Simulating vector meson production at an EIC with the eSTARlight Monte Carlo

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- Photoproduction and electroproduction at an EIC
- The eSTARlight Monte Carlo
  - ep simulations
  - eA simulations
  - Future plans
- Conclusions

Vector mesons at an EIC

- By the time the EIC sees first light, we will have good data on vector meson photoproduction cross-sections at a wide range of energies, down to Bjorken-x << 10^{-5}.
- EIC has some key advantages
  - Precise control of Q^2
    - Scan production cross-sections vs. Q^2
  - Better separation of coherent & incoherent VM production.
    - Better selection of single-photon exchange
    - Two limitations:
      - Nuclear excitation in an independent reaction
      - Missing photons from nuclear de-excitation
  - Higher luminosity
    - Multi-dimensional binning
    - Studies of Q^2 evolution of nuclear shape
      - Via Fourier-Bessel transform of $d\sigma_{coherent}/dt$

eSTARlight

- Monte Carlo for photoproduction and electroproduction of vector mesons at an EIC
  - Here, photoproduction is defined as $Q^2 < 1$ GeV^2, while electroproduction is $Q^2 > 1$ GeV^2
- Physics model follows STARlight UPC event generator, but covers photons with arbitrary Q^2
- A fast, complete, reasonably accurate model of vector meson production, not a sophisticated theoretical calculation
  - For detector simulations, etc.
  - 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
- Designed to be easily extensible

M. Lomnitz & S. Klein, arXiv:1803.06420

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
- Arbitrary beam energies…

Final states

- ρ, ω, ϕ, ρ' (i. e. $\pi\pi\pi\pi$), ρ + direct $\pi\pi$ (with interference), J/ψ, ψ', Υ(1S), Υ(2S), Υ(3S)
  - Simple final states are decayed in STARlight, with proper accounting for photon polarization and angular distributions
  - Complex final states via PYTHIA interface, but photon polarization information is lost
  - It is easy to add new states
- Incoherent photonuclear interactions w/ DPMJET
  - Real photon approximation
- eSTARlight tracks outgoing electron & proton/nucleon
- eSTARlight outputs photon 4-vector

Electronuclear interactions

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

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

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

V. Budnev *et al.*, Phys. Rept. 15, 181 (1975)

Cross-sections

- Parameterized from HERA data

$$\sigma_{\gamma p}(W) = \sigma_P \cdot W^{\epsilon} + \sigma_M \cdot W^{\eta}$$

$$\sigma_{\gamma p} = \left(\frac{1}{1+Q^2/M_v^2}\right)^n \sigma_{\gamma p}(W)$$

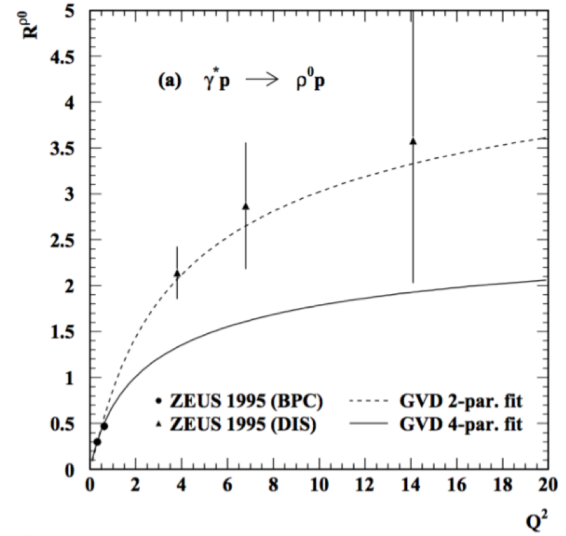
- $n=c_1+c_2(Q^2+M_V^2)$
- Pomeron & Reggeon (meson) exchange
  - Reggeon exchange matters at an EIC

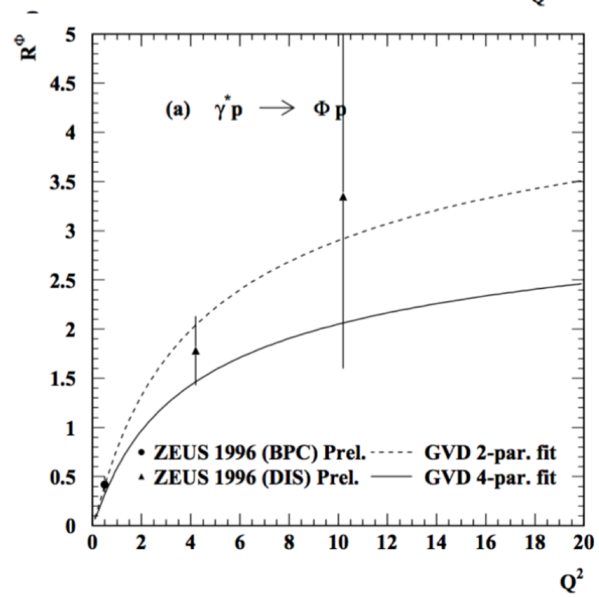
Meson	c_1	c_2 $(10^{-2}\mathrm{GeV}^{-2})$
ρ	2.09 ± 0.10	0.73 ± 0.18
ϕ	2.15 ± 0.17	0.74 ± 0.46
J/ψ	2.36 ± 0.20	0.29 ± 0.43

- 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 $Q^2 \to 0$, 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:
- Only known for some mesons; use most ‘similar’ meson where needed





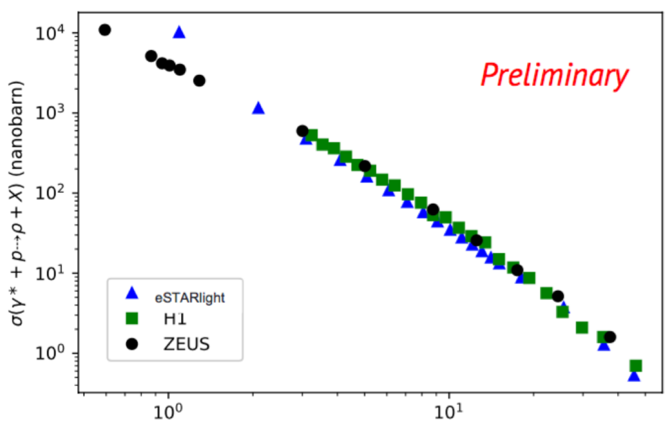
$$R_v = \frac{1}{\epsilon} \frac{r^{04}_{00}}{1 - r^{04}_{00}}$$

Comparison with HERA data

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

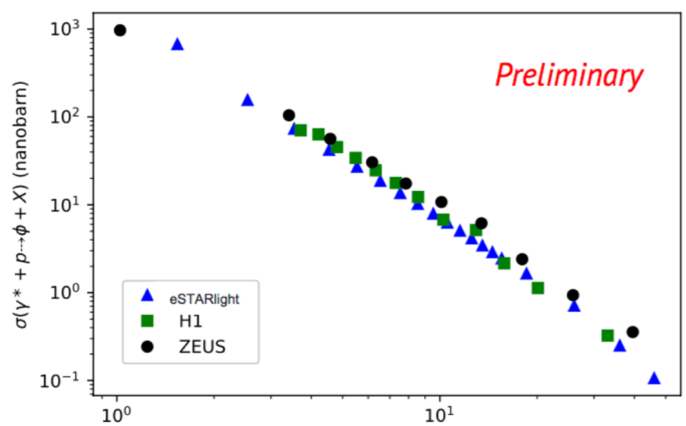
- HERA shows γ*p cross-sections
  - Remove the photon flux from the eSTARlight calculations

ρ



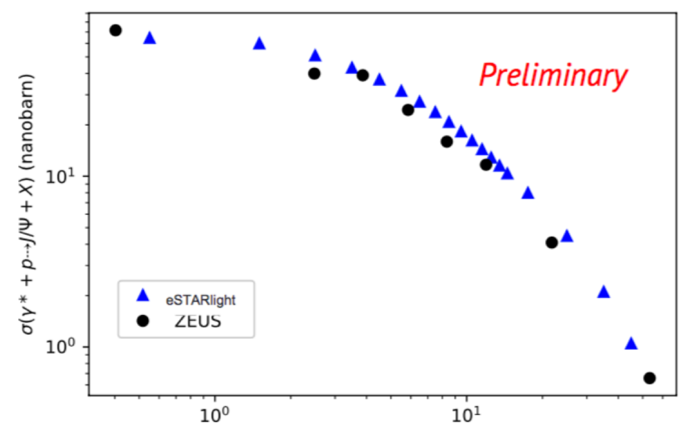
Q²+M²

ϕ

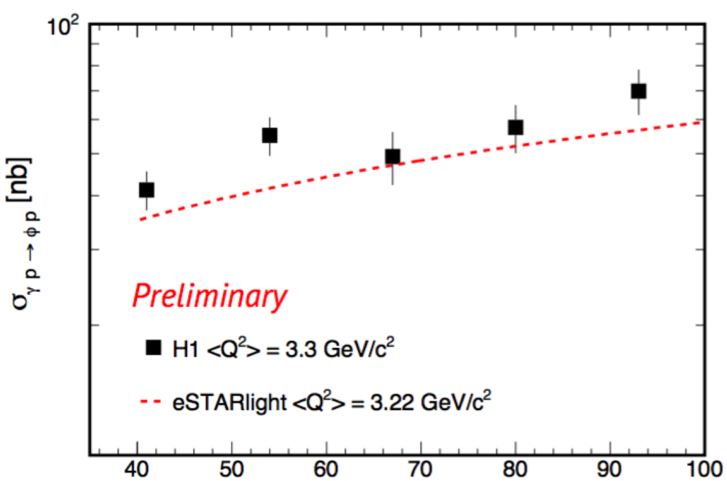


Q²+M²

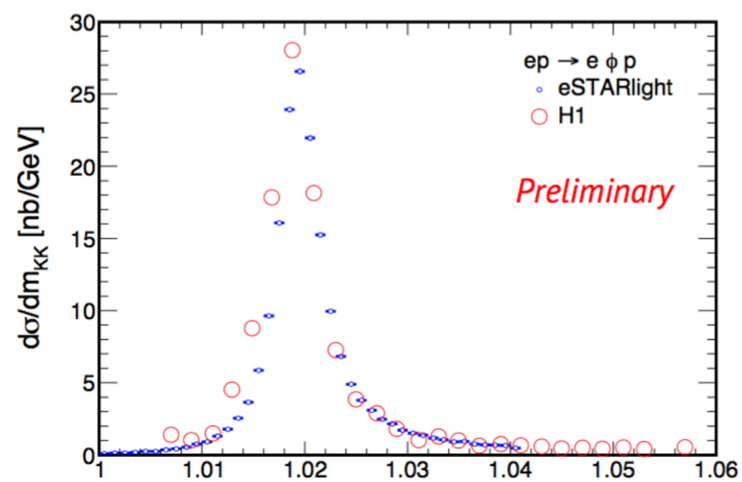
J/ψ



Q²



W [GeV]



M_{KK} [GeV]

From γp to γA

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

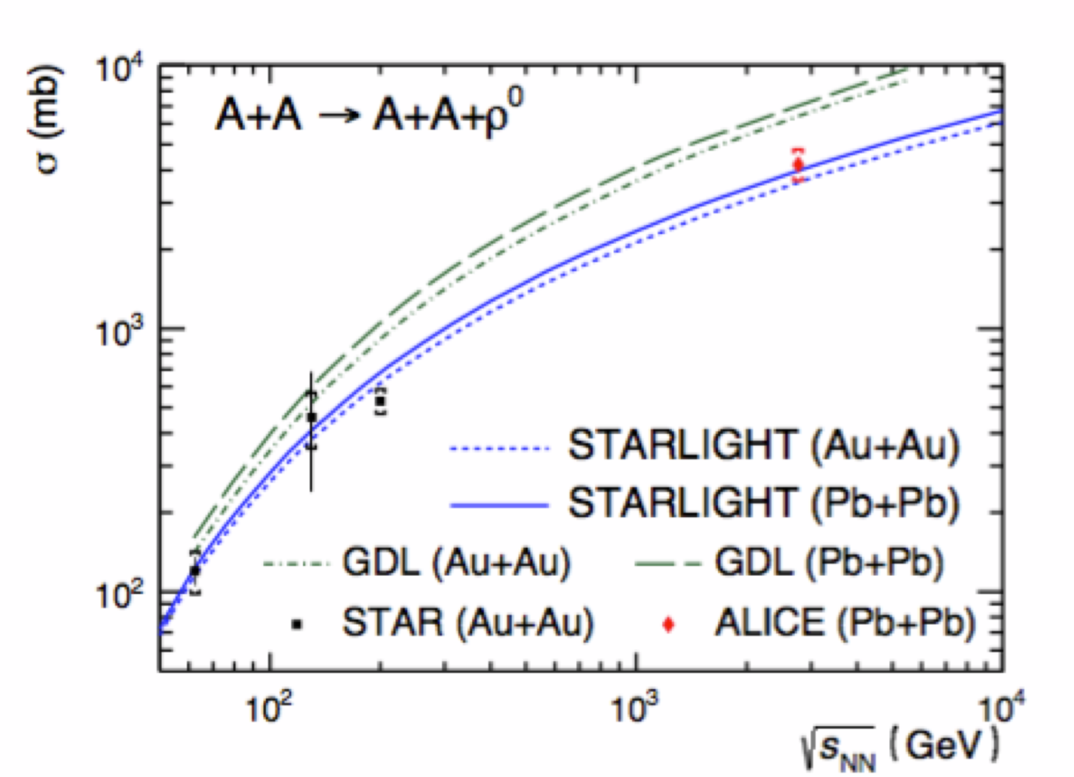
$$\sigma_{tot}(VA) = \int d^2b \left[2 \cdot \left(1 - e^{-\sigma_{tot}(Vp)T_{AA}(b)/2}\right)\right]$$

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

- For heavy mesons (small dipoles), $d\sigma/dt|_{t=0} \sim A^2$
- For the ρ^0 (large dipoles), $d\sigma/dt|_{t=0} \sim A^{4/3}$
- We require complete coherence, $l_c = 2k/(Q^2+M_V^2) > R_A$
  - Affects near-threshold production
- Gluon shadowing is not included
  - Overestimates cross—section by 30% for heavy nuclei?

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)

EIC parameters

- The calculations that follow use:

Accelerator	Collision System	Electron Energy	Heavy Ion Energy
eRHIC [21]	ep	18 GeV	275 GeV
-	eA	18 GeV	100 GeV/A
JLEIC [22]	ep	10 GeV	100 GeV
-	eA	10 GeV	40 GeV/A
LHeC [23]	ep	60 GeV	7 TeV
-	eA	60 GeV	2.8 TeV/A
HERA	ep	27.5 GeV	920 GeV

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

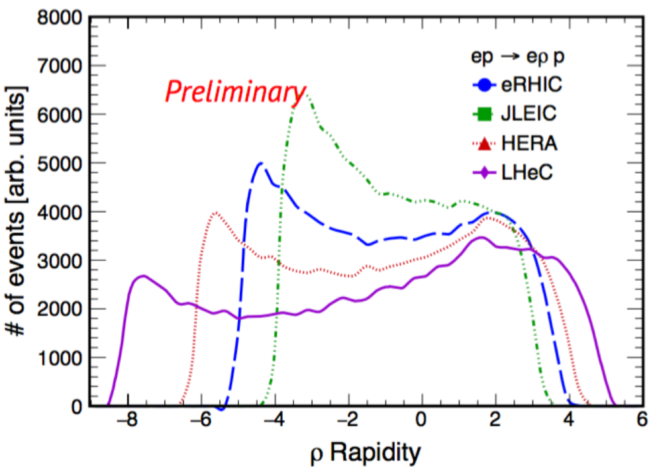
- Photoproduction
  - High rates (>10^9/year) for light mesons
  - Good rates (>10^6/year) for ccbar
  - Usable rates for Upsilon
- Electroproduction
  - Rates from ~<1% of photoproduction (light mesons), rising to 15% of photoproduction rates for the Upsilon

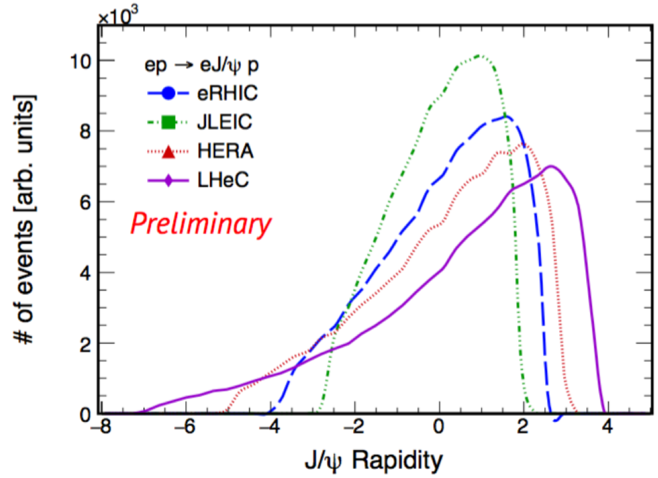
Implication for physics program

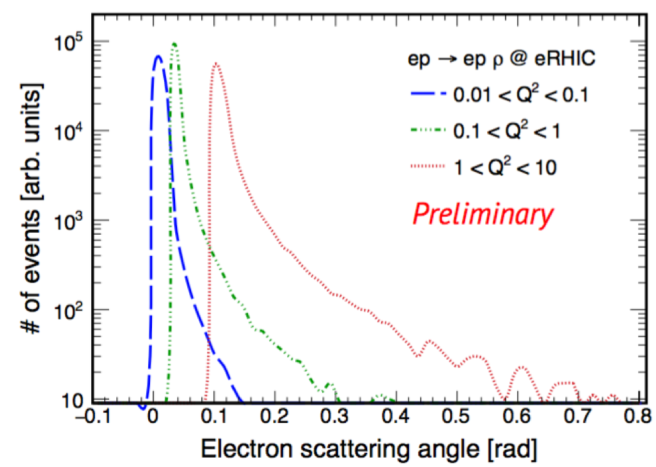
- Can measure rates and $d\sigma/dy$ for all mesons, in at least a couple of Q^2 bins
- Tomographic studies should be possible for all light mesons and the J/ψ
- Good data for spin-dependence studies
- $\psi(3770)$, $\psi(4040)$ should be accessible, even after accounting for small branching ratios to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

Rapidity and Angular distributions

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



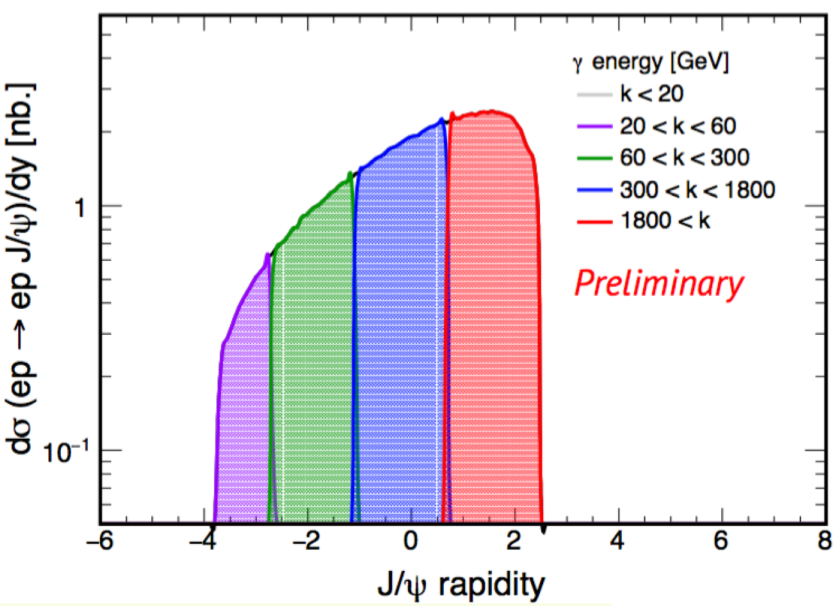


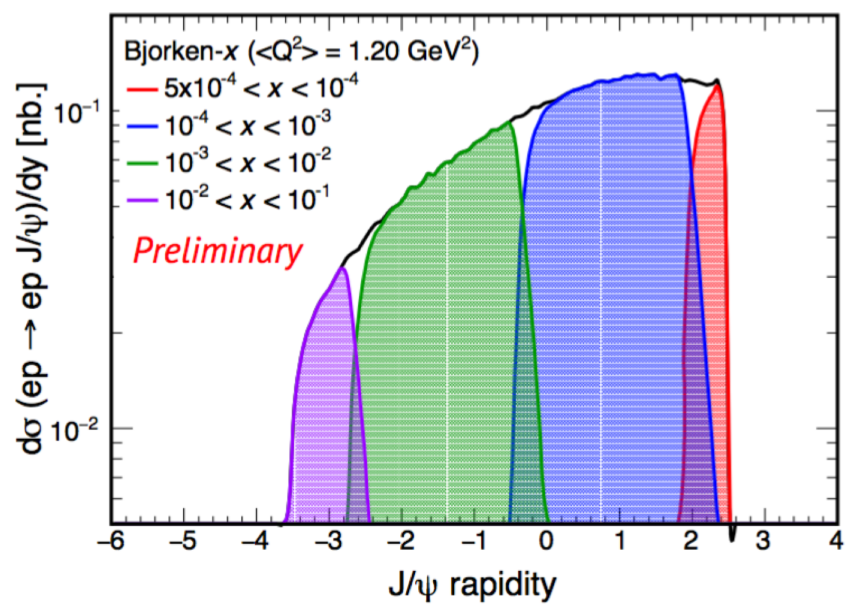


- ρ^0 ‘double peak’ is due to Reggeon exchange (near threshold) and Pomeron exchange at large k/rapidity
- If pure Pomeron exchange is important need to go to large rapidity, or use ϕ or J/ψ, which are not produced via Reggeon exchange
- Electrons scattering angle is small (no surprise)

ep production vs. photon energy, Bjorken-x

- Photon energy maps into rapidity
  - For photoproduction, k= $M_V/2 \ln(y)$
  - Electroproduction shifts this slightly to the right

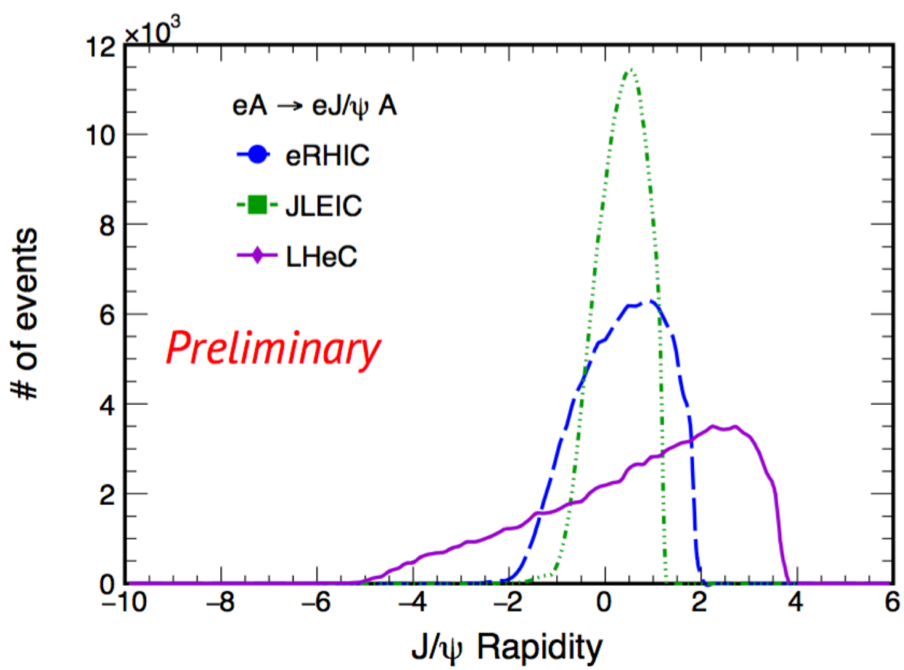


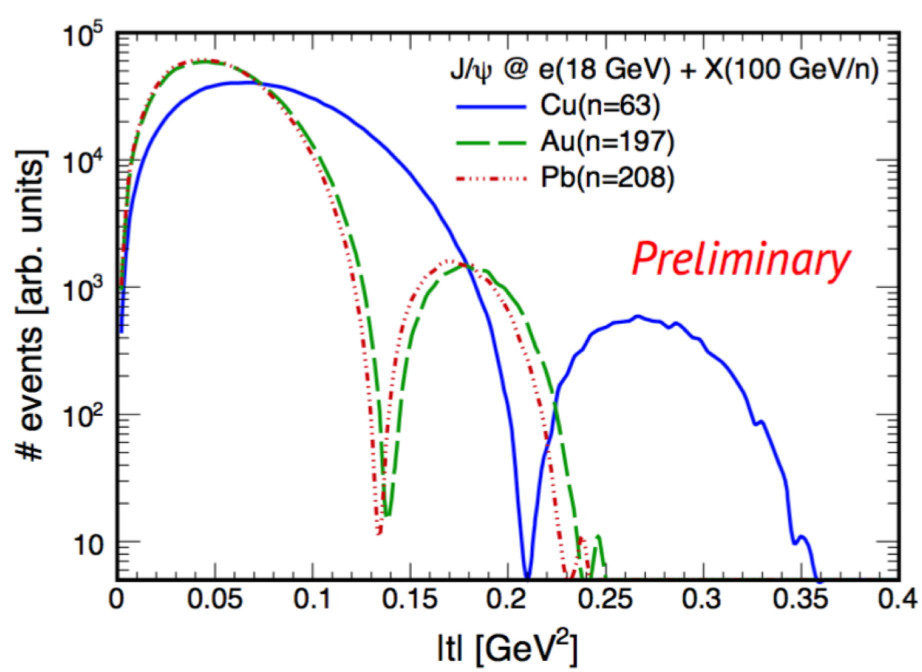


- Photon energy also maps onto Bjorken-x
- For maximum energy/Bjorken-x reach, need to detect vector mesons forward, with y ~ 2.5
- Near threshold, production is at large negative rapidity
  - Could shift to mid-rapidity by lowering beam energy

Production in eA

- Smaller γ-nucleon center of mass energy
  - Narrower rapidity range
- Lower Pomeron p_z -> production is more central
- Expect clean diffractive minima
  - Unlike in UPCs, photon momentum can be removed

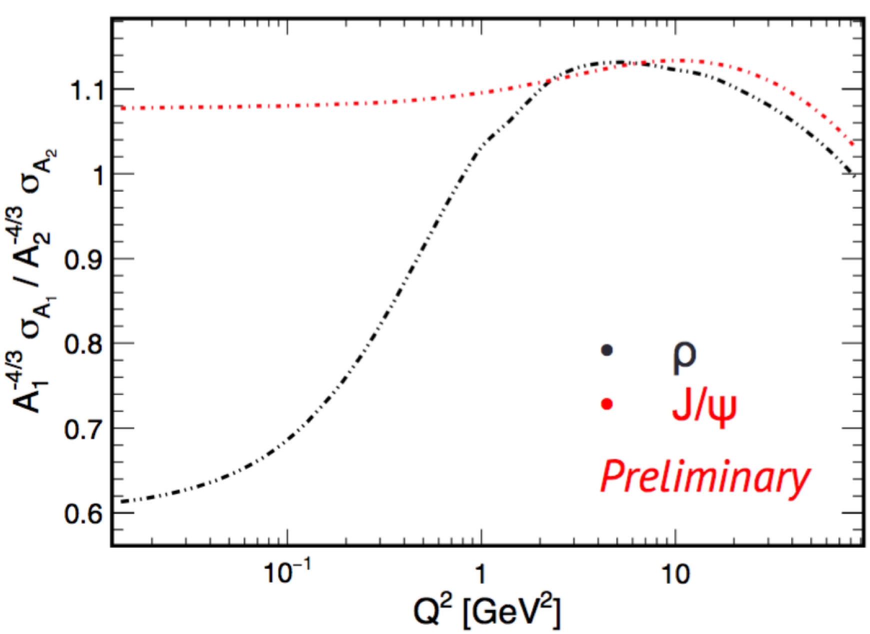




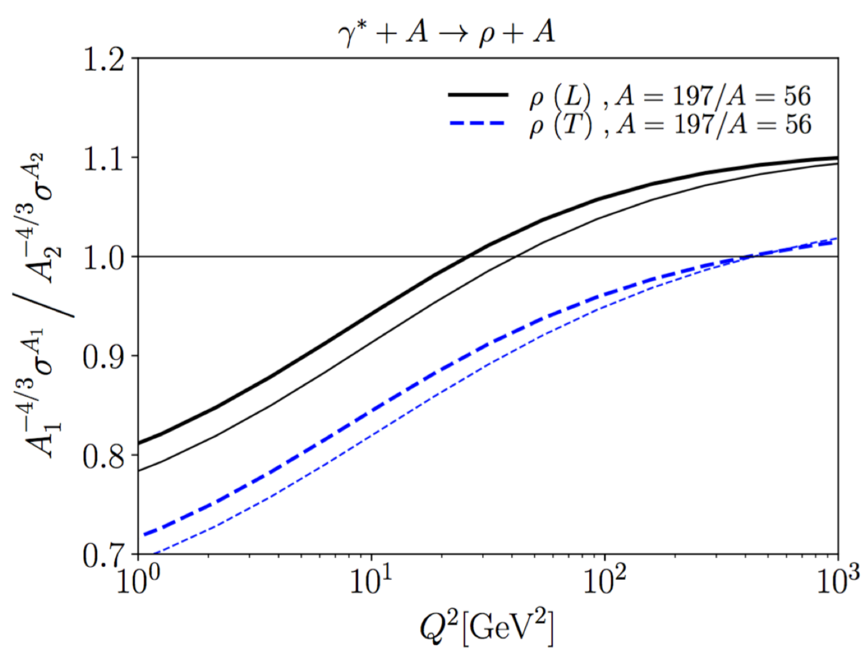
Cross-section vs. A & Q^2: shadowing

- 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



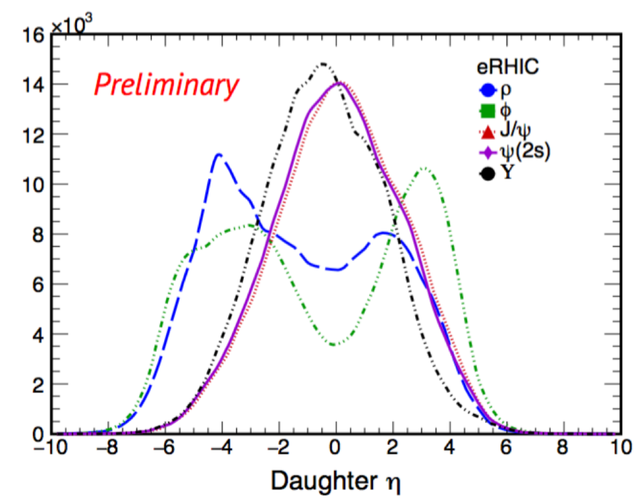
Mantysaari & Venugopalan



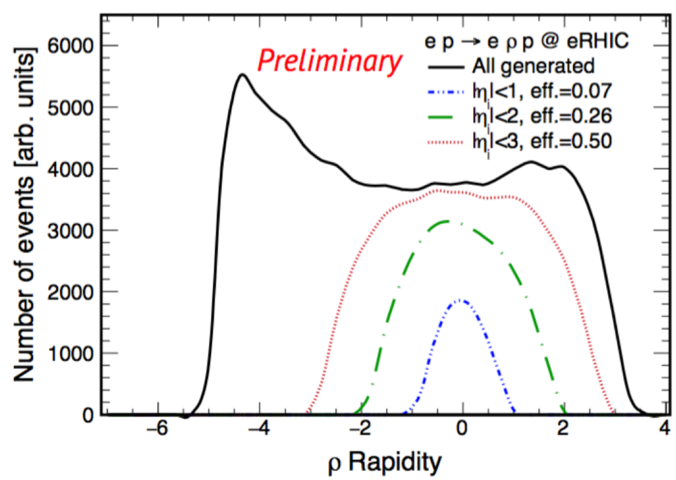
Phys.Lett. B781 (2018) 664-671

Final state particle distributions

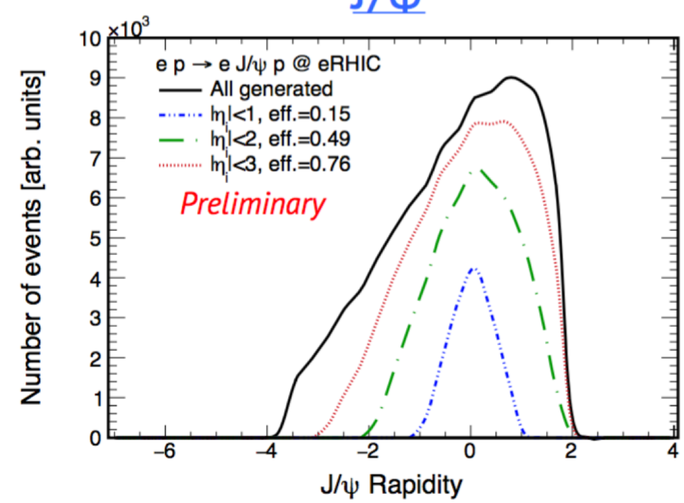
- The vector meson daughter particles generally follow the rapidity distribution of their vector meson parents
- The final state matters: VM -> spin 0 spin – (e. g. $\pi\pi$) has a very different angular distribution from VM -> spin ½ spin ½
  - Clebsch Gordon coefficients



ρ

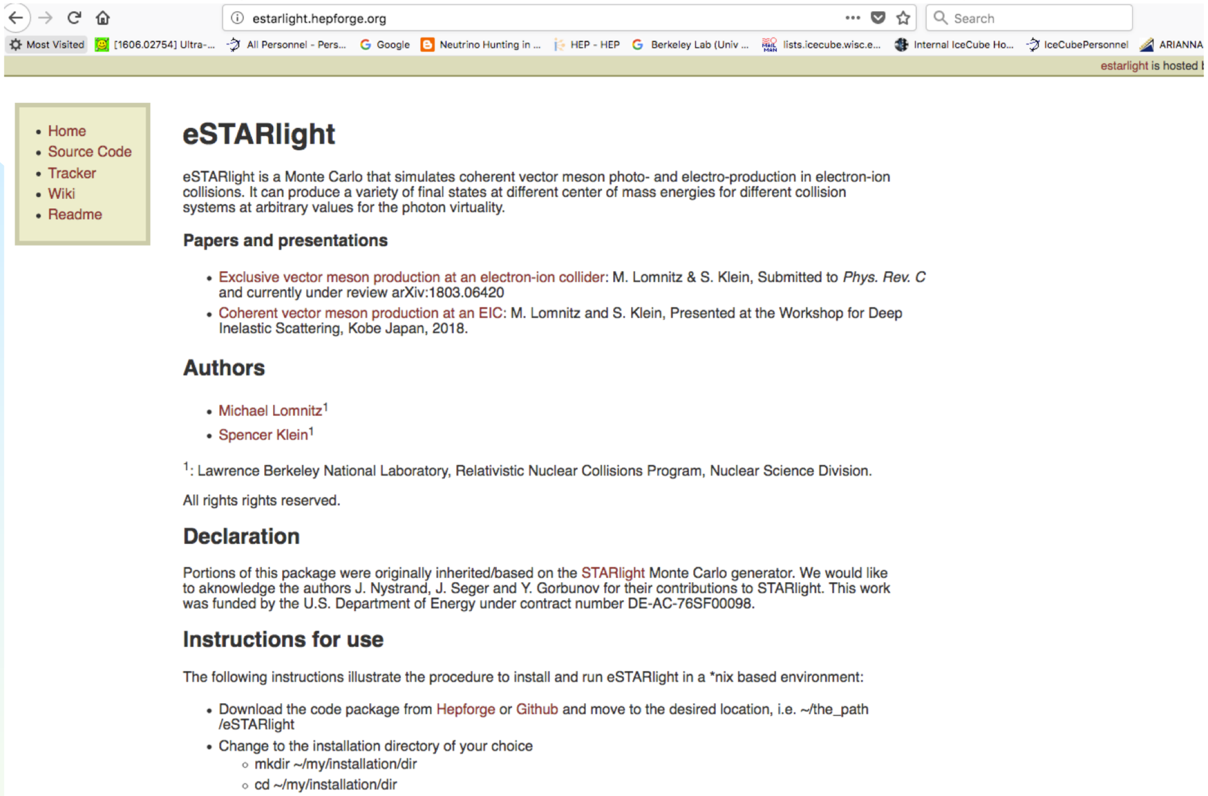


J/ψ



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

eSTARlight at: http://starlight.hepforge.net



- Straightforward C++ code
  - Optional inclusion of PYTHIA8 (for complex decays) and DPMJET3 for arbitrary eA interactions (w/Q^2=0 for DPMJET)
  - Easy to download and install
- If you need a hepforge account, please request one
- 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

- UPCs at hadron colliders and an EIC are complementary. UPCs have a larger photon energy/Bjorken-x, but lack good control of Q^2
- The EIC will also offer the luminosity to collect enormous data samples $d\sigma_{coheren}/dp_t^2$, to study the effective shape of the nucleus, as a function of Q2
- STAR has made a preliminary study of shape changes with varying Q2, using dipion $M_{\pi\pi}$ to select events with different dipole size
- We have developed the eSTARlight Monte Carlo event generator which simulates production of vector mesons at an EIC
    - It covers arbitrary ranges of Q^2
    - Initial runs show the importance of a wide detector acceptance. Forward acceptance is needed to probe the highest energy photons
- The eSTARlight code is available on hepforge. Please try it.
- We welcome both feedback and co-development efforts to add features to the code.