Imaging baryon number within the proton

Mathias Labonté

Exclusive/Diffractive/Tagging Meeting
April 6
Based on arXiv:2603.03730

Imaging baryon number density within the proton

Spencer R. Klein
*Nuclear Science Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720 USA**

Mathias C. Labonté and Zachary Sweger
Department of Physics and Astronomy, University of California, Davis, CA 95616 USA

Gerald A. Miller
Department of Physics, University of Washington, Seattle, WA 98195 USA

Ramona Vogt
Nuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94551 and
Department of Physics and Astronomy, University of California, Davis, CA 95616 USA

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Diffractive scattering

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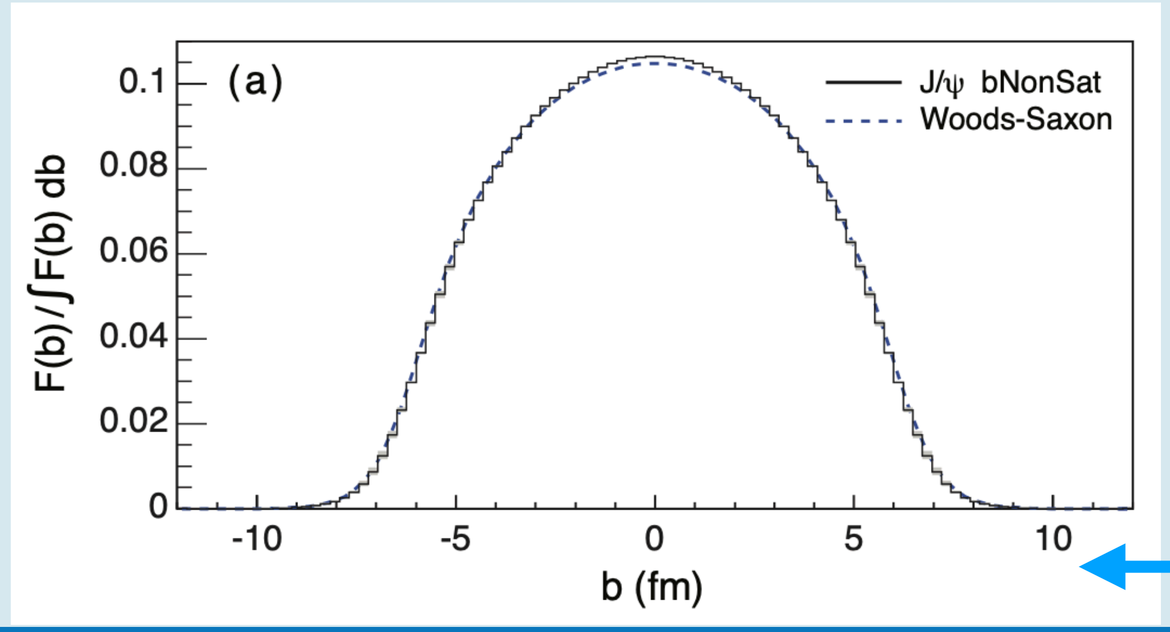
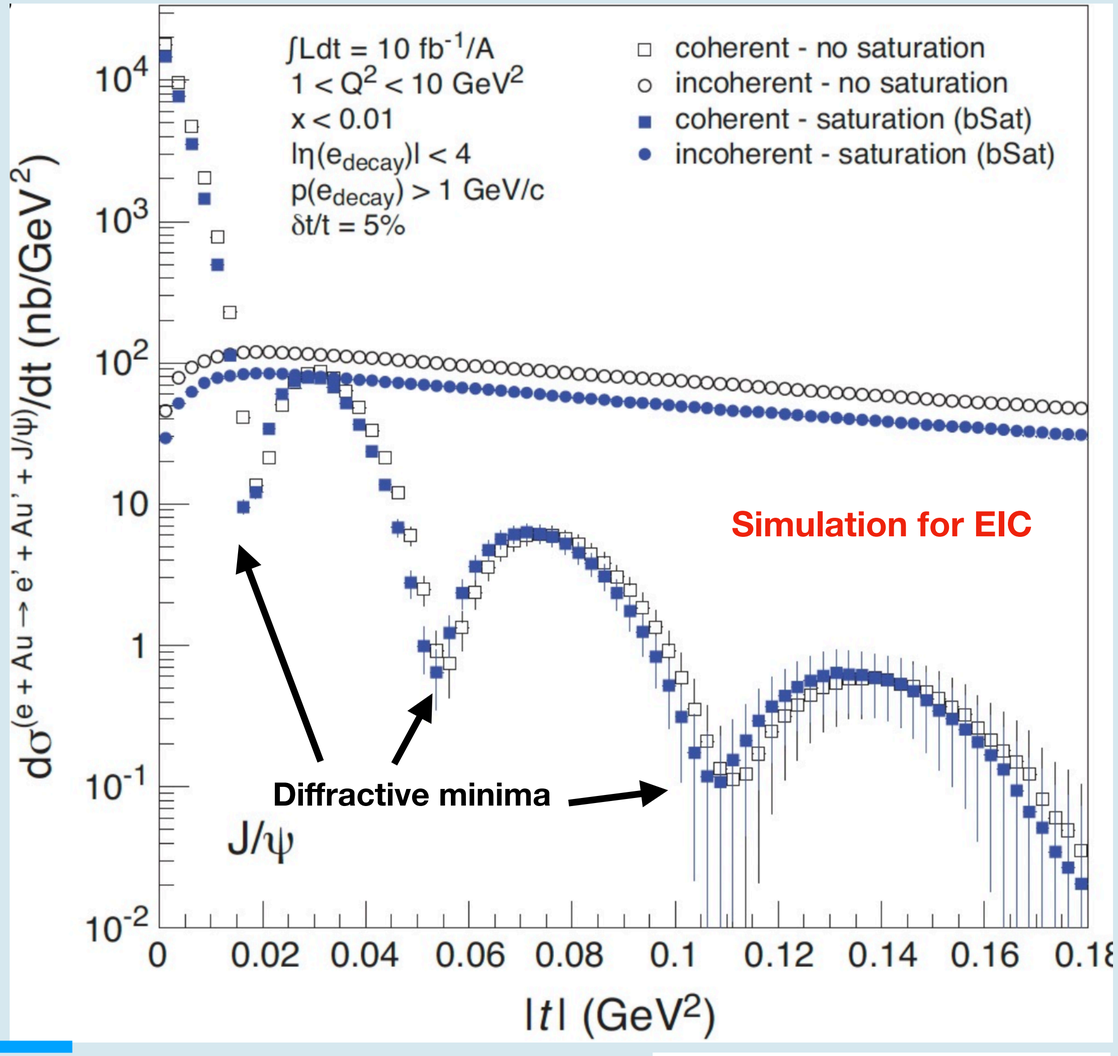
- Since p_T and b are conjugate variables, we can Fourier transform these distributions to image the transverse gluon distribution in the nucleus or nucleon

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





Phys. Rev. C 87, 024913 (2013)

What about the u-Channel?

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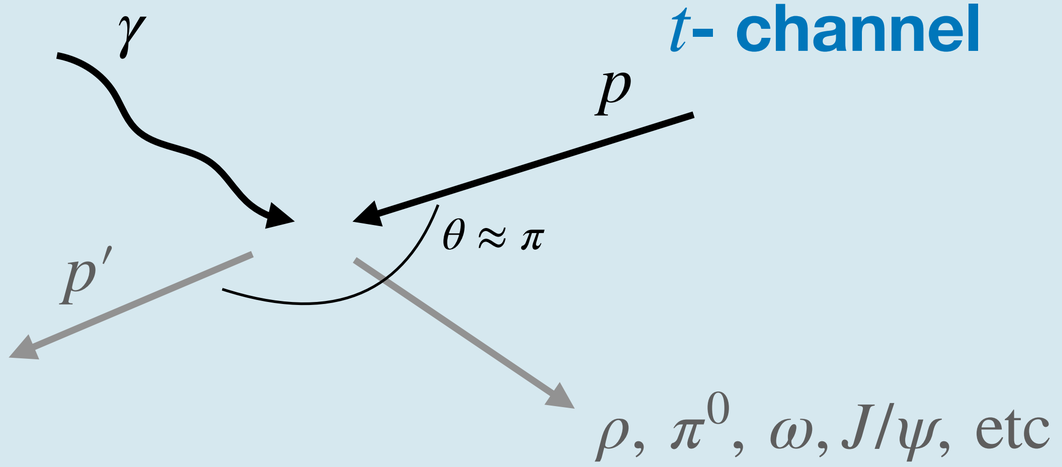
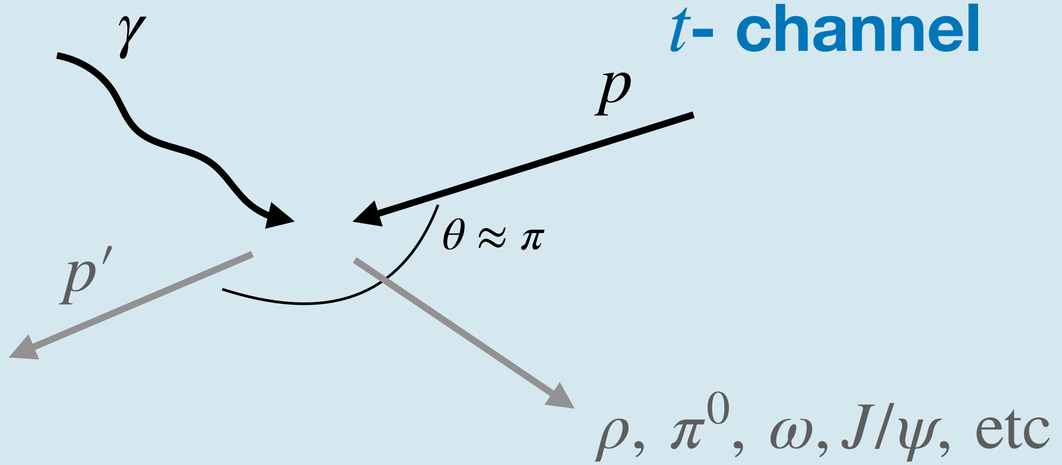
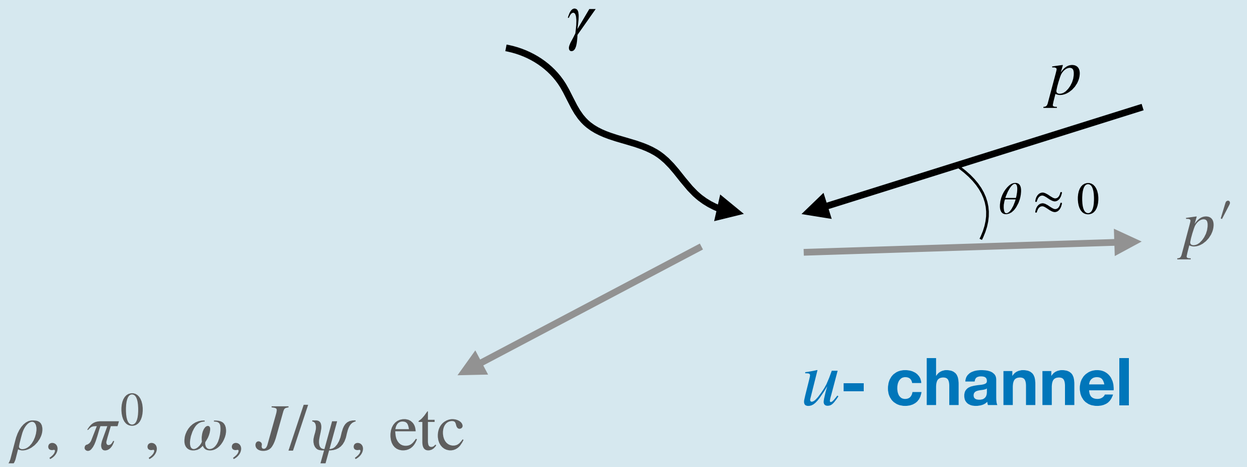
- Most of the time, the mesons are produced in the t-channel, where the protons momentum is minimally modified
    - Meson at midrapidity



What about the u-Channel?

- Most of the time, the mesons are produced in the t-channel, where the protons momentum is minimally modified
    - Meson at midrapidity
- Sometimes, the proton receives a large change in momentum, and we call this u-channel production
    - Meson produced at roughly the incident proton's momentum





What about the u-Channel?

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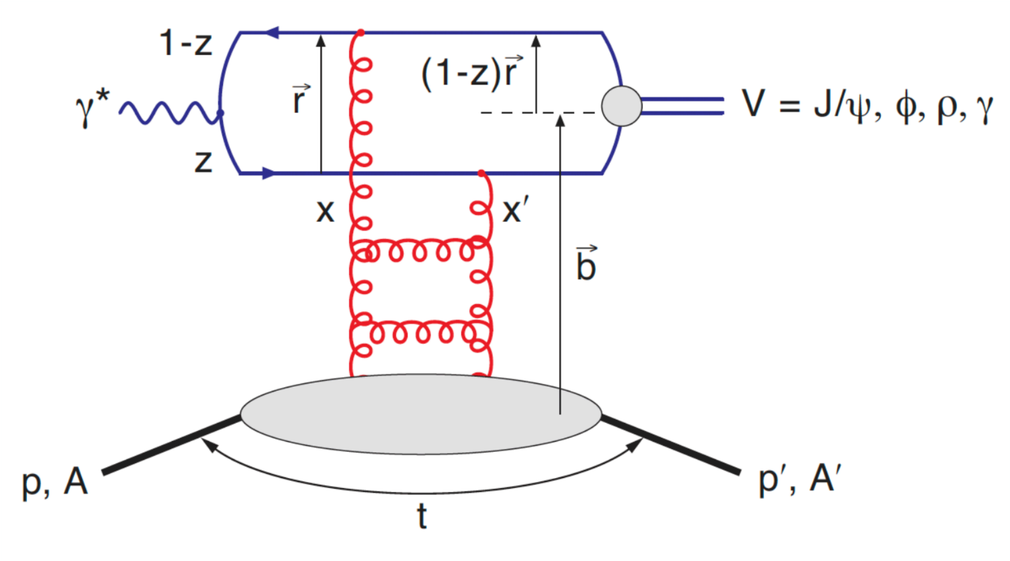
t- channel

u- channel

- Scattering off Pomeron maps gluon/quark density distribution



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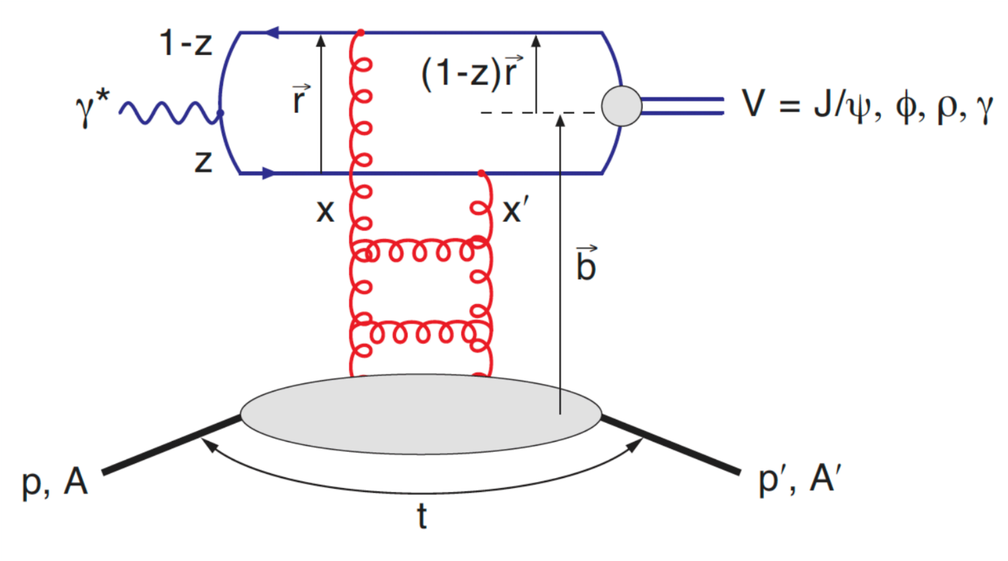

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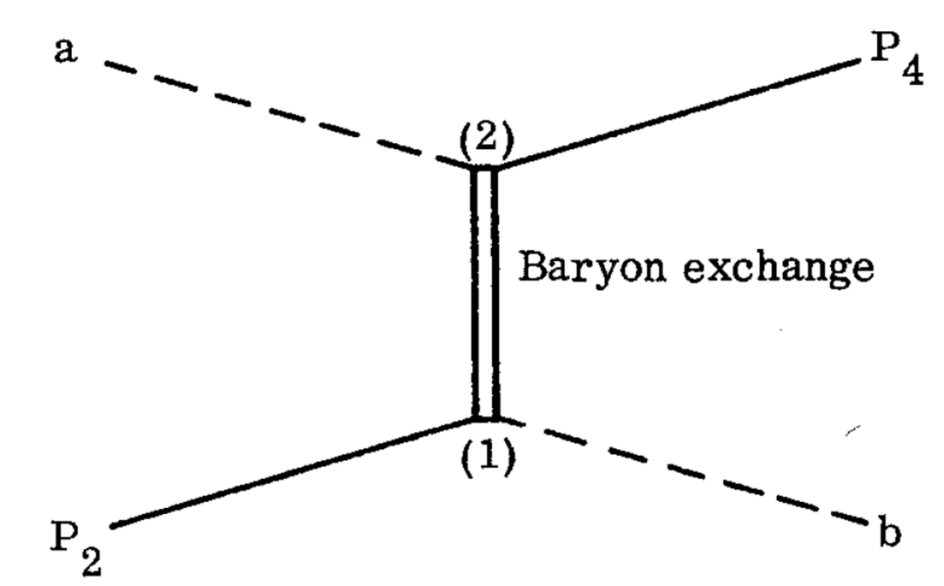
u- channel

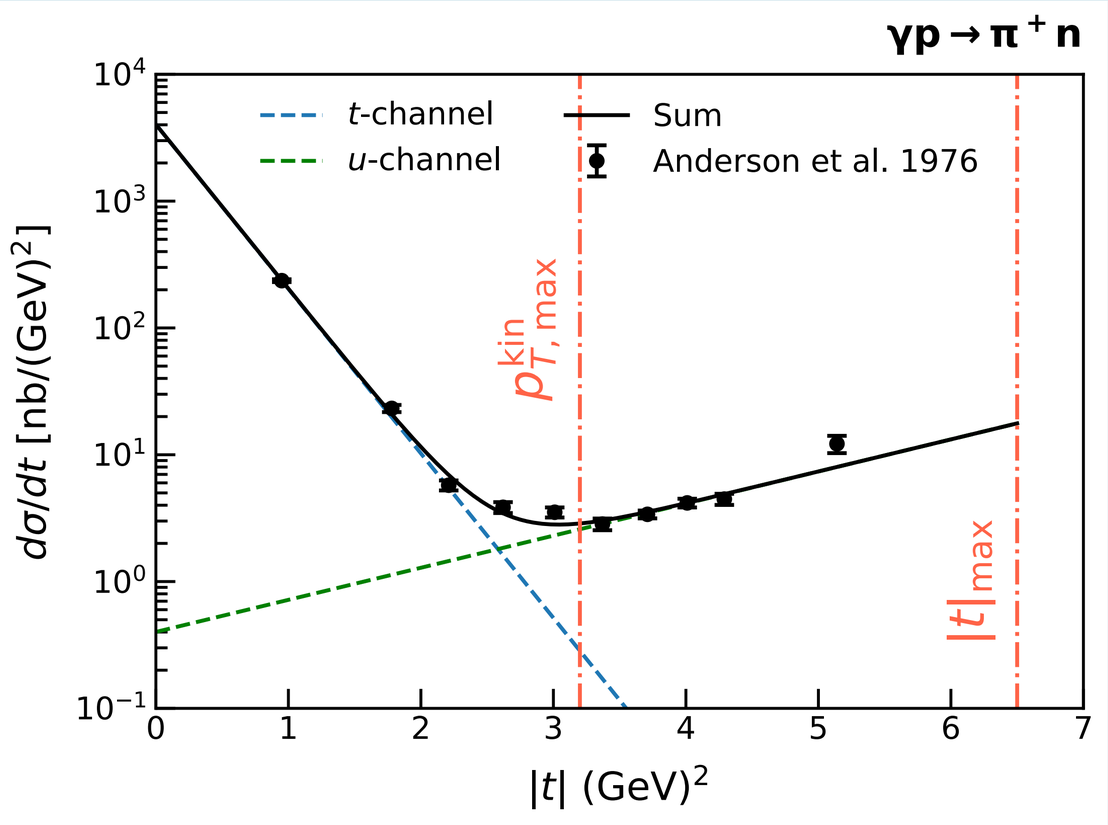
- Implies the exchange of something carrying baryon number



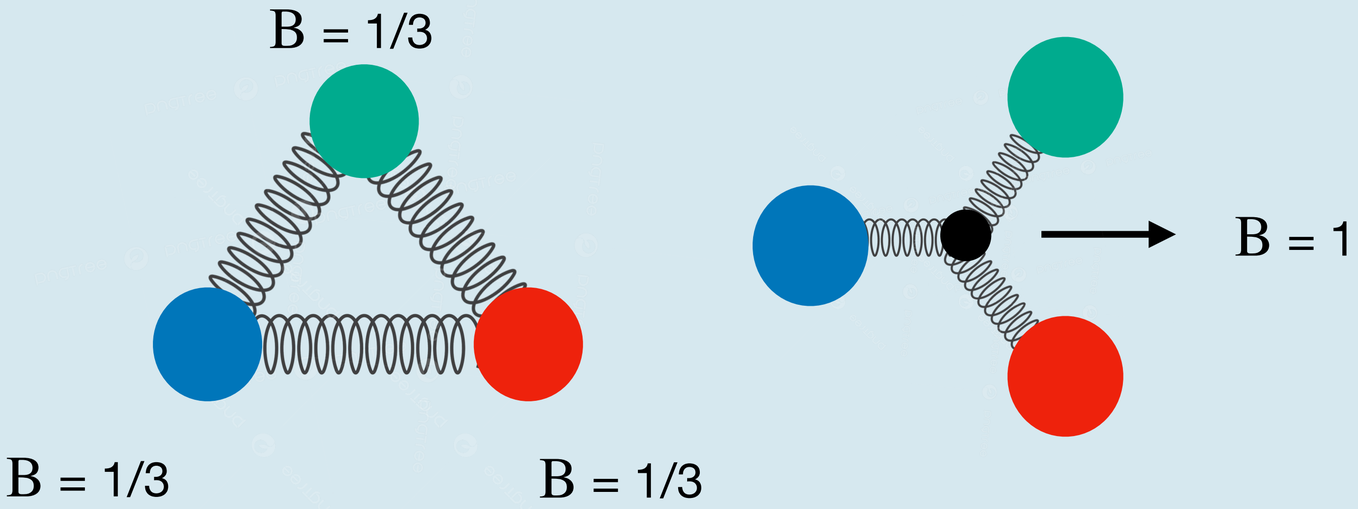
Tompkins, D. H. (1970). Backward Photoproduction of π0 Mesons at 6 to 18 GeV (No. SLAC-R-109)

Comparing t and u channels

- Here we can see exclusive photoproduction of pions over a wide kinematic range
    - The entire range can be described by two exponentials modeling the t and u channel contributions
- We see that there is a maximum kinematically allowed p_T, and a maximum kinematically allowed t



Baryon Junctions



Tracking the baryon number with nuclear collisions

Short Title: Do quarks or gluons carry baryon number?

The STAR Collaboration

arXiv:2408.15441

- Recent work from STAR supports the baryon junction picture
- Compares charge and baryon stopping in isobar data, and compares to models with different baryon number distributions
- The requirement of gauge invariance implies a configuration of gluons in the center of the nucleon connected to the valence quarks

Procedure

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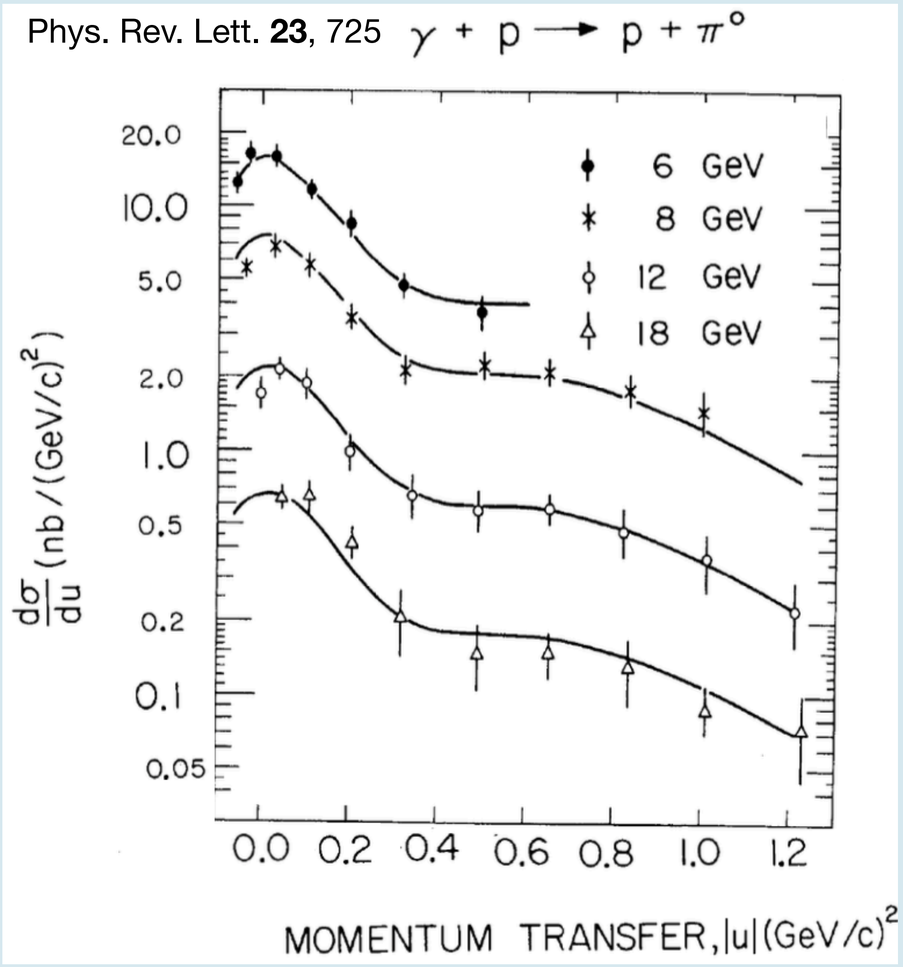
1. Find a dataset
2. Fourier transform

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

3. Extract HWHM
4. Bootstrap
   - Resample the cross section data around its error bars, and then transform again



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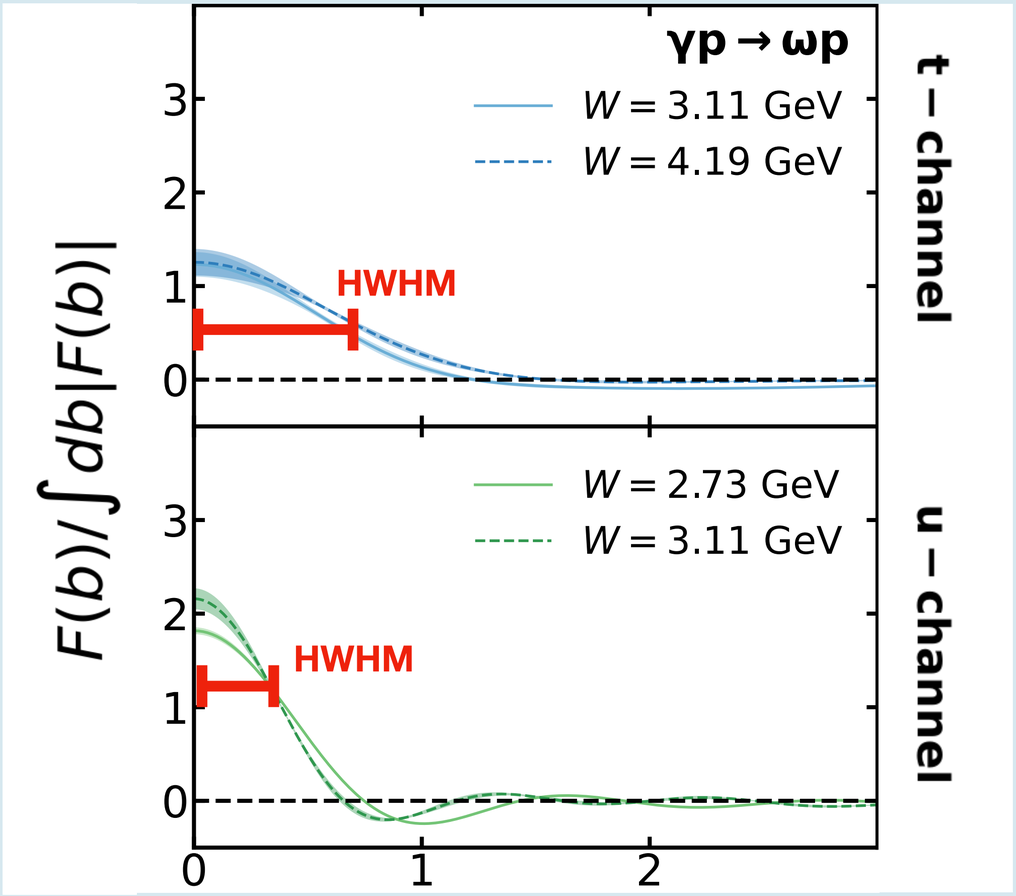

Details on the Fourier transform

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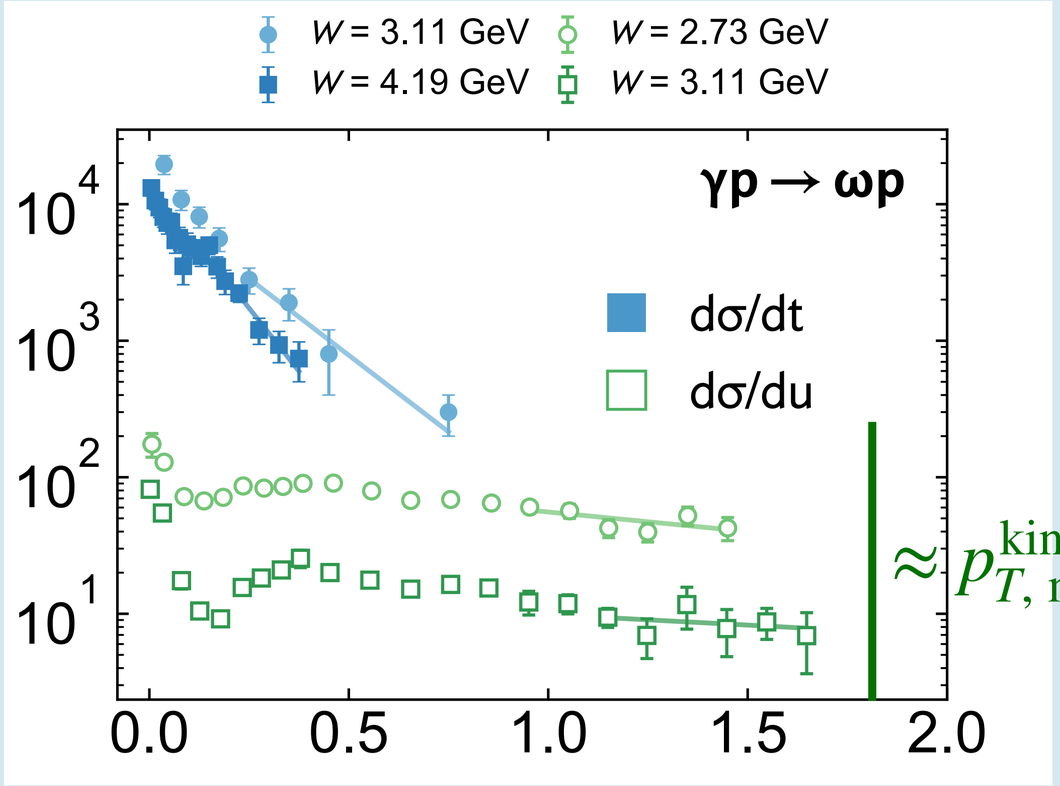
- Integral is defined from $p_T \in [0, \infty]$, but there is a maximum kinematically allowed p_T, $p_{T,\,\mathrm{max}}^{\mathrm{kin}}$
- The data doesn't cover the full kinematic range, and has its own maximum, $p_{T,\,\mathrm{max}}^{\mathrm{data}}$
- Effectively evaluate the integral from $p_T \in [0, p_{T,\,\mathrm{max}}^{\mathrm{data}}]$, and induces a windowing artifact

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

$$F(b) \propto \frac{1}{2\pi} \int_0^{p_{T,\,\mathrm{max}}^{\mathrm{data}}} dp_T \; p_T \, J_0(b p_T) \sqrt{\frac{d\sigma}{du}}$$

Details on the Fourier transform

- Need to assess how the finite data range affects the measurement on $F(b)$
- Can do this by extrapolating into the unmeasured p_T range
  - Fit the last few (3-5) data points with an exponential, and extrapolate to the maximum kinematically allowed p_T
- Assess a systematic error, or try to correct it



The general idea

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- Transform t and u-channel data, and look at the size of the source
- $\gamma + p \rightarrow (\pi^0, \pi^+, \omega, \rho) + p/n$ (archival SLAC and Daresbury data)
- How do they compare to other proton size measurements like **charge radii?**

Some important considerations:

- We should make apples-to-apples comparisons. This means:
  - We should select the same mesons across t and u channels
  - We should select similar values of W (collision energy of the photon and proton)
  - We should select a similar p_T range covered across measurements

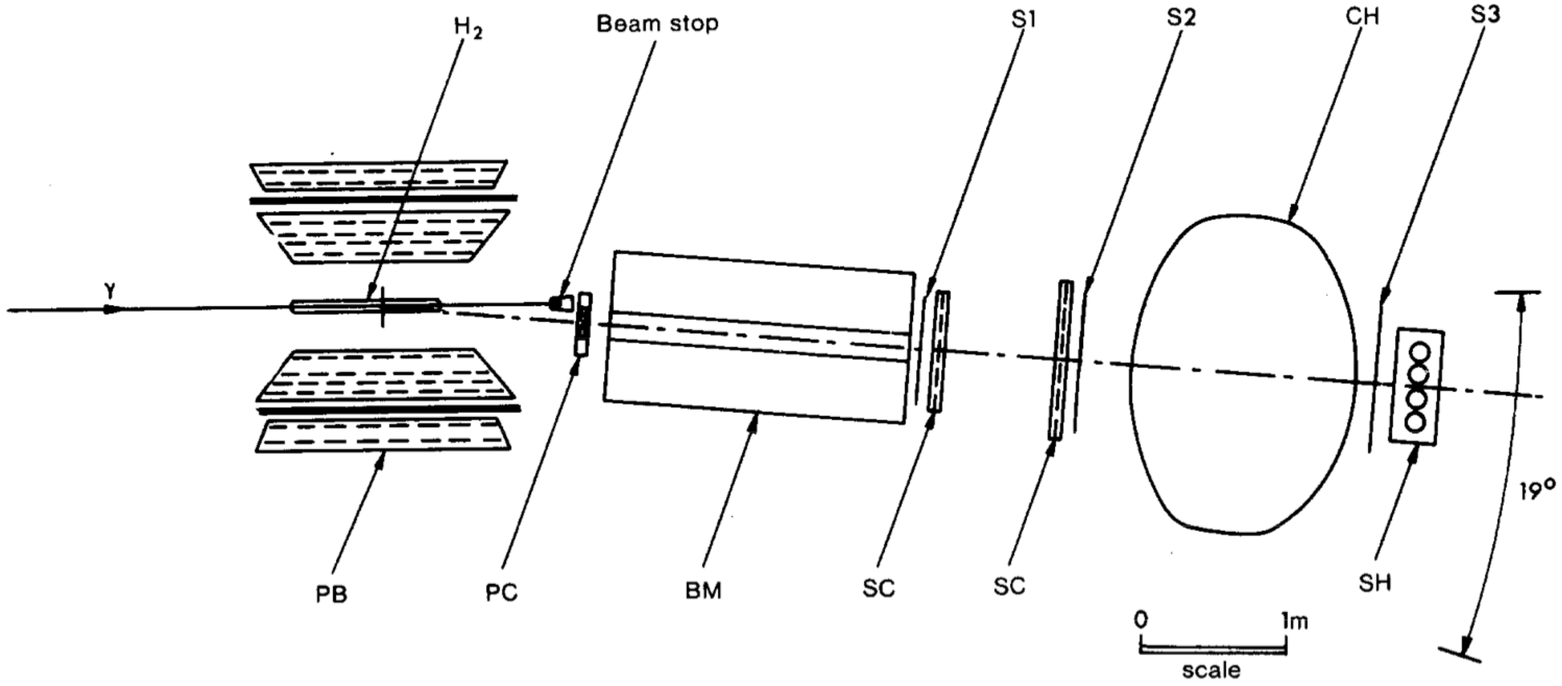
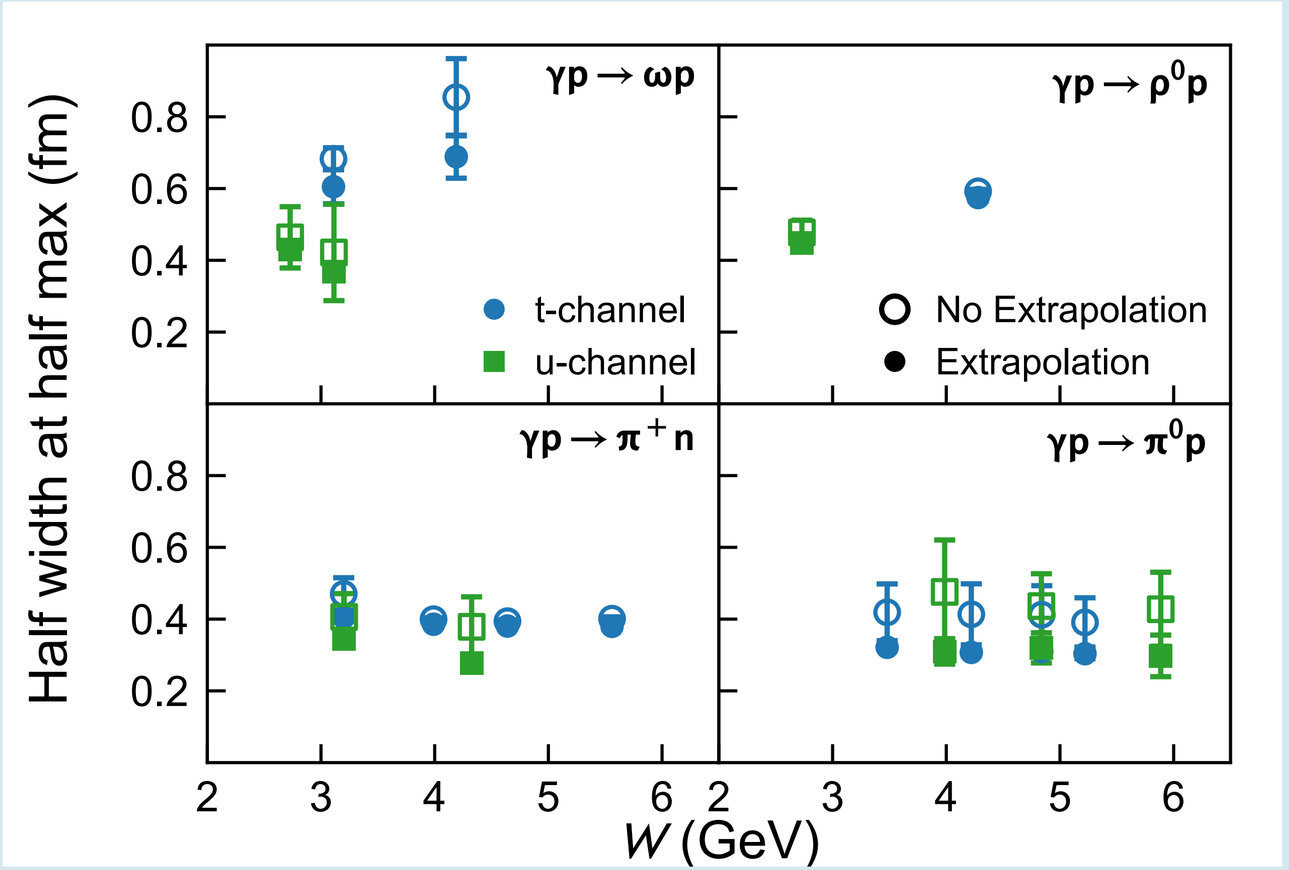


Fig. 1. Experimental arrangement showing the hydrogen target (H_2) surrounded by wire chamber and scintillation counter array (PB) and the forward proton spectrometer consisting of proportional chamber (PC), dipole magnet (BM), scintillation counters (S1, S2, S3), wire chambers (SC), large aperture threshold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

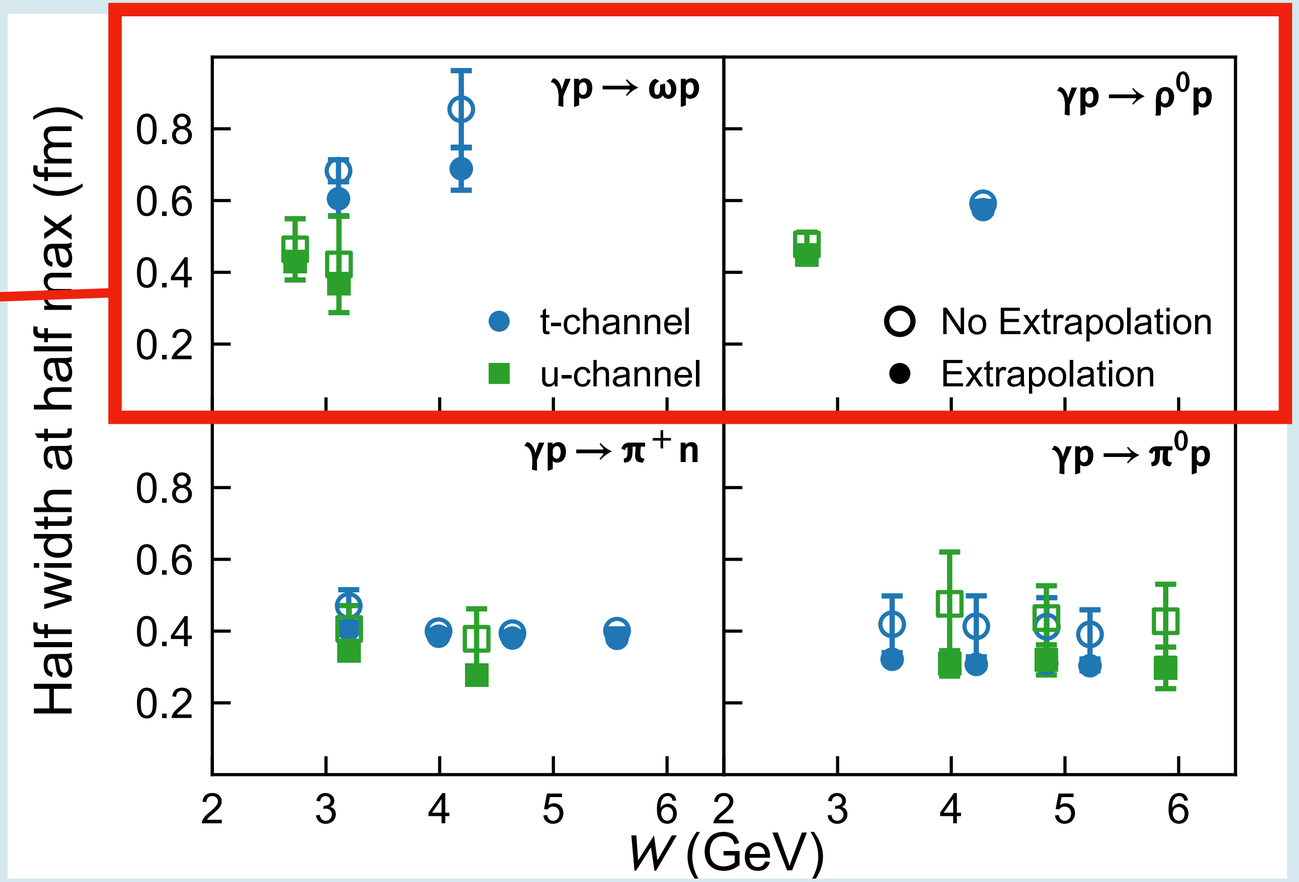
Results

- Plotted: HWHM for different produced mesons as a function of collision energy
- **Blue** - t channel
- **Green** - u channel
- **Open markers** - using incompleteness uncertainty
- **Closed markers** - correcting for incompleteness (taken as nominal results)



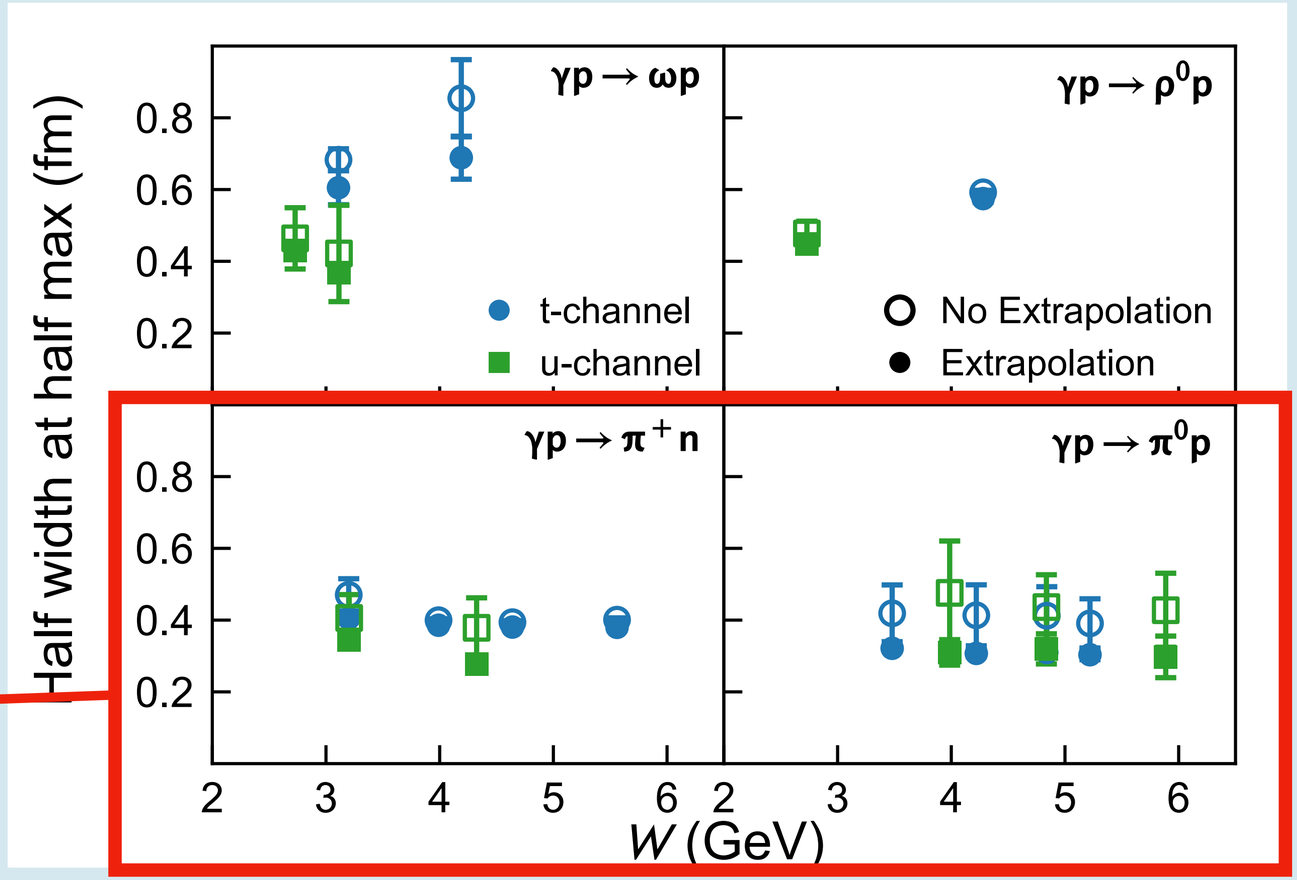
Results

- Significant difference in HWHM between t and u channel for vector mesons
- Difference seen in both finite window control methods
- Proceed via Pomeron exchange (gluons) → sensitive to baryon number
- Constant baryon number radius ~ 0.4 fm



Results

- Small (π^+) or no (π^0) difference seen between t and u channel
- Proceed via meson or quark exchange → sensitive to high x quarks in proton target
- Species dependence in the t-channel - from intermediate meson sizes



Results

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- Can start comparing across other proton size measurements
- Different techniques are sensitive to different components of the proton
- World data comes from measurements of muonic hydrogen, t-channel VM production, and electron scattering

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

Baryon junctions?

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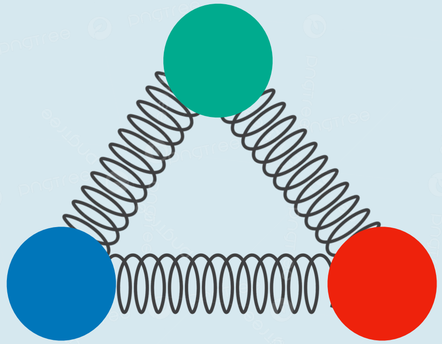
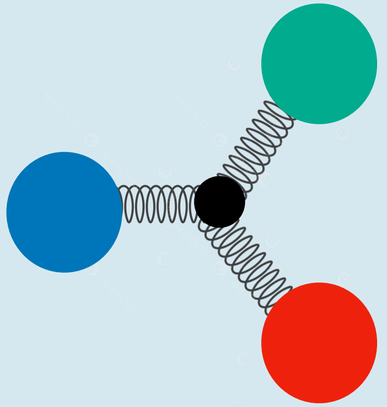
- Unable to discriminate the carrier of the baryon number region
- Baryon junctions or high-x quarks?
- Both would produce a compact baryon number distribution
- GlueX or EIC could reveal more (ϕ or J/ψ production)





New picture of the proton size?

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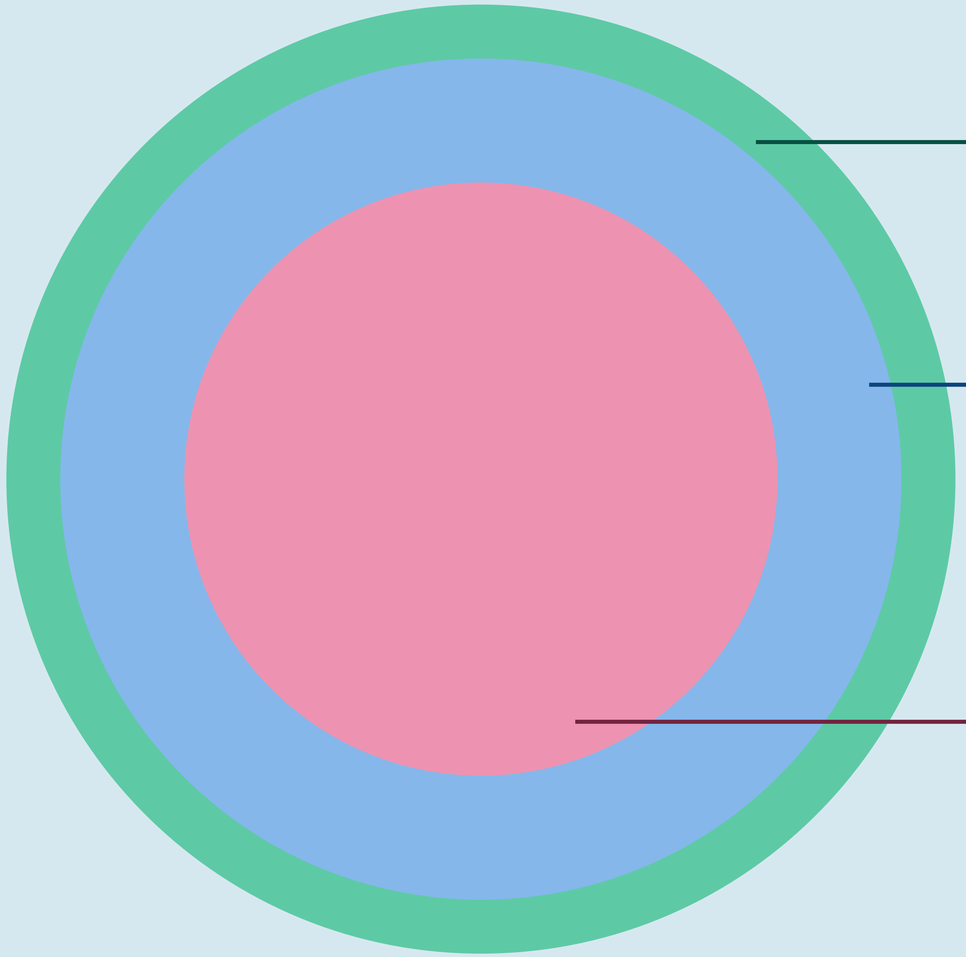
2D RMS radii



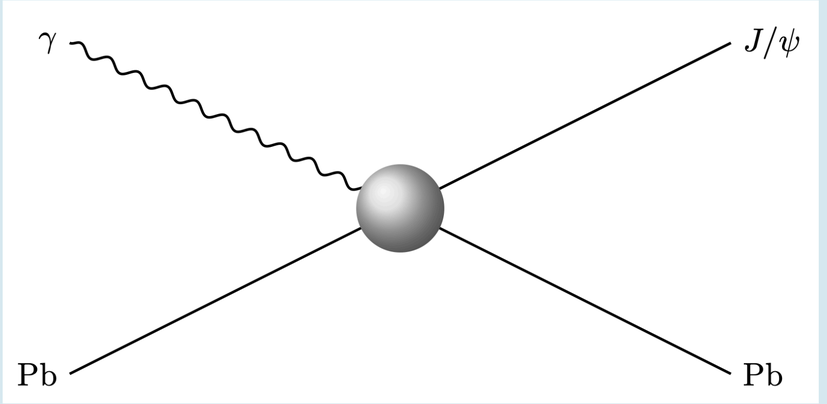
Charge radius ~ 0.69 fm
A. Antognini et al., Science 339, 417 (2013)

Mechanical radius ~ 0.61 fm
P. E. Shanahan, W. Detmold, PRL 122, 072003 (2019)

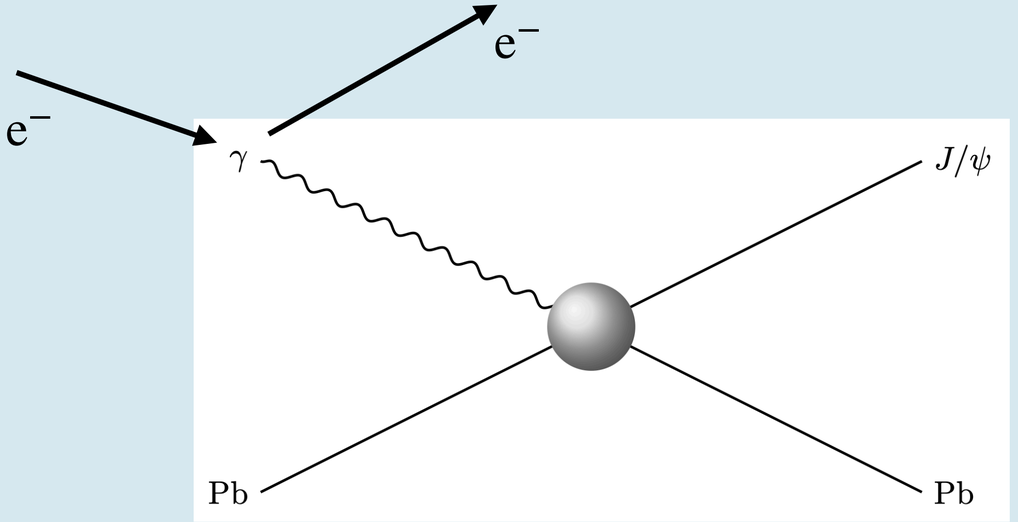
Baryon number radius ~ 0.33–0.53 fm
arXiv:2603.03730 (This work)

Outlook for EIC

- Shown today were results for real photons ($Q^2 = 0$)
- EIC can show us the Q^2 dependence
- Studies suggest we will be able to measure backward production at the EIC
    - Sweger, Klein et. al: Physical Review C 108, 055205 (2023), Physical Review C 106, 015204 (2022)
- ω and ρ capabilities sensitive to details of the B0 detector



Today's talk



EIC

Conclusion

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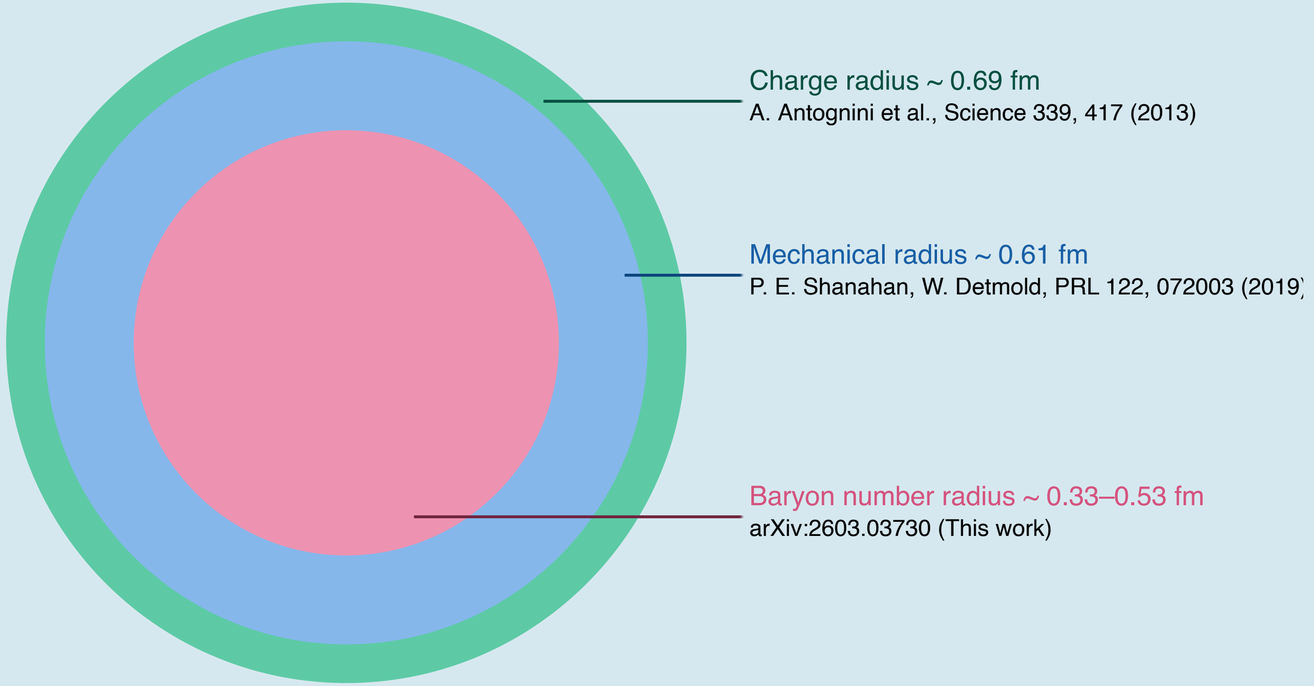
- u-channel production of vector mesons are sensitive to the baryon number distribution
- We analyzed historical data (~60 years ago) from SLAC and Daresubry Lab
- We find baryon number is confined to a compact region smaller than the charge and mechanical radii
- Opportunities at EIC and JLAB to test if this is the result of baryon junctions



Thank you!

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