The Proton Radius
– Extracted from J/Psi Production at 20+ GeV CEBAF

- “Mass radius of the proton” – Kharzeev’s talk at the INT workshop
- QCD factorization for exclusive J/Psi production with a diffractive proton
- Photo-production vs. lepton-production of J/Psi
- Exclusive single diffractive hard processes for extracting GPDs and 3D tomography
- Advantage of CEBAF at 20+ GeV

Jianwei Qiu
Jefferson Lab, Theory Center

Kharzeev's talk at the INT workshop

Mass radius of the proton

Dmitri Kharzeev

Based on: DK, Phys. Rev. D104 (2021) 5, 054015 [arXiv:2102.00110]

+ ongoing work

Outline

- Gravitational formfactors and the mass distribution
- Scale invariance and scale anomaly in QCD
- Measuring the mass radius of the proton in quarkonium photoproduction near the threshold
- The mass radius puzzle?

INT WORKSHOP INT-20R-77

Origin of the Visible Universe: Unraveling the Proton Mass

June 13, 2022 - June 17, 2022

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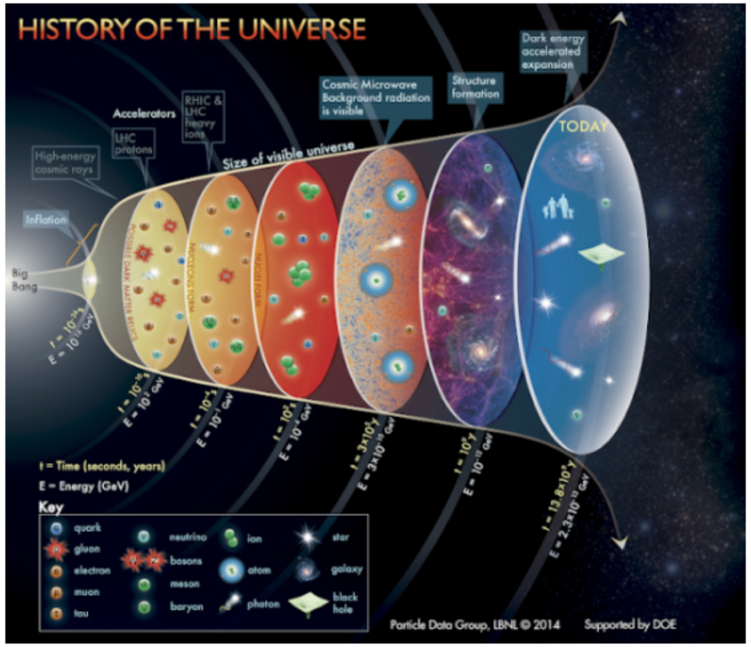
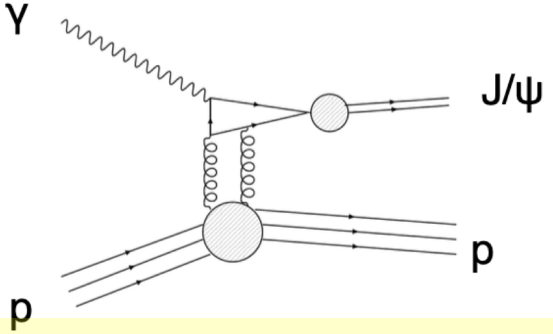


OVERVIEW

Note to applicants: This is a "hybrid" workshop, meaning there will be a combination of virtual and in-person participants. In the COMMENTS section of the Application Form, please write [In-person], [Virtual], or [Either] to reflect your preferred mode of attendance. Please be aware that all In-person participants must show proof of vaccination against COVID-19 upon arrival to the INT.

Kharzeev's talk at the INT workshop

Threshold photoproduction of quarkonium as a probe of mass distribution inside the proton



Near threshold, dominance of

$$g^2\mathbf{E}^{a2} = \frac{8\pi^2}{b}\theta^\mu_\mu + g^2\theta^{(G)}_{00}$$

Assuming the validity of vector meson dominance, can relate photoproduction to quarkonium scattering amplitude and probe the mass of the proton

DK '96; DK, Satz, Syamtomov, Zinovjev '99

Other approaches to threshold photoproduction:

Hatta, Yang '18; Hatta, Rajan, Yang '19; Mamo, Zahed '19-'22;
Ji, 2102.07830; Gao, Ji, Liu, 2103.11506; Sun, Tong, Yuan, 2103.12047…

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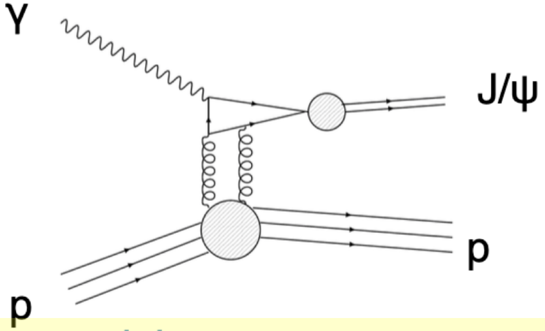
Threshold photoproduction of quarkonium as a probe of mass distribution inside the proton



Large minimum momentum transfer at threshold:

$$t_{min} = -\frac{M_\psi^2 M}{M_\psi + M} \simeq -2.23\ \mathrm{GeV}^2 \simeq -(1.5\ \mathrm{GeV})^2$$

–> VDM questionable.
but, scanning the energy range near the threshold, we measure the scalar gravitational formfactor – can extract the proton mass distribution!

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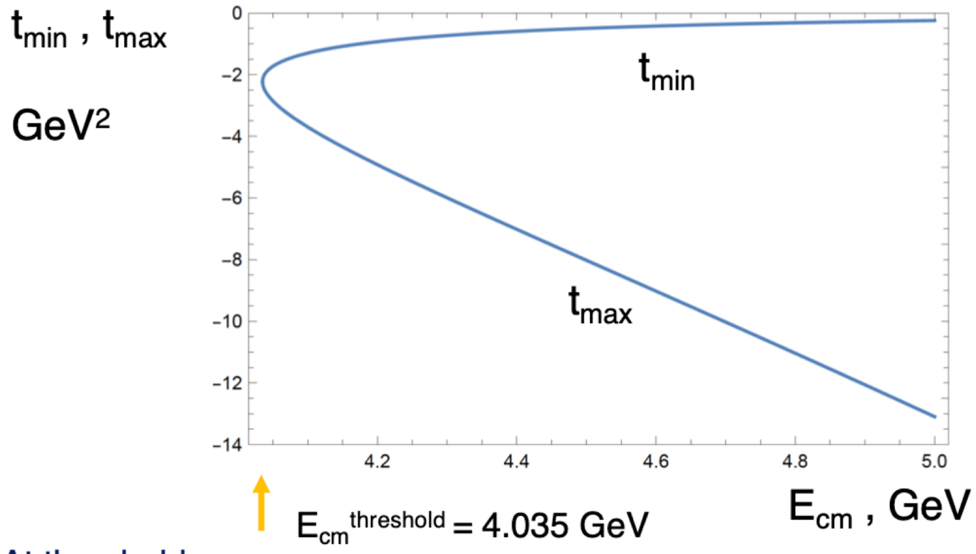
Kharzeev’s talk at the INT workshop

Threshold photoproduction of quarkonium as a probe of mass distribution inside the proton



Can measure scalar gravitational formfactor in a broad kinematical domain!

At threshold:

$$t_{min} = -\frac{M_\psi^2 M}{M_\psi + M} \simeq -2.23 \text{ GeV}^2 \simeq -(1.5 \text{ GeV})^2$$

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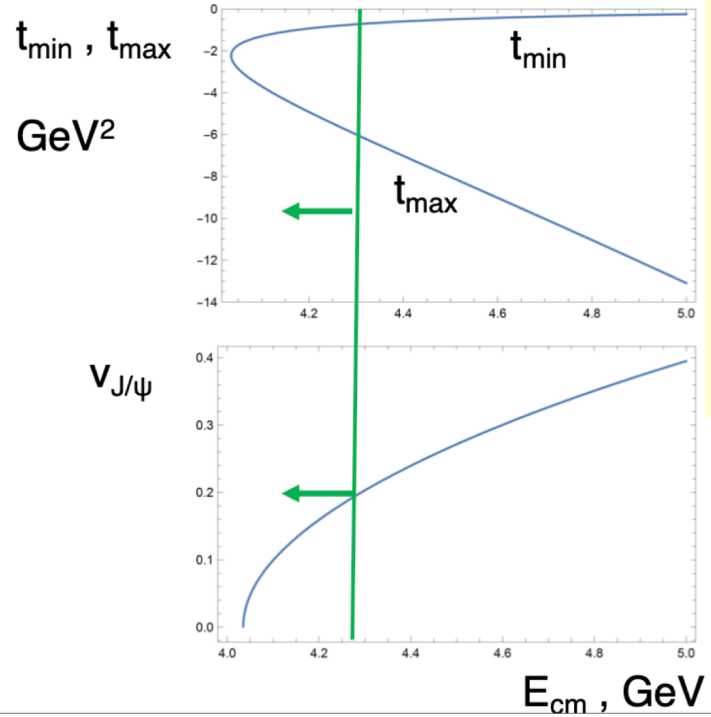
Threshold photoproduction of quarkonium as a probe of mass distribution inside the proton



The scalar operator dominates for small velocity of heavy quarkonium;

Limiting $v_{J/\psi} < 0.2$, (corrections ~ $v_{J/\psi}^2$) the optimal kinematical region is:

$E_{cm} < 4.25$ GeV
$E_\gamma < 9.2$ GeV

$-t < 6$ GeV²

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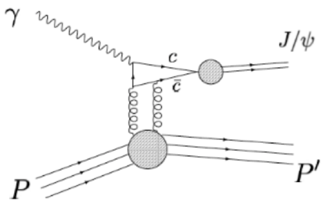
Kharzeev’s talk at the INT workshop

Threshold photoproduction of quarkonium as a probe of mass distribution inside the proton

The amplitude:

$$\mathcal{M}_{\gamma P\to\psi P}(t) = -Qe\ c_2\ 2M\ \langle P'|g^2\mathbf{E}^{a2}|P\rangle,$$



$$Qe = 2e/3$$

$$\mathcal{M}_{\gamma P\to\psi P}(t) = -Qe\ c_2\ \frac{16\pi^2 M}{b}\ \langle P'|T|P\rangle$$

Differential cross section:

$$\frac{d\sigma_{\gamma P\to\psi P}}{dt} = \frac{1}{64\pi s}\frac{1}{|\mathbf{p}_{\gamma cm}|^2}|\mathcal{M}_{\gamma P\to\psi P}(t)|^2$$

DK, PRD’21

$$\sigma_{\gamma P\to\psi P}(s) = \int_{t_{min}}^{t_{max}} dt\ \frac{d\sigma_{\gamma P\to\psi P}}{dt},$$

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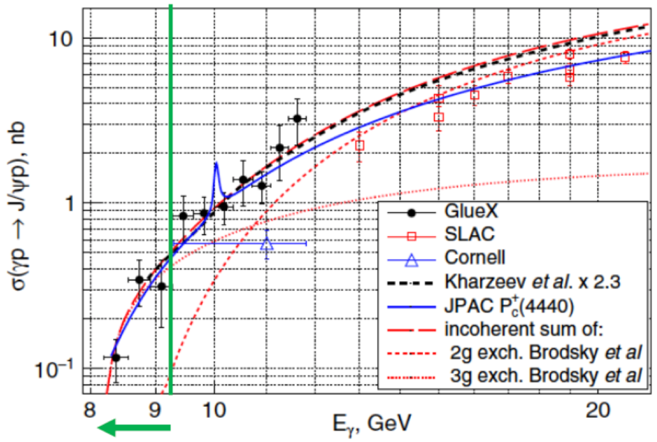
PHYSICAL REVIEW LETTERS **123,** 072001 (2019)

Editors' Suggestion

First Measurement of Near-Threshold J/ψ Exclusive Photoproduction off the Proton

A. Ali,[10] M. Amaryan,[22] E. G. Anassontzis,[2] A. Austregesilo,[3] M. Baalouch,[22] F. Barbosa,[14] J. Barlow,[7] A. Barnes,[3] E. Barriga,[7] T. D. Beattie,[23] V. V. Berdnikov,[17] T. Black,[20] W. Boeglin,[6] M. Boer,[4] W. J. Briscoe,[8] T. Britton,[14] W. K. Brooks,[24] B. E. Cannon,[7] N. Cao,[11] E. Chudakov,[14] S. Cole,[1] O. Cortes,[8] V. Crede,[7] M. M. Dalton,[14] T. Daniels,[20] A. Deur,[14] S. Dobbs,[7] A. Dolgolenko,[13] R. Dotel,[6] M. Dugger,[1] R. Dzhygadlo,[10] H. Egiyan,[14] A. Ernst,[7] P. Eugenio,[7] C. Fanelli,[16] S. Fegan,[8] A. M. Foda,[23] J. Foote,[12] J. Frye,[12] S. Furletov,[14] L. Gan,[20] A. Gasparian,[19] V. Gauzshtein,[25,26] N. Gevorgyan,[27] C. Gleason,[12] K. Goetzen,[10] A. Goncalves,[7] V. S. Goryachev,[13] L. Guo,[6] H. Hakobyan,[24] A. Hamdi,[10] S. Han,[29] J. Hardin,[16] G. M. Huber,[23] A. Hurley,[28] D. G. Ireland,[9] M. M. Ito,[14] N. S. Jarvis,[3] R. T. Jones,[5] V. Kakoyan,[27] G. Kalicy,[4] M. Kamel,[6] C. Kourkoumelis,[2] S. Kuleshov,[24] I. Kuznetsov,[25,26] I. Larin,[15] D. Lawrence,[14] D. I. Lersch,[7] H. Li,[3] W. Li,[28] B. Liu,[11] K. Livingston,[9] G. J. Lolos,[23] V. Lyubovitskij,[25,26] D. Mack,[14] H. Marukyan,[27] V. Matveev,[13] M. McCaughan,[14] M. McCracken,[3] W. McGinley,[3] J. McIntyre,[5] C. A. Meyer,[3] R. Miskimen,[15] R. E. Mitchell,[12] F. Mokaya,[5] F. Nerling,[10] L. Ng,[7] A. I. Ostrovidov,[7] Z. Papandreou,[23] M. Patsyuk,[16] P. Pauli,[9] R. Pedroni,[19] L. Pentchev,[14,*] K. J. Peters,[10] W. Phelps,[8] E. Pooser,[14] N. Qin,[21] J. Reinhold,[6] B. G. Ritchie,[1] L. Robison,[21] D. Romanov,[17] C. Romero,[24] C. Salgado,[18] A. M. Schertz,[28] R. A. Schumacher,[3] J. Schwiening,[10] K. K. Seth,[21] X. Shen,[11] M. R. Shepherd,[12] E. S. Smith,[14] D. I. Sober,[4] A. Somov,[14] S. Somov,[17] O. Soto,[24] J. R. Stevens,[28] I. I. Strakovsky,[8] K. Suresh,[23] V. Tarasov,[13] S. Taylor,[14] A. Teymurazyan,[23] A. Thiel,[9] G. Vasileiadis,[2] D. Werthmüller,[9] T. Whitlatch,[14] N. Wickramaarachchi,[22] M. Williams,[16] T. Xiao,[21] Y. Yang,[16] J. Zarling,[12] Z. Zhang,[29] G. Zhao,[11] Q. Zhou,[11] X. Zhou,[29] and B. Zihlmann[14]

(GlueX Collaboration)



Need to focus on the threshold region!

$E_{cm} < 4.25$ GeV

$E_\gamma < 9.2$ GeV

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Kharzeev’s talk at the INT workshop

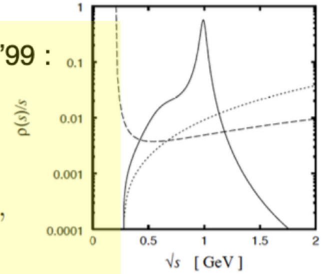
Threshold photoproduction of quarkonium: the effect of the scalar gravitational formfactor

The scalar gravitational formfactor can be constrained theoretically by using:

i) dispersion relations;
ii) low-energy theorems of broken scale invariance;
iii) experimental data on ππ phase shifts and scalar mesons

However, as a first step, can try a simple dipole formfactor of the type used for electromagnetic formfactor:

See e.g. Fujii, DK’99 :



$$G(t) = \frac{M}{(1 - t/M_s^2)^2} \quad \text{radius} \quad \langle R_{\rm M}^2 \rangle = \frac{6}{M} \frac{dG}{dt}\Big|_{t=0},$$

Dipole formfactor was also used for 2-gluon coupling in perturbative models

See e.g. Frankfurt, Strikman ‘02

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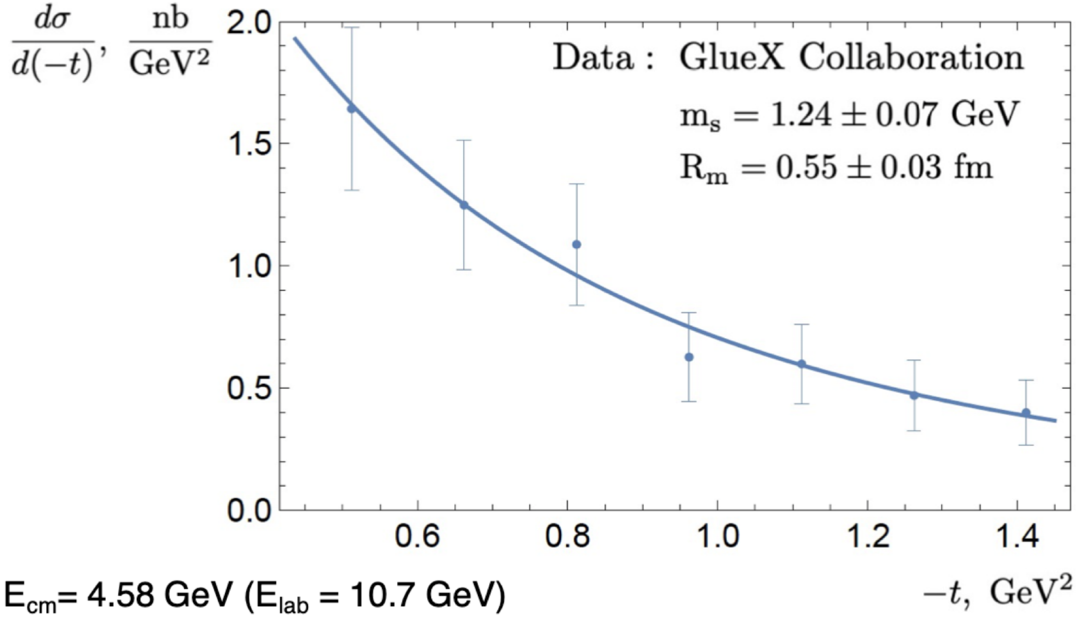
Differential cross section

DK, arXiv:2102.00110



E_{cm}= 4.58 GeV (E_{lab} = 10.7 GeV)

$$|c_2|^2 = 0.043 \pm 0.006 \ \text{fm}^4$$

Lattice QCD, P. Shanahan, W. Detmold PRD’19:

$m_s = 1.13 \pm 0.06$ GeV (Traceless gluon operator)

$c_2 \sim \pi r_{c\bar{c}}^2$ $\quad r_{c\bar{c}} \simeq 0.1$ fm

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Kharzeev's talk at the INT workshop

The proton mass radius

The r.m.s. "proton mass radius" from GlueX data:

DK, arXiv:2102.00110

$$R_{\rm m} \equiv \sqrt{\langle R^2_{\rm m} \rangle} = 0.55 \pm 0.03 \text{ fm}$$

Compare to the proton charge radius:

$$\bar{\rm R}_{\rm c} \equiv \sqrt{R^2_c} = 0.8409 \pm 0.0004 \quad \text{fm}$$

See J.Bernauer, EPJ 234 (2020) for review

A more compact mass distribution? Need more data!

VALUE (fm)		DOCUMENT ID		TECN	COMMENT
0.8409 ± 0.0004		**OUR AVERAGE**			
0.833 ±0.010	1	BEZGINOV	2019	LASR	2S-2P transition in H
0.831 ±0.007 ±0.012	2	XIONG	2019	SPEC	$e\,p \to ep$ form factor
0.84087 ±0.00026 ±0.00029		ANTOGNINI	2013	LASR	μp -atom Lamb shift
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.877 ±0.013	3	FLEURBAEY	2018	LASR	1S-3S transition in H
0.8335 ±0.0095	4	BEYER	2017	LASR	2S-4P transition in H
0.8751 ±0.0061		MOHR	2016	RVUE	2014 CODATA value
0.895 ±0.014 ±0.014	5	LEE	2015	SPEC	Just 2010 Mainz data
0.916 ±0.024		LEE	2015	SPEC	World data, no Mainz
0.8775 ±0.0051		MOHR	2012	RVUE	2010 CODATA, ep data
0.875 ±0.008 ±0.006		ZHAN	2011	SPEC	Recoil polarimetry
0.879 ±0.005 ±0.006		BERNAUER	2010	SPEC	$e\,p \to ep$ form factor

2020 Review of Particle Physics.
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Some day:
p MASS RADIUS in PDG?

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Theoretical uncertainties

- Higher dimensional operators (suppressed by $1/m_c$)
- Chiral limit (we omitted the scalar quark operator)
- Gluon operators with derivatives (~ 5% close to threshold)
- t-dependence of short-distance coefficient c_2 (~ $t/4m_c^2$)
- Dipole parameterization of formfactor

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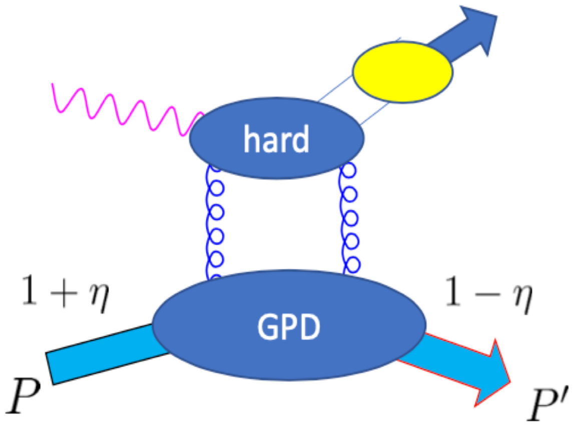
Hatta's talk at this workshop

Theory approach 4: QCD factorization

Light-cone dominance when $Q^2 \to \infty$ or $M_{QQ} \to \infty$

GPD factorization at high energy Collins, Frankfurt, Strikman (1996)
Ivanov, Schafer, Szymanowski, Krasnikov (2004)

Let's assume factorization is valid and see what happens.



Amplitude proportional to Compton form factor

$$\int_{-1}^{1} \frac{dx}{x} \left(\frac{1}{\eta - x - i\epsilon} - \frac{1}{\eta + x - i\epsilon} \right) H_g(x, \eta, t)$$

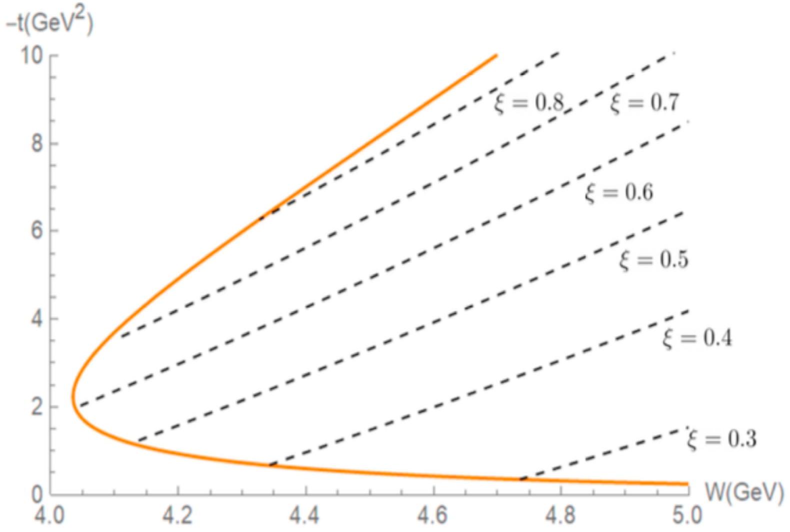
Gluon GPD

Skewness $\eta = \dfrac{P^+ - P'^+}{P'^+ + P^+}$

1 graviton $\approx$ 2 gluons ??

Skewness

J/ψ Photoproduction



Guo, Ji, Liu (2021)

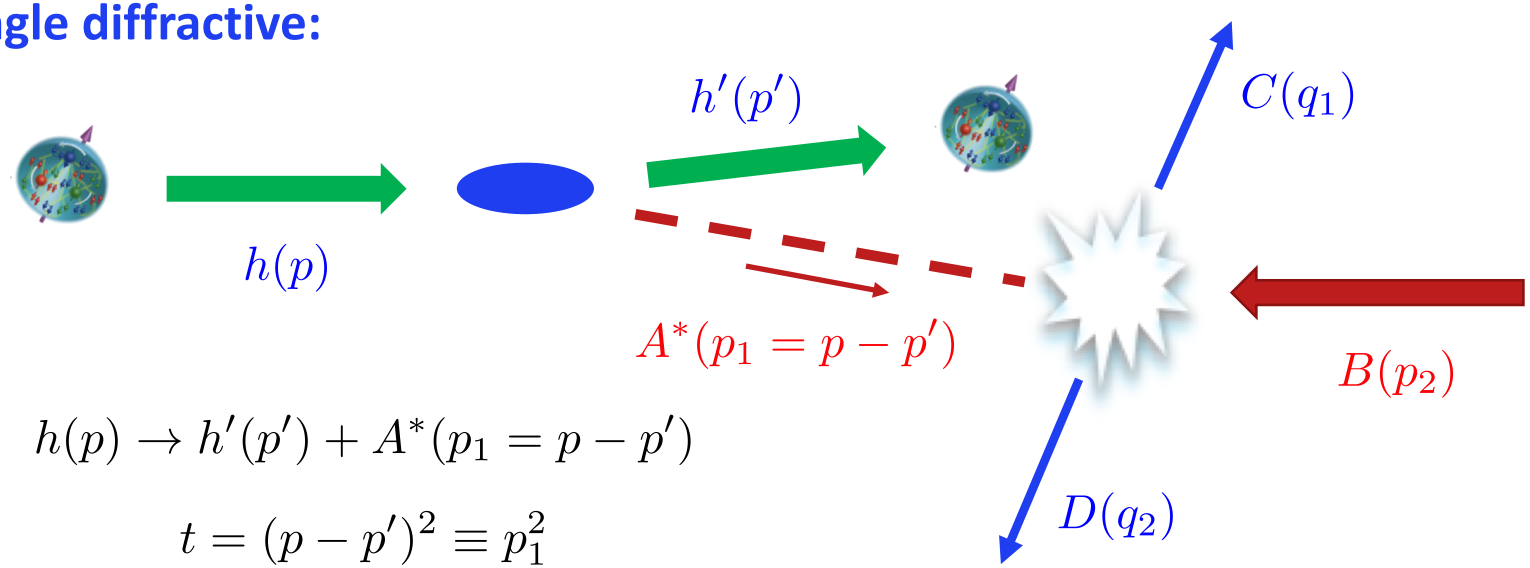
the ideal limits $Q^2 \to \infty$ or $m_V \to \infty$

Extracting Two-gluon Correlation from Experiments

❑ QCD factorization of diffractive $2 \to 3$ exclusive hard processes:

Qiu & Yu, 2022

- **Single diffractive:**



$$h(p) \to h'(p') + A^*(p_1 = p - p')$$

$$t = (p - p')^2 \equiv p_1^2$$

Photo-production of J/Psi:

$$B(p_2) \;\to\; \gamma(p_2)$$

$$C(q_1) \;\to\; \ell(q_1),\;\; D(q_2) \;\to\; \bar{\ell}(q_2)$$

with $(q_1 + q_2)^2 \sim M_{J/\psi}$

Lepton-production of J/Psi:

$$B(p_2) \;\to\; \ell(p_2)$$

$$C(q_1) \;\to\; \ell(q_1)$$

$$D(q_2) \;\to\; J/\psi(q_2)$$

$\quad \hookrightarrow \; \ell + \bar{\ell}$

- **Hard probe:** $2 \to 2$ **high** q_T **exclusive process**

$$A^*(p_1) + B(p_2) \to C(q_1) + D(q_2)$$

$$|q_{1_T}| = |q_{2_T}| \gg \sqrt{-t}$$

- **The single diffractive** $2 \to 3$ **exclusive hard processes:**

$$h(p) + B(p_2) \to h'(p') + C(q_1) + D(q_2)$$

- **Necessary condition for QCD factorization:**

$$|q_{1_T}| = |q_{2_T}| \gg \sqrt{-t}$$

The state $A^*(p_1)$ **lives much longer than** $2 \to 2$ **hard exclusive collision!**

Not necessarily sufficient!

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Extracting Two-gluon Correlation from Experiments

Qiu & Yu, 2022

- QCD factorization of diffractive $2 \to 3$ exclusive hard processes:
  - Single diffractive:

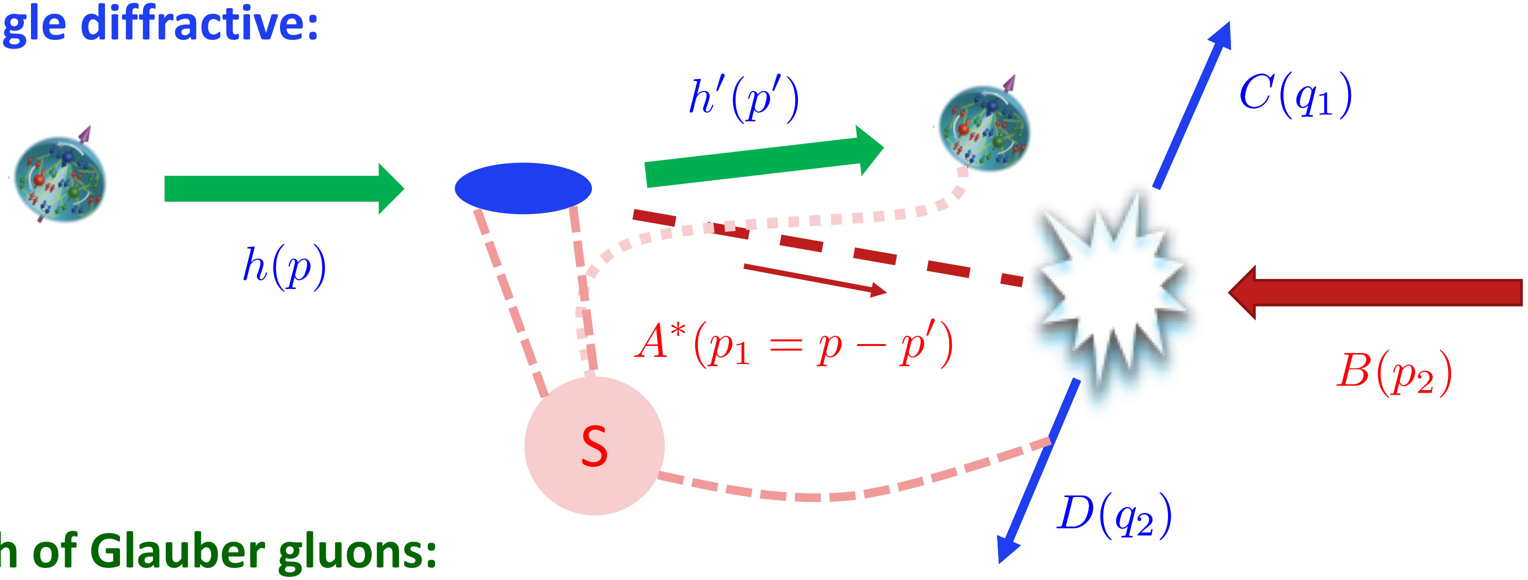


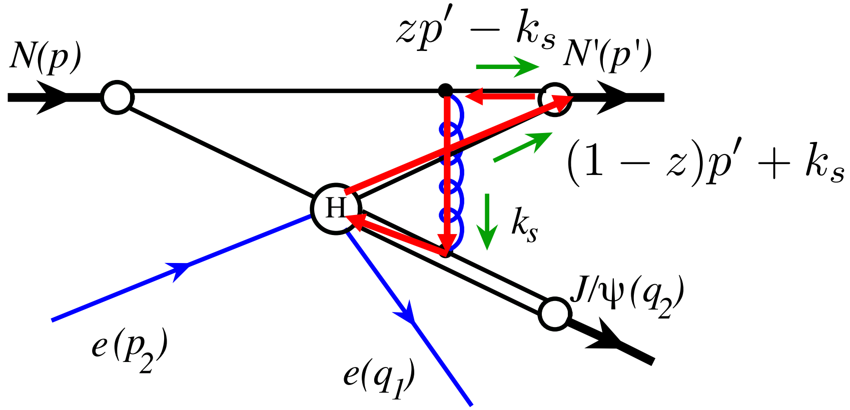
Photo-production of J/Psi:

$B(p_2) \to \gamma(p_2)$
$C(q_1) \to \ell(q_1)$
with $(q_1 + q_2)^2 \sim M_{J/\psi}$

Lepton-production of J/Psi:

$B(p_2) \to \ell(p_2)$
$C(q_1) \to \ell(q_1)$
$D(q_2) \to J/\psi(q_2)$
$\quad \to \ell + \bar{\ell}$

- Pinch of Glauber gluons:



Gluons in the Glauber region:

$k_s = (\lambda^2, \lambda^2, \lambda)\, Q$

$$\frac{1}{((1-z)p' + k_s)^2 + i\epsilon} \to \frac{1}{k_s^- + i\epsilon}$$

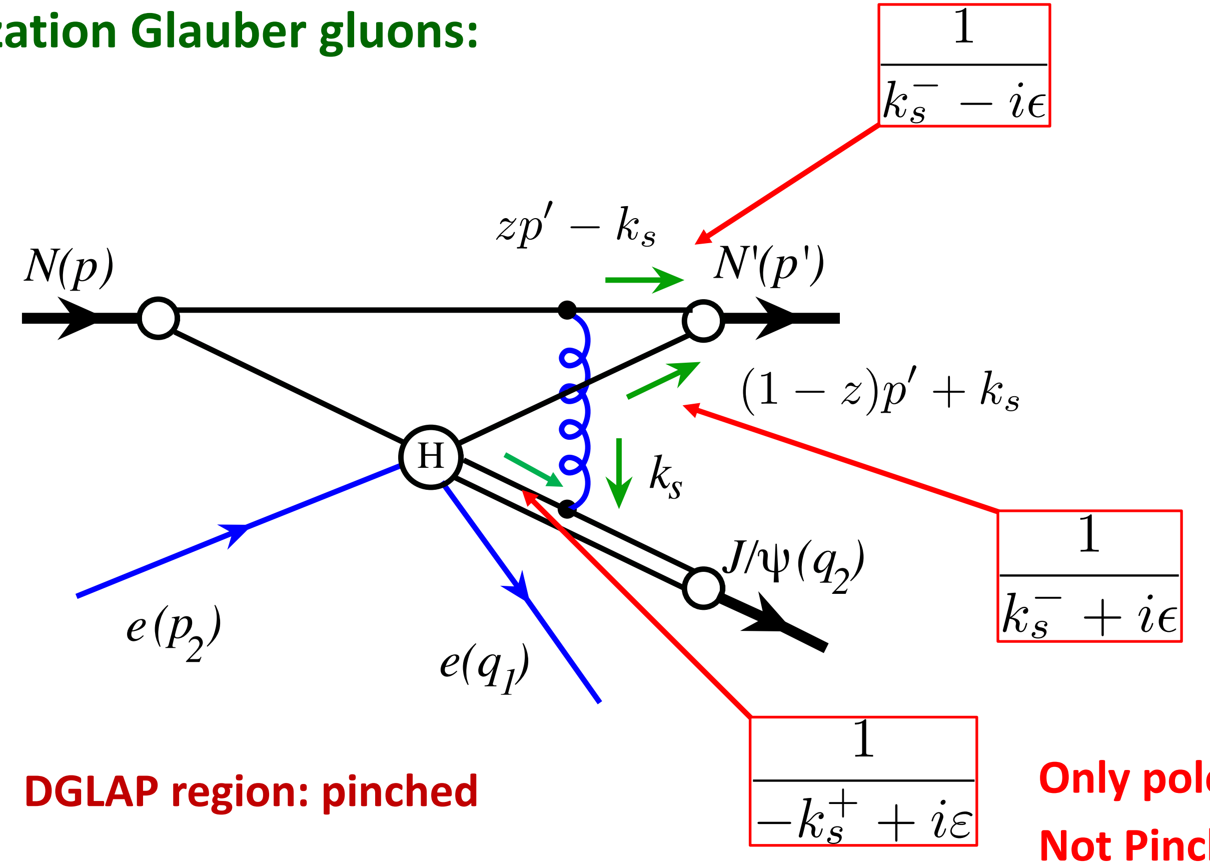
$$\frac{1}{(zp' - k_s)^2 + i\epsilon} \to \frac{1}{k_s^- - i\epsilon}$$

Pinched!

Extracting Two-gluon Correlation from Experiments

- **Factorization Glauber gluons:**

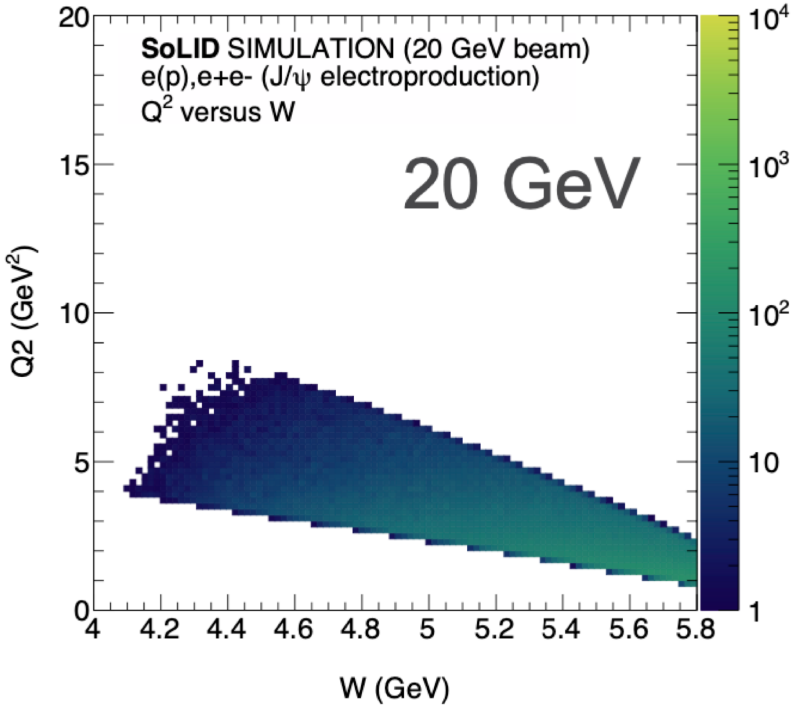
Qiu & Yu, 2022



DGLAP region: pinched

Only pole for k_s^+

Not Pinched!



Deformation out of the Glauber region:

$$k_s^+ \to k_s^+ - i\mathcal{O}(Q) \quad \Rightarrow \quad k_s \sim (1, \lambda^2, \lambda)Q$$

Collinear region

Factorize all soft gluon attached to J/ψ jet $\Rightarrow$ $q_{2T} \gtrsim m_{J/\psi}$ **Higher beam energy!**

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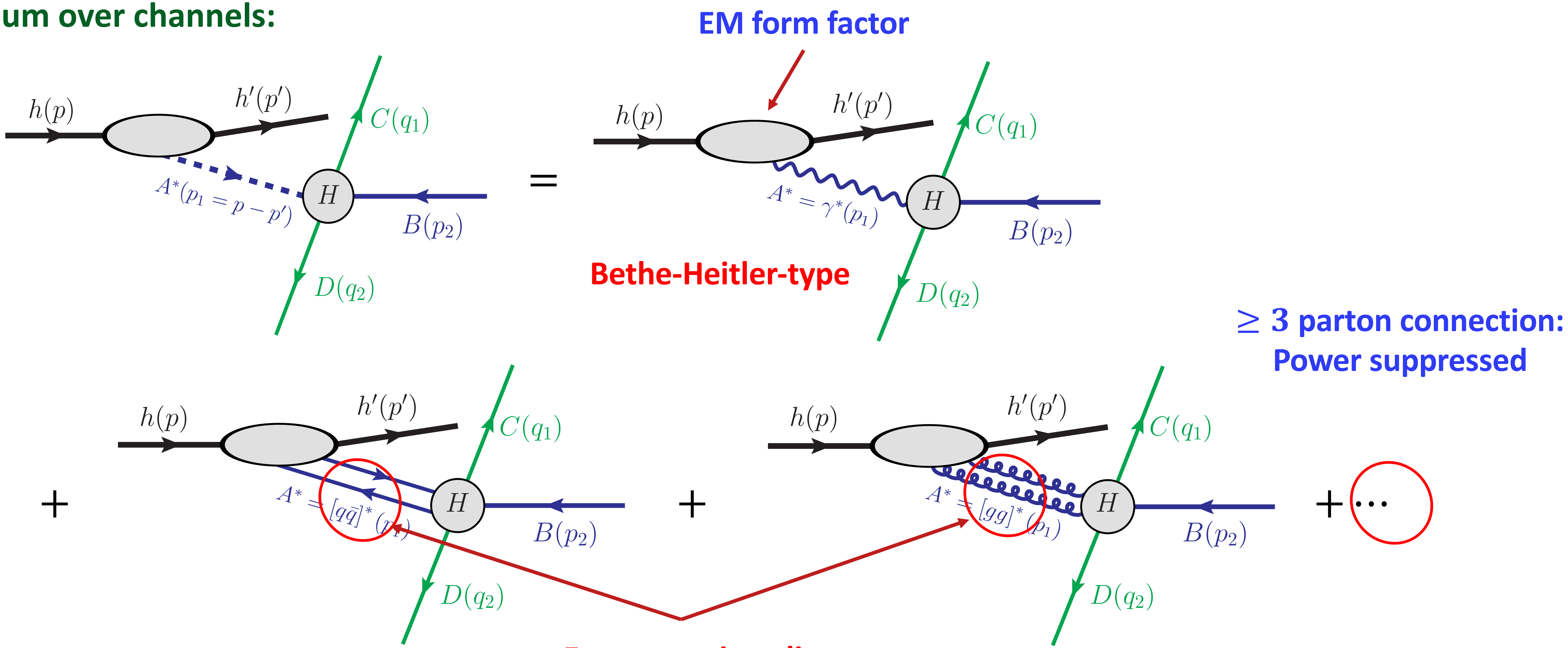
Factorization in the Two-stage Paradigm

- **Sum over channels:**



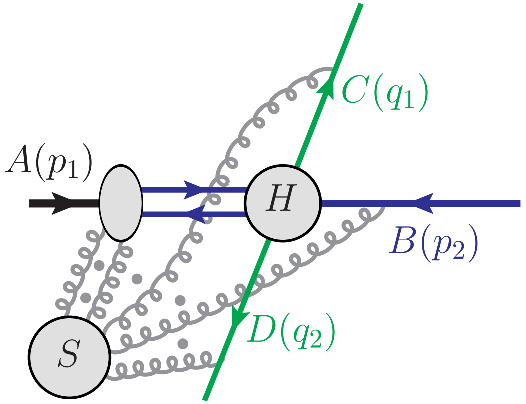
Energy $\gg$ virtuality

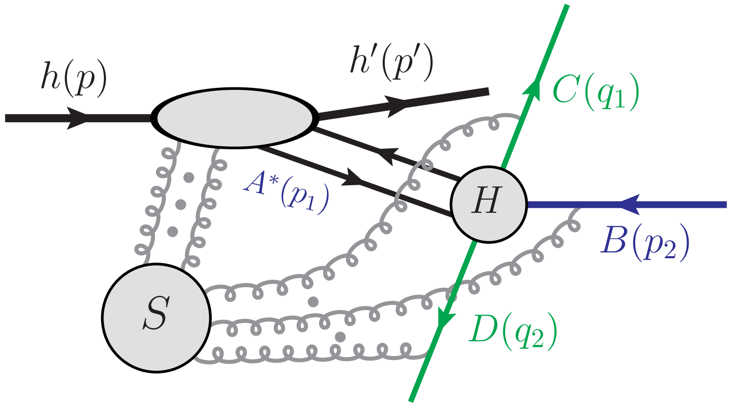
→ **To be factorized into GPD**

Factorization in the Two-stage Paradigm

Qiu & Yu, 2205.07846 (JHEP in press)

- **Factorization for 2-parton channel factorization:**





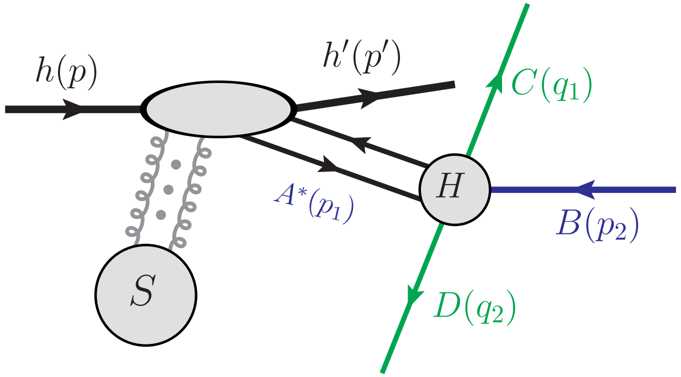
Only complication:

k_s^- **is pinched in Glauber region for DGLAP region.**

$$k_s^+ \mapsto k_s^+ \pm i\mathcal{O}(Q)$$

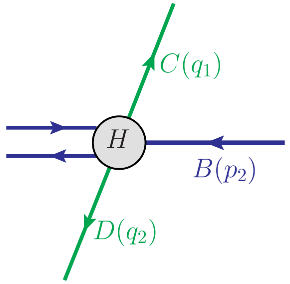
Glauber → h-collinear region

- **Soft gluons cancel for the meson-initialized process if *C* and *D* are mesons:**

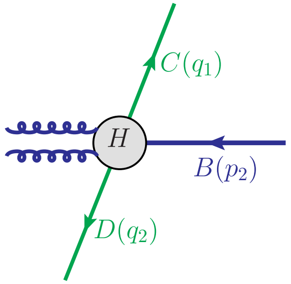


Soft gluons are no longer pinched and can be deformed into h-collinear region

$\text{GPD} \otimes$



or

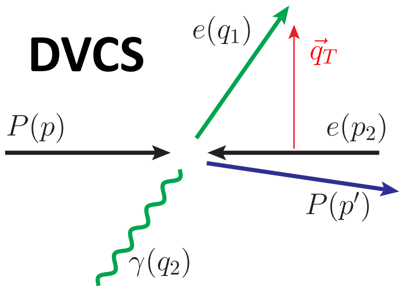


Classification of these New Processes for GPDs

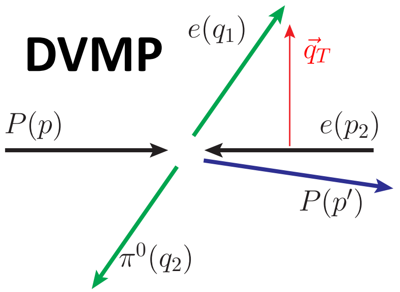
Qiu & Yu, 2205.07846 (JHEP in press), 2207.xxxxx

- **Electro-production (JLab, EIC, …)**

DVCS

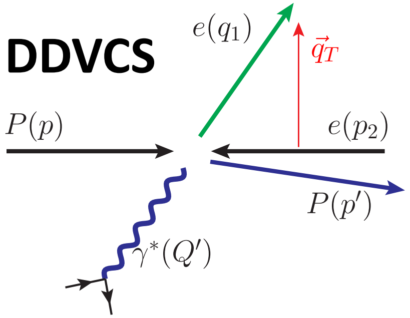


DVMP



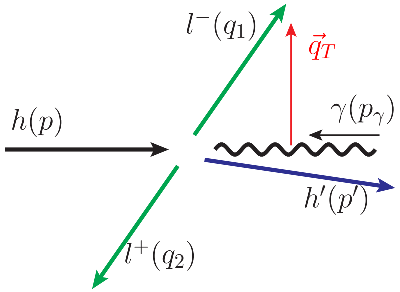
add virtuality

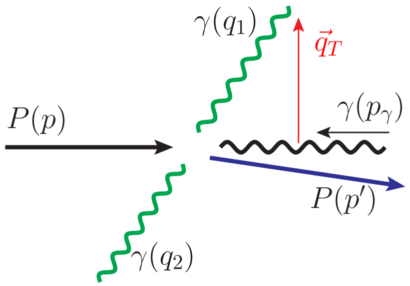
DDVCS

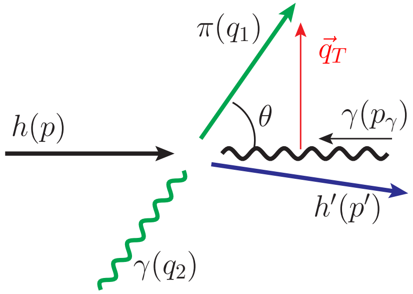


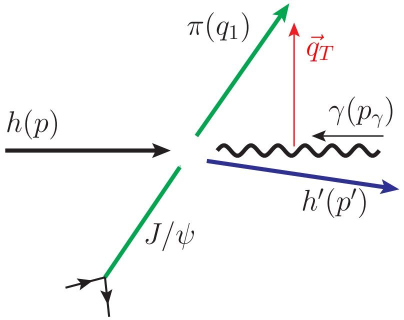
DHQP…

- **Photo-production (JLab Hall-D, …)**

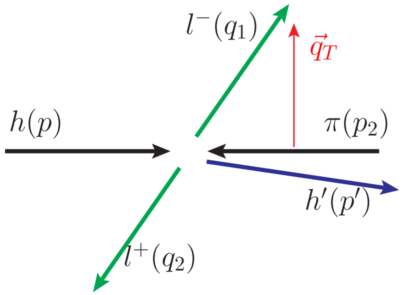


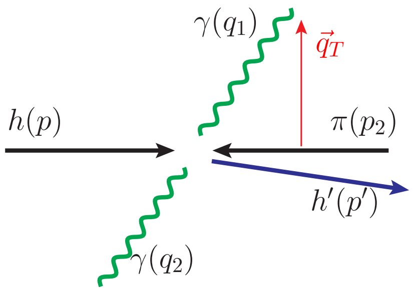






- **Meson-production (AMBER, J-PARC, …)**



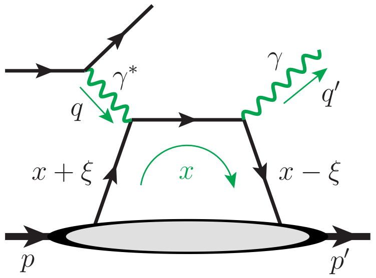


…

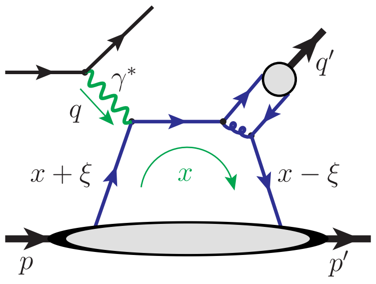
One can easily list more processes by using mesons, adding virtuality…

GPDs – QCD Tomography

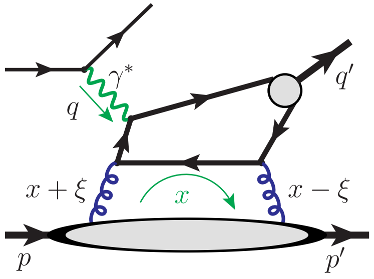
- **Imagining spatial distribution of quarks and gluons:**



DVCS: Q² >> |t|



DVMP



DVQP

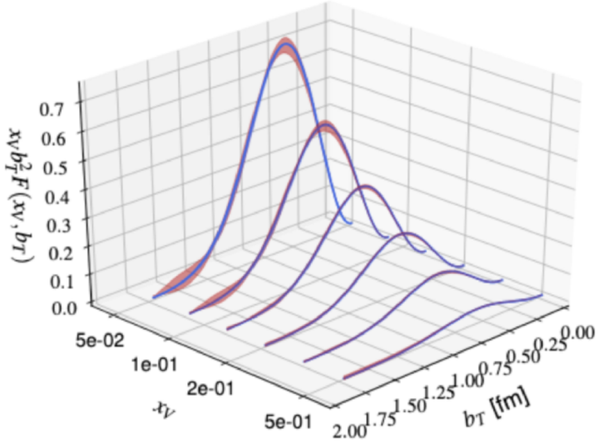
$$\frac{d\sigma}{dt} \qquad t = (p - p')^2$$

Factorization $Q^2 \gg |t|$

GPDs: $f_{i/h}(x, \xi, t; \mu)$

F.T. t_T **to** b_T

at $\xi \propto (p - p')^+ \to 0$



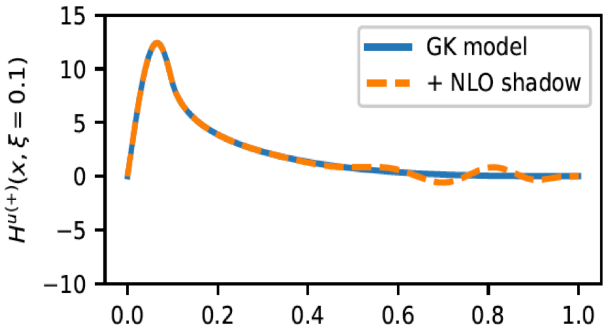
- **Proton radii of quark and gluon spatial distribution,** $r_q(x)$ **&** $r_g(x)$

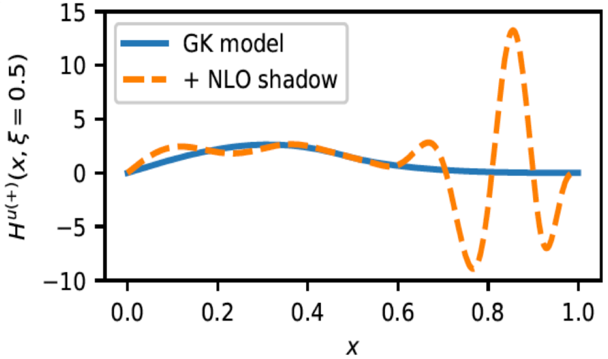
  Should $r_q(x)$ **>** $r_g(x)$**, or vice versa? Could** $r_g(x)$ **saturate as** $x \to 0$ **?**

  …

- **But, all these observables are not very sensitive to the *x*-dependence!**

  Sensitive to the total momentum of the pair, not the relative momentum





Blue and dashed
Fit the same CFFs !

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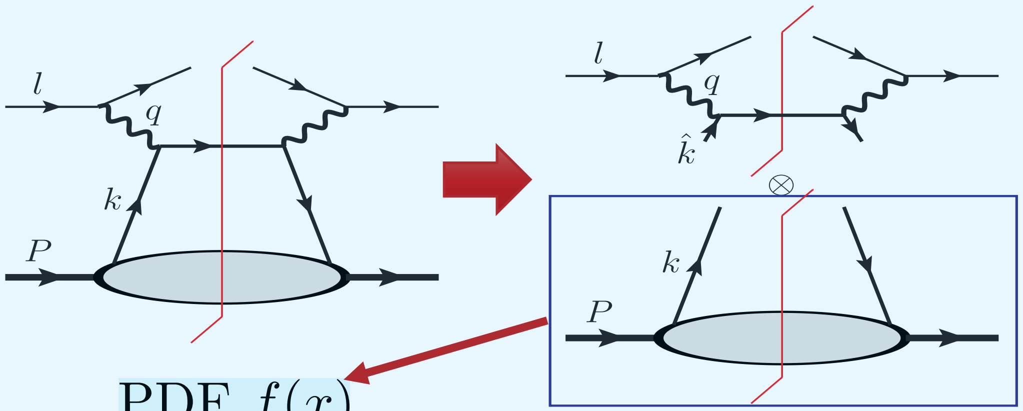
Inclusive Process vs. Exclusive Process

❑ Deeply Inelastic Scattering (DIS):



PDF $f(x)$

$x = k^+/P^+$

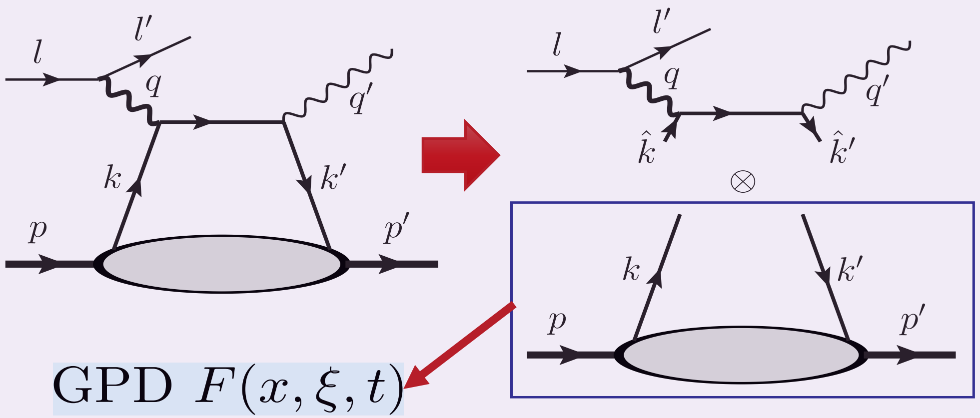
Cross section: **Cut diagrams**

$$\sigma_{\rm DIS} \simeq \int_{x_B}^{1} \mathrm{d}x\, f(x)\, \hat{\sigma}(x/x_B)$$

- **PDF ~ probability**
- **At LO: $x = x_B$**
- **Beyond LO: $x \in [x_B, 1]$**

x-dependence: **Part of measurement**

❑ Deeply Virtual Compton Scattering (DVCS)



GPD $F(x, \xi, t)$

$$x = \frac{(k+k')^+}{(p+p')^+}$$

$$\xi = \frac{(p-p')^+}{(p+p')^+}$$

$$t = (p-p')^2$$

Amplitude: **Uncut diagrams**

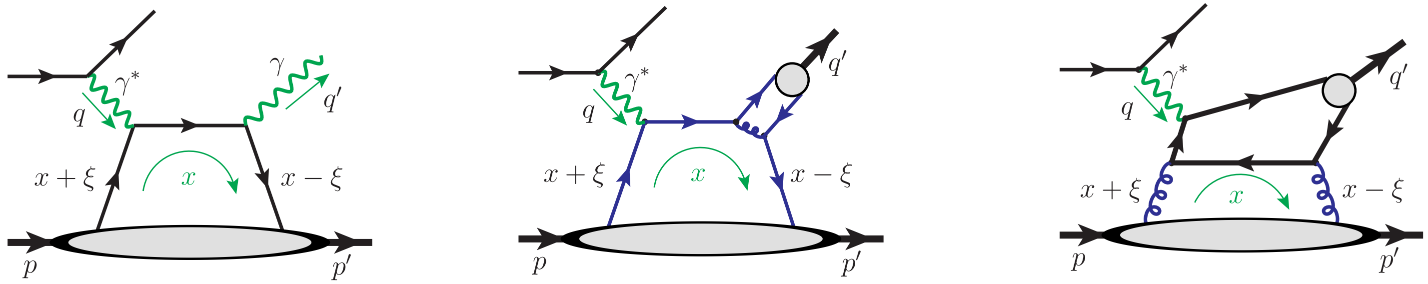
$$\mathcal{M}_{\rm DVCS}(\xi, t) \simeq \int_{-1}^{1} \mathrm{d}x\, F(x, \xi, t)\, \hat{\mathcal{M}}(x, \xi)$$

- **GPD ~ amplitude**
- **$k^+ = (x + \xi)\, P^+$ is loop momentum**
- **At any order: $x \in [-1, 1]$**

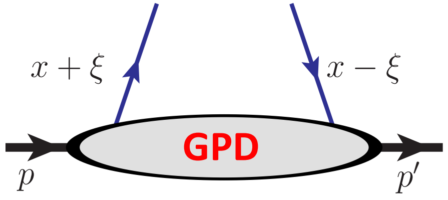
x-dependence: **Hard to measure**

GPDs – QCD Tomography

- **Imagining spatial distribution of quarks and gluons:**



Factorization



$$i\mathcal{M} \sim \int_{-1}^{1} \mathrm{d}x\, F(x,\xi,t)\cdot C(x,\xi;Q/\mu)$$

x ~ loop momentum

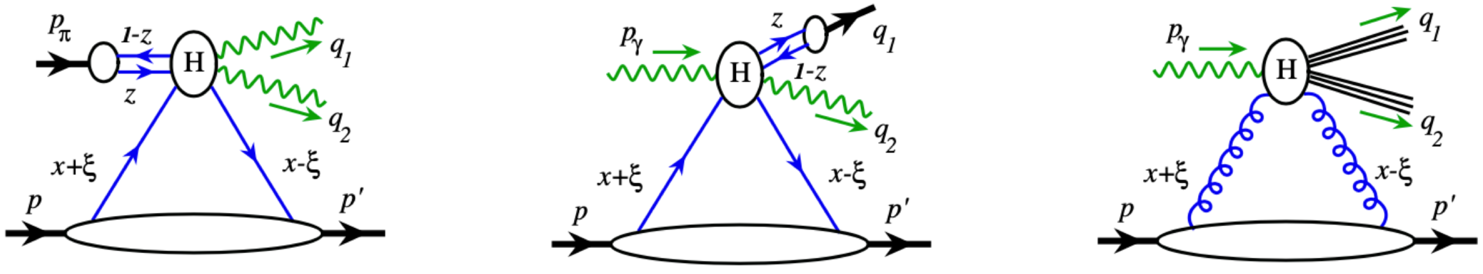
t, ξ ~ directly meassured

- **Sensitivity to x comes from $C(x,\xi;Q/\mu)$:**

DVCS: $C(x,\xi;Q/\mu) \propto \dfrac{1}{x-\xi+i\varepsilon}$ ⇒ $i\mathcal{M} \propto \int_{-1}^{1} \mathrm{d}x \dfrac{F(x,\xi,t)}{x-\xi+i\varepsilon} \equiv \text{“}F_0(\xi,t)\text{”}$

Not ideal if: $C(x,\xi;Q/\mu) \Rightarrow C_Q(Q/\mu)\cdot C_x(x)\cdot C_\xi(\xi)$

- **Exclusive massive pair production with high-P_T (two-scale observables):**



+ ...

Hard scale: $q_T \gg \Lambda_{\rm QCD}$

in $p_\pi - (p-p')$ frame

Soft scale: $t = (p-p')^2$

Factorization: $q_T \gg \sqrt{|t|}$

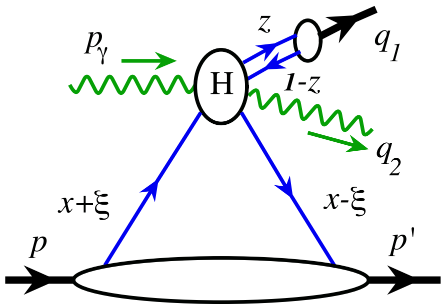
Introduced by G. Duplancic et al.
JHEP 11 (2018) 179

Introduced by Y. Hatta et al.
Phys.Rev.Lett. 116 (2016) 202301

Exclusive Photo-Production of a $\pi\gamma$ Pair

- **Process:** $\gamma(p_\gamma) + h(p) \to \pi^\pm(q_1) + \gamma(q_2) + h'(p')$

  Introduced by G. Duplancic et al. [JHEP 11 (2018) 179],
  No contribution from gluon GPDs



Hall D at JLab

$$\frac{d\sigma}{dt\,d\xi\,dq_T^2} \quad \text{or} \quad \frac{d\sigma}{dt\,d\xi\,d\cos\theta}$$

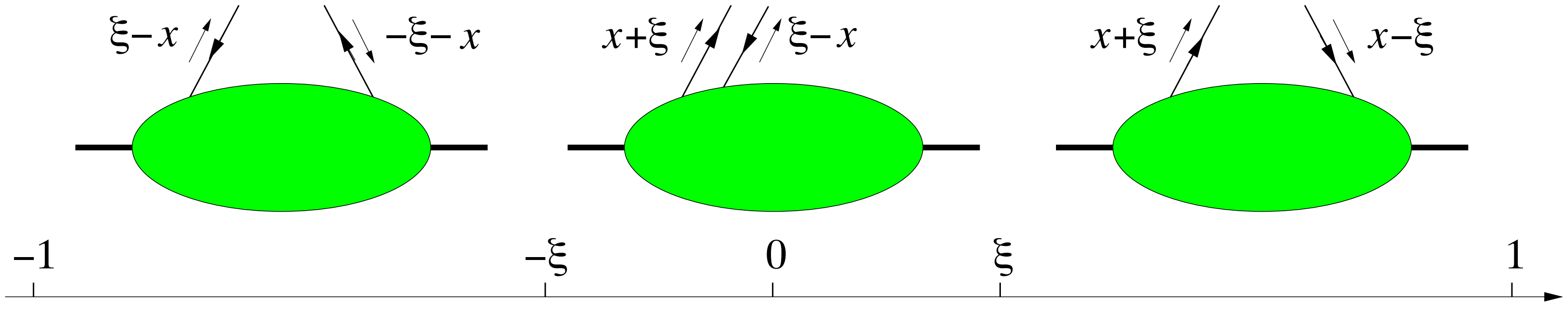
- **Factorization:**

  Proved to be valid when $q_T \gg \sqrt{|t|} \gtrsim \Lambda_{\rm QCD}$

- **Cancellation of unwanted propagators & cosθ dependence:**

$$\mathrm{Re}\,O_{++} = (e_1 - e_2)^2 \left[\frac{1-\cos\theta}{1+\cos\theta}\cdot P\frac{x+z-2xz}{2\,x\,z\,(1-x)\,(1-z)}\right] + (e_1^2 - e_2^2)\left[\frac{2}{1-\cos\theta}\cdot P\frac{x-z}{x\,z\,(1-x)\,(1-z)}\right]$$
$$- e_1 e_2 P\frac{1-\cos\theta}{x\,z\,(1-x)\,(1-z)}\cdot\frac{(xz+(1-x)(1-z))\,(x(1-x)+z(1-z))}{(2(1-x)(1-z)-(1+\cos\theta)xz)\,(2xz-(1+\cos\theta)(1-x)(1-z))}$$

- **Sensitive to ERBL region (complementary)**



Also sensitive to DA in the bulk region.

Exclusive $\pi^0\gamma$ Pair Production

- **Phenomenology:**

$$\frac{d\sigma}{d|t|\,d\xi\,d\cos\theta_\pi\,d\phi_\pi} = \frac{|\mathcal{A}|^2}{32\,s\,(2\pi)^4\,(1+\xi)^2}$$

$$\frac{1}{2}\overline{|\mathcal{A}|^2} = \left(\frac{2\pi\alpha_s}{s}f_\pi\right)^2\left(\frac{C_F}{N_c}\right)^2\left(\frac{1+\xi}{\xi}\right)^2(1-\xi^2) \times\left[|O_{++}^{[\widetilde{H}]}|^2 + |O_{+-}^{[\widetilde{H}]}|^2 + |\widetilde{O}_{++}^{[H]}|^2 + |\widetilde{O}_{+-}^{[H]}|^2\right]$$

- **Factorized helicity amplitude:**

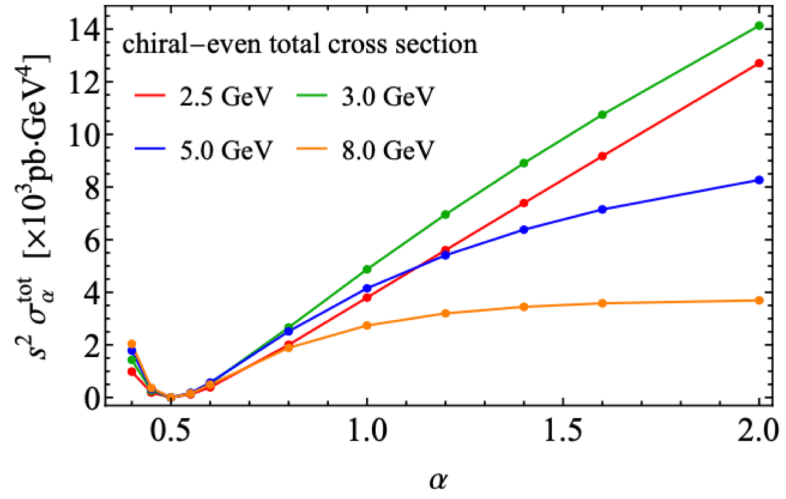
$$O_{\lambda\lambda'}^{[\widetilde{H}]} = \sum_q \int_{x_L}^{x_R} dx \int_0^1 dz\, \widetilde{H}^q(x,\xi,t)\,\phi_\pi^q(z)\,O_{\lambda\lambda'}^q(x,z)$$

- **Pion distribution amplitude:**

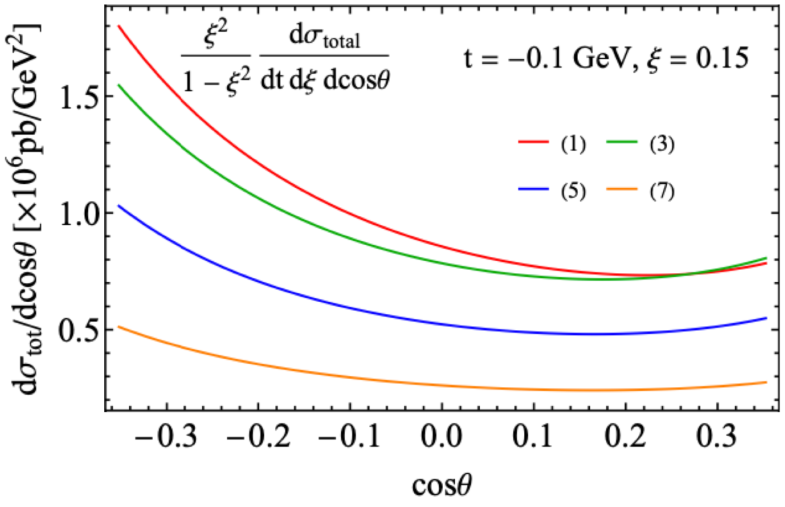
$$\phi_{\pi^0}^d(z) = \phi_{\pi^0}^u(z) = \frac{1}{\sqrt{2}}\frac{z^\alpha(1-z)^\alpha}{\mathrm{B}(1+\alpha,1+\alpha)}, \quad (\alpha>0)$$

- **Model GPDs = simplified GK model:**
  - Taking $n_i = 0$
  - Parametrizing the forward limit as $x^a(1-x)^b$
  - Neglecting the D-term

- **Sensitivity on DAs (total – q_T > 1 GeV):**



- **Sensitivity on GPDs (α = 0.63):**



Exclusive $\pi^0\gamma$ Pair Production

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$$\frac{1}{2}\overline{|\mathcal{A}|^2} = \left(\frac{2\pi\alpha_s}{s}f_\pi\right)^2\left(\frac{C_F}{N_c}\right)^2\left(\frac{1+\xi}{\xi}\right)^2(1-\xi^2)$$
$$\times\left[|O_{++}^{[\widetilde{H}]}|^2 + |O_{+-}^{[\widetilde{H}]}|^2 + |\widetilde{O}_{++}^{[H]}|^2 + |\widetilde{O}_{+-}^{[H]}|^2\right]$$

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  - Neglecting the D-term

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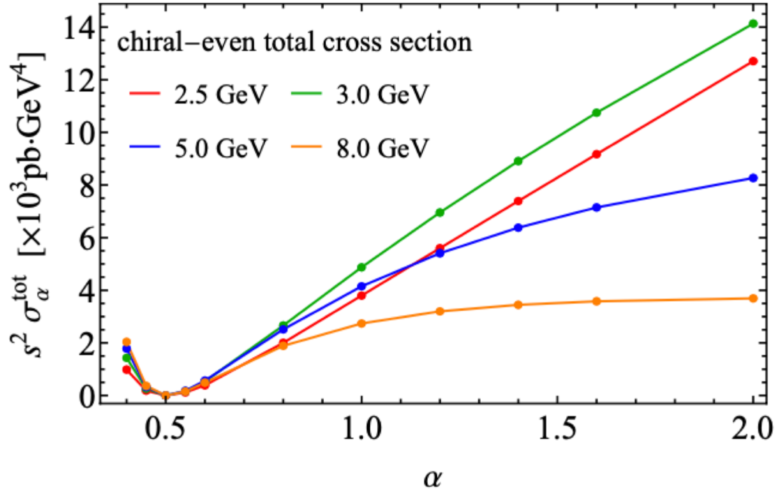
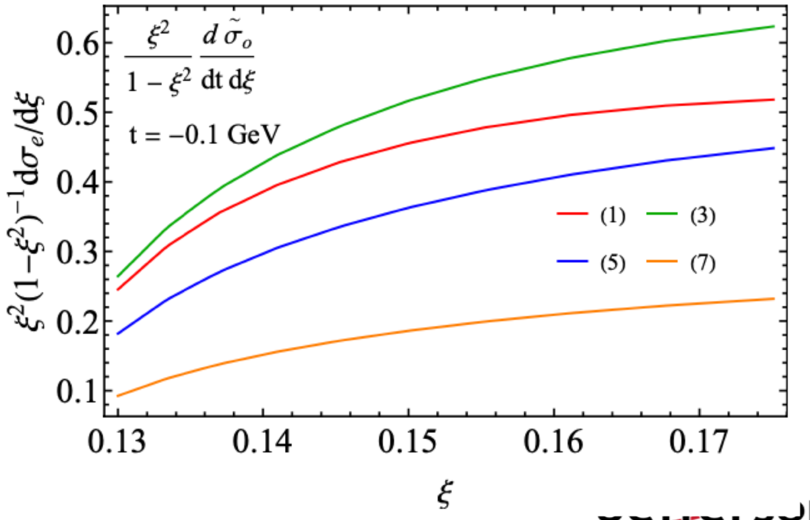


❑ **Sensitivity on GPDs (α = 0.63):**



Summary and Outlook

- ❑ Summarized the part of Kharzeev's talk at the INT on probing mass radius from quarkonium photo-production near threshold

- ❑ Introduced the diffractive $2 \to 3$ exclusive hard processes for extracting GPDs, …
  - Provide both necessary and sufficient conditions for leading power factorization
  - Including existing/known processes for extracting GPDs, ..
  - Identify new factorizable exclusive processes for GPDs more sensitive to x-dependence

Introduce a path forward to identify more factorizable exclusive processes for extracting GPDs, and multi-parton correlations, …

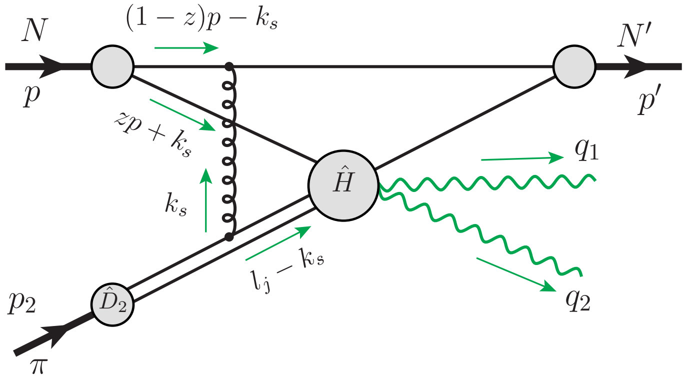
- ❑ QCD factorization requires a sufficient P_T of J/ψ in the lab frame (or Q^2) for lepto-production
  - 20+ GeV is sufficient for exploring gluon GPDs from lepto-production of J/ψ at high Q^2

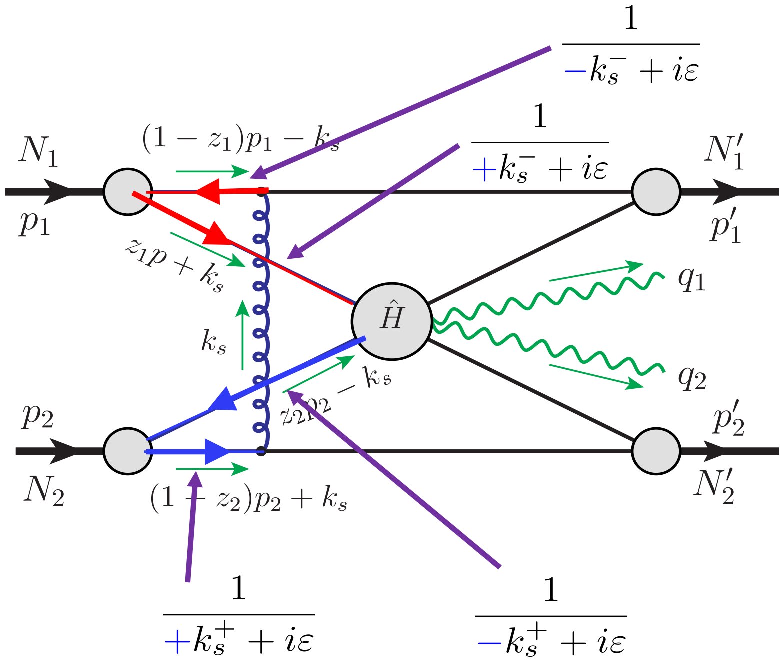
Thanks!

Why *single* diffractive?

- Double diffractive process

Glauber pinch for diffractive scattering

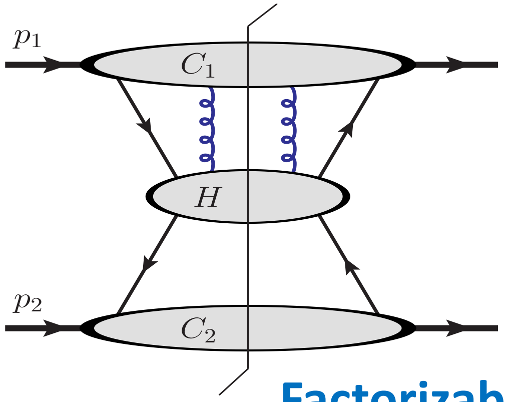




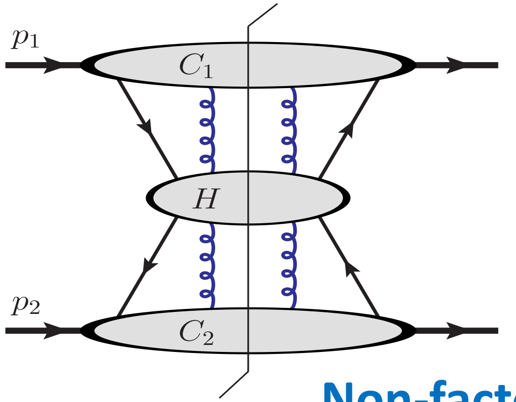
Factorizable if all pion momentum flows into hard part

Both k_s^+ and k_s^- are pinched in Glauber region!

- Compare: Drell-Yan process at high twist:



Factorizable



Non-factorizable

Only the 1st sub-leading twist is factorizable!

Qiu & Sterman, NPB, 1991

Jefferson Lab