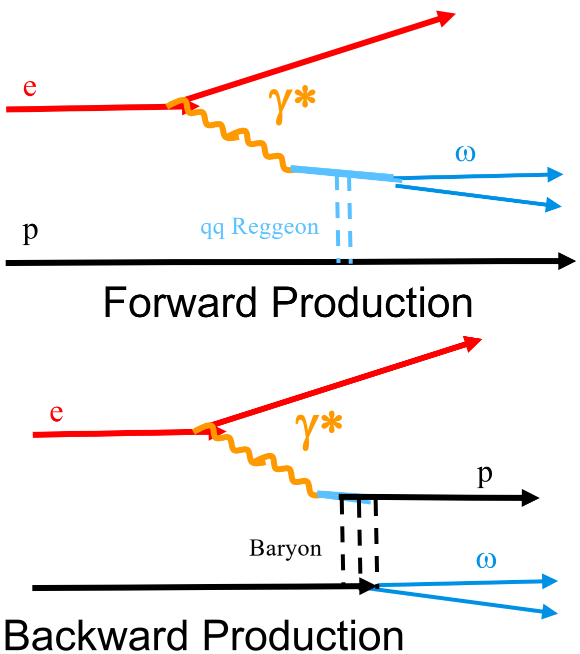
Imaging baryon number within the proton

Spencer Klein, LBNL

- How big is the proton?
- Imaging in exclusive reactions
- Backward production & imaging baryon number
- Dataset and measurement
- What carries baryon number?
- Conclusions

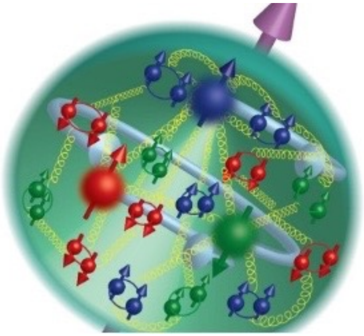


Based on arXiv:2603.03730

SK, Mathias Labonte, Zachary Sweger,
Gerald Miller and Ramona Vogt

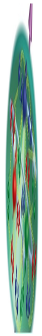
How big is the proton?

- Depends what you measure and how you measure it
- 2d vs, 3d radii?
  - In the nuclear rest frame, a 3-d radius makes sense
  - At large Lorentz boosts, nuclei become pancakes, and 3-d radius is not uniquely defined
    - Use 2-dimensional radius



- Conversion, for spherically symmetric objects

$$\langle r_2^2 \rangle = \frac{2}{3} \langle r_3^2 \rangle \,.$$



- Today: everything is 2-d radius
  - 3-d radii converted using the above formulae

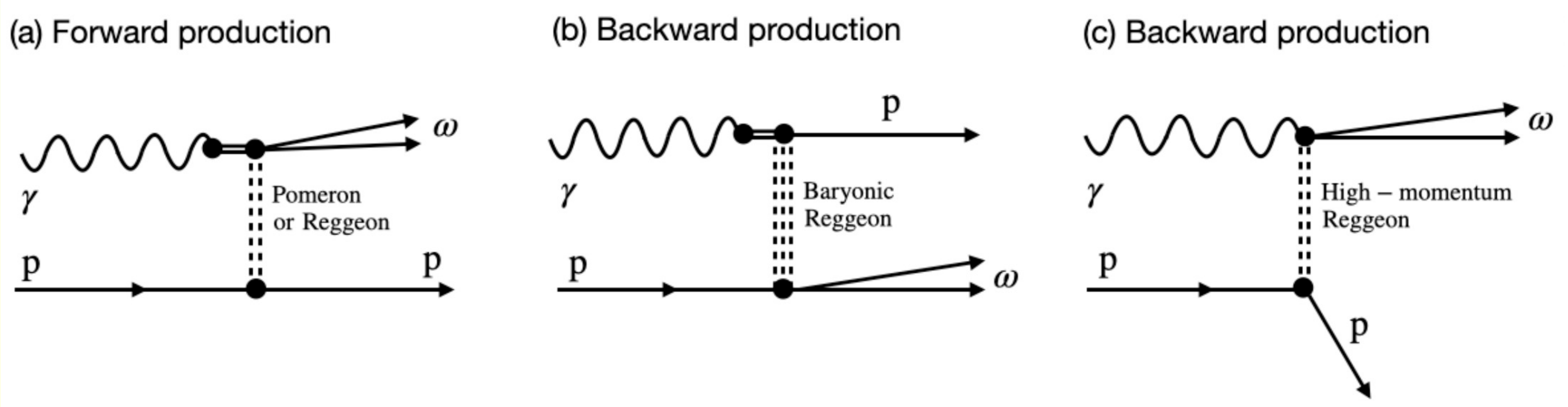
Different (2d) proton radii

- Charge radius, via electron scattering
  - 0.69-0.72 fm
- Charge radius, via hydrogen spectroscopy
  - 0.69 fm
  - Similar results from studies of muonic hydrogen
- Hadronic (gluonic) radius, via forward vector meson photoproduction
  - Vector meson radius must be removed -> some uncertainty
  - 0.86-0.99 fm
- Gravitational (mass) radius
  - Probably hard to measure using gravity
  - Mechanical (stress) properties of the proton
  - $R_{3D} \sim 0.62$ fm; $R_{2D} = 0.5$ fm
- One can also ask: what is the radius of the baryon number within the proton?

V. Burkert et al., arXiv:2310.11568

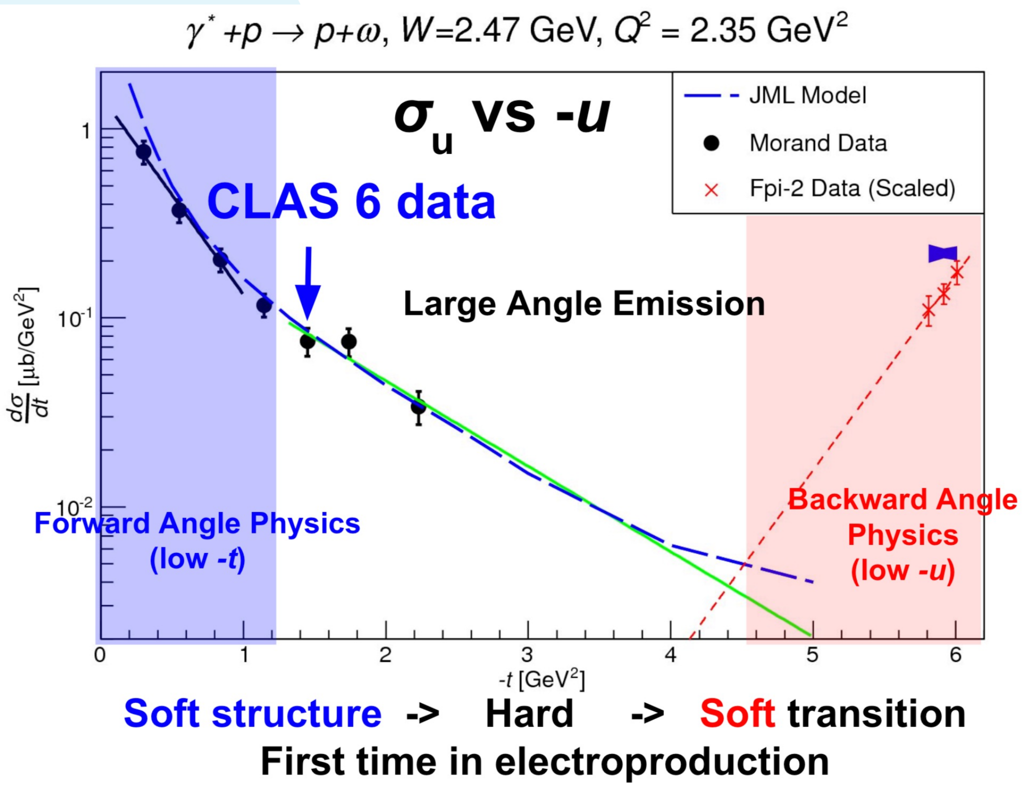
How can we probe the baryon number radius?

- With a reaction that is sensitive to baryon number
  - Backward exclusive meson production
- In forward production, the exchanged Mandelstaam t is small
  - The meson takes most of the photon momentum
  - Exchanged Pomeron/Reggeon momentum is small
- In backward production, either:
  - Very high momentum transfer
    - Not very viable, because high momentum transfer implies a high degree of 3-d localization
  - Low momentum transfer, but the transfer includes baryon number
    - Target is baryon=number containing region



Backward production

- For a given collision energy t+u=constant
  - Separate peaks at low t and at low u
  - Two components to the cross section
- Two component model implies two different reactions



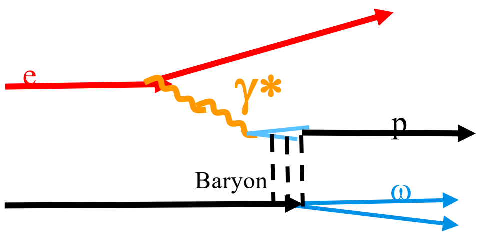
Larger slope for dσ/du than dσ/dt -> smaller exchanged object

Plot from Bill Li (Stony Brook); data from W. B. Li et al. (JLab Fπ) PRL **123**, 182501 (2019).

Exclusive photoproduction and imaging

- b (impact parameter) and p_T are conjugate variables
  - Fourier transform changes $f(p_T)$ to $f(b)$

$$F(b) = \int_0^\infty p_T dp_T J_0(bp_T) \sqrt{\frac{d\sigma}{dX}}$$



Backward Production

    J_0 is a Bessel function
  - Square root converts from σ to amplitude and $t \sim p_T^2$ to p_T.
    - X = u or t (including $u_{||}/t_{||}$)
    - Exact conversion between u/t and p_T
    - Need to flip sign when going across diffractive minima
- p_T integral goes to infinity, but data cuts off at finite p_T, due to
  - Kinematic limit (finite energy) – natural $p_{T,max}$
  - Limited statistics
  - Separation of dσ/dt and dσ/du
    - Fourier transform is the convolution of dσ/du with box function

(Limited statistics; Separation of dσ/dt and dσ/du:) If these are limiting factors -> artifacts

Minimizing imaging artifacts

- For the data used here, typically
  - Coverage = $p_{\text{Tmax-in-data}}/p_{\text{Tmax,kinematics}}$ is 0.4-0.8
  - Likely windowing artifacts
- The uncertainty can be estimated as an incompleteness error

$$\Delta_{\rm inc} = \left| \frac{1}{2\pi} \int_{p_{T,\,\rm max}^{\rm data}}^{p_{T,\,\rm max}^{\rm kin}} p_T\, dp_T\, J_0(bp_T) \sqrt{\frac{d\sigma}{dX}} \right|$$

- We also attempt to correct for/minimize the error by extrapolating $d\sigma/du$ to the kinematic limit, using the last four points
  - The extrapolation uses an exponential form
    - A good assumption, modulo diffractive dips
- The extrapolation leads to radii (HWHM) that are systematically smaller than without it, by less than the incompleteness error.
  - In agreement with expectations.

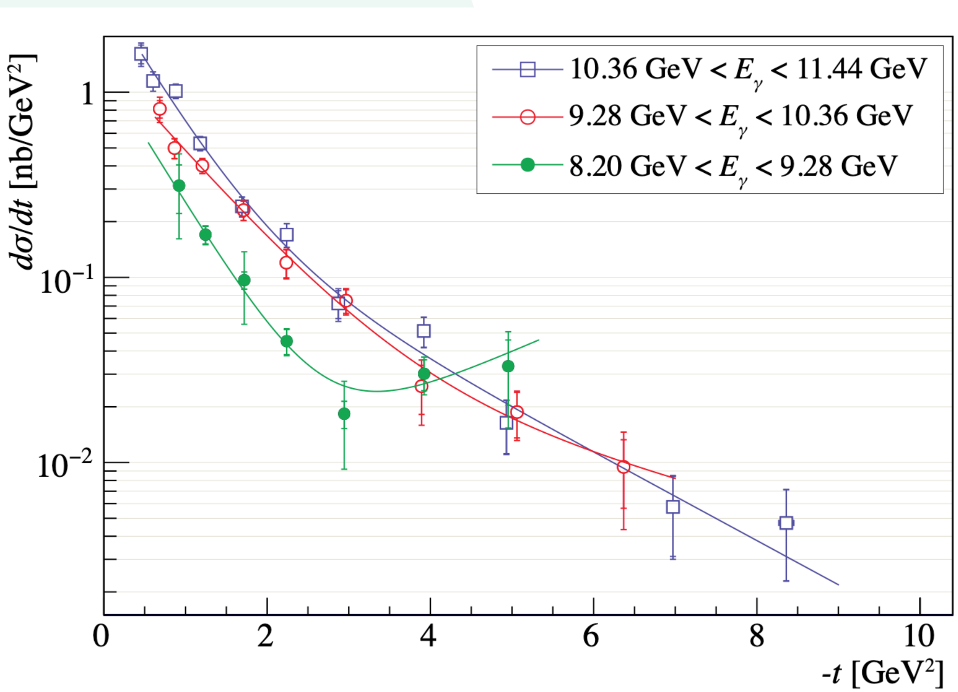
Backward production data

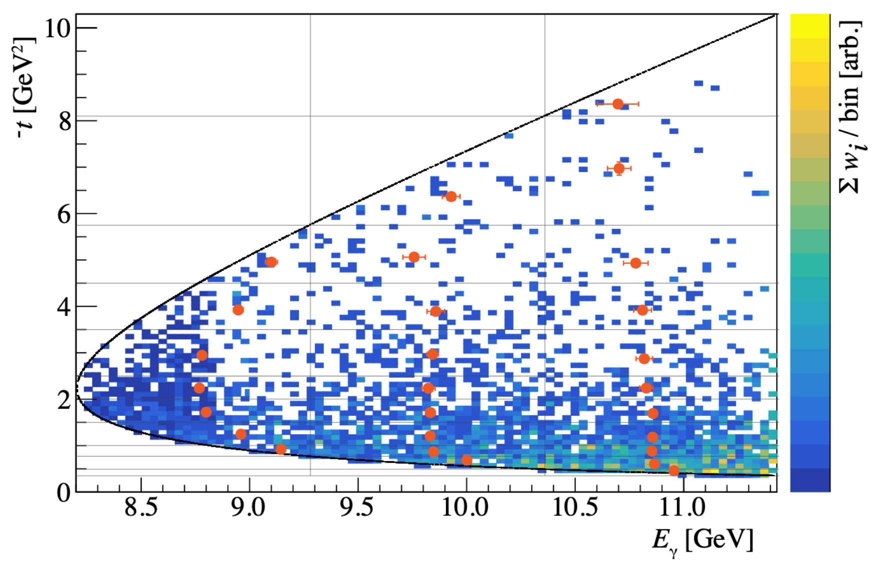
- Observed in many different fixed-target reactions
  - Jefferson Lab included (cf. Bill Li's talk)
    - $\gamma p \to \omega p$
- We selected well-studied reactions
  - Photoproduction ($Q^2=0$) to allow comparison with forward production
  - Covering a wide range of u
  - Reactions with data from multiple photon energies
  - CM energy above the resonance region: W > 2.5 GeV
  - Presence of similar t-channel comparison data
    - Similar, but not always identical γ energy and t/u range
- Four reactions: $\gamma p \to \omega p$, $\gamma p \to \rho p$, $\gamma p \to \pi^0 p$, $\gamma p \to \pi^+ p$
  - Exchanged particles with different isospin, charge

Good Review: C. Ayerbe Gayoso *et al.,* Eur. Phys. J. A **57**, 342 (2021)

Backward J/ψ production?

- Intriguing near-threshold J/ψ data from Glue-X @ Jlab
- At the lowest photon energy, dσ/dt turns upward at large t
  - Small-u region
- As the photon energy rises, u->0 corresponds to larger t
- The J/ψ shares no quarks with the incident baryon





Glue-X,
arXiv:2304.03845

Experimental data

- SLAC tagged photon beam: 4.1-18 GeV
  - 3.5 GeV data covered too narrow a range in u
- Daresbury electron synchrotron NINA: 2.7-4.8 GeV
- Data collected late 1960's to mid 1970's.

Volume 64B, number 2 PHYSICS LETTERS 13 September 1976

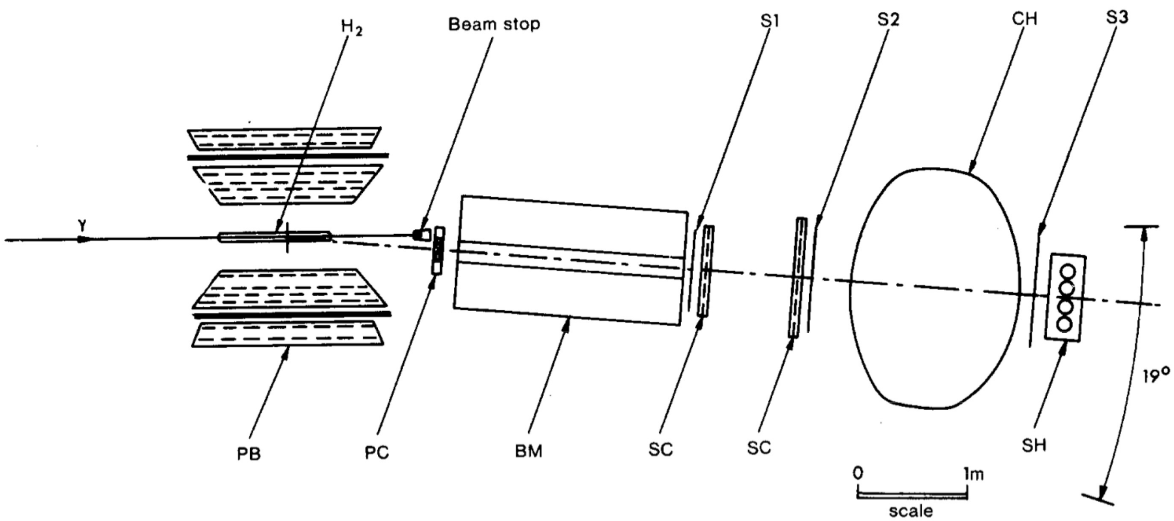
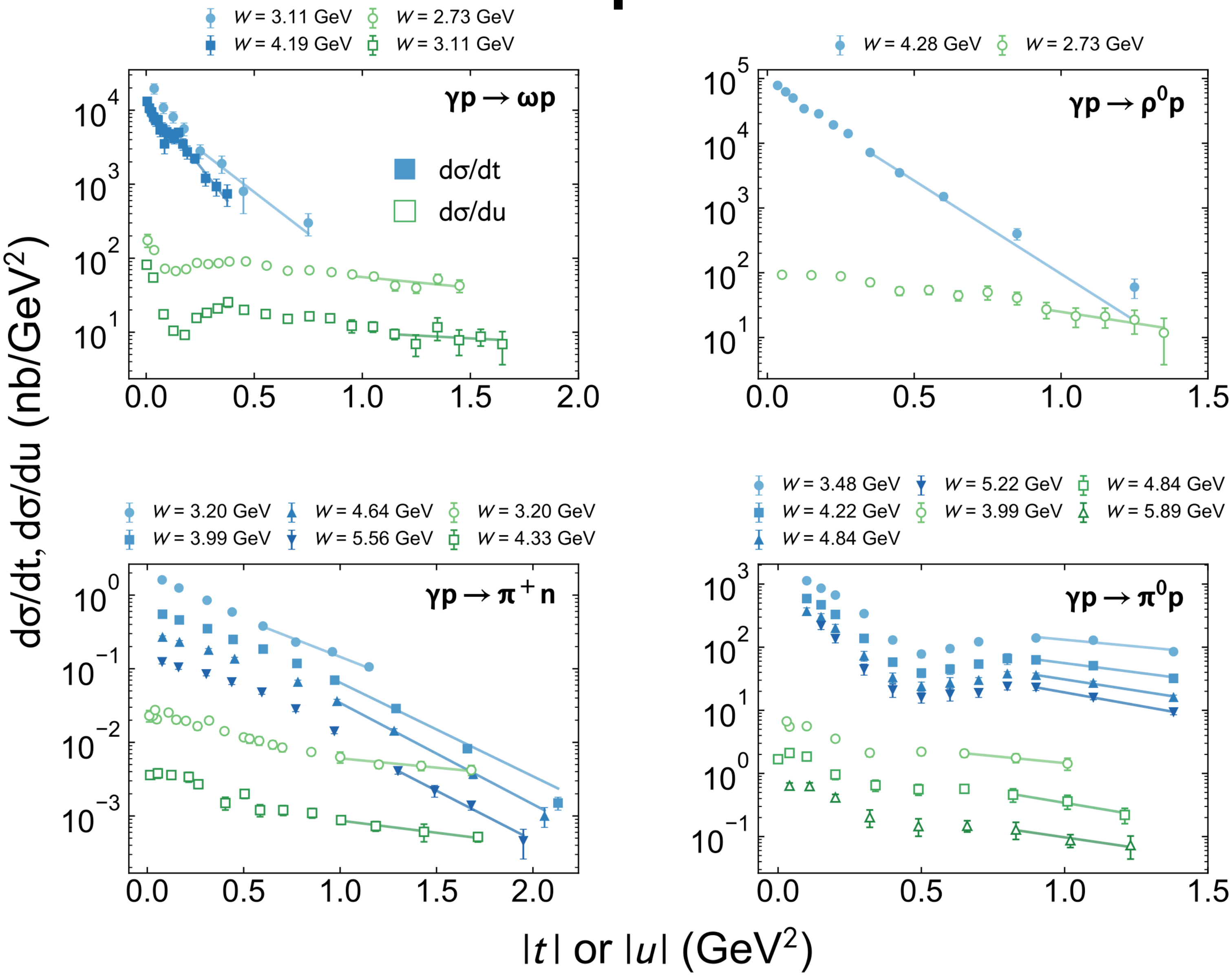


Fig. 1. Experimental arrangement showing the hydrogen target (H_2) surrounded by wire chamber and scintillation counter array (PB) and the forward proton spectrometer consisting of proportional chamber (PC), dipole magnet (BM), scintillation counters (S1, S2, S3), wire chambers (SC), large aperture threshold Cherenkov counter (CH) and shower counter SH).

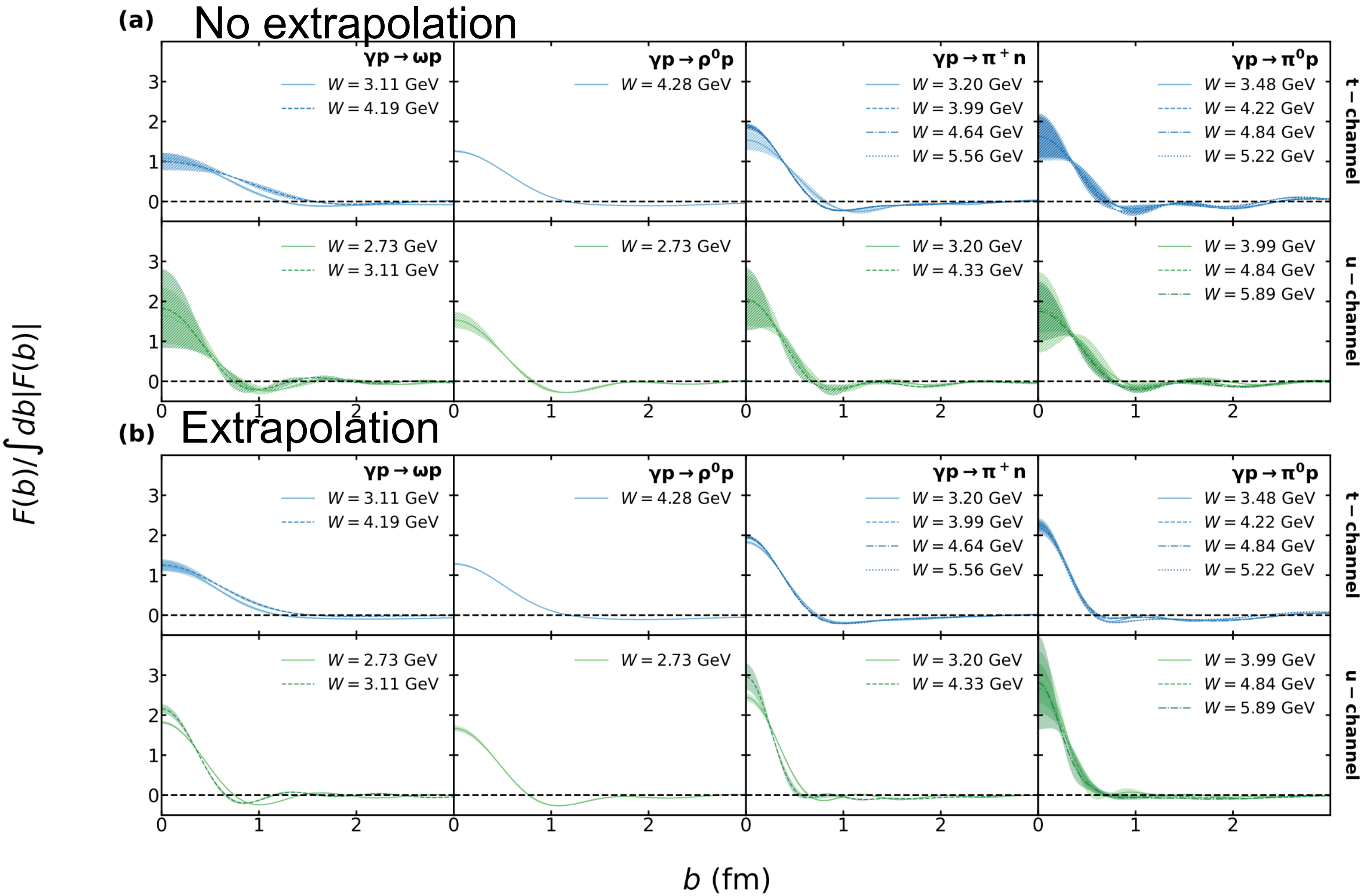
Input data



Some data exhibit diffractive minima, some do not

Diffractive minima are associated with sharp edges

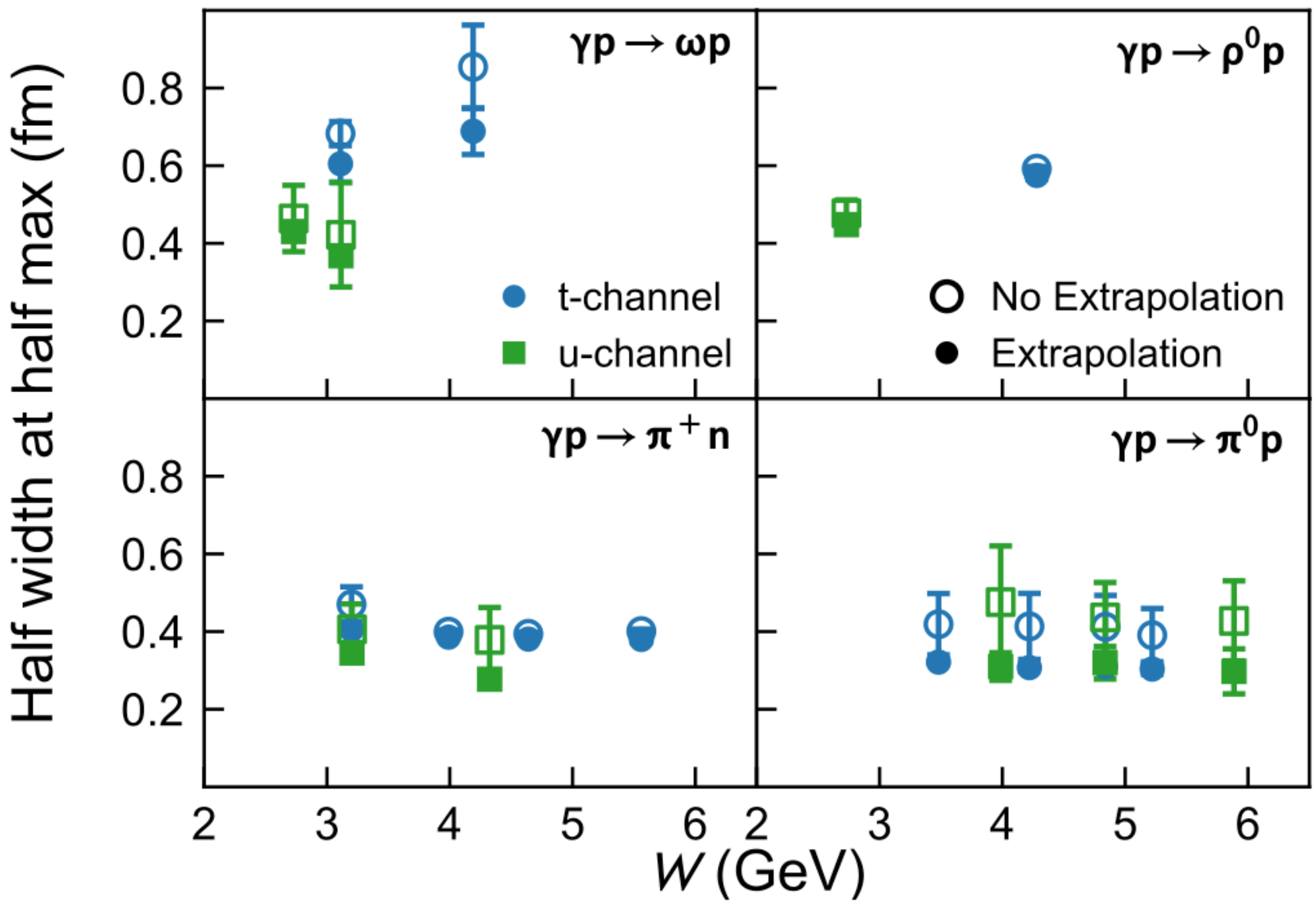
Transformed data



Excursions below zero, wiggles -> noise or artifacts. Characterize by HWHM
Extrapolated radii are smaller than non-extrapolated by an average of 14%
Error bands are estimated by resampling the data 1,000 times

Summarizing the data - FWHMs

- On average, the u-channel radii are a bit smaller than the t-channel equivalents. For the ω, the differences are significant.



Exchanged particles

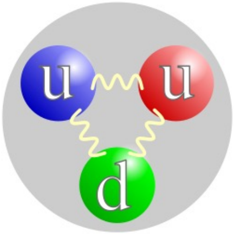
- Forward production: Pomerons (mostly gluons) and Reggeons (meson trajectories)
  - Reggeon trajectories dominate at low energies
  - At these low γ energies, higher -x quarks and antiquarks dominate the exchange
- Backward production: Reggeons that carry baryon number
- For both, we should subtract the size of the photon/dipole that interacts with the target
- At higher (HERA) energies, where Pomerons dominate, the sizes are larger
  - ρ^0 data from H1: r_ρ=0.99 fm
    - Uncertainty from removing ρ^0 size
  - J/ψ data from H1: r_ρ=0.84 fm, not including J/ψ size

How do the sizes compare?

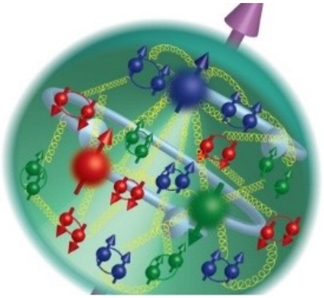
Reaction	Sensitive to	RMS Radius (fm)
Low-energy forward VM photoproduction	High-x quarks and gluons	0.67 – 0.77
Forward π^0 and π^+ photoproduction	High-x quarks	0.33 – 0.45
Backward meson production	Baryon number	0.33 – 0.53
High-energy forward VM photoproduction	Gluons	0.86 – 0.99
Electron scattering	Net charge	0.69 – 0.72
Hydrogen spectroscopy	Charge	0.69

- The baryon number size is in the range 0.33-0.53 fm, depending on reaction.
- This is significantly smaller than the proton size measured via reactions sensitive to gluons, net charge or charge.
- We conclude that the baryon number is somewhat concentrated in the center of the proton

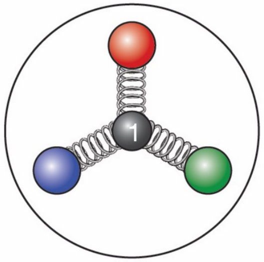
What carries baryon number?



- Naïve quark model
  - 3 quarks
- Parton model
  - 3*(quarks – antiquarks)



- pQCD
  - Local gauge invariance -> must consider gluons
  - string operators act on quark fields
  - Baryon number could be connected with a nonperturbative configuration of gluon fields where these strings meet
    - These are baryon junctions



- Our data would support a model where baryon number is carried by either a baryon junction or by high-x quarks.

Cf. also Dimas talk this morning

Rossi & Veneziano, Nucl. Phys. B **123**, 507 (1977); D. Kharzeev, Phys. Lett. B **378**, 238 (1996)

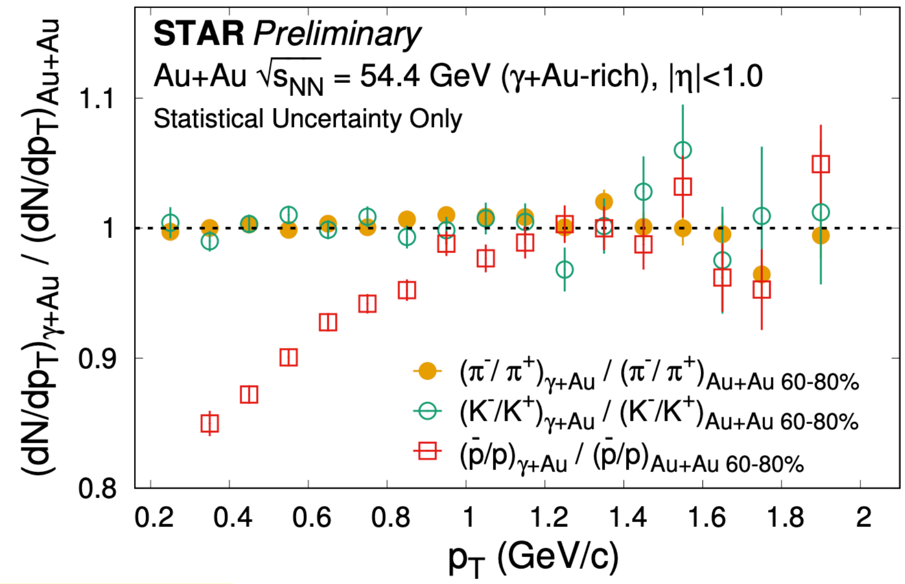
Backward production and baryon stopping

- In both backward production and baryon stopping in relativistic heavy ion collisions, baryons are shifted several units of rapidity
  - Backward production is the simplest baryon stopping reaction
    - Baryon stopping and backward production should be studied together
- In baryon junction models, baryon stopping follows Regge trajectories, like backward production
  - Trajectories seem similar
- Similar mechanisms?
  - Deeper connections?

D. Cebra *et al.*, Phys. Rev. C **106**, 015204 (2022);
D. Kharzeev, Phys. Lett. B **378**, 238 (1996)

Baryon stopping at RHIC

- RHIC data on baryon stopping tends to support baryon junction models
  - Stopping follows baryon number, rather than charge,etc.
- Excess of soft protons in γA collisions
  - Not seen in charge or strangeness ratios



STAR Collaboration: arXiv:2408.15441; N. Lewis for STAR, Acta Phys. Polon. Supp. 16, 1 (2023).

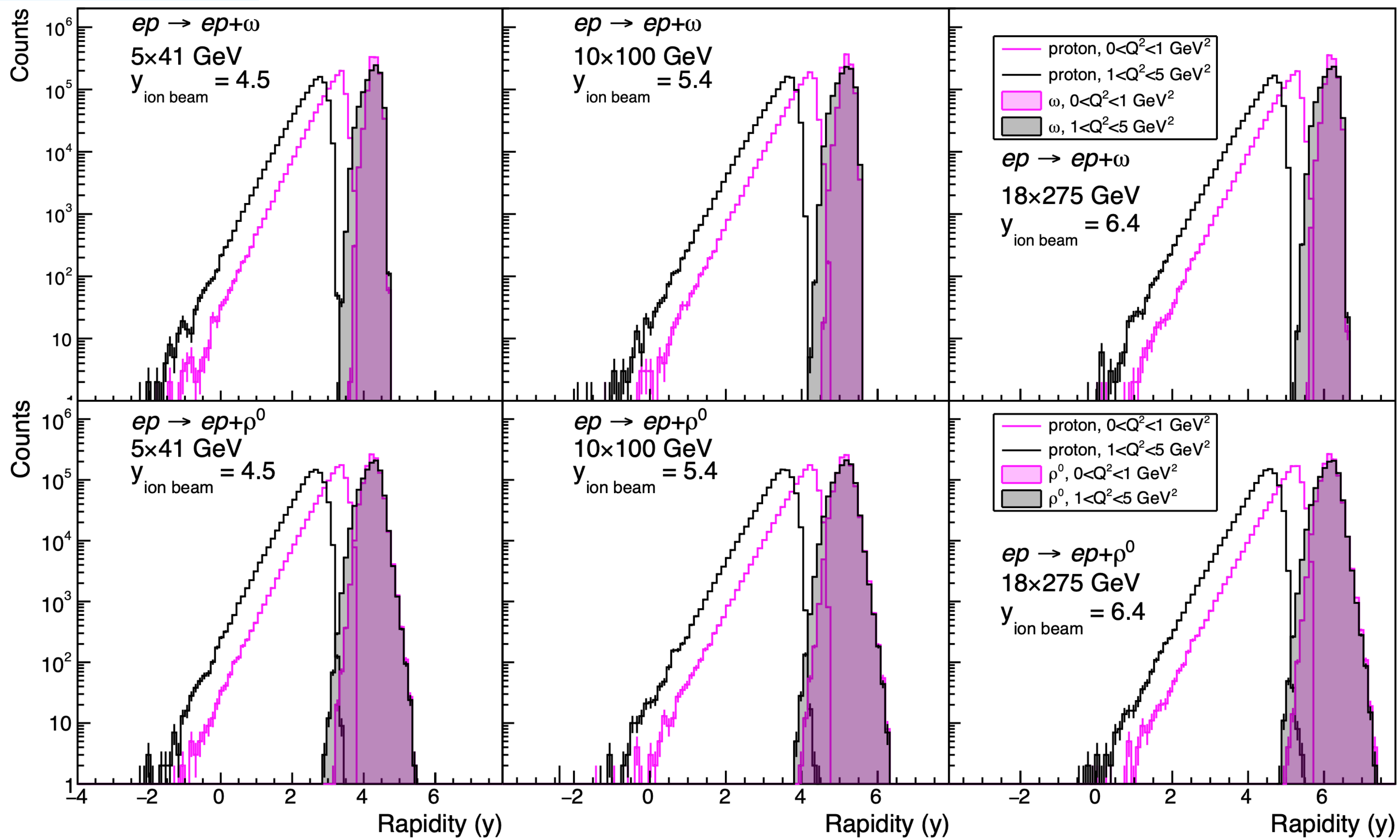
Making progess at the EIC

- Higher E_γ, to reduce nearish-threshold effects, especially $t_{||}$.
  - Higher energies help differentiate between exchange via high-x quarks vs. baryon junctions.
- More mesons, especially those that do not share quark content with the target baryon
  - Φ (s-sbar)
  - J/ψ (c-cbar)
- The EIC is ideal for backward production at high energies
  - Proton in the central detector +
  - ZDC for π^0 and $\omega \to \pi^0 \gamma$
    - ZDC can also study backward Compton scattering
  - B0 for charged + neutral states
- EIC rates are high
- N. b. backward production is implemented in eSTARlight, so is easy to study

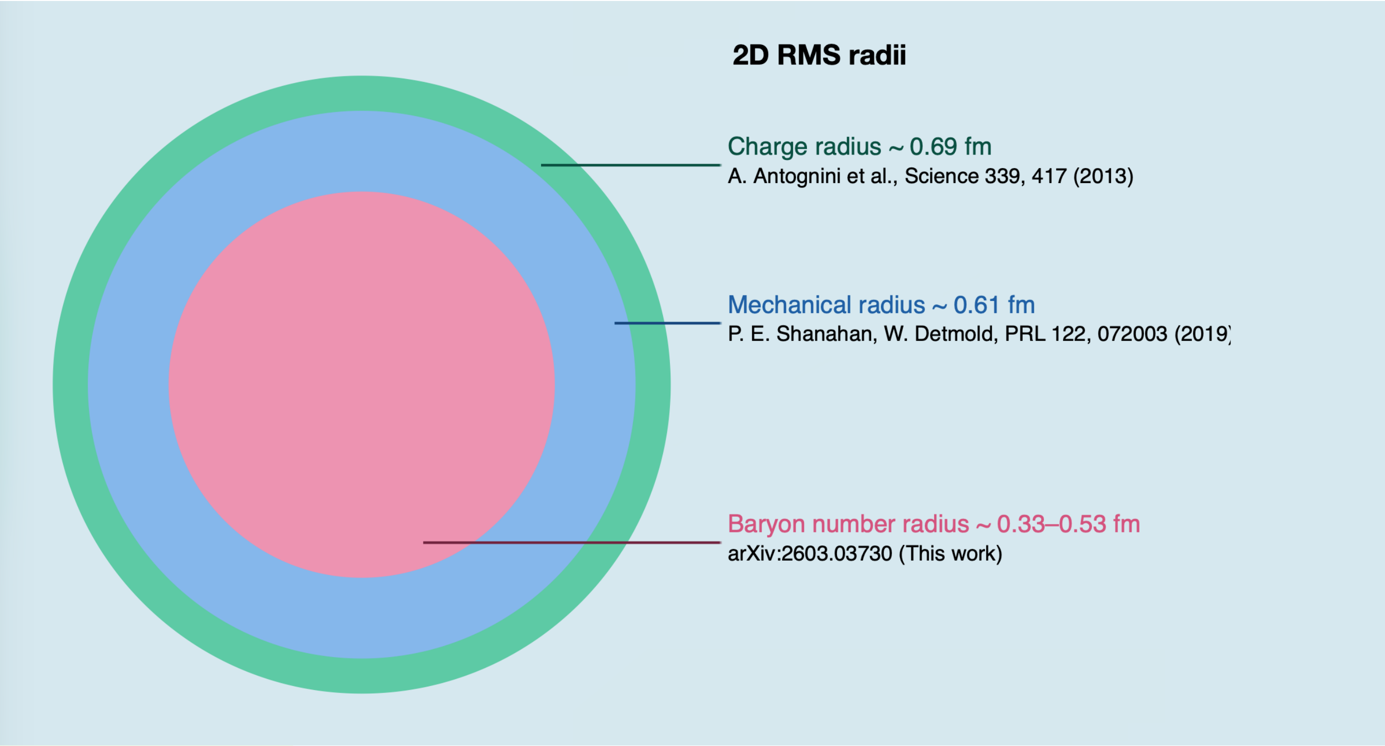
D. Cebra *et al.*, Phys. Rev. C **106**, 015204 (2022);
Z. Sweger et al., Phys. Rev. C **108**, 055205 (2023)

Proton and meson rapidities

- Proton is mostly visible in central detector
- Meson is mostly at rapidity 4-7, increasing with beam energy
- The heavier the meson, the more central the meson final state



The proton through different microscopes



Graphic by Mathias Labonte

Conclusions

- In exclusive reactions, transverse momentum distributions can be Fourier transformed to give transverse spatial target distributions
  - Different reactions are sensitive to different types of targets.
  - Backward production reactions occur via the exchange of reggeons containing baryon number. So, $d\sigma/du$ is sensitive to the distribution of baryon number in the target.
- We have analyzed multiple data sets for four different backward reactions, and found that $d\sigma/du$ is consistent with a 2D baryon number HWHM of 0.33-0.53 fm.
- This is significantly smaller than the proton charge and hadronic (gluon) radii of at least 0.69 fm.
  - Baryon number is concentrated near the center of the proton.
    - Consistent with it residing in either high-x quarks or baryon junctions.
- Backward production has similarities to baryon stopping in heavy-ion collisions. It would be worth pursuing combined studies.