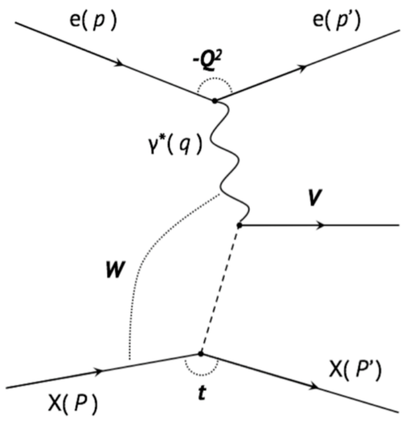
Backward production at high energies, in ultra-peripheral collisions and at an EIC

Presented at the backward-angle (u channel) workshop, Sept., 2020

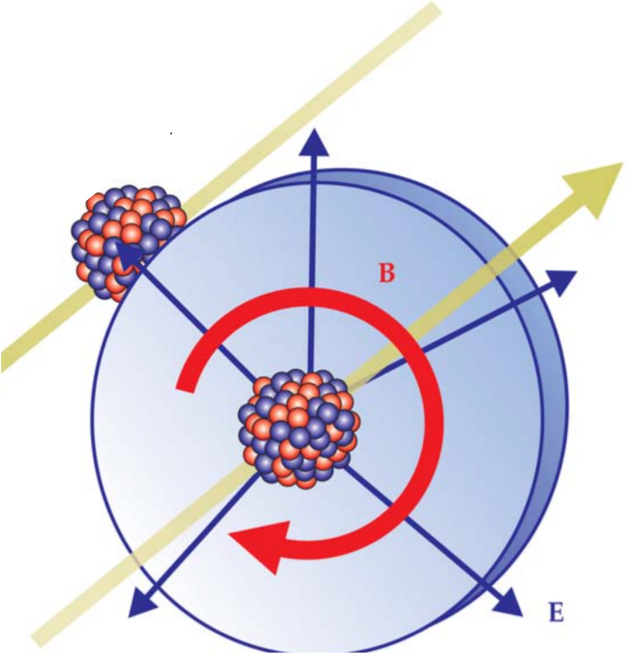
Spencer Klein, *LBNL*

- Intro to ultra-peripheral collisions (UPCs)
- A backward production model
- Parameterization of fixed target data and extrapolation to high energies
- Detector Acceptances
- Backward photoproduction via baryon exchange & baryon stopping
- Conclusions



Work done in collaboration with Aaron Stanek

Ultra-peripheral collisions



- Ultra-peripheral collisions between two colliding (ultra-)relativistic nuclei
- No hadronic interactions (roughly $b>2R_A$)
- The photons come from the electric and magnetic fields of the nucleus
  - Weizsacker-Williams
  - Flux ~ Z^2
  - Max photon energy = 2 γ hbar c/R_A
  - Photons are nearly real -> photoproduction only
- Photonuclear and two-photon reactions possible
  - Multi-photon exchange also possible
- UPCs at the LHC are the energy frontier for photons.
- UPCs at RHIC are comparable in energy to the EIC

Maximum energy reach

Facility	$\sqrt{s_{NN}}$ or $\sqrt{s_{eN}}$	Maximum E_γ	Maximum $W_{\gamma p}$	Maximum $\sqrt{s_{\gamma\gamma}}$
RHIC (16)				
Au+Au	200 GeV	320 GeV	25 GeV	6 GeV
p+Au	200 GeV	1.5 TeV	52 GeV	30 GeV
pp	500 GeV	20 TeV	200 GeV	150 GeV
LHC (17)				
Pb+Pb	5.1 TeV	250 TeV	700 GeV	170 GeV
p+Pb	8.16 TeV	1.1 PeV	1.5 TeV	840 GeV
pp	14 TeV	16 PeV	5.4 TeV	4.2 TeV
FCC-hh (18), **SPPC** (7)				
Pb+Pb	40 TeV	13 PeV	4.9 TeV	1.2 TeV
p+Pb	57 TeV	58 PeV	10 TeV	6.0 TeV
pp	100 TeV	800 PeV	39 TeV	30 TeV
eRHIC (19)				
e+Au	89 GeV	4.0 TeV	89 GeV	15 GeV
LHeC (20)				
e+Pb	820 GeV	360 TeV	820 GeV	146 GeV

- The LHC is equivalent to a fixed-target machine with PeV (10^{15} eV beams). $\gamma\gamma$ and γp center of mass energies are in the TeV range.

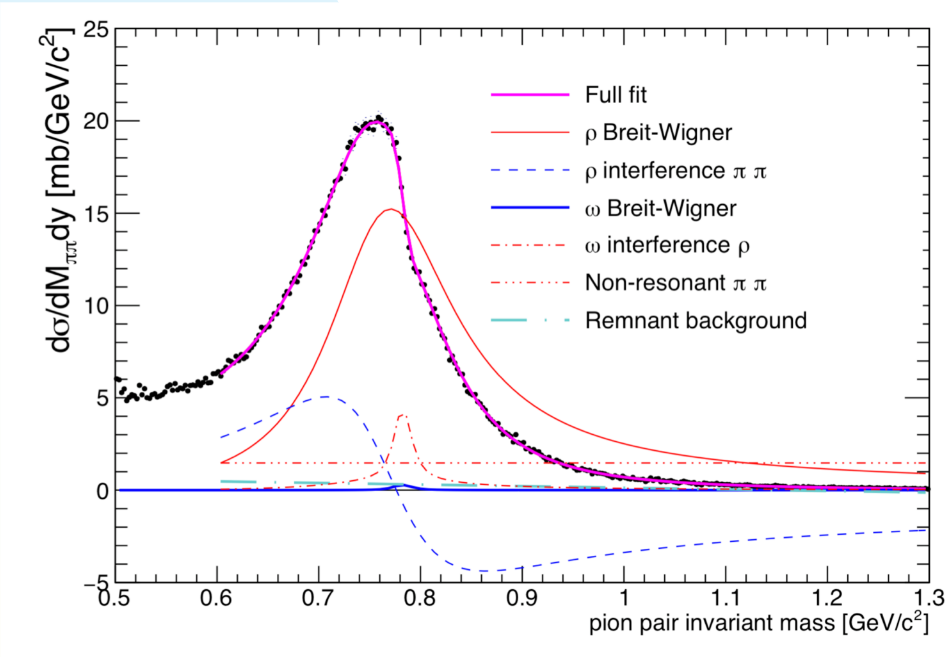
From SK, P. Steinberg, arXiv:2005.01872

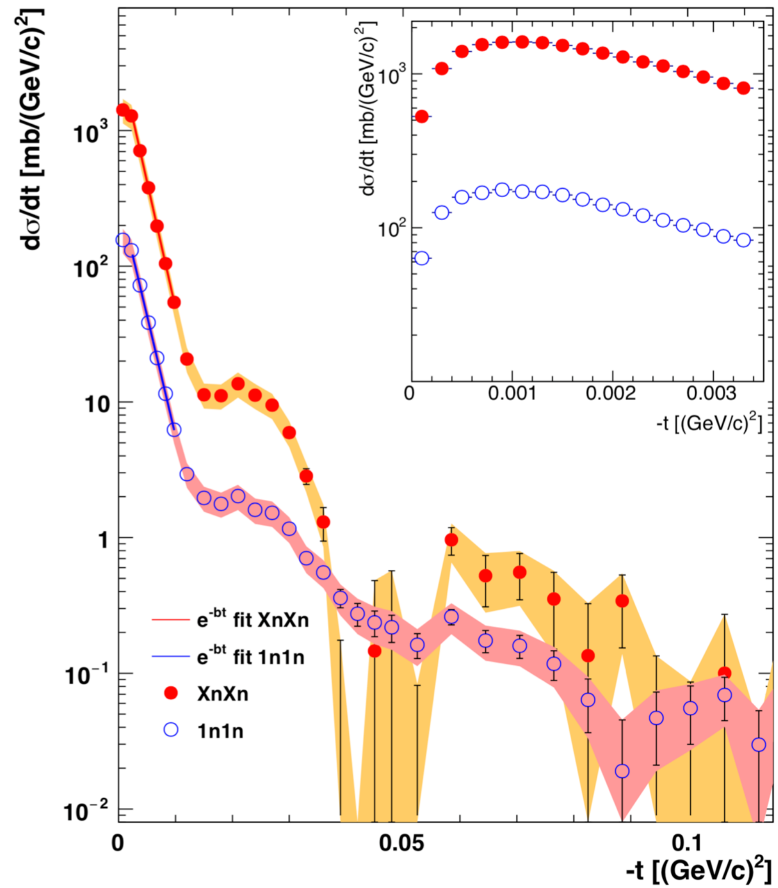
Experimental physics program to date

- Vector meson photoproduction:
  - ρ, ω, direct $\pi^+\pi^-$ ρ', J/ψ,ψ',Υ states
    - ρ/ω/ direct $\pi^+\pi^-$ interference
    - ρ'-> $\pi^+\pi^-\pi^+\pi^-$ & meson spectroscopy
    - Bidirectional interference (between two photon directions)
  - Proton and ion targets
    - Proton targets studied in pp and pA collisions
  - Coherent and incoherent production
  - Probes gluon distributions down to $x\sim10^{-5}$ at $Q^2=M_V^2/4$
    - Two gluon exchange -> some theoretical uncertainties
- Photoproduction of dijets
  - Probes gluon distributions more directly
- $\gamma\gamma\to l^+l^-$
- $\gamma\gamma\to\gamma\gamma$
  - Limits on beyond standard model physics

High precision results

- Coherently produced ππ samples with 500,000 = 1 M events
  - Can study channels with $\sigma \sim 10^{-3}\ \sigma_\rho$ – plenty for backward production

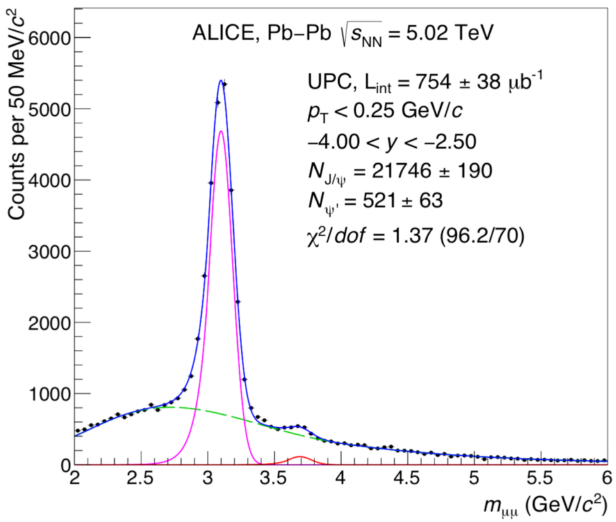


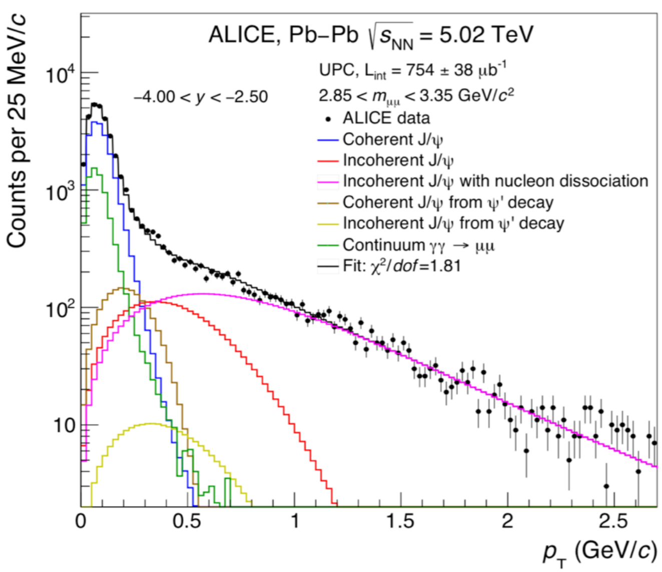


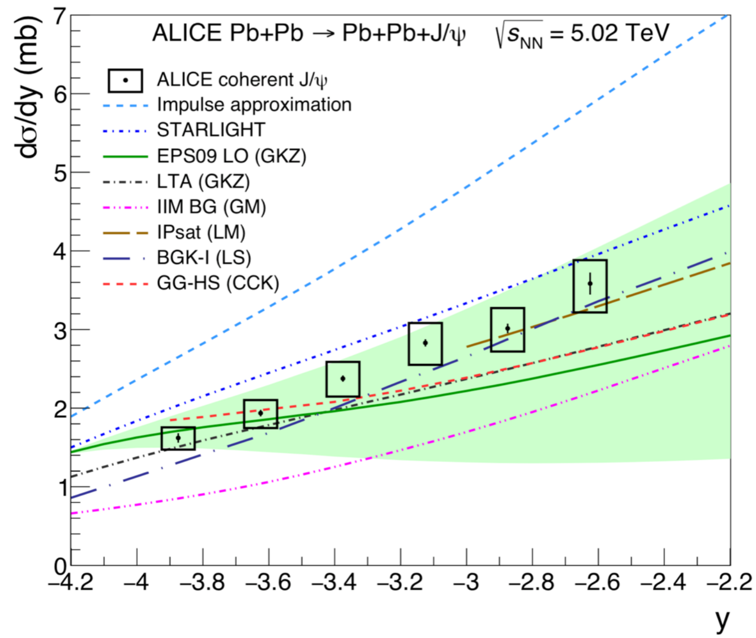
STAR, Phys. Rev. C96, 054904 (2017)

J/ψ production probes gluon distributions

- 20,000 event samples; search for backward J/ψ production?







Moderate gluon shadowing is favored

ALICE, Phys. Lett. B798, 134926 (2017)

Looking ahead

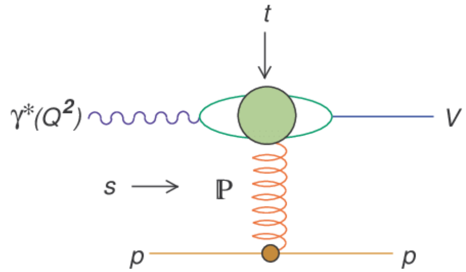
- LHC runs 3 & 4 promise many orders of magnitude more data
  - Higher luminosity, especially for ALICE
  - Streaming DAQs improve UPC triggering

			PbPb			
Meson	σ	All Total	ALICE Central	~ CMS Central	ALICE Forward	LHCb
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2S) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$\Upsilon(1S) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

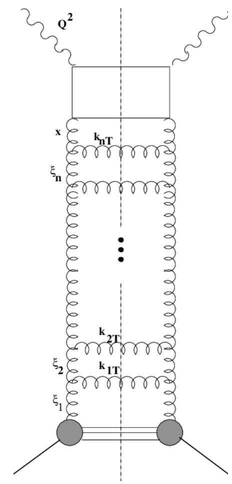
New physics: meson spectroscopy (including exotics), $\gamma\gamma \to \tau^+\tau^-$, photoproduction of open charm, incoherent photoproduction and gluonic hot spots, multiple reactions and quantum correlations

Z. Citron *et al.*, arXiv:1812.06772

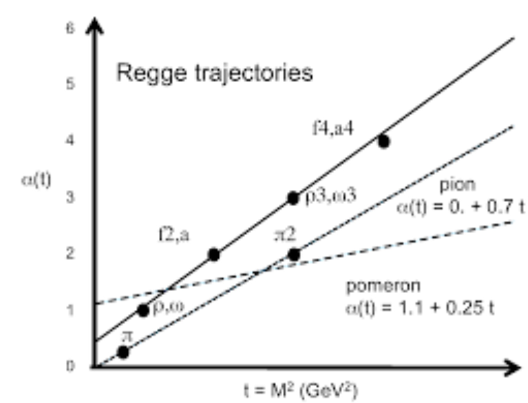
Model for vector meson photoproduction



- The photon fluctuates to a q-$\bar{q}$ dipole
- Dipole scatters elastically from the target nucleus
  - Elastic scattering -> no color exchange; quantum numbers of the vacuum: $J^{PC}=0^{++}$
    - The "Pomeron"
    - In pQCD, the Pomeron is a gluon ladder



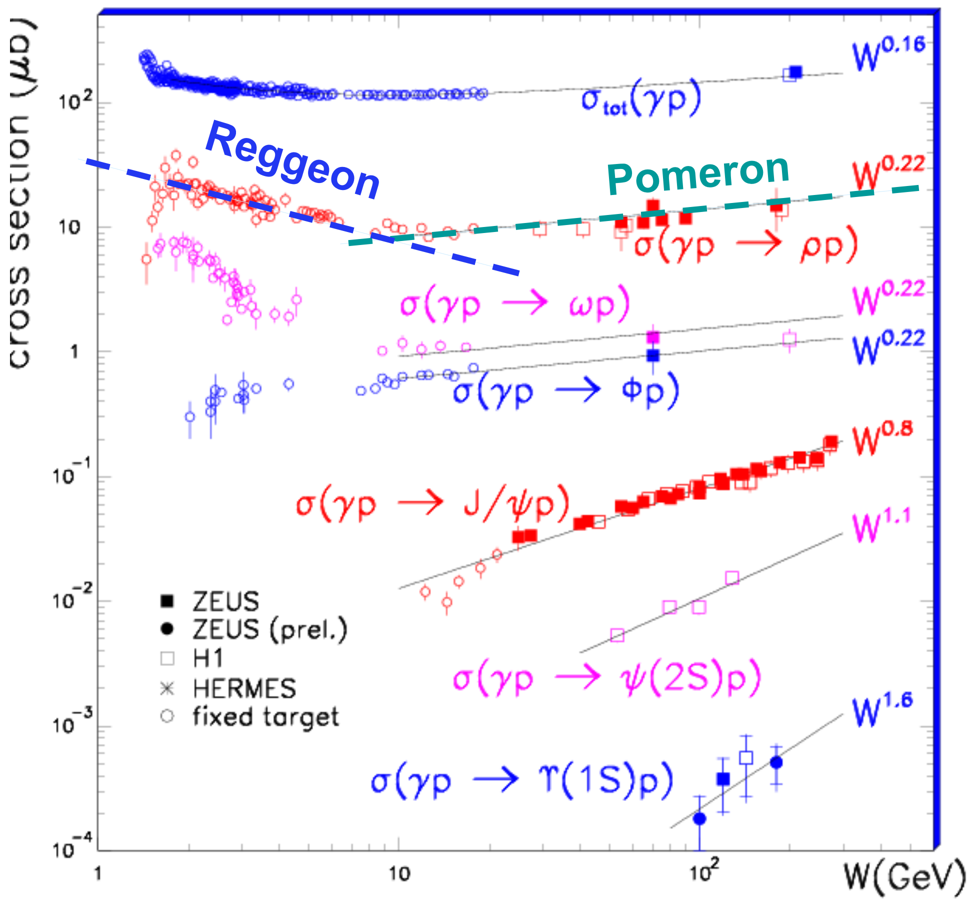
- At lower γp energies, Reggeon exchange contributes
  - Reggeons are meson trajectories -> mostly quarks
  - Wider range of quantum numbers, including charge
- Coherent photoproduction -> add amplitudes
  - $d\sigma/dt|_{t=0} \sim A^2$
- Incoherent photoproduction $\sigma \sim A$, plus multiple nuclear effects
  - Relevant for backward production



Reggeons in photoproduction

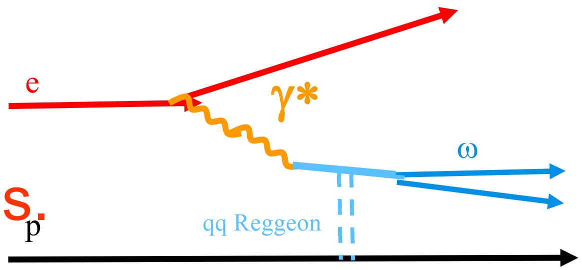
- HERA photoproduction cross-sections well fit by
- $\sigma(W) = XW^{\epsilon} + YW^{-\eta}$
  - W=γp CM energy
- XW^{ϵ}: Pomeron (gluons)
  - ε ~ > 0.2 – meson dependent
  - $J^{PC}=0^{++}$
- $YW^{-\eta}$: 'Reggeon' (~~qqbar)
  - η~~1.5
  - Summed light-quark trajectories
    - ~valence quarks
  - Range of spin/parity/charge
    - charged photoproduction possible: $a_2^+(1320)$
  - Photon + Reggeon -> exotica
- Q^2 dependence – power law

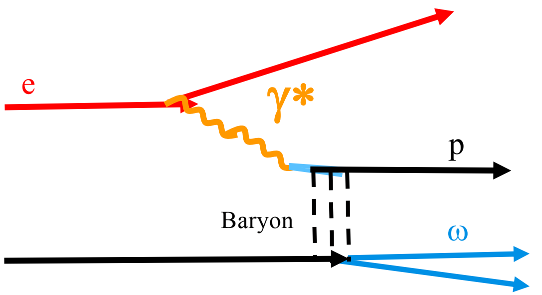
Photoproduction data

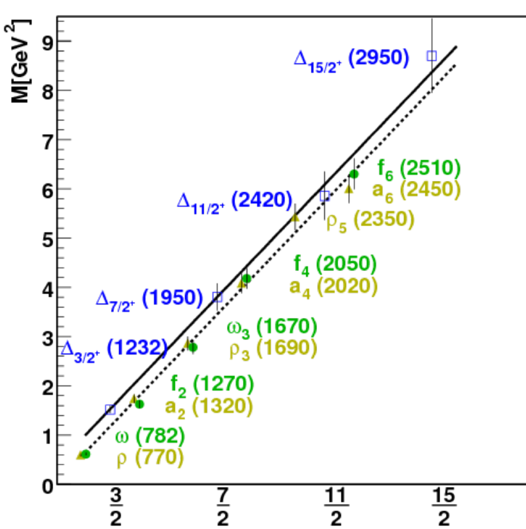


A Regge model for backward production

- Add baryon trajectories, which carry baryon number
- Simple and allows easy quantitative predictions.
- Key trajectories: N, Δ
  - Λ/Σ for strangeness (not today)
- So far, only consider proton targets
  - pA UPCs and ep at EIC
- Probably extensible to incoherent AA/pA
  - With clean nucleon ejection
  - Could probe neutron targets

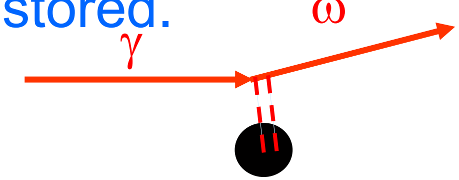


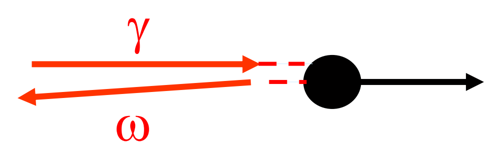




Baryon exchange parameterization

- Baryonic Regge trajectories are like meson trajectories
  - $\sigma(W) = YW^{-\eta}$
  - Replace t with u, and much familiar behavior is restored.
- Normally, photoproduction is maximal when t (momentum transfer from target) is small
  - Standard: $d\sigma/dt \sim \exp(-Bt)$
  - B~ hbar/target size
  - Swap t with u: $d\sigma/dt \sim \exp(-Bu)$





- In baryon exchange, in the CM frame, the meson scatters backward 180 degrees causing the baryon to recoil
  - In γp CM frame, baryon and photon/meson trade momentum
  - Mandelstam u is small, but t is large ($t>Q^2$)

Backward ω data for fit

- The ω is one of the better studied mesons for backward production. There is more data available than for the ρ.
  - Reasonable lever arm for photon energy.

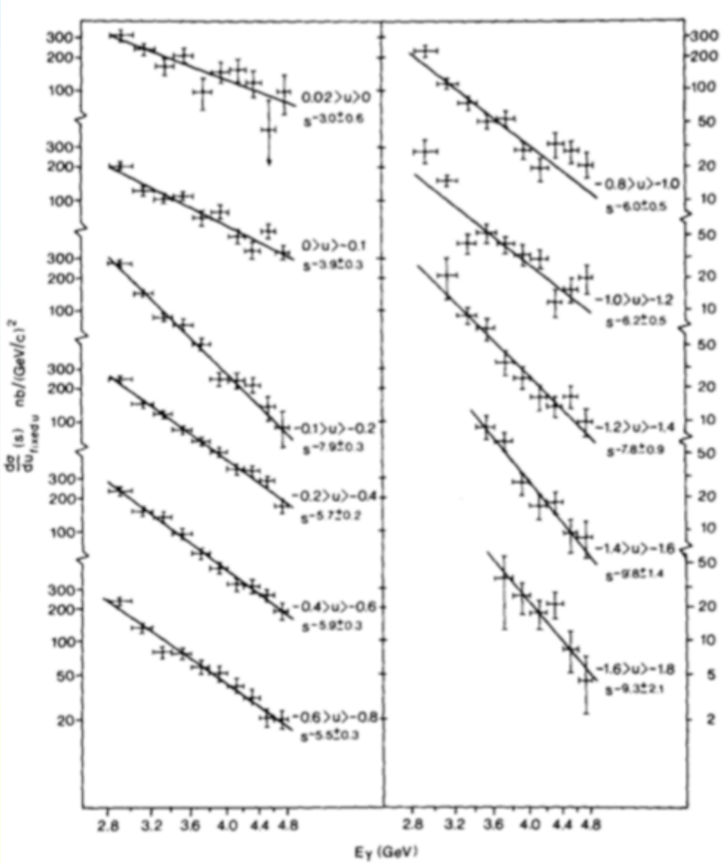


TABLE I. The compiled data. Errors on original data were around 25% of the listed value. Error due to transcription from figure is estimated to be less than 5%.

E_γ GeV	$d\sigma/du(u \approx 0)$ nb/GeV^2	Source
2.9	200	Sibirtsev et al.[6] Figure 1
3.0	300	Clifft et al.[4] Figure 3
3.0	200	Sibirtsev et al.[6] Figure 7
3.2	240	Clifft et al.[4] Figure 3
3.3	110	Sibirtsev et al.[6] Figure 7
3.5	170	Clifft et al.[4] Figure 2
3.5	170	Sibirtsev et al.[6] Figure 1
3.5	100	Sibirtsev et al.[6] Figure 7
3.6	210	Clifft et al.[4] Figure 3
3.6	100	Sibirtsev et al.[6] Figure 7
3.8	90	Clifft et al.[4] Figure 3
3.9	60	Sibirtsev et al.[6] Figure 7
4.0	150	Clifft et al.[4] Figure 3
4.1	70	Sibirtsev et al.[6] Figure 7
4.2	160	Clifft et al.[4] Figure 3
4.3	40	Sibirtsev et al.[6] Figure 7
4.4	120	Clifft et al.[4] Figure 3
4.4	30	Sibirtsev et al.[6] Figure 7
4.5	50	Sibirtsev et al.[6] Figure 7
4.6	30	Sibirtsev et al.[6] Figure 7
4.7	75	Clifft et al.[4] Figure 2
4.7	80	Sibirtsev et al.[6] Figure 1
4.8	100	Clifft et al.[4] Figure 3

[4] R. Clifft *et al.*, Physics Letters **72B**, 144 (1977).
[5] B.-G. Yu and K.-J. Kong, Physical Review D **99** (2019).
[6] R. Sibirtsev *et al.*, arXiv:nucl-th/0202083v1 (2002).

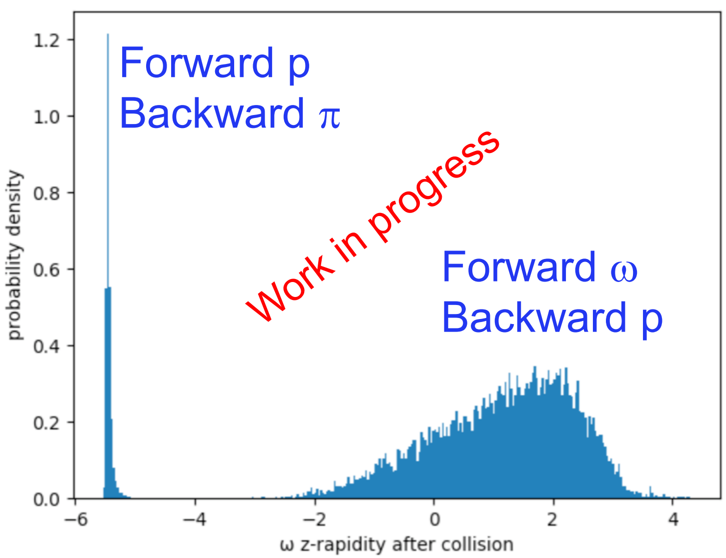
Parameterization of backward $\gamma p \to \omega p$

- Fit to data from two experiments (see backup), after selection
- Follow approach used for vector meson dominance production:
  - $d\sigma/dt|_{t=0} \sim A\,(s/1\text{GeV})^B$ embodies physics of reaction
  - $d\sigma/dt \sim \exp(-Ct)$ accounts for form factor (size) of target
  - Swap u for t, to match behavior of backward kinematics
- $d\sigma/du|_{u\sim 0} = A\,(s/1\text{GeV})^B$
  - $A = 4.4\ \mu b/\text{GeV}^2$
    - $A=180\ \mu b/\text{GeV}^2$ for forward ω photoproduction
  - $B = -2.7$
    - $B=-1.92$ for forward ω photoproduction
- $d\sigma/du \sim \exp(-Cu)$, with $C=-21\ \text{GeV}^{-2}$
  - Similar slope as C in e^{Ct} term for forward $\gamma p \to \rho p$
- Rate is few % of the forward rate for k~ GeV
  - Falls off a bit faster with increasing energy.
  - Cross-sections are large enough to be easily accessible.

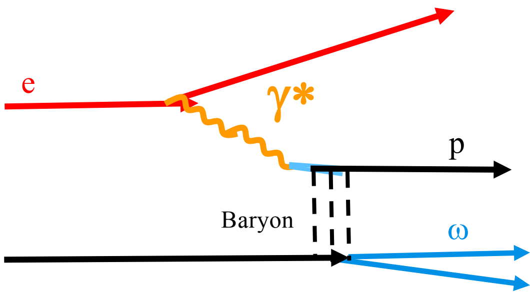
Implications for UPC photoproduction & EICs

- UPCs create ω at near-beam rapidity, with a mid-rapidity proton
- Similar expectations at an EIC.
- Two approaches:
  - Far-forward detectors for the meson
    - Bill Li's talk
  - Try to shift the meson into the acceptance of a central detector
    - At an EIC, Q^2 will help with this

UPC Au p->Au p ω at RHIC



Rapidity distributions for UPCs and an EIC



- Model as forward production, except:
  - In γp CM frame, swap ω and p rapidities
    - Photon is soft
    - ω is in far-forward region (near beam rapidity)
    - Proton is at mid-rapidity
- Simplified kinematics; ignore all transverse momentum
  - Neglect some masses….indicative of final states.
- Consider subreaction γ+B-> proton
  - k is photon energy, E is baryon trajectory mometnum
  - $M_{proton}^2 = 4kE$
  - Proton rapidity y=ln(k/E)
  - -> k=M/2 exp(y) E=M/2exp(-y)
- For a proton at mid-rapidity, $k=E=M_{proton}/2$ in lab frame
  - ω momentum = $p_{init\text{-}proton} - M_{proton}/2 \sim p_{init\text{-}proton}$

Can we move the ω away from the beam?

- By changing the proton rapidity, we increase K and reduce the ω longitudinal momentum
- Omega p_Z & rapidity vs. proton rapidity
  - Here, EIC, with 275 GeV/c proton beams

proton rapidity	B_z	p_z,ω	E- ω	ω-rapidity
0	0.469	274.531	274.5321138	6.554114
1	1.274874	273.7251258	273.7262429	6.551174
2	3.465467	271.5345327	271.5356587	6.543139
3	9.420117	265.5798832	265.5810345	6.520966
4	25.60653	249.3934676	249.3946937	6.458082
5	58.02955	216.9704548	216.9772722	5.5306

- No solution keeps both proton and ω in central tracking region

Lower proton energies

- Consider 41 GeV protons

proton rapidity	B_z	p_z,ω	E- ω	ω-rapidity
0	0.469	40.531	40.5385432	4.641208
1	1.274874	39.72512582	39.73282202	4.621128
2	3.465467	37.53453269	37.54267796	4.564418
3	9.420117	31.57988318	31.58956388	4.391721
4	25.60653	15.39346763	15.41331794	3.673636
5	69.60577	-28.60577162	28.61645844	-4.292843

- There is a solution where both the proton and omega have rapidity ~ 4, so may be within range of a central tracker.
- Might also be possible with UPC, for lower-energy RHIC running (63 GeV)
- Heavier mesons would also be produced slightly more centrally.
- Electroproduction at the EIC should be a bit easier, since the electron provides a p_T kick to the final state.

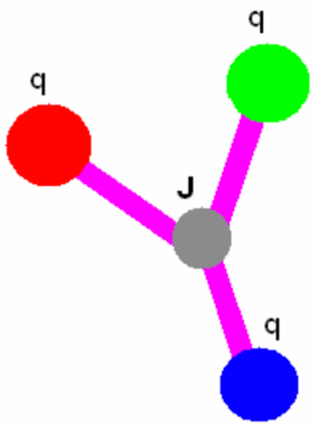
Backward production detection with UPCs

- The final state is a mid-rapidity struck baryon plus a forward meson. As the proton is moved toward the forward direction, the meson is shifted toward mid-rapidity.
  - The STAR forward upgrade may be a good place to look.
  - The LHC has a variety of forward instrumentation, including the proposed ALICE FoCal. However, the energy is higher than desired.
  - These forward detectors have less acceptance than the proposed EIC far-forward systems.
- Production is largest near-threshold (lower photon energies), which correspond to forward rapidities.
  - Production is more central at lower beam energies, so RHIC may be favored over the LHC.
  - Lower RHIC energies may be particularly attractive, except that luminosity is an issue.

Backward production detection at an EIC

- Is it necessary to detect both the produced meson and the proton, or can missing-mass techniques suffice?
  - Electron is only detectable for electroproduction; at Q^2~0, the electron goes down the beampipe.
  - The electron beam energy spread (~ 20 MeV) limits the reconstruction accuracy, but this could be workable.
- EIC detectors have good far-forward calorimetry, to detect all-photon final states
  - π^0 photoproduction, as studied by Bill Li.
  - Backward γ studies, proposed by Bernard Pire.
- Far-forward charged particle detection is more limited.
  - For the ω, ρ, etc., running at lower proton beam energy (41 GeV; even lower would be better) will help shift the production toward mid-rapidity.
    - The Chinese EIC would be a good place for this work.
- An LHCb-like detector would be ideal for backward prod.

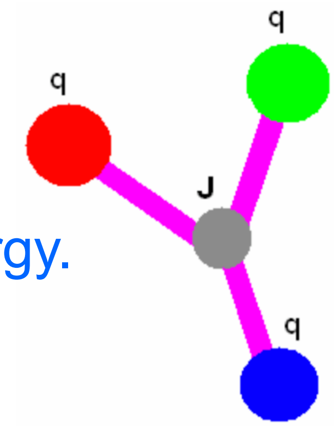
Connection to baryon stopping in heavy ion collisions



- Baryon stopping occurs in relativistic heavy ion collisions, where baryons are readily transferred from beam rapidity to mid-rapidity.
  - Not a-priori expected
- One explanation – baryon junction model. A baryon three quarks connected by color flux tubes to a central junction.
  - That junction holds baryon number. It is a gluonic configuration, so is more easily shifted in rapidity.
  - pp/pbar-p scattering is explained with new Regge trajectories, which lead to three-jet events, leading to three leading mesons, plus a baryon composed of former sea quarks.
  - Can explain some Regge phenomenology, including difference between pp and pbar-p cross-sections

Vance, Gyulassy and Wang, Phys. Lett. B443, 45 (1998)

Connection to baryon stopping in heavy ion collisions



- Conventional wisdom: Regge phenomenology only matters at low energy
  - But… the relevant energy is the dipole-baryon CM energy.
  - soft dipole -> small CM energy.
    - Low-energy UPC photon
    - A soft virtual π
    - A low-x q-qbar dipole
    - Other configuration within an incident nucleus
- The baryon recoils but remains intact
  - Transport over multiple units in rapidity.
    - Like baryon stopping.
- Phenomenology is very reminiscent of the baryon junction model.
  - Are there connections?

Future work

- Methodical kinematic studies to map out final states for various beam energy combinations and detector acceptances.
  - Separate 'central' and 'far forward' acceptance?
- Consideration of other mesons: is the ω optimum?
  - Higher mass -> more central production
  - The ρ may be a better candidate than the ω
    - Br($\rho \to \pi^+\pi^-$)=100%
    - Production rate may be higher (it is for Pomeron exchange)
- What happens with A>1 targets?

Conclusions

- Ultra-peripheral collisions are the energy frontier for photon physics. They provide insight into diverse topics, including gluon shadowing, meson spectroscopy and strong field QED.
- Baryon trajectory models can be used to predict the cross-sections and kinematic distributions for backward production in UPCs and at an EIC.
- The rates seem quite comfortable for both pA UPCs and ep at an EIC. However, there is a huge experimental challenge because the meson is produced in the far-forward region.
- The cross-section is largest for lower γp energies, so moving to lower proton-target energies will improve detectability and also shift the products toward mid-rapidity
  - RHIC at lower beam energies (luminosity will be a challenge)
  - 41 GeV (or lower?) proton beams at an EIC.
  - Alternately, far-forward detectors can detect the meson.

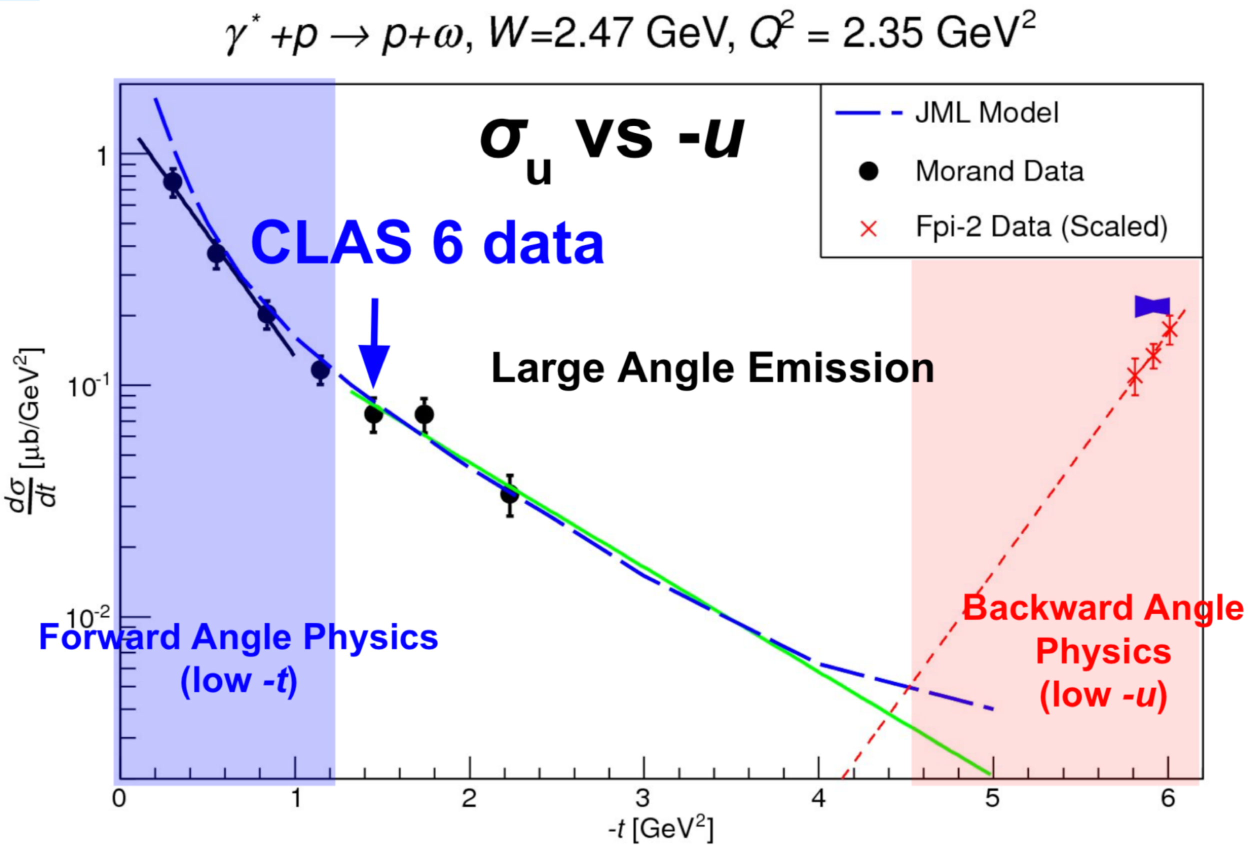
Backup

Photoproduction & electroproduction model

- Convolution of photon flux from electron with $\sigma(\gamma p \to Vp)$
  - Both depend on Q^2
- Weizsacker-Williams photon flux (with non-zero Q^2)
- VM cross-sections parameterized from HERA data/theory….
  - Reggeon and Pomeron exchange
    - Q^2 dependence via a power law from HERA data
- Other cross-sections from theory predictions
- Nuclear targets included with a Glauber calculation
- Vector mesons retain the photon spin
  - For $Q^2 \sim 0$, transversely polarized
  - As Q^2 rises, longitudinal polarization enters
  - Spin-matrix elements quantified with HERA data
- Embodied in eSTARlight code, available at: http://starlight.hepforge.org

γp -> ωp+ ρp

- Electroproduction data from Clas 6 at Jlab
- Forward & backward interactions are soft; intermediate is hard



Soft structure -> Hard -> Soft transition

First time in electroproduction

Plot from Bill Li (William & Mary).

Theoretical approach - I

- GPD-like model, with Transition Distribution Amplitude quantifying baryon trajectories.

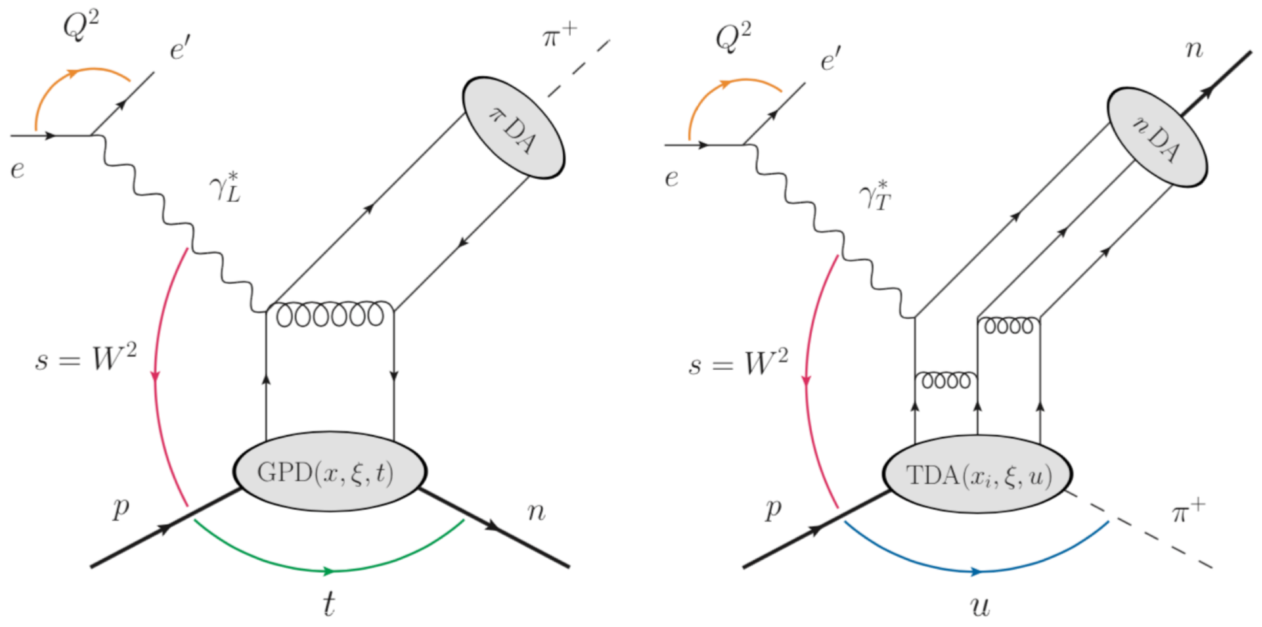


Diagram from K. Park et al., Phys. Lett. B780, 340 (2018)