Vector meson production in UPCs and the eSTARlight Monte Carlo

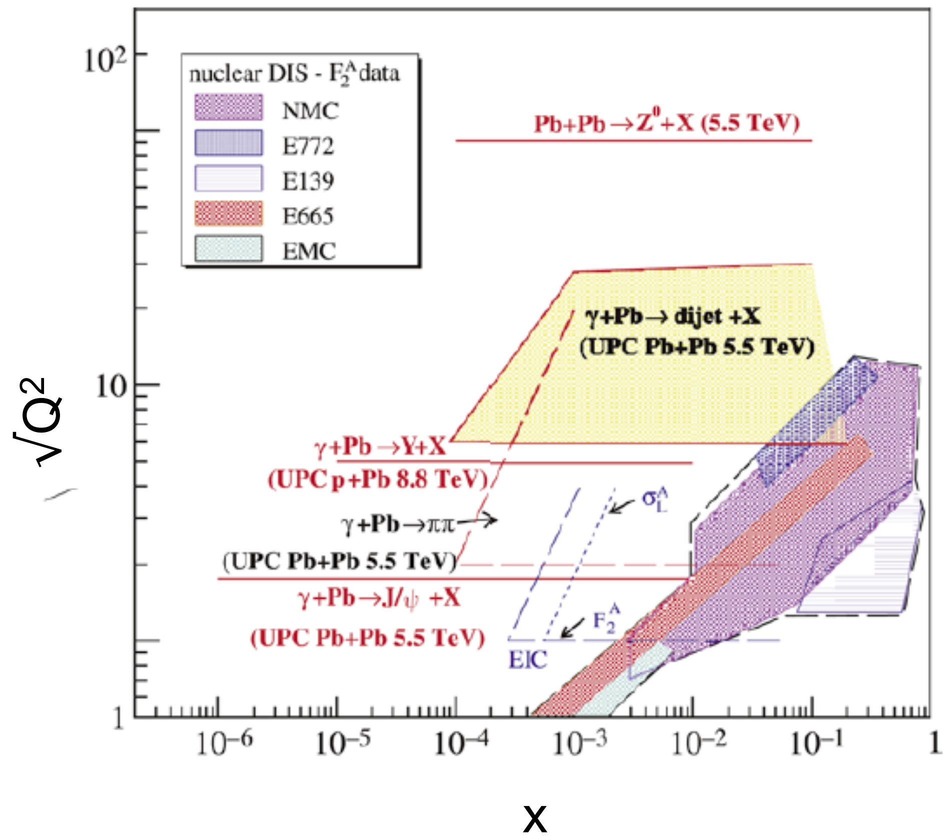
Spencer Klein, LBNL

Presented at the workshop on "Next-generation GPD studies with exclusive meson production at EIC"

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

UPCs & an EIC are complementary

- UPCs at the LHC is and will be the energy frontier for photoproduction studies
  - Down to $x \sim 10^{-6}$
  - $Q^2 = M_V^2 + p_T^2$
    - Correlated with p_T
    - t and Q^2 not quite independent
- EIC is the intensity frontier
  - Independent Q^2 measurement via outgoing electron
  - Multi-dimensional binning, precision studies and other event-hungry analyses



A. J. Baltz *et al.,* Phys. Rept. 458 (2008) 1

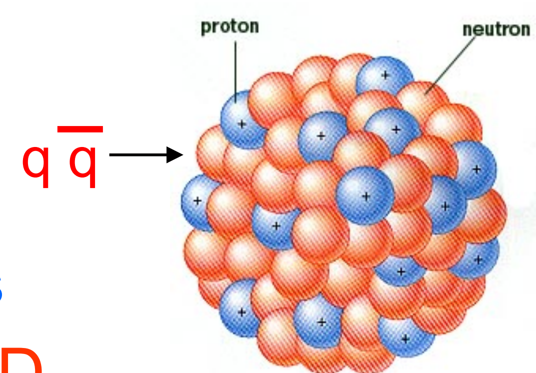
UPCs with large data samples

- UPCs do offer large γA integrated luminosity
  - With an appropriate trigger, large samples can be collected
    - ~ 10^6 events for light mesons
    - HL-LHC could reach > 10^5 ccbar mesons
- UPCs do not offer good control of Q^2
- But, can use $Q^2 = M_V^2 + p_T^2 \sim M_V^2$ to scan in Q^2
  - Not quite, since $p_{longitudinal}$ depends on M_V, but close
- Today: one STAR analysis in this direction:
  - Study evolution of nuclear shape with increasing Q2
  - $d\sigma_{coherent}$ /dt gives nuclear shape, through Fourier transform

Thanks to Ramiro Debbe, Thomas Ullrich and Markus Diehl for developing the Fourier transform technique.

Nucleon shadowing of dipoles

- A photon fluctuates to a $q\bar{q}$ dipole which then scatters elastically from the nucleus, emerging as (for today) a ρ^0 or $\pi\pi$
  - $\omega \to \pi\pi$ also contributes, mostly through interference
- Large dipoles (small $M_{\pi\pi}$) interact on the front of the nucleus
  - "Black disk limit"
  - Multiple interactions from one dipole
- Small dipoles (high $M_{\pi\pi}$) penetrate more deeply and see internal nucleons
  - Woods-Saxon distribution
- Dipole size most important near b=0
  - Shadowing changes effective shape of nucleus
- $\rho^0 + \pi\pi$ photoproduction too low in Q^2 for pQCD
- Nucleon shadowing affects $d\sigma/dt$



L. Frankfurt *et al.*, Phys. Lett. **B752**, 51 (2016)

From $d\sigma/dt$ to nuclear density profiles

- For coherent production in low-density targets
  - $\sigma = |\Sigma_i A_i \exp(ikx_i)|^2$
    - A_i, x_i are nucleon interaction amplitudes and positions
      - The interaction sites differ for the low-$M_{\pi\pi}$ and high $M_{\pi\pi}$ cases
- $d\sigma/dt$ ($t=p_T^2+p_{||}^2$) depends on the shape of the nucleons
  - $p_{||}$ is negligible here, and will be neglected
- Fourier transform of $d\sigma/dt$ gives nuclear density profile

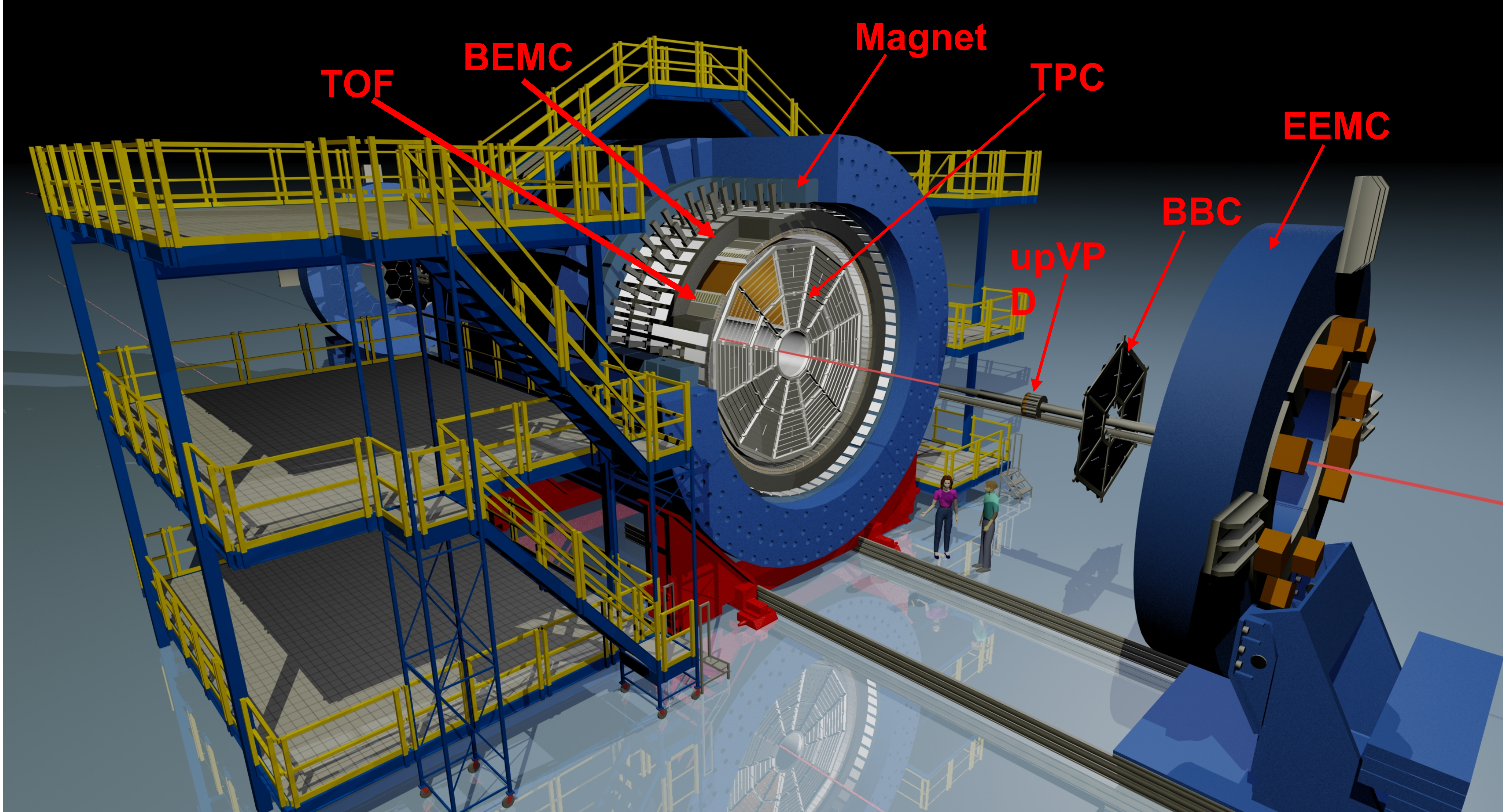
$$F(b) \propto \frac{1}{2\pi} \int_0^\infty dp_T p_T J_0(bp_T) \sqrt{\frac{d\sigma}{dt}}$$

* = flips sign after each minimum

  - In data, there is an upper limit to t -> windowing problems
- Gives the two-dimensional (traverse) distribution of interaction sites within the nuclear target
  - Changes with dipole size/$M_{\pi\pi}$/reaction Q^2

Toll & Ullrich, Phys. Rev. **C87**, 024913 (2013), STAR, Phys. Rev. **C96**, 054904 (2017)

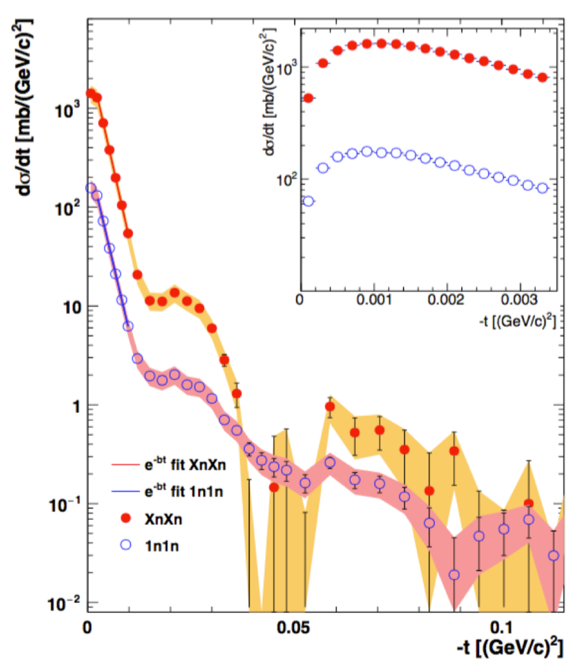
The Solenoid Tracker At RHIC (STAR)

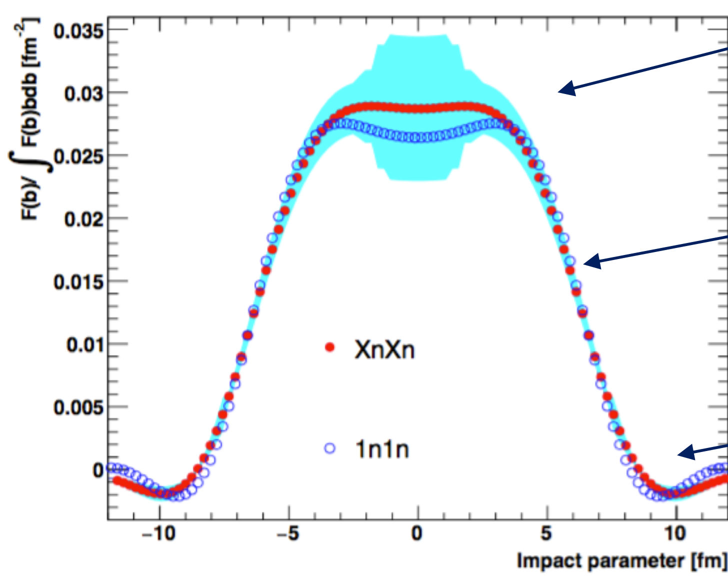


Detectors for |y|<1 – TPC, time-of-flight system, EM Calorimeter
Zero degree calorimeters at large |y|
Beam-Beam Counters veto events w/ charged particles in 2 < |y|<5

Previous STAR analysis

- 294,000 photoproduced $\pi\pi$ pairs
  - Tight cuts to minimize background
  - $M_{\pi\pi}$ spectrum well fit to ρ^0 + direct $\pi\pi$ + ω-> $\pi\pi$ cocktail
- $d\sigma_{coherent}/dt = d\sigma_{total}/dt - d\sigma_{incoherent}/dt$
- $d\sigma_{incoherent}/dt$ found at larger |t|, where $d\sigma_{coherent}/dt$ is small
  - Fit to a dipole form factor, and extrapolate to small |t|





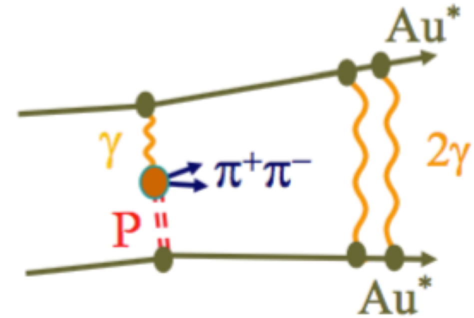
Large variation with t_{max} Windowing?

Sharp edges

Negative due to destructive interference

STAR, Phys. Rev. **C96**, 054904 (2017)

The current analysis



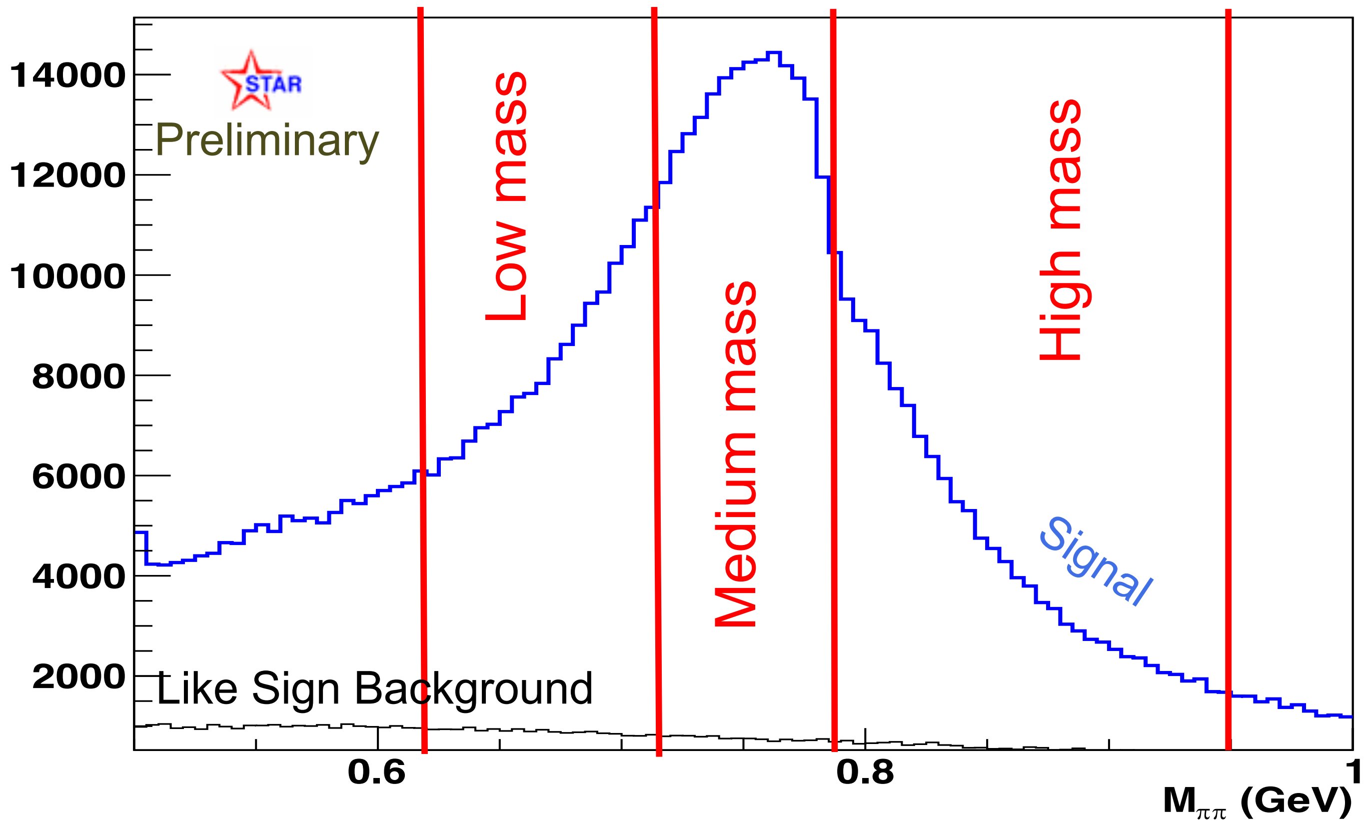
- Similar approach as in 2017 STAR paper
- Uses 2 years of data (2010 and 2011)
- Divide $M_{\pi\pi}$ spectrum into 3 mass bins, with similar number of events
- See how $d\sigma_{coherent}/dt$ and F(b) vary with $M_{\pi\pi}$ range
  - How does the apparent nuclear shape vary with dipole size
  - Look for evidence of nuclear shadowing
- STAR 'minimum bias UPC trigger'
  - Low multiplicity + neutrons in both ZDCs
- $\pi\pi$ photoproduction + mutual Coulomb exchange
  - Three-photon exchange
    - One to produce the $\pi\pi$, one to excite each nucleus
  - Good control of impact parameter (photon p_T spectrum)
- Reconstruction efficiency is independent of $\pi\pi$ p_T

Data set and cuts

- Trigger: 2-6 tracks with $|y|<1$ and 1-4 neutrons in each ZDC
- Select $\pi\pi$ pairs coming from a single vertex with tight cuts
  - $|Z_{vtx}| < 50$ cm
  - $|Y_{\pi\pi}| > 0.04$ (removes cosmic-ray muons)
  - Each track must have at least 25 space points
  - $N_{primary\ tracks} = 2$
- Mass Cut: 0.62 GeV $< M_{\pi\pi} < 0.95$ GeV
- Backgrounds:
  - $M_{\pi\pi} > 0.62$ GeV removes most $\gamma A \to \omega \to \pi^+ \pi^- \pi^0$ and $\gamma\gamma \to ee$
    - $N(\pi\pi$ from $\omega \to \pi^+ \pi^- \pi^0)/N(\pi\pi$ from $\rho) \sim 0.05\%$
    - For $M_{\pi\pi} > 0.62$ GeV, $\pi^+\pi^-$ from ω are at low p_T,
      - Similar p_T as most ρ + direct $\pi\pi \to$ not a problem
  - Like sign pairs represent the hadronic background
    - Signal: like-sign background ratio > 10:1 in the coherent region

The $\pi\pi$ mass spectrum

- Divide $M_{\pi\pi}$ spectrum into three bins
  - Similar numbers of events in each range
  - Look at $d\sigma/dt$ spectrum in each region



Very few like sign pairs -> very little hadronic background

Q^2 bins

Mass Range	$<Q^2>$	N_{events} (Net)
0.62-0.72 GeV/c^2	~0.45 $(GeV/c)^2$	149K
0.72-0.78 GeV/c^2	~0.56 $(GeV/c)^2$	148K
0.78-0.95 GeV/c^2	~0.7 $(GeV/c)^2$	140K
0.62-0.95 GeV/c^2		437K

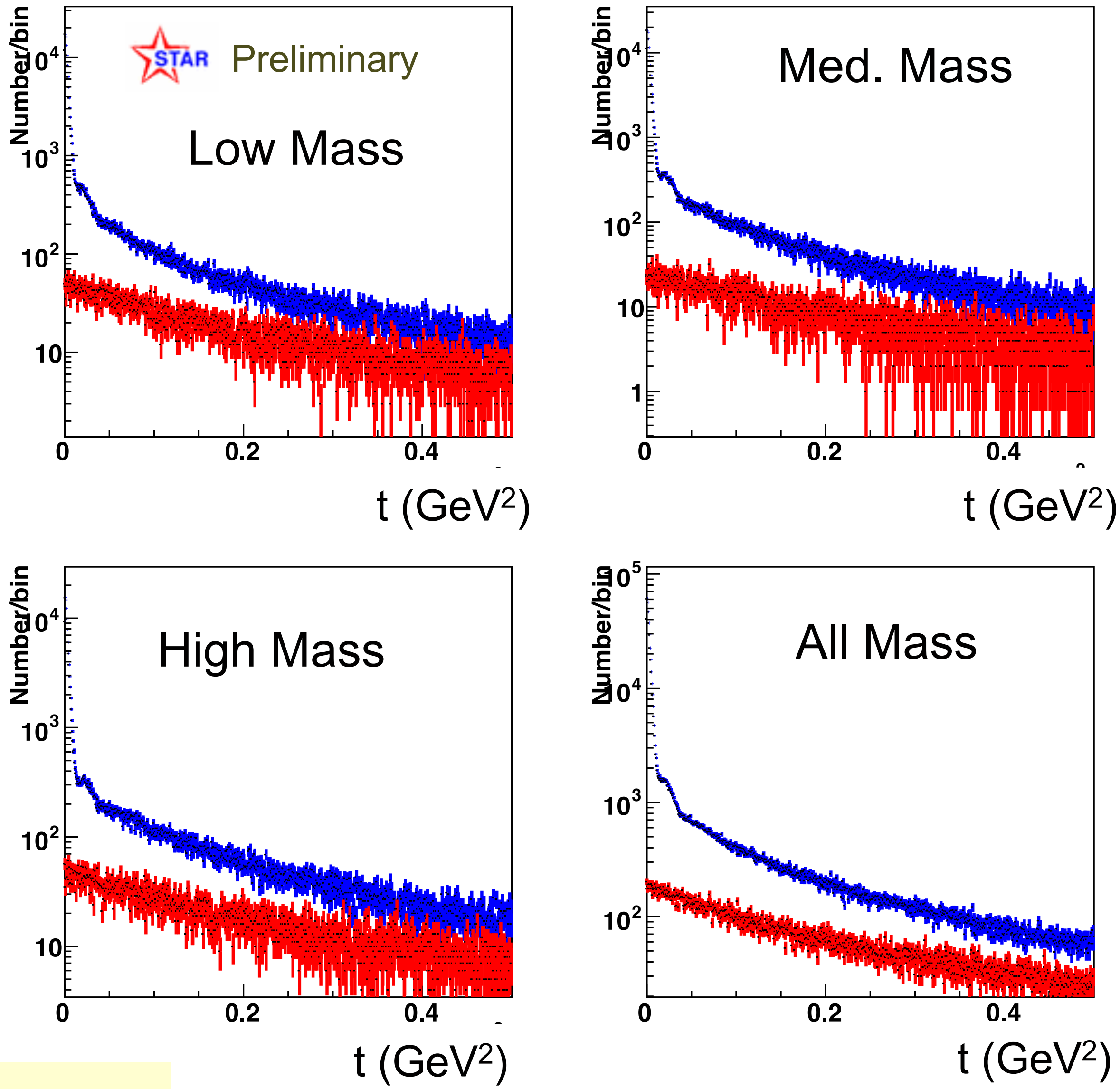
Net = after background subtraction

Unfortunately, a somewhat limited lever arm

Like-sign background subtraction

Tight cuts lead to signal:noise ratio > 10:1 in coherent region

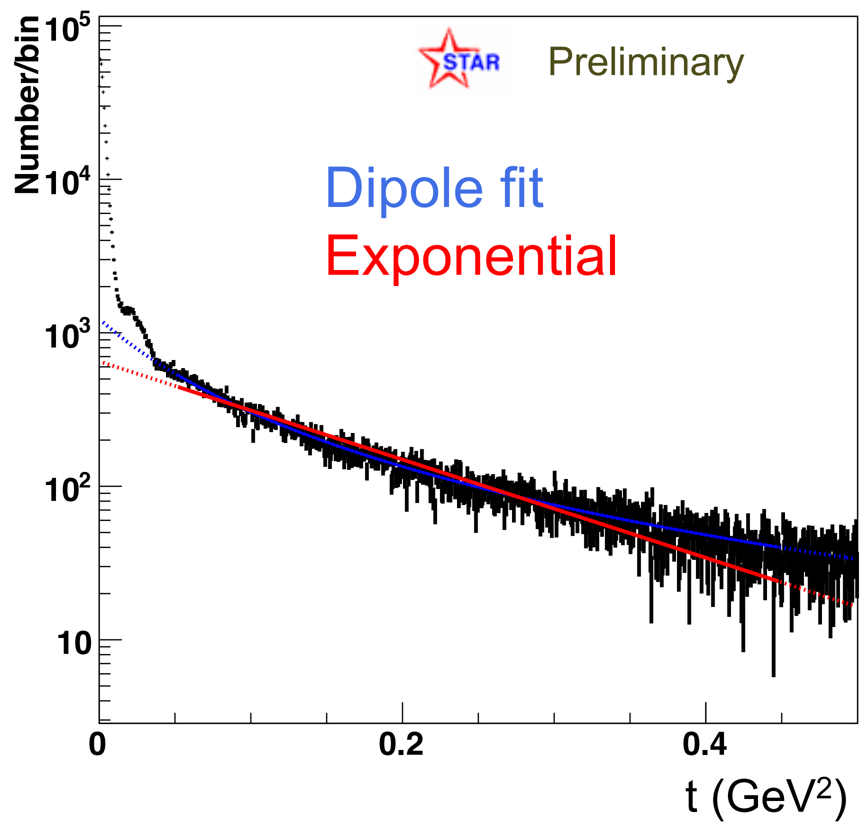
Signal
Like sign BG



Incoherent fitting

- $d\sigma_{incoherent}/dt$ fit to a dipole form factor
  - Q_0^2=0.099 GeV^2 from STAR paper
- Fit in range 0.05< t < 0.45 GeV^2
  - Wider than in the STAR paper
  - Minimize statistical uncertainty & distance for extrapolation
- χ^2/DOF = 659/639 -> OK
- Why not an exponential?
  - Poor fit to data
    - χ^2/DOF – 1345/639
- Results similar to those in the STAR paper

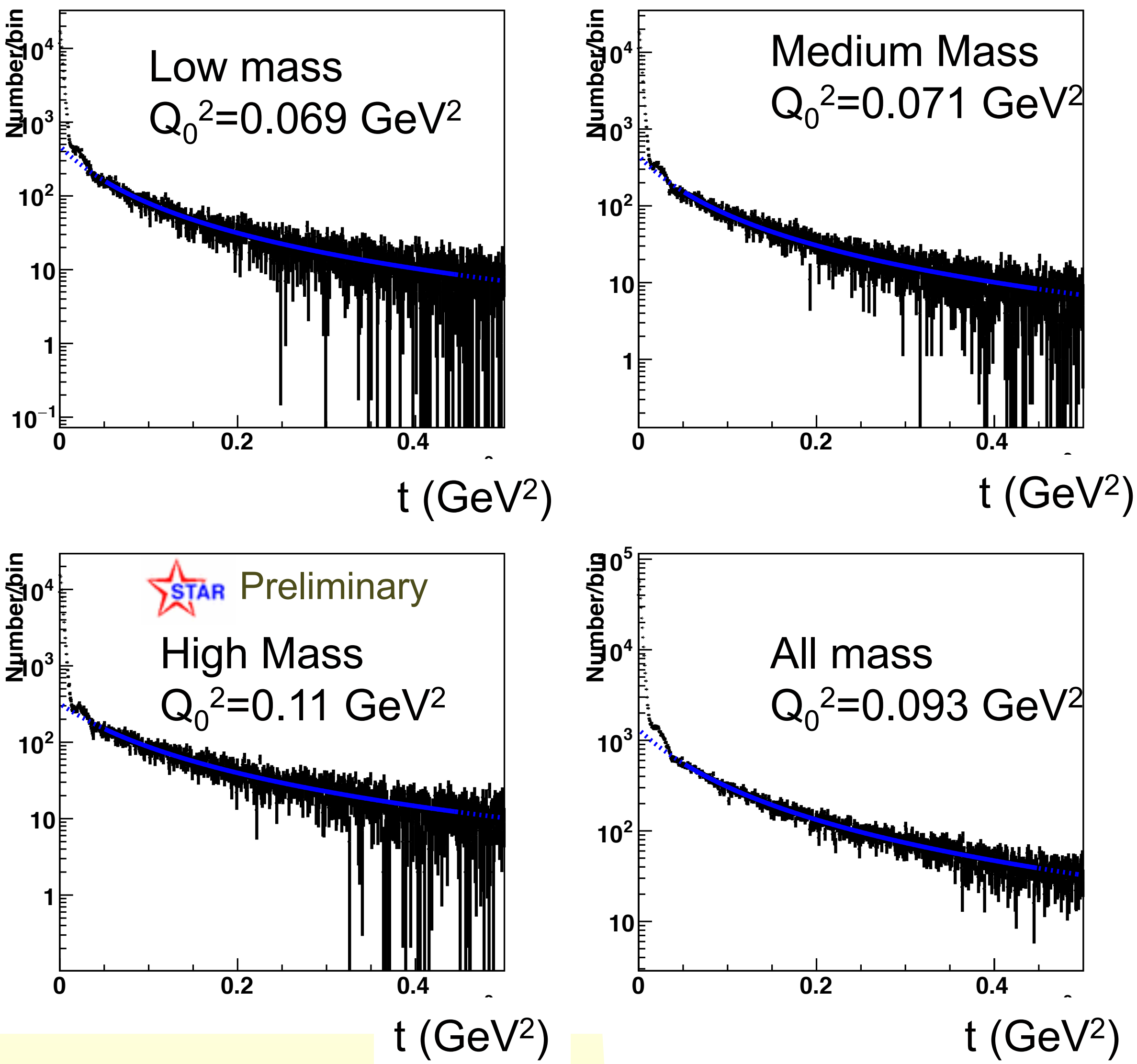
$$\frac{d\sigma}{dt} = \frac{A/Q_0^2}{(1+|t|/Q_0^2)^2}$$



STAR, Phys. Rev. **C96**, 054904 (2017)

Incoherent fitting in $M_{\pi\pi}$ bins

Let Q_0 float

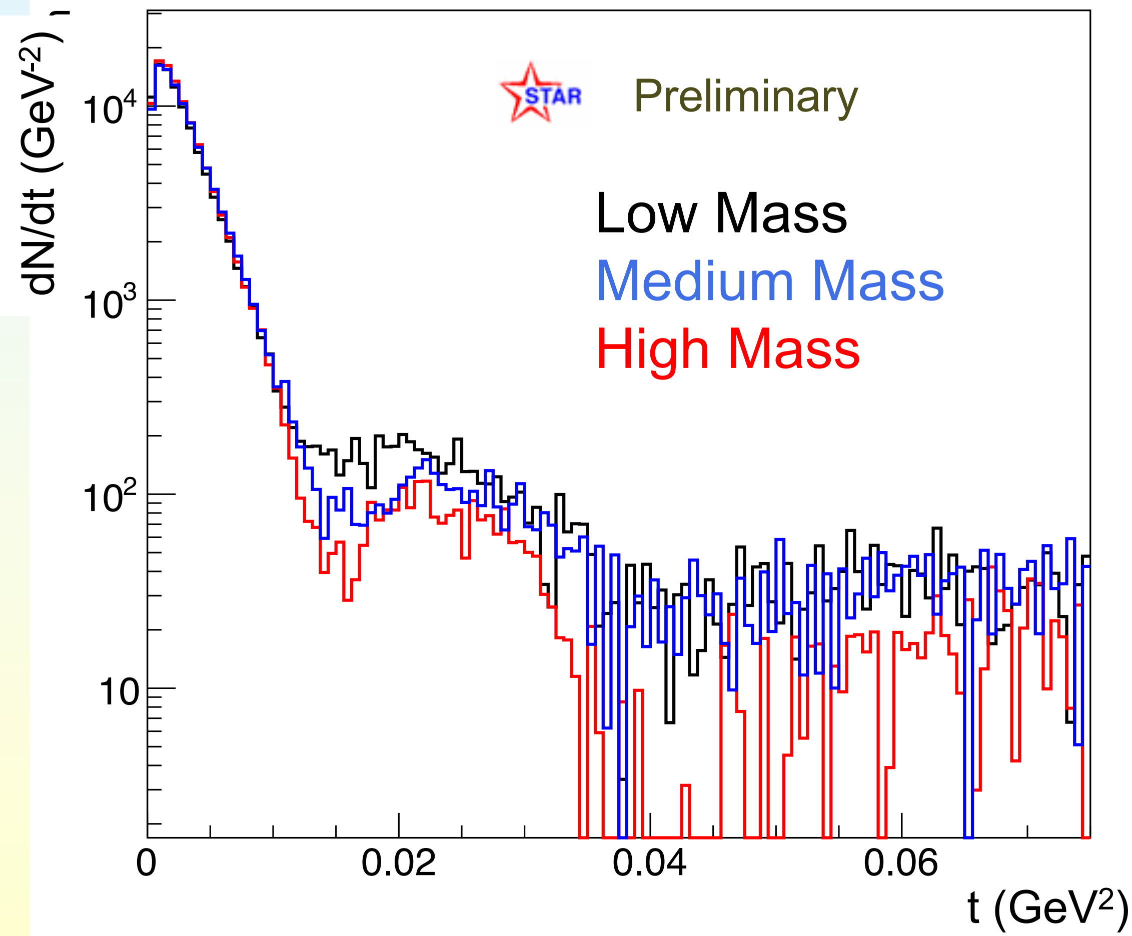


Sample	Q_0
Low	0.2626 ± 0.0045 GeV
Medium	0.2687 ± 0.0039 GeV
High	0.3299 ± 0.0046 GeV
All	0.3050 ± 0.0024 GeV

All fits have: χ^2/DOF ~ 1 & $Q_0^2$is insensitive to loosening of cuts
Higher $M_{\pi\pi}$ -> higher Q_0^2-> may be reflective of smaller dipole

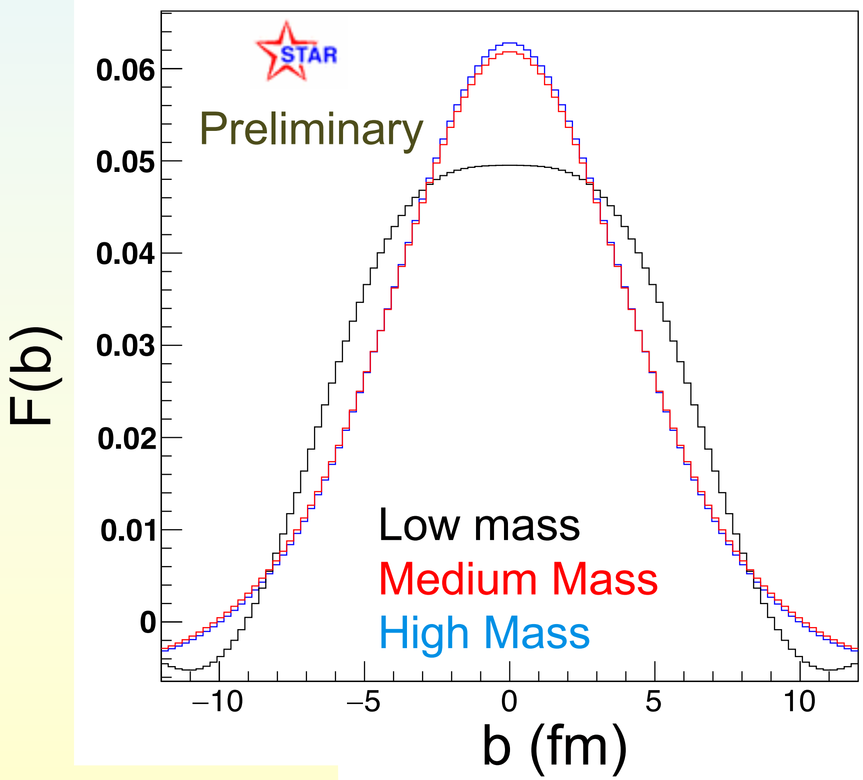
Coherent dσ/dt

- Subtract fitted incoherent contribution
- Normalize to the same number of events/$M_{\pi\pi}$ bin



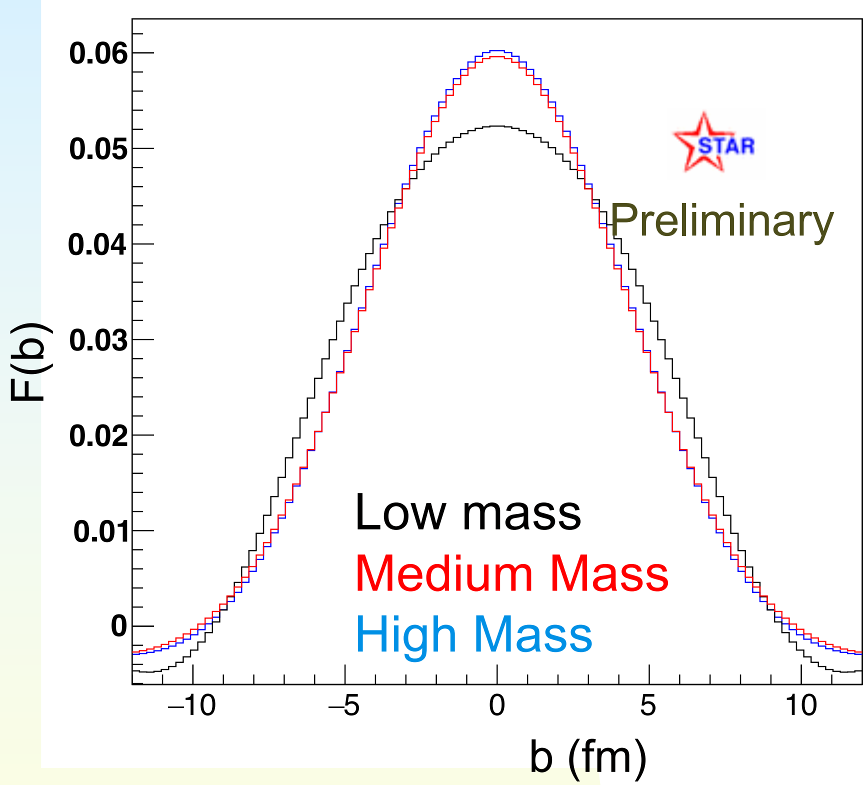
Transforming to F(b)

- Use t_{max}=0.006 GeV^2 for baseline to match the STAR paper
  - Below first minima: avoids uncertainties in dip positions
  - Vary t_{max} as a systematic error
- Normalize F(b) to the same area.
- Clear shape differences -> low mass has a flat-top, as expected in shadowing models

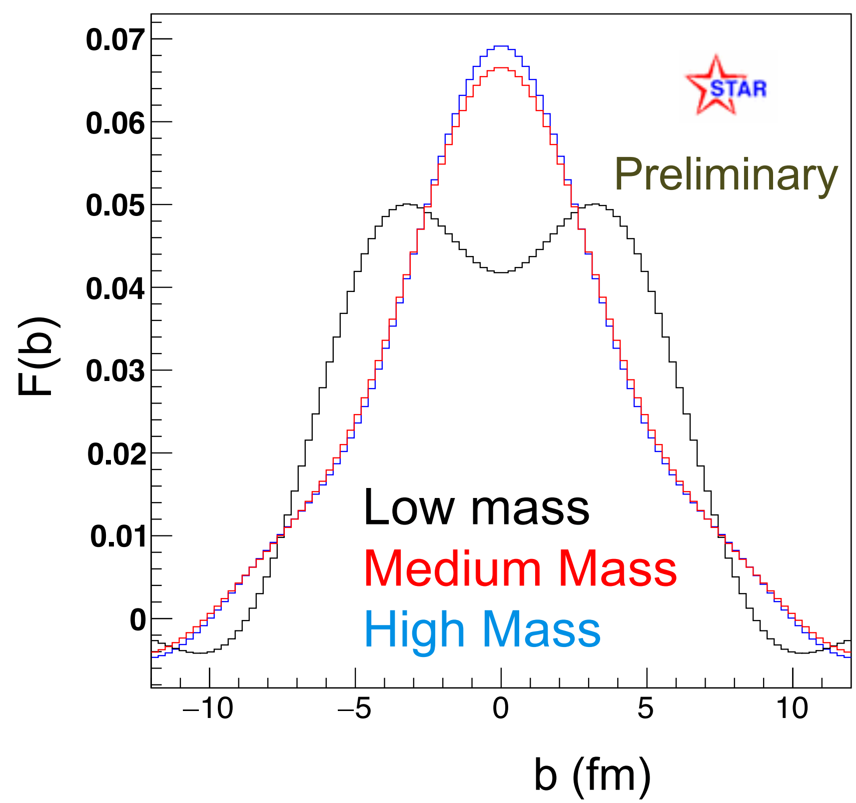


Effect of changing t_{max}

t_{max}=0.005 GeV^2



t_{max}=0.009 GeV^2



Variation with t_{max}, due to windowing

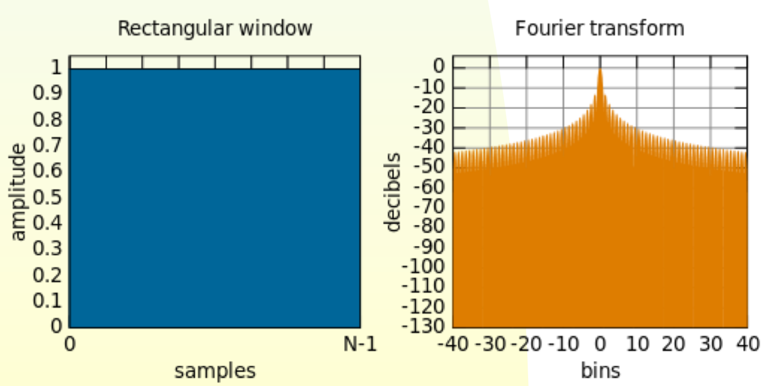
Especially for the low-mass curve

However, the trend does not vary with t_{max}

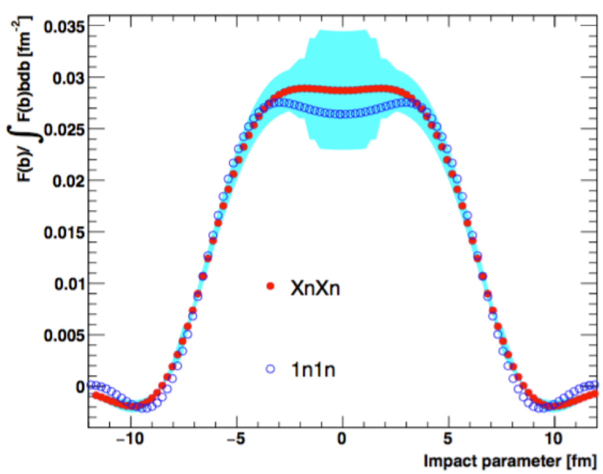
The low-mass distribution is always wider than the others, etc.

t_{max} sensitivity and windowing

- Fourier transforms assume integration over the full t range
  - The data have a finite range, so we need to choose t_{max} below the noise-dominated region.
- Input is $d\sigma/dt$ times a square window from 0 to t_{max}
  - -> Output is the convolution of the two transforms
- The biggest impact is in the region around $1/t_{max}$ -> small b
  - Change t_{max} -> change result at small b
  - This might be alleviated with a different windowing function, but the phase space is large.

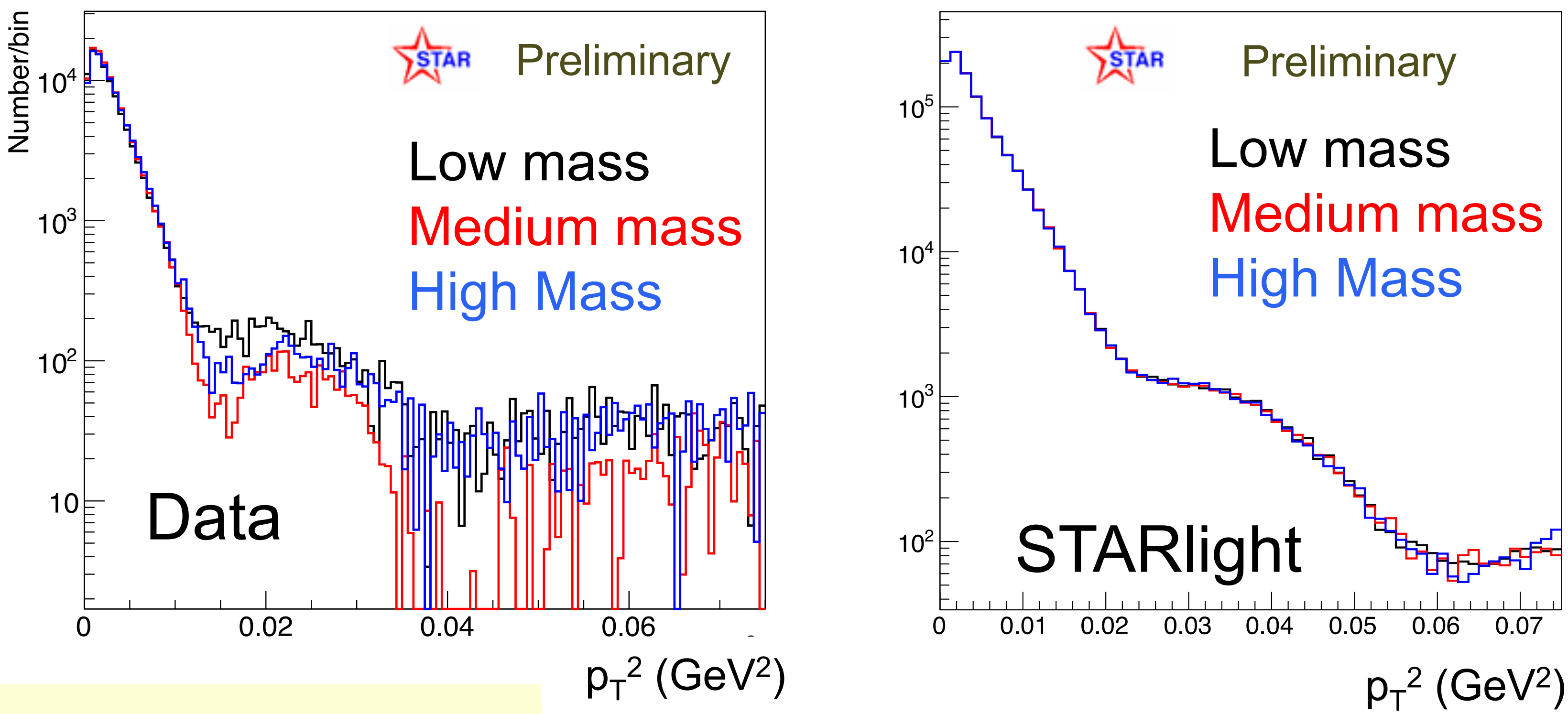


From wikipedia



STARlight simulations

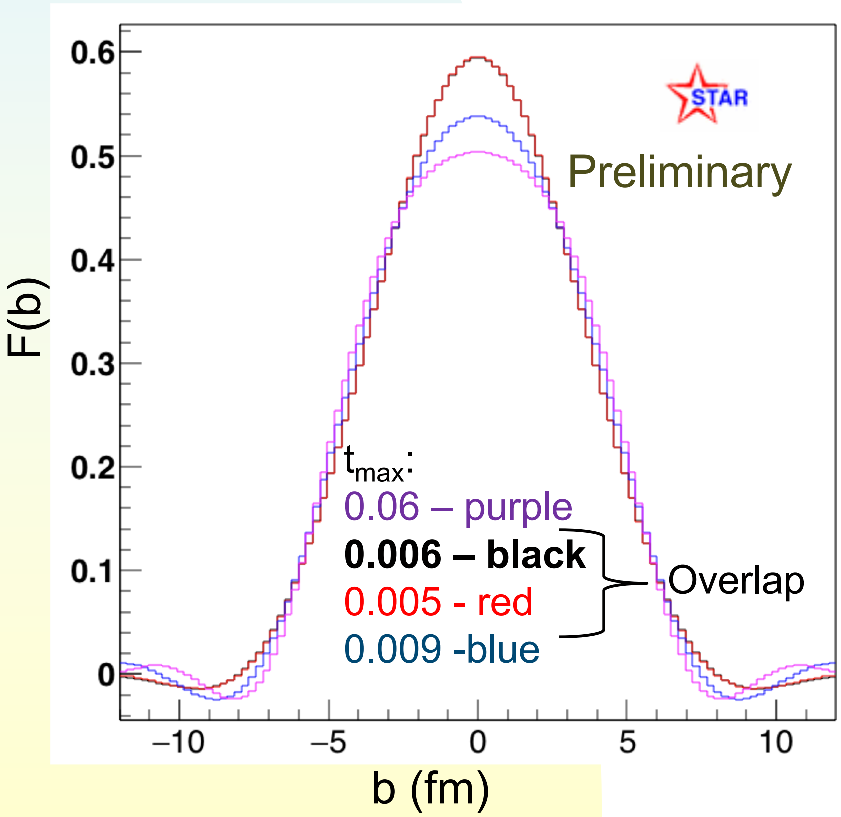
- In STARlight, $\sigma_{dipole\text{-}nucleon}$ does not vary with $M_{\pi\pi}$
- It handles the event kinematics & photon p_T well
  - Good agreement with data, except for nuclear slope
  - A good "null experiment"
- STARlight $d\sigma/dt$ coherent shows no variation with $M_{\pi\pi}$



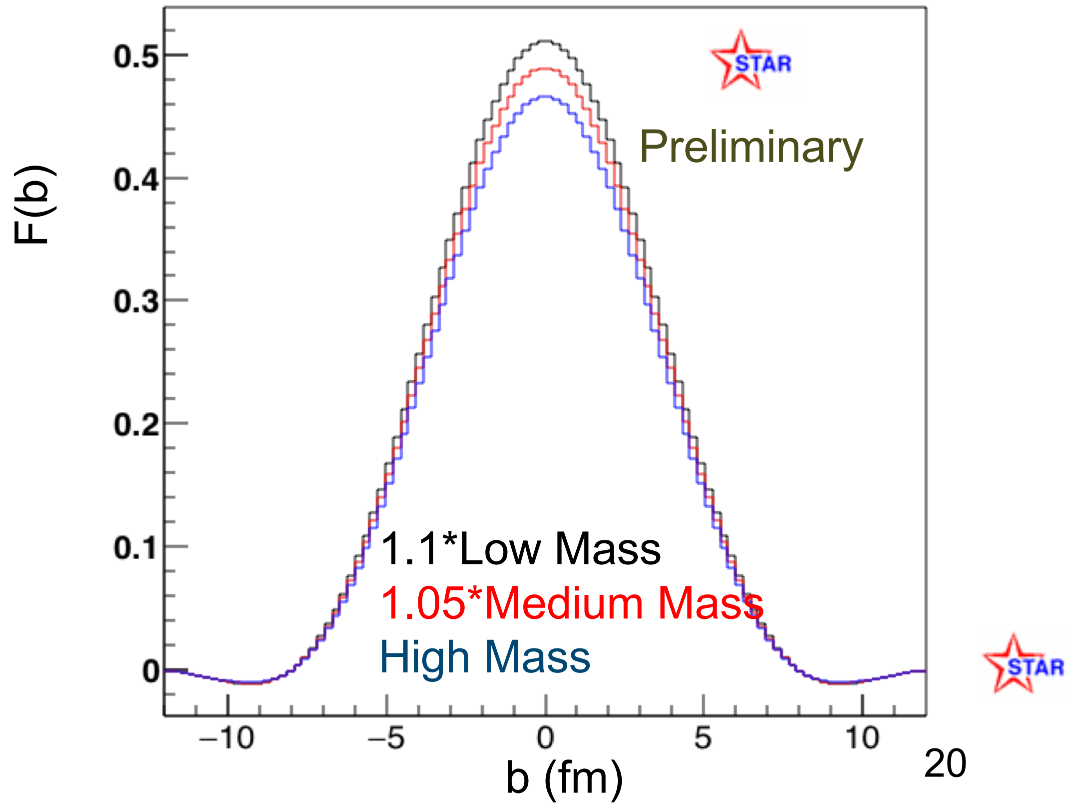
STARlight F(b)

- STARlight F(b) shows significant variation in shape with t_{max},
  - Similar to data
- STARlight shows no variation in F(b) with varying $M_{\pi\pi}$
  - The curves below are scaled so you can see them all

STARlight variation with t_{max}



STARlight variation with $M_{\pi\pi}$



Systematic Uncertainties

- The uncertainties in the determination of the nuclear shape are dominated by the choice of t_{max} and windowing function.
  - A hard cut on t_{max} *is* a windowing function
- Other systematic uncertainties
  - Incoherent $d\sigma/dt$ subtraction
    - Variation of the fit range leads to small changes in $d\sigma/dt_{coherent}$ & F(b)
    - Small; slow variation with t -> is only important at small |b|
  - Backgrounds
    - Variation in cuts leads to variation in signal to noise ratio, but only small changes in $d\sigma/dt_{coherent}$ & F(b)
- The data are a mixture of interfering ρ^0, direct $\pi\pi$ and $\omega\text{–>}\pi\pi$. We assume that these have the same relationship between $M_{\pi\pi}$ and dipole size.
- We do not account for the photon p_T here.

From UPCs to 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.
- EIC will be able to focus on more data-hungry analyses, and those requiring precise control of Q^2, like measuring the spatial dependence of shadowing.
- With an EIC:
  - Scan in Q^2 with M_V fixed
  - Higher statistics allow multi-dimensional binning
  - Trigger and analyze for exclusive $\pi\pi$, without nuclear excitation from the $\pi\pi$-producing photon or additional photon exchange
    - N. b. EIC is not 100% efficient at separating coherent and incoherent events
      - Nuclear excitation in an independent reaction
      - Missing photons from nuclear de-excitation
  - Larger reach in t -> better Fourier transform

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

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
  - 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

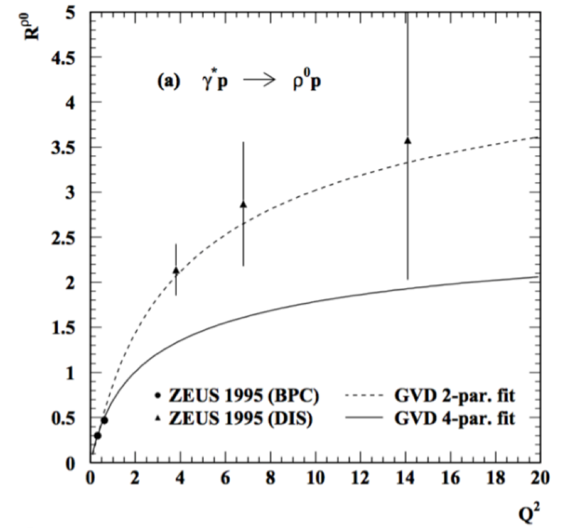
$$\sigma_{\gamma p} = \left(\frac{1}{1+Q^2/M_v^2}\right)^n \sigma_{\gamma p}(W) \qquad \sigma_{\gamma p}(W) = \sigma_P \cdot W^\epsilon + \sigma_M \cdot W^\eta$$

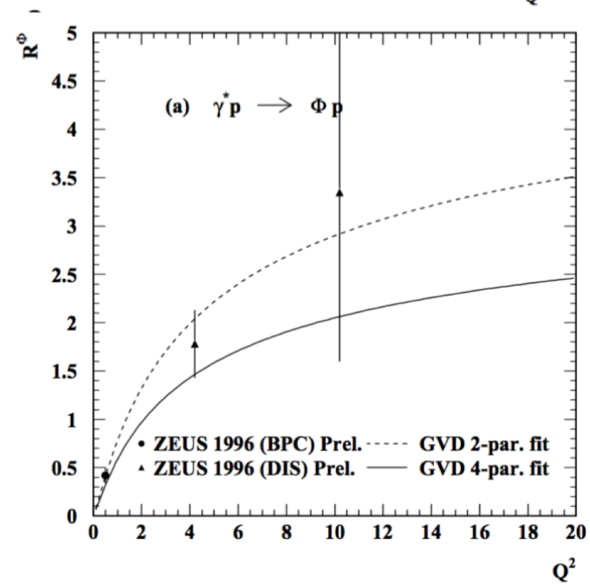
Meson	c_1	c_2 $(10^{-2}\mathrm{GeV}^{-2})$
ρ	2.09 ± 0.10	0.73 ± 0.18
ϕ	2.15 ± 0.17	0.74 ± 0.46
J/ψ	2.36 ± 0.20	0.29 ± 0.43

- $n=c_1+c_2(Q^2+M_V^2)$
- 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:
- Only known for some mesons; use most 'similar' meson where needed





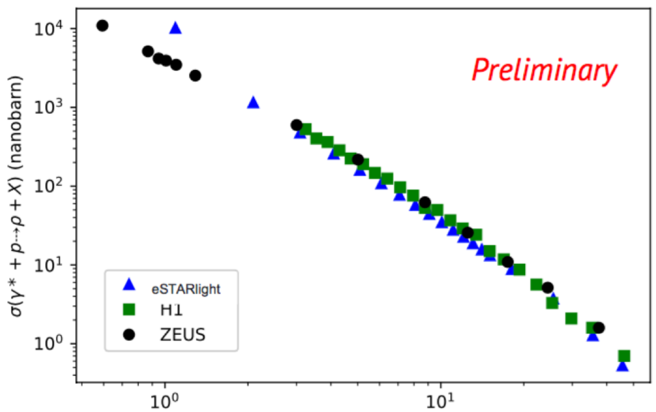
$$R_v = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}}$$

Comparison with HERA data

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

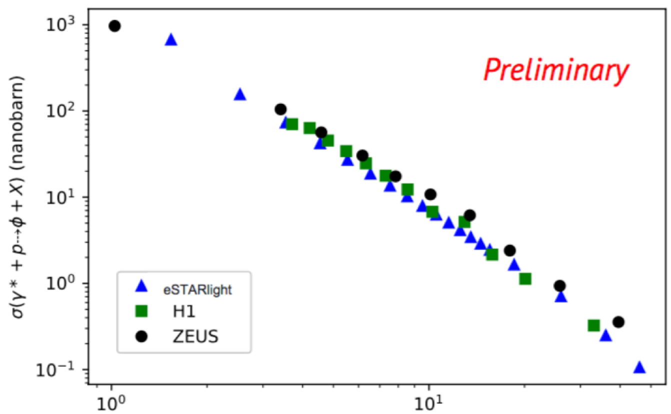
- HERA shows γ^*p cross-sections
  - Remove the photon flux from the eSTARlight calculations

ρ



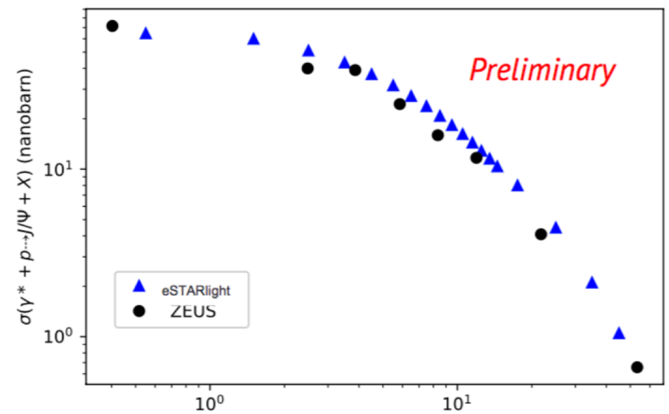
Q^2+M^2

ϕ

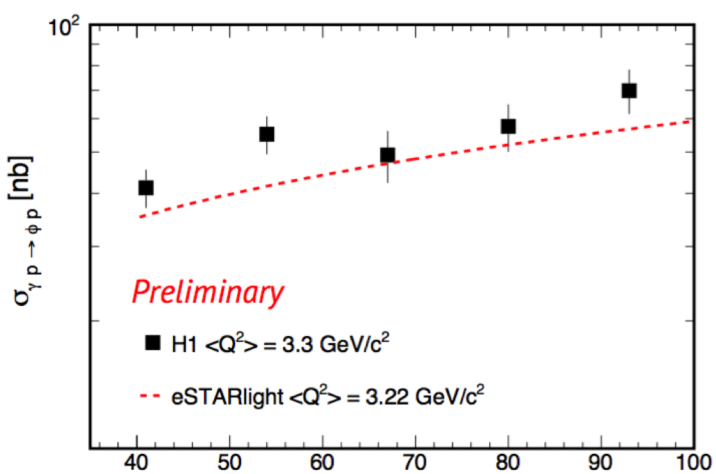


Q^2+M^2

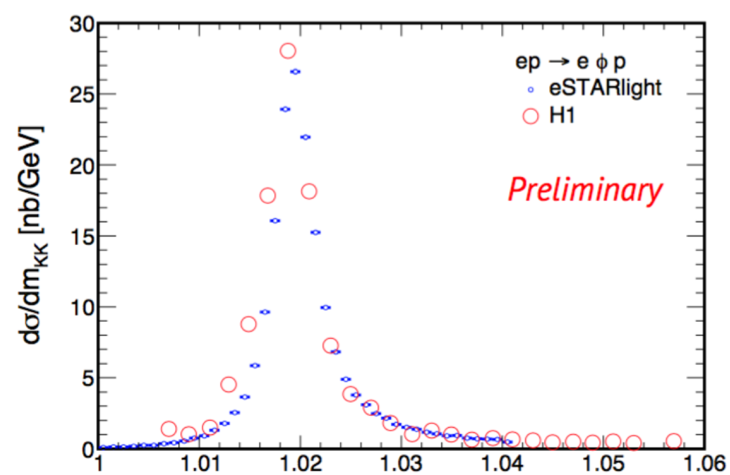
J/ψ



Q^2



W [GeV]



M_{KK} [GeV]

From γp to γA

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

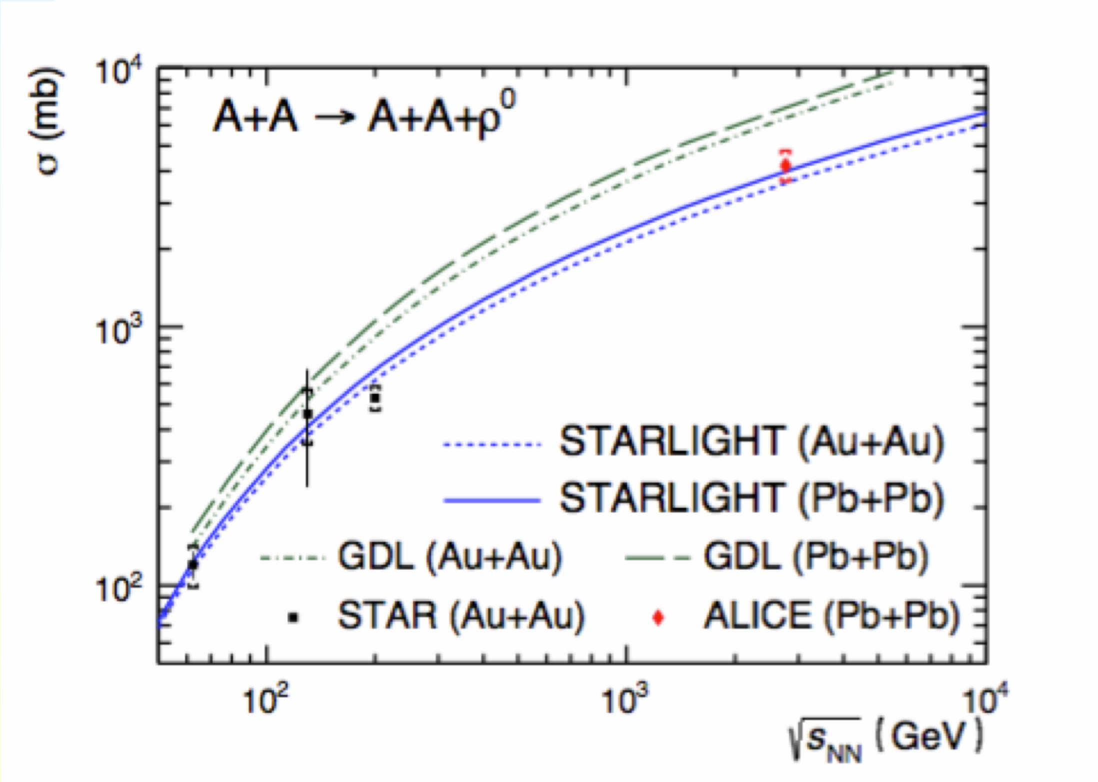
$$\sigma_{tot}(VA) = \int d^2b \left[2 \cdot \left(1 - e^{-\sigma_{tot}(Vp)T_{AA}(b)/2}\right)\right]$$

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

- 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)

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

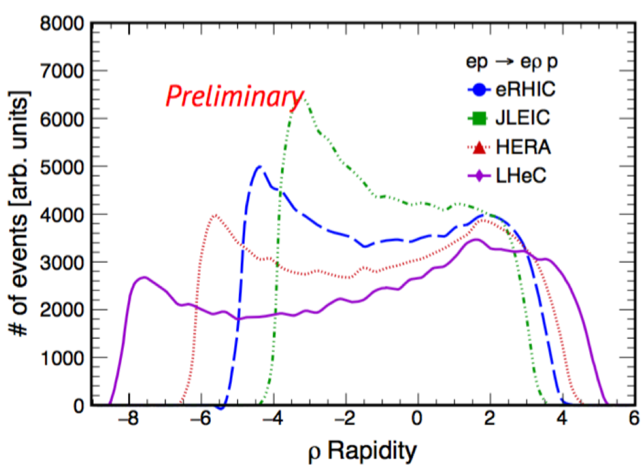
- Photoproduction
  - High rates ($>10^9$/year) for light mesons
  - Good rates ($>10^6$/year) for ccbar
  - Usable rates for Upsilon
- Electroproduction
  - Rates from ~<1% of photoproduction (light mesons), rising to 15% of photoproduction rates for the Upsilon

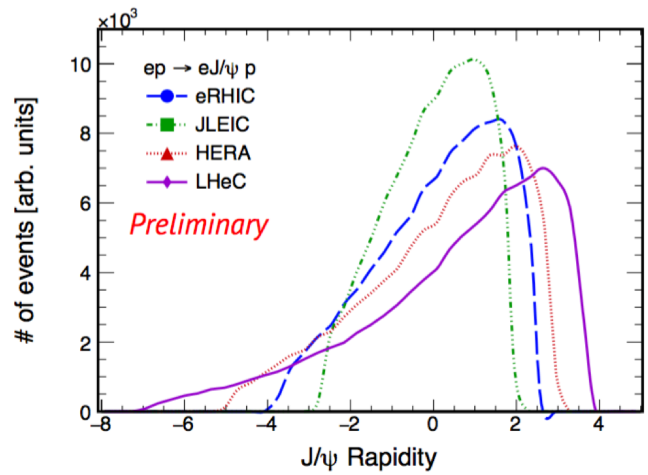
Implication for physics program

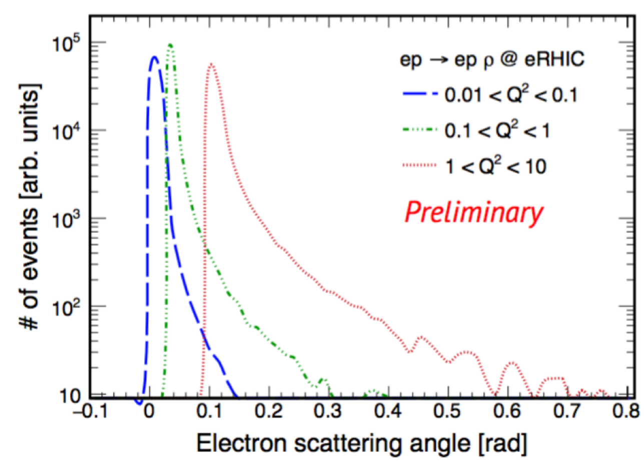
- Can measure rates and $d\sigma/dy$ for all mesons, in at least a couple of Q^2 bins
- Tomographic studies should be possible for all light mesons and the J/ψ
- Good data for spin-dependence studies
- $\psi(3770)$, $\psi(4040)$ should be accessible, even after accounting for small branching ratios to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



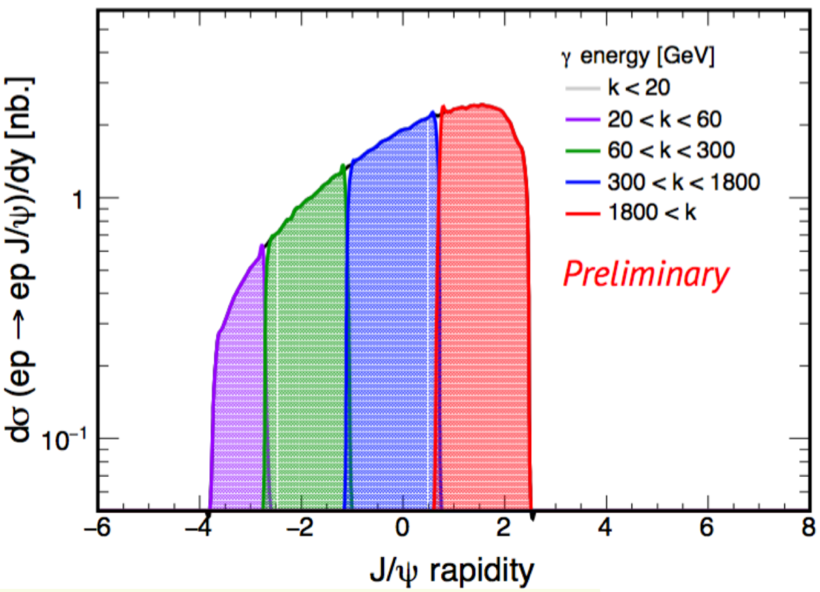


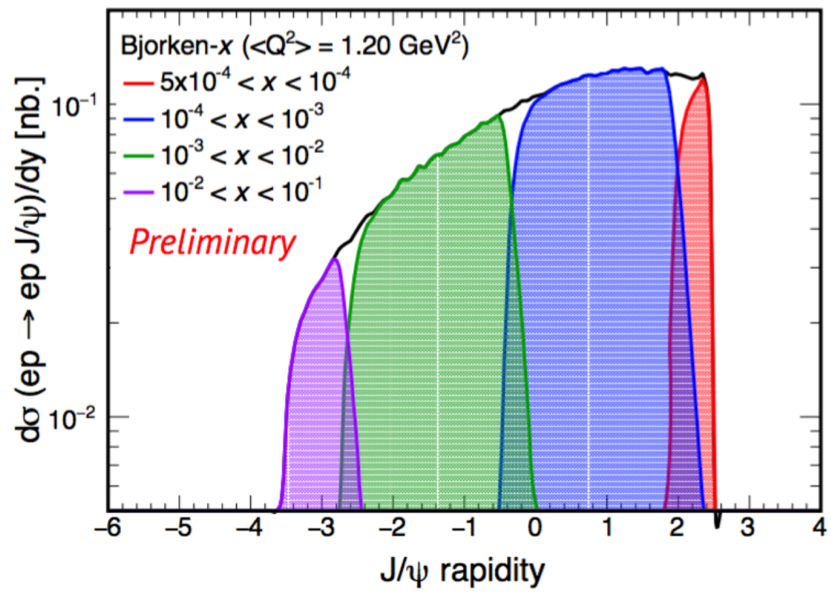


- ρ^0 'double peak' is due to Reggeon exchange (near threshold) and Pomeron exchange at large k/rapidity
- If pure Pomeron exchange is important need to go to large rapidity, or use ϕ or J/ψ, which are not produced via Reggeon exchange
- Electrons scattering angle is small (no surprise)

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

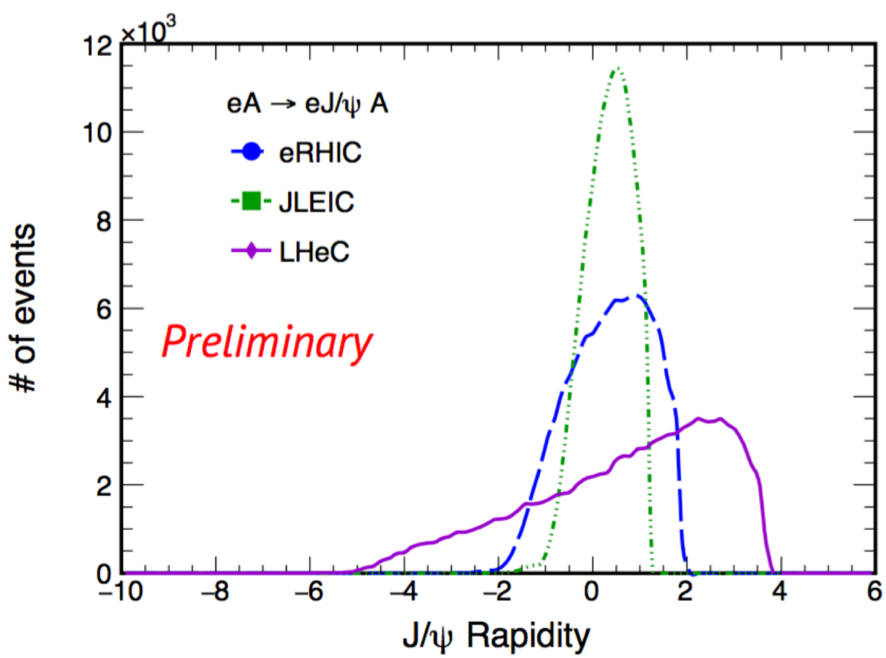


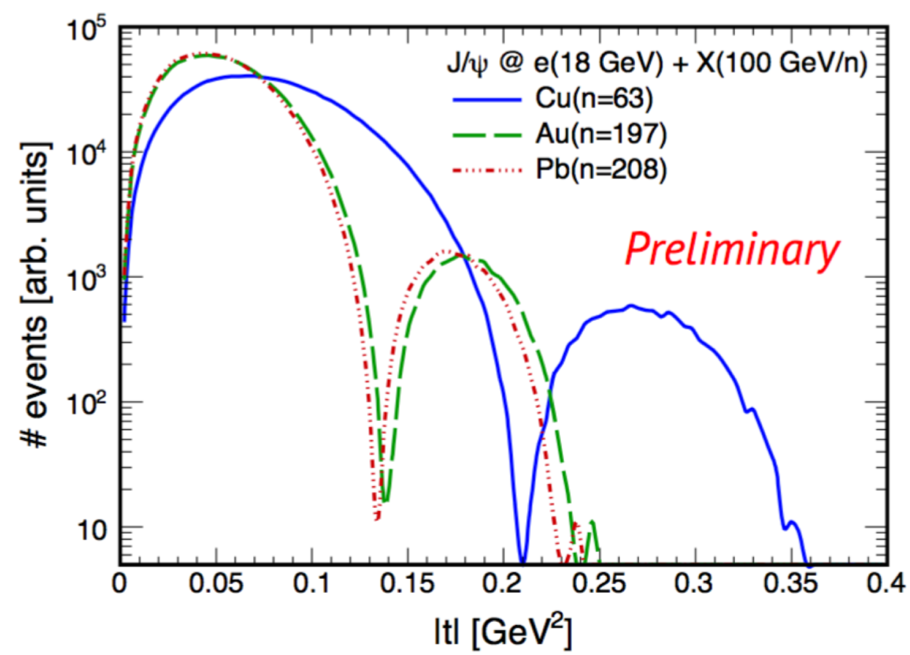


- Photon energy also maps onto Bjorken-x
- For maximum energy/Bjorken-x reach, need to detect vector mesons forward, with y ~ 2.5
- Near threshold, production is at large negative rapidity
  - Could shift to mid-rapidity by lowering beam energy

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

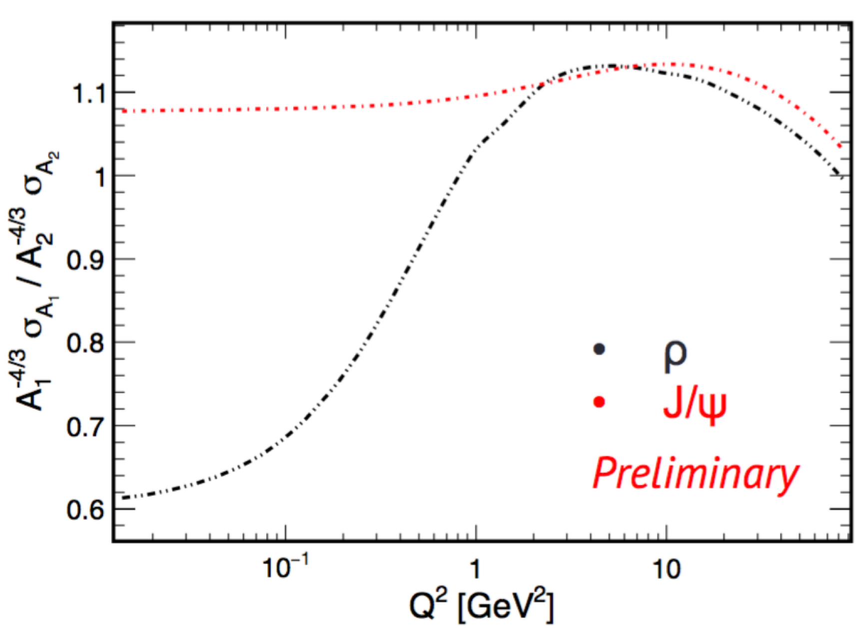




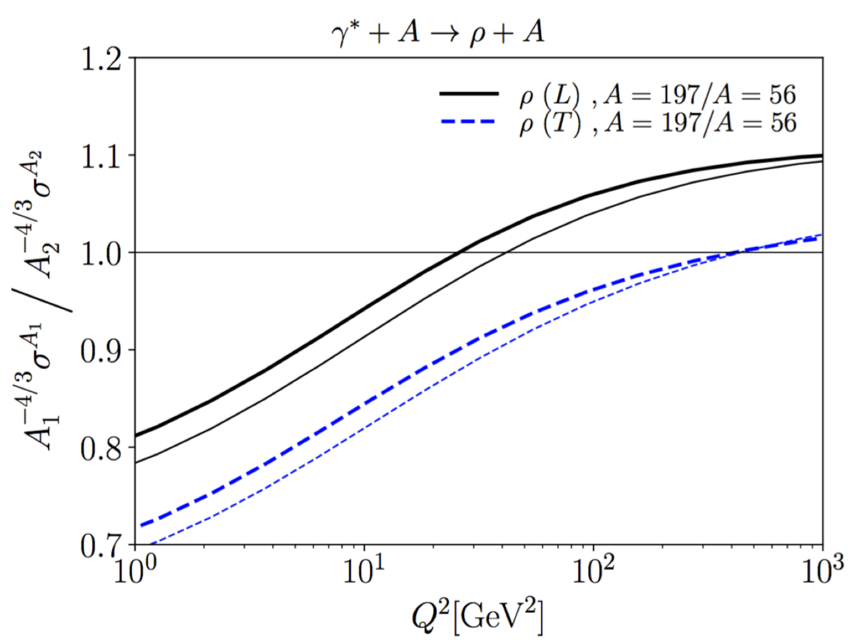
Cross-section vs. A & Q^2: shadowing

- 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



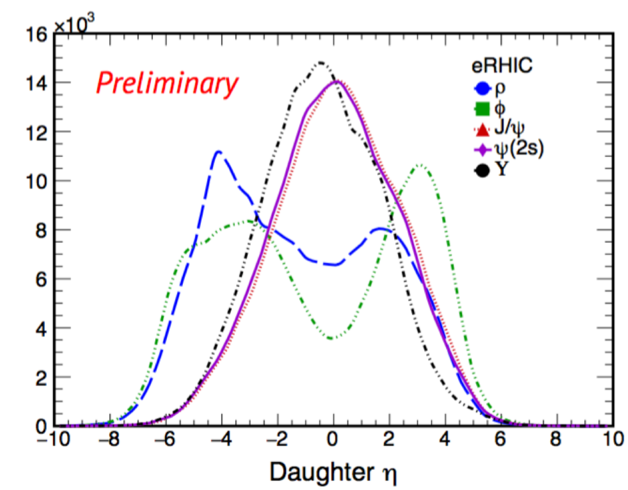
Mantysaari & Venugopalan



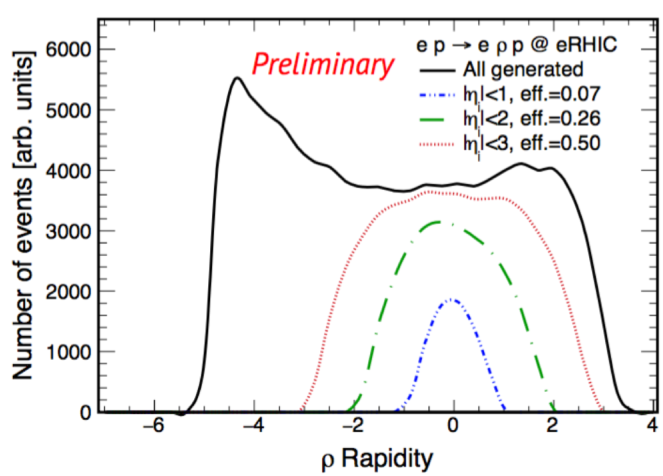
Phys.Lett. B781 (2018) 664-671

Final state particle distributions

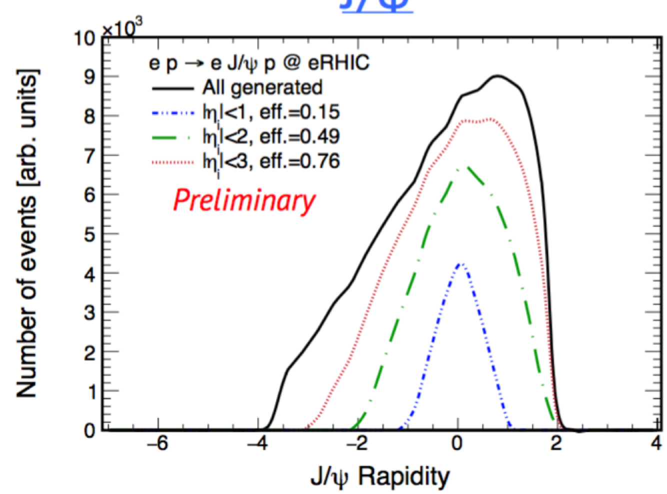
- The vector meson daughter particles generally follow the rapidity distribution of their vector meson parents
- The final state matters: VM -> spin 0 spin – (e. g. $\pi\pi$) has a very different angular distribution from VM -> spin ½ spin ½
  - Clebsch Gordon coefficients



ρ

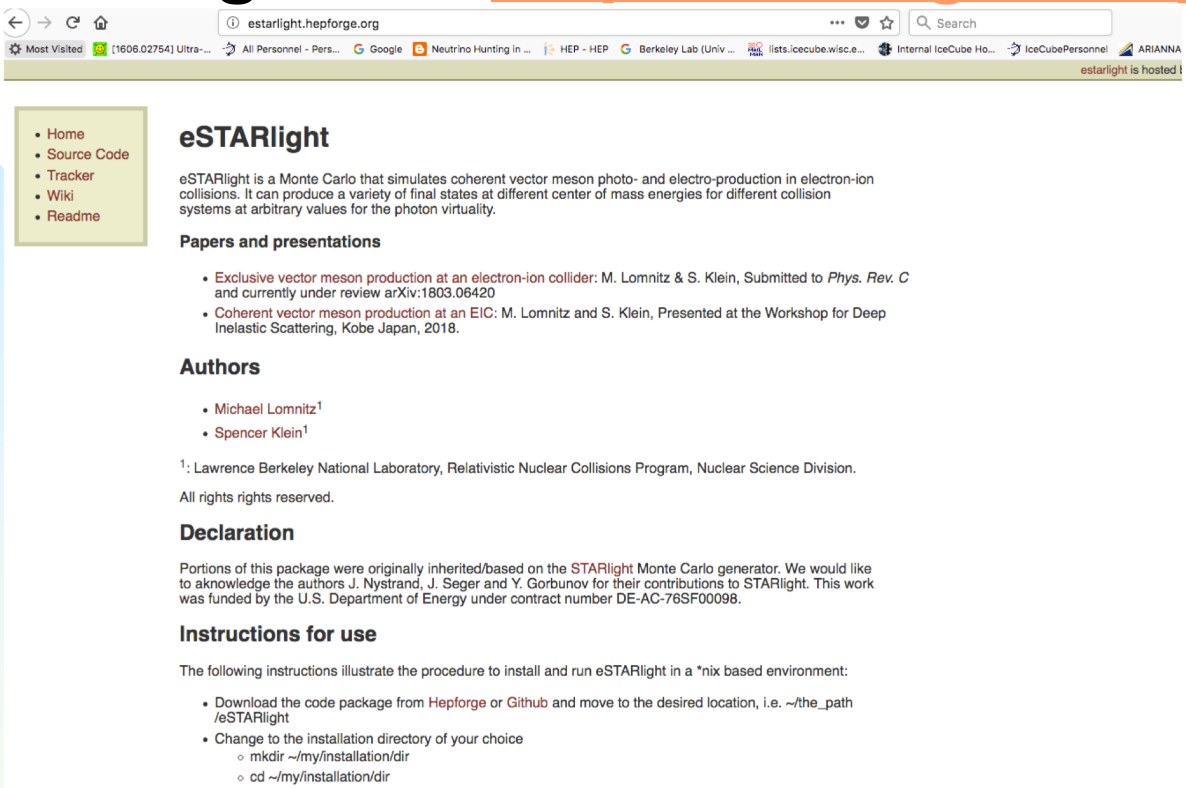


J/ψ



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

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



estarlight.hepforge.org

Most Visited [1606.02754] Ultra-... All Personnel - Pers... Google Neutrino Hunting in ... HEP - HEP Berkeley Lab (Univ ... lists.icecube.wisc.e... Internal IceCube Ho... IceCubePersonnel ARIANNA

- Home
- Source Code
- Tracker
- Wiki
- Readme

eSTARlight

eSTARlight is a Monte Carlo that simulates coherent vector meson photo- and electro-production in electron-ion collisions. It can produce a variety of final states at different center of mass energies for different collision systems at arbitrary values for the photon virtuality.

Papers and presentations

- Exclusive vector meson production at an electron-ion collider: M. Lomnitz & S. Klein, Submitted to *Phys. Rev. C* and currently under review arXiv:1803.06420
- Coherent vector meson production at an EIC: M. Lomnitz and S. Klein, Presented at the Workshop for Deep Inelastic Scattering, Kobe Japan, 2018.

Authors

- Michael Lomnitz[1]
- Spencer Klein[1]

[1]: Lawrence Berkeley National Laboratory, Relativistic Nuclear Collisions Program, Nuclear Science Division.

Declaration

Portions of this package were originally inherited/based on the STARlight Monte Carlo generator. We would like to aknowledge the authors J. Nystrand, J. Seger and Y. Gorbunov for their contributions to STARlight. This work was funded by the U.S. Department of Energy under contract number DE-AC-76SF00098.

Instructions for use

The following instructions illustrate the procedure to install and run eSTARlight in a *nix based environment:

- Download the code package from Hepforge or Github and move to the desired location, i.e. ~/the_path /eSTARlight
- Change to the installation directory of your choice
  - mkdir ~/my/installation/dir
  - cd ~/my/installation/dir

- 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.