Interpreting *u*-channel Cross Sections

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University of California, Davis

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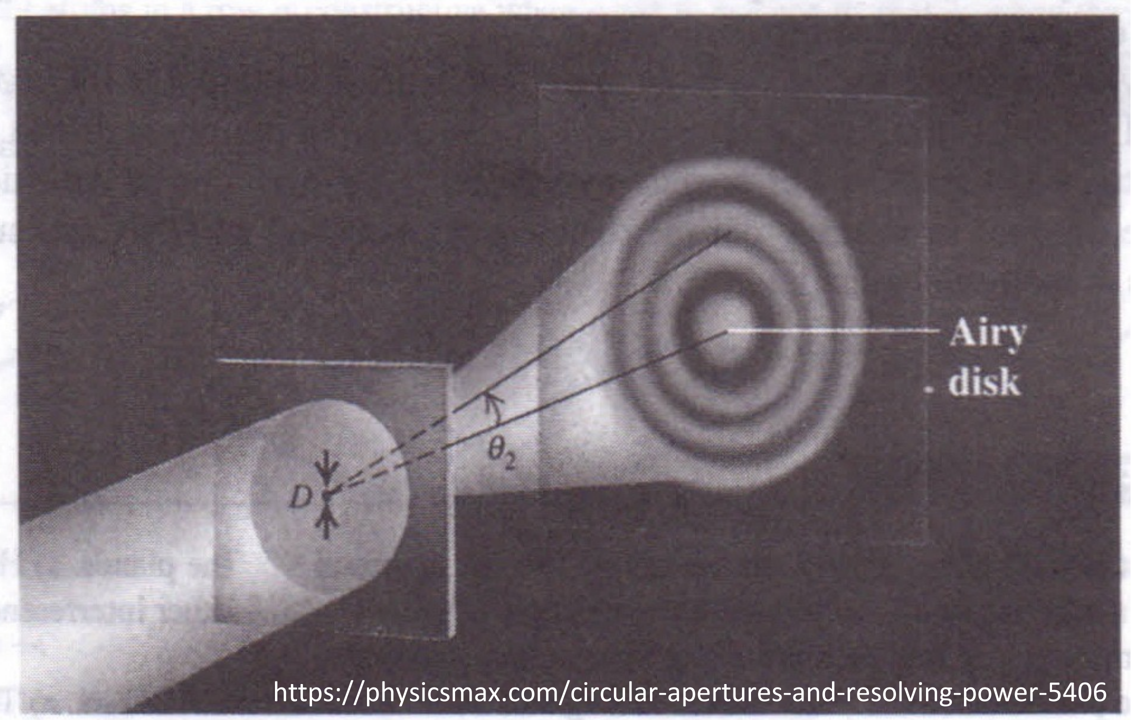
Supported in part by

Diffractive Scattering

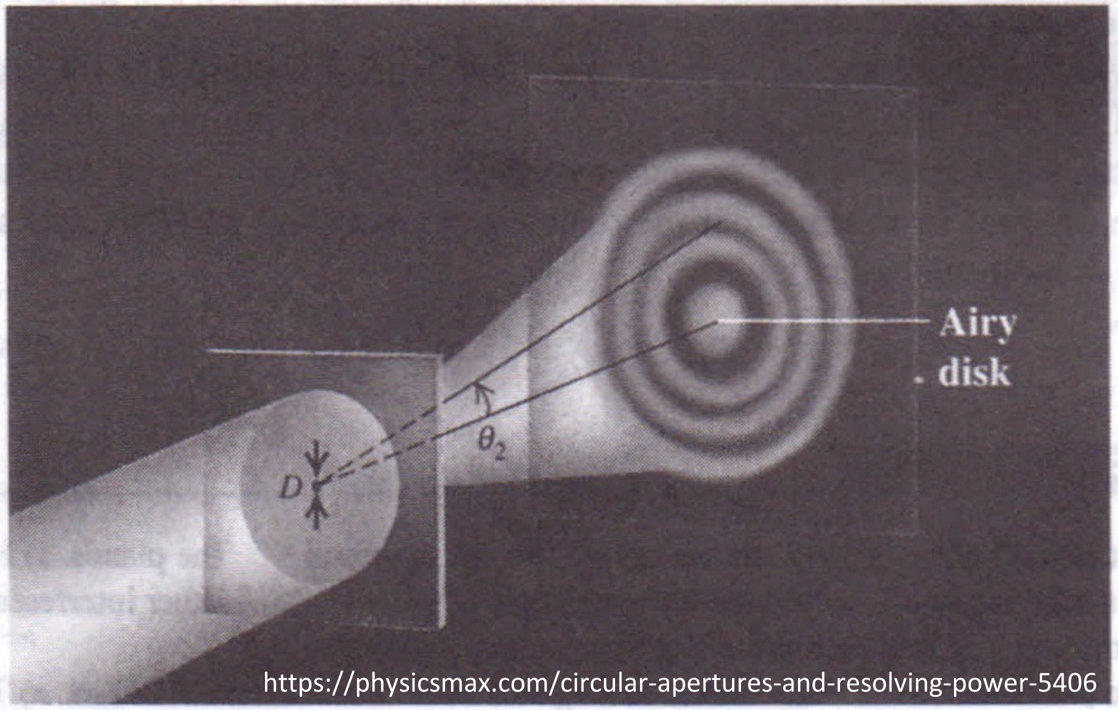
- Scattering has long been used to image the nucleus
- Think of black disk diffraction. Diffraction pattern → disk size. But partial absorption complicates picture



https://physicsmax.com/circular-apertures-and-resolving-power-5406

Diffractive Scattering

- Scattering has long been used to image the nucleus
- Think of black disk diffraction. Diffraction pattern → disk size. But partial absorption complicates picture
- Send in a high-energy projectile (such as a photon or proton) and measure diffractive dips
- Larger momenta → greater resolving power for small sizes!
- p_T (transverse momentum) and b (transverse scattering distance) are conjugate variables!



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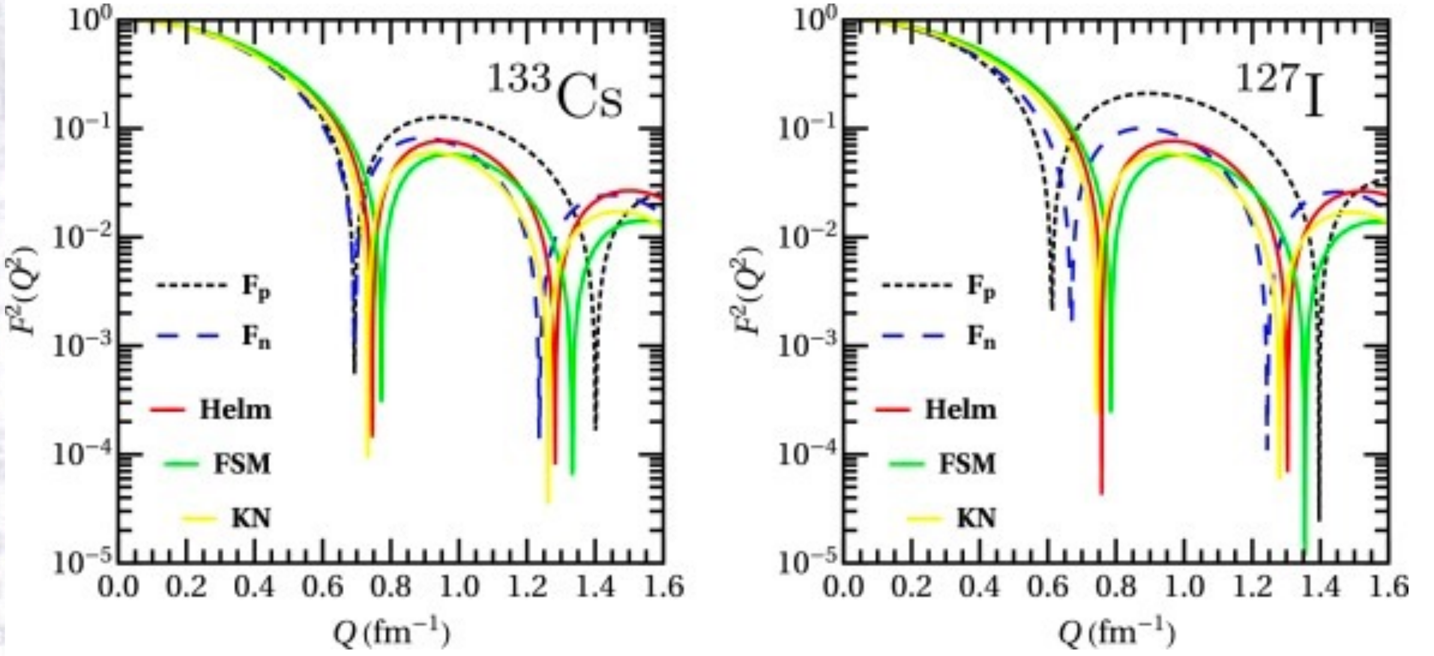
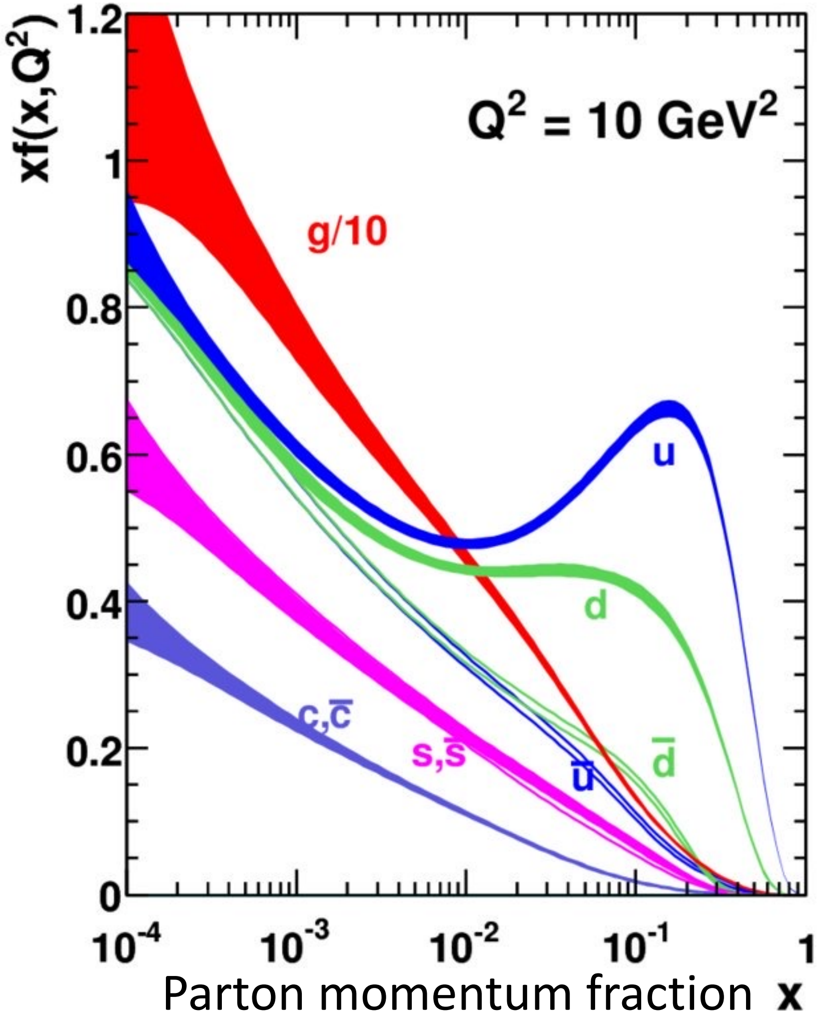


D.K. Papoulias et al. / Physics Letters B 800 (2020) 135133

Nucleons Change with Momentum Fraction



M. Krasny et al. European Physical Journal C. 69. 379-397. 10.1140/epjc/s10052-010-1417-0 (2010)

- We can look inside nucleons to see what makes them up

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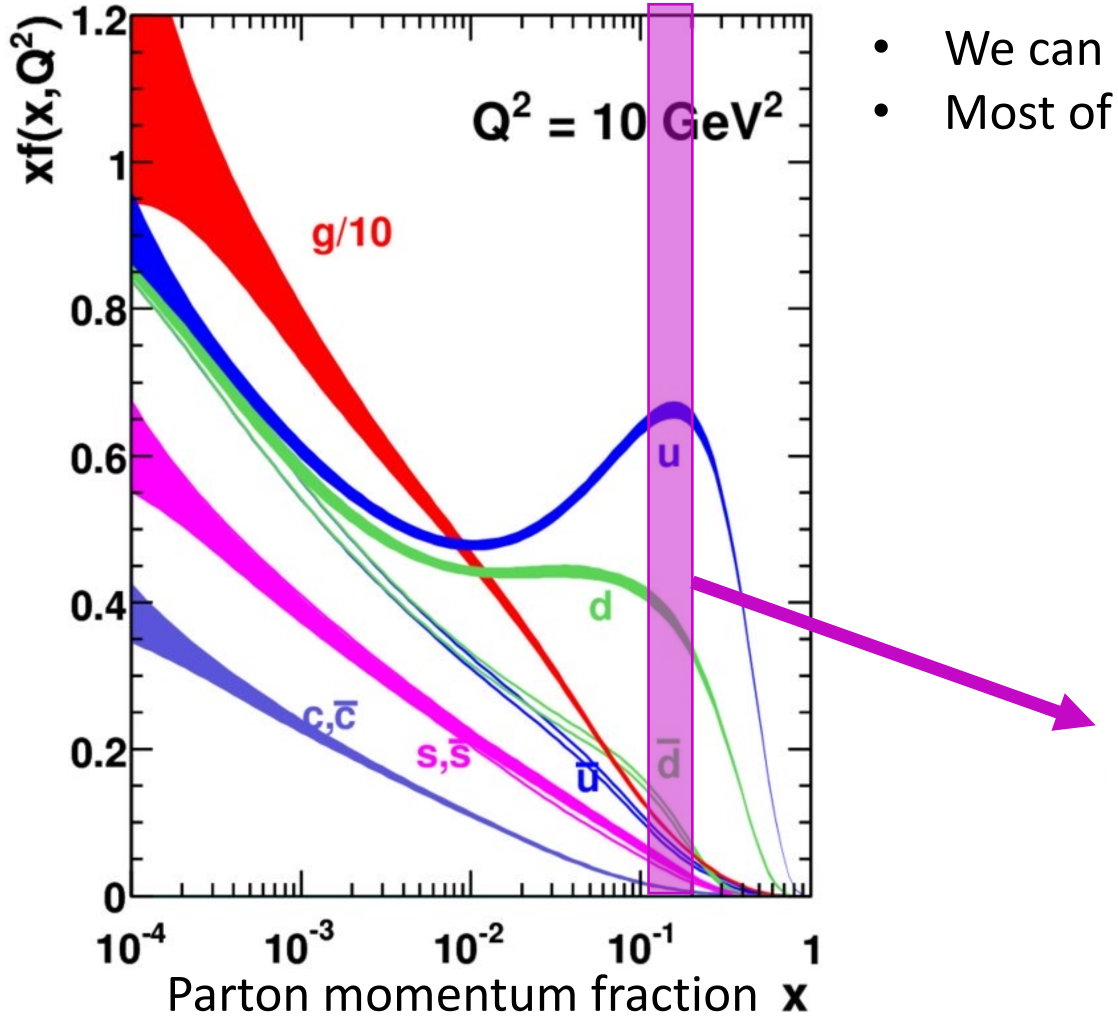
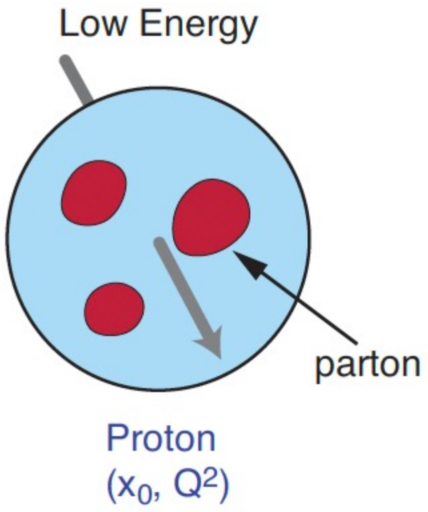


- We can look inside nucleons to see what makes them up
- Most of nucleon’s momentum comes from valence quarks (up, down)



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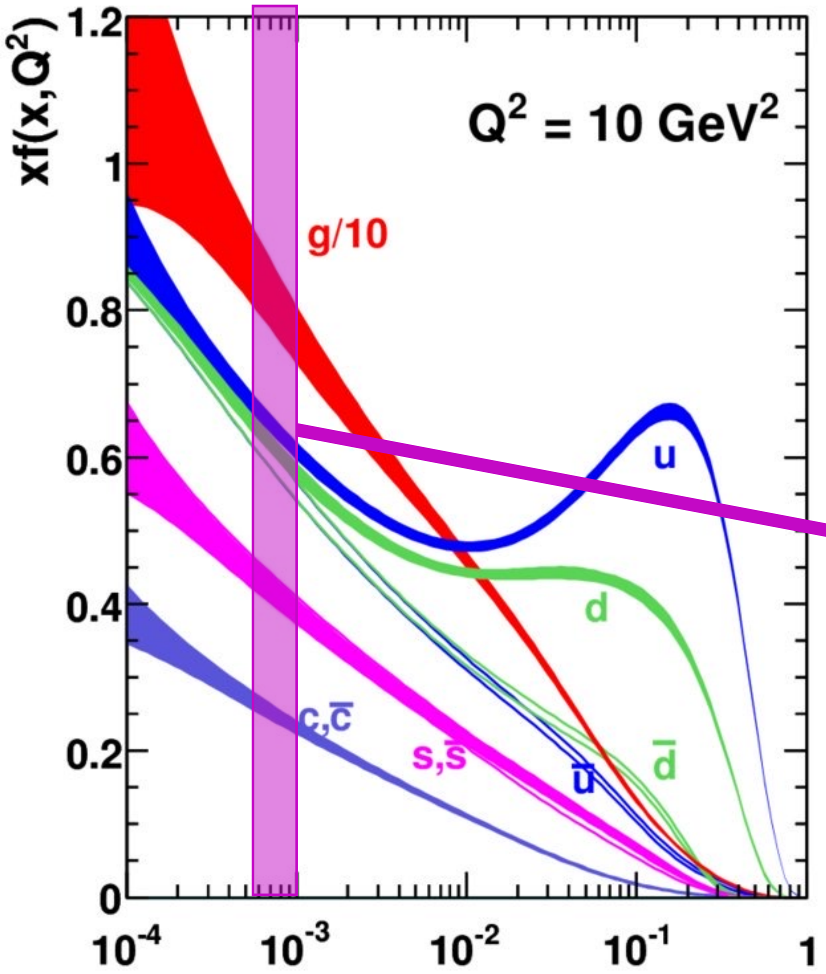

Parton momentum fraction x

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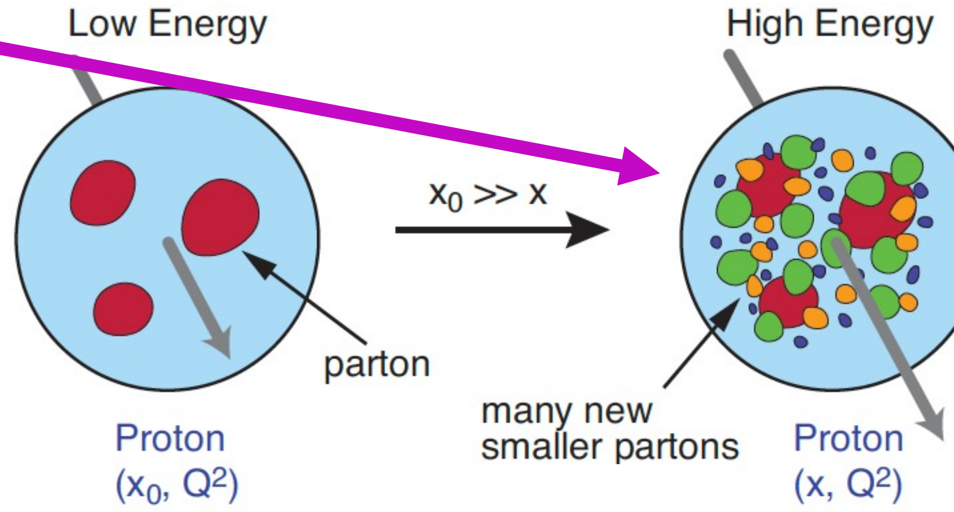
- We can look inside nucleons to see what makes them up
- Most of nucleon's momentum comes from valence quarks (up, down)
- When we look deeper, MANY sea quarks and gluons contribute as well
- up(u), down(d), charm(c), strange(s), antiquarks (ū,đ,c̄,s̄) and gluons (g)



EIC White Paper (2012)

Nucleons Change with Momentum Fraction

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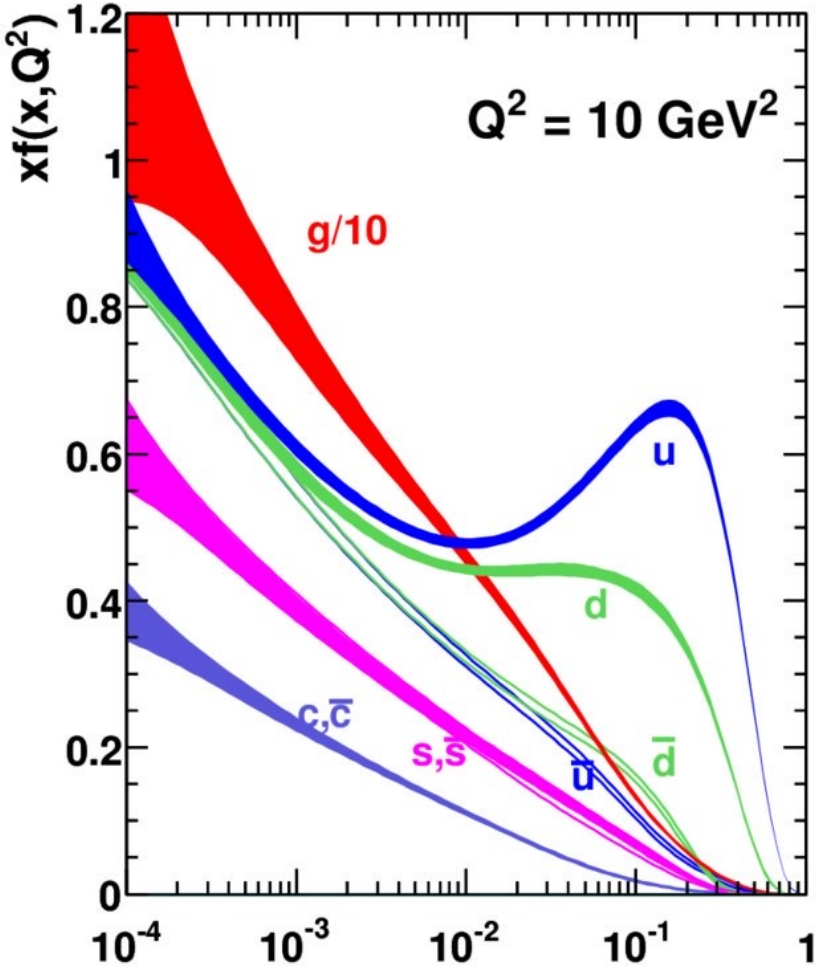

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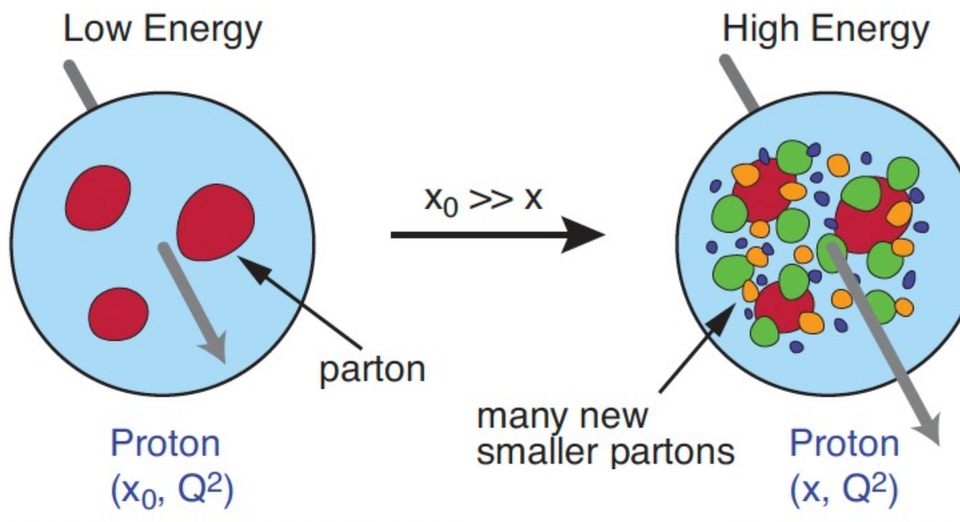
- When we look deeper, MANY sea quarks and gluons contribute as well
- up(u), down(d), charm(c), strange(s), antiquarks (ū,đ,c̄,s̄) and gluons (g)
- Nucleons and the nucleus change with energy
- We aim to measure these nucleus/nucleon distributions at high energies



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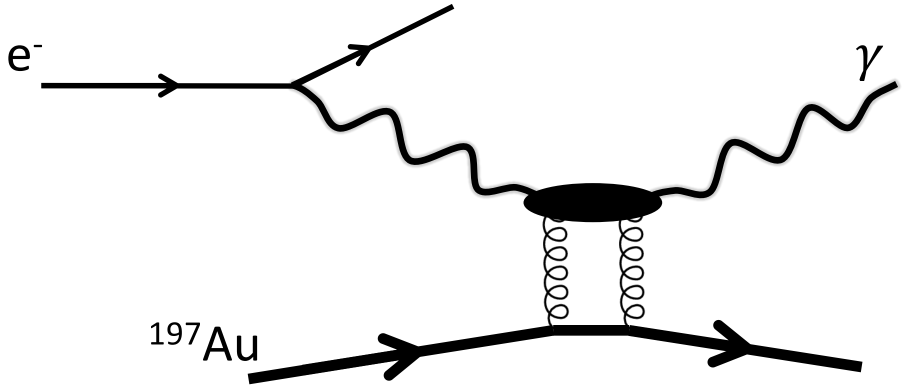
Imaging Nuclei/nucleons at the Electron-Ion Collider (EIC)

- Scattering mediated by virtual photon at EIC
- Image nucleus by scattering off nucleus' "gluon cloud"



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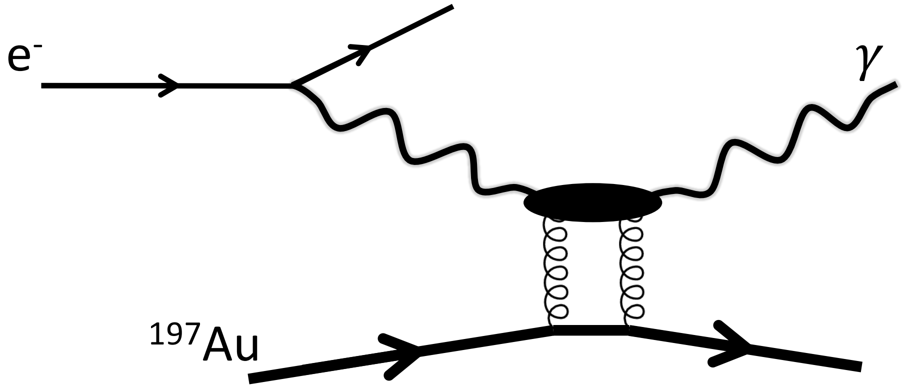

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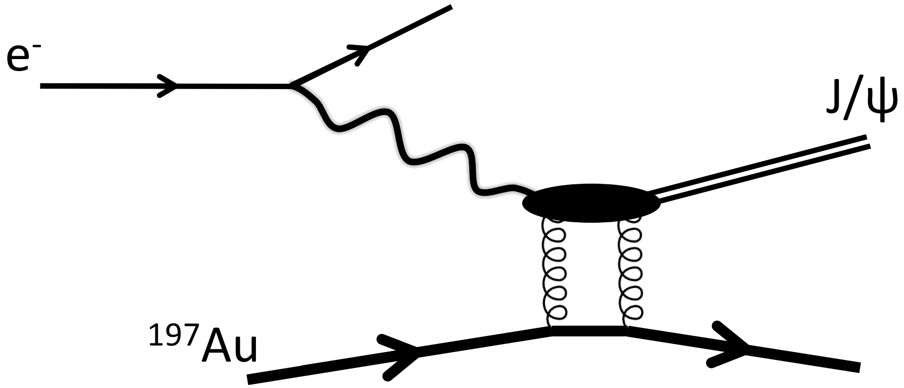

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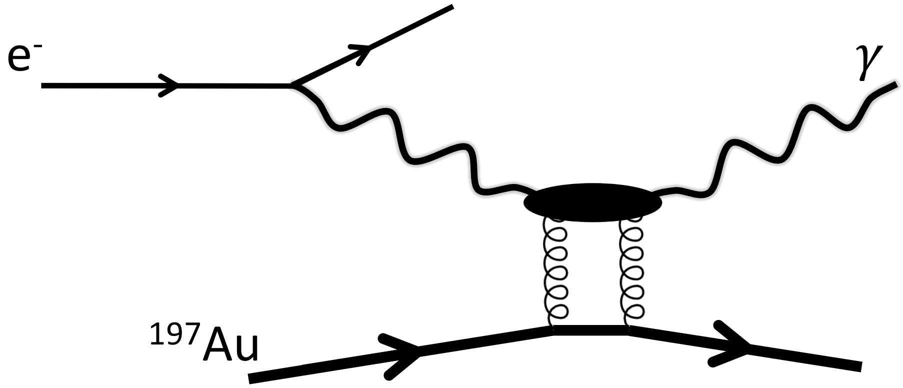

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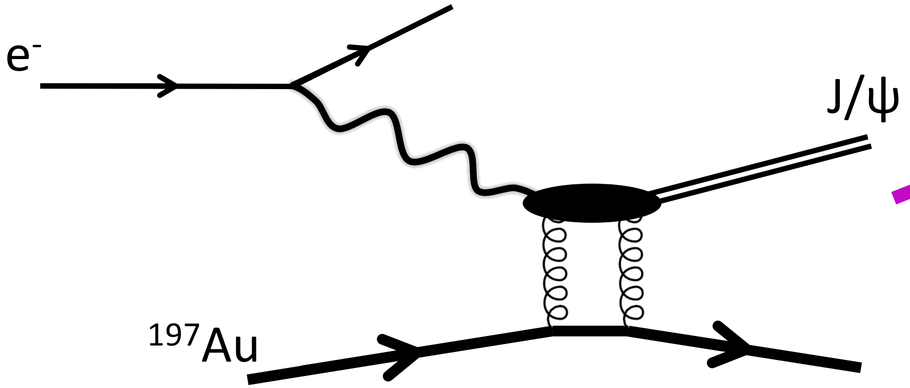
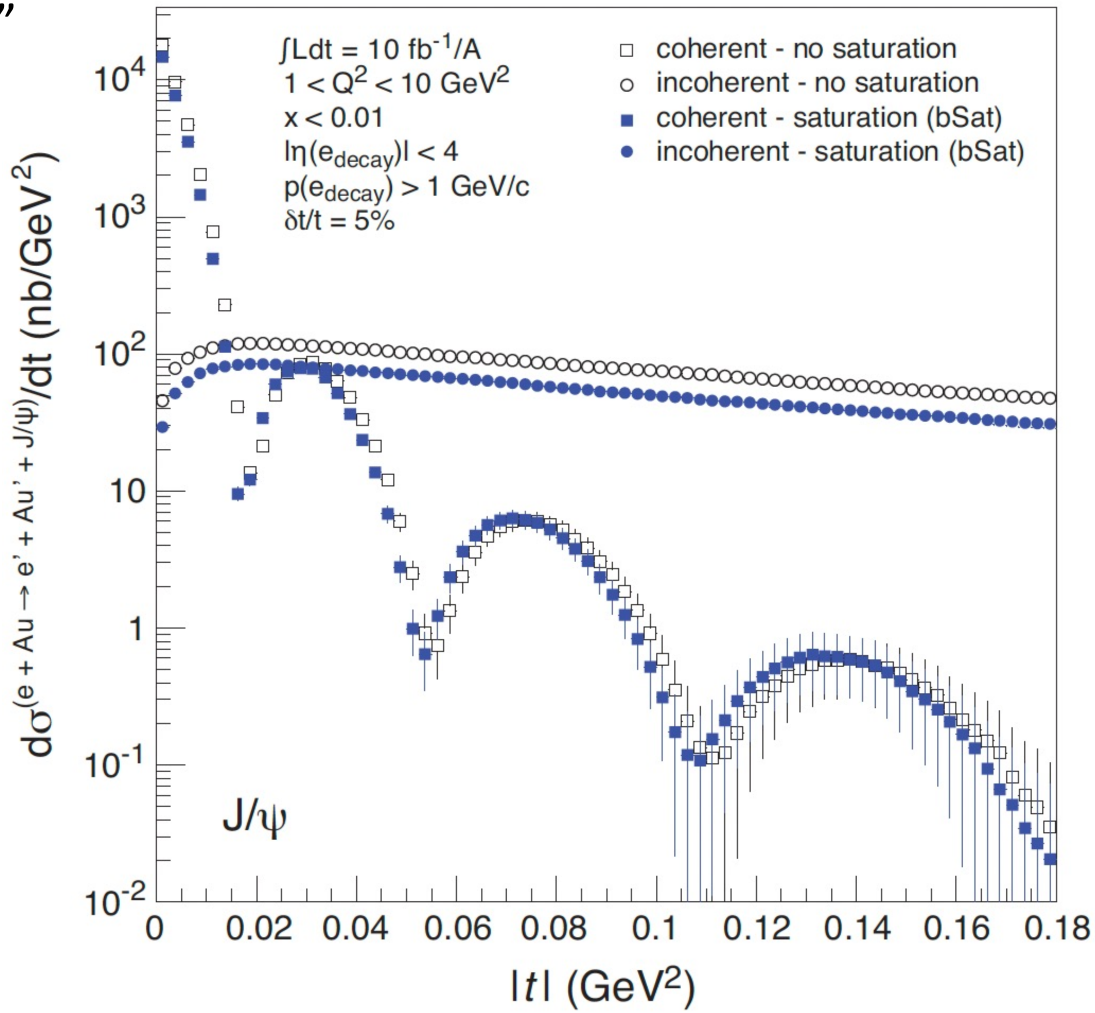


J/ψ production cross section



Phys. Rev. C **87**, 024913 (2013)

Imaging Nuclei/nucleons at the Electron-Ion Collider (EIC)

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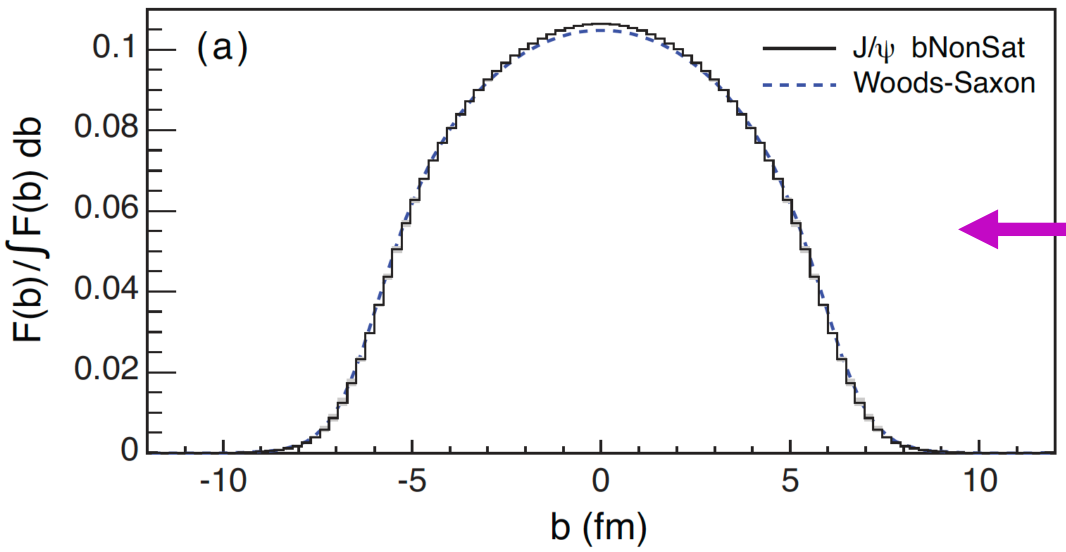
- Scattering mediated by virtual photon at EIC
- Image nucleus by scattering off nucleus' "gluon cloud"
- Cross-section is a Fourier transform of the shape
- Inverse transform to get nuclear shape (low-x gluons)

low-x gluon density vs impact parameter



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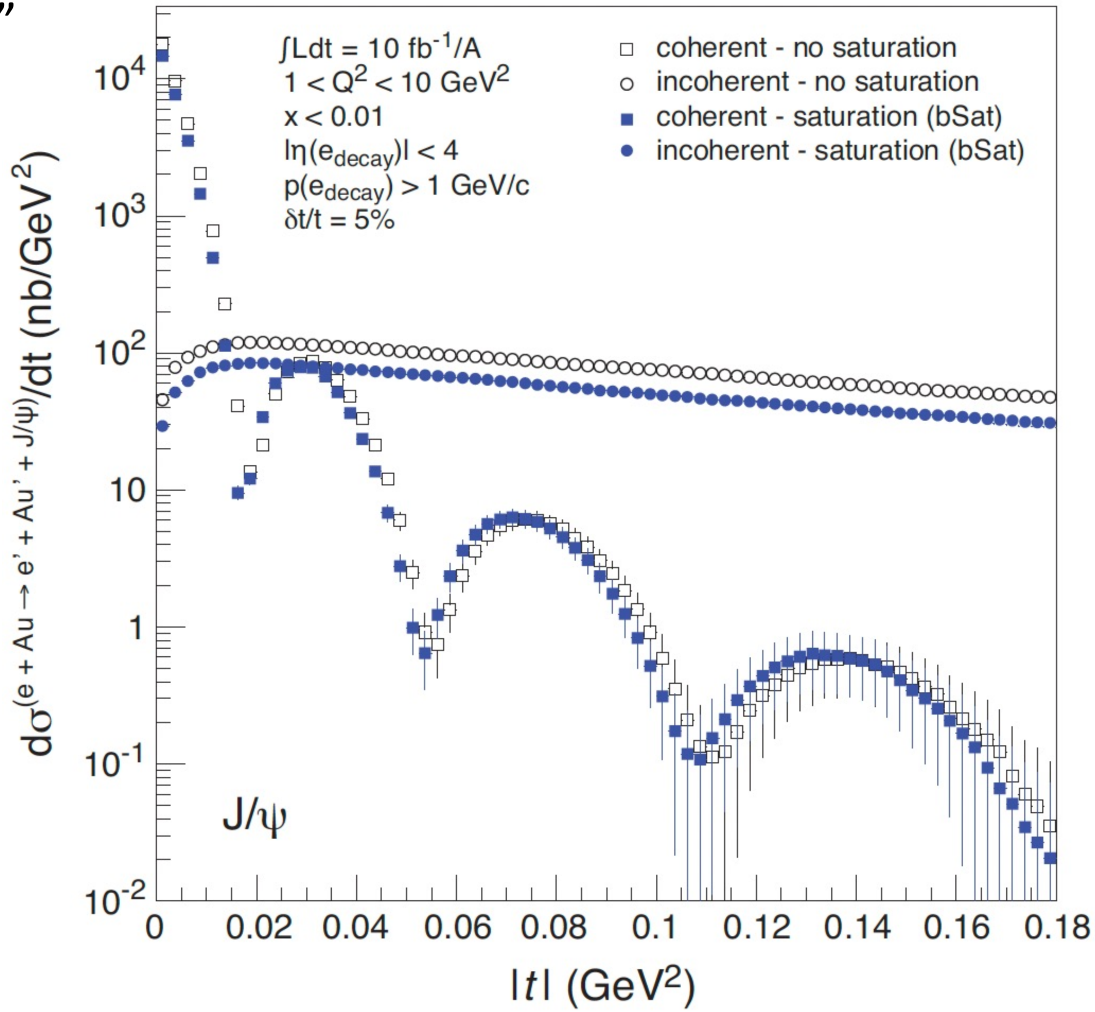
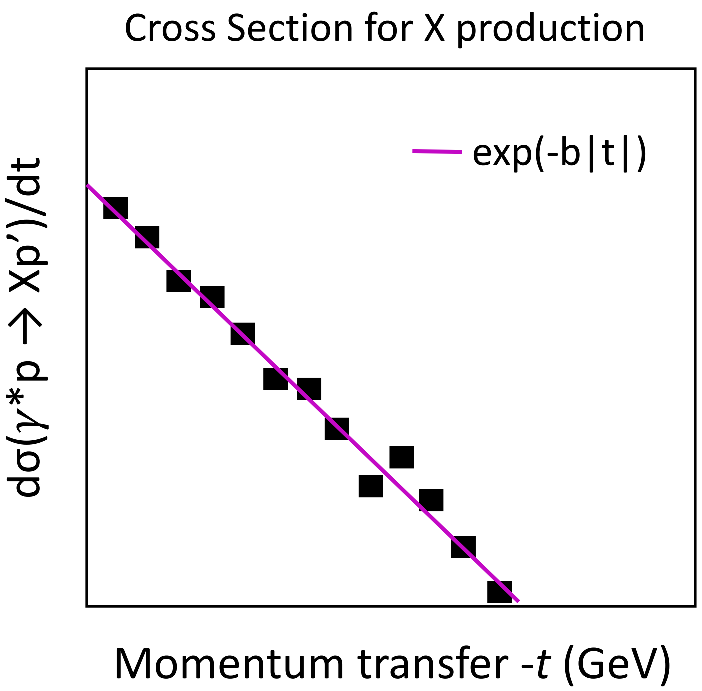


Phys. Rev. C **87**, 024913 (2013)

Transforming Forward (ep→e'p'X) Cross Section

Forward cross sections → nucleon form factors

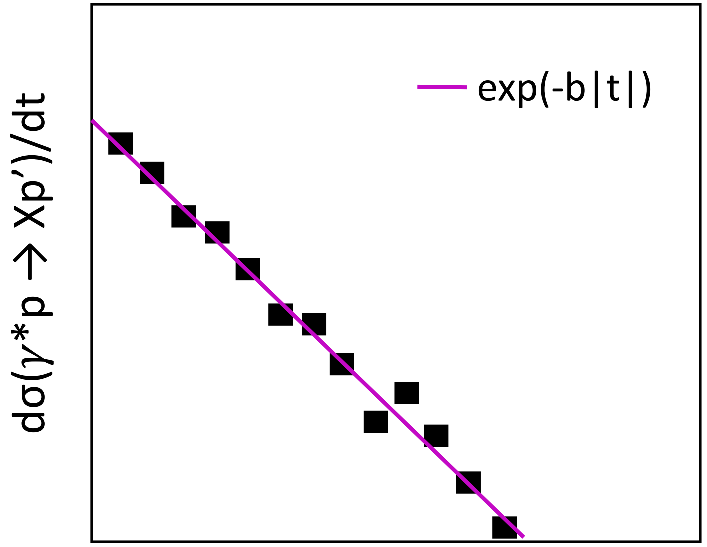
- We measure meson/photon production Xsec vs momentum transfer t



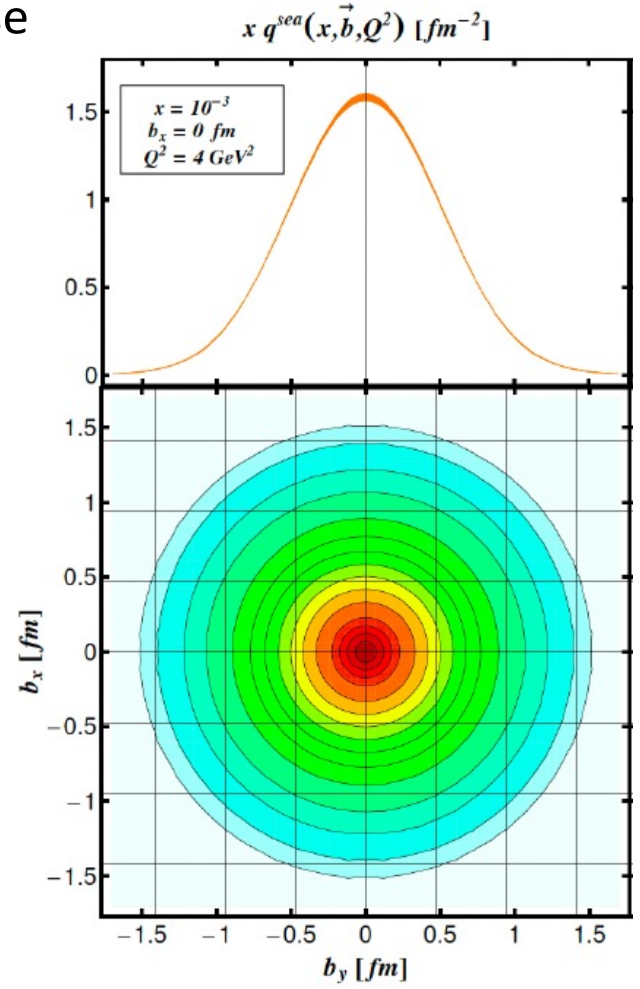
Transforming Forward (ep→e'p'X) Cross Section

Forward cross sections → nucleon form factors

- We measure meson/photon production Xsec vs momentum transfer t
- By transforming this in the transverse plane, we can map transverse distribution of partons within proton (or nucleus)



$$F(b) \propto \frac{1}{2\pi}\int_0^{\sqrt{t_{\max}}} dp_T\, p_T J_0(bp_T)\sqrt{\frac{d\sigma_c}{dt}}$$



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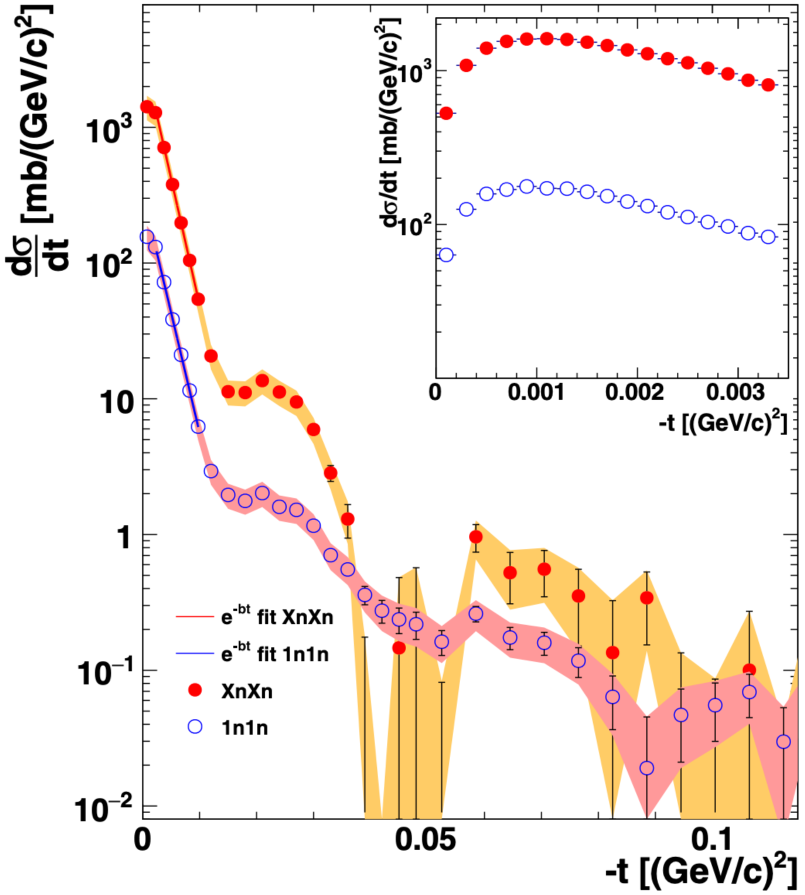
Resolution down to $b \sim 1/\sqrt{t_{max}}$

ρ Production in UPCs

- Photoproduction cross section of the ρ in Au+Au collisions measured by STAR



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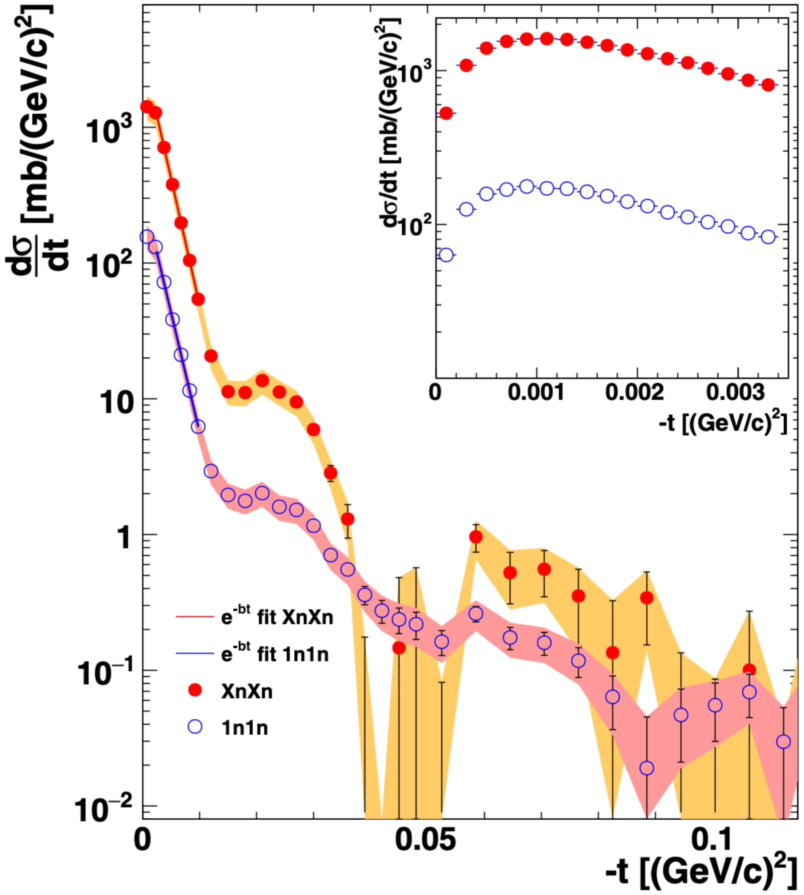

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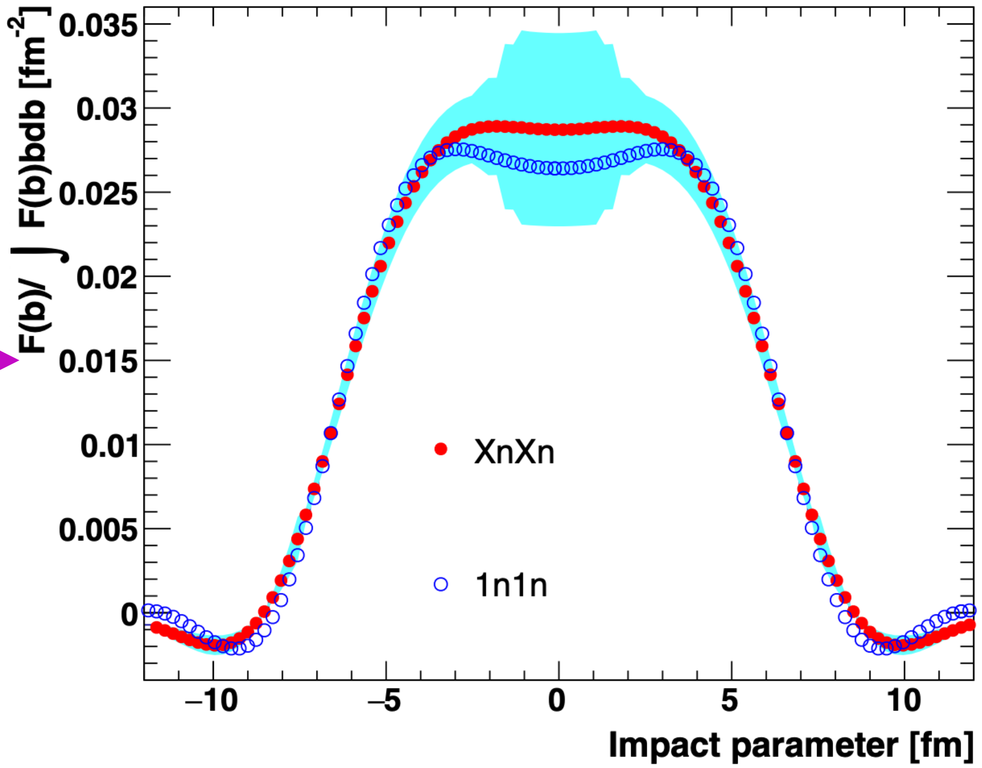
The STAR Collaboration,
Phys Rev C 96, 054904 (2017)



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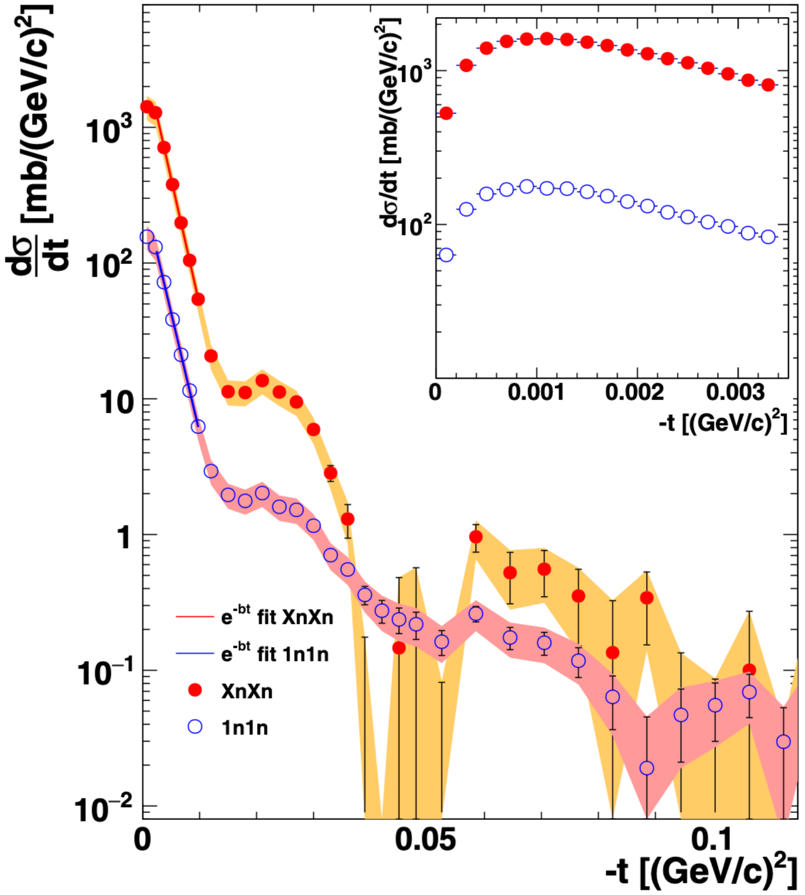
ρ Production in UPCs

- Photoproduction cross section of the ρ in Au+Au collisions measured by STAR
- dσ/dt transformed into the transverse plane reproduces Woods-Saxon shape
- Meaning of negative amplitude at edges unclear. May be due to interference between two nuclei



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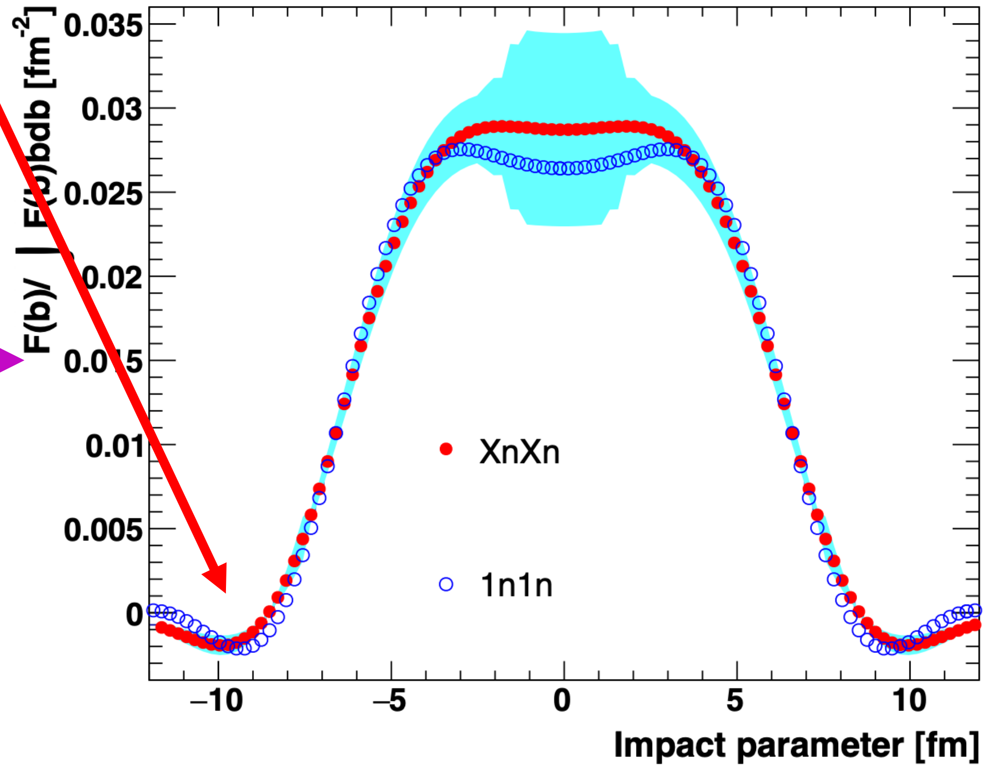

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Contributions to Meson Production

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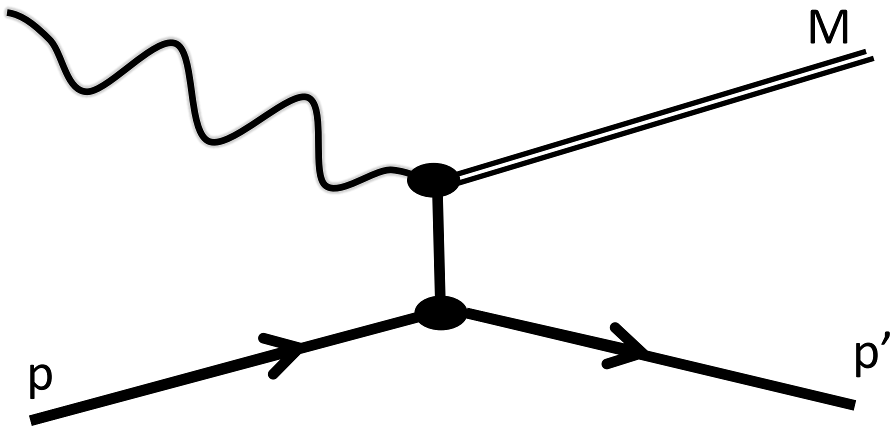
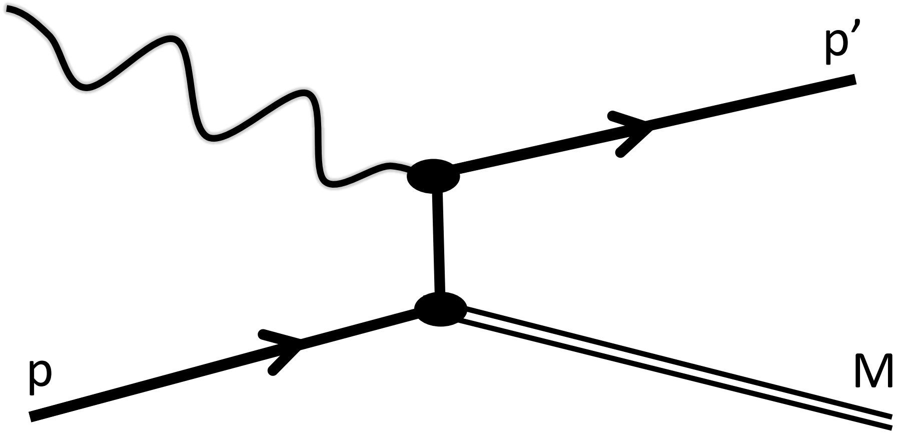
t-channel **vs** **u-channel**





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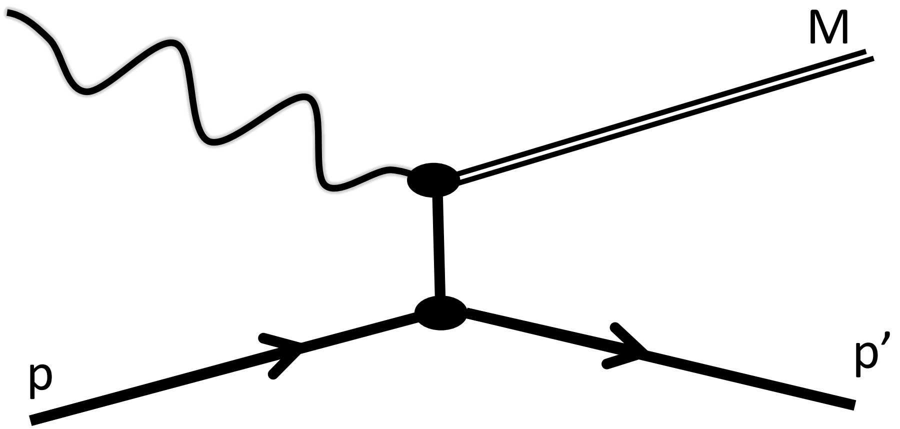
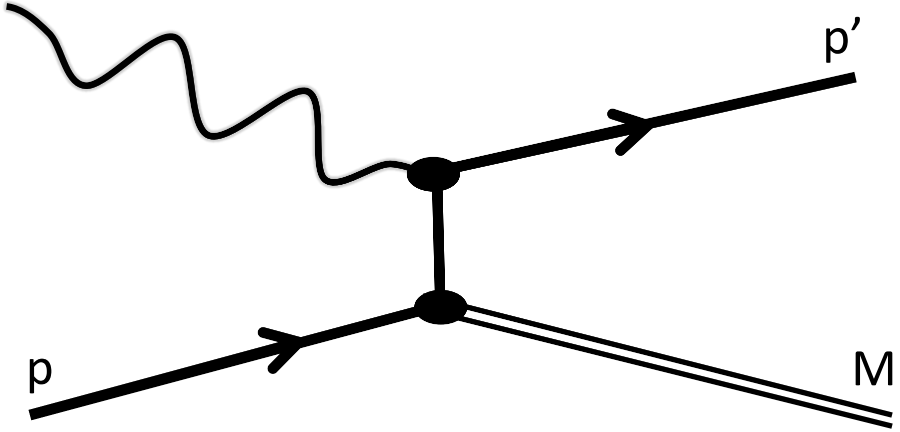
- proton momentum slightly modified





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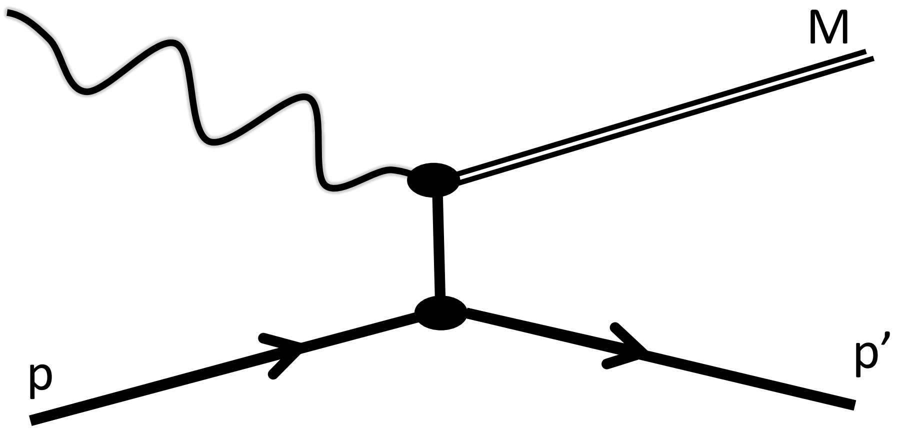

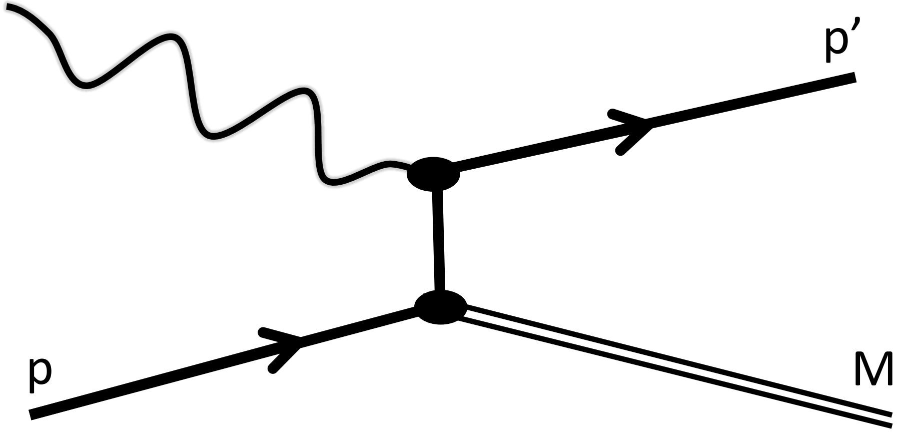

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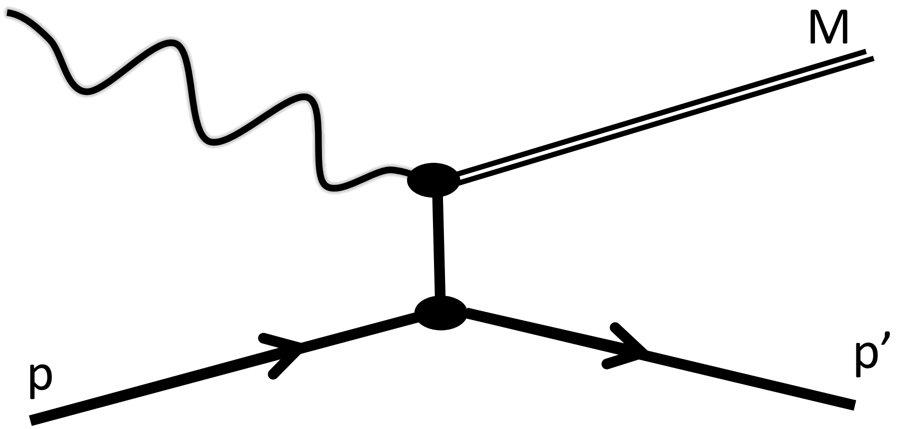

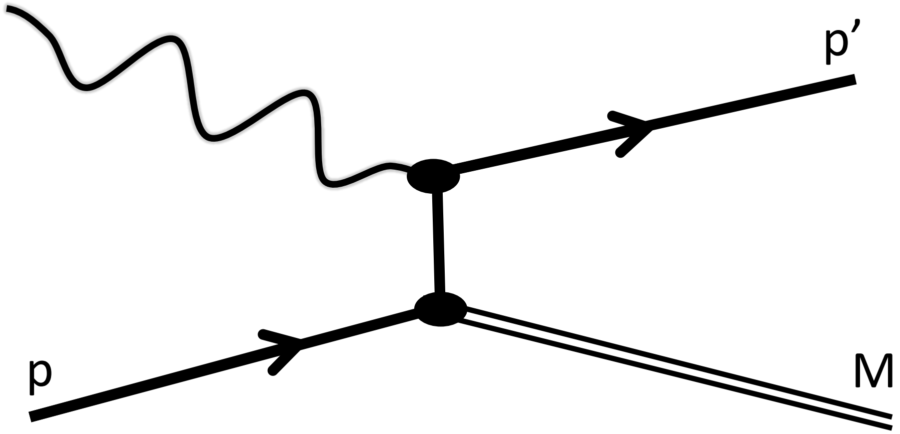

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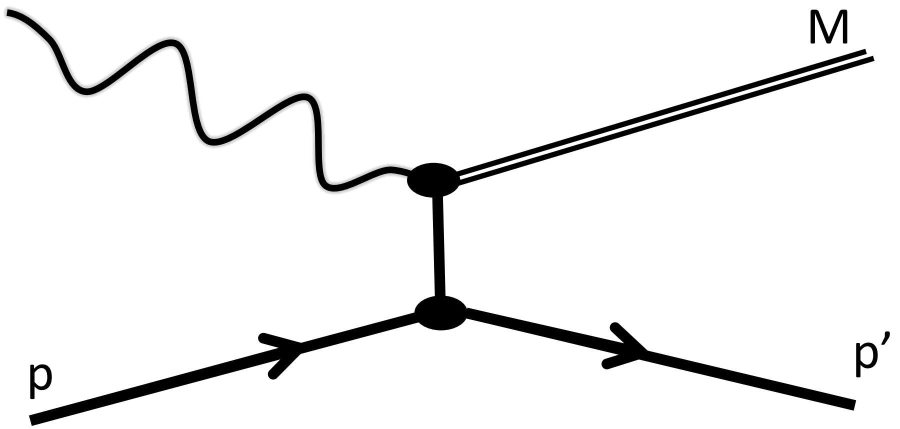

u-channel

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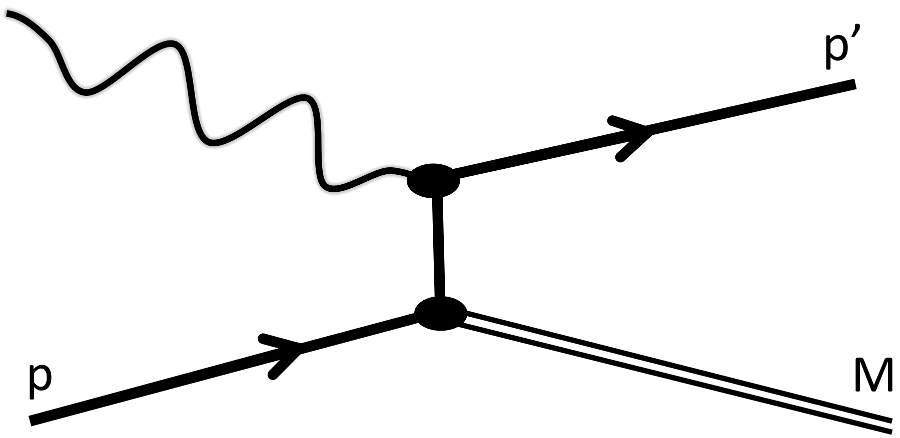

Contributions to Meson Production

t-channel vs u-channel

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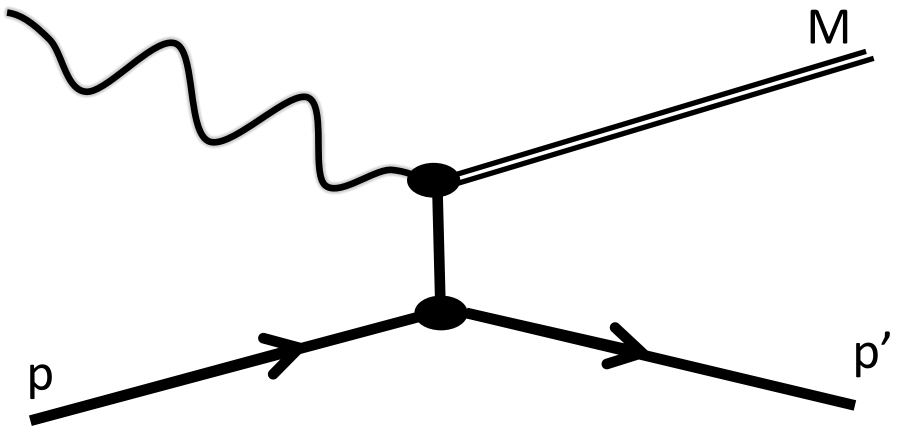

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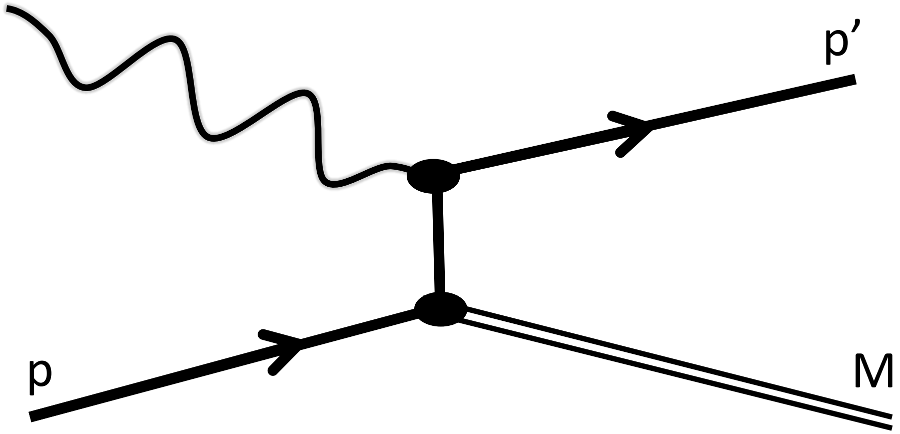

Contributions to Meson Production

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t-channel **vs** **u-channel**

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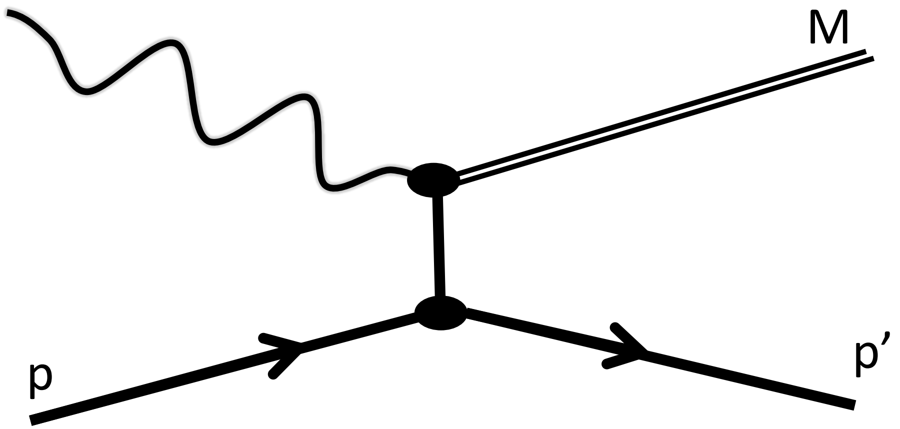
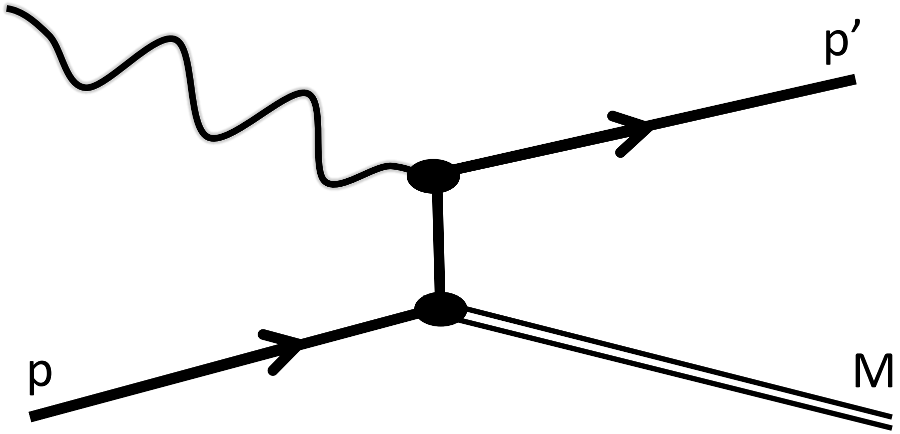


u-channel

- proton momentum largely modified
- meson produced near beam proton's momentum
- suppressed cross section relative to t-channel



u-channel Processes We've Simulated

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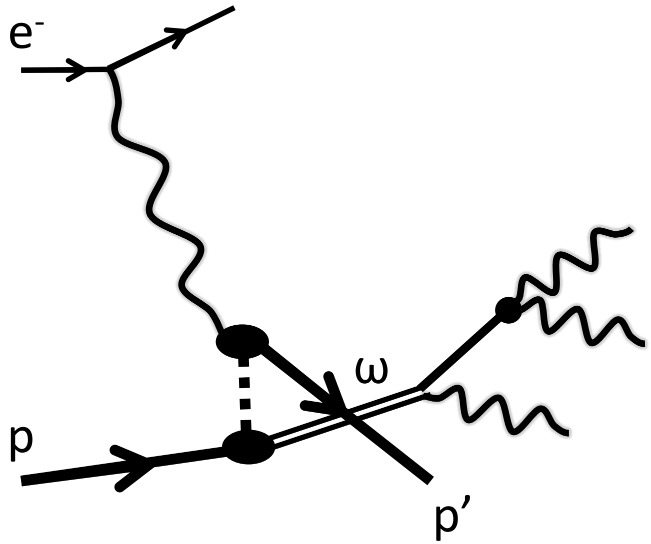
- Omega meson production: $\omega \rightarrow \gamma\gamma\gamma$ } Phys. Rev. C 106, 015204 (2022)



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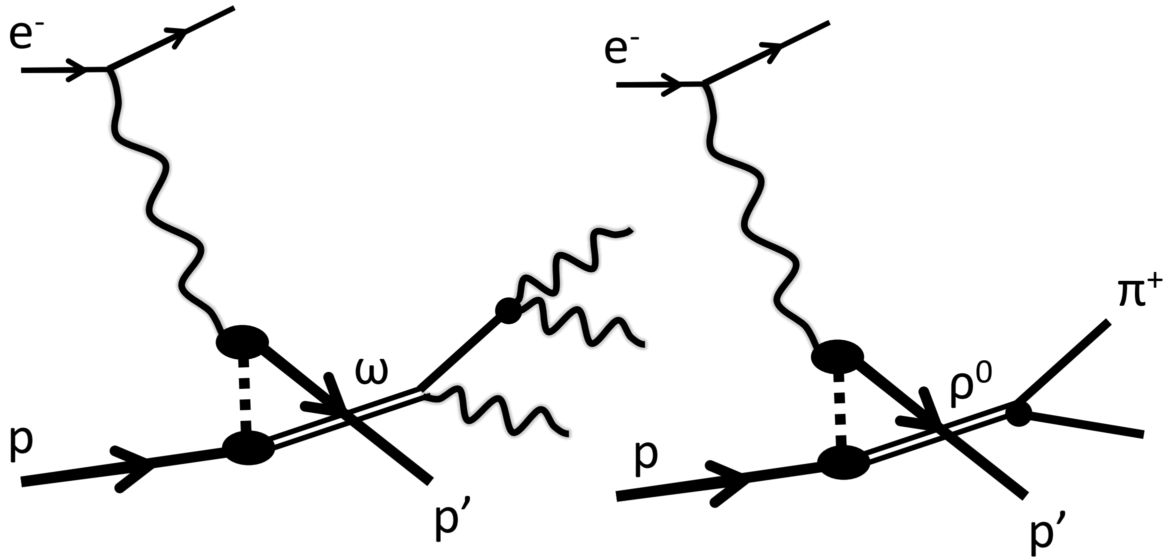

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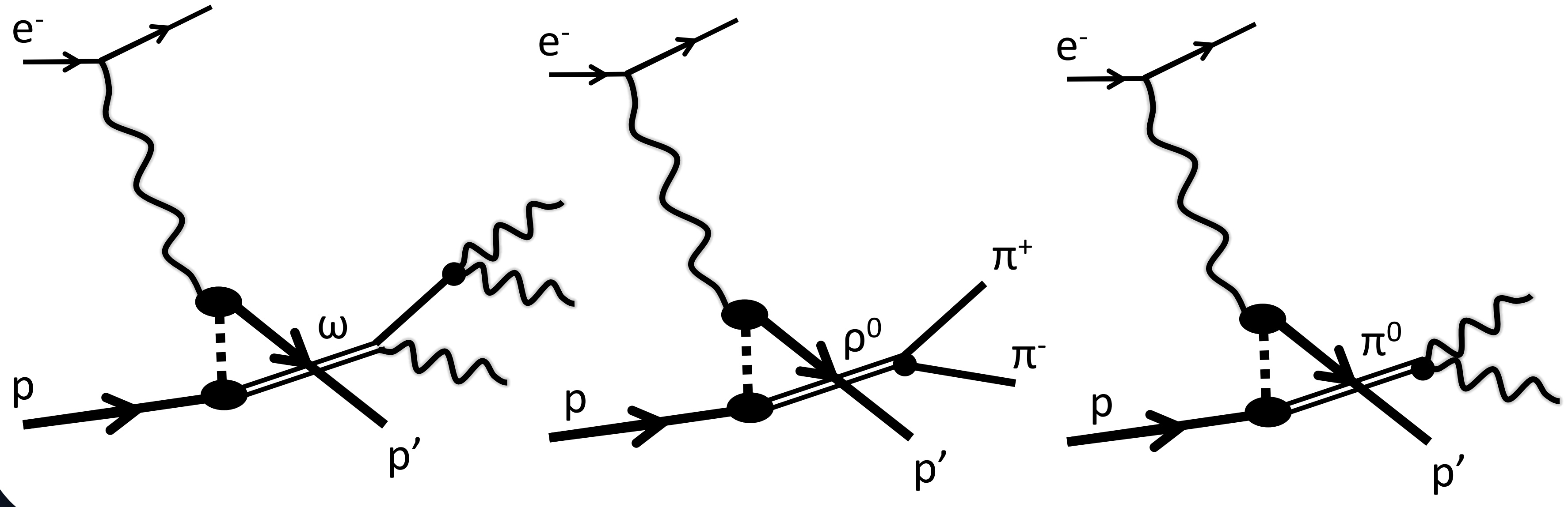
} Phys. Rev. C 108, 055205 (2023)



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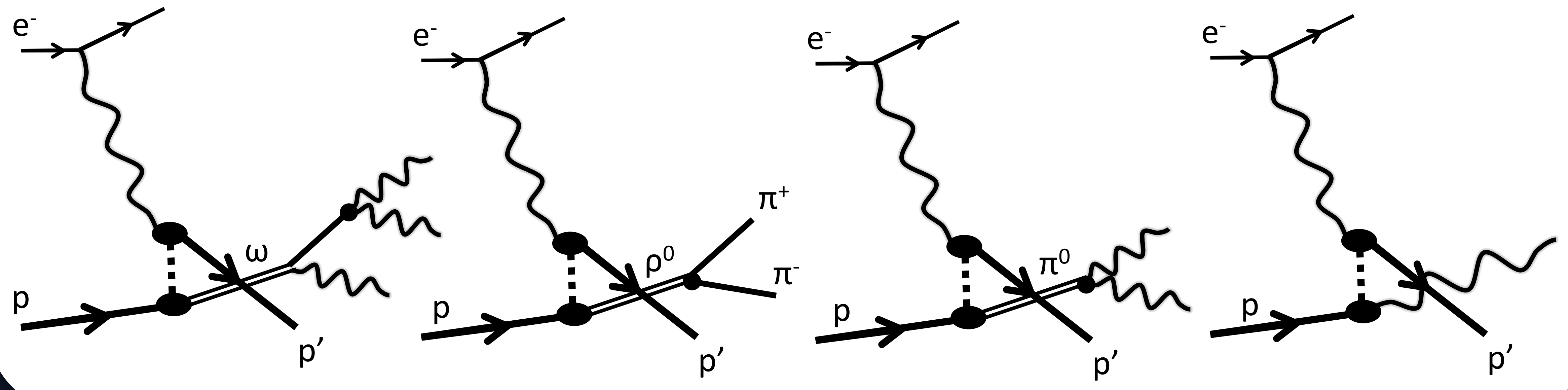
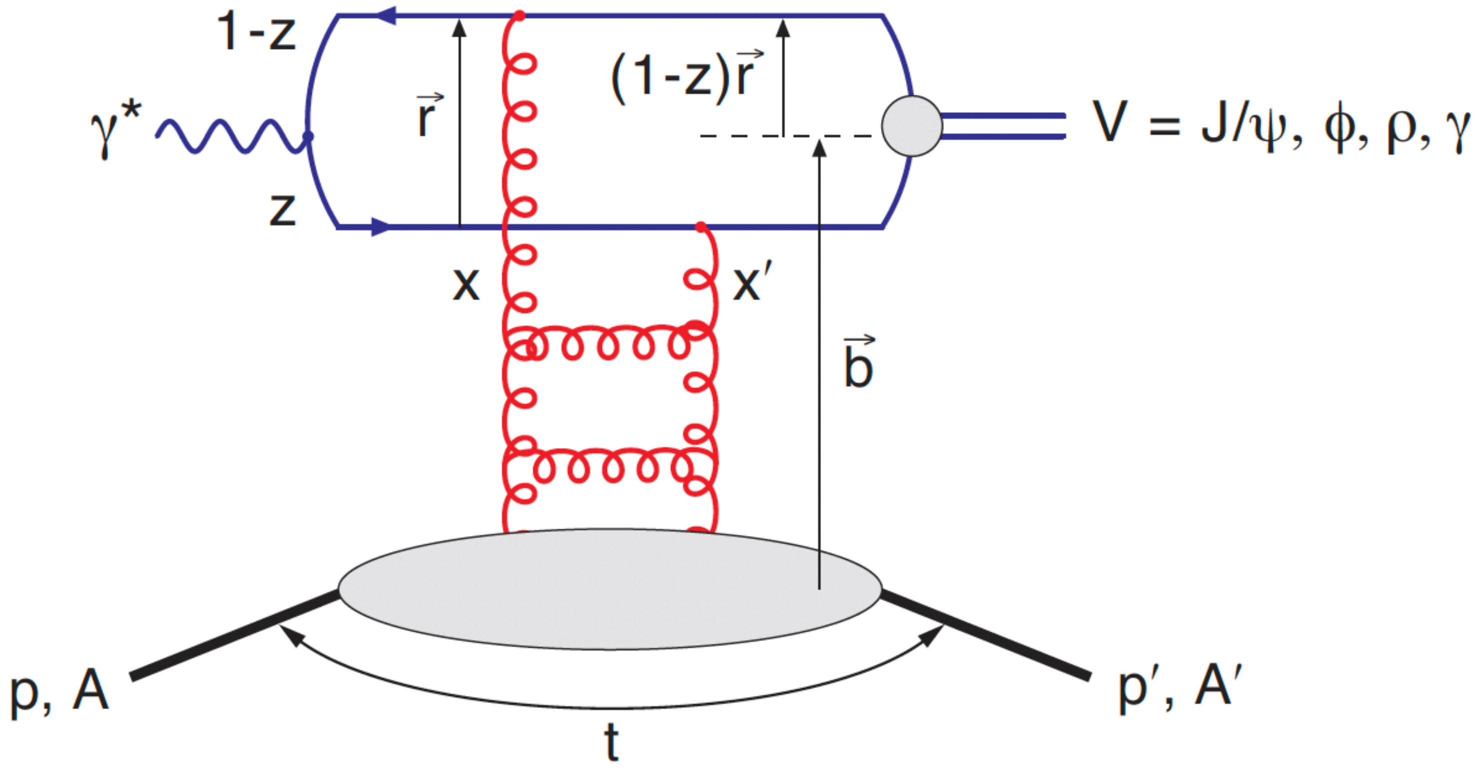


Why u-Channel Production?

Why u-Channel Production?

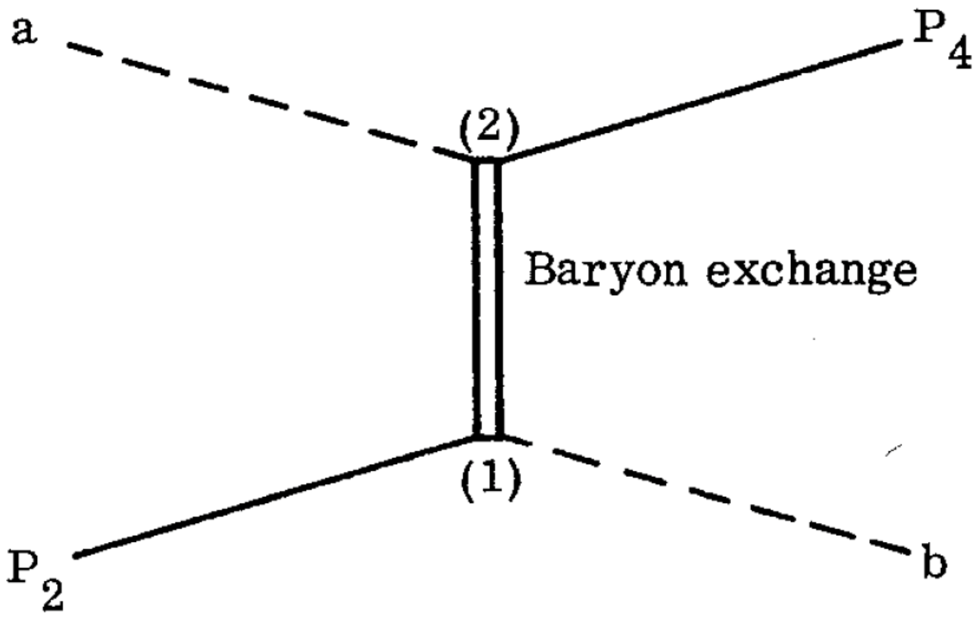
t-channel scattering off Pomeron maps gluon density distribution

Phys. Rev. C 87, 024913 (2013)



Why u-Channel Production?

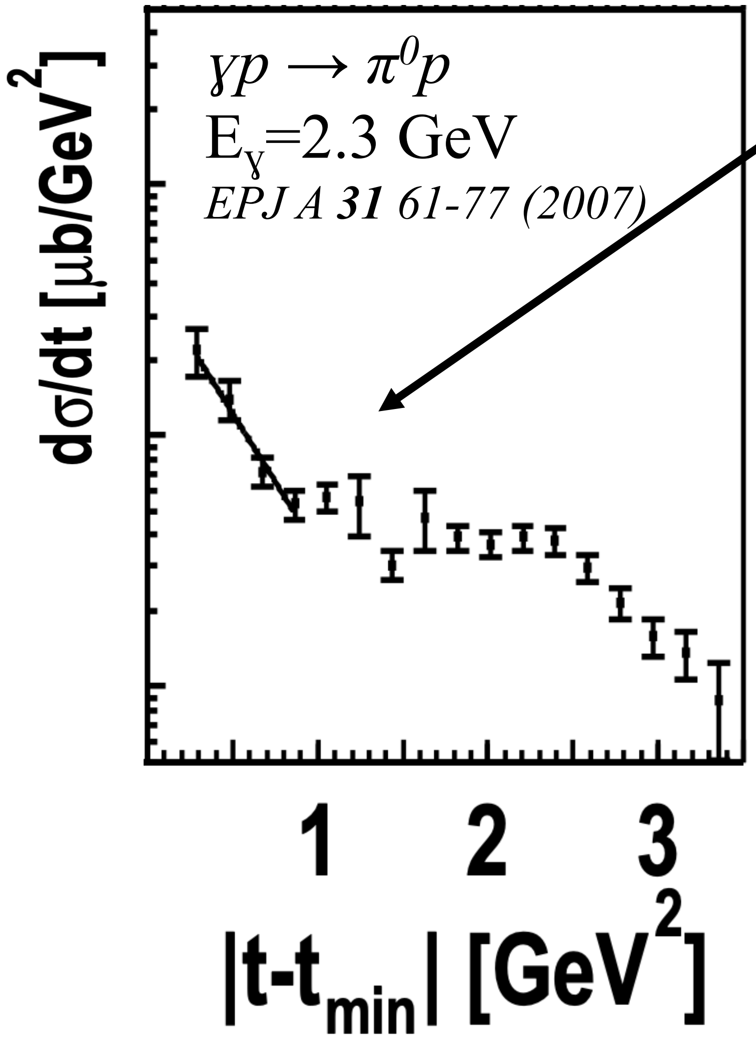
u-channel processes necessarily involve exchange of baryon number or very large momentum transfer



D.H. Tompkins SLAC (1970) Backward Photoproduction of π^0 mesons at 6 to 18 GeV

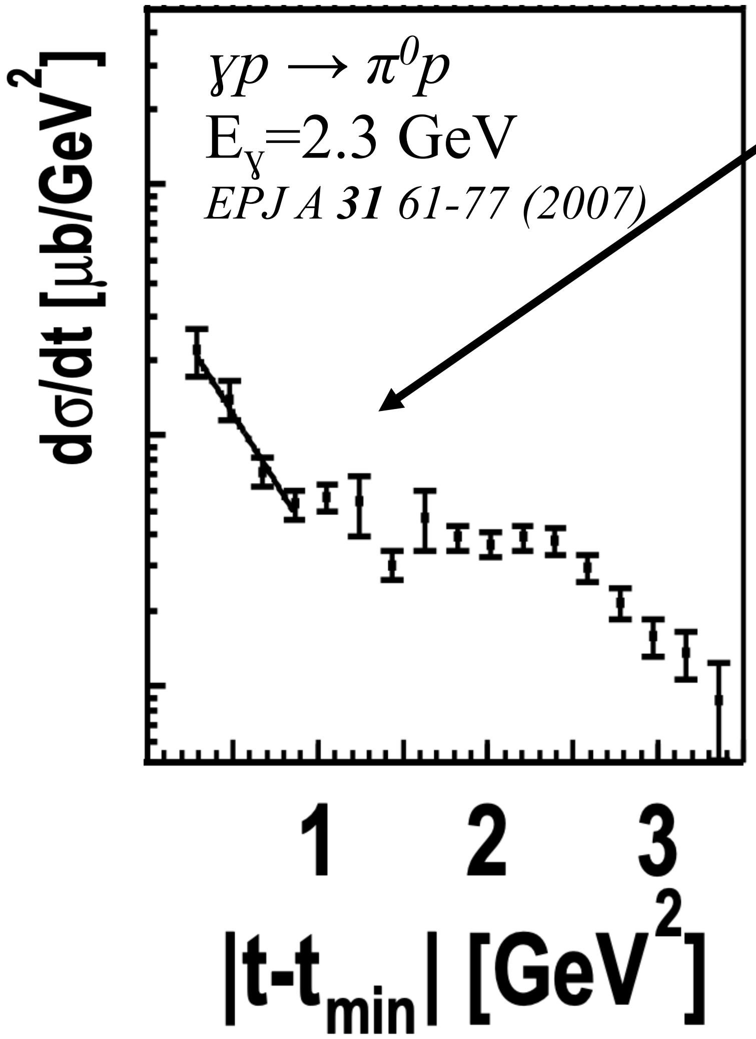
Fig. 1.1--Figure indicates a "backward" reaction mediated by baryon exchange. Particles P_2 and P_4 are baryons while particles "a" and "b" are not. Particle "b" is taken to be emitted in the backward direction in the center-of-mass system.

Why u-Channel Production?



- In t-channel production, the shape of this cross-section is meaningful

Why u-Channel Production?



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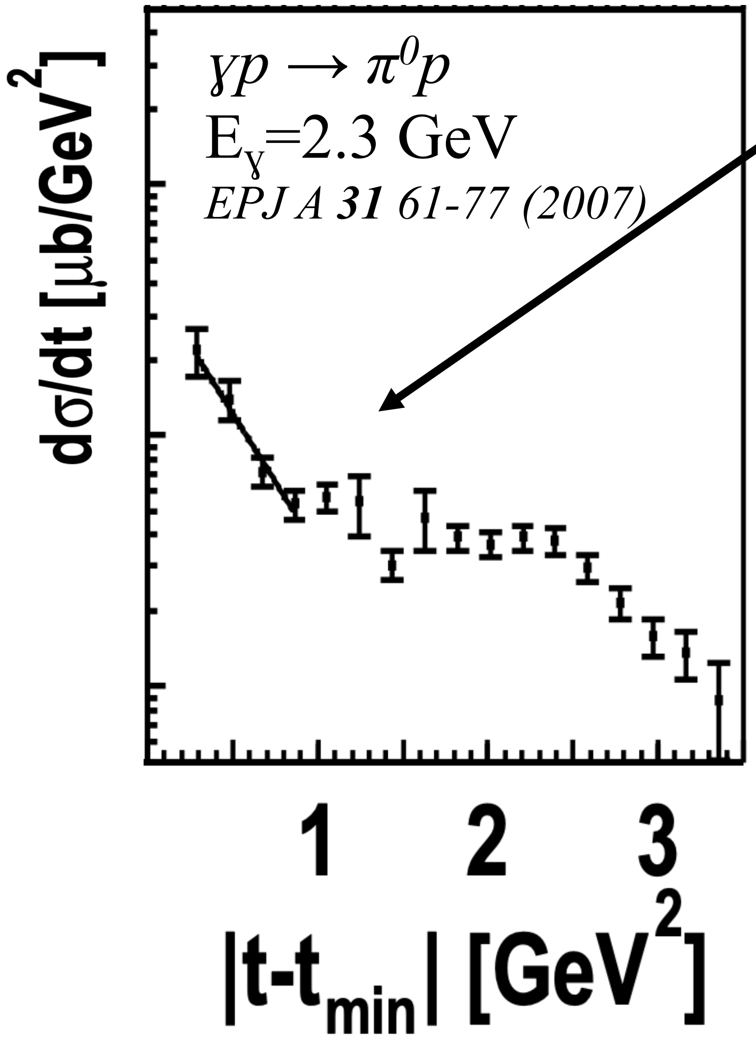

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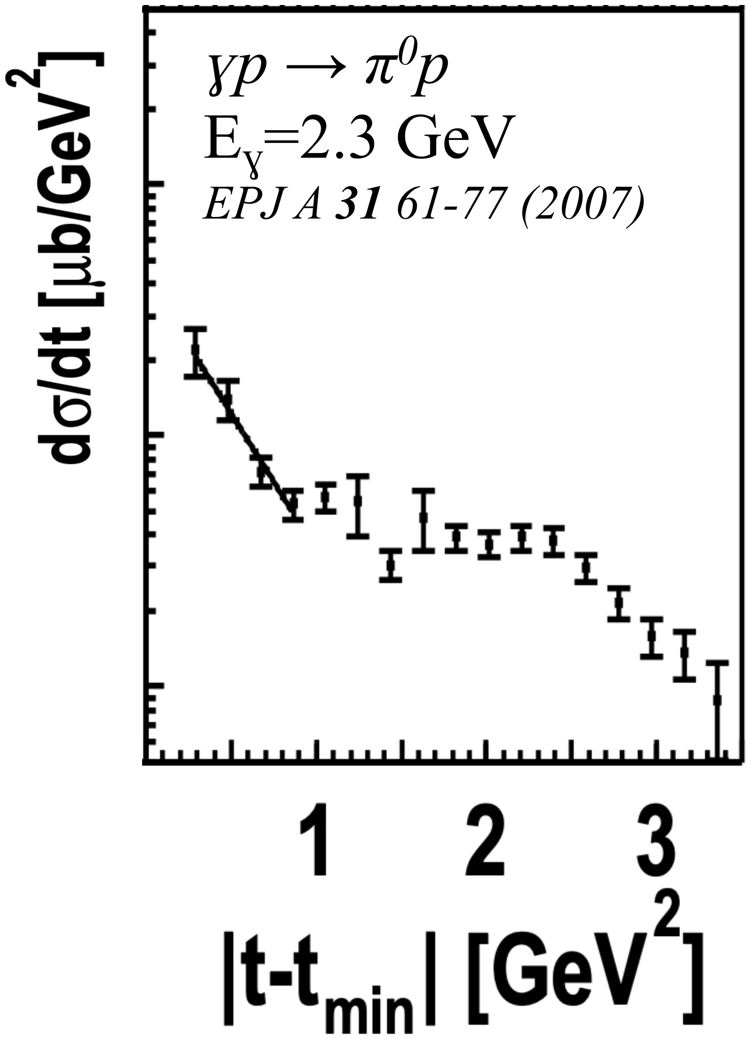
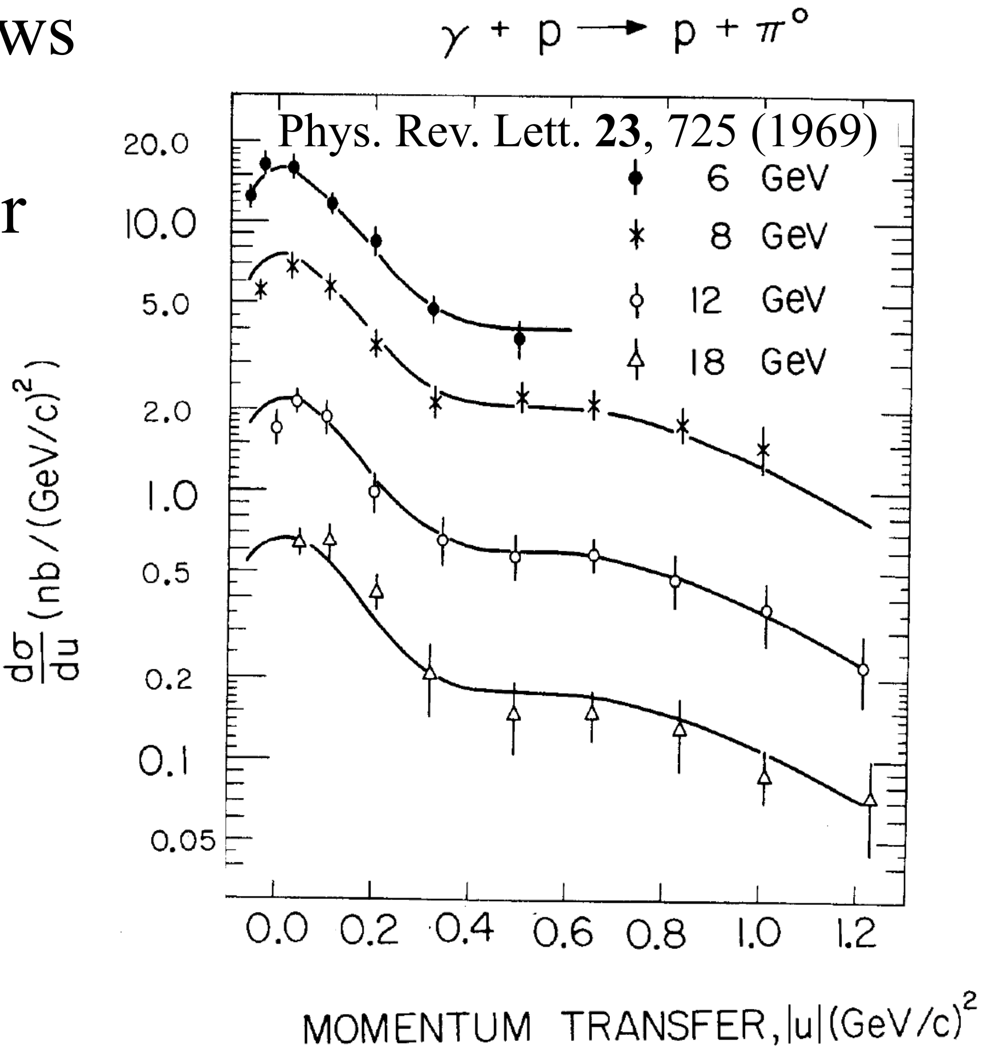


u-channel follows suggestively similar behavior



Transition Distribution Amplitudes

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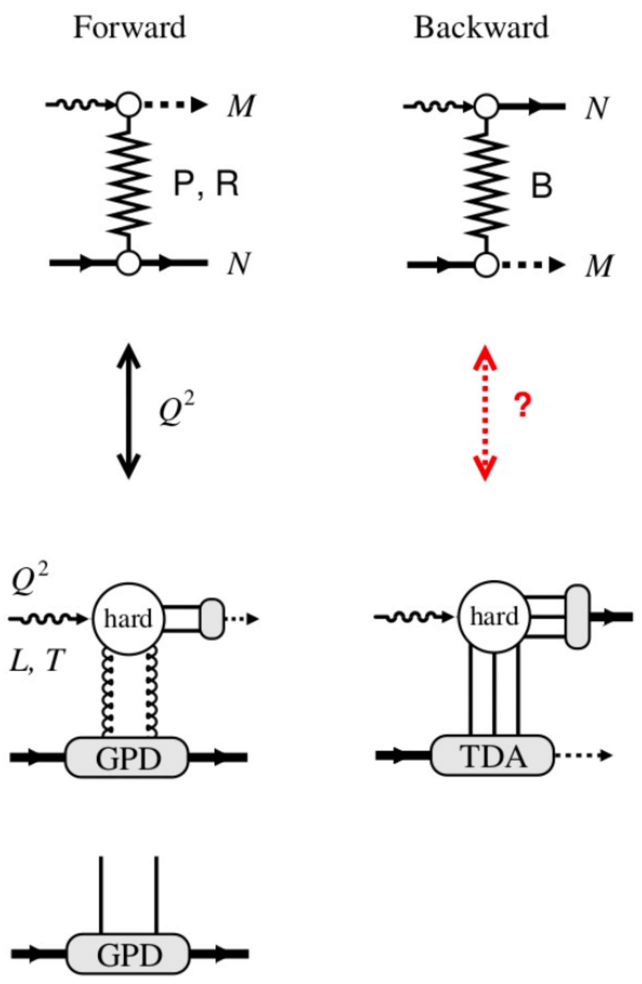

Fig. 11 Forward and backward collinear factorization schemes.

EPJ A, Vol. 57 **342** (2021)

- Mathematical structure around u-channel mechanism is similar to t-channel
- Forward collinear QCD factorization is in terms of GPDs
- Backward collinear factorization is in terms of TDAs: transition distribution amplitudes describing exchange of 3 quarks
- Similar limit as $\mathbf{\Delta}_T \rightarrow 0$ yields impact-parameter space interpretation

Connection to Baryon Junctions

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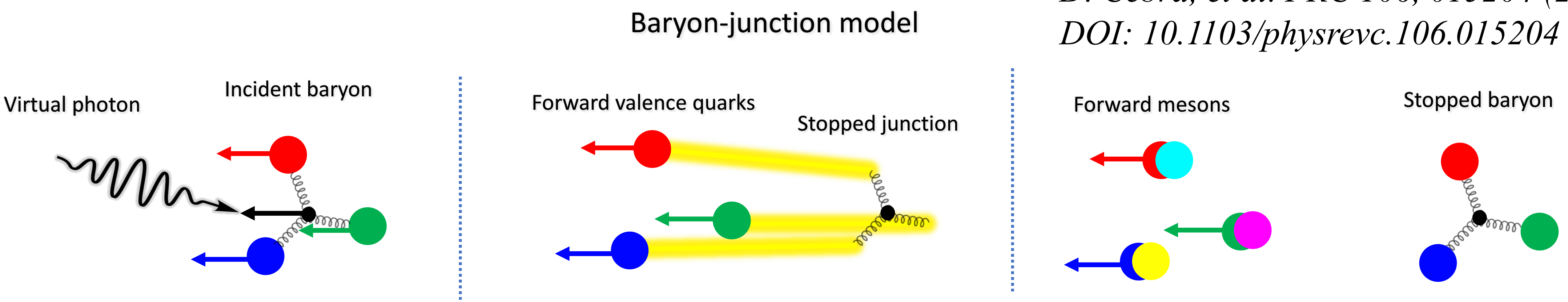
- In our 2022 paper, we make connection between u-channel mechanism and baryon junctions
- Junction model can help explain baryon transport to midrapidity
- Far-forward mesons and a stopped baryon are expected in ɣ+Junction scattering
- Is interpretation of TDAs in the transverse plane able to provide insight into distribution of baryon number within proton?

D. Cebra, et al. PRC 106, 015204 (2022)
DOI: 10.1103/physrevc.106.015204



Existing Data: π^0 at SLAC

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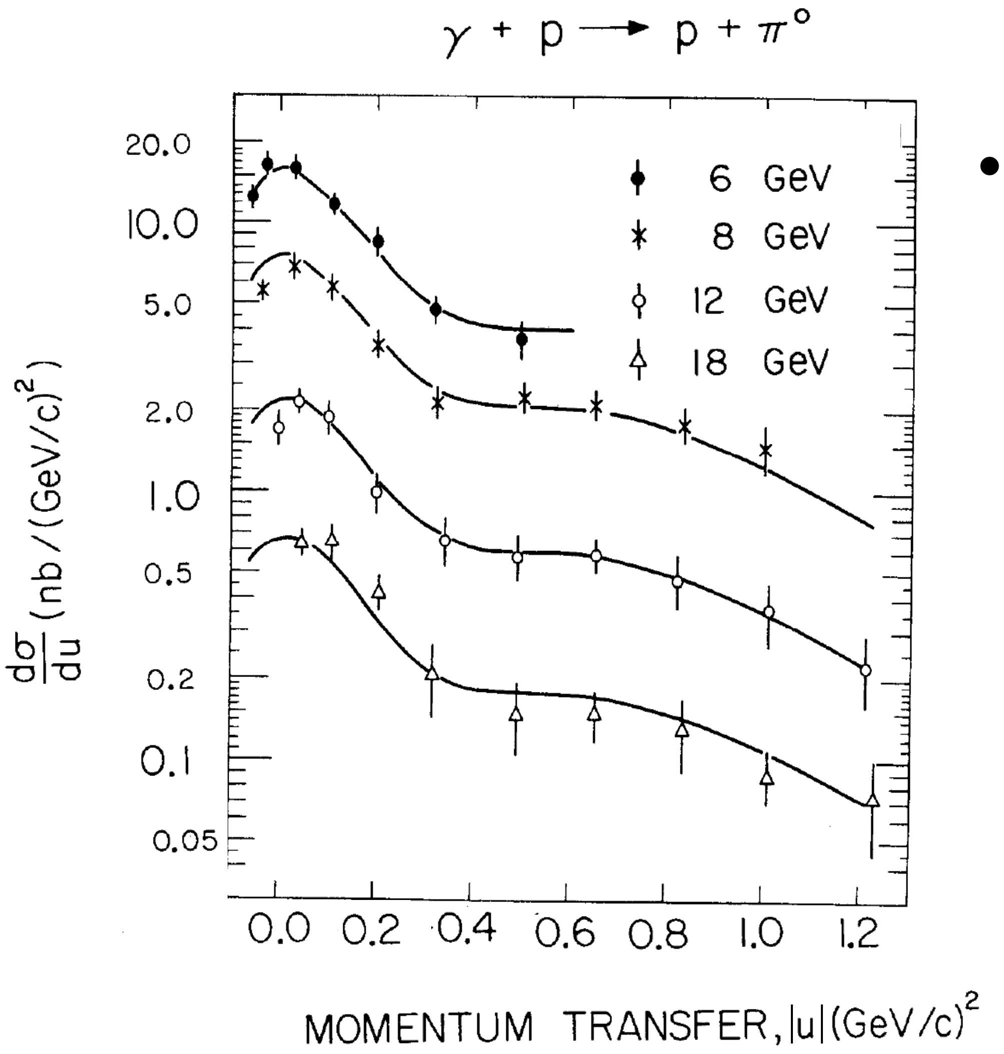
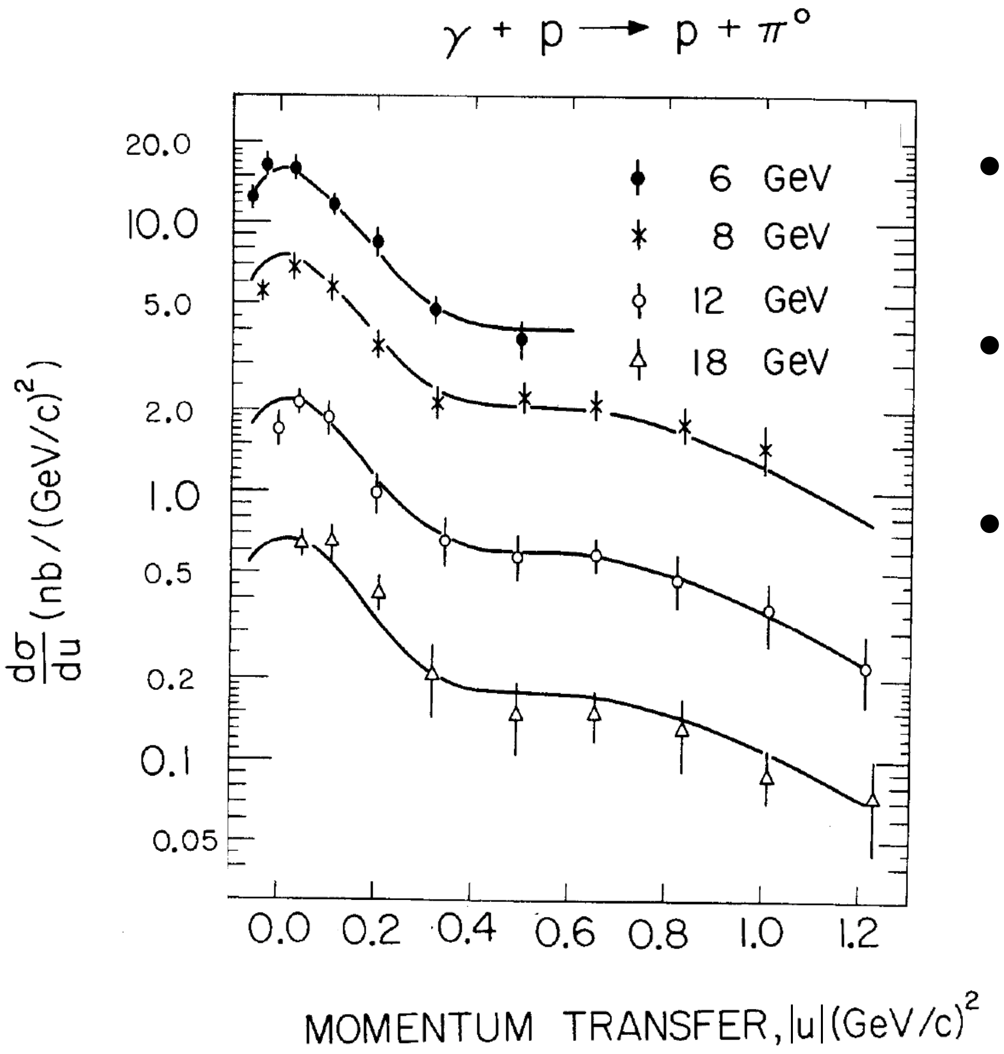


- Backward photoproduction of π^0 measured at SLAC in 1969

Phys. Rev. Lett. **23**, 725 (1969)

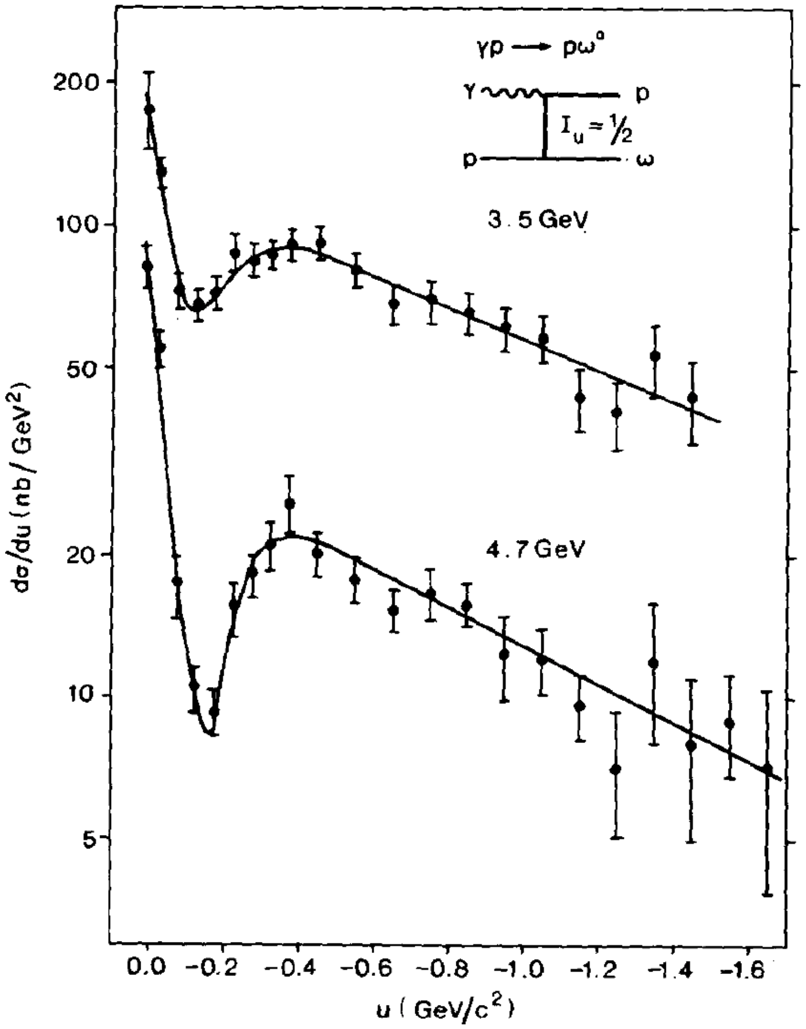
Existing Data: π^0 at SLAC



- Backward photoproduction of π^0 measured at SLAC in 1969
- Real photons, four energies above the hadron resonance region
- Wide range of Mandelstam u

Phys. Rev. Lett. **23**, 725 (1969)

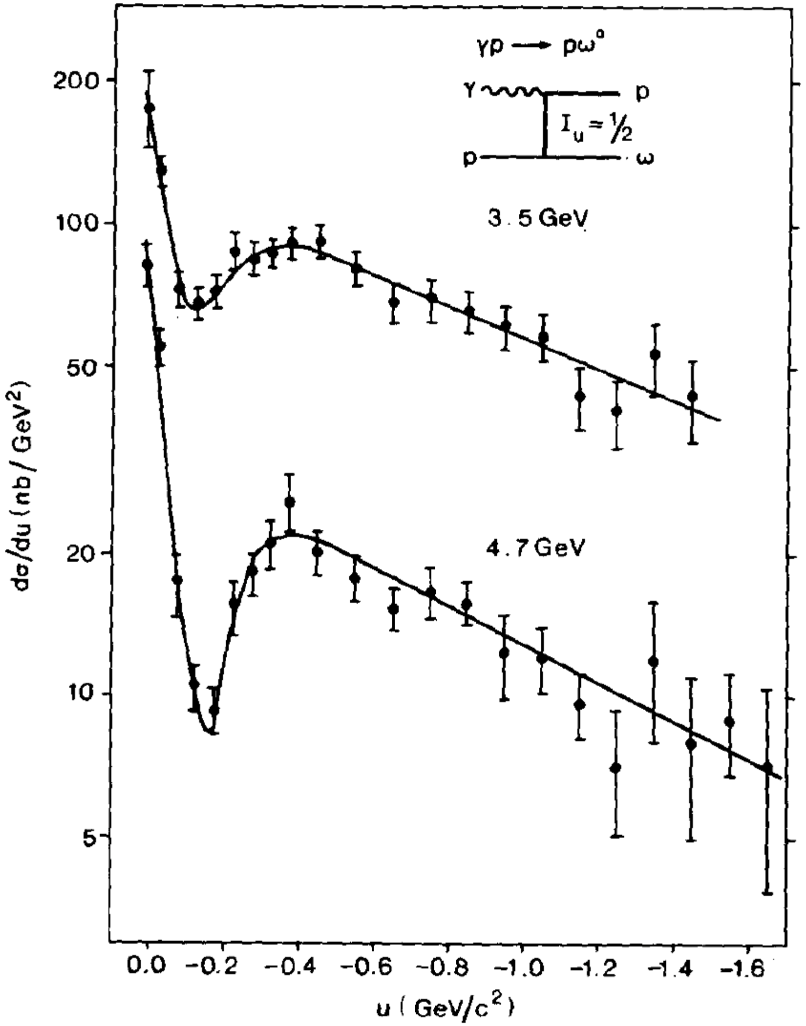
Existing Data: ω at NINA (Daresbury)



- Backward photoproduction of ω measured at Daresbury Laboratory's NINA synchrotron in 1977

Phys. Lett. B **72**, 144 (1977)

Existing Data: ω at NINA (Daresbury)

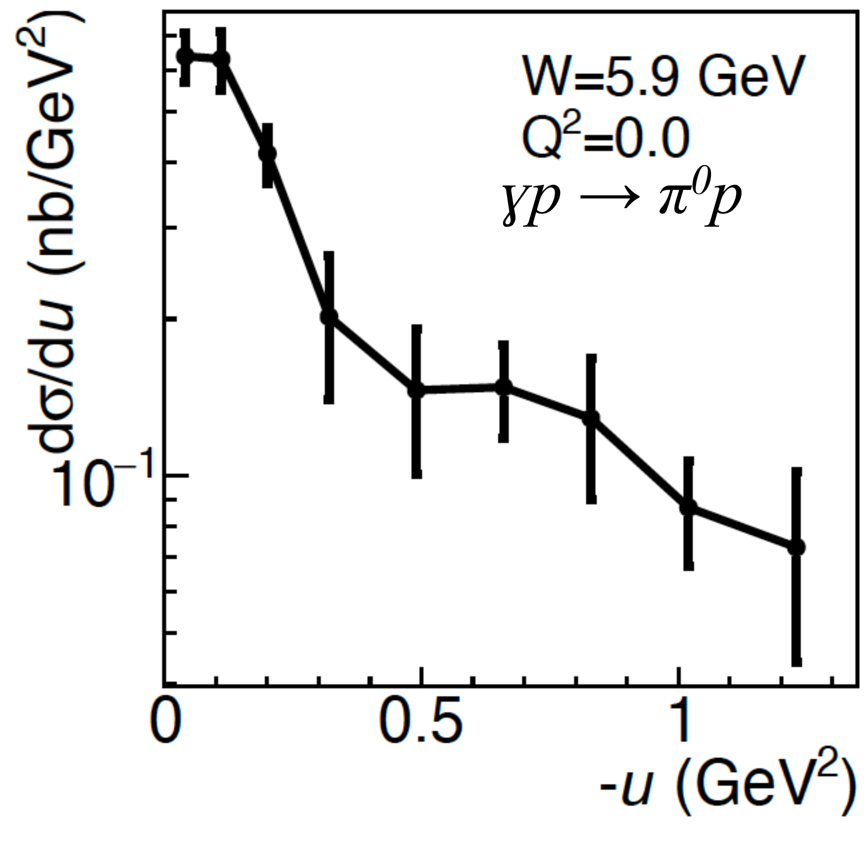


- Backward photoproduction of ω measured at Daresbury Laboratory's NINA synchrotron in 1977
- Real photons, two energies above the hadron resonance region
- Wide range of Mandelstam u, very fine bins

Phys. Lett. B **72**, 144 (1977)

Transformation Procedure

1. Grab an existing dataset



Transformation Procedure

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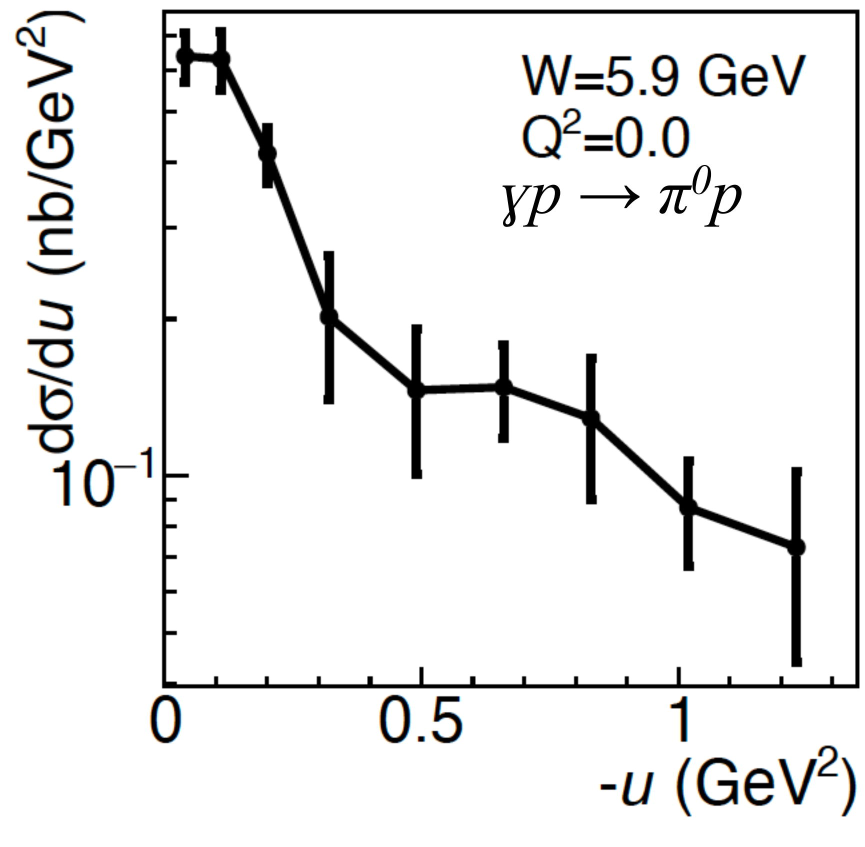
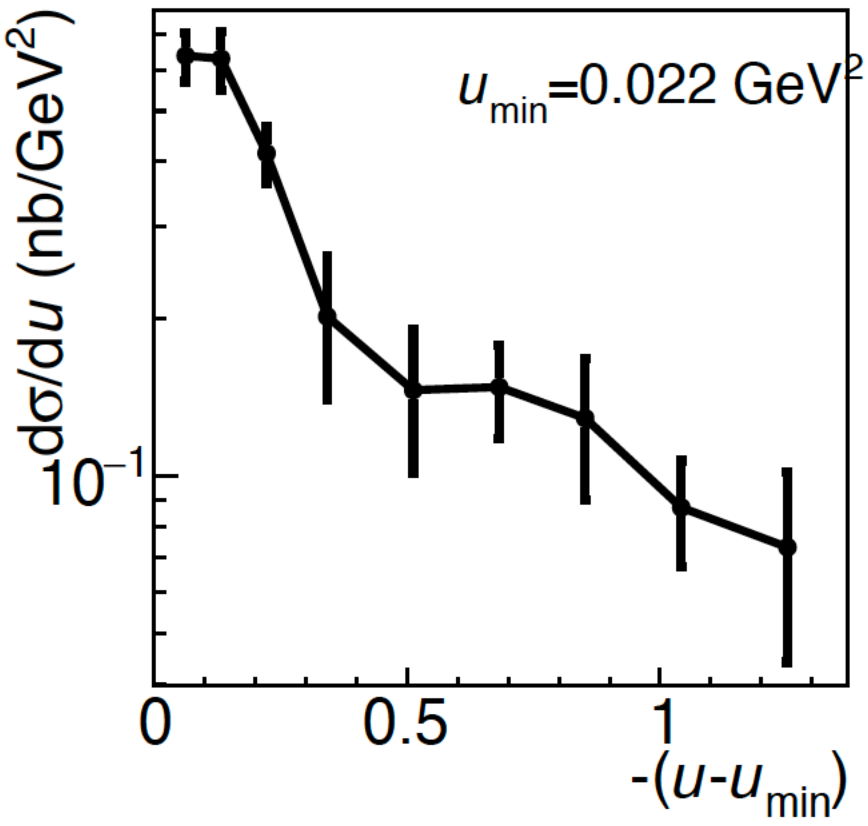
1. Grab an existing dataset
2. To get closer to p_T, calculate and subtract off u_{min}, corresponding to exactly backward production (180°)

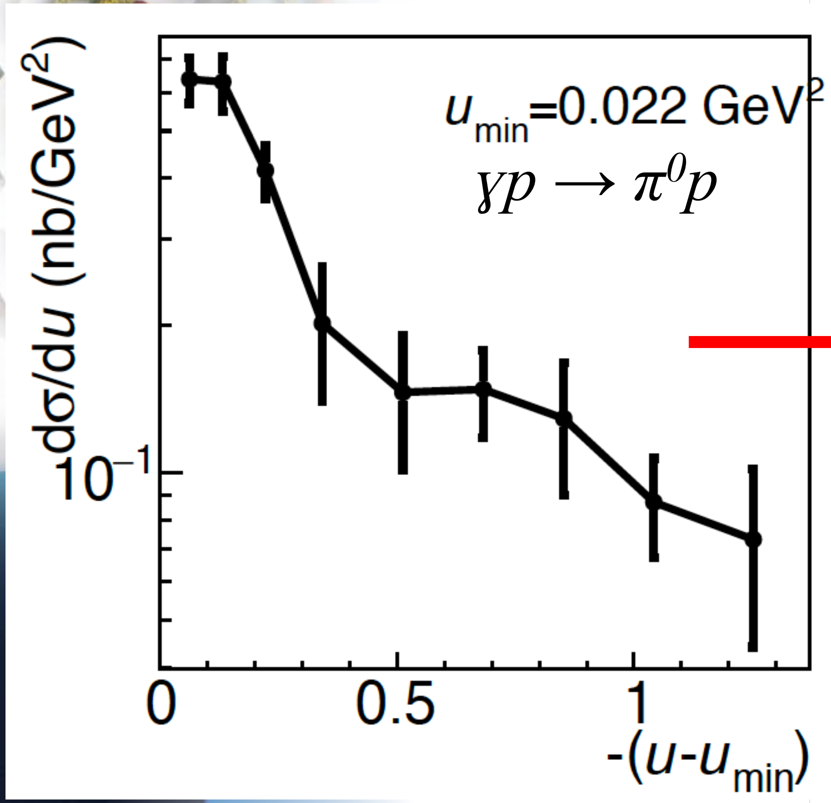


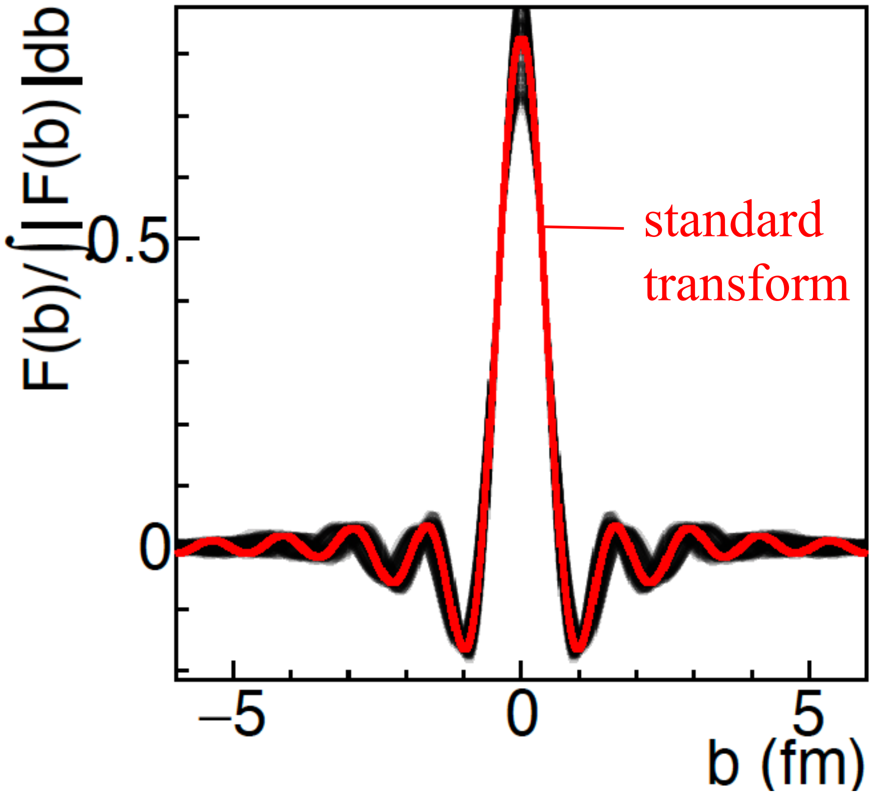


Transformation Procedure

3. Transform to impact-parameter space

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





Transformation Procedure

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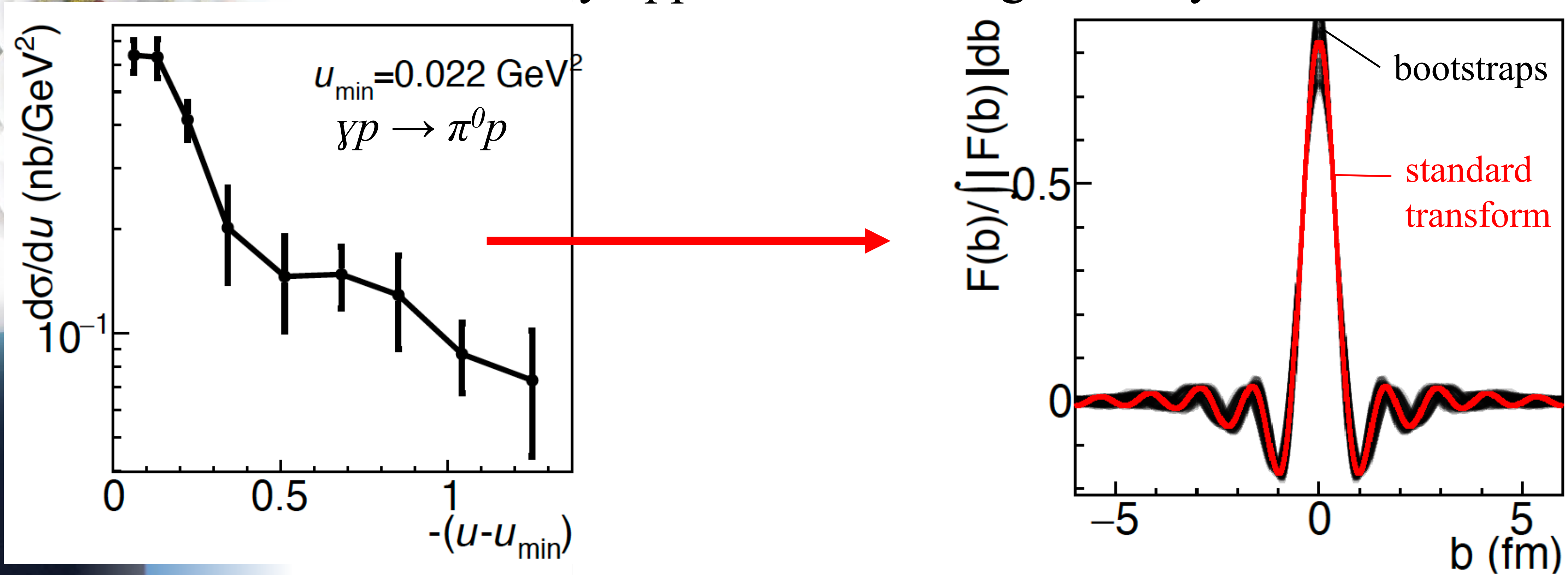
3. Transform to impact-parameter space
4. Bootstrap data many times and re-transform
   a. vary data points according to errors
   b. vary upper limit of integration by ±20%



Transformation Results

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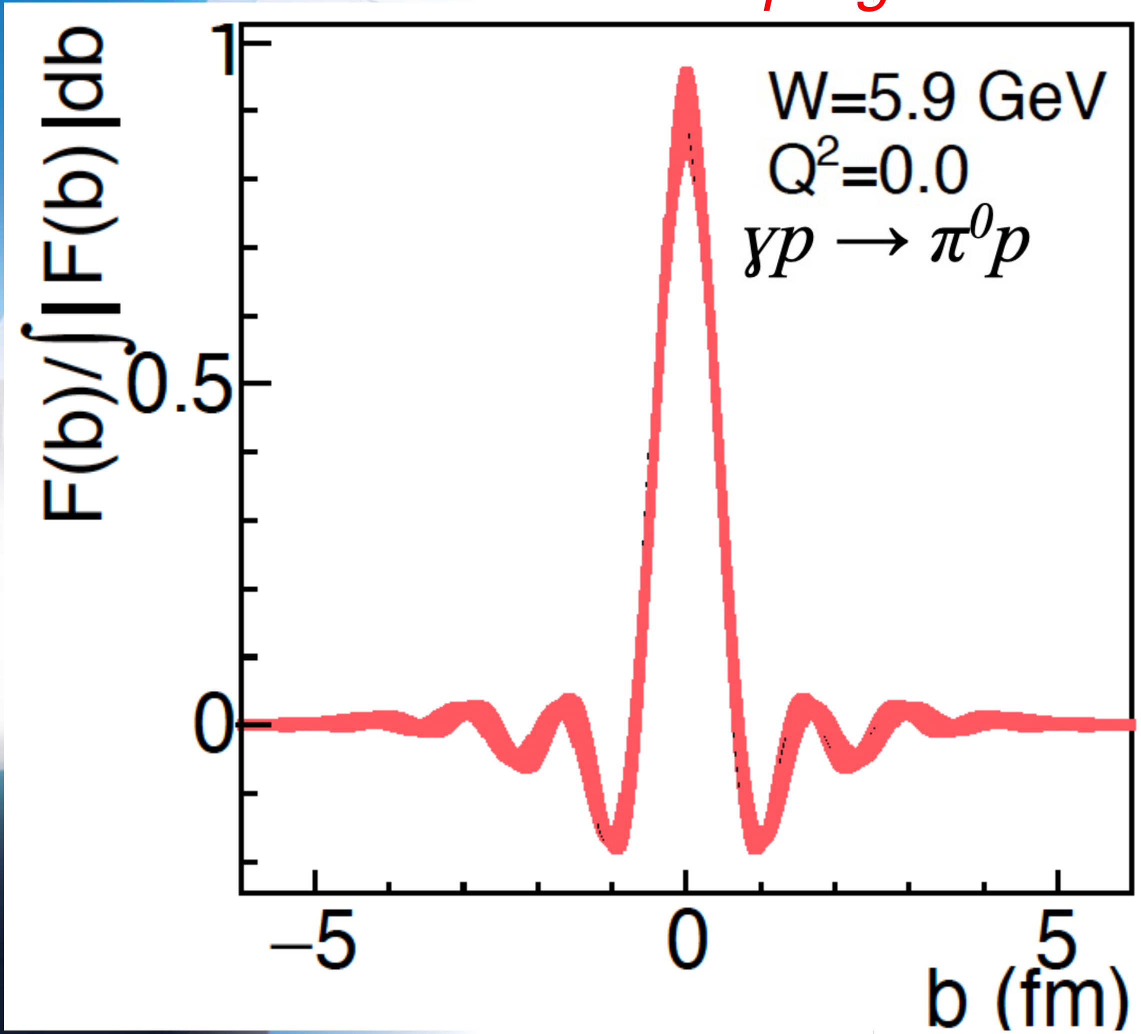
Work in progress



- F(b) is density of production region in impact parameter space
- We can approximate source radius with width at half-max
  b_0=0.41±0.03fm
- Regions of negative F(b) are unphysical artifacts of finite transformation range
- We believe these to be windowing artifacts→ effects of transforming a box function. Further investigation needed

Transformation Results

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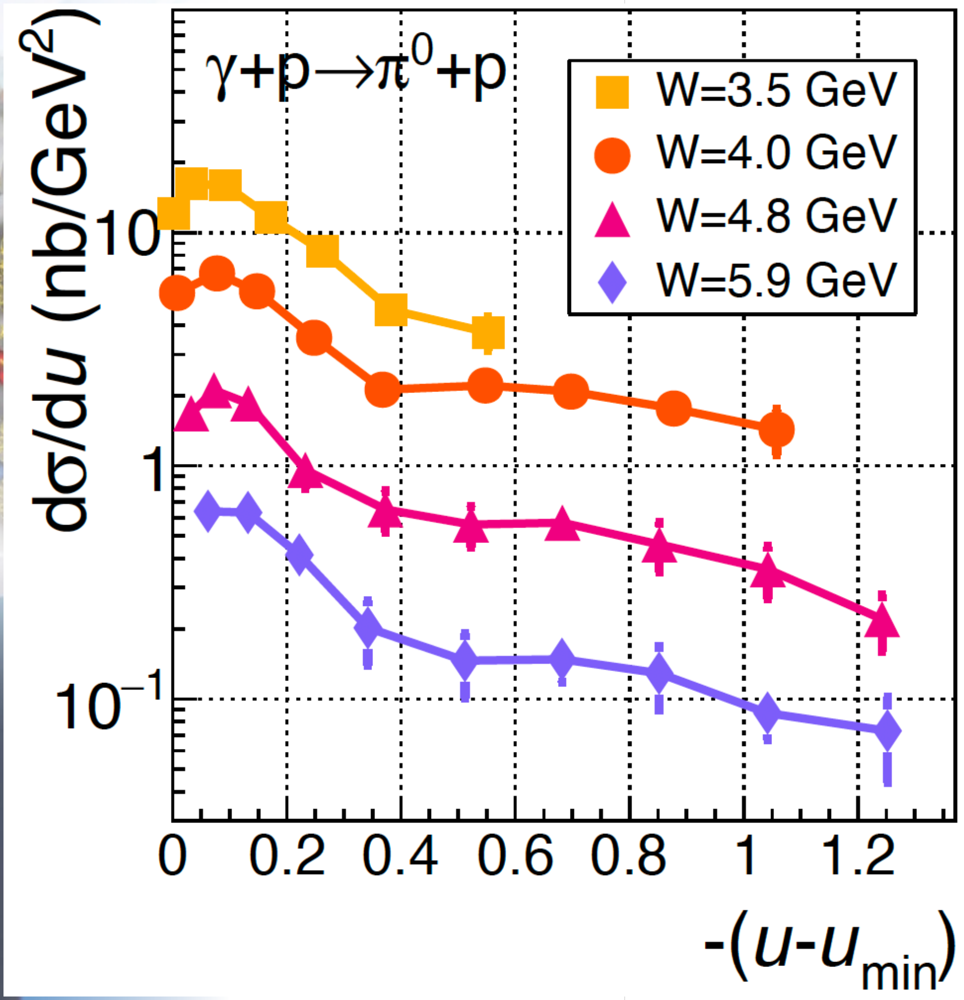
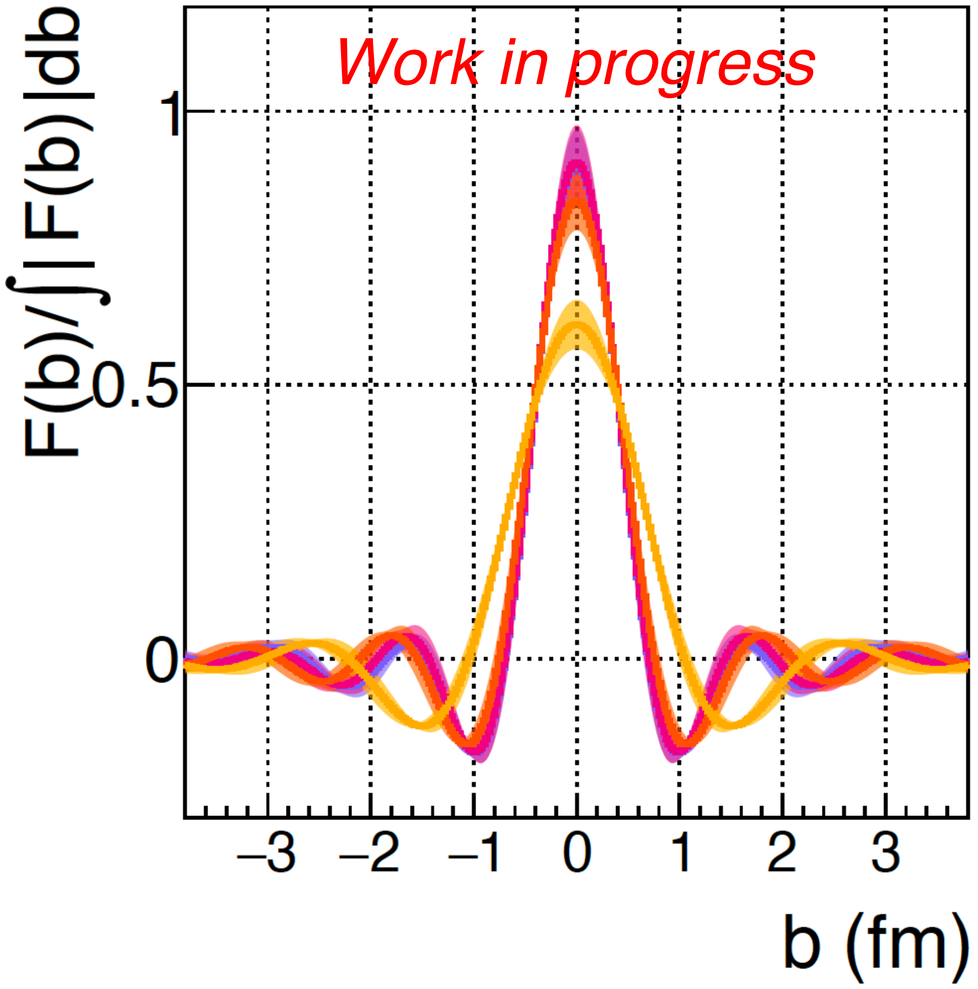
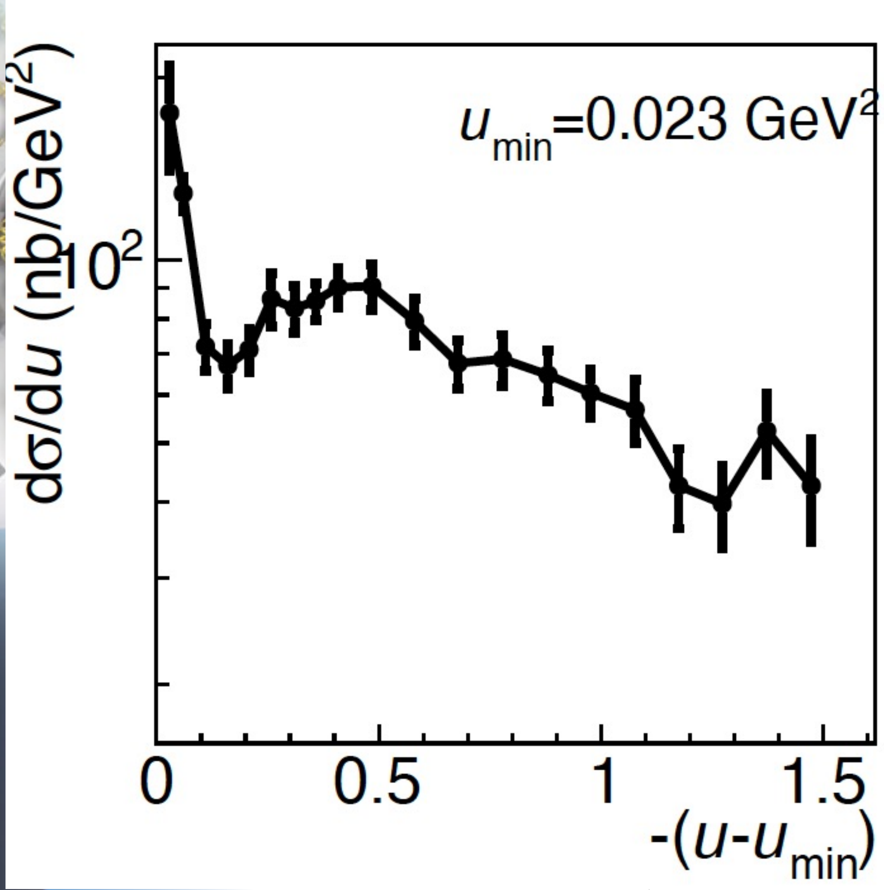
- At W=3.5 GeV, limited data results in slightly wider transverse shape
- At other energies, interaction region size converges quickly



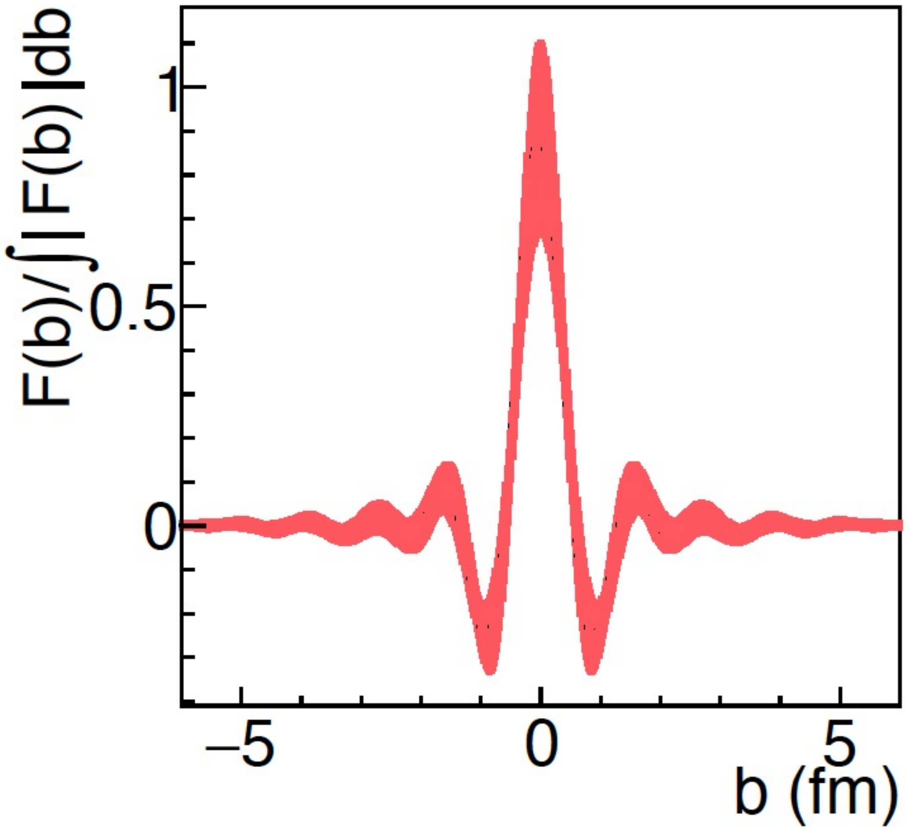


Transformation Results

- ω transform has larger spread, esp. for b<0.2fm



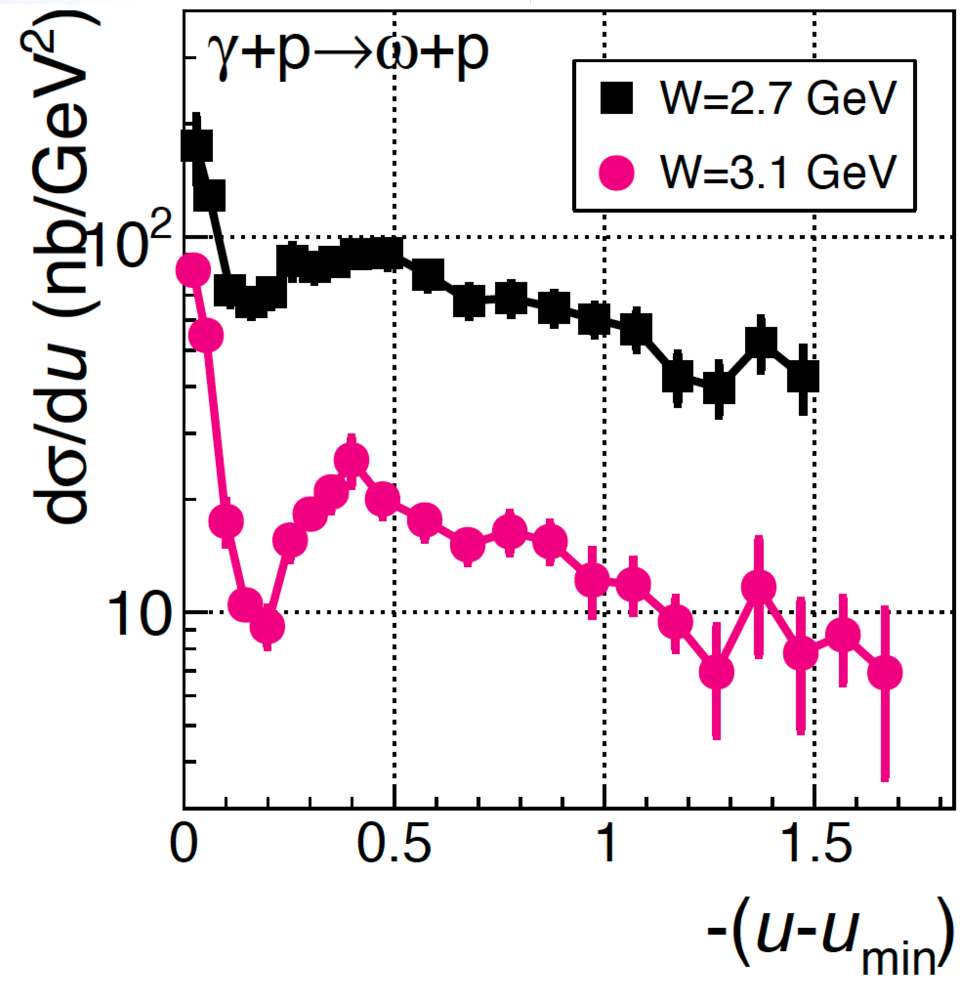
Work in progress

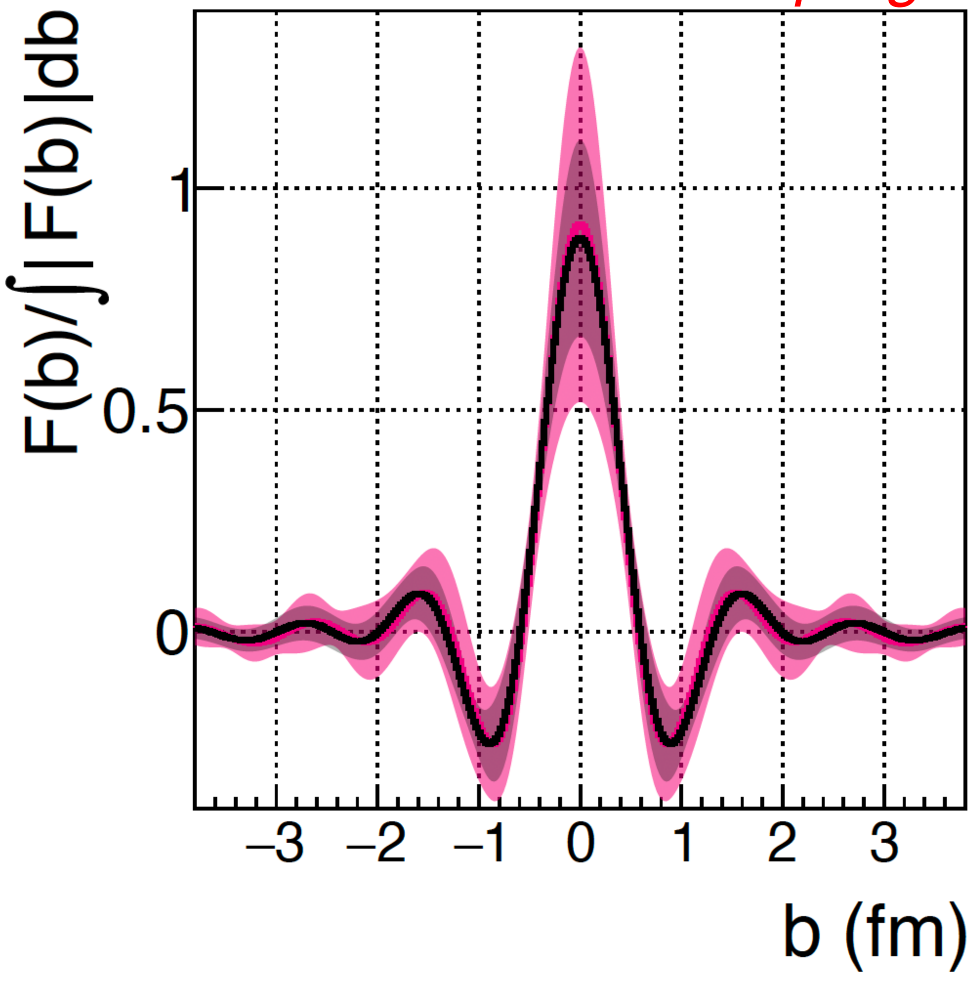


Transformation Results

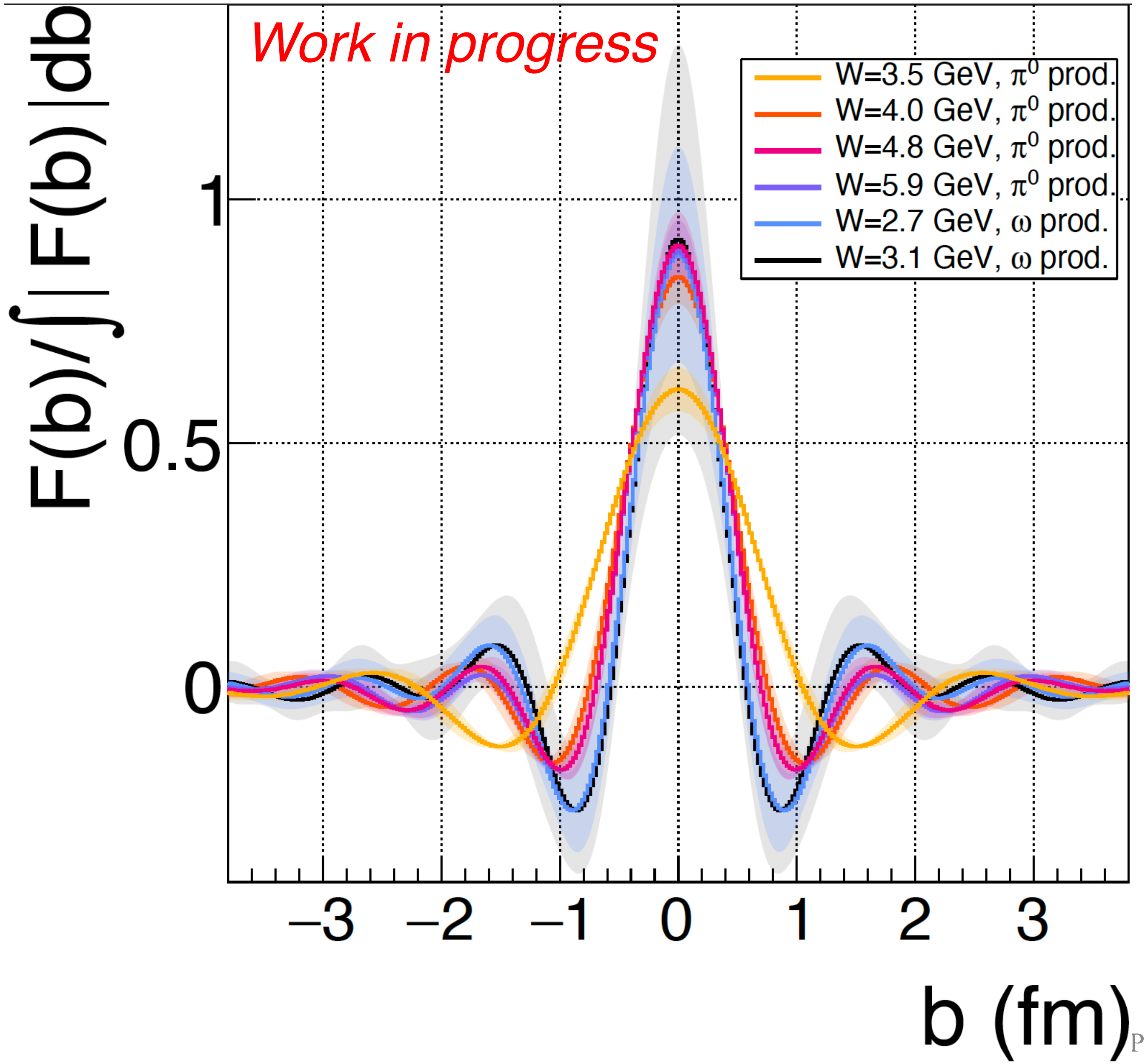
- ω transform has larger uncertainty, esp. for b<0.2fm
- Both cross sections give similar size

Work in progress





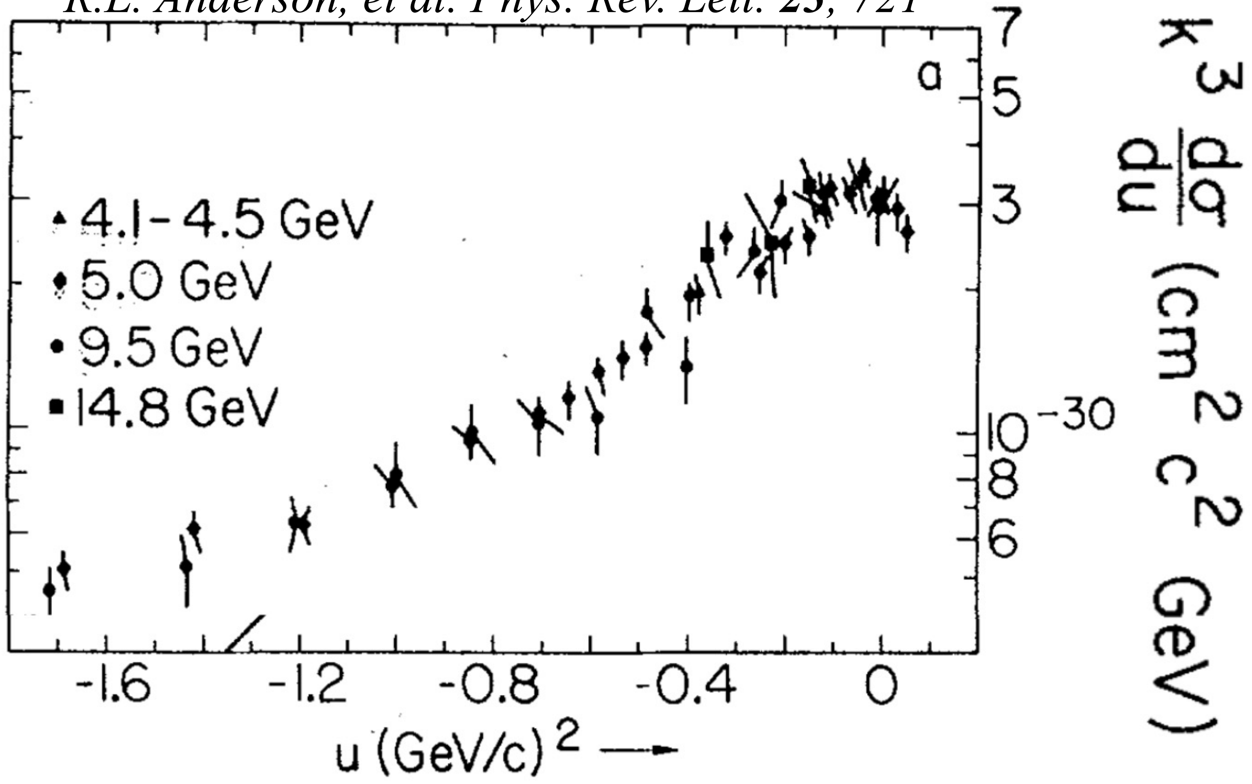
Transformation Results



u-Channel $\gamma p \rightarrow \pi^{+} n$

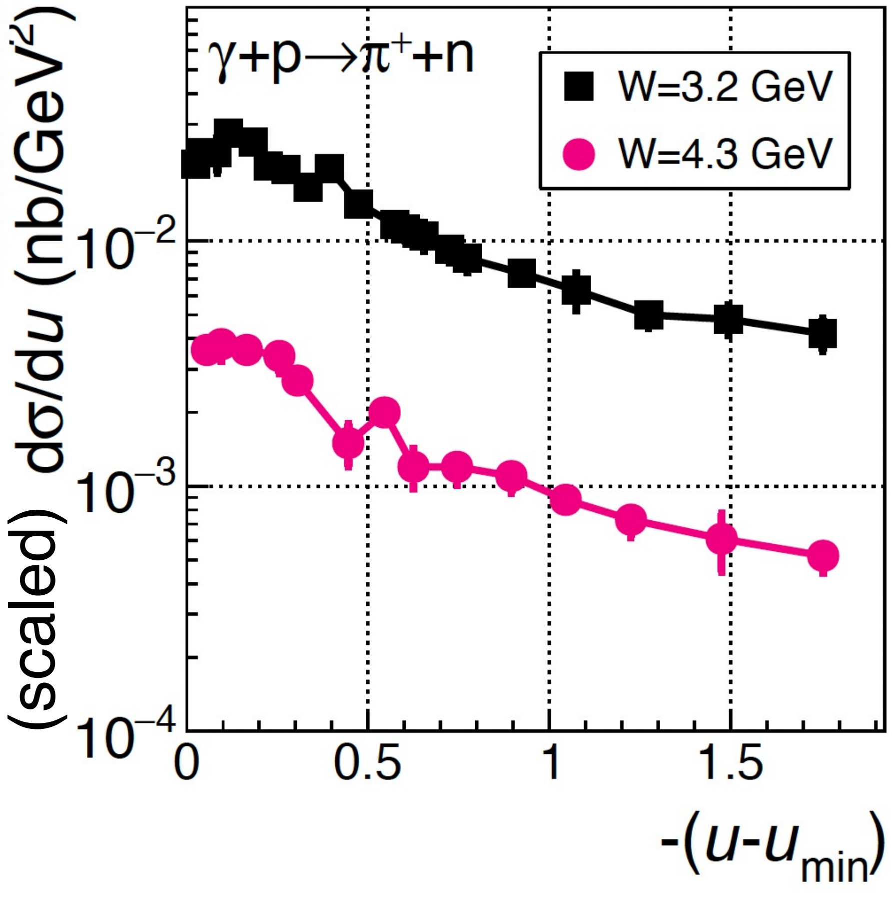
- Charged pion production measured in the u-channel at SLAC as well
- Involves charge-transfer in the cross channel in addition to baryon number transfer

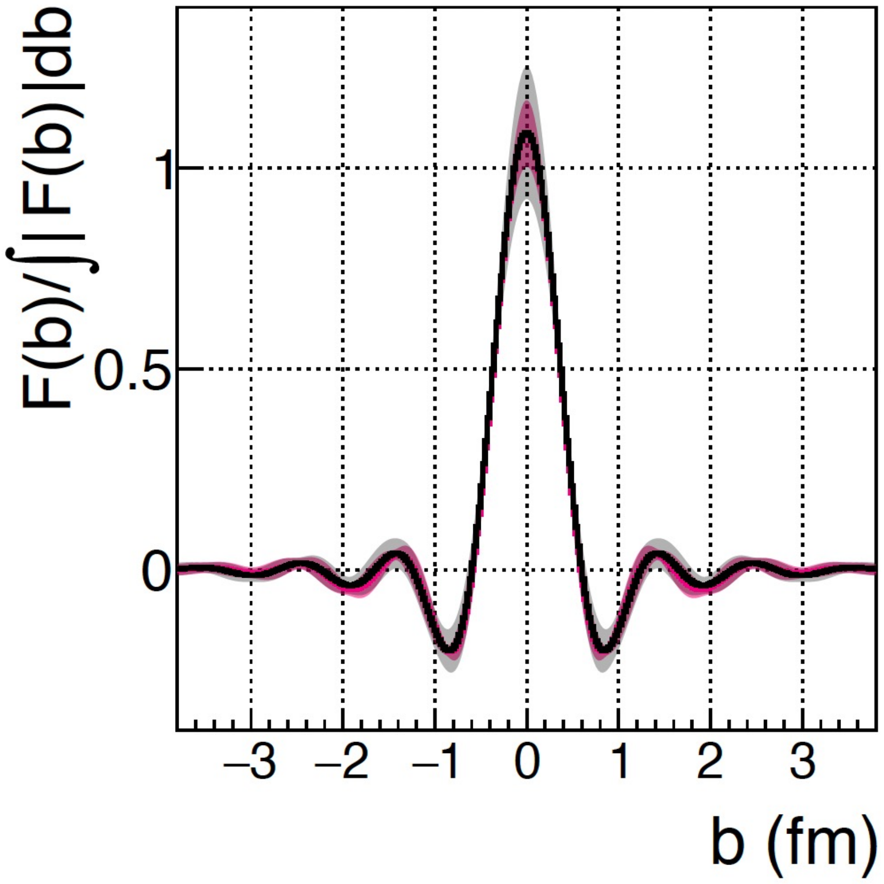
R.L. Anderson, et al. Phys. Rev. Lett. ***23****, 721*



u-Channel $\gamma p \to \pi^+ n$

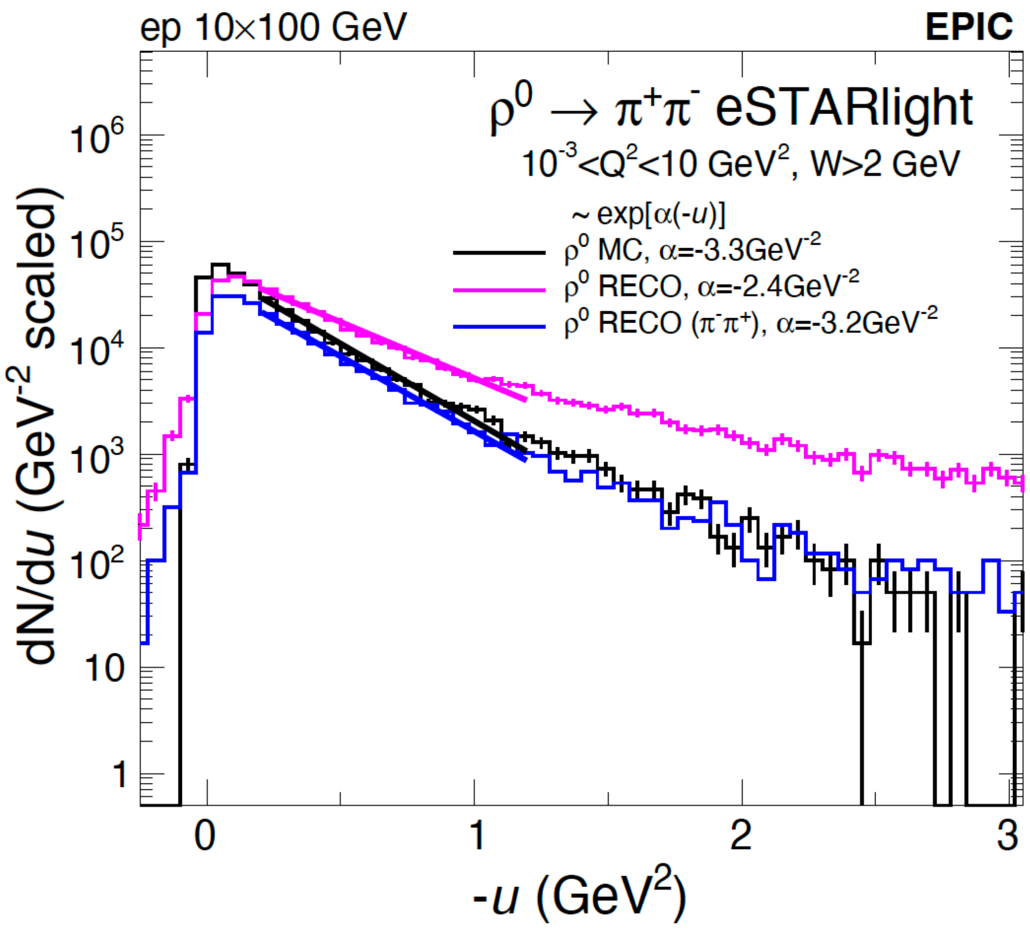
- Transforms at different center-of-mass energies give consistent picture of source size

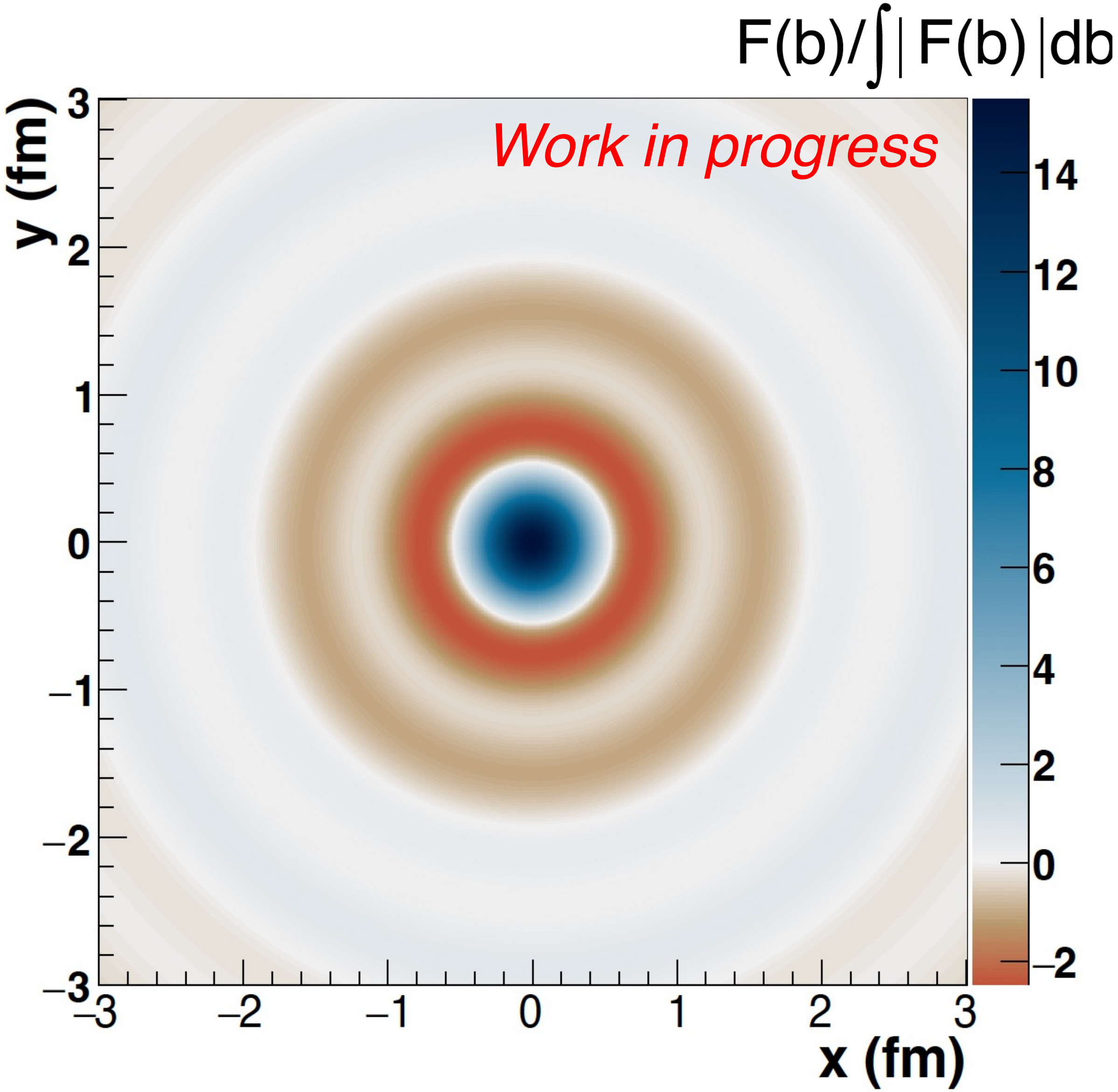




u-channel at the EIC

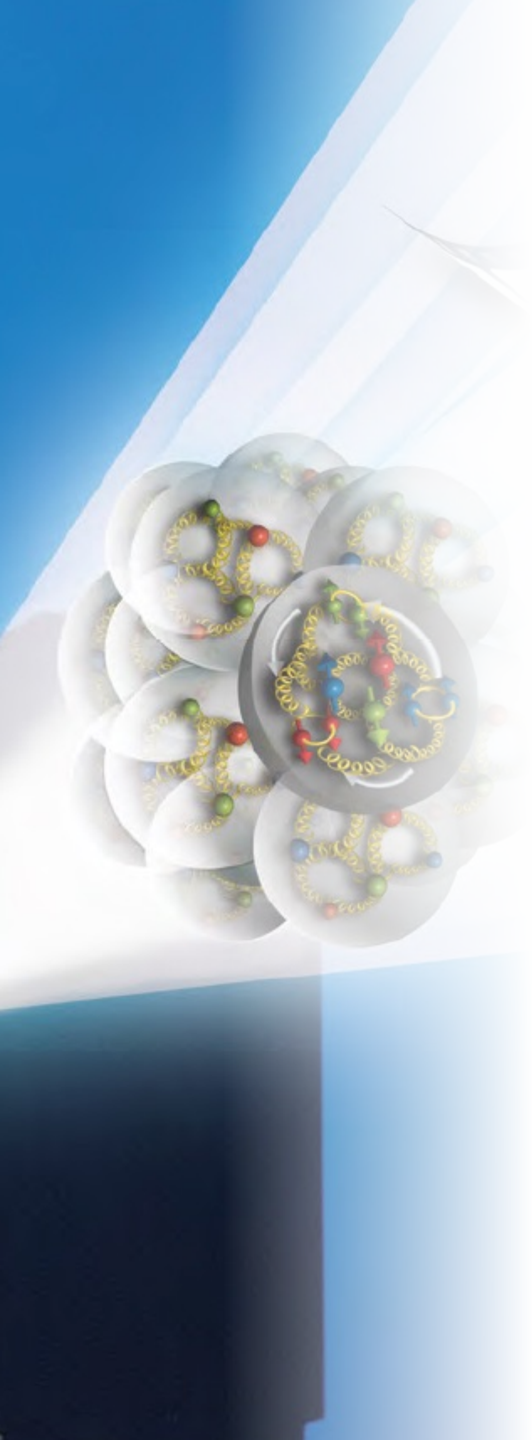
- Currently all the best u-channel data is for photoproduction (Q^2=0)
- EIC may provide opportunity to describe Q^2 evolution of this ``object”
- Studies suggest that certain channels like ρ production will be measurable





Conclusions

- Spencer and I are working on interpreting u-channel production/scattering cross sections
- By transforming to the transverse plane, these cross-sections may map the distribution of baryon number in the nucleon.
- Early studies suggest an ``object" with size $b_0 \cong 0.4$fm. This is still a work in progress!



Thank you for your attention!

zwsweger@ucdavis.edu