

Observables through J/ψ and ϕ production

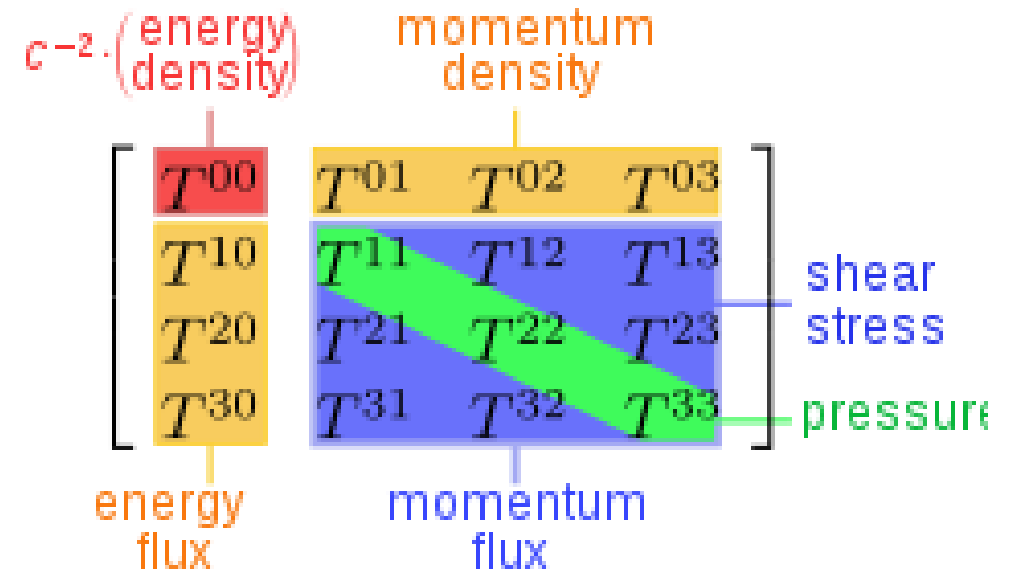
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BNL/RIKEN BNL

Workshop on physics program with high luminosity facilities
October 5-9, 2026

Gravitational form factors

QCD energy momentum tensor

$$T^{\mu\nu} = \sum_f \bar{\psi}_f \gamma^{(\mu} i D^{\nu)} \psi_f - F^{\mu\rho} F^{\nu}_{\rho} + \frac{g^{\mu\nu}}{4} F^{\alpha\beta} F_{\alpha\beta}$$



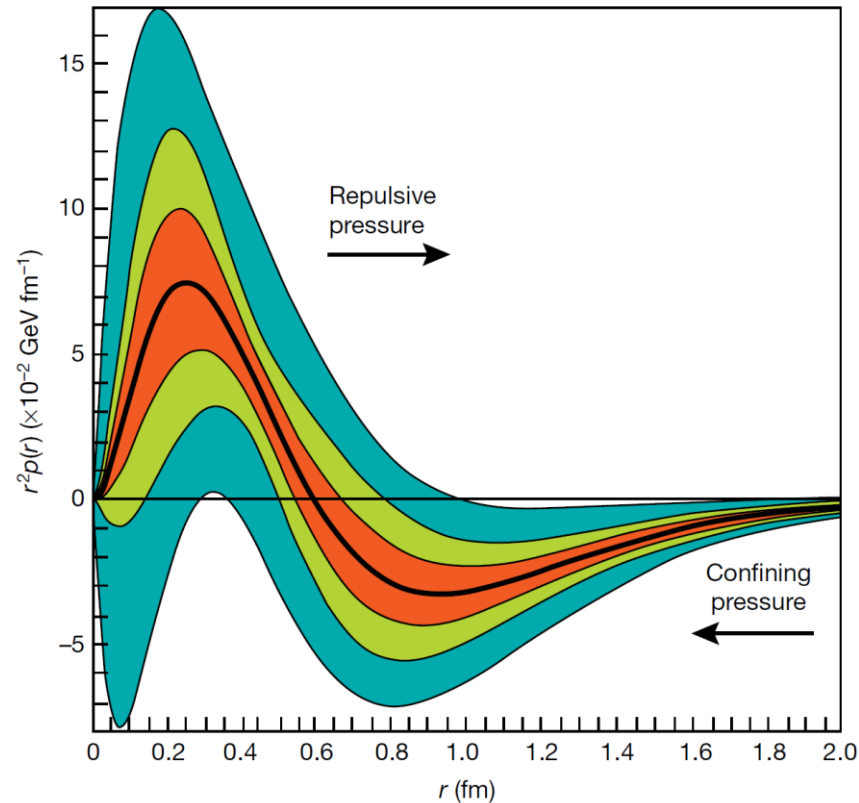
Associated form factors

$$\langle P' | T^{\mu\nu} | P \rangle = \bar{u}(P') \left[A(t) \gamma^{(\mu} \bar{P}^{\nu)} + B(t) \frac{\bar{P}^{(\mu} i \sigma^{\nu)\alpha} \Delta_{\alpha}}{2M} + \textcolor{red}{D}(t) \frac{\Delta^{\mu} \Delta^{\nu} - g^{\mu\nu} \Delta^2}{4M} \right] u(P)$$

$$A(0) = 1, \quad B(0) = 0 \quad D(0) = ??$$

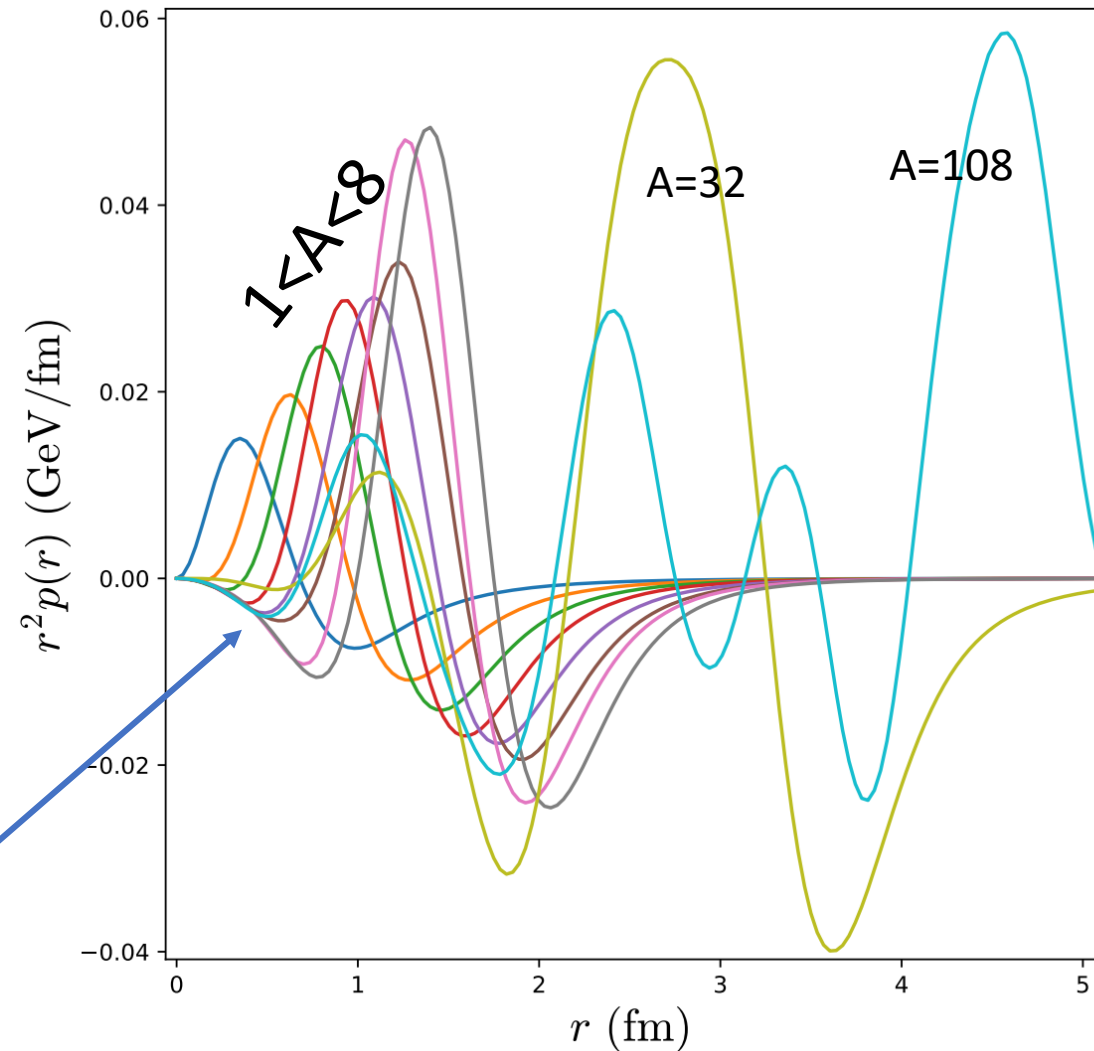
'Pressure' inside nucleon and nuclei

Burkert, Elouadrhiri, Girod (2018)



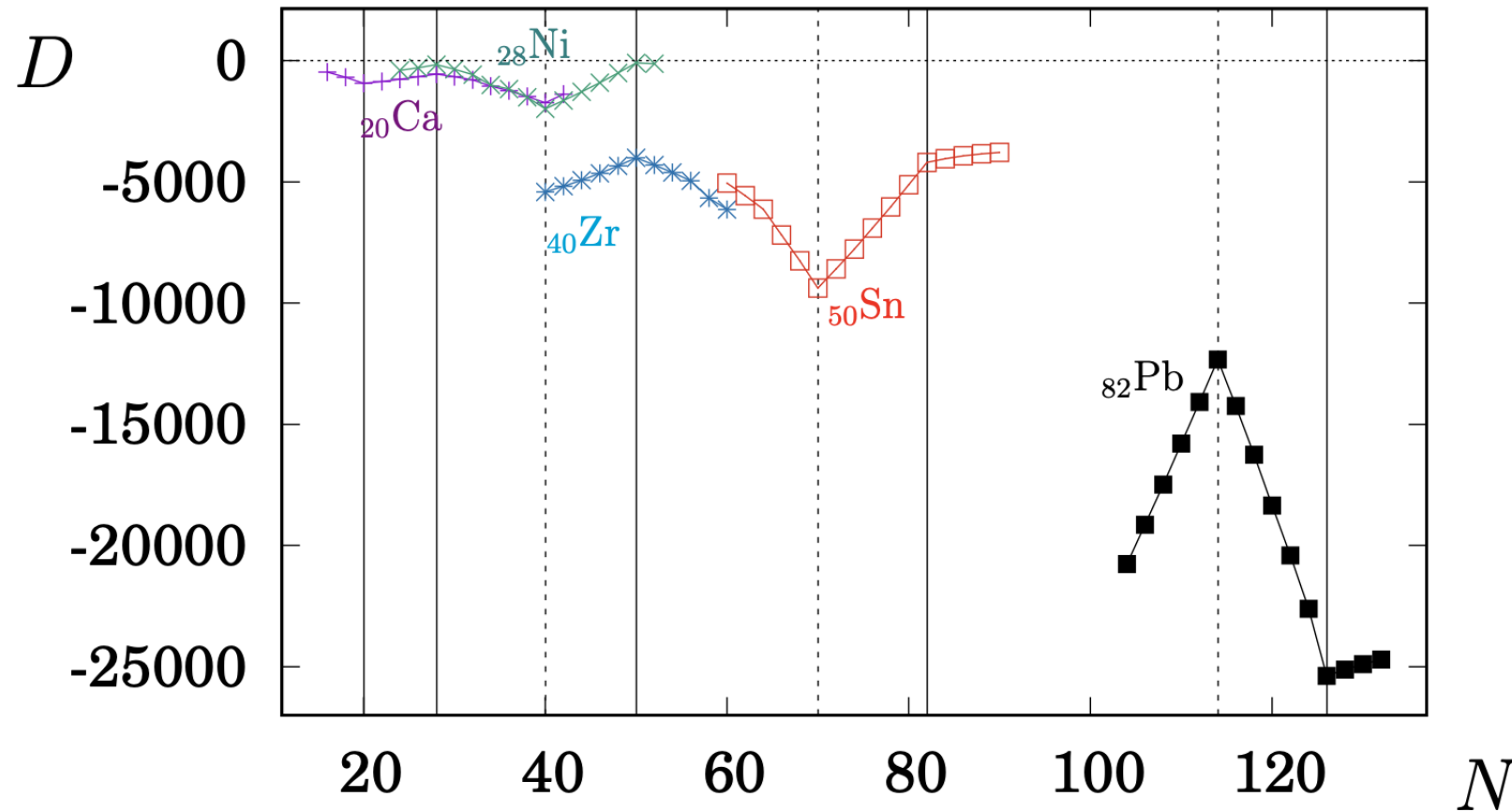
Negative near the core for nuclei $A > 1$
see also, Freese, Cosyn (2022), He, Zahed (2023)

Martin-Caro, Huidobro, YH, 2312.12984



D-term of nuclear isotopes

YH, Oishi, Oka, 2605.12023



Kinks at

Magic numbers

$N=20, 28, 50, 82, 126$

Sub-magic numbers

$N=40, 70, 114$

Very sensitive to the
nuclear shell structure!

Simple scaling $D \propto A^\beta$, only in some average sense

$^{90}_{40}\text{Zr}$ has largest binding energy per nucleon among Zr isotopes, yet it has smallest $|D|$!

Ratio of form factors perturbatively calculable at large- t !

YH, Schoenleber, 2508.01529

QCD factorization of GPD at large, but not too large- t

$$H_q^{\text{Feyn}}(x, \xi, t, \mu_{\text{UV}}) = K_{qq}(x, \xi, t, \mu_{\text{UV}}, \mu_F) U(\mu_F, \mu_{hc}) f_1^q(t, \mu_{hc}) + \mathcal{O}(\lambda^{10})$$

Coefficient function

Sudakov factor

Nonperturbative

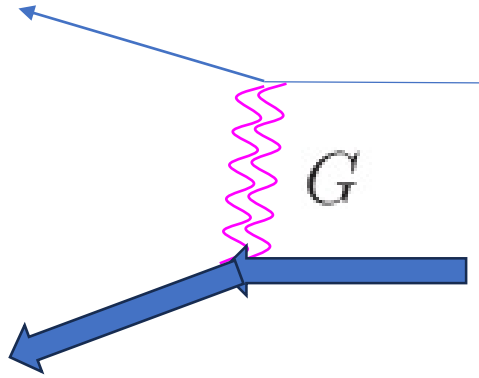
$$\frac{A_q^{\text{Feyn}}(t, \mu_{\text{UV}})}{F_{1q}^{\text{Feyn}}(t)} = 1 + \frac{\alpha_s C_F}{4\pi} \left(\frac{8}{3} \ln \frac{-t}{\mu_{\text{UV}}^2} - \frac{52}{9} \right) + \mathcal{O} \left(\alpha_s^2, \frac{1}{\sqrt{-t}} \right) \approx 0.85$$

Consistent with lattice QCD calculation
Dutrieux et al. 2604.21476

Experimental study of GFFs?

- Introduced theoretically in the 60s.
- Received far less attention than EM form factors, **not** because they are less interesting/important.
- The obvious reason: We cannot measure them directly!

One-graviton exchange cross section



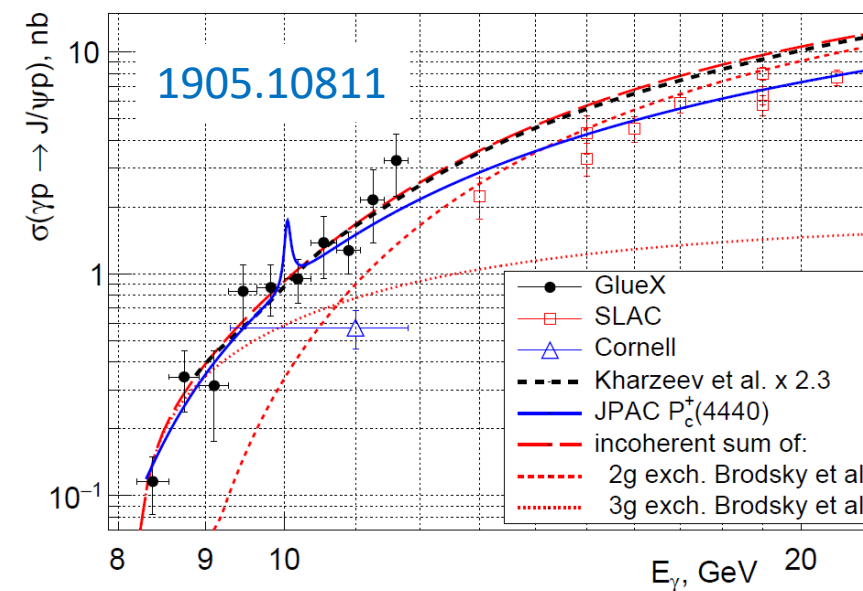
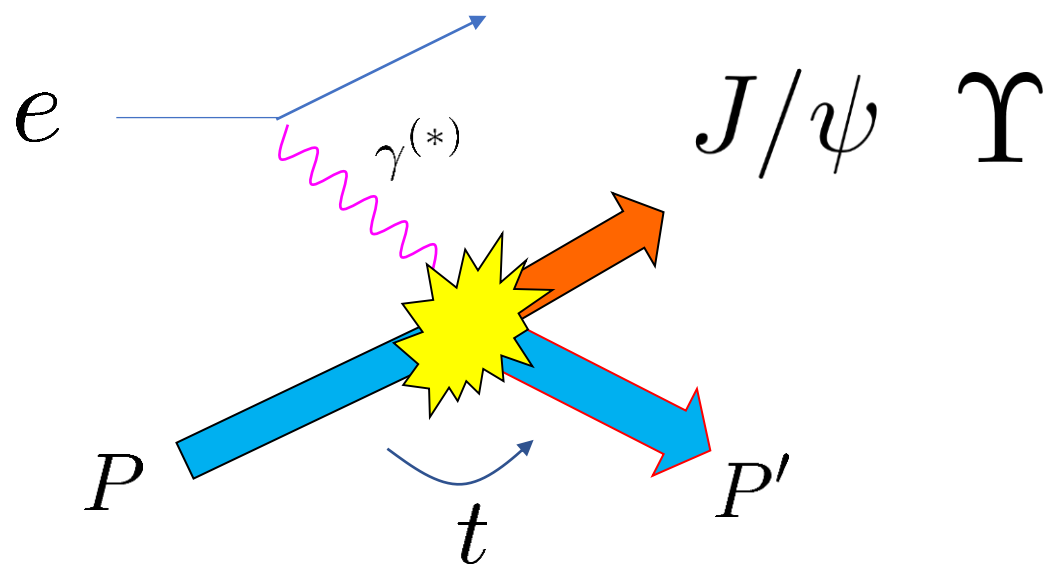
$$\frac{d\sigma}{dt} \sim G_N^2 \frac{s^2}{t^2}$$

$$G_N \sim 1/M_P^2$$

$$M_P \sim 10^{19} \text{ GeV}$$

- But theorists are bad losers... DVCS, near-threshold meson production,...

Quarkonium photo-production near threshold



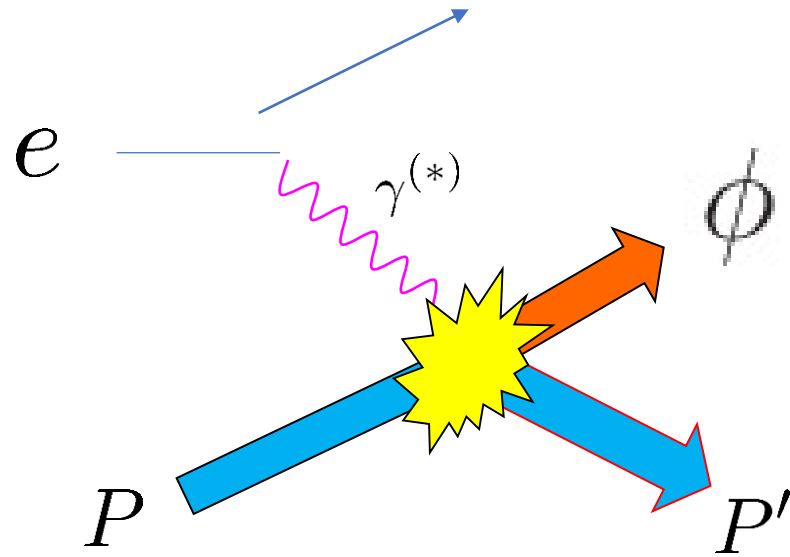
Ongoing experiments at JLab, future measurement at EIC?

Originally proposed by [Kharzeev, Satz, Syamtomov, Zinovev \(1997\)](#) to probe the gluon condensate.

One can also study **gluon** GFFs in this process [YH, Yang \(2018\)](#), [Mamo, Zahed \(2019\)](#), [Guo, Ji, Liu \(2021\)](#)

1 graviton $\approx$ 2 gluons

ϕ -meson electro-production near threshold



YH, Strikman (2021)

YH, Klest, Passek-K, Schoenleber (2025)

talk by Henry tomorrow

Complementary to J/ψ .

Need more than one observable for global analysis.

Pros

As sensitive to gluons as J/ψ production (maybe even better).

Unique channel for strangeness GFFs.

Standard GPD factorization. No need to combine with NRQCD.

Alternative interpretations of J/ψ photoproduction. Less ambiguity for high- Q

ϕ -electroproduction

Cons

Factorization only for the longitudinally polarized photon

L/T separation crucial $\rightarrow$ SoLID and EIC?

After all, 1 graviton $\neq$ 2 gluons

what is measurable

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

what we want

$$\int_{-1}^1 dx H_g(x, \xi, t) = A_g(t) + \xi^2 D_g(t)$$

Essentially the same problem as in the extraction of quark D-term from DVCS

HOWEVER, two important differences

Leading contribution from **gluon** GPD

There is a tunable **skewness** parameter ξ which becomes large near the threshold.

Energy momentum tensor strikes back

YH, Strikman 2102.1263

Guo, Ji, Liu 2103.11506

When $\xi \approx 1$, one can Taylor expand.

$$\frac{1}{1-x} = 1 + x + x^2 + \dots$$

$$\int_{-1}^1 \frac{dx}{x} \left(\frac{1}{\eta - x - i\epsilon} - \frac{1}{\eta + x - i\epsilon} \right) H_g(x, \eta, t) \approx 2 \int dx (1 + x^2 + x^4 + \dots) H_g(x, \eta, t)$$

spin=2 (energy momentum tensor)

spin=4 spin=6

Asymptotic form $H_g(x, \eta = 1) \approx (1 - x^2)^2$

all spins $\int dx \frac{H_g(x, \eta = 1, t)}{1 - x^2} \sim \int_0^1 dx \frac{(1 - x^2)^2}{1 - x^2} = \frac{2}{3}$

spin-2 only $\int_0^1 dx (1 - x^2)^2 = \frac{8}{15} \quad \leftarrow 80\% \text{ of the total}$

EMT dominates over all the other twist-2 operators combined!

Threshold approximation

YH, Strikman 2102.12631 (Mellin moment)

Guo, Ji, Liu 2103.11506 (Mellin moment)

Guo, Ji, Yuan 2308.13006 (conformal moment)

what is measurable

what we want

$$\int_{-1}^1 dx \frac{1}{\xi - x - i\epsilon} \begin{cases} \frac{1}{2} H^{q(+)}(x, \xi, t, \mu^2) \\ \frac{1}{x} H^g(x, \xi, t, \mu^2), \end{cases} \approx \frac{2}{\xi^2} \frac{5}{4} (A^a(t, \mu^2) + \xi^2 D^a(t, \mu^2))$$

Keep only the first term in the conformal partial wave expansion

Very good approximation when $\xi = \mathcal{O}(1)$ and for **gluon** and **strangeness** GPDs

Recently extended to NLO Guo, Yuan, Zhao, 2501.10532; YH, Klest, Passek-K, Schoenleber, 2501.12343
YH, Schoenleber 2502.12061

However, ξ cannot be too large (factorization breakdown)

In electro-production, $\frac{1-\xi}{2\xi} Q^2 \gg |t|, M^2$ YH, Klest, Passek, Schoenleber (2025)

Example: NLO ϕ -electroproduction

YH, Klest, Passek-K, Schoenleber (2025)

Compare the full NLO amplitude ([Muller et al. \(2013\)](#)) with the truncated version, also at NLO

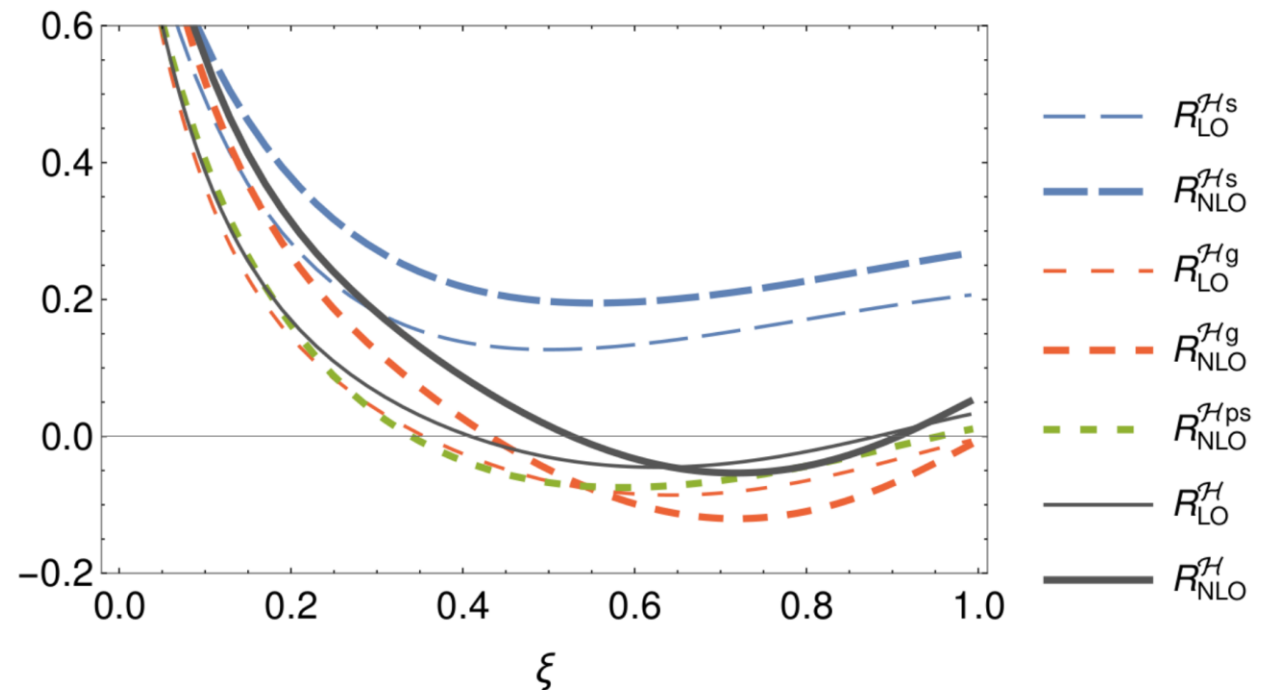
$$\mathcal{H}(\xi, t, Q^2) \approx \frac{2\kappa}{\xi^2} \frac{15}{2} \left[\left\{ \alpha_s(\mu) + \frac{\alpha_s^2(\mu)}{2\pi} \left(25.7309 - 2n_f + \left(-\frac{131}{18} + \frac{n_f}{3} \right) \ln \frac{Q^2}{\mu^2} \right) \right\} (A_s(t, \mu) + \xi^2 D_s(t, \mu)) \right. \\ \left. + \frac{\alpha_s^2}{2\pi} \left(-2.3889 + \frac{2}{3} \ln \frac{Q^2}{\mu^2} \right) \sum_q (A_q + \xi^2 D_q) + \frac{3}{8} \left\{ \alpha_s + \frac{\alpha_s^2}{2\pi} \left(13.8682 - \frac{83}{18} \ln \frac{Q^2}{\mu^2} \right) \right\} (A_g + \xi^2 D_g) \right]$$

Goloskokov-Kroll (GK) model for nucleon GPD

Truncation error

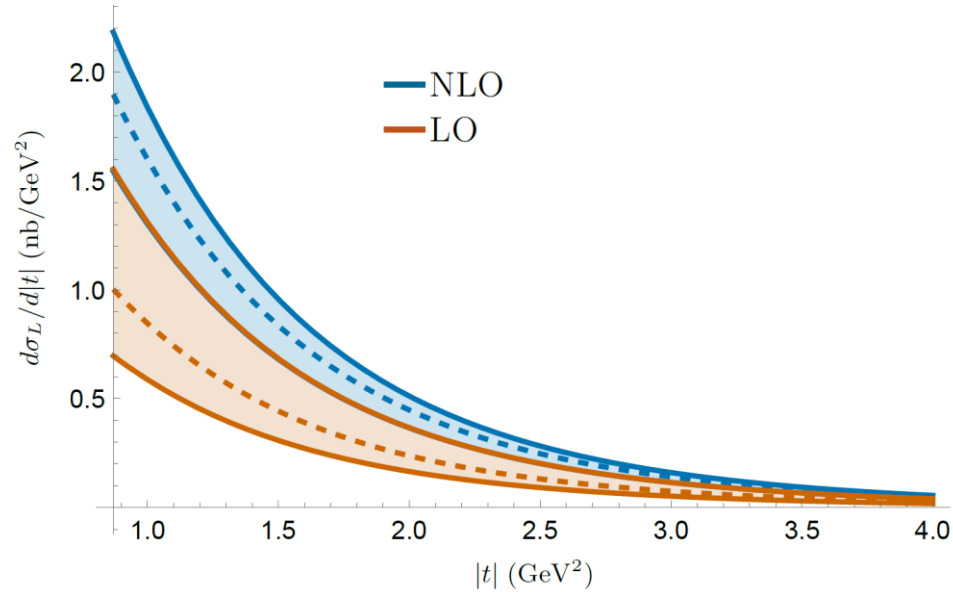
$$R = 1 - \frac{|\mathcal{H}_{\text{full}}|}{\mathcal{H}_{\text{trunc}}}$$

less than 10% already for $\xi \gtrsim 0.4$



ϕ -electroproduction at NLO

YH, Klest, Passek-K, Schoenleber (2025)

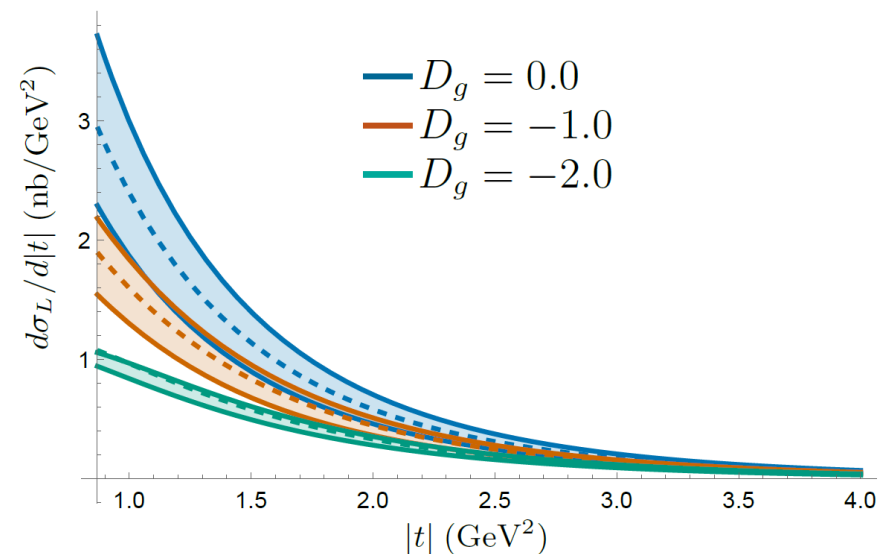
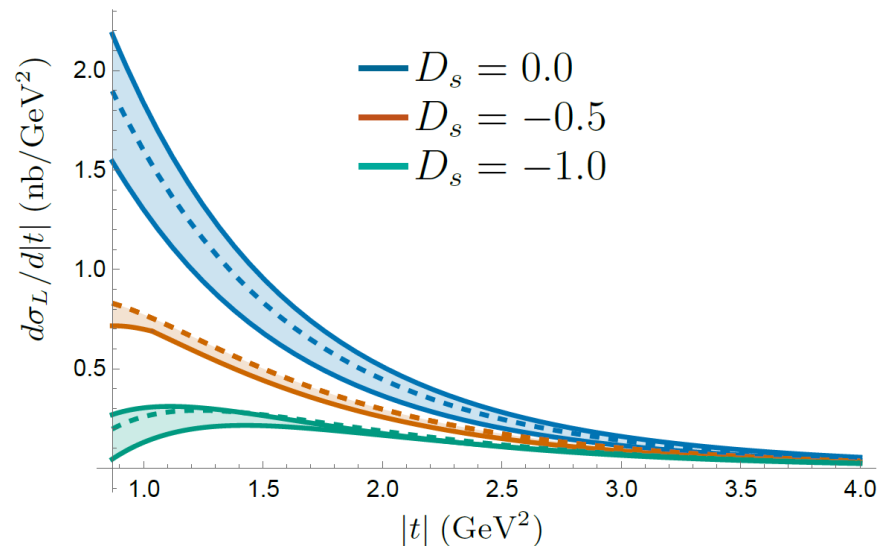


Dominated by gluons.

Cancellation between LO strangeness and NLO valence

Strangeness is important if $D_s = O(1)$

Combined fit to J/psi production data desirable

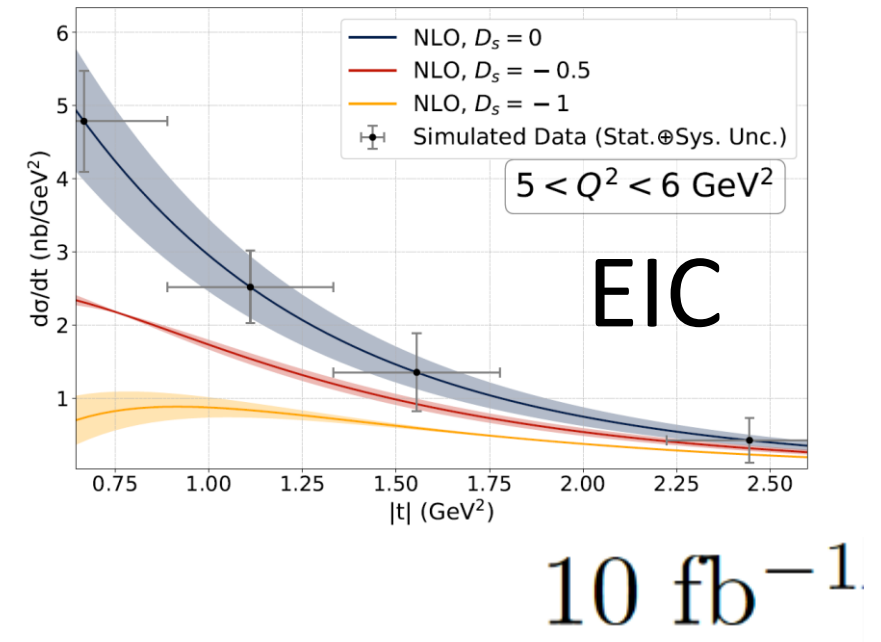
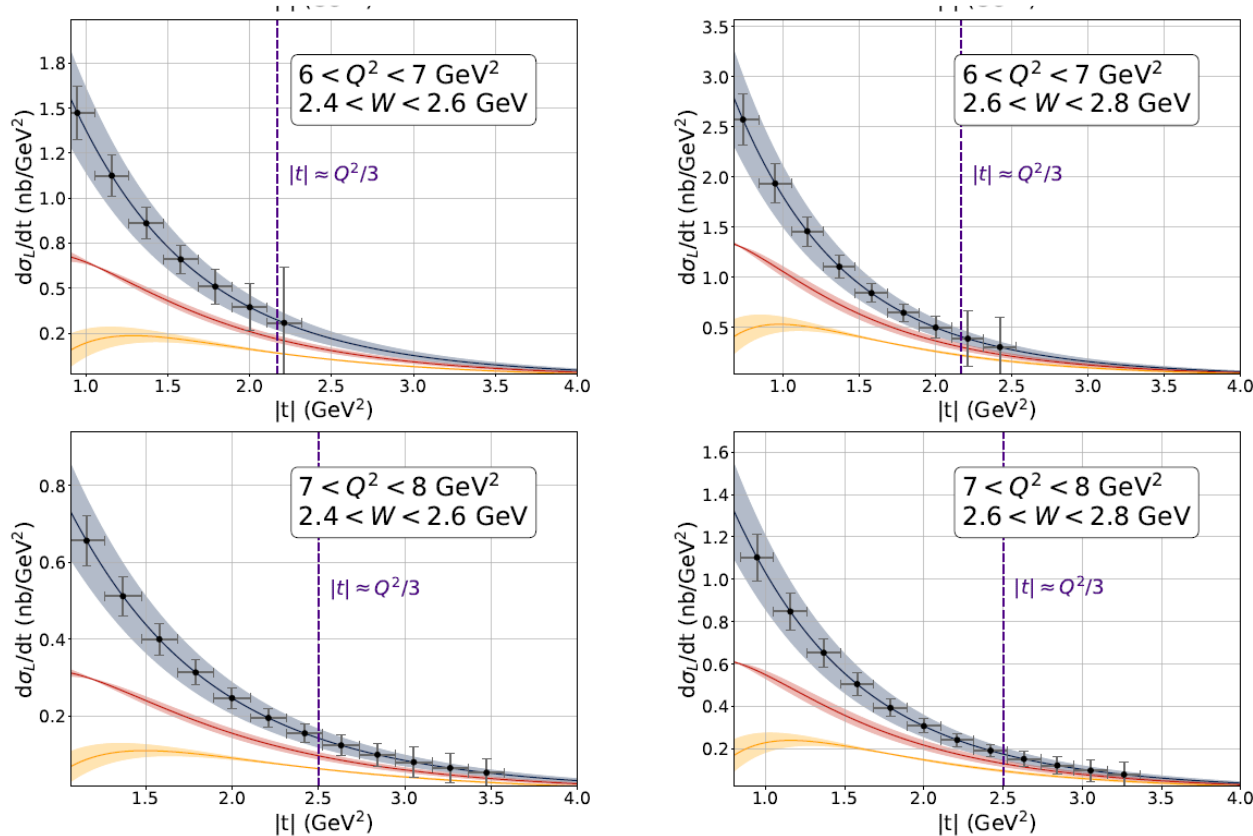


ϕ -electroproduction: Monte Carlo simulation

YH, Klest, Passek-K, Schoenleber (2025)

SoLID

43.2 ab^{-1}



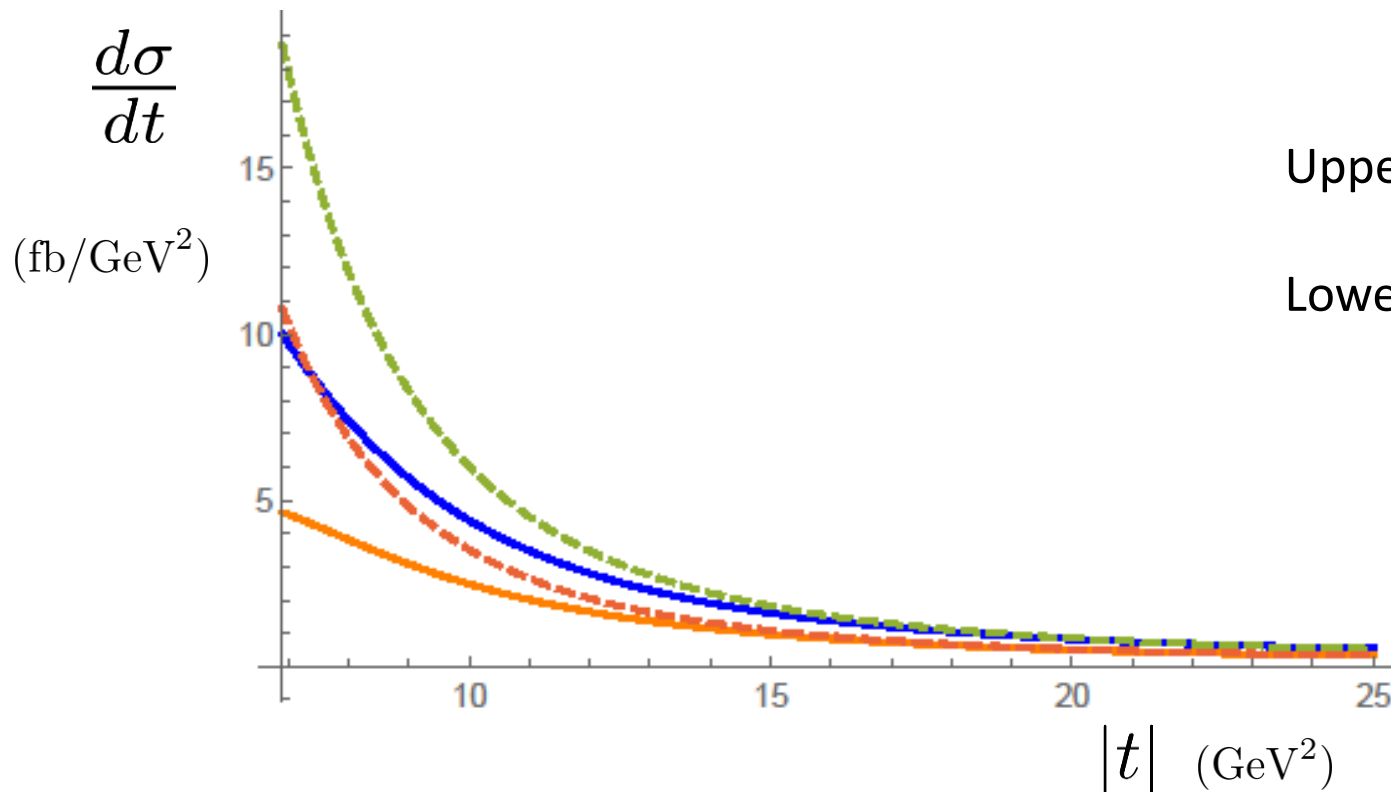
Looks like a feasible measurement!

Sensitivity to the gluon condensate

Boussarie, YH (2020)

J/ψ electro-production at the EIC

$$\sqrt{S_{ep}} = 20 \text{ GeV} \quad Q^2 = 64 \text{ GeV}^2 \quad W = 4.4 \text{ GeV}$$



$$\langle P | \frac{\beta}{2g} F^2 | P \rangle = 2M^2(1 - b)$$

Pion GFFs from Sullivan process

YH, Schoenleber 2502.12061

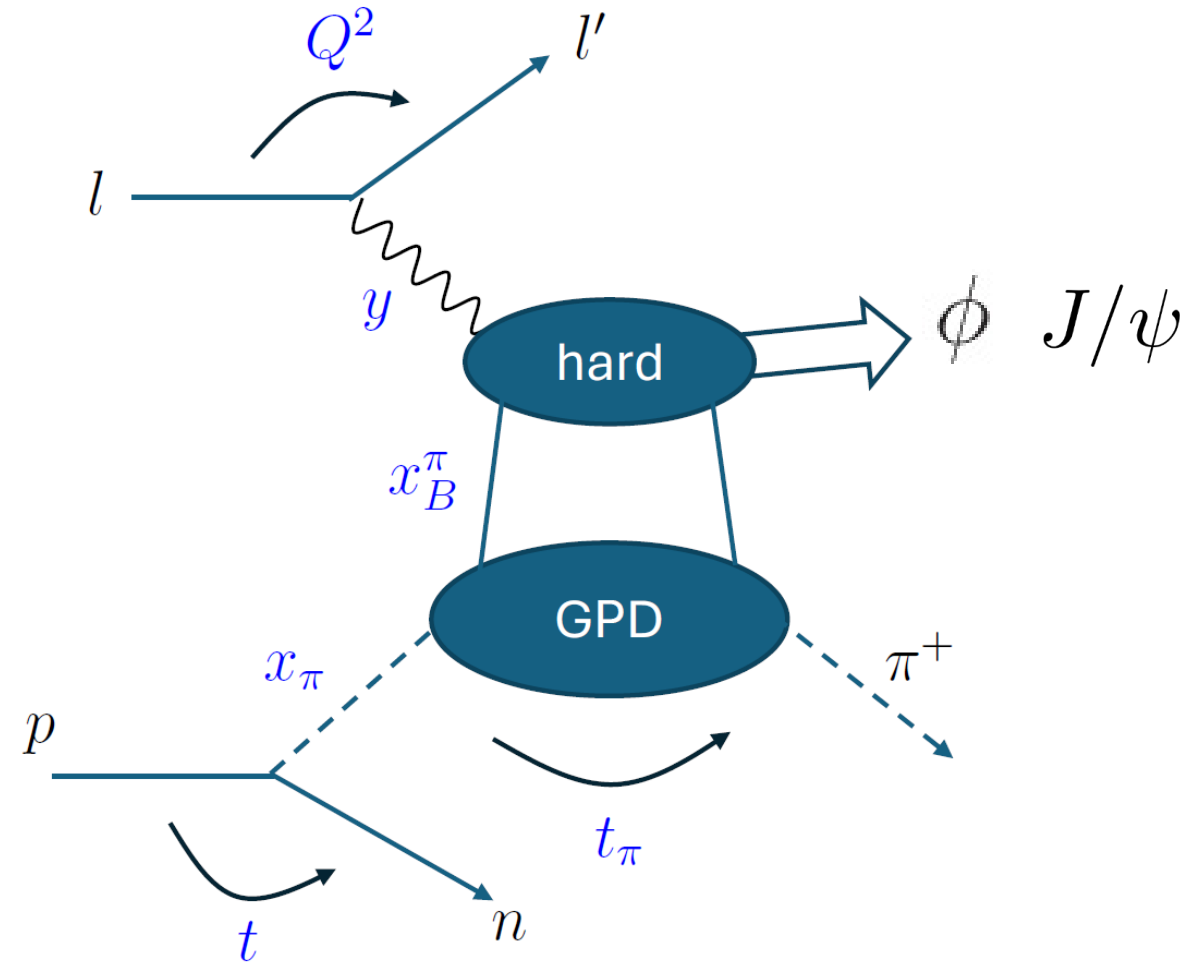
Originally proposed in 1972 to access the pion **EM form factors**, measurements at JLab

Pion **GPDs** from DVCS

Amrath, Diehl, Lansberg (2008)

Chavez, et al. (2022)

Pion **GFFs** from
 J/ψ photoproduction
 ϕ electroproduction
near threshold



Pion GFFs

Spin-0 hadron $\rightarrow$ 2 GFFs $\langle p' | T^{\mu\nu} | p \rangle = 2A(t)P^\mu P^\nu + \frac{D(t)}{2}(\Delta^\mu \Delta^\nu - \Delta^2 g^{\mu\nu})$

Soft pion theorem:

$$\text{In the chiral limit of QCD, } D(0) = -1$$

Write $D(0) = -A(0)$

This relation actually holds for each parton species

[YH, Schoenleber 2502.12061](#)

$$D_u(0) = -A_u(0) \quad D_d(0) = -A_d(0) \quad D_g(0) = -A_g(0)$$

Sullivan process near threshold

Measure the cross section $\frac{d\sigma}{dx_B dx_\pi}$

$$x_\pi = \frac{p_\pi \cdot l}{p \cdot l} \quad x_B = \frac{Q^2}{2p \cdot q}$$

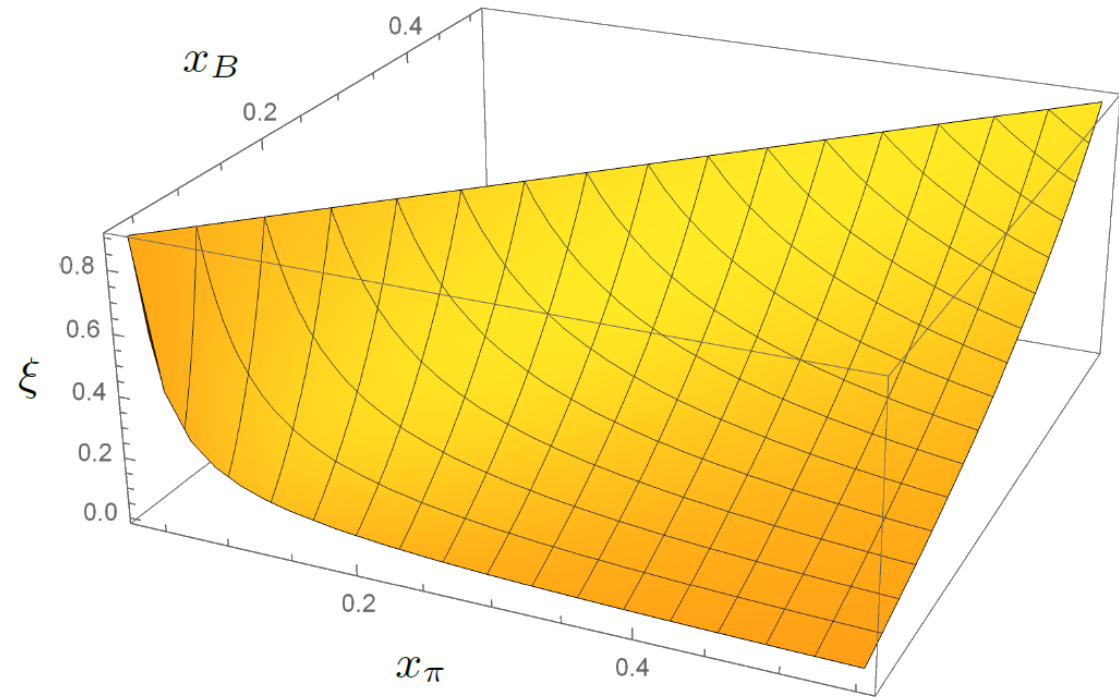
Threshold region along the diagonal line

$$x_B \approx x_\pi$$

Thanks to the light pion mass, relatively easier to achieve large skewness while keeping t small

$$t_{min} = -\frac{4\xi^2 m_\pi^2}{1 - \xi^2}$$

--> Less higher twist corrections



Threshold approximation

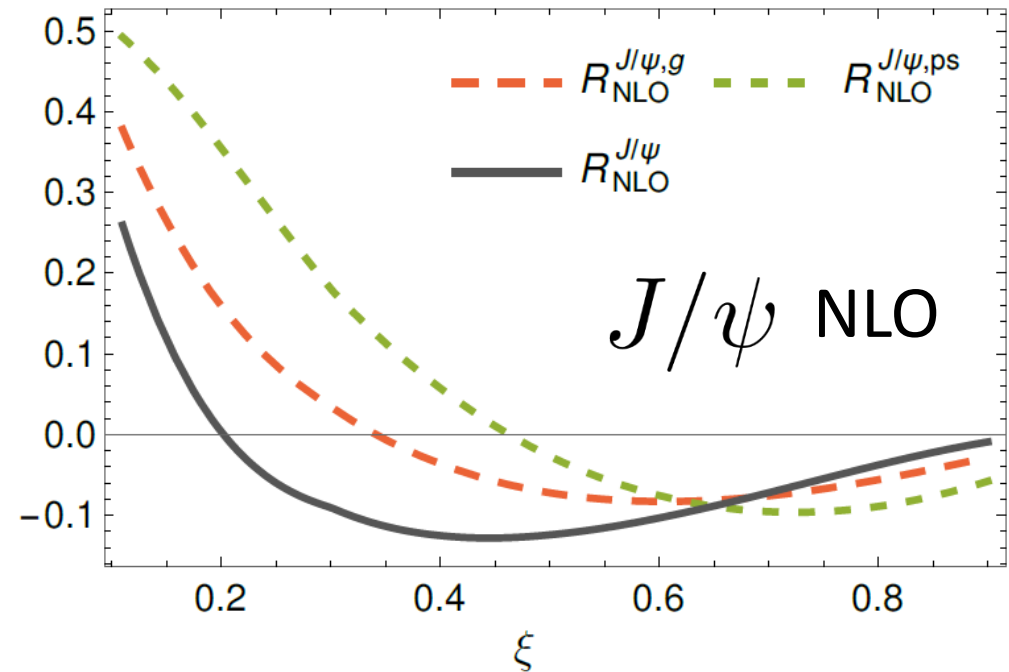
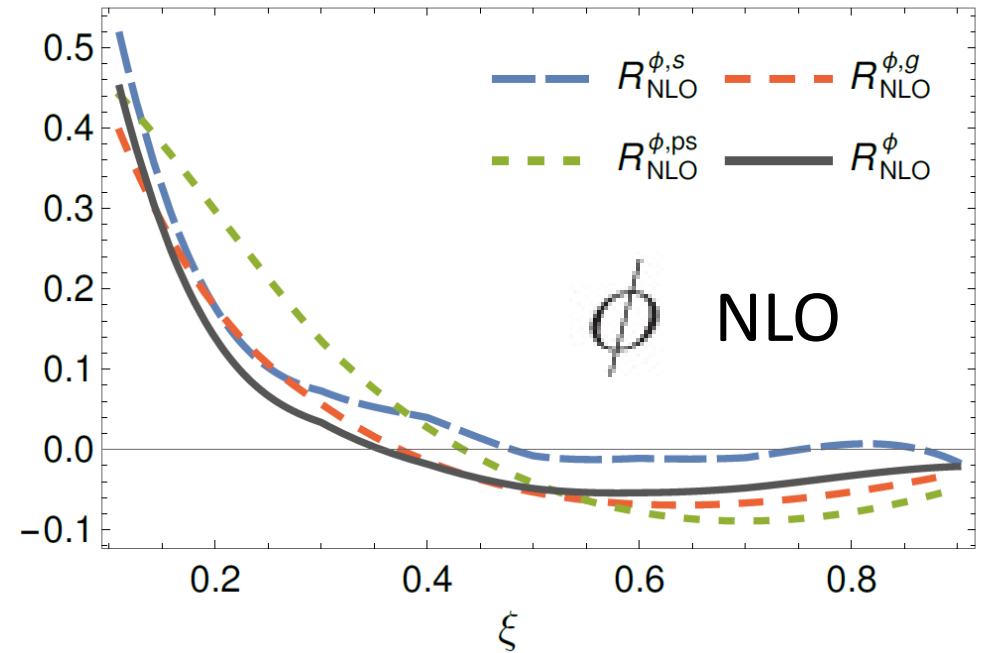
Input: Pion GPD at $\mu^2 = 10 \text{ GeV}^2$

Chavez et al. 2110.06052

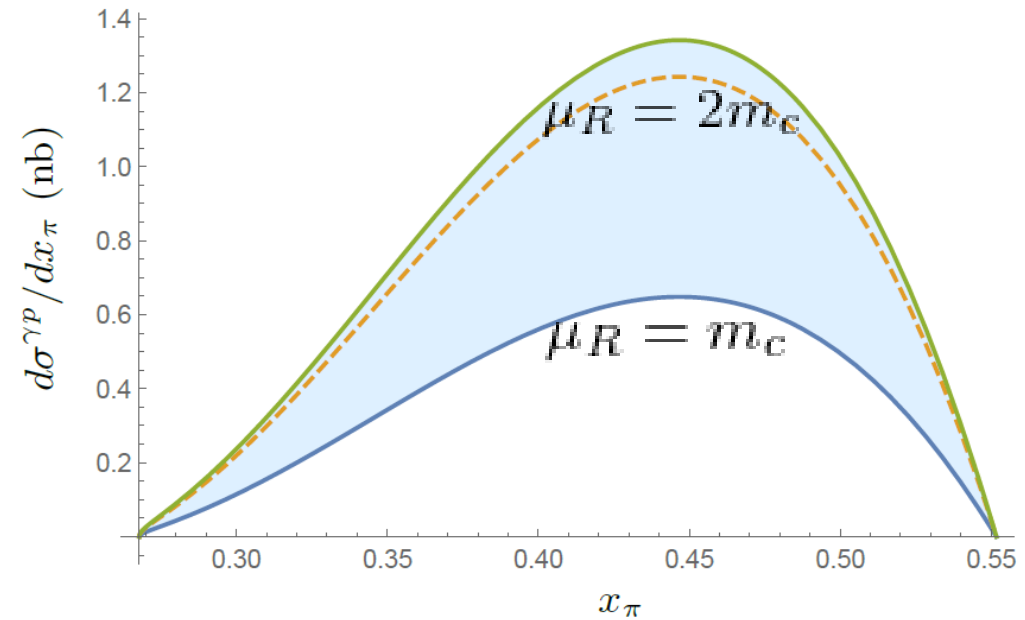
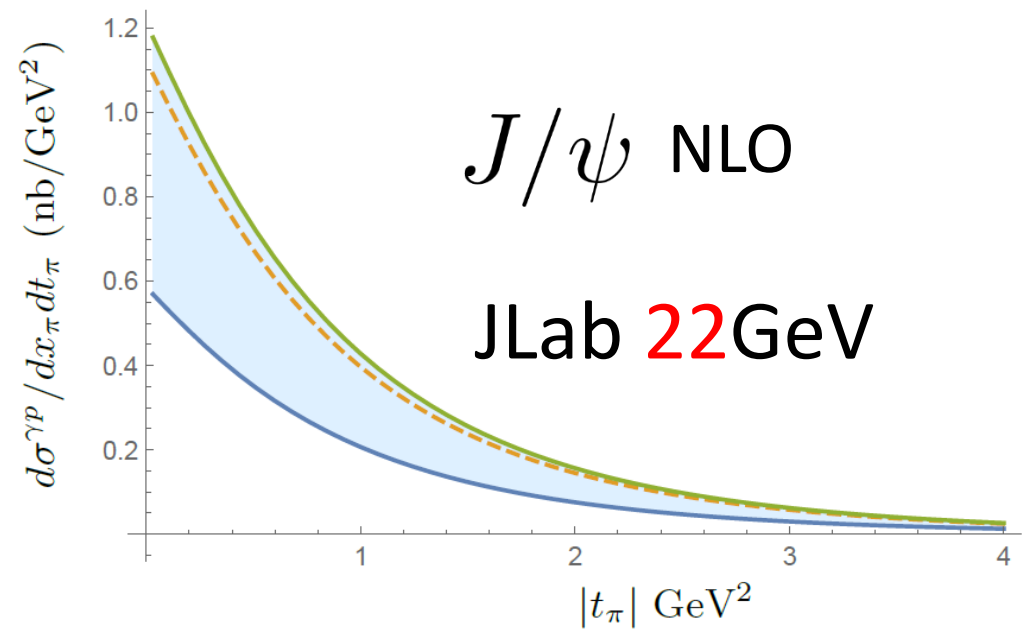
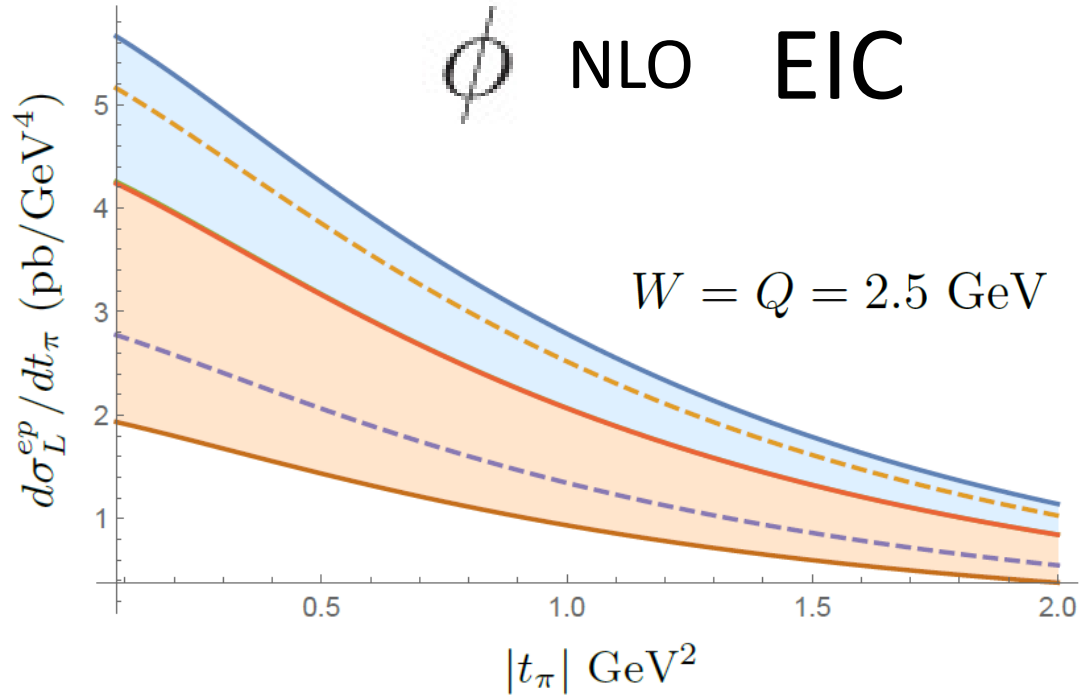
Truncation error

$$R = 1 - \frac{|\mathcal{H}_{\text{full}}|}{\mathcal{H}_{\text{trunc}}} \quad 5 \sim 10\%$$

Cancellation between LO gluons and NLO valence quarks in the J/ψ case.
 $\rightarrow$ approximation works better for ϕ



Prediction for JLab and EIC



Cross section well in the measurable range

Conclusions

- EM form factors: very active field even after 70 years, aiming for sub-percent precision
- GFFs: Still in the beginning phase. Initial excitement, growing pains, toward a sustainable field.