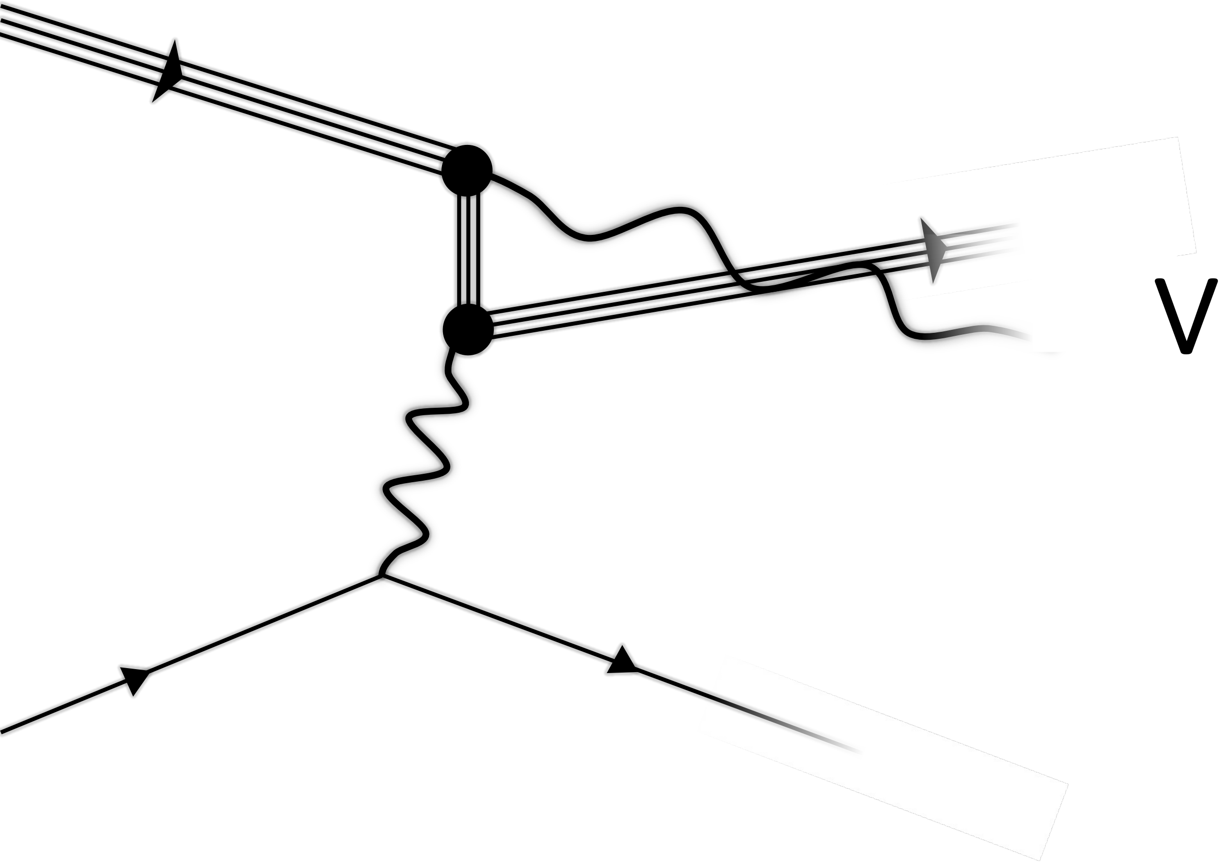


u-channel Virtual Compton Scattering (VCS) at the EIC

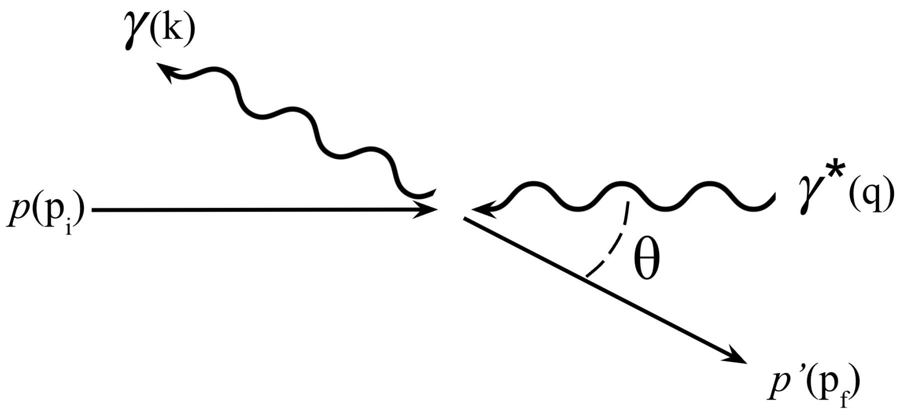
Zachary Sweger

University of California, Davis

Supported in part by

Forward and Backward Compton Scattering

Forward Compton Scattering (COM Frame)



Glancing collision, small momentum transfer

Forward and Backward Compton Scattering

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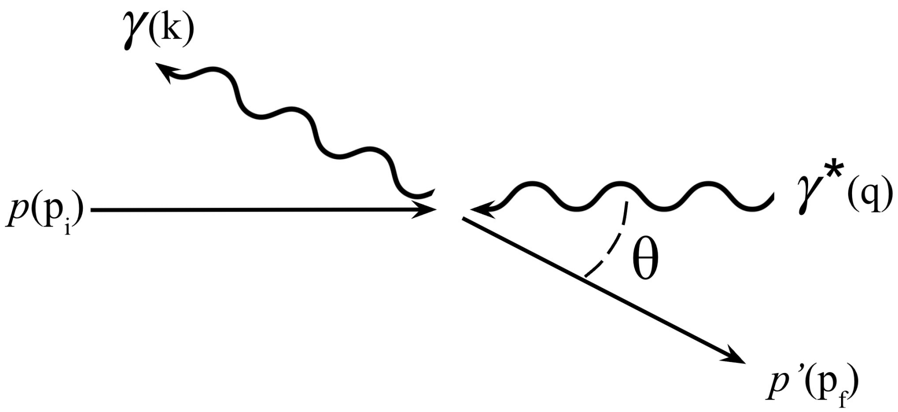

Glancing collision, small momentum transfer

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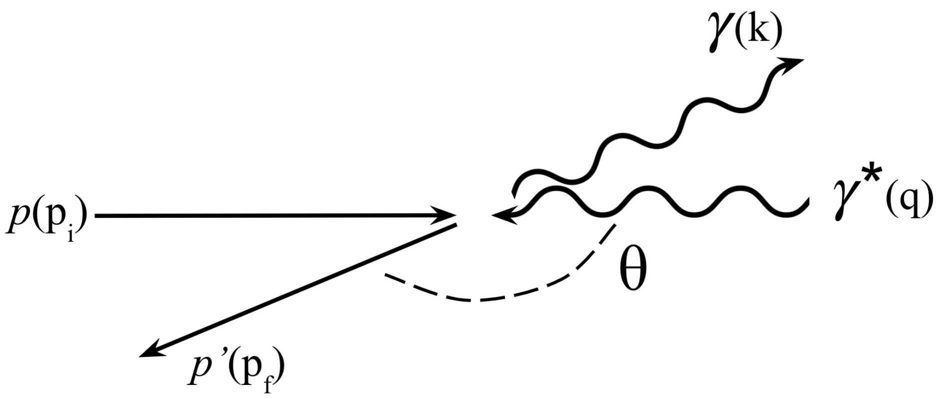
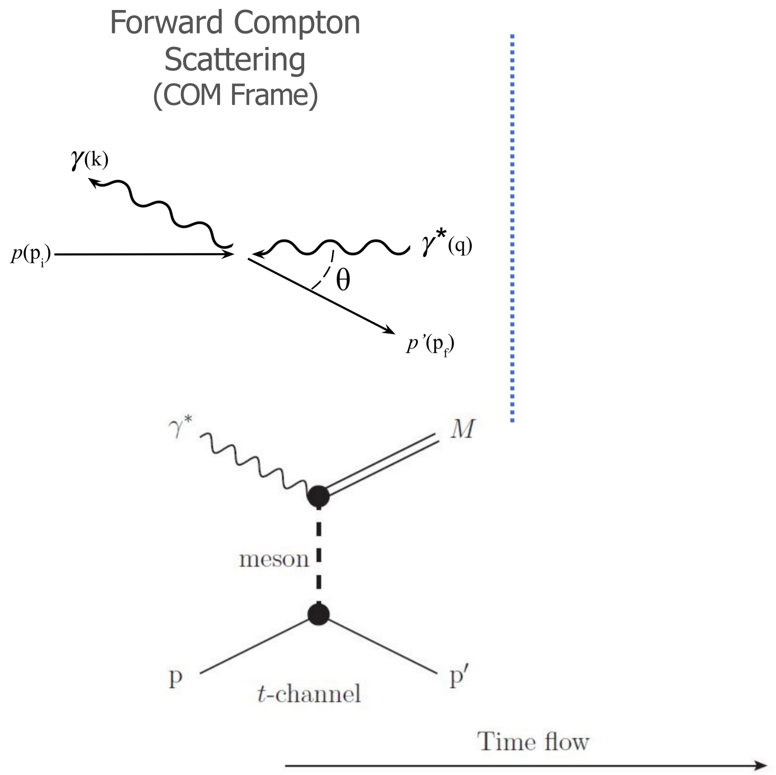
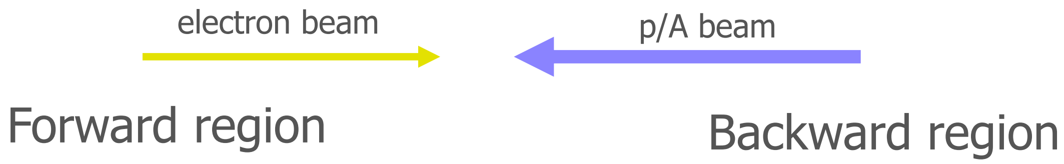


Backscattering, large momentum transfer

Backward (u-channel) Compton Scattering



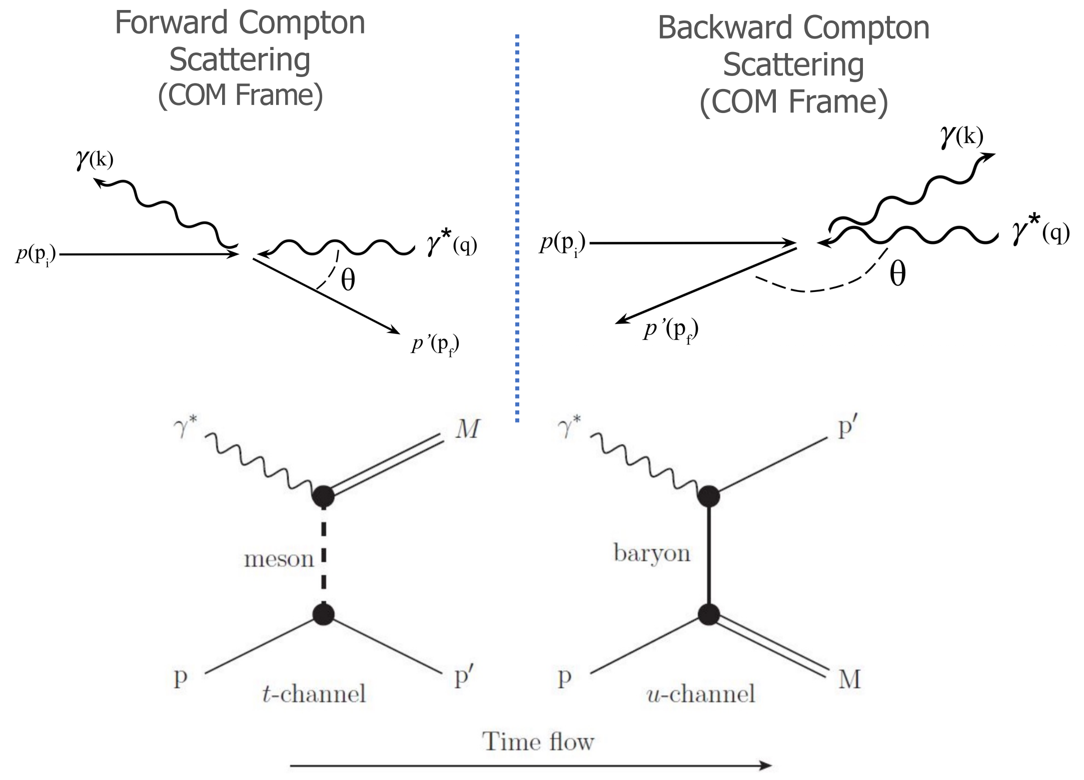
Contributions to VM production from Mandelstam variables. Wenliang (Bill) Li (William and Mary). GPD Workshop at Stony Brook University



Forward vs Backward Compton Scattering

- Forward Production
  - t-channel: low Mandelstam t, high u
  - γ produced in backwards (e^--going) direction
  - Proton continues in forward direction

Backward (u-channel) Compton Scattering



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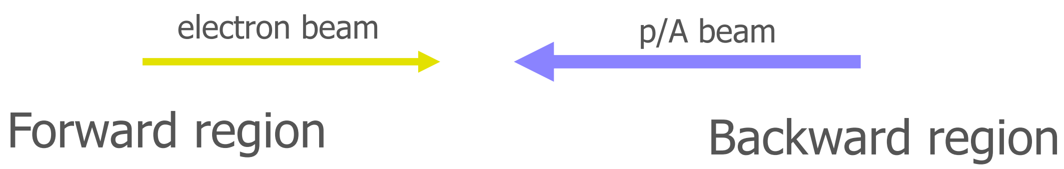


electron beam

p/A beam

Forward region

Backward region

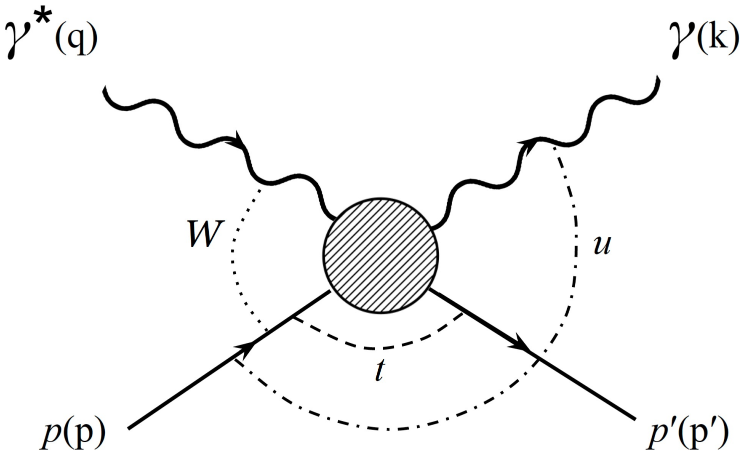
Forward vs Backward Compton Scattering

- Forward Production
  - t-channel: low Mandelstam t, high u
  - γ produced in backwards (e^--going) direction
  - Proton continues in forward direction

- Backwards Production
  - u-channel: low Mandelstam u, high t
  - γ produced in forwards (p-going) direction
  - Proton shifted many units in rapidity

Kinematics

- VCS can be parameterized in terms of:
    - Q^2 ← when $Q^2 \neq 0$, this is virtual CS (VCS)



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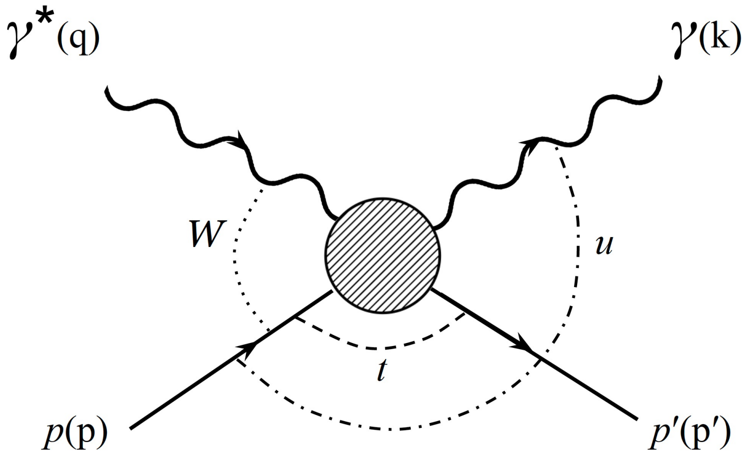

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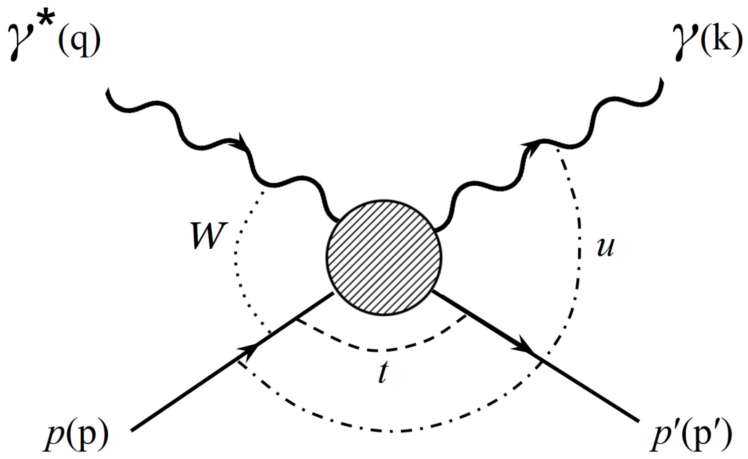
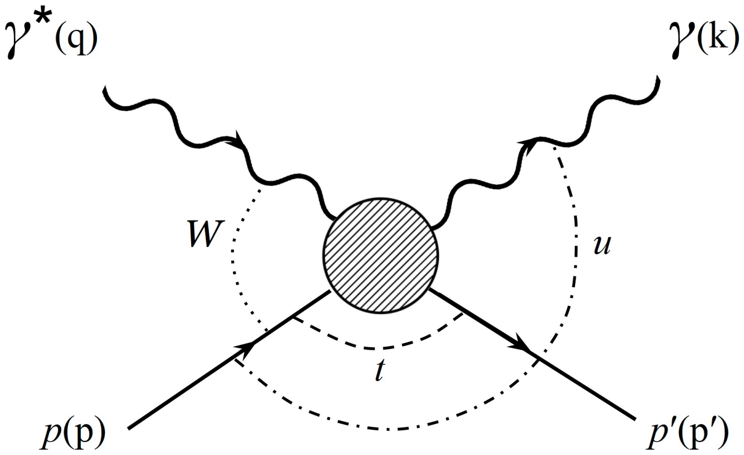
  - $|u| = |(p-k)^2|$
  - θ_{CM}

$\}$ *t*, *u*, and θ each parameterize mom. transfer in reaction. Only one needed.



Kinematics



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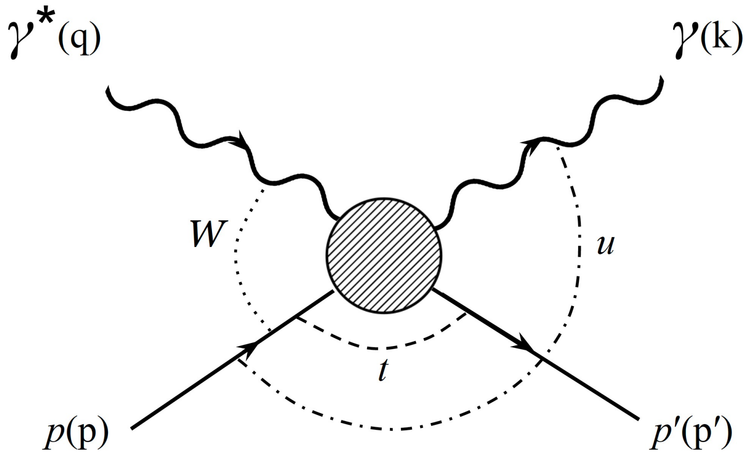
Kinematics



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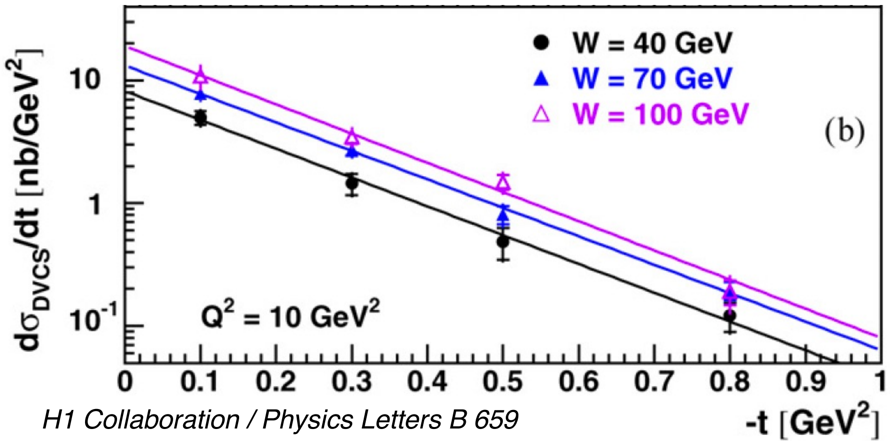
} *t*, *u*, and θ each parameterize mom. transfer in reaction. Only one needed.

$$\frac{d^4\sigma[ep \to e'p'\gamma]}{dQ^2 dW d\phi dt} = \Gamma(Q^2, W)\frac{d^2\sigma[\gamma^* p \to p'\gamma]}{d\phi dt}(Q^2, W, \phi, t)$$

A u-channel Peak?



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

Typical Description of VCS cross section

- Cross section at fixed Q^2 and W is typically modeled using an exponential: $e^{-b|t|}$
- This cross section encodes information about the proton GPDs in impact-parameter space
- So why care about cross section at very high $|t|$?

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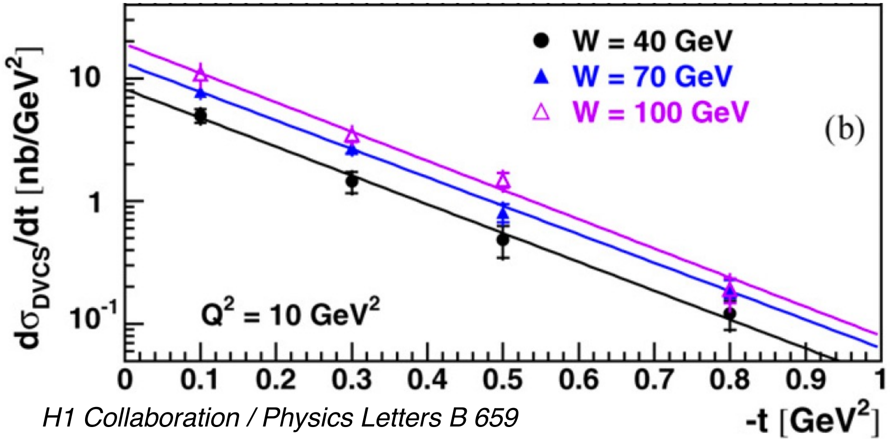

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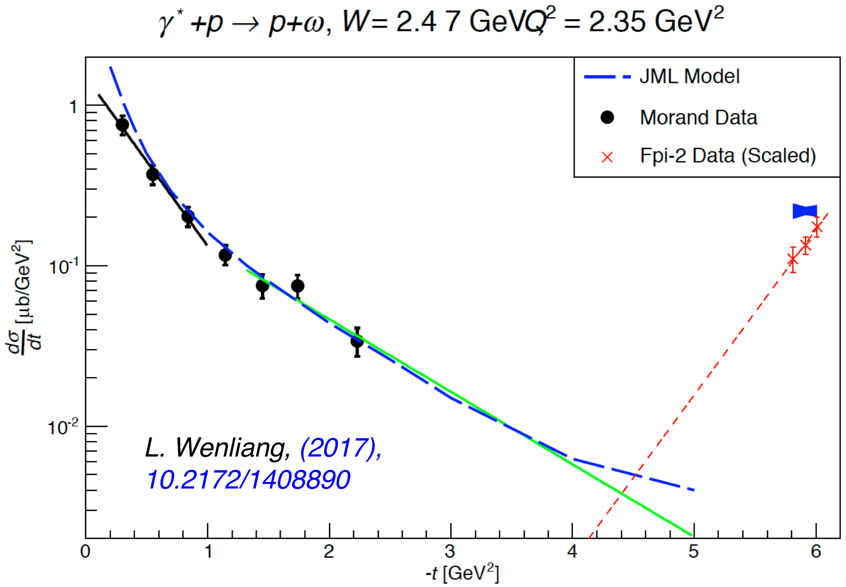
Non-trivial Behavior at High t

- Cross sections for mesons have exponential drop-off with $|t|$, BUT also an exponential rise at the highest $|t|$ values
- This is from u-channel contributions which may also be expected in VCS



L. Wenliang, (2017), 10.2172/1408890

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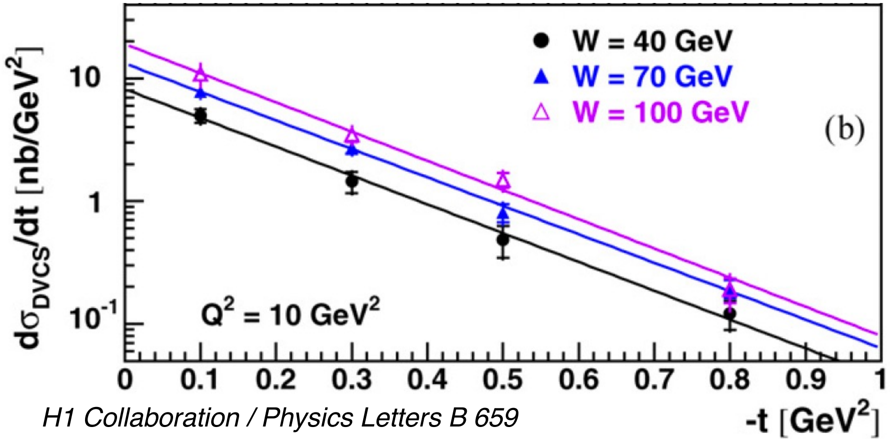

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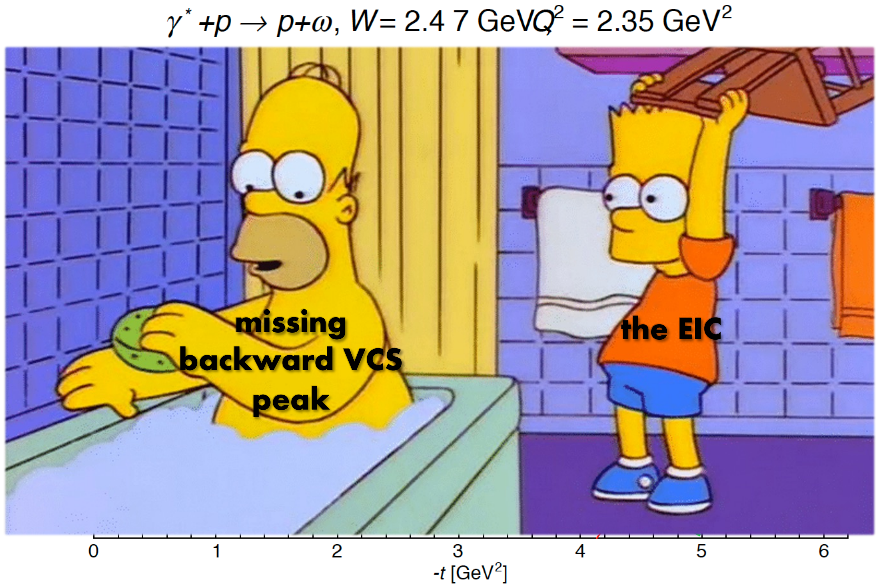
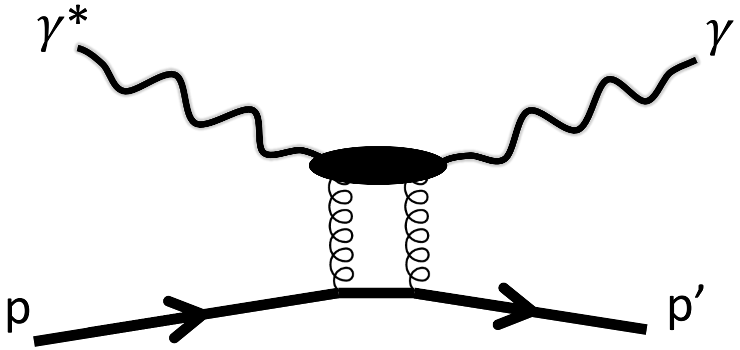


Meaning of Backward Cross Section

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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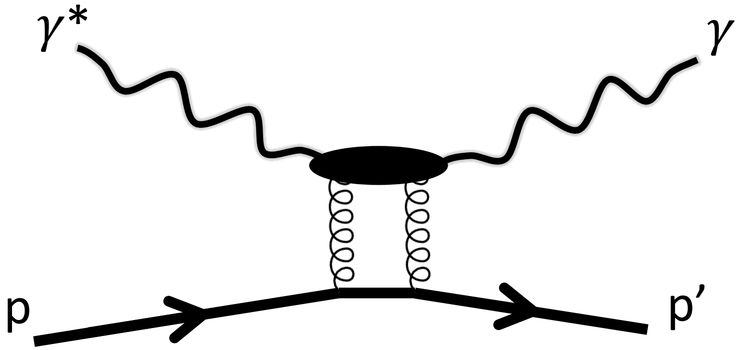
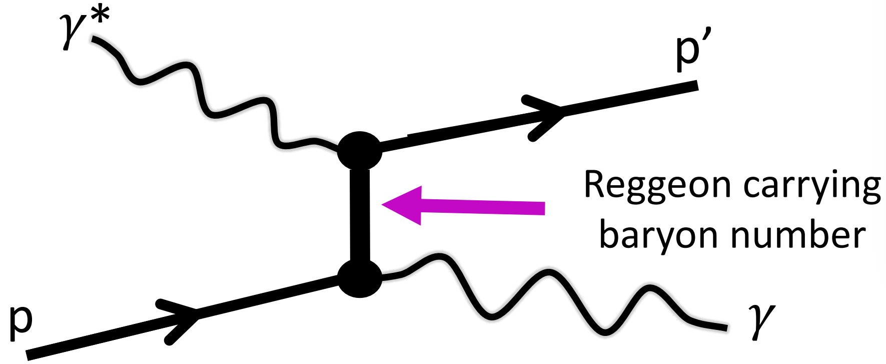


Backward scattering off proton's… baryon number?
gluon junction?
di-quark clusters?



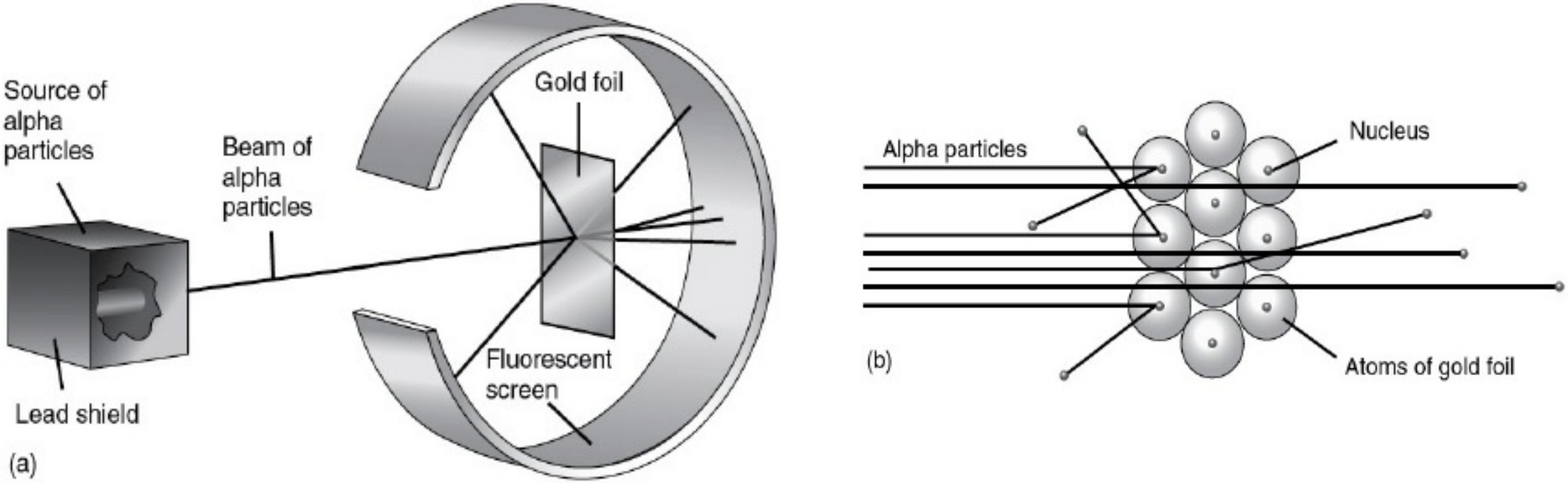
Backward Xsecs → partonic correlations and baryon number?

- 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."

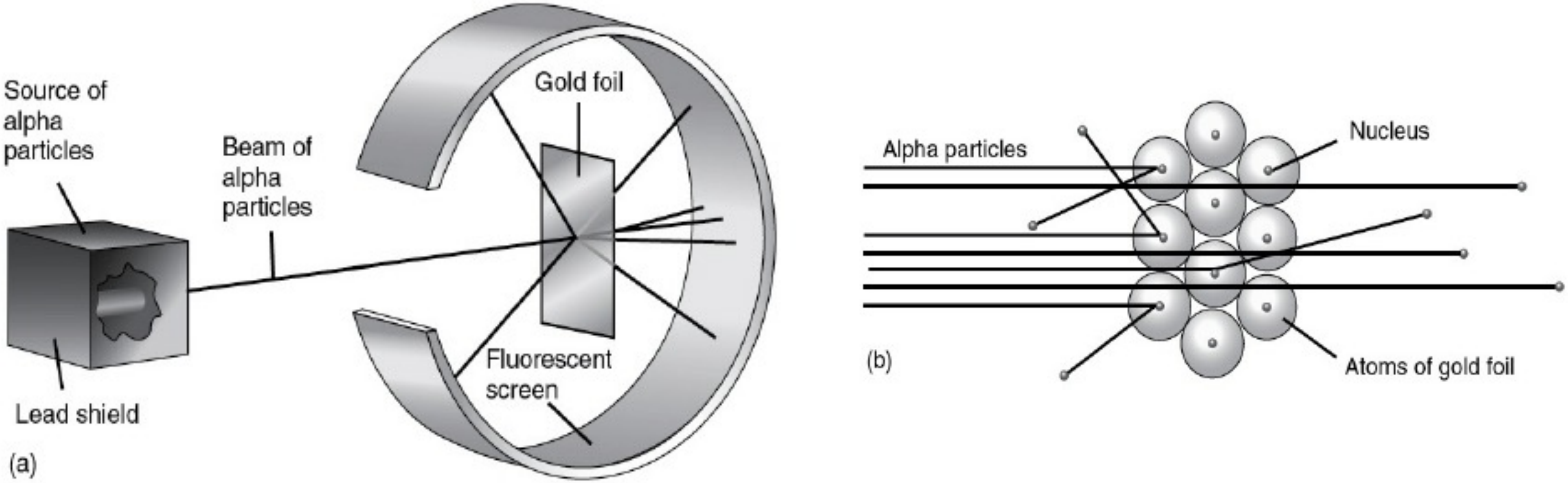
B. Pire, K. Semenov-Tian-Shansky, and L. Szymanowski, Phys. Rept. 940, 1 (2021), arXiv:2103.01079 [hep-ph].

Backward Scattering



Bertulani, Carlos. (2009). Nuclear Reactions.

Backward Scattering



"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

Bertulani, Carlos. (2009). Nuclear Reactions.

Our Backward VCS Model

Our Backward DVCS Model: u-Dependence

Modeling u-channel DVCS

- We presuppose peak at backward angles ($u=u_0$) as seen in meson production
- **The strategy:**

L. Wenliang, (2017), 10.2172/1408890.

D. Cebra, Z. Sweger, X. Dong, Y. Ji, and S. R. Klein, Phys. Rev. C 106, 015204 (2022).

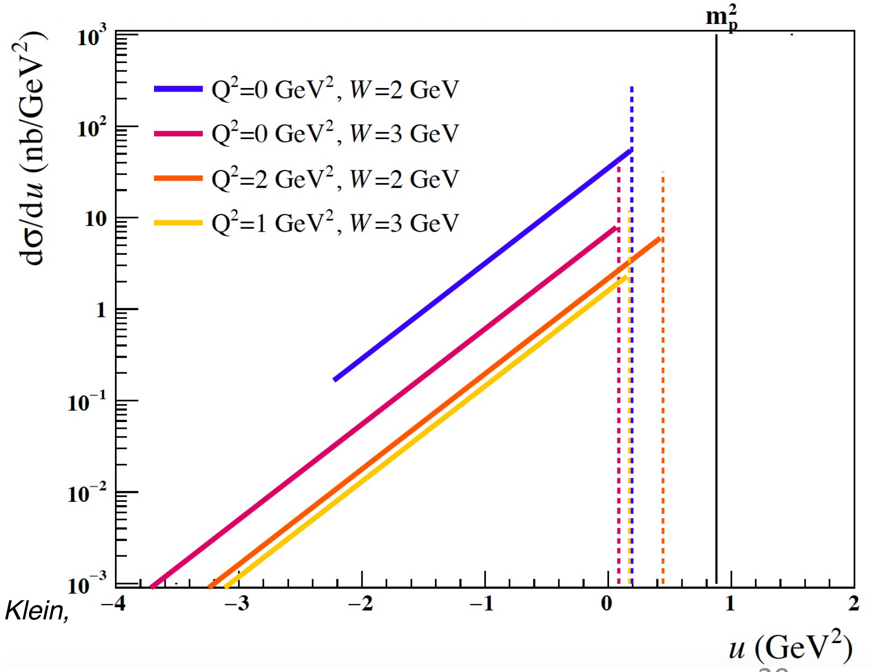
Our Backward DVCS Model: u-Dependence

Modeling u-channel DVCS

- We presuppose peak at backward angles ($u=u_0$) as seen in meson production
- **The strategy: exploit similarities to t-channel**

$$\frac{d\sigma}{dt}(t) \sim \exp(-B|t-t_0|) \longrightarrow \frac{d\sigma}{du}(u) \sim \exp(-D|u-u_0|)$$

- D has not been measured for backward DVCS, so for our models we test values measured for backward vector-meson production



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D. Cebra, Z. Sweger, X. Dong, Y. Ji, and S. R. Klein, Phys. Rev. C 106, 015204 (2022).

Our Backward DVCS Model: W-Dependence

Modeling W-Dependence

- Backward physics is dominated by Regge-exchange trajectories for which the cross sections typically scale as $W^{-\alpha}$
- In our backward ω/ρ paper, we used a data-driven $(W^2-m_p^2)^{-2.4}$ dependence

D. Cebra, Z. Sweger, X. Dong, Y. Ji, and S. R. Klein, Phys. Rev. C 106, 015204 (2022).

- Several sources suggest rough $(W^2-m_p^2)^{-2}$ scaling which is what we start from.

G. Laveissi`ere et al., Physical Review C 79 (2009), 10.1103/physrevc.79.015201.

S. J. Brodsky, F. J. Llanes-Estrada, and A. P. Szczepaniak, Phys. Rev. D 79, 033012 (2009).

W. B. Li et al. (Jefferson Lab Fπ Collaboration), Phys. Rev. Lett. 123, 182501 (2019).

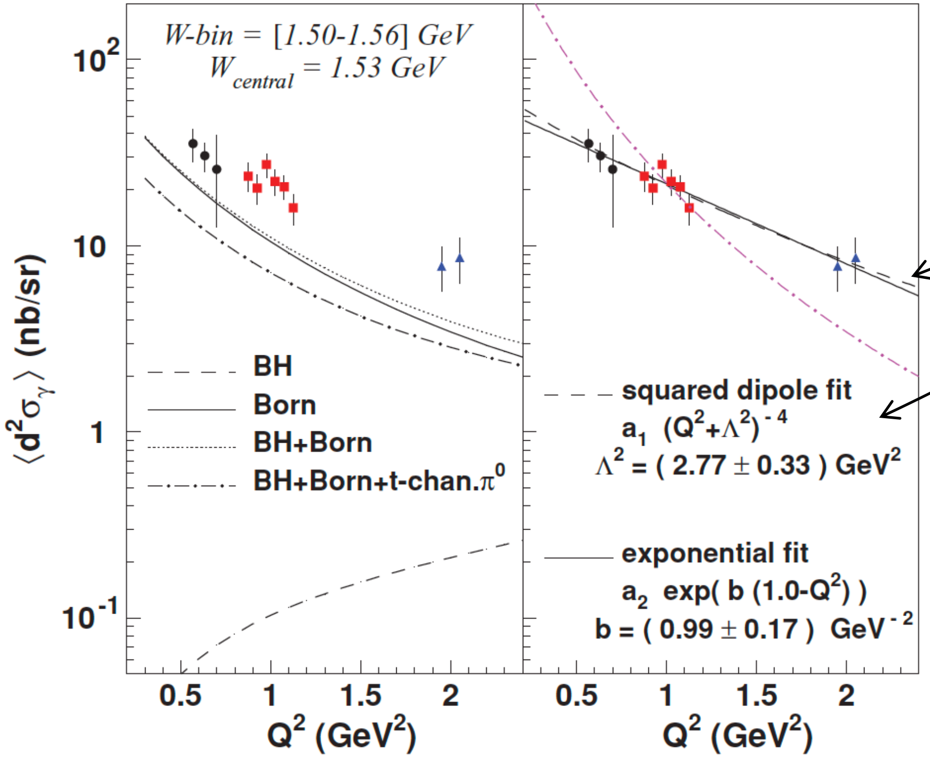
$$\frac{d\sigma}{du}(W,u) \sim \frac{1}{(W^2-m_p^2)^2}\exp(-D|u-u_0|)$$

Our Backward DVCS Model: Q^2-Dependence

Backward VCS in Resonance Region

- There is some limited data available for this
- For backward VCS in the resonance region, JLab measured $(Q^2+2.77\ \mathrm{GeV}^2)^{-4}$ dependence

G. Laveissi`ere et al., Physical Review C 79 (2009), 10.1103/physrevc.79.015201.



Full Cross Section Behavior

- We combine these contributions to yield the form:

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

- In order to anchor the amplitude, we can fit this model to 11 VCS (Q^2=1 GeV^2) data points from JLab from 1.77<W<1.96 GeV (above strong resonances)

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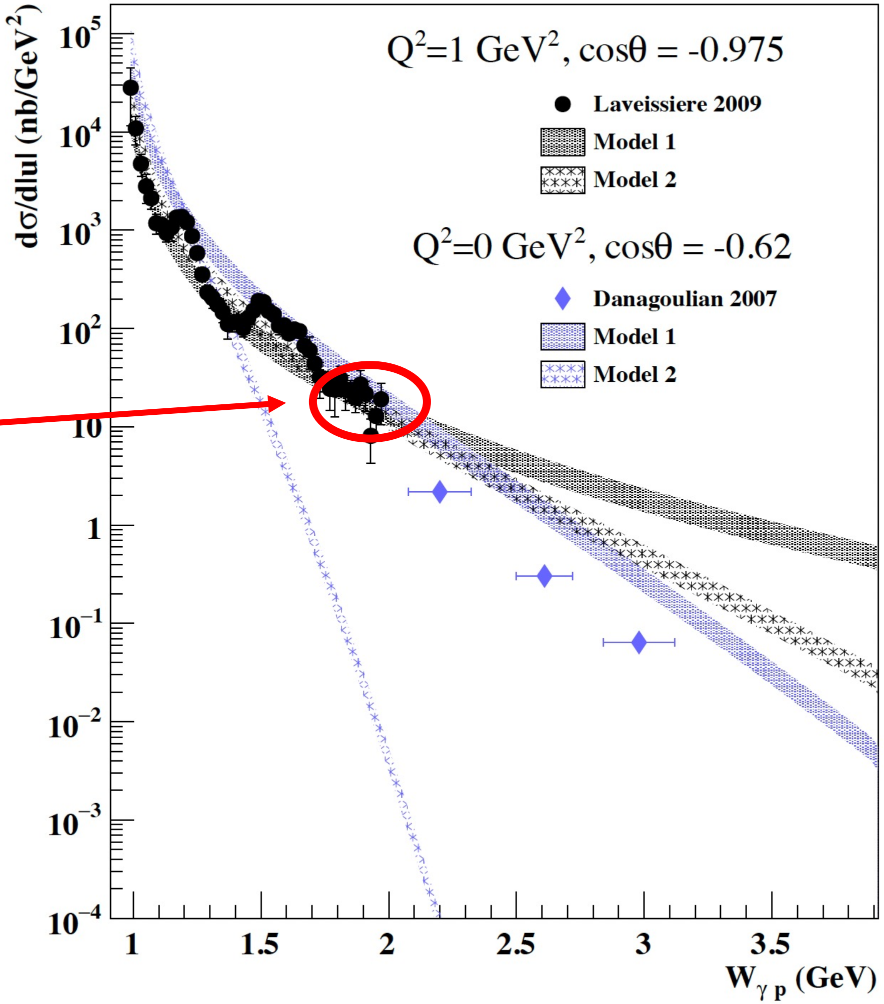
- Where
  - $\boldsymbol{\Lambda}^2$ = 2.77 GeV^2
  - Model 1: D = 2.4 GeV^{-2}, A = 32 μb/GeV^2
  - Model 2: D = 21.8 GeV^{-2}, A = 65 μb/GeV^2



G. Laveissi`ere et al., Physical Review C 79 (2009), 10.1103/physrevc.79.015201.

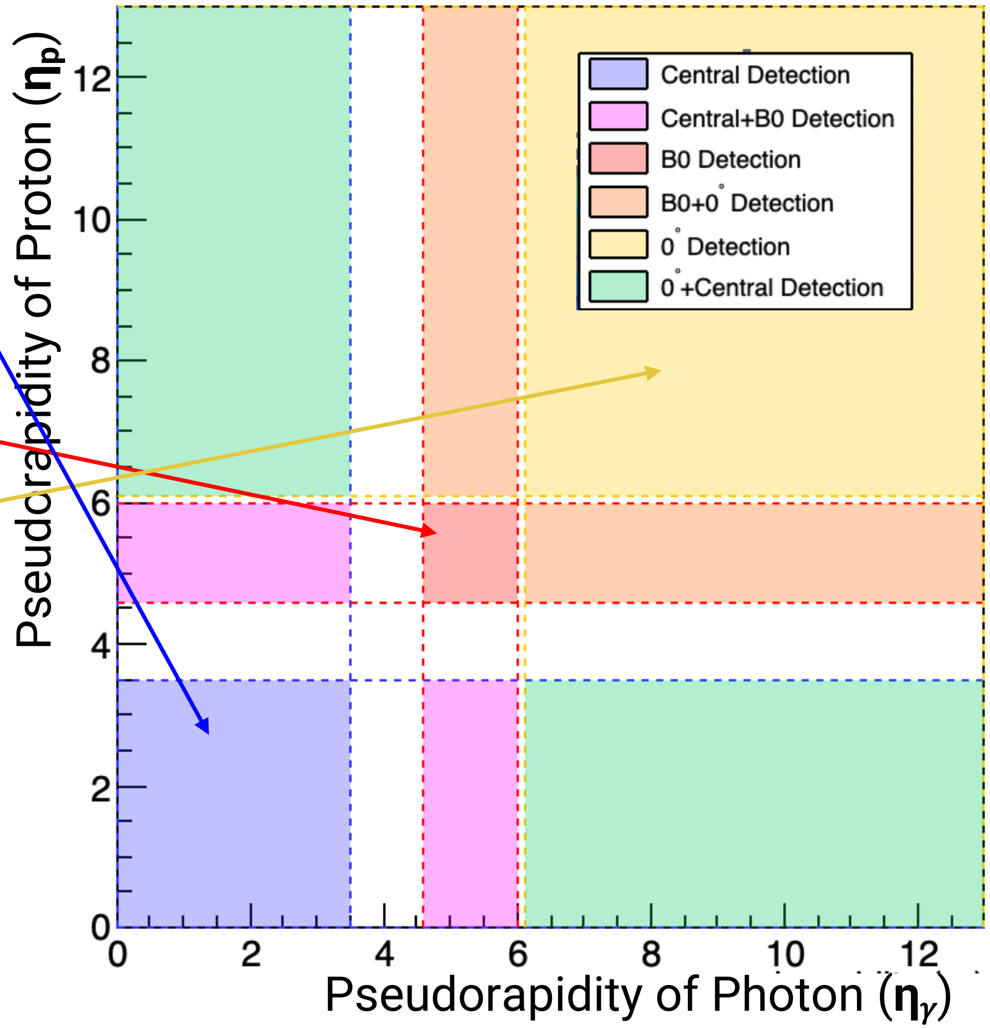
A. Danagoulian et al. (Jefferson Lab Hall A Collaboration), Phys. Rev. Lett. 98, 152001 (2007)

Simulation Studies

Detectors of Interest For u-channel Production

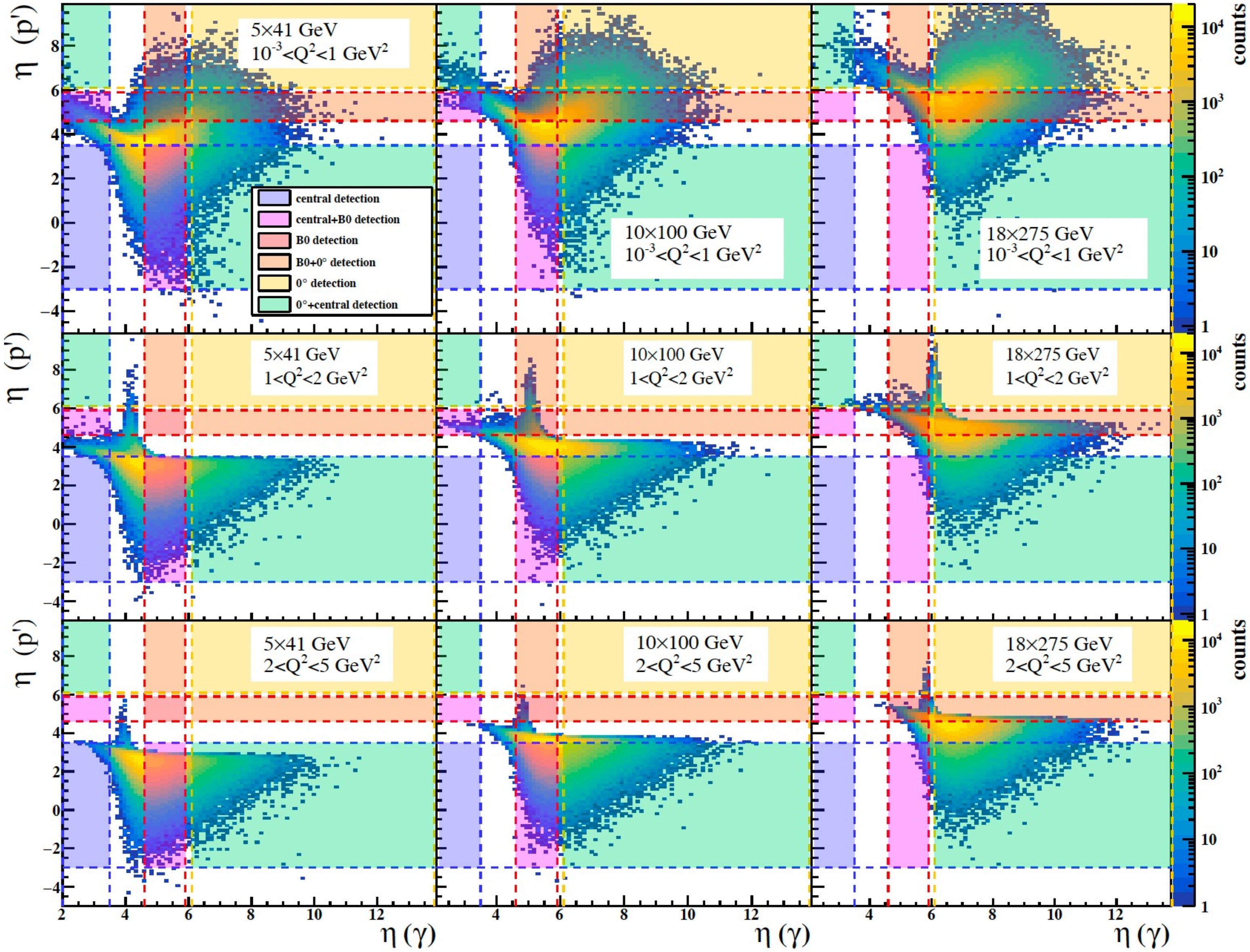
There are three detector regions of interest for backwards production

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



Backward DVCS Acceptances

- Used Model 1 with W > 2 GeV
- 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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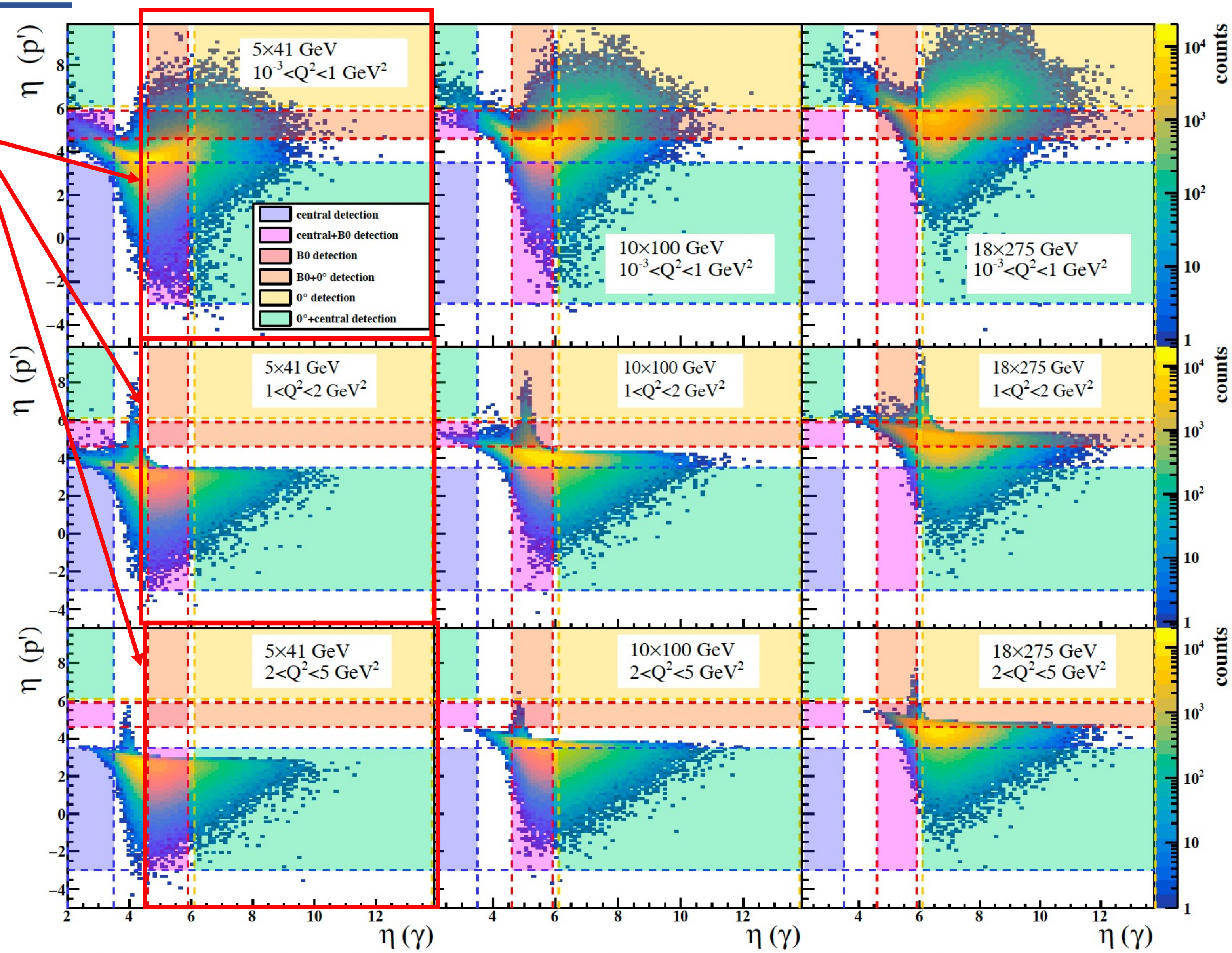

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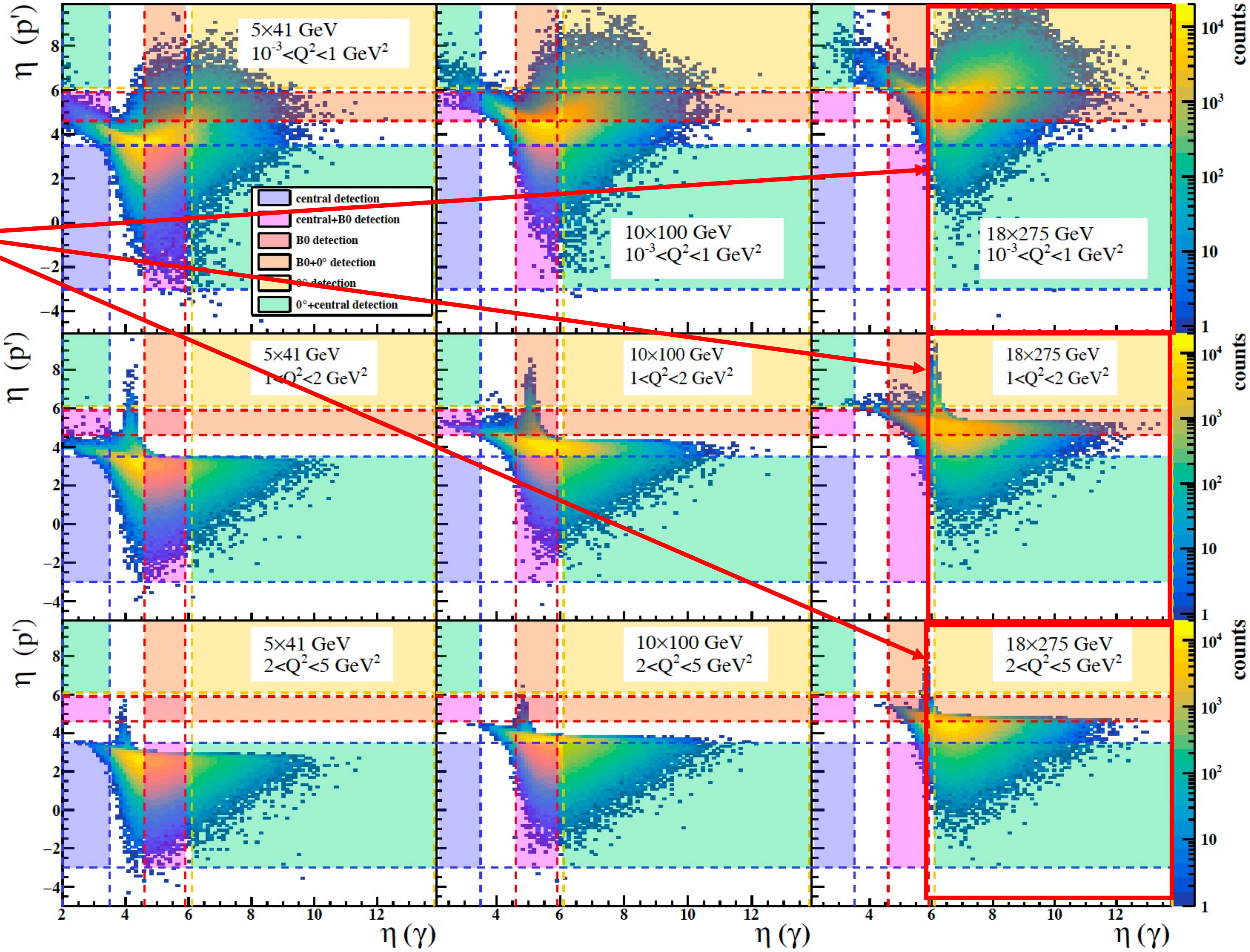

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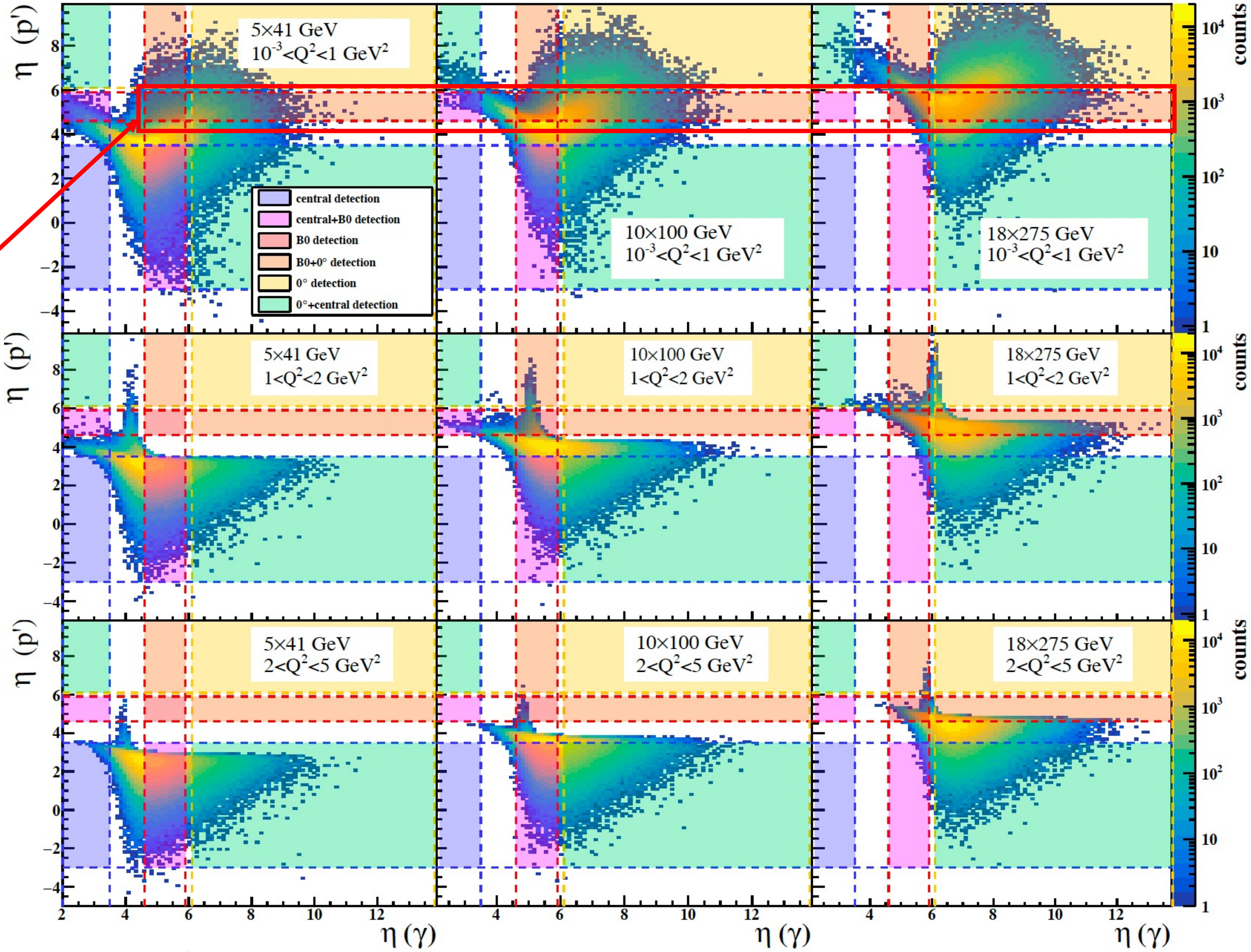

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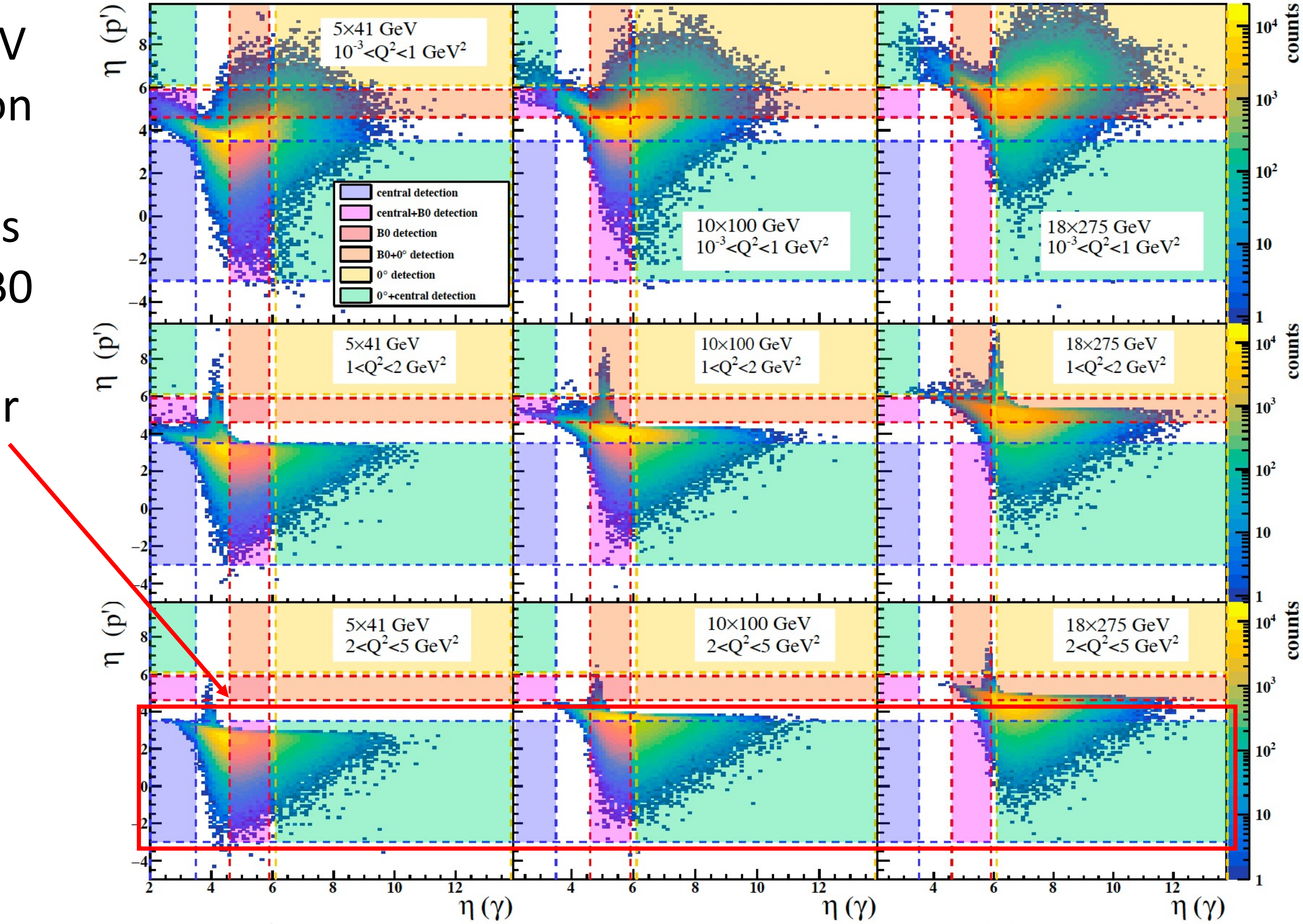
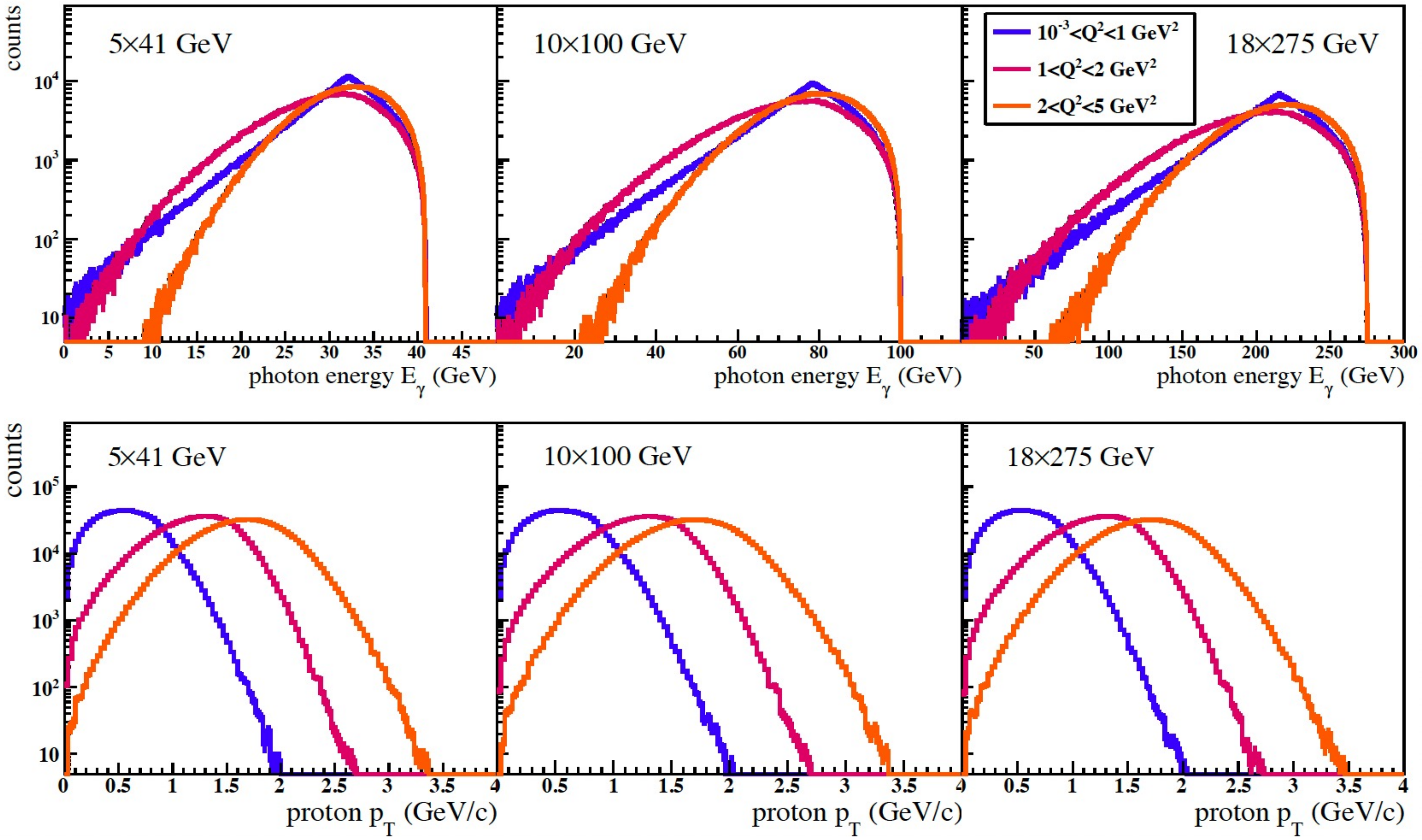


Kinematics of Final-State Particles

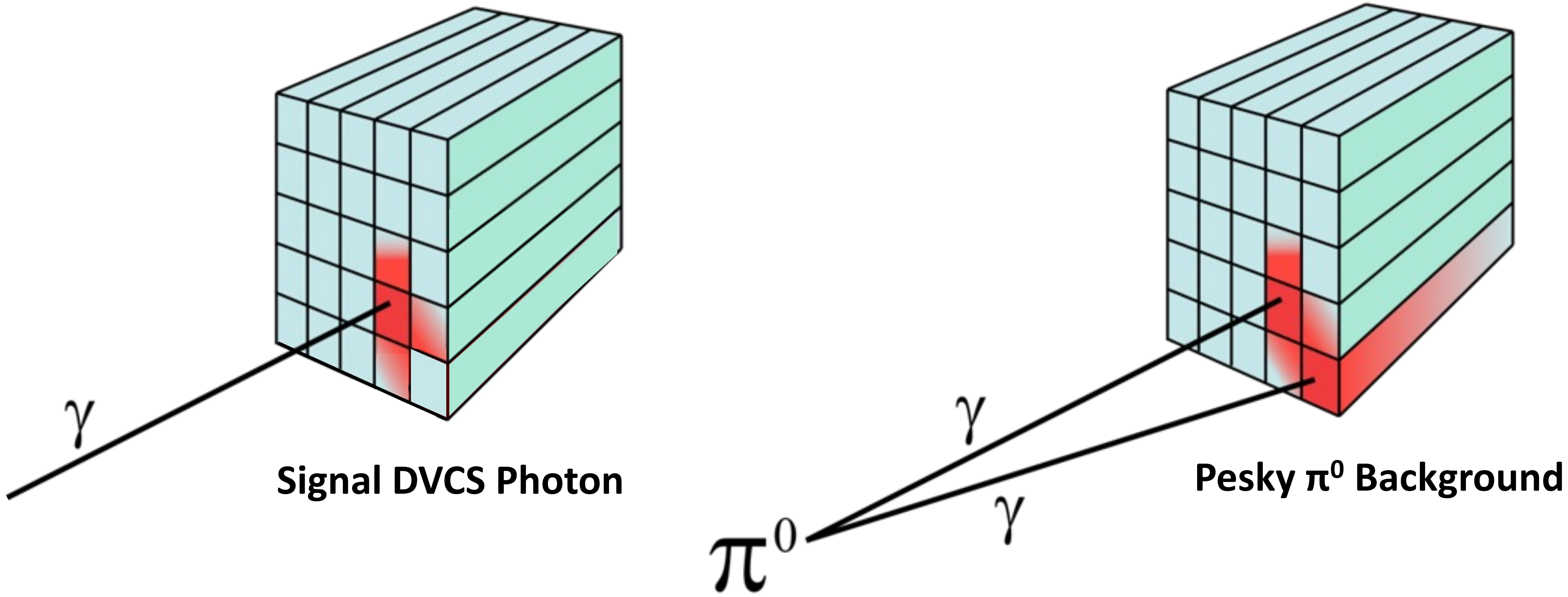
- Final-state photons in B0 and ZDC between 10 and 275 GeV
- Low-Q^2 events have low-pT protons
- Need to focus on detecting these due to large cross section



π^0 Background

Primary Challenge: π^0 Background

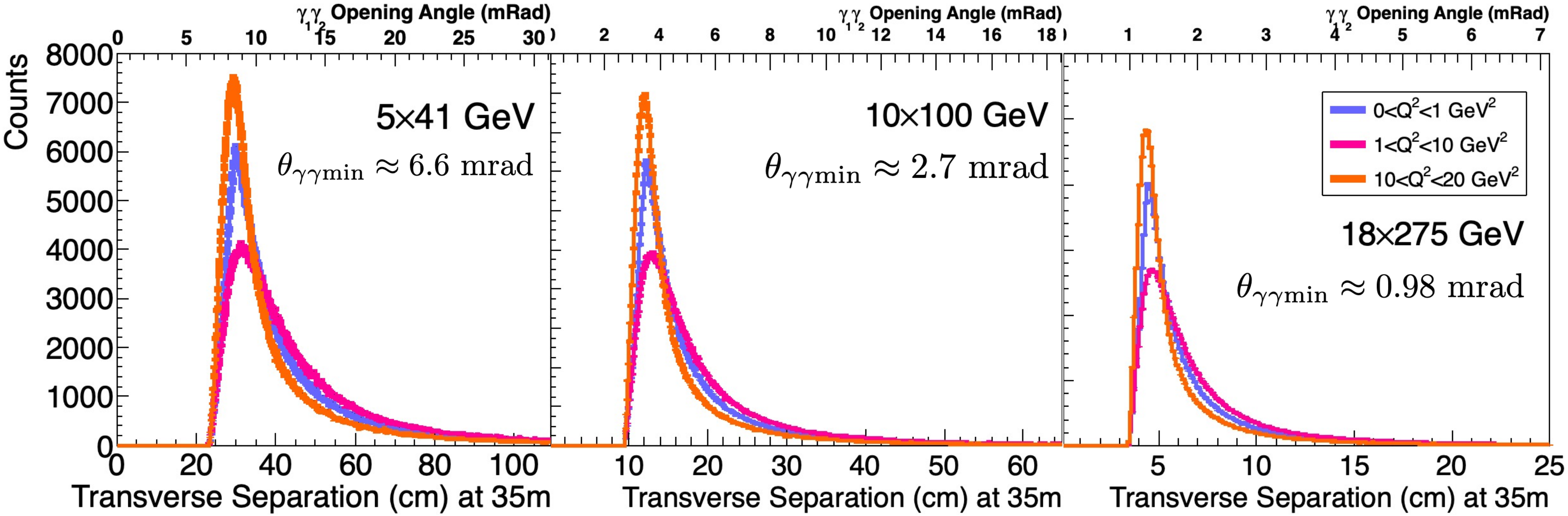
- Backward π^0s expected ~100-1000 stronger than backward CS
- Need to resolve one CS photon from two π^0 photons
- ZDC made of PbWO4 towers with 2cm transverse size
- ZDC ~35m downstream of IP



π^0 Background Photon Separation

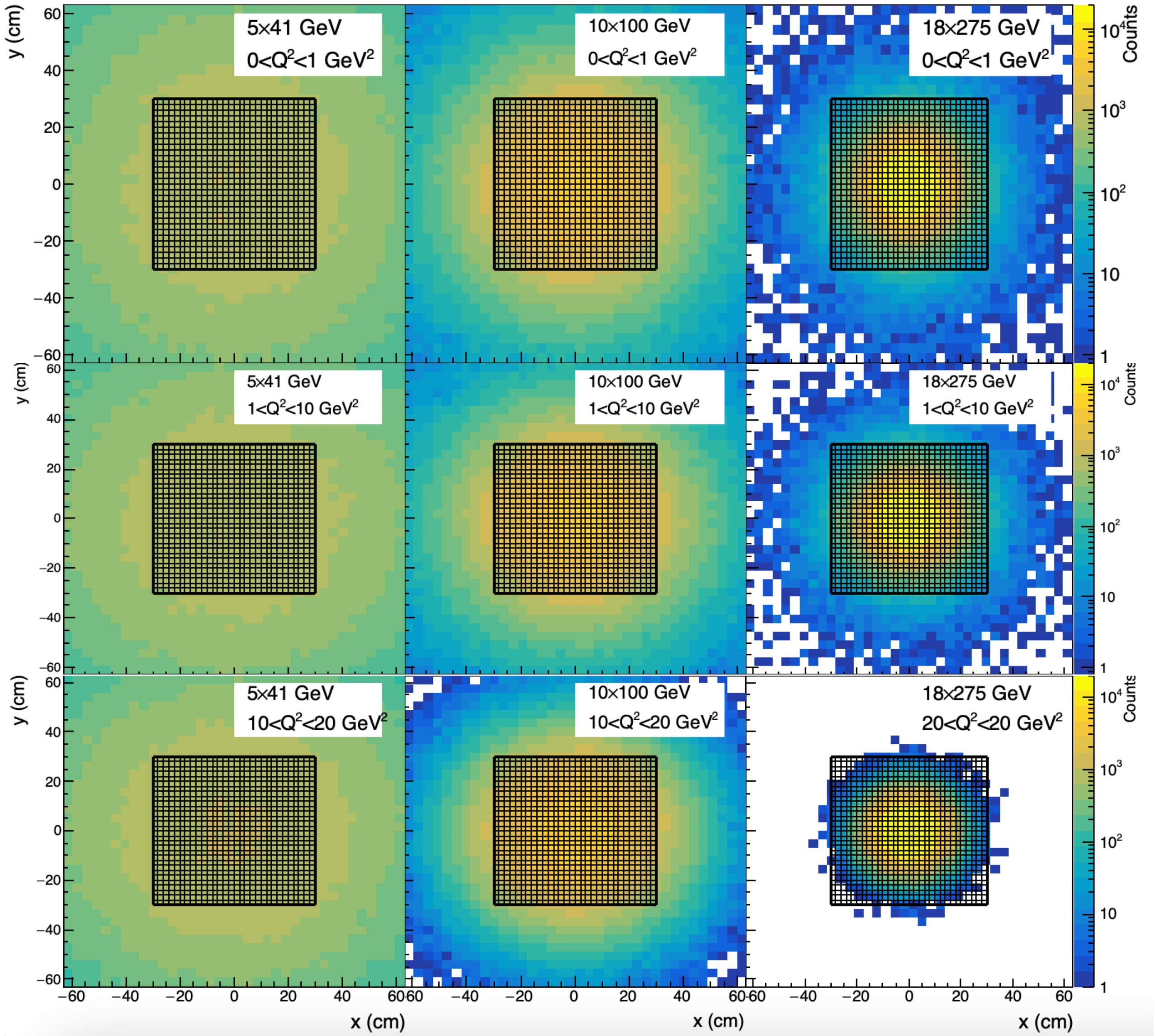
- I generated π^0s with the same kinematics as predicted VCS photons
- Photons were well-separated
- Photons from π^0s merging in the same tower will not be the main issue

- Theoretical minimum opening angle: $\theta_{\gamma\gamma\mathrm{min}} \approx 2\,\mathrm{arctan}(m_{\pi^0}/E_p)$



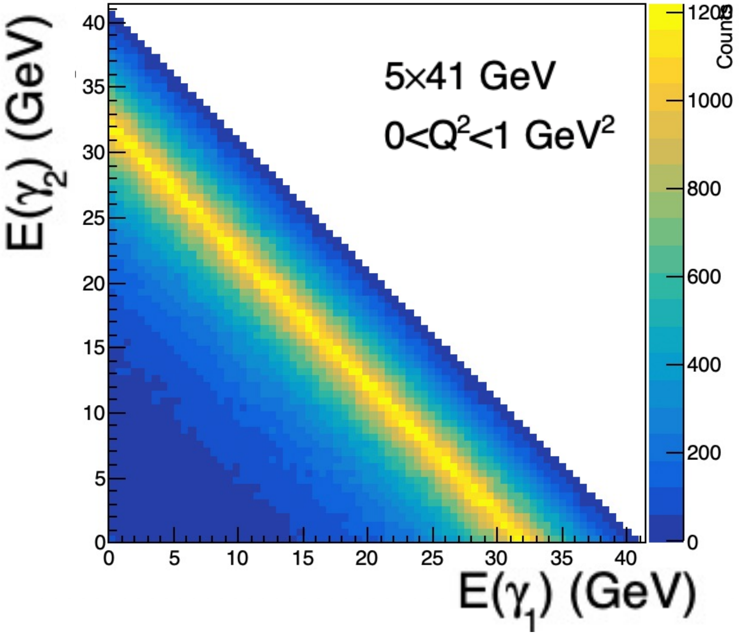
$\pi^0 \rightarrow \gamma\gamma$ CoM Distribution

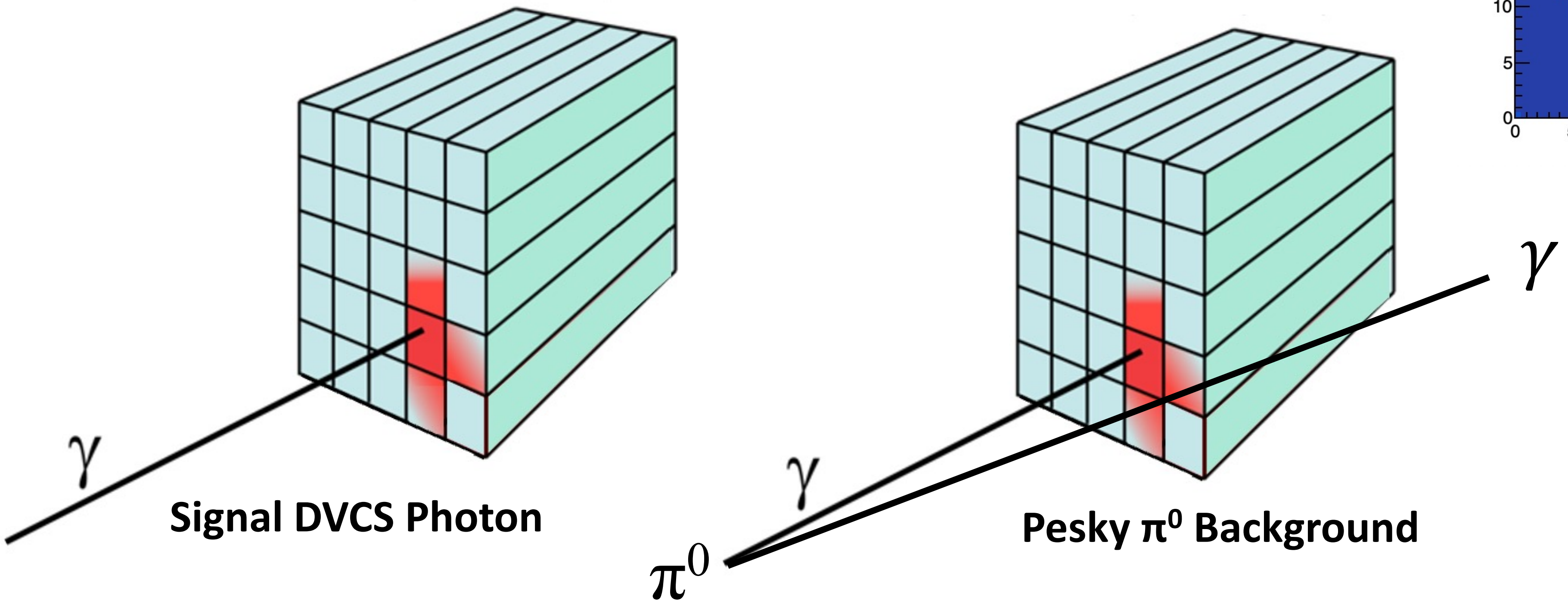
- The figure at right shows CoM distribution of $\gamma\gamma$ pairs from backward π^0s
- Overlaid on 60x60cm ZDC w/ 2x2cm towers
- At low energy and Q^2, the CoM is broad and often misses ZDC
- Taken with the previous slide, this gives an important conclusion



True Cause of $\pi^0 \rightarrow \gamma\gamma$ Background

Conclusion: the background will be dominated by events in which one of the π^0 photons carries most of the energy and the other misses the ZDC entirely. Depending on the high-energy resolution, this may easily be mistaken for backward VCS.



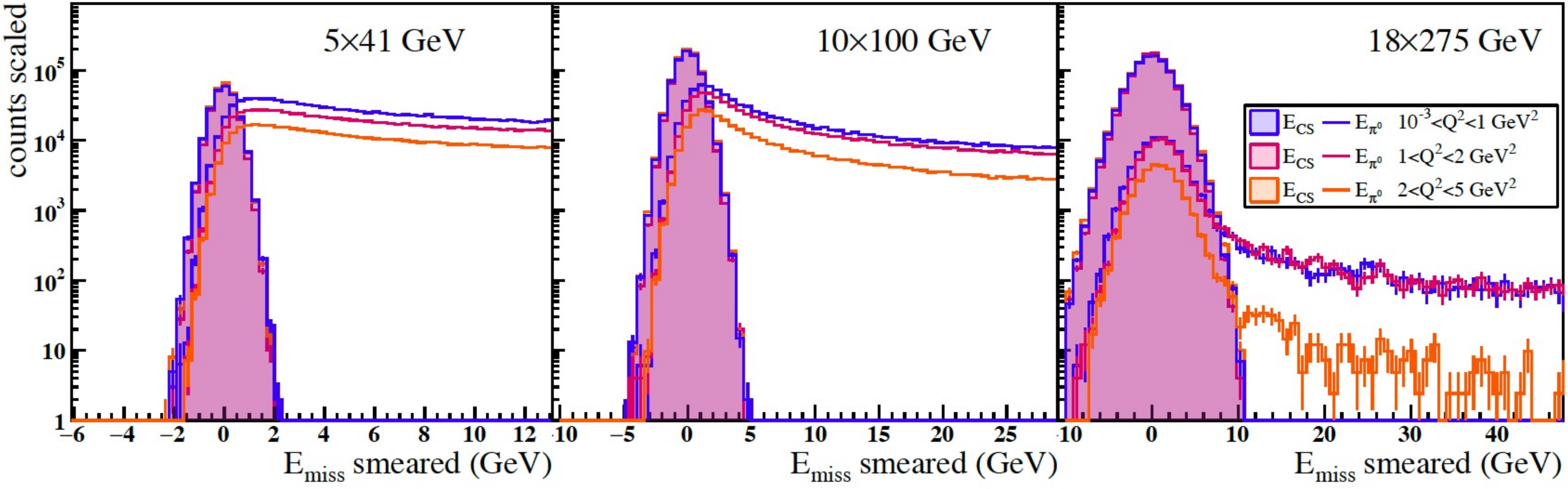


Signal DVCS Photon

Pesky π^0 Background

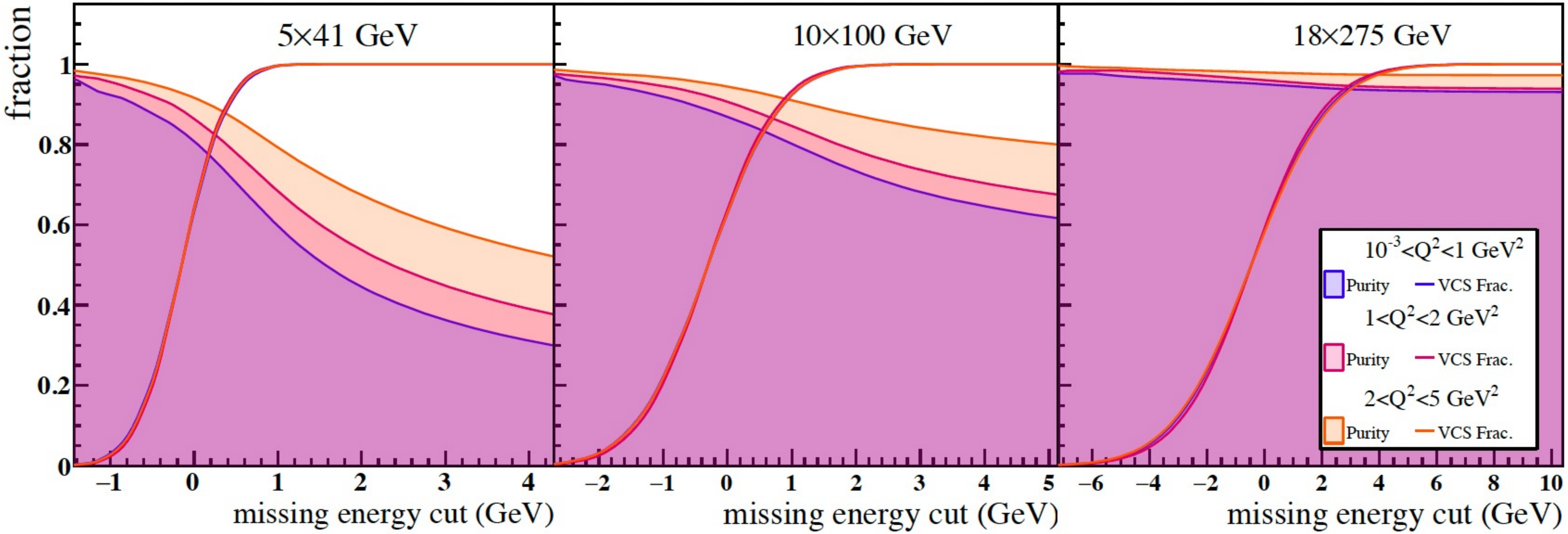
Exclusivity Cuts on π^0 Background

- Simulated effect of ZDC smearing on single-photon π^0 and Compton photons
- Tabulated missing energy using this smearing
- Scaled π^0 events by the ratio of their cross section with VCS
- A missing energy cut can reduce much of the single-photon π^0 events



Exclusivity Cuts on π^0 Background

- We can simulate missing energy cut using the ZDC smearing
- For a given cut ($E_{missing}<E_{cut}$) this shows the fraction of our backward VCS signal collected
- Purity of VCS signal (shaded graphs) also plotted as a function of missing energy cut



Exclusivity Cuts on π^0 Background

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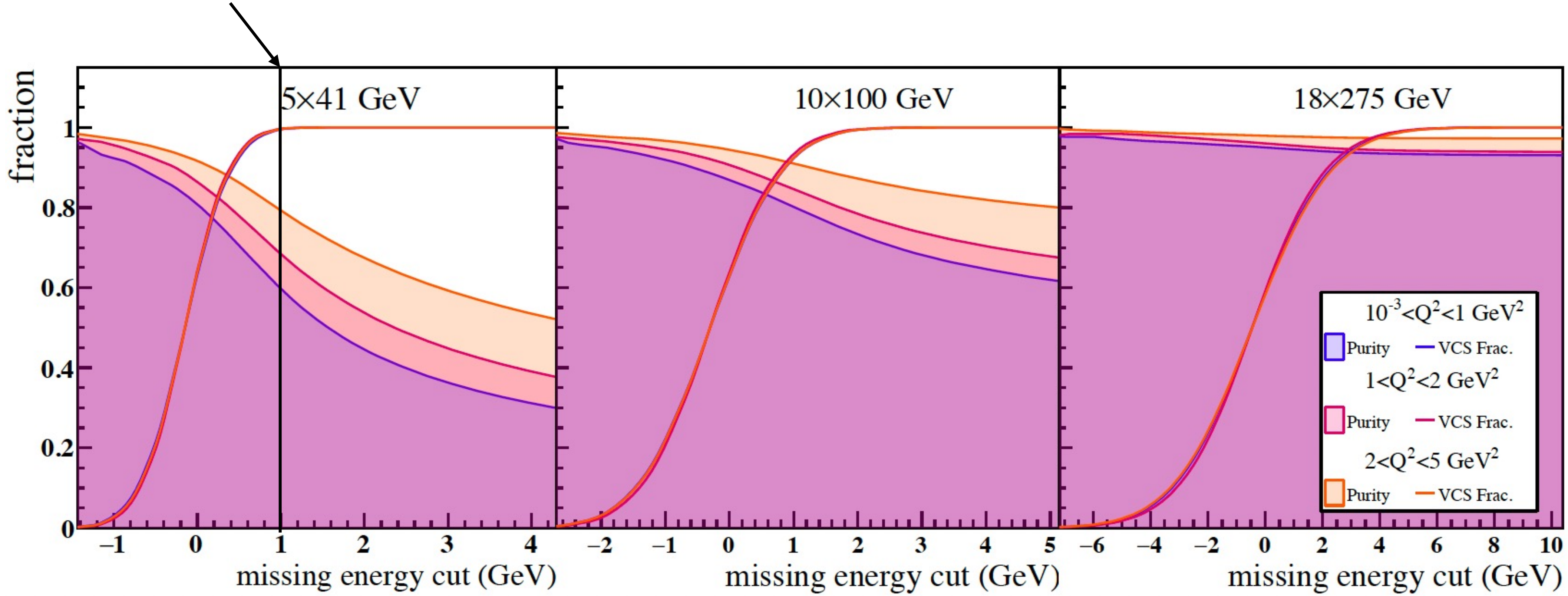
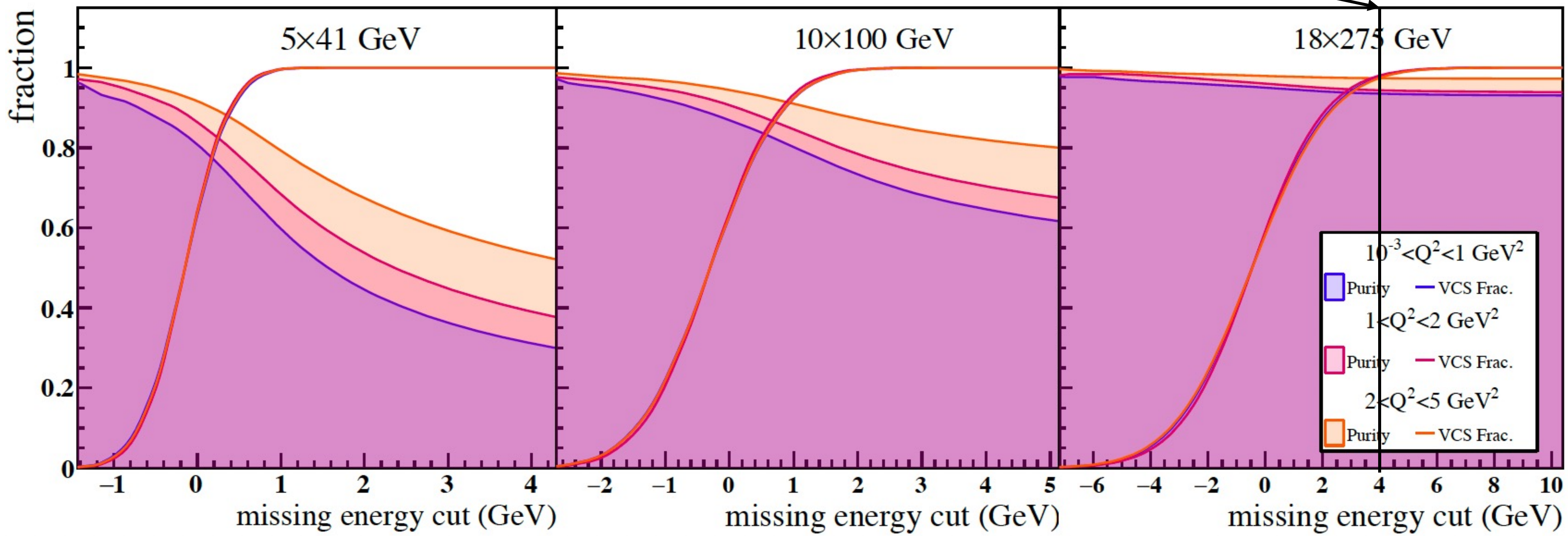


Exclusivity Cuts on π^0 Background

- We can simulate missing energy cut using the ZDC smearing
- For a given cut ($E_{missing}<E_{cut}$) this shows the fraction of our backward VCS signal collected
- Purity of VCS signal (shaded graphs) also plotted as a function of missing energy cut
- For example at 5×41 GeV, a cut of $E_{missing}<$ 1 GeV is sufficient to collect entire signal. Any larger cut just decreases purity.
- At 18×275 GeV, a cut of $E_{missing}<$ 4 GeV may collect signal with ~95% purity!

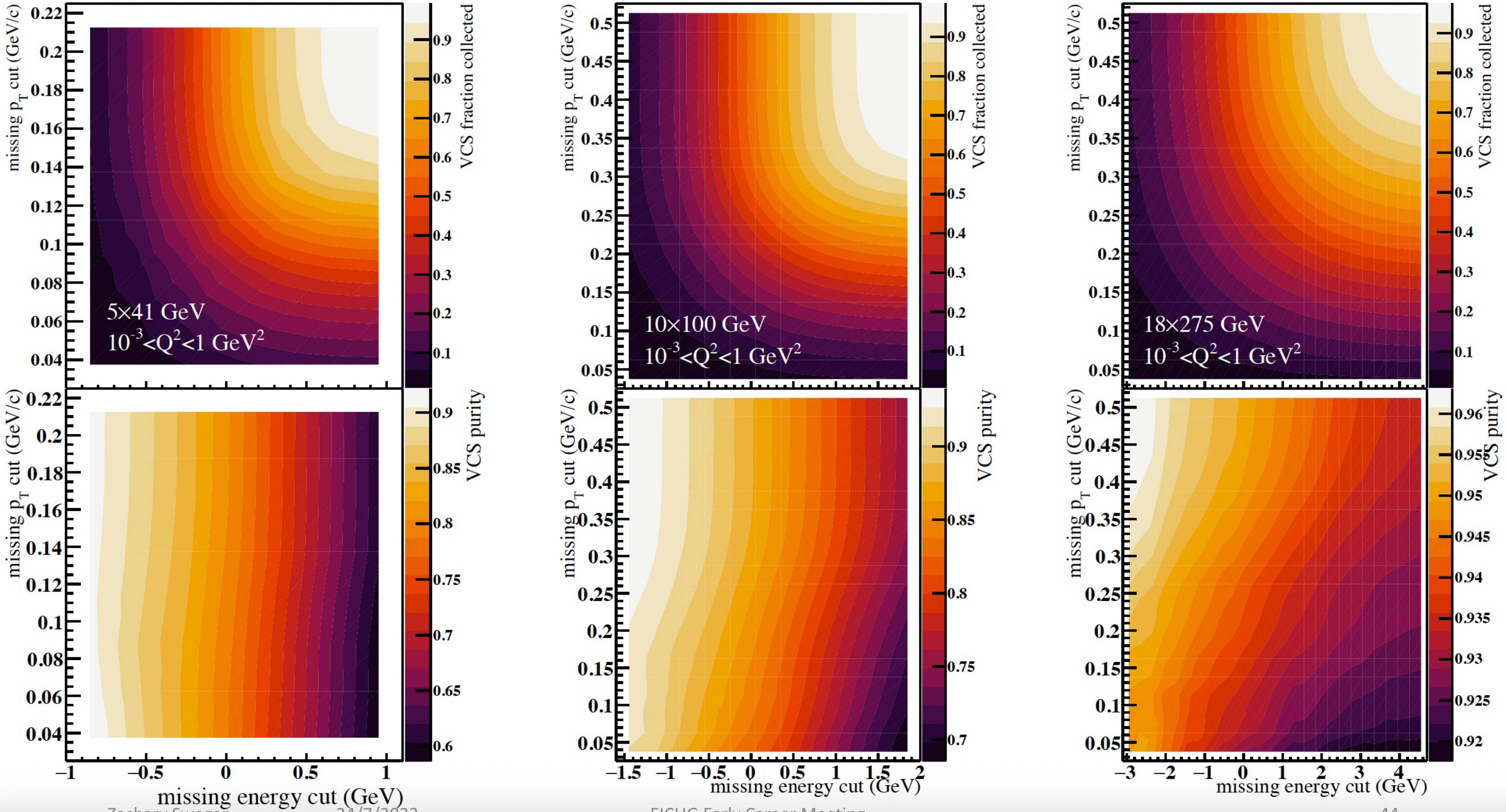


Exclusivity Cuts on π^0 Background

- We can simulate missing pT cuts in the same way

Exclusivity Cuts on π^0 Background

- We can simulate missing pT cuts in the same way
- These may be redundant with missing energy cuts so we plot them together…


5×41 GeV
$10^{-3}<Q^2<1$ GeV^2
10×100 GeV
$10^{-3}<Q^2<1$ GeV^2
18×275 GeV
$10^{-3}<Q^2<1$ GeV^2
VCS fraction collected
VCS purity
missing p_T cut (GeV/c)
missing energy cut (GeV)

Conclusions and Outlook

- Backward production is interesting for encoding unique information about proton GPDs, an active and evolving topic of research
- Early simulations demonstrate importance of B0 and ZDC calorimetry especially for high-energy photons.
- Contributions from π^0 background need to be explored in simulations
- Our team is writing a paper on backward Compton scattering so stay tuned!

Thank you for your attention!

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Backup Slide: Meaning of t-channel Cross Section

Yellow Report, R. Abdul Khalek et al., *arXiv:2103.05419*.

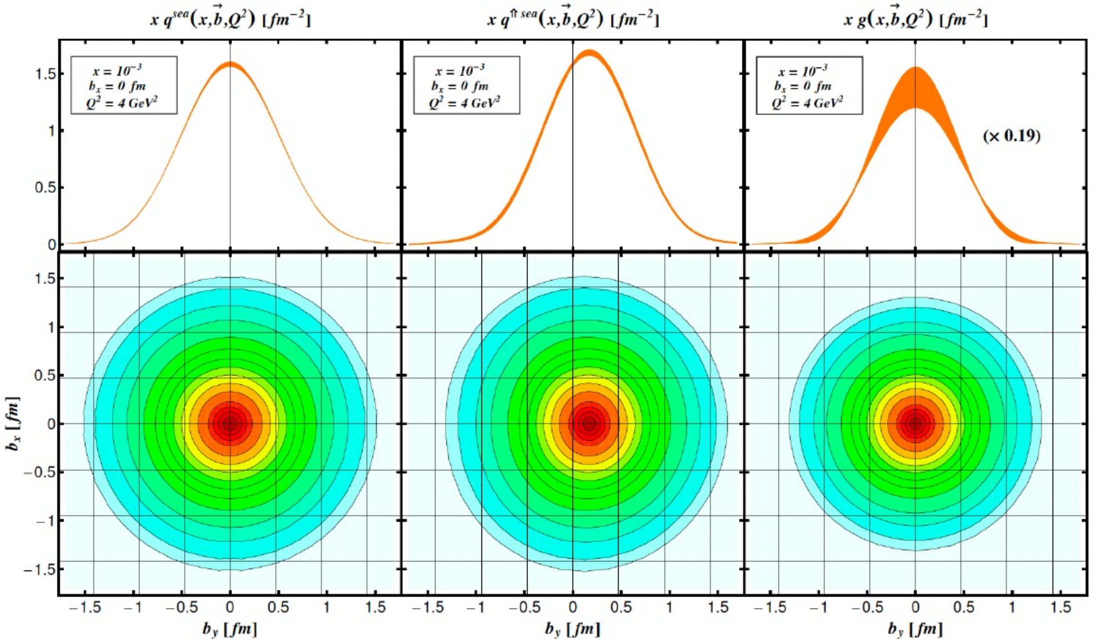

Figure 7.46: Impact parameter distributions at $x = 0.001$ and $Q^2 = 4\,\mathrm{GeV}^2$ for unpolarized sea quarks in an unpolarized proton (left), a transversely polarized proton (middle), and for unpolarized gluons in an unpolarized proton (right), obtained from a combined fit to the HERA collider data and EIC pseudodata [23]. Top row: IPDs at fixed $b_x = 0$ as a function of $b = b_y$. Bottom row: density plots of IPDs in the (b_x, b_y)-plane.

Forward DVCS cross section → proton GPDs

- Differential cross section as a function of t encodes information about proton GPDs
- GPDs can be translated into an impact-parameter description of the proton via a Fourier transform in t
- Thus the forward DVCS cross section is meaningfully related to the parton structure of the proton