THE STRANGE MECHANICAL STRUCTURE OF THE PROTON IN HALL C

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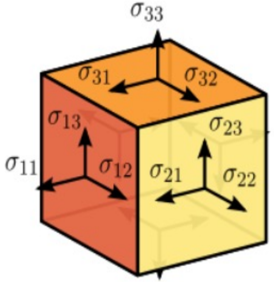
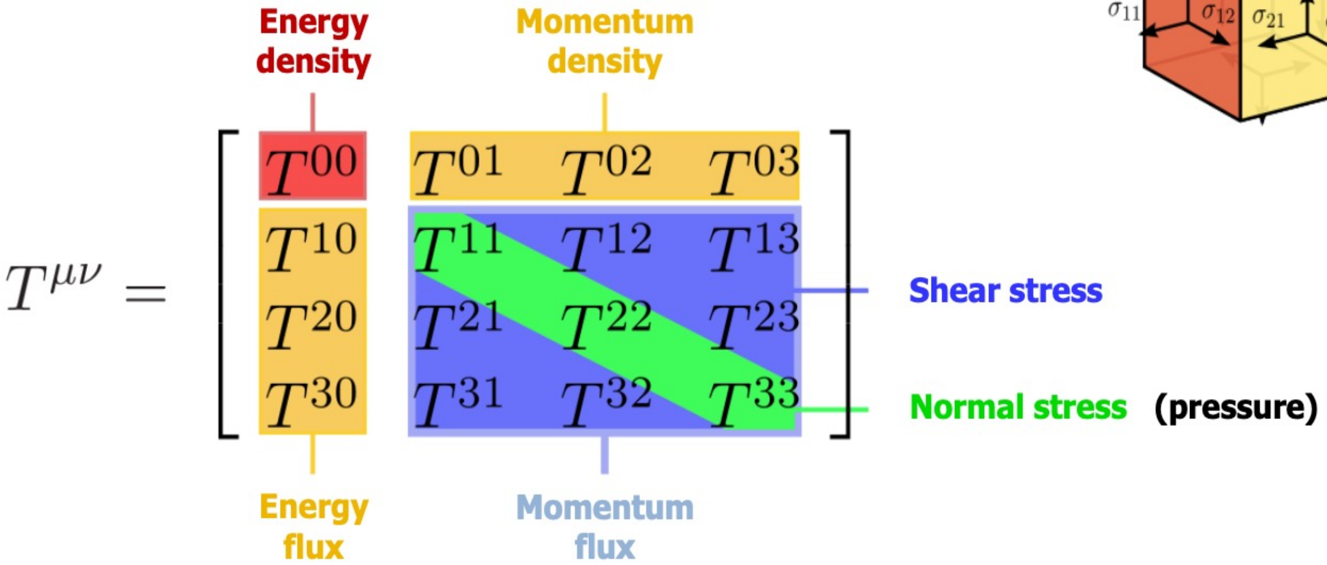
PROTON MECHANICAL STRUCTURE

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





GRAVITATIONAL FORM FACTORS

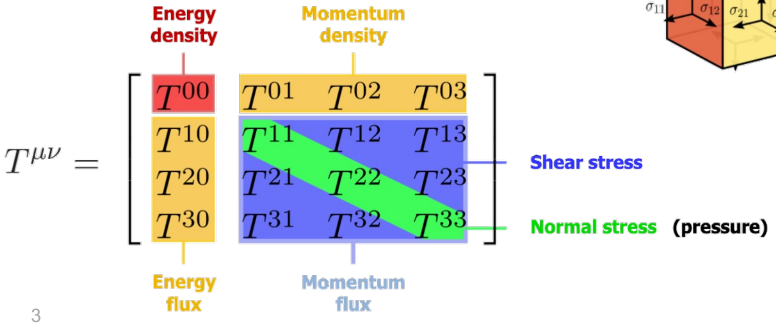
- Proton gravitational form factors (GFFs) encode information about the matrix elements of the QCD energy-momentum tensor

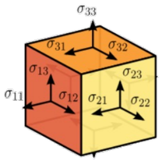
$$\langle p', s' | \hat{T}^a_{\mu\nu}(x) | p, s \rangle = \bar{u}' \left[A^a(t) \frac{\gamma_{\{\mu} P_{\nu\}}}{2} + B^a(t) \frac{i\, P_{\{\mu} \sigma_{\nu\}\rho} \Delta^\rho}{4m} + D^a(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2}{4m} + m\, \bar{c}^a(t)\, g_{\mu\nu} \right] u\, e^{i(p'-p)x}$$

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

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

EMT Matrix Elements





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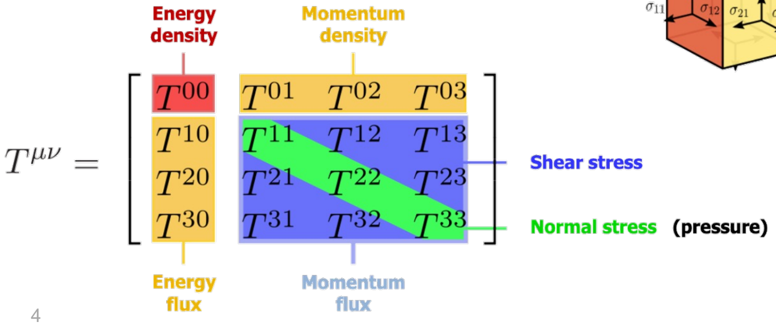
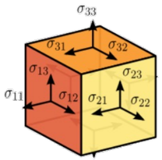
Form factors

Fourier transforms of spatial distributions





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Form factors

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“Gravitational”

Describing the energy-momentum tensor

I.e. what would be seen from proton-graviton scattering

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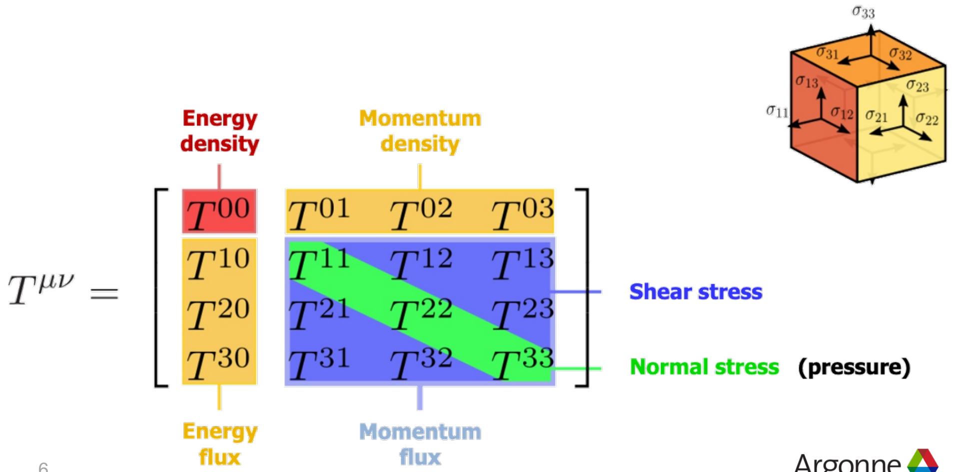
D-term

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

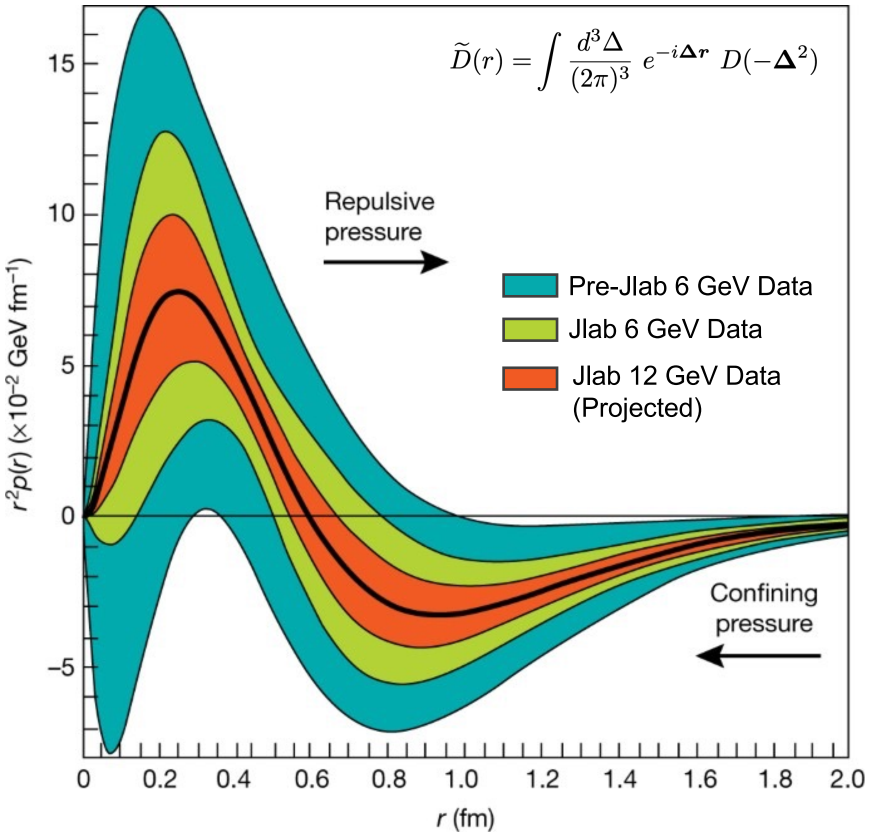
On par with spin, charge, mass!



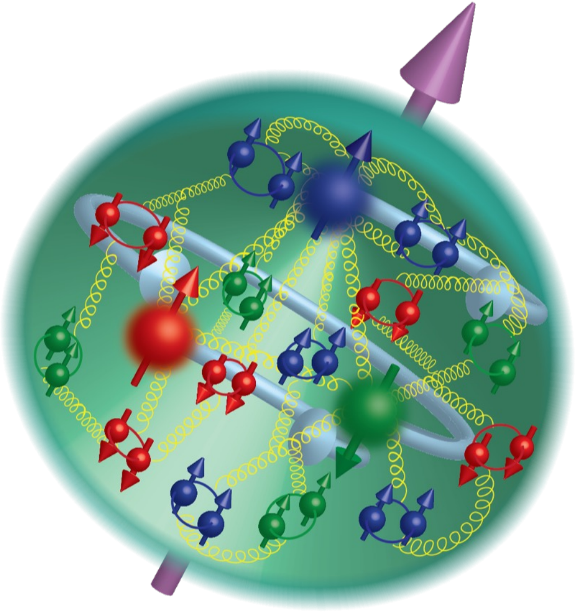
MECHANICAL PROPERTIES

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

- 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



ASIDE: UNDER PRESSURE



Proton:

10^{30} atmospheres!?

At r = 0.3 fm

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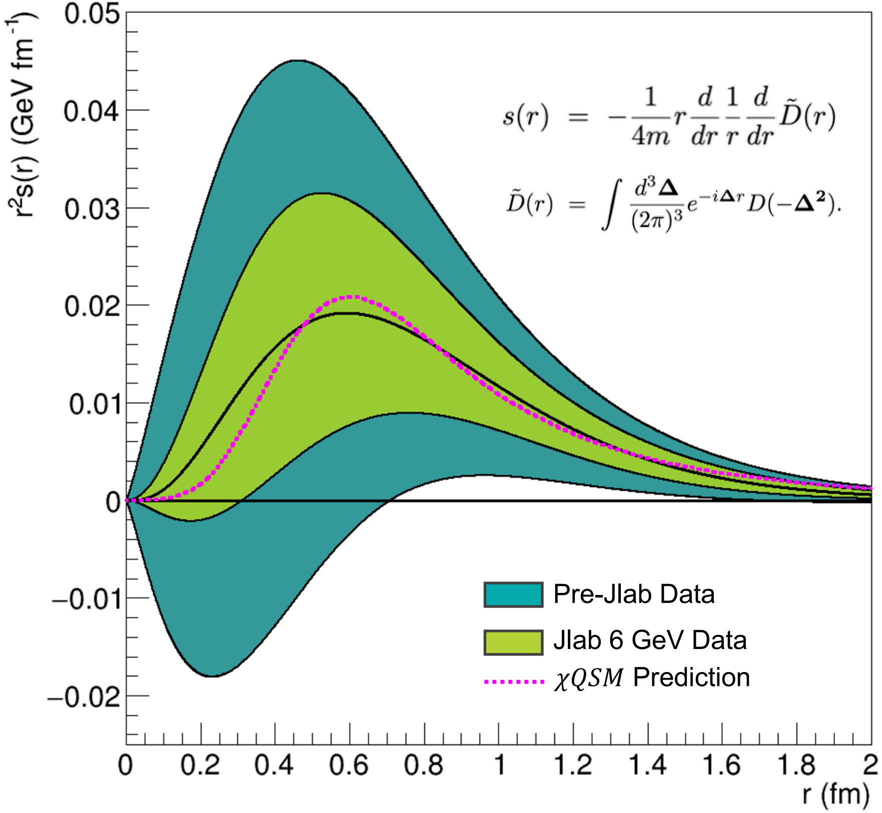

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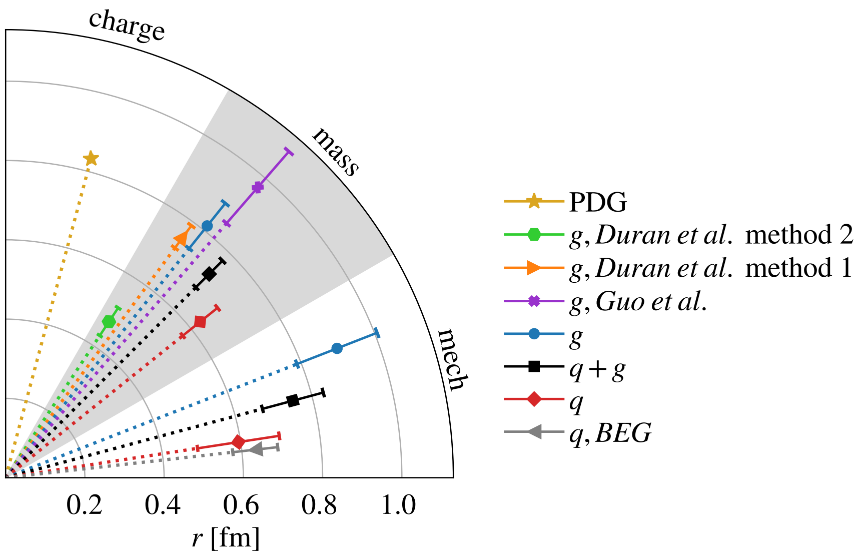
$$\langle r^2 \rangle_{\text{mech}} = \frac{\int d^3r\ r^2\ \left[\frac{2}{3}s(r) + p(r)\right]}{\int d^3r\ \left[\frac{2}{3}s(r) + p(r)\right]} = \frac{6D}{\int_{-\infty}^{0} dt\ D(t)}$$



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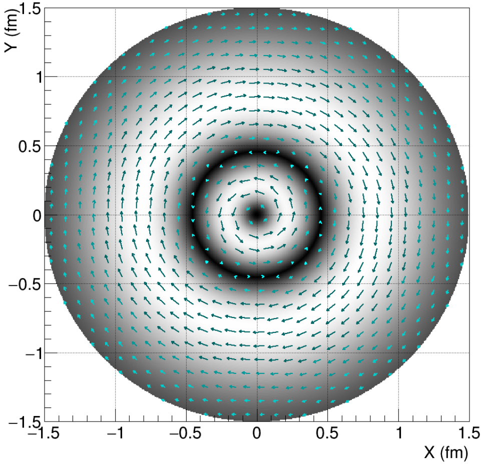
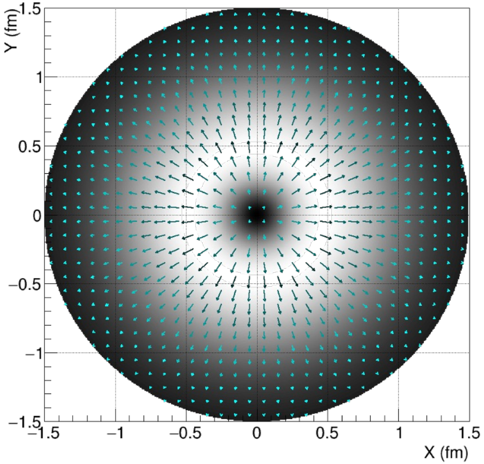


Tangential force

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



Normal force

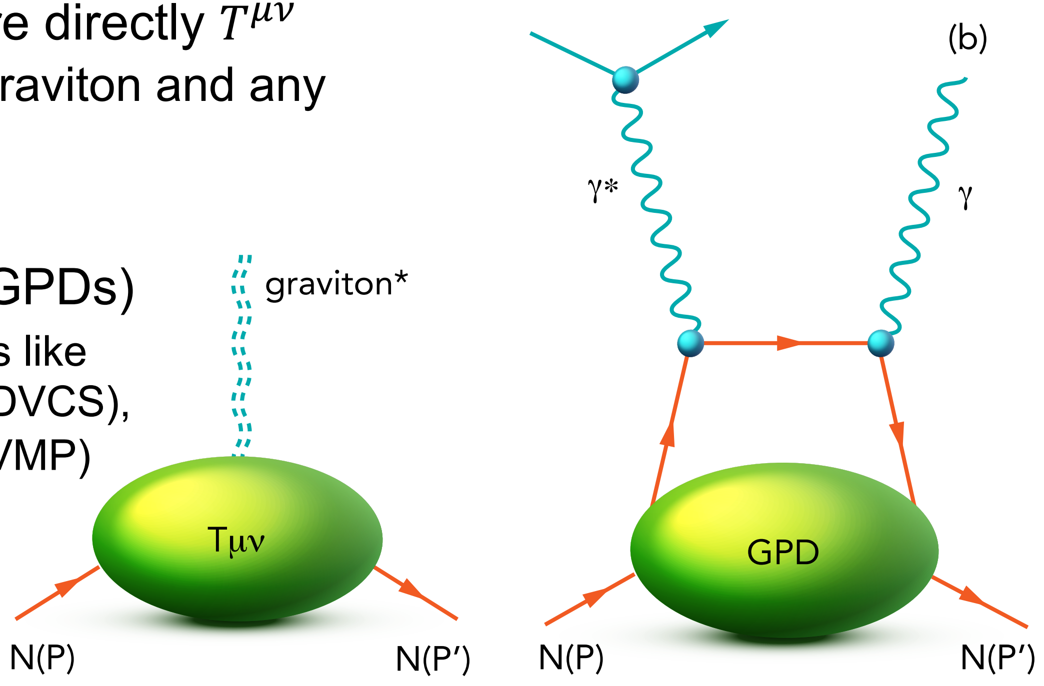
$$\frac{dF_r}{dS_r} = \frac{2}{3}s(r) + p(r)$$

HOW DO WE MEASURE THIS STUFF?

- Graviton scattering would measure directly $T^{\mu\nu}$
  - Exploit the duality between the graviton and any massless spin-2 field

- D-term is a contribution to the generalized parton distributions (GPDs)
  - Measured in hard exclusive reactions like Deeply Virtual Compton Scattering (DVCS), Deeply Virtual Meson Production (DVMP)

- Extractions of D-term can go through GPDs, or use models to bypass them depending on the process



Graviton exchange ≈ Deeply Virtual Compton Scattering

HOW DO WE MEASURE THIS STUFF?

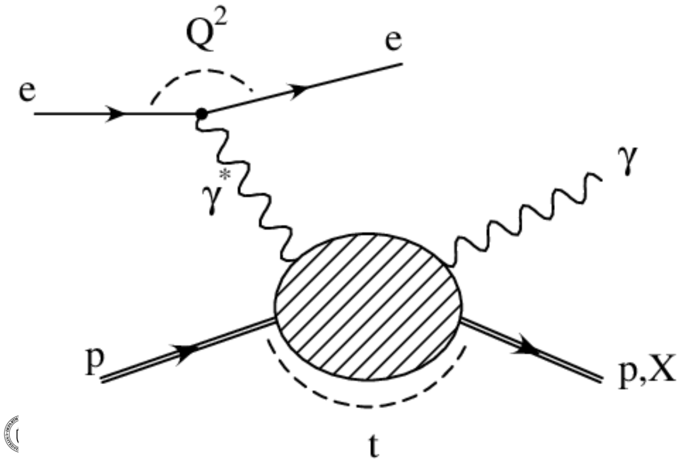
The total D-term is related to the partonic D-terms by a sum rule:

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

Different exclusive processes provide access to the different partonic D-terms!

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

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

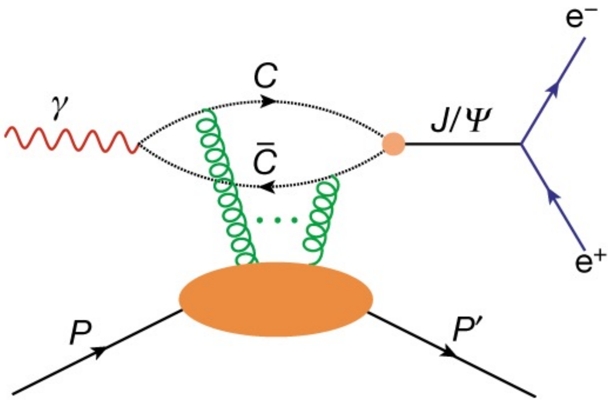


The pressure distribution inside the proton

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

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

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

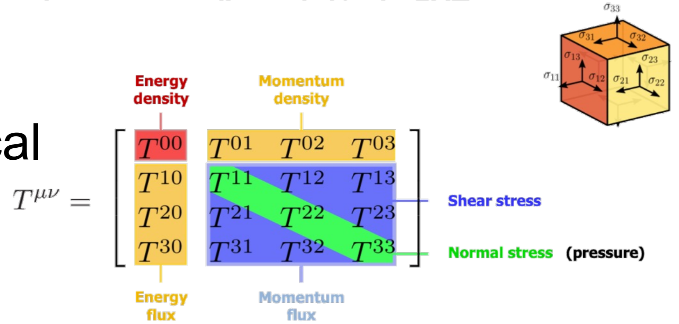


Determining the Proton's Gluonic Gravitational Form Factors

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]

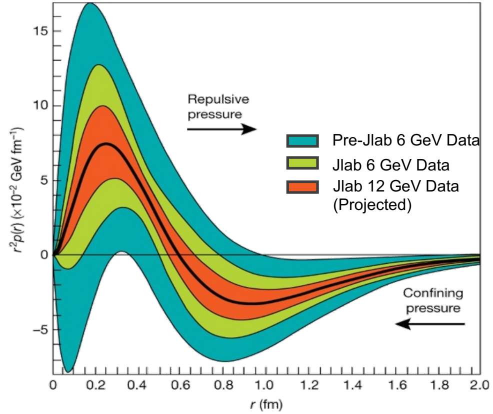
$\bar{c}$ CAVEAT

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



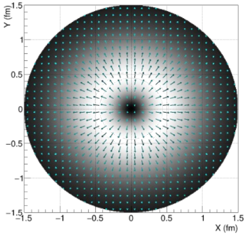
$$\langle p', s'|\hat{T}^a_{\mu\nu}(x)|p, s\rangle = \bar{u}'\left[A^a(t)\frac{\gamma_{\{\mu}P_{\nu\}}}{2} + B^a(t)\frac{i\,P_{\{\mu}\sigma_{\nu\}\rho}\Delta^\rho}{4m} + D^a(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{4m} + m\,\bar{c}^a(t)\,g_{\mu\nu}\right]u\,e^{i(p'-p)x}$$

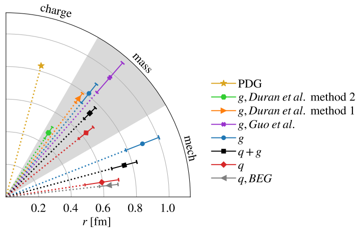
Pressure defined as: $p^a(r) = \frac{1}{6m}\frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr}\widetilde{D^a}(r) - m\int\frac{d^3\Delta}{(2\pi)^3}\,e^{-i\mathbf{\Delta r}}\,\widetilde{C}^a(-\mathbf{\Delta}^2)$



- However, $\bar{c}_q = -\bar{c}_g$! → Total $\bar{c}$ **cancels** due to EMT conservation **if summing over all parton species!**
  - Only shear force has no contribution from T^{ii} components of the EMT, and thus no contribution from $\bar{c}$

This caveat means that to extract the rest of the mechanical properties rigorously, all partonic D-terms must be known!





Since we need all terms in the sum rule to extract pressure, mechanical radius, force distributions…

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

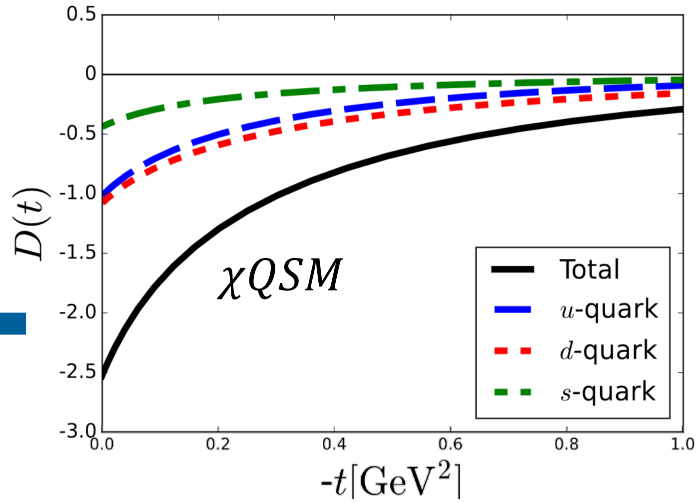
Strange quarks: Can we just neglect them…?

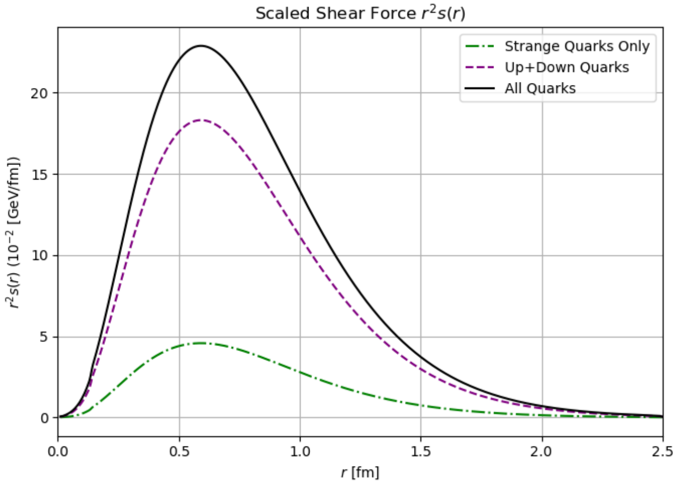
THEORY PREDICTIONS

ArXiv: 2307.00740

- Large-N_c theory predicts that the D-term is "flavor-blind"
  - i.e. $D_u \sim D_d$ despite their different number densities, this is supported by lattice results
- Extending this argument, could $D_u \sim D_d \sim D_s$?
- Chiral quark soliton model: $D_u \sim D_d \sim 2D_s$

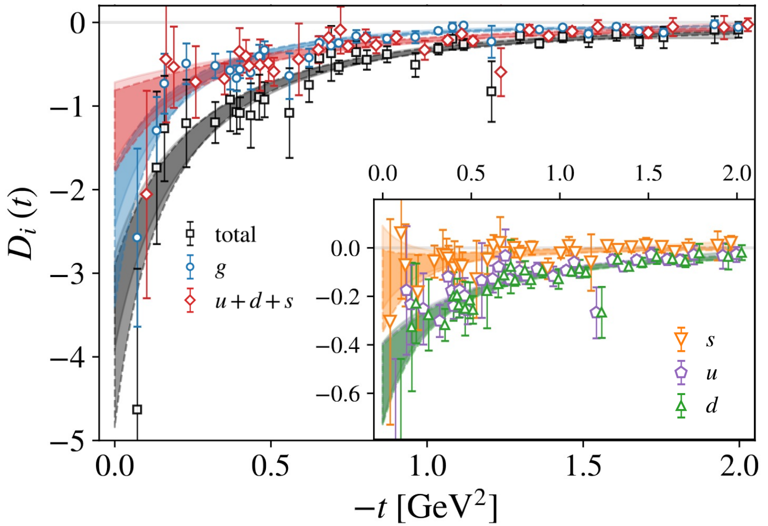
This would make D_s a non-negligible contributor to the total D-term, and thus **necessary for a full extraction of many of the mechanical properties of the proton!**





THEORY PREDICTIONS

- On the other hand, lattice results of Hackett et al. predict D_s consistent with zero
  - Uncertainties are still large, but the results do not exclude ***positive* values of D_s**
- Opposite signs of sea & valence quarks is a distinct possibility, predicted by χQSM



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

	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)

- **The pop-sci articles write themselves…**

Variety of theory predictions giving very different values for D_s, let's measure it!

But how…?

Variety of theory predictions giving very different values for D_s, let's measure it!

But how…?

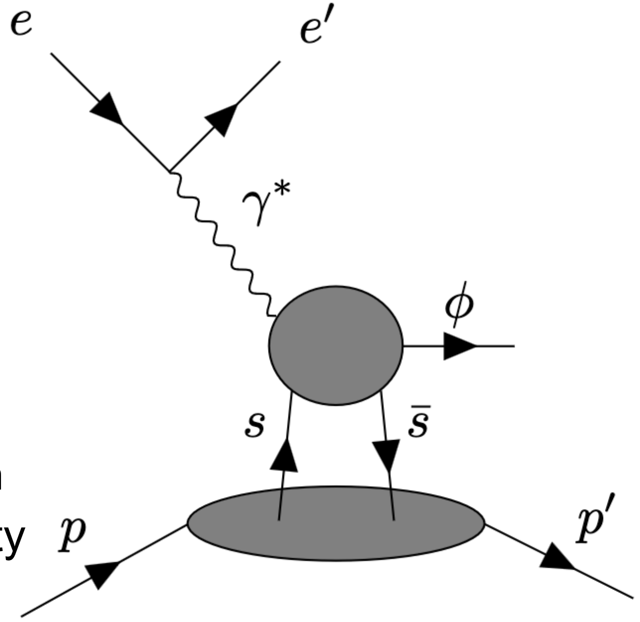
Exclusive ϕ in Hall C!

ACCESSING THE STRANGENESS D-TERM

- Information on strangeness in the proton is limited
  - Disentangling it from up & down requires use of specialized processes
  - e.g. W/Z exchange or kaon production in SIDIS

- Recently, it was proposed that *near-threshold electroproduction of ϕ mesons* could provide sensitivity to the strangeness D-term
  - ϕ meson is very nearly a pure $s\bar{s}$ state
    - Expected to couple strongly to strangeness in the proton
  - Only imaginable process to cleanly access this quantity

- Never measured in the required kinematic region!

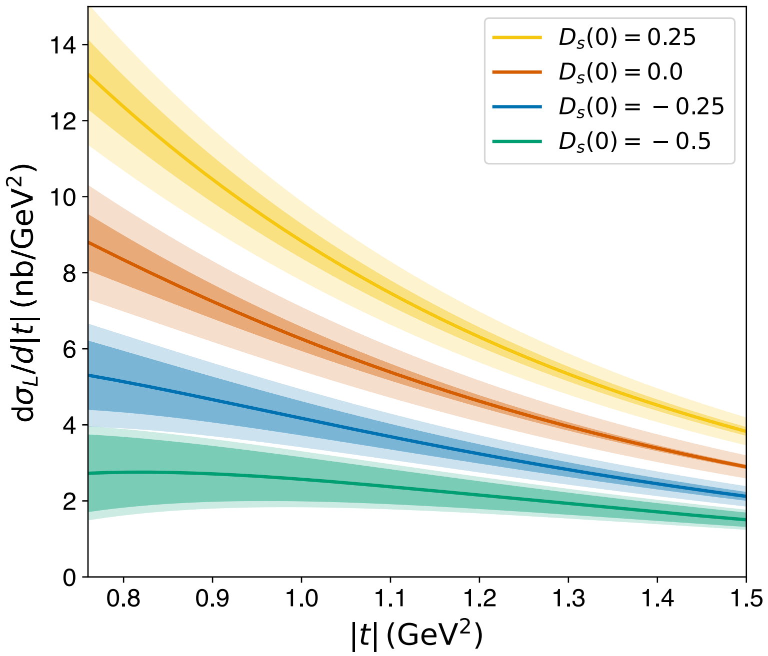


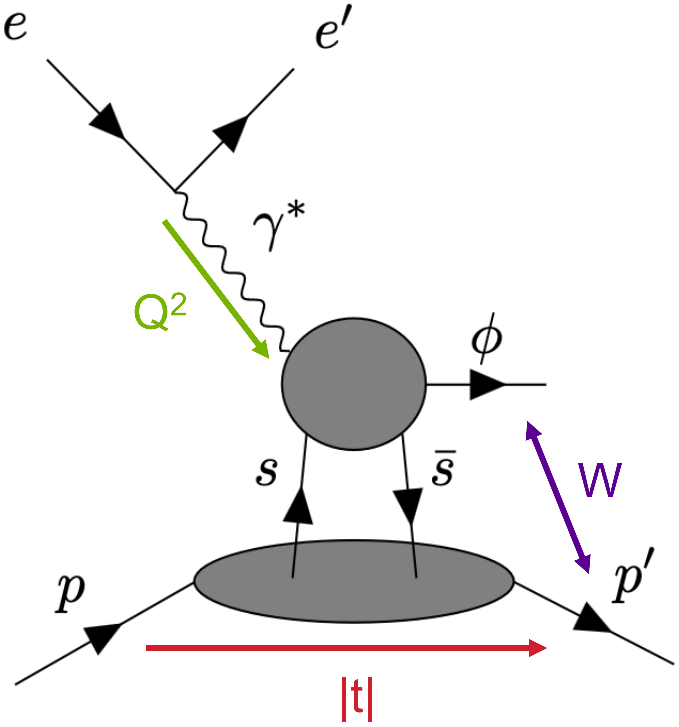
ϕ-meson lepto-production near threshold and the strangeness D-term

Yoshitaka Hatta [a b], Mark Strikman [c]

DEEP NEAR-THRESHOLD ϕ KINEMATICS

- Near-threshold = invariant mass of final-state hadrons $\mathbf{W \sim M_\phi + M_p}$ ~ 1.96 GeV
- Small momentum transfer to proton = **Low-|t|**
  - Strong sensitivity to strangeness D-term!





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Yoshitaka Hatta [a b], Mark Strikman [c]

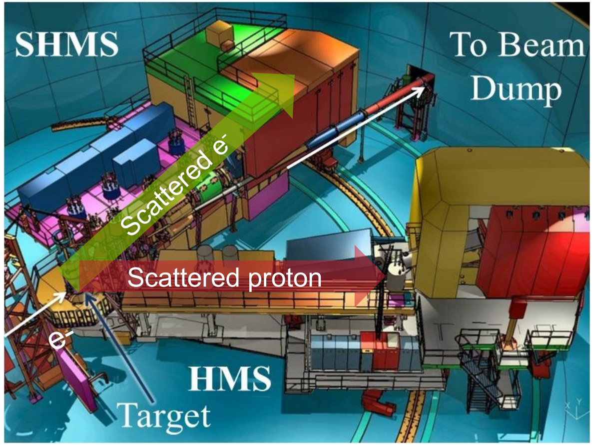
Deeply virtual ϕ-meson production near threshold

Y. Hatta, HK, K. Passek-K., J. Schoenleber

THE STRANGENESS D-TERM IN HALL C

2501.01582

- **Proposed Measurement:** Exclusive ϕ meson electroproduction near threshold in Hall C at Jefferson Lab (2024 LOI & 2025 PAC Proposal)
  - — Measure the |t|-dependence of the electroproduction cross-section using the reaction H(e, e′p)ϕ
  - — Uses the missing mass technique with standard Hall C spectrometers to identify exclusive events
    - No hit from $\phi \rightarrow KK$ BR, but large DIS background!



- **Theoretical Challenges:**

Two points raised by the PAC to the LOI:

- — Final-state Interactions: Extracting D_s requires understanding the dynamics of ϕ meson production and **final-state interactions**
- — Separating Quark and Gluon Contributions: **Need ability to distinguish between strange quark and gluonic effects**

Hall C Phi Collaboration, *"Studying the Strangeness D-Term in Hall C via Exclusive ϕ Electroproduction," JLab PAC 52 LOI (2024)*

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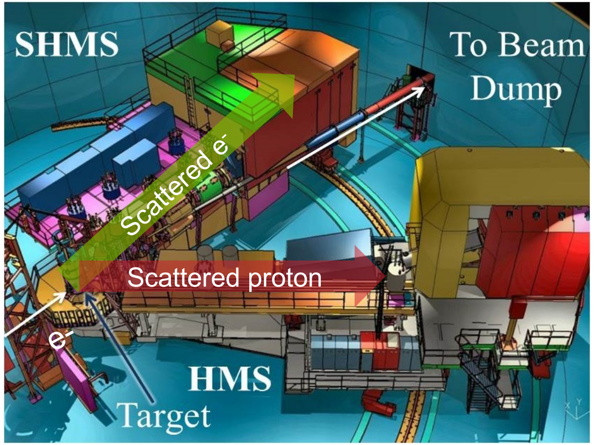

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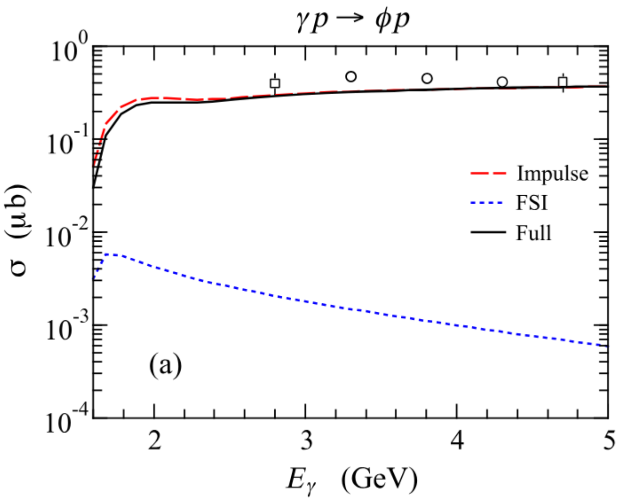
Jobs for theorists…

Hall C Phi Collaboration, *"Studying the Strangeness D-Term in Hall C via Exclusive ϕ Electroproduction," JLab PAC 52 LOI (2024)*

Argonne NATIONAL LABORATORY

THEORISTS HAVE BEEN BUSY!

FSI negligible



S.H Kim et al. (2108.12039)

NLO GPD calculation: ϕ Near-threshold exhibits factor ~ 4 greater sensitivity to D_s compared to D_g!

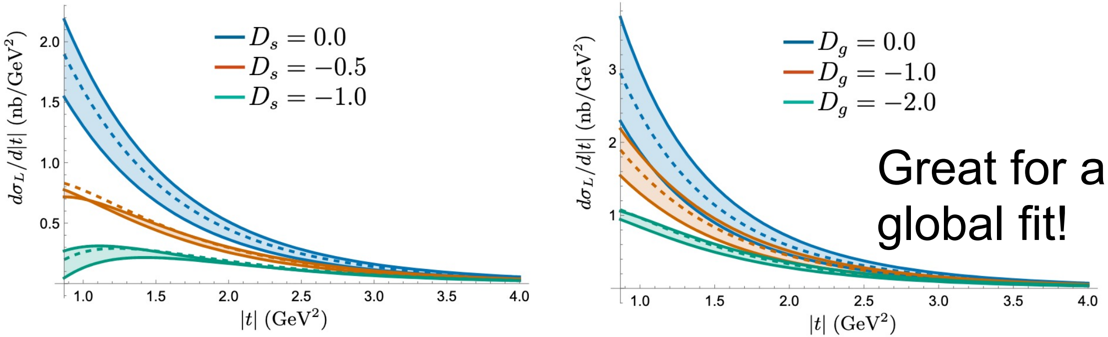


FIG. 7: NLO longitudinal cross section at $W = Q = 2.5$ GeV as a function of $|t|$. Left: $D_s = 0, -0.5, -1$ from top to bottom at fixed $D_g = -1$. Right: $D_g = 0, -1, -2$ from top to bottom at fixed $D_s = 0$.

Great for a global fit!

Hatta, HK, Passek, Schoenleber (2501.12343)

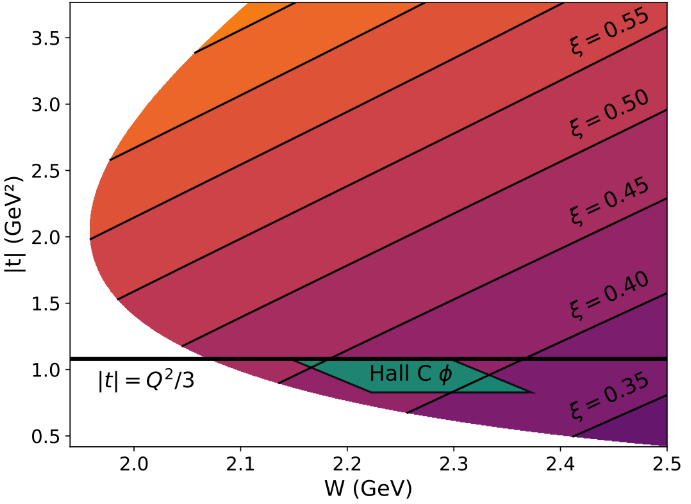
This is the green light for our experiments to measure D_s, so let's go!

KINEMATICS

- Challenging kinematic constraints from NLO GPD predictions

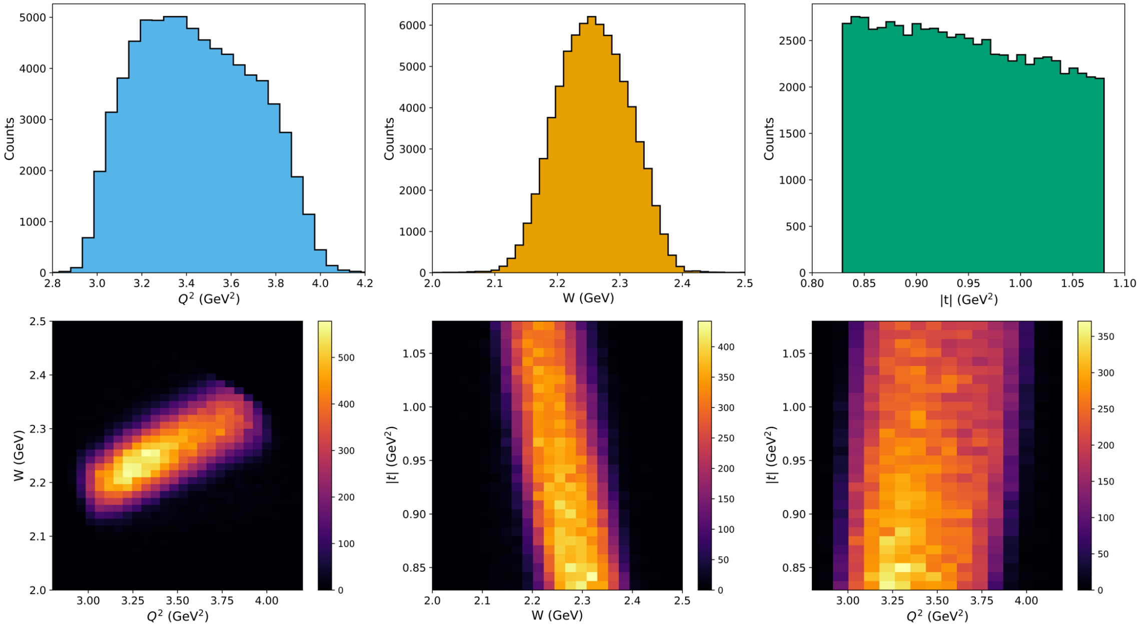
$$|t| \ll Q^2, W \sim W_{th.}, \xi > 0.4$$

- Very hard to go to higher Q^2
- DIS background scales as Q^4 while this process scales as $\sim Q^{9.5}$



- 75 μA on 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

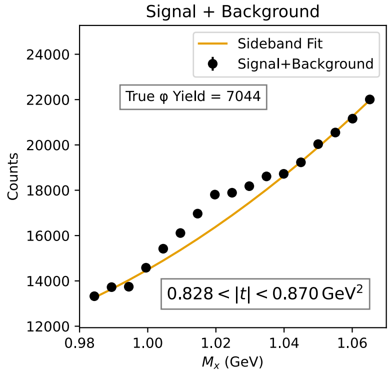
$Q^2 \sim 3.4$ GeV^2 W ~ 2.25 GeV $|t| \sim 0.95$ GeV^2

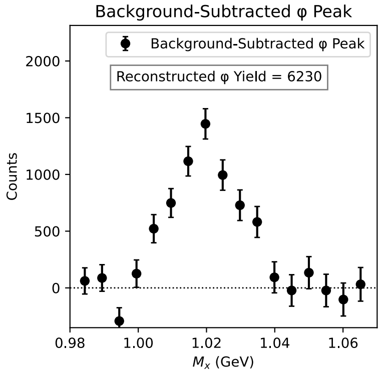


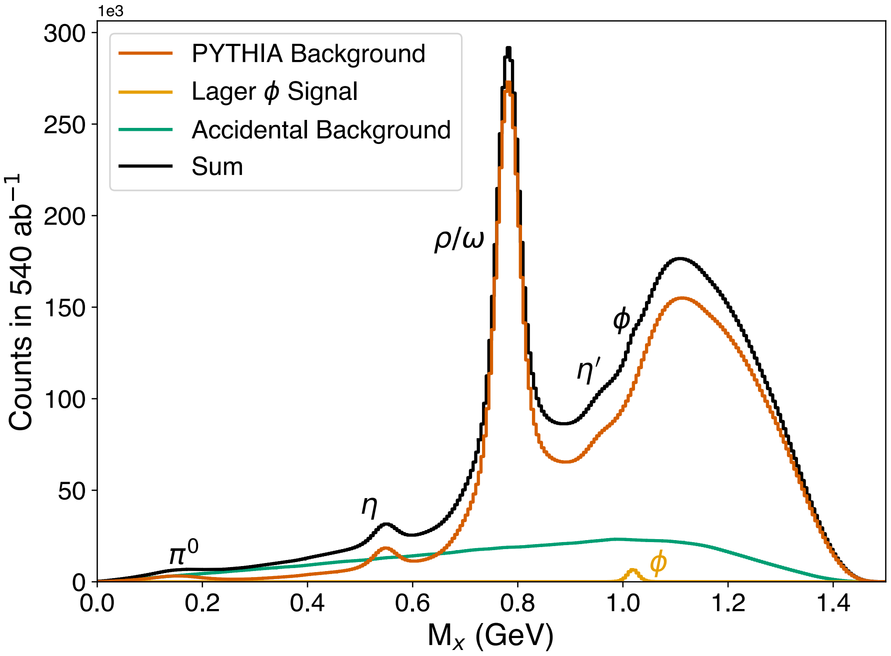
EXPERIMENTAL MEASUREMENT

- GPD Model wants $d\sigma_L/d|t|$
  - Use the Hall C spectrometers to get $e + p \rightarrow e' + p' + \phi$ by measuring the scattered electron and proton and inferring the ϕ via missing mass
    - Infer σ_L from σ_e and existing world data on R

- Large and irreducible DIS background!
  - However, missing mass resolution of the Hall C spectrometers is good enough to fit + subtract background



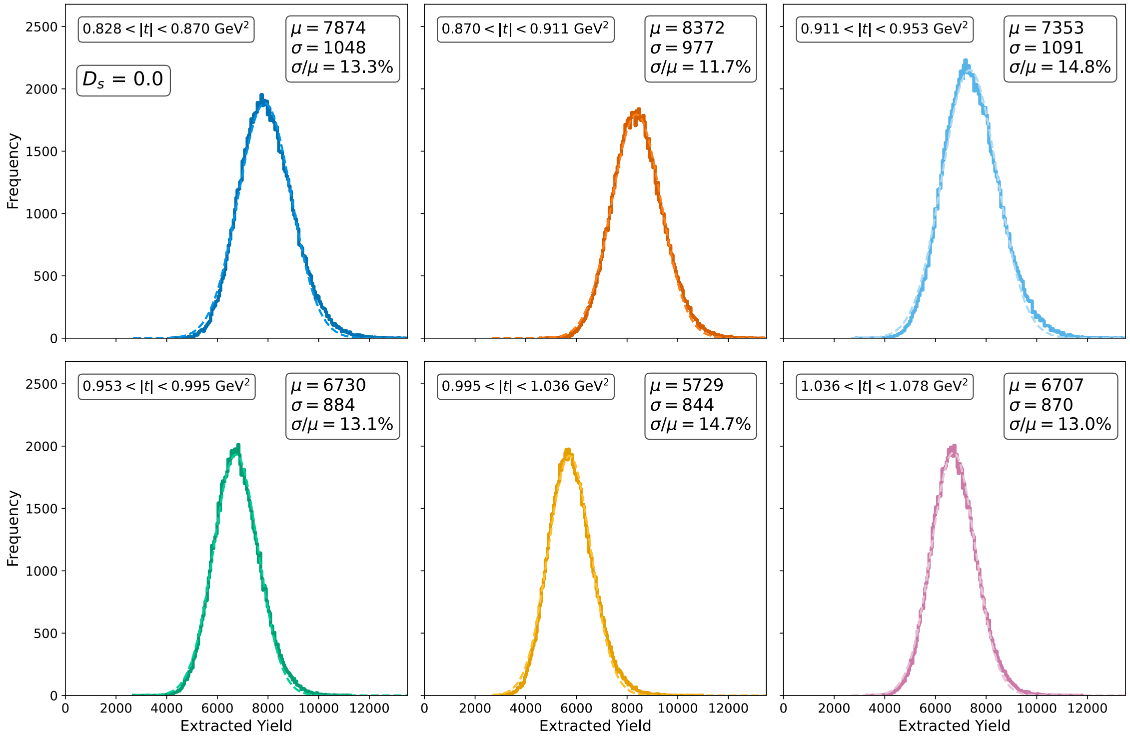




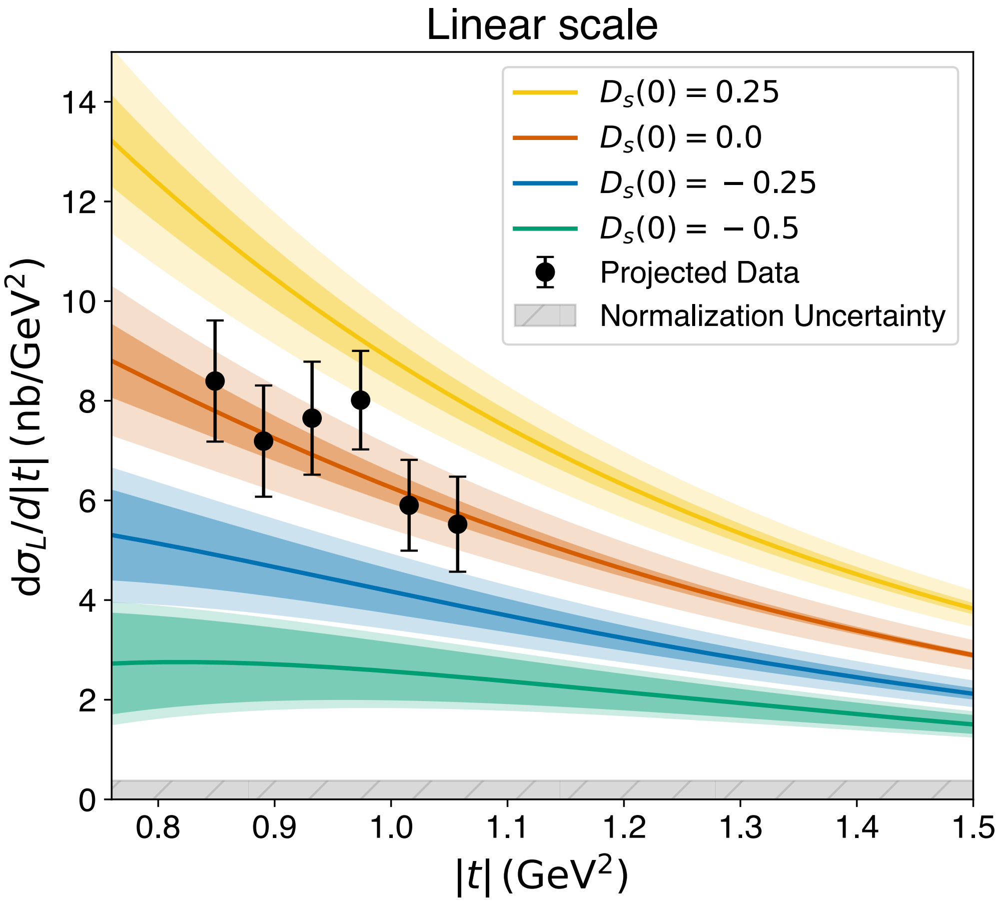
SIGNAL EXTRACTION

- Perform the background generation, fitting, and sideband background subtraction on pseudodata for many iterations

- Results of pseudoexperiments shown for 6 bins in $|t|$
  - Can bin less finely if cross section is smaller than predicted



CROSS SECTION PROJECTIONS



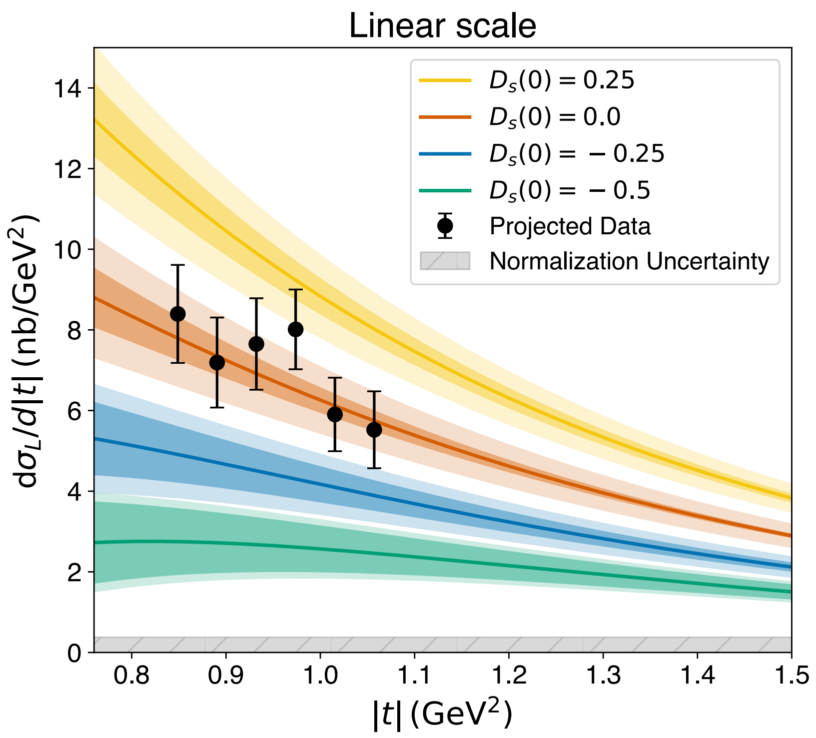
- Theoretical uncertainty from perturbative scale variation (inner) and uncertainty on D_g (outer)
- Experimental uncertainty from these sources:

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!

HOW WELL CAN WE EXTRACT D_S?

- Jitter datapoints and fit to theory predictions at different values of D_s
- Resolution depends strongly on size of cross section (which itself depends on D_s)
- Anticipate resolutions of 0.1 to 0.2 on $D_s(0)$
  — Similar to lattice uncertainty!
  — Precise enough to validate or invalidate the claim that $D_s \approx D_{u,d}$



$D_s(0)$ 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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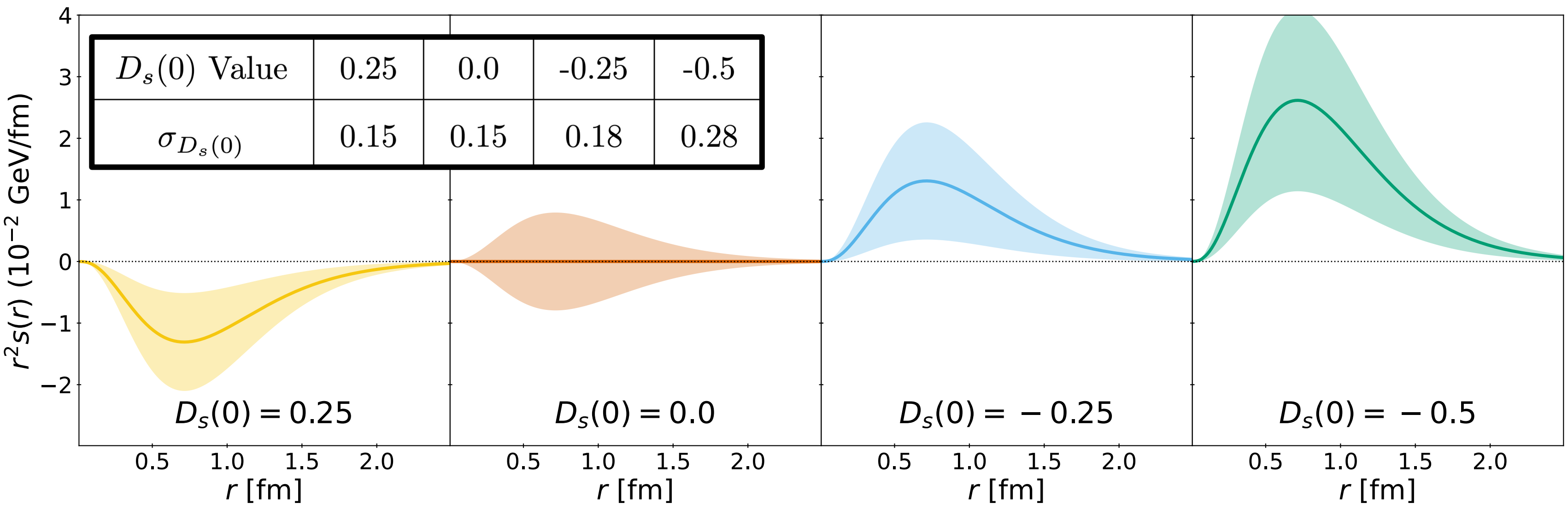
WHAT CAN WE LEARN?

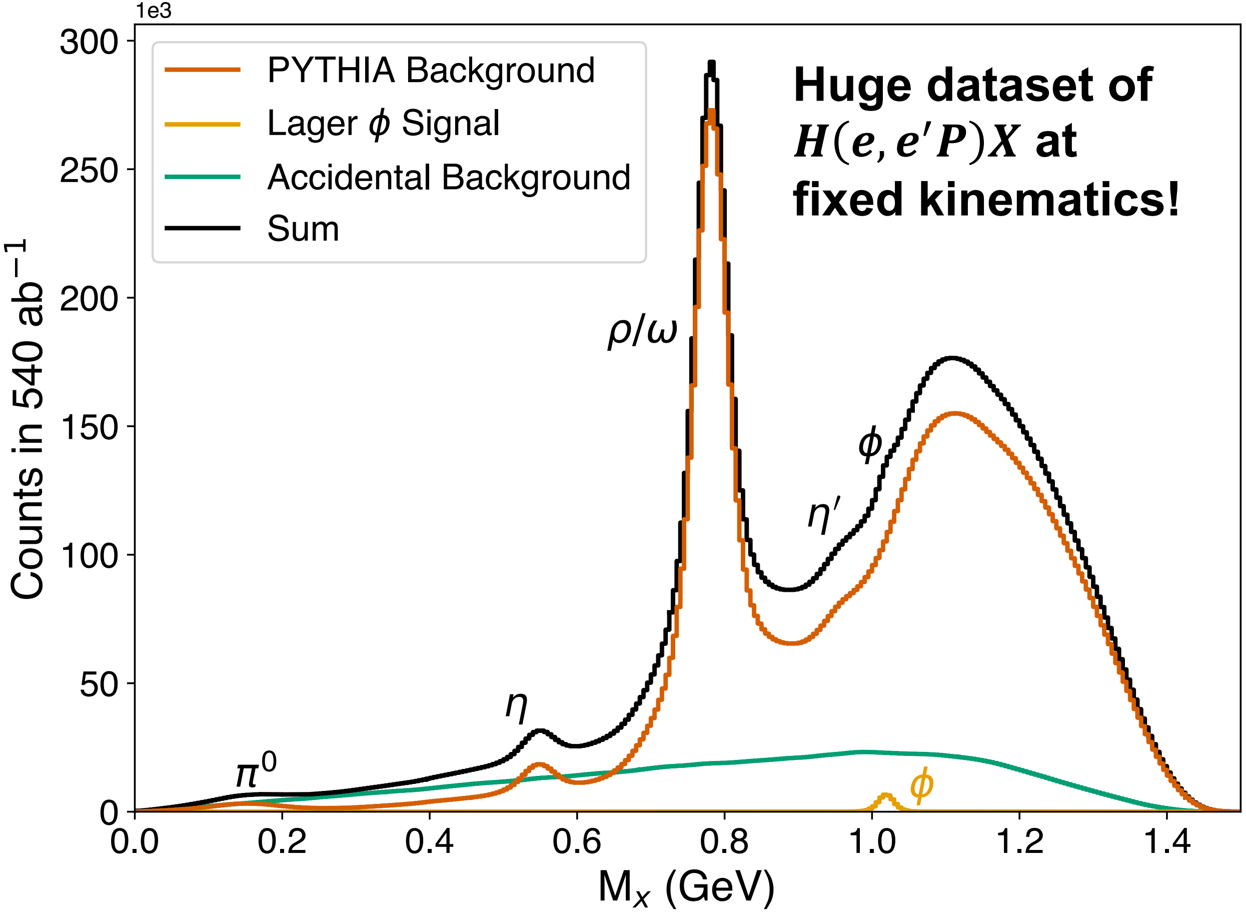
Using these resolutions on $D_s(0)$ and the standard functional form, can estimate the (model dependent) sensitivity to the **strangeness shear force distribution**

First ever measurement for sea quarks! Terra incognita…



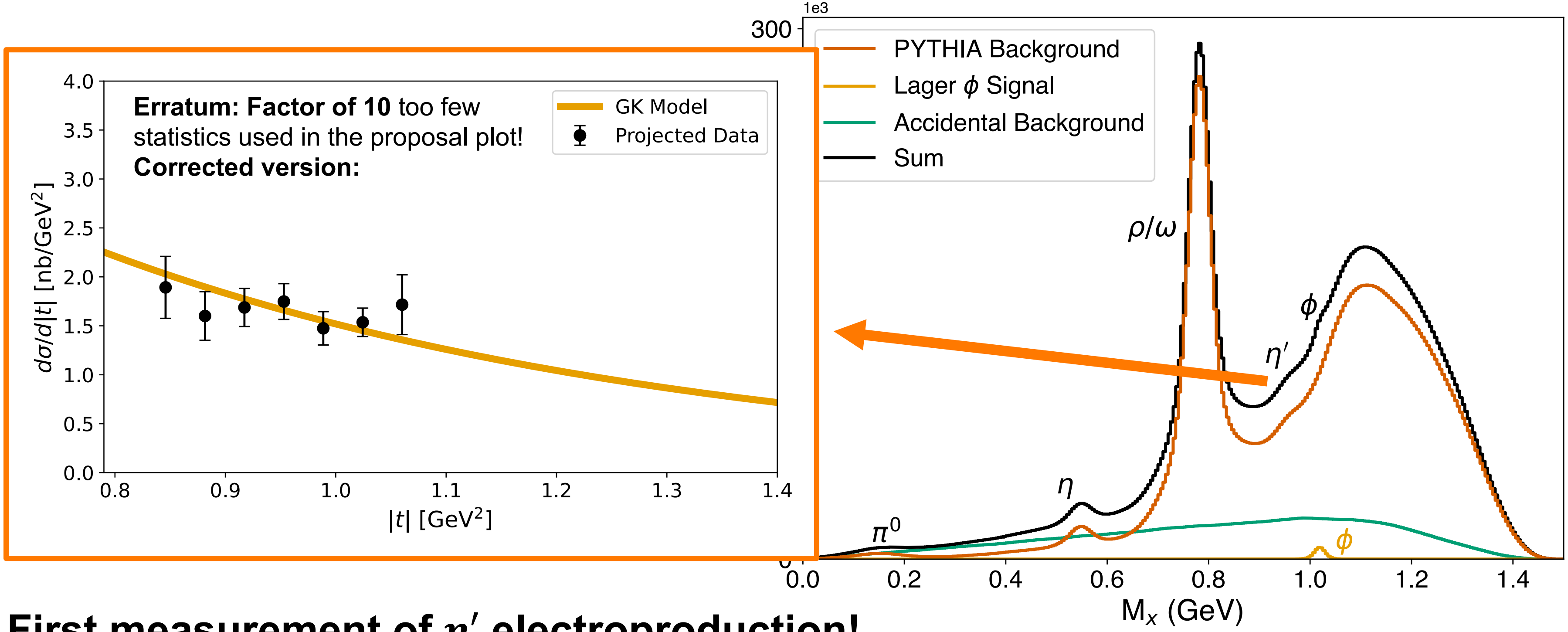
$D_s(0)$ Value	0.25	0.0	-0.25	-0.5
$\sigma_{D_s(0)}$	0.15	0.15	0.18	0.28

WHAT ELSE CAN WE LEARN FROM THIS DATA?



Huge dataset of $H(e, e'P)X$ at fixed kinematics!

WHAT ELSE CAN WE LEARN FROM THIS DATA?



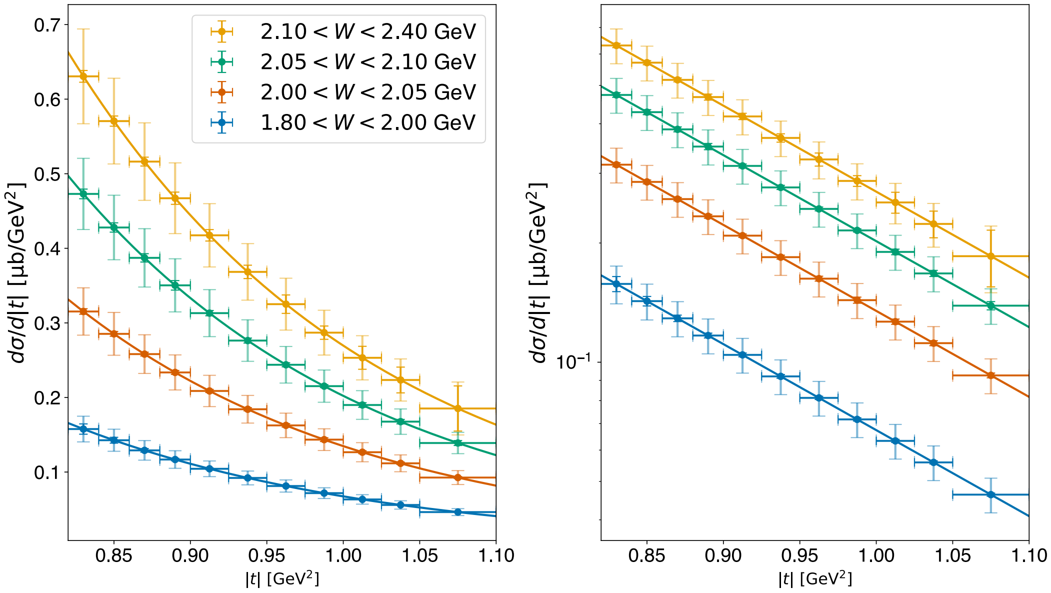
First measurement of η' electroproduction!

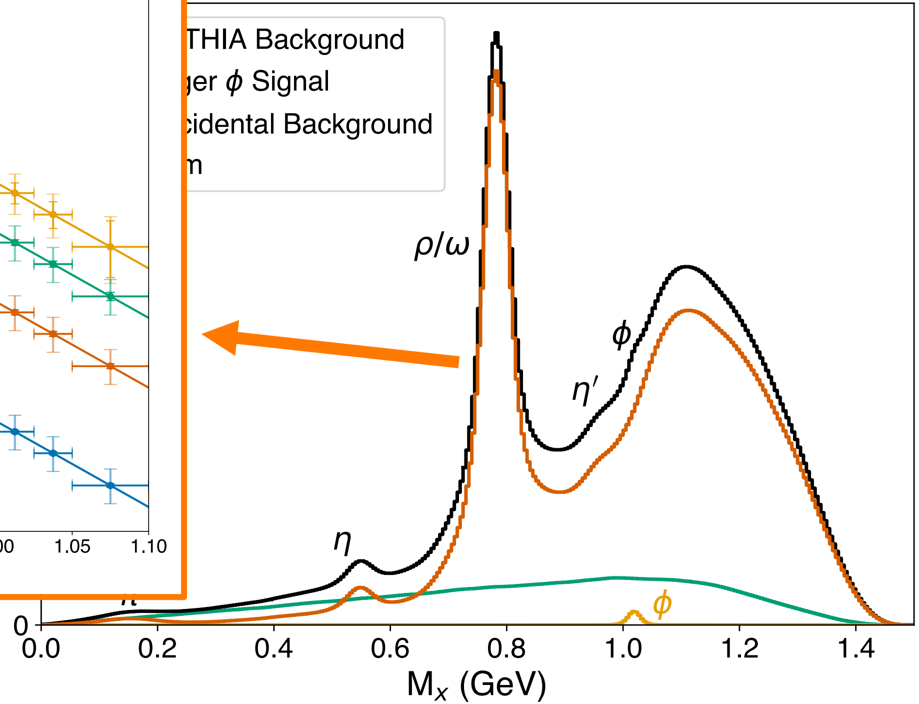
Unexpectedly large η' mass is generated by the QCD chiral anomaly,

What can electroproduction teach us?

WHAT ELSE CAN WE LEARN FROM THIS DATA?

Erratum: Factor of 10 too few statistics used in this plot (but systematics dominate in both cases)



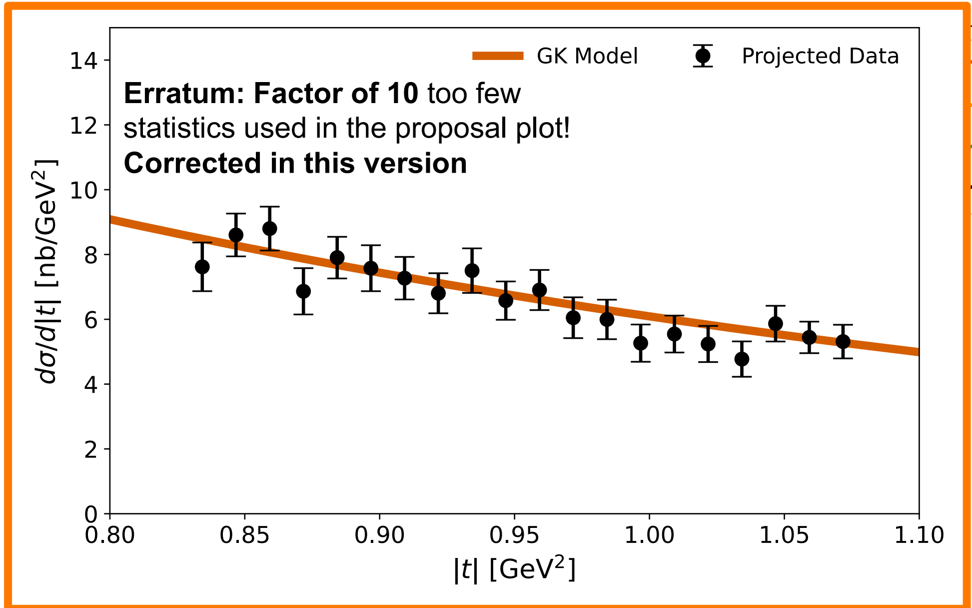


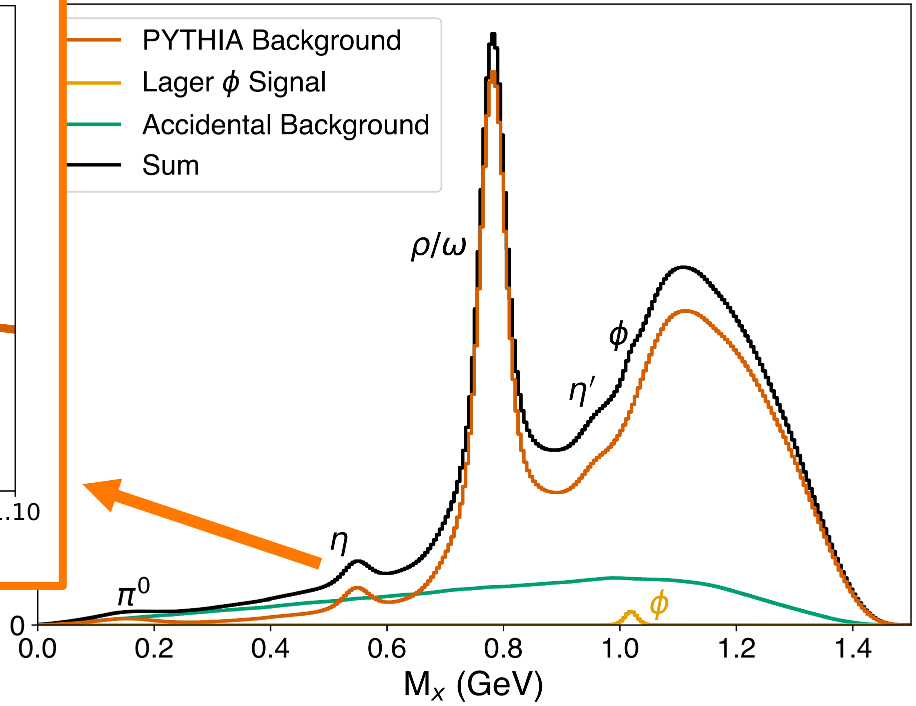
Most differential measurement of near-threshold ω electroproduction!

Connection to the proton mass radius?

Wang et al. PhysRevD.103.L091501

WHAT ELSE CAN WE LEARN FROM THIS DATA?





Comparison of η and η':

What is the role of the chiral anomaly in electroproduction?

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

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

Eides, Frankfurt, Strikman
PhysRevD.59.114025

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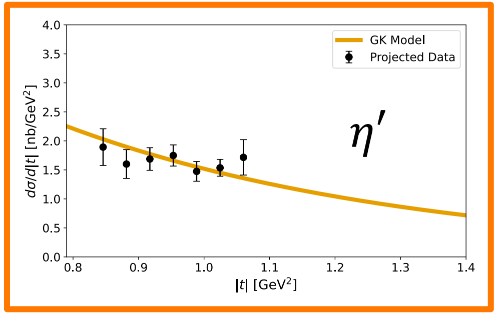
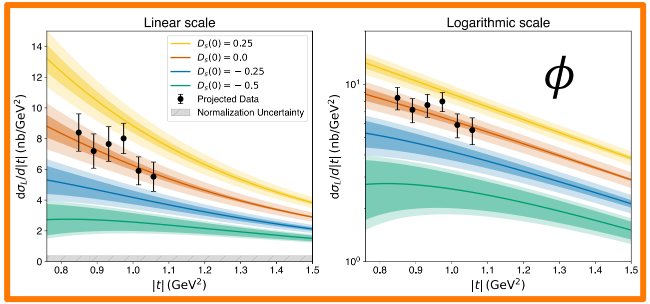
WHAT ELSE CAN WE LEARN FROM THIS DATA?

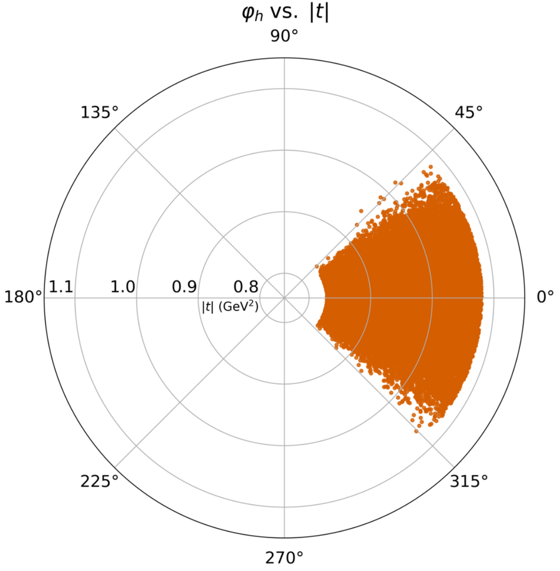
Beam Spin Asymmetries for all!

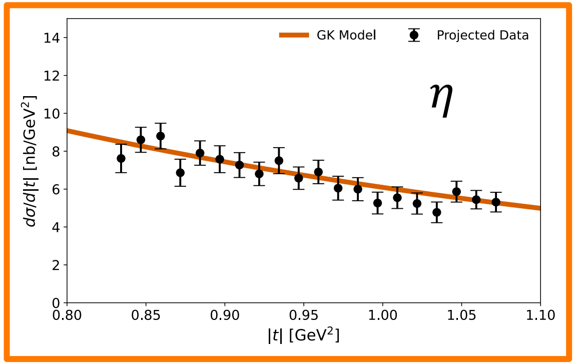
(Kind of)

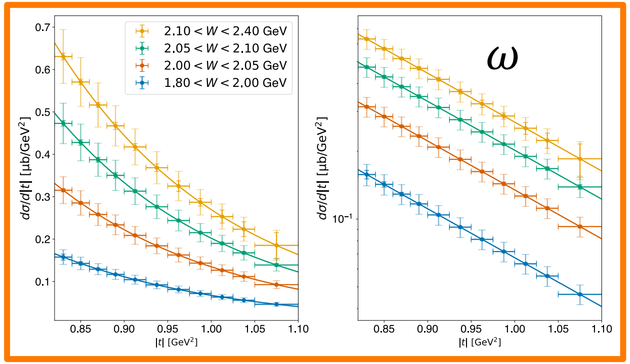
$$\mathrm{BSA} = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi_h}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi_h+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi_h}$$











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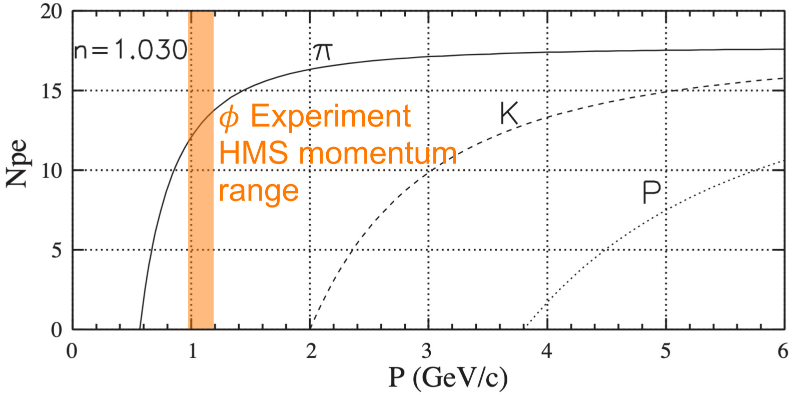
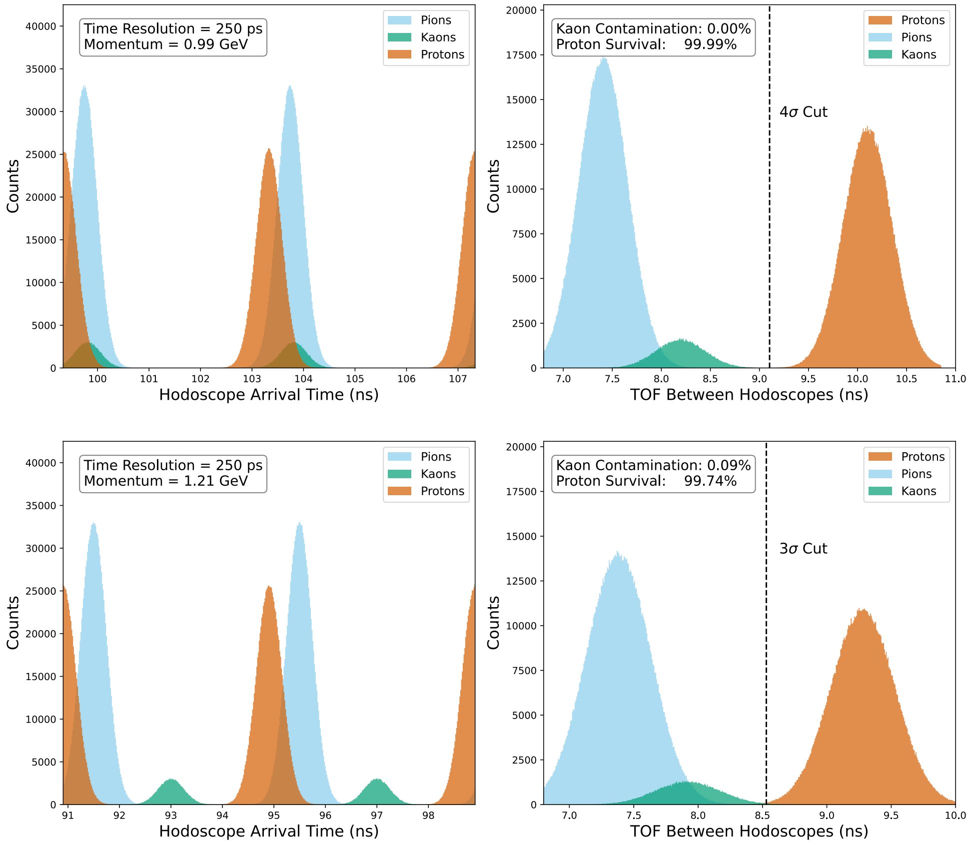
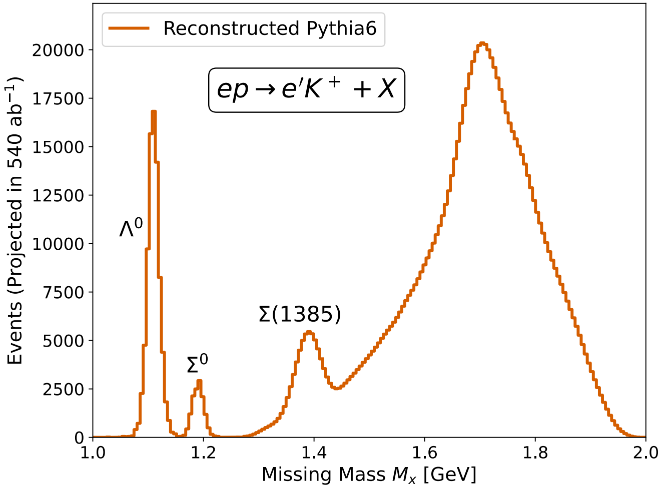
CAN WE DO *U*-CHANNEL?

- 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

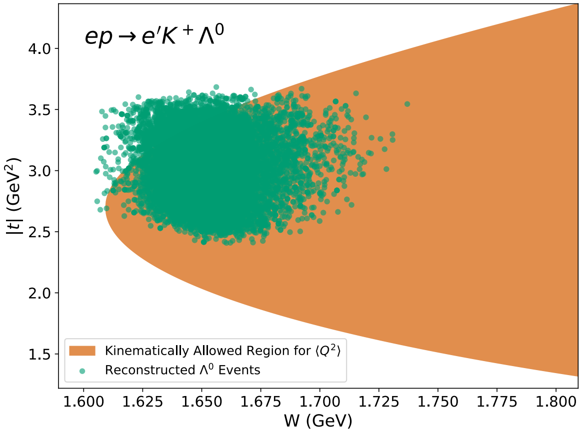


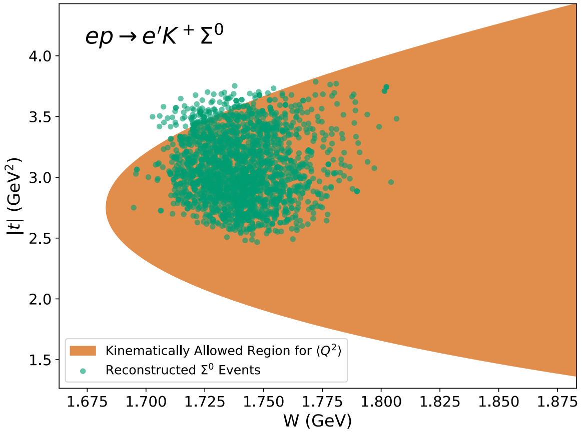


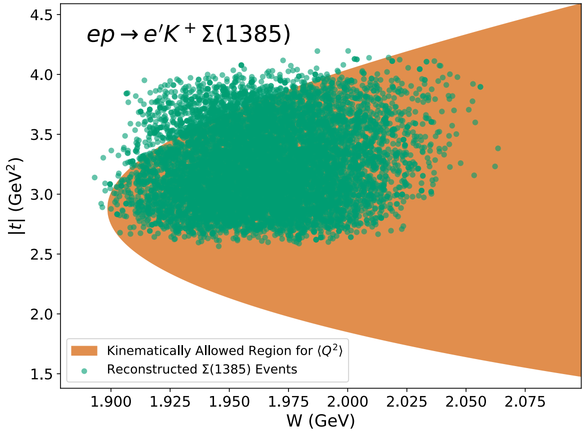
WE CAN DO *U*-CHANNEL!



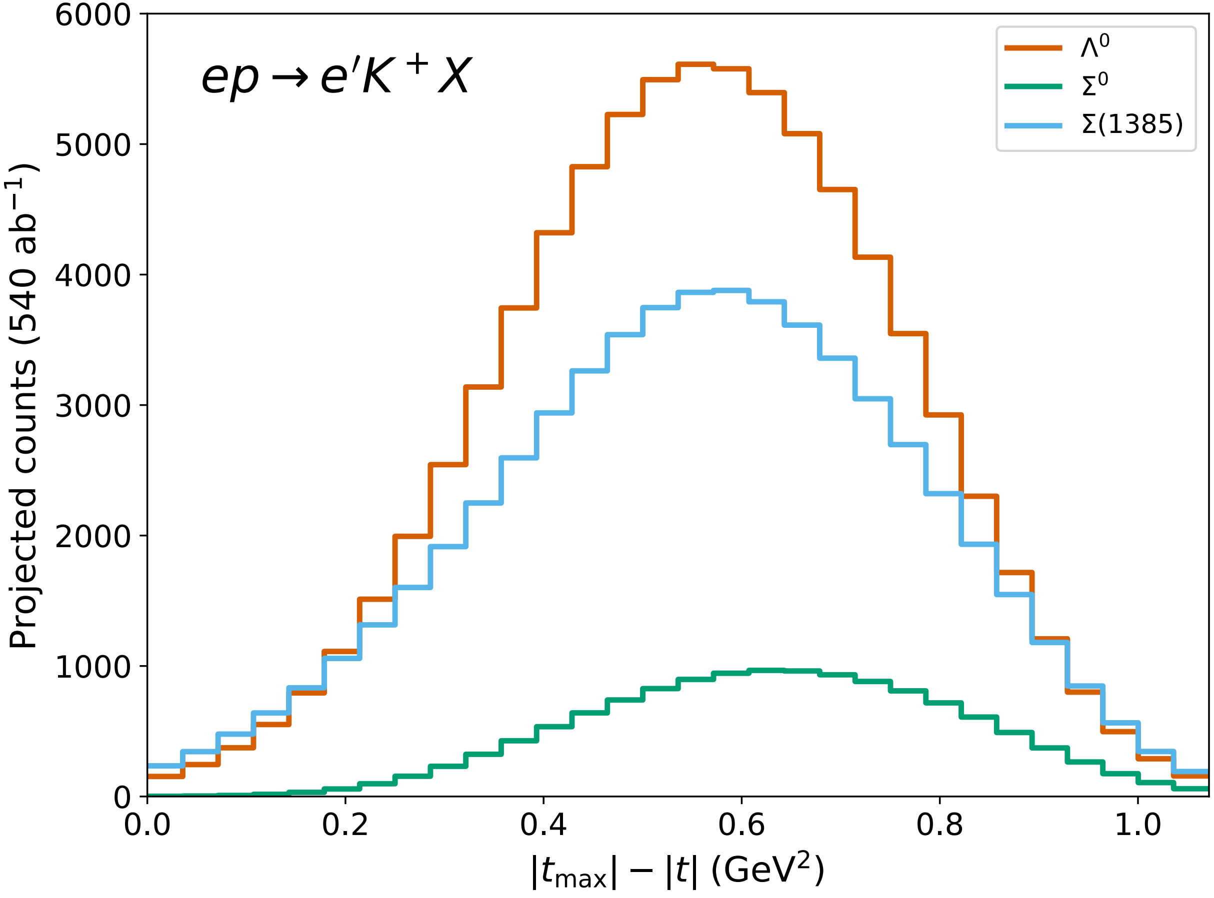
- Near-threshold, u-channel hyperon production is accessible **if K^+ can be efficiently ID'd**
- **Likely requires refurbishment of HMS aerogel**
  - Move SHMS aerogel to HMS?
- Note, PYTHIA6 resonance region cross sections are unreliable (especially in u-channel)
  - However, SIMC acceptance is correct,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







WE CAN DO *U*-CHANNEL!

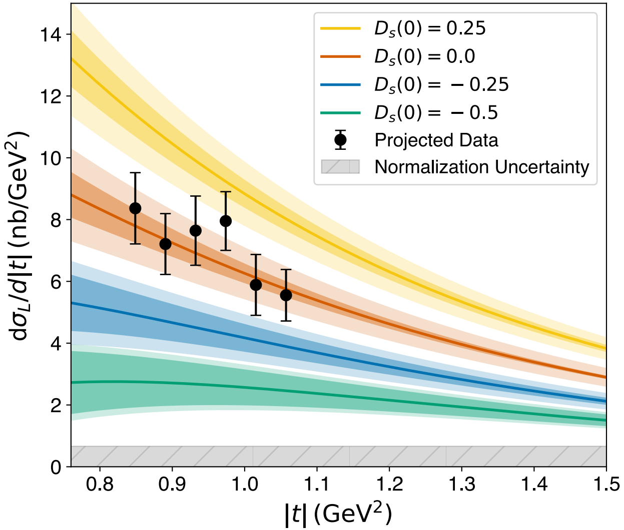


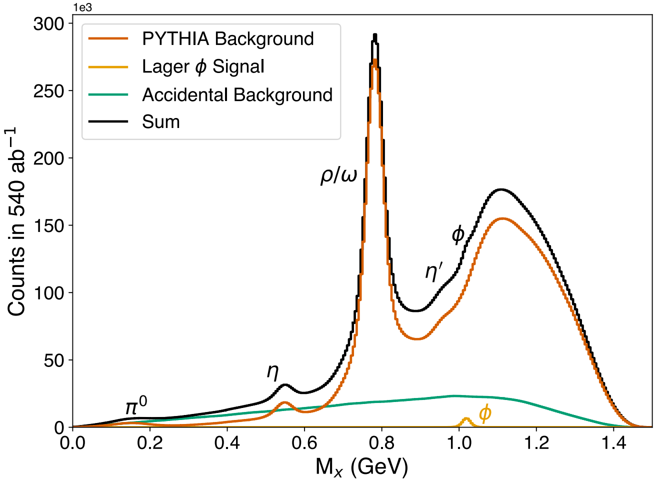
MEASURING THE PROTON POLARIZATION IN $H(e,e'P)X$?

- In the HMS, ϕ DVMP requires **only the four scintillator planes and drift chambers**
- Can we replace the calorimeter with a polarization analyzer?
  - HRS graphite analyzer optimal for ~1 GeV protons?
- See how polarization is transferred in $\vec{e}p \rightarrow e\vec{p} + \omega, \eta(\eta'? \phi? X?)$
  - Under s-channel helicity conservation, produced ω takes all the photon polarization → **Proton should remain totally unpolarized**
    - CLAS data analyzing ω decay products suggest ω electroproduction strongly violates SCHC, unnatural parity exchanges occur
  - For **η/η' production**, situation is opposite → **Proton should take all of photon's polarization**
  - For **ϕ production**, a measurement of **non-zero recoil polarization could be a sign of intrinsic strangeness**
  - **Validity of SCHC can be studied by measuring the recoil polarization!**
  - At large W & M_X, can study **proton recoil polarization in DIS**!
    - (Background to DVMP)

CONCLUSION

- To put proton mechanical structure on solid ground, **need to measure the strangeness D-term**
  - **Only** places in the world capable of this measurement are **CEBAF Halls A & C**
- **35 days in Hall C with HMS/SHMS, one setting!**
  - 32 days of physics for small ϕ cross section
  - Huge general-purpose dataset of $H(e,e'p/\pi^+/K^+)$
  - **ω,η,η' DVMP**, **beam-spin asymmetries**, **u-channel**, **(recoil polarization?)** come for free! → **Analyzers needed!**
- **SoLID** promises greatly **improved precision on D_s** and cross check of our results (+ SBS?)





>50 Collaborators

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Jefferson Lab

MISSISSIPPI STATE UNIVERSITY

University of Regina

FIU

TEMPLE UNIVERSITY

ODU

NM STATE UNIVERSITY

JAMES MADISON UNIVERSITY

A. ALIKHANYAN National Laboratory

VIRGINIA TECH

SUNO SOUTHERN UNIVERSITY at NEW ORLEANS

University of Zagreb

If you want to be a part of this experiment,

Let me know!

Send me an email! **hklest@anl.gov**

BACKUP

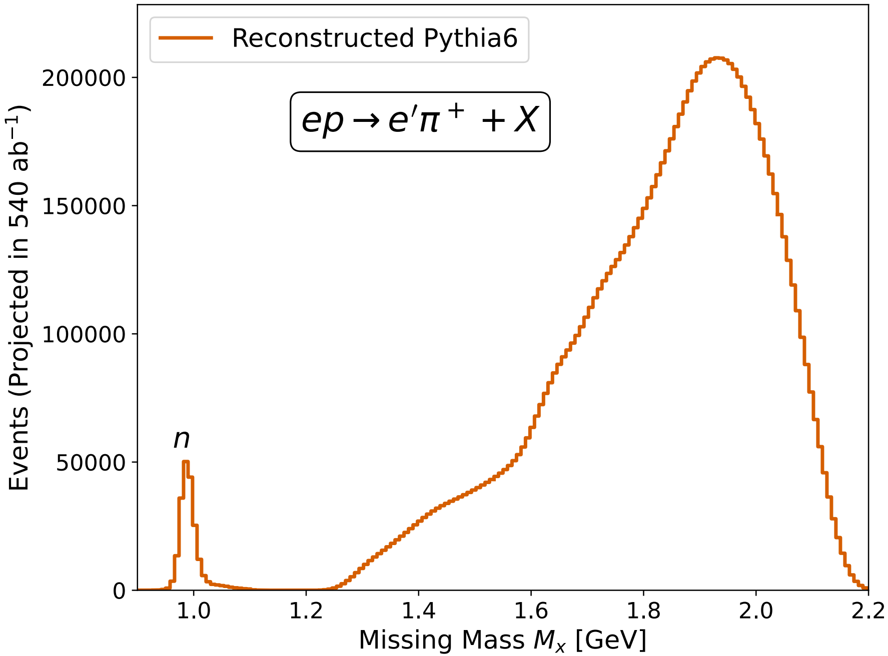
PID STRATEGY

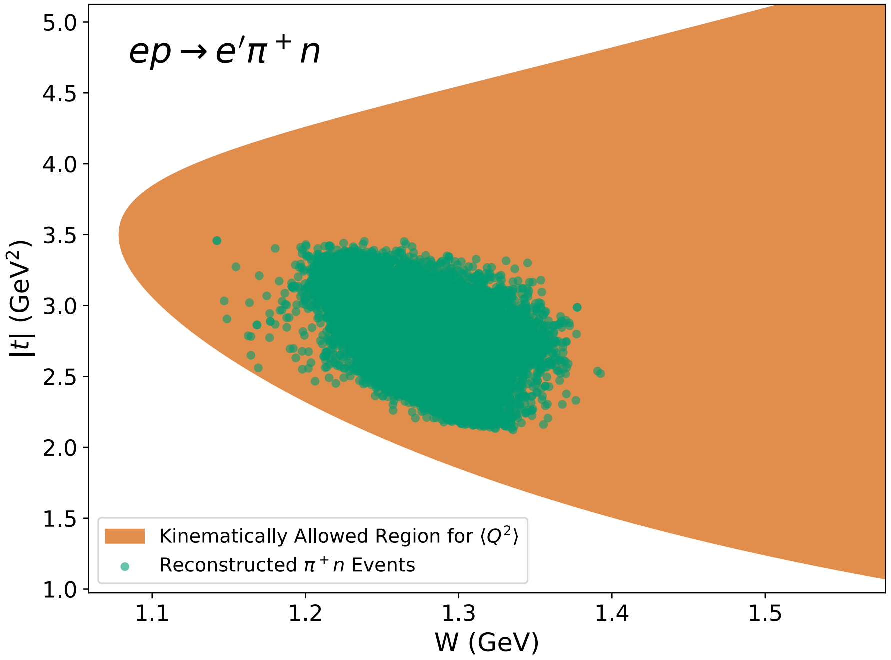
- In SHMS:
  - Electron ID'd with standard calo+Cherenkov conditions
- In HMS:
  - Proton ID'd as slow TOF between scintillator planes, no Cherenkov signals
  - Kaon ID'd as fast TOF between scintillator planes and no Cherenkov signals
    - Timing w.r.t the RF may also provide some separation at larger 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	✓			✓	✓

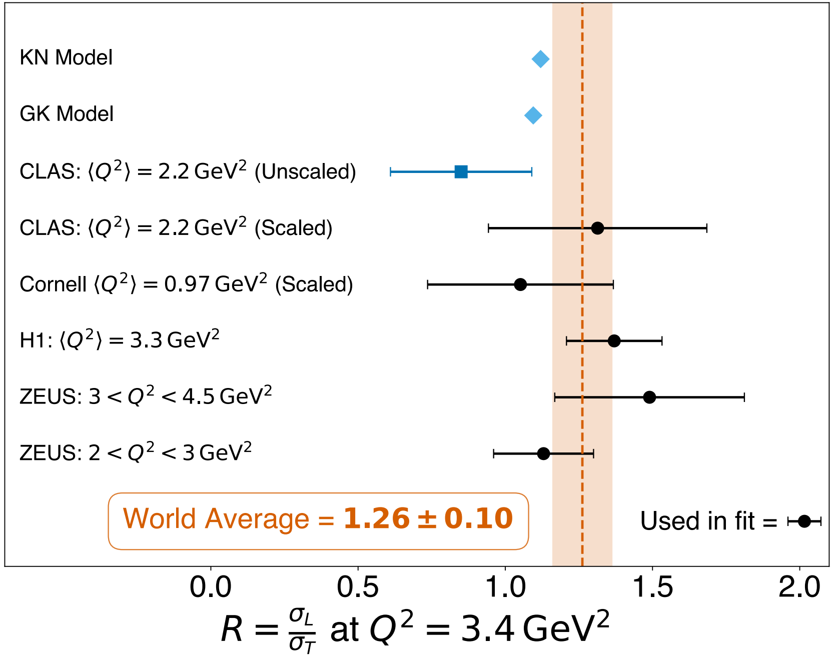
U-CHANNEL PION PRODUCTION

- Pythia6 seems to have exclusive $\pi^+ n$ events, but no other nucleon resonances pop out of the M_X distribution
  - Limited by cut on W in the generator & lack of resonances

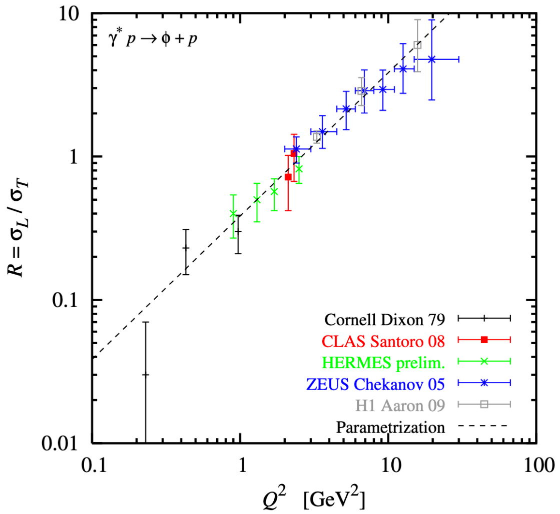




GETTING $d\sigma_L/d|t|$



- 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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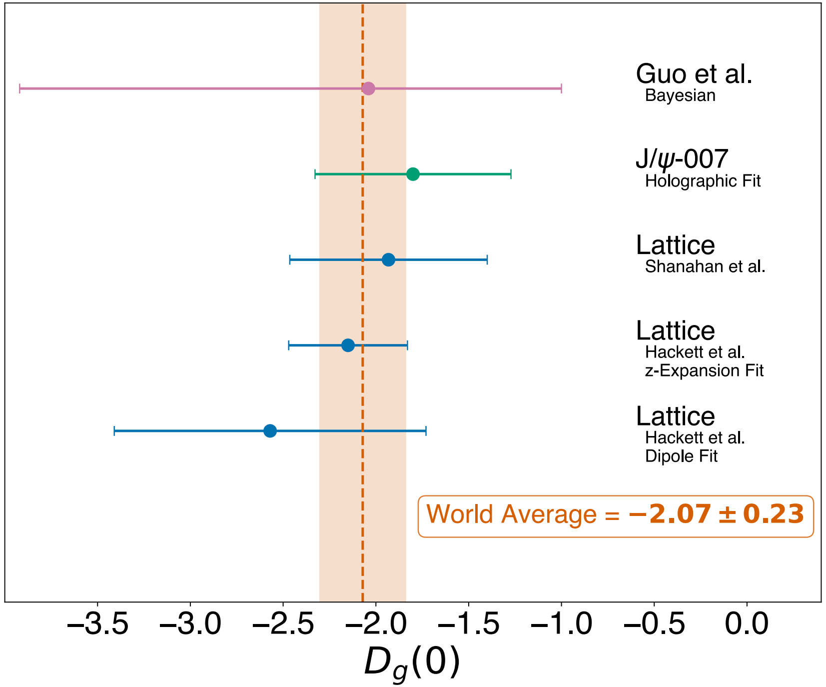
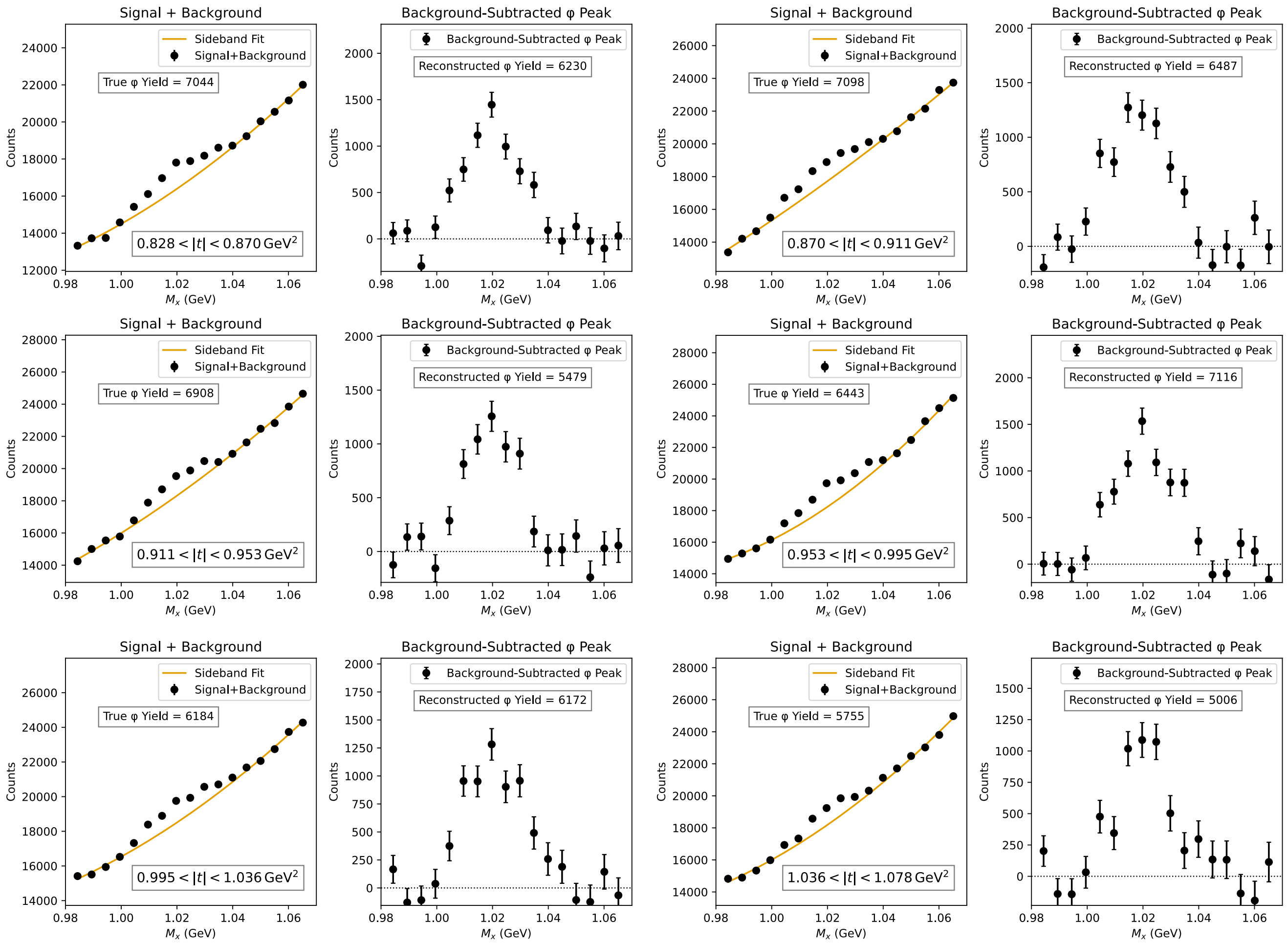
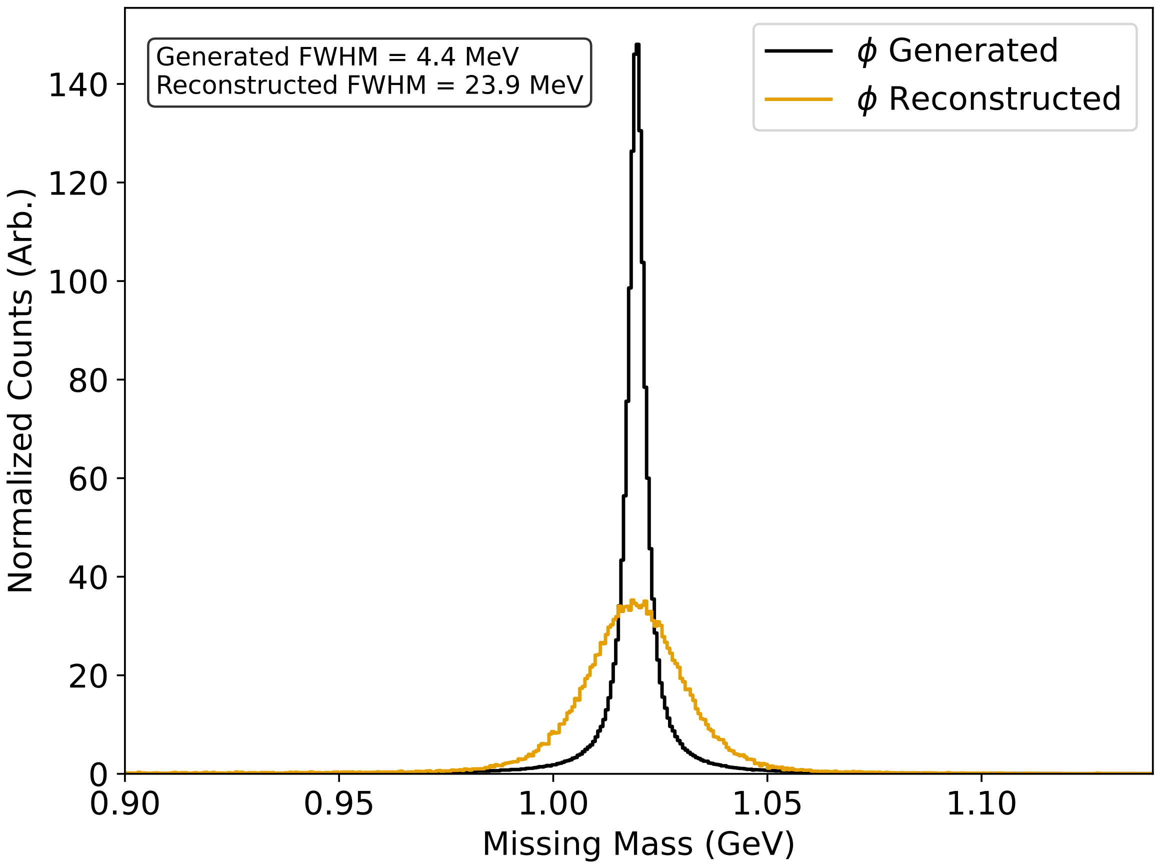
GETTING D_g



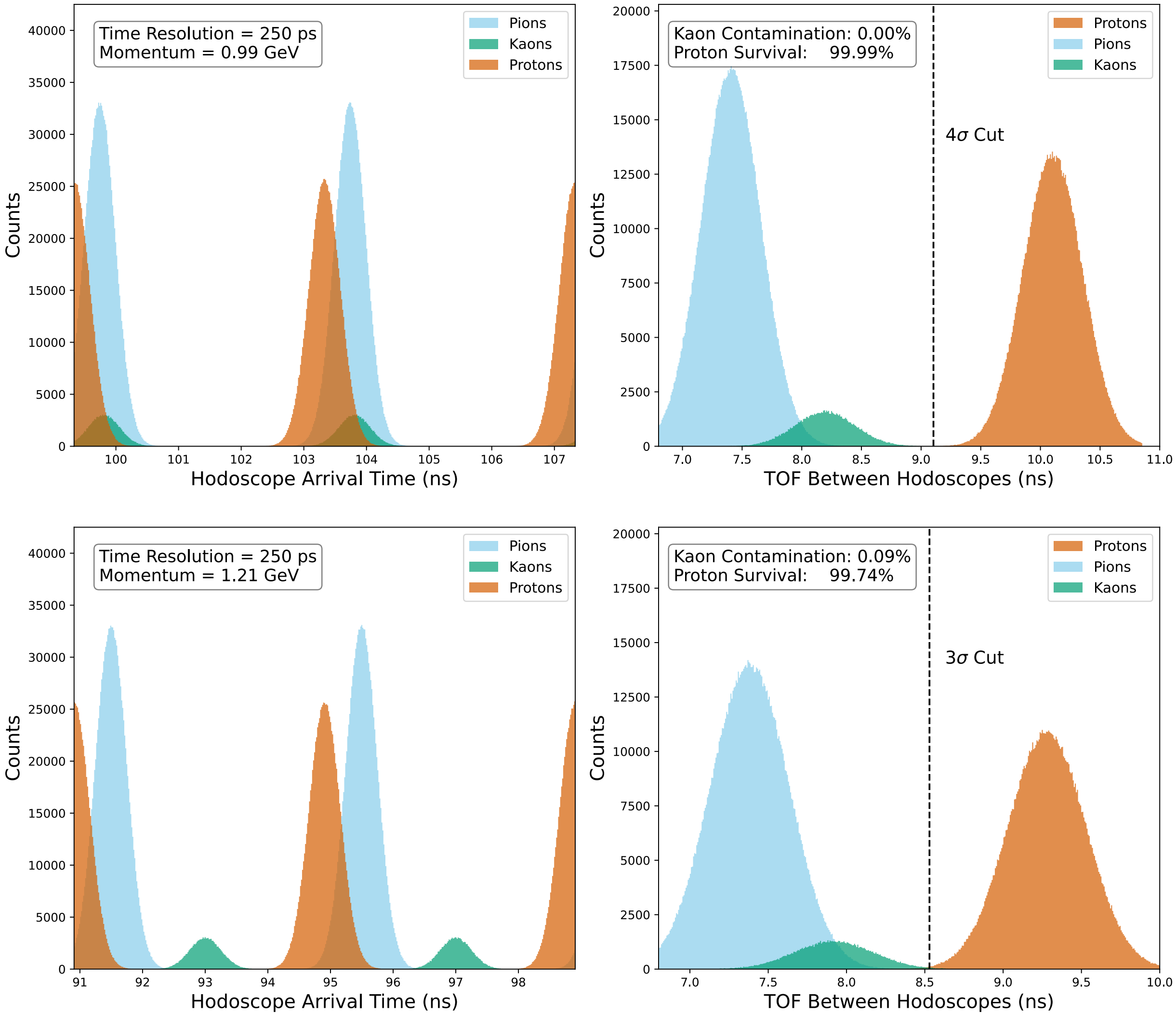
- Sensitivity of cross section to D_g isn't as large as D_s, but large uncertainties on D_g can still rain on our parade
  - Average the results of lattice + Hall C data + Guo/Yuan Bayesian analysis to reduce the overall uncertainties by a bit
  - Hopefully there will be more results soon (CLAS12?)
  - 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 here…


Signal + Background
Sideband Fit
Signal+Background
True φ Yield = 7044
0.828 < |t| < 0.870 GeV²
Background-Subtracted φ Peak
Reconstructed φ Yield = 6230
Signal + Background
True φ Yield = 7098
0.870 < |t| < 0.911 GeV²
Background-Subtracted φ Peak
Reconstructed φ Yield = 6487
Signal + Background
True φ Yield = 6908
0.911 < |t| < 0.953 GeV²
Background-Subtracted φ Peak
Reconstructed φ Yield = 5479
Signal + Background
True φ Yield = 6443
0.953 < |t| < 0.995 GeV²
Background-Subtracted φ Peak
Reconstructed φ Yield = 7116
Signal + Background
True φ Yield = 6184
0.995 < |t| < 1.036 GeV²
Background-Subtracted φ Peak
Reconstructed φ Yield = 6172
Signal + Background
True φ Yield = 5755
1.036 < |t| < 1.078 GeV²
Background-Subtracted φ Peak
Reconstructed φ Yield = 5006
Counts
M_x (GeV)



Generated FWHM = 4.4 MeV
Reconstructed FWHM = 23.9 MeV
ϕ Generated
ϕ Reconstructed
Normalized Counts (Arb.)
0
20
40
60
80
100
120
140
0.90
0.95
1.00
1.05
1.10
Missing Mass (GeV)



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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.)

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

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

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

"Threshold Approximation" – Keep only j = 1

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

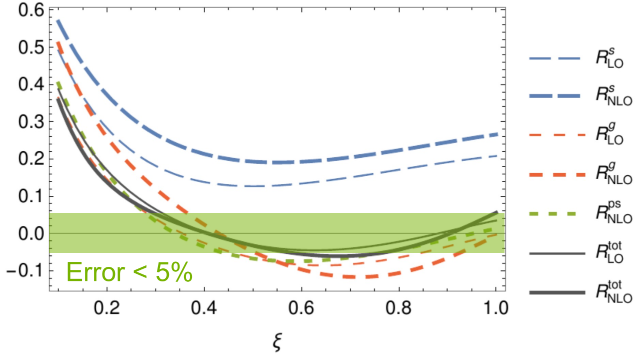
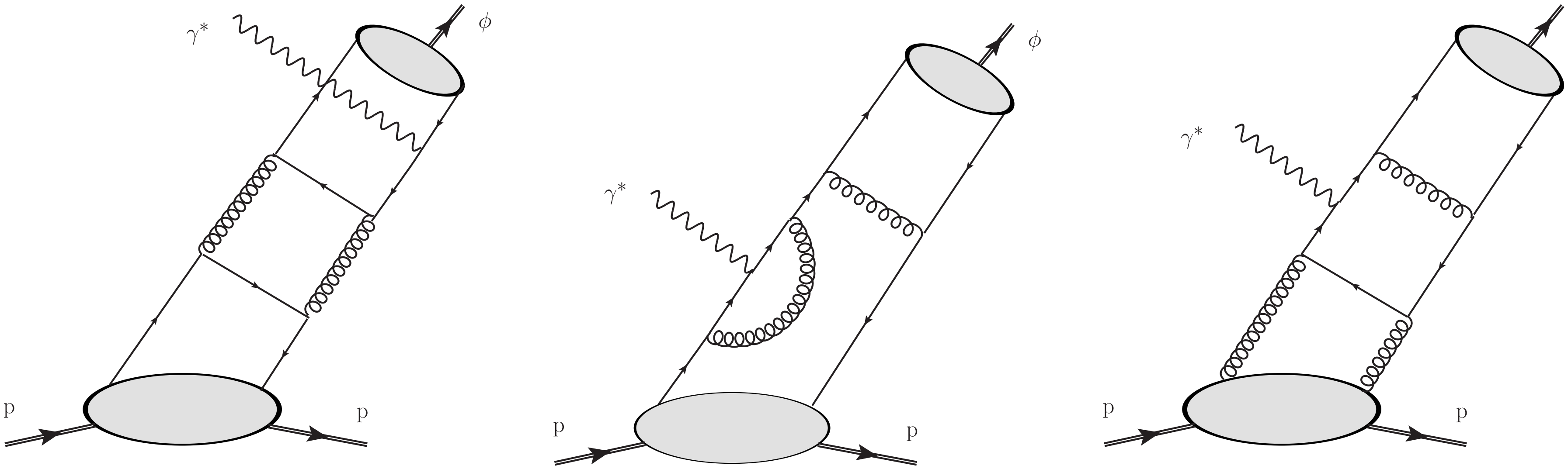


FIG. 4: Relative error for the amplitude $\mathcal{H}$ from truncating the conformal partial wave expansion after the first term. Plotted quantities are defined in (40). The subscript denotes whether the leading order (LO) or next-to-leading order (NLO) coefficient function has been used. In this and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

THEORY PREDICTIONS

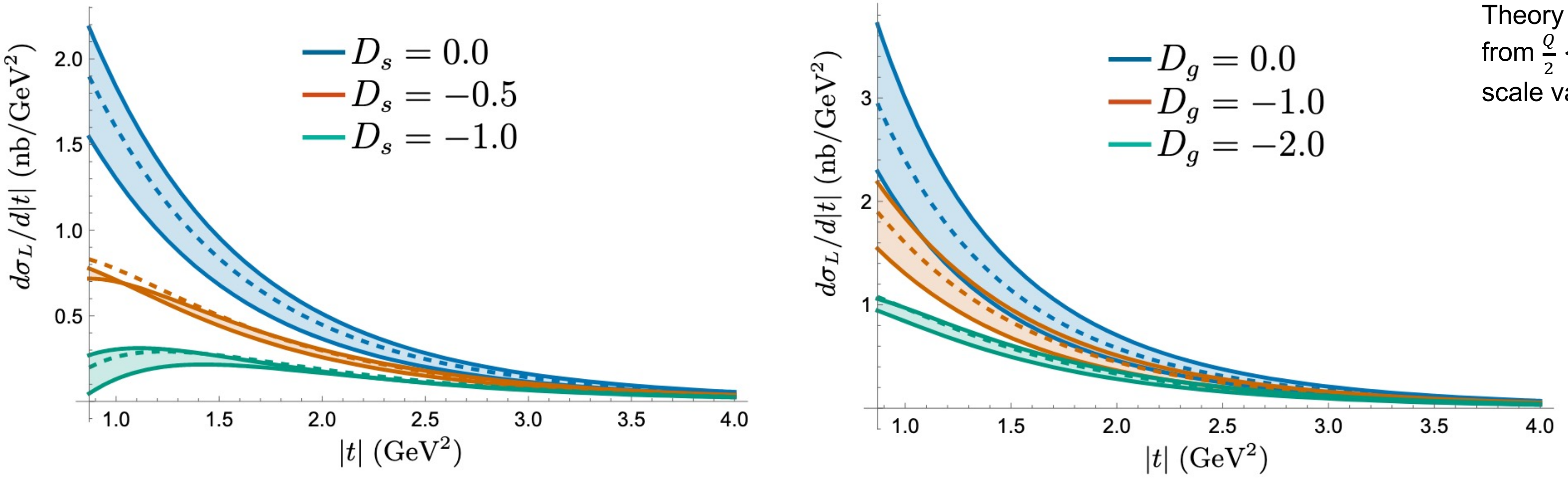
Hatta, HK, Passek, Schoenleber (2501.12343)

- Predictions available at NLO for $\frac{d\sigma_L}{d|t|}$!
  - Requires our experiment to have an L/T separation (or modelling of R) for comparison



THEORY PREDICTIONS

Hatta, HK, Passek, Schoenleber (2501.12343)



Theory uncertainty from $\frac{Q}{2} < \mu < 2Q$ scale variation

FIG. 7: NLO longitudinal cross section at $W = Q = 2.5$ GeV as a function of $|t|$. Left: $D_s = 0, -0.5, -1$ from top to bottom at fixed $D_g = -1$. Right: $D_g = 0, -1, -2$ from top to bottom at fixed $D_s = 0$.

Near-threshold ϕ exhibits factor ~ 4 greater sensitivity to D_s compared to D_g!

THEORY PREDICTIONS

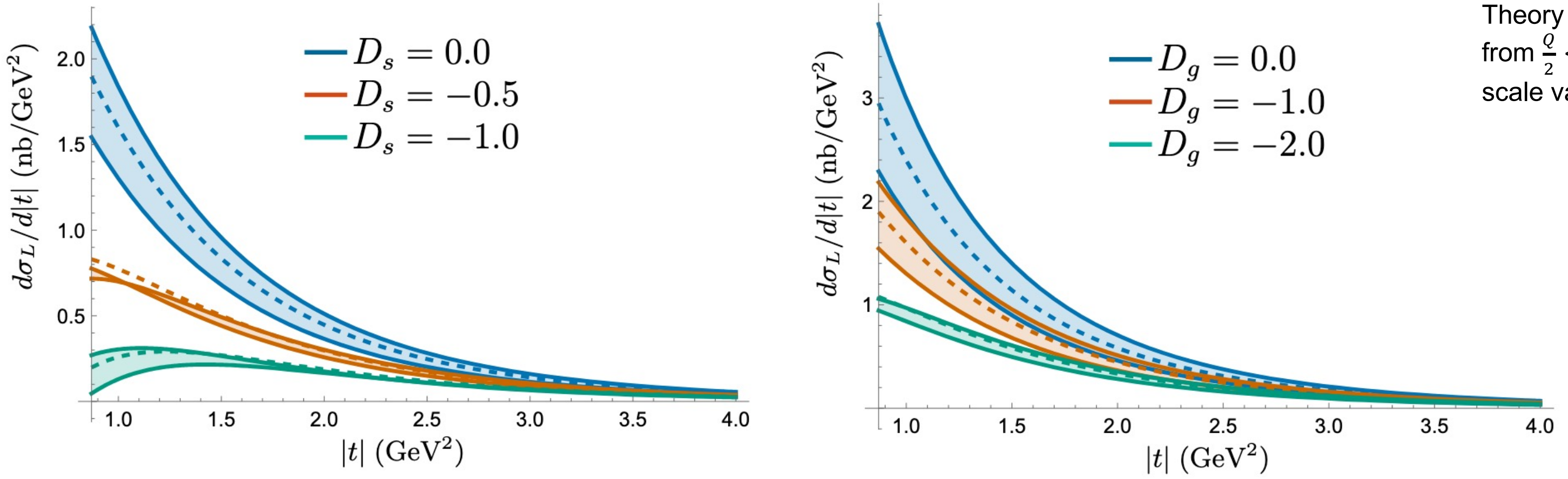
Hatta, HK, Passek, Schoenleber (2501.12343)

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

$\xi \sim 0.5$

$A_g \sim A_{u,d} \gg A_s$

$D_g \sim D_{u,d} \sim D_s$?



Theory uncertainty from $\frac{Q}{2} < \mu < 2Q$ scale variation

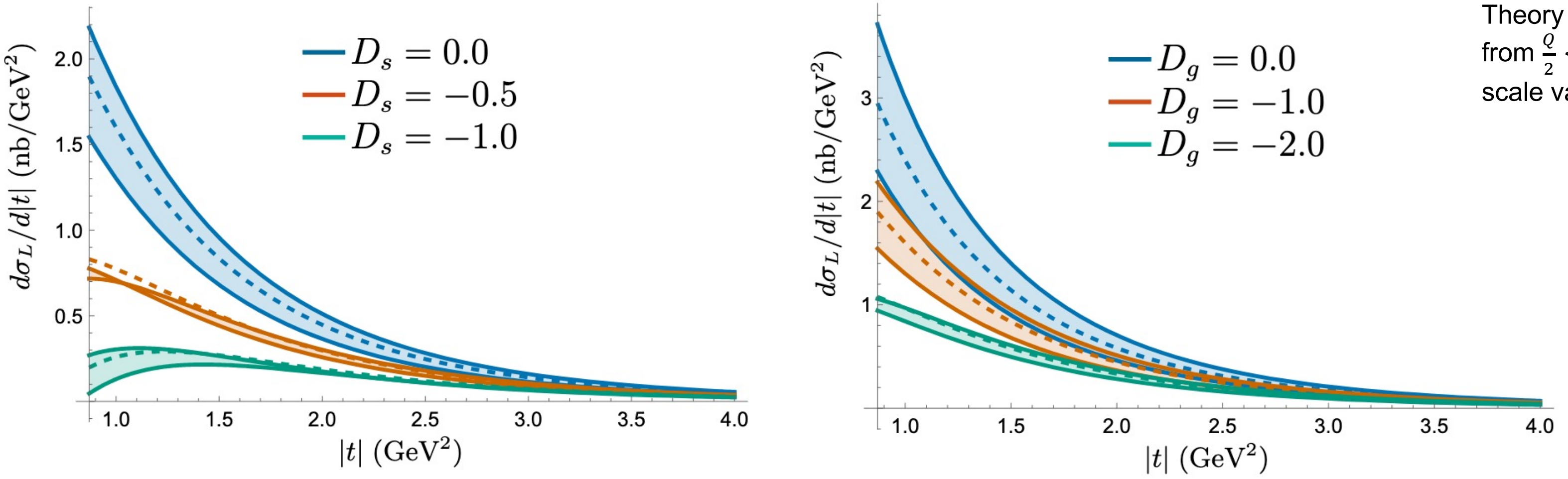
FIG. 7: NLO longitudinal cross section at $W = Q = 2.5$ GeV as a function of $|t|$. Left: $D_s = 0, -0.5, -1$ from top to bottom at fixed $D_g = -1$. Right: $D_g = 0, -1, -2$ from top to bottom at fixed $D_s = 0$.

THEORY PREDICTIONS

Hatta, HK, Passek, Schoenleber (2501.12343)

Near-threshold ϕ exhibits factor ~ 4 greater sensitivity to D_s compared to D_g!

This is the green light for our experiments to measure D_s, so let's go!



Theory uncertainty from $\frac{Q}{2} < \mu < 2Q$ scale variation

FIG. 7: NLO longitudinal cross section at $W = Q = 2.5$ GeV as a function of $|t|$. Left: $D_s = 0, -0.5, -1$ from top to bottom at fixed $D_g = -1$. Right: $D_g = 0, -1, -2$ from top to bottom at fixed $D_s = 0$.