Gravitational form factors: theory and phenomenology

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CNF seminar March 26, 2026

Proton electromagnetic form factors

EM form factors from elastic scattering

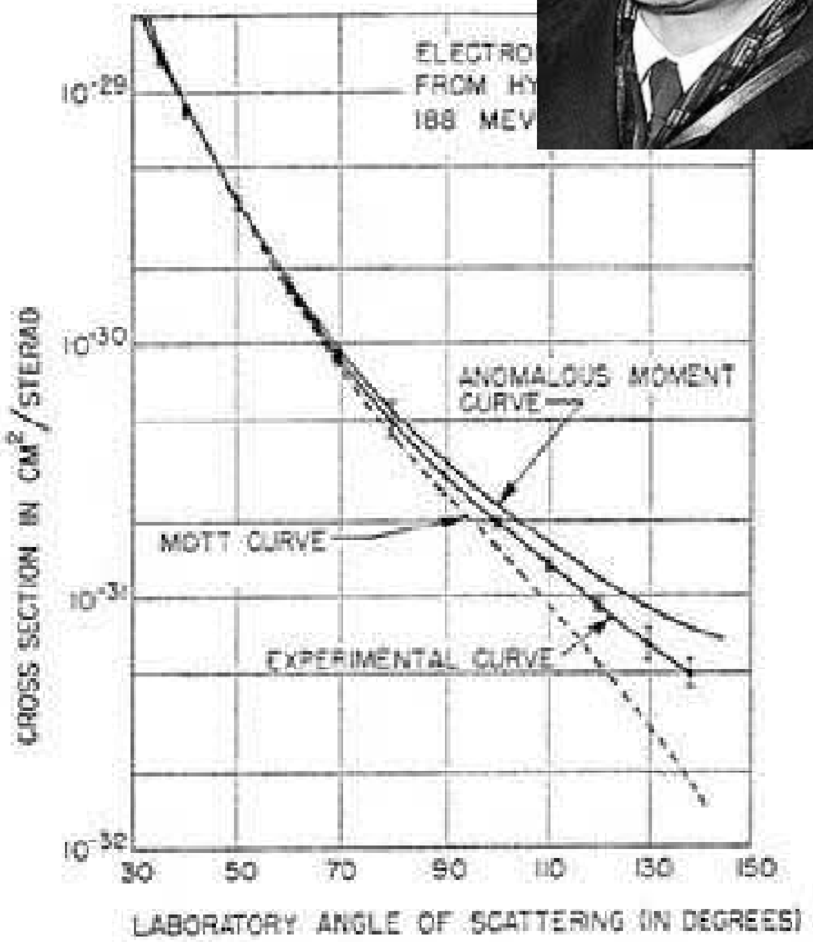
$$\langle p'|J^\mu(0)|p\rangle = \bar{u}(p')\left[\gamma^\mu F_1 + \frac{i\sigma^{\mu\nu}\Delta_\nu}{2m}F_2\right]u(p)$$

Electric form factor

$$G_E(t) = F_1(t) + \frac{t}{4M^2}F_2(t)$$

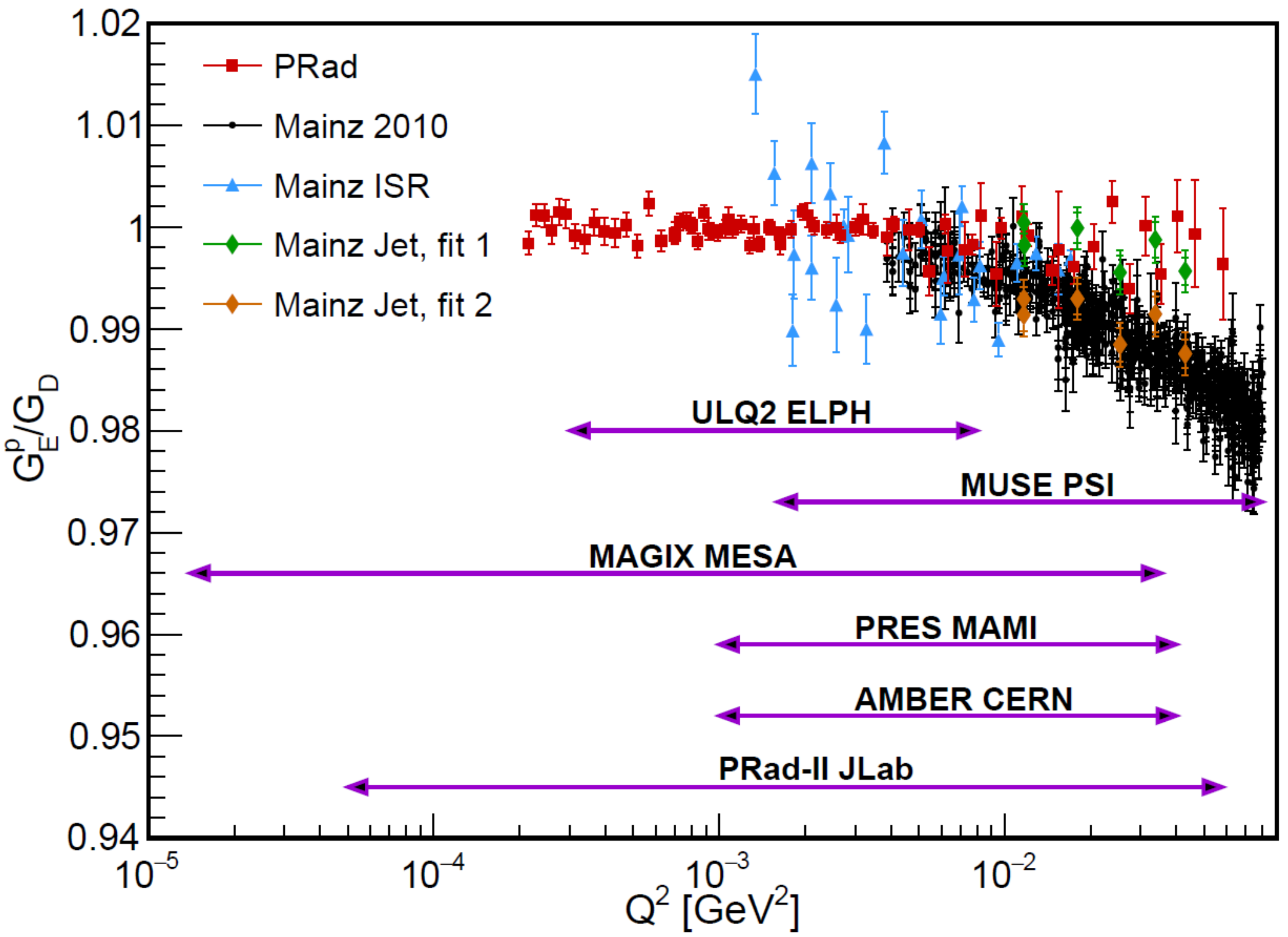
Proton charge radius $$\langle r^2\rangle = 6\frac{dG_E(t)}{dt}\bigg|_{t=0}$$

R. Hofstadter



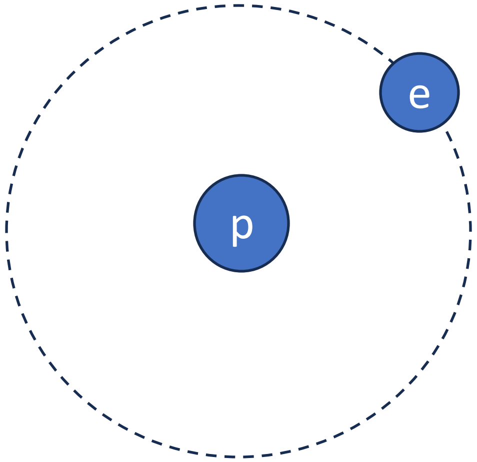
Elastic scattering 70 years later

Xiong, Peng, 2302.13818



Charge radius from hydrogen atom spectrum

Coulomb potential modified in a hydrogen atom



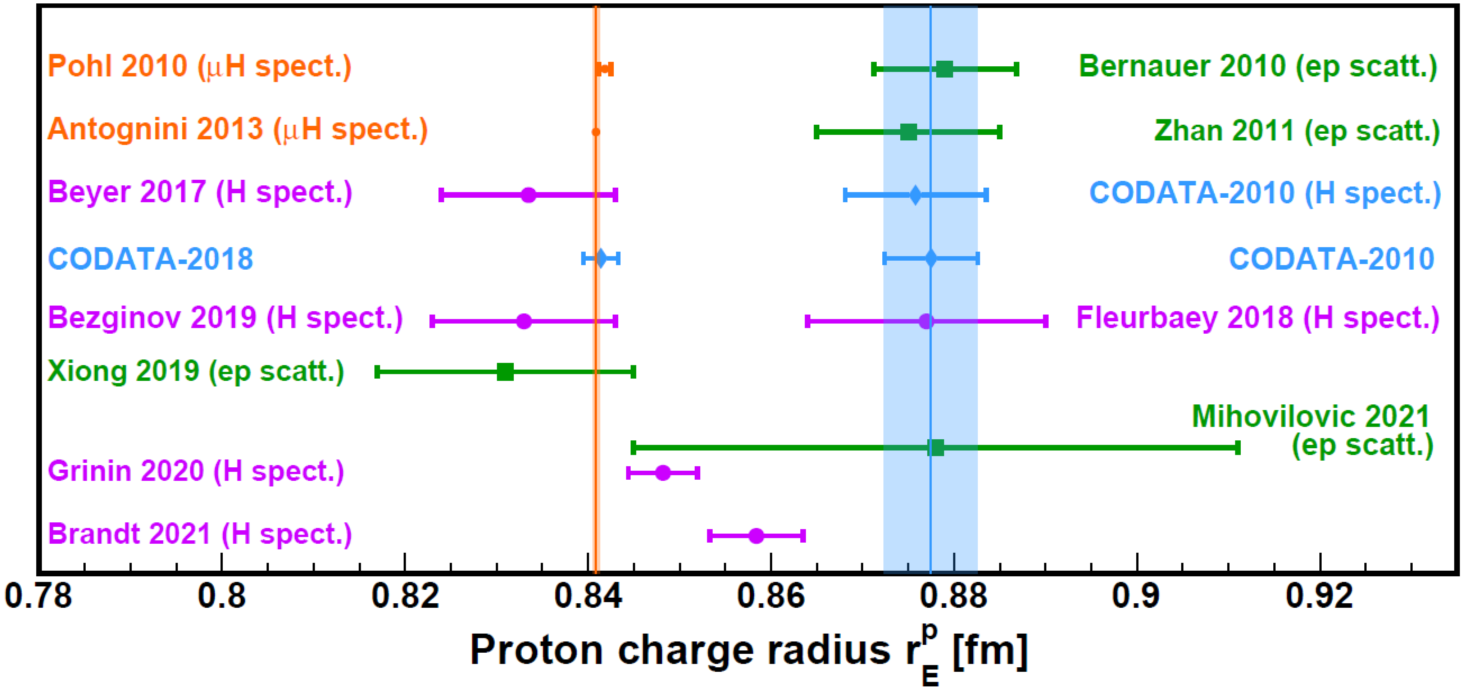
$$V(r) = \frac{-e^2}{4\pi r} \Rightarrow -e^2 \int \frac{d^3k}{(2\pi)^3} \frac{G_E(k^2) e^{-i\vec{k}\cdot\vec{r}}}{k^2}$$

$$\Delta E_{l=0} = \frac{2\alpha^4 m^3}{3n^3} \langle r^2 \rangle$$ ← Proton charge radius!

Part of the Lamb shift.

Enhanced in the muonic hydrogen! $m_\mu \approx 200 m_e$

Proton radius puzzle?



Both CODATA and PDG now recommend the smaller value ~0.84fm.

Several future experiment planned, aim for less than 1% precision

PRad (2019) $r_p = 0.831 \pm 0.007_{\text{stat}} \pm 0.012_{\text{syst}}$

Radius zoo

2312.12984

Charge radius $$\langle r^2\rangle_c = \frac{\int d\boldsymbol{x} x^2 \rho_c(\boldsymbol{x})}{\int d\boldsymbol{x} \rho_c(\boldsymbol{x})} = \frac{6}{G_E(0)} \frac{dG_E(t)}{dt}\bigg|_{t=0}$$

Magnetic radius $$\langle r^2\rangle_M = \frac{6}{G_M(0)} \frac{dG_M(t)}{dt}\bigg|_{t=0}$$

Baryon number radius $$\langle r^2\rangle_B = \frac{\int d\boldsymbol{x} x^2 \rho_B(\boldsymbol{x})}{\int d\boldsymbol{x} \rho_B(\boldsymbol{x})}$$

Mass radius $$\langle r^2\rangle_m = \frac{\int d\boldsymbol{x}\, x^2 T^{00}(\boldsymbol{x})}{\int d\boldsymbol{x} T^{00}(\boldsymbol{x})} = 6\frac{dA(t)}{dt}\bigg|_{t=0} - \frac{3D(0)}{2M^2}$$

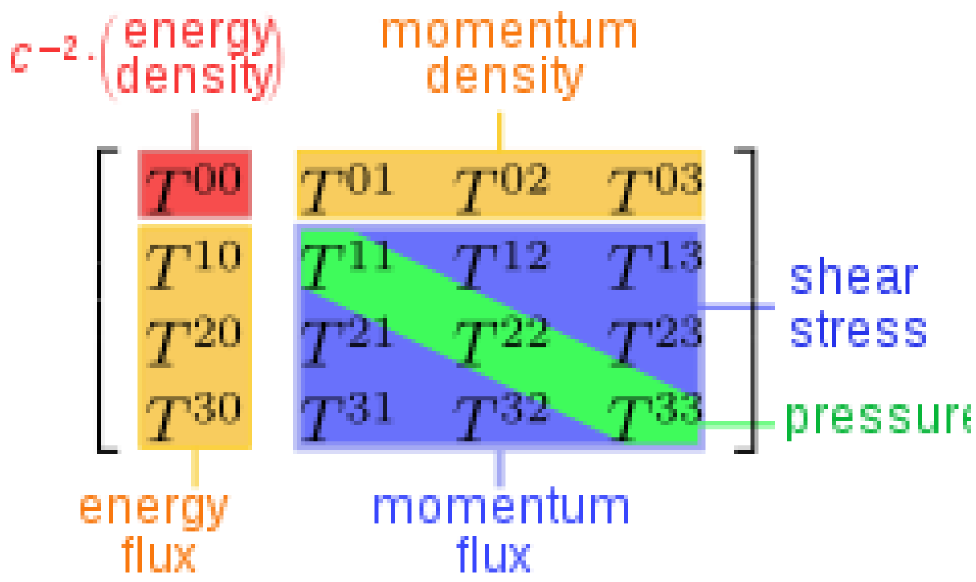
Scalar radius $$\langle r^2\rangle_s = \frac{\int d\boldsymbol{x}\, x^2 T^{\mu}_{\mu}(\boldsymbol{x})}{\int d\boldsymbol{x} T^{\mu}_{\mu}(\boldsymbol{x})} = 6\frac{dA(t)}{dt}\bigg|_{t=0} - \frac{9D(0)}{2M^2}$$

Tensor radius $$\langle r^2\rangle_t \equiv \frac{\int d\boldsymbol{x}\, x^2 \left(T^{00}(\boldsymbol{x}) + \frac{1}{2}T_{ii}(\boldsymbol{x})\right)}{\int d\boldsymbol{x} \left(T^{00} + \frac{1}{2}T_{ii}\right)} = 6\frac{dA(t)}{dt}\bigg|_{t=0}$$

Mechanical radius $$\langle r^2\rangle_{mech} = \frac{\int d\boldsymbol{x} x^2 \frac{x_i x_j}{x^2} T_{ij}(\boldsymbol{x})}{\int d\boldsymbol{x} \frac{x_i x_j}{x^2} T_{ij}(\boldsymbol{x})} = \frac{6D(0)}{\int_{-\infty}^{0} dt D(t)}$$

…

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

$$\bar{P} = \frac{P + P'}{2}, \quad \Delta = P' - P$$

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

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

D-term—the last global unknown

$$\langle P'|T^{ij}|P\rangle \sim (\Delta^i\Delta^k - \delta^{ik}\Delta^2)D(t)$$

$D(t=0)$ is a conserved charge of the nucleon, similar to the magnetic moment

Fourier transform $\vec{\Delta} \to \vec{r}$ interpreted as `pressure' inside a nucleon Polyakov (2003)

$$T^{ij}(r) = \left(\frac{r^i r^j}{r^2} - \frac{1}{3}\delta^{ij}\right) s(r) + \delta^{ij} p(r)$$

$$p(r) = \frac{1}{6M}\int \frac{d\boldsymbol{\Delta}}{(2\pi)^3} e^{i\boldsymbol{\Delta}\cdot\boldsymbol{r}} t D(t) \qquad D = M\int d^3r\, r^2 p(r)$$

Explosion of interest in the past years.
Models, interpretation, lattice, experiments...

Nucleon D-term in the Sakai-Sugimoto model

Fujita, YH, Sugimoto, Ueda (2022)

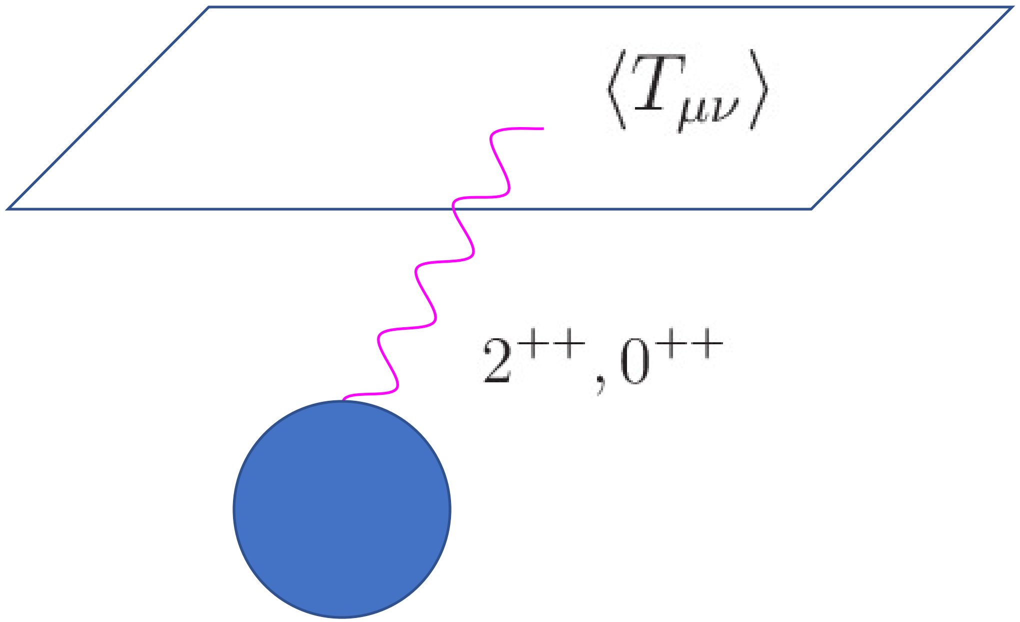
Baryons = instantons on D8 branes in type-IIA superstring

QFT energy momentum tensor from holographic renormalization

Graviton in 7D AdS = QCD glueballs

Glueball dominance in large-Nc QCD

$$D(|\vec{k}|) \sim \sum_{n=1}^{\infty} \frac{c_n^{\mathrm{T}}(|\vec{k}|)}{\vec{k}^2 + (m_n^{\mathrm{T}})^2} + \sum_{n=1}^{\infty} \frac{c_n^{\mathrm{S}}(|\vec{k}|)}{\vec{k}^2 + (m_n^{\mathrm{S}})^2}$$



At $t = |\vec{k}|^2 = 0$, the infinite sum can be performed in a closed form

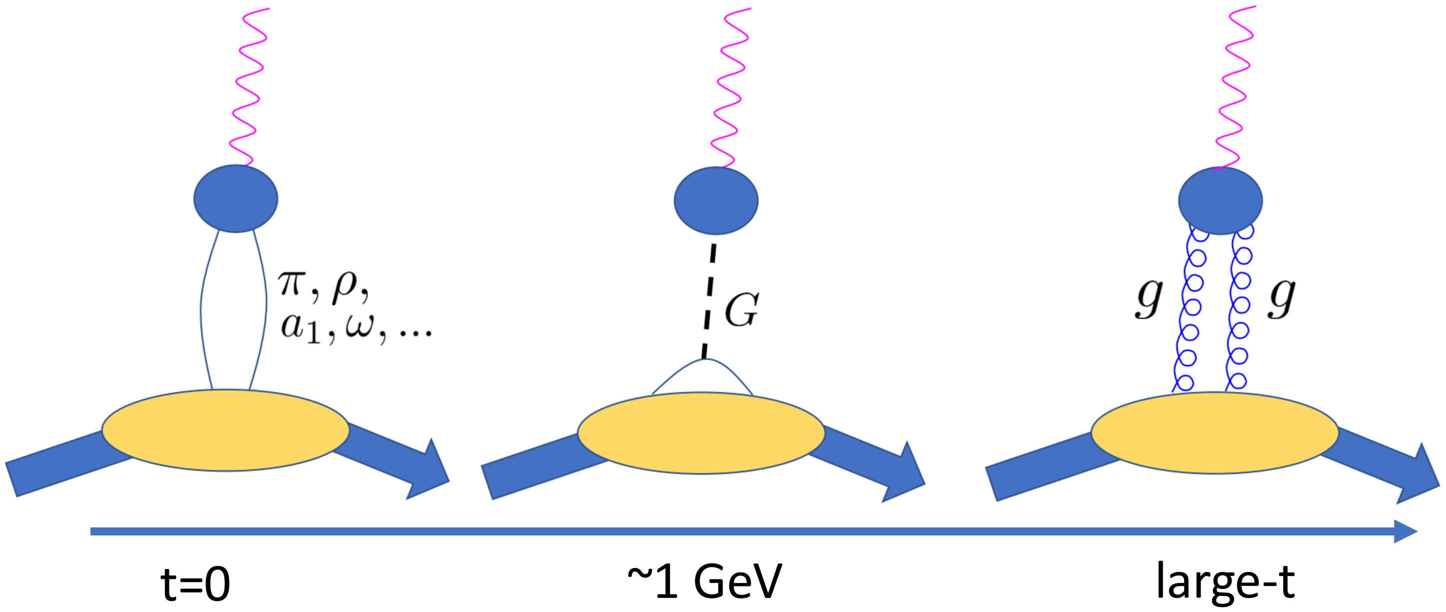
Meson pair dominance at t=0

Numerical result revised in Sugimoto, Tsukamoto, 2503.19492

$$D(0) = -3.42 + 1.36 = -2.06$$

Negative (attractive) contribution from isovector mesons $\pi, \rho, a_1, \cdots$

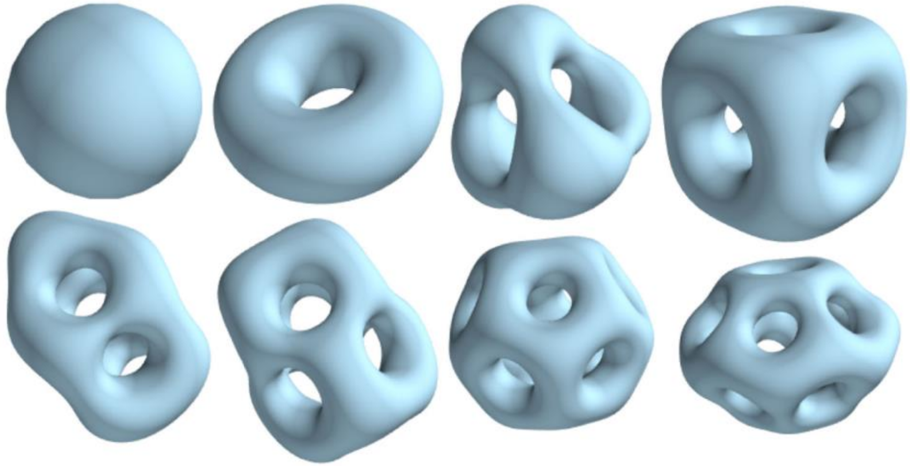
Positive (replusive) contribution from isoscalar mesons ω



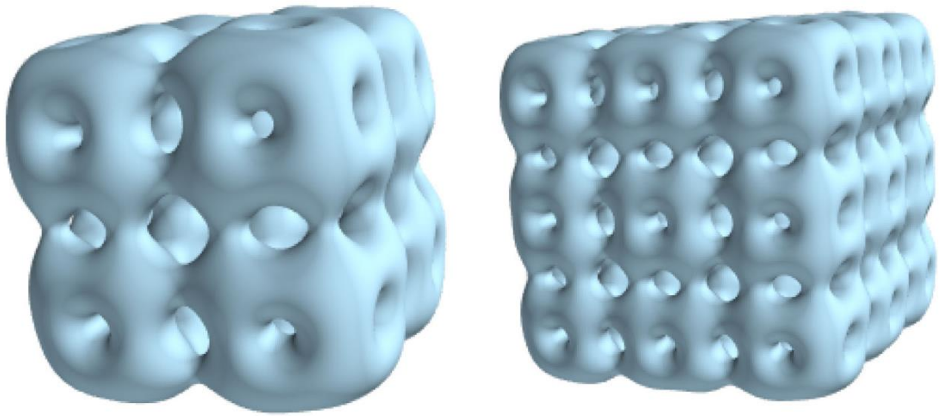
D-term of atomic nuclei in the Skyrme model

Martin-Caro, Huidobro, YH 2304.05994; 2312.12984

$B = 1 \sim 8$



$B = 32$ $B = 108$



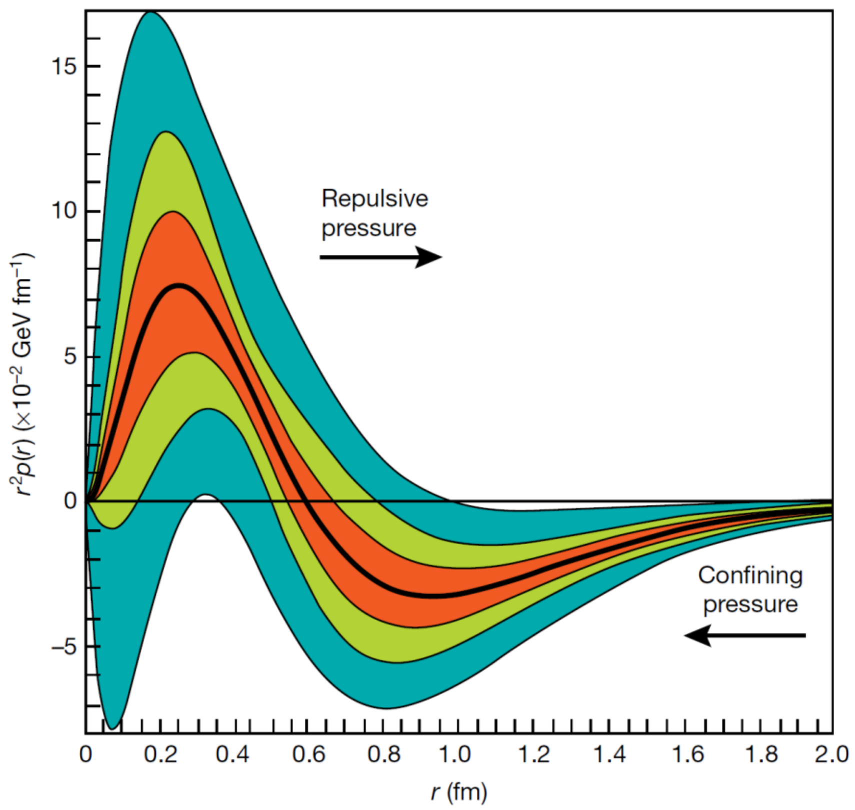
B	1	2	3	4	5	6	7	$8a$	$8b$	32	108
$D(0)$	-3.701	-13.126	-26.757	-43.304	-62.72	-85.95	-106.596	-128.368	-140.816	-1.874×10^3	-2.152×10^4

The value D(0) grows quickly with increasing B

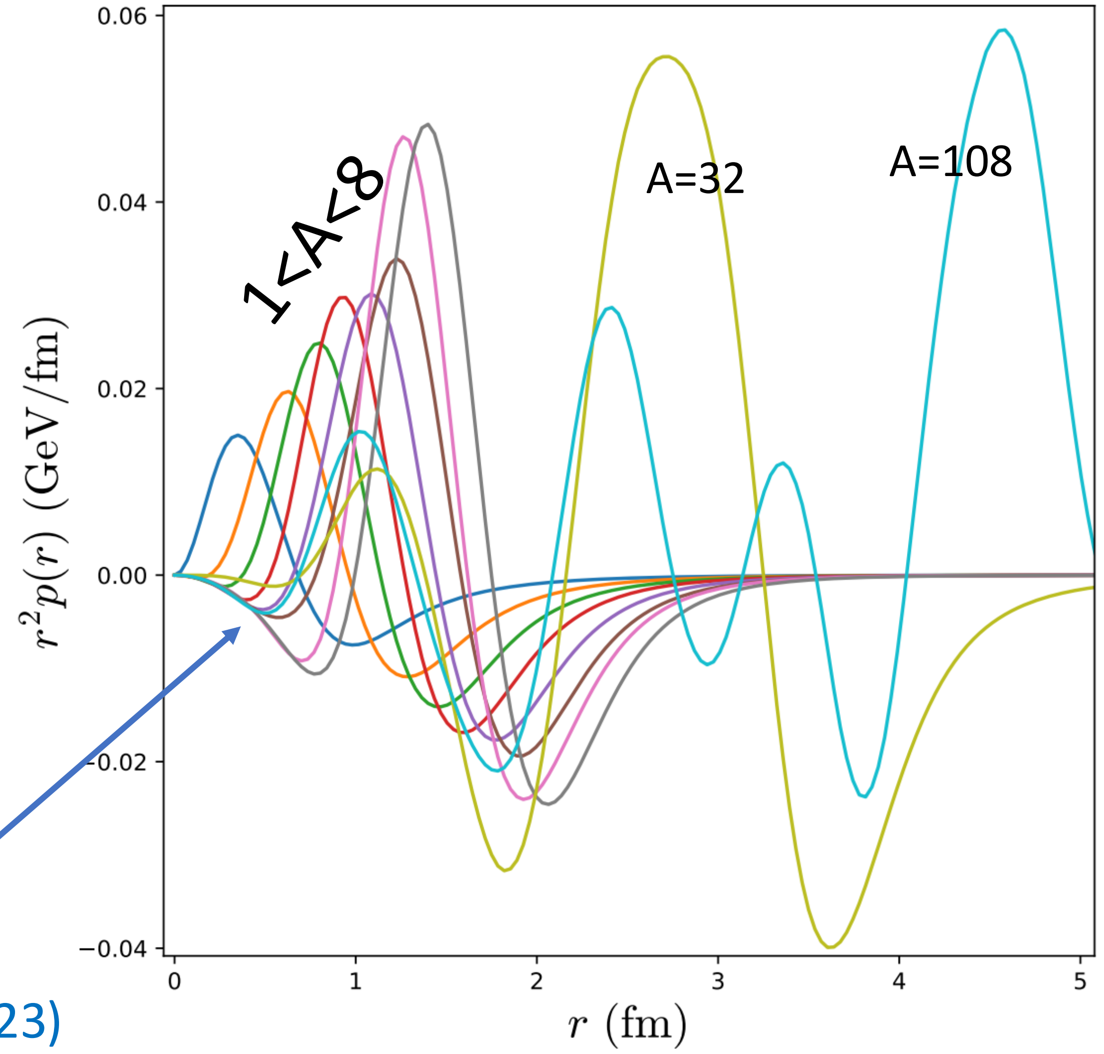
cf. Polyakov (2003); Liuti, Taneja (2005); Guzey, Siddikov (2005)

`Pressure' inside nucleon and nuclei

Burkert, Elouadrhiri, Girod (2018)



Martin-Caro, Huidobro, YH, 2312.12984



Negative pressure near the core for nuclei A>1

see also, Freese, Cosyn (2022,2026), He, Zahed (2023)

Nuclear mass radius in relativistic mean field theory

YH, Oishi, Oka, in preparation

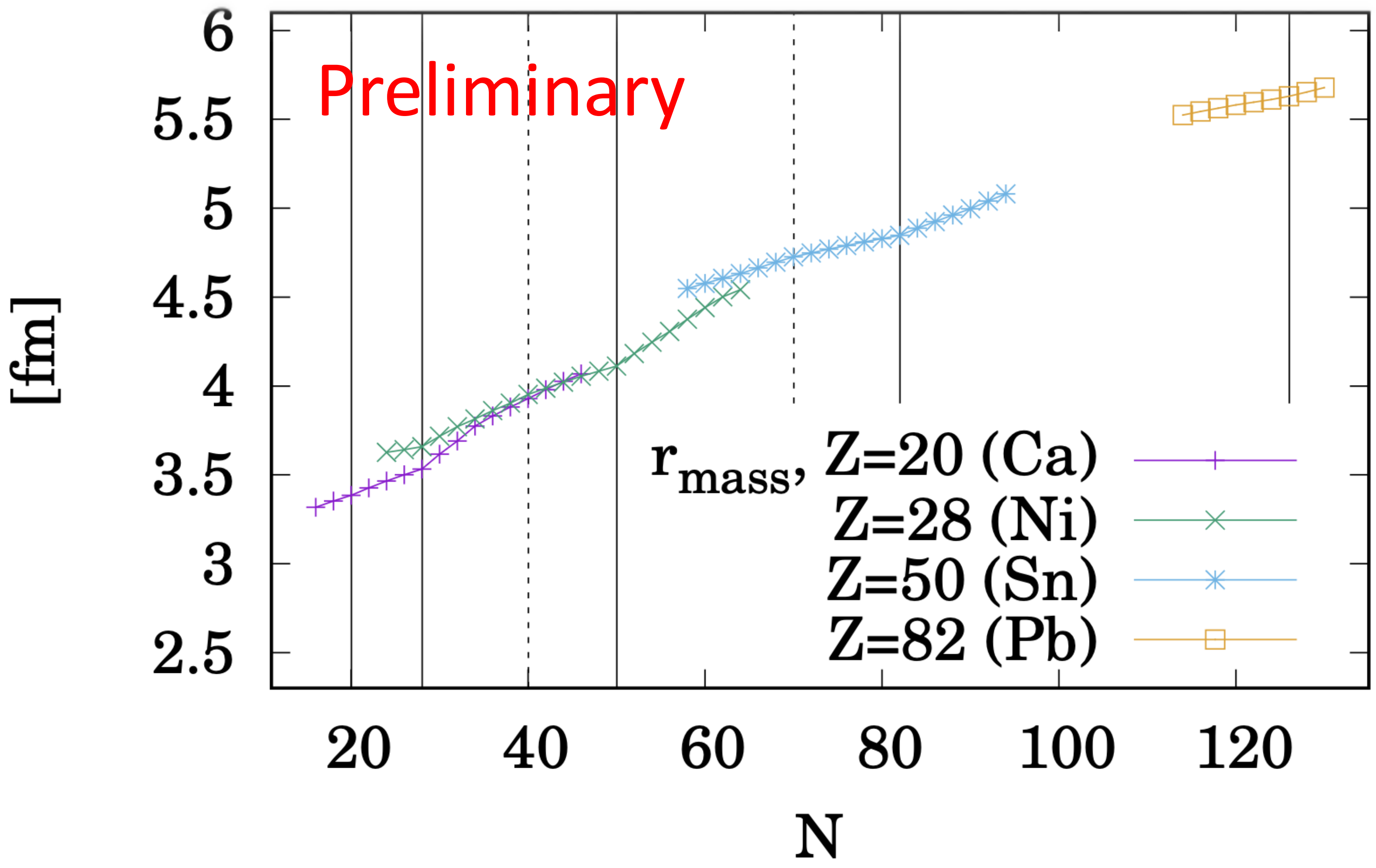
$$\begin{aligned}\mathcal{L} \;=\;& \bar{\psi}(i\partial\!\!\!/ - m)\psi - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{m_\omega^2}{2}\omega_\mu\omega^\mu - g_\omega\omega_\mu\bar{\psi}\gamma^\mu\psi \\ & -\frac{1}{4}\vec{R}_{\mu\nu}\cdot\vec{R}^{\mu\nu} + \frac{m_\rho^2}{2}\vec{\rho}_\mu\cdot\vec{\rho}^\mu - g_\rho\vec{\rho}_\mu\cdot\bar{\psi}\gamma^\mu\vec{\tau}\psi \\ & +\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{m_\sigma^2}{2}\sigma^2 - g_\sigma\sigma\bar{\psi}\psi \\ & -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - eA_\mu\bar{\psi}\gamma^\mu\frac{1+\tau^3}{2}\psi.\end{aligned}$$

One of the most successful, time-tested models of atomic nuclei with A>16
Reproduce binding energies and charge radii with percent-level accuracy
Relativistic Lagrangian formulation --> Ideal for GFF studies.

Earlier work on Walecka model: Guzey, Siddikov (2005)

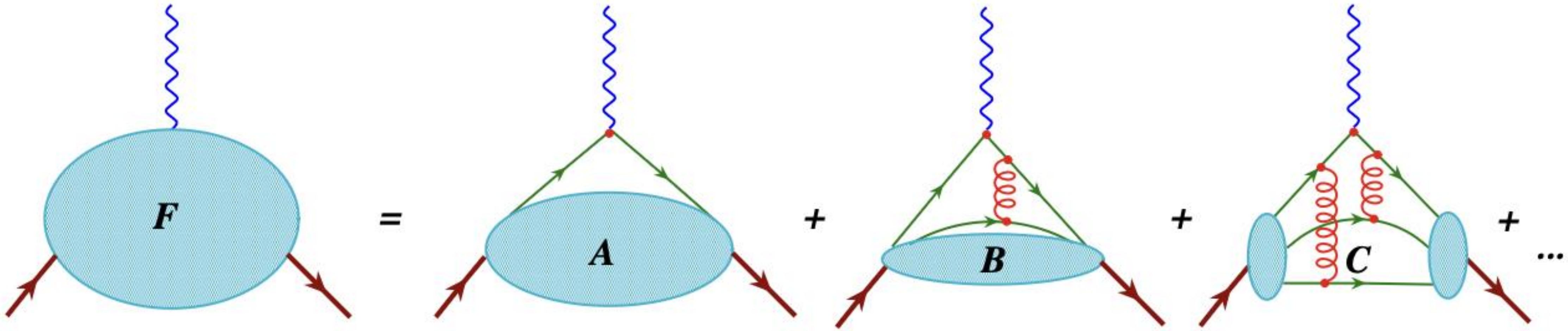
Mass radius of nuclear isotopes

YH, Oishi, Oka, in preparation



Kinks at neutron magic numbers, reflecting nuclear shell structure!

Gravitational form factors at large (but not too large)-t



Feynman contribution

$$\sim \frac{\Lambda^6}{t^3}$$

Hard scattering contribution

Efremov, Radyushkin,
Brodsky, Lepage, Li, Sterman

$$\sim \left(\frac{\alpha_s}{\pi}\right)^2 \frac{\Lambda^4}{t^2}$$

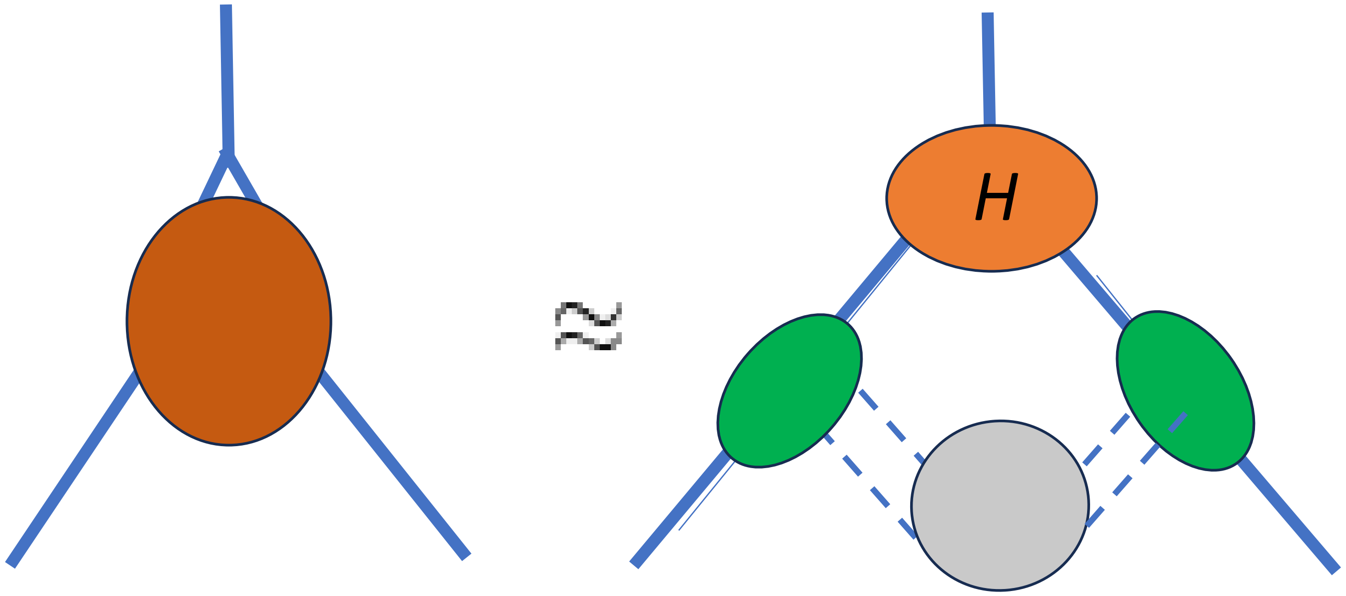
Feynman contribution dominantes until

$$|t| \sim \frac{\Lambda^2}{(\alpha_s/\pi)^2} = 10 \sim 100\mathrm{GeV}^2$$

Factorization of quark-in-quark GPD

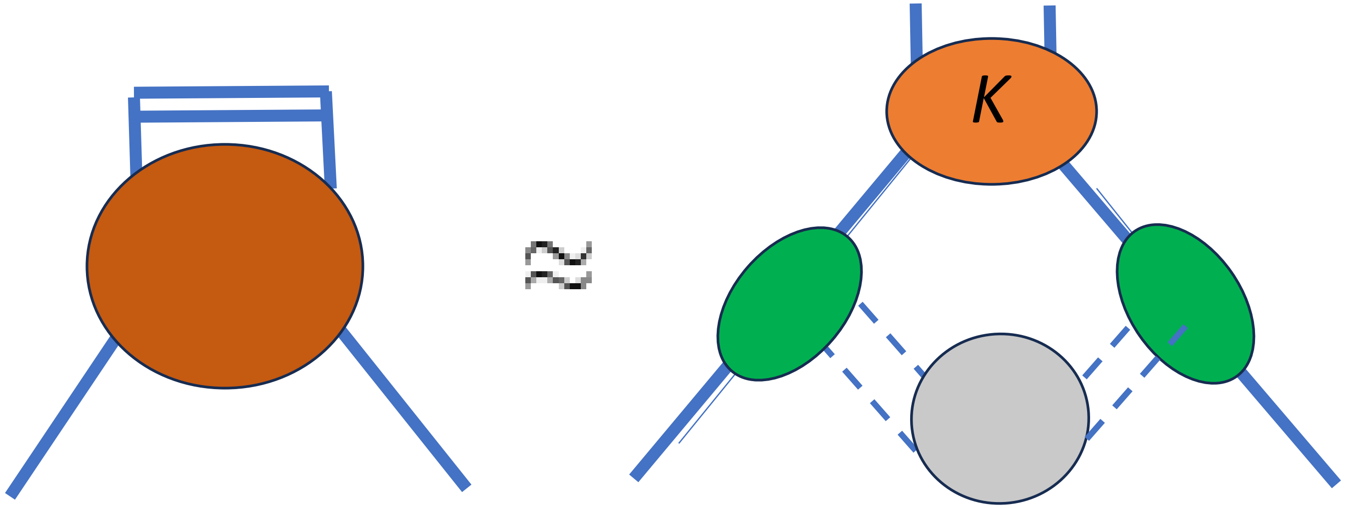
Factorization of quark Sudakov form factor at large-t

Collins et al., and many others



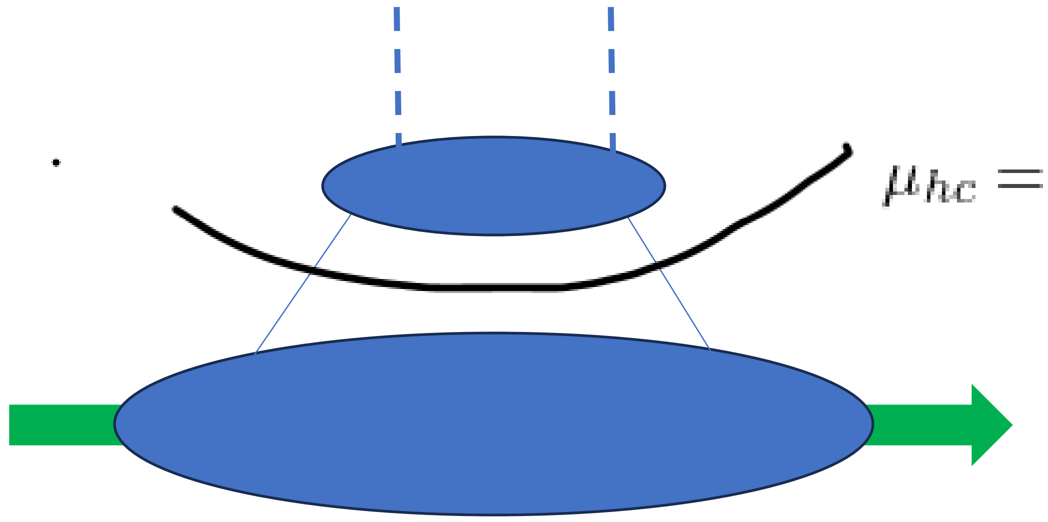
Factorization of nonlocal Sudakov, a.k.a. quark GPD of a quark

YH, Schoenleber, 2508.01529



SCET analysis of GPD

YH, Schoenleber, 2508.01529
see also, Kivel, 2010~



$$\mu_{hc} = \lambda\sqrt{-t}$$

$$\lambda = \frac{\sqrt{\Lambda}}{(-t)^{1/4}}$$

QCD factorization of the Feynman contribution,
dominant in the pre-asymptotic region

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

Coefficient function

Sudakov factor

Nonperturbative
matrix element

First moment --> elemag FF

Second moment --> gravitational FF

Nonperturbative function $f_1^q(t)$ cancels in the ratio

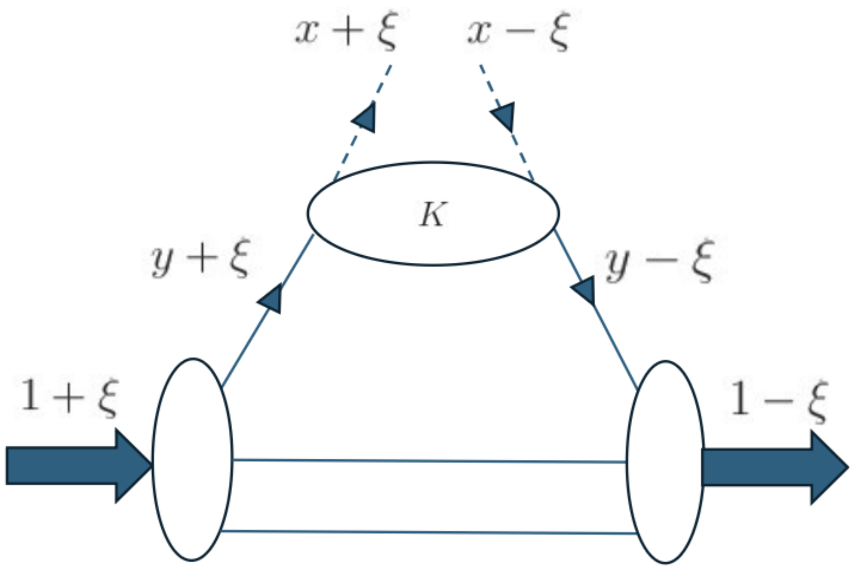
Ratio of the two form factors perturbatively calculable!

YH, Schoenleber, 2508.01529

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

Overlap representation of GPD/GFF

Diehl, Feldman, Kroll,...



$y = 1$ in strict power counting.
One parton carries 100% of proton momentum

More realistically, $1 - y \sim \frac{\Lambda}{\sqrt{-t}} \ll 1$

Drell, Yan, West

$$A_q(t) \sim U \left(\frac{\Lambda^2}{-t}\right)^{\delta+1} + \left(\frac{\alpha_s}{\pi}\right)^2 \left(\frac{\Lambda^2}{-t}\right)^2,$$

$$D_q(t) \sim U \frac{\alpha_s}{\pi} \left(\frac{\Lambda^2}{-t}\right)^{\delta+2} + \left(\frac{\alpha_s}{\pi}\right)^2 \left(\frac{\Lambda^2}{-t}\right)^3$$

Feynman contribution New

YH, Schoenleber, 2508.01529

Hard scattering contribution

Tong, Ma, Yuan (2022)

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

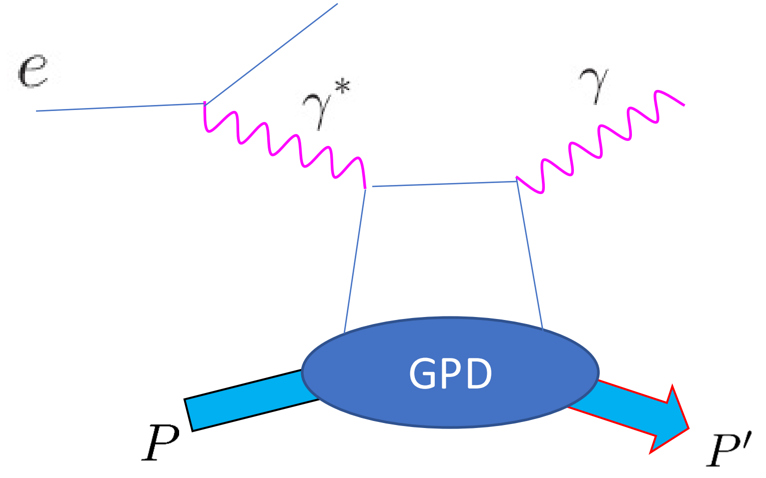
$$G_N \sim 1/M_P^2 \qquad M_P \sim 10^{19}\ \mathrm{GeV}$$

- But theorists are bad losers…

Indirect measurement of GFF

Spin-2 particle not readily available.
But if there are two spin-1 particles (two photons, two gluons), can they mimic a spin-2 exchange?

1+1=2



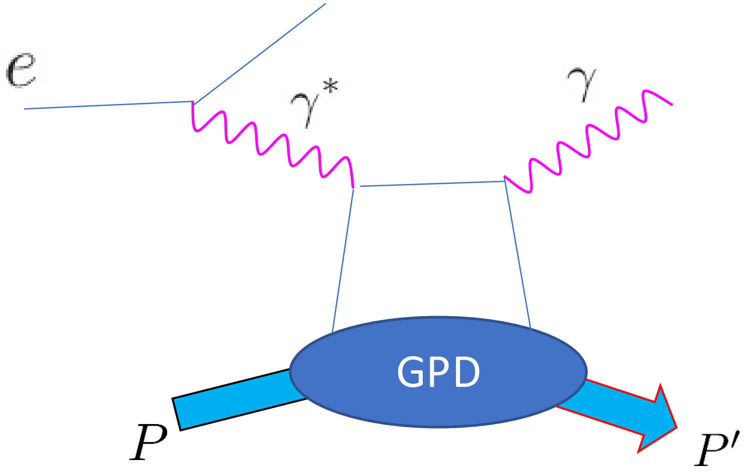
For example, Deeply Virtual Compton Scattering (DVCS)

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

Skewness $\xi = \frac{P^+ - P'^+}{P + + P'^+}$

Quark D-term from DVCS

$$D = D_u + D_d + D_s + D_g + \cdots$$

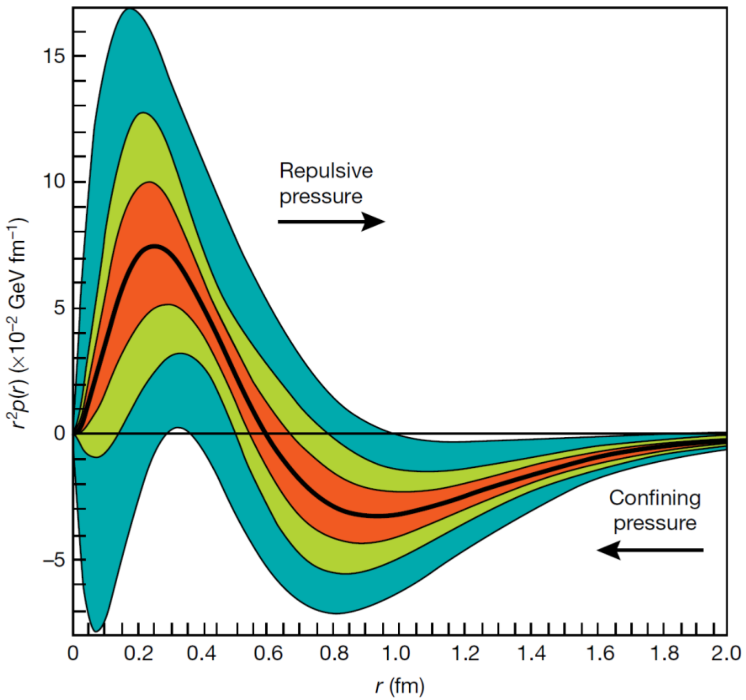


$D_{u,d}$ related to the subtraction constant in the dispersion relation for the Compton form factor   Teryaev (2005)

$$\mathrm{Re}\mathcal{H}_q(\xi,t) = \frac{1}{\pi}\int_{-1}^{1} dx \mathrm{P}\frac{\mathrm{Im}\mathcal{H}_q(x,t)}{\xi - x} + 2\int_{-1}^{1} dz \frac{D_q(z,t)}{1-z}$$

$$\int_{-1}^{1} dz z D_q(z,t) = D_q(t)$$

1 graviton ≈ 2 photons



After all, 1 graviton $\neq$ 2 photons

$$\int_{-1}^{1} dz \frac{D_q(z,t)}{1-z}$$

what is measurable

$$\int_{-1}^{1} dz z D_q(z,t)$$

what we want

2-photon state couples to operators with arbitrary spin.
How can one isolate the spin-2 component?

$$\frac{1}{1-z} = 1 + z + z^2 + z^3 + \cdots$$

spin-2 (EMT) → z

spin-4 → z^3

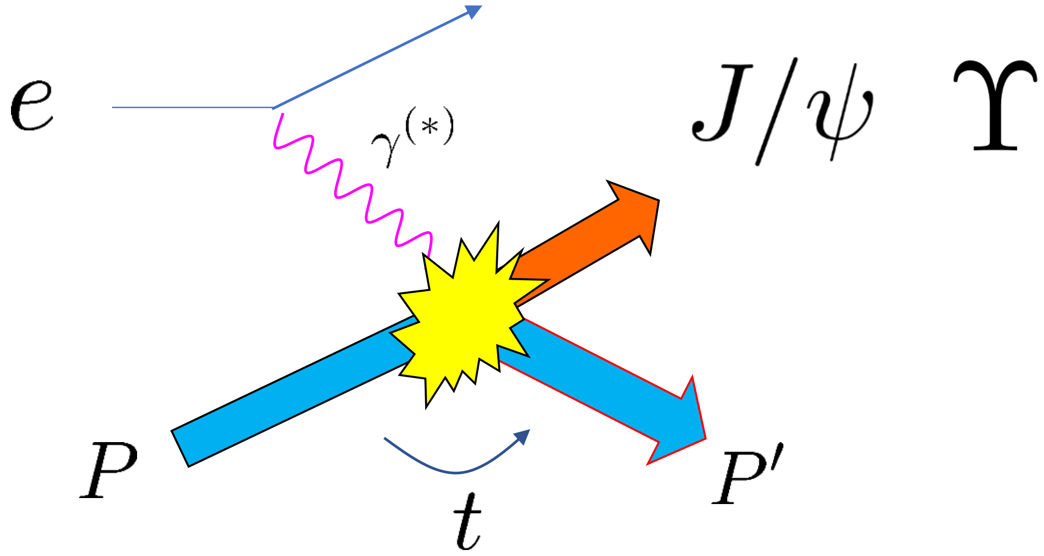
1+1= anything

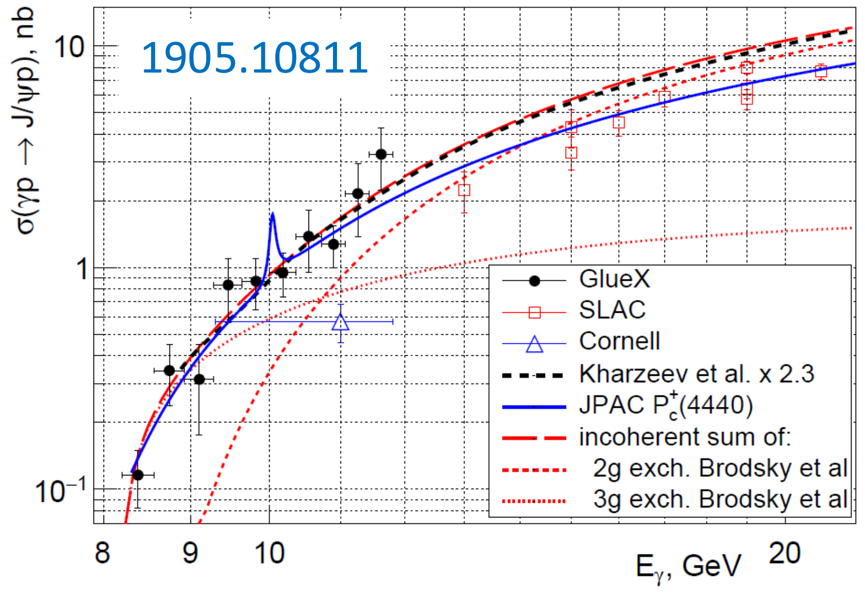
$$d_1^{uds}(t=0, 2\ \mathrm{GeV}^2) = -1.7 \pm 21$$
$$d_3^{uds}(t=0, 2\ \mathrm{GeV}^2) = 0.7 \pm 15$$
$$d_1^{g}(t=0, 2\ \mathrm{GeV}^2) = -2 \pm 30$$
$$d_3^{g}(t=0, 2\ \mathrm{GeV}^2) = 0.1 \pm 2.3$$

(NLO n=3 radiativ

Dutrieux, Meisgny, Mezrag, Moutarde (2024)

Quarkonium photo-production near threshold





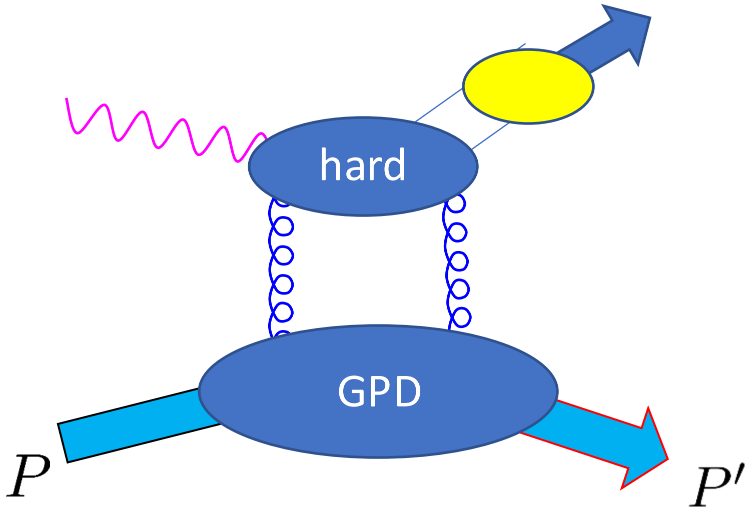
Ongoing experiments at JLab, future measurement at EIC?

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~)

1 graviton $\approx$ 2 gluons

GPD factorization



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

GPD factorization
valid near threshold,
(but not too close to threshold)

Collins, Frankfurt, Strikman (1996)
Ivanov, et al. (2004)
Guo, Ji, Liu (2021)

Necessary condition for factorization

YH, Klest, Passek, Schoenleber (2025)

$$\frac{1-\xi}{2\xi} Q^2 \gg |t|, M^2$$

Stricter than the usual $Q^2 \gg |t|$
as soon as $\xi > 0.3$

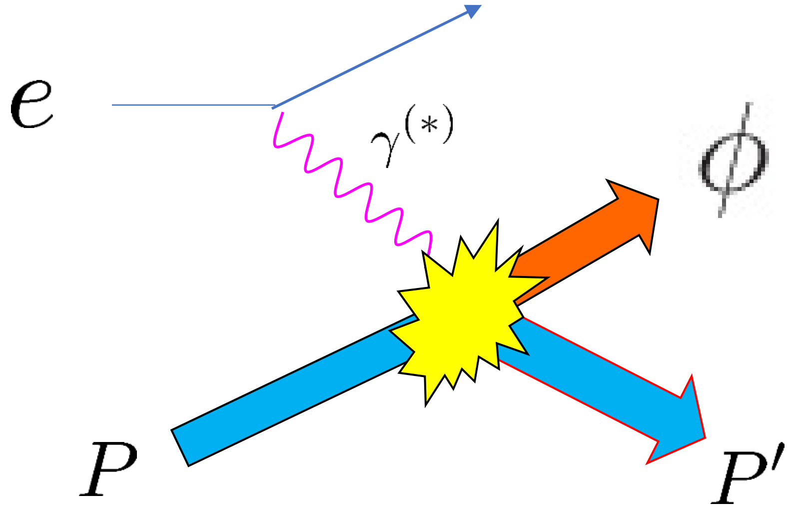
Amplitude proportional to Compton form factor

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

Skewness $\xi = \frac{P^+ - P'^+}{P + +P'^+}$

Gluon GPD

ϕ -meson electro-production near threshold



YH, Strikman (2021)
YH, Klest, Passek-K, Schoenleber (2025)

Complementary to J/ψ.
Need more than one observable for global analysis.

As sensitive to gluons as in J/ψ production (maybe even better).
Unique channel for strangeness GFFs.
Standard GPD factorization. No uncertainty from NRQCD.
Alternative scenarios for J/ψ photoproduction? Less ambiguity for ϕ electroproduction

Factorization only for the longitudinally polarized photon
L/T separation crucial → SoLID and EIC?

Again, 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

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

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

spin=2 (energy momentum tensor)

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

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 $\int_0^1 dx (1-x^2)^2 = \frac{8}{15}$ ← 80% 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

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

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
(but not for valence-quark GPDs)

Recently extended to NLO

Guo, Yuan, Zhao, 2501.10532
YH, Klest, Passek-K, Schoenleber, 2501.12343
YH, Schoenleber 2502.12061

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

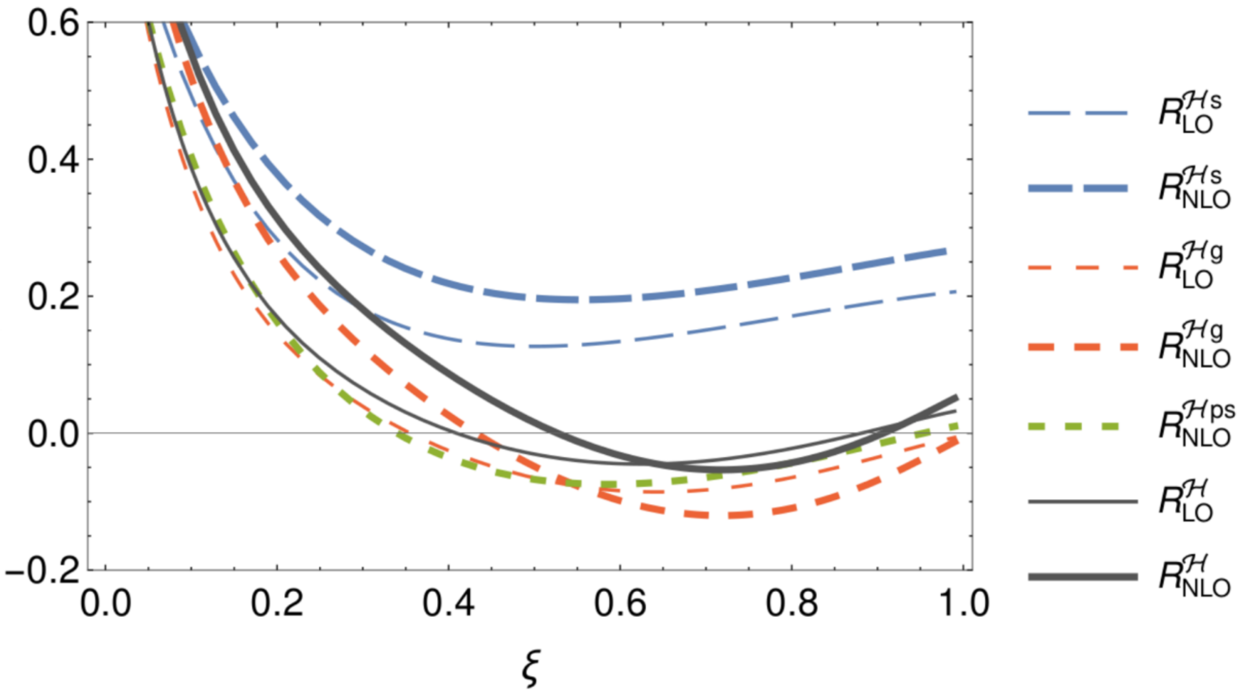
$$\mathcal{H}(\xi,t,Q^2) \approx \frac{2\kappa}{\xi^2}\frac{15}{2}\left[\left\{\alpha_s(\mu)+\frac{\alpha_s^2(\mu)}{2\pi}\left(25.7309-2n_f+\left(-\frac{131}{18}+\frac{n_f}{3}\right)\ln\frac{Q^2}{\mu^2}\right)\right\}(A_s(t,\mu)+\xi^2 D_s(t,\mu))\right.$$
$$\left.+\frac{\alpha_s^2}{2\pi}\left(-2.3889+\frac{2}{3}\ln\frac{Q^2}{\mu^2}\right)\sum_q(A_q+\xi^2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

Goloskokov-Kroll (GK) model for nucleon GPD

Truncation error

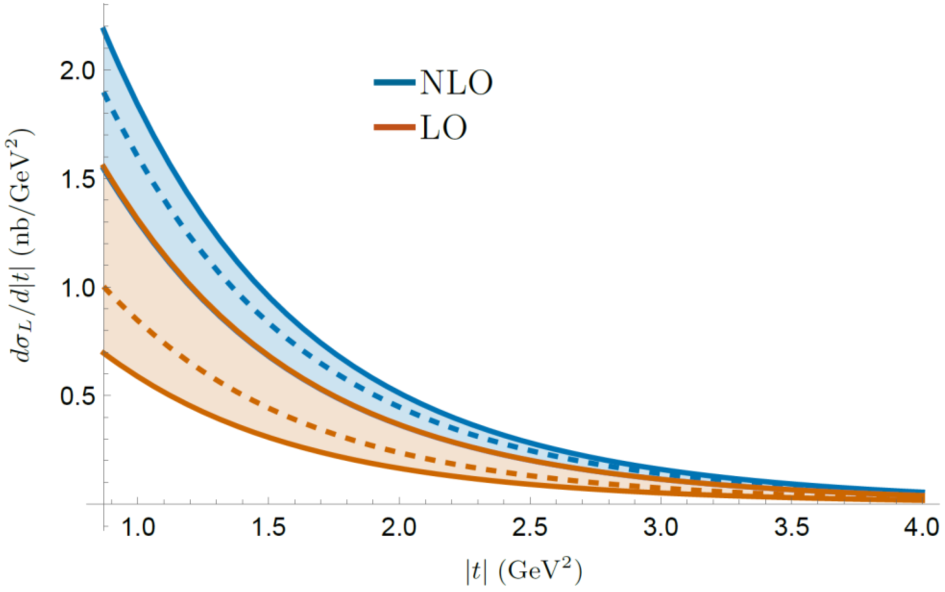
$$R = 1 - \frac{|\mathcal{H}_{\rm full}|}{\mathcal{H}_{\rm trunc}}$$

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



ϕ -electroproduction at NLO

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

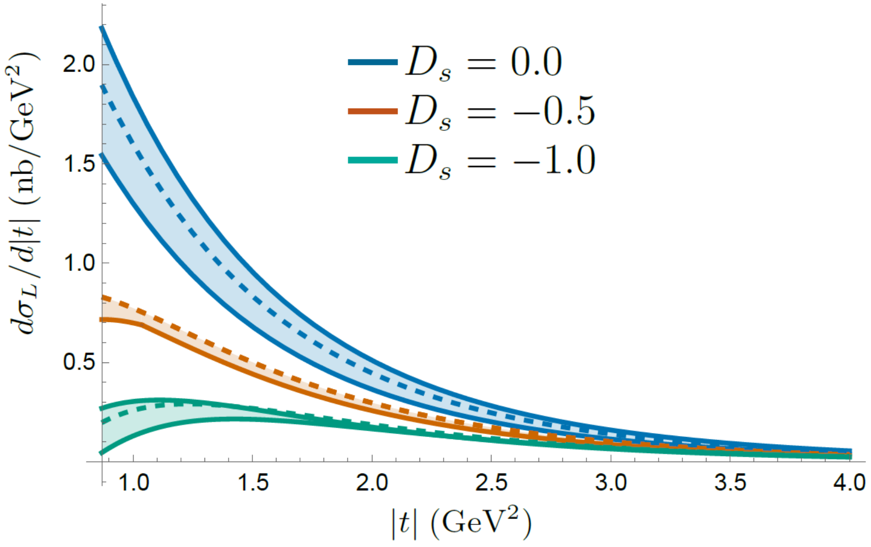


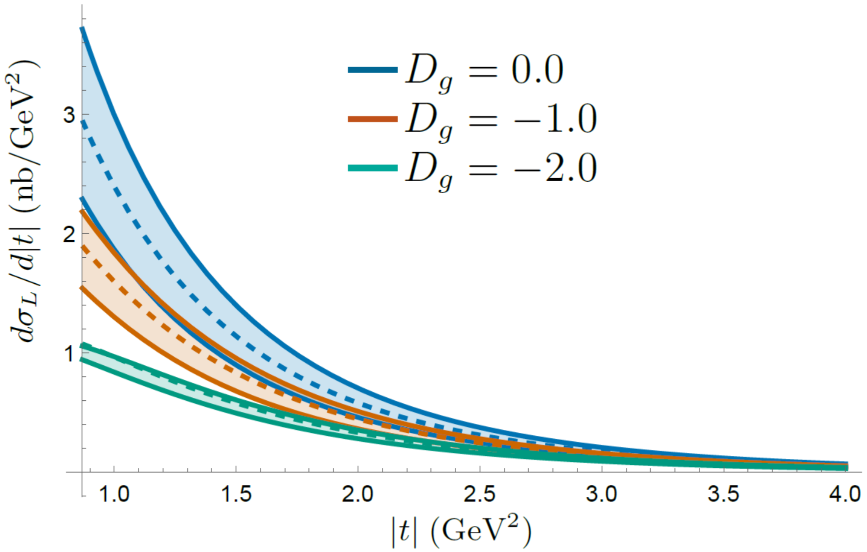
Dominated by gluons.

Cancellation between LO strangeness and NLO valence

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

Combined fit to J/psi production data desirable

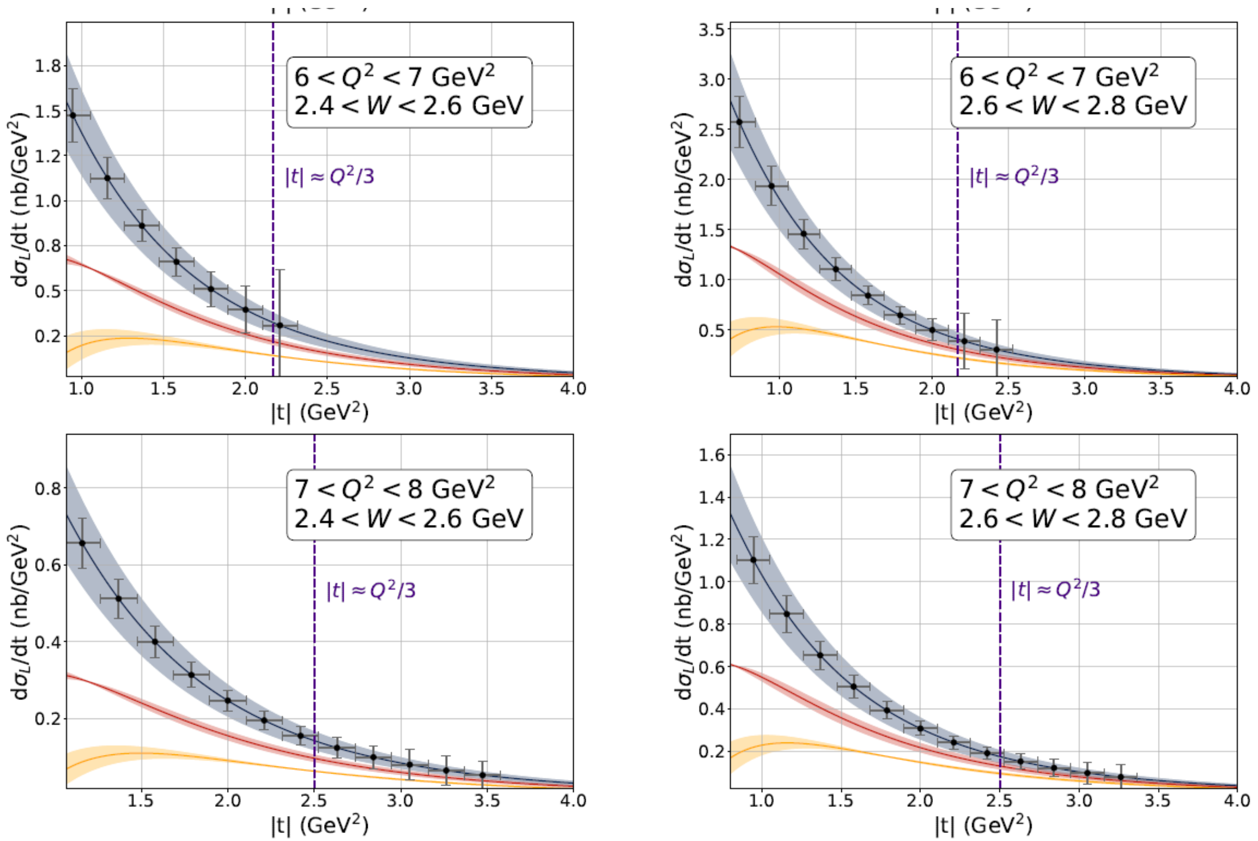


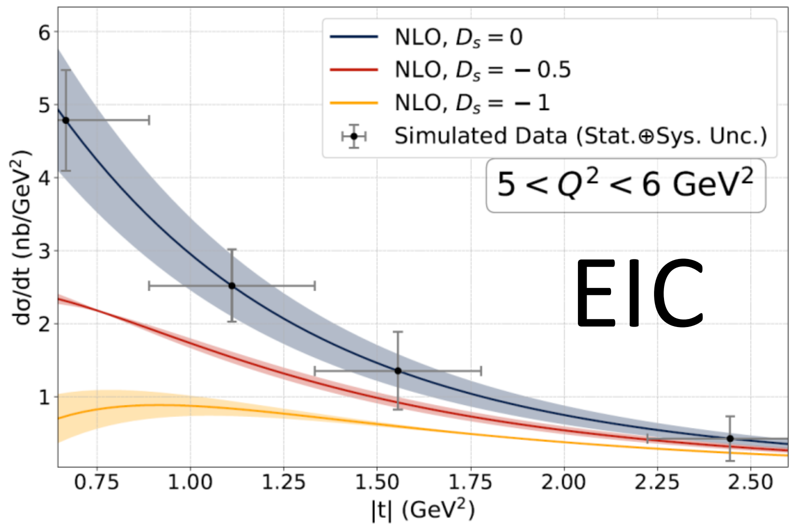


ϕ -electroproduction: Monte Carlo simulation

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

SoLID (Jlab) 43.2 ab^{-1}



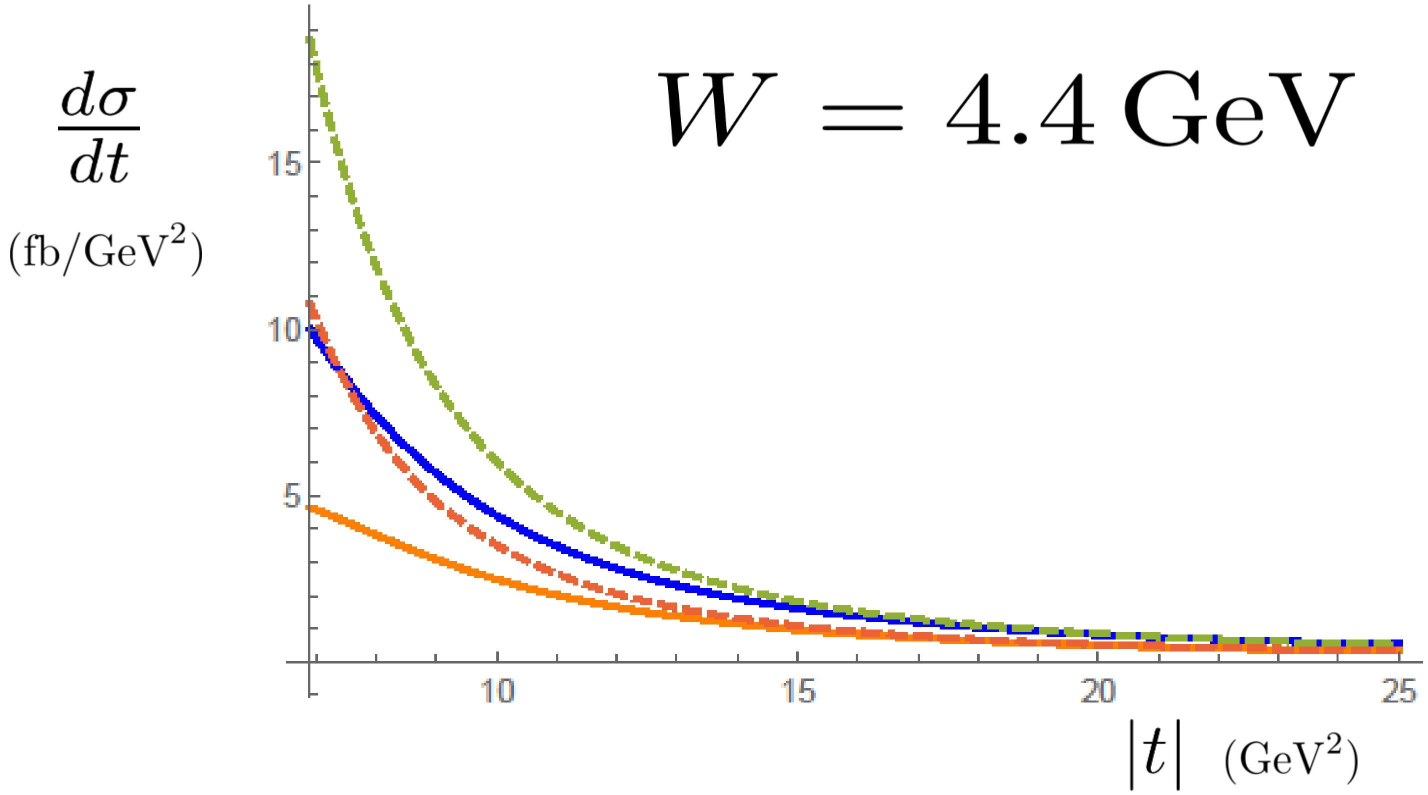


10 fb^{-1}

Looks like a feasible measurement!

J/ψ electroproduction at the EIC

Boussarie, YH (2020)



Dashed curves:
without gluon D-term

Solid curves: with gluon D-term

Upper solid $b = 1$

Lower solid $b = 0$

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

$$Q^2 = 64\,\mathrm{GeV}^2$$
$$\sqrt{S_{ep}} = 20\,\mathrm{GeV}$$

Leading order but includes the effect of the gluon condensate

Pion GFFs from Sullivan process

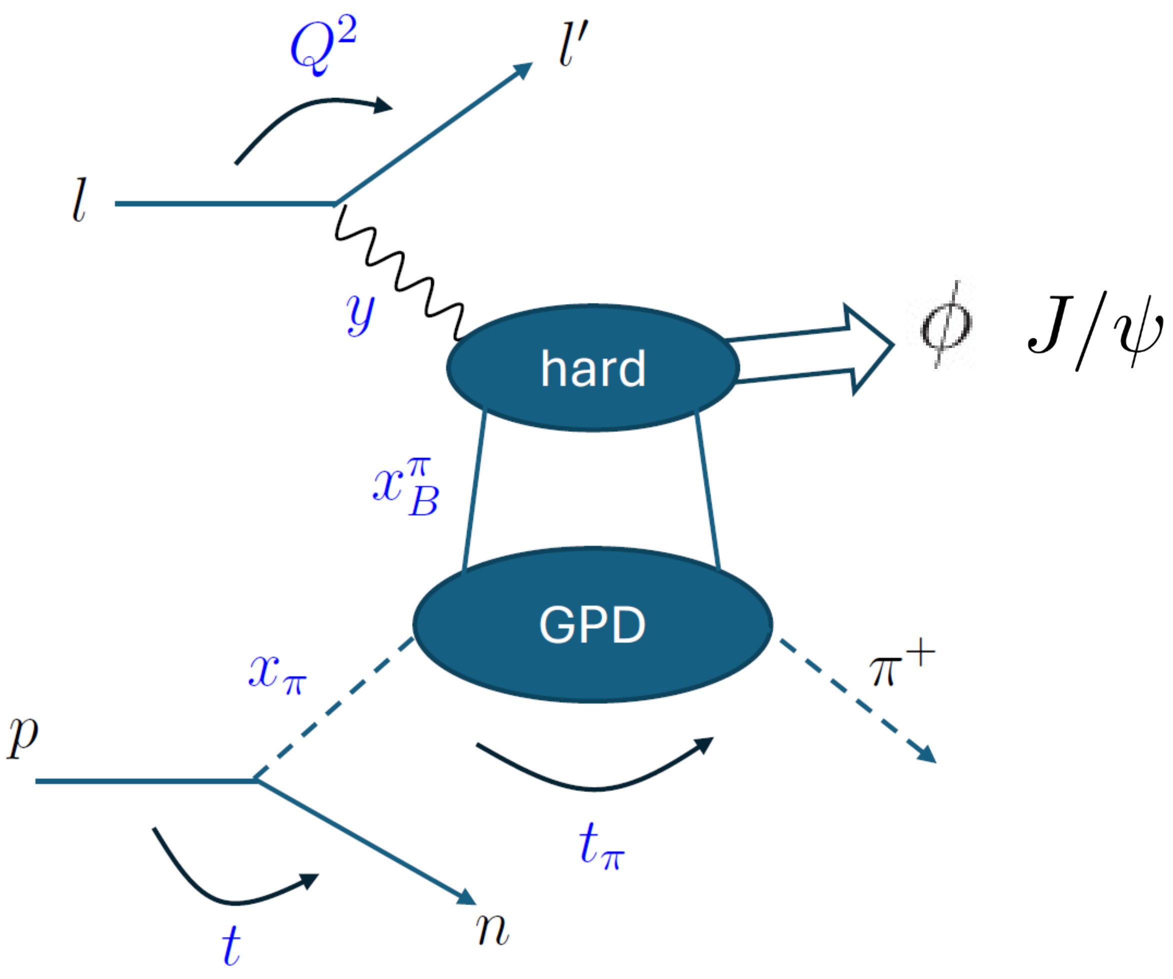
YH, Schoenleber 2502.12061

Originally proposed in 1972 to access the pion EM form factors

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 → 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:

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

$$D_i(0) = -A_i(0) \qquad i = u, d, s, g, \cdots$$

Sullivan process near threshold

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

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

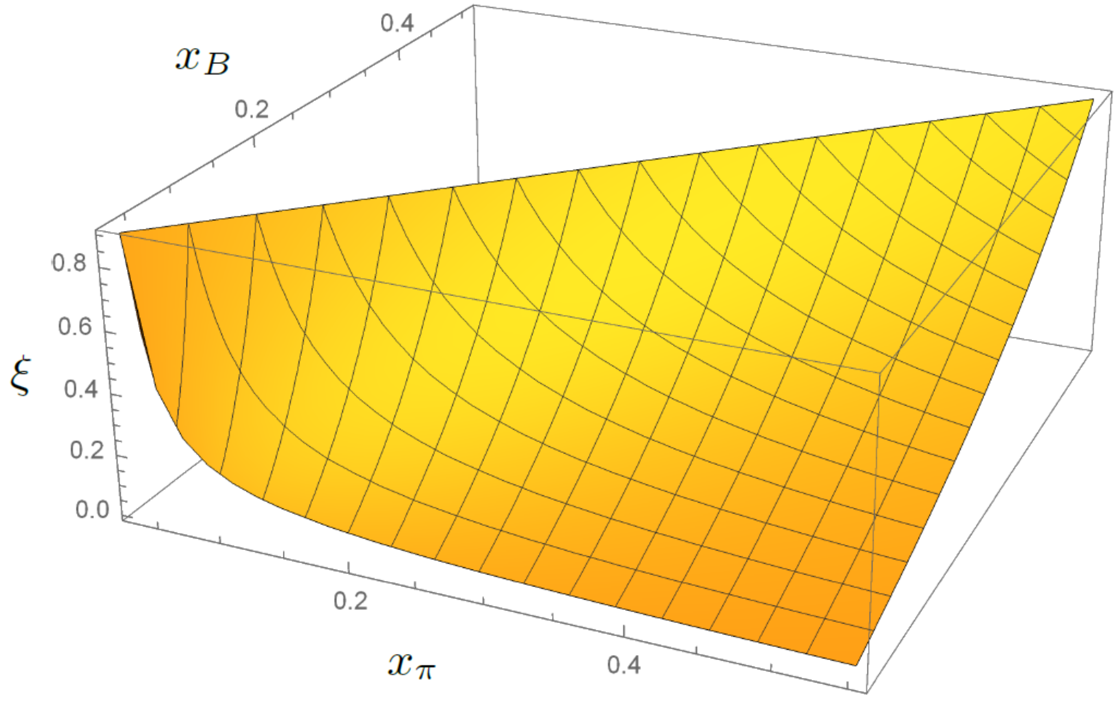
Threshold region along the diagonal line

$$x_B \approx x_\pi$$

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

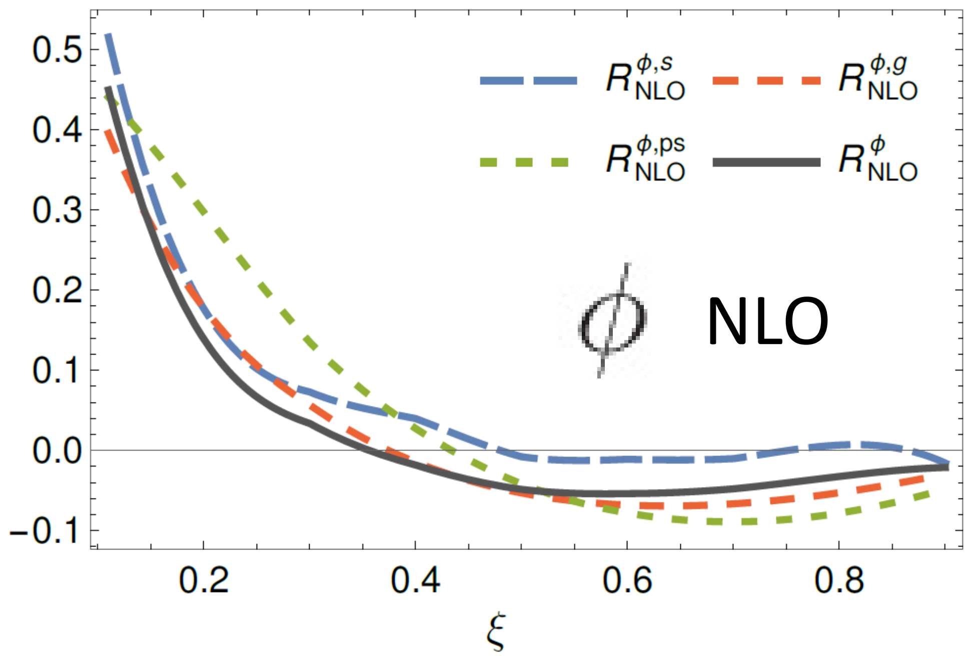
Input: Pion GPD at $\mu^2 = 10\,\mathrm{GeV}^2$

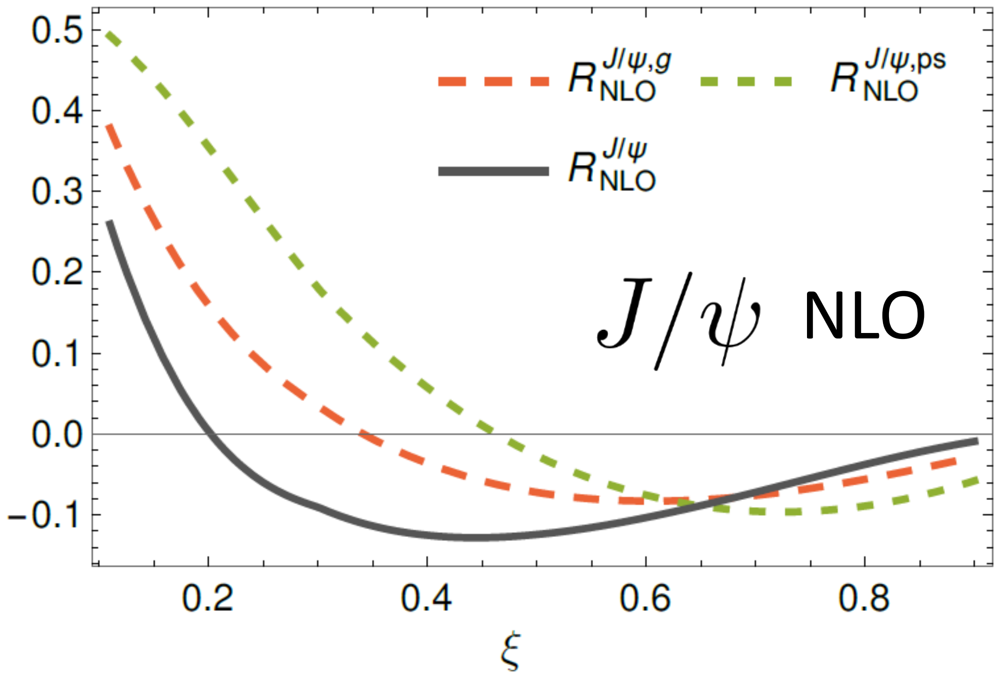
Chavez et al. 2110.06052

Truncation error

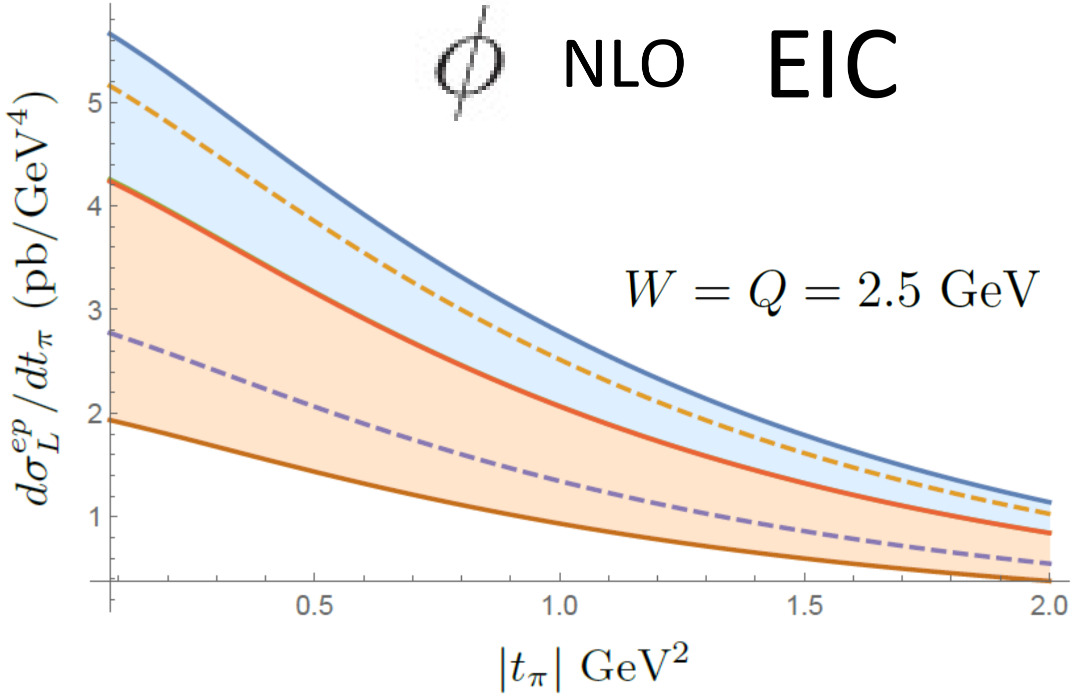
$$R = 1 - \frac{|\mathcal{H}_{\mathrm{full}}|}{\mathcal{H}_{\mathrm{trunc}}} \qquad 5 \sim 10\%$$

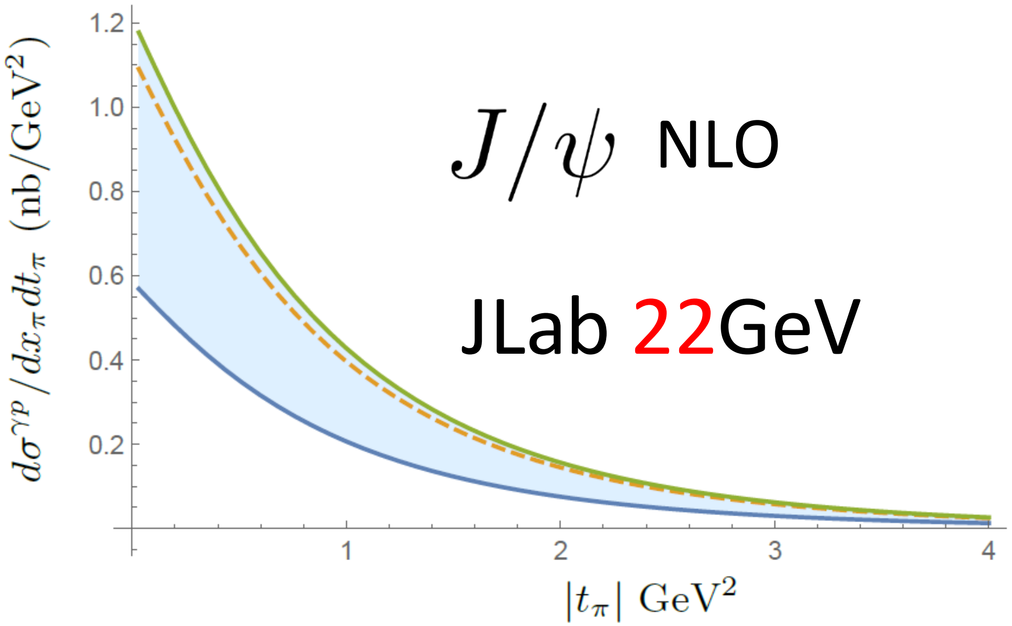
Cancellation between LO gluons and NLO valence quarks in the gluon case.
--> approximation works better for ϕ

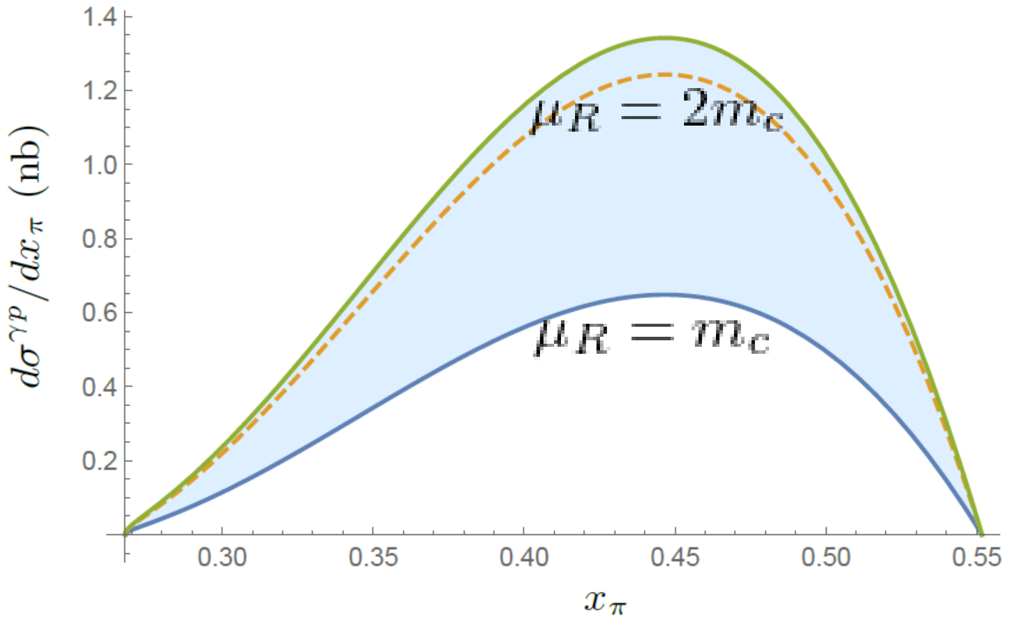




Prediction for JLab and EIC







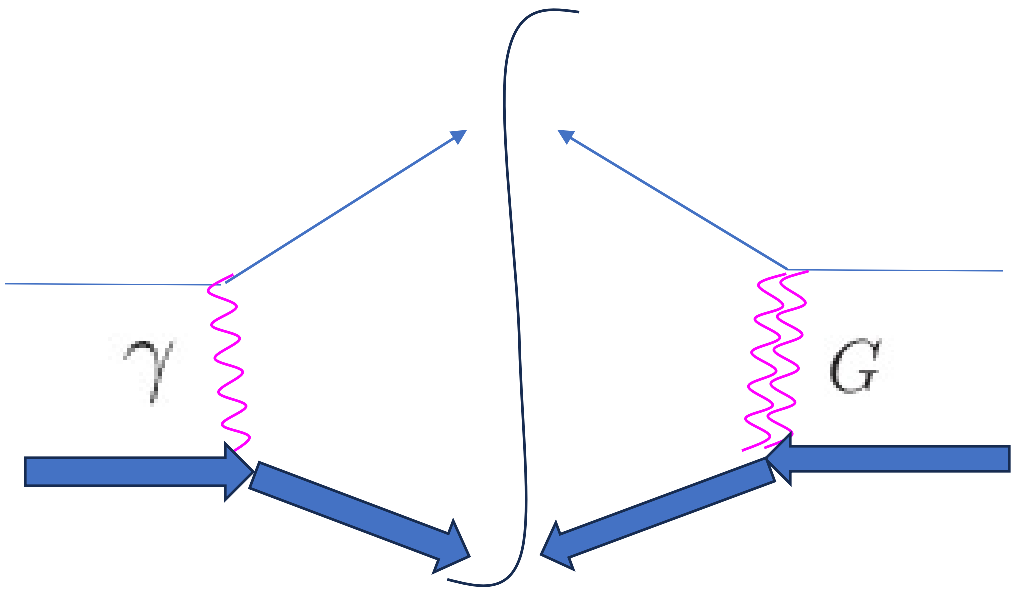
Cross section well in the measurable range

Conclusions

- EM form factors: very active field even after 70 years, aiming for 1% precision
- GFFs: Still in the beginning phase. Initial excitement, growing pains, toward a sustainable field.

TeV-scale elastic ep, eA scattering

YH, 2311.14470

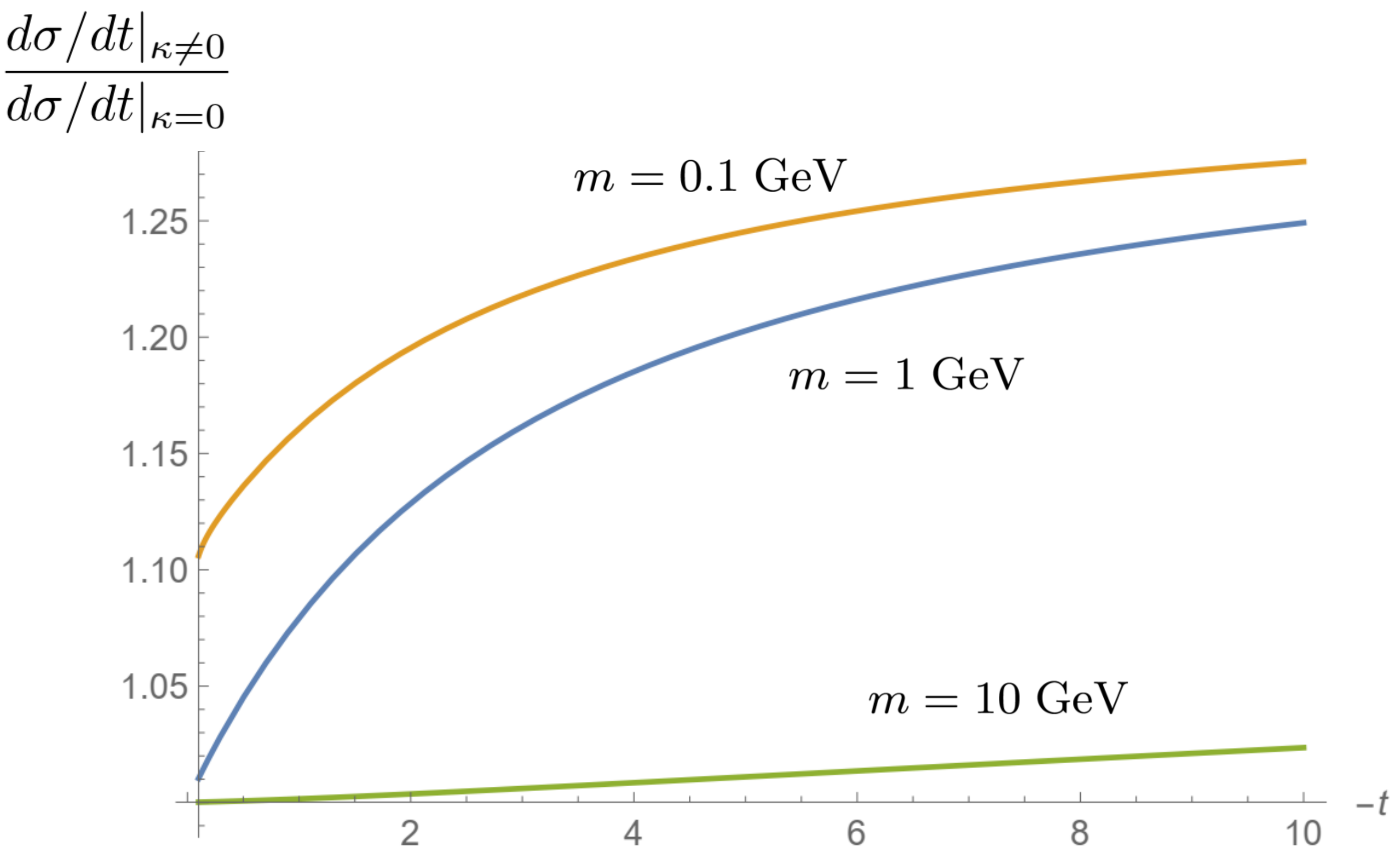


Look for the graviton-photon interference in elastic scattering

Rosenbluth

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha_{em}^2}{t^2}\left\{\left(1+\frac{t-2M^2}{s}+\frac{M^4}{s^2}\right)\left(F_1^2(t)-\frac{tF_2^2(t)}{4M^2}\right)+\frac{t^2}{2s^2}(F_1(t)+F_2(t))^2\right\}$$
$$+\frac{\alpha_{em}\kappa^2 s}{t(t-m^2)}\left\{\left(1+\frac{3(t-2M^2)}{2s}\right)\left(A(t)F_1(t)-\frac{tB(t)F_2(t)}{4M^2}\right)+\mathcal{O}(s^{-2})\right\}+\mathcal{O}(\kappa^4)$$

Notice that the D-form factor drops out.



Input:

$$\kappa = 10^{-4}\ \mathrm{GeV}^{-1}$$

$$\sqrt{s} = 1\ \mathrm{TeV}$$

$$G_E(t) = \frac{G_M(t)}{\mu_p} = \frac{1}{\left(1 - \frac{t}{0.71\mathrm{GeV}^2}\right)^2}$$

$$A(t) = \frac{1}{\left(1 - \frac{t}{M_A^2}\right)^2}$$

Upward deviation from the QED prediction (EM and gravitational forces are both attractive)
Easily extended to atomic nuclei

Where to look for?

MuIC : a future TeV-scale Muon-ion collider at BNL   Acosta, Li 2107.02073