eSTARlight

An event generator for the EIC

Michael R. Lomnitz
Postdoctoral fellow, Nuclear Science Division
Lawrence Berkeley National Laboratory

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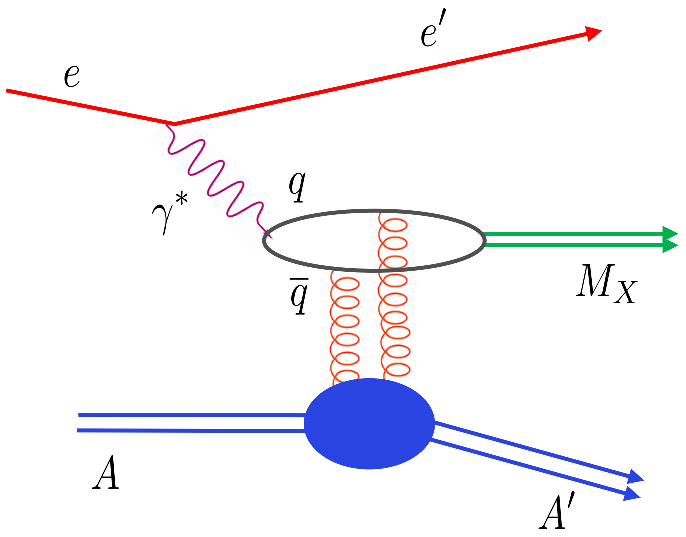
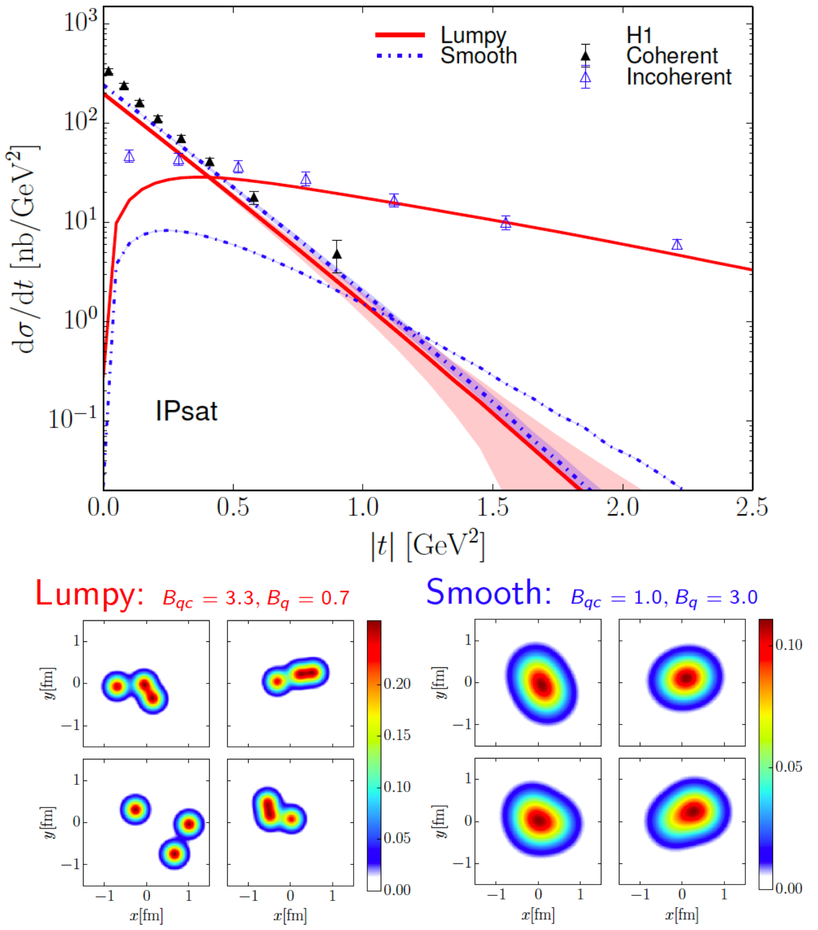
Outline

- Motivation
- STARlight: our predecessor
- Photo-nuclear interaction in eSTARlight:
  - $\gamma p \rightarrow$ V.M. +p vector meson production
  - Comparison to data
  - Extension to γA
- Vector meson production at an EIC
- Estimating rates
- Caveats and outlook
- Summary

Diffraction at an EIC

- How are the quarks and gluons distributed within the nucleon? What about nucleus?
- Initial state geometry is necessary input for hydro:
  - Initial state (IS) geometry → final state collectivity
  - Collective phenomena has been observed in p-p and p-A collisions





H. Mäntysaari, QM17 parallel session 5.2

- Diffractive processes (no color exchange) can probe:
  - Target remains intact: *Coherent* (small |t|) probes average gluon density and their spatial distribution
  - Target break up: *Incoherent* (large |t|) is sensitive to fluctuations in IS

Electron-ion collisions

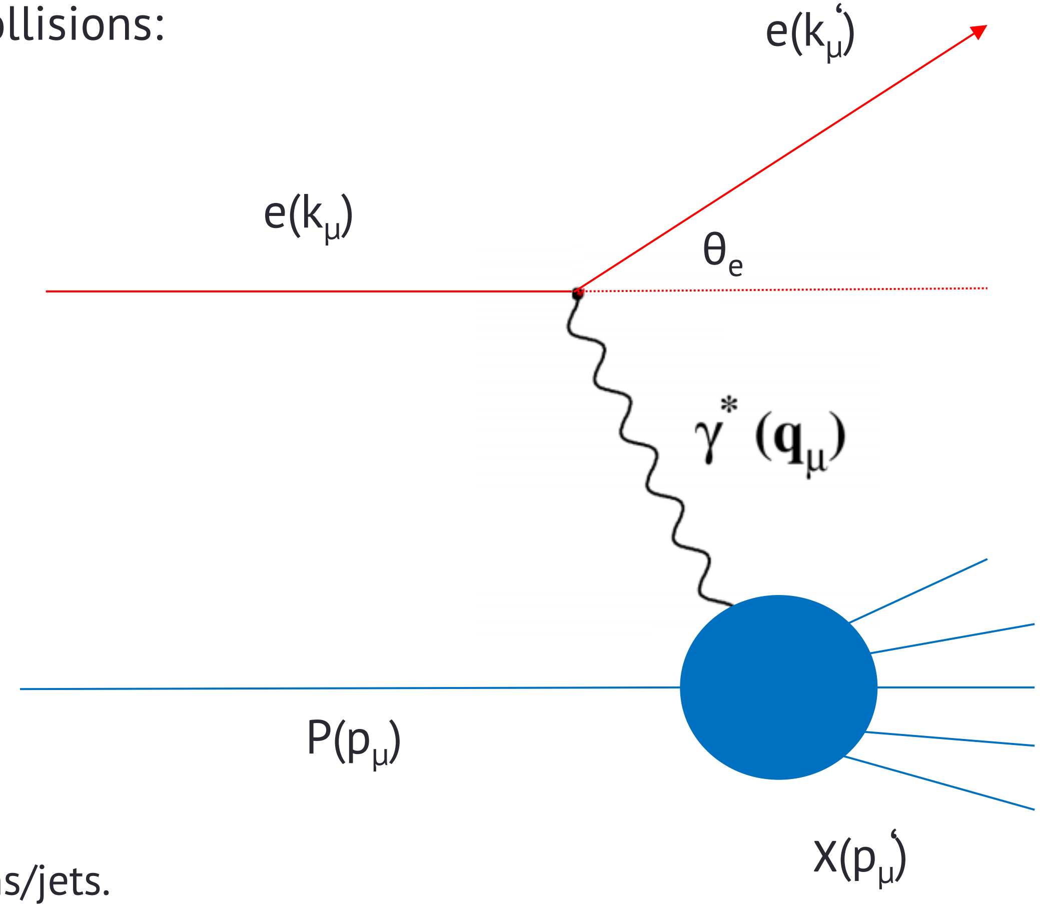
Some important kinematic quantities to consider in electron-ion collisions:

- Resolving power
$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$
$$= 2E_e E'_e (1 - \cos\theta_e)$$

- Momentum of struck quark
$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

- Measure of inelasticity
$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta_e}{2}\right)$$

$$s = 4E_p E_e$$



Inclusive: Detect scattered lepton. e+p/A → e' + X

Semi-inclusive: Detect scattered lepton in coincidence with identified hadrons/jets.

e+p/A → e' + h + X

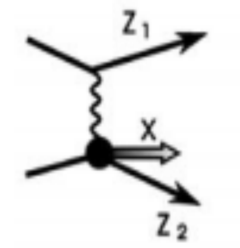
Exclusive: Detect scattered lepton, id'd hadrons/jets and target fragments.

Our predecessor - STARlight

Widely used M.C. in ultra-peripheral collisions (UPCs). Choice of channels mostly driven by experimental accessibility

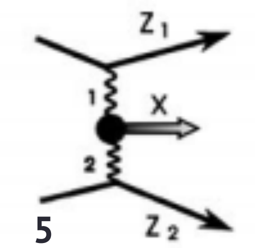
Photonuclear: Photon-Pomeron (γP) final states

- Light vector mesons: ρ, ω, ϕ, ρ'->ππππ,
- Heavy vector mesons (VM): J/ψ, ψ', Υ(1S), Υ(2S), Υ(3S)
- VM follows photon polarization (along beam)
  - Correct angular distributions
- p_T distributions include (optionally) 2-site interference
- General photonuclear interactions, via DPMJET interface
- Direct $\pi^+\pi^-$



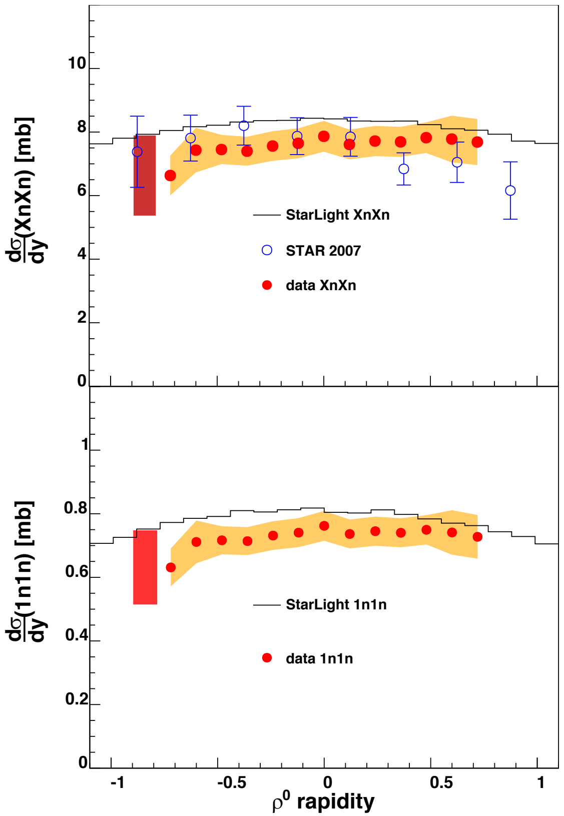
γγ final states

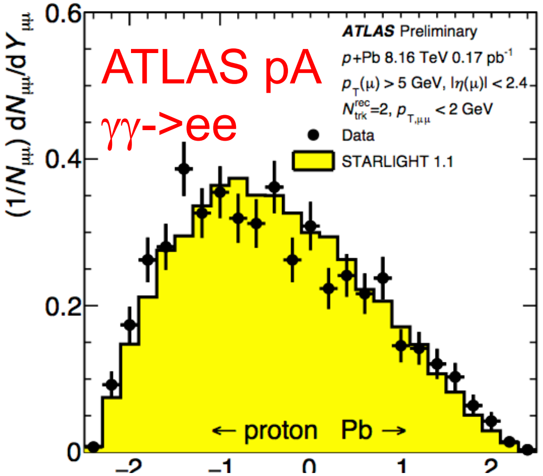
- Lepton pairs e^+e^-,$\mu^+\mu^-$,$\tau^+\tau^-$
- Single mesons: η, η', $f_0(980)$, $f_2(1270)$, $f_{2'}(1525)$, η_c
  - "Simple" decays in STARlight ensure correct angular distribution
  - "Complex" final states decayed via PYTHIA 8
- $\rho^0\rho^0$
- Heavy axions

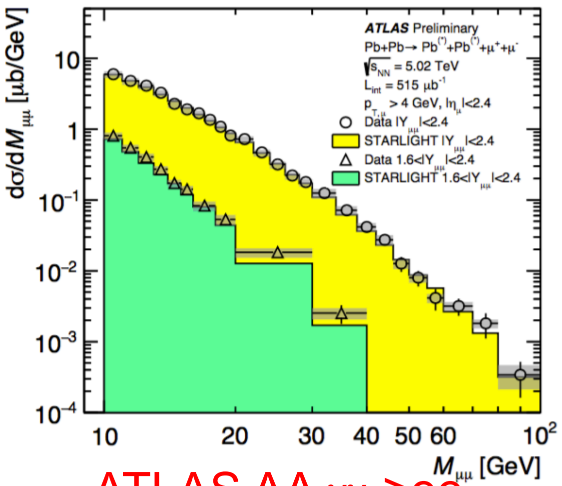


STARlight versus data

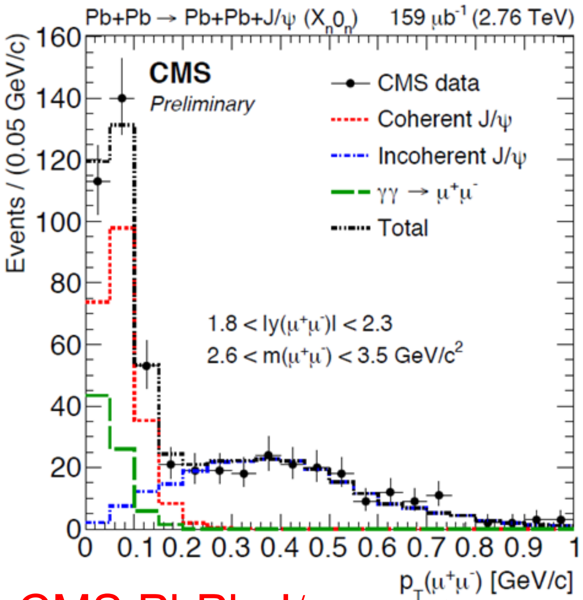
STAR
AuAu ->ρ^0



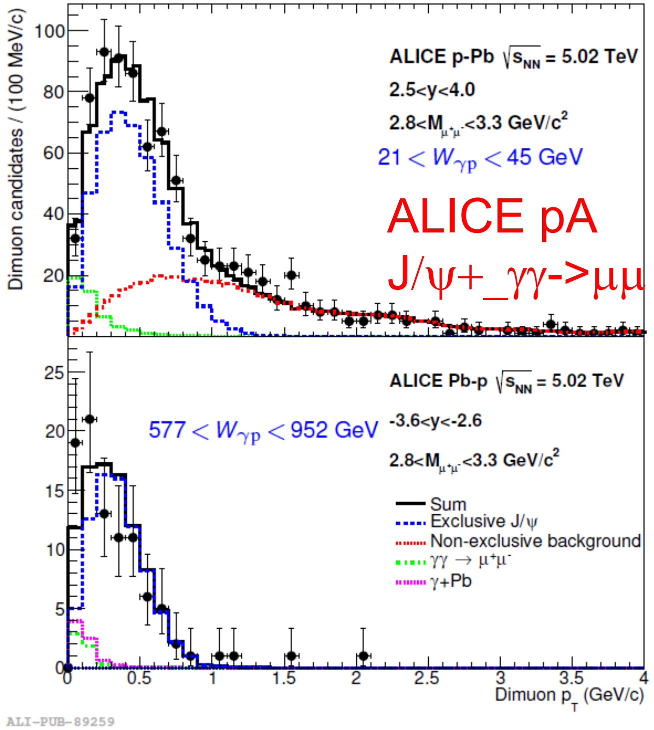




ATLAS AA γγ->ee



CMS PbPb J/ψ+_γγ->μμ



- Good track record proven by many experiments and collision energies in UPC collision
- Confidence in description of nucleus targets: helpful in eSTARlight given the lack of eA data

CMS - arXiv:1605.06966
ALICE - PRL**113** 232504 (2014)
ALTAS - QM17, M. Dyndal
STAR - DIS16

Electro-nuclear interactions

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

Photon flux

Photonuclear cross section

$$= \int dQ2 \int dE_\gamma \frac{dN_\gamma(E_\gamma, Q^2)}{dE_\gamma dQ2} \left(\frac{1}{1 + Q^2/M_v^2} \right)^n \sigma_{\gamma X}(W)$$

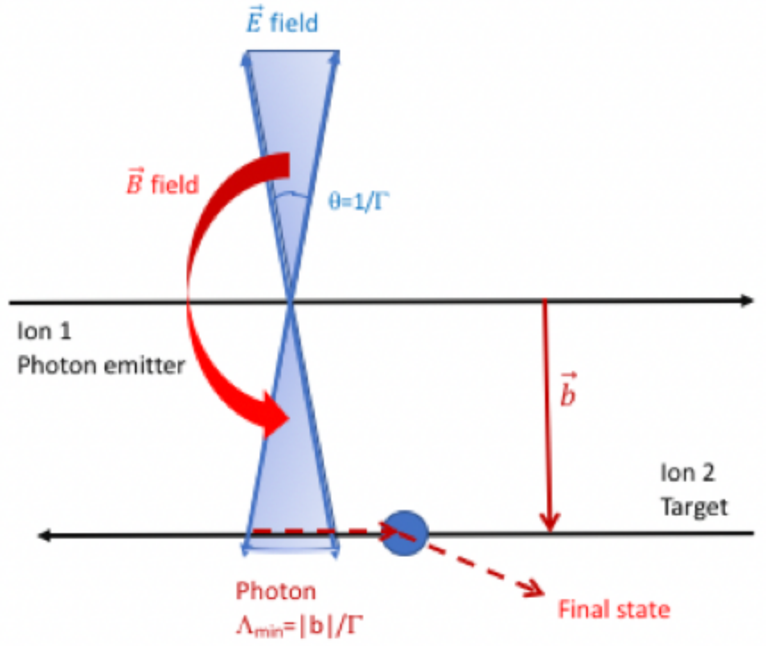
Effective Photon flux $f(E_\gamma, Q^2)$

Reduced photonuclear cross section

- Differential x-section sampled to produce events:
  - Rejection sampling used to draw from distributions
  - Two look up tables used to speed up event generation:
    1. Draw E_γ and Q^2 pair from f(E_γ, Q^2) to construct e-γ vertex
    2. Sample $\sigma_{\gamma X}(W)$ with input photon and desired V.M. state

Photon flux

- Using equivalent photon approach (EPA):
  - Electric field radially outwards from e and Lorentz contracted in target (p,A) frame => Looks like a pancake in transverse direction
  - Magnetic field circles around beam axis
- Perpendicular fields resemble EM radiation: treat each source as dressed by photons



- Include necessary corrections to account for the virtuality of the exchanged photon[1]:

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

- And the available q^2 range:

$$Q^2_{\min} = \frac{m_e^2 E_\gamma^2}{E_e(E_e - E_\gamma)} \leq Q^2 \leq 4E_e(E_e - E_\gamma)$$

1: Phys.Rept. 15 181-281 (1975)

Photonuclear Cross Section

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

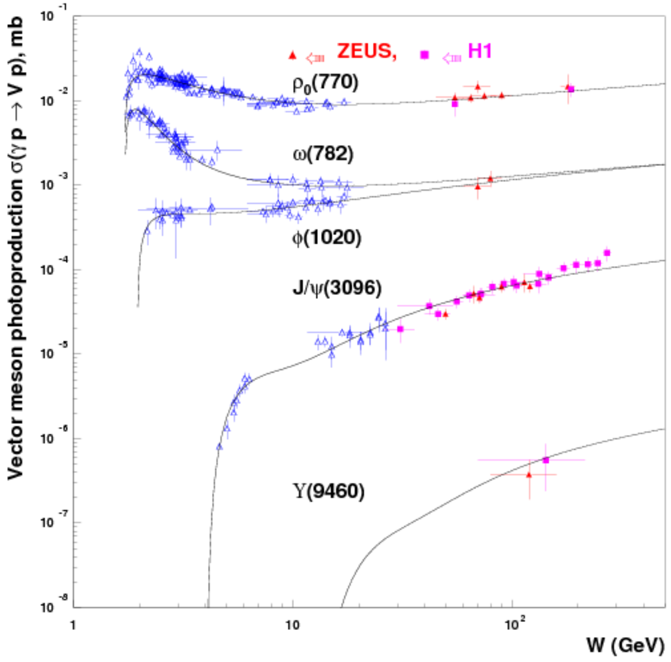
- Interactions are done, mostly, with parameterization from HERA[1] for γp→Vp in terms of the γp center of mass energy $W_{\gamma p}$.

$$\sigma_{\gamma p}(W) = \underbrace{\sigma_P \cdot W^{\epsilon}}_{\text{Pomeron exchange}} + \underbrace{\sigma_M \cdot W^{\eta}}_{\text{Meson exchange}}$$

- Only ρ and ω can be produced via meson exchange ($\sigma_M > 0$)
- For the J/ψ, ψ' and Υ states the power law is supplemented with factor to account for the near-threshold decrease in cross section

$$\sigma_{\gamma p}(W) = \sigma_P \cdot \left[1 - \frac{(m_p + m_{VM})}{W^2}\right]^2 \cdot W^{\epsilon}$$

- The n is also obtained from fits to data[2]

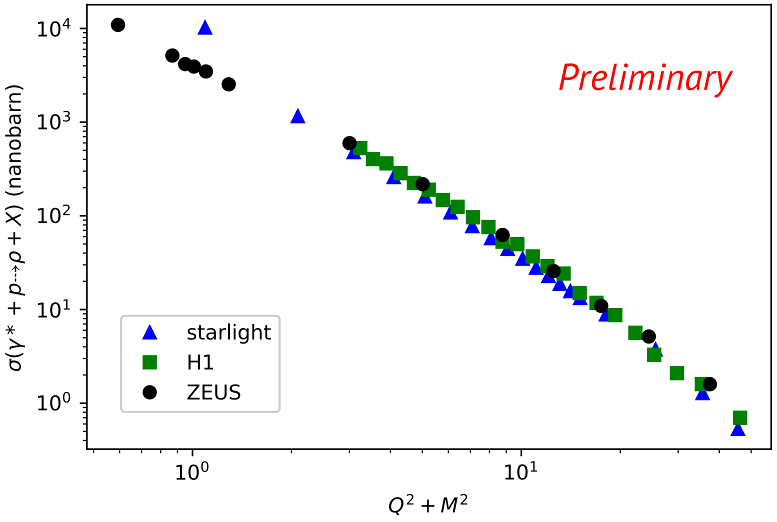


Vector Meson	σ_P	ϵ	σ_M	η
ρ^0 & ρ'	5.0 μb	0.22	26.0 μb	1.23
ω	0.55 μb	0.22	18.0 μb	1.92
ϕ	0.34 μb	0.22	–	–
J/ψ	4.06 nb	0.65	–	–
$\psi(2S)$	0.674 nb	0.65	–	–
Υ(1S)	6.4 pb	0.74	–	–
Υ(2S)	2.9 pb	0.74	–	–
Υ(2S)	2.1 pb	0.74	–	–

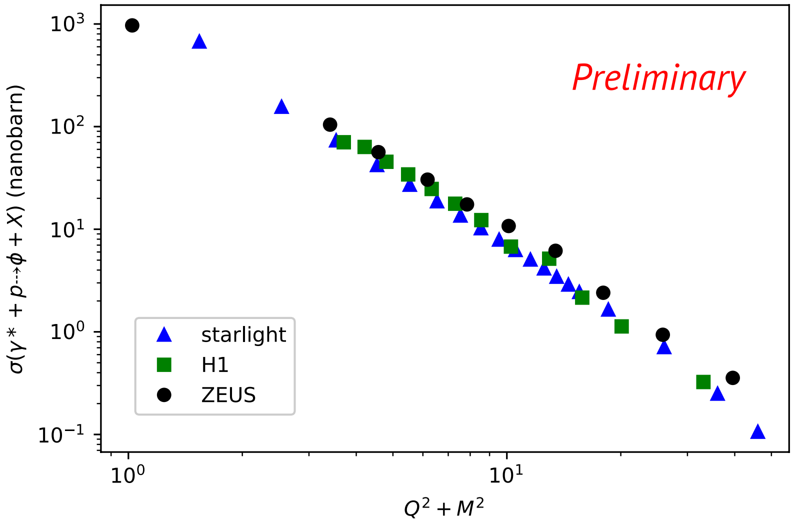
[1]: S.R.Klein, *et. al.*, Computer Physics Communications **212** 0010-4655 (2017)
[2]: Phys.Lett.B377:259-272(1996), JHEP 1005:032(2010), Nucl.Phys.B695:3-37(2004)

HERA comparison to data: σ(γ* + p → V.M. + p)

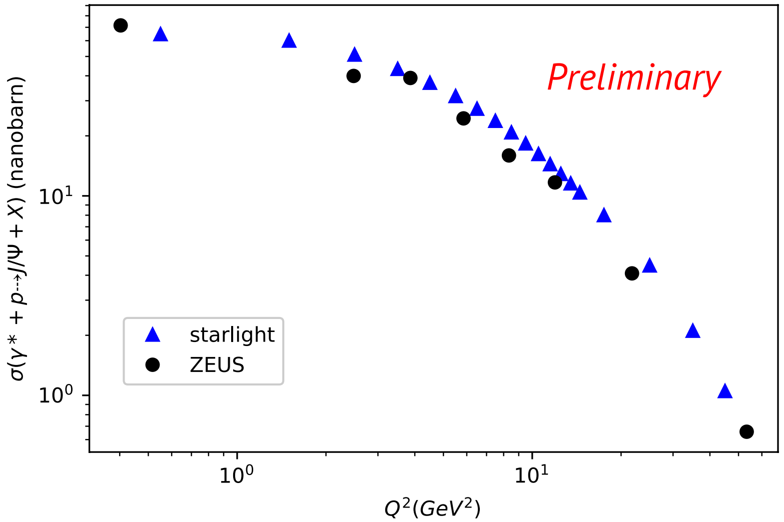
ρ



ϕ



J/ψ



- Gamma-proton cross-sections obtained following same procedure in experiment:

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

- $\sigma_{\gamma p}$ measured at HERA is well described by eSTARlight over a broad Q^2 range

ϕ: Phys.Lett.B377:259-272(1996)
ρ: JHEP 1005:032(2010)
J/ψ: Nucl.Phys.B695:3-37(2004)

Coherent Photonuclear Cross Section σ(γA → VA)

- Extrapolate photonuclear cross section from γp to γA using Quantum Glauber calculation to take into account the nuclear form factor:

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

- Generalized vector dominance model and optical theorem used to obtain the photo-nuclear cross section

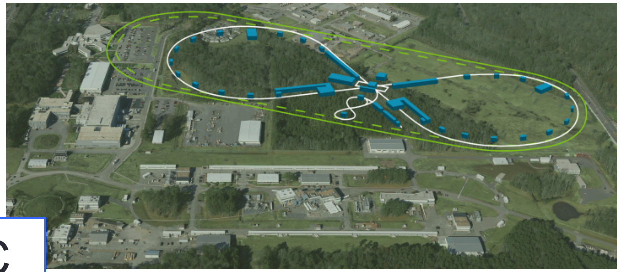
$$\sigma(\gamma A \rightarrow VA) = \left.\frac{d\sigma(\gamma A \rightarrow VA)}{dt}\right|_{t=0} \int_{t_{min}}^{\infty} dt |F(t)|^2$$

- There are two modes in eSTARlight to calculate the cross sections:
  - Assuming a narrow resonance for the vector mesons, in which case: $t_{min} = (M_V^2/4k\gamma)^2$
  - Convoluting the spectrum with a Breit-Wigner shape. The difference can be substantial (~ 5% reduction in cross section ρ^0 in heavy-ion collisions)

EIC prediction: σ(e+X→e+V.M.+X)

- eSTARlight can be used to estimate e+X → e+X+V.M. cross sections for:
  - Different center of mass energies (accelerator facilities)
  - Different V.M. species
  - Different collision systems (X = p, Au, etc.)
  - Arbitrary virtuality Q^2
- Heavy-ions provide considerable production (larger CM energy) at the cost of Q^2 due to kinematic reach
- Still have considerable production Q^2 > 1 GeV → electrons sufficiently scattered away from beam for exclusive measurements

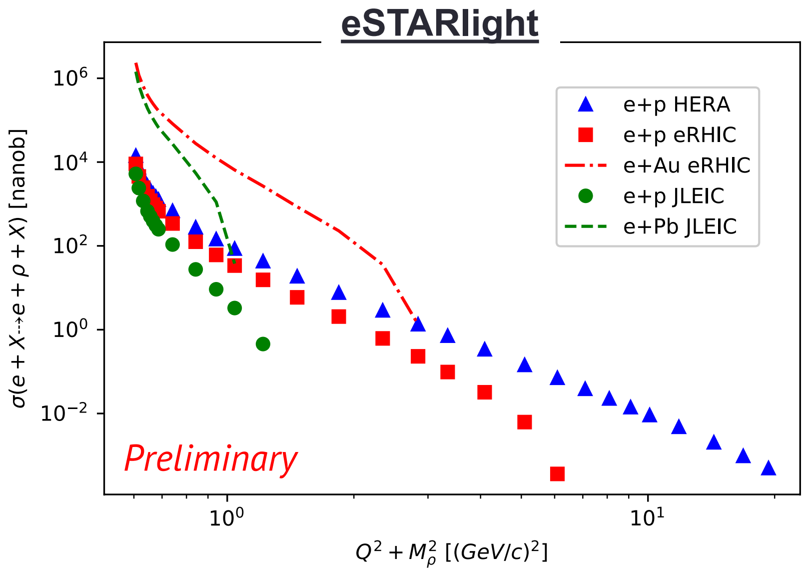
JLEIC



eRHIC

	JLEIC (JLAB)	eRHIC (BNL)	HERA (DESY)
electron e [GeV]	5	10	27.5
proton p [GeV]	60	250	920
Heavy-Ion A [GeV/n]	$^{208}Pb^{82+}$	$^{197}Au^{79+}$	n/a
	40	100	n/a

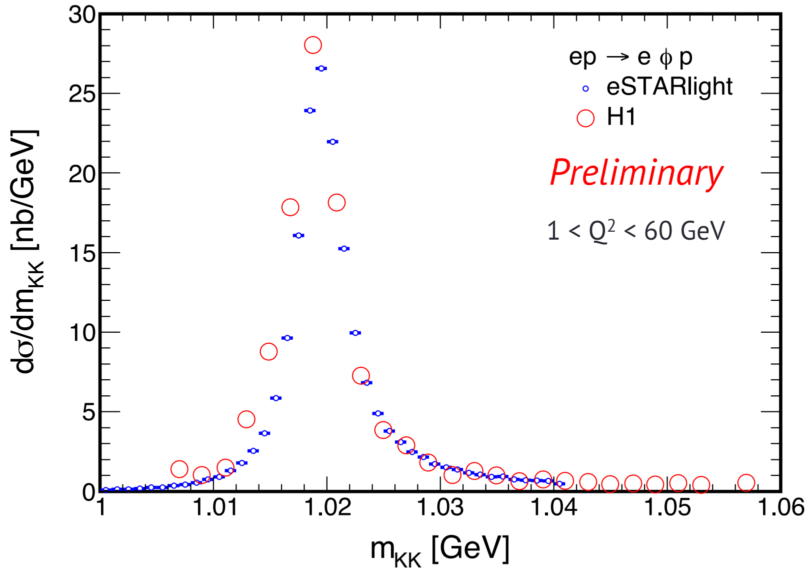
Table 1: EIC energies from whitepaper *A. Accardi et. al., Eur. Phys. J. A, 52 9(2016)*. HERA energies for comparison.

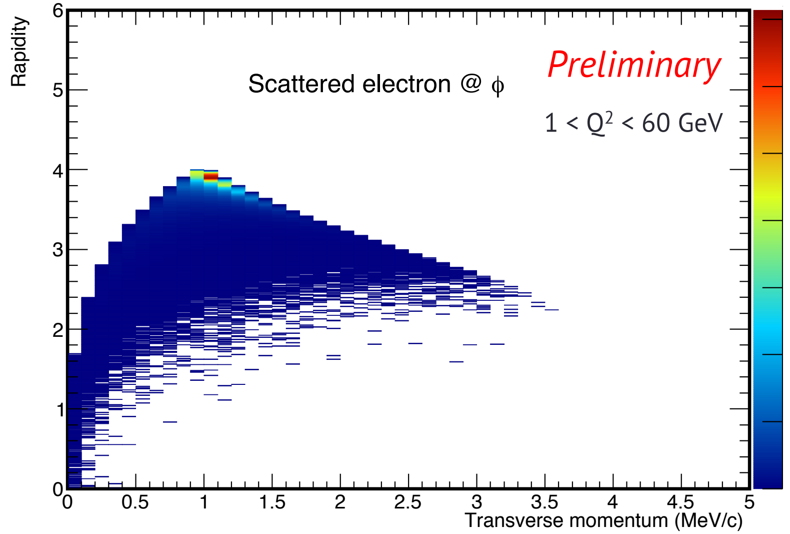


Event generation

H1 data corrected for exp. resolution and background subtraction JHEP05(2010)032

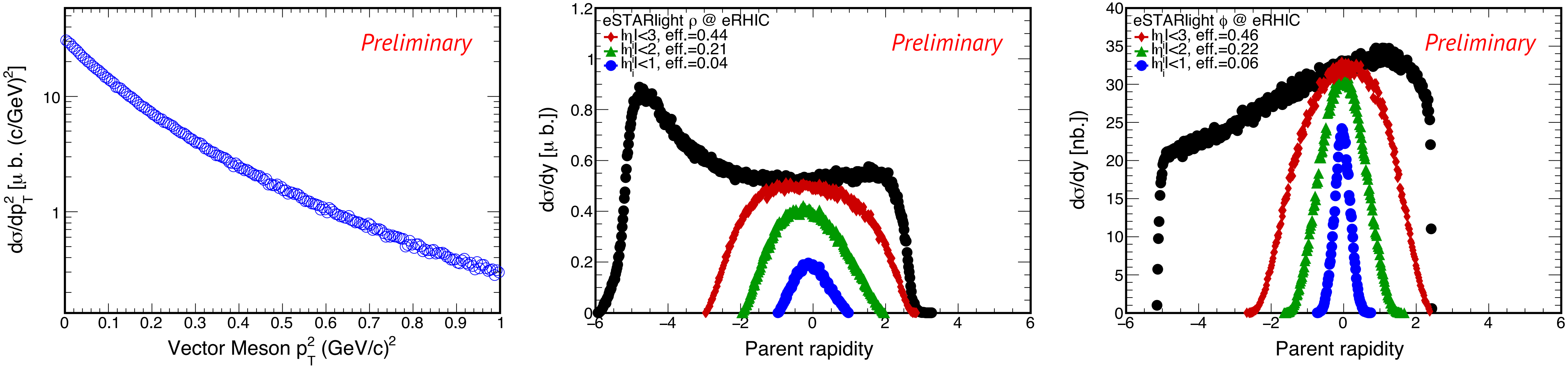
- Coherent or incoherent(pending) final states
  - Coherent: couples to nucleus as a whole
    - p_T distribution of Pomeron determined by nuclear form factor
  - Incoherent: couples to a single nucleon in the nucleus
    - p_T distribution of Pomeron determined by proton form factor (same as proton targets)
- Generates final states for input to GEANT to simulate detector response.
- Track outgoing electron and target(pending) for semi-inclusive and exclusive measurements
- Simple decays handled by eSTARlight. Can couple to PYTHIA for more complex decays
  - Can put requirements on decay product η, p_T





Event generation and distributions eRHIC

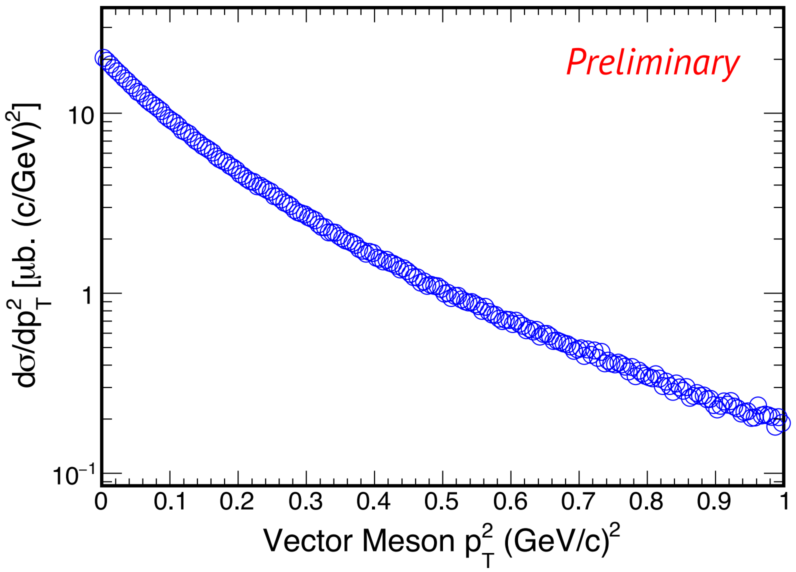
ρ φ

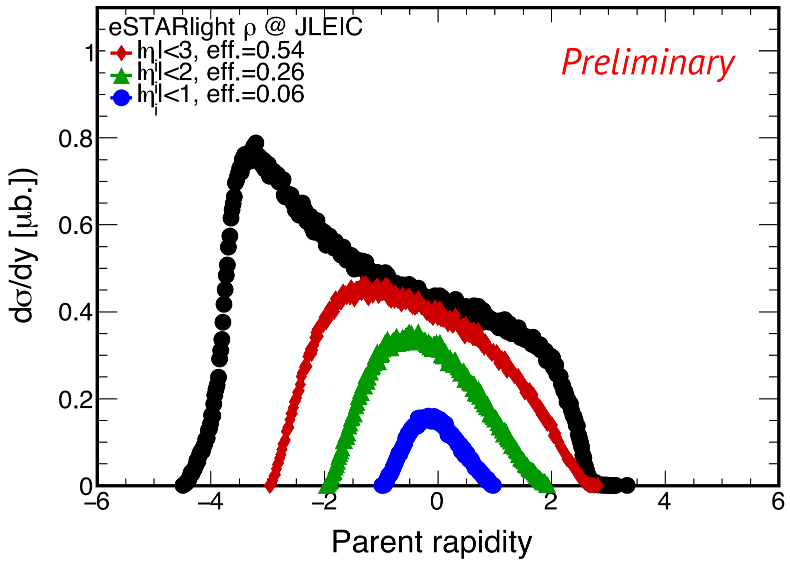


- Vector meson production occurs over a large rapidity window (roughly matches photon energy).
- ρ peak at y = -4.5 due to photon-meson exchange (mostly near threshold). Not present in ϕ (production only occurs through photon-pomeron exchange)
- Color curves illustrate V.M.'s with both daughters within a given pseudo-rapidity (η) range.
- Mid-rapidity detectors would sample between ~50% (|η|<5) and <5% (|η|<1) of production:
  - eSTARlight kinematics can inform detector design

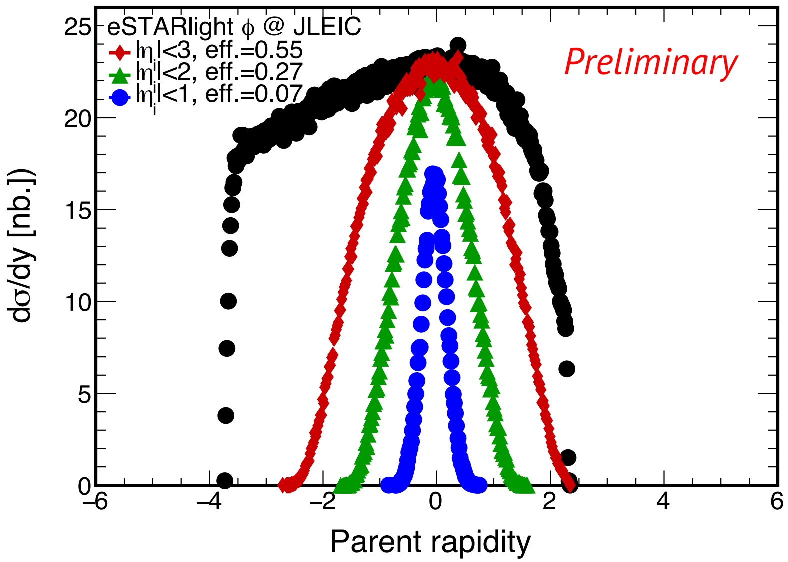
Event generation and distributions JLEIC

ρ





ϕ



- Generally lower production at JLEIC relative to eRHIC (different scales).
- Mid-rapidity detectors sample a larger fraction of produced vector-mesons (relative to eRHIC)
- Color curves illustrate V.M.'s with both daughters within a given pseudorapidity (η) range.
- Mid-rapidity detectors would sample between ~55% (|η|<5) and <10% (|η|<1) of production:
  - eSTARlight kinematics can inform detector design

Estimating rates for an EIC

eRHIC[1]:

electrons*: 10 GeV

protons: 250 GeV

$^{197}Au^{79+}$: 100 GeV/n

	σ(e + X → e + V.M. + X)		Rates (L_{int} = 10 fb^{-1}/A)	
V.M.	X = p	X = Au	X = p	X = Au
ρ	4.68 μb	1.4 mb	46.8 x 10^9	71 x 10^9
ϕ	211 nb	80 μb	2.1 x 10^9	4 x 10^9
J/ψ*	7.8 nb	2.3 μb	78 x 10^6	120 x 10^6
Υ(1S)*	11.3 pb	3.5 nb	113 x 10^3	180 x 10^3

JLEIC[1]:

electrons: 5 GeV

protons: 60 GeV

$^{208}Pb^{82+}$: 40 GeV/n

	σ(e + X → e + V.M. + X)		Rates (L_{int} = 10 fb^{-1}/A)	
V.M.	X = p	X = Pb	X = p	X = Pb
ρ	3.1 μb	1.0 mb	31 x 10^9	48 x 10^9
ϕ	121 nb	55 μb	1.2 x 10^9	2.6 x 10^9
J/ψ**	2.2 nb	930 nb	22 X 10^6	45 x 10^6
Υ(1S)**	2.0 pb	710 pb	20 x 10^3	34 x 10^3

Don't account for branching ratios

[1]: EIC whitepaper: A. Accardi et. al., Eur. Phys. J. A, 52 9(2016)
*: Latest design uses 21.5 GeV electron beam @ eRHIC. Rates need to be revisited
**: Likely overestimated: Doesn't account for loss of longitudinal coherence

Estimating rates for an EIC ($Q^2 > 1$ [GeV^2/c^2])

eRHIC[1]:

electrons*: 10 GeV

protons: 250 GeV

$^{197}Au^{79+}$: 100 GeV/n

	σ(e + X → e + V.M. + X)		Rates (L_{int} = 10 fb^{-1}/A)	
V.M.	X = p	X = Au	X = p	X = Au
ρ	16 nb	5.1 μb	160 x 10^6	260 x 10^6
ϕ	1.7 nb	660 nb	17 x 10^6	34 x 10^6
J/ψ**	440 pb	150 nb	4 x 10^6	7.7 x 10^6
Υ(1S)**	1.7 pb	550 pb	17 x 10^3	28 x 10^3

JLEIC[1]:

electrons: 5 GeV

protons: 60 GeV

$^{208}Pb^{82+}$: 40 GeV/n

	σ(e + X → e + V.M. + X)		Rates (L_{int} = 10 fb^{-1}/A)	
V.M.	X = p	X = Pb	X = p	X = Pb
ρ	12 nb	4 μb	120 x 10^6	190 x 10^6
ϕ	1.1 nb	490 nb	11 x 10^6	24 x 10^6
J/ψ**	150 pb	68 nb	1.5 x 10^6	3.3 x 10^6
Υ(1S)**	330 fb	130 pb	3 x 10^3	6.3 x 10^3

Don't account for branching ratios

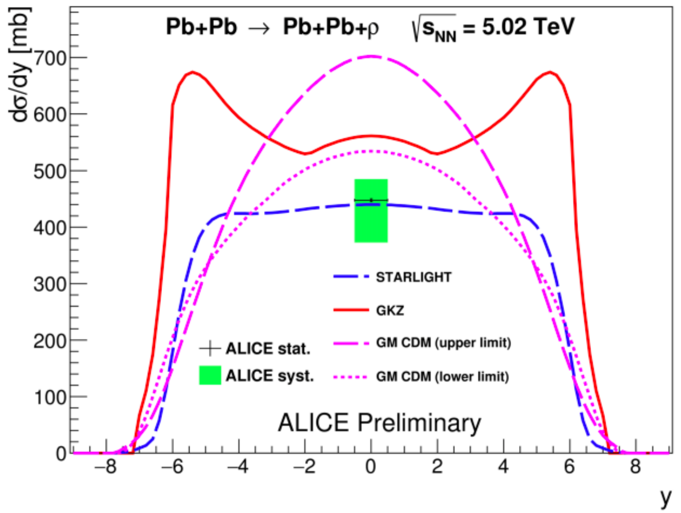
- Q^2 restriction affects V.M. species to different degree:
  ρ (x10^{-3}) vs. J/ψ (x 10^{-1} – 10^{-2})

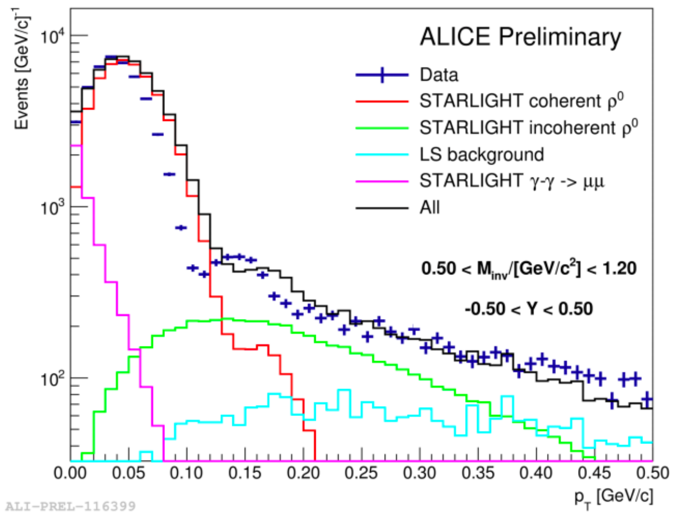
Some caveats:

- Classical vs. quantum Glauber calculation:
  - Quantum calculations predict dips but over estimate cross sections (factor 2)[1] for UPC ρ^0 photoproduction at RHIC and LHC.
  - Option for classical Glauber available.
- Assumes complete longitudinal coherence
  - Under investigation, should only affect near threshold (small y)

Next steps:

- No neutron skin:
  - Form factor in eSTARlight from electron-nucleus elastic scattering measurements → only probes the protons.
  - Shift in ρ coherent peak.
- Vet all angular distributions – (also parametrization to data)
- Implement γ-γ interactions
- Production of exotic final states
- Include charge exchange interactions, i.e γ+p → $Z_c(4430)$+n





1: J. High Energ. Phys. (2015) 2015: 95
2: arXiv:1611.05471 (2016)

Summary

- eSTARlight can simulate a wide variety of final states:
  - Evaluate feasibility (cross sections, rates, …) of different physics topics to be studied
- Vector mesons are produced over a wide rapidity range, roughly corresponding to photon energies
  - Drive detector design by understanding final state kinematics
  - Detector covering +/- 2 units of η would sample ~20-25% of vector meson cross sections
  - Forward detector would sample high energy photons, while backward rapidity samples near threshold
- Generally high enough production rates for $Q^2 > 1$ GeV events
- High enough Υ(1S) production at an EIC to allow limited studies ($Q^2 > 1$ GeV rates are somewhat low)
- Are the rates are large enough to study rare events (exotica)?

Thank you

Back – ups (or might get removed)