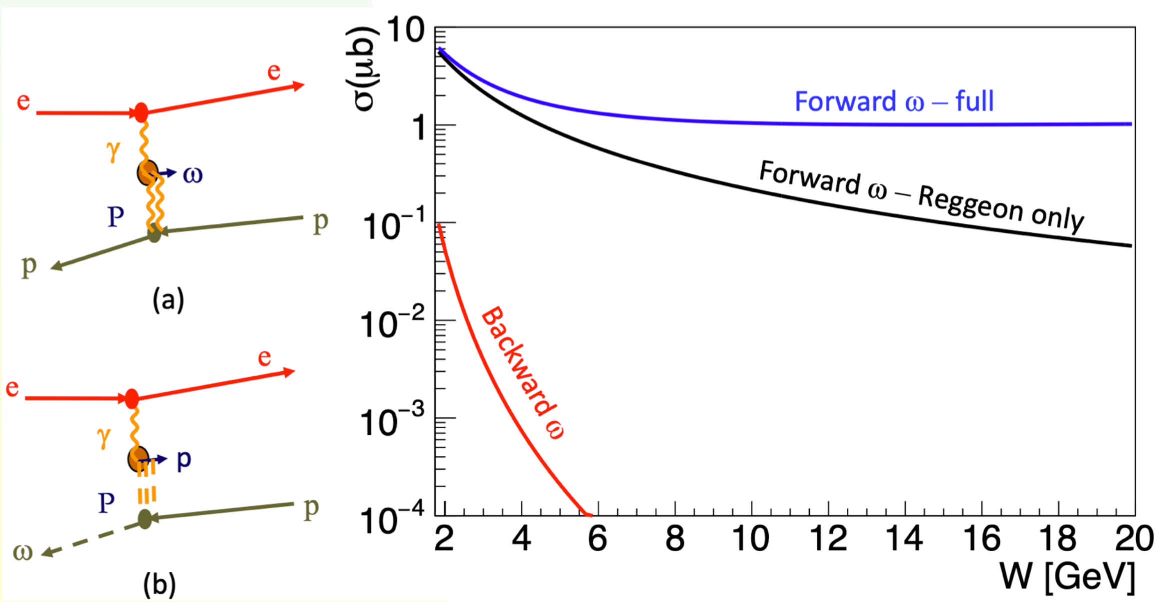
- The vector meson daughter particles generally follow the rapidity distribution of their vector meson parents
- The final state matters: VM -> spin 0 spin – (e. g. ππ) has a very different angular distribution from VM -> spin ½ spin ½
  - Clebsch Gordon coefficients



- Large detector acceptance is key to high acceptance.
  - Otherwise, we waste beam

One recent addition: backward production

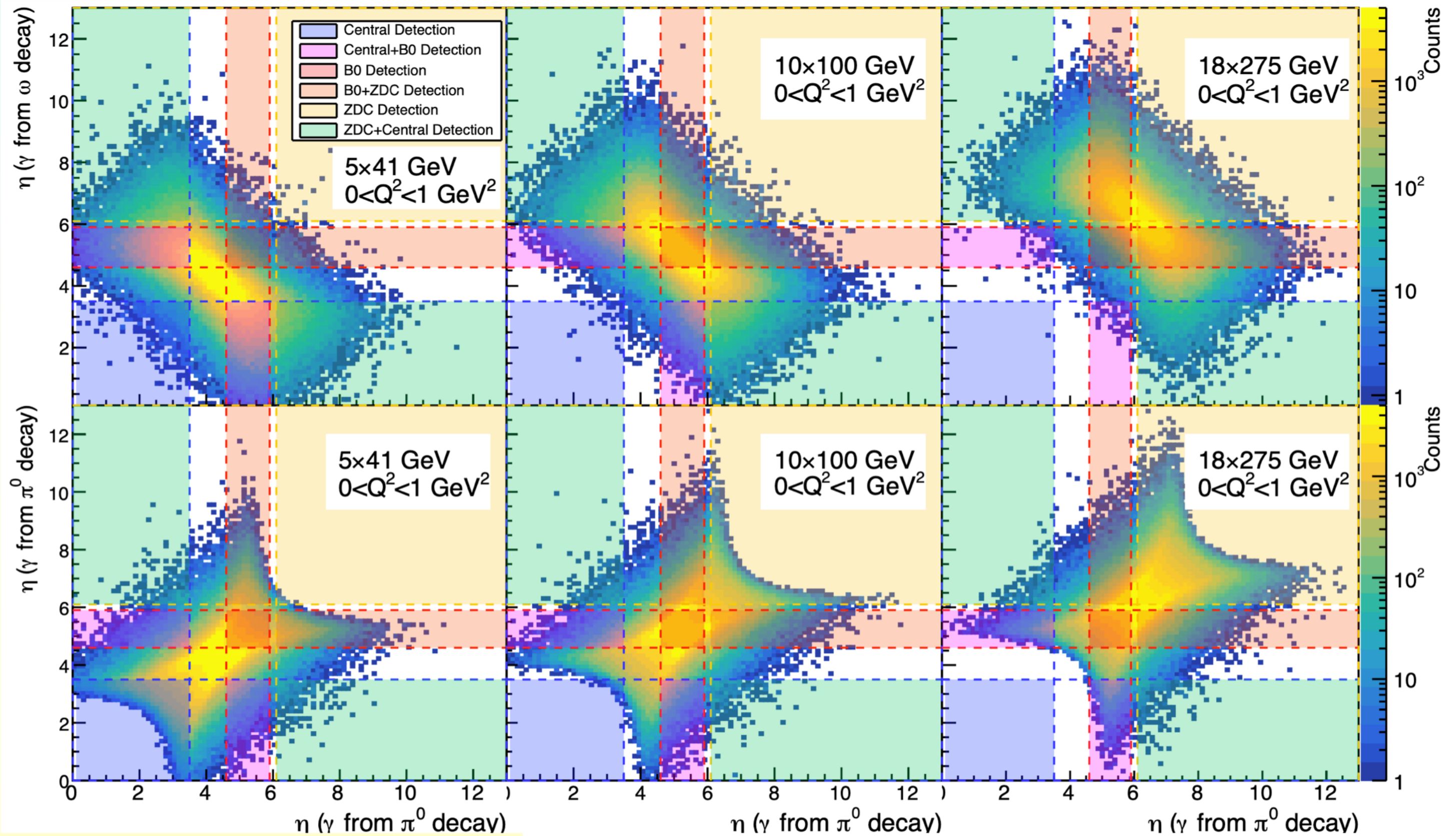
- In backward production, |t| is large, but |u| is small
- Transports baryon number over several units of rapidity
  - Baryon transport
  - Vector meson takes most of baryon momentum
- Fixed-target backward ω data parametrized with a Regge model
  - Usual dσ/dt~exp(-bt) swapped for dσ/du ~ exp(-ct)



D. Cebra *et al.*, Phys. Rev. C **106**, 015204 (2022)

Backward production at the EIC

- $\omega \to \pi^0\gamma$ and $\rho \to \pi^+\pi^-$ simulations in ATHENA framework
  - (and, soon, we hope, in EPIC)
- Forward detectors are critical
- Detection best at less than full beam energies
- Rates are ample; heavier VM should also be in reach



eSTARlight at: http://github.com/eic/estarlight

- Moved from hepforge
- C++ code
  - Should be compliant with C++ 17 (we hope)
    - Issues with new compilers are fixed as they are reported
- Dependencies
  - PYTHIA8 (for complex decays)
  - DPMJET3 for arbitrary eA photoproduction (w/Q^2=0)
  - HEPMC3 if HEPMC3 output desired
- Easy to download and install
- Please try it, and provide feedback

Future eSTARlight plans

- Additional mesons
- Charge exchange reactions $\gamma p \to X^+ n$
- Exotica?

- We welcome interested parties as co-developers
  - Spin effects?
  - GPDs?

Conclusions

- eSTARlight simulates photoproduction and electroproduction of vector mesons in ep/eA collisions
- It is designed as a tool for experimentalists, so it is based on parameterizations of HERA data, supplemented with theoretical input (such as a Glauber calculation to go from ep to eA collisions).
  - It includes a wide range of vector mesons with a wide range of decays.
  - It accounts for the photon polarization, and that polarization's effect on the vector meson decays.
- We welcome both feedback and co-development efforts to add features to the code.
- The code is available on github. Please try it and let us know what you think.

Implication for physics program

- Can measure rates and $d\sigma/dy$ for all mesons, in at least a couple of Q^2 bins
- Tomographic studies should be possible for all light mesons and the J/ψ
- Good data for spin-dependence studies
- $\psi(3770)$, $\psi(4040)$ should be accessible, even after accounting for small branching ratios to specific final states
- A host of ρ', ω', and ϕ', etc. states should be accessible
  - For meson spectroscopy, and to probe nucleons with different types of dipoles
- One could also look for exotica, and/or study rare light vector meson decays