Exclusive Massive Photon-Pair Production in Meson-Baryon Collisions

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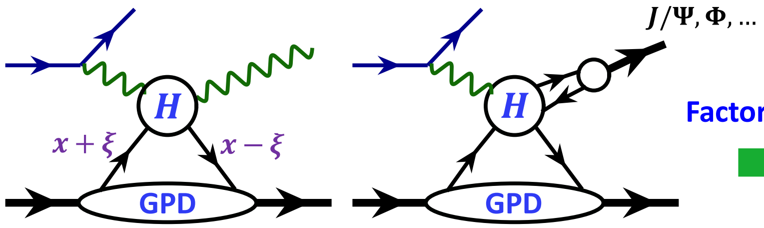
Why generalized parton density (GPD)?

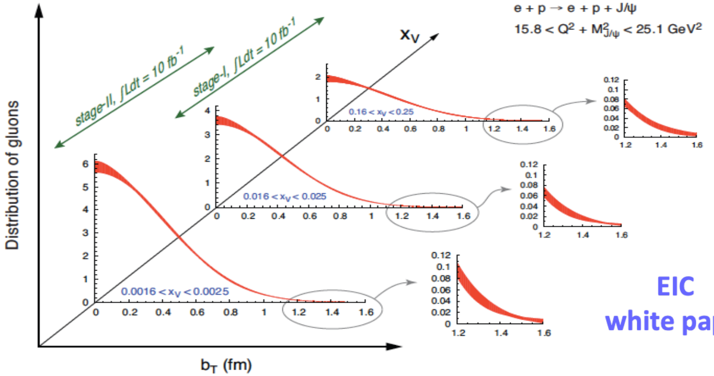
❑ Parton's spatial imaging



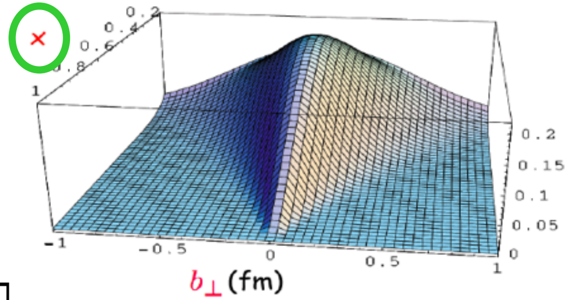
DVCS: $Q^2 \gg |t|$

DV Meson Production

Factorization → **GPDs** F.T. →

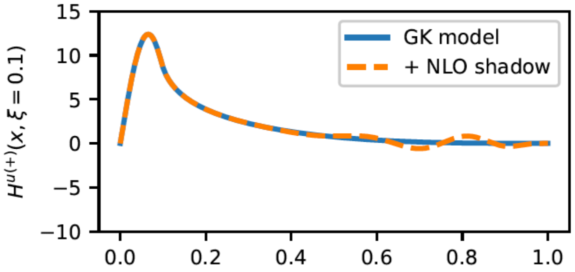


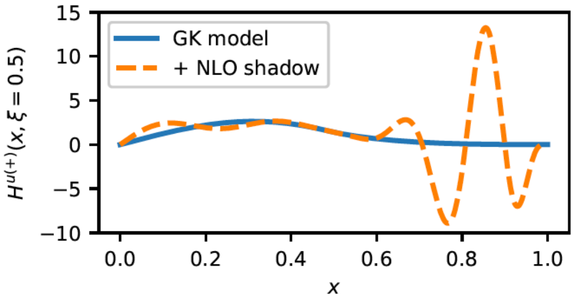
EIC white paper



❑ Hard to measure

*These observables are only sensitive to the **total** momentum (ξ) from the diffracted proton, **not the "x" – relative** momentum of the parton pair!*





Blue and dashed Fit the same CFF!

2104.03836

Overview

- Propose a New exclusive process

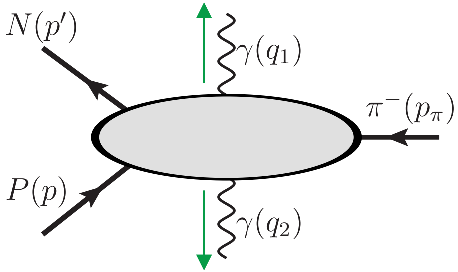
$$\pi^-(p_\pi) + P(p) \to \gamma(q_1) + \gamma(q_2) + N(p')$$

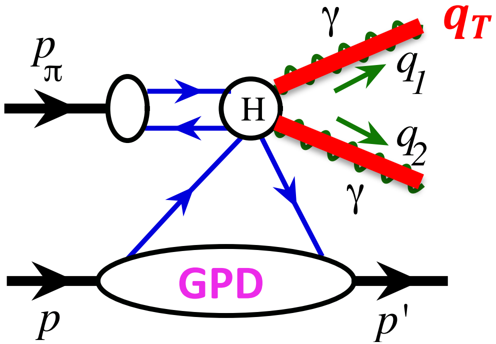
- The sensitive observable: $\boldsymbol{q_T}$ (in $\gamma\gamma$ CM, with π^- in $-\hat{z}$ direction)

$$\gamma(\boldsymbol{q}_T) + \gamma(-\boldsymbol{q}_T)$$

- Prove it is factorizable when: $\boldsymbol{q_T} \gg \Lambda_{\mathrm{QCD}}$

- $\mathrm{d}\sigma/\mathrm{d}\boldsymbol{q_T}$ provides sensitivity to $\boldsymbol{x}$*-dependence* of GPD





Exclusive massive two-photon production

- **Process**

$$\pi^-(p_\pi) + P(p) \to \gamma(q_1) + \gamma(q_2) + N(p')$$

- **Kinematics – factorization region**

$$\Delta = p - p' \qquad t = \Delta^2 \qquad \xi = \frac{\Delta^+}{(p+p')^+}$$

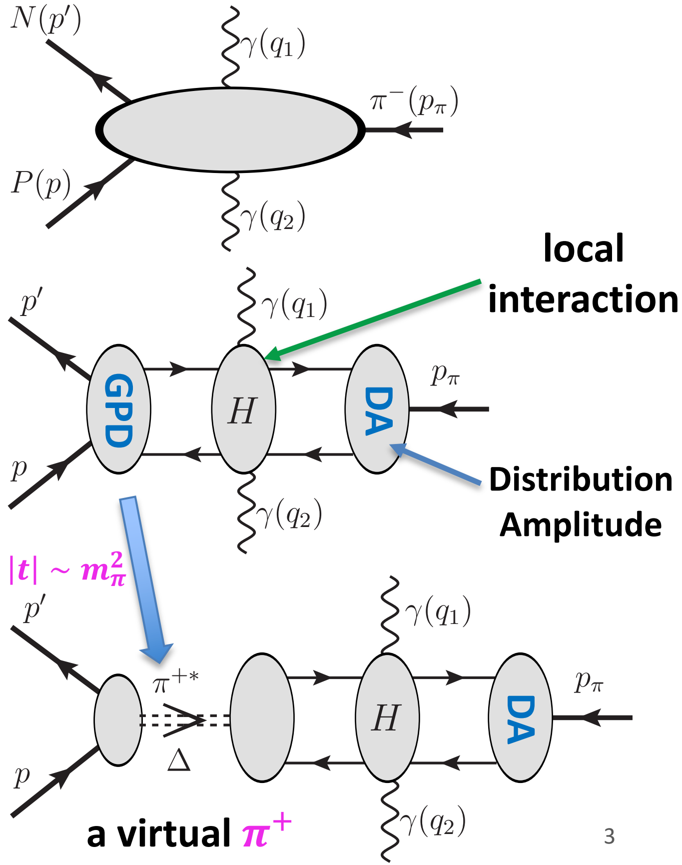
Large components in CM frame:

$$P^+ = \frac{p^+ + p'^+}{2}, \quad p_\pi^-$$

Require $\hat{s} \equiv (q_1+q_2)^2 \gg |t| \gtrsim \Lambda_{\mathrm{QCD}}^2$

$$q_T^2 \gg \Lambda_{\mathrm{QCD}}^2$$

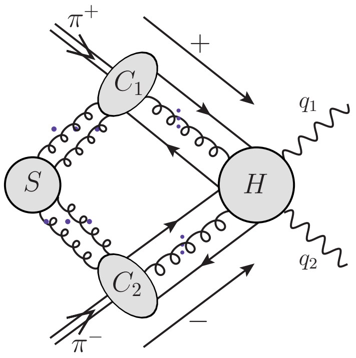
$$\Delta^+ = 2\xi P^+ \gg \sqrt{|t|}$$



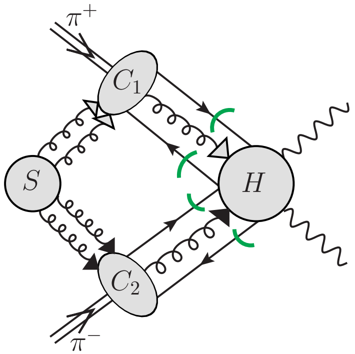
- ***Two*** **photons come out of hard part.**
- q_T^2 **provides extra sensitivity to *x-dependence* of GPD.**

Simplified process $\pi^+\pi^- \to \gamma\gamma$: Factorization (simplified)

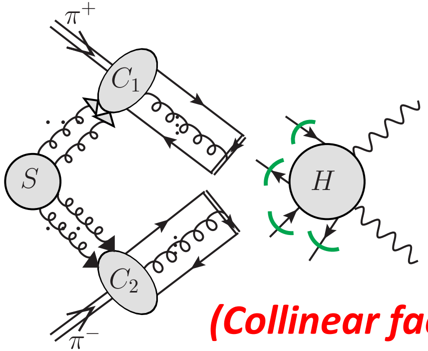
- ❑ **Leading region**



- ❑ **Approximations**



- ❑ **Ward identity for collinear gluons**

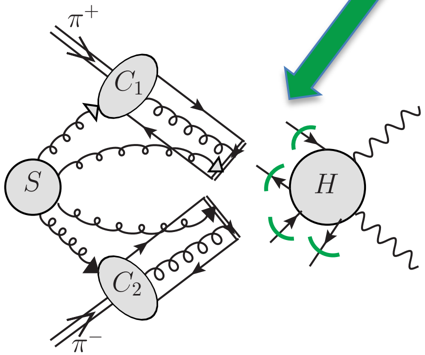


(Collinear factorization)

- ❑ **Ward identity for soft gluons**

  - ➢ **Soft gluons are as if attached to a "*closed fermion loop*"**
  - ➢ **Sum over diagrams**

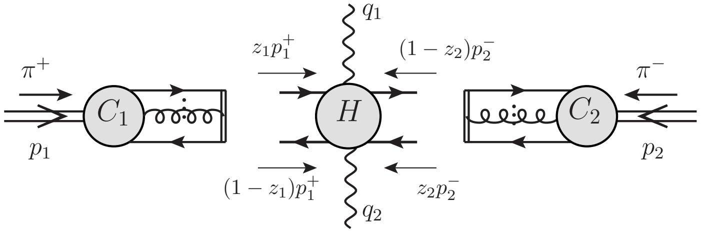
$$\Rightarrow \boldsymbol{S = 0}$$



Soft gluons cancel because collinear parton lines are in color singlet states.

Simplified process $\pi^+\pi^- \to \gamma\gamma$: Factorization

❑ Factorization



$$\mathcal{M} = \frac{s}{2}\int_0^1 \mathrm{d}z_1 \mathrm{d}z_2\, \phi_{\pi^+}(z_1)\phi_{\pi^-}(z_2)\cdot \mathrm{Tr}\left[\frac{\gamma_5\gamma^-}{2} H(\hat{k}_1,\hat{k}_2;q_1,q_2;\mu)\frac{\gamma_5\gamma^+}{2}\right] + \mathcal{O}\left(\frac{m_\pi}{q_T}\right) \longrightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}q_T} \propto |\mathcal{M}|^2$$

❑ Hadron functions: distribution amplitudes (DA)

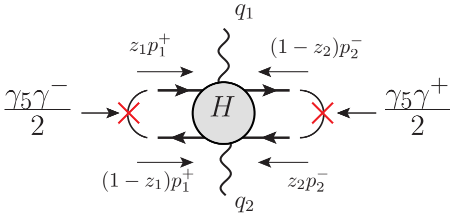
$$\phi_{\pi^+}(z_1) = \int \frac{dx^-}{4\pi} e^{i\, z_1\, p_1^+ x^-} \langle 0|\, \bar{d}(0)\, \gamma^+\gamma_5\, W(0,x^-)\, u(x^-)\, |\pi^+(p_1)\rangle$$

$$\phi_{\pi^-}(z_2) = \int \frac{dx^+}{4\pi} e^{i\, z_2\, p_2^- x^+} \langle 0|\, \bar{u}(0)\, \gamma^-\gamma_5\, W(0,x^+)\, d(x^+)\, |\pi^-(p_2)\rangle$$

$\boldsymbol{\phi_{\pi^+}(z) = \phi_{\pi^-}(z) = \phi(z)}$
are universal DAs

❑ Hard coefficient

$$C\left(z_1, z_2; \frac{q_T^2}{s}; \frac{q_T^2}{\mu^2}\right) =$$



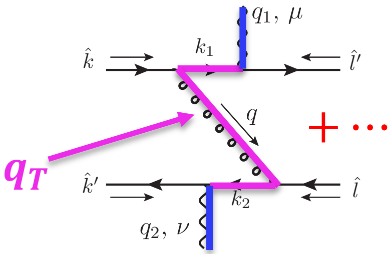
$\gamma_5\gamma^\pm$

Projections (for $\pi^\mp$):

1. **Spin-0**
2. **P-odd**

Simplified process $\pi^+\pi^- \to \gamma\gamma$: Hard part

❑ Hard part A



New

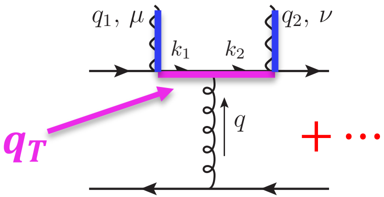
$\kappa = 4\,q_T^2/\hat{s}$

- **Gluon propagator** $q^2 = -\frac{\hat{s}}{4}\left[\left(2z_1 - 1 - \sqrt{1-\kappa}\right)\left(2z_2 - 1 - \sqrt{1-\kappa}\right) + \kappa\right]$

$$\mathcal{M} \propto \int_0^1 \mathrm{d}z_1\,\mathrm{d}z_2\,\frac{\phi(z_1)\phi(z_2)}{(1-z_1)(1-z_2)\left[\left(2z_1 - 1 - \sqrt{1-\kappa}\right)\left(2z_2 - 1 - \sqrt{1-\kappa}\right) + \kappa\right]}$$

- **Change q_T changes the z_1-z_2 integral.**
- **$\mathrm{d}\sigma/\mathrm{d}q_T^2$ provides sensitivity to the DA's functional form of z.**

❑ Hard part B



Like "time-like" form factor

- **Gluon propagator** $q^2 = z_2(1-z_1)\hat{s}$

$$\mathcal{M} \propto \int_0^1 \mathrm{d}z_1\,\mathrm{d}z_1\,\frac{\phi(z_1)\phi(z_2)}{z_1\,(1-z_1)\,z_2\,(1-z_2)} \sim \left[\int_0^1 \mathrm{d}z\,\frac{\phi(z)}{z\,(1-z)}\right]^2$$

- ***Not* sensitive to DA functional form.**
- **Relies on $\phi(z) = 0$ at end points.**
- **Sudakov resummation could suppress the end-point sensitivity.**

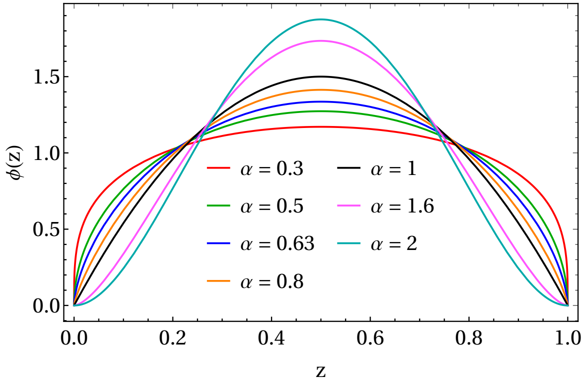
Li, Sterman 1992

Simplified process $\pi^+\pi^- \to \gamma\gamma$: DA sensitivity

❑ DA parametrization

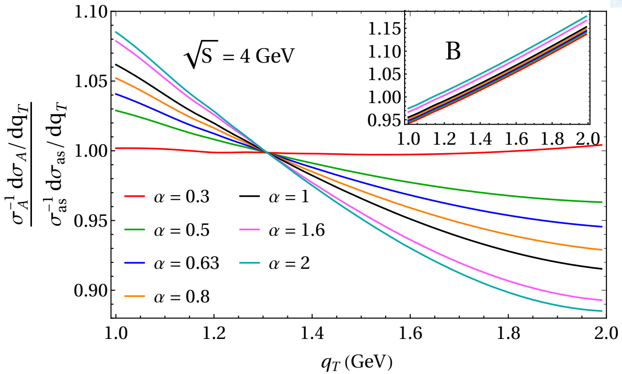
$$\phi_\alpha(z) = \frac{i\, f_\pi}{2} \cdot \left[\frac{z^\alpha (1-z)^\alpha}{B(1+\alpha, 1+\alpha)}\right]$$

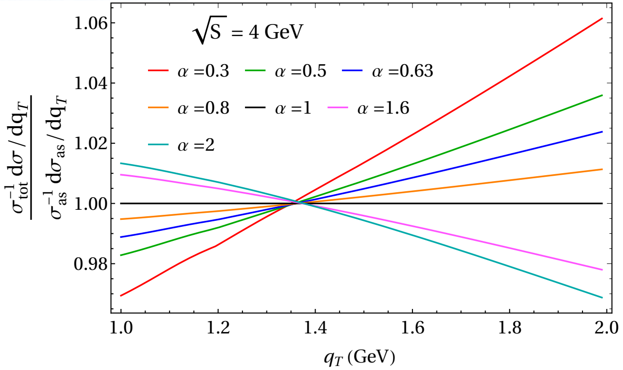
Change $\alpha \Longrightarrow$ Change z dependence

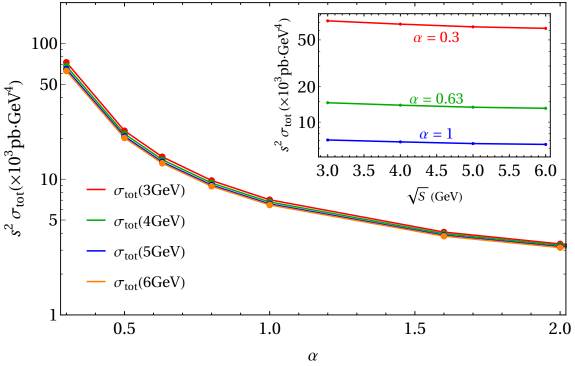


❑ q_T distribution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T} \sim |\phi(z)|^2$$







A: photons from *two* quark lines

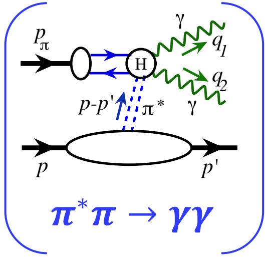
B: photons from *one* quark line

Combine A and B

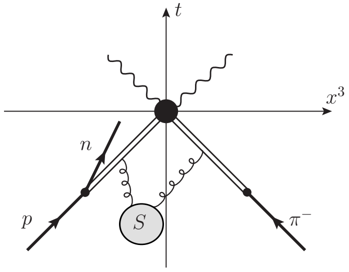
$$\sigma_{\text{tot}} = \int_{1\ \text{GeV}}^{\sqrt{s}/2} \mathrm{d}q_T \, \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}$$

$\pi^- p \to n\gamma\gamma$: Factorization

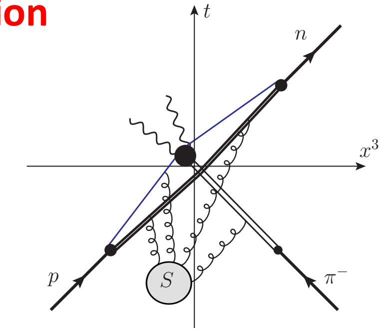
- **Additional region: DGLAP region**



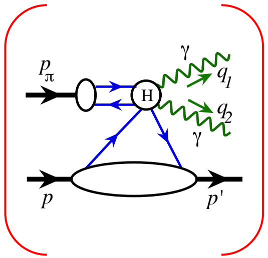
(Efremov, Radyushkin, Brodsky, Lepage)



ERBL region



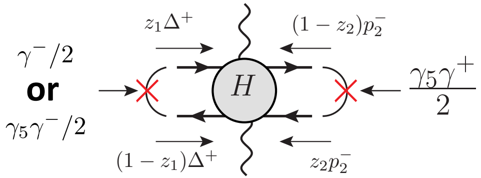
DGLAP region



- Different soft structures
- Factorization proof needs to be modified

$$\mathcal{M} = \mathrm{GPD} \otimes \mathrm{DA} \otimes \mathrm{Hard}$$

- **Additional hard coefficient**



$\gamma^-/2$ corresponds to $F_{pn}^u \supset (H, E)$

$\gamma_5\gamma^-/2$ corresponds to $\widetilde{F}_{pn}^u \supset (\widetilde{H}, \widetilde{E})$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t\,\mathrm{d}\xi\,\mathrm{d}q_T^2} \propto |\mathcal{M}|^2$$

- **Factorization**

$$\mathcal{M} = \frac{\hat{s}}{2}\int \mathrm{d}z_1\,\mathrm{d}z_2 \left[F_{pn}^u(z_1,\xi,t)\,\phi(z_2)\,\widetilde{C}(z_1,z_2) + \widetilde{F}_{pn}^u(z_1,\xi,t)\,\phi(z_2)\,C(z_1,z_2)\right] + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{q_T}, \frac{|t|}{\hat{s}}\right)$$

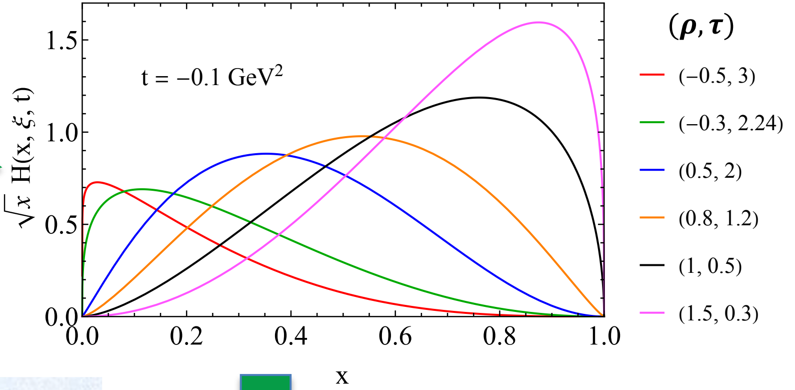
$\pi^- p \to n\gamma\gamma$: sensitivity to GPD x

❑ GPD models: simplified GK model

Goloskokov, Kroll
hep-ph/0501242
arXiv: 0708.3569
arXiv: 0906.0460

$$H_{pn}(x,\xi,t) = \theta(x)\, x^{-0.9\,(t/\mathrm{GeV}^2)}\, \frac{x^{\rho}(1-x)^{\tau}}{B(1+\rho, 1+\tau)}$$

$$\widetilde{H}_{pn}(x,\xi,t) = \theta(x)\, x^{-0.45\,(t/\mathrm{GeV}^2)}\, \frac{1.267\, x^{\rho}(1-x)^{\tau}}{B(1+\rho, 1+\tau)}$$



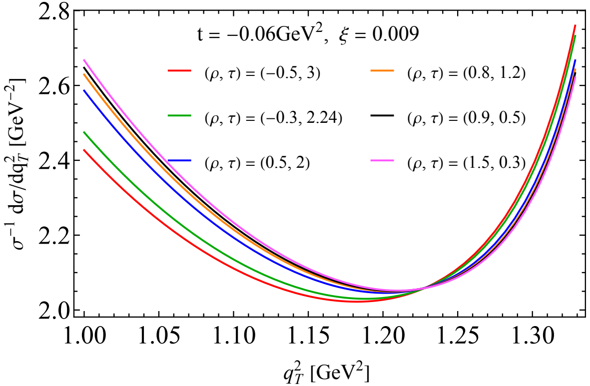
- **Neglect $E, \widetilde{E}$. Neglect evolution effect.**
- **Tune (ρ, τ) to control x shape.**

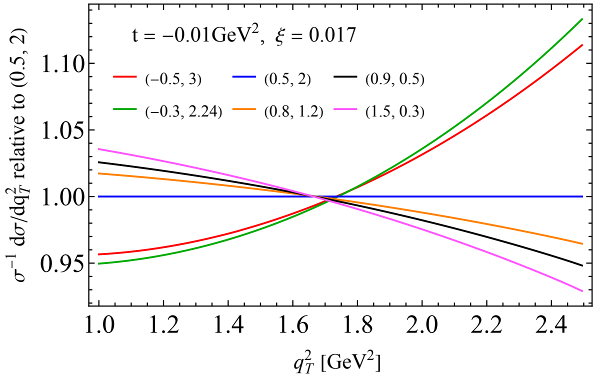
❑ Normalized q_T distribution

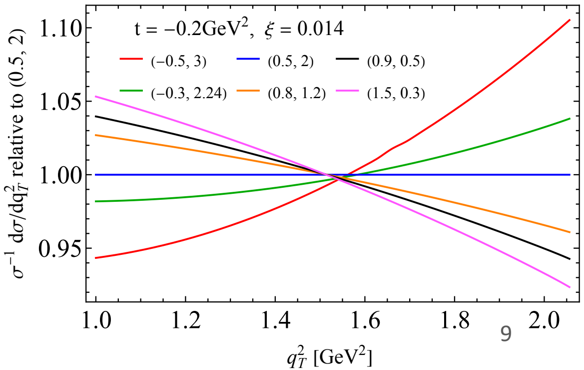
$$\frac{d\sigma}{dt\, d\xi\, dq_T^2} \sim |H(x,\xi,t)|^2$$

(Fix DA: $D(z) = N\, z^{0.63}(1-z)^{0.63}$)

$E_\pi = 150$ GeV







$\pi^- p \to n\gamma\gamma$: sensitivity to GPD ξ

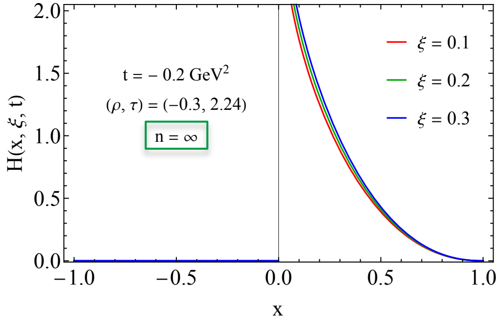
- **GPD models: modified GK model**

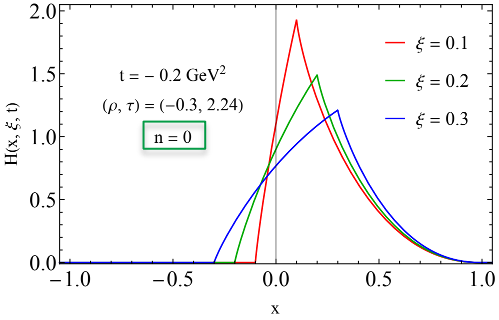
$$H(x,\xi,t) = \int \mathrm{d}\beta\,\mathrm{d}\alpha\;\delta(x-\beta-\xi\alpha)\,f(\beta,\alpha,t)$$

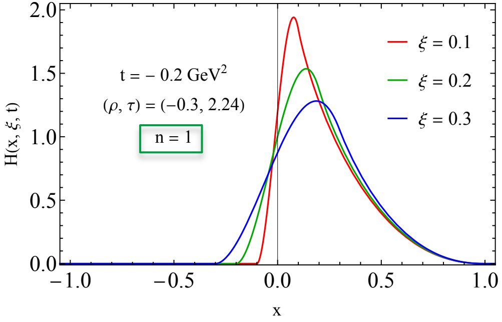
$$f(\beta,\alpha,t) = e^{\left(b+\alpha' \ln|\beta|^{-1}\right)t}\cdot h(\beta)\cdot w(\beta,\alpha)$$

$$w(\beta,\alpha) = \frac{\Gamma(2n+2)}{2^{2n+1}\Gamma^2(n+1)}\,\frac{\left[(1-|\beta|)^2-\alpha^2\right]^n}{(1-|\beta|)^{2n+1}}$$

  - **Change n to change ξ dependence**
  - **Choose $n = 0, 1, \infty$**

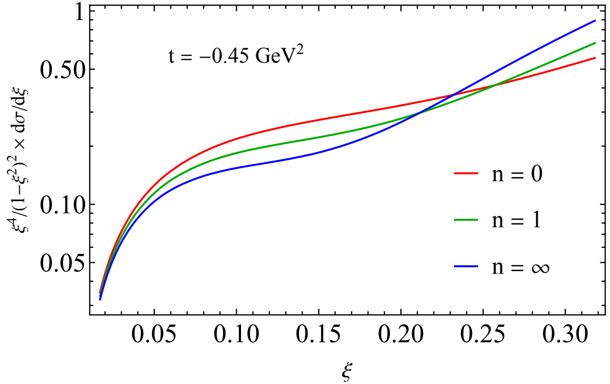


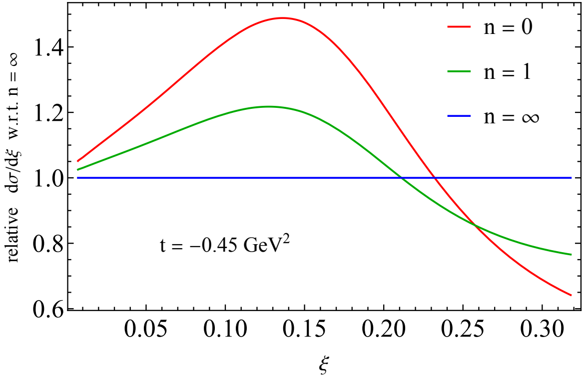




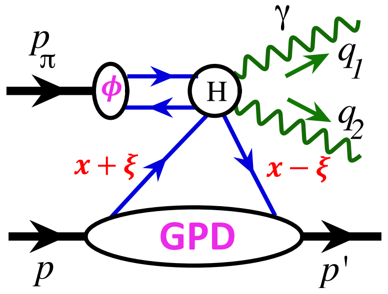
- **ξ distribution (integrate out q_T)**

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t\,\mathrm{d}\xi\,\mathrm{d}q_T^2} \sim |H(x,\xi,t)|^2$$





Conclusion



- **Proposed a new exclusive process**
  - $\pi^- p \to n\gamma\gamma$ (or $\pi^+\pi^- \to \gamma\gamma$)
  - ***Can be studied within perturbative QCD***
  - ***Provides sensitivity to GPD/DA functional form***
  - ***Possible to study at COMPASS/AMBER, J-PARC***

- **Outlook**
  - ***Similar processes can be proposed***
  - ***At least two particles come out of the hard interaction***
  - ***Extra observable to provide sensitivity to GPD/DA functional form***

Thank you!