THE STRANGE MECHANICAL STRUCTURE OF THE PROTON IN HALL C

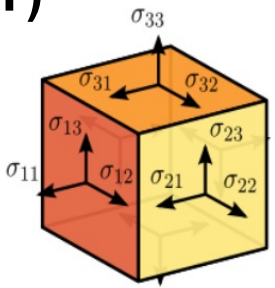
HENRY KLEST
Argonne National Laboratory

On behalf of the ϕ-007 Collaboration

Spokespersons: S. Joosten, H. Klest, H. Szumila-Vance

PROTON MECHANICAL STRUCTURE

Proton ***mechanical*** structure is defined by analogy to continuum mechanics via the **QCD energy-momentum tensor (EMT)**



$$T^{\mu\nu} = \begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$

Energy density

Momentum density

Shear stress

Normal stress (pressure)

Energy flux

Momentum flux

GRAVITATIONAL FORM FACTORS

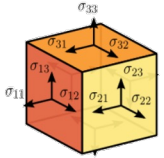
- Proton **gravitational form factors** (GFFs) encode information about the matrix elements of the **QCD energy-momentum tensor**

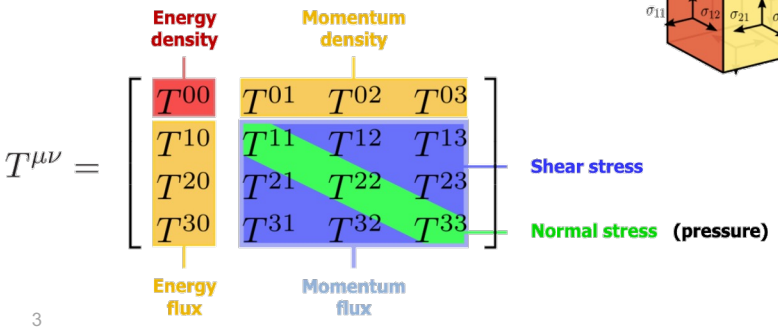
$$\langle p', s' | \hat{T}^a_{\mu\nu}(x) | p, s \rangle = \bar{u}' \left[A^a(t) \boxed{\frac{\gamma_{\{\mu} P_{\nu\}}}{2}} + B^a(t) \boxed{\frac{i\, P_{\{\mu} \sigma_{\nu\}\rho} \Delta^\rho}{4m}} + D^a(t) \boxed{\frac{\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2}{4m}} + m\, \bar{c}^a(t) \boxed{g_{\mu\nu}} \right] u\, e^{i(p'-p)x}$$

$$P = \frac{p + p'}{2} \qquad \Delta = p' - p = q - q'$$

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

EMT Matrix Elements





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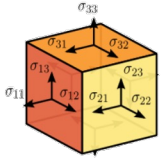
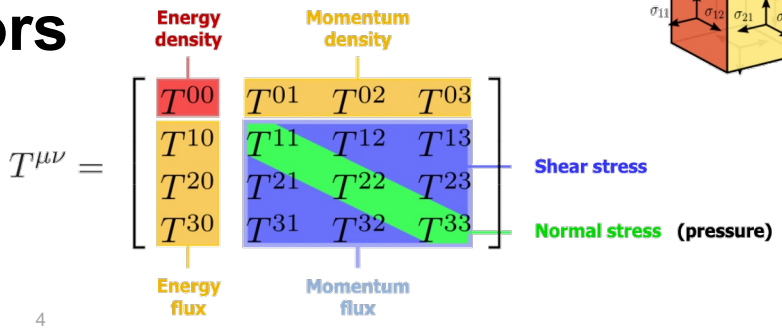


"Gravitational" Form factors

Fourier transforms of spatial distributions



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D-term

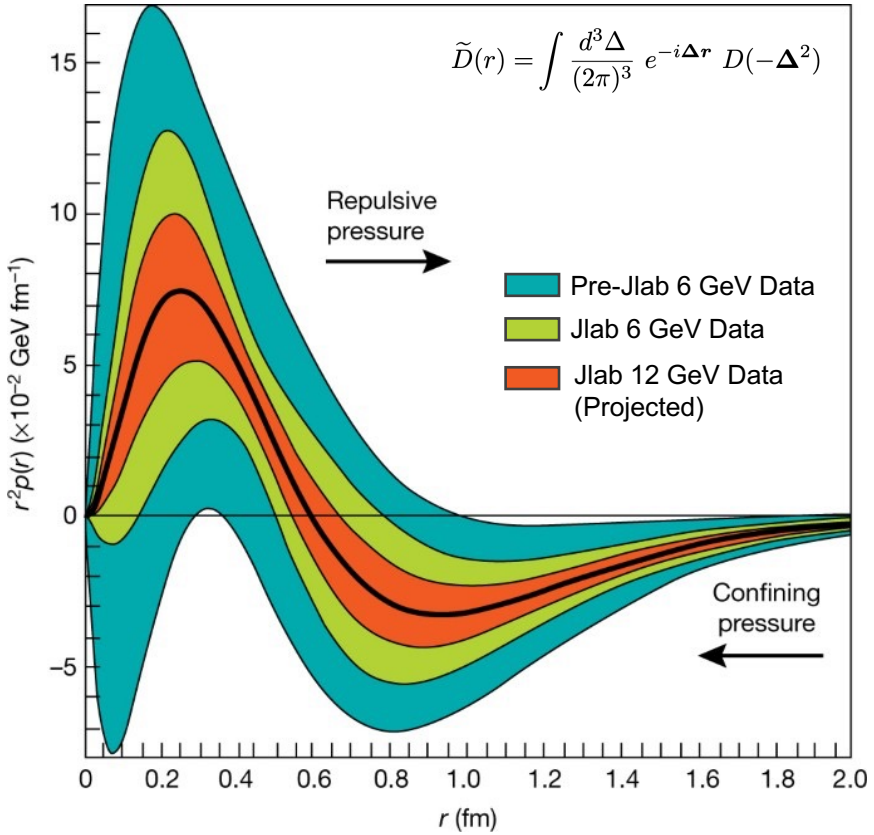
$D(0)$ represents a **fundamental property of the proton**

On par with spin, charge, mass!

MECHANICAL PROPERTIES

$$p^a(r) = \frac{1}{6m}\frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr}\widetilde{D}^a(r) - m\int\frac{d^3\Delta}{(2\pi)^3}\,e^{-i\Delta r}\,\bar{c}^a(-\Delta^2)$$

- The total D-term provides a gateway for extraction of various **mechanical** properties of the proton, including:
  - **Pressure distribution**
  - Shear force distribution
  - Mechanical radius
  - Tangential & normal force distributions



[1] - Burkert et al.: **The pressure distribution inside the proton,** *Nature, 2018*

MECHANICAL PROPERTIES

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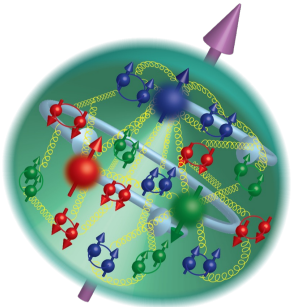
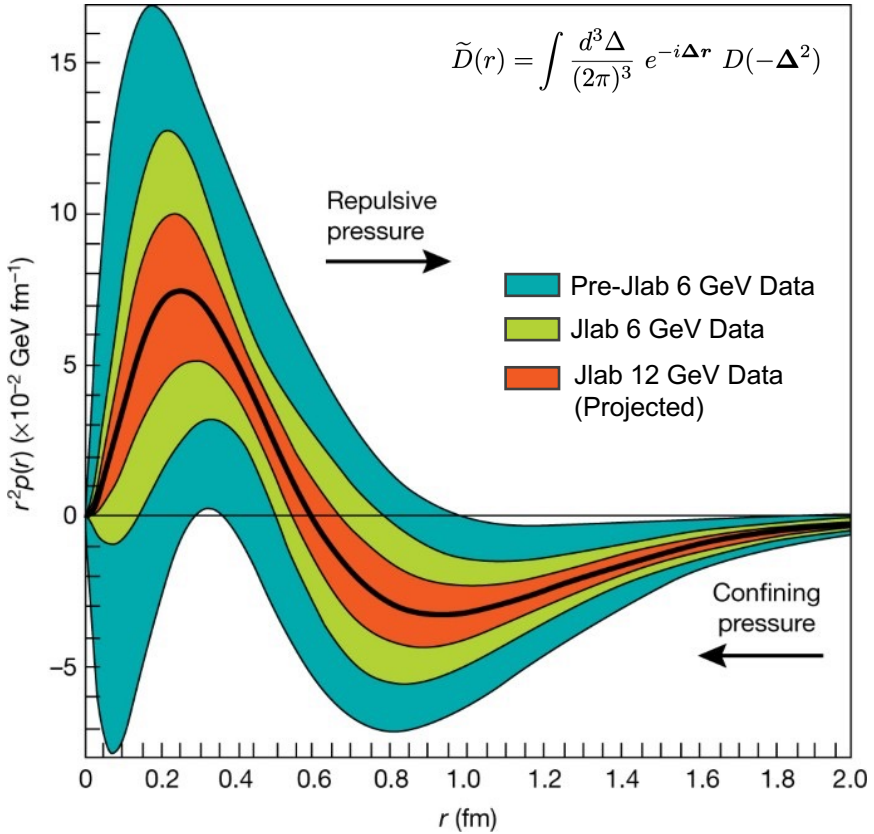
  - **Pressure distribution**

10^{29} atmospheres!?

At r = 0.3 fm





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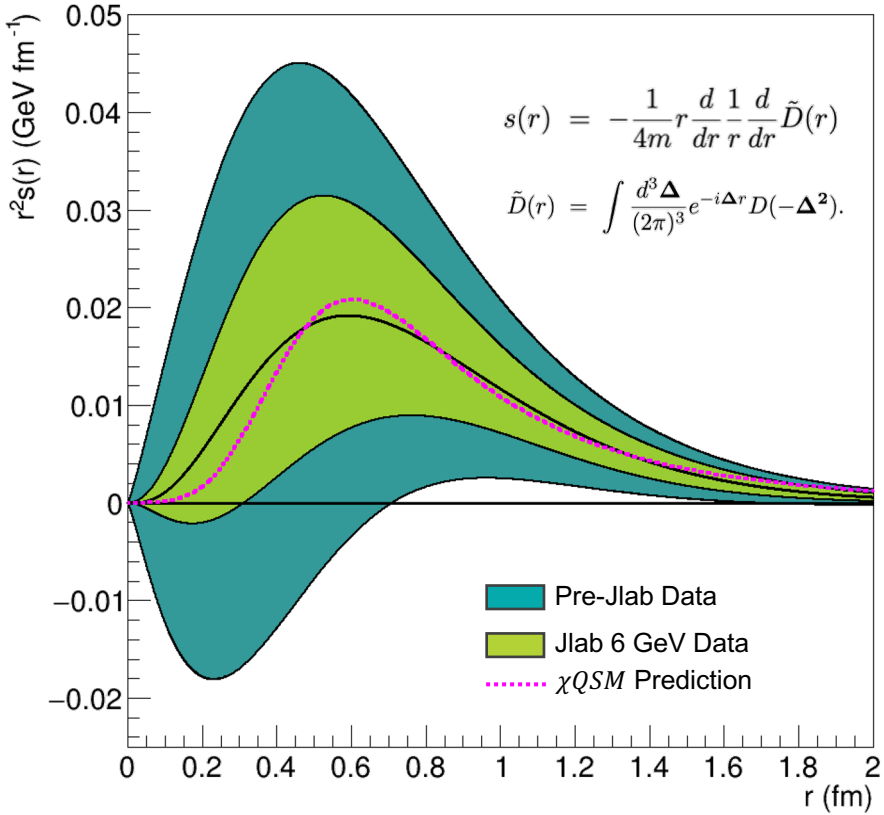

[1] - Burkert et al.: **Determination of shear forces inside the proton,** *2021*

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MECHANICAL PROPERTIES

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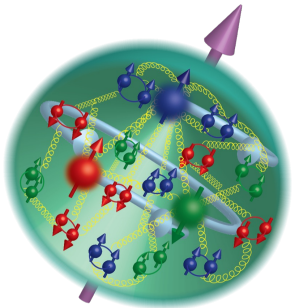
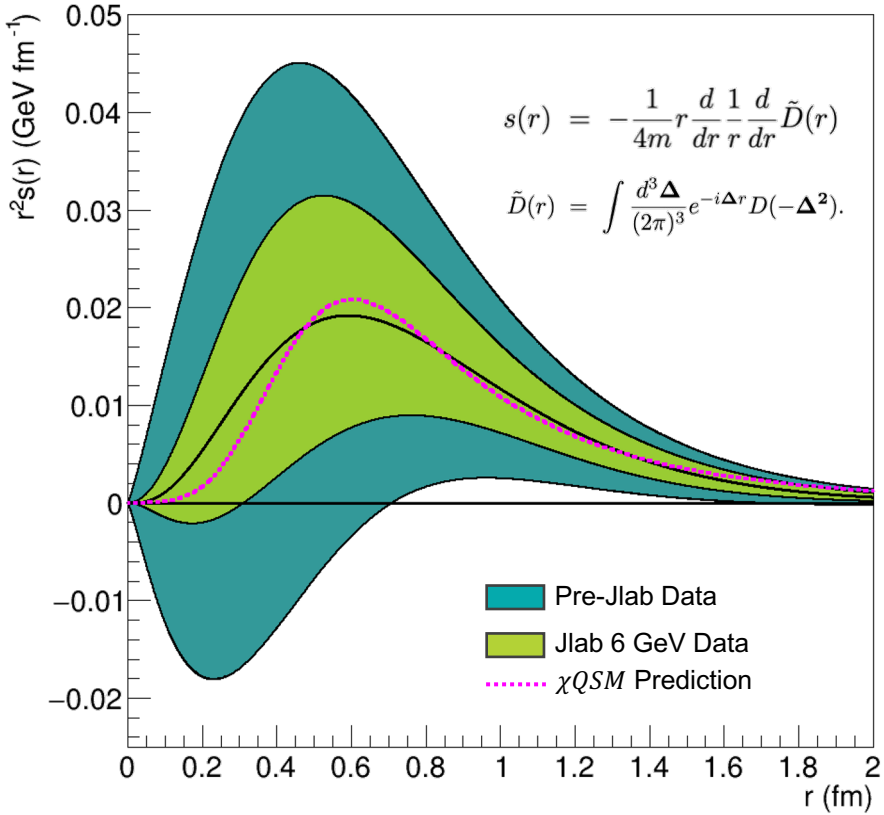
  — **Shear force distribution**

40000 Newtons!?

At r = 0.6 fm





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  - **Mechanical radius**
  - Tangential & normal force distributions

$$\langle r^2 \rangle_{\text{mech}} = \frac{\int d^3r \; r^2 \; \left[\frac{2}{3}s(r) + p(r)\right]}{\int d^3r \; \left[\frac{2}{3}s(r) + p(r)\right]} = \frac{6D}{\int_{-\infty}^{0} dt \; D(t)}$$

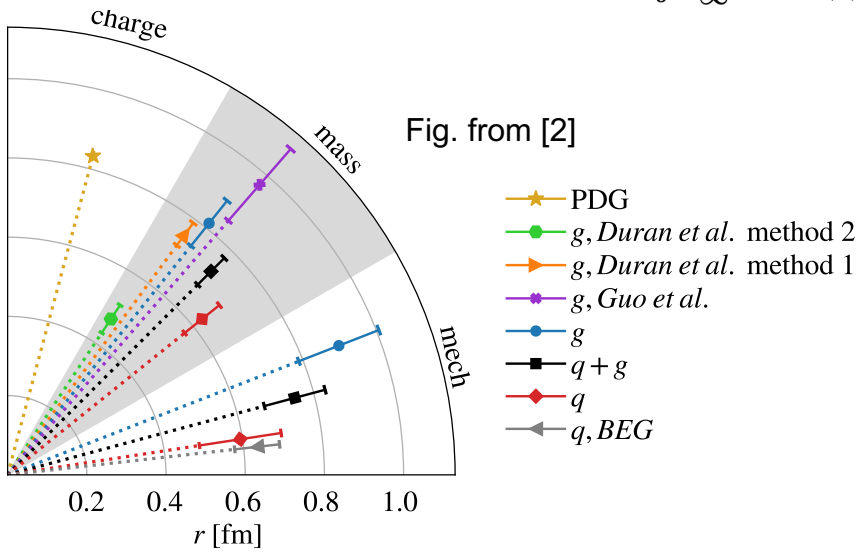

Fig. from [2]

[1] – Polyakov, Schweitzer: **Forces inside hadrons: pressure, surface tension, mechanical radius, and all that,** *Int.J.Mod.Phys.A, 2018*

[2] - Hackett et al.: **Gravitational form factors of the proton from lattice QCD,** *PRL, 2024*

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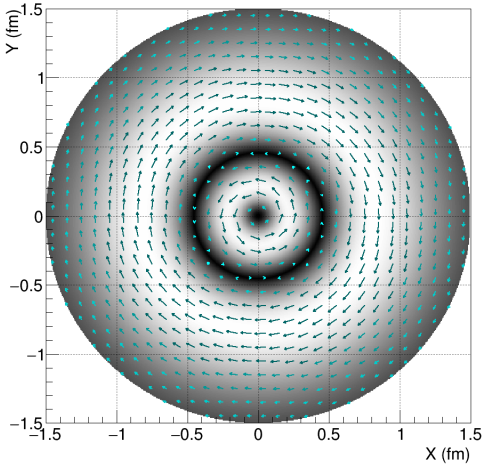
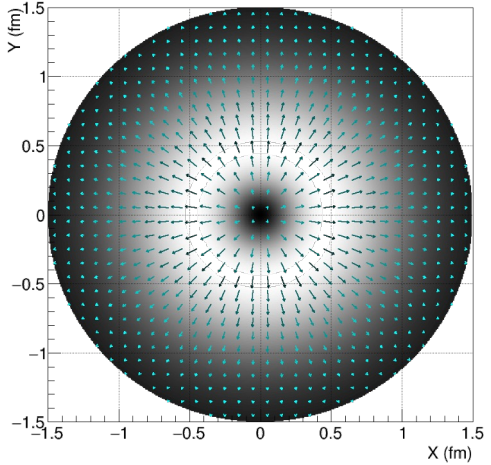


Tangential force[1]



Normal force [1]

$$\frac{dF_\phi}{dS_\phi} = -\frac{1}{3}s(r) + p(r).$$

$$\frac{dF_r}{dS_r} = \frac{2}{3}s(r) + p(r)$$

[1] – Burkert et al.: **Colloquium: Gravitational Form Factors of the Proton**

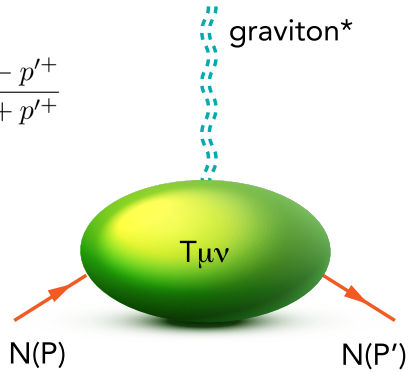
HOW DO WE ACCESS THE D-TERM?

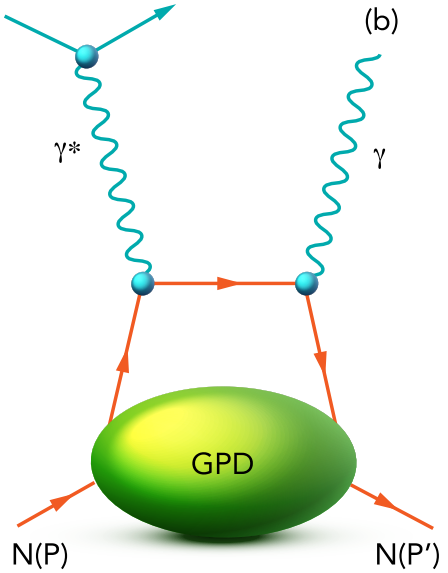
- Graviton scattering would measure directly $T^{\mu\nu}$
- Can access GFFs via the second Mellin moments of the generalized parton distributions (GPDs)

$$\int_{-1}^{1} \mathrm{d}x\, x\, H^a(x,\xi,t) = A^a(t) + \xi^2 D^a(t)$$

$$\int_{-1}^{1} \mathrm{d}x\, x\, E^a(x,\xi,t) = B^a(t) - \xi^2 D^a(t)$$

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





In certain regions, hard exclusive reaction cross sections reduce to **simple functions of the GFFs!**

Graviton exchange ≈ Deeply Virtual Compton Scattering

[1] - Polyakov: **Generalized parton distributions and strong forces inside nucleons and nuclei,** *PLB, 2003*
[2] - Polyakov, Schweitzer: **Forces inside hadrons: pressure, surface tension, mechanical radius, and all that,** *Int.J.Mod.Phys.A, 2018*

HOW DO WE ACCESS THE D-TERM?

The total D-term arises from its partonic contributions via a sum rule:

Total *D*-term

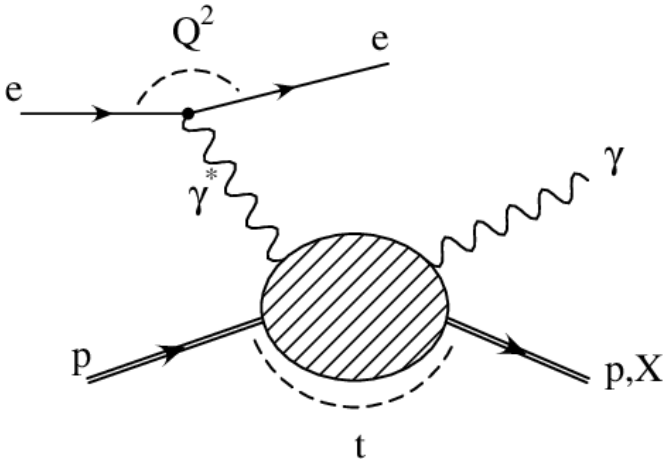
Partonic *D*-term contributions

$$D(0) = D_g(0) + D_u(0) + D_d(0) + D_s(0) + \dots .$$

Different exclusive processes access the **contributions of different parton species** to the total proton D-term!

Up & Down quarks:
Accessible via DVCS cross section &
beam-spin asymmetries

$$D(0) = D_g(0) + D_u(0) + D_d(0) + D_s(0) + \ldots.$$



The pressure distribution inside the proton

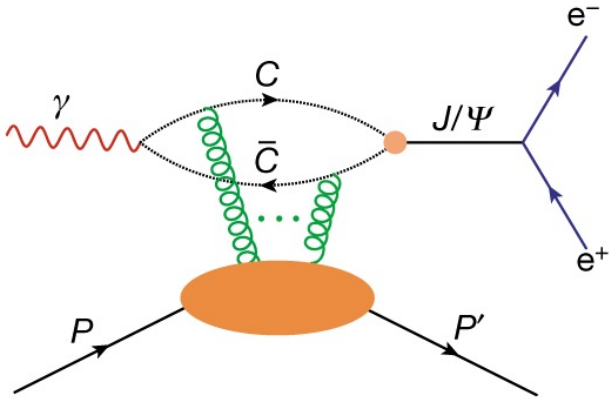
V. D. Burkert ✉, L. Elouadrhiri & F. X. Girod

Gluons:
Accessible via near-threshold production of J/ψ and Υ

$$D(0) = D_g(0) + D_u(0) + D_d(0) + D_s(0) + \ldots.$$

Determining the Proton's Gluonic Gravitational Form Factors

B. Duran[3,1], Z.-E. Meziani[1,3**], S. Joosten[1], M. K. Jones[2], S. Prasad[1], C. Peng[1], W. Armstrong[1], H. Atac[3], E. Chudakov[2], H. Bhatt[5], D. Bhetuwal[5], M. Boer[11], A. Camsonne[2], J.-P. Chen[2], M. M. Dalton[2], N. Deokar[3], M. Diefenthaler[2], J. Dunne[5], L. El Fassi[5], E. Fuchey[9], H. Gao[4], D. Gaskell[2], O. Hansen[2], F. Hauenstein[6], D. Higinbotham[2], S. Jia[3], A. Karki[5], C. Keppel[2], P. King[7], H.S. Ko[10], X. Li[4], R. Li[3], D. Mack[2], S. Malace[2], M. McCaughan[2], R. E. McClellan[8], R. Michaels[2], D. Meekins[2], M. Paolone[3], L. Pentchev[2], E. Pooser[2], A. Puckett[9], R. Radloff[7], M. Rehfuss[3], P. E. Reimer[1], S. Riordan[1], B. Sawatzky[2], A. Smith[4], N. Sparveris[3], H. Szumila-Vance[2], S. Wood[2], J. Xie[1], Z. Ye[1], C. Yero[6], and Z. Zhao[4]



Only **two** existing experimental results on gravitational form factors,
both high-profile, ~ 50 citations/year!

Interest in this subject is clear!
The field is rapidly growing!

P. E. Reimer[1], S. Riordan[1], B. Sawatzky[2], A. Smith[4], N. Sparveris[3], H. Szumila-Vance[2], S. Wood[2], J. Xie[1], Z. Ye[1], C. Yero[6], and Z. Zhao[4]

$$D(0) = D_g(0) + D_u(0) + D_d(0) + D_s(0) + \ldots.$$

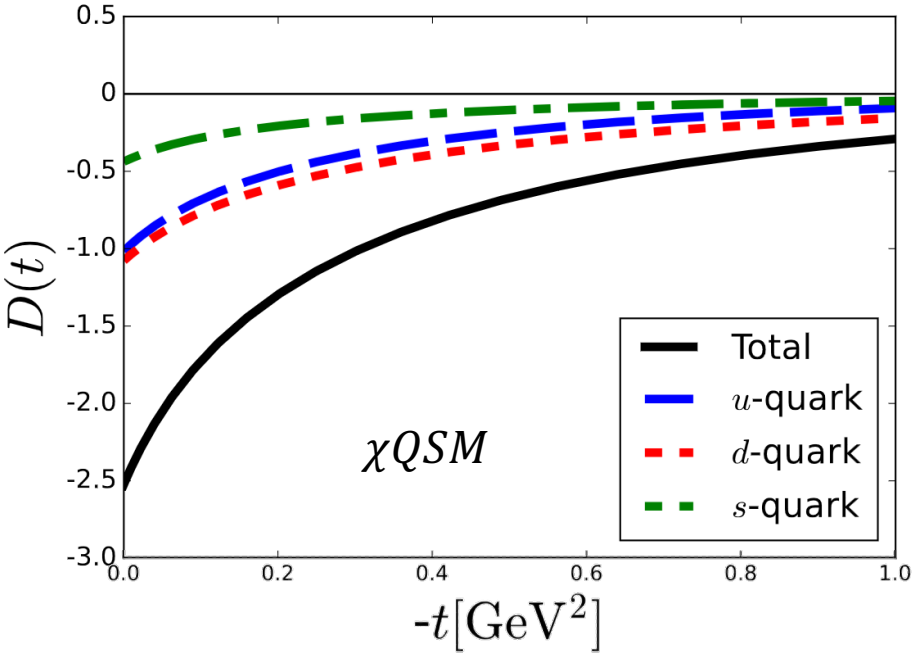
Strange quarks:
Can we just neglect them…?

THEORY PREDICTIONS

- Large-N_c theory predicts that the D-term is "**flavor-blind**"[1]
  - i.e. $D_u \sim D_d$ despite their different number densities, this is supported by lattice results[2]

- Extending this argument, **could $D_u \sim D_d \sim D_s$?**

- Chiral quark soliton model[3] prediction: $D_u \sim D_d \sim 2D_s$



[1] - Goeke et al.: **Hard exclusive reactions and the structure of hadrons**, *Prog.Part.Nucl.Phys, 2001*
[2] - Hackett et al.: **Gravitational form factors of the proton from lattice QCD,** *PRL, 2024*
[3] - Won et al.: **Role of strange quarks in the D-term and cosmological constant term of the proton,** *PRD, 2023*

THEORY PREDICTIONS

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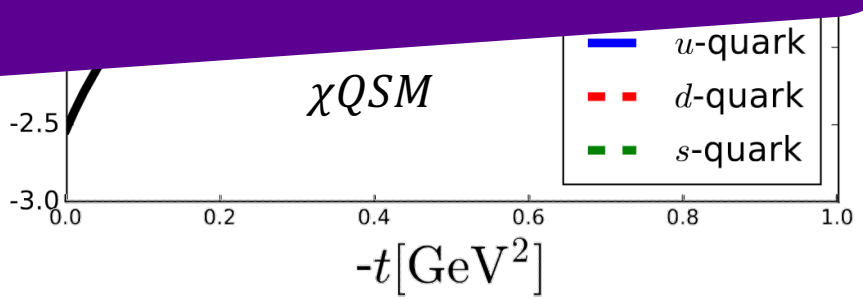
  - i.e. $D_u \approx D_d$ d[illegible]

"The contributions of strange quarks play a particularly significant role in the D-term. Therefore, when extracting these contributions from experimental data, **it is essential to take into account the influence of strange quarks.**"[3]



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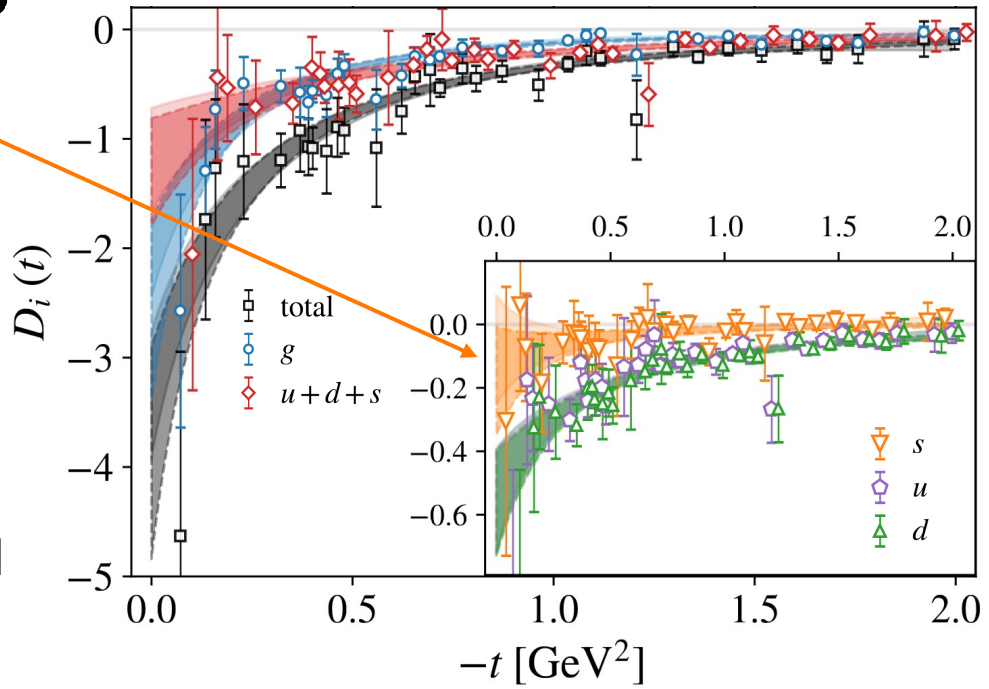
THEORY PREDICTIONS

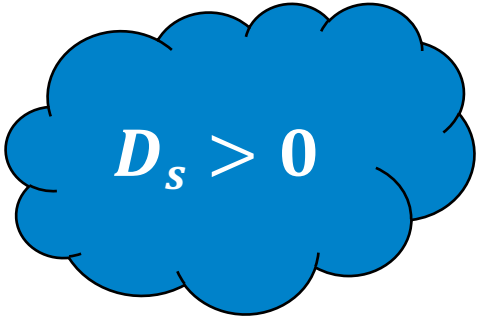
- D_s calculated on the lattice[1]
  - — **Uncertainties are large!**
  - — Lattice does not exclude $D_u \sim D_d \sim 2D_s$ or $D_s > 0$

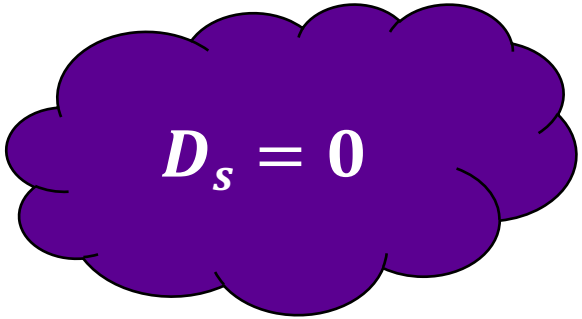
- **Opposite signs of sea & valence** quarks is a distinct possibility, predicted by χQSM[1]

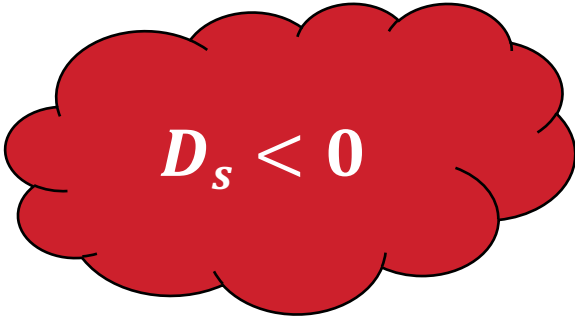


$D_s > 0$ would mean that strange quarks feel forces of opposite direction to up & down quarks!

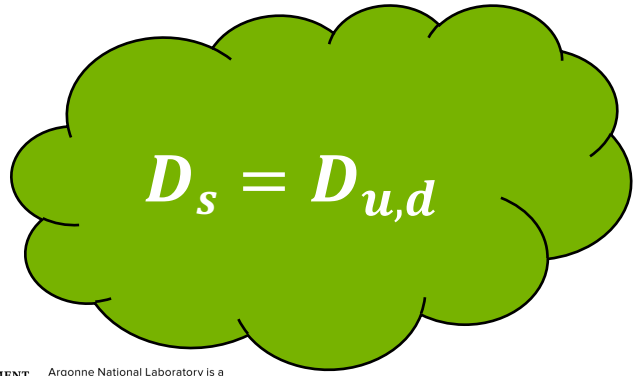
[1] - Hackett et al.: **Gravitational form factors of the proton from lattice QCD,** *PRL, 2024*
[2] - Won et al.: **Role of strange quarks in the D-term and cosmological constant term of the proton,** *PRD, 2023*

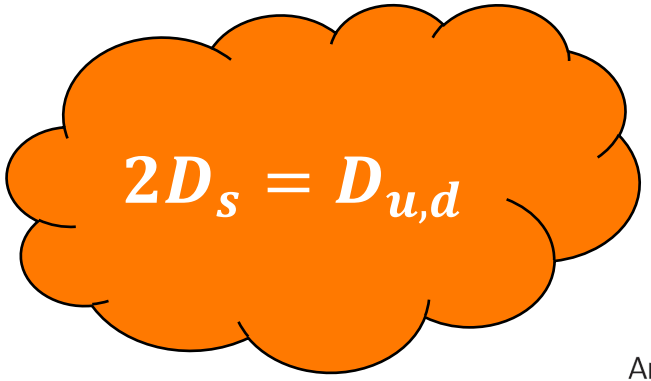






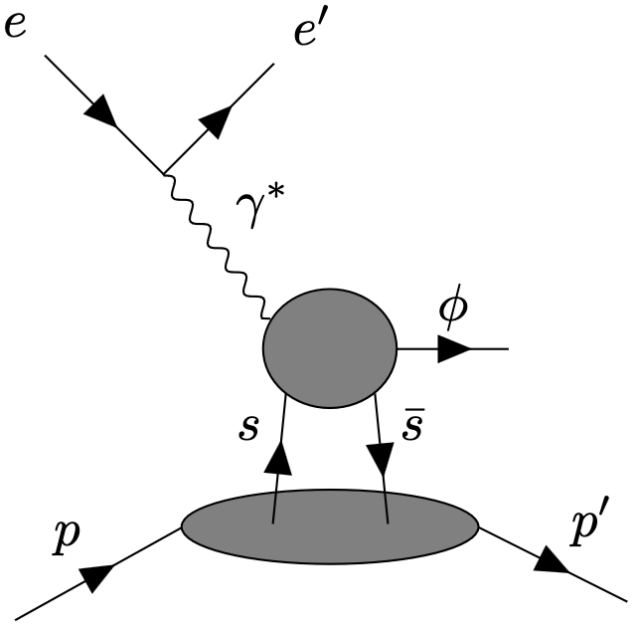
Variety of theory predictions giving very different values for D_s, can we extract it experimentally?





ACCESSING THE STRANGE QUARK CONTRIBUTION TO THE PROTON D-TERM

- ***Electroproduction of ϕ mesons at large ξ*** provides sensitivity to the strangeness D-term[1,2]
  - ϕ meson is very nearly a pure $s\bar{s}$ state
    - Couples strongly to strangeness in the proton
  - **Only known process** to access D_s



But never measured in the required kinematic region!

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[1] – Hatta, Strikman: **ϕ-meson lepto-production near threshold and the strangeness D-term,** *PLB, 2021*
[2] – Hatta, HK, et al.: **Deeply virtual ϕ-meson production near threshold,** *PTEP, 2025*

THEORY PREDICTIONS

NLO GPD calculation for ϕ DVMP cross section now available[1]!

$$\frac{d\sigma_L}{dt} = \frac{2\pi^2\alpha_{em}}{(W^2-M^2)Wp_{cm}}\left((1-\xi^2)|\mathcal{H}|^2 - \left(\frac{t}{4M^2}+\xi^2\right)|\mathcal{E}|^2 - 2\xi^2\mathrm{Re}(\mathcal{H}\mathcal{E}^*)\right)$$

DVMP amplitudes $\mathcal{H}, \mathcal{E}$ have **direct dependence** on partonic *D*-term contributions for large ξ!

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

Large cancellation for D_g!

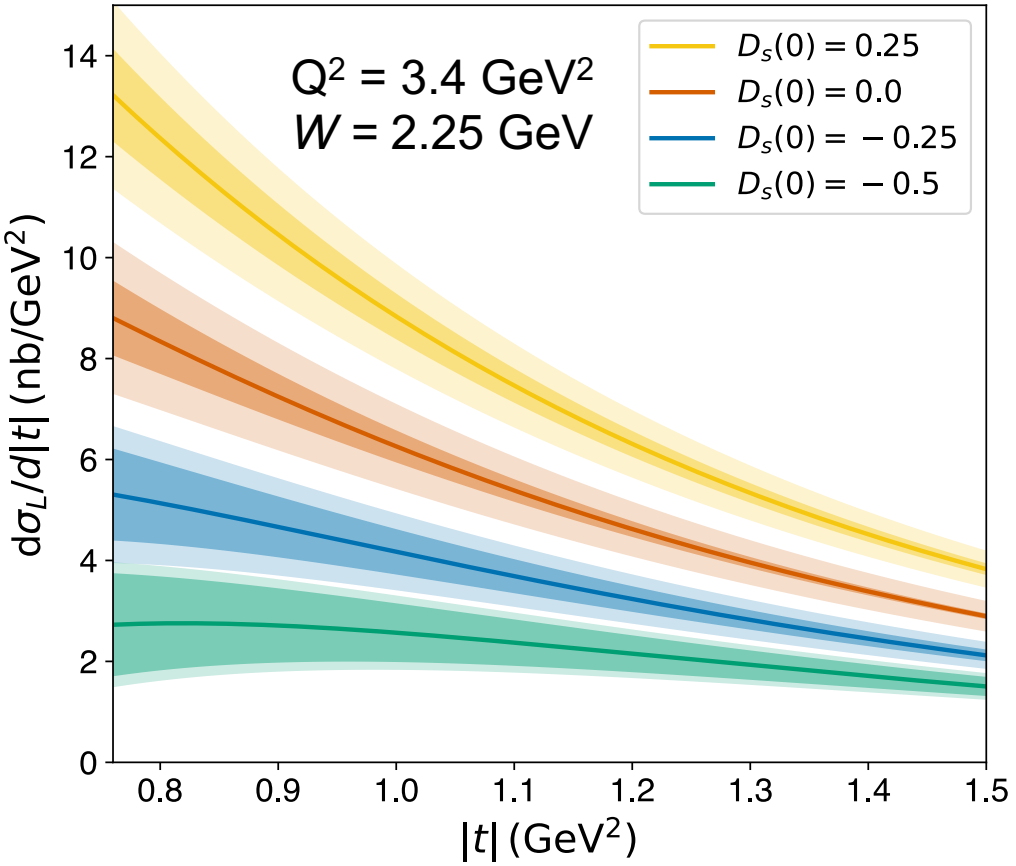
$A_g \approx 0.4, D_g \approx -2$

While D_s contributes directly!

$A_s \approx 0.03, D_s \approx ?$

[1] – Hatta, HK, et al.: **Deeply virtual ϕ-meson production near threshold,** *PTEP, 2025*

THEORY PREDICTIONS



Inner uncertainty band:
pQCD scale variation
$\mu/2 < Q < 2\mu$

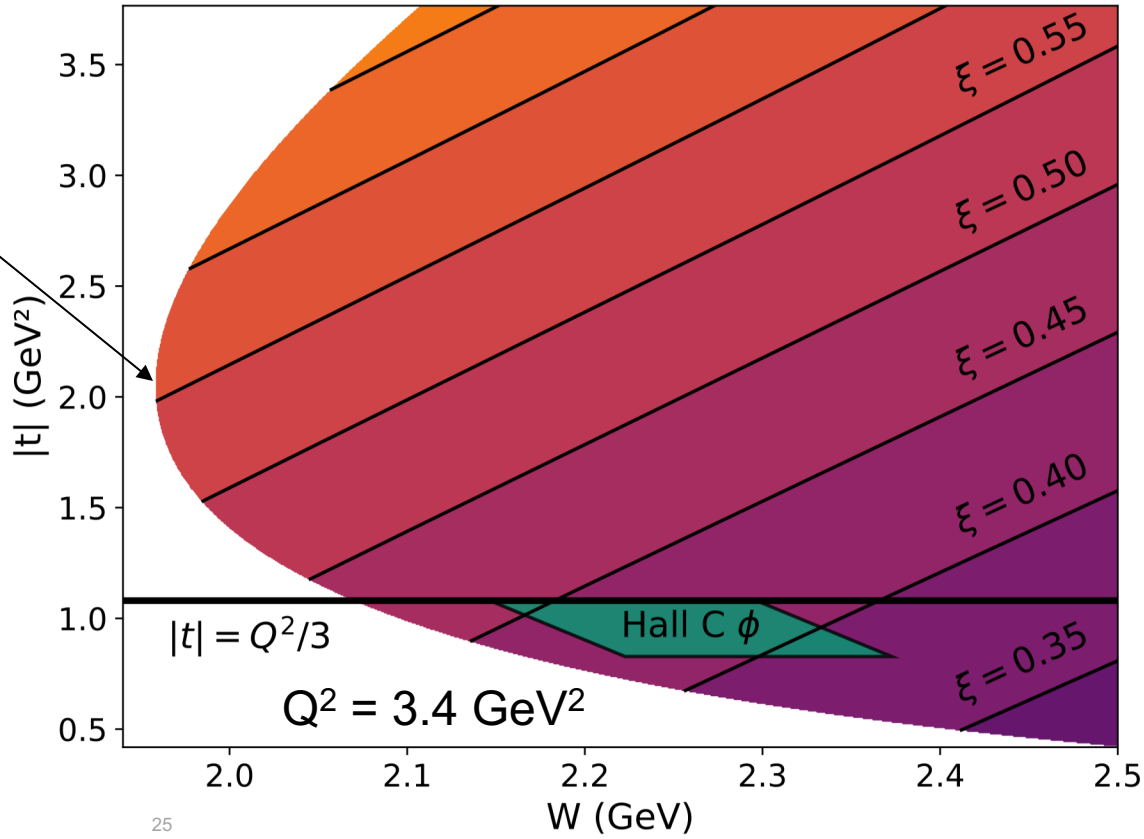
Outer uncertainty band:
Uncertainty on $D_g \oplus$ pQCD
Total prediction uncertainty

[1] – Hatta, HK, et al.: **Deeply virtual ϕ-meson production near threshold,** *PTEP, 2025*

KINEMATICS

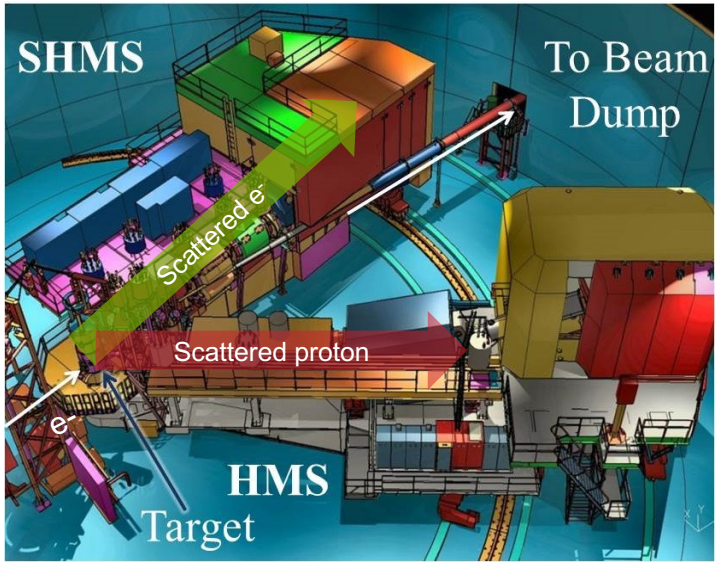
- Challenging kinematic constraints to access D_s experimentally
  - $\xi \geq 0.4$
  - $|t| \ll Q^2$
  - **Not too close** to the threshold $W = 1.96$ **GeV**
- Cross section $\propto Q^{-9}$!
- Requires **high luminosity** and precise kinematic reconstruction

Use the Hall C spectrometers!

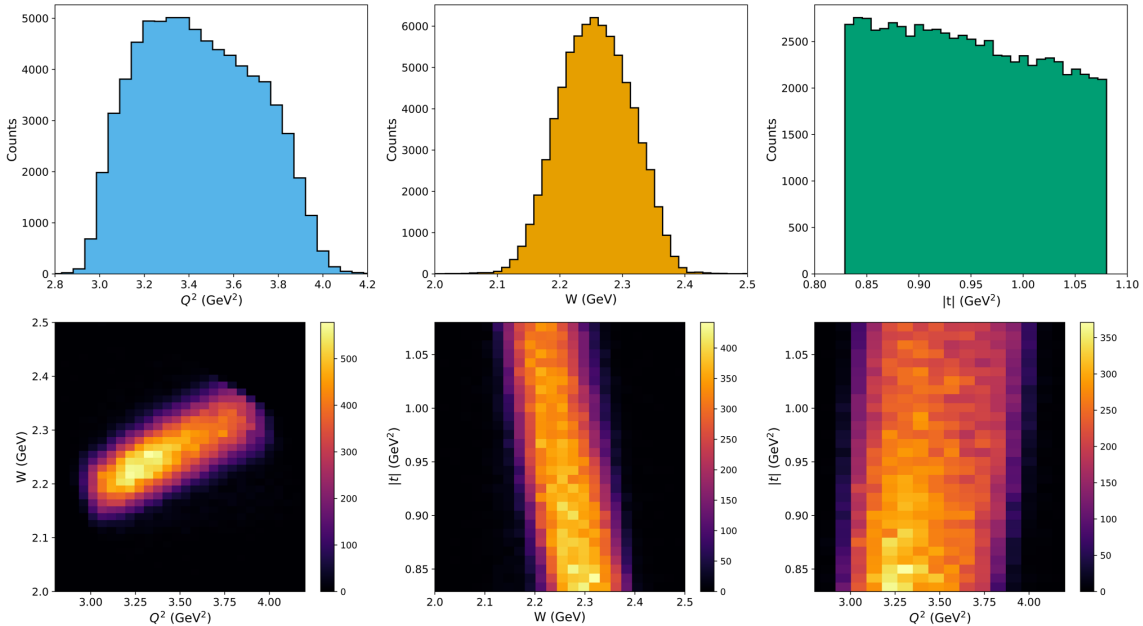


- 75 μA 10.6 GeV beam, Standard 10 cm LH_2 target
- Measure proton in HMS, electron in SHMS
  - SHMS: $\theta_{e'} = 13°,\ p_{e'} = 6.7$ GeV
  - HMS: $\theta_{p'} = 32°,\ p_{p'} = 1.1$ GeV
  - Couple HMS directly to scattering chamber to reduce multiple scattering

Standard Hall C equipment
Could run as **soon as next year!**

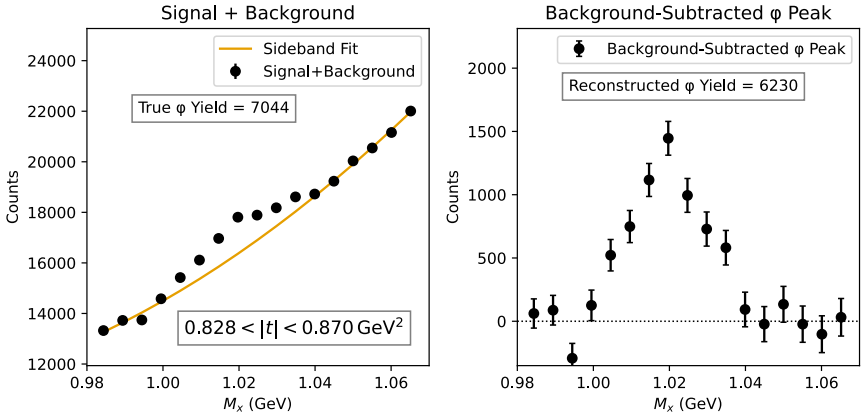


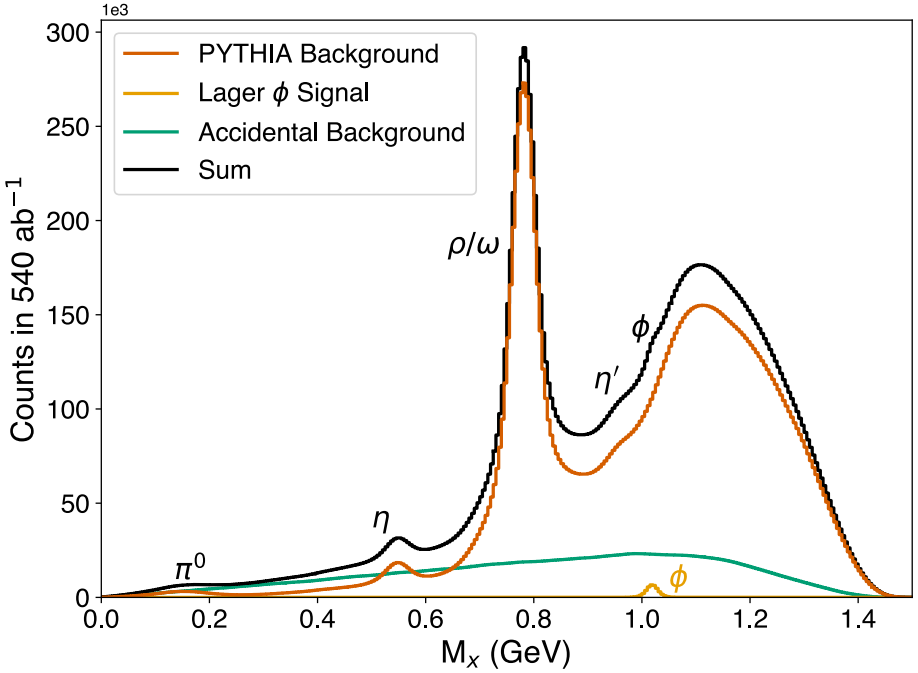
Q^2 ~ 3.4 GeV^2 W ~ 2.25 GeV |t| ~ 0.95 GeV^2



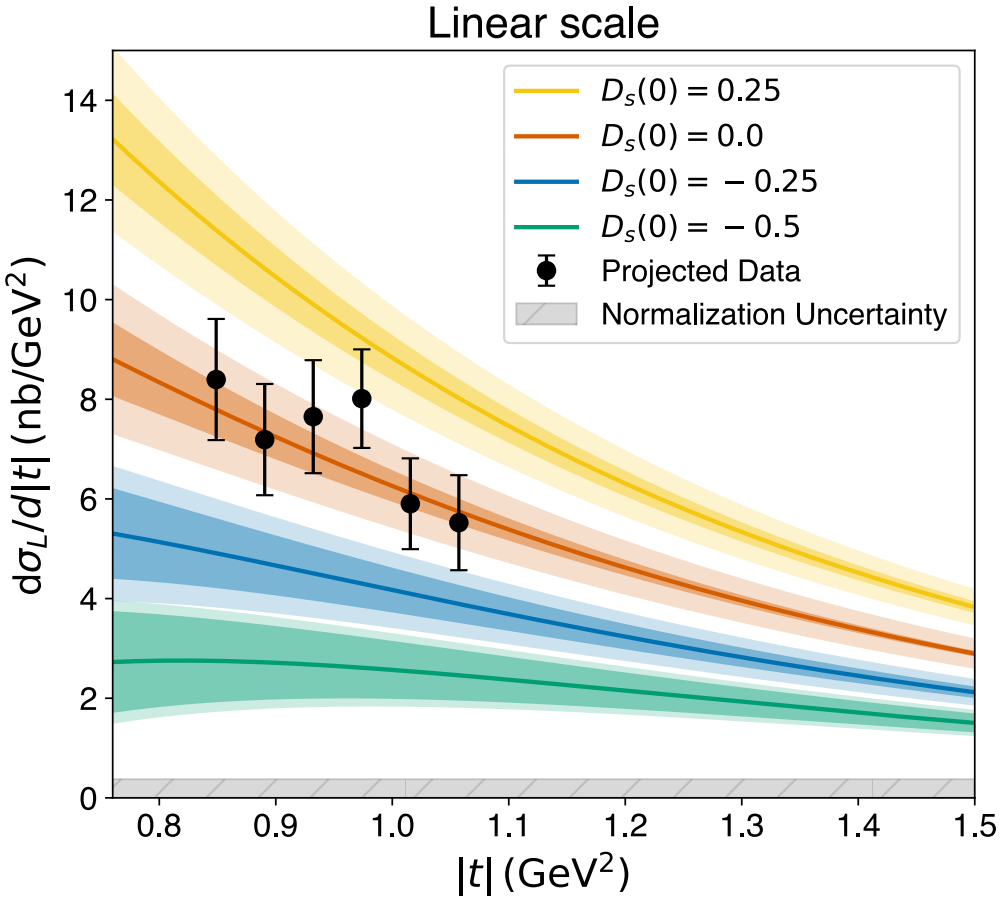
EXPERIMENTAL MEASUREMENT

- Measure $e + p \rightarrow e' + p' + \phi$ via **missing mass technique**
- **Large and irreducible** continuum background from $e + p \rightarrow e' + p' + X$!
  - However, missing mass resolution of the Hall C spectrometers is good enough to **fit + subtract background with the data itself**





CROSS SECTION PROJECTIONS



- Experimental uncertainty from these sources:

Source	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6
Signal Extraction	14.0%	13.6%	14.9%	13.6%	13.3%	15.1%
Radiative Correction	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
Background Modeling	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
Tracking Efficiency	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Rescattering Correction	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Other Systematics	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
Total Point-to-point	15.6%	15.2%	16.4%	15.2%	14.9%	16.6%
Acceptance Correction	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
Value of R[11]	3.8%	3.8%	3.8%	3.8%	3.8%	3.8%
Total Normalization	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%

Dominated by signal extraction!
→ Needs high statistics, 540 ab^{-1}

- Theoretical uncertainty and experimental uncertainty are of similar size

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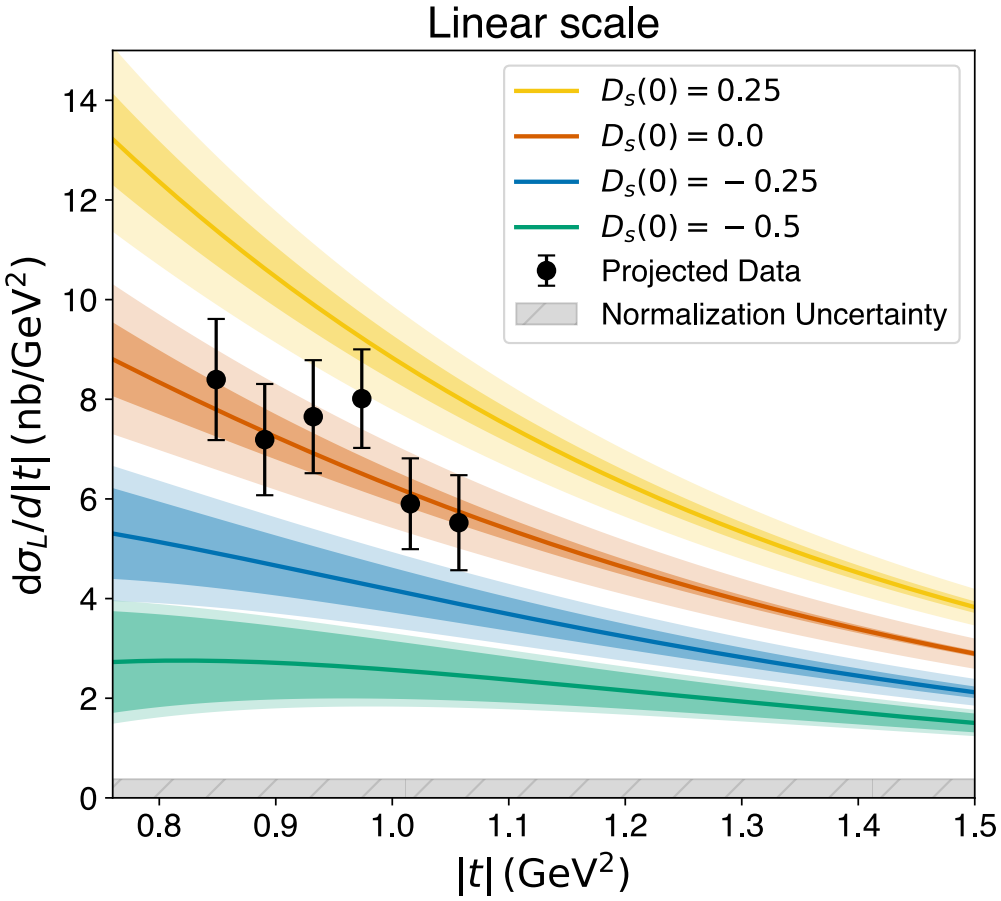
HOW WELL CAN WE EXTRACT D_s?



- Jitter datapoints and fit to theory predictions at different values of D_s
- Anticipate resolutions of 0.1 to 0.2 on $D_s(0)$

Precise enough to validate or invalidate the claim that $D_s = D_{u,d}$!

$D_s(0)$ Value	0.25	0.0	-0.25	-0.5
$\sigma_{D_s(0)}$	0.15	0.15	0.18	0.28

Extracted resolutions on $D_s(0)$ for various values of $D_s(0)$.

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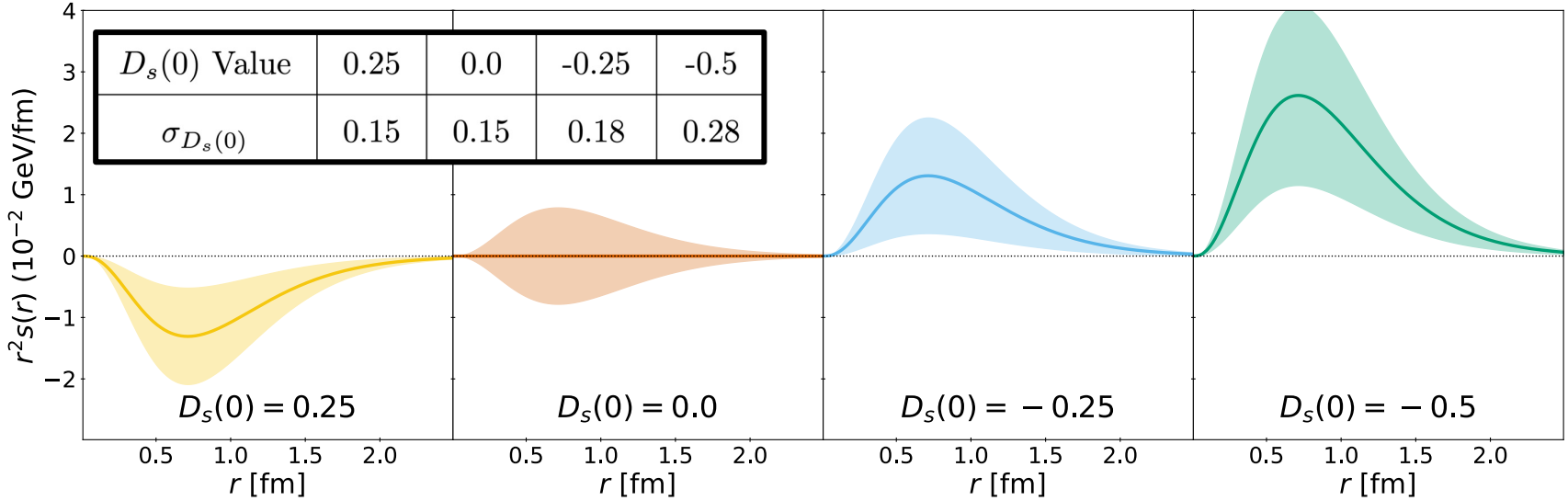
WHAT CAN WE LEARN?

Using these resolutions on $D_s(0)$ and the functional form measured on the lattice, can project uncertainties for the **strangeness shear force distribution**

First ever extraction! Terra incognita…



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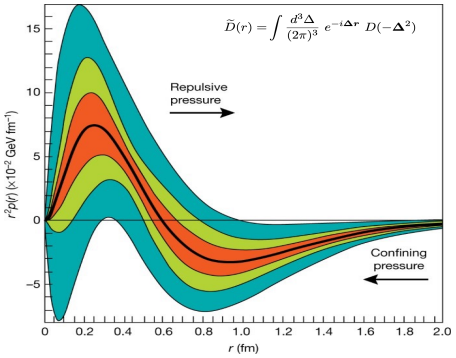
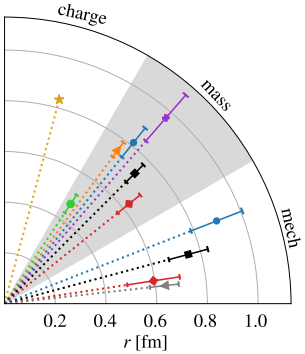
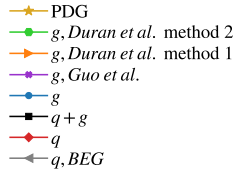
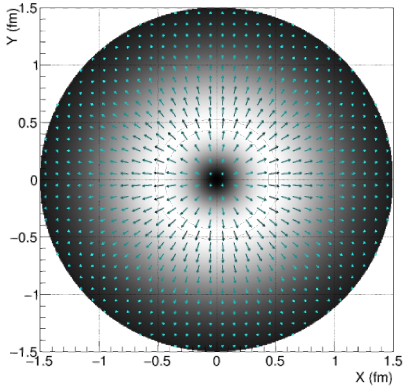
Armed with the **missing piece** D_s, can finally do global analyses of ***total*** D-term from **experimental data!**

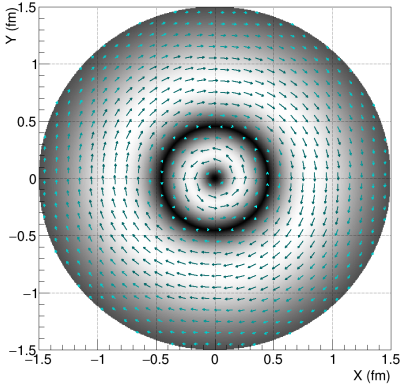
$$D(0) = \underbrace{D_g(0)}_{J/\psi} + \underbrace{D_u(0) + D_d(0)}_{\text{DVCS}} + \underbrace{D_s(0)}_{\phi\ \text{DVMP}} + \ldots.$$











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Armed with the **missing piece** D_s, can finally do global analyses of ***total*** D-term from **experimental data!**

$$D(0) = \underbrace{D_g(0)}_{J/\psi} + \underbrace{D_u(0) + D_d(0)}_{\text{DVCS}} + \underbrace{D_s(0)}_{\phi\ \text{DVMP}} + \ldots.$$

These quantities teach us about the strength of the strong force inside nucleons, it's important we get them right!

THEORY COMMENTS

PR12-25-007: *Studying the Strangeness D-Term in Hall C via Exclusive Phi Electroproduction*

C. Weiss and A. Radyushkin

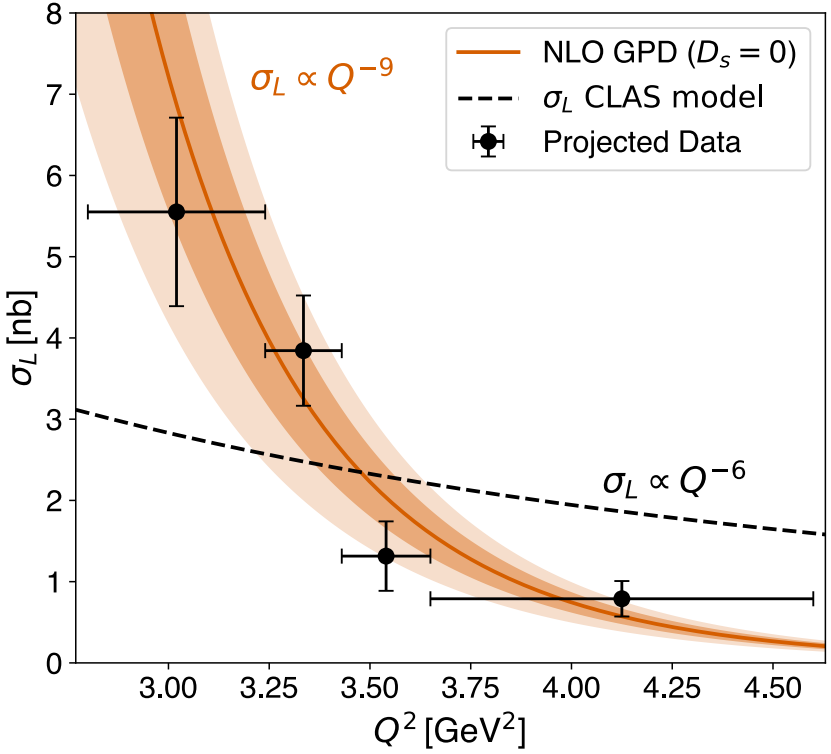
- ***Prediction of Hatta et al. based on collinear factorization needs to be tested in the required kinematic region***
  - Produced hadrons can have final-state interactions
    - Calculations show these are negligible for our kinematics (see backup)
  - Hadronic coupled-channels can contribute e.g. $ep \to K\Lambda \to \phi p$
- Theory reviewers prefer a **hadronic interpretation** of this kinematic region
  - Asymptotically near-threshold, soft hadronic interactions will dominate over hard partonic ones

These comments generated a vigorous discussion amongst the theorists!

TESTING THE THEORY

- **Q^2 scaling lets us test!**
- Hatta et al. predicts a very steep scaling with Q^2 in our range of W
  - Predicts $\sigma_L \propto Q^{-9}$ due to the **GFFs and hard coefficients**
    - **Unique feature of the near-threshold framework[1]!**
  - Standard GPD predicts $\sigma_L \propto Q^{-6}$
  - VMD predicts $\sigma_L \propto Q^{-4}$

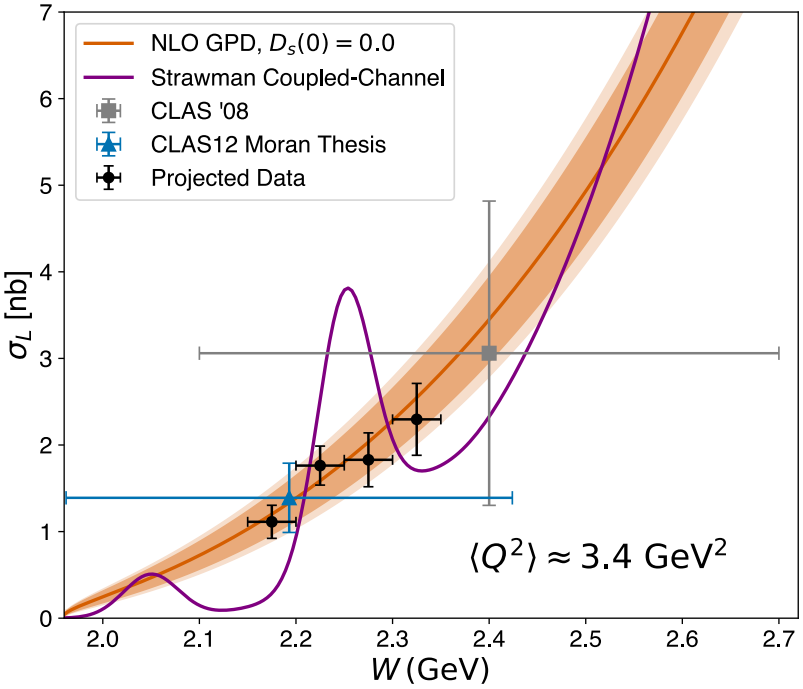
Can validate or invalidate collinear factorization at these kinematics with our data!



[1] – Hatta, HK, et al.: **Deeply virtual ϕ-meson production near threshold,** *PTEP, 2025*

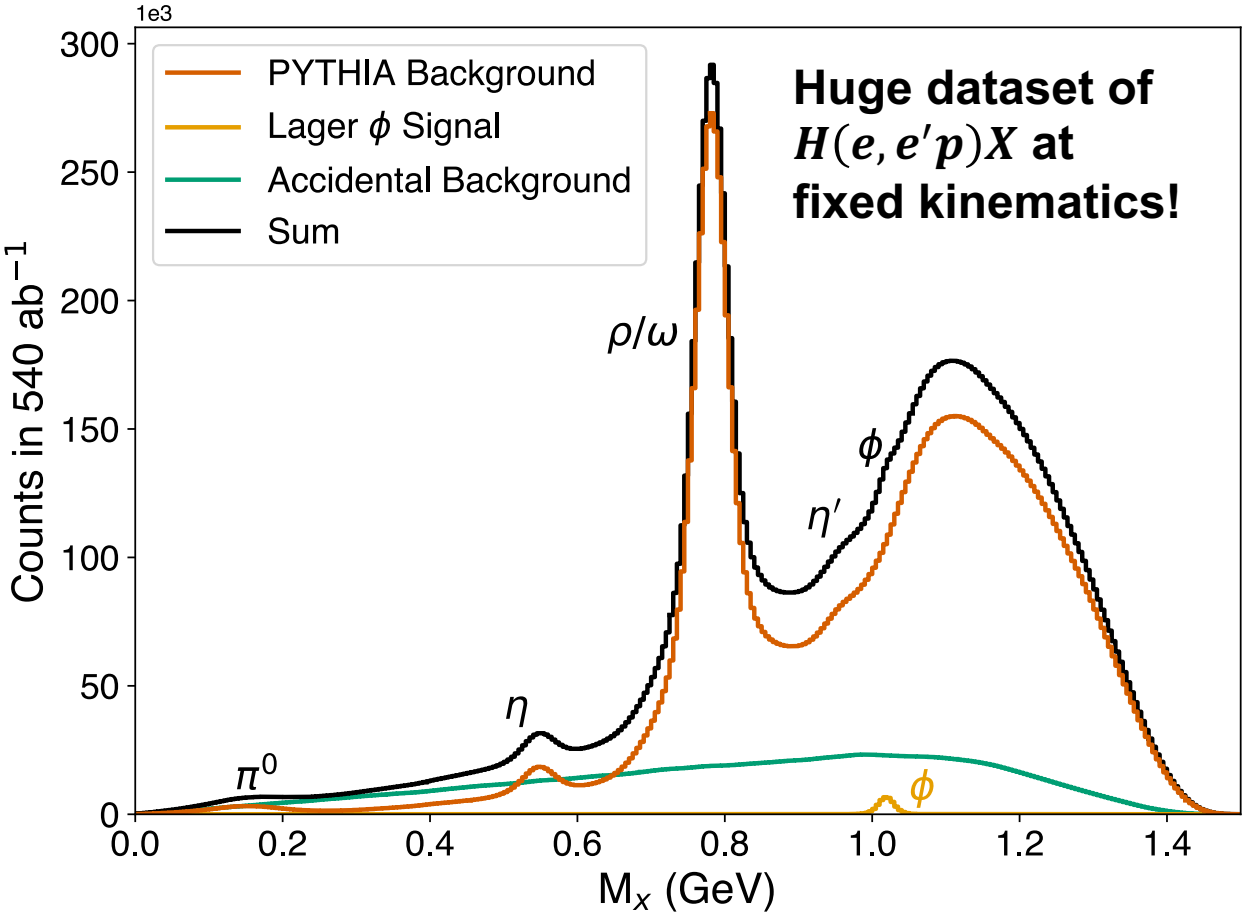
TESTING THE THEORY

- The prediction of Hatta et al. “**agrees**” with CLAS data and preliminary results from CLAS12
  - **Data uncertainties are very large!**
- Almost any model can describe the existing data due to poor precision & large bins
- The speculation surrounding this topic is precisely why these **data are sorely needed!**



Only way to resolve this debate is with **data!**

WHAT ELSE CAN WE LEARN FROM THIS DATA?



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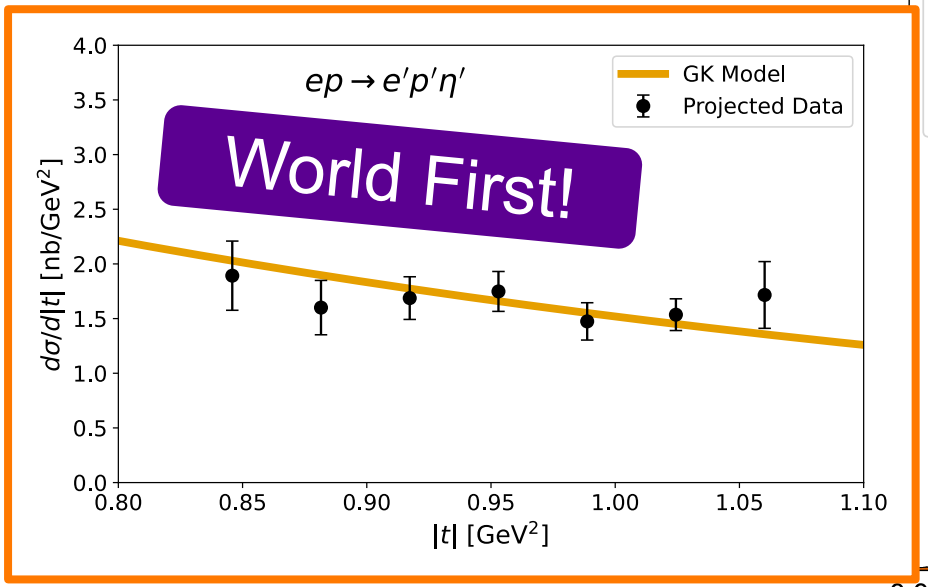
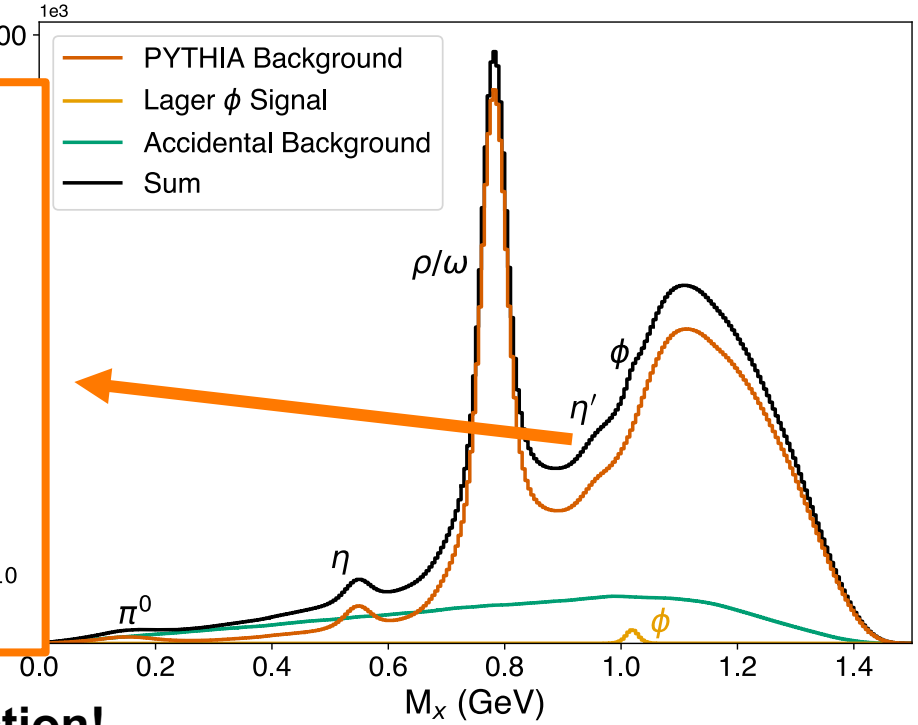
WHAT ELSE CAN WE LEARN FROM THIS DATA?





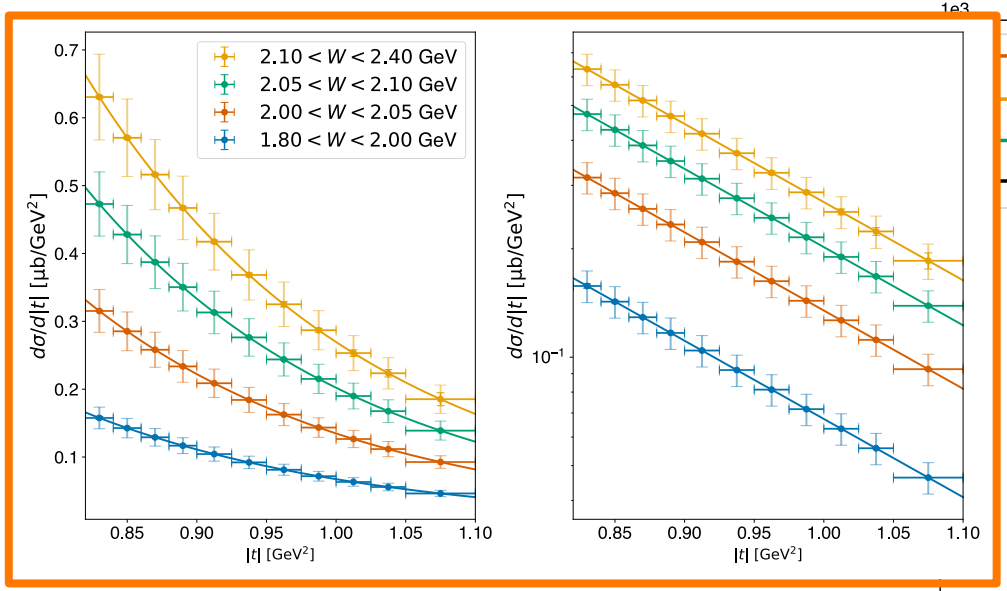
First measurement of η' electroproduction!

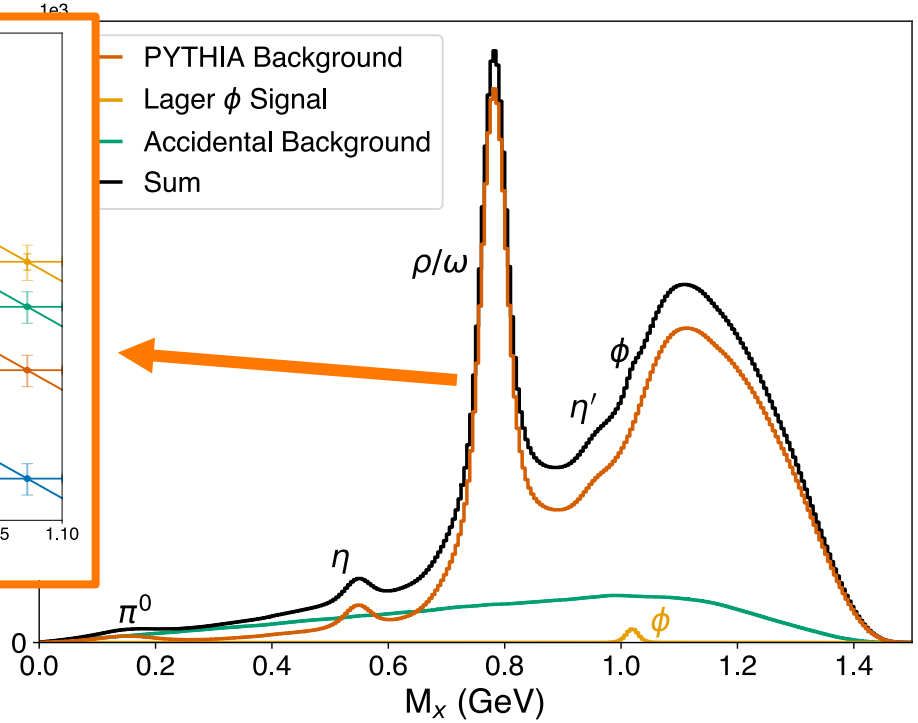
Unexpectedly large η' mass is generated by the **QCD chiral anomaly**,

What can electroproduction teach us?

[1] Eides, Frankfurt, Strikman - **Hard Exclusive Electroproduction of Pseudoscalar Mesons and QCD axial anomaly**, *PRD, 1999*

WHAT ELSE CAN WE LEARN FROM THIS DATA?



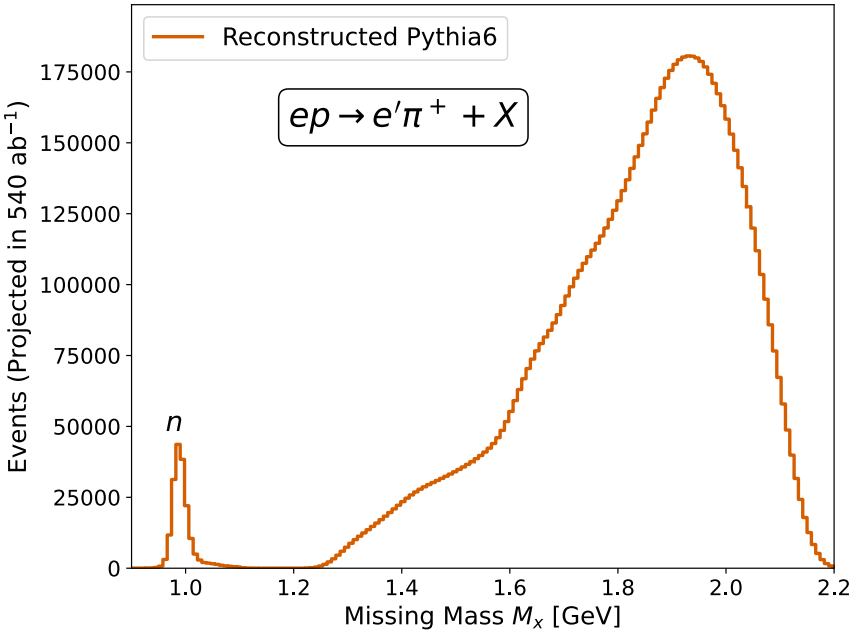


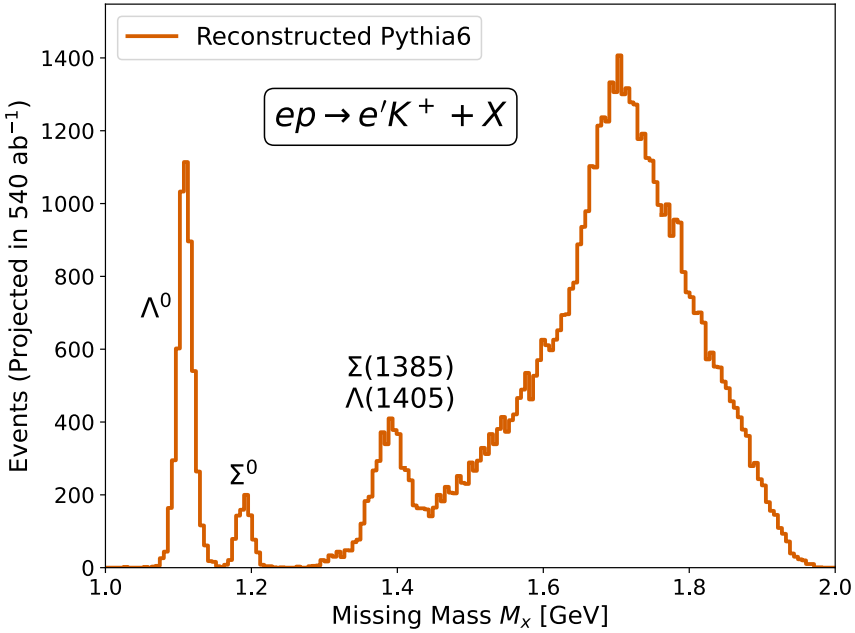
Most differential measurement of near-threshold ω electroproduction! + BSA!

Connection to the proton mass radius[1]?

[1] - Wang et al. **Extraction of the proton mass radius from the vector meson photoproductions near thresholds,** *PRD, 2021*

WHAT ELSE CAN WE LEARN FROM THIS DATA?





u-channel $\pi^+ n$ and $K^+ Y$ electroproduction

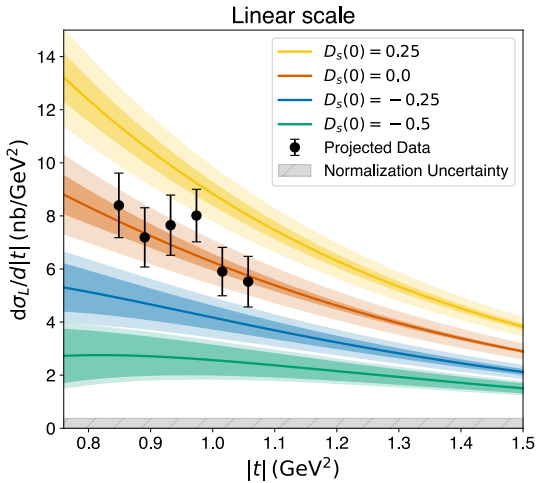
Baryon takes most of the γ^* momentum
Compare to pQCD TDA predictions

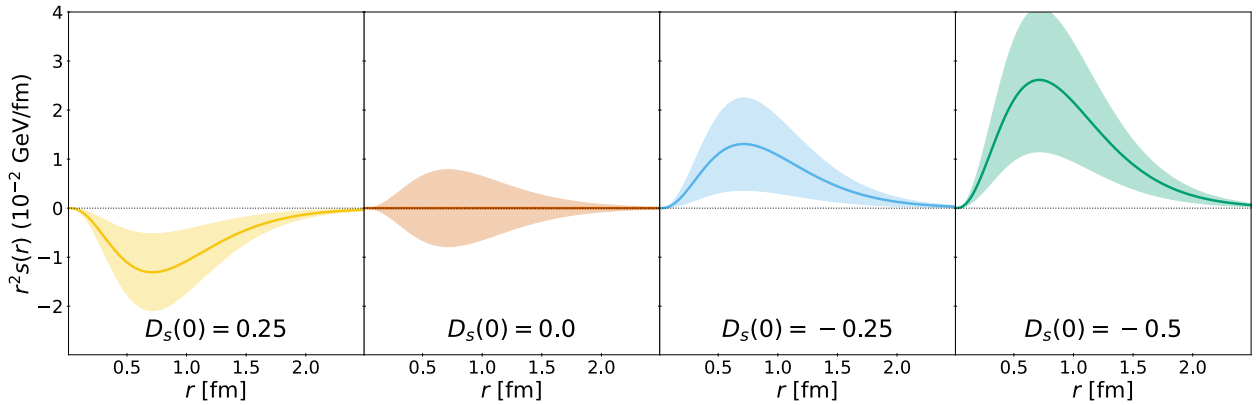
Connection to how baryon number is distributed in the nucleon[1]?

[1] Pire et al. - **Toward an advanced phenomenology of πN transition distribution amplitudes,** *2025*

CONCLUSION

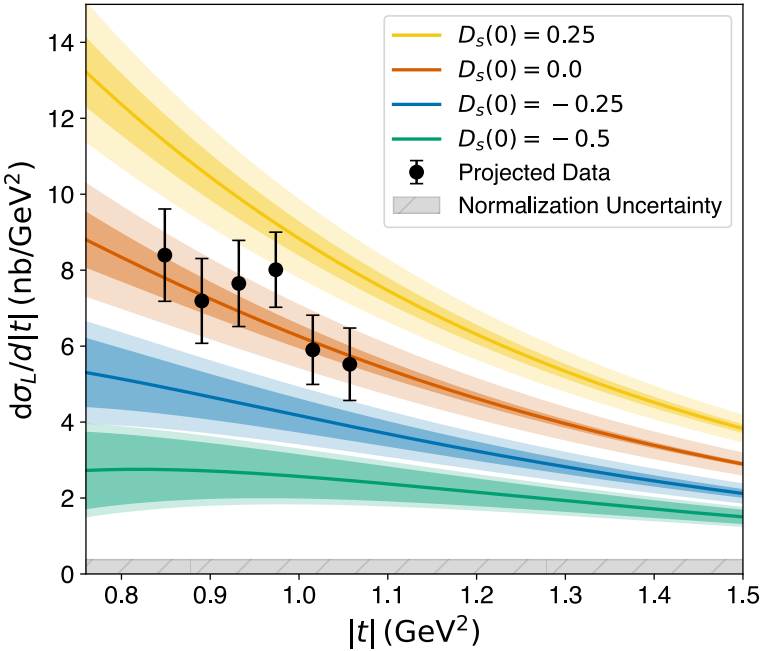
- To fully understand proton mechanical structure,
  need to extract the contribution of strangeness to the D-term
  - **Only place in the world** capable of this measurement is **CEBAF**
  - Need **data** to **validate** near-threshold collinear factorization
  - Result of $D_s(0) = 0 \rightarrow$ **Supports existing results on mechanical quantities**
  - Observation of $D_s(0) \neq 0 \rightarrow$ **Discovery of the contribution of strangeness to the mechanical structure of the nucleon!**

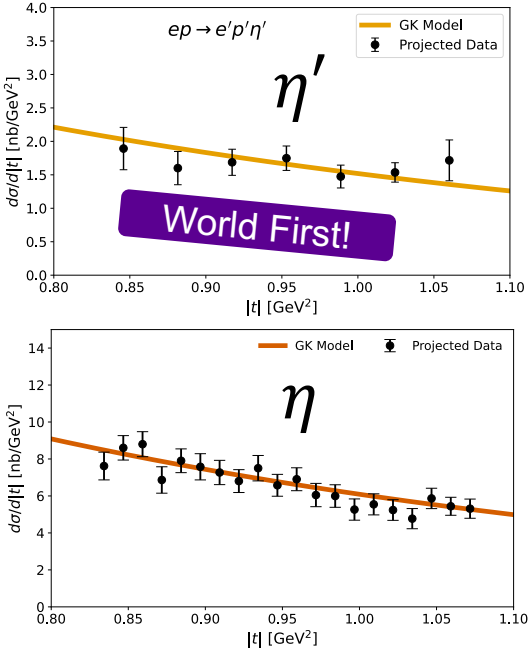


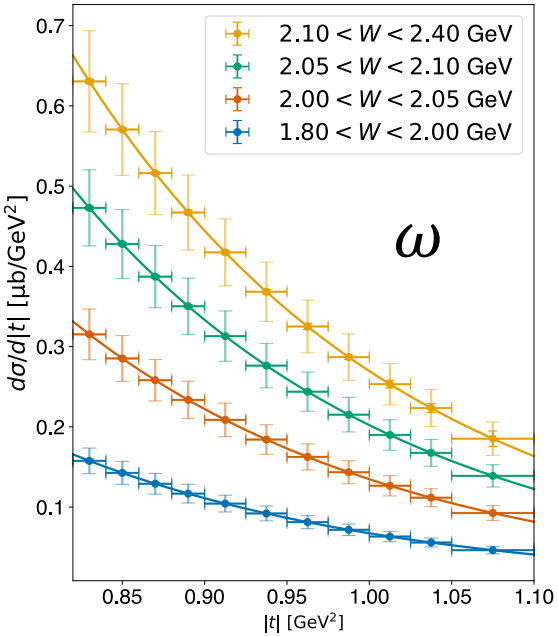


SUMMARY

- **High-impact, Low-risk experiment using understood equipment**
  - **Many** additional opportunities for **novel** measurements!
- **We ask the PAC to approve our proposal for 35 days in Hall C**
  - 32 days of physics (540 ab^{-1})







59 Collaborators

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BACKUP

59 Collaborators, international collaboration!

W. Armstrong, F. A. Flor, S. Joosten*, B. Kim, M. H. Kim, H. T. Klest*†, V. Klimenko, S. Lee, Z.-E. Meziani, C. Peng, N. Pilleux, P. E. Reimer, J. Xie, Z. Xu, M. Żurek
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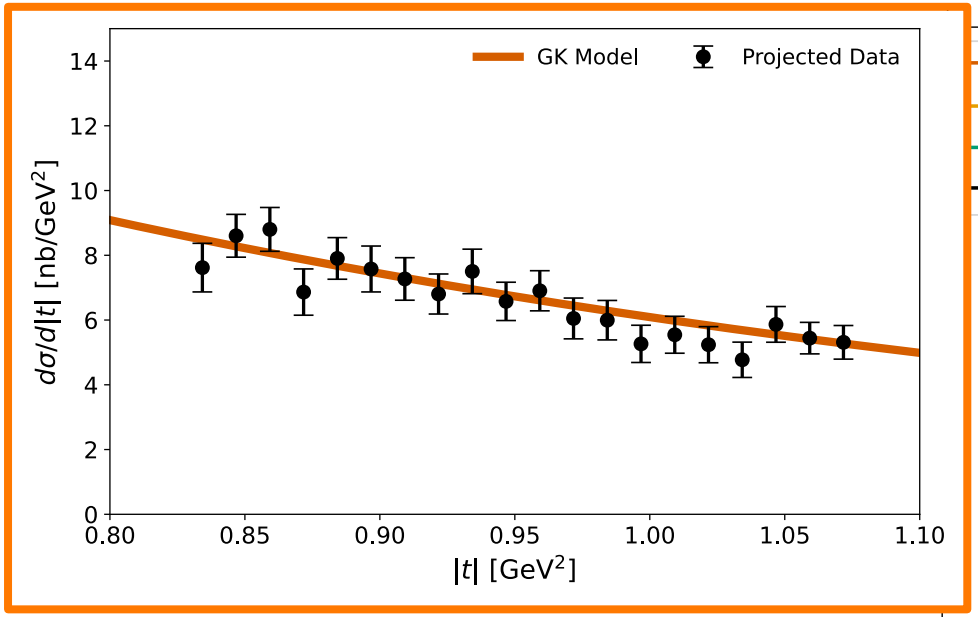
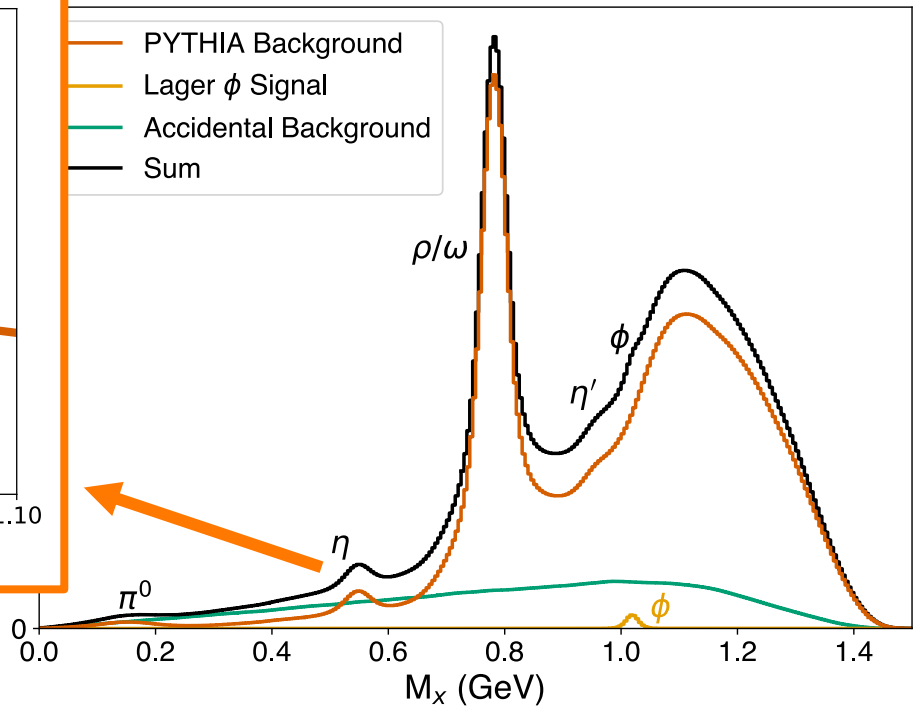
WHAT ELSE CAN WE LEARN FROM THIS DATA?





Comparison of η and η':

What is the role of the chiral anomaly in electroproduction[1]?

$\eta : \eta' = 1 : 2$ → Naïve cross section ratios neglecting the anomaly

$\eta : \eta' = 1 : 0.87$ → With the anomaly included

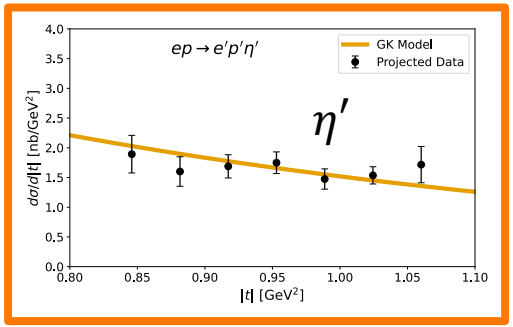
[1] Eides, Frankfurt, Strikman - **Hard Exclusive Electroproduction of Pseudoscalar Mesons and QCD axial anomaly**

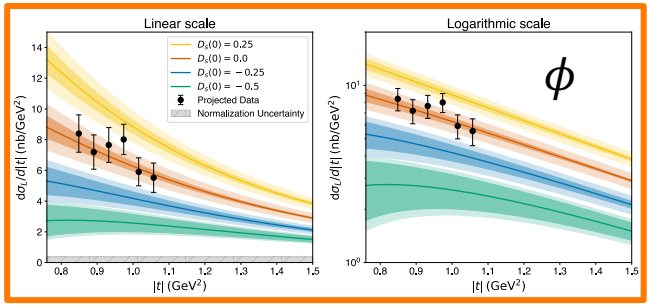
WHAT ELSE CAN WE LEARN FROM THIS DATA?

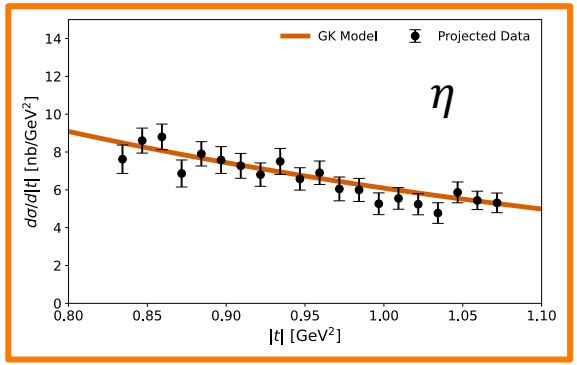
Beam Spin Asymmetries for all!

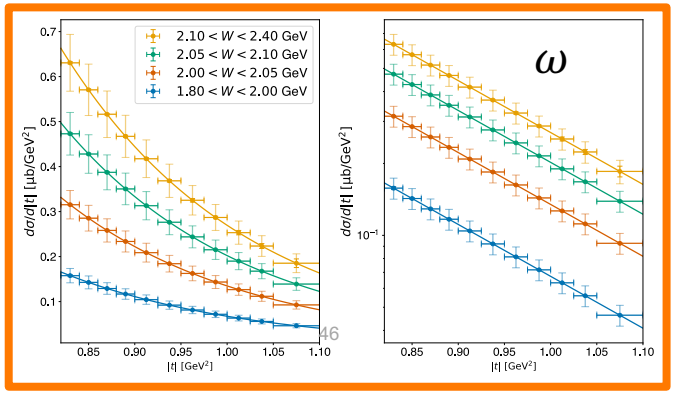
(Partially)

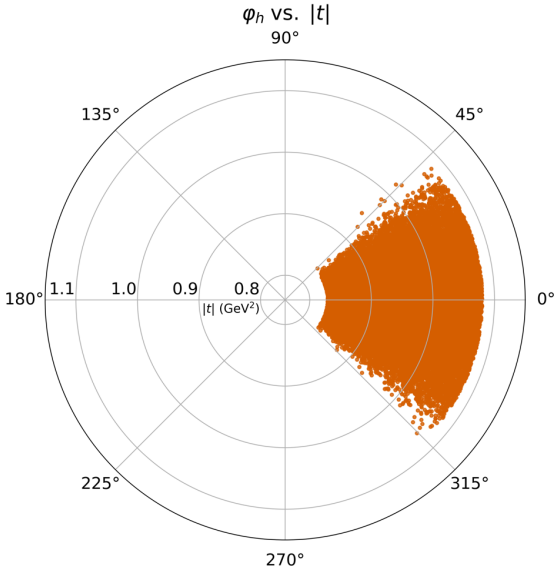
$$\mathrm{BSA} = \frac{\sqrt{2\epsilon(1-\epsilon)}\,\frac{\sigma_{LT'}}{\sigma_0}\sin\phi_h}{1+\sqrt{2\epsilon(1+\epsilon)}\,\frac{\sigma_{LT}}{\sigma_0}\cos\phi_h+\epsilon\,\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi_h}$$











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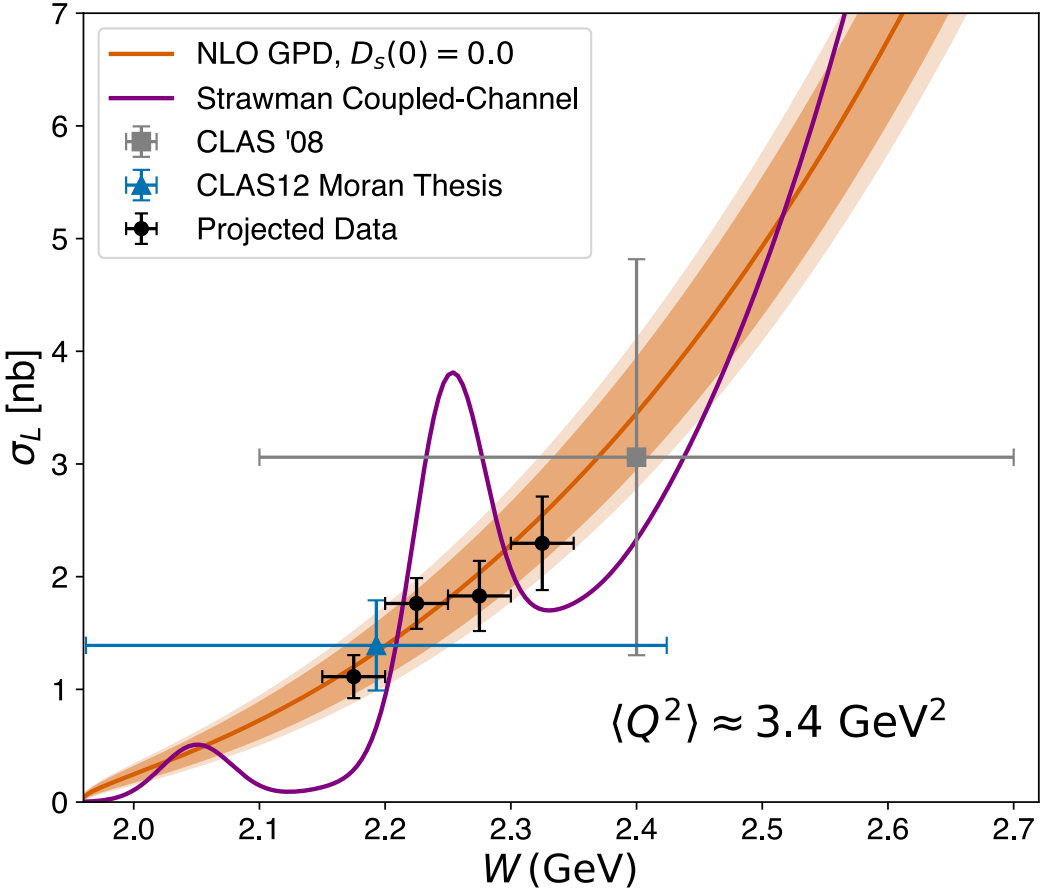
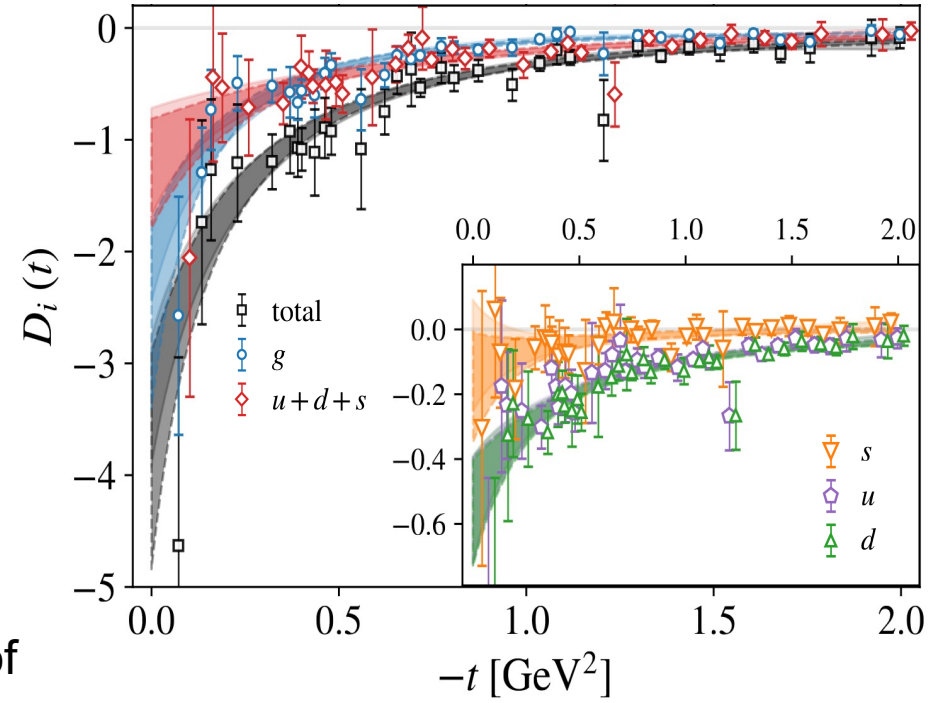


Data Source	$\langle W \rangle$ (GeV)	Data σ_L	GPD σ_L
CLAS '08 data	2.40	3.06 ± 1.76	3.44 ± 0.66
CLAS12 Moran thesis data	2.19	1.39 ± 0.30	1.28 ± 0.33

THEORY PREDICTIONS

	Dipole	z-expansion
	D_i	D_i
u	$-0.56(17)$	$-0.56(17)$
d	$-0.57(17)$	$-0.56(17)$
s	$-0.18(17)$	$-0.08(17)$
$u+d+s$	$-1.30(49)$	$-1.20(48)$
g	$-2.57(84)$	$-2.15(32)$
Total	$-3.87(97)$	$-3.35(58)$



Quark masses tuned for a pion mass of 170 MeV, lattice spacing of 0.091 fm.
Calculations not yet in the continuum limit

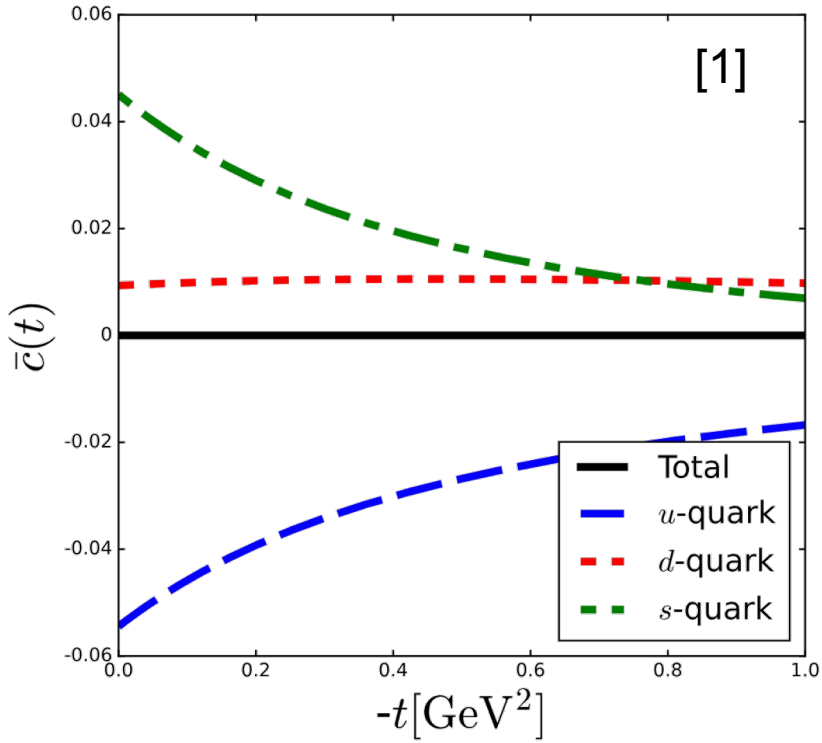
$\bar{c}$ CAVEAT

- $\bar{c}$ form factor contributes to many of the mechanical properties (Radial pressure, radii, etc.)
  - $\bar{c}$ currently inaccessible to experiment

Pressure defined as:

$$p^a(r) = \frac{1}{6m}\frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr}\widetilde{D^a}(r) - m\int\frac{d^3\Delta}{(2\pi)^3}e^{-i\Delta r}\bar{c}^a(-\Delta^2)$$

- However, $\bar{c}_q = -\bar{c}_g$! → Total $\bar{c}$ **cancels** due to EMT conservation **if summing over all parton species!**

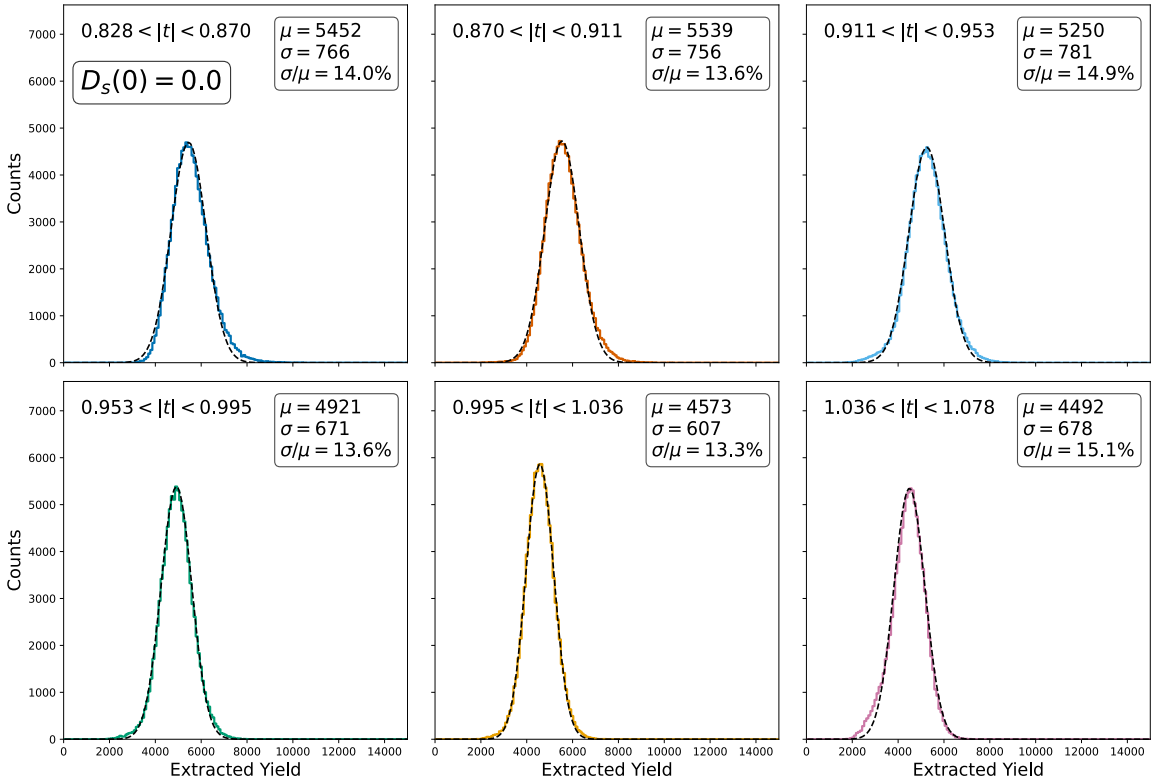


This caveat means that to extract the full set of mechanical properties, ***all* partonic D-term contributions must be known!**

[1] - Won et al.: **Role of strange quarks in the D-term and cosmological constant term of the proton**

SIGNAL EXTRACTION

- Perform the background generation, fitting, and sideband background subtraction on pseudodata 100000 times
- Results of pseudoexperiments shown for 6 bins in $|t|$
  - Can bin less finely if cross section is smaller than predicted



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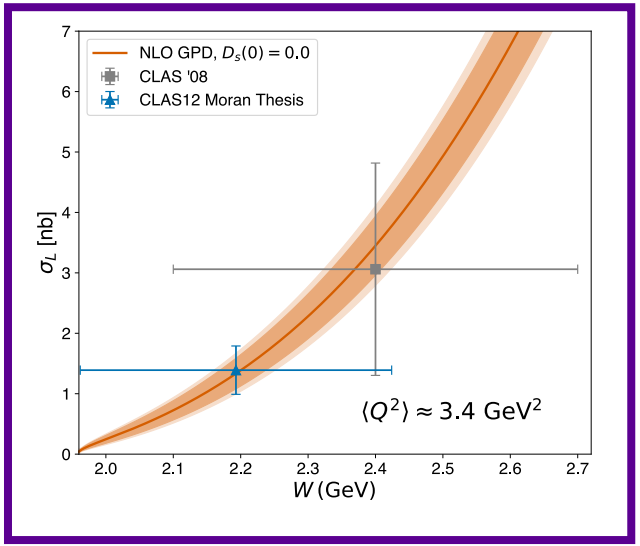
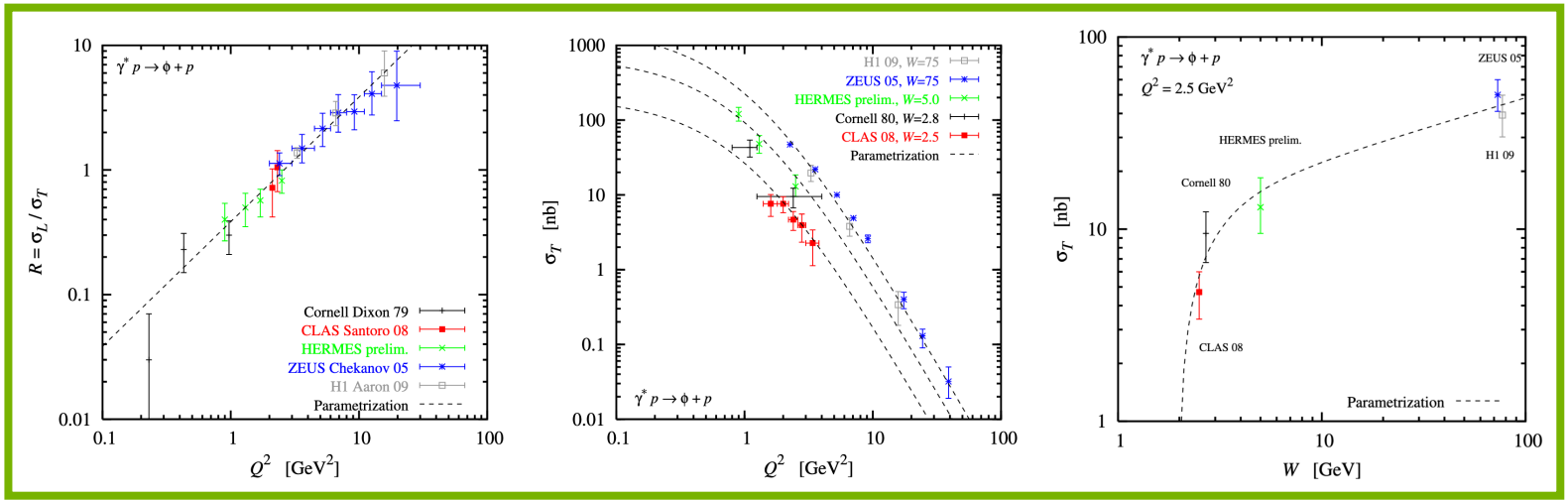
CROSS SECTION PROJECTIONS

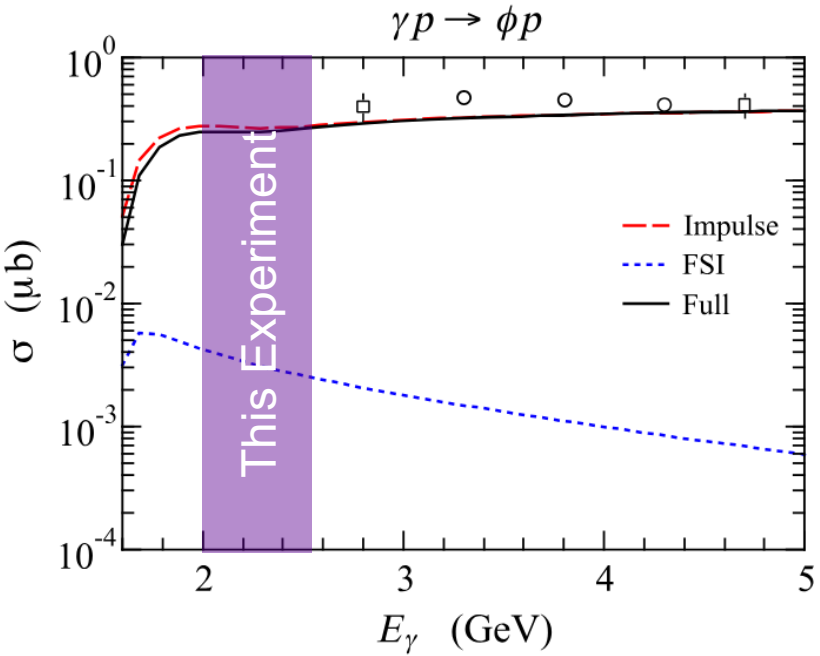
- ϕ Cross section conservatively estimated as the smaller of two predictions in our projections
  - **NLO GPD prediction**
  - **Model based on existing world data developed for CLAS12**



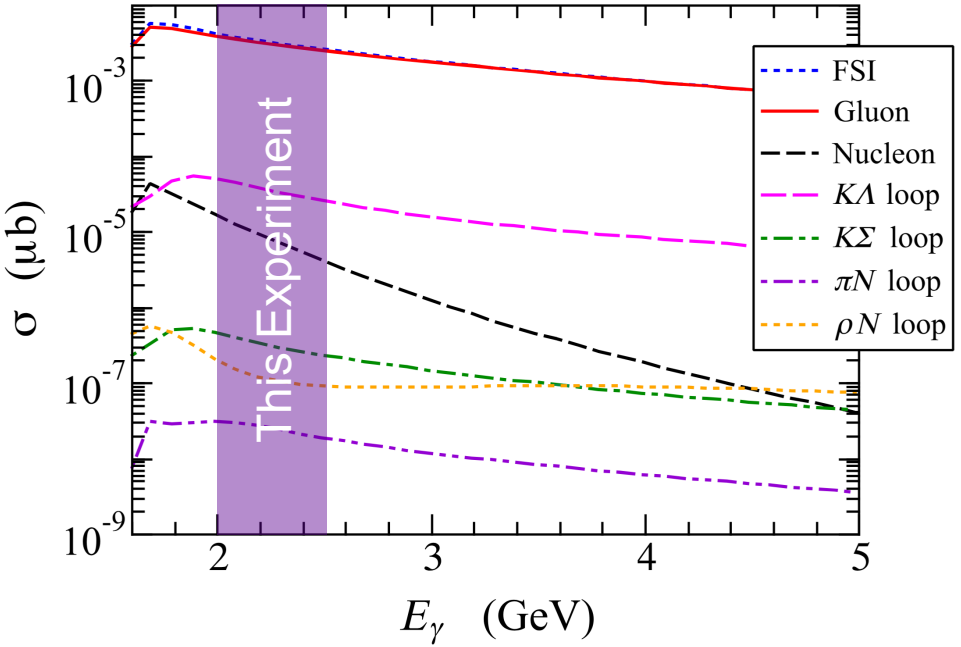


FINAL-STATE INTERACTIONS

- FSI calculated for ϕ photoproduction[1]
  - Determined to be orders of magnitude smaller than the production cross section – **negligible**



- Even the individual FSI channels are calculated and shown to be tiny



[1] – S.H. Kim et al. **Dynamical model of ϕ meson photoproduction on the nucleon and ^{4}He**

THEORY RESPONSES

Furthermore, **duality** tells us that partonic and hadronic descriptions are **not exclusive!**

- The points raised against Hatta et al. do not apply to **holographic predictions** since holography does not rely on collinear factorization
  - —Holographic predictions for ϕ already exist![1]
- In contact now with holographic theorists, a new calculation for our kinematics is possible

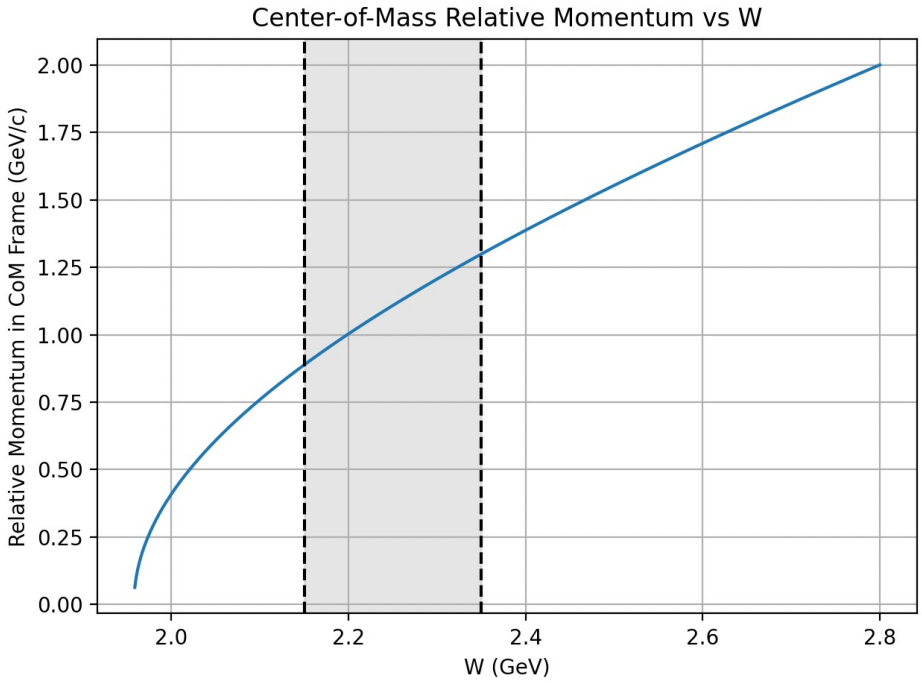
[1] - Mamo, Zahed: **Electroproduction of heavy vector mesons using holographic QCD: from near threshold to high energy regimes**

“NEAR-THRESHOLD”?

- **Asymptotically close to the threshold** of W = 1.96 GeV, collinear factorization indeed breaks down

- However, the ***W* of this experiment was chosen to be large enough** that the relative momentum between the ϕ and proton is still reasonably large
  — **“Near-threshold” is misleading!**

The only way to test whether collinear factorization holds quantitatively is with **data!**



Total momentum between the ϕ and proton in the center-of-mass frame

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The forward values $A_a(\mu)$ represent the momentum fraction of the proton carried by partons $\sum_{a=q,g} A_a(\mu) = 1$. We consider their one-loop QCD evolution using

$$A_s(\mu_0) = 0.03, \qquad A_g(\mu_0) = 0.42, \qquad A_{u+d+c}(\mu_0) = 1 - A_s(\mu_0) - A_g(\mu_0), \tag{49}$$

at the reference scale $\mu_0 = 2$ GeV [67]. The one-loop evolution of the D-terms $D_{q,g}(\mu)$ is the same as that for $A_{q,g}(\mu)$ and is explicitly given by

$$\begin{aligned} D_q(\mu) \;=\; & \frac{D}{4C_F + n_f} + \frac{1}{n_f\,(4C_F + n_f)} \left(\frac{\alpha_s(\mu_0)}{\alpha_s(\mu)}\right)^{-\frac{2}{3\beta_0}(4C_F+n_f)} \left(4C_F D - (4C_F + n_f)\, D_g(\mu_0)\right) \\ & + \left(\frac{\alpha_s(\mu_0)}{\alpha_s(\mu)}\right)^{-\frac{8C_F}{3\beta_0}} \left(D_q(\mu_0) - \frac{1}{n_f}\sum_{q'} D_{q'}(\mu_0)\right), \end{aligned} \tag{50}$$

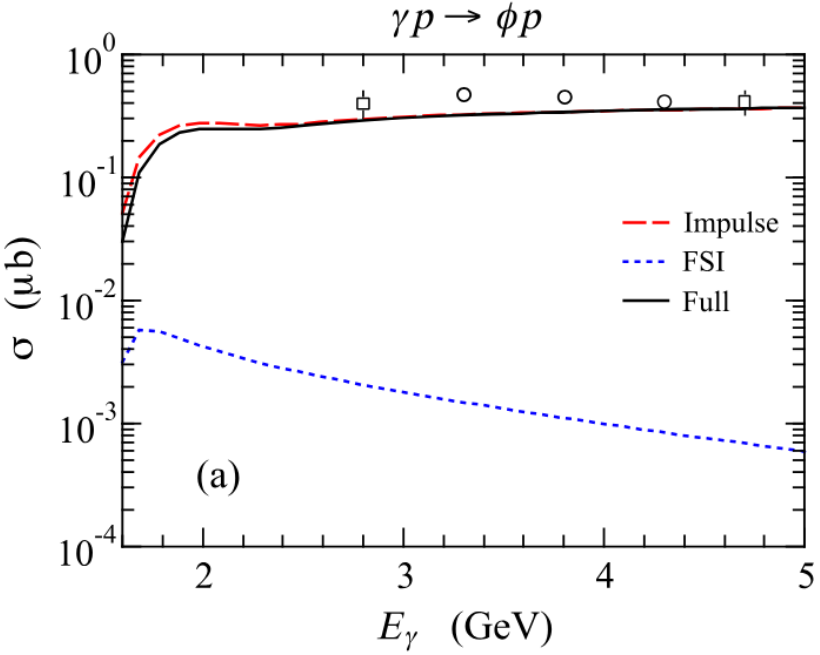
$$\begin{pmatrix} \mathcal{H}(\xi,t,Q^2) \\ \mathcal{E}(\xi,t,Q^2) \end{pmatrix} = e_s \frac{C_F f_\phi}{N_c Q} \sum_{a=q,g} \begin{pmatrix} H^a(x,\xi,t,\mu^2) \\ E^a(x,\xi,t,\mu^2) \end{pmatrix} \otimes T^a\left(x,\xi,u,\frac{Q^2}{\mu^2}\right) \otimes \varphi(u,\mu^2)$$

PAC 52 COMMENTS TO LETTER-OF-INTENT

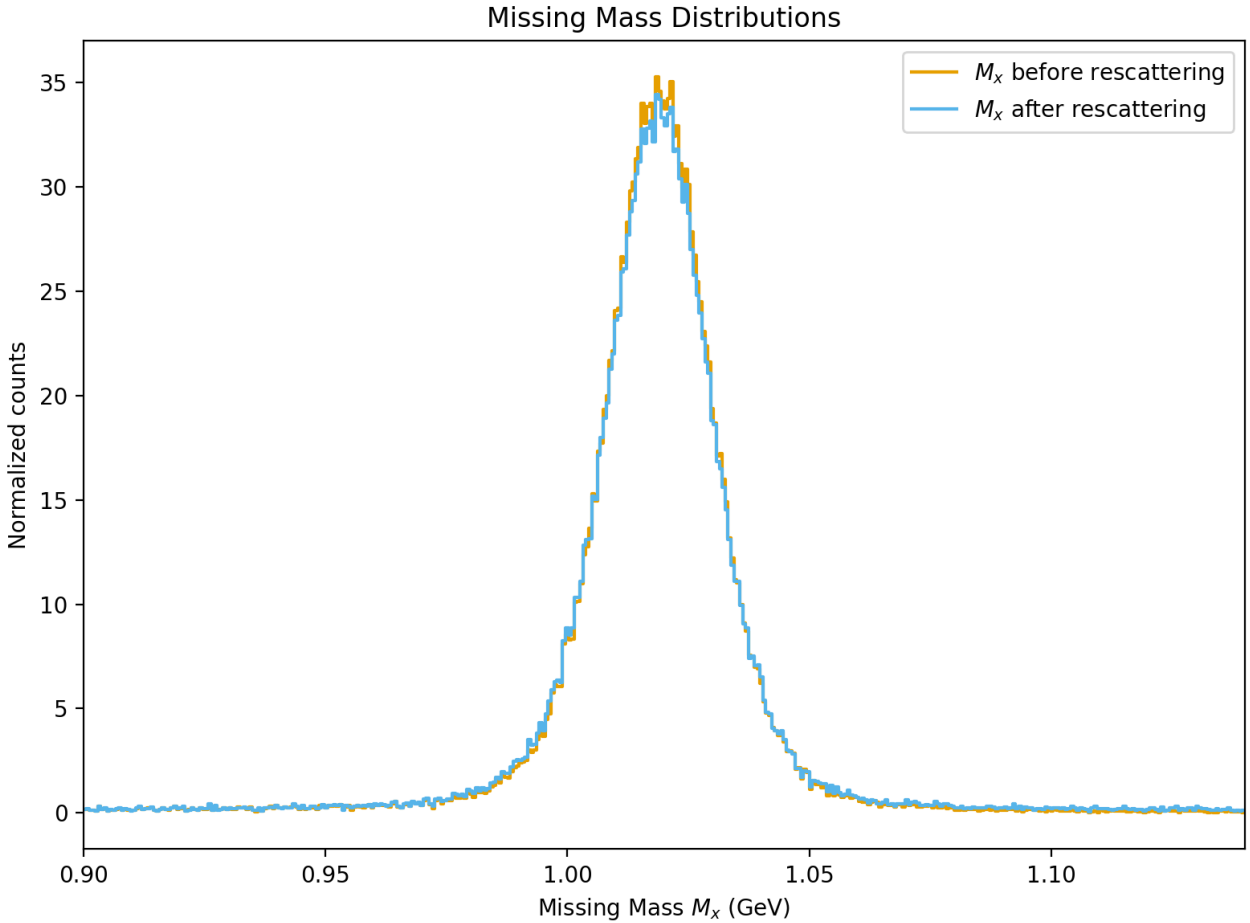
- Need to include **final-state interactions**
- Need a model that can separate gluons and strangeness

PAC52 - FINAL-STATE INTERACTIONS

- FSI calculated for ϕ photoproduction[1]
  - Determined to be orders of magnitude smaller than the production cross section – **negligible**
- However, ϕ decay products can also rescatter on the proton!
  - $\phi \rightarrow KK$: 83% BR
  - $\phi \rightarrow \pi\pi\pi$: 15% BR
    - Estimate πp & Kp cross sections ~100 mb for our kinematics
- Using ϕ lifetime & black disk limit, **likelihood of rescattering is 2%**
  - Assume a 100% uncertainty on this for cross section measurement

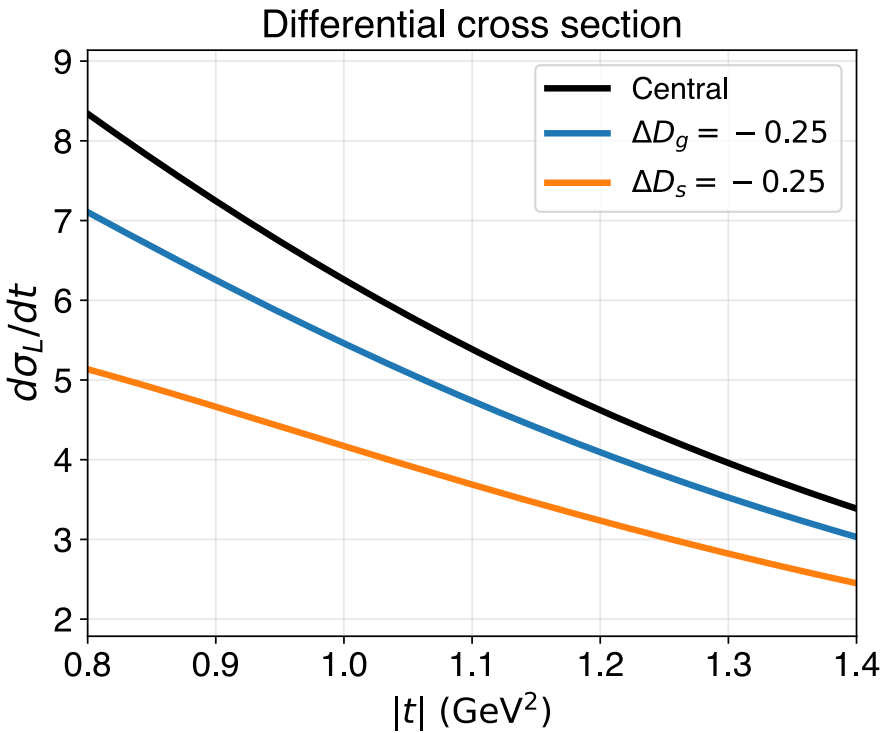


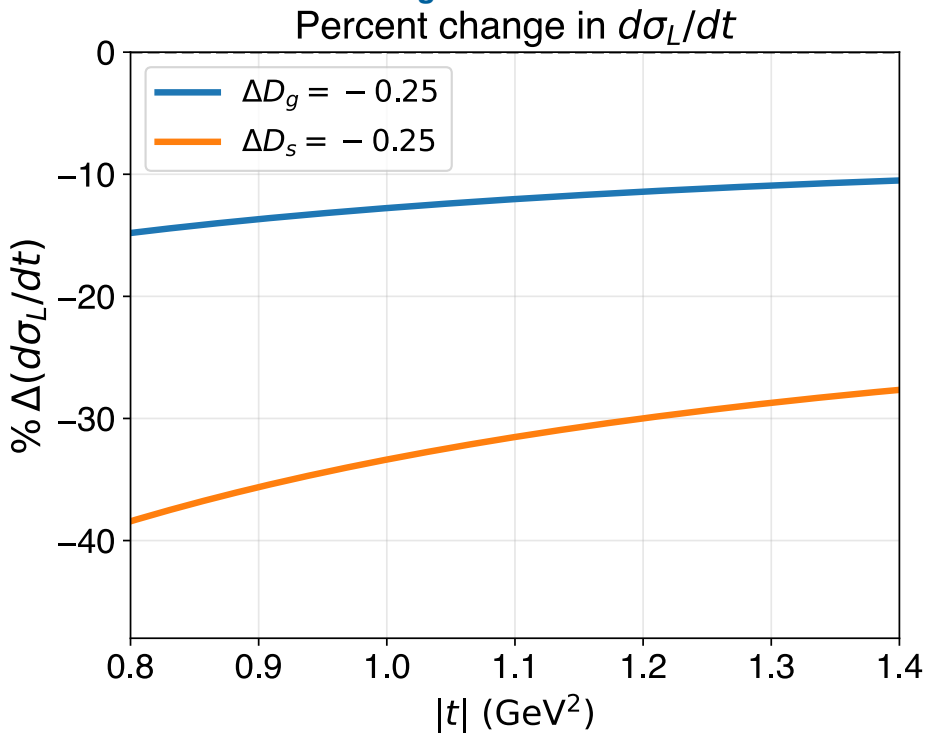
[1] – S.H. Kim et al. **Dynamical model of ϕ meson photoproduction on the nucleon and ^{4}He**


Missing Mass Distributions
M_x before rescattering
M_x after rescattering
Normalized counts
0
5
10
15
20
25
30
35
0.90
0.95
1.00
1.05
1.10
Missing Mass M_x (GeV)

PAC52 - FLAVOR DEPENDENCE

Vary D_s and D_g by the same amount





Cross section significantly **more sensitive to D_s than D_g!**

[1] – Hatta, HK, **Deeply virtual ϕ-meson production near threshold**

PID STRATEGY

- In SHMS:
  - — Electron ID'd with standard Calo+Cherenkov conditions
- In HMS:
  - — Proton ID'd as slow TOF between scintillator planes, no Cherenkov signals
  - — Kaon ID'd as fast TOF between scintillator planes and no Cherenkov signals
    - Timing w.r.t the RF may also provide some separation at larger momenta
  - — Pion ID'd as fast TOF + Aerogel signal, but no gas Cherenkov signal
  - — Positron ID'd as fast TOF, Aerogel signal, plus gas Cherenkov signal

Particle	TOF (fast)	TOF (slow)	TOF w.r.t. RF	Aerogel Cherenkov	Gas Cherenkov
Proton		✓			
Kaon	✓		✓		
Pion	✓			✓	
Positron	✓			✓	✓

The rate of single charged particles entering the spectrometer acceptances was determined using PYTHIA6 with no cuts on any kinematic variables and independently via the Wiser parameterization. We estimate based on the thickness and density of the aluminum target windows that around 10% of the rate will originate from the target windows. PYTHIA and Wiser both predict that the rate of random coincidences between a negatively charged particle in the SHMS acceptance and a positively charged particle in the HMS acceptance is around 650 Hz for a trigger coincidence time window of 70 ns. Assuming the trigger is formed by a coincidence of the HMS and SHMS hodoscopes, the rates are well within the capabilities of the data acquisition system and the livetime should be close to 100%. The rate of protons in the HMS is around 165 kHz, and the rate of electrons in the SHMS is around 25 kHz. The relevant singles rates are given in Tab. 3. The central momentum and angle of the HMS setting were chosen in part to minimize the singles rate.

	Total Rate SHMS	e^- Rate SHMS	Total Rate HMS	p^+ Rate HMS	K^+ Rate HMS
PYTHIA6	23 kHz	22.5 kHz	380 kHz	160 kHz	14 kHz
Wiser	26 kHz	25 kHz	370 kHz	170 kHz	21 kHz

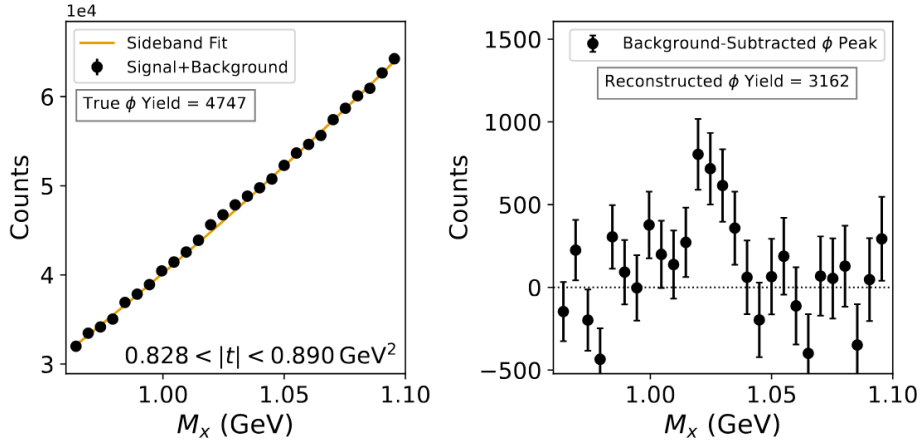


Figure 11: Example ϕ peak in the case of $D_s(0) = -0.5$. The statistical significance of the peak is around 4σ. The requirement that this peak can be resolved above background drives the requested integrated luminosity.

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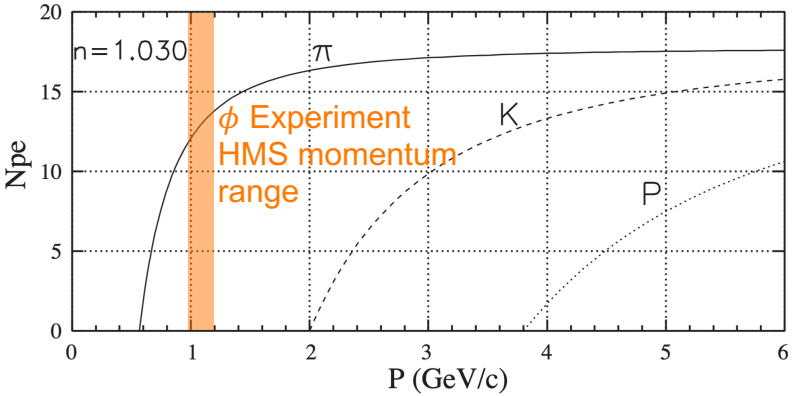
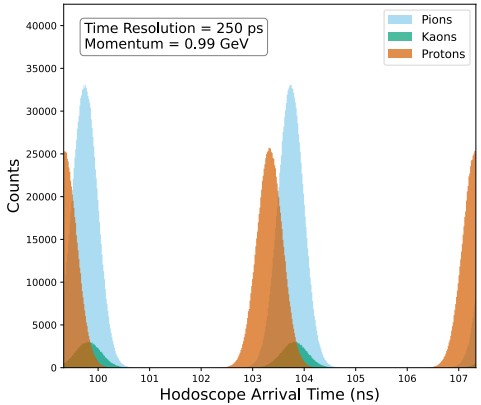
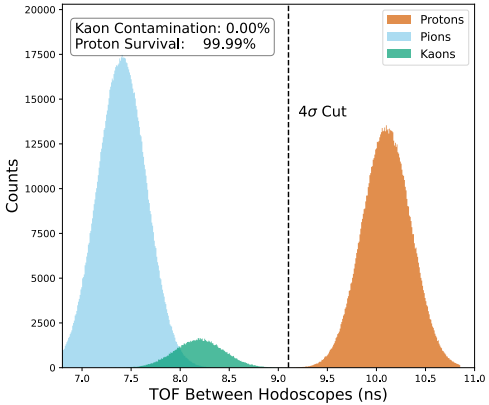
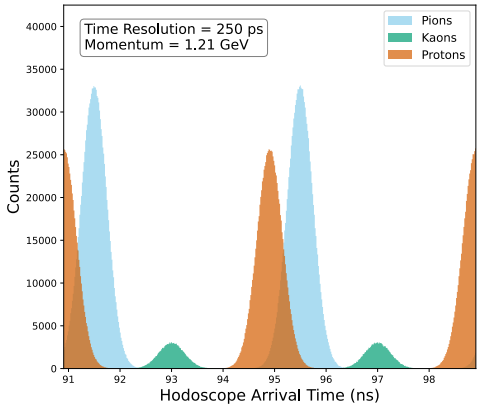
CAN WE DO *U*-CHANNEL?

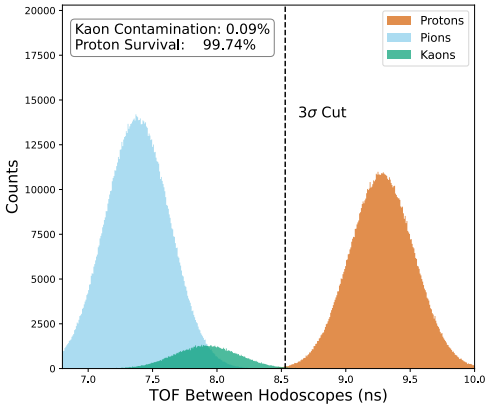
- u-channel: baryon takes most of the virtual photon momentum
- Instead of $H(e,e'P)X$, can we do $H(e,e'K)$X or $H(e,e'\pi)$X with our dataset?
  - — HMS Aerogel would likely be able to cover π/K separation
    - Kaons are below Cherenkov threshold, pions reasonably far above it











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EXCLUSIVE PION PRODUCTION

- *u*-channel is sensitive to transition distribution amplitudes
  - Connected to **how baryon number is distributed** inside of nucleons[1]

[1]

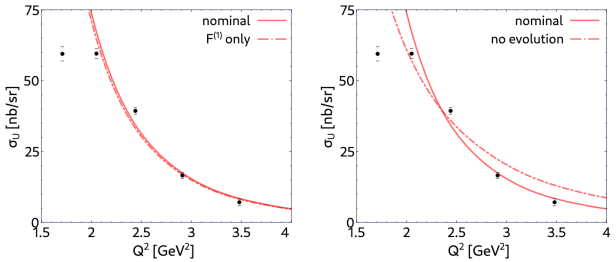
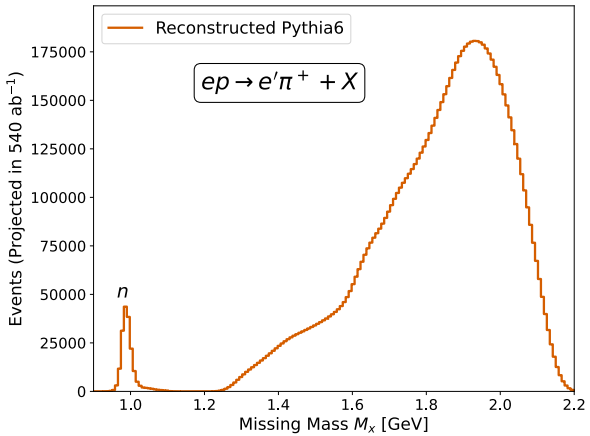
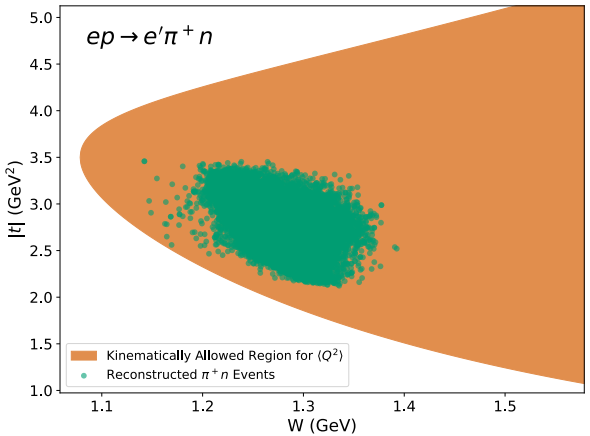
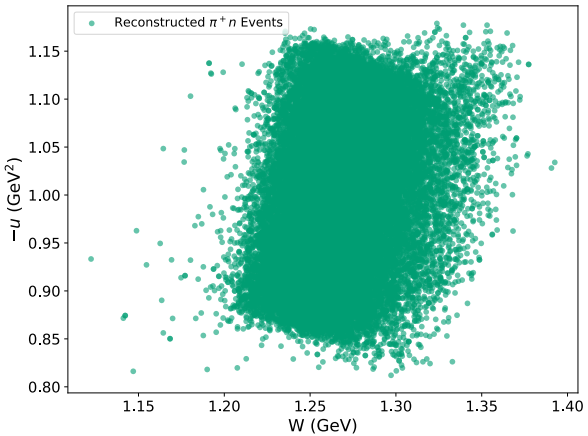


FIG. 5: CLAS data for the unseparated cross-section $\frac{d\sigma_U}{d\Omega^*_\pi}$ of the $\gamma^* p \to \pi^+ n$ reaction at backward angles [8], with $W = 2.2\,\text{GeV}$ and $u = -0.5\,\text{GeV}^2$. The solid curves represent the corresponding results obtained using the default version of our TDA model. The dash-dot curve in the left plot corresponds to a version of our model that includes only the second component, i.e., $F^{(1)}(\sigma, \rho, \omega, \nu, u)$, with $F^{(0)}(\kappa, \theta, \mu, \lambda, u)$ set to zero. The dotted curve shown in the right plot represents the modeling scenario when all evolution effects are neglected.







[1] Pire et al. - **Toward an advanced phenomenology of πN transition distribution amplitudes**

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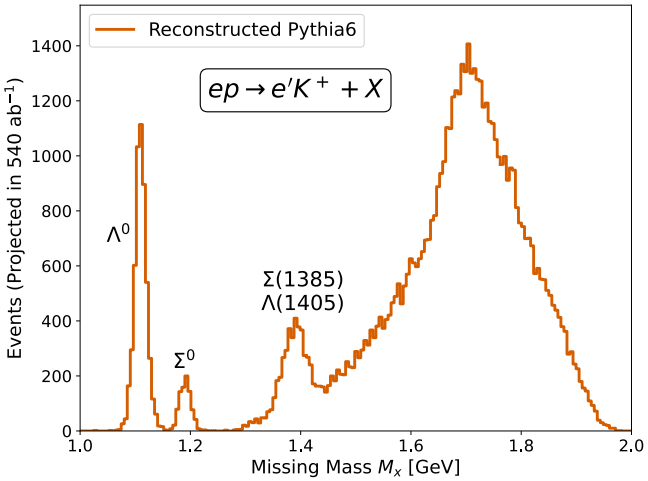
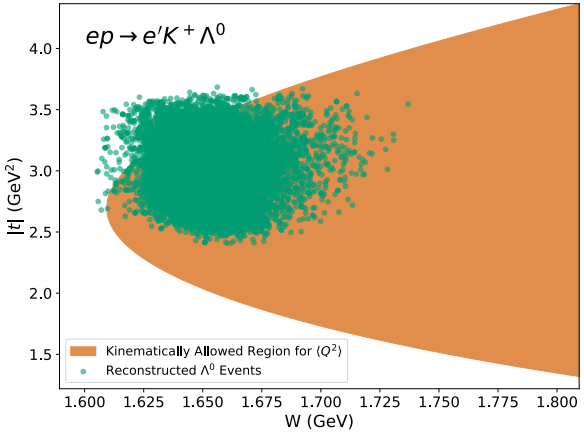
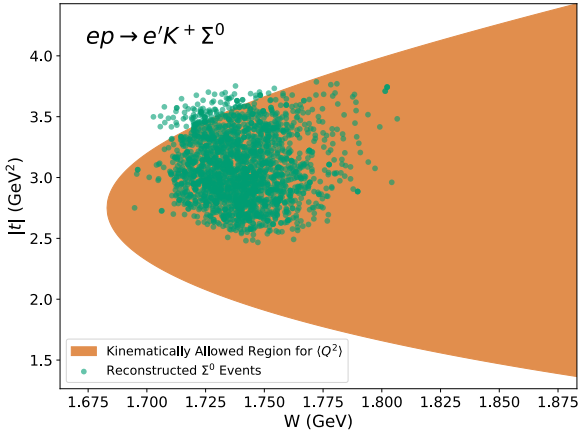
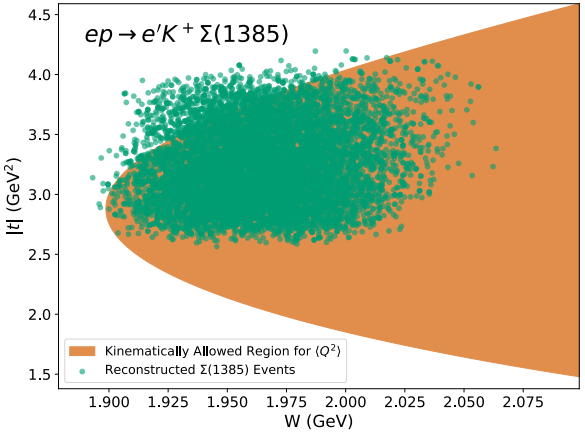
WE CAN DO *U*-CHANNEL!



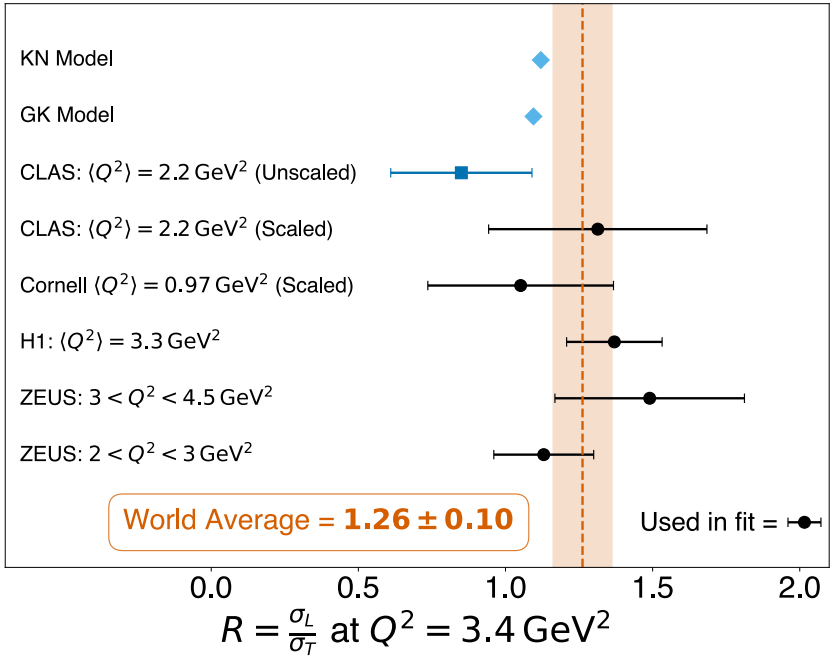
- Near-threshold, u-channel hyperon production is accessible **if K^+ can be efficiently ID'd**
- **Likely requires refurbishment of HMS aerogel**
- Note, PYTHIA6 resonance region cross sections are unreliable (especially in u-channel)
  - However, SIMC acceptance is correct, so these hyperons are well within our acceptance



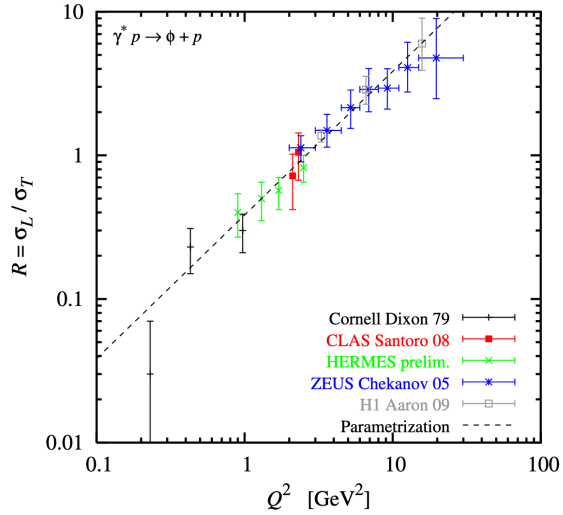




GETTING $d\sigma_L/d|t|$



- With $d\sigma_e/d|t|$, need R to get $d\sigma_L/d|t|$
  - Fit the world data to get an idea (and uncertainty) on this quantity within our phase space ($Q^2 \sim 3.4$ GeV²)
- World data suggests $R(Q^2)$ **not** $R(Q^2, W, |t|)$



- Use CLAS12 parameterization to scale nearby world datapoints

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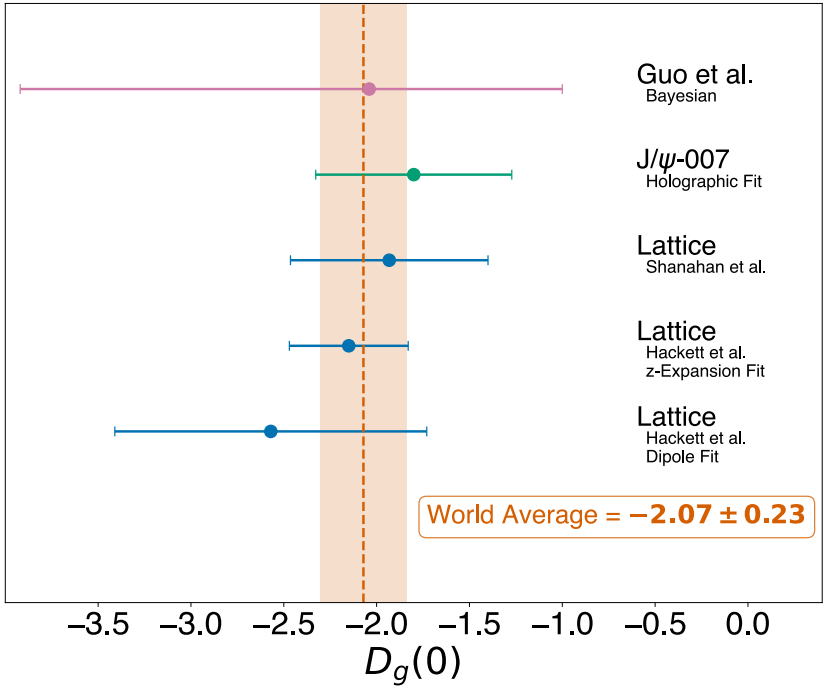
GETTING D_g



- Sensitivity of cross section to D_g isn't as large as D_s, but large uncertainties on D_g can still rain on our parade
  - Average the results of lattice + Hall C data + Guo/Yuan Bayesian analysis
  - Hopefully should more results soon (CLAS12)
  - Can also include some theoretical values in here if they seem realistic

- **In the end, it's obvious that a global fit to both D_g and D_s is the way to go!**

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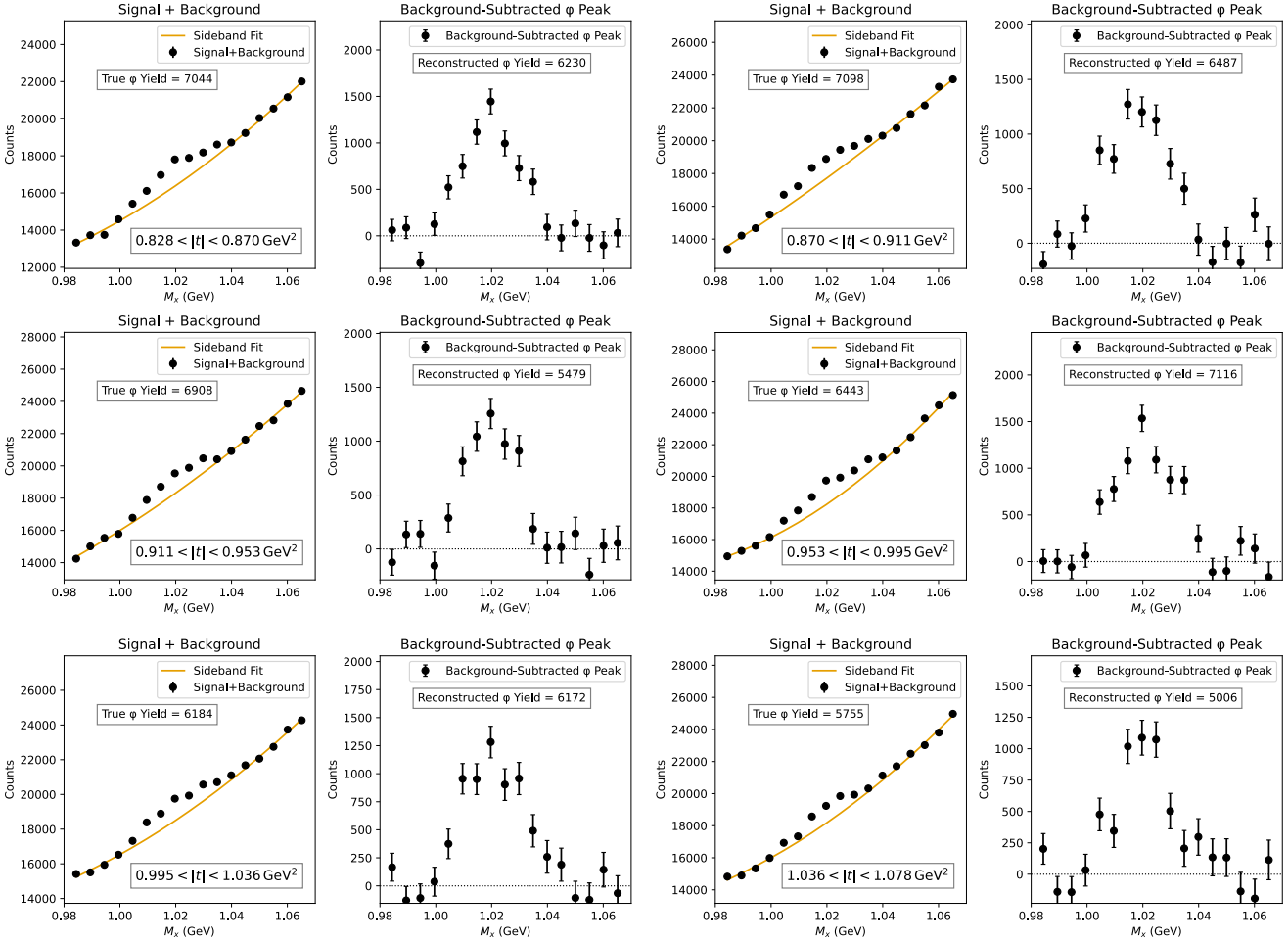

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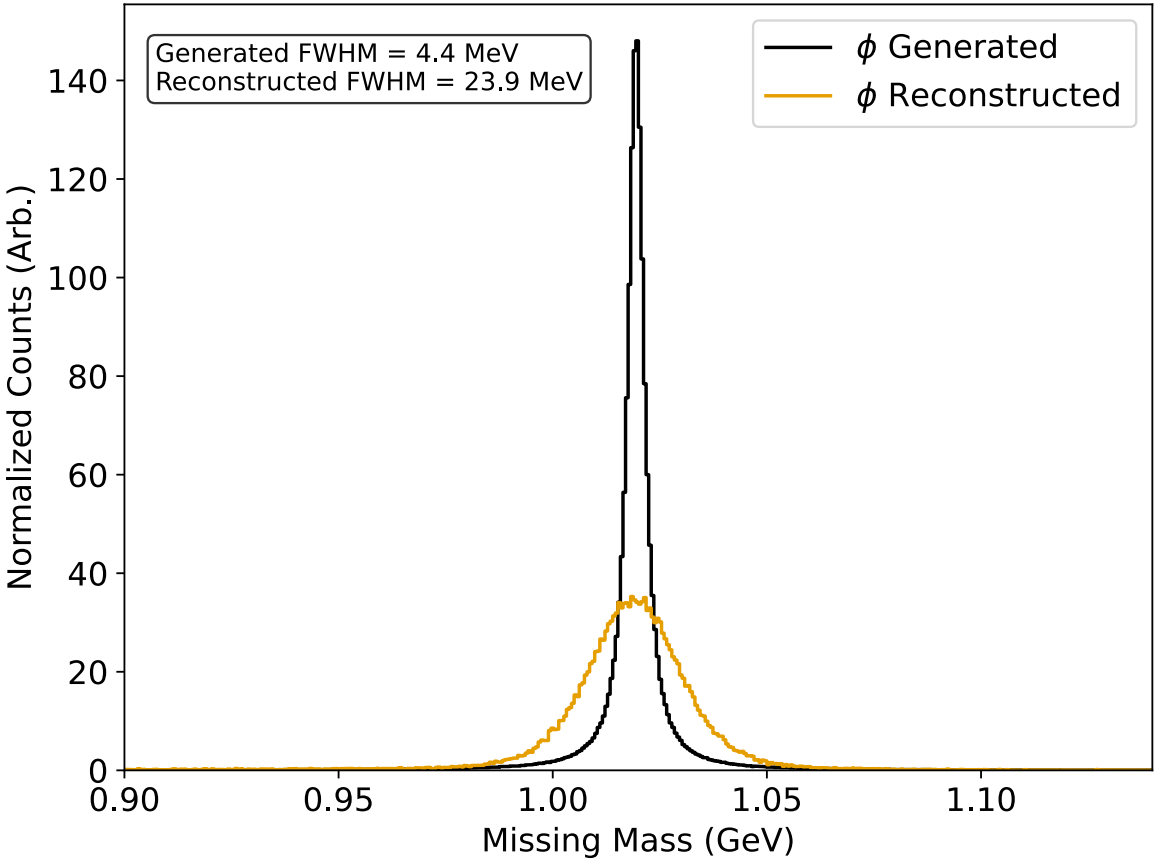

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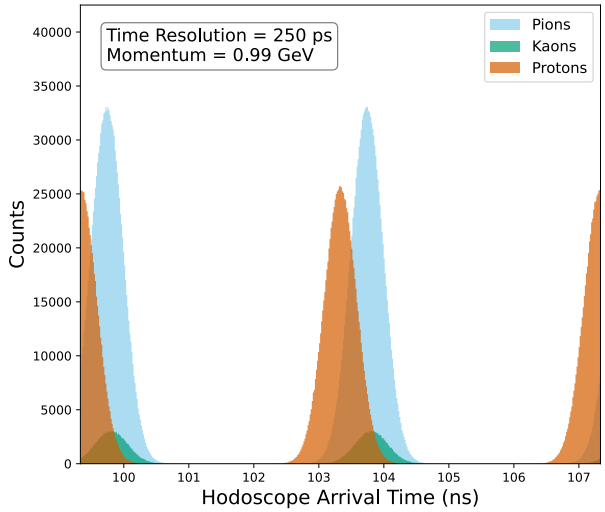

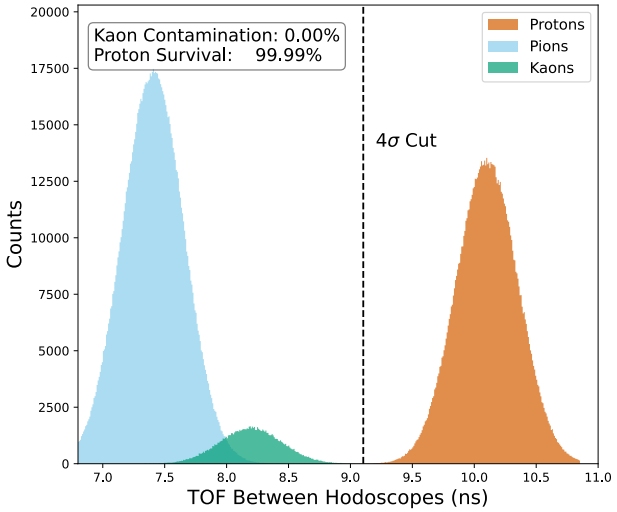

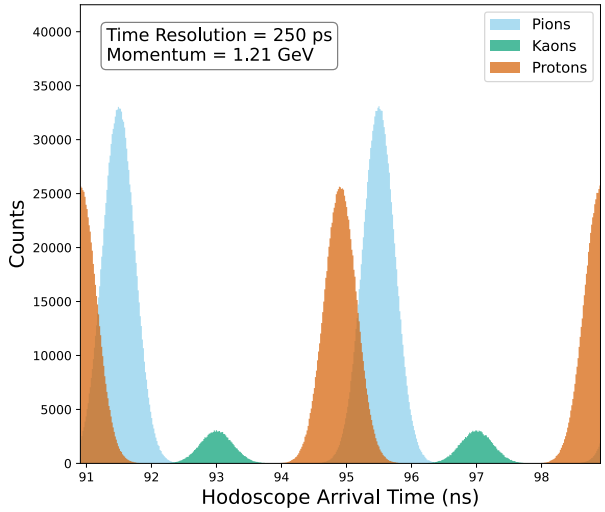

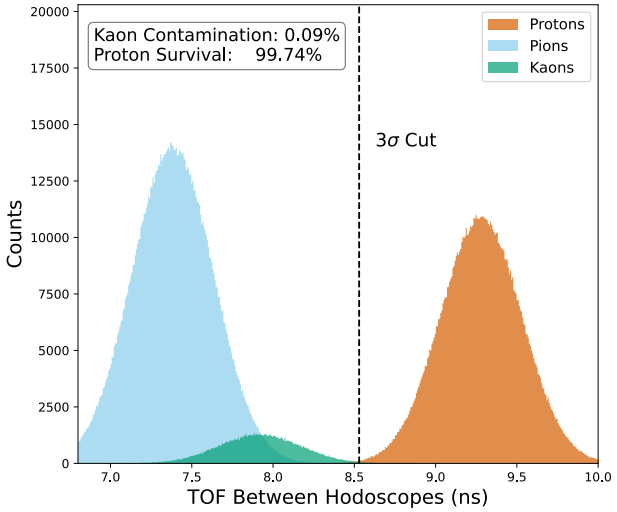

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THEORY PREDICTIONS

Hatta, HK, Passek, Schoenleber (2501.12343)

- New predictions available from Hatta et al. using GPD framework in the near-threshold region
  - Typical issue for GPDs near-threshold is final-state interactions
  - FSI calculated to be 2-3 orders of magnitude smaller than production cross section for $\phi + p$ in photoproduction (S. H. Kim et al.)

$$\frac{d\sigma_L}{dt} = \frac{2\pi^2 \alpha_{em}}{(W^2 - M^2) W p_{cm}} \left((1-\xi^2)|\mathcal{H}|^2 - \left(\frac{t}{4M^2} + \xi^2 \right) |\mathcal{E}|^2 - 2\xi^2 \mathrm{Re}(\mathcal{H}\mathcal{E}^*) \right)$$

$$\begin{pmatrix} \mathcal{H}(\xi,t) \\ \mathcal{E}(\xi,t) \end{pmatrix} = \kappa \sum_{j=1}^{\text{odd}} \sum_{k=0}^{\text{even}} \sum_a \frac{2}{\xi^{j+1}} \begin{pmatrix} H_j^a(\xi,t) \\ E_j^a(\xi,t) \end{pmatrix} T_{jk}^a(\xi) \varphi_k, \qquad \kappa \equiv e_s \frac{C_F f_\phi}{N_c Q}.$$

"Threshold Approximation" – Keep only j = 1

$$\begin{pmatrix} \mathcal{H}(\xi,t) \\ \mathcal{E}(\xi,t) \end{pmatrix} \approx \frac{2\kappa}{\xi^2} \sum_a \begin{pmatrix} H_1^a(\xi,t) \\ E_1^a(\xi,t) \end{pmatrix} T_{10}^a(\xi,\mu^2).$$

- Theoretical uncertainty on cross section from this approximation is ~10% or less for $\xi > 0.3$!
  - Focus on high ξ

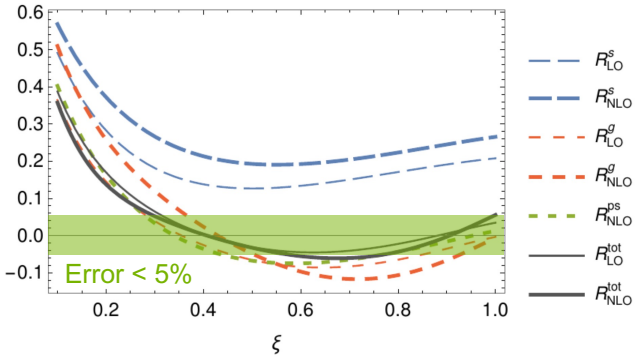
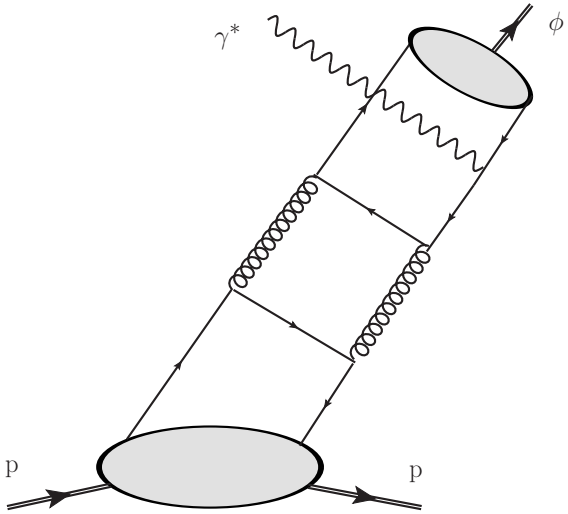
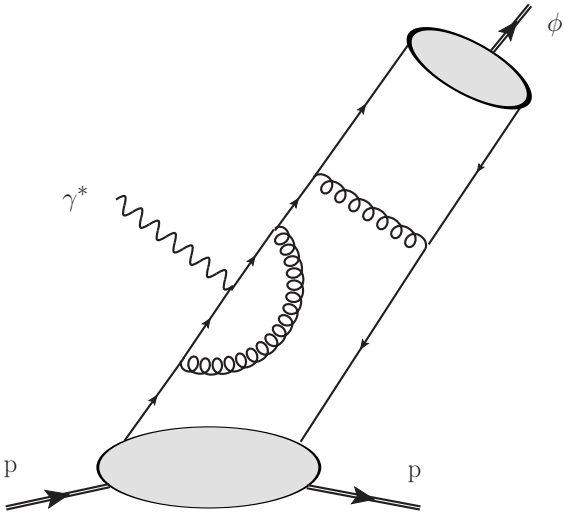


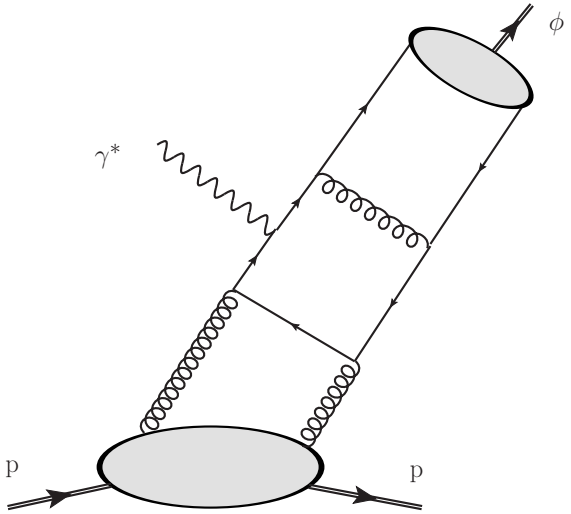
FIG. 4: Relative error for the amplitude $\mathcal{H}$ from truncating the conformal partial wave expansion after the first term. Plotted quantities are defined in (40). The subscript denotes whether the leading order (LO) or next-to-leading order (NLO) coefficient function has been used. In this and the next plots, we have set $t = t_{\min}(\xi)$, $\alpha_s = 0.3$ and $\kappa = 1$.

THEORY PREDICTIONS

Hatta, HK, Passek, Schoenleber (2501.12343)

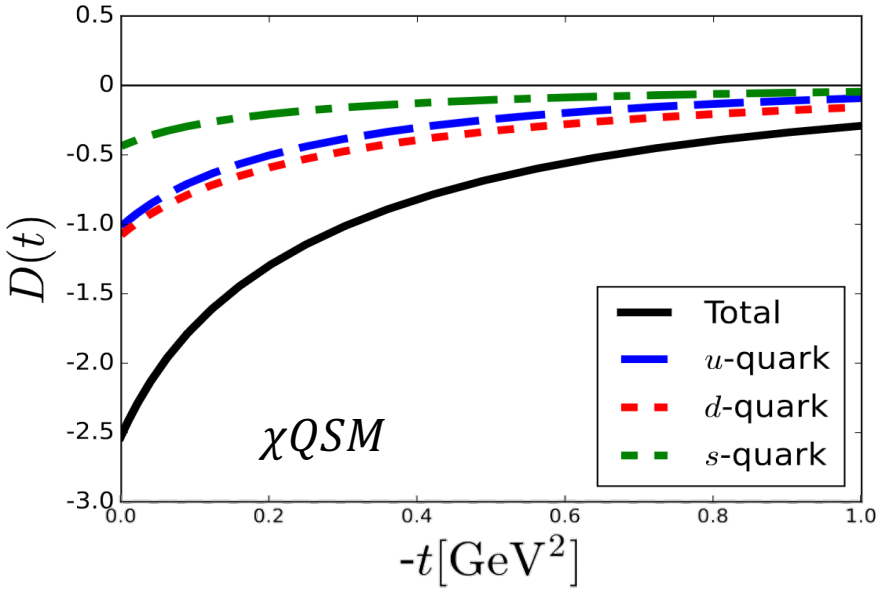


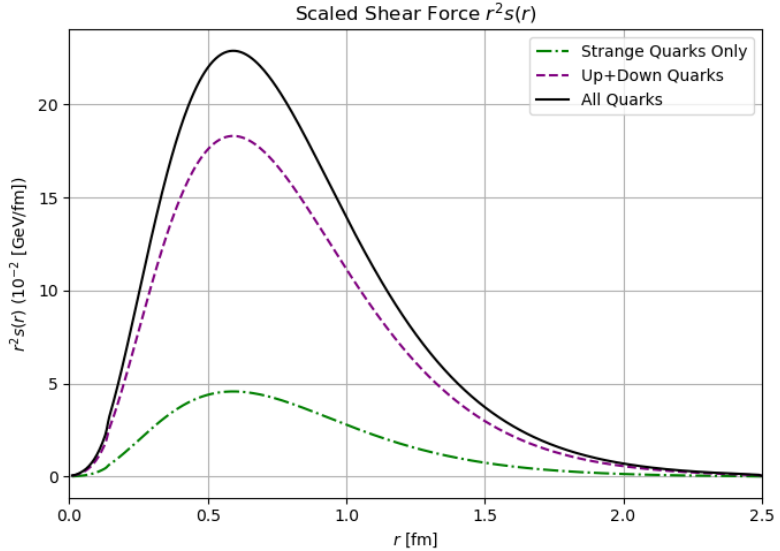




THEORY PREDICTIONS

D_s is a non-negligible contributor to the total D-term, and thus **necessary for a full extraction of many of the mechanical properties of the proton!**





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