STARlight[1] and eSTARlight

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INT Workshop - 2017

[1]: S.R.Klein, *et. al.*, *STARlight: A Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions,* Computer Physics Communications **212** 0010-4655 (2017)

Outline

- Introduction to STARlight:
  - Initial states
  - Final states
- Photonuclear production:
  - Photon flux
  - σ(γp → VP) and extension to σ(γA → VA)
  - Nuclear form factor
  - p_T spectra
- γγ interaction
- Acceptance criteria
- Nuclear excitation/break-up
- Comparison to data
- EIC and eSTARlight

Initial States

<u>Protons, gold, lead, and arbitrary other ions</u>

- Proton, gold and lead are hard-coded.
- Others use general formula
  - Accurate form factors -> p_T distributions are accurate
- pp, pA, Ap, AA
  - pA and Ap are 'proton-shine' and 'gold-shine' respectively
- Upgrade to include electron beam

<u>Can handle arbitrary beam energies (with Lorentz boost ~ >> 1)</u>

<u>Non-collision requirement</u>

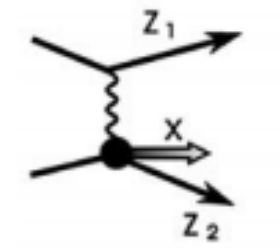
- Impact parameter $b>2R_A$, or no hadronic collisions (Glauber)
- Optional mutual Coulomb excitation to 1n1n or XnXn or 0nXn
- Upgrade to $b_1 < b < b_2$ for peripheral collisions possible, especially for γγ final states

Final states

Mostly, choices are driven by experimental accessibility

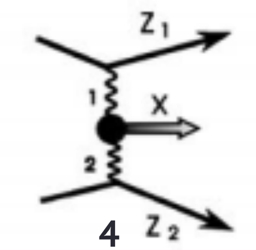
Photonuclear: Photon-Pomeron (γP) final states

- Light vector mesons: ρ, ω, φ, ρ'->ππππ,
- Heavy vector mesons: 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



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
- Direct $\pi^+\pi^-$



Coherent and Incoherent production

- Coherent or incoherent 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

- Final state mass, rapidity range selectable
- Generates final states for input to GEANT to simulate detector response
  - Can put requirements on decay product η, p_T

Photo-nuclear interactions

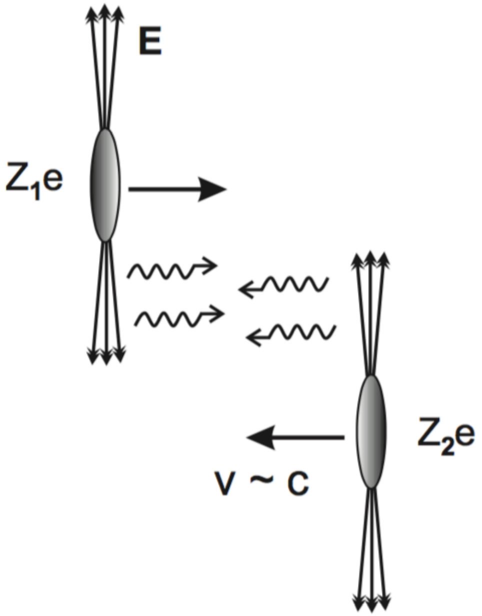
$$\sigma = \int dk \sigma_{\gamma X \to V X}(k) \int d^2 b \frac{dN_\gamma(b)}{dk} P_{No-had}(b) P_{XN}(b) P_{XN}(b)$$

Photonuclear cross section

Photon flux

Acceptance criteria:

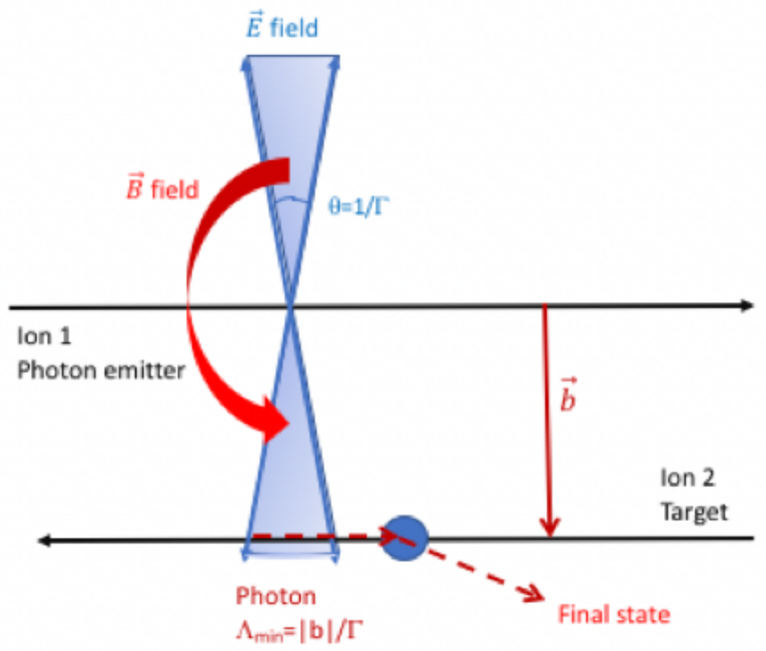
- No hadronic break up
- Options for desired Coulomb break up



$\int d^2b \frac{dN(b)}{dk}$

Photon flux

- Using equivalent photon approach:
  - Electric field radially outwards from p or A and Lorentz contracted in lab 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 virtual photons



- For heavy ions use :

$$N_\gamma(\omega, b) = \frac{Z^2\alpha\omega^2}{\pi^2\gamma^2\hbar^2\beta^2c^2}\left(K_1^2(x) + \frac{1}{\gamma^2}K_0^2(x)\right) \qquad x = \frac{ER}{\gamma}$$

For light ions (1 < Z < 7) a Gaussian form factor is introduced

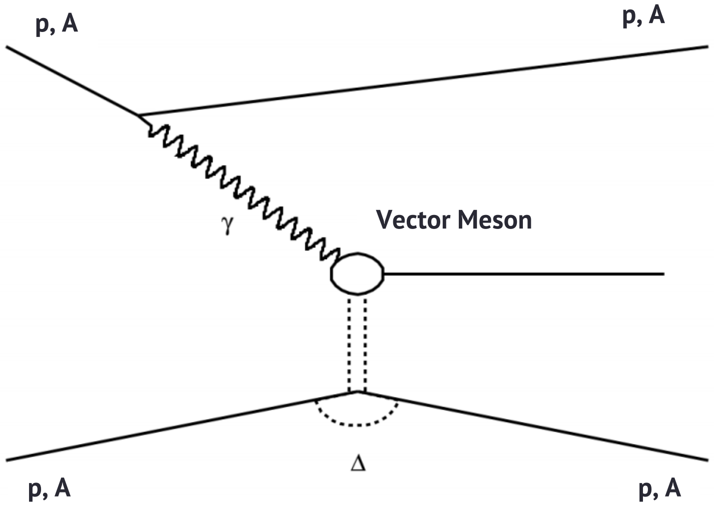
- For protons: take into consideration the form factor of the proton:

$$\frac{dN_\gamma}{dk} = \frac{\alpha}{2\pi k}\left[1 + (1 - \frac{2k}{\sqrt{s}})^2\right]\left(\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\right)$$

Photonuclear Cross Section σ(γp → Vp)

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

$$\sigma(\gamma p \to Vp) = \underbrace{\sigma_P \cdot W_{\gamma p}^{\epsilon}}_{\text{Pomeron exchange}} + \underbrace{\sigma_M \cdot W_{\gamma p}^{\eta}}_{\text{Meson exchange}}$$



- Only ρ and ω can be produced via meson exchange, so $\sigma_M = 0$ for all other vector mesons. Values used are shown in the table
- 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

$$\sigma(\gamma p \to Vp) = \sigma_P \cdot \left[1 - \frac{(m_p + m_V)^2}{W_{\gamma p}^2}\right]^2 \cdot W_{\gamma p}^{\epsilon}$$

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	–	–
ψ(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	–	–

- General photonuclear events can also be simulated with interface to DPMJet

[1]: J.A. Crittenden, Exclusive photoproduction of neutral vector mesons at the electron-proton collider HERA, Springer-Verlag (1997)

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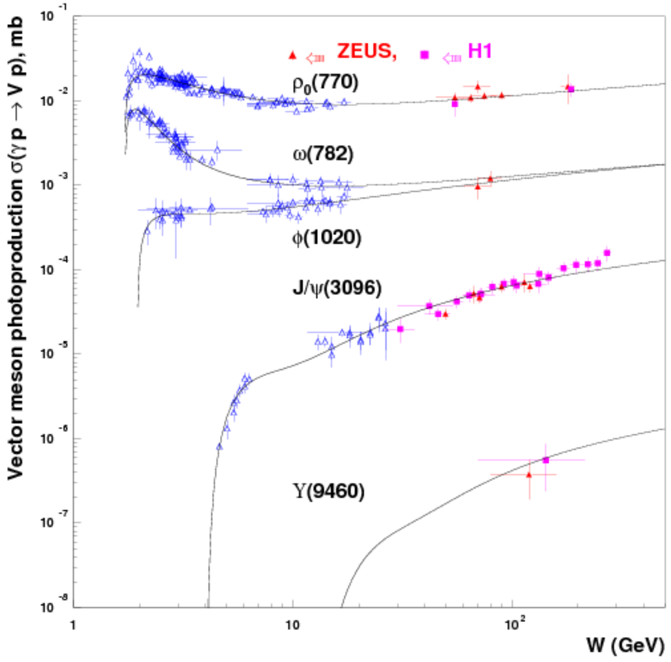

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Coherent Photonuclear Cross Section σ(γA → VA)

- Extrapolate photonuclear cross section from γp to γA using Clasical Glauber calculation to take into account the nuclear form factor[1]:

$$\sigma(AA \to AAV) = 2\int dk \frac{dN_\gamma(k)}{dk}\sigma(\gamma A \to VA)$$

$$= 2\int_0^\infty dk \frac{dN_\gamma(k)}{dk}\int_{t_{min}}^\infty dt \left.\frac{d\sigma(\gamma A \to VA)}{dt}\right|_{t=0} |F(t)|^2$$

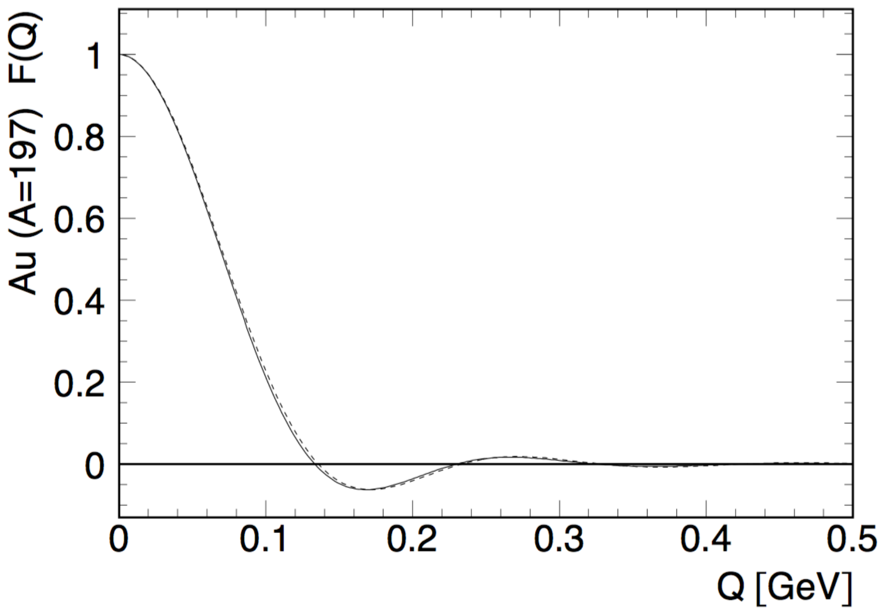
- For a given impact parameter, the photon flux N_γ striking the nucleus is determined and then spread over the entirety of the nucleus.
- There are two modes in STARlight to calculate the cross sections:
  - Assuming a narrow resonance for the vector mesons, in which case: $t_{min} = (M_V^2/4k\gamma)^2$
  - Convoluting the spectrum with a Breit-Wigner shape. The difference can be substantial (~ 5% reduction in cross section ρ^0 in heavy-ion collisions)

[1]: Annu. Rev. Nuc. Part. 2005.55.271-310

Nuclear form factors

- Determine how coherence is lost as t rises
- Assume Woods-Saxon distribution
- Represent Fourier transform of WS distribution as the convolution of a hard sphere with a Yukawa potential
  - Yukawa range a = 0.7 fm. R_A=nuclear radius

$$F(q = \sqrt{|t|}) = \frac{4\pi\rho_0}{Aq^3}\left[\sin(qR_a) - qR_a\cos(qR_A)\right]\left[\frac{1}{1+a^2q^2}\right]$$



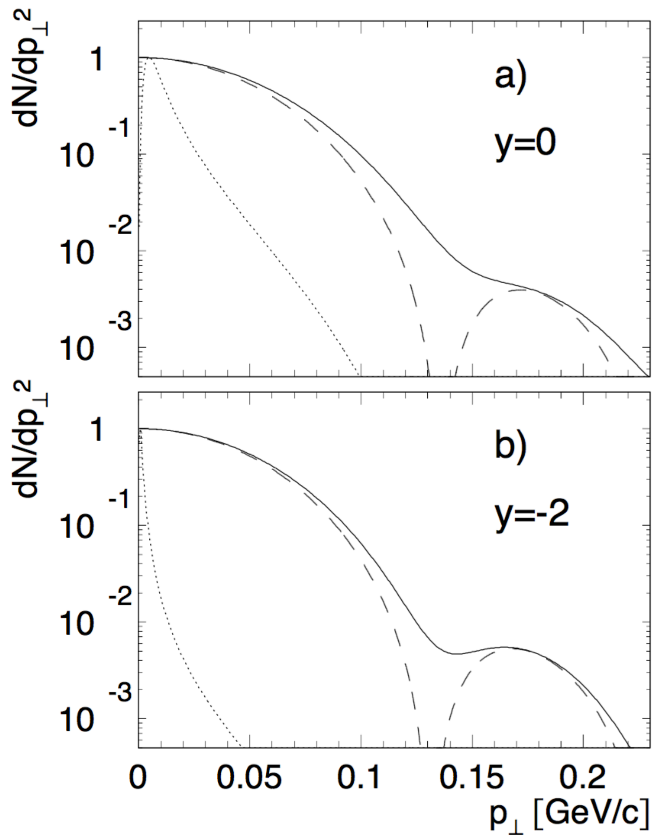
  - Almost perfect agreement with exact calculation
  - Analytic -> fast!
- Use exact nuclear data where available
  - Electron scattering data -> no neutron skin

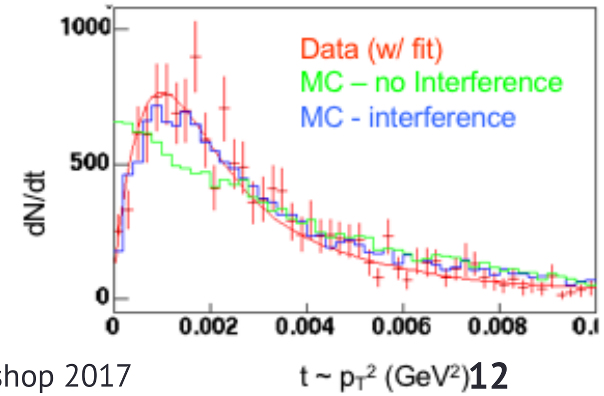
p_T Spectra and interference in γP interactions

- Final state $p_T = p_T(\gamma) + p_T(\text{Pomeron})$
  - Quadrature sum
  - Pomeron p_T dominate, Regulated by nuclear form factor
- Account for both diagrams and their interference
  - $\sigma \sim |A_1 - A_2 \exp(ikb/\hbar)|^2$, interference can be implemented with following:

$$\sigma(y, p_T) = \int d^2b[\sigma(y, p_T) - c\sigma(-y, p_T)]$$

- Calculate p_T spectrum once, sample from distribution for each event
  - Do this as a function of $y = \ln(k/2m_V)$





Incoherent Photonuclear Cross Section $\sigma(\gamma A \rightarrow VA')$

- Incoherent cross section obtained under the assumption that it scales the same way as the total inelastic vector meson nuclear cross section:

$$\frac{\sigma_{inc}(\gamma A \rightarrow VA')}{\sigma(\gamma p \rightarrow Vp)} = \frac{\sigma_{inel}(VA)}{\sigma_{inel}(Vp)}$$

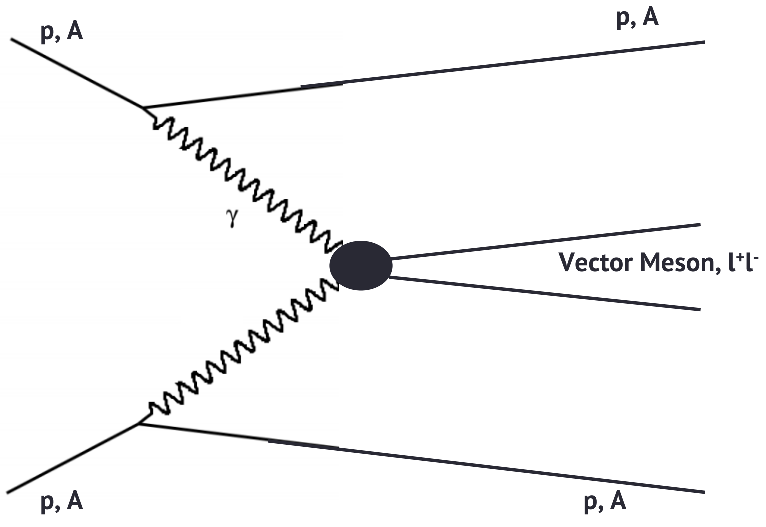
- Using classical Glauber approach as well, and assuming vector dominance model :

$$\sigma_{inc}(\gamma A \rightarrow VA') = \frac{4\pi\alpha}{f_\nu^2} \int \left(1 - e^{\sigma_{VN} T(b)}\right) db^2$$

- Transverse momenta is generated the same way as in coherent production.
  - Use nucleon form factor instead of Woods-Saxon
  - For light vector mesons, ρ^0 and ω, a dipole form factor is used: $F(Q^2) = \frac{1}{(1+Q^2/Q_0^2)^2}$ $\quad Q_0^2 = 0.45\ \mathrm{GeV}^2$
  - For heavier VM a narrower p_T has been observed, so we use: $F(Q^2) = e^{-bQ^2}$

γγ Production

$$\frac{d^2N_{\gamma\gamma}(k_1,k_2)}{dk_1dk_2} = \int\int d^2b_1 d^2b_2 P_{NoHad}(|\mathbf{b_1}-\mathbf{b_2}|)N(k_1,\mathbf{b_1})N(k_2,\mathbf{b_2})$$



- Two photon energies related to final state invariant mass W through:

$W^2 = 4k_1k_2$ $\qquad$ $Y = 1/2\ln(k_1/k_2)$

- The γγ luminosity is the integral in 2-d space of the products of the two photon densities
  - Subject to the two nuclei not colliding
- σ(γγ-> final states) follows standard formulae
  - Lepton pair production follows Breit-Wheeler
    - Heavily peaked in forward-backward topology.

$$\sigma(\gamma\gamma\to l^+l^-) = \frac{4\pi\alpha^2}{W^2}\left[\left(2+\frac{8m^2}{W^2}-\frac{16m^4}{W^4}\right)\ln\left(\frac{W+\sqrt{W^2-4m^2}}{2m}\right) - \sqrt{1-\frac{4m^2}{W^2}}\left(1+\frac{4m^2}{W^2}\right)\right]$$

  - σ(single meson) depends on two photon width $\Gamma_{\gamma\gamma}$ and spin

$$\sigma_{\gamma\gamma}(W) \approx 8\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}}{2M_R^2}\delta(W-M_R)$$

  - $\sigma(\rho^0\rho^0)$ follows a crude parameterization

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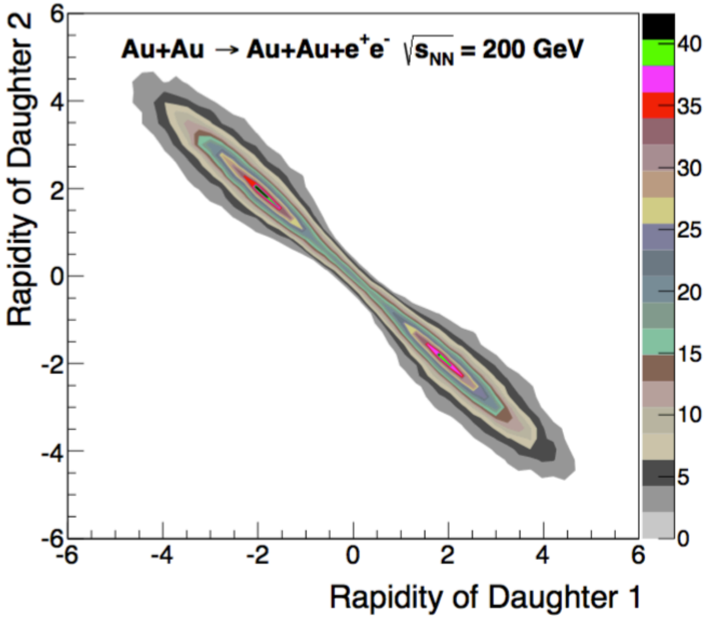

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  - σ($\rho^0\rho^0$) follows a crude parameterization

Acceptance criteria $\underbrace{P_{No-had}(b)}P_{XN}(b)P_{XN}(b)$

- No hadronic interactions criteria (AA):
    - Using Woods-Saxon overlap T_{AA}

$$P_{No-had}(b) = e^{-\sigma_{NN}T_{AA}(b)}$$

And nucleon nucleon cross sections follow PDG parametrization *pp* for $\sqrt{s_{NN}} > 7$ GeV

$$\sigma = (33.73 + 0.2838\ln^2(r) + 13.7r^{-0.412} - 7.77r^{0.5626})mb$$

-
    - ~20% reduction in γγ luminosities compared to simple $b > 2R_A$ req.
- No hadronic interactions criteria (pA):
    - The probability of having hadronic interactions is calculated from the Fourier transform of the Form factor $\Gamma(s,b)$ with b_0=19.8 GeV^{-2}:

$$P_{No-had}(b) = |1 - \Gamma(s,b)|^2 \qquad \Gamma(s,b) = e^{-b^2/2b_0}$$

-
    - Roughly equivalent to a cut in minimum impact parameter of $b > 1.4$ fm

Nuclear break-up

$$P_{No-had}(b)\underbrace{P_{XN}(b)P_{XN}(b)}$$

- Experimentally it is easier to study UPC's when accompanied by nuclear break-up: neutrons can be easily detected in forward calorimeters.
- Breakup only depends on impact parameter, easily incorporated into STARlight:
  - Photonuclear cross section and γγ luminosity multiplied by the probability $P_X(b)$ of breakup at a given impact parameter.
- Two types of breakup considered:
  - Breakup leading to any number of emitted neutrons (*Xn*).
  - Giant dipole resonance (GDR) excitation, which usually leads to a single neutron emission (*1n*).
- The cross-section for a nucleus to be excited is given by:

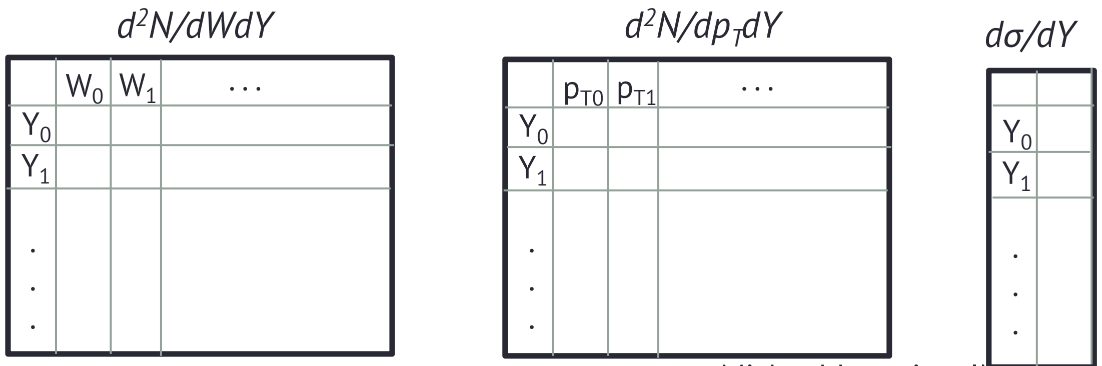
$$P_1(b) = \int dk \frac{d^3n(k,b)}{dkdb^2}\sigma_{\gamma A\rightarrow A^*}$$

- The excitation cross section $\sigma_{\gamma A\rightarrow A^*}$ is obtained from parametrization to exp. data so it is only available for gold or lead nuclei

How does STARlight work?

- STARlight runs in two stages to speed up event generation.
- First stage calculates cross sections and other kinematic distributions and stores them in look-up tables to speed up event generation:

1. 2 dimensional table for event mass and rapidity $d^2N/dWdY$:
    - For photonuclear these follow Breit-Wigner distribution using mass and width from PDG.
    - For γγ production of dileptons this follows Breit-Wheeler convoluted with photon fluxes.
    - For γγ production of vector mesons the mass distribution from PDG values.
2. For photonuclear $d^2N/dYdp_T$ look-up table is also generated, ignoring the p_T dependence on W. For γγ p_T is obtained semi-analytically at run time.
3. A collapsed version of tables $d\sigma/dY$ is also stored to determine the value of Y



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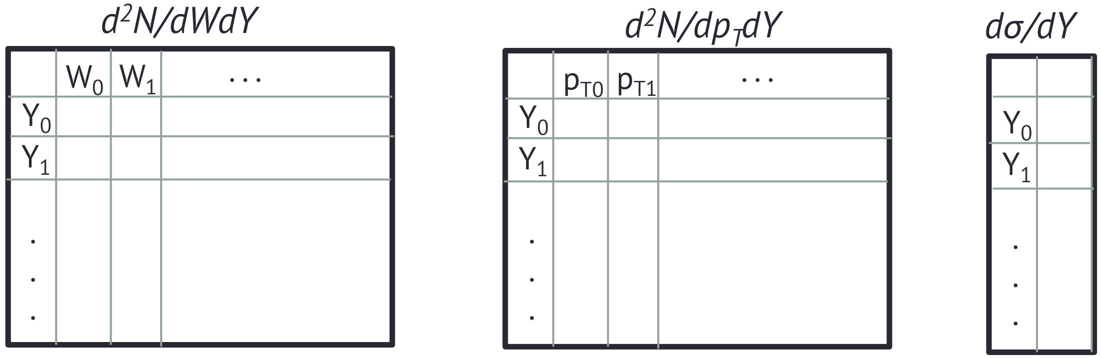
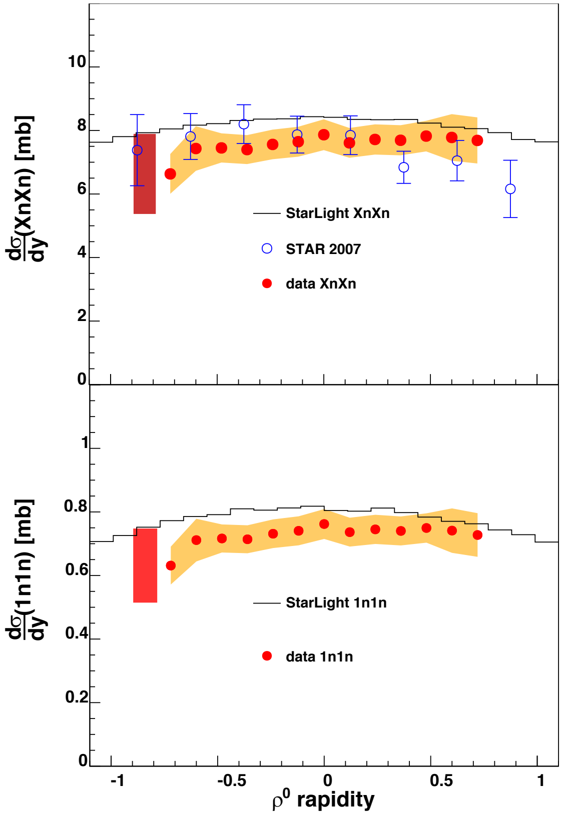


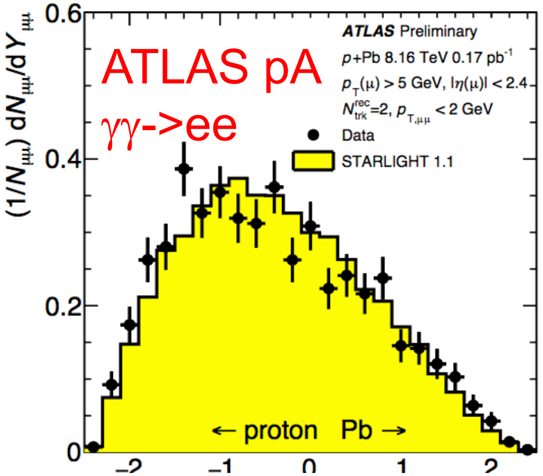
- During the second stage events are generated. A value of Y is selected using $d\sigma/dY$.
  - STARlight uses the two "bins" that straddle each random number and a linear interpolation between these is used to find the associated value from the tables.
- A second random number is used to find the value of W and p_T that correspond to the Y value from the 2D tables.

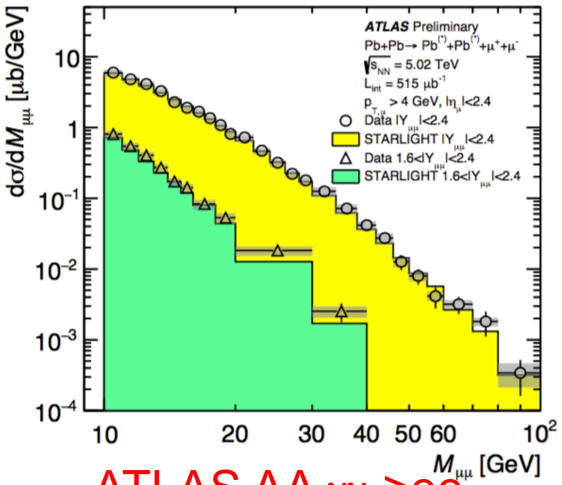
STARlight versus data

STAR
AuAu -> ρ^0

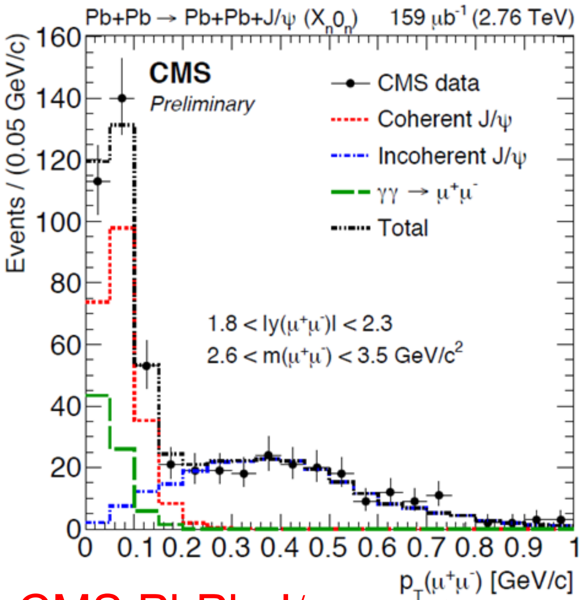


ATLAS pA
$\gamma\gamma$->ee

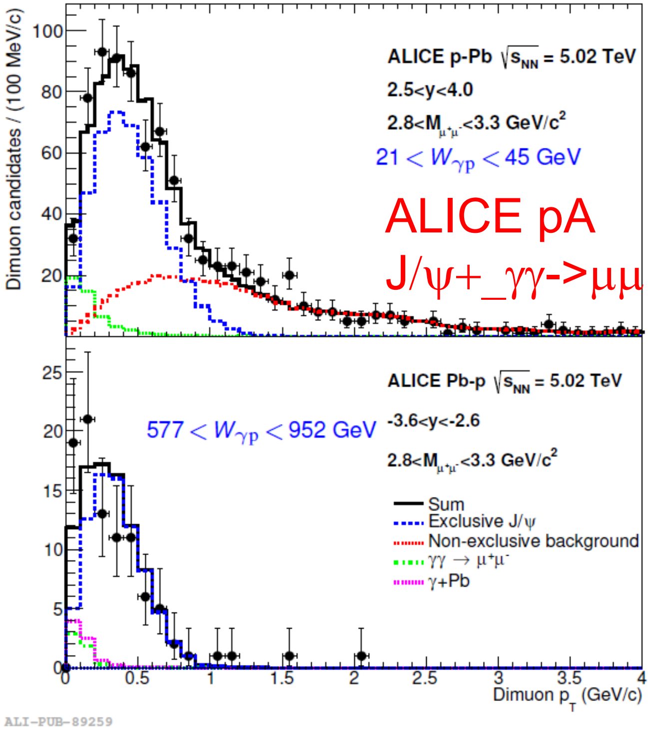




ATLAS AA $\gamma\gamma$->ee



CMS PbPb J/ψ+_$\gamma\gamma$->$\mu\mu$



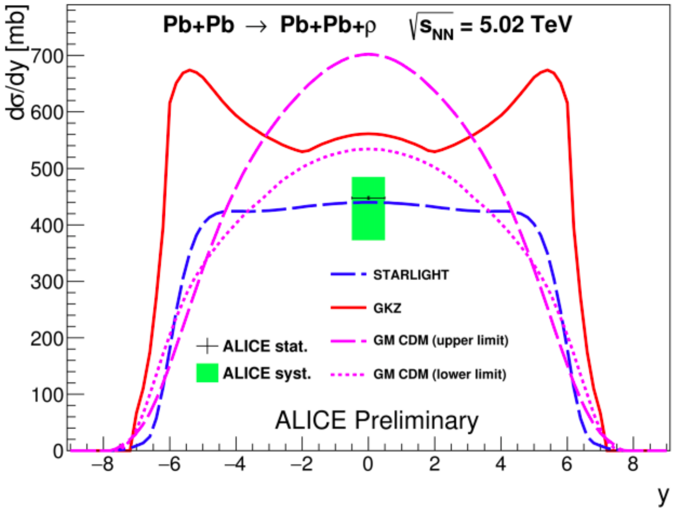
ALICE pA
J/ψ+_$\gamma\gamma$->$\mu\mu$

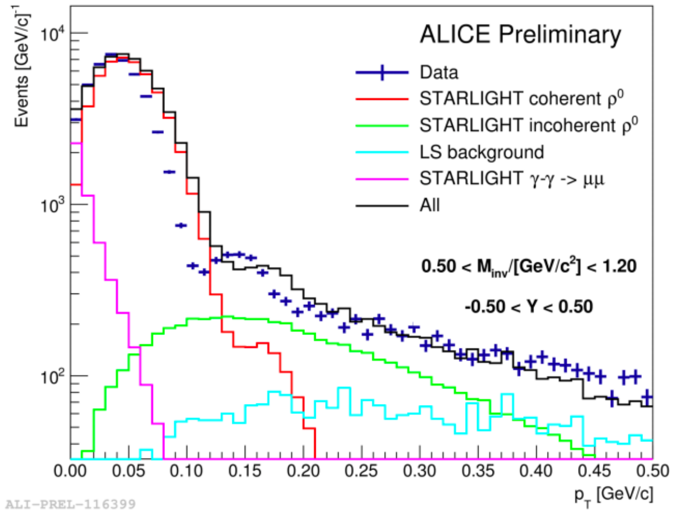
- Good track record proven by many experiments and collision energies in UPC collision

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

STARlight approximations

- Simplifying by spreading the photon flux evenly across the nucleus:
  - Doesn't work so well at small impact parameters.
  - Particularly problematic for interference.
- No neutron skin:
  - Form factor in STARlight from elastic eA which → only probes the protons.
  - Shift in ρ coherent peak.
- Classical vs. quantum Glauber calculation:
  - Quantum calculations predict dips but over estimate cross sections (factor 2)[1].
  - Recent attempts (including shadowing) improve on the cross section but miss dips
- Assumes complete longitudinal coherence – could be an issue in EIC





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

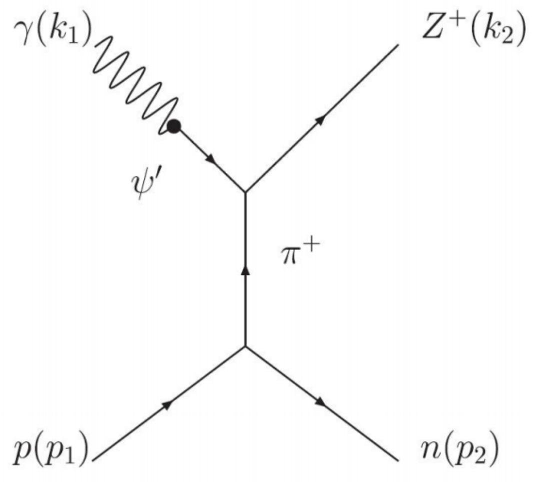
VM photo-production in an EIC

- Due to interference in AA and pA, one cannot tell which nucleus emitted the photon and which the Pomeron.

  i.e. for a given a known vector meson p_T it is not easy to apportion the p_T between the two nuclei. This is not the case for eA

- Study the limits of photoproduction physics in an EIC
  - How high can we go in Q^2 for different mesons (lower production for higher γ energy)?
  - Optimize detector design and location.

- Can we study exotic meson (hybrid, tetraquark) states in e+A→e+A'+X (X=meson) processes?
  - High luminosity at EIC (100-1000 x HERA) vs. low cross section.
  - Production cross section can be used to analyze tetraquark composition: diquark-antidiquark bound state versus meson-meson molecule.



Phys Rev C **83** 065203 (2011)

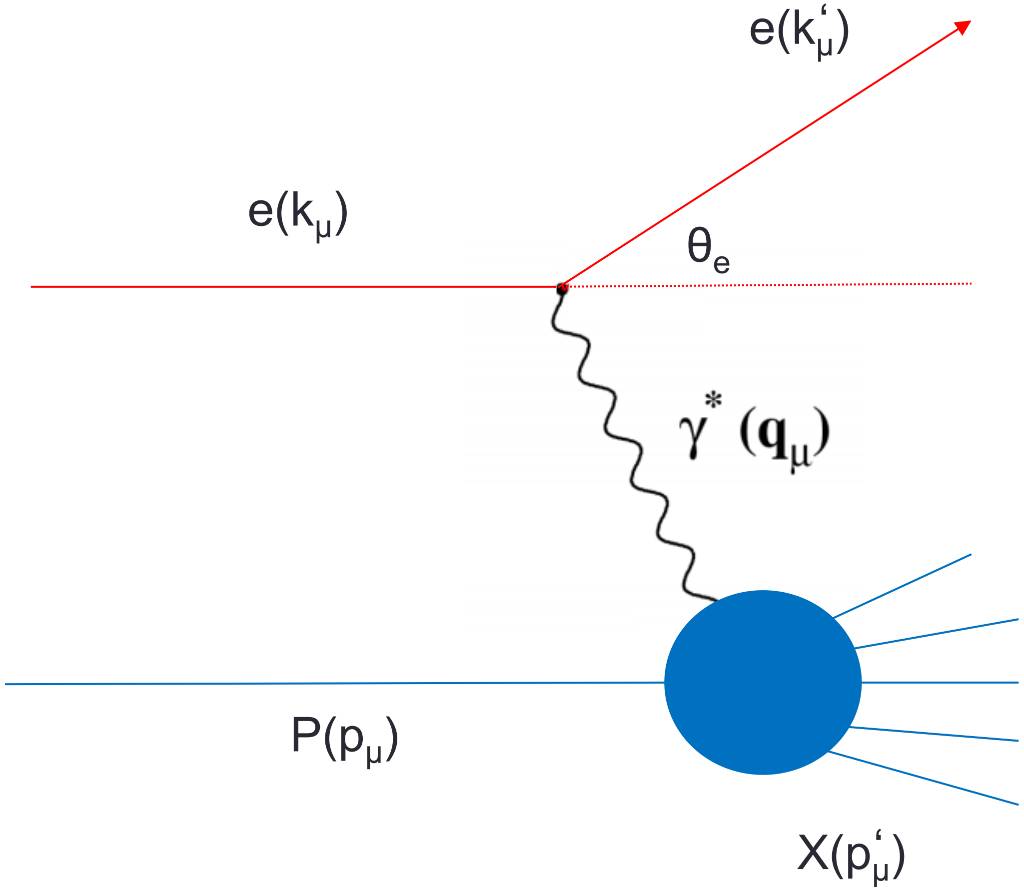
Electron-ion collisions

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

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

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

$$s = 4E_pE_e$$



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. e+p/A → e' + h + p'/A'

STARlight → eSTARlight

- Include electron beam source/target.
- Track the virtuality of photons and propagate through to final states.
  - For photonuclear interaction. The Electron photon flux[1]:

$$dn = \frac{\alpha}{\pi}\frac{d\omega}{\omega}\frac{d(-q^2)}{|q|^2}\left[1 - \frac{\omega}{E} + \frac{\omega^2}{2E^2} - \left(1 - \frac{\omega}{E}\right)\left|\frac{q^2_{min}}{q^2}\right|\right]$$

  - Include effect of polarization on secondary momentum, and modification to angular distributions due to finite Q^2 ([1])

$$d\sigma_{ep} = \sigma_\gamma(\omega)dn(\omega, q^2) \rightarrow d\sigma_{ep} = \left[\frac{d\sigma_\gamma}{d^3k_1} + \frac{1}{2}\xi\cos 2\phi \frac{d(\sigma_\parallel - \sigma_\perp)}{d^3k_1}\right] d^3k_1 dn(\omega, q^2)\frac{d\phi}{2\pi}$$

  - ξ = polarization of photon, ϕ = angle between electron scattering and production plane and σ_i are the absorption cross sections for transversely polarized γ in plane parallel and perp. to it

$$\cos\phi \approx \frac{p'_\perp k_{1\perp}}{|p'_\perp| \cdot |k_{1\perp}|} \qquad d\sigma_\gamma = \frac{1}{2}d(\sigma_\parallel + \sigma_\perp)$$

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

STARlight → eSTARlight

- Or parametrize to data[2]?

$$W(\phi) \propto 1 - \epsilon \cos 2\phi (2r^1_{11} + r^1_{00}) + \sqrt{2\epsilon(1+\epsilon)} \cos\phi (2r^5_{11} + r^5_{00})$$

Extracting the Q^2, W and t dependence of the matrix elements *r*.

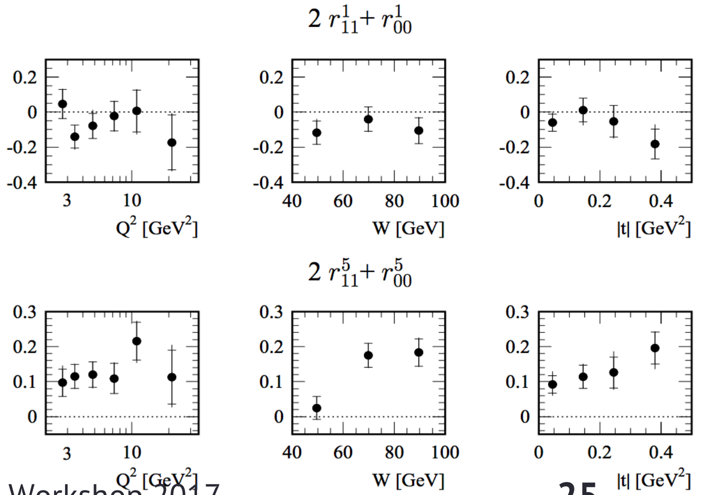
Tables shown are for ρ photoproduction from HERA

- γγ production [1]:

$$d\sigma_{ee} = \left[\sigma_{\gamma\gamma} + \frac{1}{2}\xi_1\xi_2\tau_{\gamma\gamma}\cos 2\phi\right] dn(\omega_1, q_1^2) dn(\omega_2, q_2^2) d\phi/2\pi$$

Q^2 (GeV^2)	W (GeV)	$\|t\|$ (GeV^2)	$2\, r^1_{11} + r^1_{00}$	$2\, r^5_{11} + r^5_{00}$
2.5 - 3.0	30 - 100	0.0 - 0.5	$0.046 \pm 0.083^{+0.025}_{-0.009}$	$0.097 \pm 0.039^{+0.029}_{-0.005}$
3.0 - 4.0	30 - 100	0.0 - 0.5	$-0.140 \pm 0.065^{+0.011}_{-0.036}$	$0.115 \pm 0.034^{+0.011}_{-0.010}$
4.0 - 6.0	30 - 120	0.0 - 0.5	$-0.079 \pm 0.072^{+0.059}_{-0.008}$	$0.120 \pm 0.036^{+0.011}_{-0.015}$
6.0 - 9.0	30 - 140	0.0 - 0.5	$-0.023 \pm 0.084^{+0.027}_{-0.029}$	$0.109 \pm 0.043^{+0.018}_{-0.005}$
9.0 - 14.	30 - 140	0.0 - 0.5	$0.006 \pm 0.119^{+0.042}_{-0.061}$	$0.216 \pm 0.054^{+0.021}_{-0.032}$
14. - 60.	30 - 140	0.0 - 0.5	$-0.173 \pm 0.156^{+0.061}_{-0.053}$	$0.113 \pm 0.077^{+0.050}_{-0.040}$
2.5 - 60.0	40 - 60	0.0 - 0.5	$-0.118 \pm 0.066^{+0.045}_{-0.013}$	$0.025 \pm 0.033^{+0.004}_{-0.009}$
2.5 - 60.0	60 - 80	0.0 - 0.5	$-0.040 \pm 0.069^{+0.016}_{-0.025}$	$0.175 \pm 0.034^{+0.011}_{-0.012}$
2.5 - 60.0	80 - 100	0.0 - 0.5	$-0.106 \pm 0.074^{+0.024}_{-0.012}$	$0.183 \pm 0.039^{+0.018}_{-0.012}$
2.5 - 60.0	30 - 140	0.0 - 0.1	$-0.060 \pm 0.049^{+0.027}_{-0.006}$	$0.092 \pm 0.025^{+0.028}_{-0.020}$
2.5 - 60.0	30 - 140	0.1 - 0.2	$0.012 \pm 0.068^{+0.008}_{-0.055}$	$0.114 \pm 0.033^{+0.018}_{-0.005}$
2.5 - 60.0	30 - 140	0.2 - 0.3	$-0.053 \pm 0.090^{+0.015}_{-0.041}$	$0.126 \pm 0.044^{+0.041}_{-0.023}$
2.5 - 60.0	30 - 140	0.3 - 0.5	$-0.182 \pm 0.085^{+0.074}_{-0.011}$	$0.196 \pm 0.046^{+0.010}_{-0.039}$

Table 9: Measurements of the combinations of matrix elements $2r^1_{11} + r^1_{00}$ and $2r^5_{11} + r^5_{00}$, as a function of Q^2, W and t, obtained from fits to the ϕ distributions. The first errors are statistical, the second systematic.



1: Phys.Rept. 15 181-281 (1975)
2: Eur.Phys.J.C13:371-396 (2000)

Implementing eSTARlight

- Add another 2D lookup table for the virtuality of photons $d^2N/d\omega d(q^2)$. What is the best binning? q^2 vs. $\log(q^2)$
- q_{min} depends on the VM to be produced:

$$q^2_{min} = \frac{m_e^2 \omega^2}{E(E-\omega)} \left[1 + O\left(\frac{m_e^2}{(E-\omega)^2} \right) \right]$$

- Can we avoid look-up table (regime where $q^2 < q_{max}{}^2 = 4E(E-\omega)$)?

$$dn = \frac{\alpha}{\pi} \left[2\left(1 - \frac{\omega}{E} + \frac{\omega^2}{2E^2}\right) \ln \frac{2E(E-\omega)}{m_e(2E-\omega)} + \frac{\omega^2}{2E^2} \ln \frac{2E-\omega}{\omega} - 1 + \frac{\omega}{E} \right] \frac{d\omega}{\omega}$$

- Generate outgoing electron and proton(ion?)

Summary

- STARlight has a proven track record over a large range of energies as well as initial and final states.
- Overall good description of several important features in UPC collisions.
- Some approximations and related issues have been discussed.
- Next step: Incorporating electrons in order to generate eA(p) collisions for an upcoming Electron Ion Collider (EIC).
- eSTARlight can be used to study the scientific case for an EIC
- Requires tracking photon virtuality by modifying fluxes and angular distributions.
- Some details of the implementation have been discussed.