ELECTROPRODUCTION OF ϕ TOWARD THE STRANGENESS D-TERM

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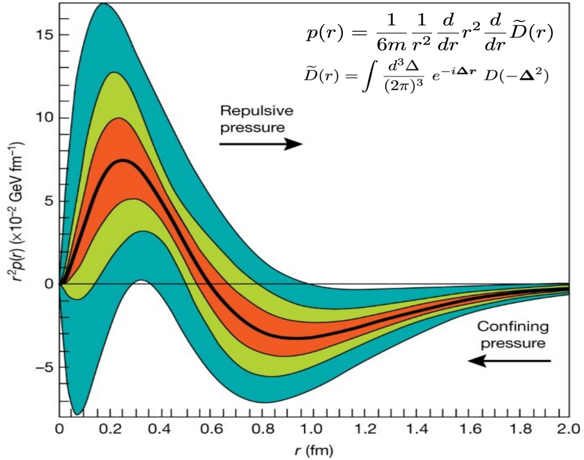
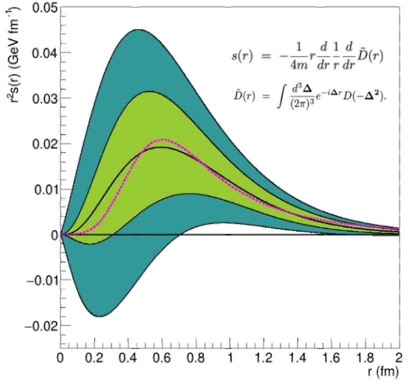
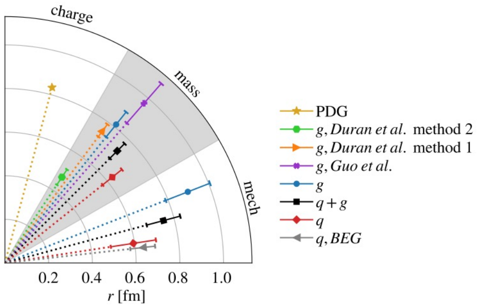
CNF Mini Workshop: Vector Quarkonia as Pressure Gauges
March 27, 2026

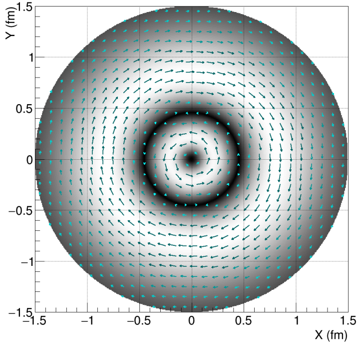
MECHANICAL PROPERTIES

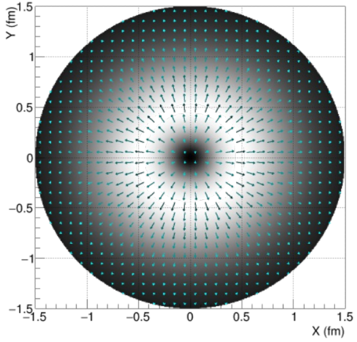
- The total D-term provides a gateway for extraction of various **mechanical** properties of the proton, including:
  - — Pressure distribution
  - — Shear force distribution
  - — Mechanical radius
  - — Tangential & normal force distributions











HOW DO WE ACCESS THE D-TERM?

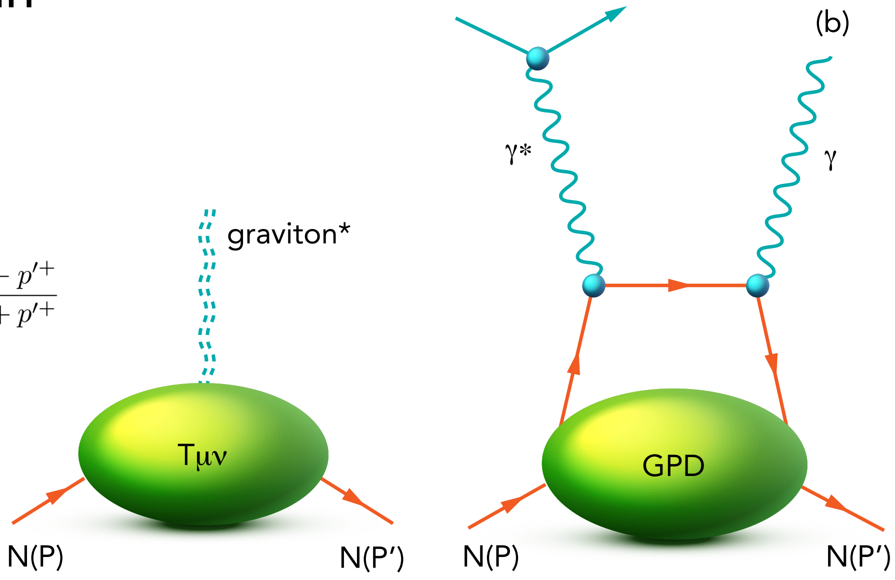
- Graviton scattering would measure directly $T^{\mu\nu}$
- Can access GFFs via the second Mellin moments of the generalized parton distributions (GPDs)

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

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

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

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:

$$\underbrace{D(0)}_{\text{Total } D\text{-term}} = \underbrace{D_g(0) + D_u(0) + D_d(0) + D_s(0) + \ldots}_{\text{Partonic } D\text{-term contributions}}$$

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

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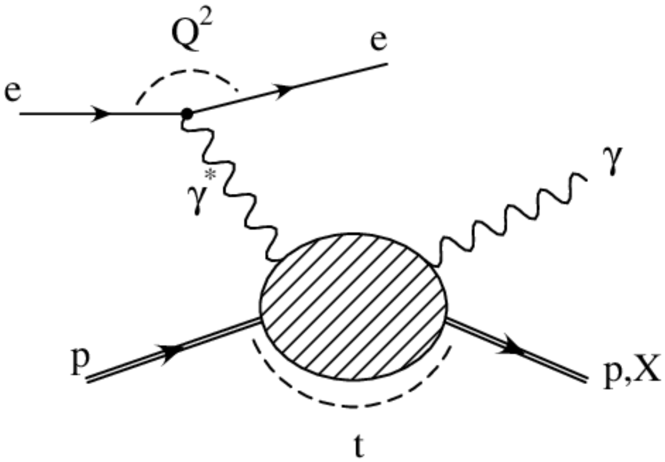
Up & Down quarks:
Accessible via DVCS cross section &
beam-spin asymmetries

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



The pressure distribution inside the proton

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

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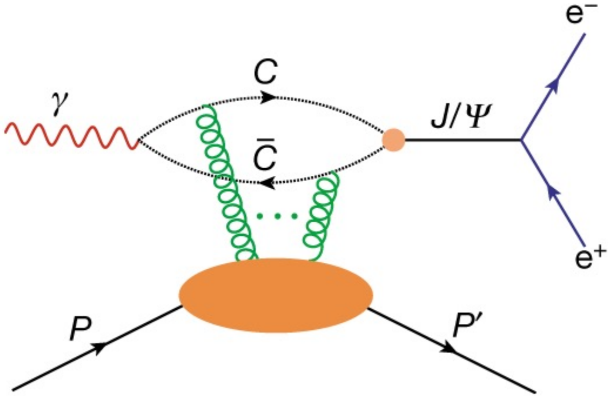
Gluons:
Accessible via near-threshold production of J/ψ and Υ

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

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]



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

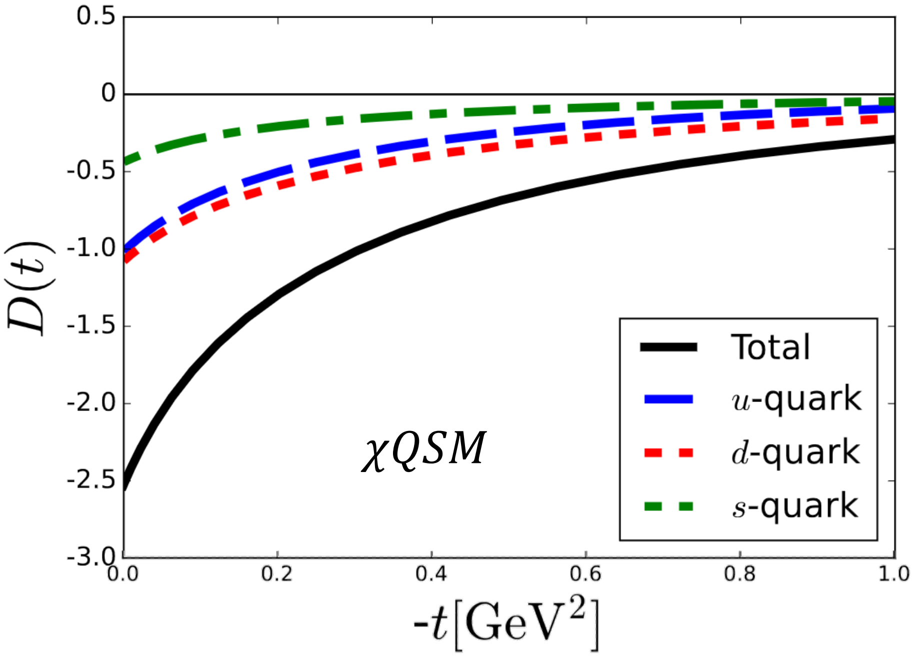
Strange quarks:
Can we just neglect them…?

THEORY PREDICTIONS

- 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: $D_u \sim D_d \sim 2D_s$

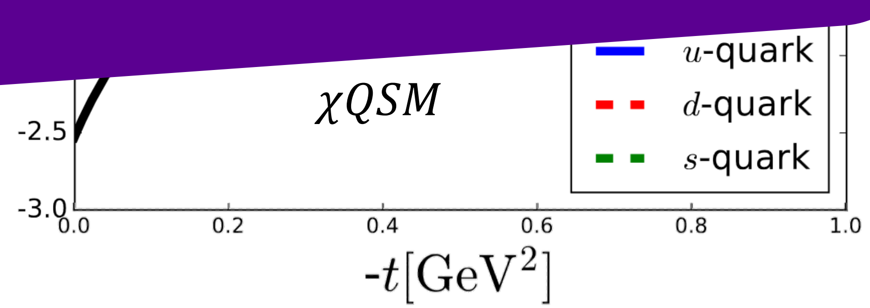


[1] - Goeke et al.: **Hard exclusive reactions and the structure of hadrons**, *Prog.Part.Nucl.Phys, 2001*
[2] - Hackett et al.: **Gravitational form factors of the proton from lattice QCD,** *PRL, 2024*
[3] - Won et al.: **Role of strange quarks in the D-term and cosmological constant term of the proton,**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

THEORY PREDICTIONS

- Large-N_c theory predicts that the D-term is "flavor blind"[1]
  - i.e. $D_u \approx D_d$ ...

"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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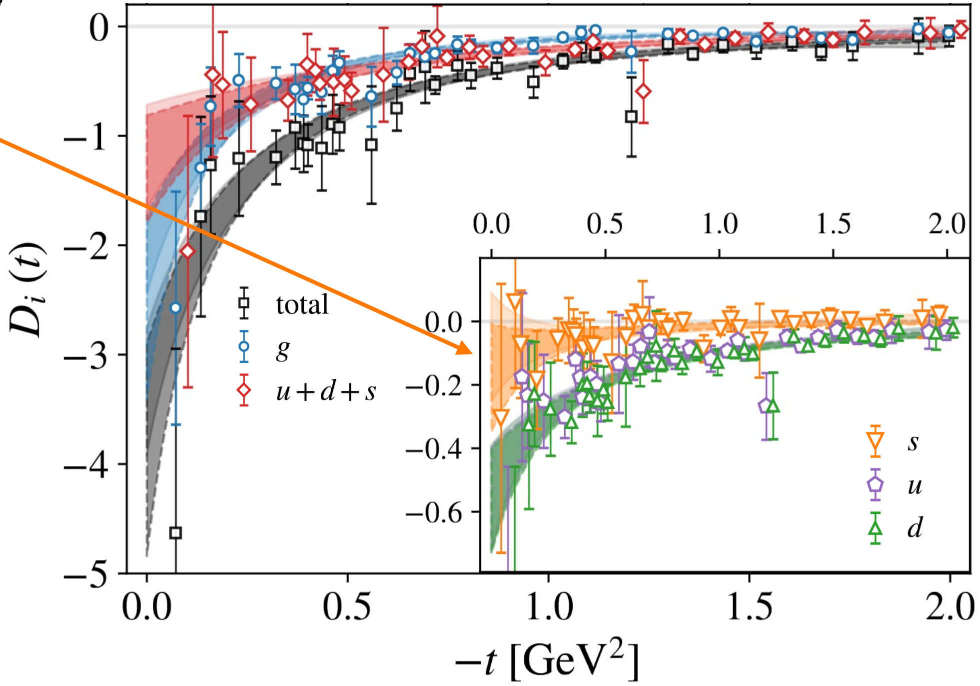
THEORY PREDICTIONS

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

- **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*

$D_s > 0$

$D_s = 0$

$D_s < 0$

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

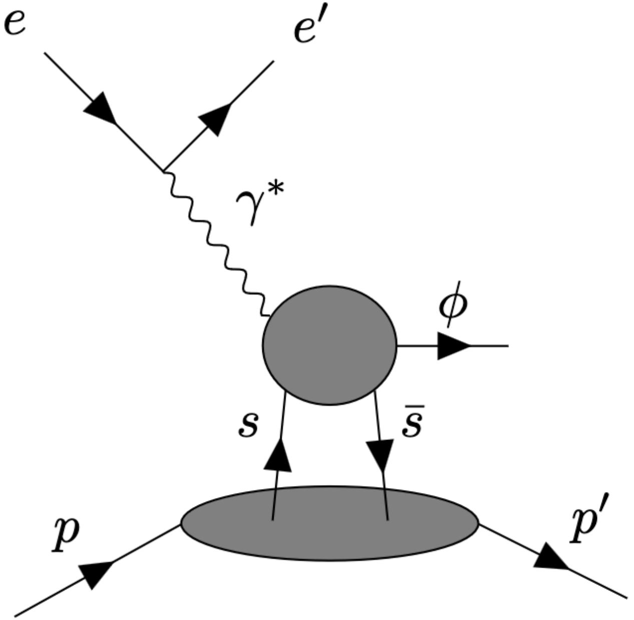
$D_s = D_{u,d}$

$2D_s = D_{u,d}$

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!



[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]!

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

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!

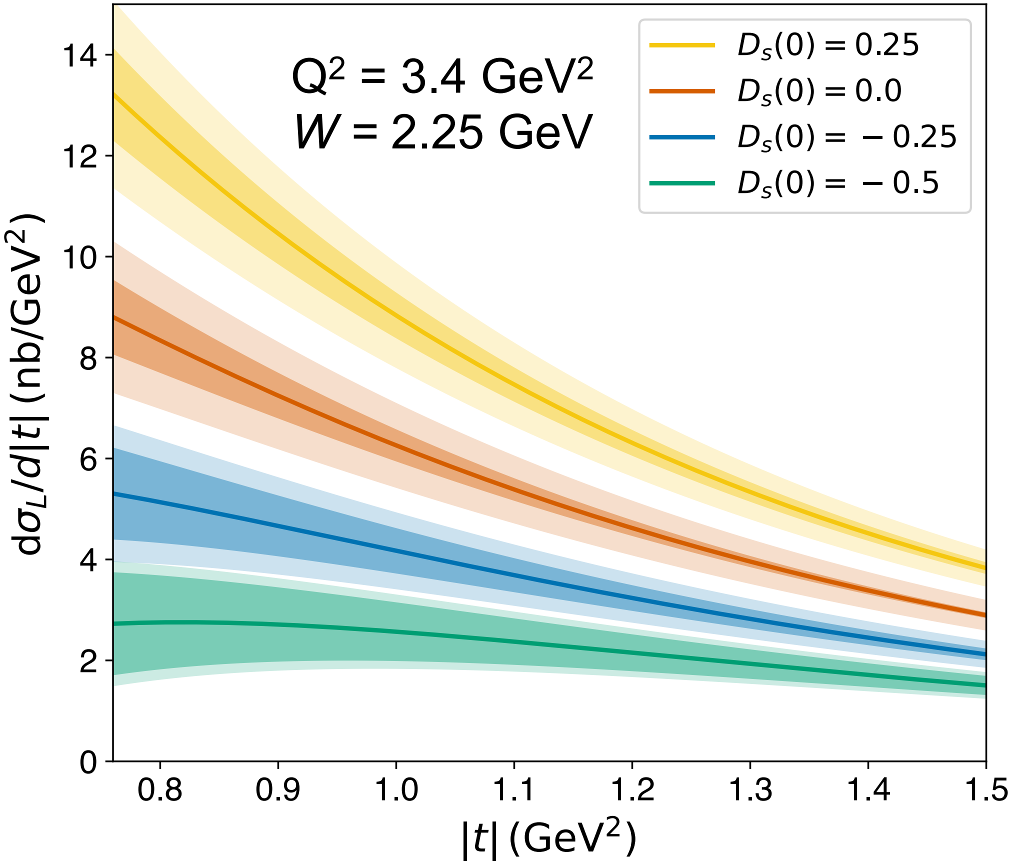
$A_g \approx 0.4, D_g \approx -2$

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 < 2μ

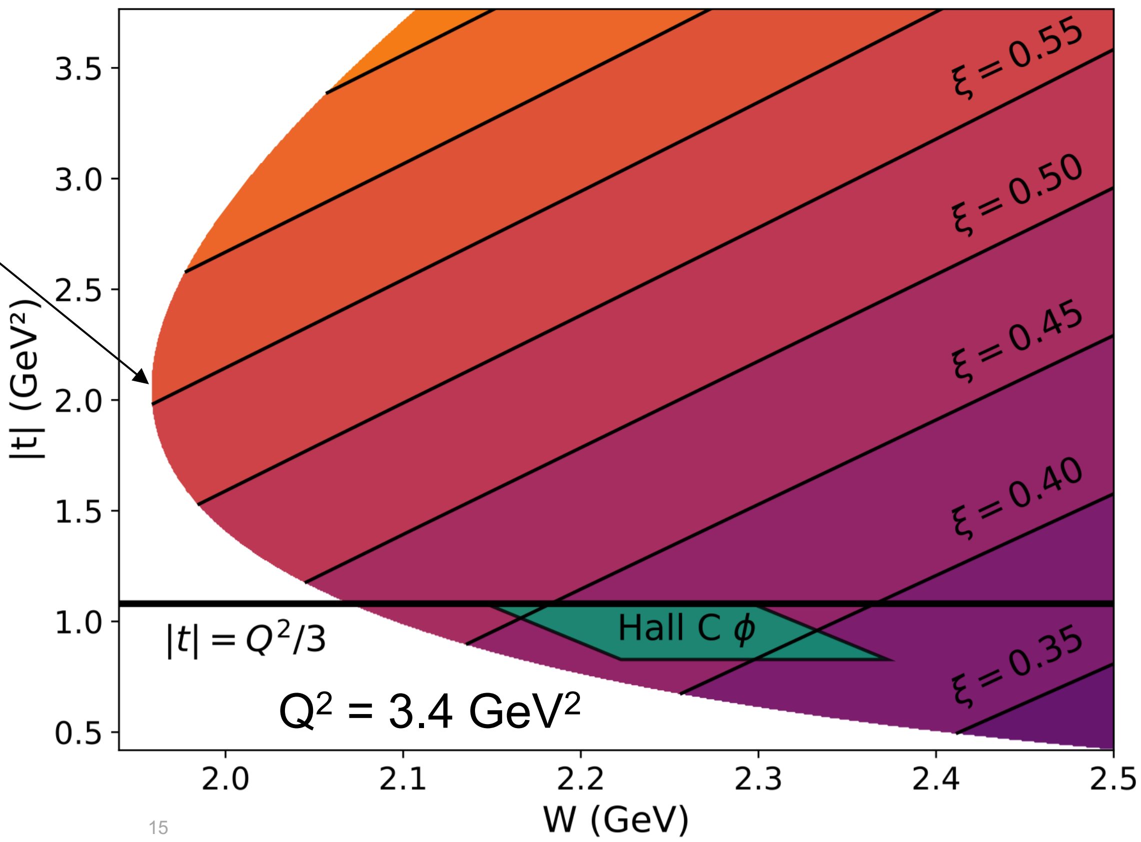
Outer uncertainty band:
Uncertainty on $D_g \oplus$ pQCD
Total prediction uncertainty

[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**
  - $|t| \ll$ $\mathbf{Q^2}$
  - **Not too close** to the threshold W = **1.96 GeV**
- Cross section $\propto$ $\mathbf{Q^{-9}}$!
- Requires **high luminosity** and precise kinematic reconstruction

Can use the Hall C spectrometers!

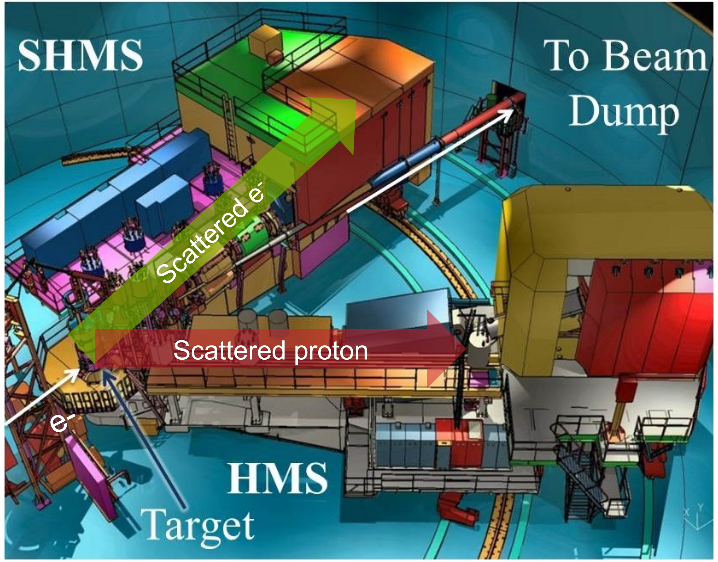


ϕ-007 EXPERIMENT IN HALL C

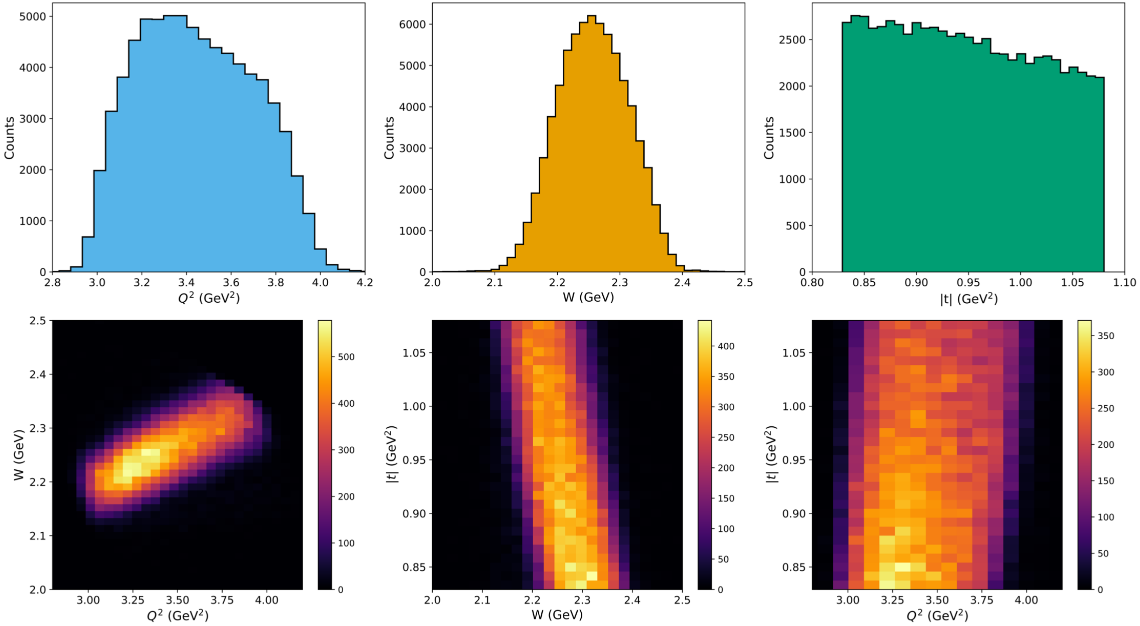
Spokespersons: H. Klest, S. Joosten, H. Szumila-Vance, W. B. Li

ϕ-007 Experiment approved at PAC53 with A$^-$ rating! Passed ERR in Feb.

- 54 μA 10.6 GeV beam, 15 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

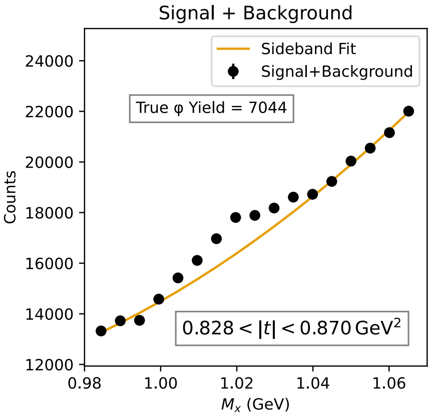


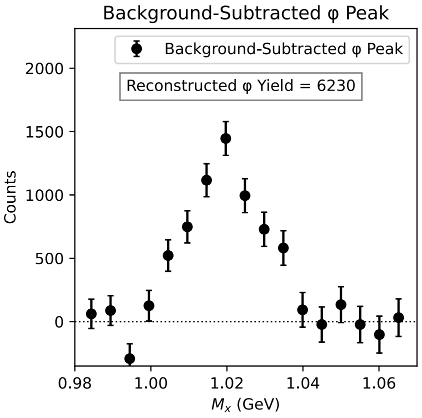
Q^2 ~ 3.4 GeV^2 W ~ 2.25 GeV |t| ~ 0.95 GeV^2

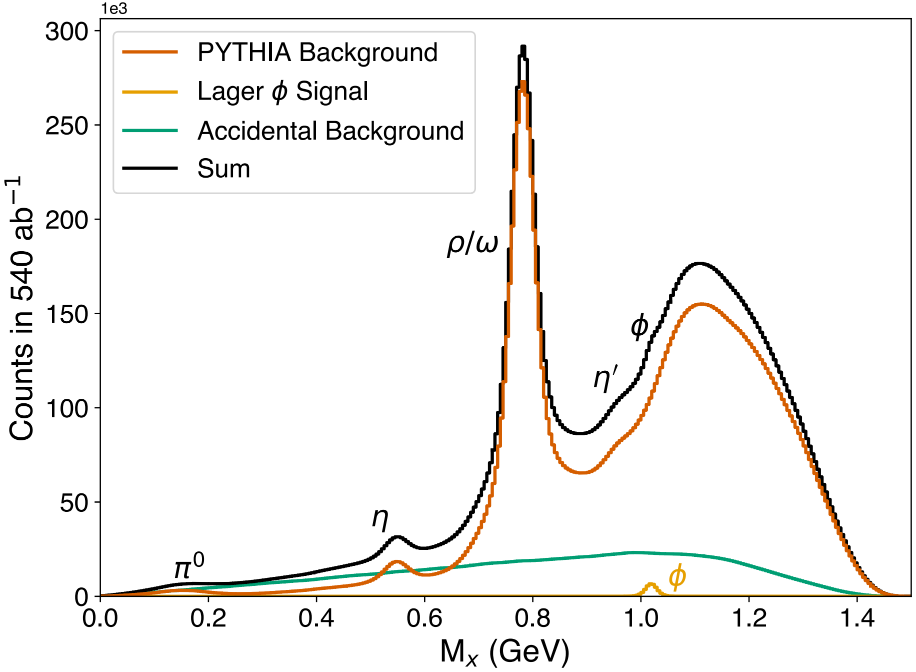


EXPERIMENTAL MEASUREMENT - ϕ-007

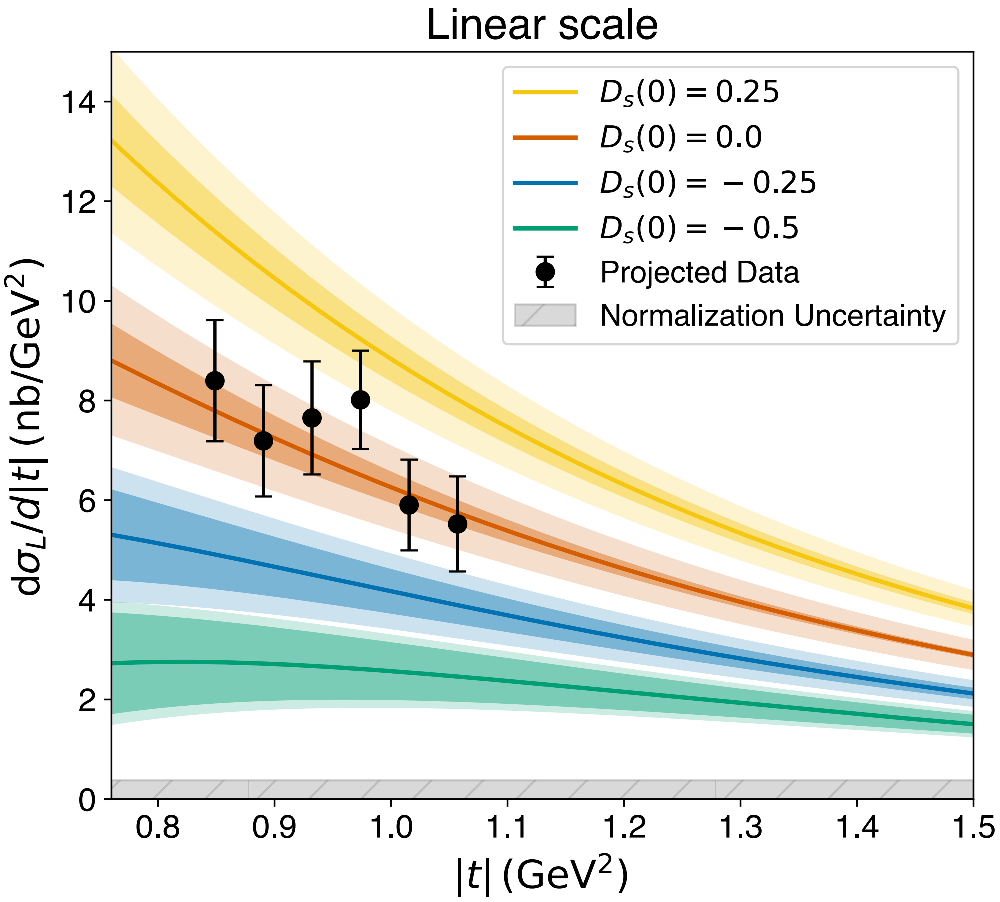
- Measure $e + p \rightarrow e' + p' + \phi$ via **missing mass technique**
- **Large and irreducible** continuum background from $e + p \rightarrow e' + p' + X$!
  - However, missing mass resolution of the Hall C spectrometers is good enough to **fit + subtract background with the data itself**







CROSS SECTION PROJECTIONS - ϕ-007



- 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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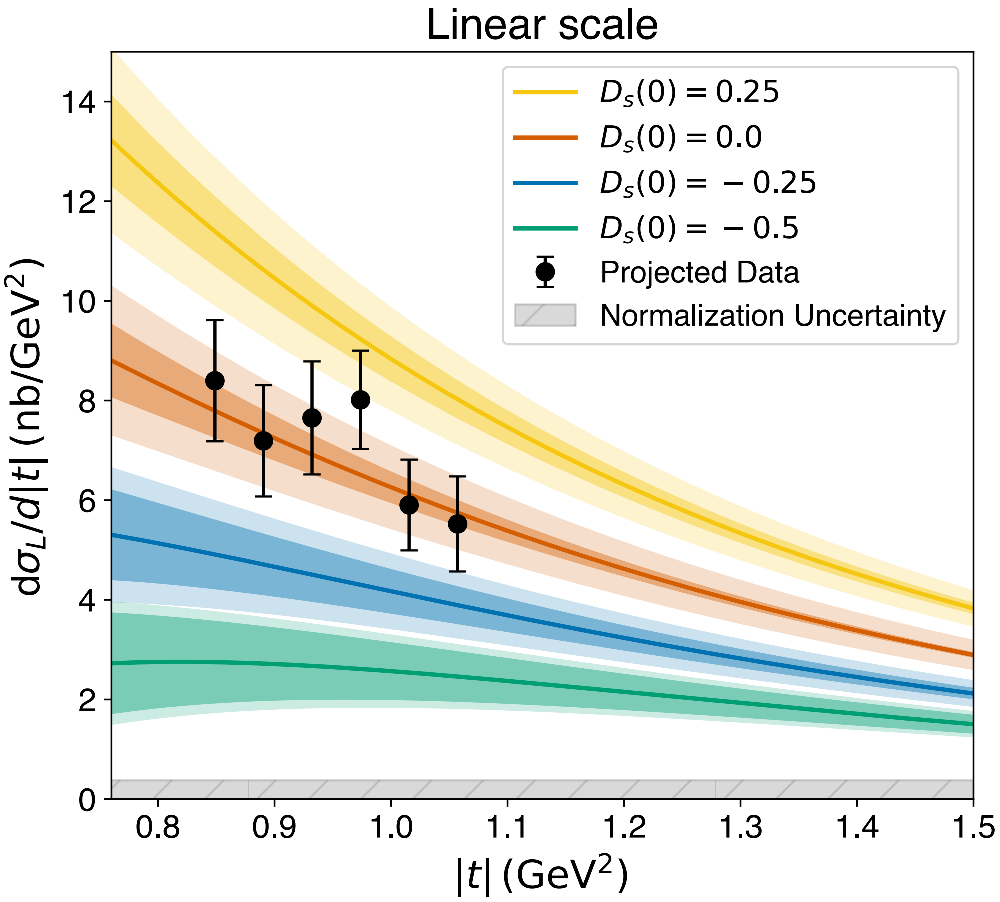
HOW WELL CAN WE EXTRACT D_S?



- 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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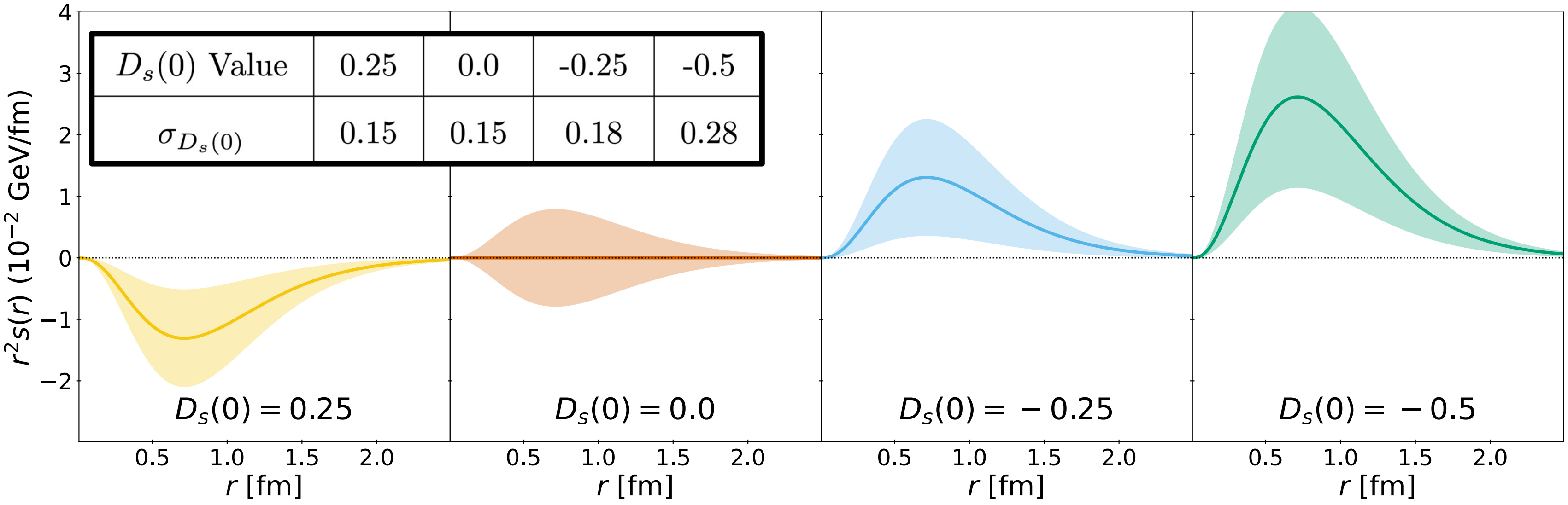
WHAT CAN WE LEARN FROM ϕ-007?

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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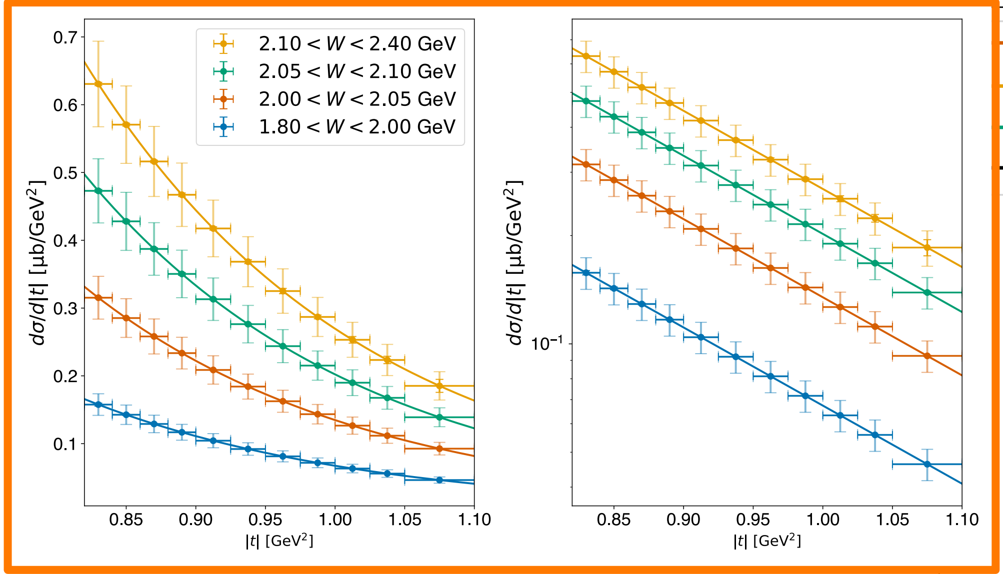
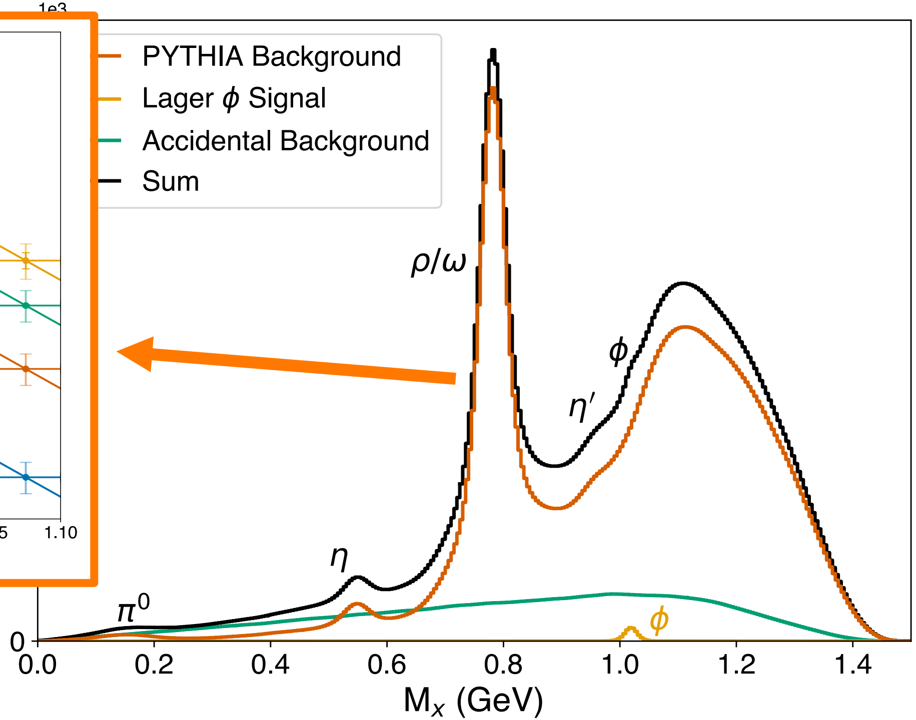
WHAT ELSE CAN WE LEARN FROM ϕ-007 ?



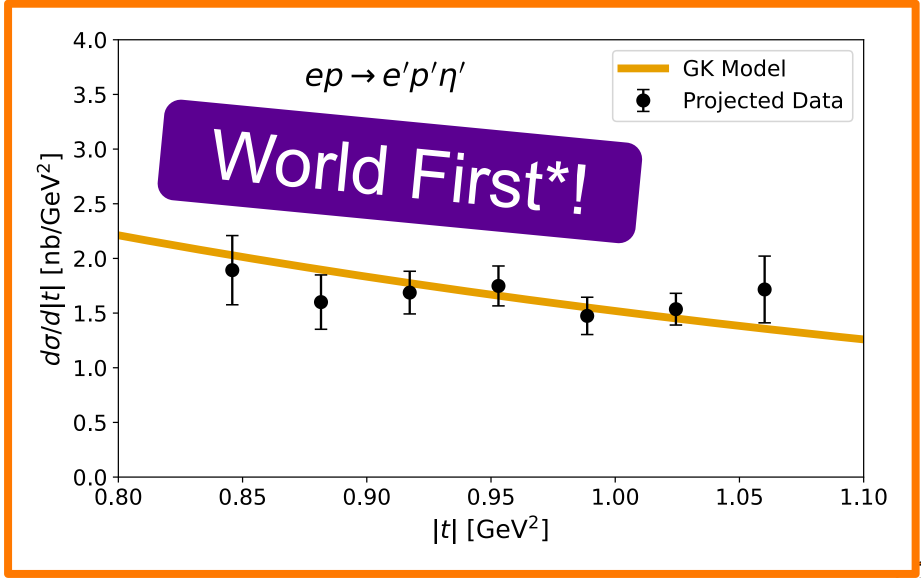


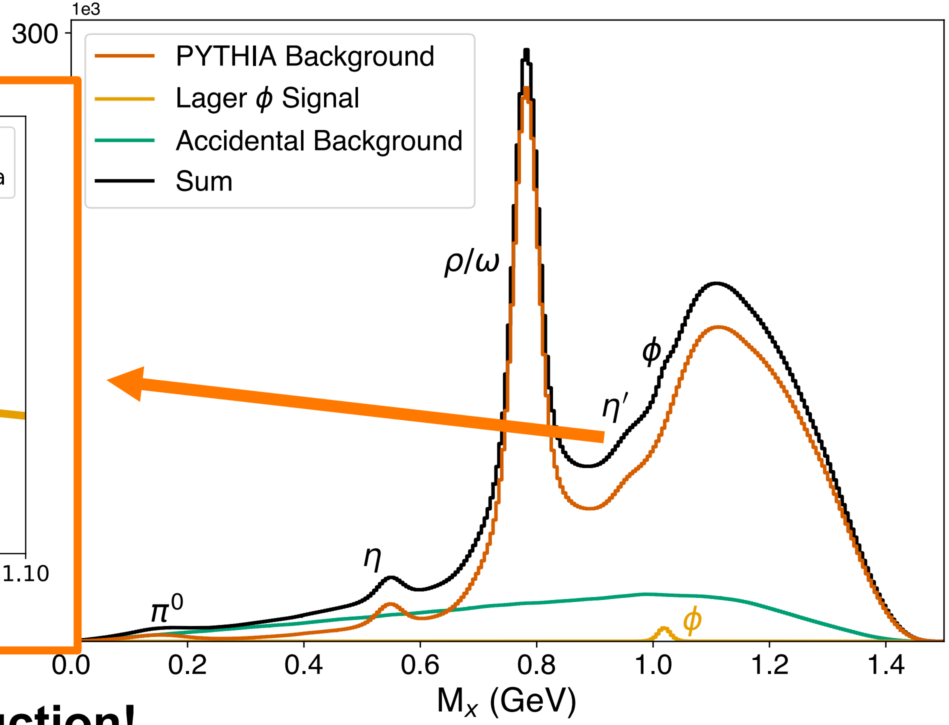
Most differential measurement of near-threshold ω electroproduction! + BSA!

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 ϕ-007 ?





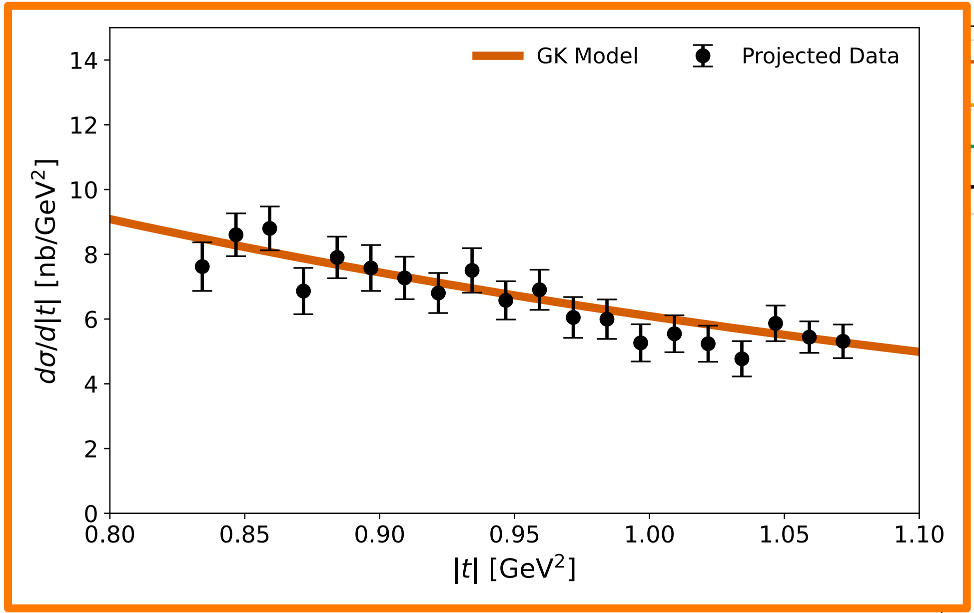
First measurement of η' electroproduction!

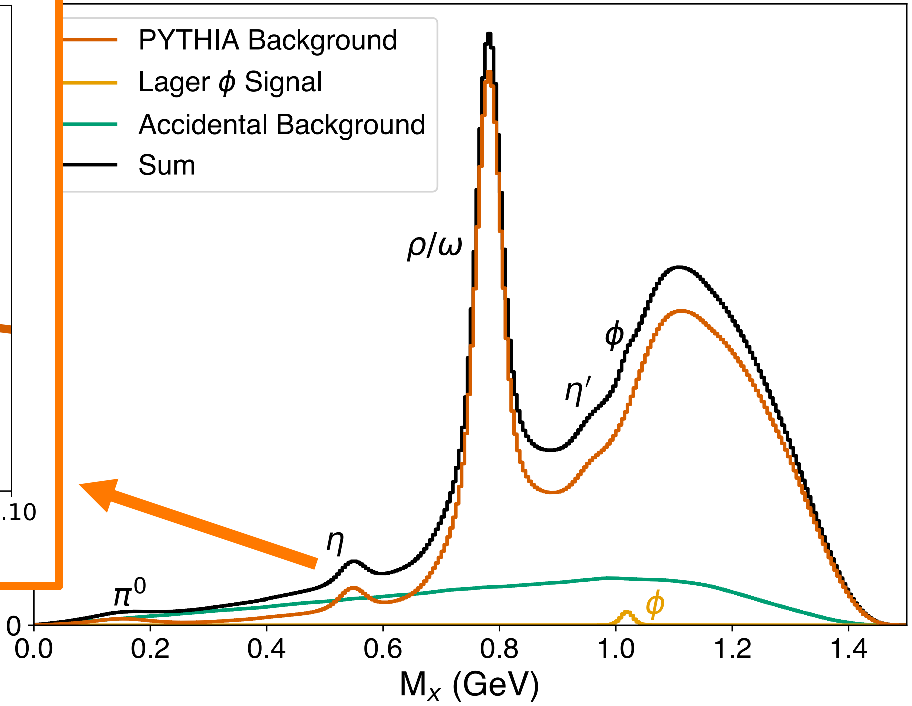
Unexpectedly large η' mass is generated by the **QCD chiral anomaly**,

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 ϕ-007 ?





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

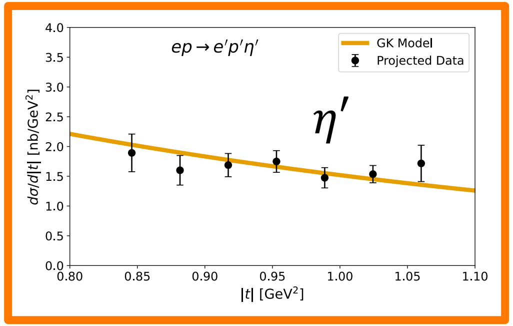
[1] Eides, Frankfurt, Strikman - **Hard Exclusive Electroproduction of Pseudoscalar Mesons and QCD axial anomaly**

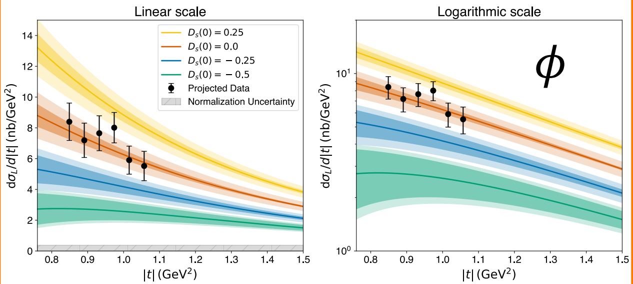
WHAT ELSE CAN WE LEARN FROM THIS DATA?

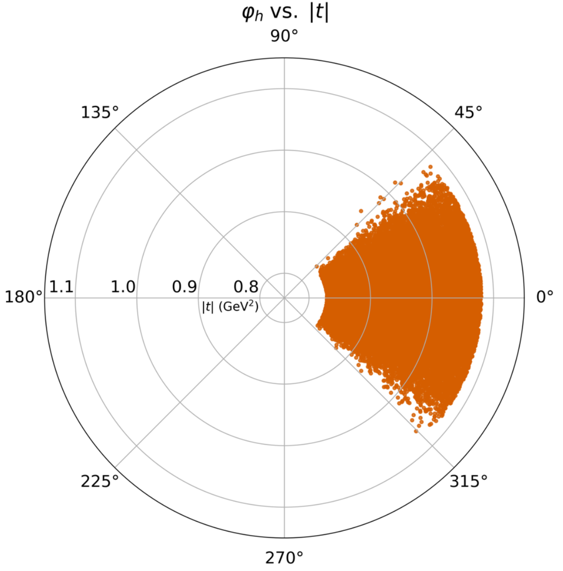
Beam Spin Asymmetries for all!

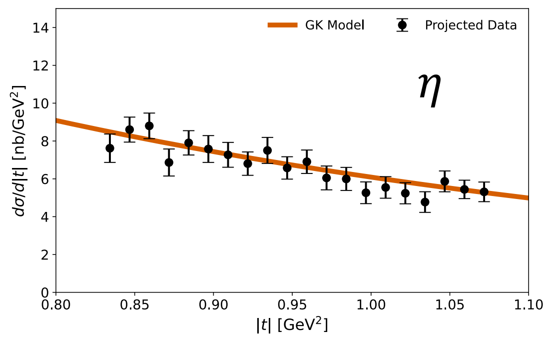
(Partially)

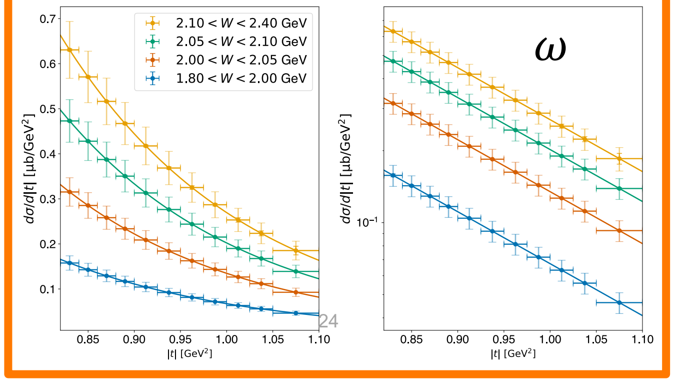
$$\mathrm{BSA} = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi_h}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi_h+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi_h}$$





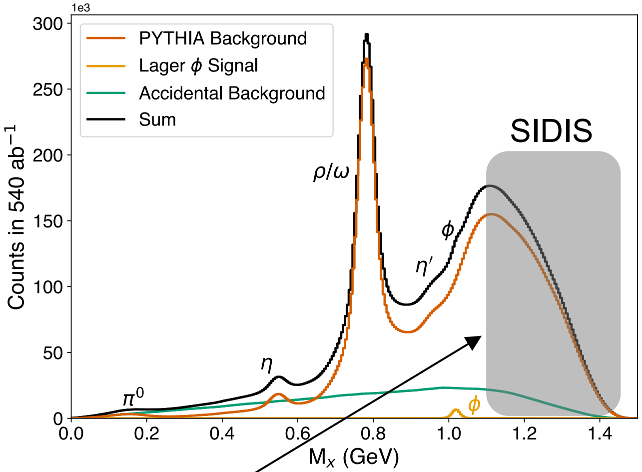


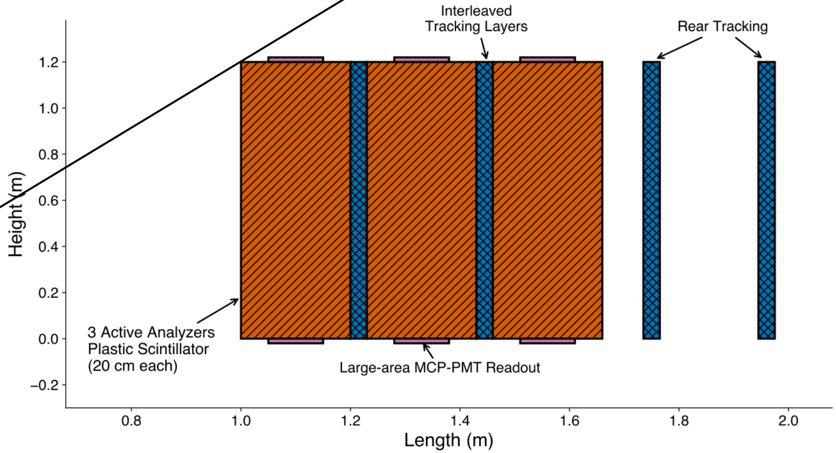




ASIDE: RECOIL POLARIZATION

- Addition of proton polarimeter in HMS would enable the **first measurement of recoil polarization in DVMP** via H(e,e'p)X reaction
  - **Test s-channel helicity conservation** in a new way
  - Recoil polarization only measured in a very limited set of reactions, almost exclusively elastic scattering
- For semi-inclusive DIS, connection to the spin-dependent odderon!?



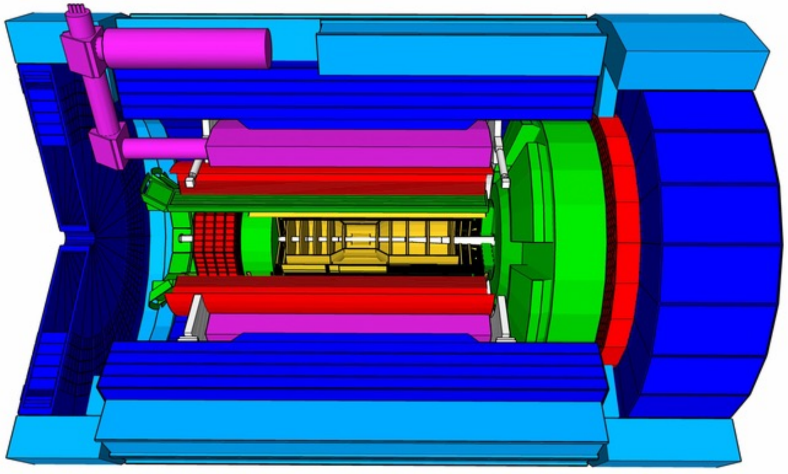


Single spin asymmetry in $e + p \to e' + B^{\uparrow} + X$

Yoshitaka Hatta[1,2] and Oleg V. Teryaev[3]

WHAT ABOUT THE EIC?

- **Large acceptance detector!**
  - Means ϕ decay products can be **measured directly**, fully exclusive
  - Use the dual-radiator RICH for PID of kaons at relatively small angles
  - **Background** can be **substantially reduced**

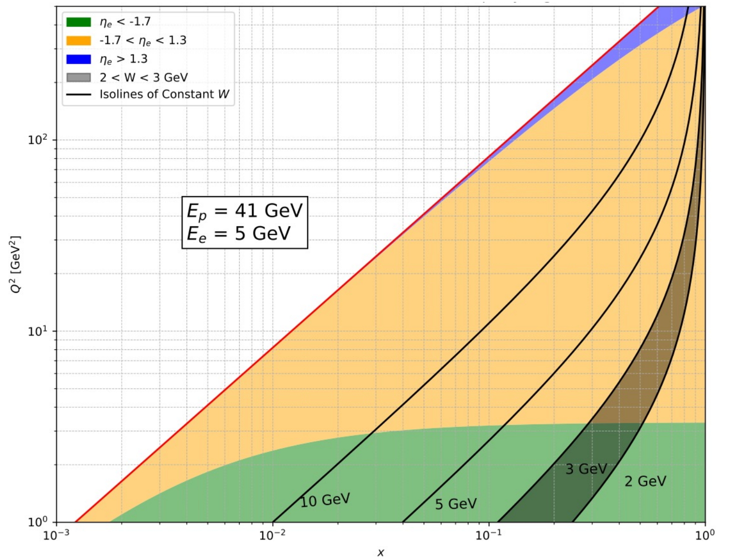


- How well can we do? Can we access $\boldsymbol{D_s}$ at the EIC?

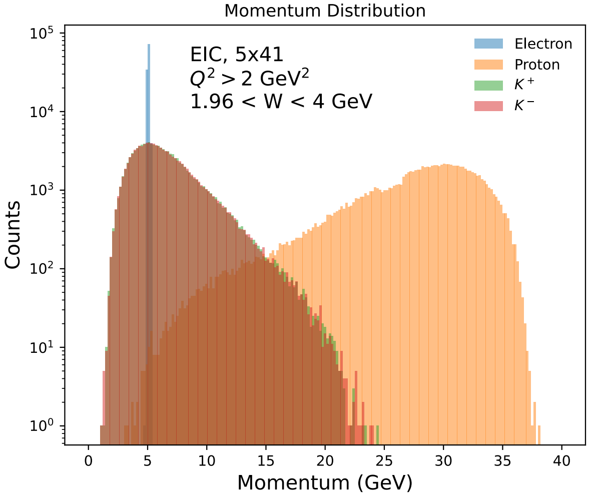
PROJECTIONS ePIC

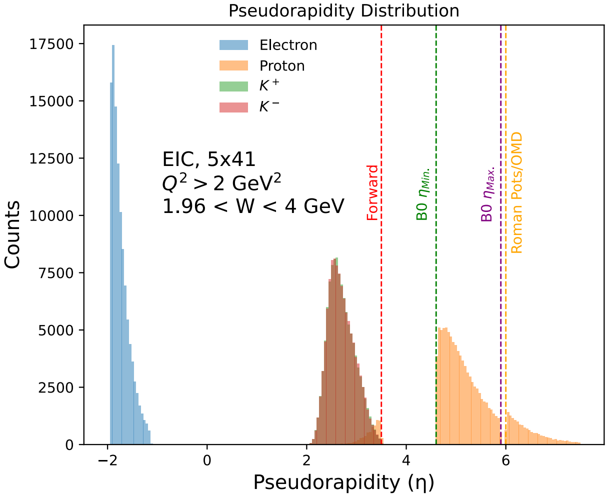
- Only 5x41 GeV mode enables access to near-threshold ϕ

- Acceptance for ϕ in central detector is nearly zero for even 10x100 GeV energy
  - — ϕ too forward boosted near-threshold



- Fully exclusive measurement only possible thanks to EIC far-forward detectors!



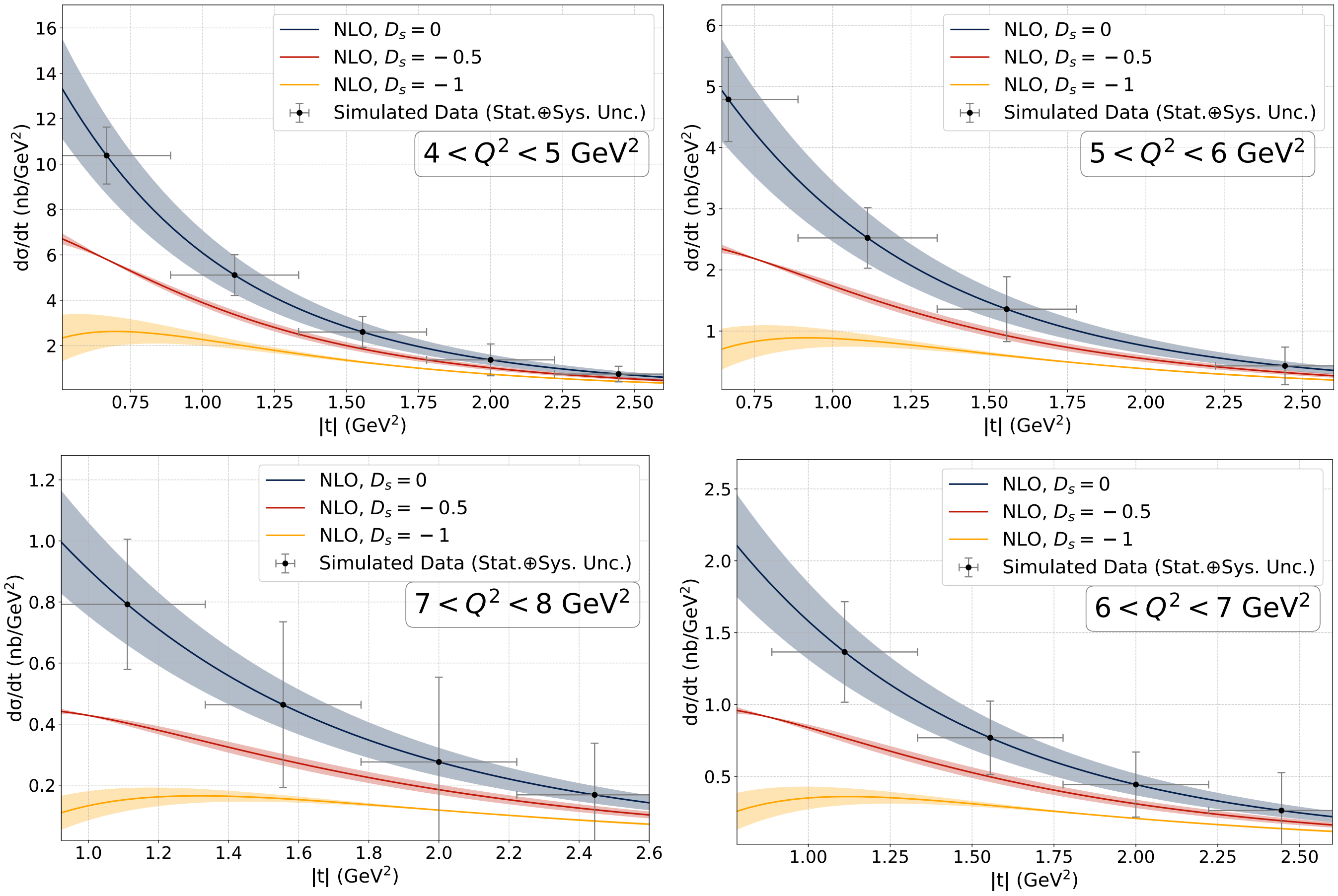


PROJECTIONS ePIC

EIC 5x41 Projections for $\frac{d\sigma_L}{d|t|}$ at **2.4 < W < 2.8 GeV**

- Assume 10 fb^{-1} (5x41)
  - Two years (40 weeks) of running at the design luminosity
- Full exclusivity
  - e$^-$, K$^{\pm}$, p all measured in the detector

Limited by statistics & forward acceptance

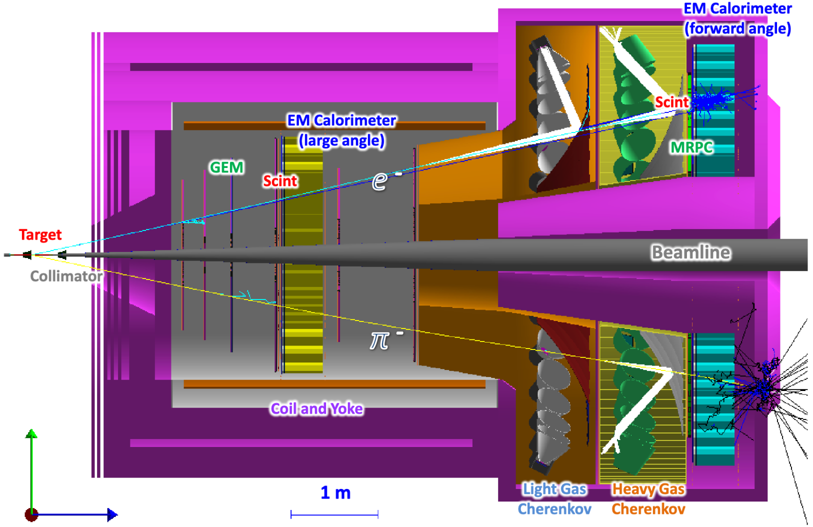


EXCLUSIVE ϕ IN SOLID

- Large acceptance & luminosity!
  - ϕ decay products can be **measured directly**
    - Fully exclusive, low background
    - Measure R to extract σ_L
  - Near-threshold is more accessible than at EIC
  - PID from **ToF, Cherenkovs**

High statistics & continuous kinematic coverage for multidimensional measurement!

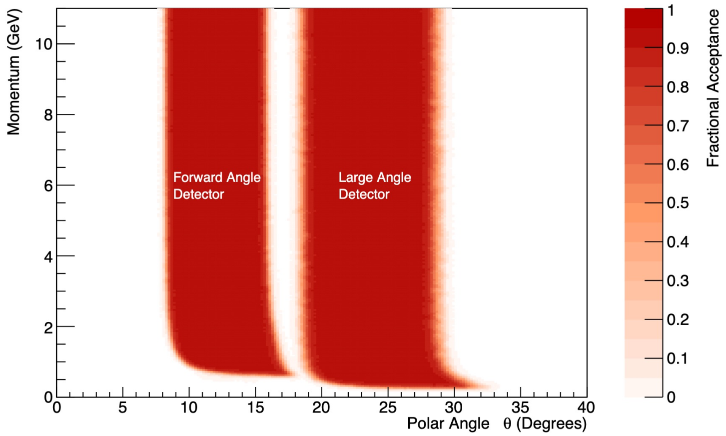
SoLID
SOLENOIDAL LARGE INTENSITY DEVICE



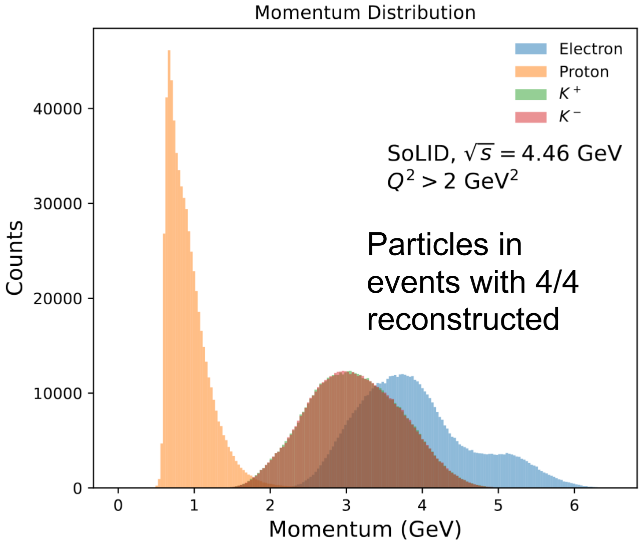
PROJECTIONS

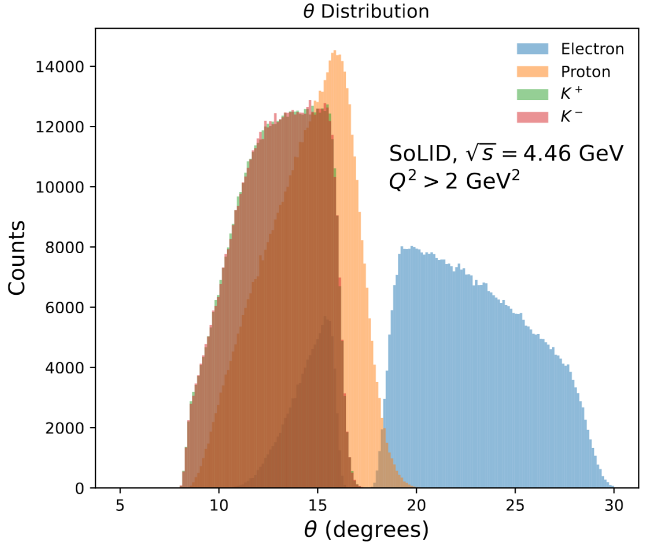
SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

- Exclusive ϕ projections for SoLID
  - 43.2 ab^{-1} (existing J/ψ proposal)
  - **Fully exclusive! -** Detect all four final state particles: e', p', K^+, K^-
- Require kaons, proton to be detected in forward angle detector
  - Better TOF PID



Particle momenta nicely suited for the SoLID PID systems!

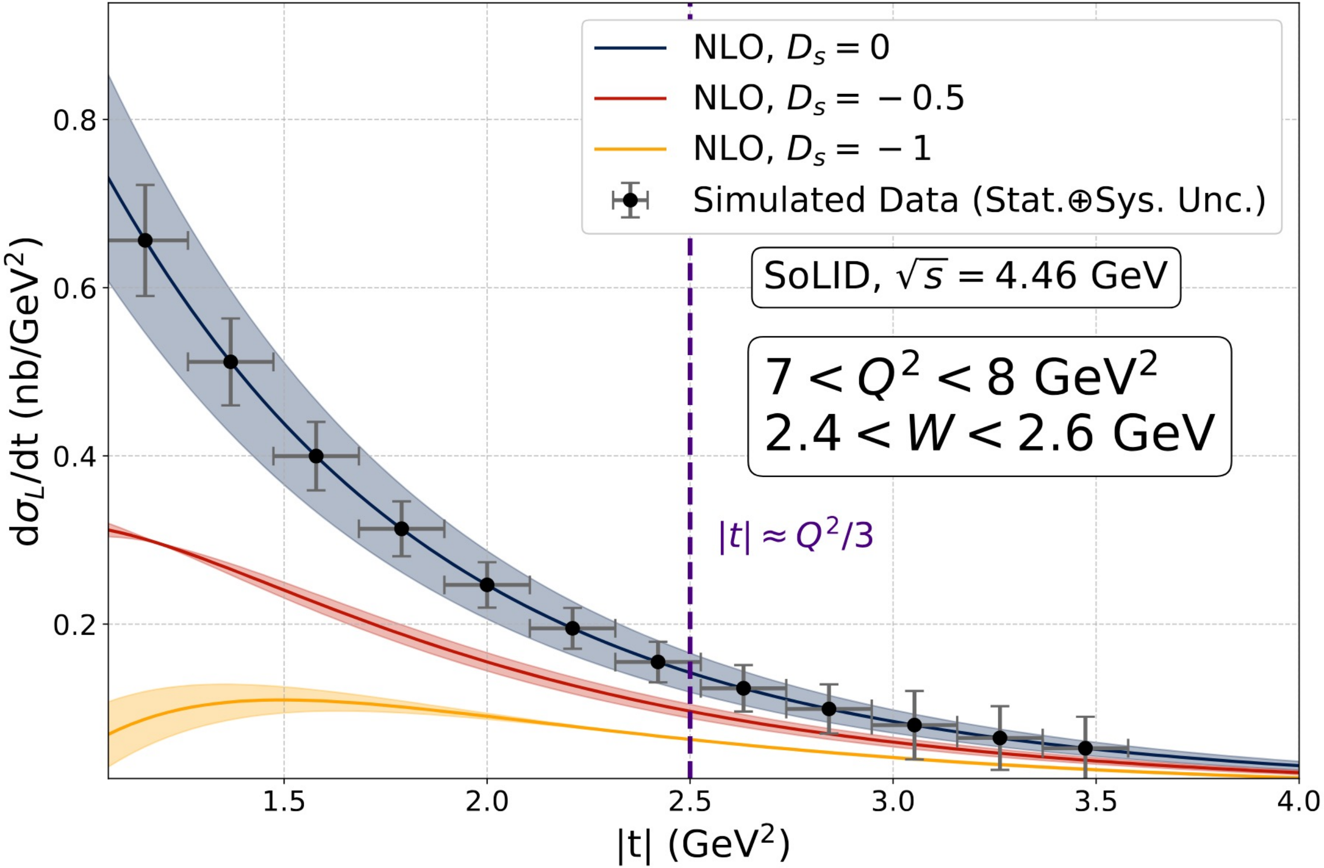




PROJECTIONS

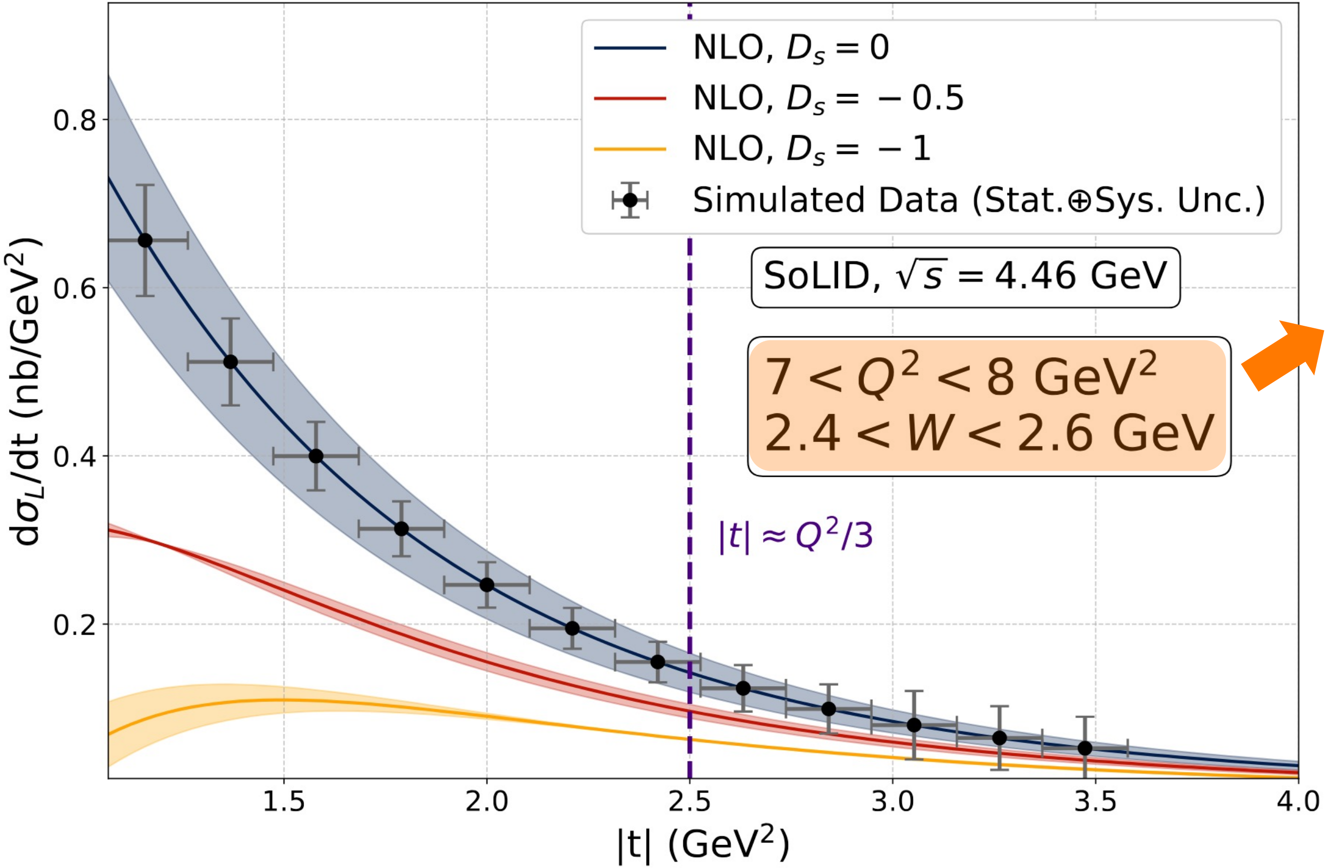
SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

Assumption of 10% systematic uncertainty still **exhibits good sensitivity to D_s!**

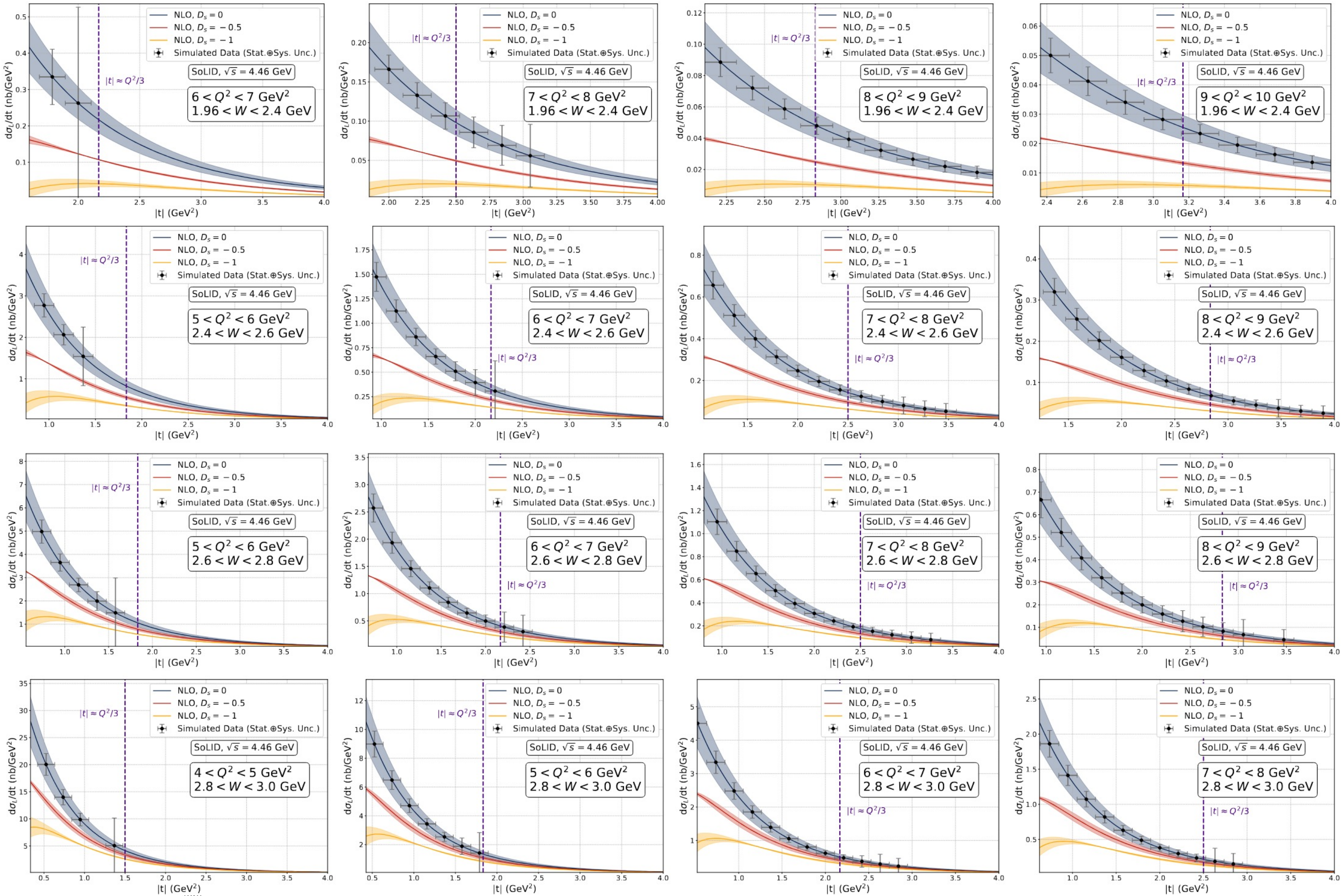


PROJECTIONS

Assumption of 10% systematic uncertainty still **exhibits good sensitivity to D_s!**



Ideal kinematics!


NLO, $D_s = 0$
NLO, $D_s = -0.5$
NLO, $D_s = -1$
Simulated Data (Stat.⊕Sys. Unc.)
SoLID, $\sqrt{s} = 4.46$ GeV
$|t| \approx Q^2/3$
$d\sigma_L/dt$ (nb/GeV^2)
$|t|$ (GeV^2)
$6 < Q^2 < 7$ GeV^2 $1.96 < W < 2.4$ GeV
$7 < Q^2 < 8$ GeV^2 $1.96 < W < 2.4$ GeV
$8 < Q^2 < 9$ GeV^2 $1.96 < W < 2.4$ GeV
$9 < Q^2 < 10$ GeV^2 $1.96 < W < 2.4$ GeV
$5 < Q^2 < 6$ GeV^2 $2.4 < W < 2.6$ GeV
$6 < Q^2 < 7$ GeV^2 $2.4 < W < 2.6$ GeV
$7 < Q^2 < 8$ GeV^2 $2.4 < W < 2.6$ GeV
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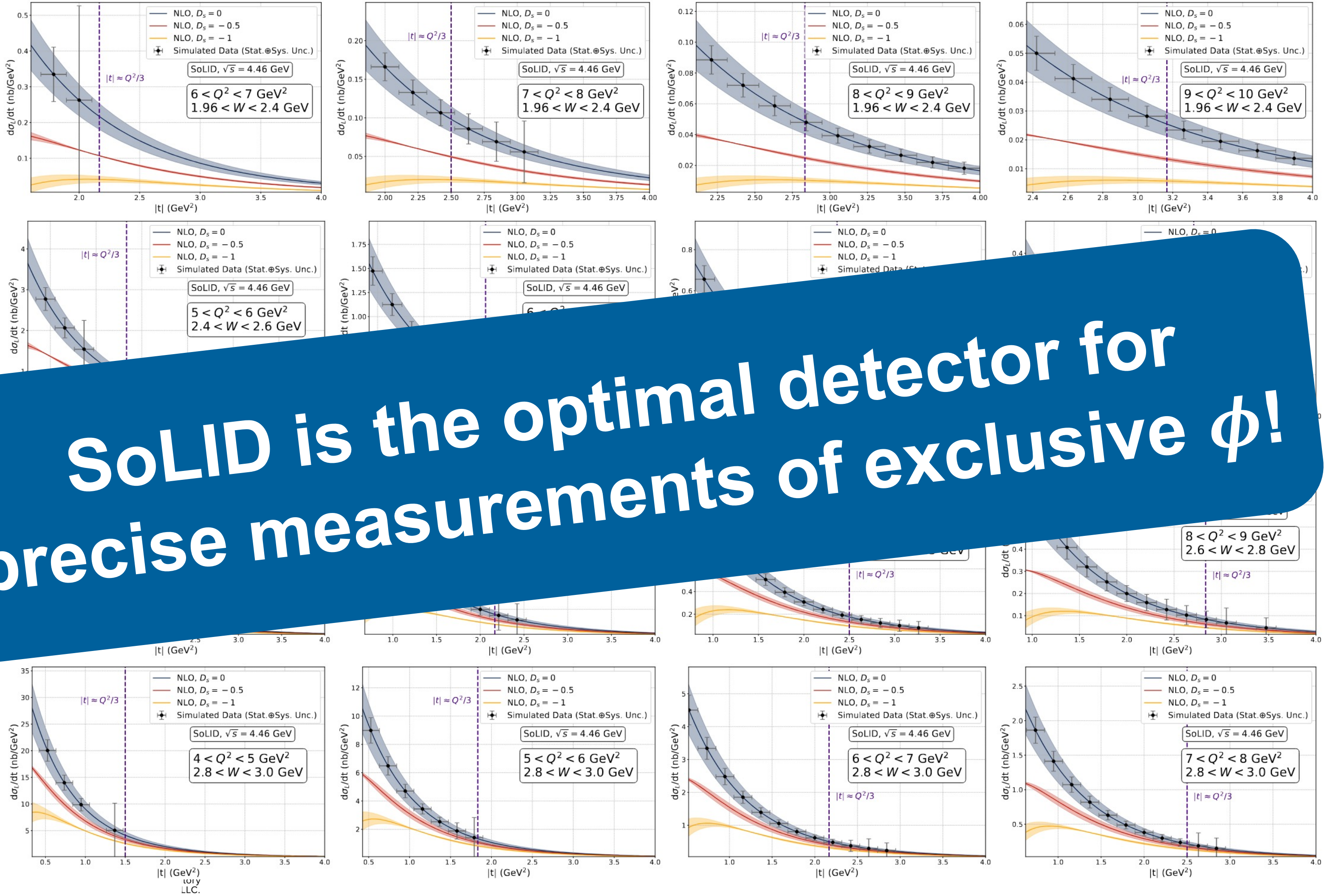
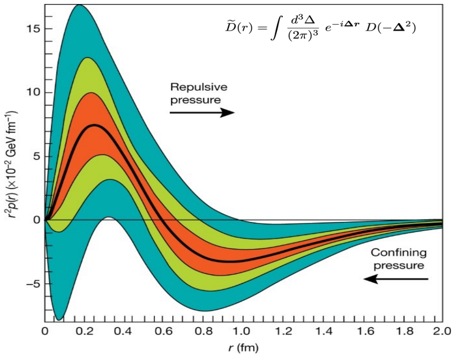
$7 < Q^2 < 8$ GeV^2 $2.6 < W < 2.8$ GeV
$8 < Q^2 < 9$ GeV^2 $2.6 < W < 2.8$ GeV
$4 < Q^2 < 5$ GeV^2 $2.8 < W < 3.0$ GeV
$5 < Q^2 < 6$ GeV^2 $2.8 < W < 3.0$ GeV
$6 < Q^2 < 7$ GeV^2 $2.8 < W < 3.0$ GeV
$7 < Q^2 < 8$ GeV^2 $2.8 < W < 3.0$ GeV

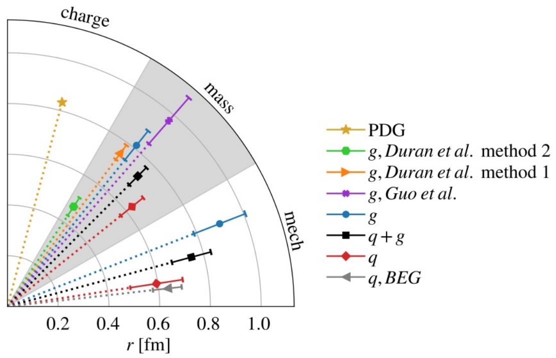


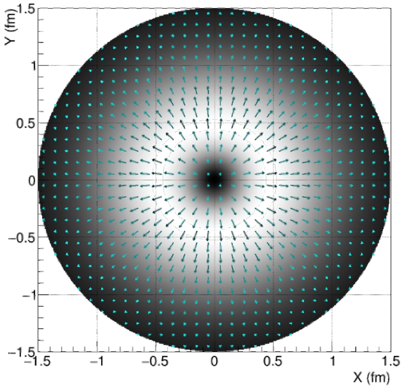
SoLID is the optimal detector for precise measurements of exclusive ϕ!

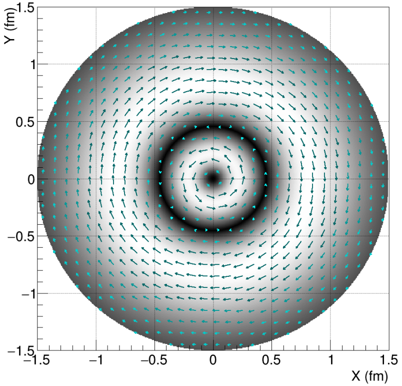
Armed with the **missing piece** D_s, can finally do global analyses of ***total*** *D*-term from **experimental data!**

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









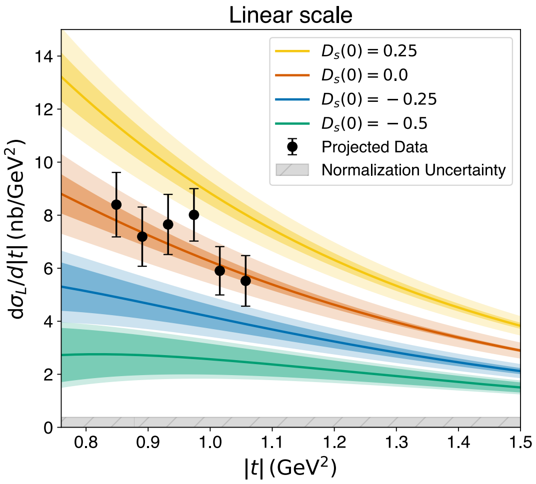
Armed with the **missing piece** D_s, can finally do global analyses of ***total*** D-term from **experimental data!**

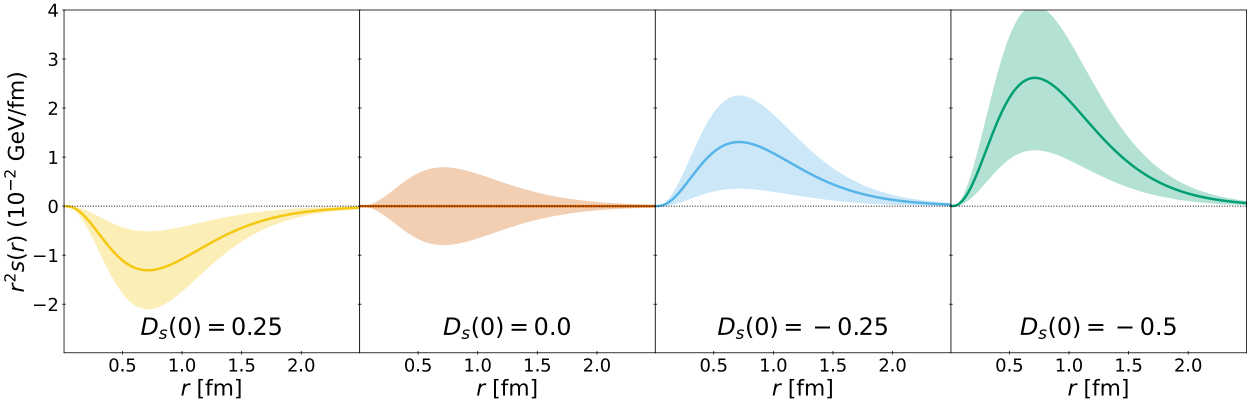
$$D(0) = \underbrace{D_g(0)}_{J/\psi} + \underbrace{D_u(0) + D_d(0)}_{\text{DVCS}} + \underbrace{D_s(0)}_{\phi\ \text{DVMP}} + \ldots$$

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

CONCLUSION

- To fully understand proton mechanical structure, **need to extract the contribution of strangeness to the D-term**
  - **Only place in the world** presently capable of this measurement is **CEBAF**
  - Need more **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!**





BACKUP

59 Collaborators

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Jefferson Lab

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University of Regina

FIU

ODU

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NM STATE UNIVERSITY

TEMPLE UNIVERSITY

A. ALIKHANYAN National Laboratory

JAMES MADISON UNIVERSITY

UNIVERSITY of York

SUNO SOUTHERN UNIVERSITY at NEW ORLEANS

University of Zagreb

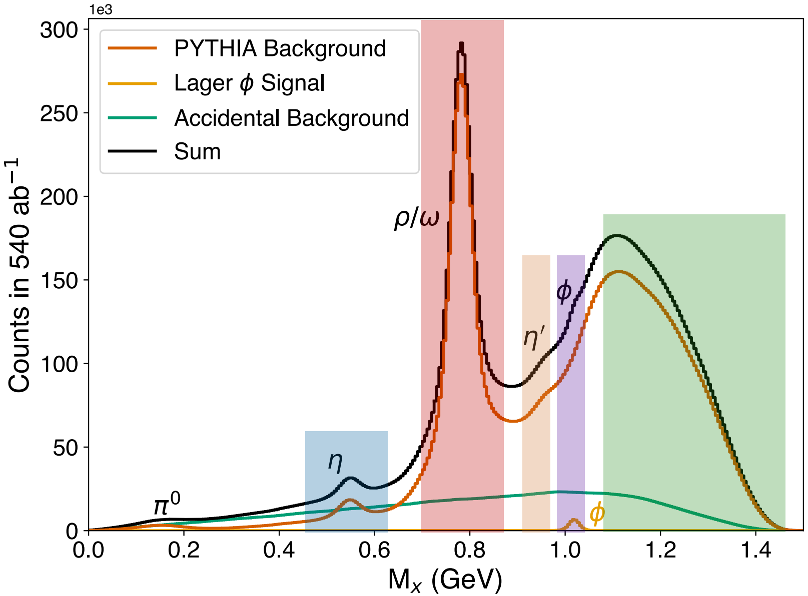
UNIVERSITY of York

VT VIRGINIA TECH

WHAT ELSE CAN WE LEARN FROM ϕ-007?

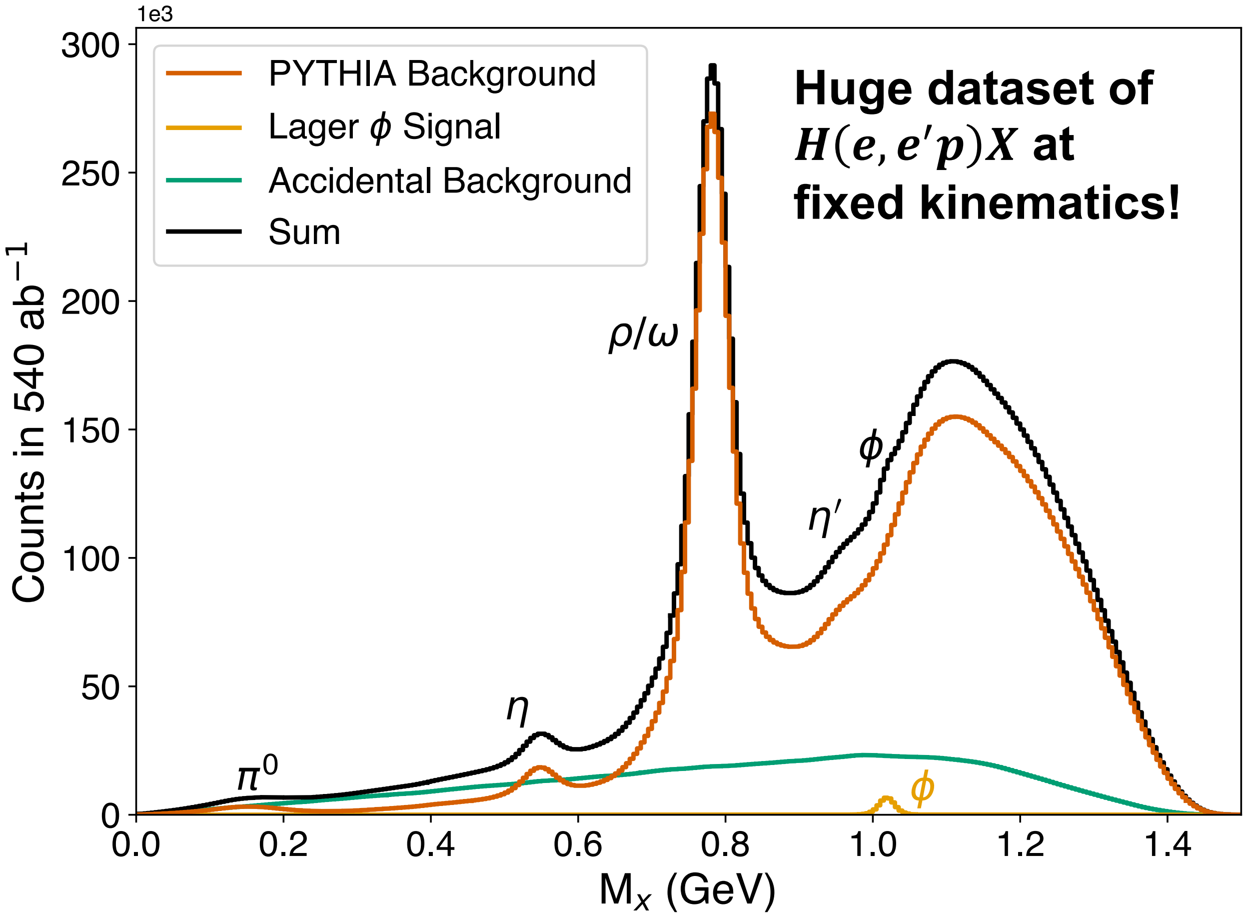
Channel	Physics Goal
ϕ BSA	Compare to GPD models
η' cross section / BSA	GPDs and/or study of the chiral anomaly
ω cross section / BSA	Compare to GPD models, Mass radius
η cross section / BSA	Baseline for η' sans anomaly
u-channel $H(e, e'\pi)X$	Baryon junction / spectroscopy
u-channel $H(e, e'K)X$	Baryon junction / spectroscopy
$\pi/K/p$ SIDIS	High statistics cross check of SIDIS validity at low-M_X

TABLE II. Planned measurements in addition to the ϕ cross section and their physics goals.

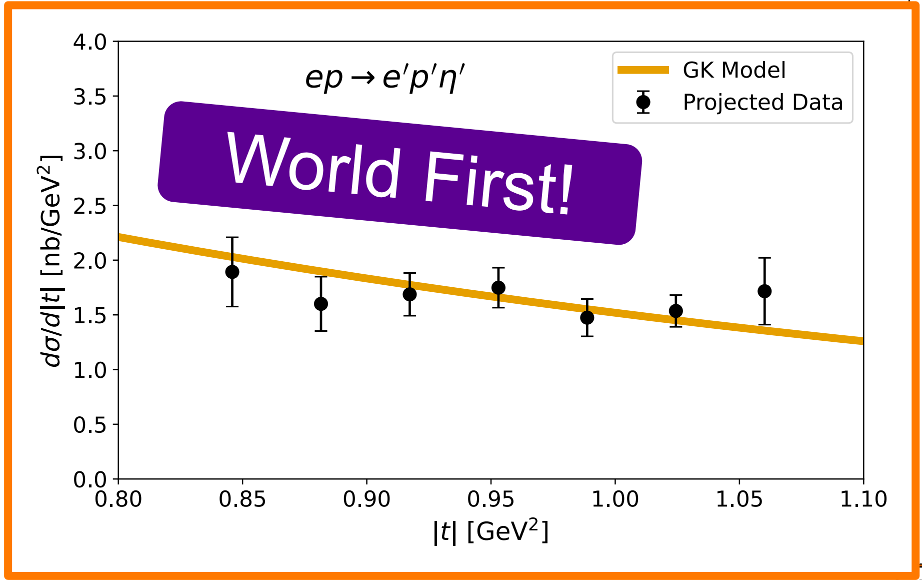


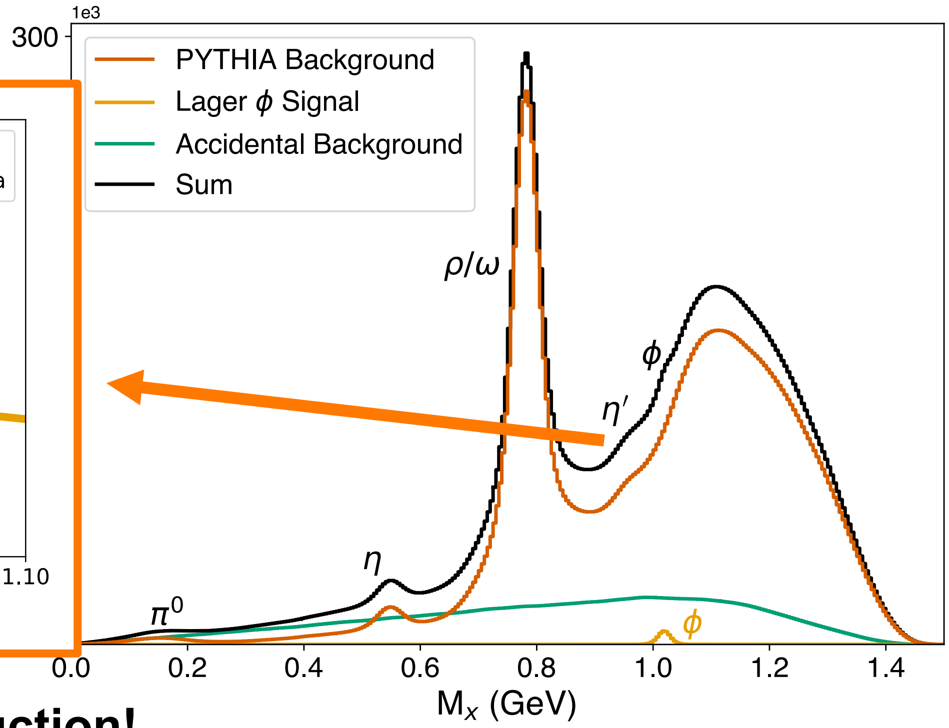
Lots of physics opportunities that come for free with this dataset!

WHAT ELSE CAN WE LEARN FROM THIS DATA?



WHAT ELSE CAN WE LEARN FROM THIS DATA?





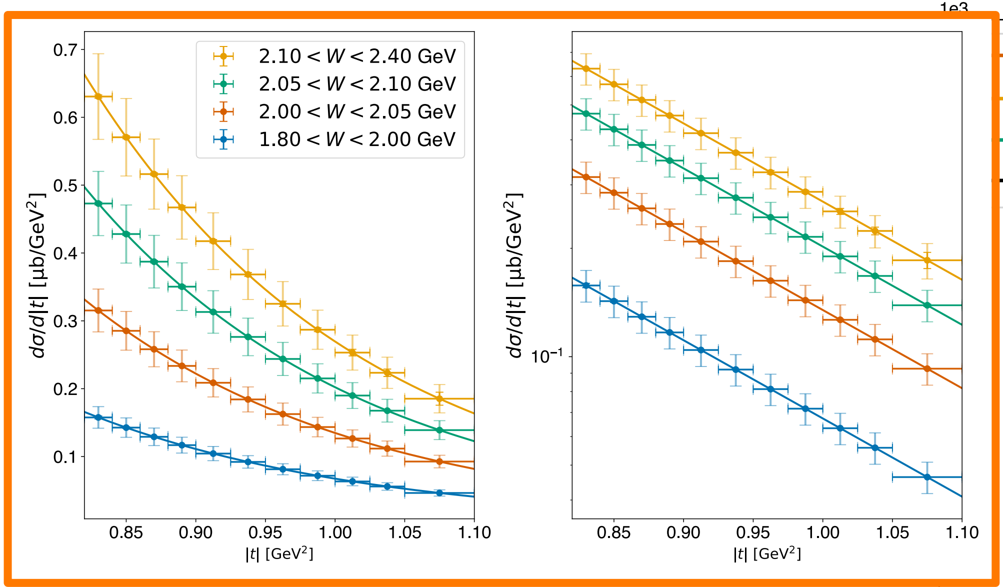
First measurement of η' electroproduction!

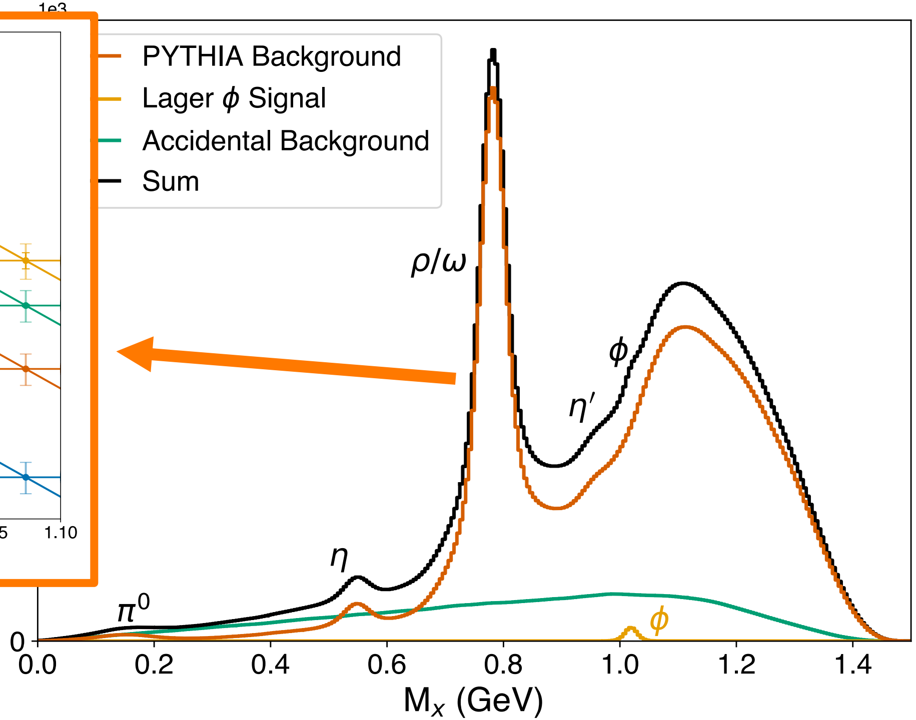
Unexpectedly large η' mass is generated by the **QCD chiral anomaly**,

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?



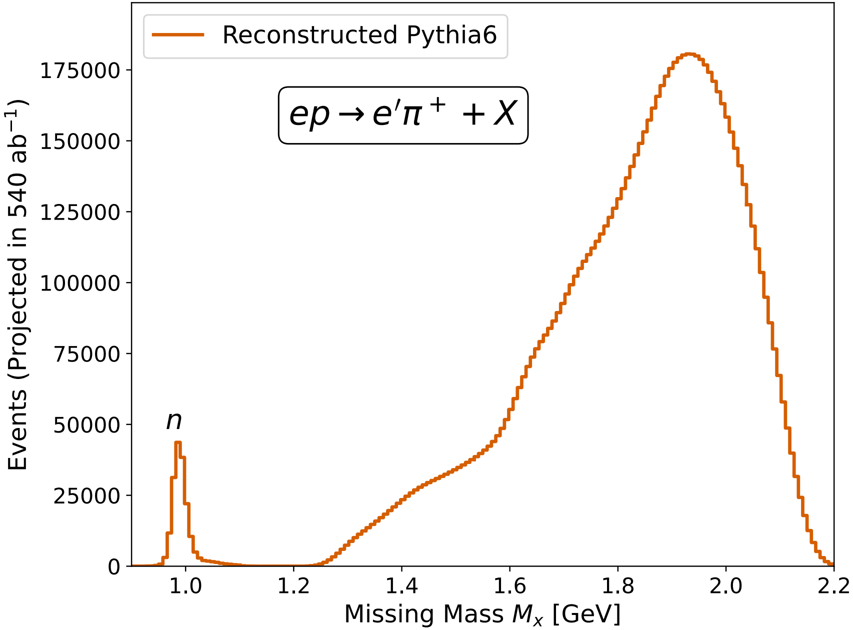


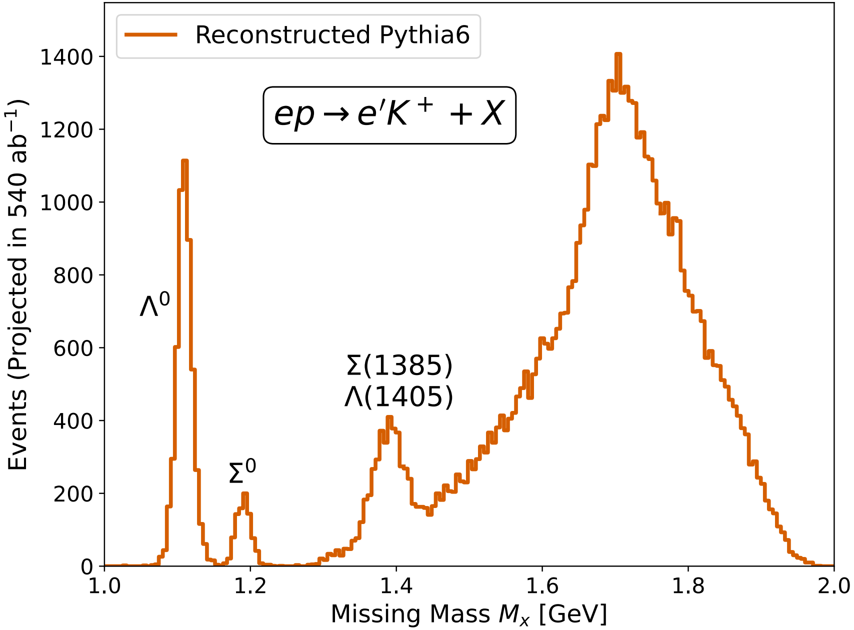
Most differential measurement of near-threshold ω electroproduction! + BSA!

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*

59 Collaborators, international collaboration!

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D. Androić
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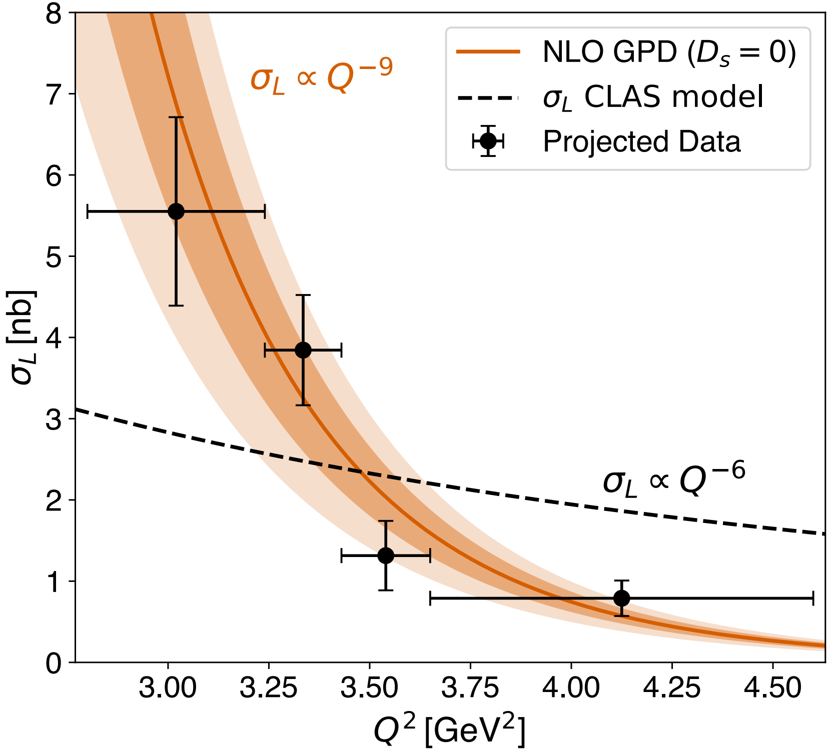
S. Kay
University of York, York, UK

J. Datta
Stony Brook University, Stony Brook, NY

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 $\sigma_L \propto Q^{-4}$

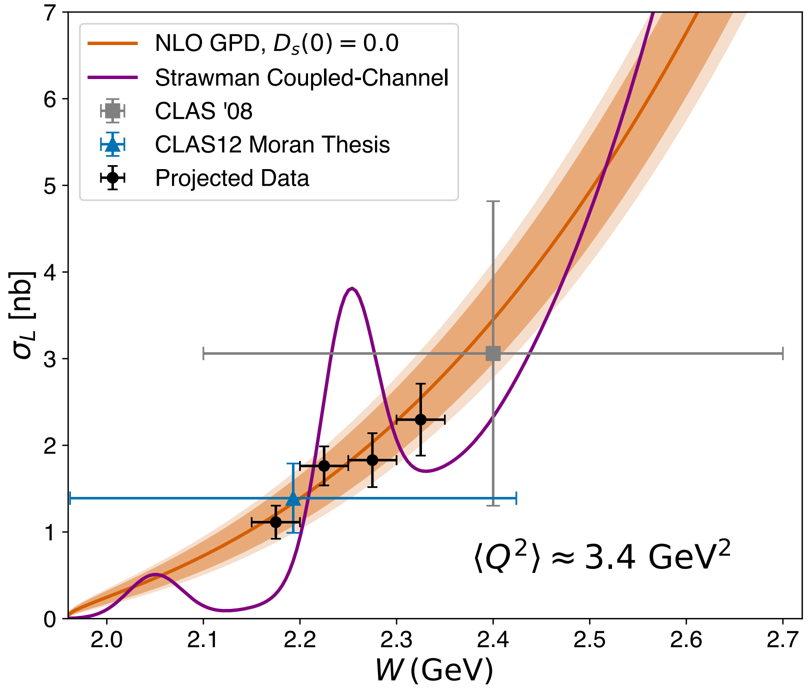
Can validate or invalidate collinear factorization at these kinematics with our data!



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

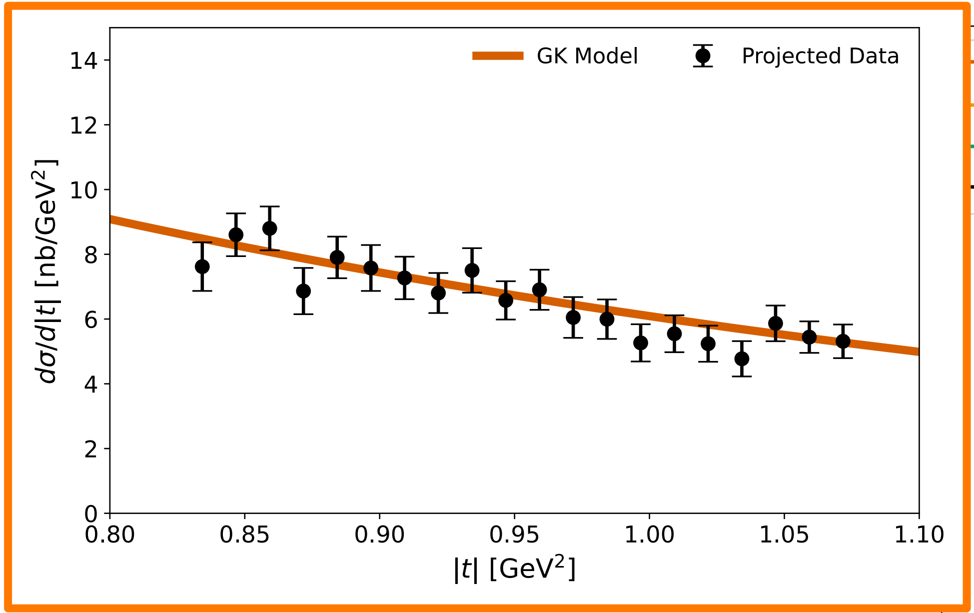
TESTING THE THEORY

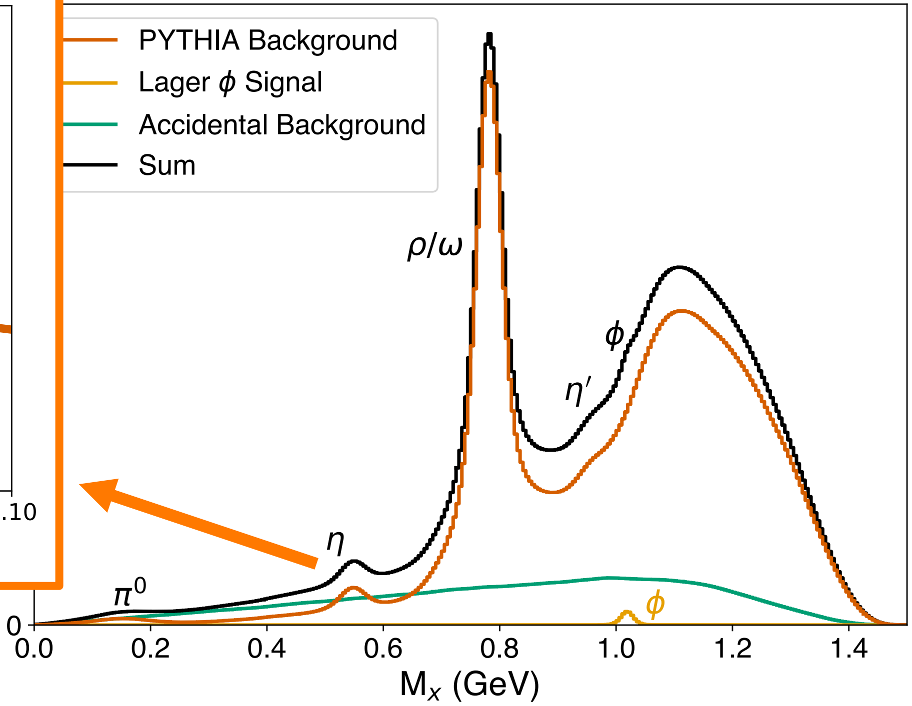
- The prediction of Hatta et al. "**agrees**" with CLAS data and preliminary results from CLAS12
  - **Data uncertainties are very large!**
- Almost any model can describe the existing data due to poor precision & large bins
- The speculation surrounding this topic is precisely why these **data are sorely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



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

WHAT ELSE CAN WE LEARN FROM THIS DATA?





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

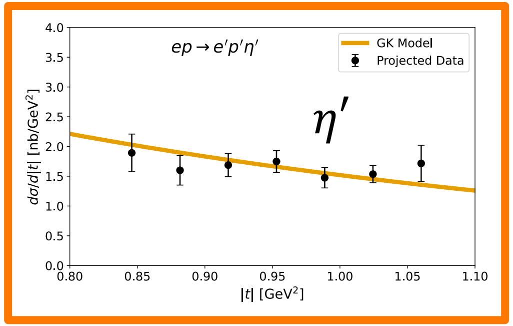
[1] Eides, Frankfurt, Strikman - **Hard Exclusive Electroproduction of Pseudoscalar Mesons and QCD axial anomaly**

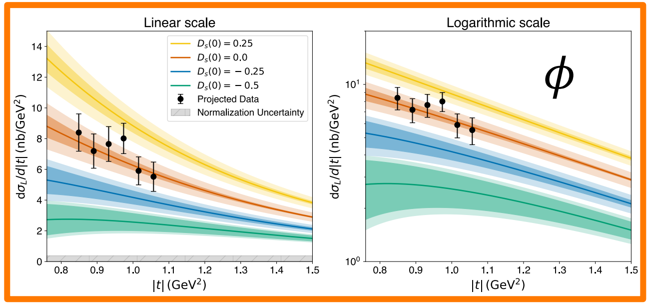
WHAT ELSE CAN WE LEARN FROM THIS DATA?

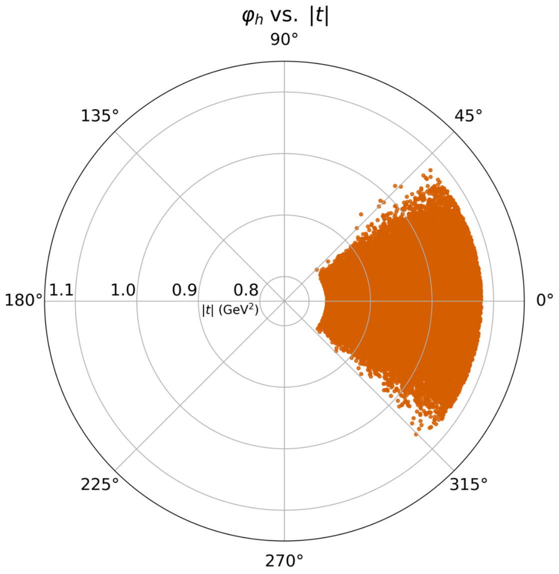
Beam Spin Asymmetries for all!

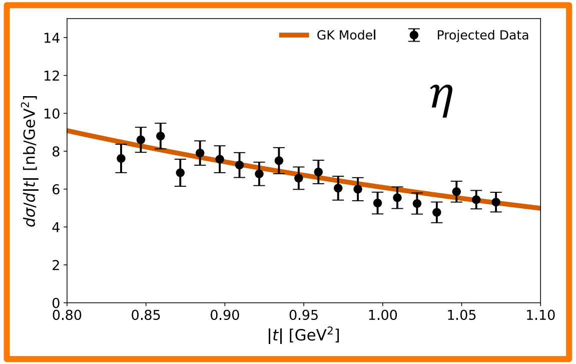
(Partially)

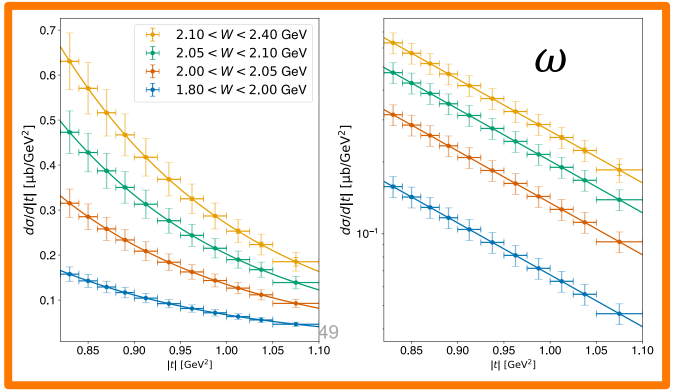
$$\mathrm{BSA} = \frac{\sqrt{2\epsilon(1-\epsilon)}\,\frac{\sigma_{LT'}}{\sigma_0}\sin\phi_h}{1+\sqrt{2\epsilon(1+\epsilon)}\,\frac{\sigma_{LT}}{\sigma_0}\cos\phi_h+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi_h}$$

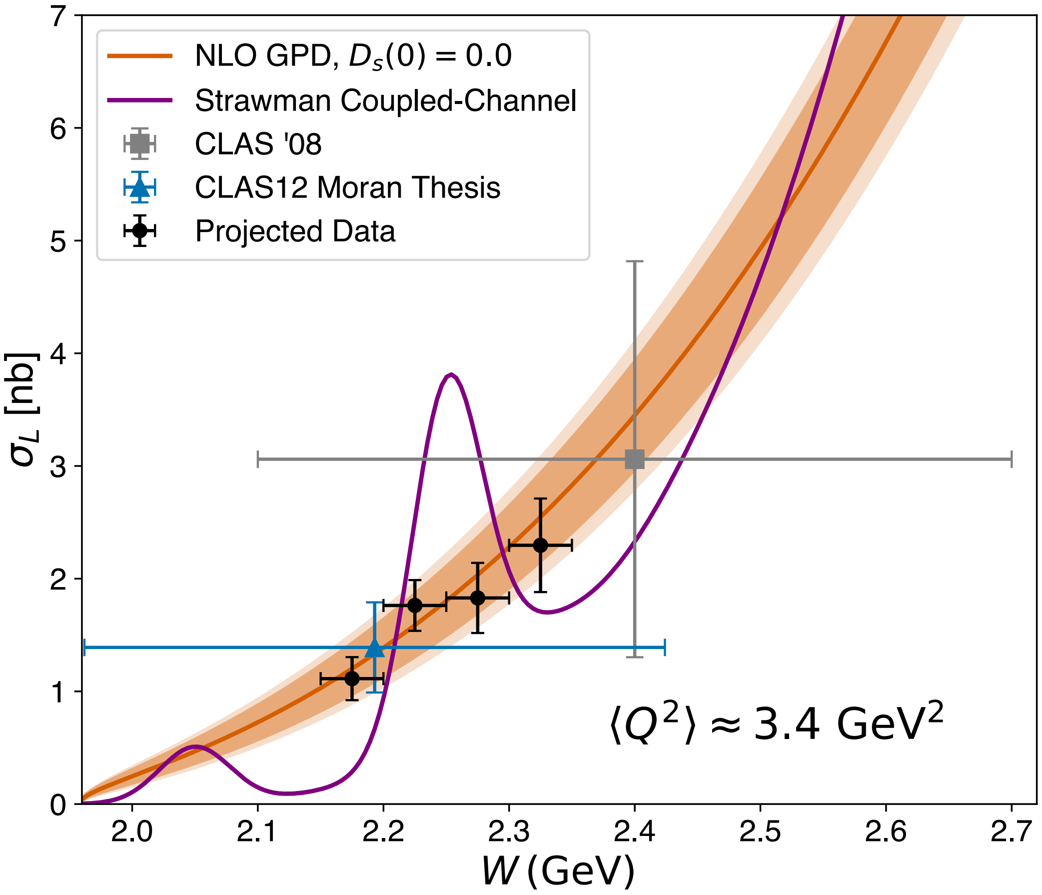








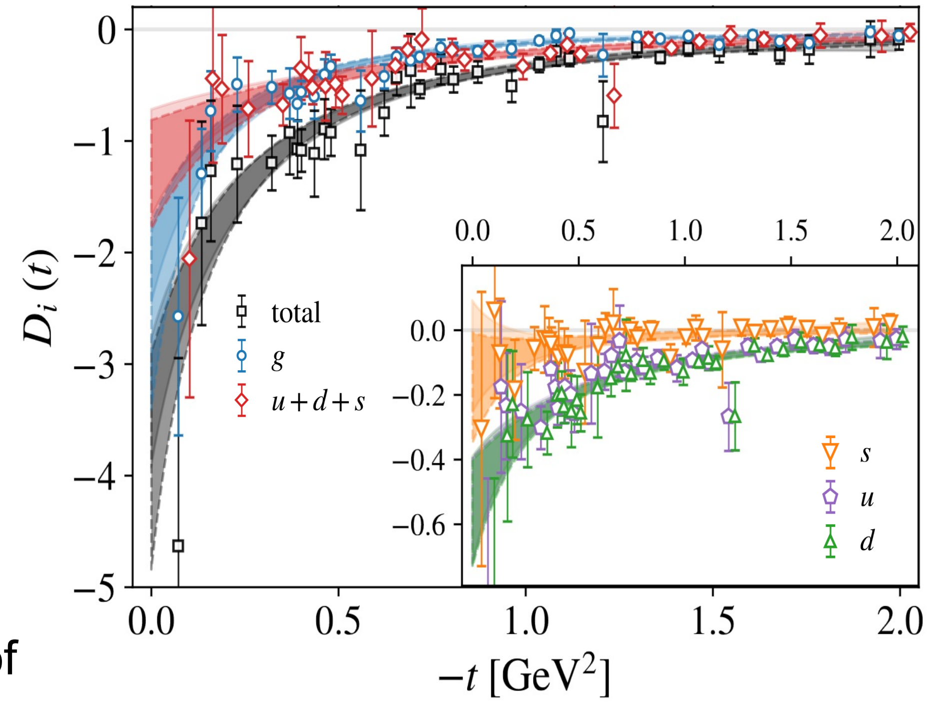




Data Source	$\langle W \rangle$ (GeV)	Data σ_L	GPD σ_L
CLAS '08 data	2.40	3.06 ± 1.76	3.44 ± 0.66
CLAS12 Moran thesis data	2.19	1.39 ± 0.30	1.28 ± 0.33

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

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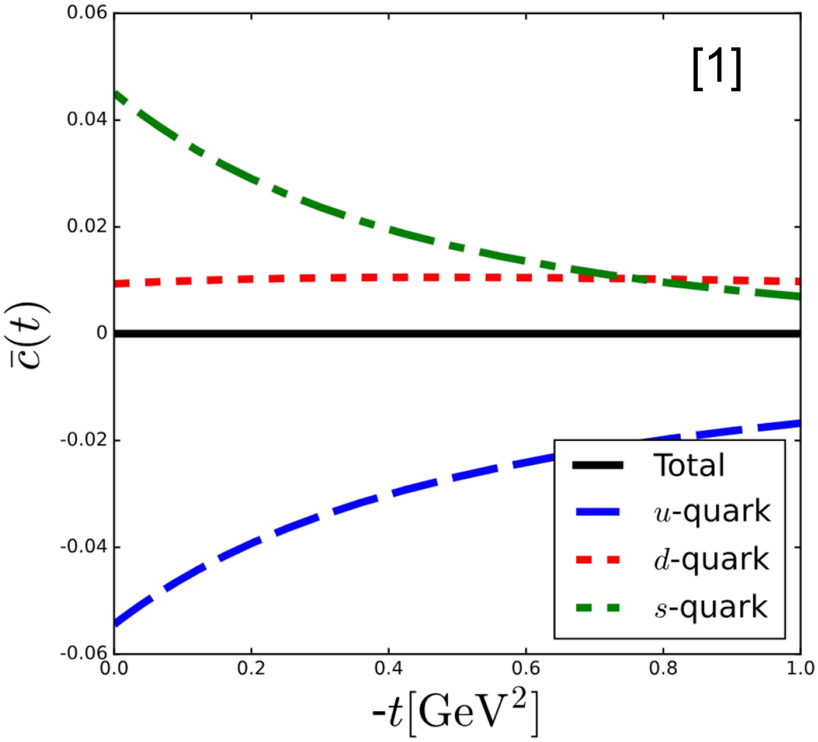
$\bar{c}$ CAVEAT

- $\bar{c}$ 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!**



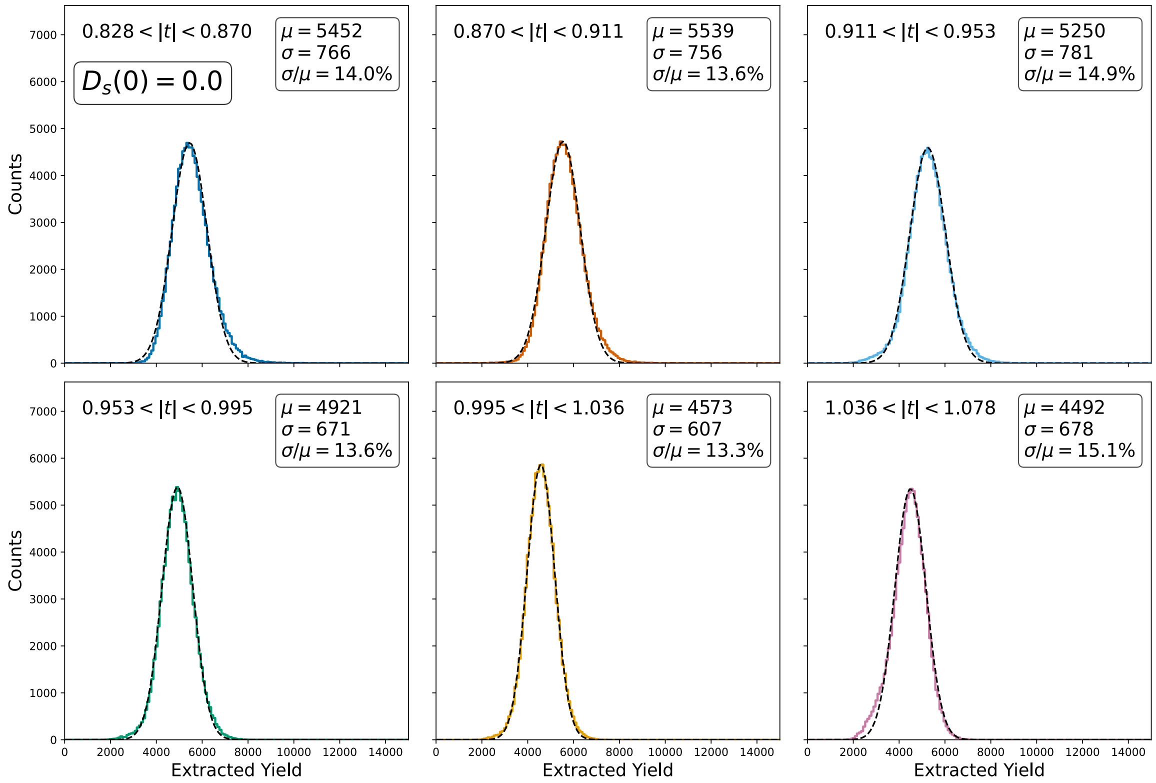
This caveat means that to extract the full set of mechanical properties, ***all* partonic *D*-term contributions must be known!**

[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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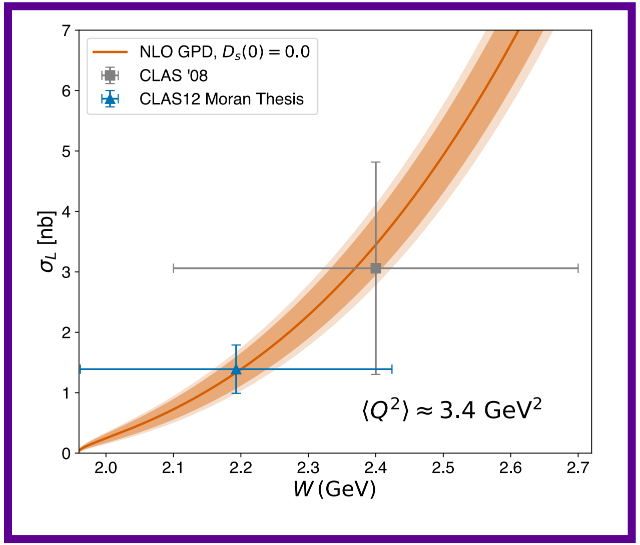
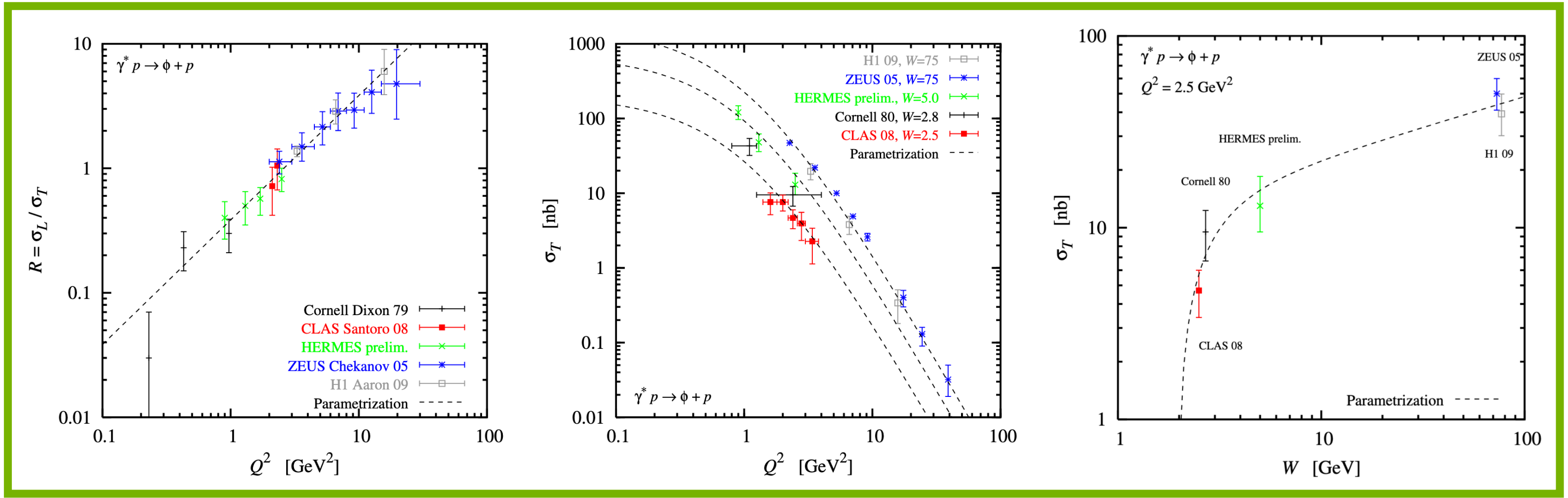
CROSS SECTION PROJECTIONS

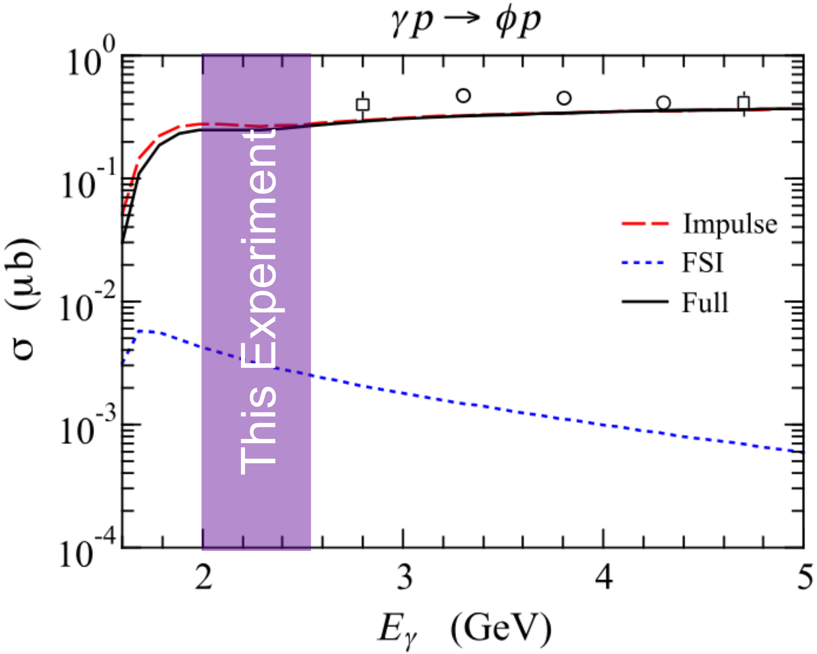
- ϕ Cross section conservatively estimated as the smaller of two predictions in our projections
  - **NLO GPD prediction**
  - **Model based on existing world data developed for CLAS12**



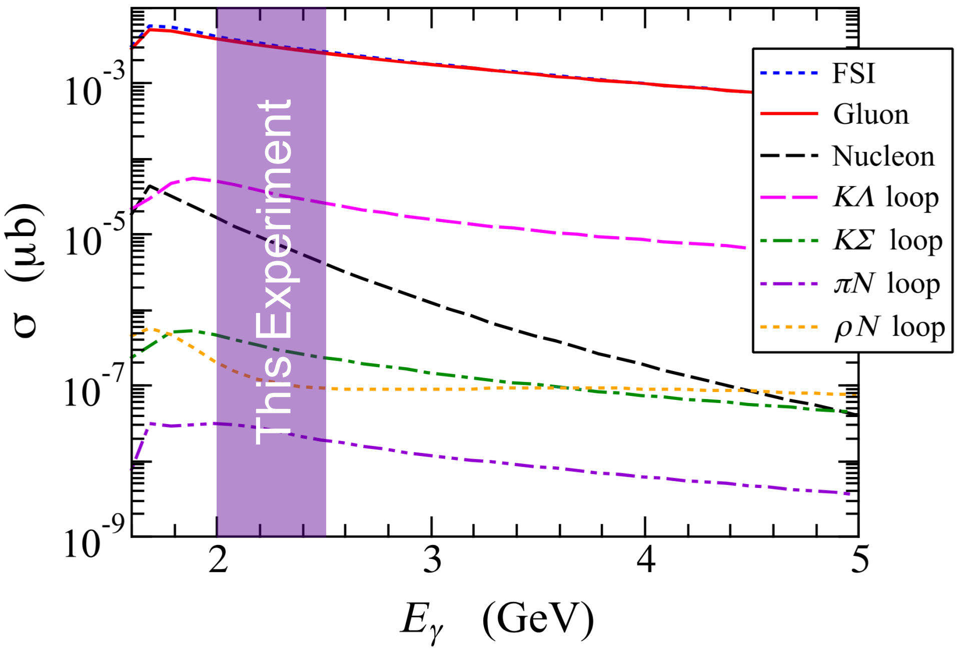


FINAL-STATE INTERACTIONS

- 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 ⁴He**

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**

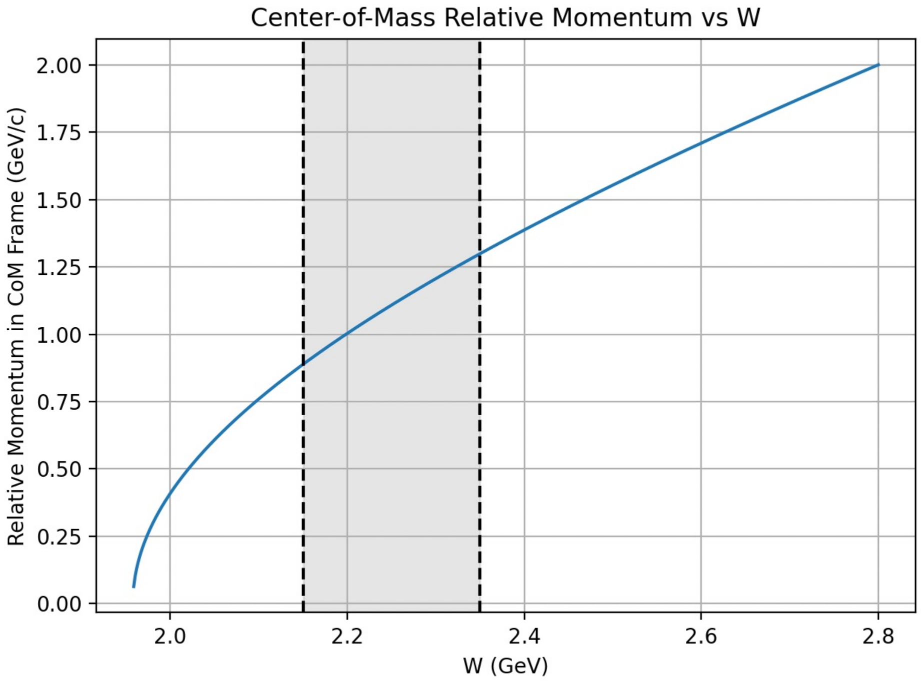
"NEAR-THRESHOLD"?

- **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!**

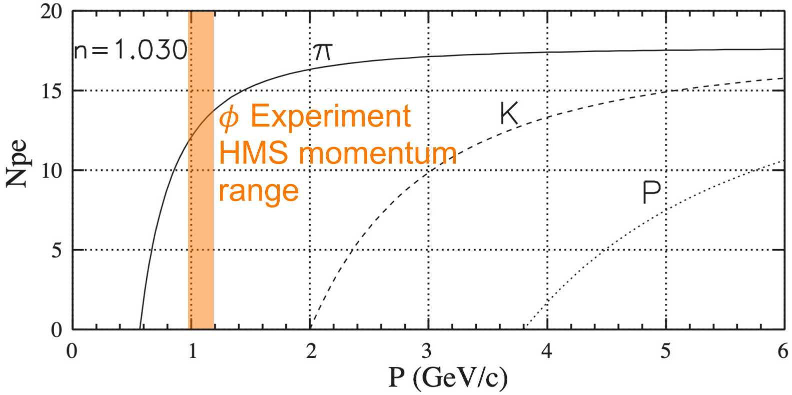
The only way to test whether collinear factorization holds quantitatively is with **data!**

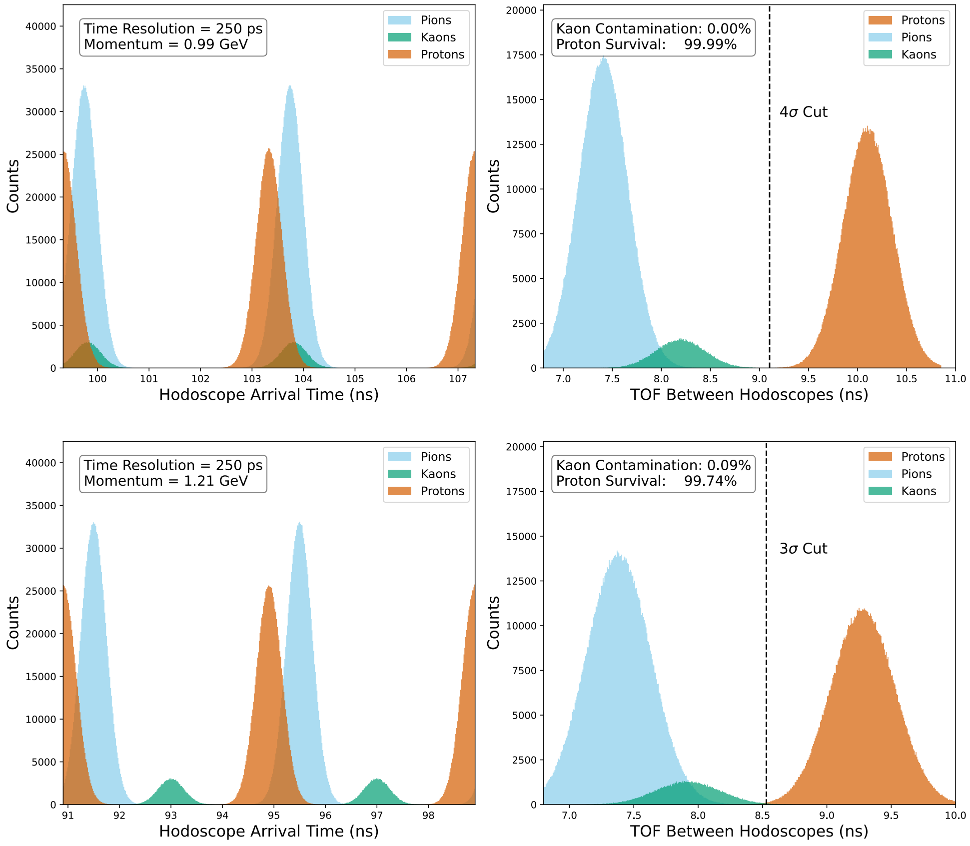


Total momentum between the ϕ and proton in the center-of-mass frame

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 $H(e,e'K)\mathrm{X}$ or $H(e,e'\pi)\mathrm{X}$ 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]

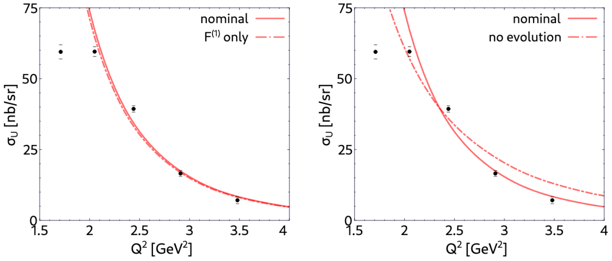
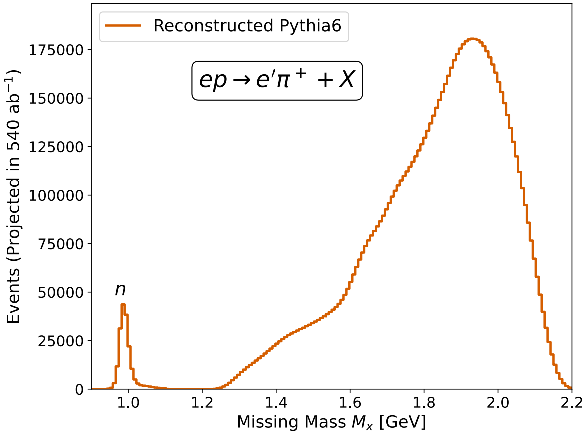
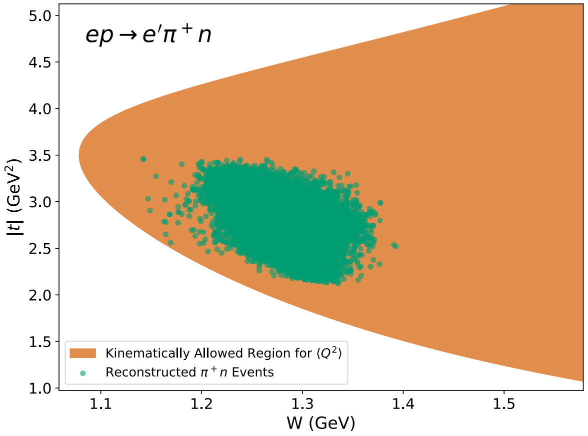
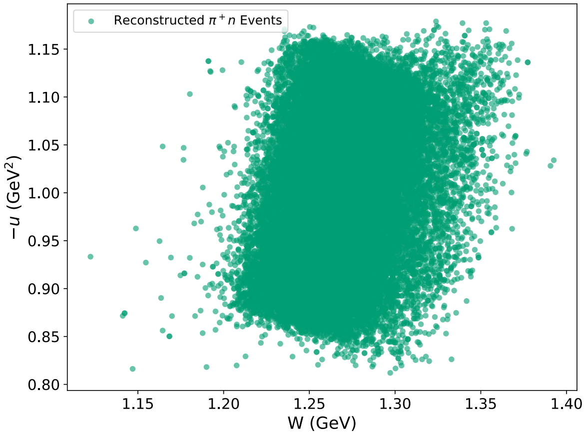


FIG. 5: CLAS data for the unseparated cross-section $\frac{d\sigma_U}{d\Omega_\pi^*}$ of the $\gamma^* p \to \pi^+ n$ reaction at backward angles [8], with $W = 2.2\,\mathrm{GeV}$ and $u = -0.5\,\mathrm{GeV}^2$. The solid curves represent the corresponding results obtained using the default version of 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.

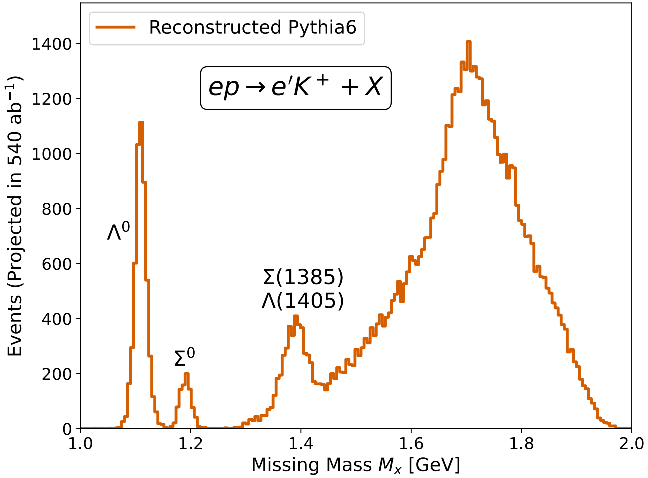




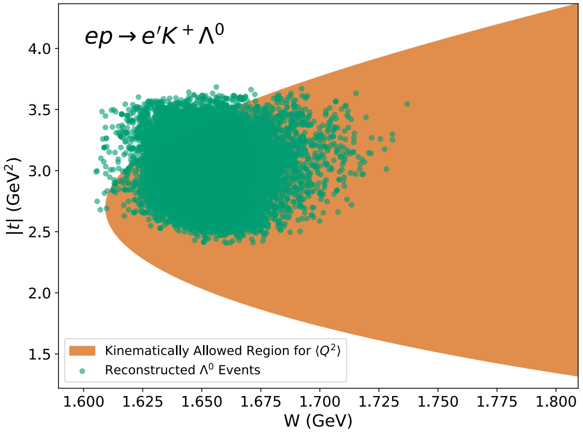


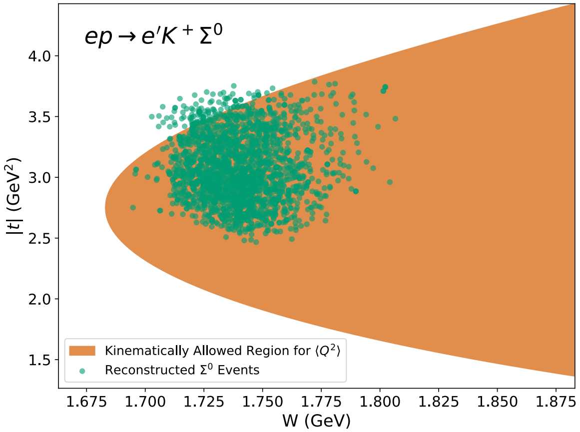
[1] Pire et al. - **Toward an advanced phenomenology of πN transition distribution amplitudes**

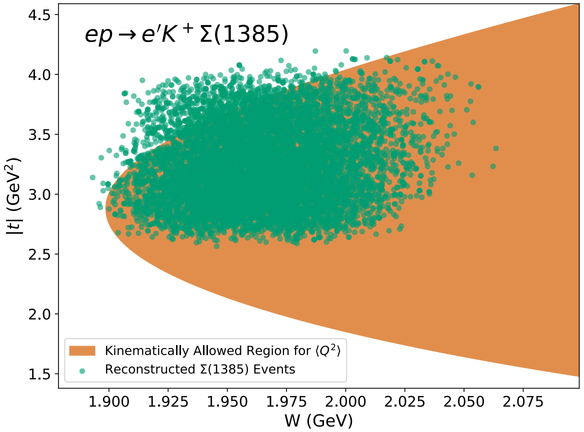
WE CAN DO *U*-CHANNEL!



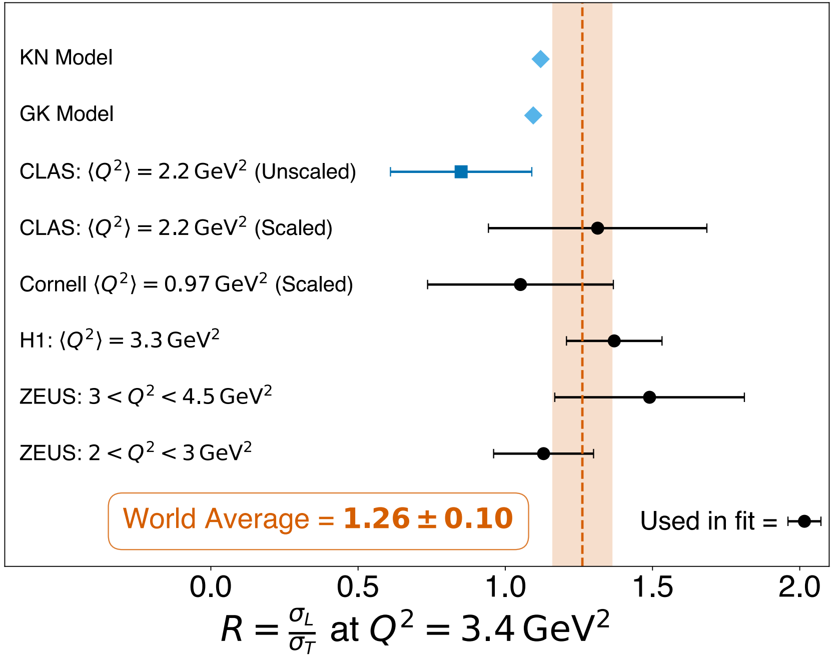
- Near-threshold, u-channel hyperon production is accessible **if K^+ can be efficiently ID'd**
- **Likely requires refurbishment of HMS aerogel**
- Note, PYTHIA6 resonance region cross sections are unreliable (especially in u-channel)
  - However, SIMC acceptance is correct, so these hyperons are well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



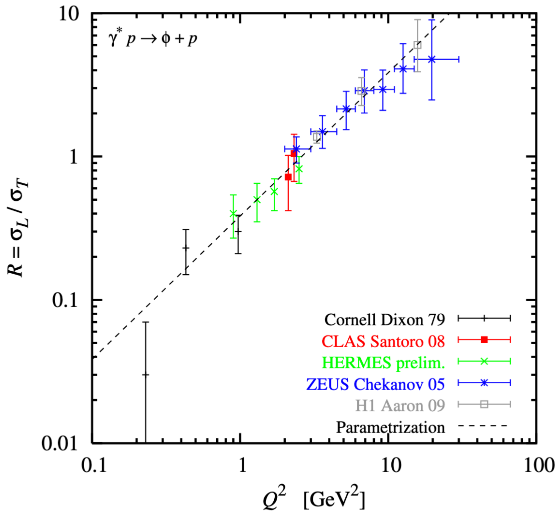




GETTING $d\sigma_L/d|t|$



- 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 ($Q^2 \sim 3.4$ GeV^2)
- World data suggests $R(Q^2)$ **not** $R(Q^2, W, |t|)$



- Use CLAS12 parameterization to scale nearby world datapoints

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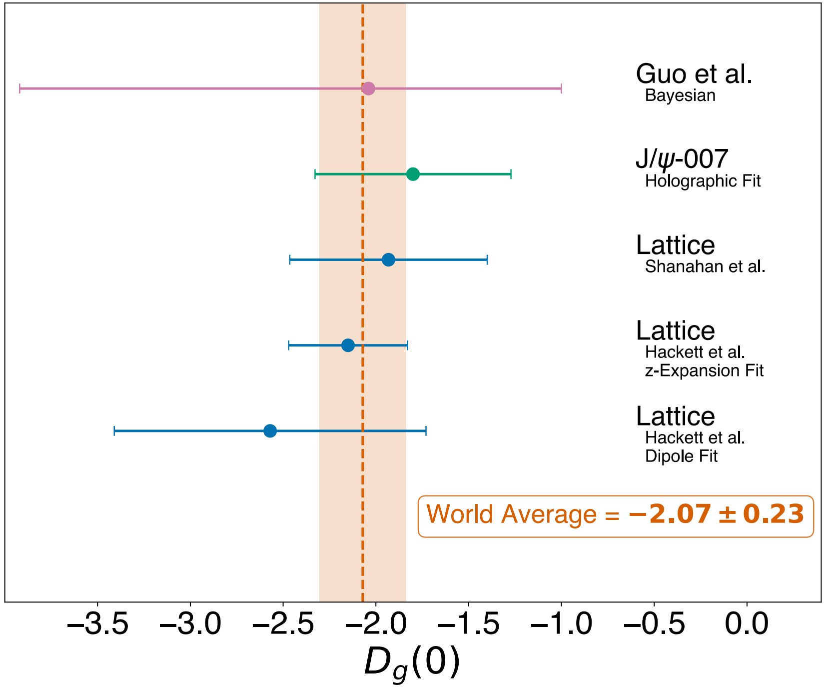
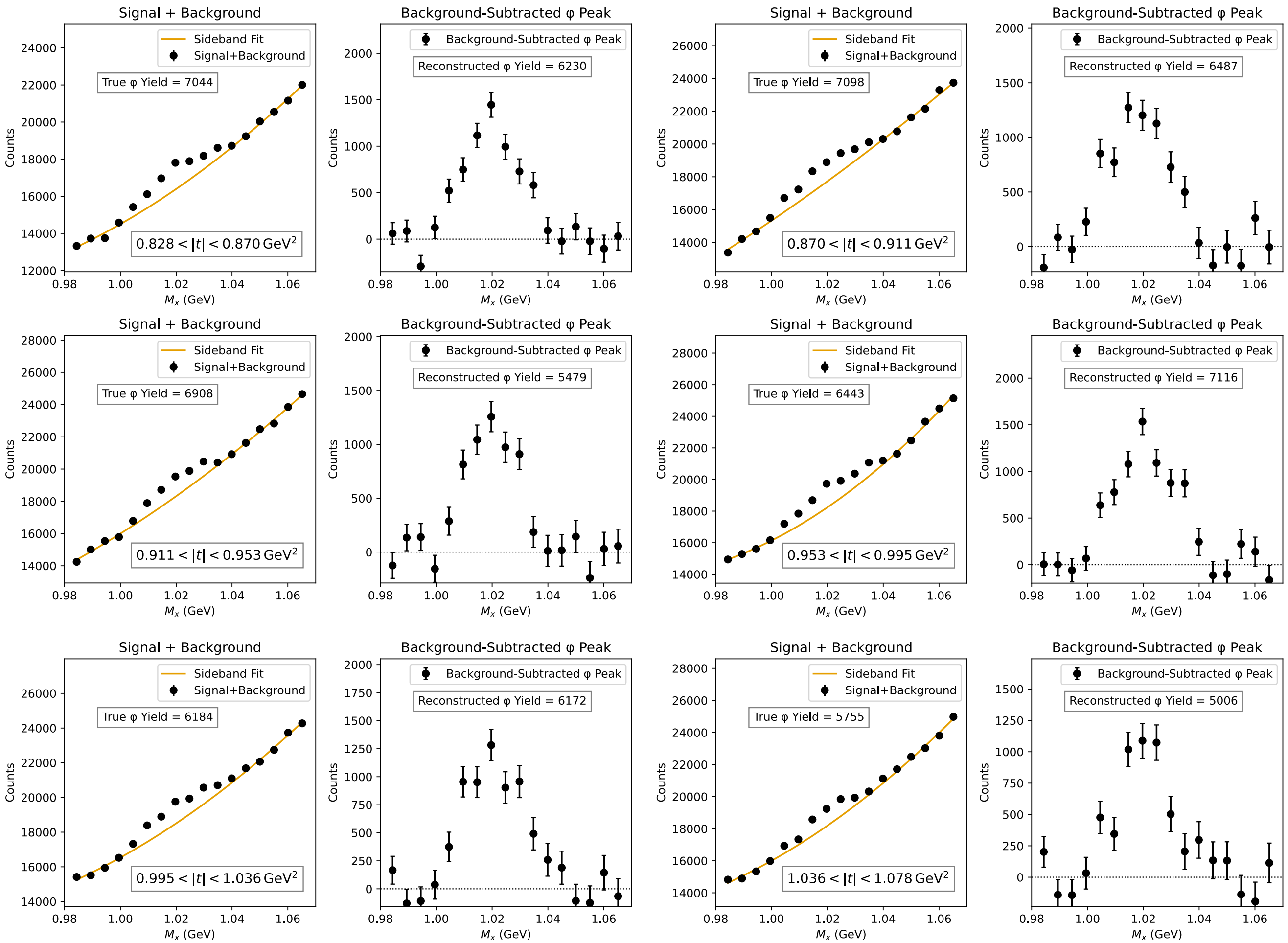
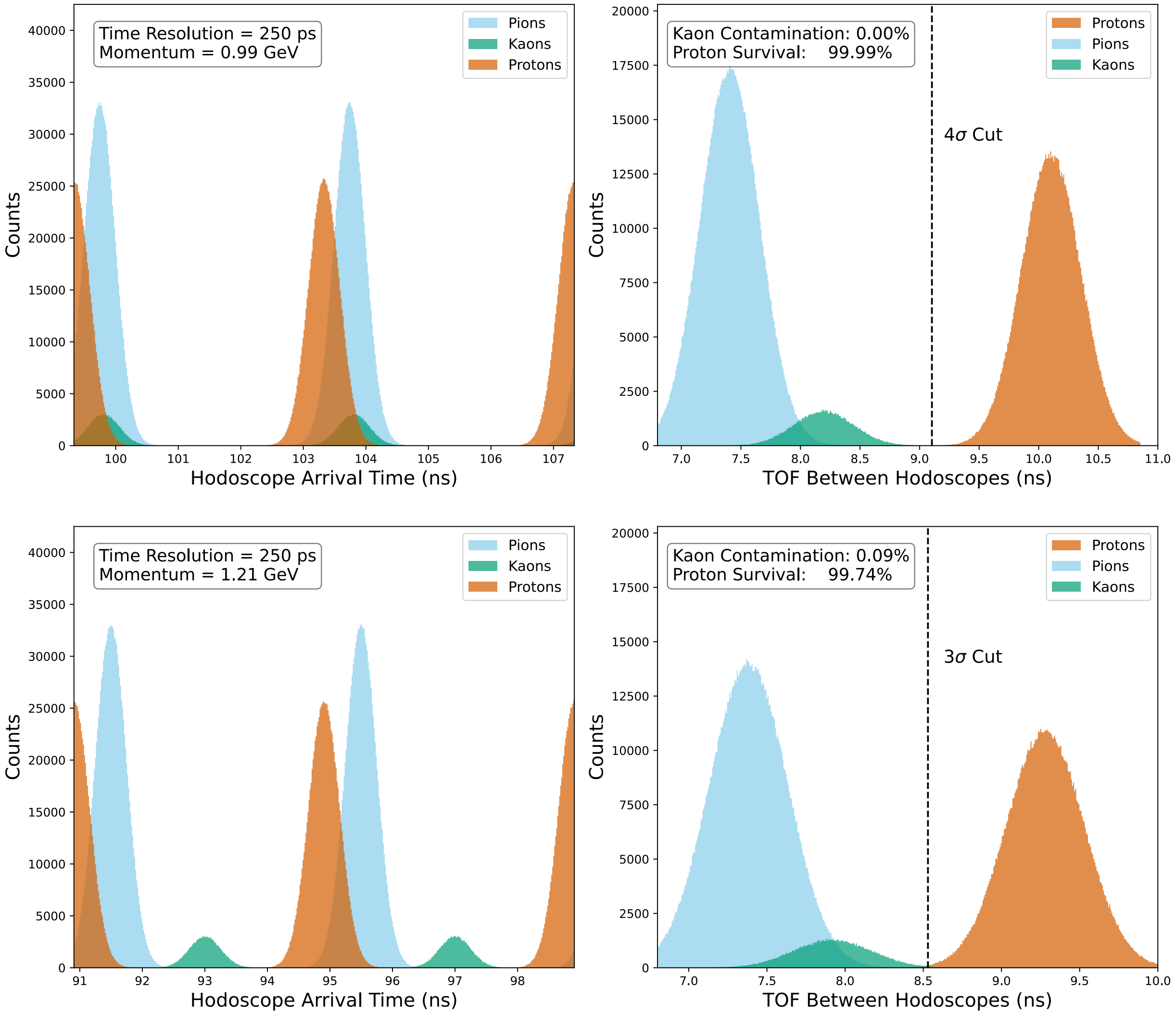
GETTING D_g



- 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!**


Signal + Background
Sideband Fit
Signal+Background
True φ Yield = 7044
$0.828 < |t| < 0.870\,\mathrm{GeV}^2$
Background-Subtracted φ Peak
Background-Subtracted φ Peak
Reconstructed φ Yield = 6230
Signal + Background
Sideband Fit
Signal+Background
True φ Yield = 7098
$0.870 < |t| < 0.911\,\mathrm{GeV}^2$
Background-Subtracted φ Peak
Background-Subtracted φ Peak
Reconstructed φ Yield = 6487
Signal + Background
Sideband Fit
Signal+Background
True φ Yield = 6908
$0.911 < |t| < 0.953\,\mathrm{GeV}^2$
Background-Subtracted φ Peak
Background-Subtracted φ Peak
Reconstructed φ Yield = 5479
Signal + Background
Sideband Fit
Signal+Background
True φ Yield = 6443
$0.953 < |t| < 0.995\,\mathrm{GeV}^2$
Background-Subtracted φ Peak
Background-Subtracted φ Peak
Reconstructed φ Yield = 7116
Signal + Background
Sideband Fit
Signal+Background
True φ Yield = 6184
$0.995 < |t| < 1.036\,\mathrm{GeV}^2$
Background-Subtracted φ Peak
Background-Subtracted φ Peak
Reconstructed φ Yield = 6172
Signal + Background
Sideband Fit
Signal+Background
True φ Yield = 5755
$1.036 < |t| < 1.078\,\mathrm{GeV}^2$
Background-Subtracted φ Peak
Background-Subtracted φ Peak
Reconstructed φ Yield = 5006
Counts
M_x (GeV)



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