High-energy ep/eA collisions with the eSTARlight Monte Carlo

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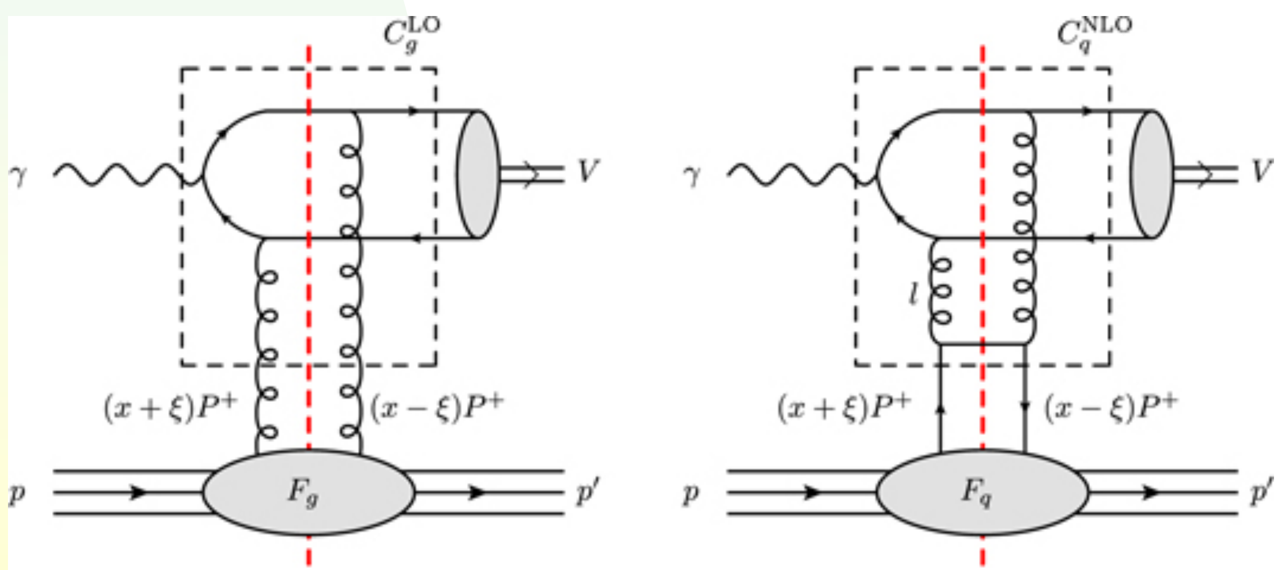
Presented at the workshop on "Electrons for the LHC - LHeC/FCCeh and Perle Workshop"

- Vector meson photo & electro-production
- The eSTARlight Monte Carlo
- ep and eA collisions
  - Current Status
  - Future plans
- Conclusions

Exclusive vector meson photo & electro production

- An important probe of nuclear structure
- LHeC/FCC-eh probe gluons at very low Bjorken-x
  - Proton or nuclear targets
- Proceeds via Pomeron or Reggeon (meson) exchange
  - Pomeron ~~ 2 gluons ~~ BFKL gluon ladder
    - Directly sensitive to gluon distribution
    - 2nd gluon complicates gluon density extraction
      - Much discussion….



Jones, Martin, Ryskin, Teubner

From now to LHeC & FCC-eh

- By the time LHeC or FCC-eh run, we will have good data on vector meson photoproduction cross-sections at a wide range of energies from UPCs
- ep/A colliders can focus on more data-hungry analyses, and those requiring precise control of Q^2, like measuring the spatial dependence of shadowing.
  - Scan in Q^2 with M_V fixed
  - Larger reach in t -> better measurement of the transverse interaction profile (like GPD, but for nuclei)
  - Better (but not perfect) separation of coherent and incoherent photoproduction.
    - Nuclear excitation in an independent reaction
      - Growing importance at higher luminoties…
    - Missing photons from nuclear de-excitation

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
- 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….
  - 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, to appear in Phys. Rev. C

Initial and final states

- Electron (or positron) on protons/ light ions (Z< 7, Gaussian distribution)/ heavy ions (Woods-Saxon distribution
- 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) states
  - Simple states decayed in STARlight
  - Complex final states via PYTHIA interface
  - Easily extensible
- Incoherent photonuclear interactions w/ DPMJET
  - Real photon approximation
- eSTARlight tracks outgoing electron & proton/nucleon
- eSTARlight outputs photon 4-vector

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

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

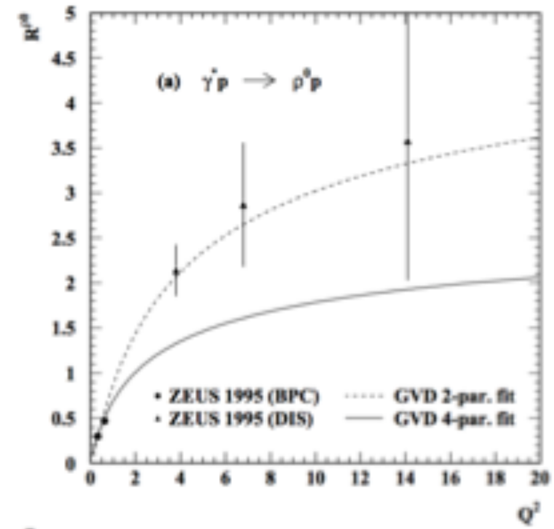
- $n=c_1+c_2(Q^2+M_V^2)$
- $\sigma_{\gamma p}$ parameterized from HERA data
  - Pomeron exchange + Reggeon exchange
    - Reggeon exchange matters for ρ/ω, at lower photon energies

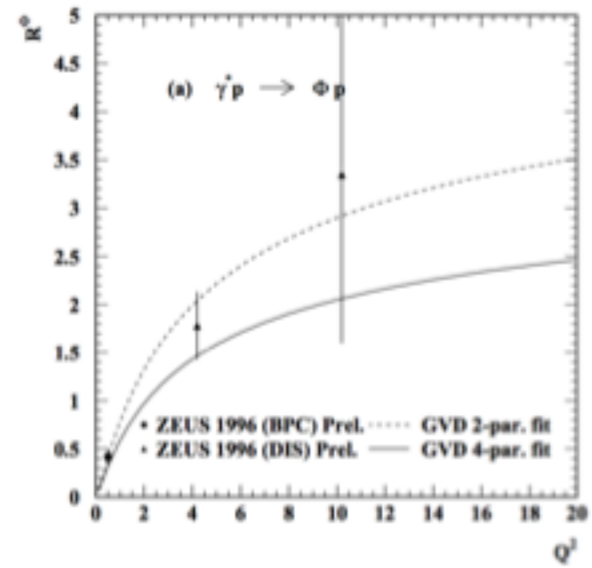
Meson	c_1	c_2 $(10^{-2}\mathrm{GeV}^{-2})$
ρ	2.09 ± 0.10	0.73 ± 0.18
ϕ	2.15 ± 0.17	0.74 ± 0.46
J/ψ	2.36 ± 0.20	0.29 ± 0.43

- Q^2 dependence included via a power-law
  - Data on power *n* is not available for all mesons; we use the 'closest' meson
- 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:
- Only known for some mesons; use most 'similar' meson where needed





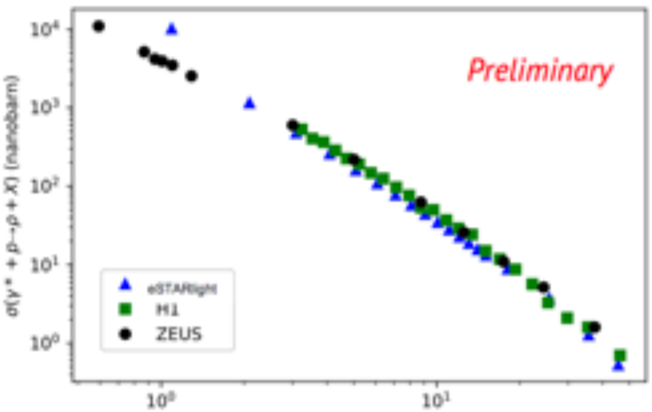
$$R_v = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}}$$

Comparison with HERA data

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

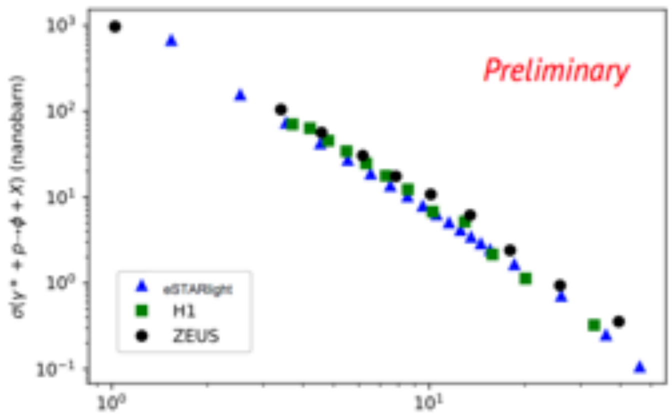
- HERA shows γ^*p cross-sections
  - Remove the photon flux from the eSTARlight calculations

ρ



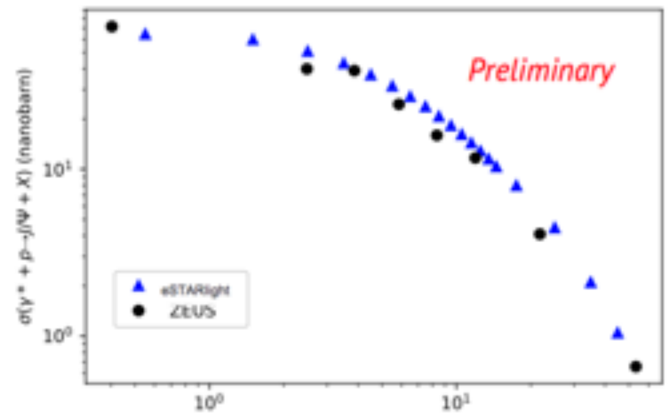
Q²+M²

ϕ

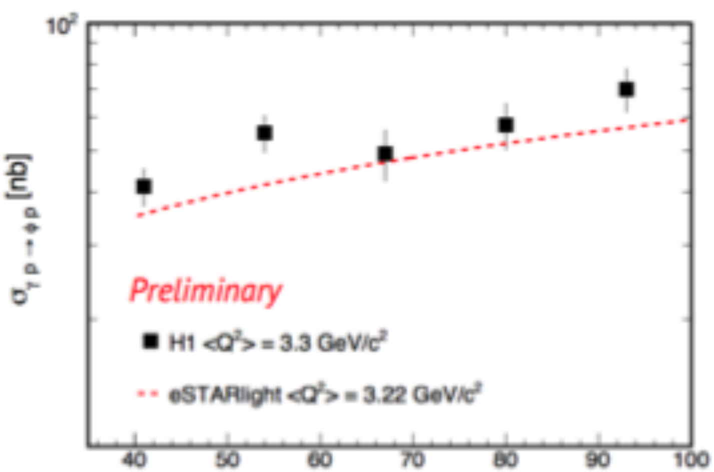


Q²+M²

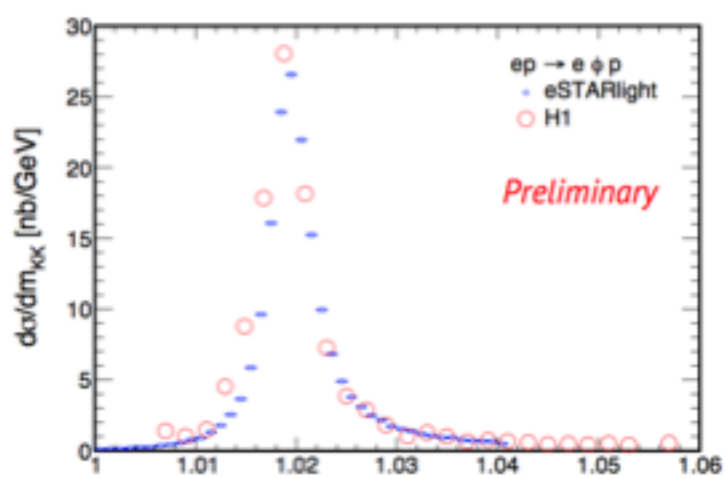
J/ψ



Q²



W [GeV]



MKK [GeV]

From γp to γA

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

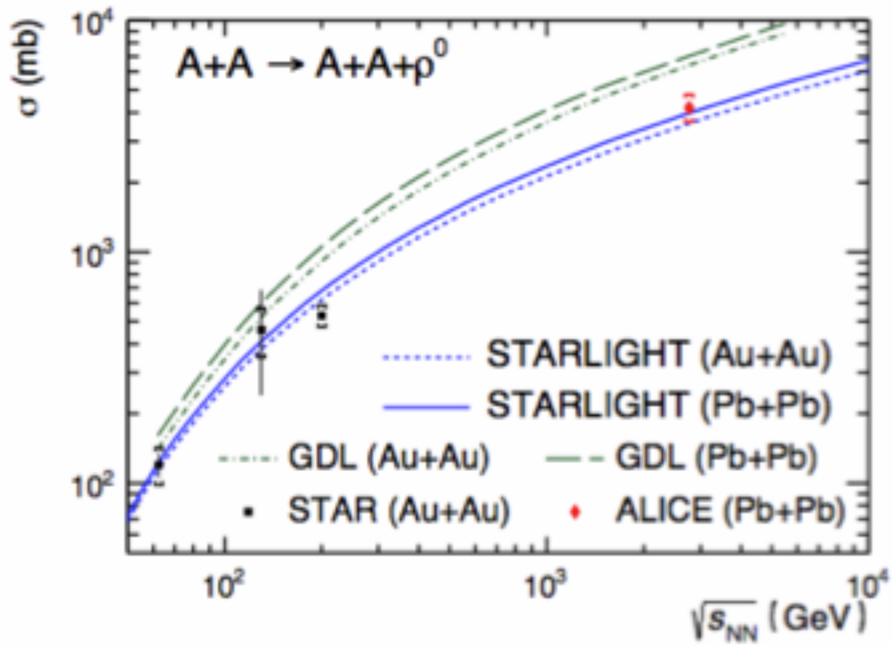
$$\sigma_{tot}(VA) = \int d^2b \left[2 \cdot \left(1 - e^{-\sigma_{tot}(Vp)T_{AA}(b)/2}\right)\right]$$

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

- 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 uses quantum Glauber; classical Glauber is an option
  - Only important for ρ/ω



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

Accelerator parameters

- The calculations that follow use:

Accelerator	Collision System	Electron Energy	Ion Energy
eRHIC	ep eA	18 GeV	275 GeV 100 GeV/A
JLEIC	ep eA	10 GeV	100 GeV 40 GeV/A
LHeC	ep eA	60 GeV	7 TeV 2.8 TeV/A
Fcc-eh	ep eA	60 GeV	50 TeV 20 TeV/A
HERA	ep	27.5 GeV	920 GeV

I will not cover PERLE here, but 1 GeV electrons colliding with 7 TeV protons is at 167 GeV center of mass energy. This can be interesting, but the extreme energy imbalance would requires a very backward detector.

Rates at EICs

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

		Photo-production ($Q^2 < 1$ GeV^2)					Electro-production ($Q^2 > 1$ GeV^2)				
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

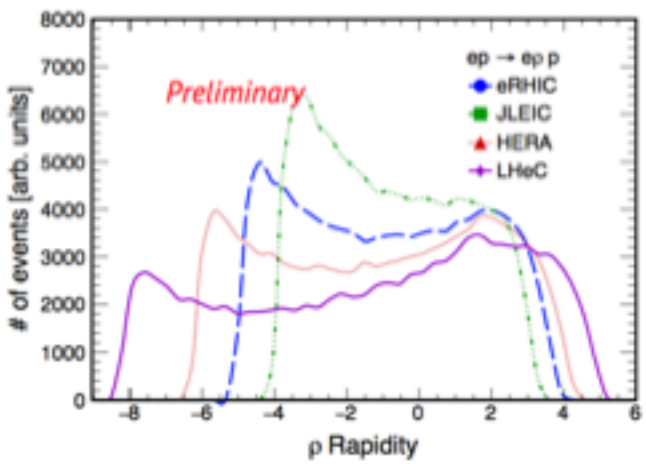
- Photoproduction at LHeC
  - High rates (>10^9/year) for light mesons
  - Good rates (>10^6/year for c-cbar, >10^5/year for b-bbar)
- Electroproduction
  - Rates from ~<1% of photoproduction (light mesons), rising to 15% of photoproduction rates for the Upsilon
- FCC-eh luminosity 15* LHeC, $\sigma(\gamma p \to J/\psi\ p)$ 12 * higher
  - Rate 180 times higher

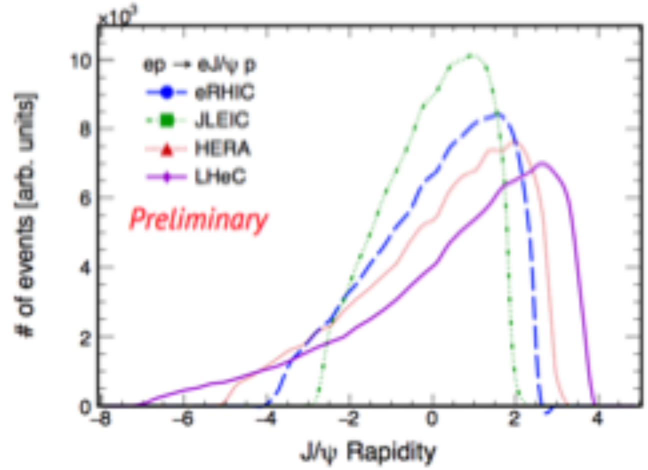
Implication for physics program

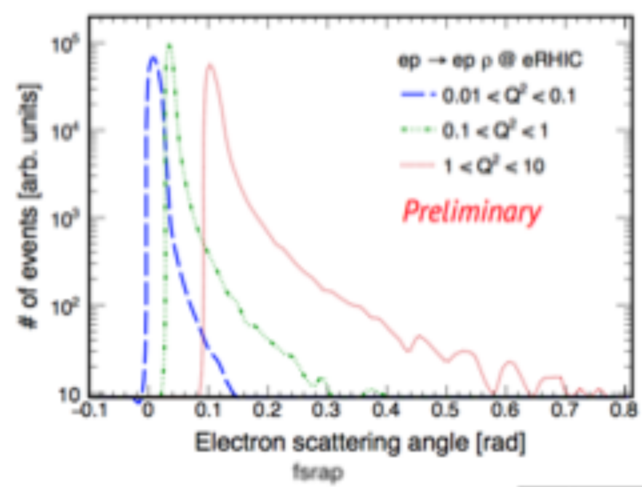
- FCC-eh & LHeC rates allow multi-dimensional binning and tomographic studies for light, c-cbar & b-bbar mesons.
  - At LHeC, statistics may be somewhat limited for b-bar mesons.
  - $\psi(3770)$, $\psi(4040)$ (even with the small branching ratios)
  - Exotica, including, at FCC-eh b-bbar exotica
- A host of ρ', ω', and ϕ', etc. states should be accessible
  - Meson spectroscopy & rare decays, and probe nucleons with different dipoles
- At FCC-eh & LHeC, exclusive t-tbar production should be visible
  - Top quarks decay before toponium can form
  - At FCC-eh, t-tbar dipole lives long enough to scatter from target
  - Usual VM width based cross—section calculation doesn't work
  - Worth further investigation

Rapidity and Angular distributions

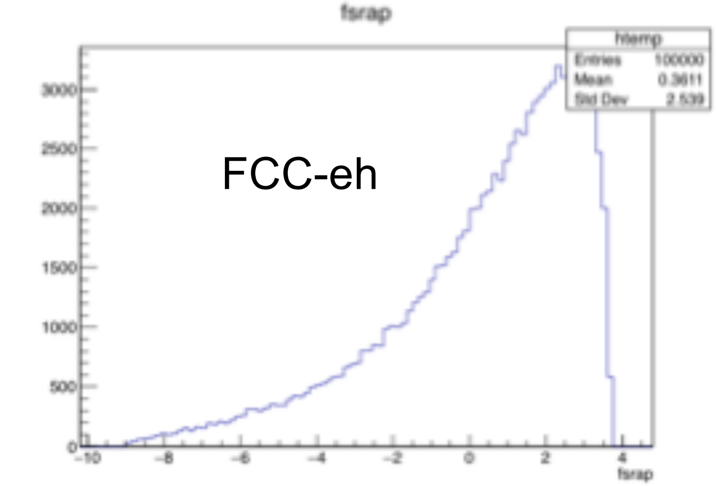
- Vector meson production over a wide rapidity range
  - N. b. unscaled distributions here







- ρ^0 ‘double peak’ is from Reggeon exchange (near threshold) and Pomeron exchange at large k/rapidity
  - ϕ or J/ψ are not produced via Reggeon exchange
- Electrons scattering angle is small (no surprise)

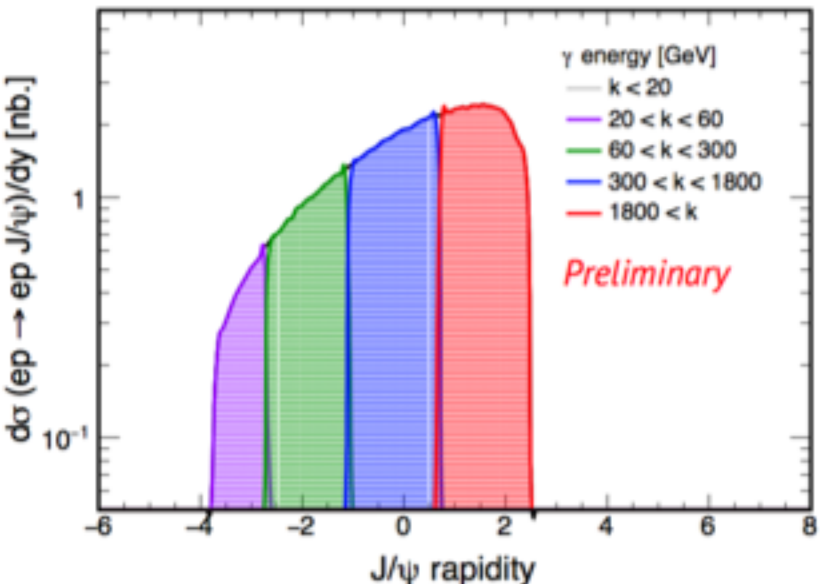


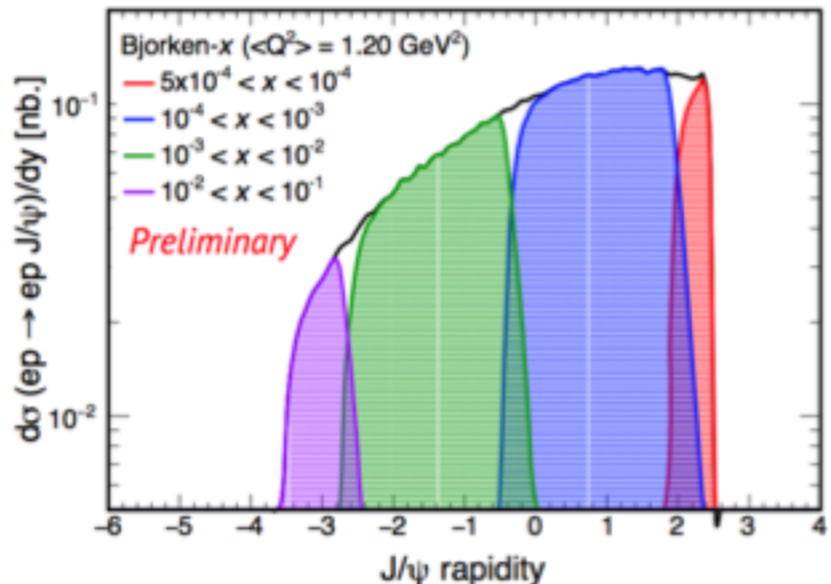
J/ψ rapidity

Rapidity peak similar to LHeC;
Tail at larger -y

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

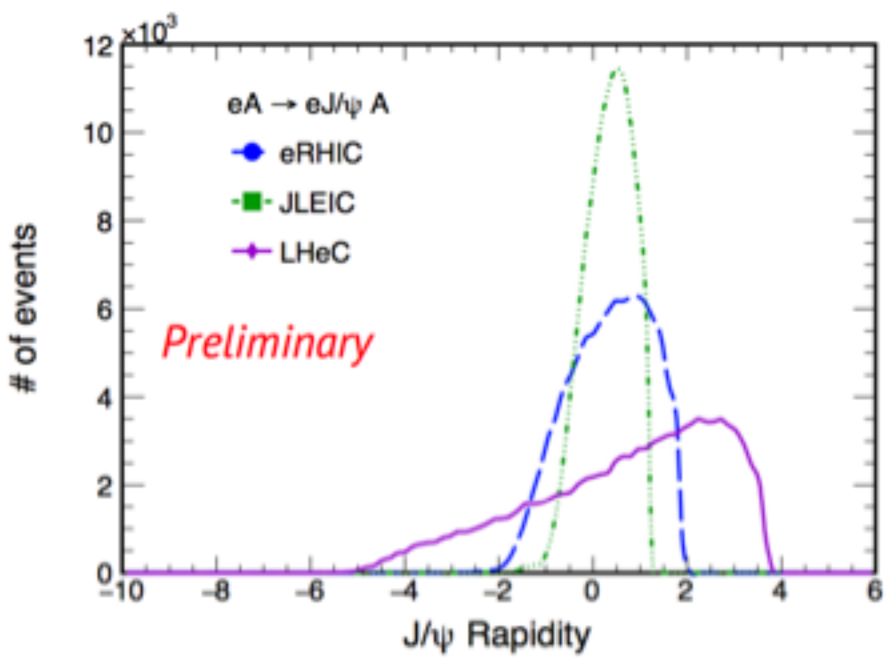


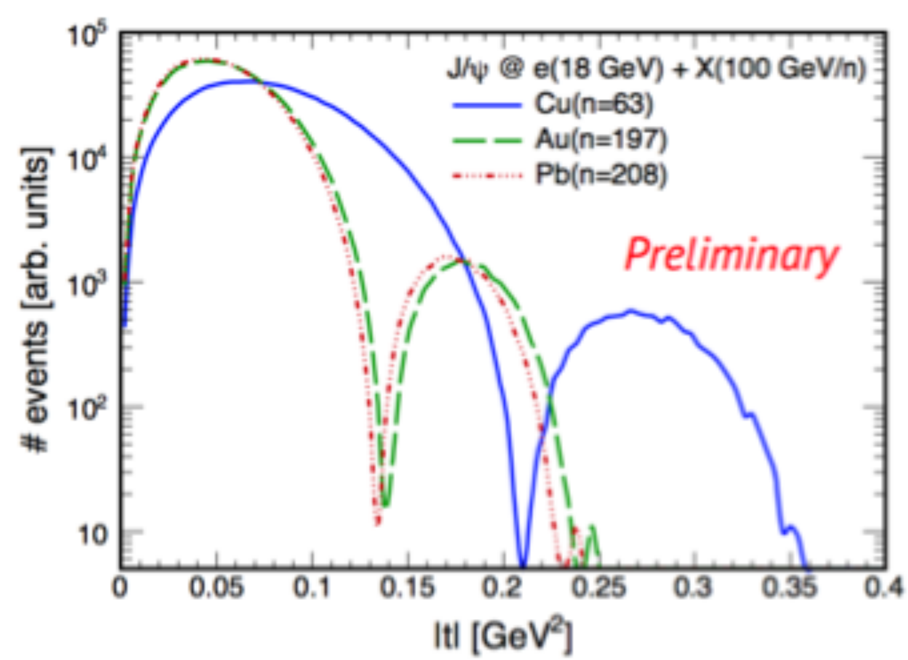


- Photon energy also maps onto Bjorken-x
- For maximum energy/Bjorken-x reach, need to detect vector mesons forward, with y ~ 2.5
- Near threshold, production is at large negative rapidity
  - Could shift to mid-rapidity by lowering beam energy

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

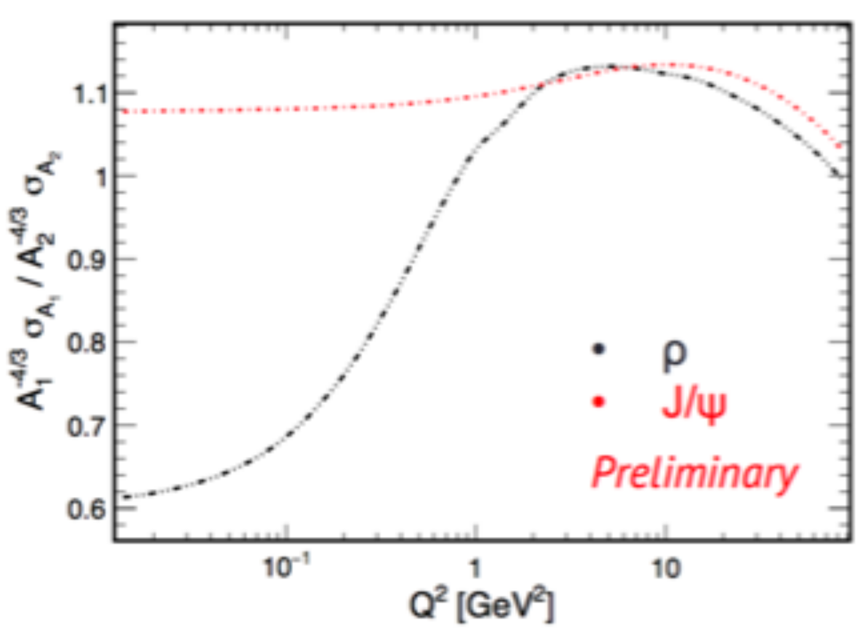




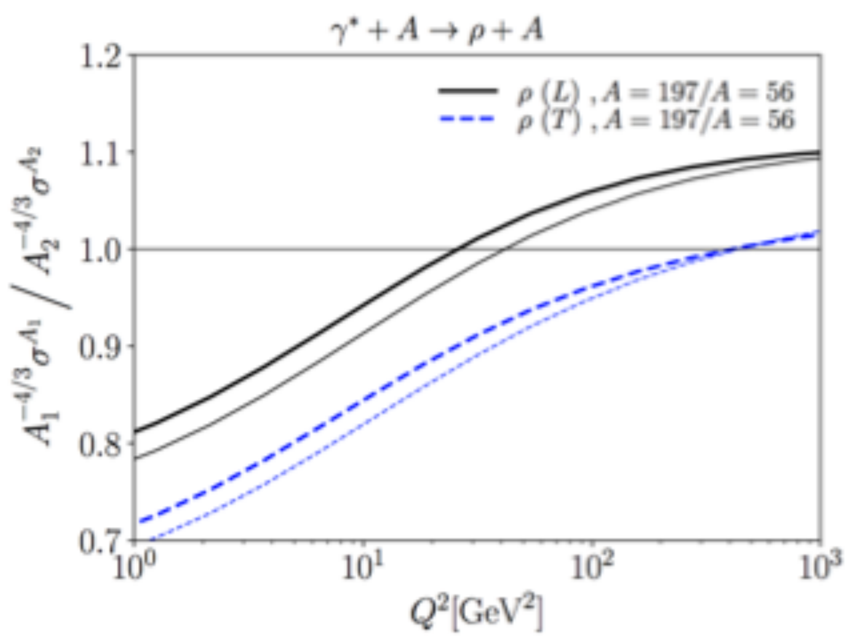
Cross-section vs. A & Q^2: shadowing

- Without shadowing (i. e. for small dipoles), $\sigma \sim A^{4/3}$
  - 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
- Shadowing should increase slowly with increasing energy
  - Eventually – reach 'black disk' limit

eSTARlight



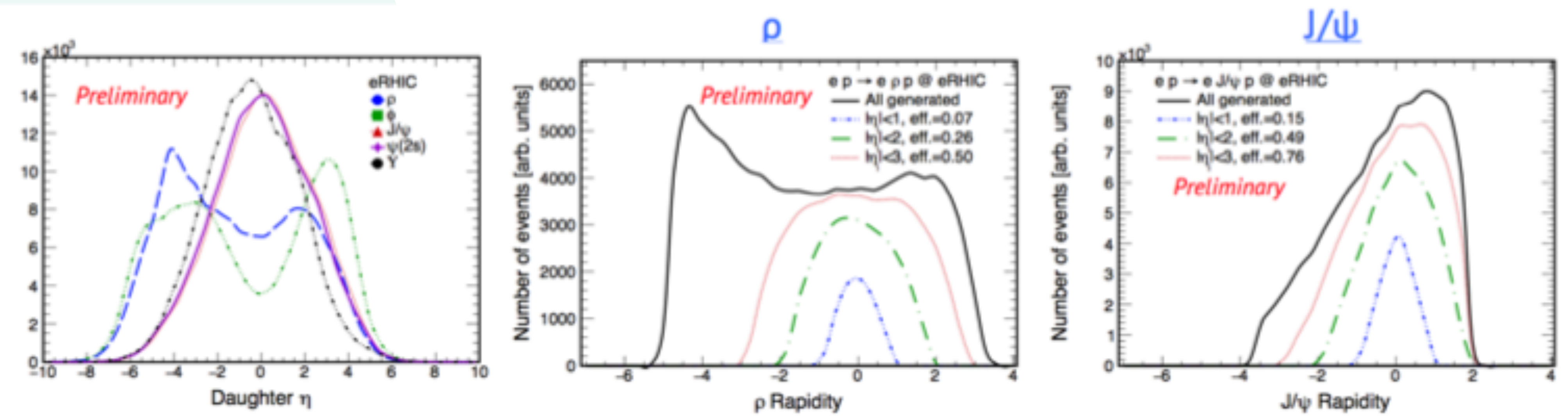
Mantysaari & Venugopalan



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



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

eSTARlight code base & future plans

- Straightforward C++ code hosted on hepforge
  - http://estarlight.hepforge.net
  - Easy to download and install
  - If you need a hepforge account, please request one
  - Please try it, and provide feedback
- Optional inclusion of PYTHIA8 (for complex decays) and DPMJET3 for arbitrary eA interactions (w/Q^2=0 for DPMJET)
- Future plans: additional mesons, charge exchange reactions (γp -> X^+n), exotica, top quarks, spin effects, GPDs?
- We welcome interested parties as co-developers

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.