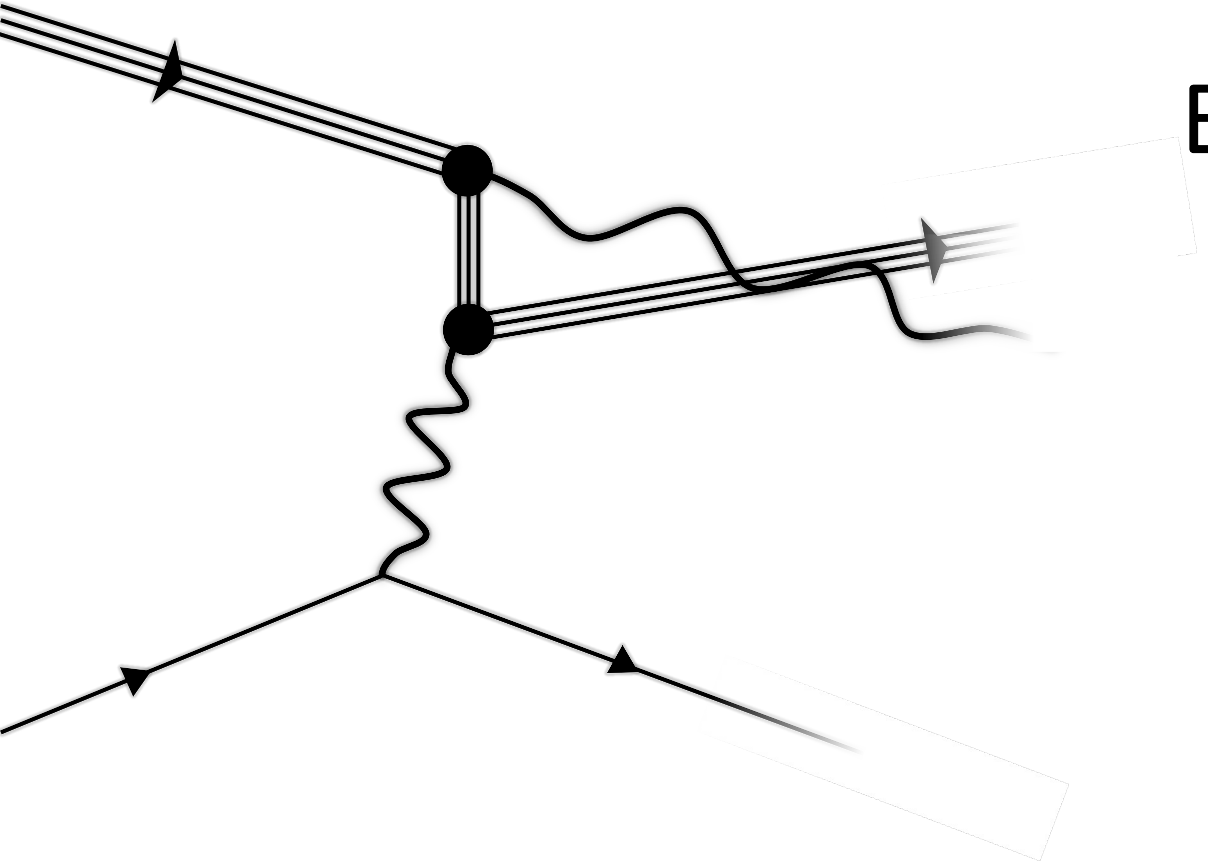

Backward Processes: Probing Novel Physics at the EIC

"It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you"
- Ernest Rutherford

Zachary Sweger

University of California Davis, and
LBNL's Relativistic Nuclear Collisions Group

Supported in part by

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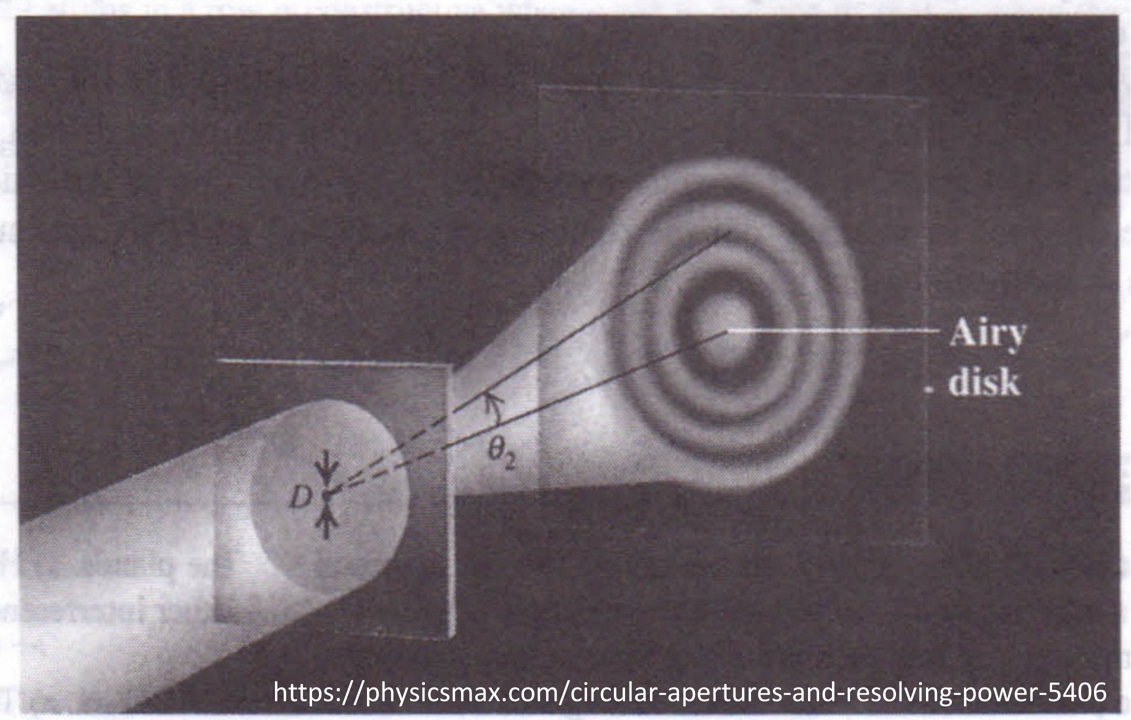
Diffractive Scattering

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



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Diffractive Scattering

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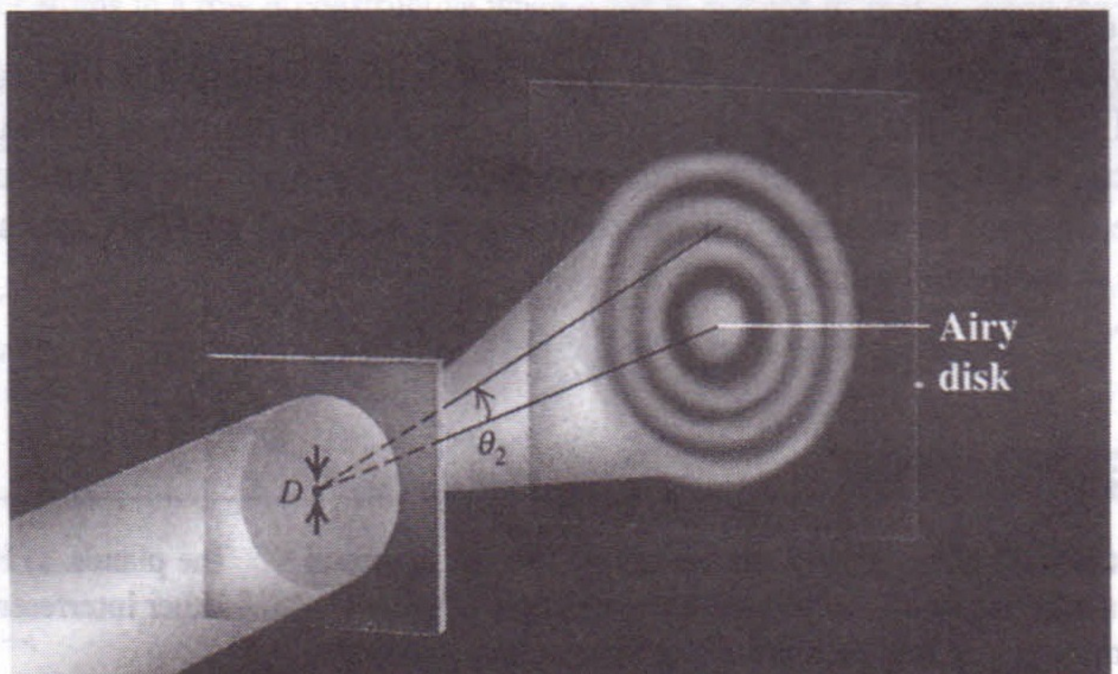
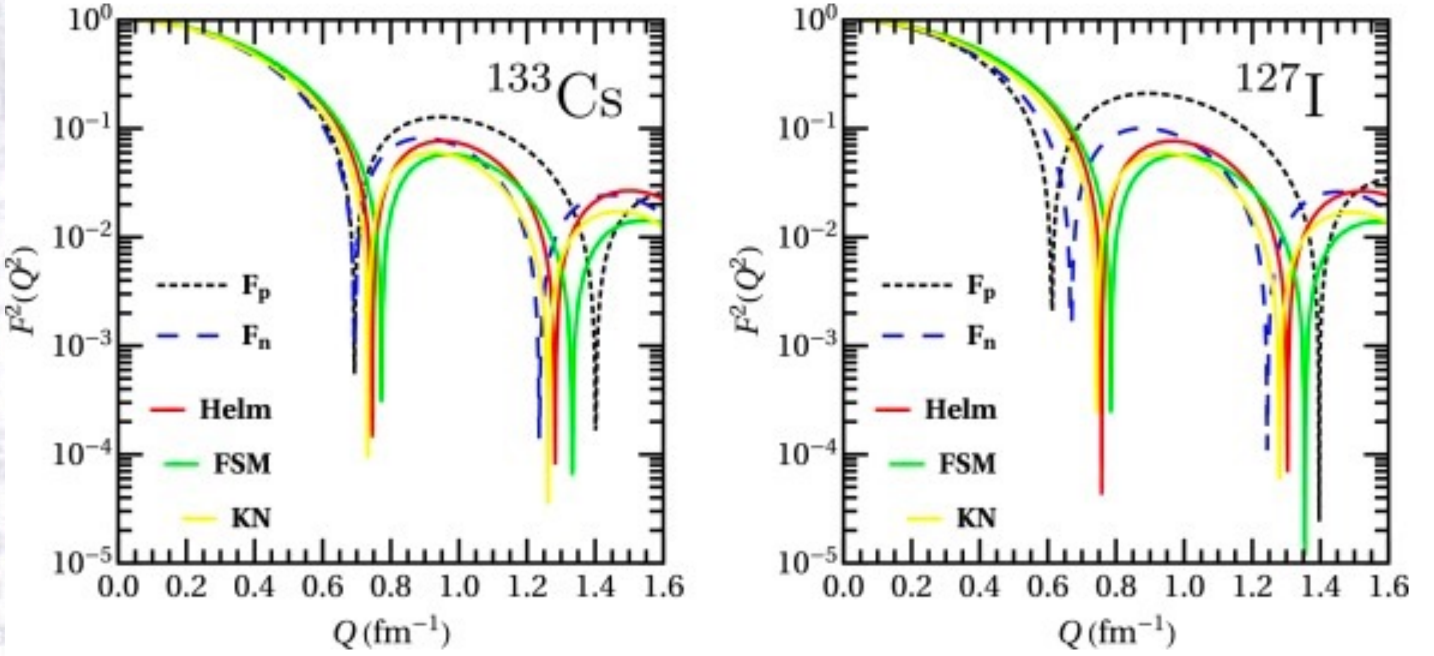
- Think of black disk diffraction. Diffraction pattern → disk size. But partial absorption complicates picture
- Send in a high-energy projectile (such as a photon or proton) and measure diffractive dips
- Larger momenta → greater resolving power for small sizes!
- p_T (transverse momentum) and b (transverse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

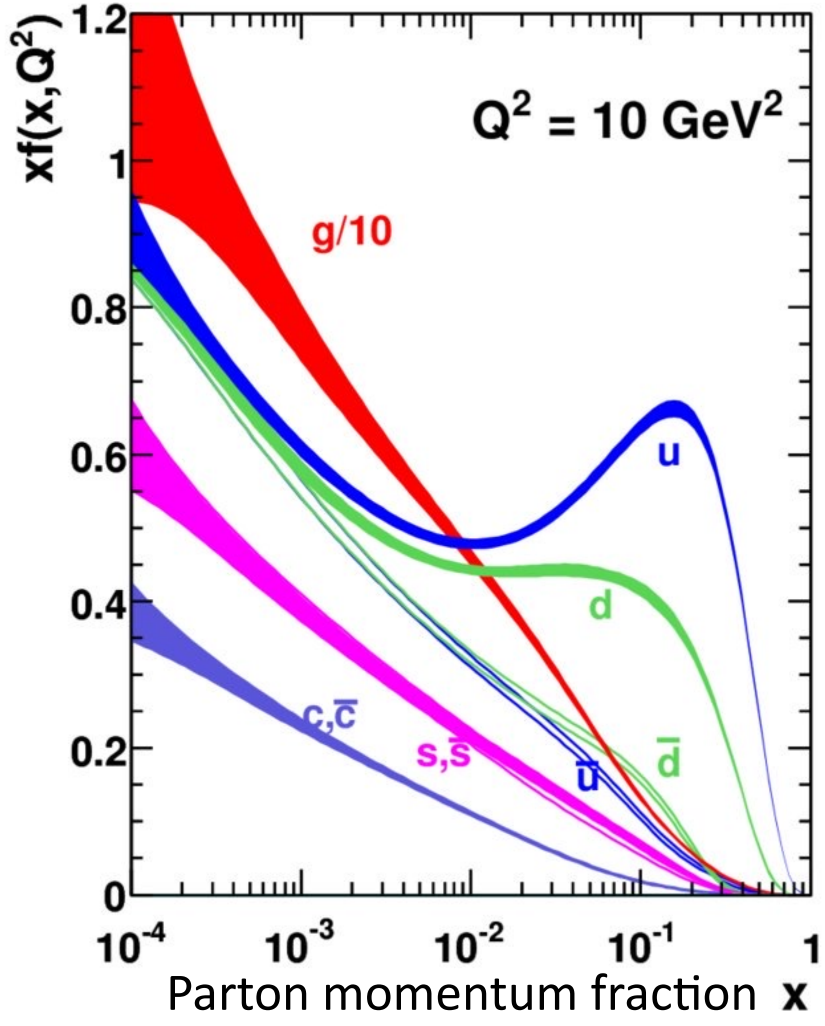


https://physicsmax.com/circular-apertures-and-resolving-power-5406



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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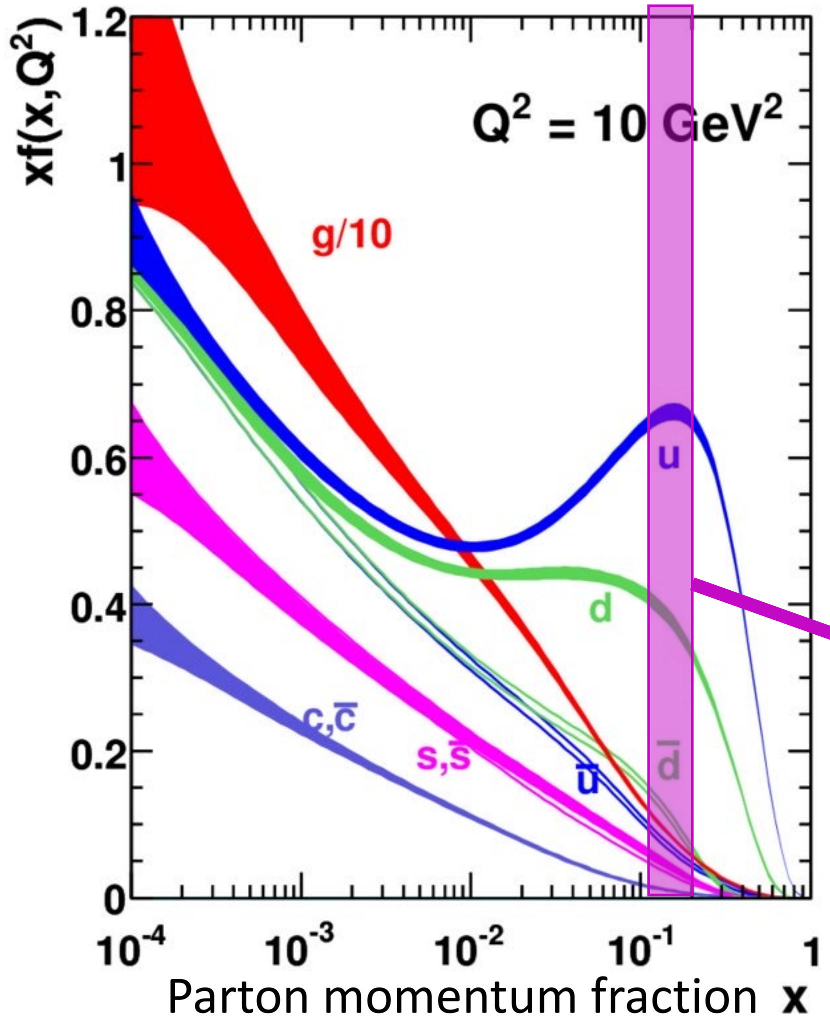

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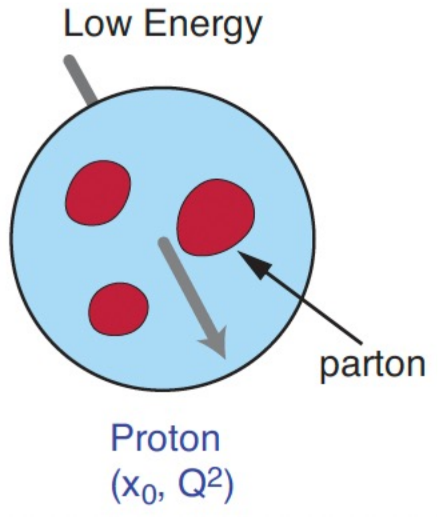

Nucleons Change with Momentum Fraction

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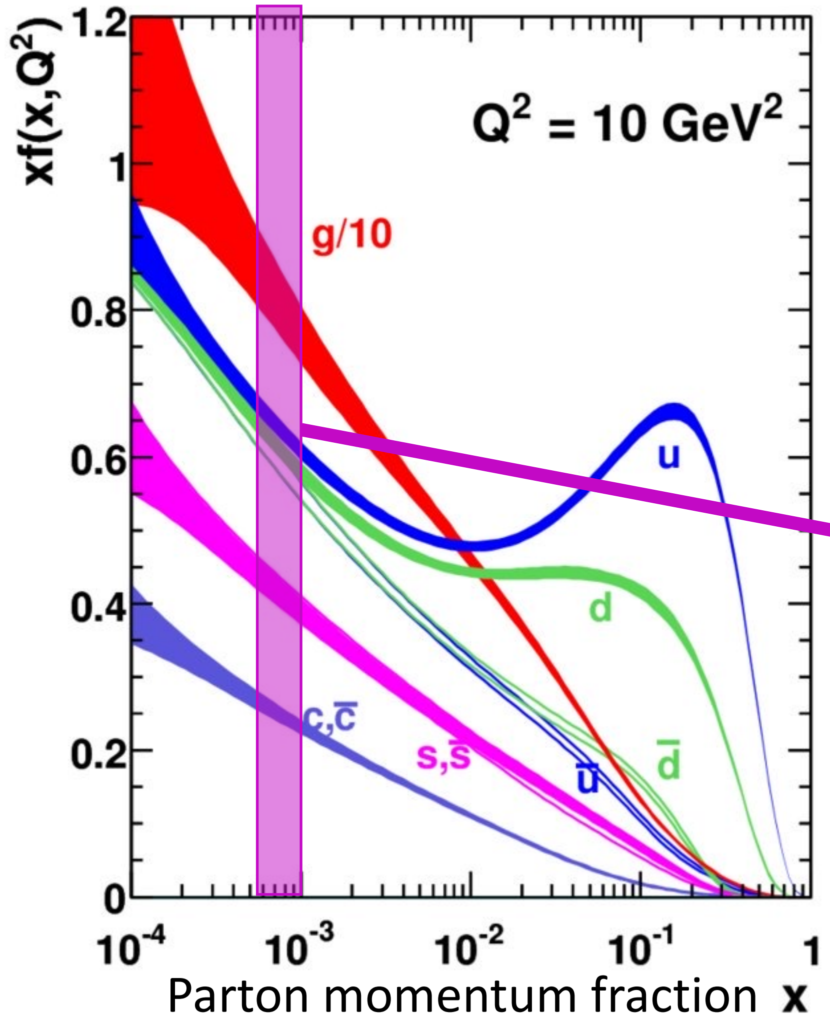

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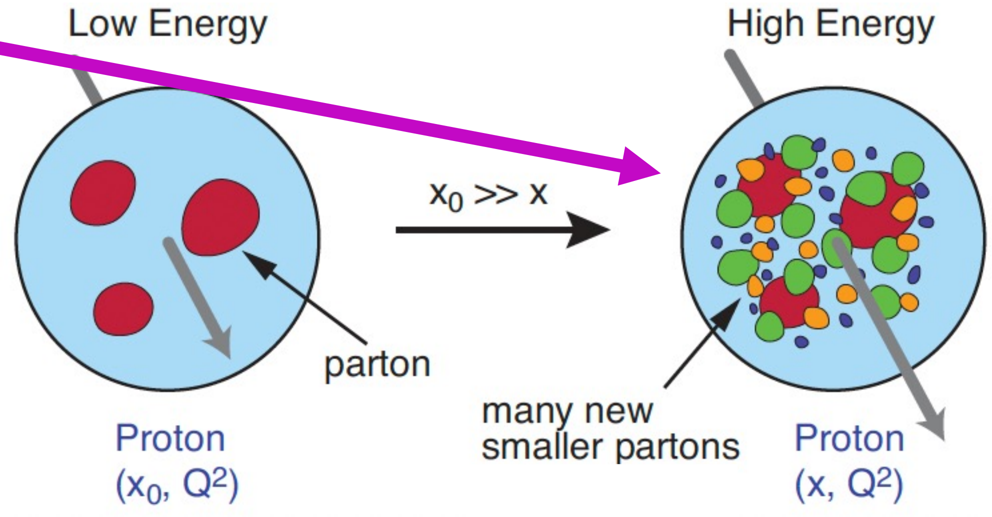
- Most of nucleon’s momentum comes from valence quarks (up, down)
- When we look deeper, MANY sea quarks and gluons contribute as well
- up(u), down(d), charm(c), strange(s), antiquarks ($\bar{u}$,$\bar{d}$,$\bar{c}$,$\bar{s}$) and gluons (g)



EIC White Paper (2012)

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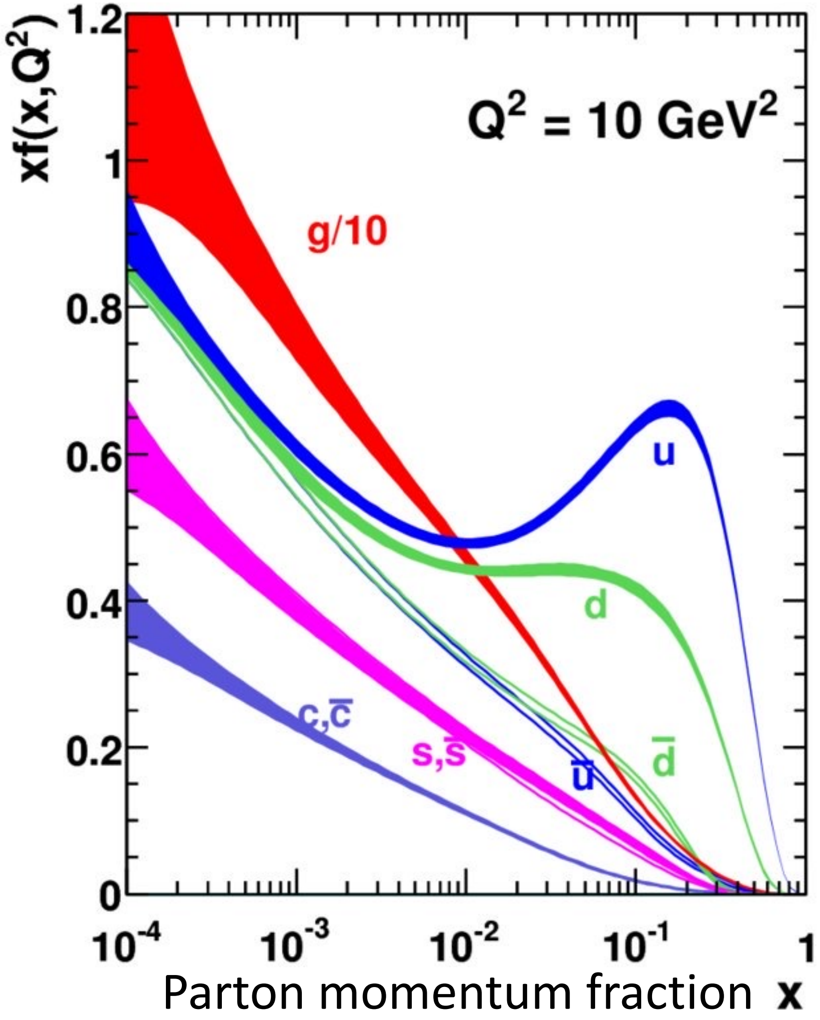

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- We can look inside nucleons to see what makes them up
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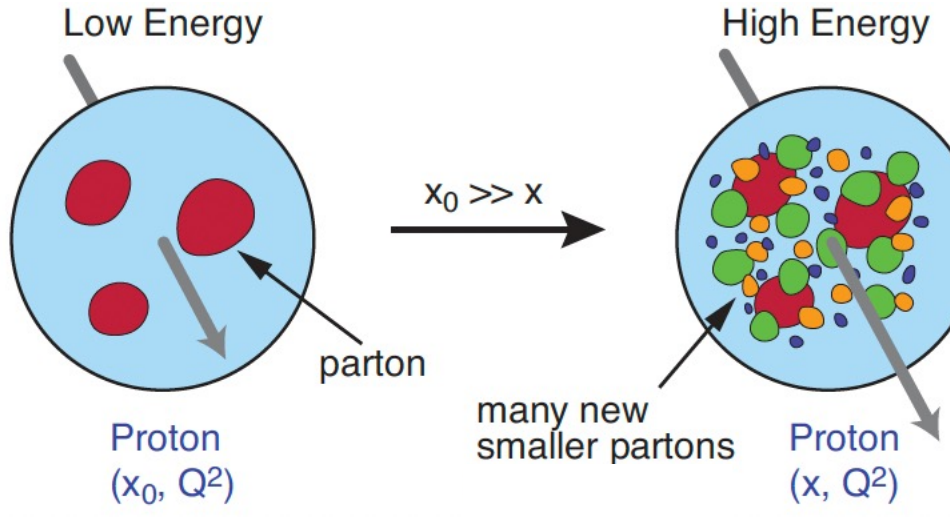
- When we look deeper, MANY sea quarks and gluons contribute as well
- up(u), down(d), charm(c), strange(s), antiquarks (ū,đ,c̄,s̄) and gluons (g)
- Nucleons and the nucleus change with energy!
- We aim to measure these nucleus/nucleon distributions at high energies



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

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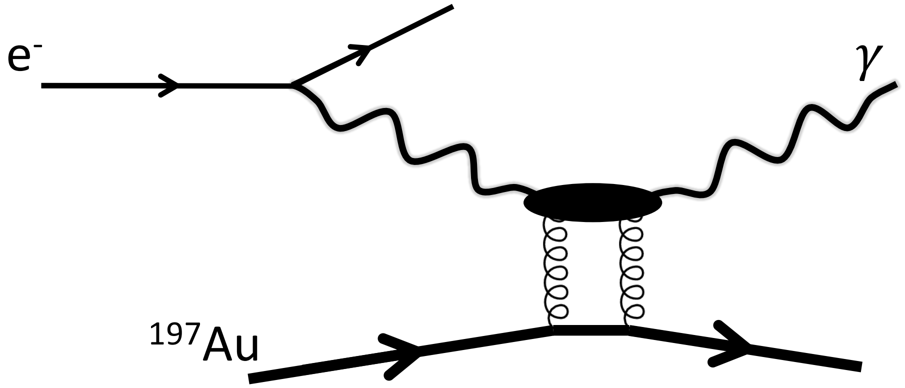
- Scattering mediated by virtual photon at EIC
- Image nucleus by scattering photon off of nucleus' "gluon cloud"



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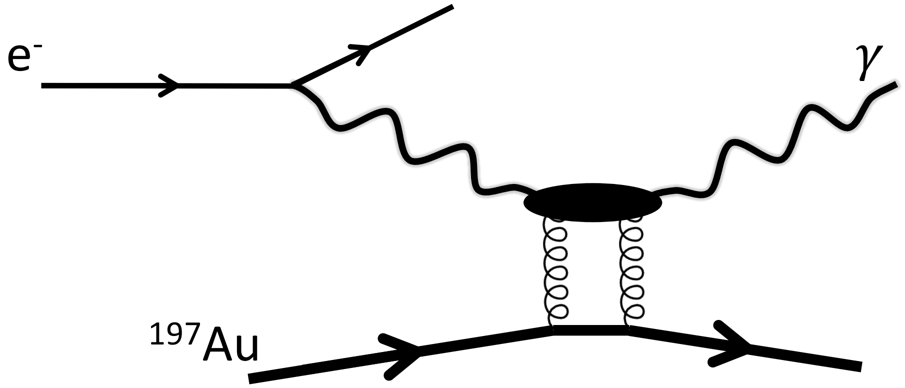

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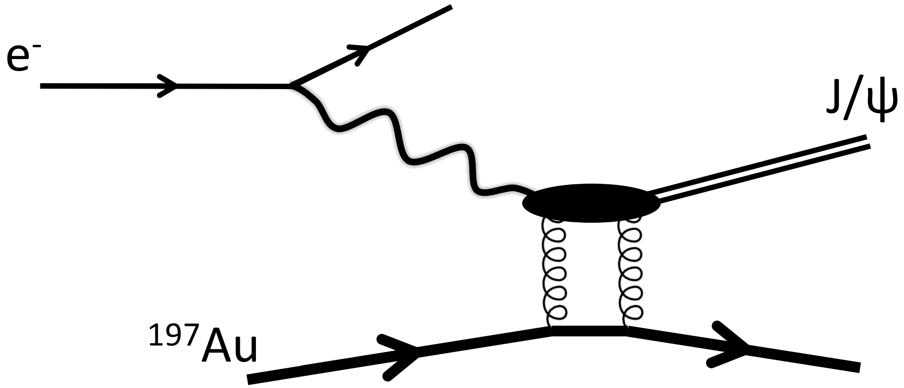

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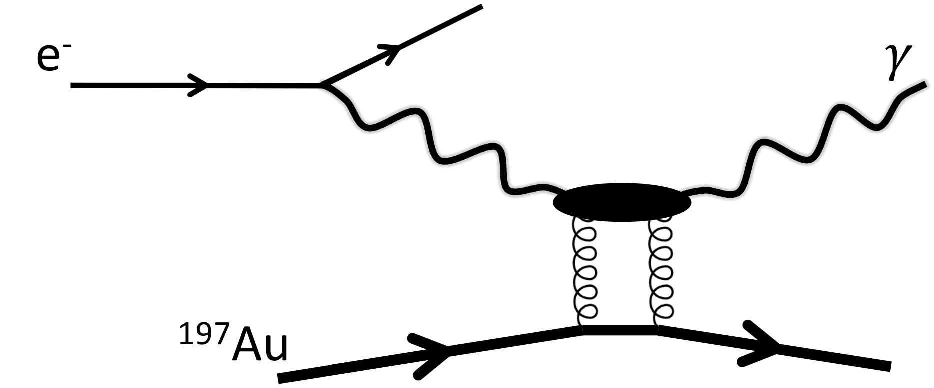

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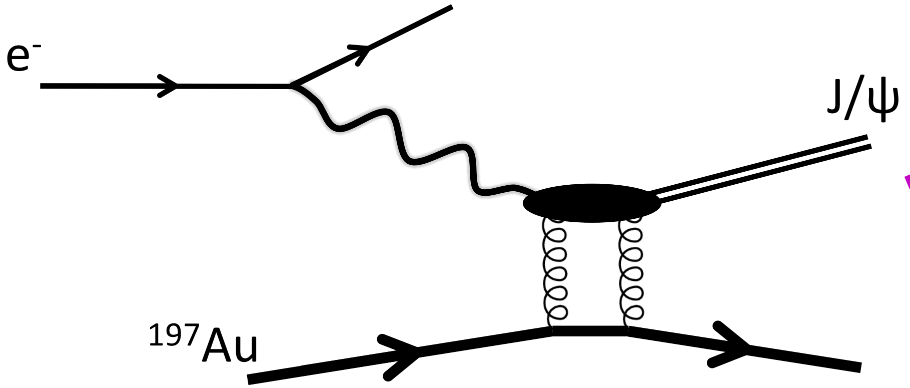
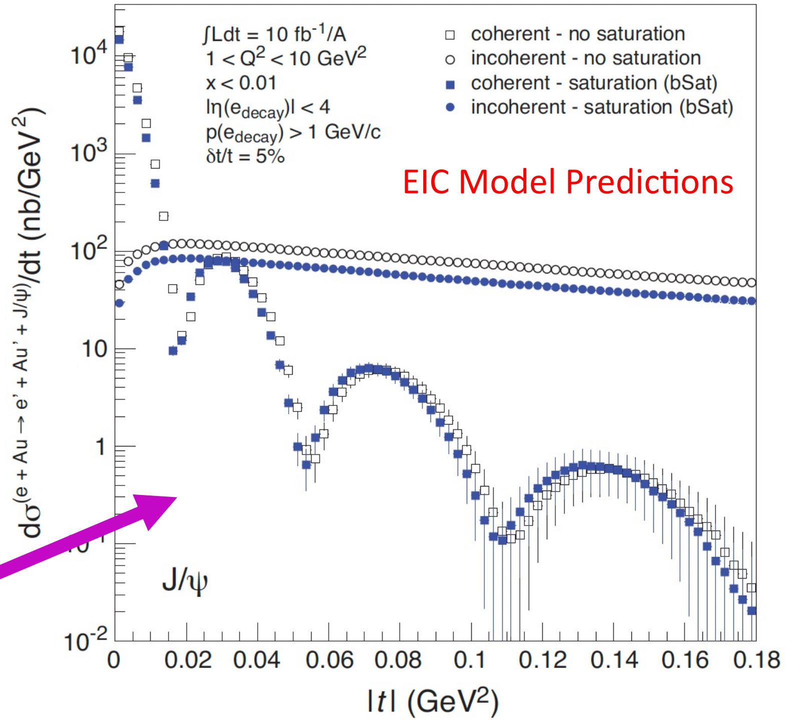


Where we want to be with the EIC

EIC White Paper (2012)



Momentum transfer to Ion

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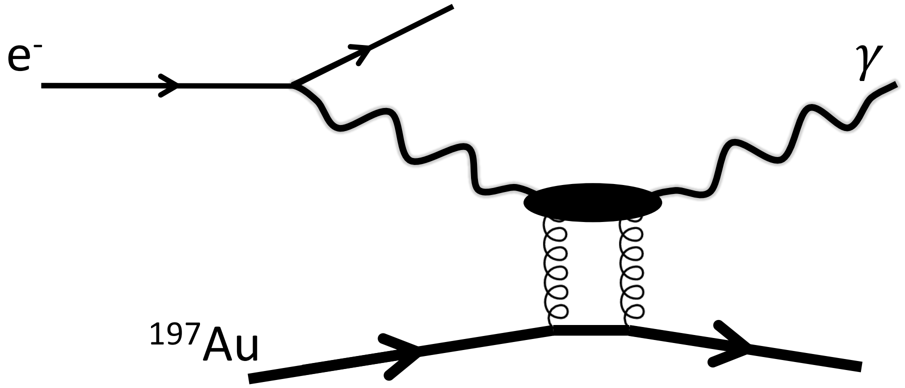

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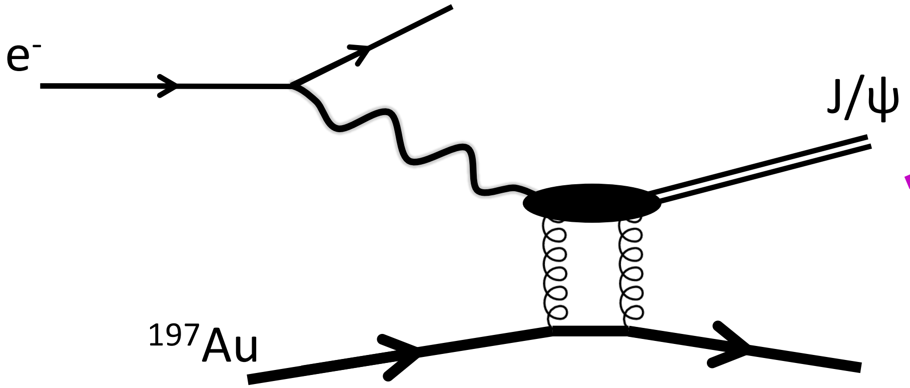

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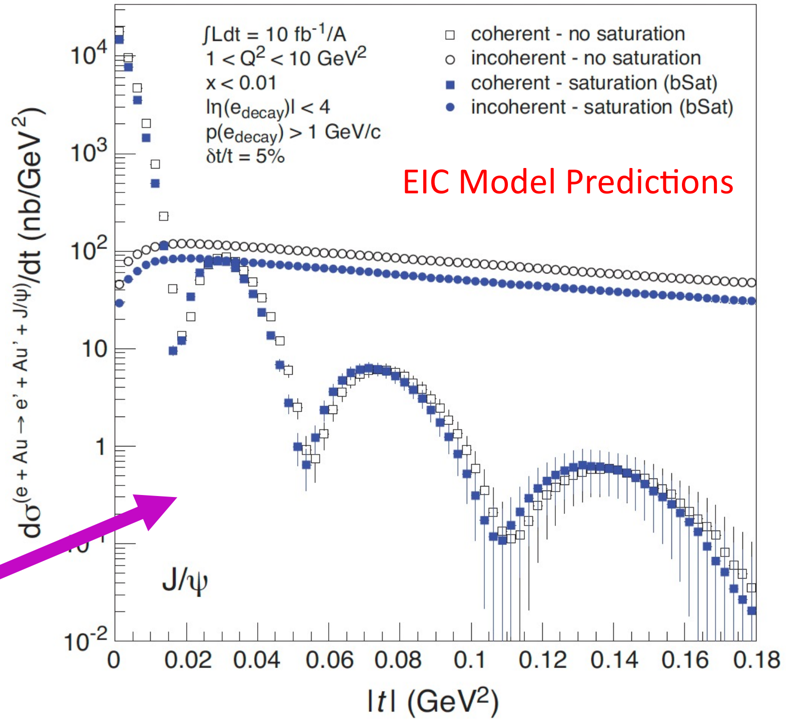
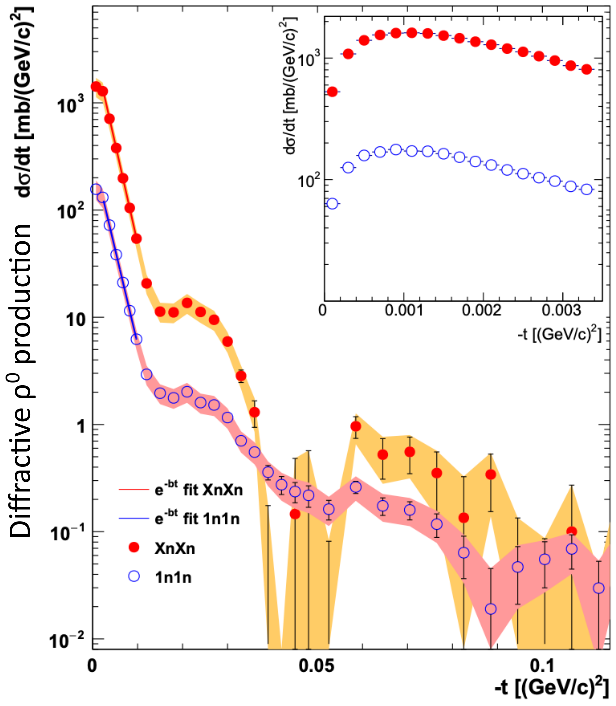


Momentum transfer to Ion

Where we are using RHIC

STAR (2017) arXiv:1702.07705

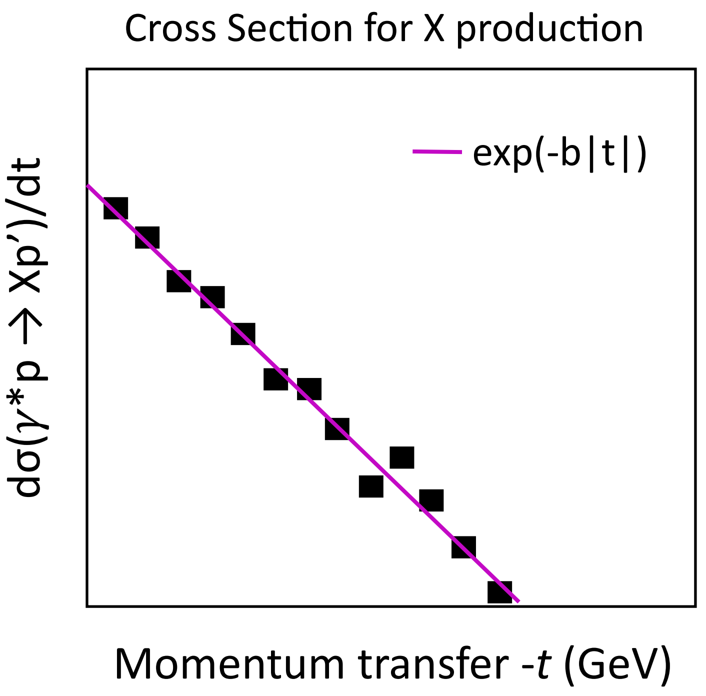


Momentum transfer to Ion

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

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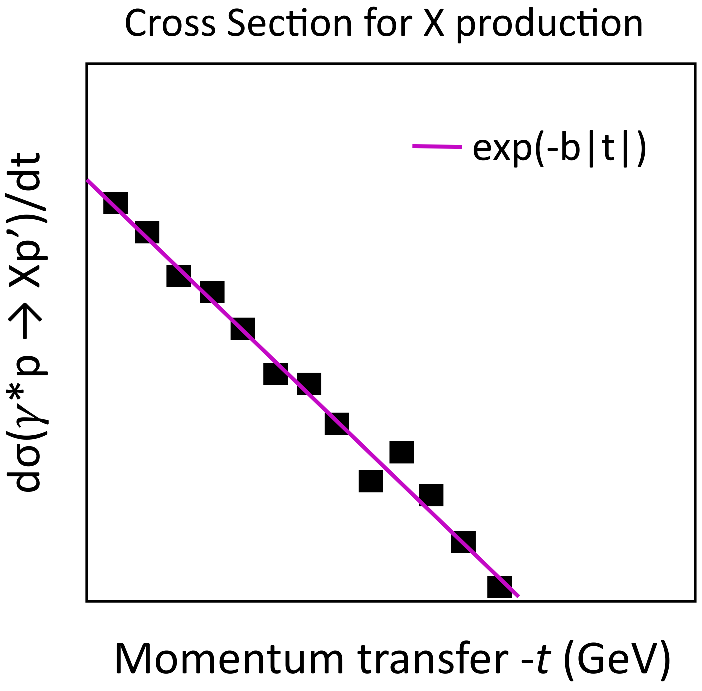
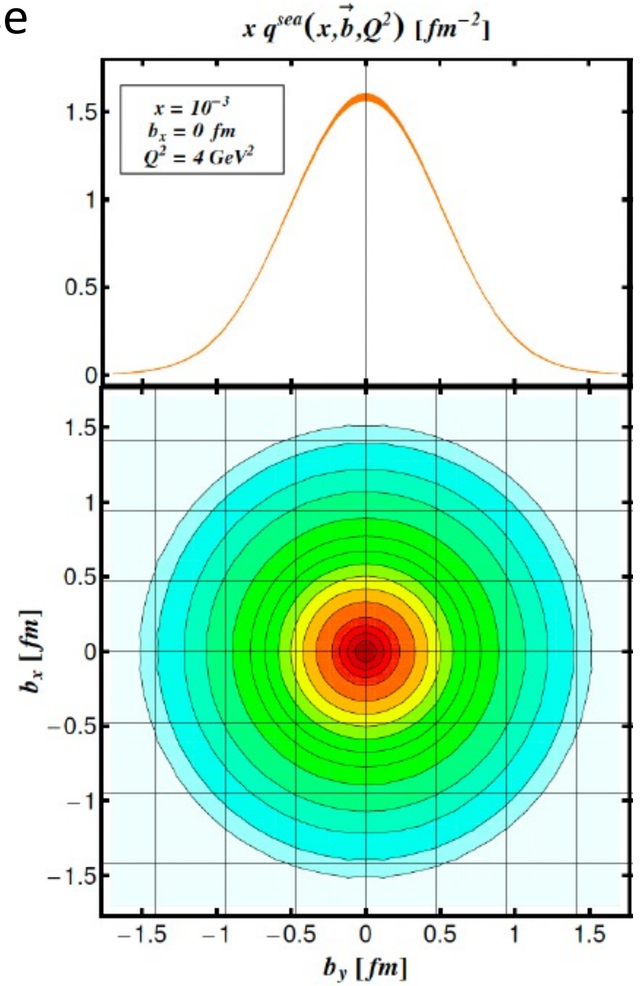
Forward cross sections → nucleon form factors

- 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)



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



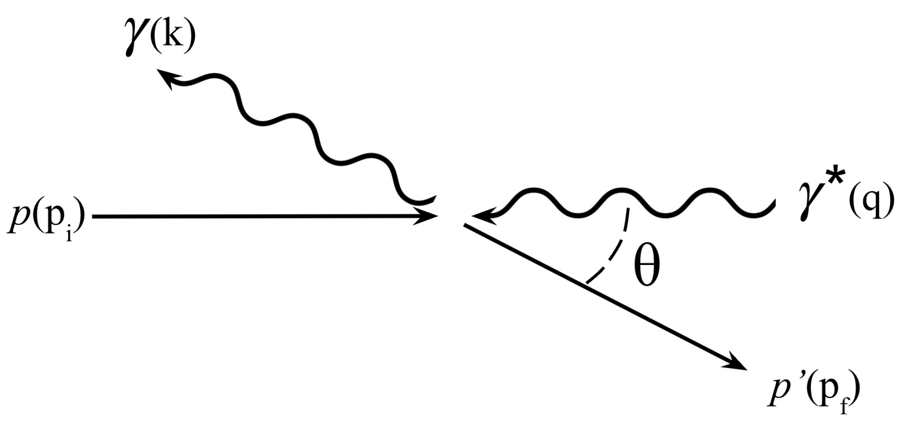
EIC Yellow Report (2021)

Backward Physics

Backward Physics

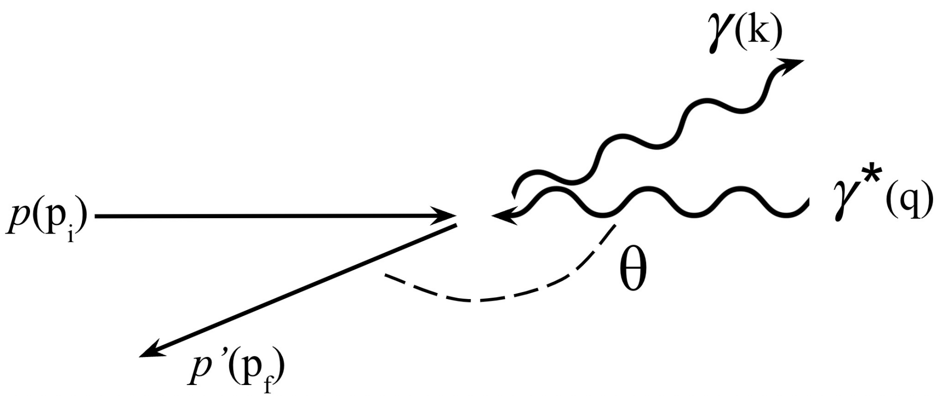
<u>The Question</u>: what does it mean when the photon and ion scatter backward?

Forward Compton Scattering (COM Frame)



Glancing collision, small momentum transfer

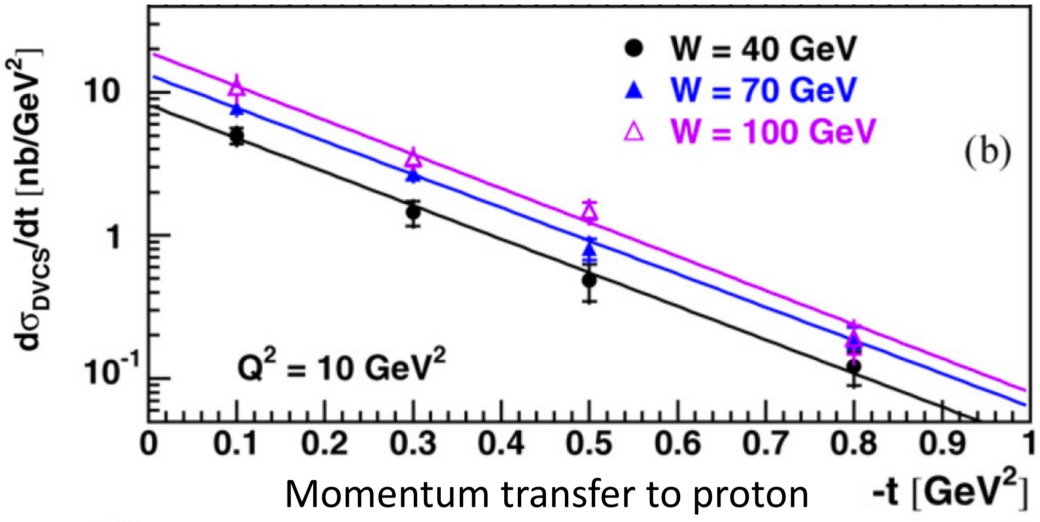
Backward Compton Scattering (COM Frame)



Backscattering, large momentum transfer

A Backward Peak?

H1 Collaboration / Physics Letters B 659 (2008) 796–806



Momentum transfer to proton

- Production Xsec on proton typically modeled by exponential decrease with increasing momentum transfer *t*:

$$\frac{d\sigma}{dt} \sim \exp(-B|t|)$$

- This is consistent with Gaussian nucleon shape profile

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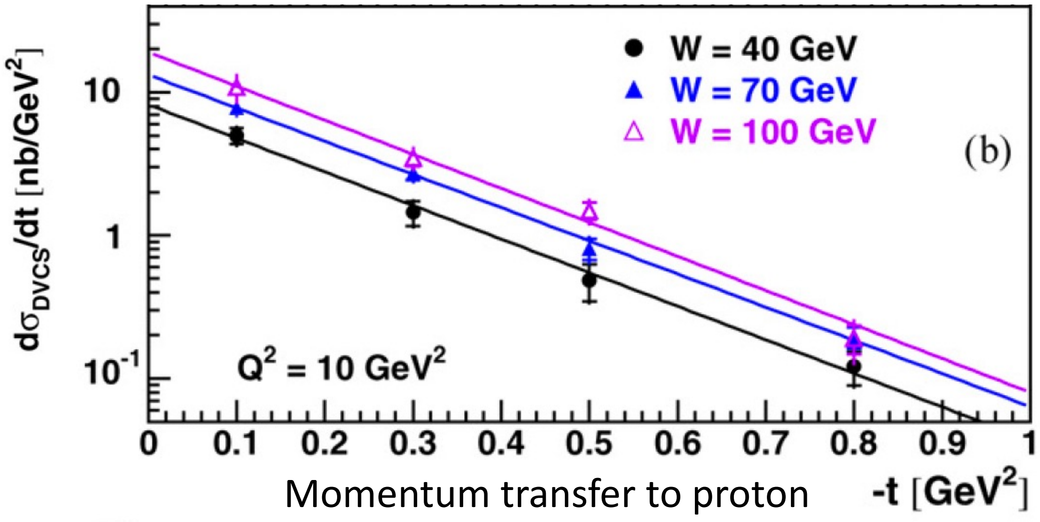

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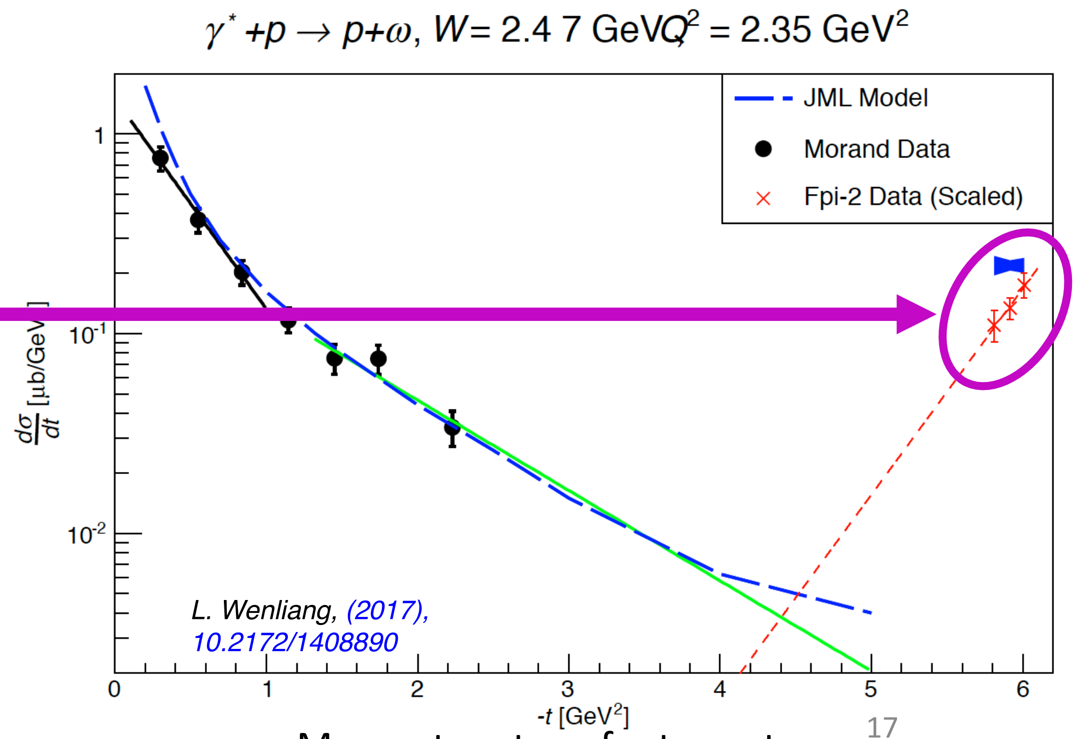
Non-trivial Behavior at High t

- Meson-production cross sections have exponential rise at the highest $|t|$ values! (backward scattering angles)



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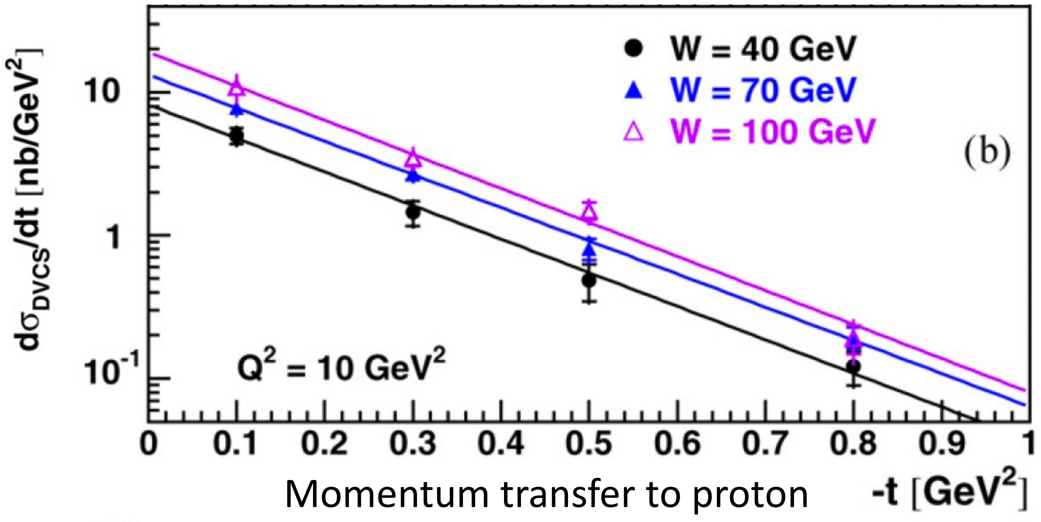

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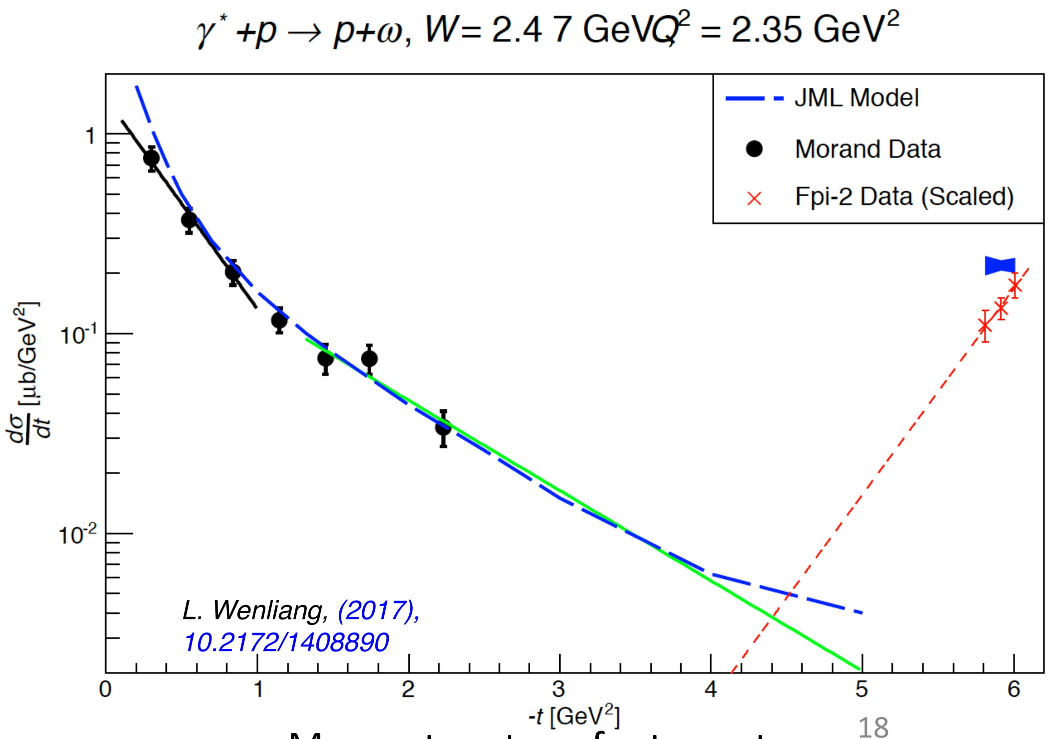
Non-trivial Behavior at High t

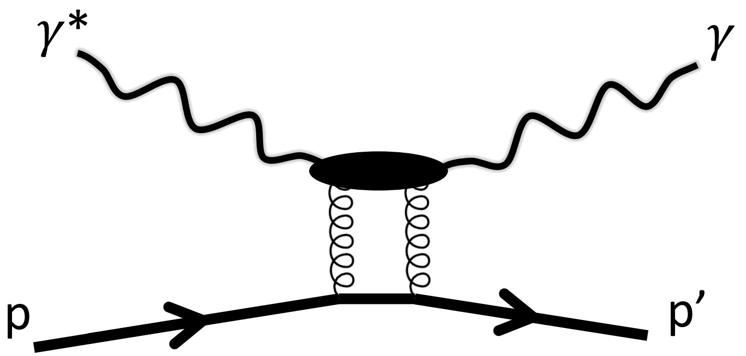
- Meson-production cross sections have exponential rise at the highest $|t|$ values! (backward scattering angles)
- This feature comes from u-channel contributions
- Characterized by high Mandelstam t and small u
- What does the peak mean?



Momentum transfer to proton

Meaning of Backward Cross Section

Forward scattering off proton's gluon field



Backward Xsecs → partonic correlations and baryon number?

- Forward production maps parton distributions within proton/nucleus

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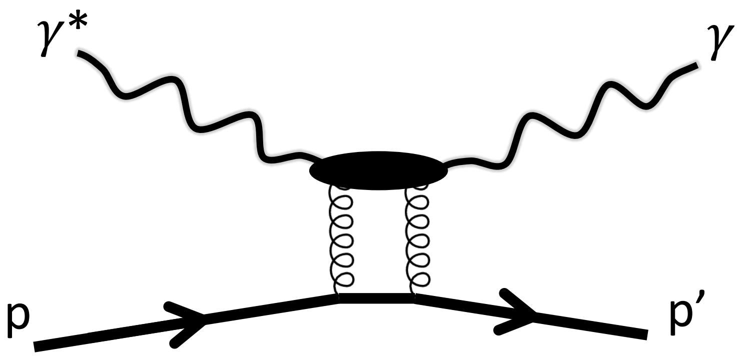
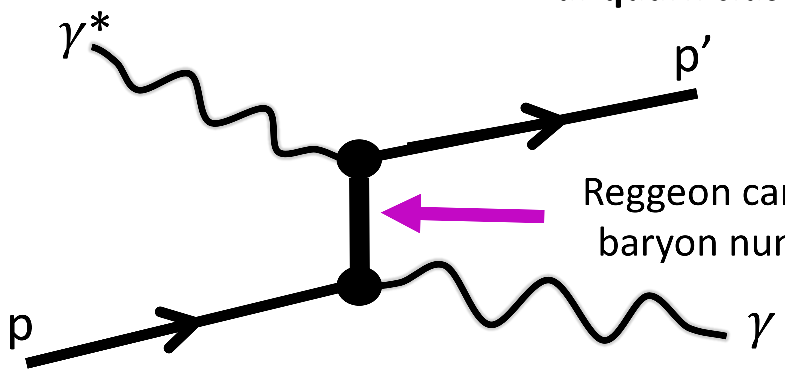


Backward scattering off proton's… baryon number?
gluon junction?
di-quark clusters?



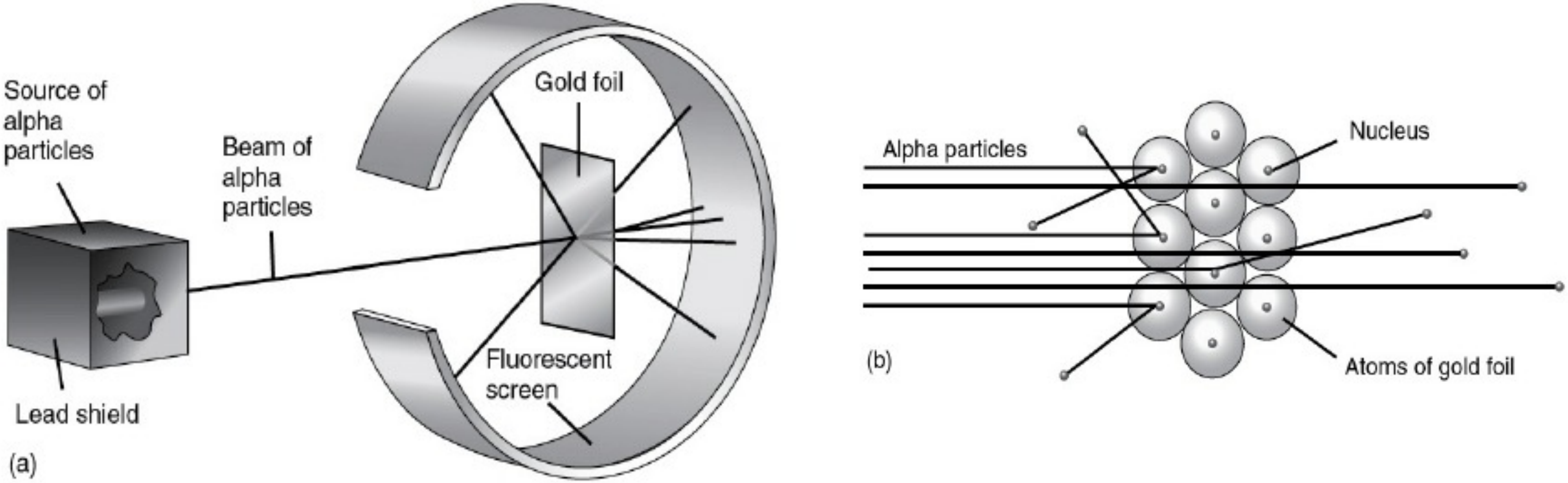
Backward Xsecs → partonic correlations and baryon number?

- Forward production maps parton distributions within proton/nucleus
- Recent (2021) work by Pire et al. formulates a similarly meaningful interpretation of backward cross sections
- They argue backward reactions may map transverse distribution of quark clusters and baryon number

> "baryon-to-meson (and baryon-to-photon) TDAs share common features both with baryon DAs and with GPDs and encode a conceptually close physical picture. They characterize partonic correlations inside a baryon and give access to the momentum distribution of the baryonic number inside a baryon. Similarly to GPDs, TDAs – after the Fourier transform in the transverse plane – represent valuable information on the transverse location of hadron constituents."

B. Pire, K. Semenov-Tian-Shansky, and L. Szymanowski, Phys. Rept. 940, 1 (2021), arXiv:2103.01079 [hep-ph].

Backward Scattering



Bertulani, Carlos. (2009). Nuclear Reactions.

Backward Scattering

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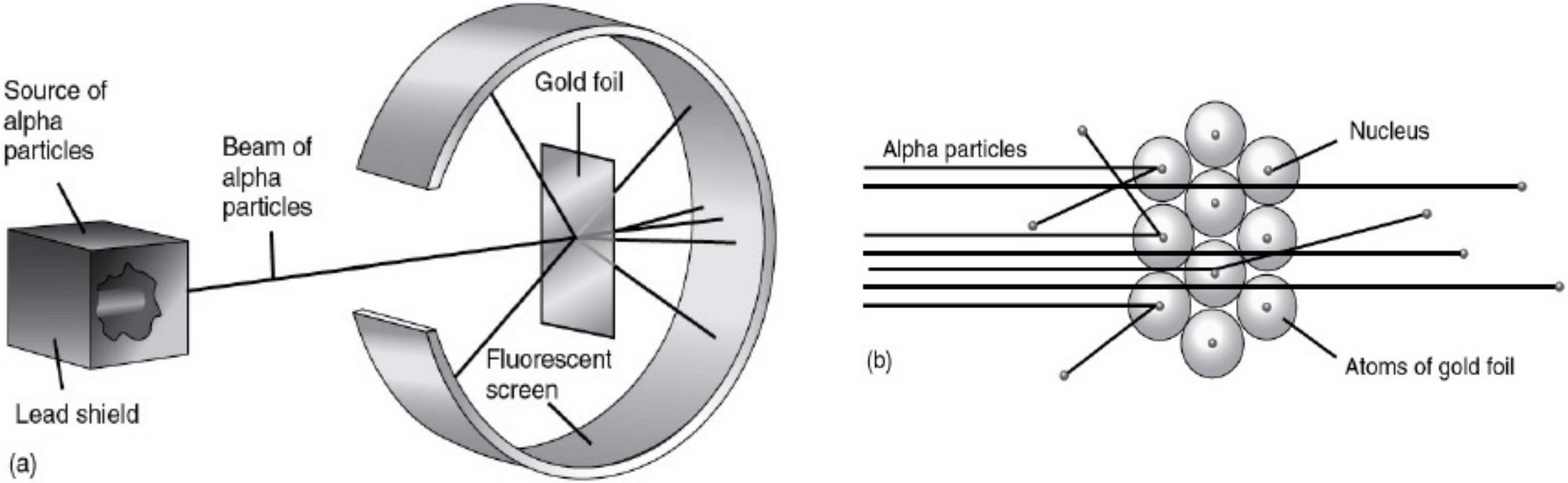

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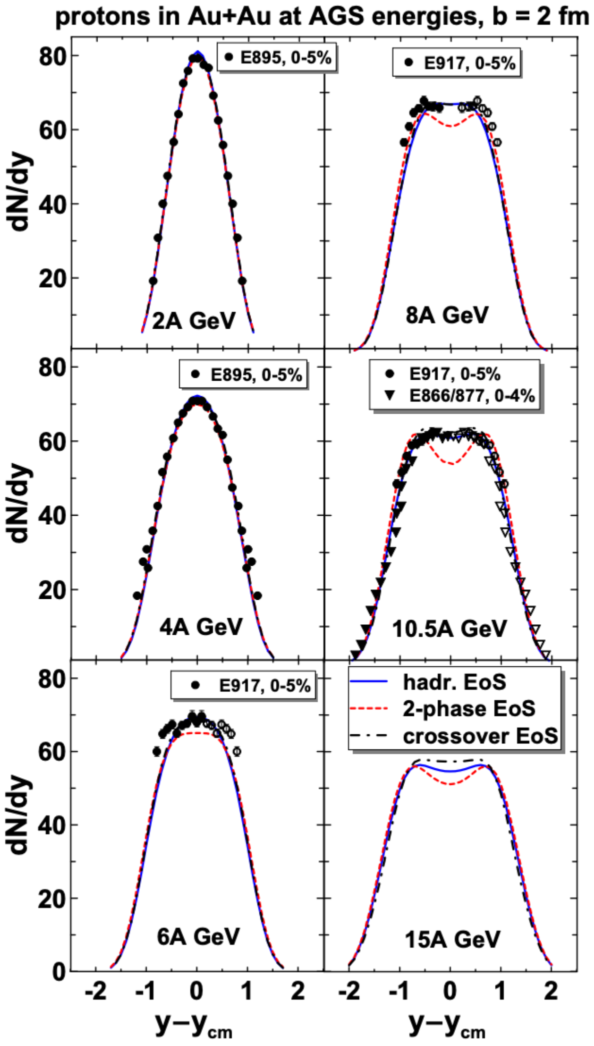
Connecting Backward Processes to Baryon Stopping and Baryon Junctions

Baryon Stopping in Heavy-Ion Collisions

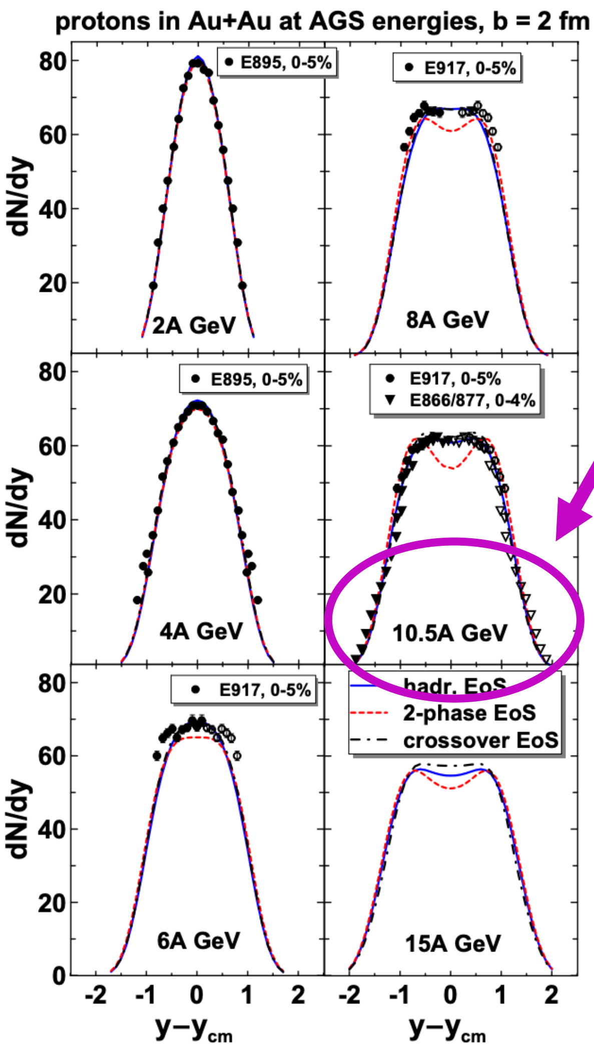


Net-proton rapidity distributions at AGS compared with three models of EoS

Yu.B. Ivanov. Phys Lett B, Vol 721, Issues 1–3, 2013, 123-130, ISSN 0370-2693

- In relativistic heavy-ion collisions, many nucleons are almost completely stopped

Baryon Stopping in Heavy-Ion Collisions



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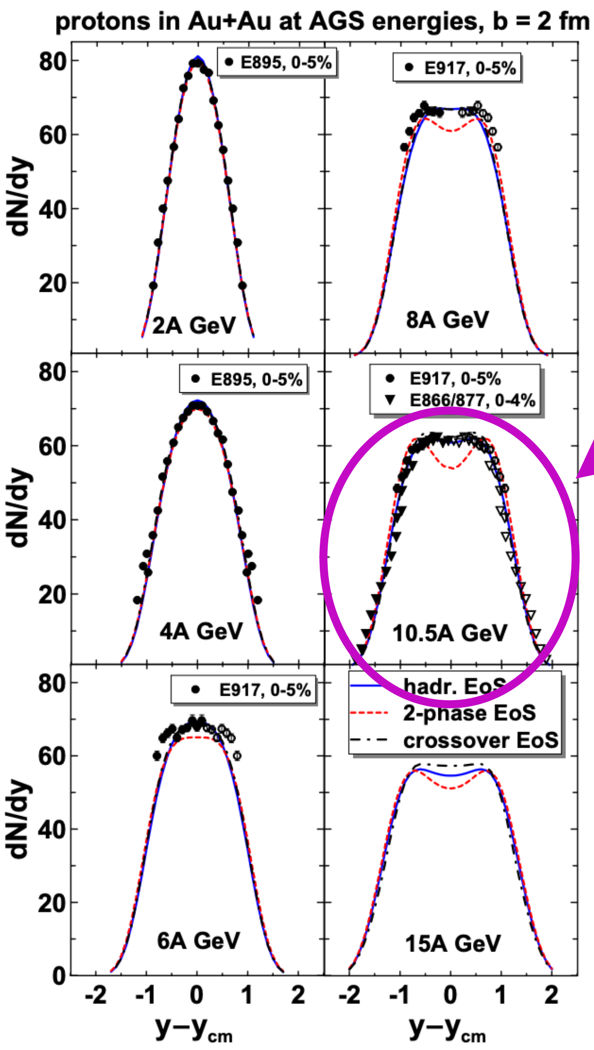

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- In relativistic heavy-ion collisions, many nucleons are almost completely stopped
- For example, we can collide ^{197}Au nuclei in which each proton and neutron individually has 10.5 GeV of kinetic energy
- After the collision, many of the protons have lost nearly all of their longitudinal momentum!
- We call this phenomenon **baryon stopping**

Connection to Baryon-Junction Model

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- In 1996, Dima Kharzeev (CERN) began laying the foundations for what would become known as the "baryon-junction model"

Kharzeev, Phys.Lett. B378 (1996) 238-246, arXiv:nucl-th/9602027

CAN GLUONS TRACE BARYON NUMBER ?

D. KHARZEEV

Theory Division, CERN, CH-1211 Geneva, Switzerland
and
Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany

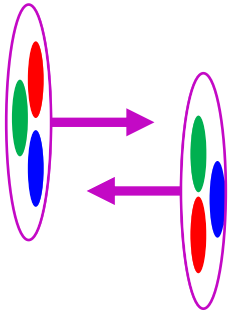
Abstract

QCD as a gauge non-Abelian theory imposes severe constraints on the structure of the baryon wave function. We point out that, contrary to a widely accepted belief, the traces of baryon number in a high-energy process can reside in a non-perturbative configuration of gluon fields, rather than in the valence quarks. We argue that this conjecture can be tested

Connection to Baryon-Junction Model

- In 1996, Dima Kharzeev (CERN) began laying the foundations for what would become known as the "baryon-junction model"
- At high energies, nucleon and valence-quark wave functions are contracted longitudinally, thereby contracting the collision time

$$t_{coll} \sim (x_V P)^{-1}$$



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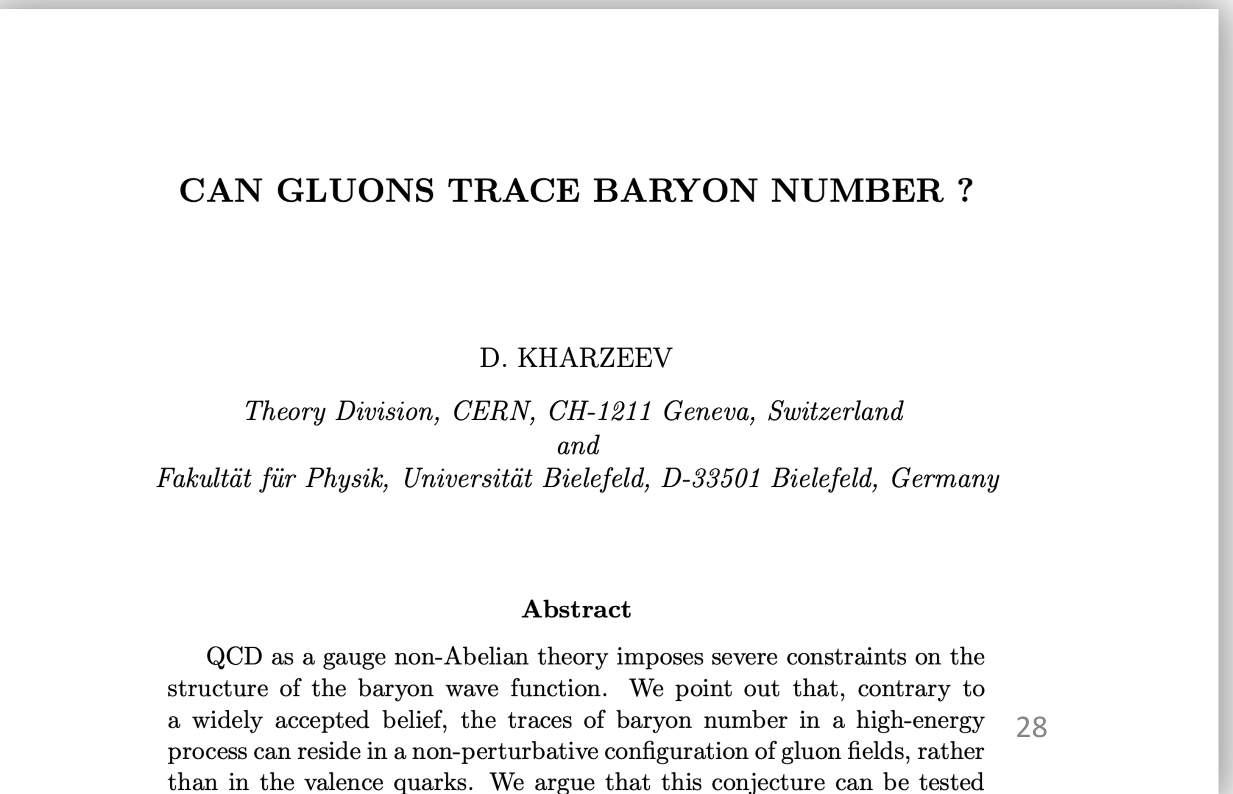

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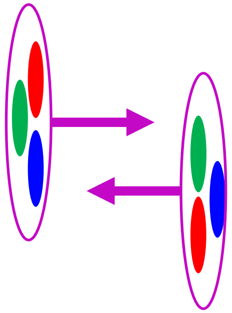

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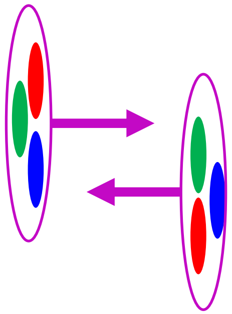

- The interaction length (transverse direction) is not likewise contracted

$$t_{int} = const \sim O(1\ fm)$$

- At high energies t_{coll} becomes too small for stopping via valence quarks to make sense

$$t_{coll} << t_{int}$$

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Abstract

QCD as a gauge non-Abelian theory imposes severe constraints on the structure of the baryon wave function. We point out that, contrary to a widely accepted belief, the traces of baryon number in a high-energy process can reside in a non-perturbative configuration of gluon fields, rather than in the valence quarks. We argue that this conjecture can be tested

Backward Physics and Baryon Junctions

- In BJM, baryon number is not just carried by valence quarks
- baryon number is also carried by a non-perturbative configuration of gluons. These gluons can be easily stopped in a collision
- In backward production protons lose most of their momenta like baryon stopping!

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Backward-angle (*u*-channel) production at an electron-ion collider

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In backward photoproduction of mesons, the produced vector meson takes most of the struck nucleon momentum. The nucleon loses most of its momentum, and so is shifted several units of rapidity. Thus the Mandelstam u is small, while the squared momentum transfer t is typically large, near the kinematic limit. In a collider geometry, backward production transfers the struck baryon by many units of rapidity, in a striking similarity to baryon stopping. We explore this similarity, and point out the similarities between the Regge theories used to model baryon stopping with those that are used for backward production. We then explore

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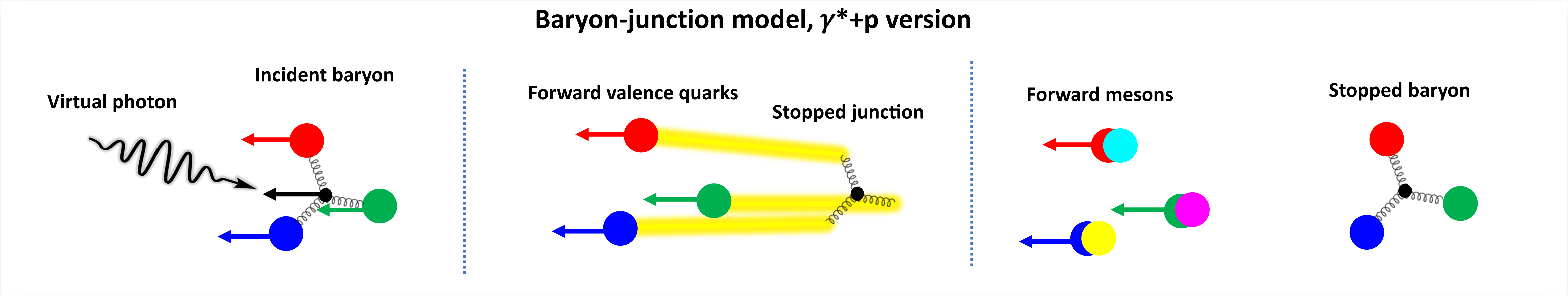
- In our recent paper, Spencer Klein makes the connection between backward production and baryon junctions
- In this model, the incident photon, fluctuating to a quark-antiquark dipole, scatters with gluon junction
- Stopped junction dressed with quarks, and high-momentum mesons produced



What Backward Measurements Do We Want?

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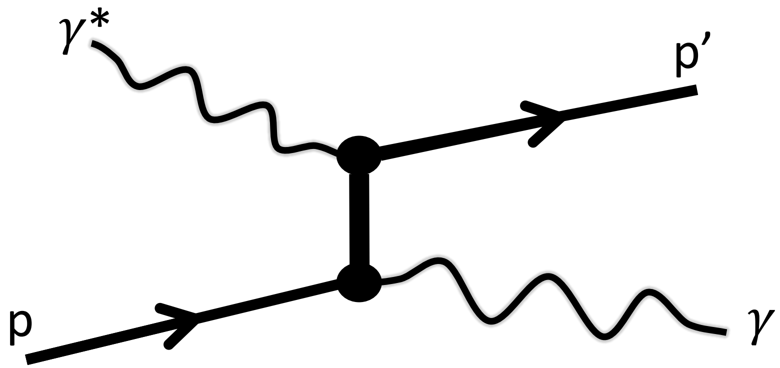
Backward scattering



What we hope to measure

- Backward production cross section measurements for ω, ρ^0, ϕ, π^0, J/ψ, γ production
- As a function of
  - ❑ Momentum transfer *t*
  - ❑ Incident photon virtuality Q^2
  - ❑ Bjorken x

Questions we hope to answer

- Can we explain backward production and baryon stopping with one theory? (BJM?)
- How are the cross sections for ω, ρ^0, ϕ, π^0, J/ψ, γ production different and do these differences allow us to develop a comprehensive model of backward processes?
- What does the behavior of the cross section with *t* tell us about the distribution of baryon number, di-quark/three-quark clusters, or a baryon junction within the nucleus?
- If we can map these distributions using backward production, how do they evolve in x and Q^2?

Modeling Backward Processes for EIC Simulations

Modeling Backward Physics

- Aside from these fundamental questions, we are working on developing models of backward processes at the EIC
- We take limited data from fixed-target experiments, and attempt to extrapolate to EIC kinematics

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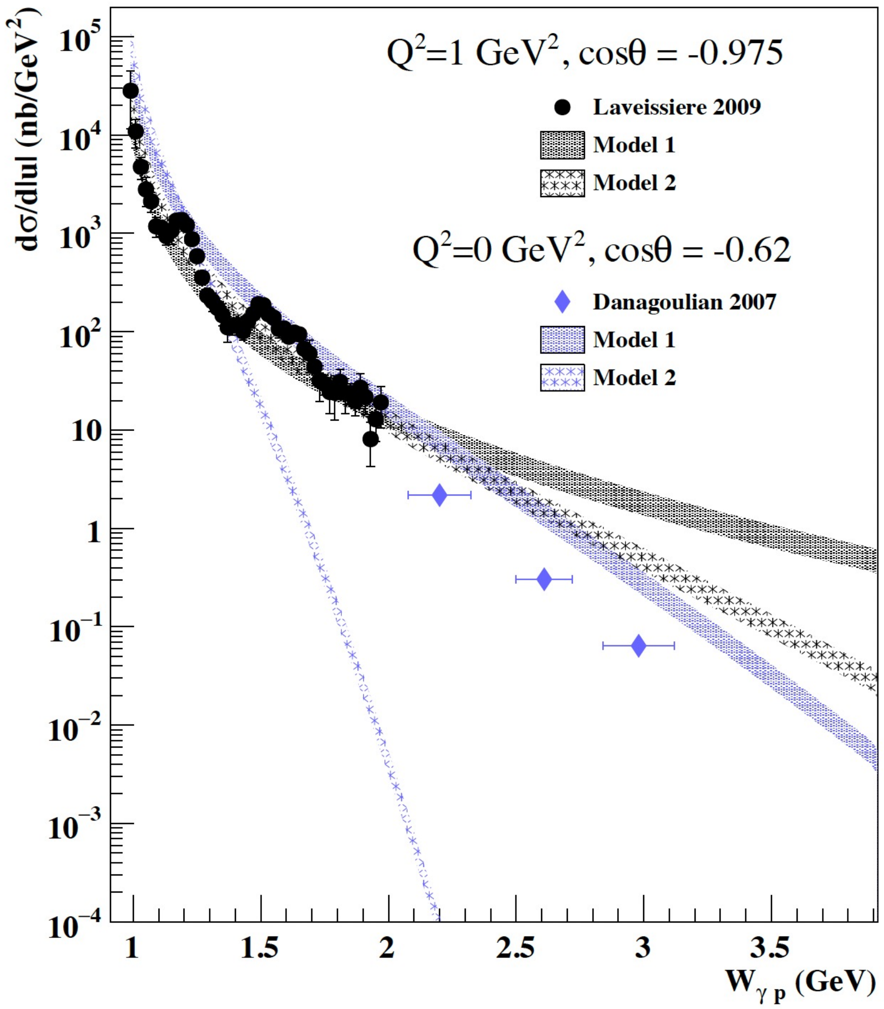
- For example, our backward Compton scattering (CS) (γ^*p→γp') models are compared against data at right



G. Laveissi`ere et al., Physical Review C 79 (2009), 10.1103/physrevc.79.015201.
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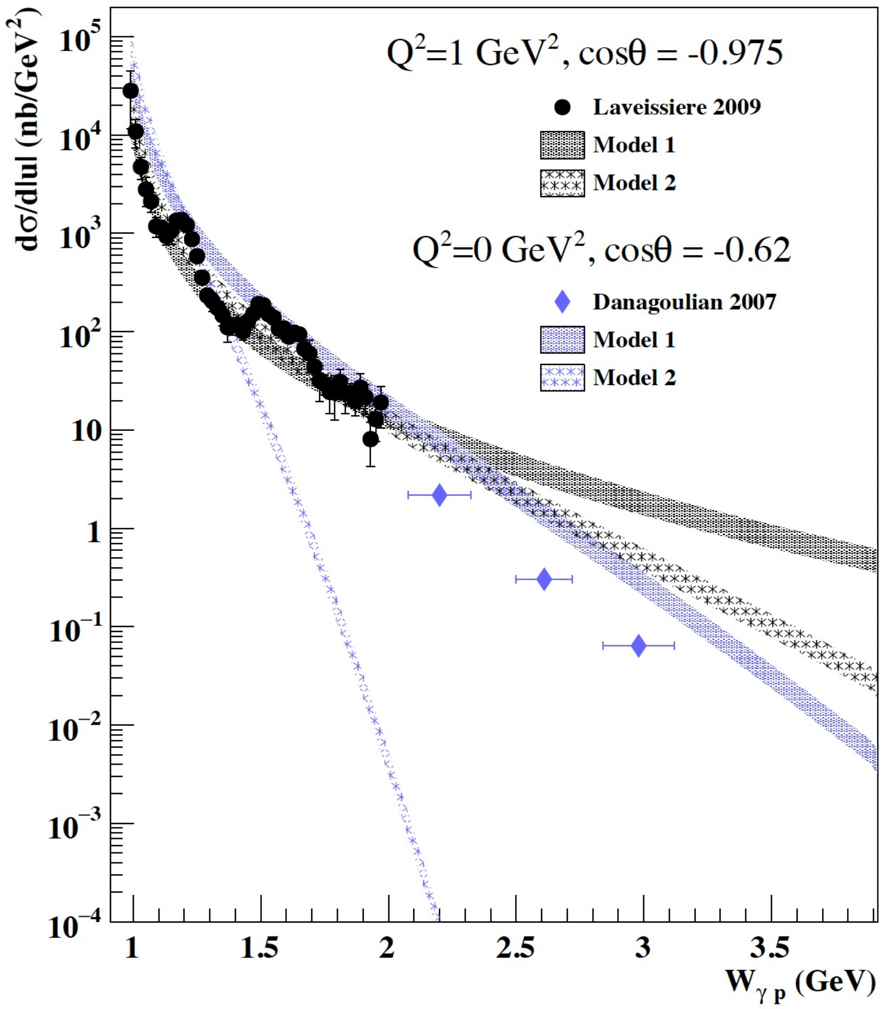
- For example, our backward Compton scattering (CS) (γ^*p→γp') models are compared against data at right
- In these models we combine predicted Xsec scalings to yield cross sections like:

$$\frac{d\sigma}{du}(Q^2, W, u) \approx \frac{A\exp(-D|u-u_0|)}{(W^2-m_p^2)^2(Q^2+\Lambda^2)^4/\mathrm{GeV}^8}$$



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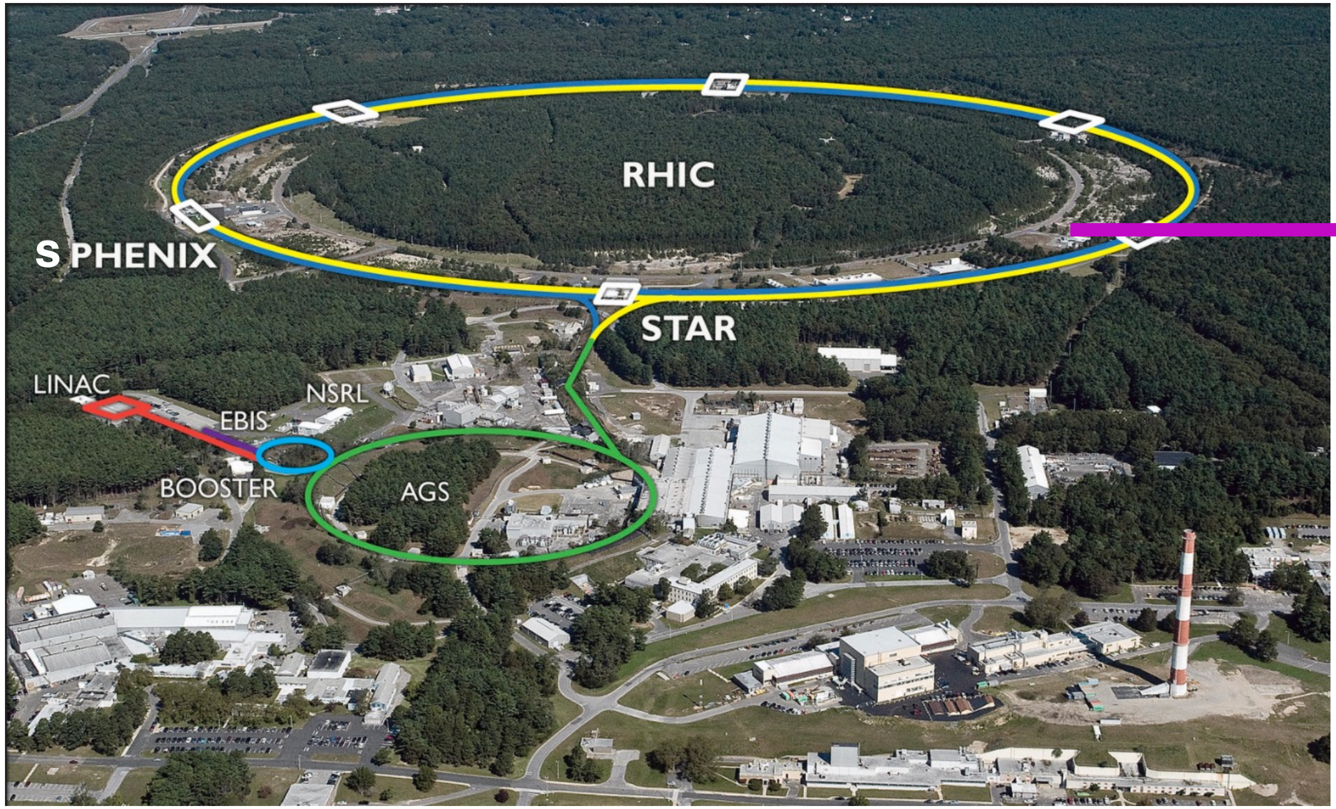
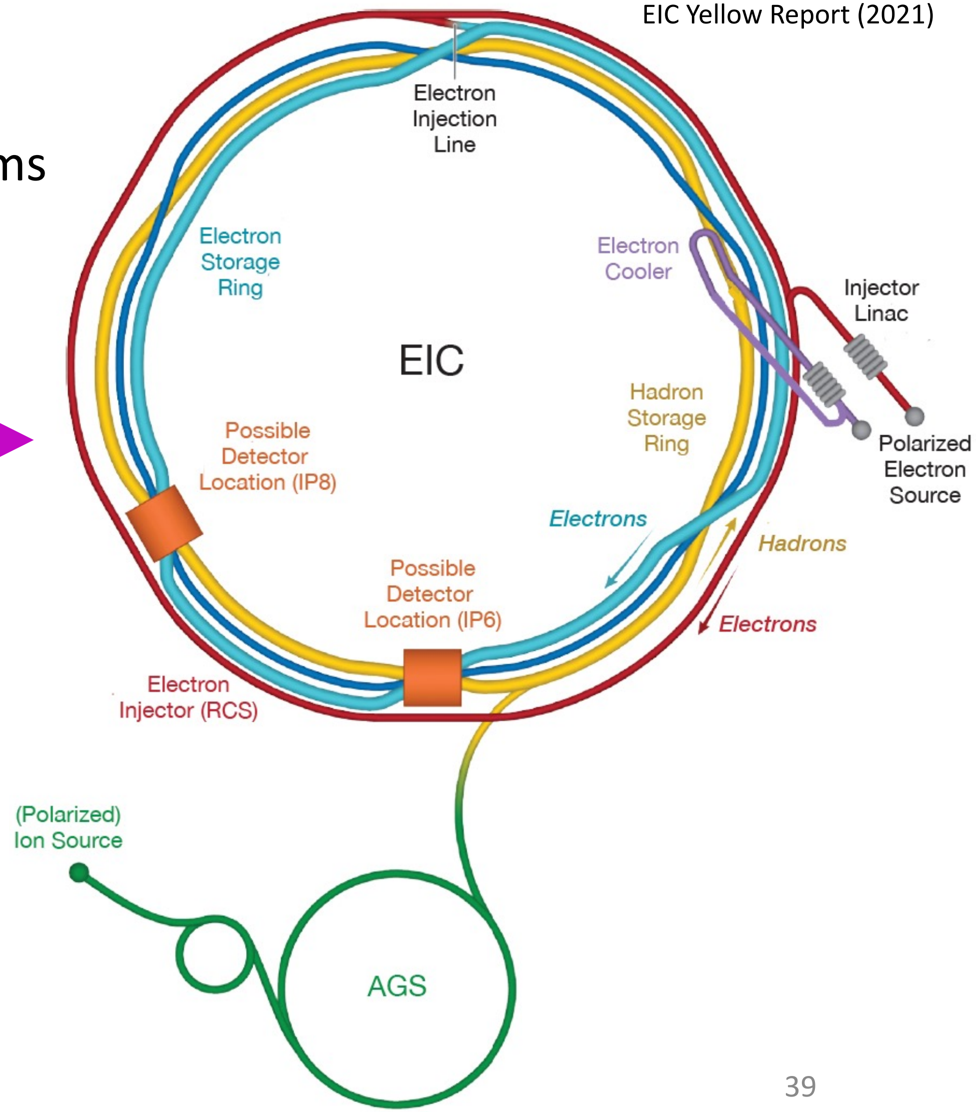
The Electron-Ion Collider (EIC)

- To be located at Brookhaven National Lab (Long Island, New York)
- Will replace existing Relativistic Heavy-Ion Collider
- Highly polarized beams
- Electron beam colliding with ion (p,d…, Au) beams
- 5, 10, and 18 GeV electron beams. 41, 100, 275 GeV proton beams



EIC Yellow Report (2021)



The Future EIC Detector

EIC Yellow Report (2021)

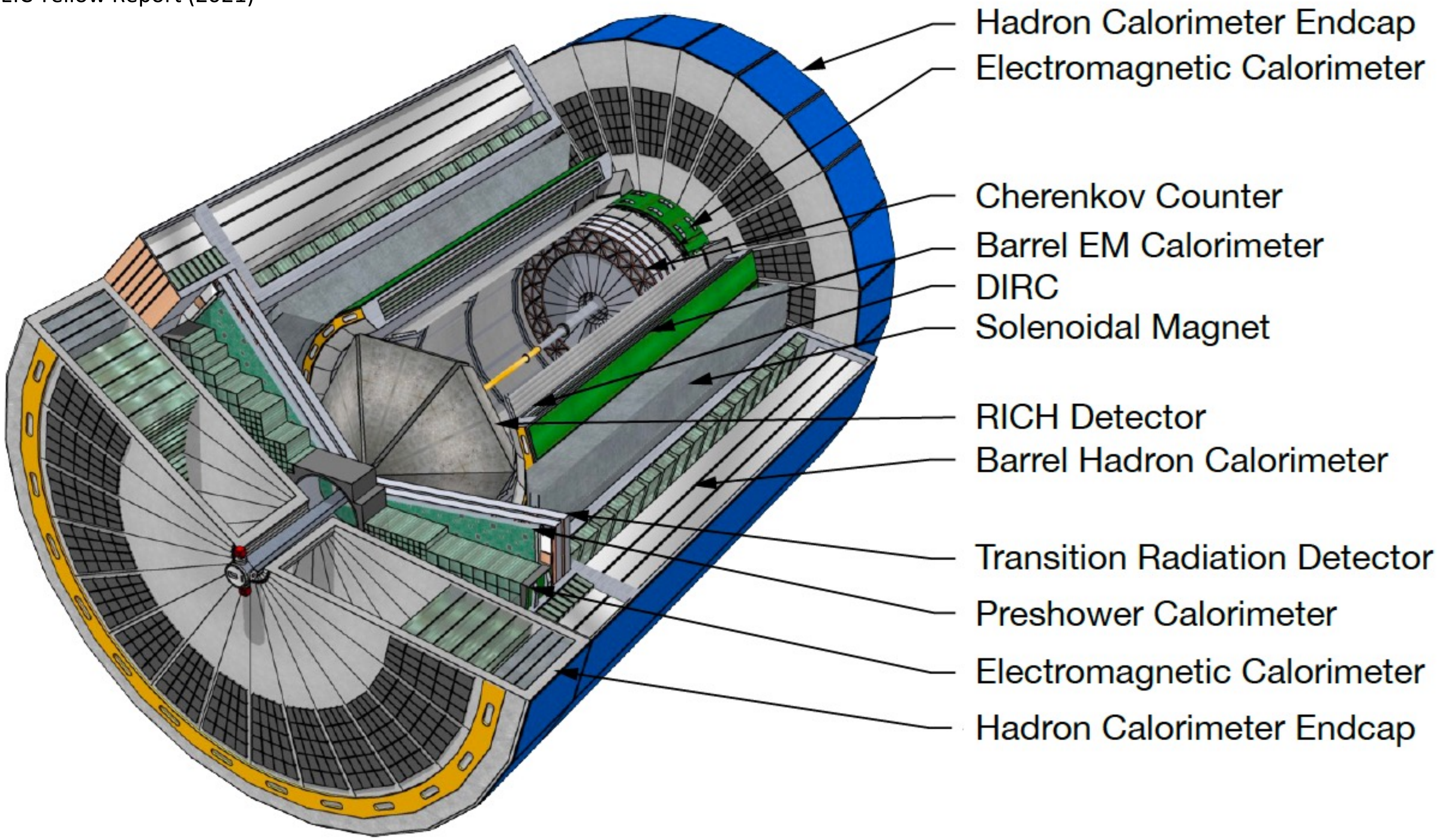


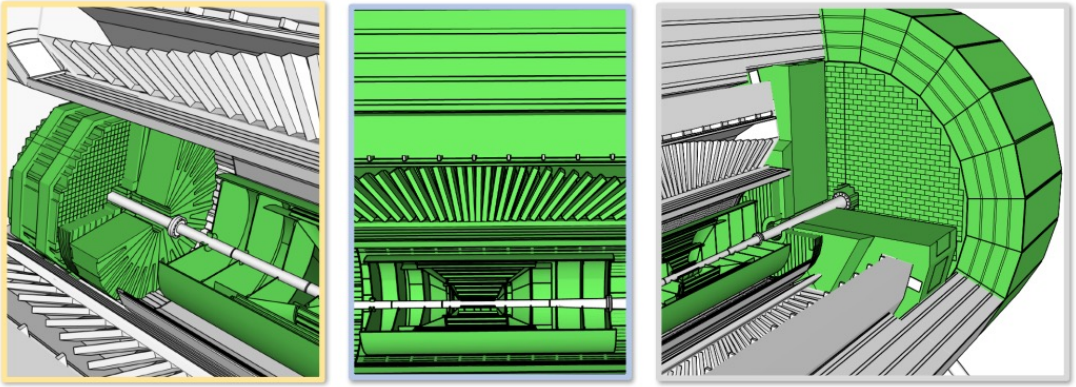
Figure 9.2: A cutaway illustration of a generic EIC concept detector.

The Future EIC Detector

- Detector development is currently underway!

ECCE Detector Proposal (2022)
arXiv:2209.02580v1

Central Detector Around Interaction Region



Backward Endcap

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)

Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- μRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)

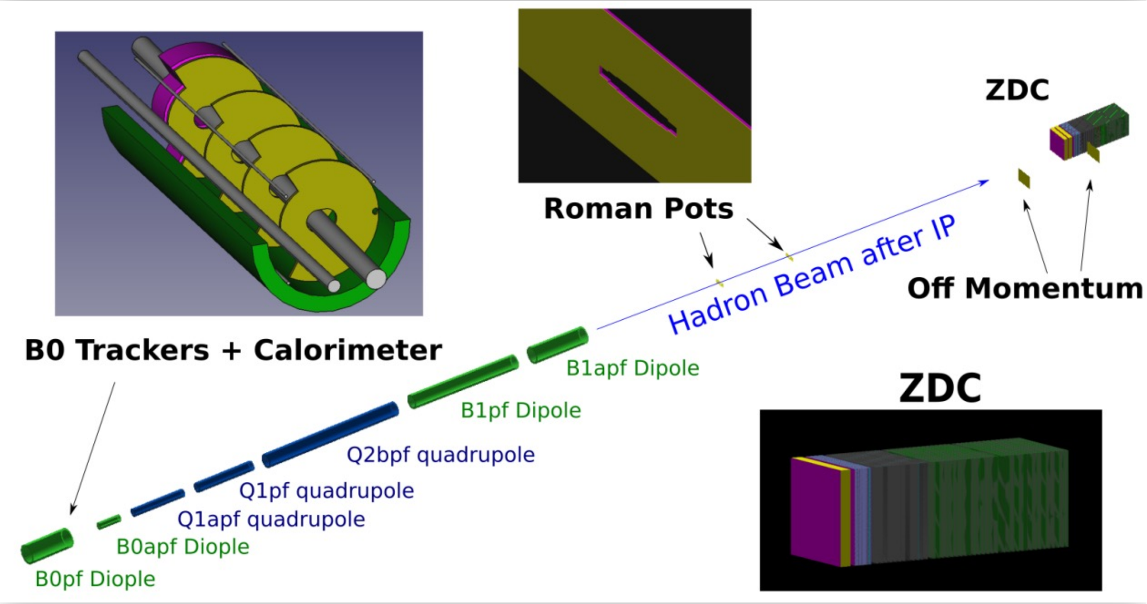
Forward Endcap

Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

PID:
- dRICH
- AC-LGAD TOF

Calorimetry:
- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LHFCAL)

Detectors and Magnets in Far-forward (ion-going) Direction



Detectors of Interest for Backward Production

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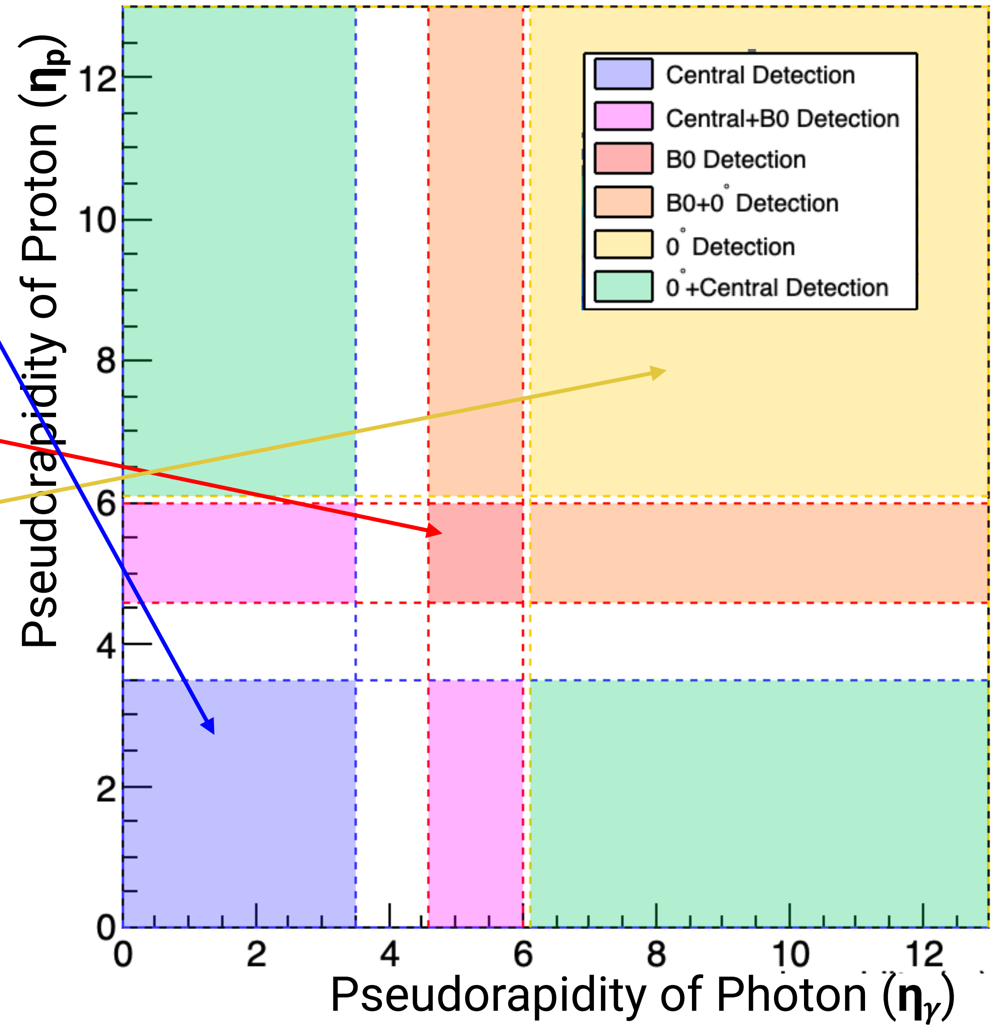
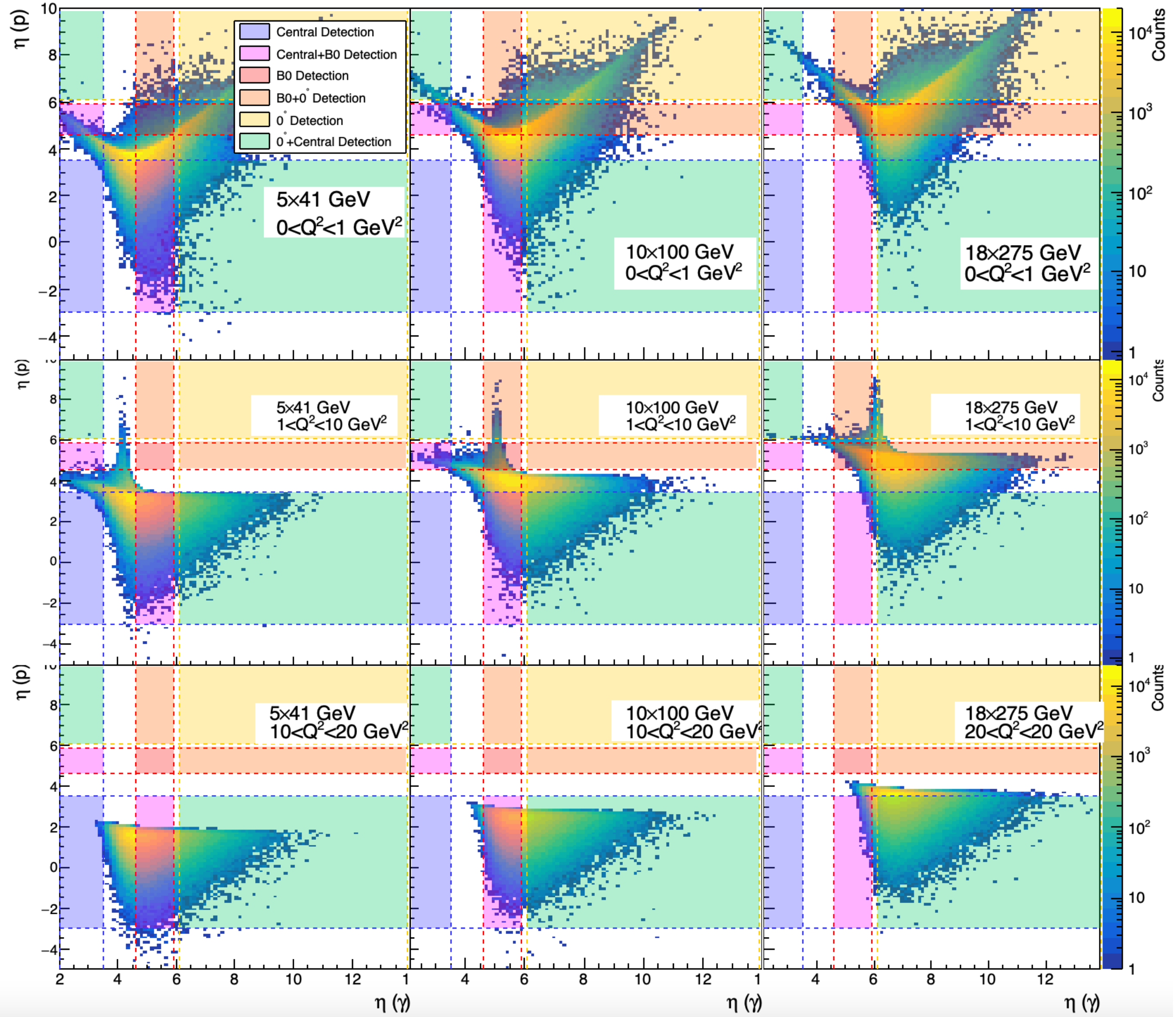
There are three detector regions of interest for backwards production

- Central Region (endcap & barrel): |η| < 3.5
  - ✓ Charged-particle tracking
  - ✓ Electromagnetic calorimetry
- B0 Magnets: 4.6 < η < 6.0
  - ✓ Charged-particle tracking
  - ? Electromagnetic calorimetry
- Zero-degree Detection: η > 6.215–5.991
  - ✓ Roman Pots: Charged-particle tracking
  - ✓ ZDC: Electromagnetic calorimetry



Backward CS Acceptances

- These simulations use model 1
- Low collision energies: photon lands in B0 and ZDC
- ZDC is critical at high energies
- At low Q^2 proton is often in B0
- At high Q^2, proton is almost exclusively in central detector region



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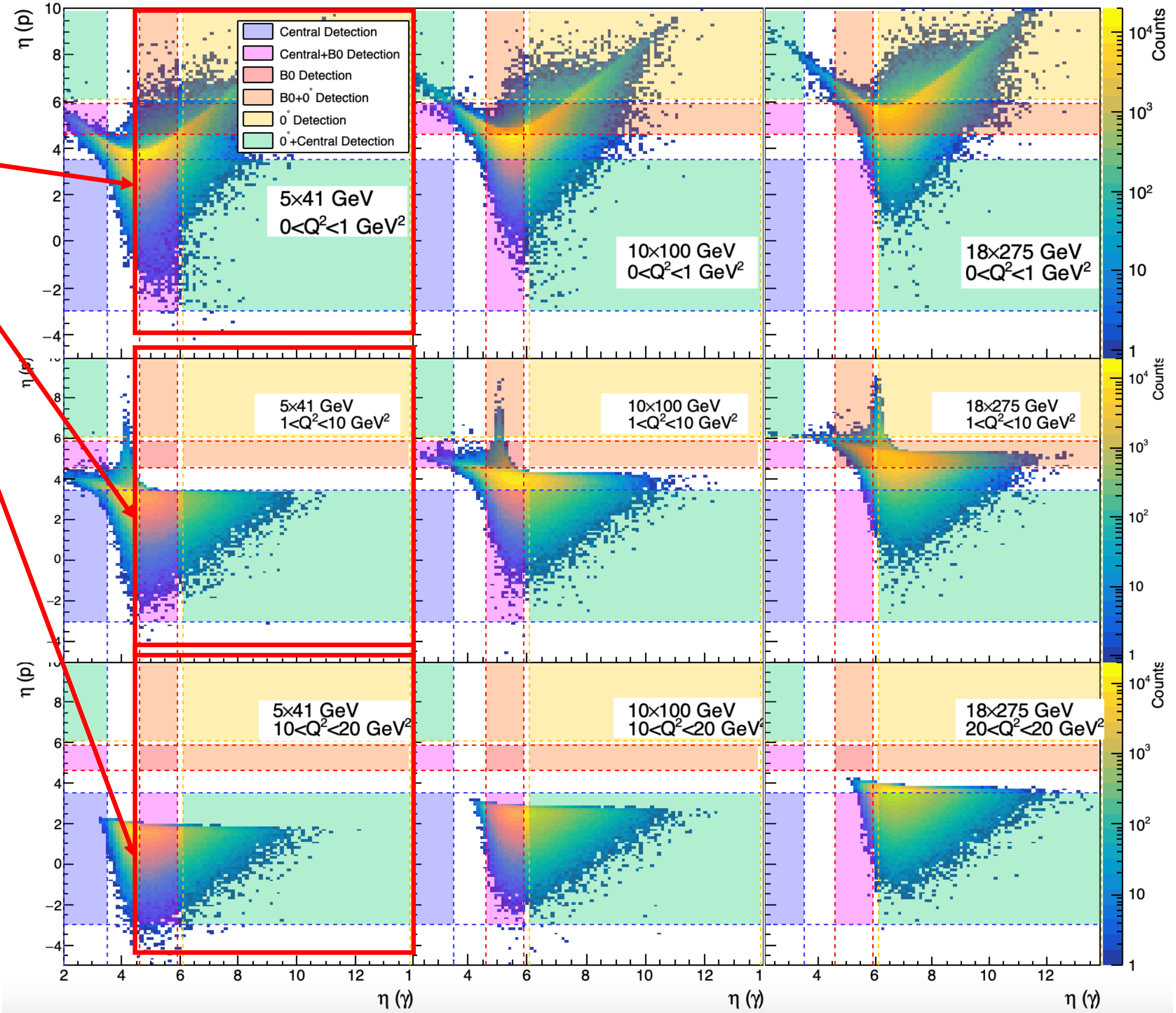

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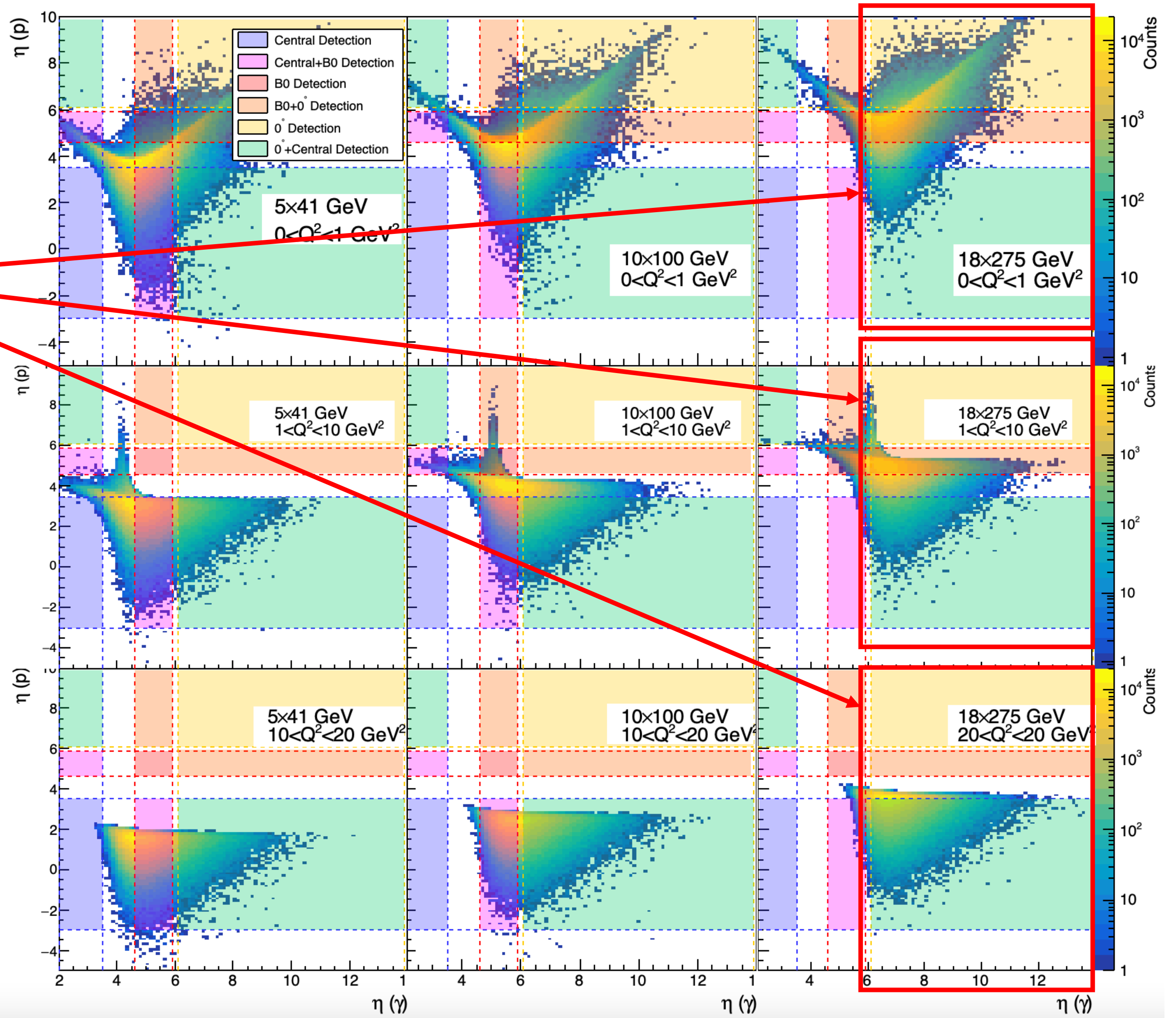

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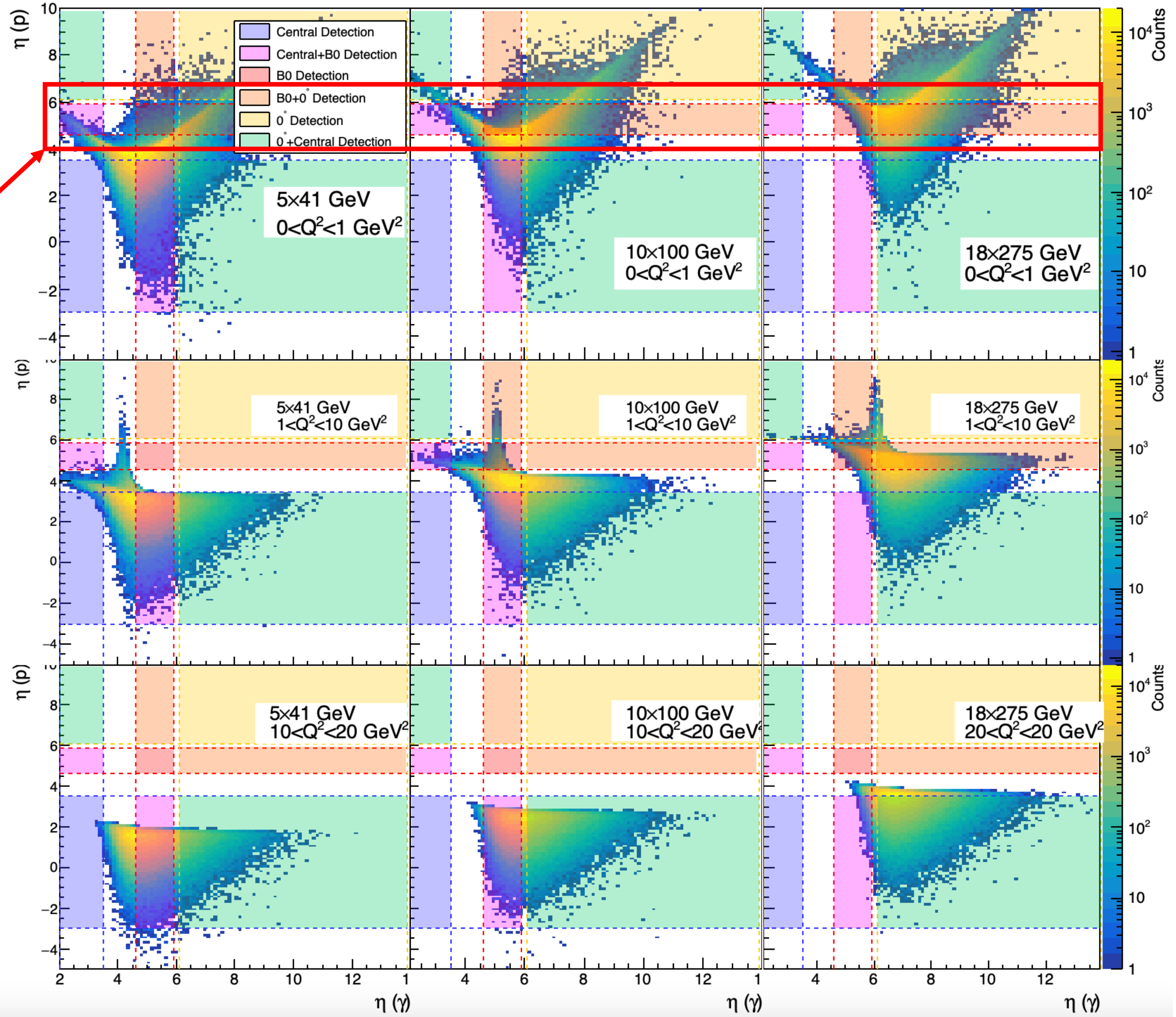

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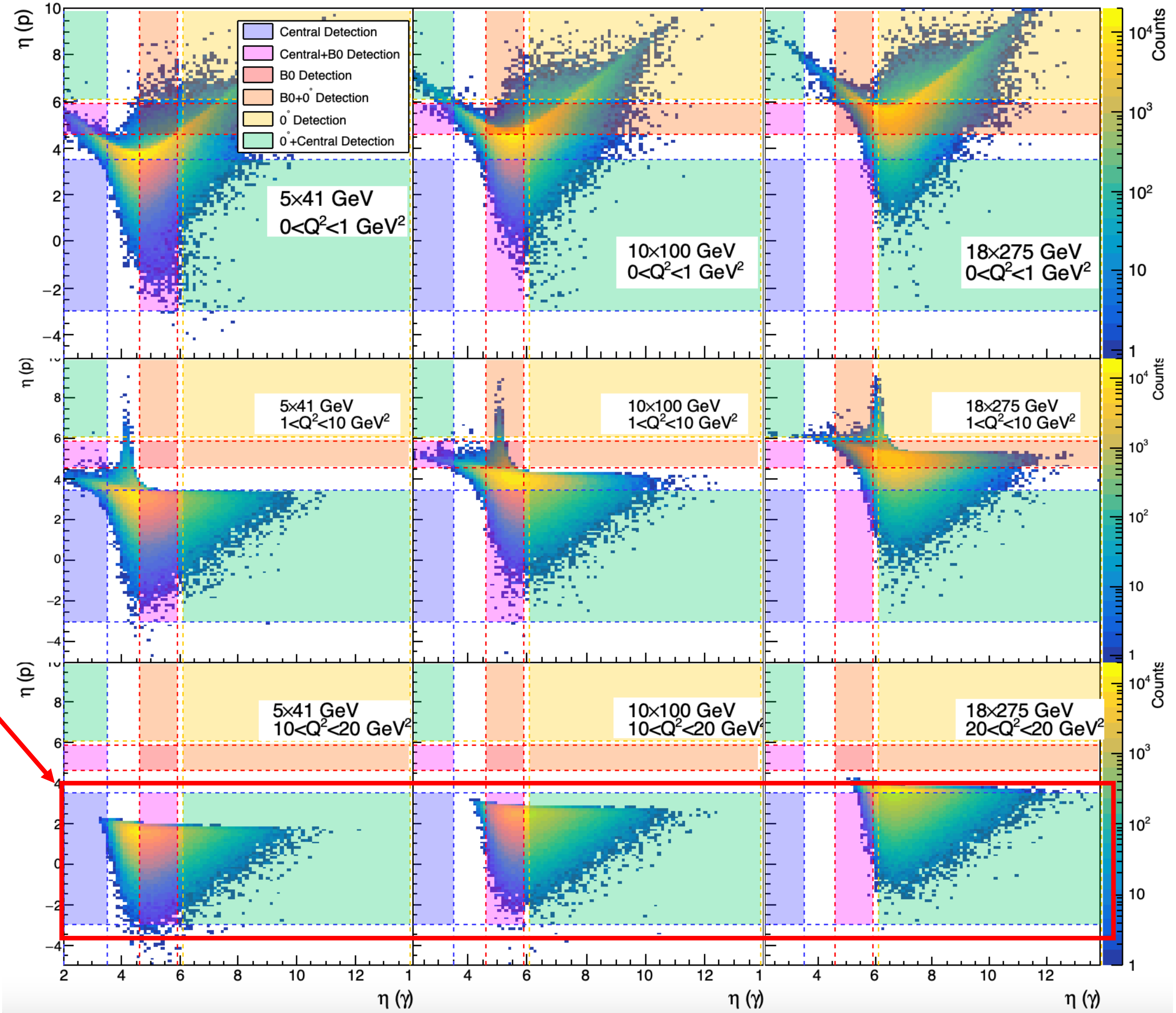
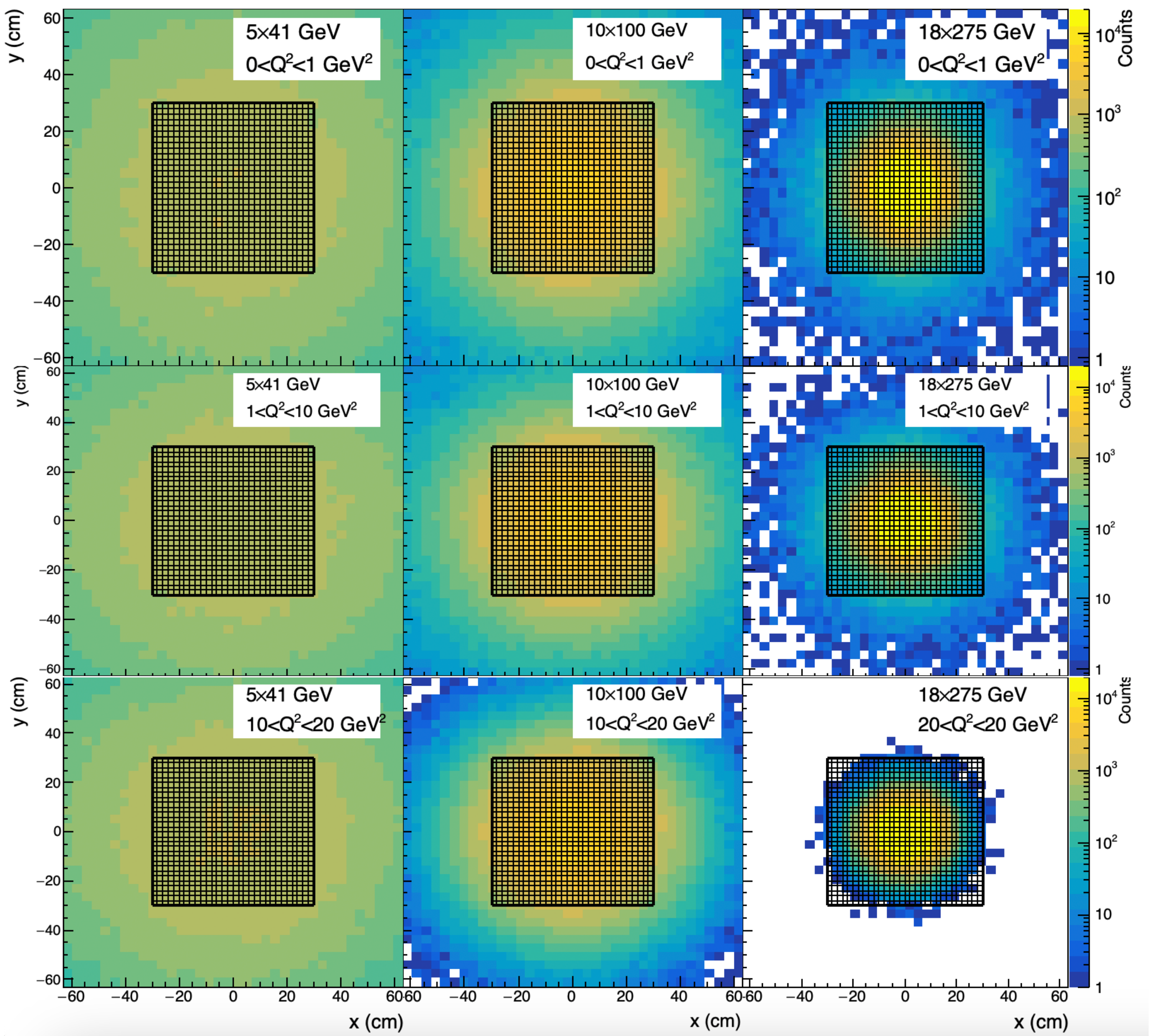


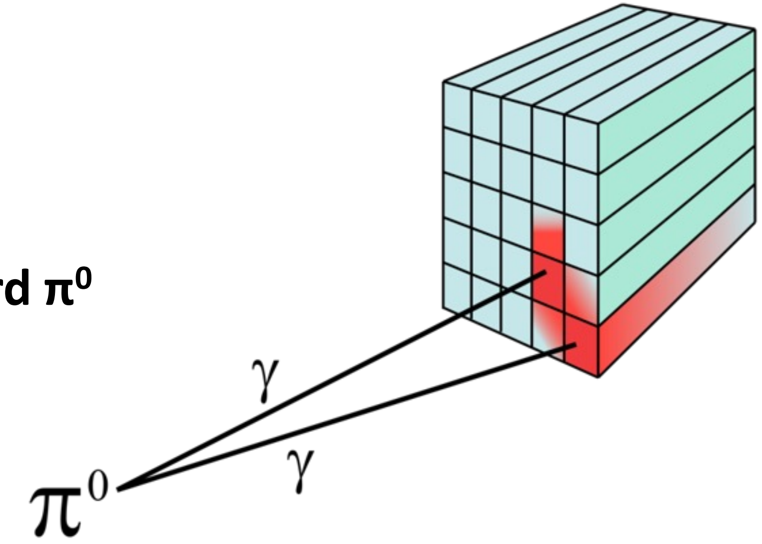
Another Channel: Backward $\pi^0 \rightarrow \gamma\gamma$ Production

- The figure at right shows CoM distribution of $\gamma\gamma$ pairs from backward π^0s
- Overlaid on 60×60cm ZDC w/ 2×2cm towers
- At low energy and Q^2, the photons often miss ZDC
- At large collider energies, the photons are forward enough to land mostly in ZDC



Zero-Degree Calorimeter (ZDC)

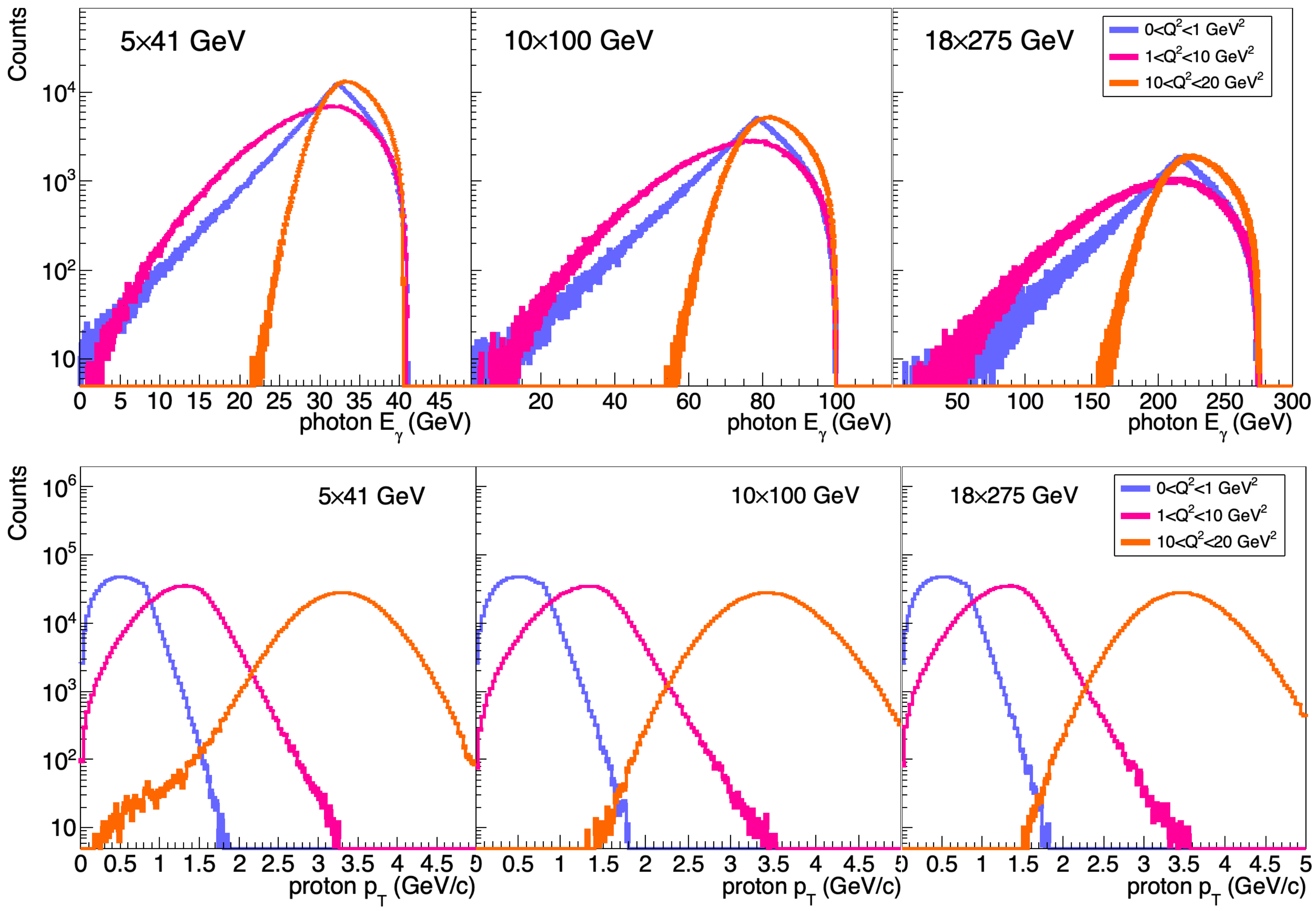
Backward π^0



Kinematics of Final-State Particles

Compton Scattering ($\gamma^*p \rightarrow \gamma p'$)

- Final-state photons have energies roughly between 10 and 275 GeV
- Scattered protons



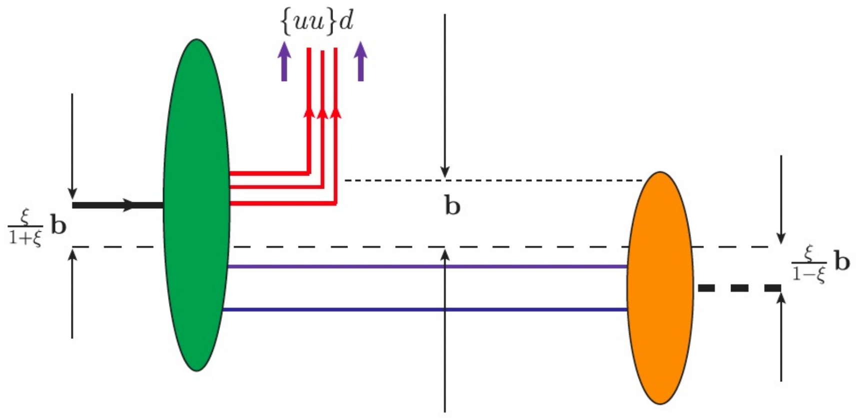
Conclusions and Outlook

- Backward production involves large (seemingly improbable) momentum transfers
- Baryon junction model shares many similarities with backward processes
- Backward production may encode unique information about parton distributions within the proton, an active and evolving topic of research
- We are modeling backward processes to help guide EIC detector development and physics priorities
- We're writing a paper on backward Compton scattering so stay tuned!

Thank you for your attention!

zwsweger@ucdavis.edu

Meaning of Backward Cross Section



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Backward Xsecs → partonic correlations and baryon number?

- Forward production maps parton distributions within proton/nucleus
- Recent (2021) work by Pire et al. formulates a similarly meaningful interpretation of backward cross section
- They argue backward reactions map transverse distribution of di-quark and three-quark (shown at right) clusters

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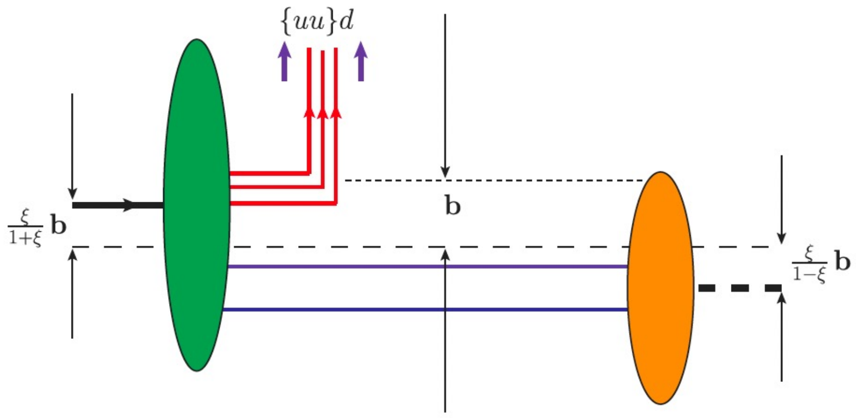

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"baryon-to-meson (and baryon-to-photon) TDAs share common features both with baryon DAs and with GPDs and encode a conceptually close physical picture. They characterize partonic correlations inside a baryon and give access to the momentum distribution of the baryonic number inside a baryon. Similarly to GPDs, TDAs – after the Fourier transform in the transverse plane – represent valuable information on the transverse location of hadron constituents."

Stopping and the Baryon Junction Model (BJM)

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