ELECTROPRODUCTION OF ϕ AT HIGH LUMINOSITY

HENRY KLEST
Argonne National Laboratory

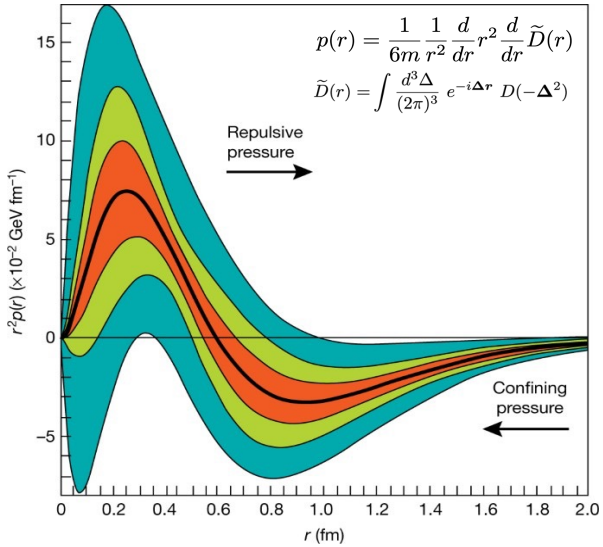
Workshop on the Physics Program with High Luminosity Facilities
October 6, 2026

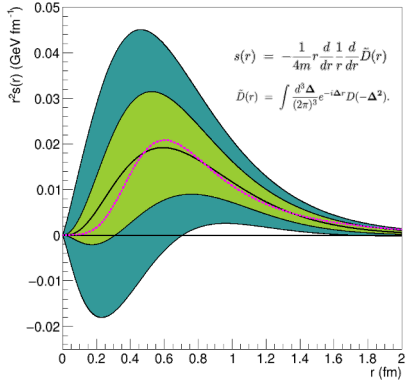
SCOPE OF THIS TALK

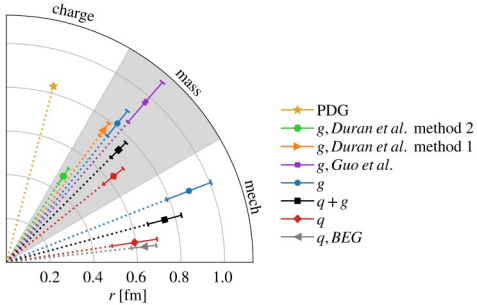
- I will talk about exclusive ϕ as our window on the **strange quark contribution to the proton gravitational form factors**
  - This requires large Q^2, large skewness ξ, and thus relatively small W
- The kinematic window sensitive to GFFs is narrow and the cross sections there are **extremely small**
  - **Perfect driver for high luminosity upgrades!**

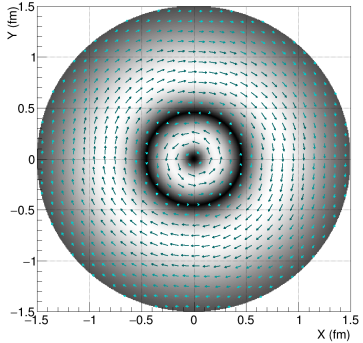
MECHANICAL PROPERTIES

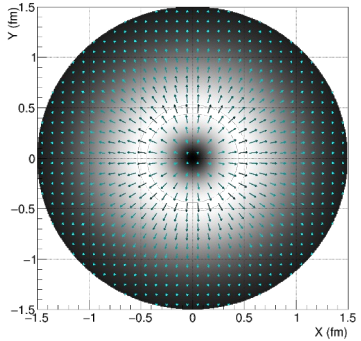
- The total D-term provides a gateway for extraction of various **mechanical** properties of the proton, including:
  - **Pressure distribution**
  - **Shear force distribution**
  - **Mechanical radius**
  - **Tangential & normal force distributions**











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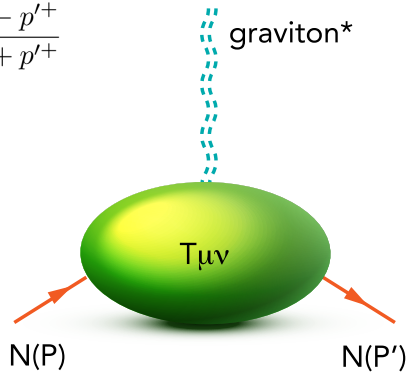
HOW DO WE ACCESS THE D-TERM?

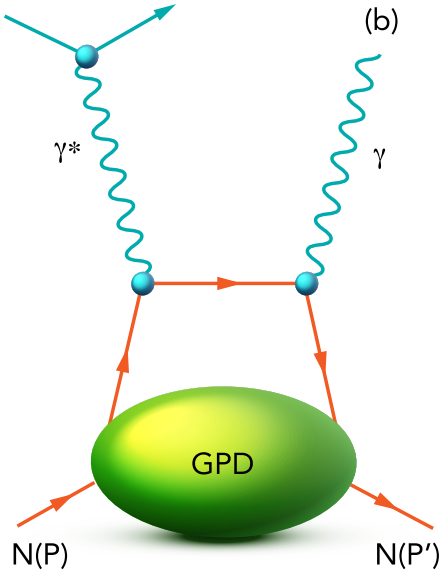
- Can access GFFs via the second Mellin moments of the generalized parton distributions (GPDs)

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

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

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





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

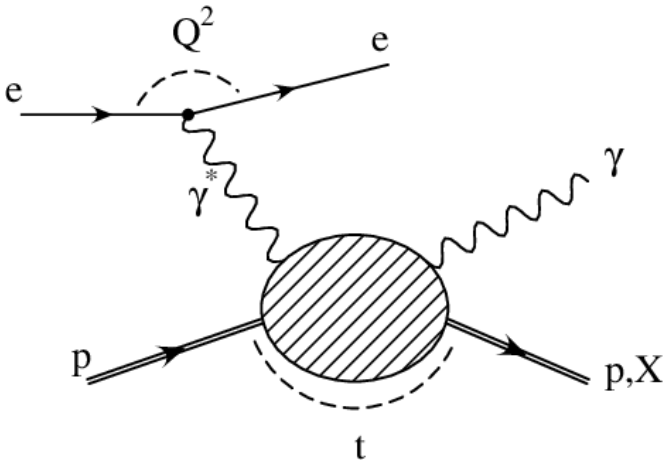
Partonic *D*-term contributions

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

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

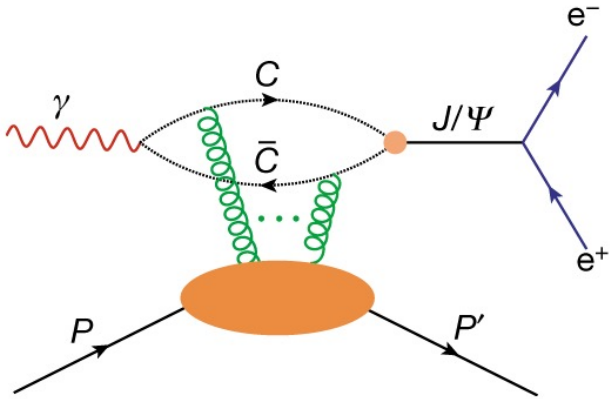
V. D. Burkert ✉, L. Elouadrhiri & F. X. Girod

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]



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

Strange quarks:
Can we just neglect them…?

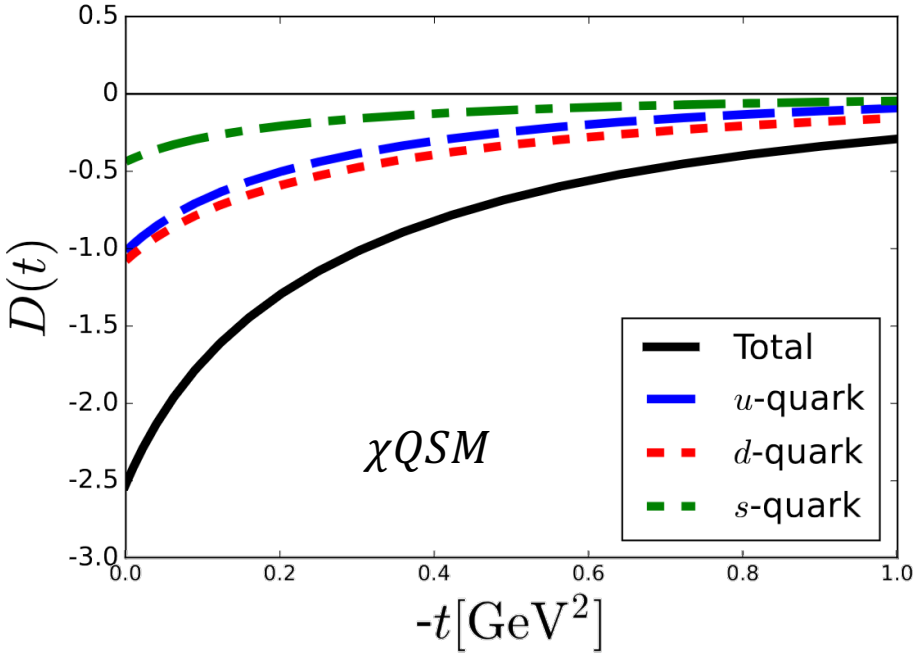
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THEORY PREDICTIONS

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

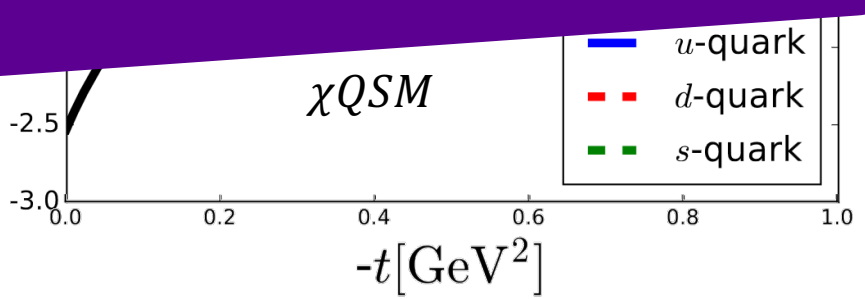


[1] - Goeke et al.: **Hard exclusive reactions and the structure of hadrons**, *Prog.Part.Nucl.Phys, 2001*
[2] - Hackett et al.: **Gravitational form factors of the proton from lattice QCD,** *PRL, 2024*
[3] - Won et al.: **Role of strange quarks in the *D*-term and cosmological constant term of the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

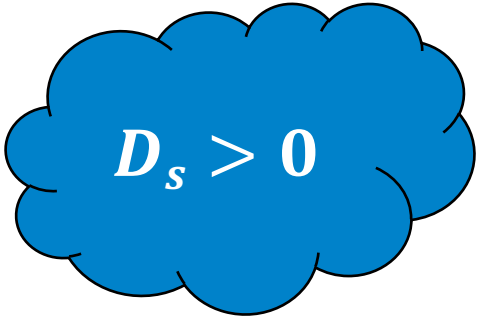
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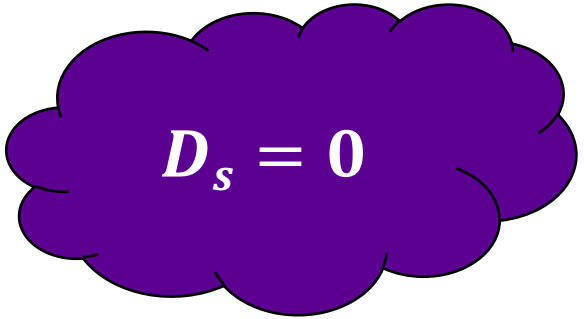
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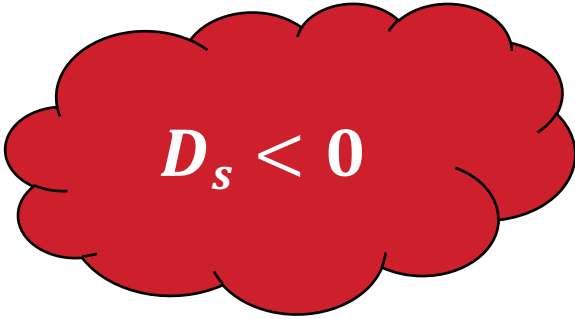
"The contributions of **strange quarks** play a **particularly significant role in the D-term.** Therefore, when extracting these contributions from experimental data, **it is essential to take into account the influence of strange quarks."**[3]



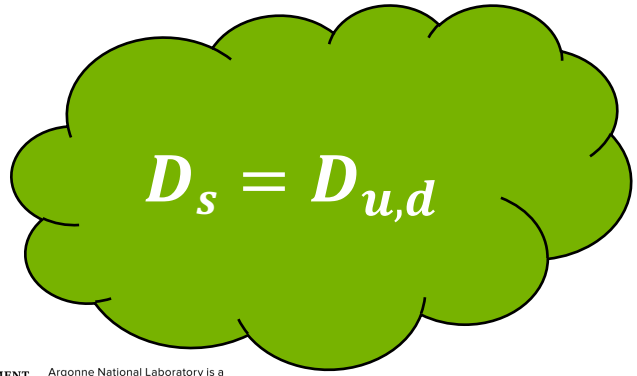
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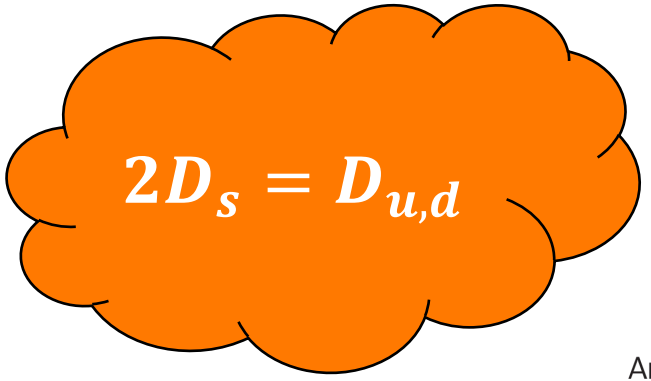






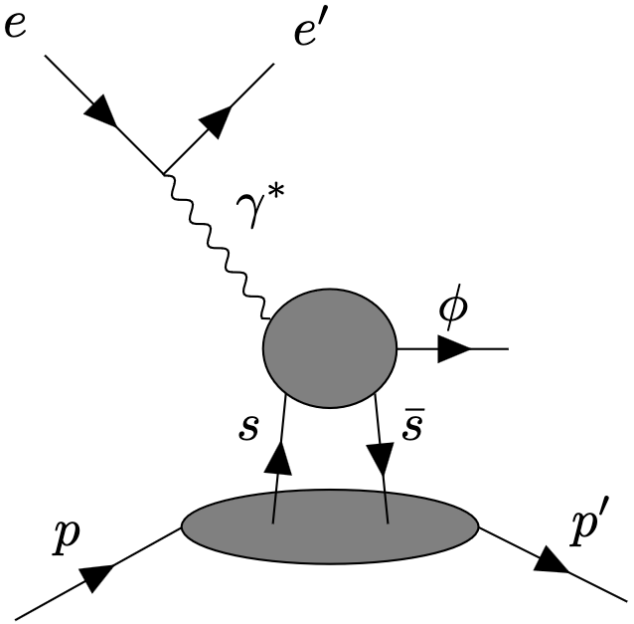
Variety of theory predictions giving very different values for D_s, can we extract it experimentally?





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!

[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!

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

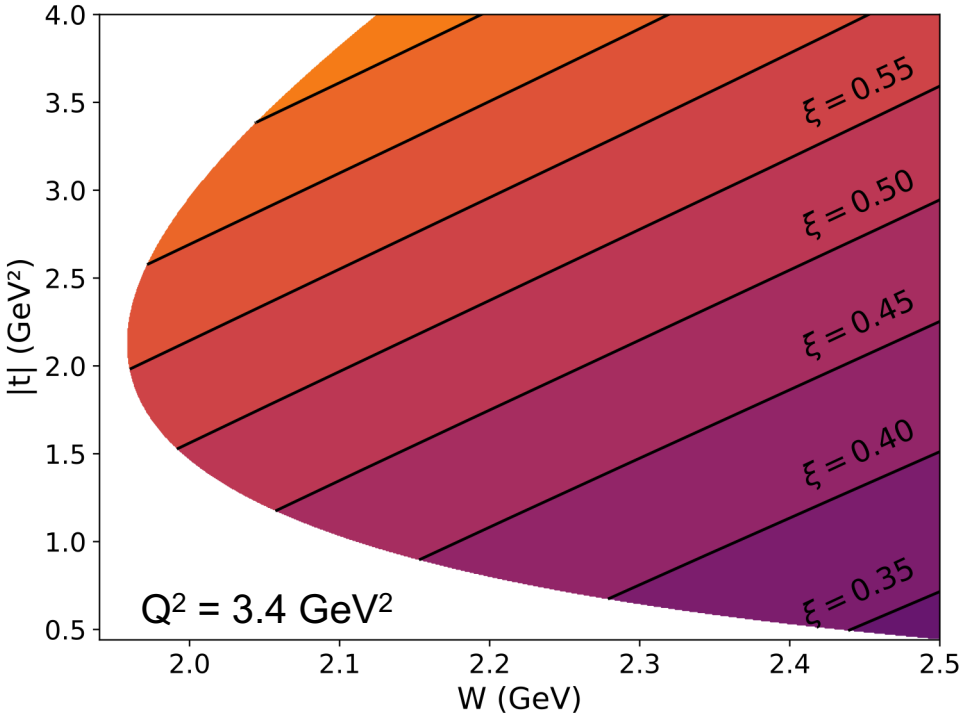
While D_s contributes directly!

$A_s \approx 0.03, D_s \approx ?$

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

KINEMATICS

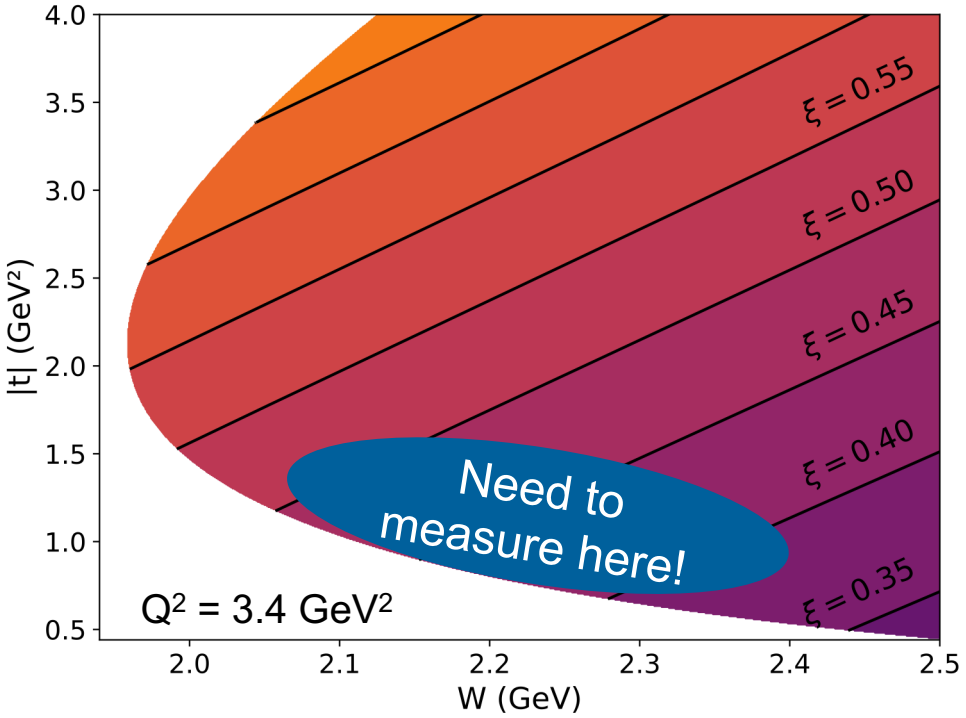
- **Challenging kinematic constraints to access D_s experimentally**
  - $\xi \geq 0.4$
  - $|t| \ll Q^2$
  - **Not too close** to the threshold $W = 1.96$ **GeV**
- Cross section $\propto Q^{-9}$!
- Need to measure in fine bins of kinematic variables
  - Ideally not $|t - t_{min}|$ due to rapid change of t_{min} near threshold
- Requires **high luminosity** and **precise kinematic reconstruction!**



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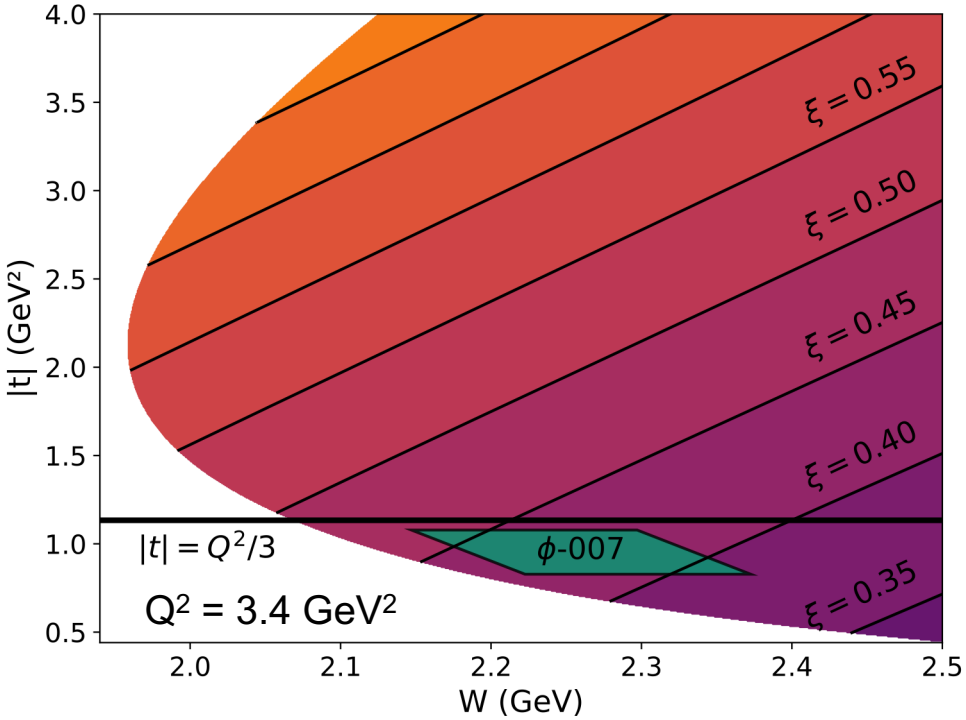


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ϕ-007 EXPERIMENT IN HALL C

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

So we designed an experiment in Hall C to do it!



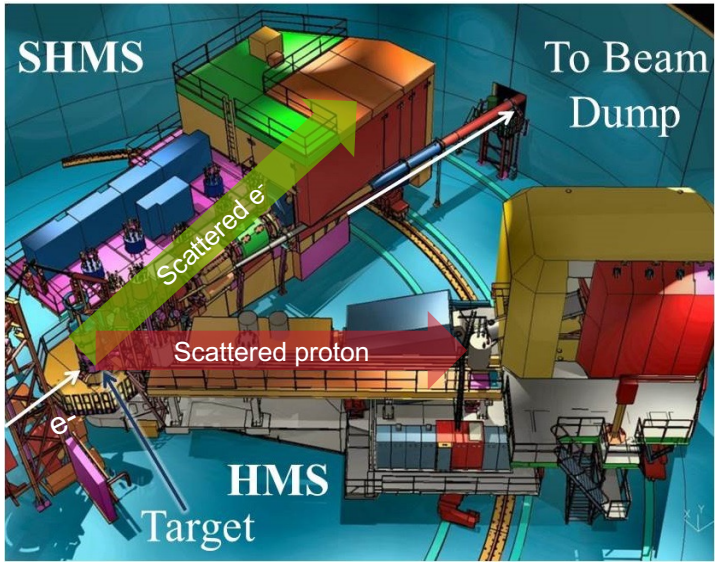
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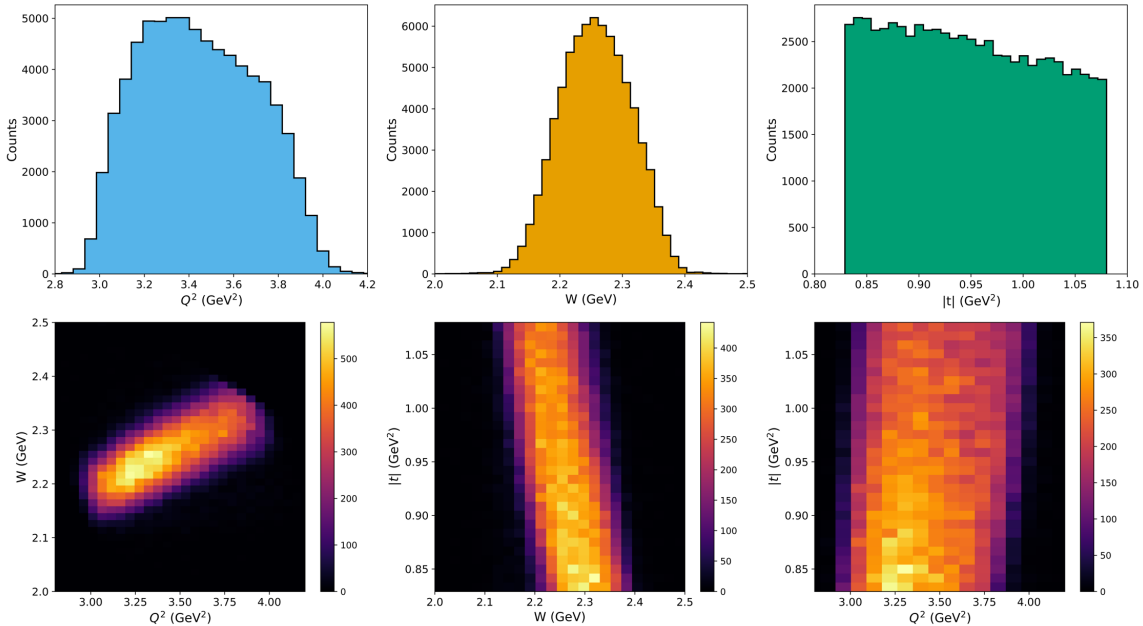
Spokespersons: H. Klest, S. Joosten,
H. Szumila-Vance, W. B. Li

- 75 μA 10.6 GeV beam, 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

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

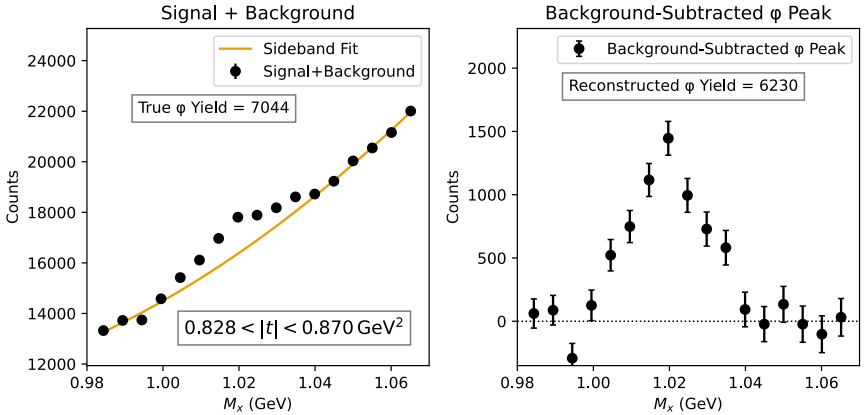


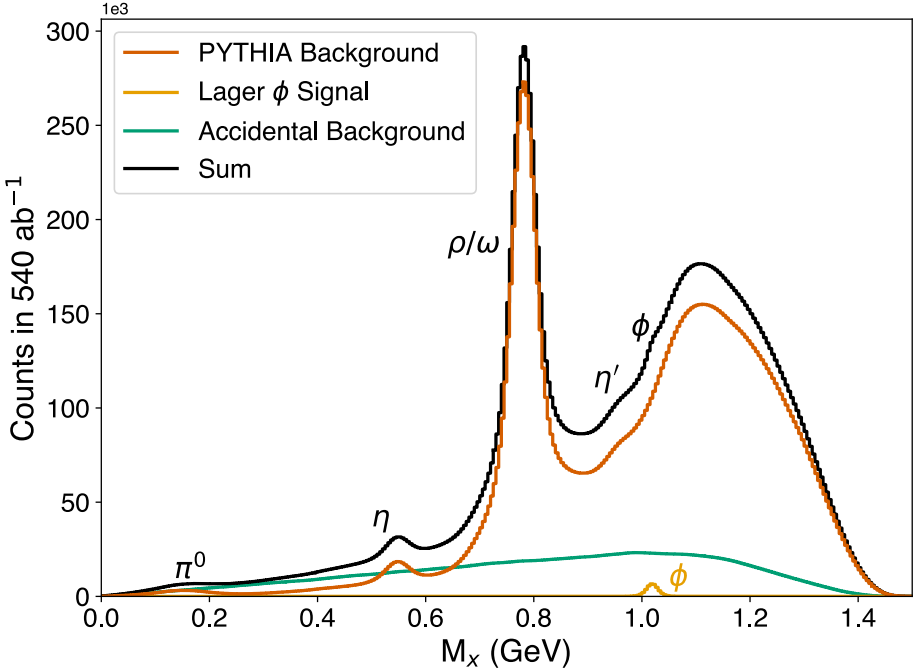
Q^2 ~ 3.4 GeV^2 W ~ 2.25 GeV |t| ~ 0.95 GeV^2



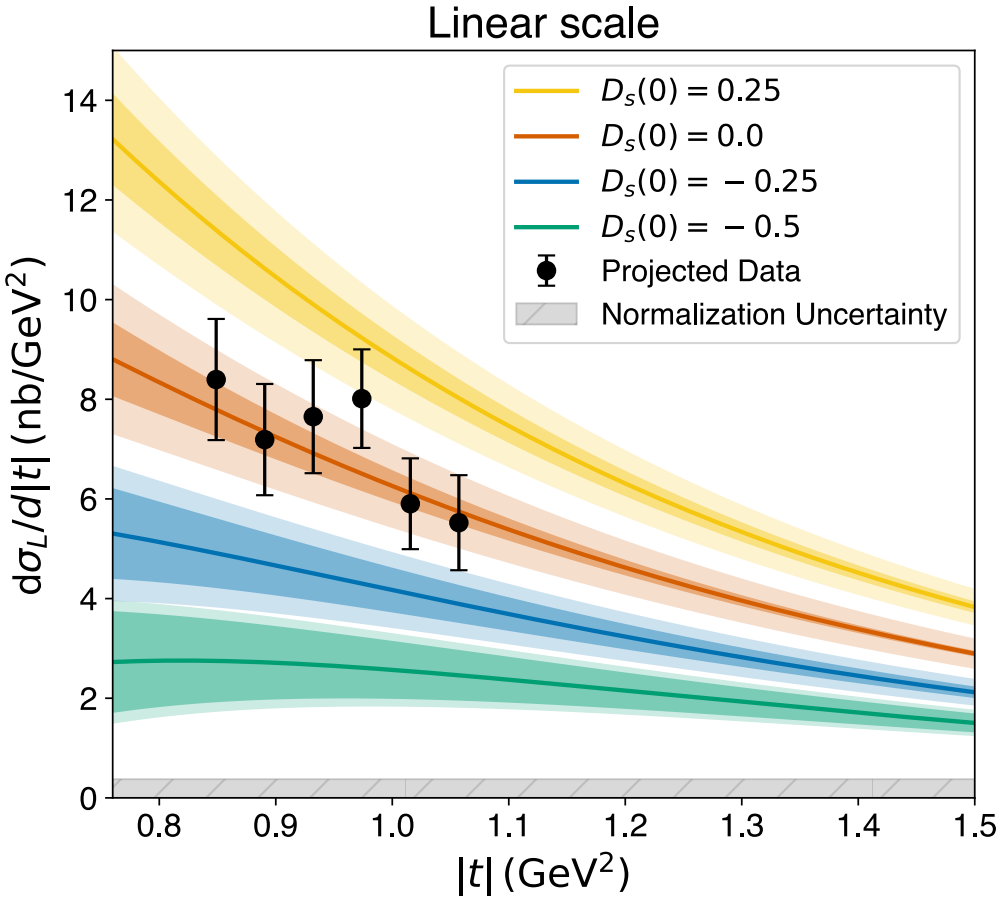
EXPERIMENTAL MEASUREMENT - ϕ-007

- Measure $e + p \rightarrow e' + p' + \phi$ via **H(e,e'p) 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



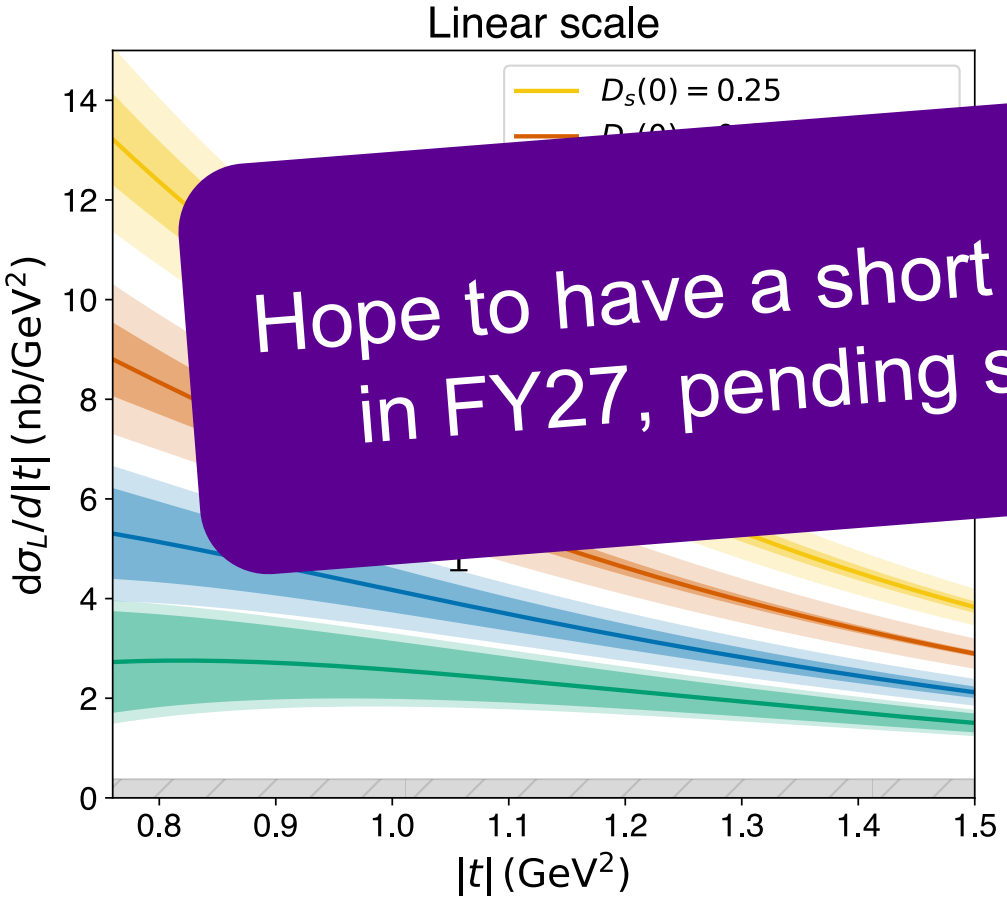
- Experimental uncertainty from these sources:

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%

Data are precise enough to distinguish between the different predictions for D_s!

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CROSS SECTION PROJECTIONS - ϕ-007



- Experimental uncertainty from

				Bin 3	Bin 4	Bin 5	Bin 6
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				%	4.0%	4.0%	4.0%
				%	1.0%	1.0%	1.0%
				%	2.0%	2.0%	2.0%
				%	3.0%	3.0%	3.0%
				%	15.2%	14.9%	16.6%
				%	3.0%	3.0%	3.0%
				%	3.8%	3.8%	3.8%
	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%

Hope to have a short run of ϕ-007 in FY27, pending scheduling!

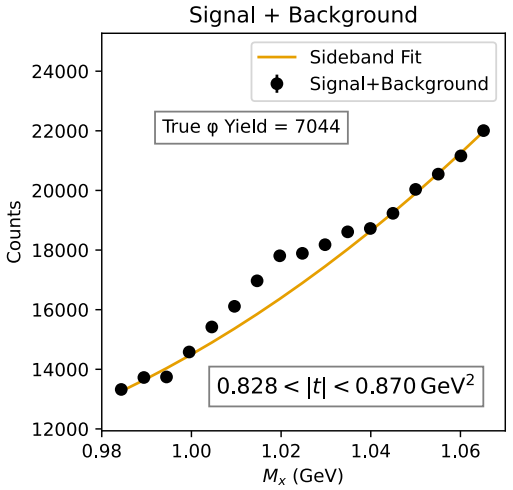
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Total Normalization	4.8%	4.8%	4.8%	4.8%	4.8%	4.8%



ϕ-007 uncertainty dominated by signal extraction!

→ To improve precision, **measure the ϕ**!

Also need to model σ_L, no *L/T* separation

→ To *L/T* separate, **measure the ϕ**!

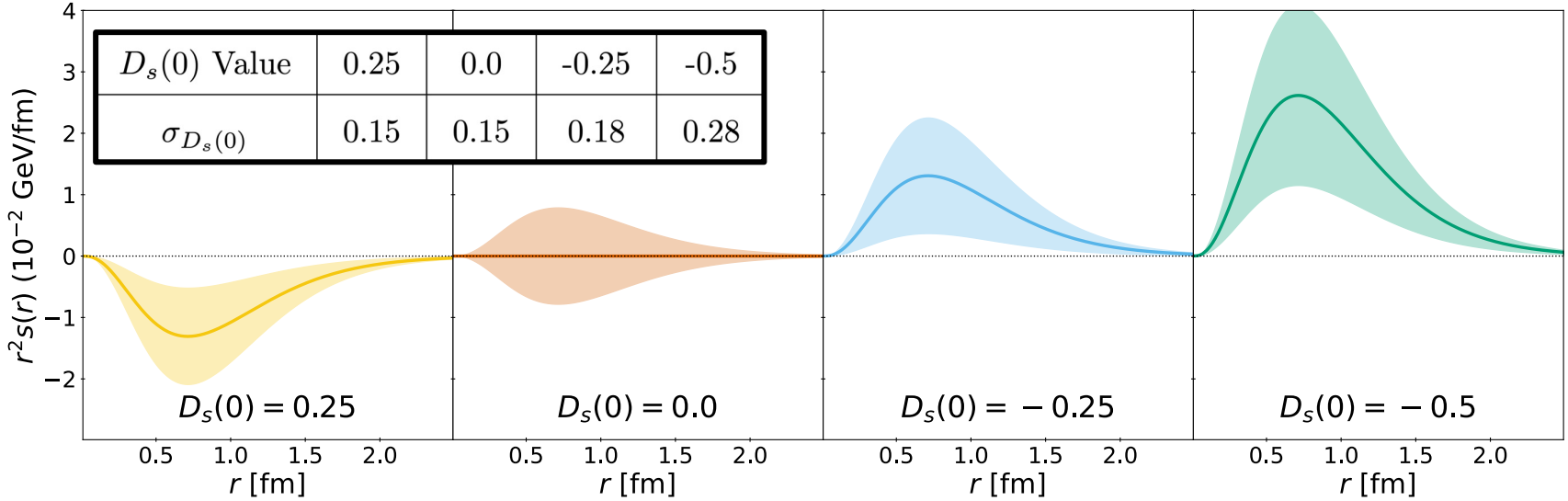
Next steps are clear!

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WHAT CAN WE LEARN FROM ϕ-007?

Using our expected resolution 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…

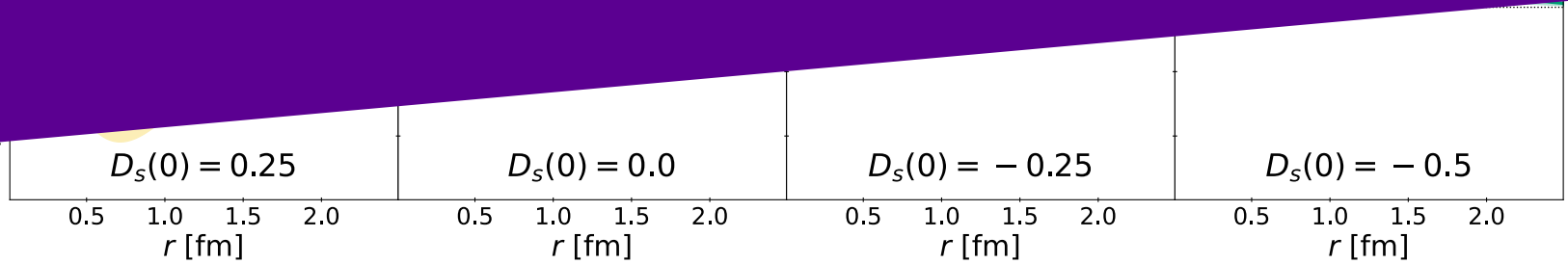


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Using our expected resolution on $D_s(0)$ and the functional form measured on the lattice, can project uncertainties for the **strangeness**

But we can do better!!!

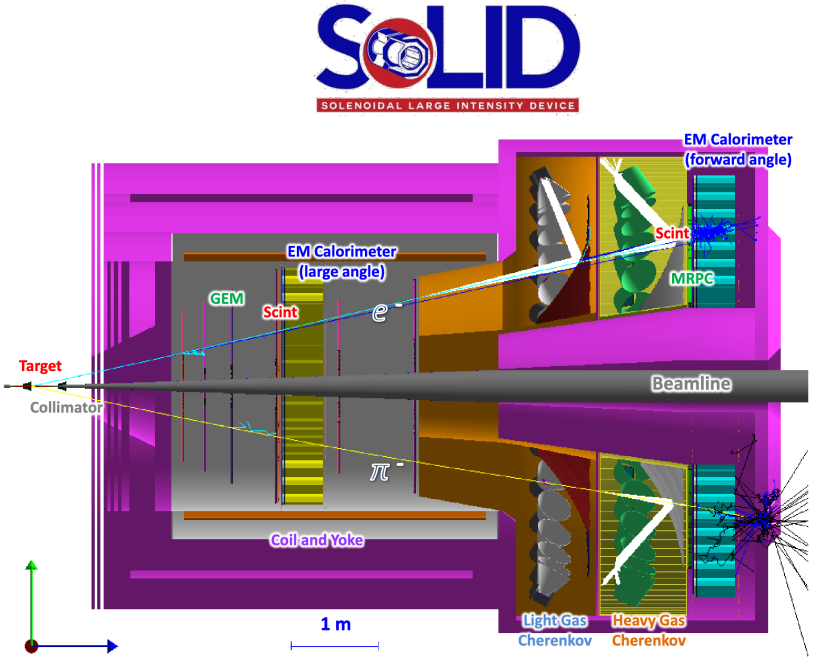


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EXCLUSIVE ϕ IN SOLID

- 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**

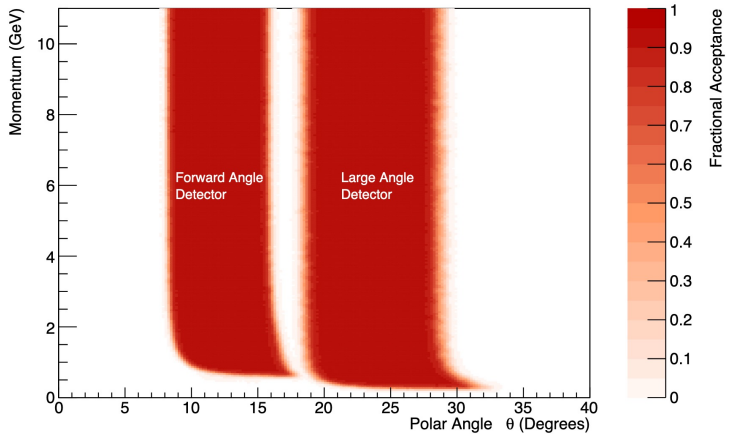
High statistics & continuous kinematic coverage for multidimensional measurement!

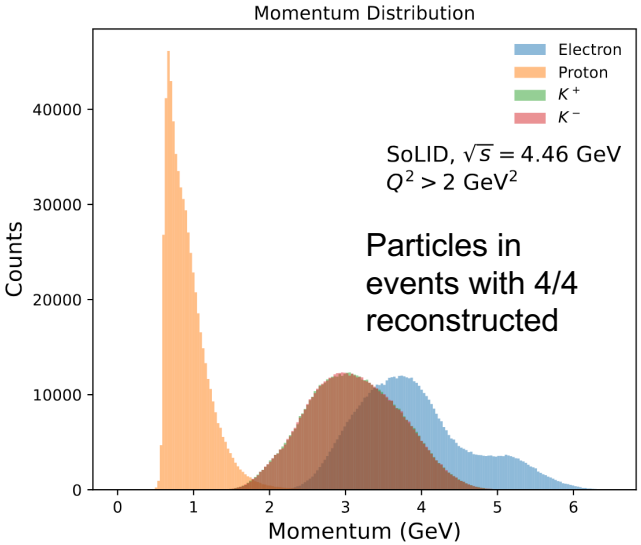


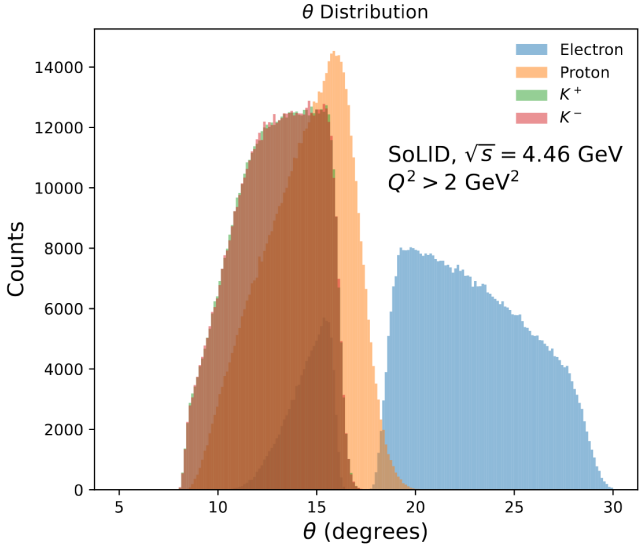
PROJECTIONS

- Exclusive ϕ projections for full 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!



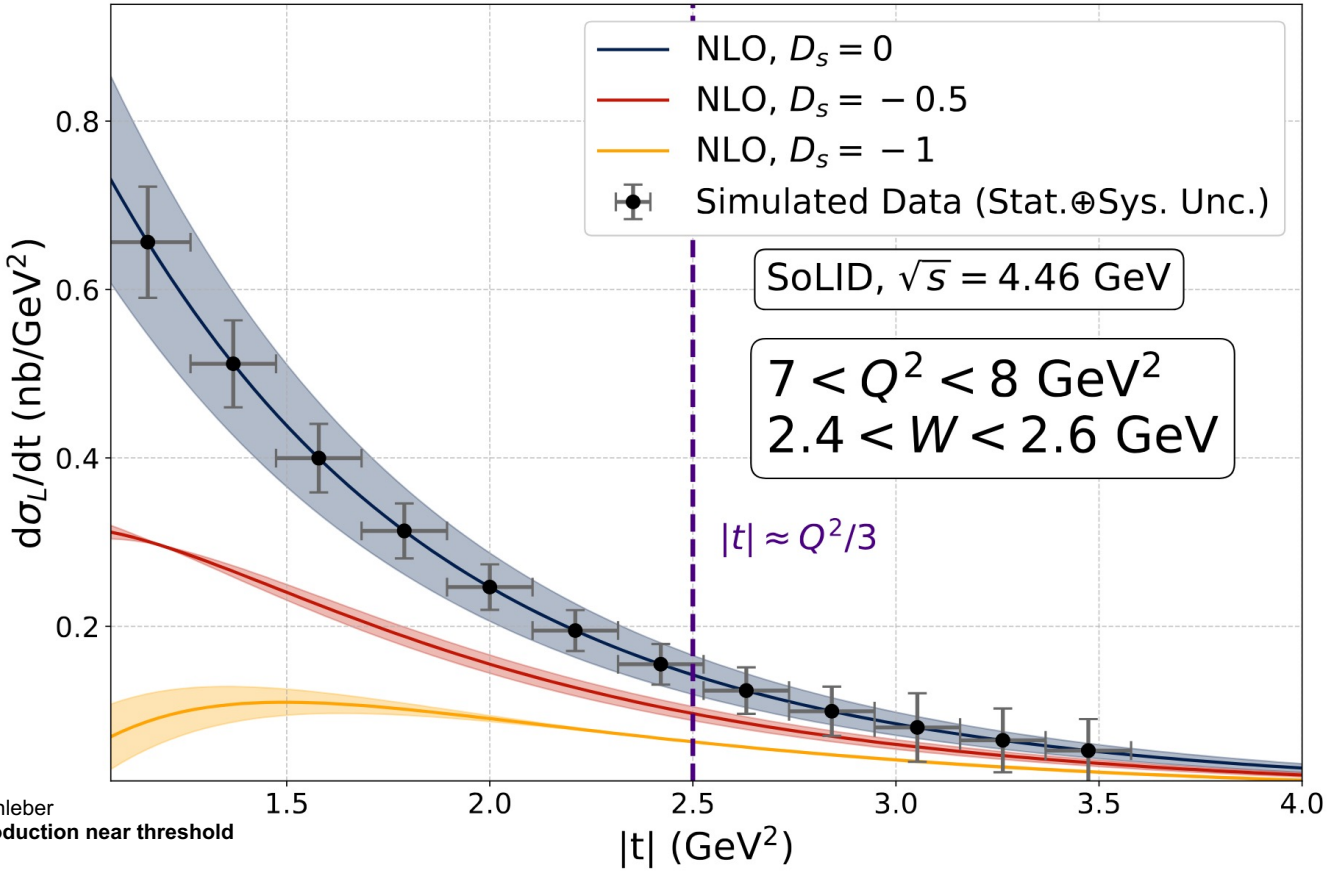




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PROJECTIONS

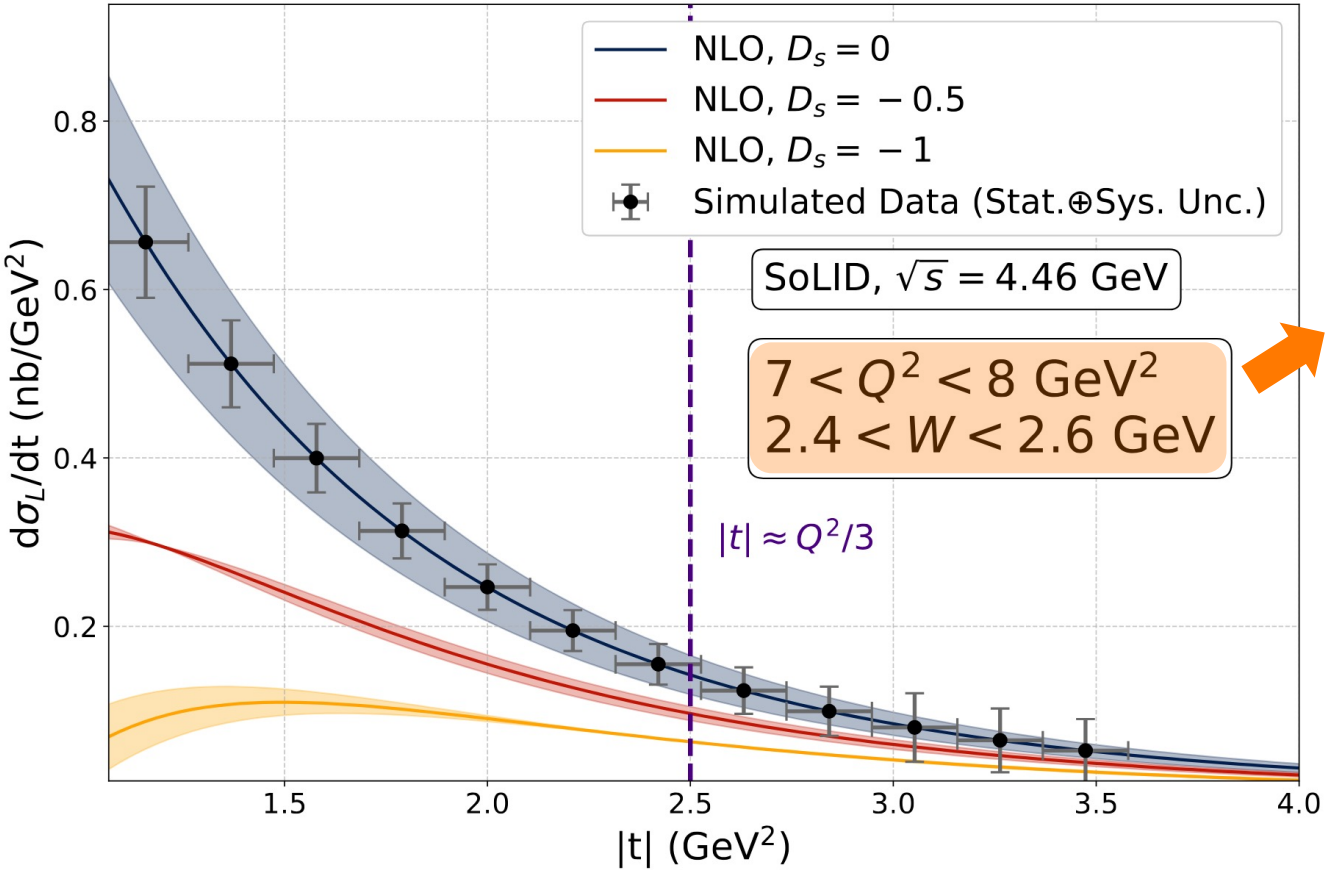
Assumption of 10% systematic uncertainty still **exhibits good sensitivity to D_s!**



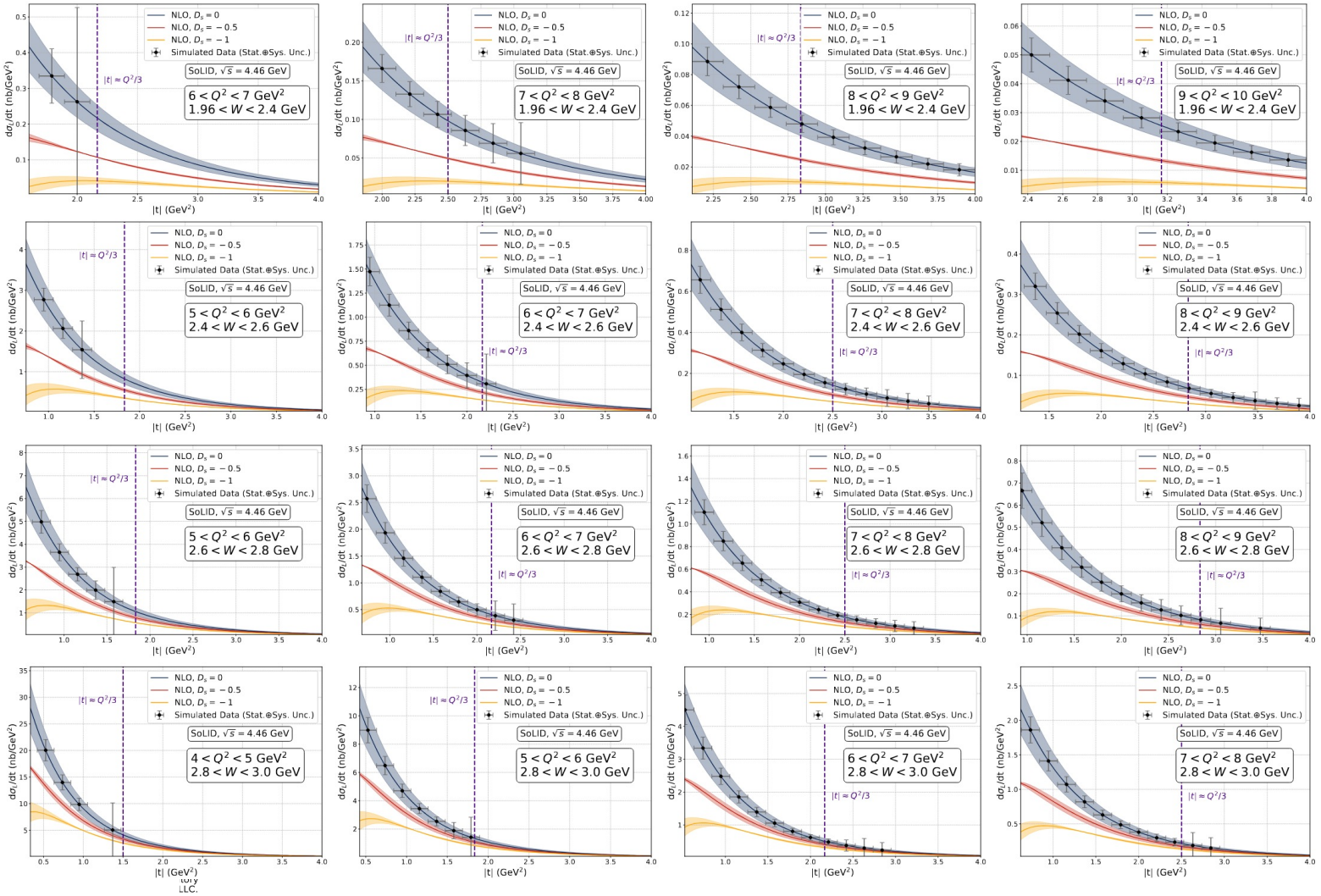
Hatta, HK, Passek-K, Schoenleber
Deeply virtual φ-meson production near threshold
PTEP, ptaf076

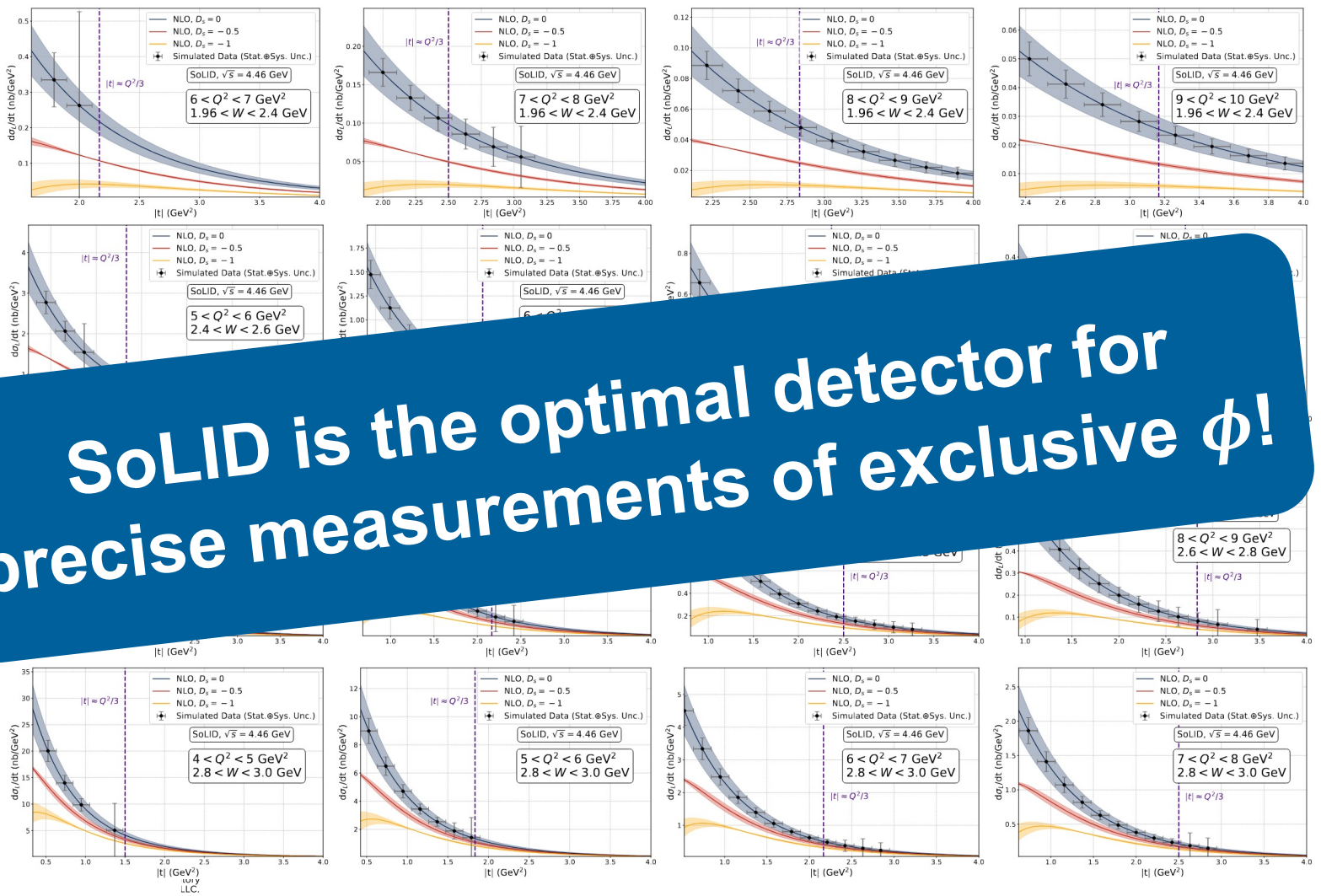
PROJECTIONS

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



Ideal kinematics!

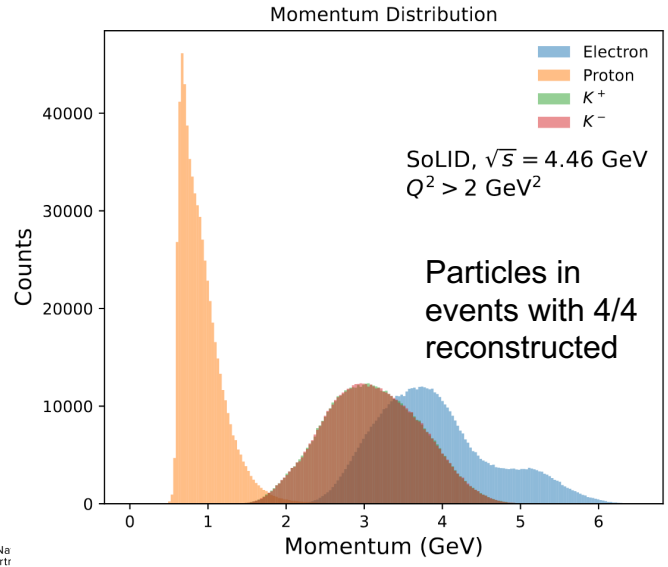

NLO, $D_s = 0$
NLO, $D_s = -0.5$
NLO, $D_s = -1$
Simulated Data (Stat.⊕Sys. Unc.)
SoLID, $\sqrt{s} = 4.46$ GeV
$|t| \approx Q^2/3$
$6 < Q^2 < 7$ GeV^2
$1.96 < W < 2.4$ GeV
$7 < Q^2 < 8$ GeV^2
$1.96 < W < 2.4$ GeV
$8 < Q^2 < 9$ GeV^2
$1.96 < W < 2.4$ GeV
$9 < Q^2 < 10$ GeV^2
$1.96 < W < 2.4$ GeV
$5 <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

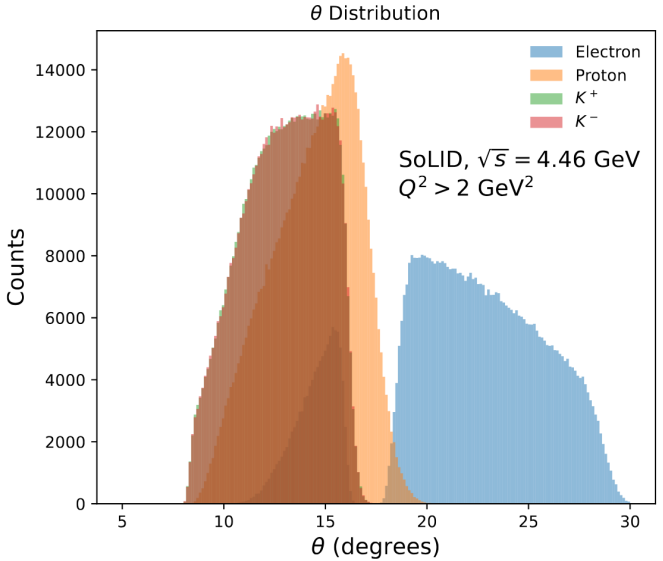


SoLID is the optimal detector for precise measurements of exclusive ϕ!

CONSIDERATIONS FOR SOLID-LITE

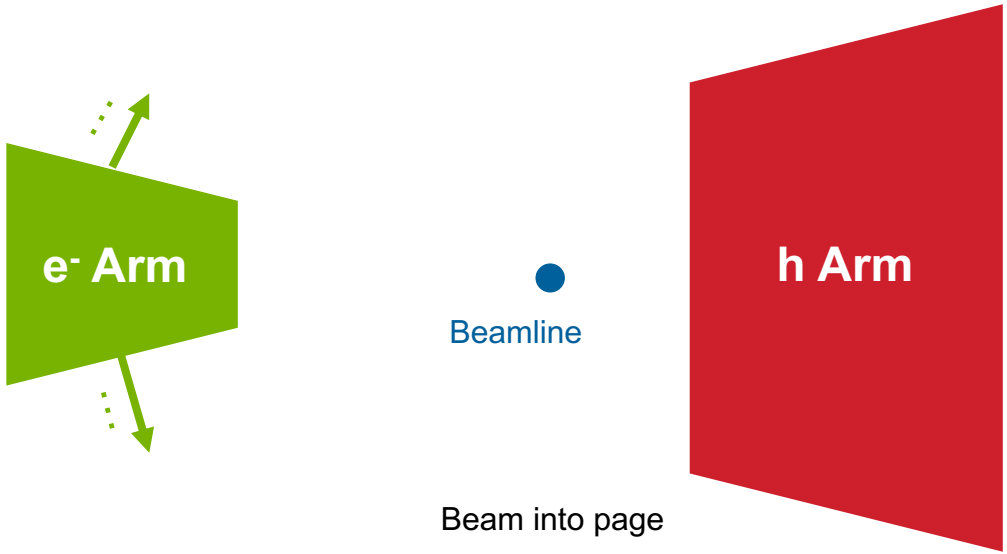
- When $W - W_{thr.}$ is small, the proton, K^+, and K^- are all relatively close together in angle
  - Solenoid field is nice to avoid bending one charge into the beamline
- Large angle e' preferable for higher Q^2





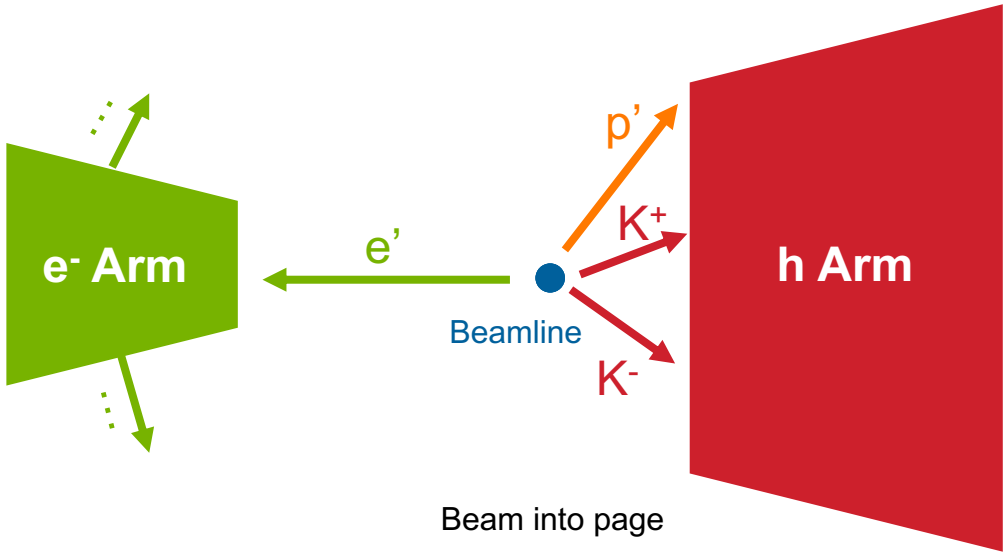
CONSIDERATIONS FOR SOLID-LITE

- Ideal reduced coverage configuration for near-threshold ϕ would have an electron arm at large angles and a larger hadron arm at smaller angles on the opposite side



CONSIDERATIONS FOR SOLID-LITE

- Ideal reduced coverage configuration for near-threshold ϕ would have an electron arm at large angles and a larger hadron arm at smaller angles on the opposite side

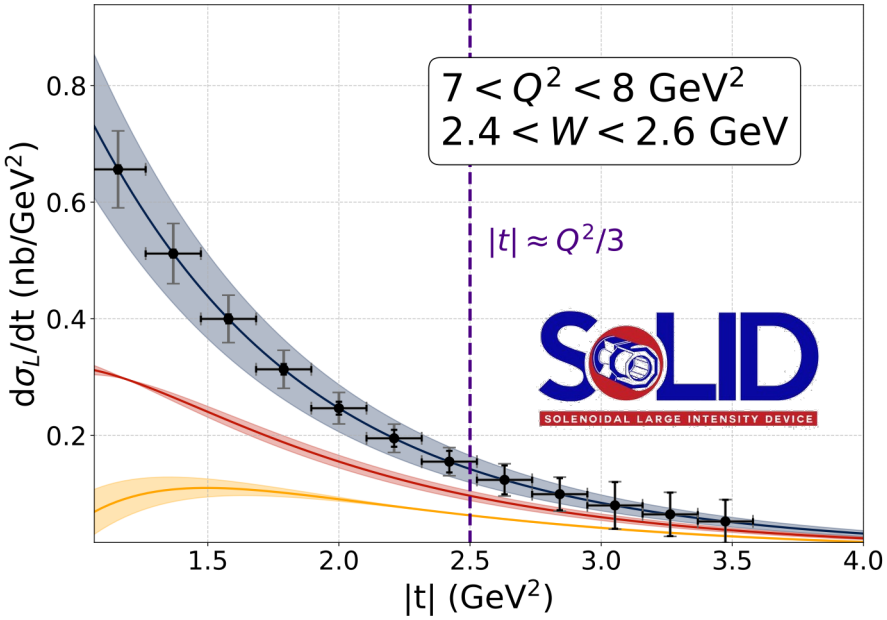


The hadron arm should ideally have PID similar to the existing SoLID forward-angle detector

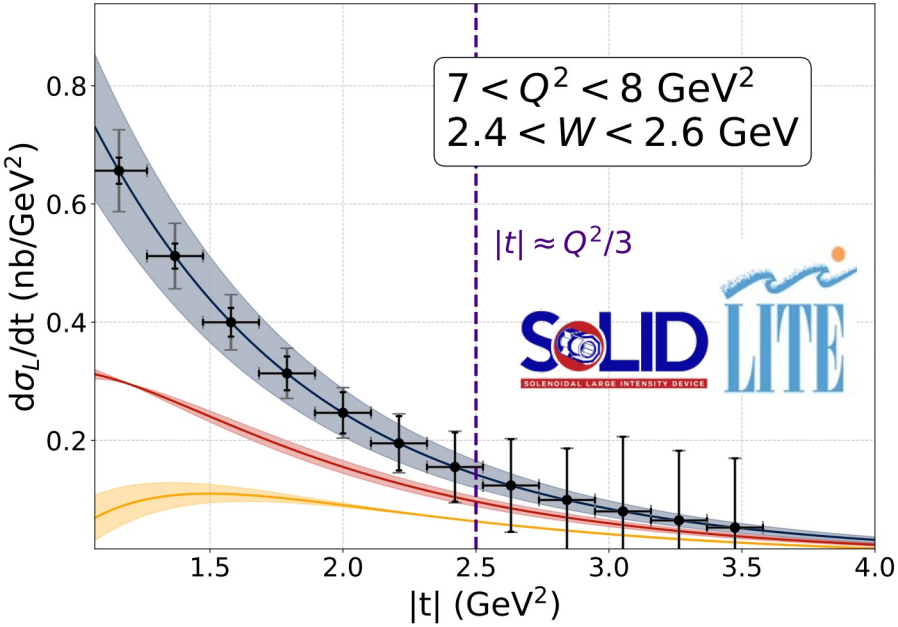
PROJECTIONS

- Very rough estimates of SoLID-LITE statistical uncertainties
  - Assume 1/10th the azimuthal coverage of SoLID

Full SoLID



SoLID-LITE



Inner error bars: statistical only

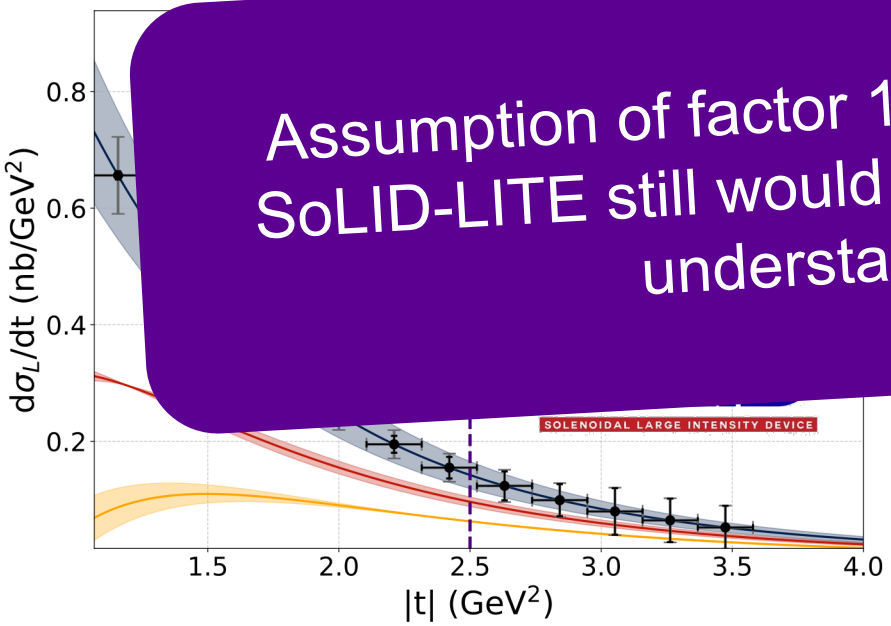
Outer error bars: statistical $\oplus$ 10% systematic

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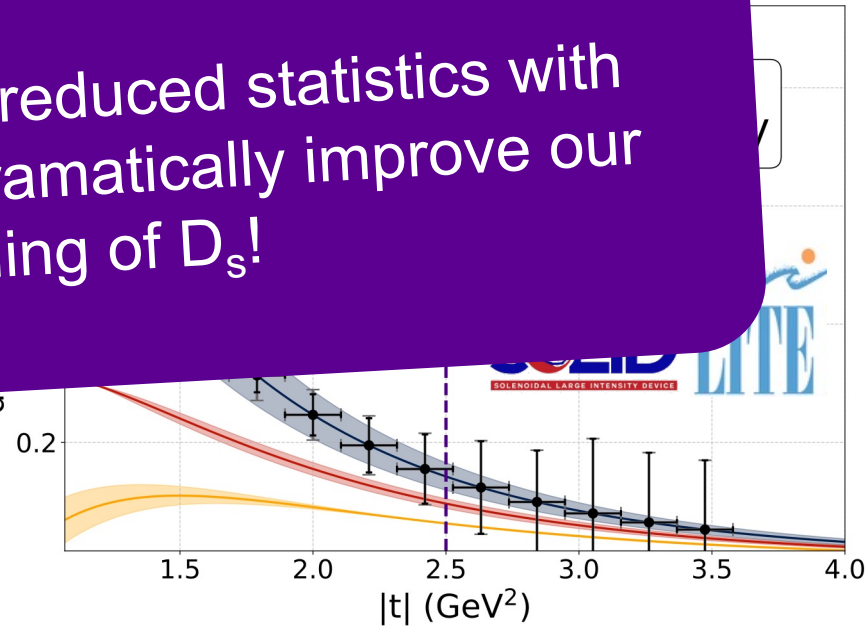
PROJECTIONS

- Very rough estimates of SoLID-LITE statistical uncertainties
  - Assume 1/10th the azimuthal coverage of SoLID

Full SoLID



Assumption of factor 10 reduced statistics with SoLID-LITE still would dramatically improve our understanding of D_s!



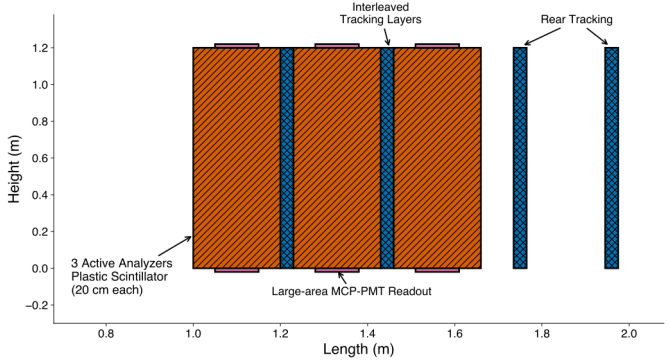
Inner error bars: statistical only

Outer error bars: statistical ⊕ 10% systematic

CONSIDERATIONS FOR SOLID-LITE

- High luminosity brings the possibility of measuring **proton recoil polarization in inelastic processes**
- In DVMP, provides the opportunity to do a **complete amplitude analysis**, with electron, VM, and proton spins all measured
  - **This would be the holy grail for GPDs!**
  - **Can provide a new test of the reaction mechanism!**

If SoLID-Lite has azimuthal gaps, could imagine sticking in a **polarimeter arm to measure proton polarization!**



Recoil proton polarization: A new discriminative observable for deeply virtual Compton scattering

Olga Bessidskaia Bylund, Maxime Defurne, and Pierre A. M. Guichon
Irfu, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

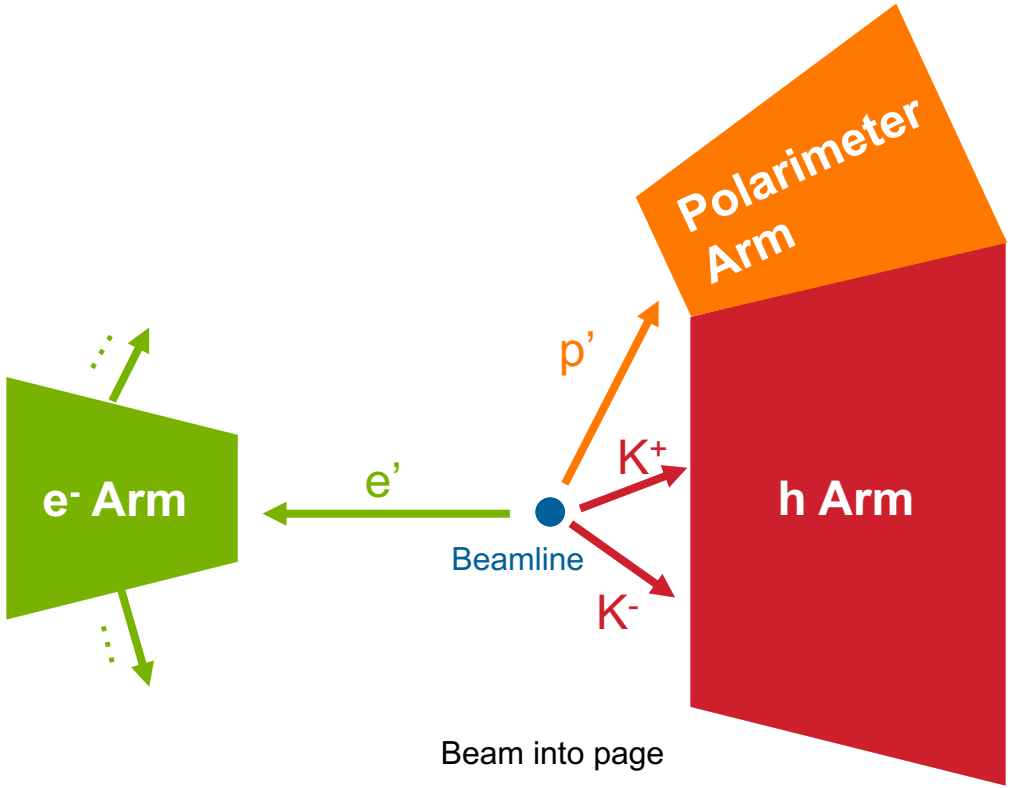
Single spin asymmetry in $e + p \to e' + B^{\uparrow} + X$

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

Double Polarization Observables in Pentaquark Photoproduction

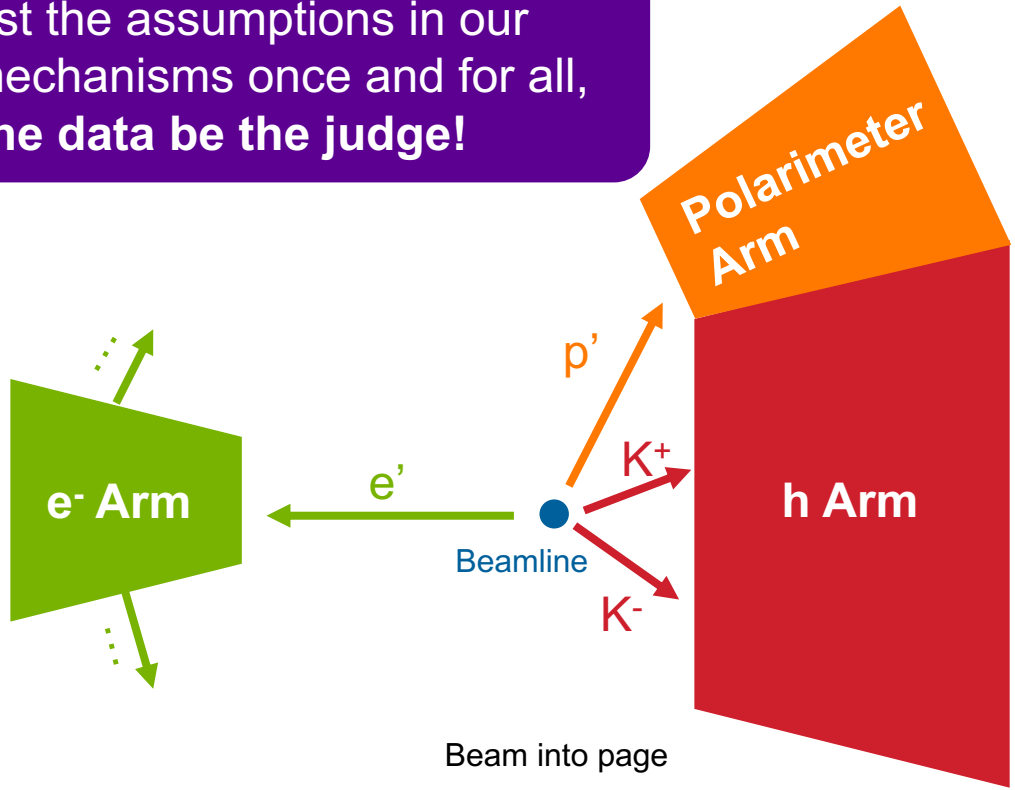
D. Winney,[1,2,*] C. Fanelli,[3,4,†] A. Pilloni,[5,6,‡] A. N. Hiller Blin,[7,§] C. Fernández-Ramírez,[8] M. Albaladejo,[9] V. Mathieu,[10] V. I. Mokeev,[9] and A. P. Szczepaniak[1,2,9]
(Joint Physics Analysis Center)

CONSIDERATIONS FOR SOLID-LITE



CONSIDERATIONS FOR SOLID-LITE

Let's test the assumptions in our reaction mechanisms once and for all, **let the data be the judge!**



OTHER OPTIONS FOR ϕ AT HIGH LUMINOSITY

- Analysis of ϕ electroproduction in CLAS12 RG-A and RG-K data is ongoing (Ask Bhawani & Krishna)
  - Reach to GFF-region is mostly limited by statistics, **this channel would benefit greatly from a CLAS12 luminosity upgrade!**

- Could measure $\phi \rightarrow \mu\mu$ with μCLAS12
  - **BR of 3E-4…** Probably not competitive with default CLAS12

- Letter-of-intent submitted to last year's PAC for measuring ϕ electroproduction using **SBS augmented with a RICH**
  - Conceptually similar to the SoLID-LITE design I sketched

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WHAT IS “HIGH LUMINOSITY”

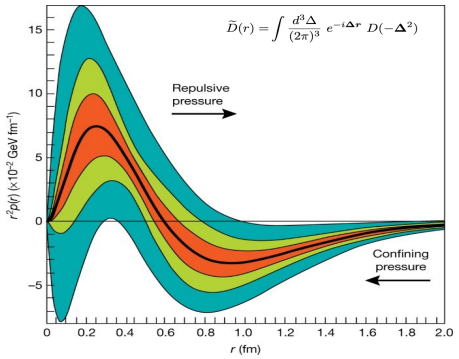
- I think most of us mean **“higher statistics for analysis”**
- For many analyses, higher luminosity ≠ more statistics **without improved DAQ** to actually record the process of interest
- For example, in SoLID using **just calorimeter and scintillator information**, the exclusive ϕ final-state of three charged “hadrons” and an electron will have a **trigger rate of ~100 kHz due to random coincidences** despite only O(100) Hz of signal
  - In such cases, **increasing the luminosity changes nothing**, the trigger rate can’t go higher
  - However, this is strictly a problem of the “standard” DAQ setup, **with streaming & a software trigger, there is no problem!**

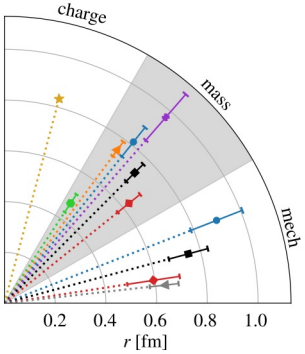
WHAT IS “HIGH LUMINOSITY”

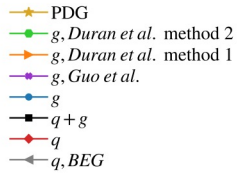
- I think most of us mean **“higher statistics for analysis”**
- **This also means higher MC statistics for unfolding!**
  - Rule of thumb is 5-10x more MC events than data events
- With more events for analysis intrinsically comes **higher demand for compute resources**
  - Current compute is already strained, a “higher luminosity facility” probably needs more resources or significantly optimized data/simulation processing
  - Can learn from HL-LHC, e.g. generative AI for fast simulation

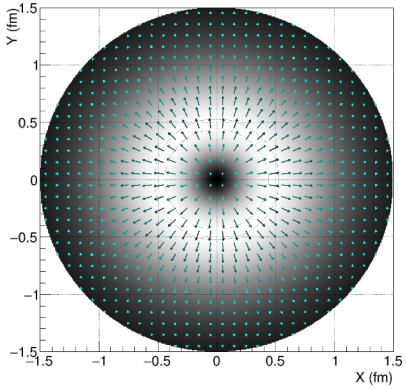
Future experiments will give us the **missing piece of the *D*-term,** D_s, enabling global analyses of ***total*** *D*-term from **experimental data!**

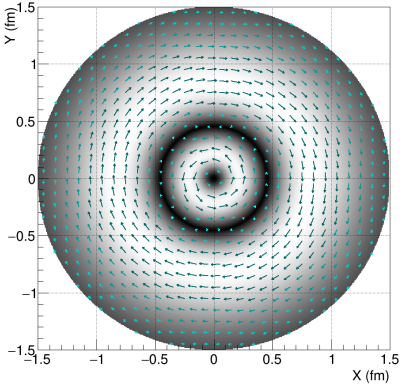
$$D(0) = \underbrace{D_g(0)}_{J/\psi} + \underbrace{D_u(0) + D_d(0)}_{\text{DVCS}} + \underbrace{D_s(0)}_{\phi\ \text{DVMP}} + \ldots.$$











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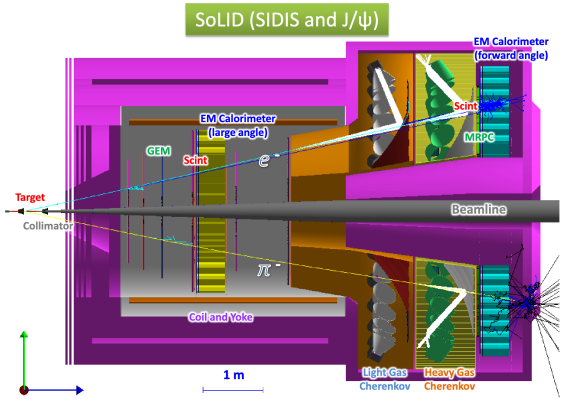
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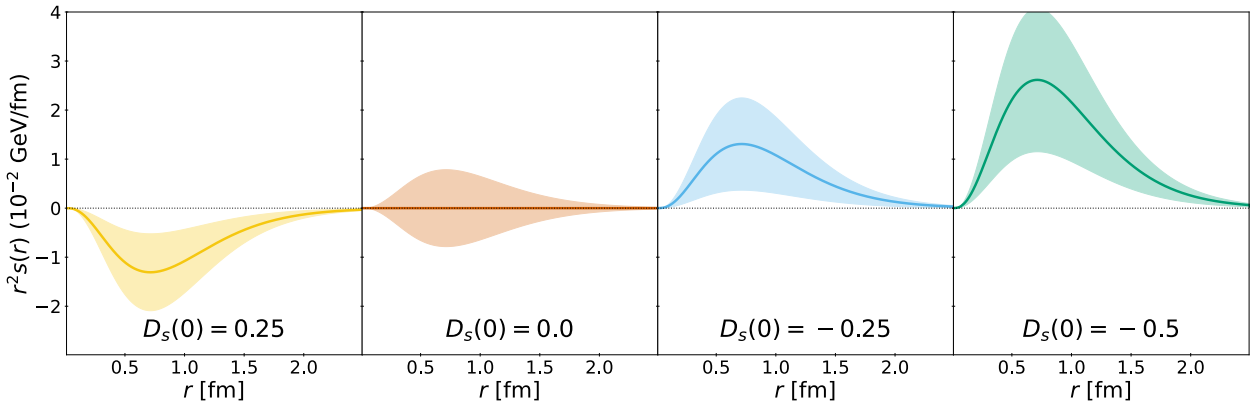
$$D(0) = \underbrace{D_g(0)}_{J/\psi} + \underbrace{D_u(0) + D_d(0)}_{\text{DVCS}} + \underbrace{D_s(0)}_{\phi\ \text{DVMP}} + \ldots.$$

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**
  - The **ϕ-007 experiment** in Hall C will give us a glimpse of D_s
- Experiments with **large acceptance** and **high luminosity** are the only way to comprehensively map D_s
  - **Seems that a SoLID-LITE would be capable of this!**





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BACKUP

59 Collaborators











































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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!

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

Large cancellation for D_g!

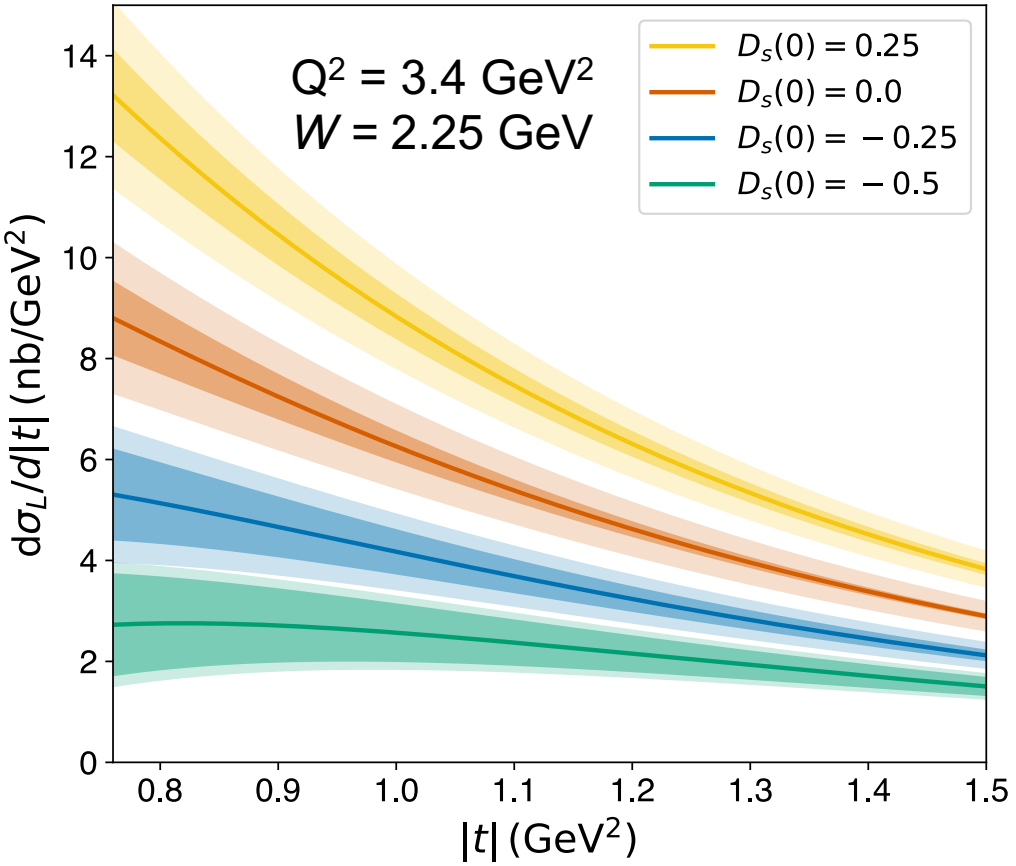
$A_g \approx 0.4, D_g \approx -2$

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

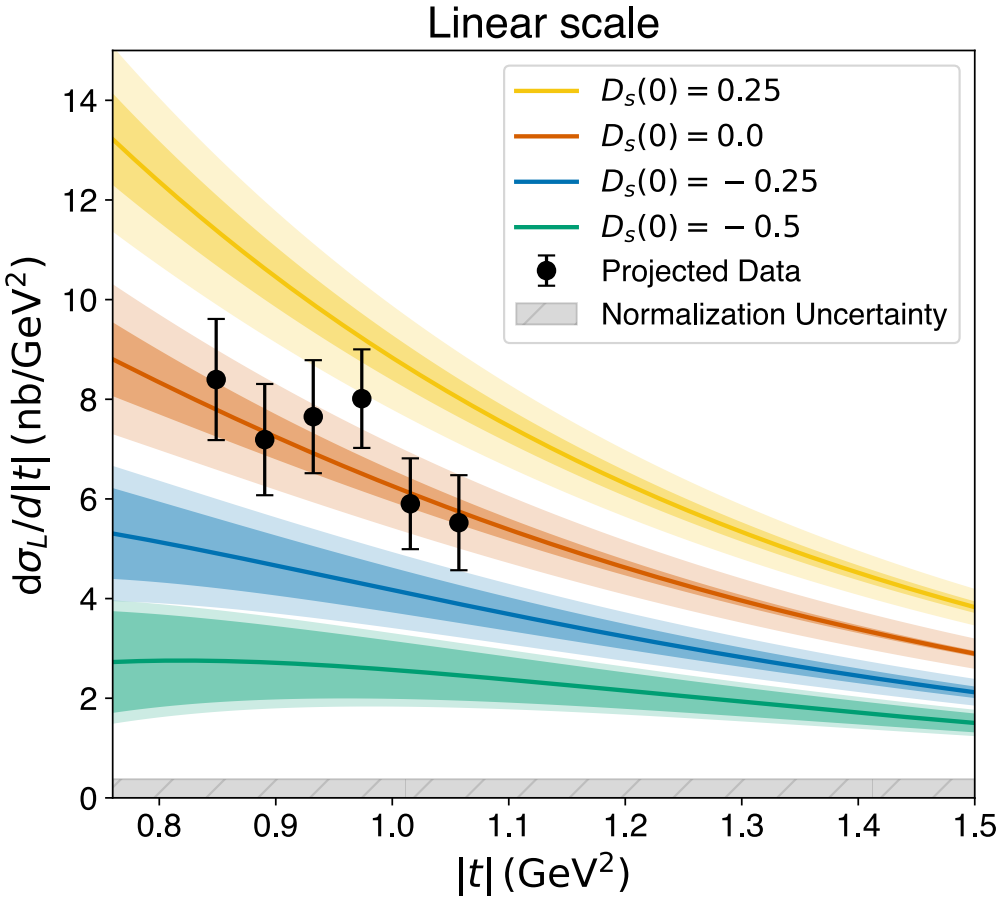


Inner uncertainty band:
pQCD scale variation
$\mu/2 < Q < 2\mu$

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*

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

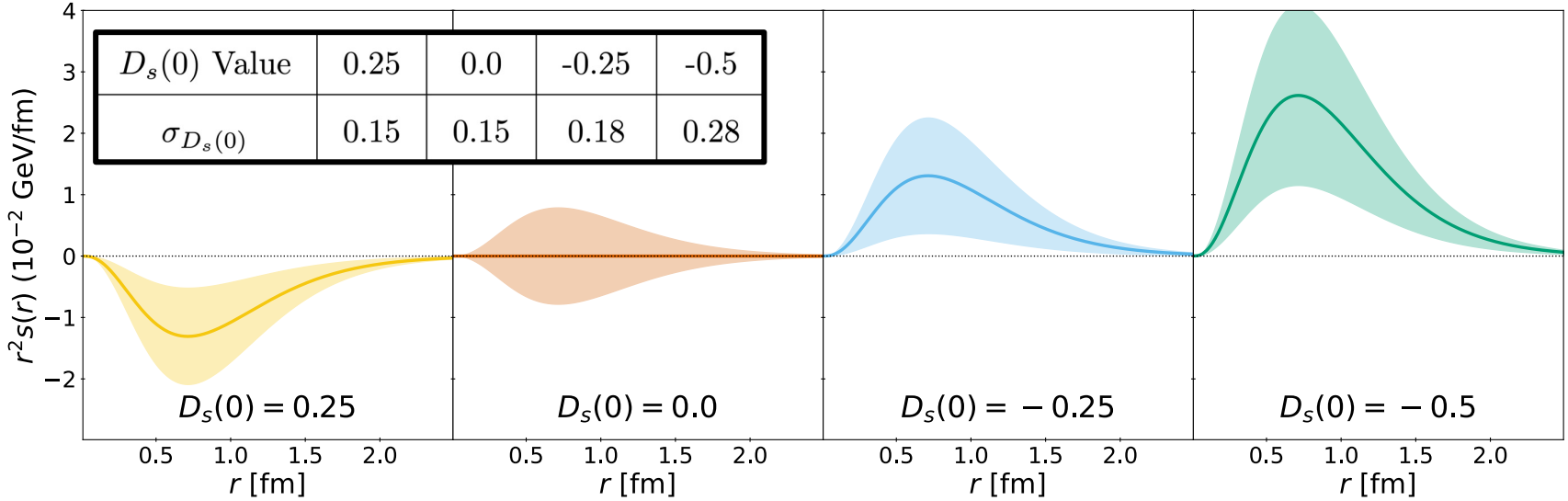
Extracted resolutions on $D_s(0)$ for various values of $D_s(0)$.

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WHAT CAN WE LEARN FROM ϕ-007?

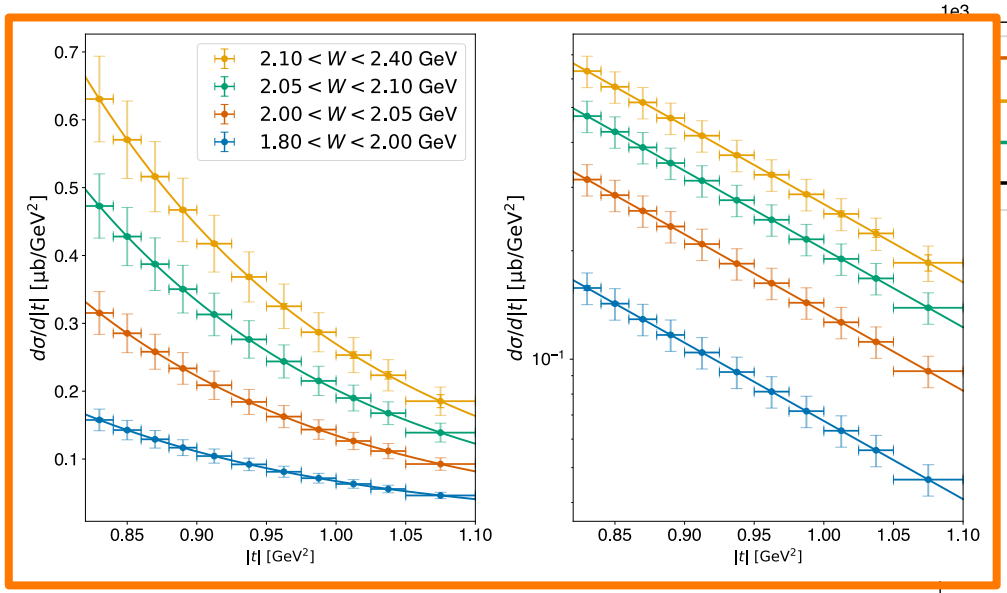
Using these resolutions on $D_s(0)$ and the functional form measured on the lattice, can project uncertainties for the **strangeness shear force distribution**

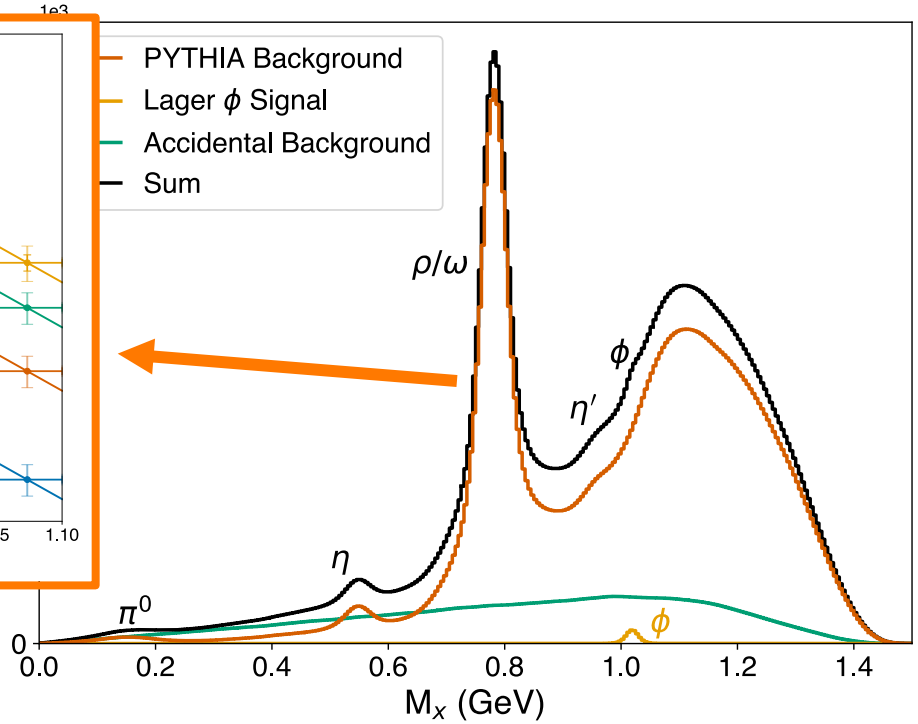
First ever extraction! Terra incognita…



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WHAT ELSE CAN WE LEARN FROM ϕ-007 ?



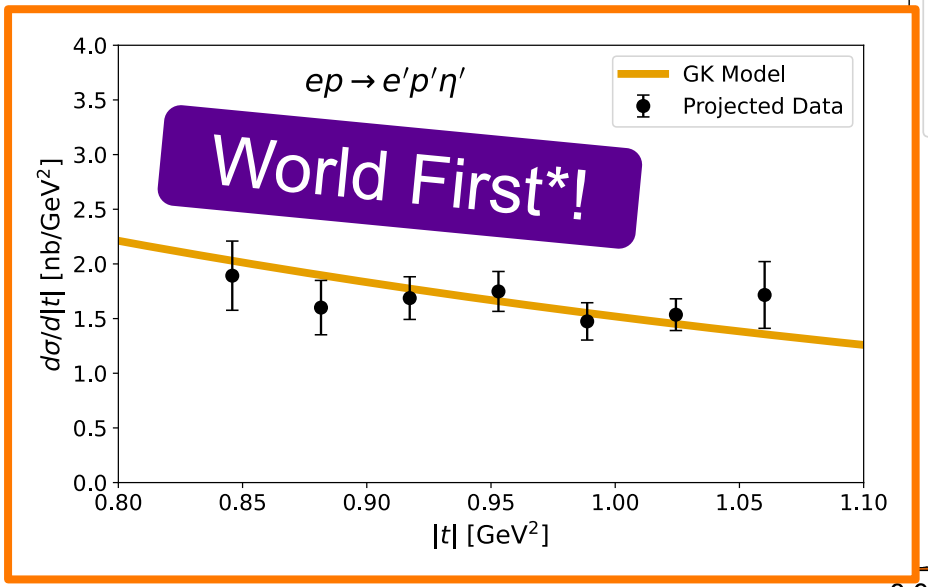


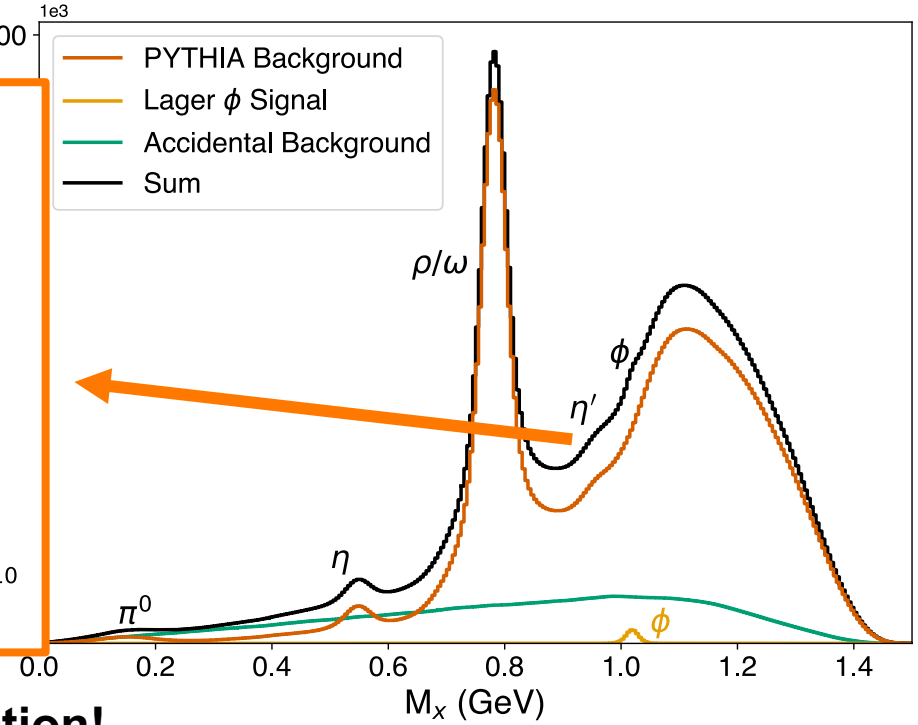
Most differential measurement of near-threshold ω electroproduction! + BSA!

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 ?





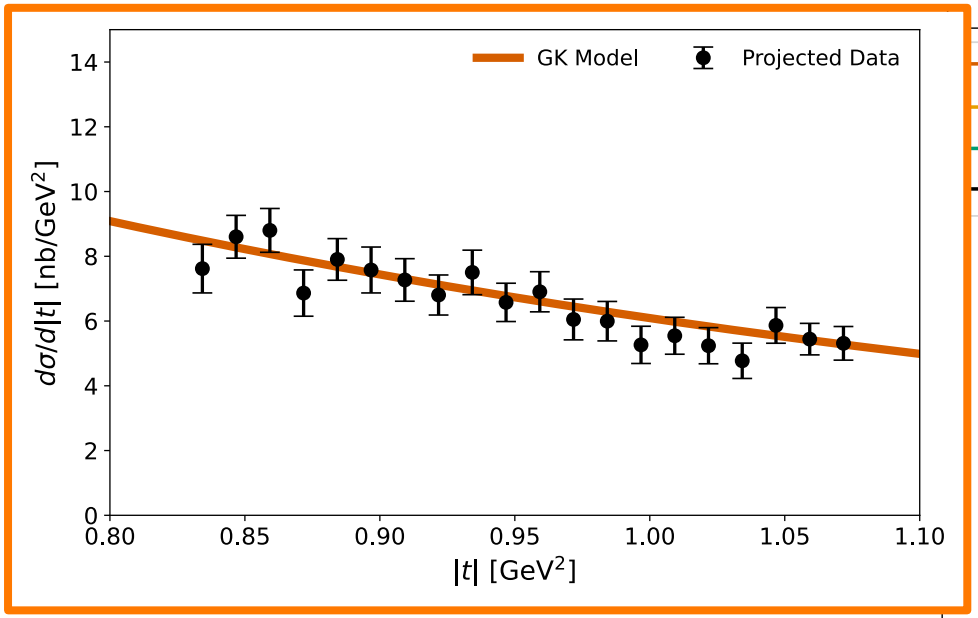
First measurement of η' electroproduction!

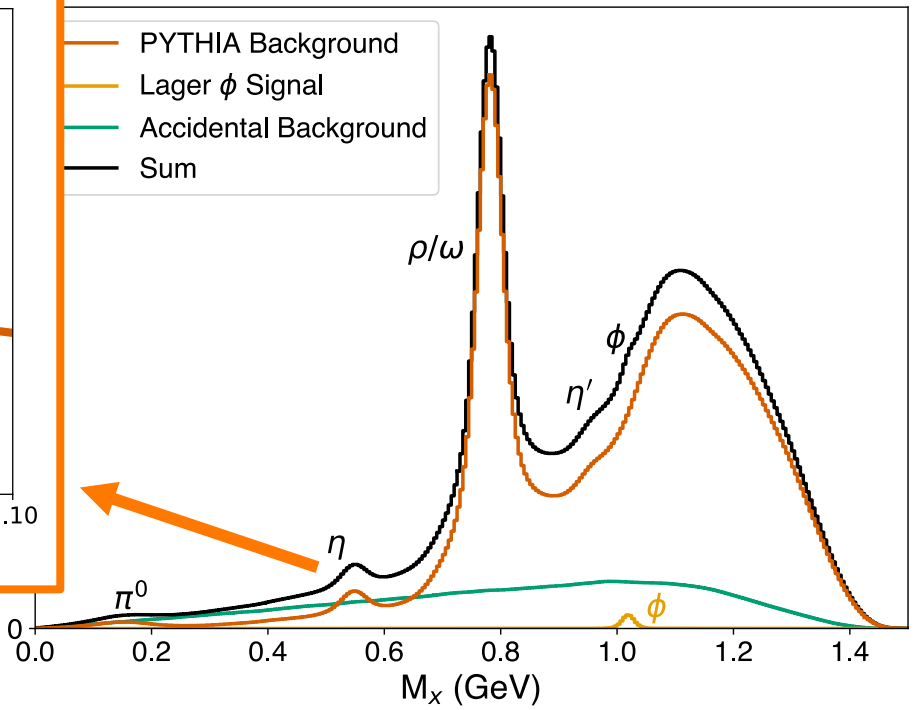
Unexpectedly large η' mass is generated by the **QCD chiral anomaly**,

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

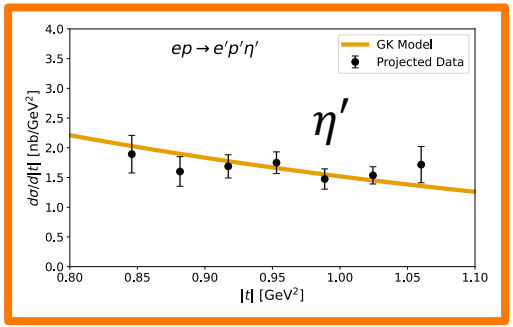
[1] Eides, Frankfurt, Strikman - **Hard Exclusive Electroproduction of Pseudoscalar Mesons and QCD axial anomaly**

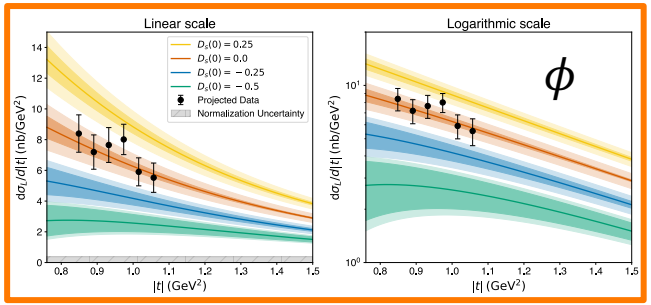
WHAT ELSE CAN WE LEARN FROM THIS DATA?

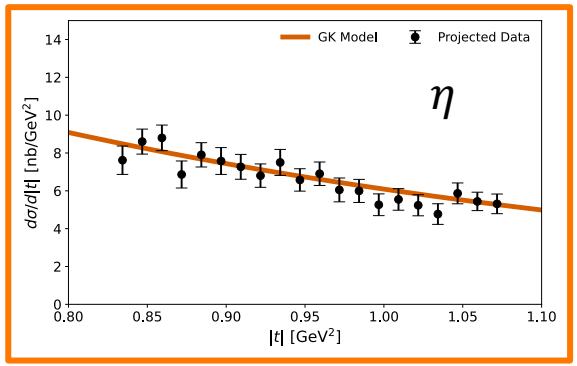
Beam Spin Asymmetries for all!

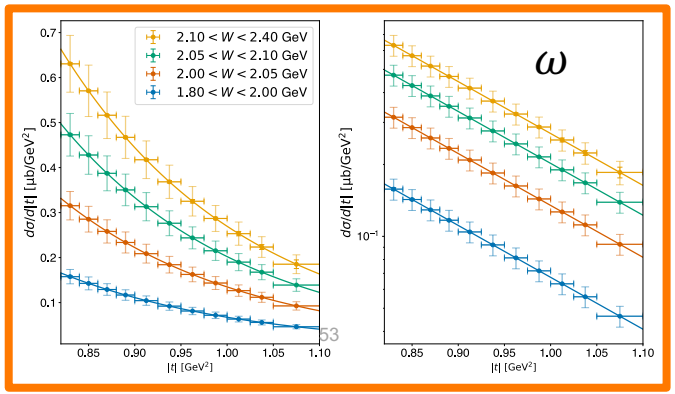
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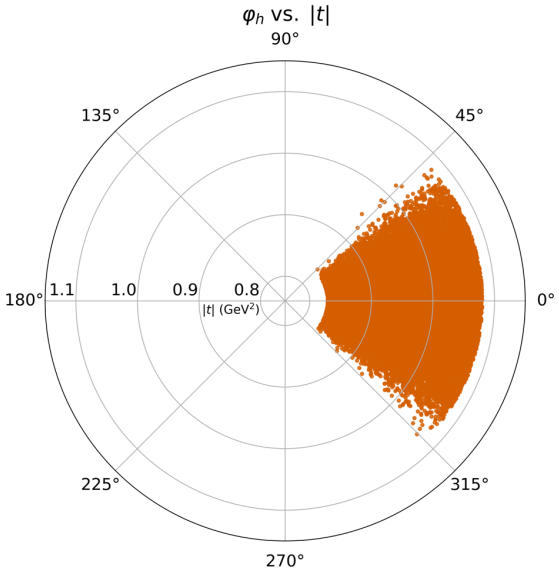
$$\mathrm{BSA} = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi_h}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi_h+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi_h}$$









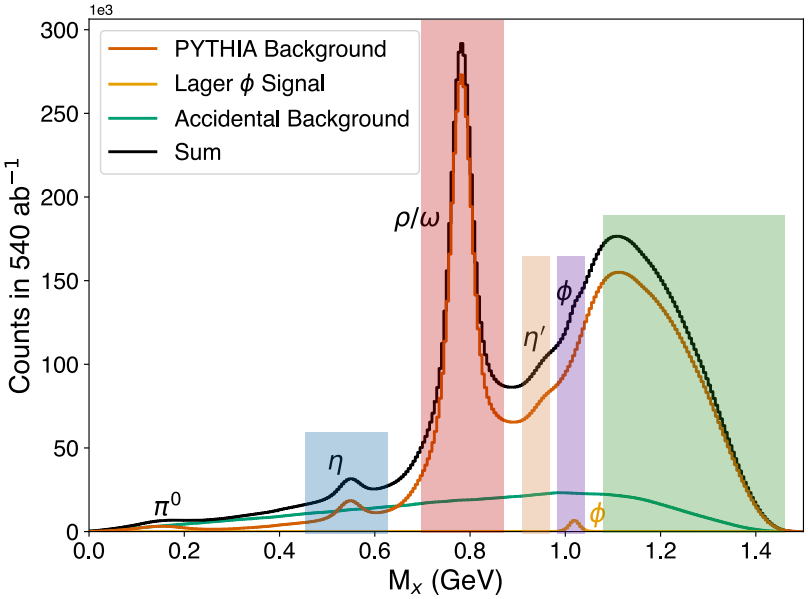


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WHAT ELSE CAN WE LEARN FROM ϕ-007?

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

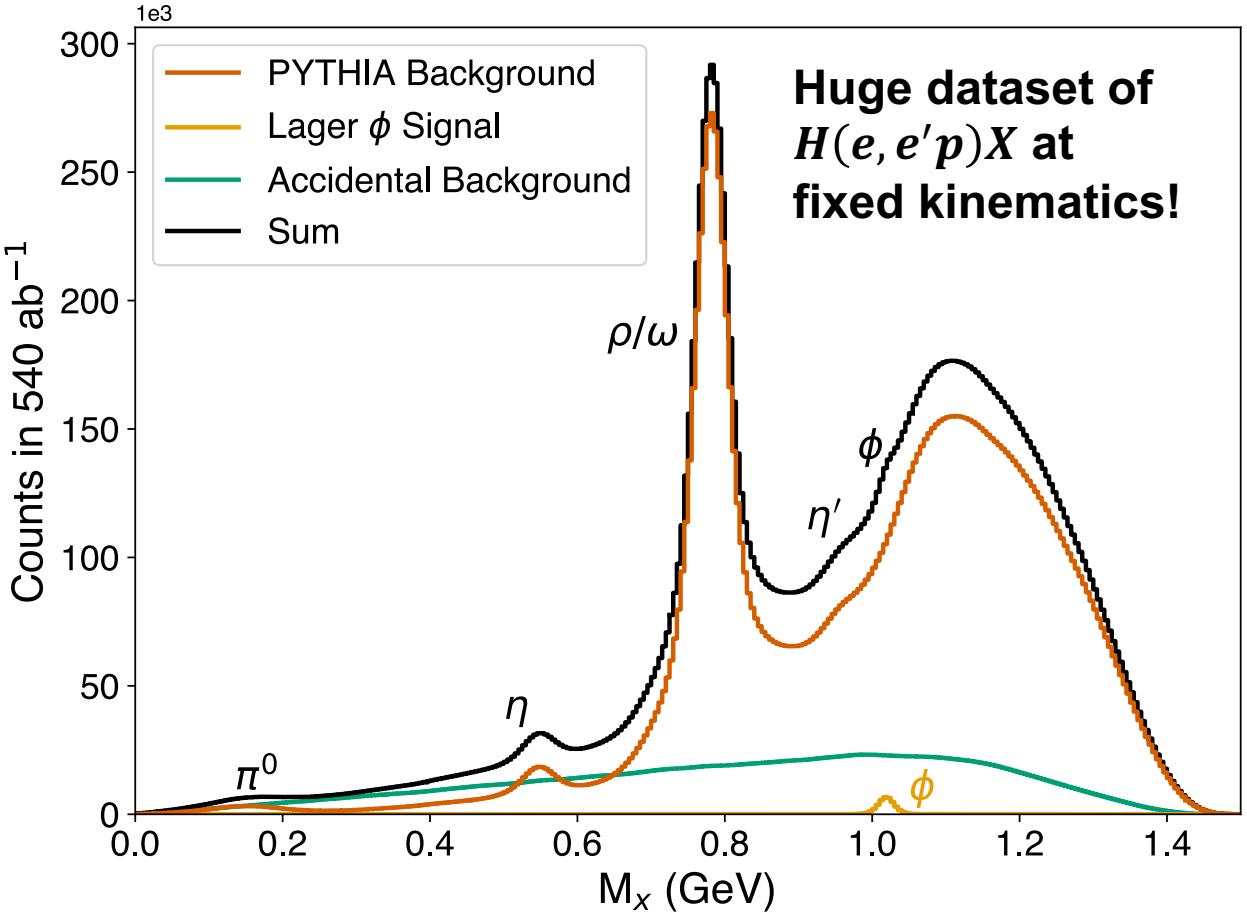
TABLE II. Planned measurements in addition to the ϕ cross section and their physics goals.



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

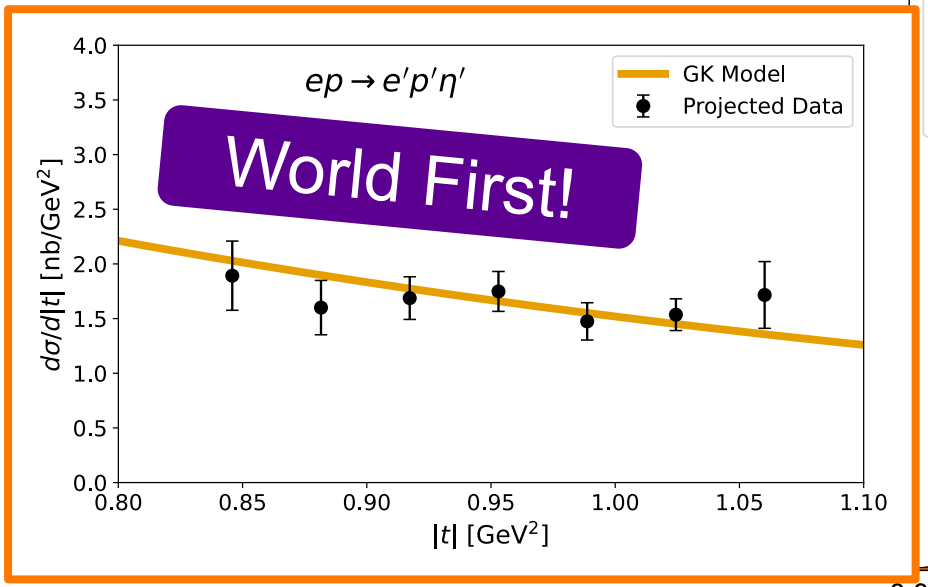
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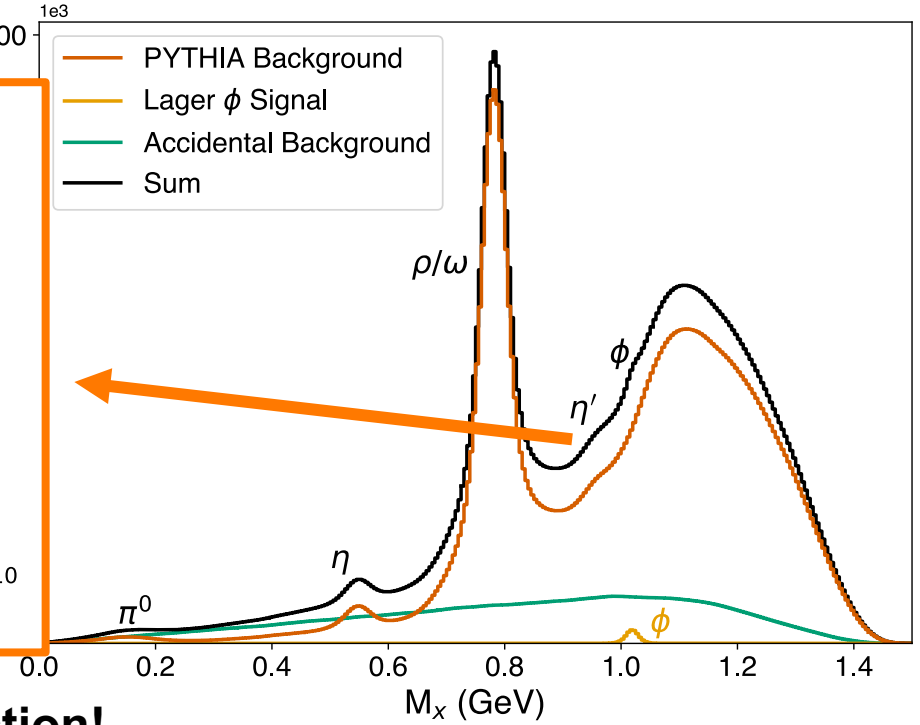
WHAT ELSE CAN WE LEARN FROM THIS DATA?



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WHAT ELSE CAN WE LEARN FROM THIS DATA?





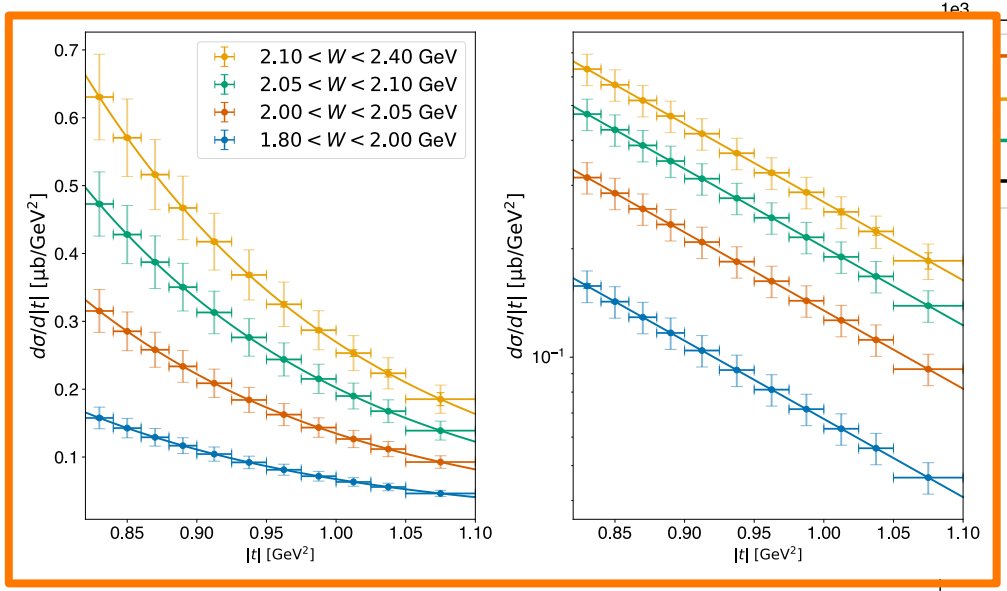
First measurement of η' electroproduction!

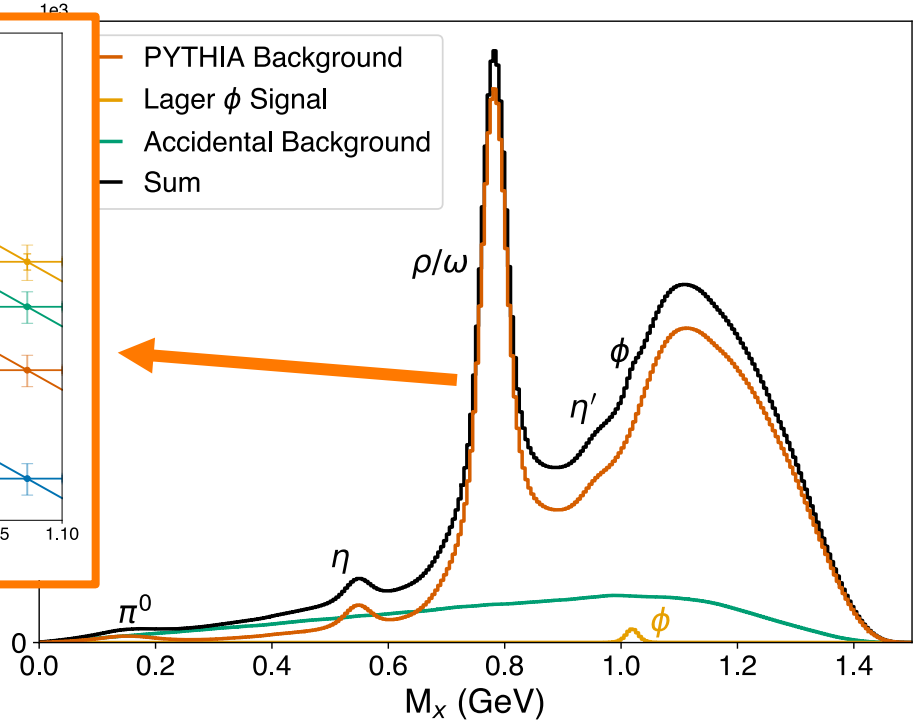
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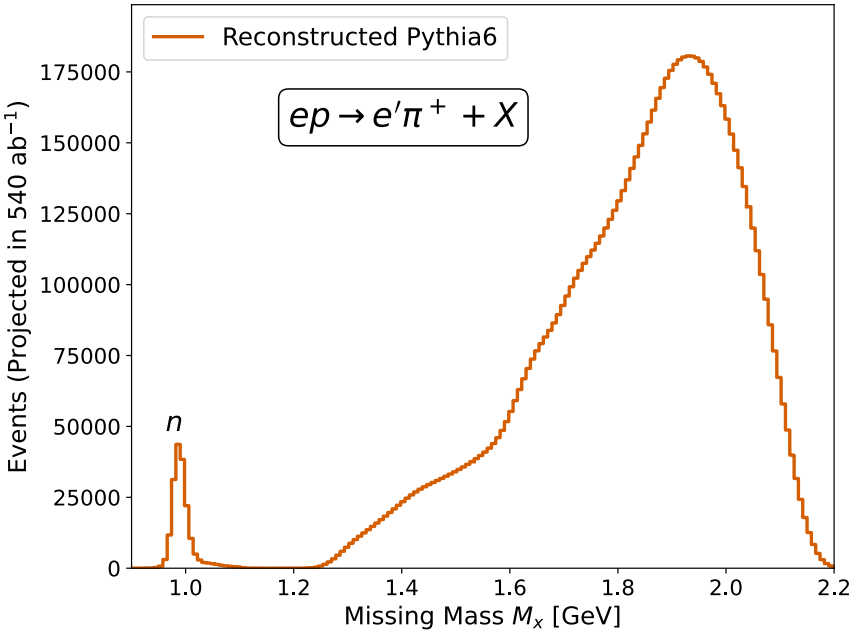


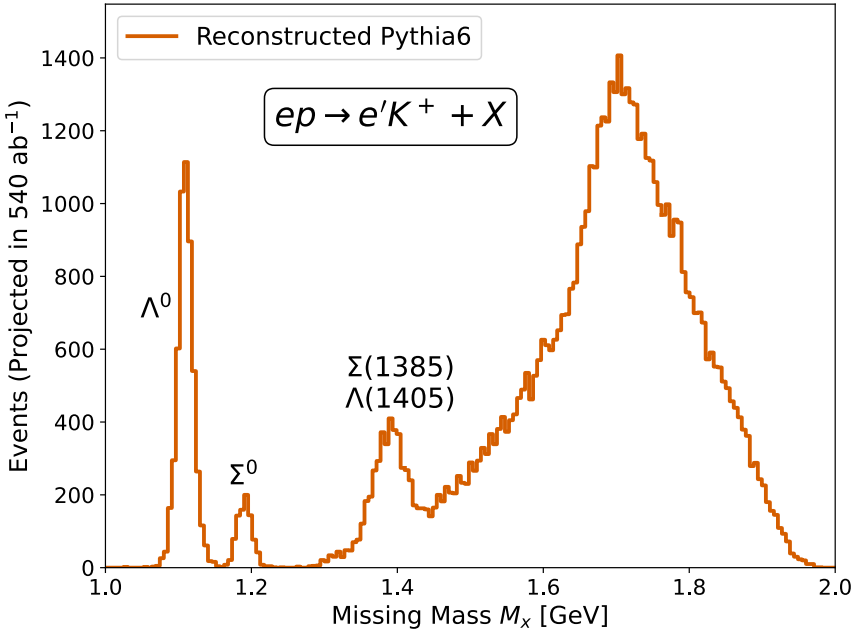
Most differential measurement of near-threshold ω electroproduction! + BSA!

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!

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
Physics Division, Argonne National Laboratory, Lemont, IL, USA

A. Hoghmrtsyan, A. Mkrtchyan, H. Mkrtchyan, V. Tadevosyan
A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute), Yerevan 0036, Armenia

Y. Hatta
Brookhaven National Laboratory, Upton, NY, USA

P. Markowitz, H. Szumila-Vance*
Florida International University, Miami, FL, USA

G. Niculescu, I. Niculescu
James Madison University, Harrisonburg, VA, USA

A. Camsonne, J.-P. Chen, S. Covrig Dusa, K. Dehmelt, D. Gaskell, J.-O. Hansen, D. W. Higinbotham, D. Mack, M. McCaughan, A. Tadepelli
Jefferson Lab, Newport News, VA, USA

C. Ayerbe Gayoso, C. E. Hyde, C. Ploen
Old Dominion University, Norfolk, VA, USA

H. Atac, N. Ifat, S. Shrestha, N. Sparveris
Temple University, Philadelphia, PA, USA

H. Bhatt, W. Li, Z. Yin
Mississippi State University, Mississippi State, MS, USA

M. Paolone, C. Paudel
New Mexico State University, Las Cruces, NM, USA

N. Heinrich, G. Huber, M. Junaid, V. Kumar, A. Postuma, A. Usman
University of Regina, Regina, SK, Canada

M. Elaasar
Southern University at New Orleans, New Orleans, Louisiana, USA

D. Biswas, M. Boër, K. Tezgin
Department of Physics, Virginia Tech, Blacksburg, VA, USA

D. Androić
University of Zagreb, Faculty of Science, Zagreb, Croatia

S. Kay
University of York, York, UK

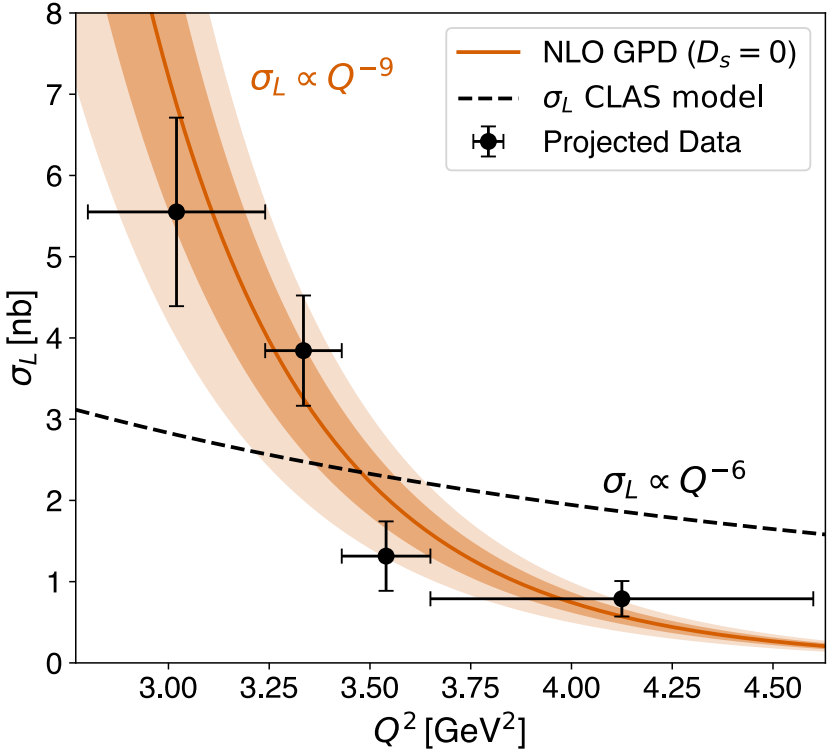
J. Datta
Stony Brook University, Stony Brook, NY

U.S. DEPARTMENT of ENERGY
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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 $\sigma_L \propto Q^{-4}$

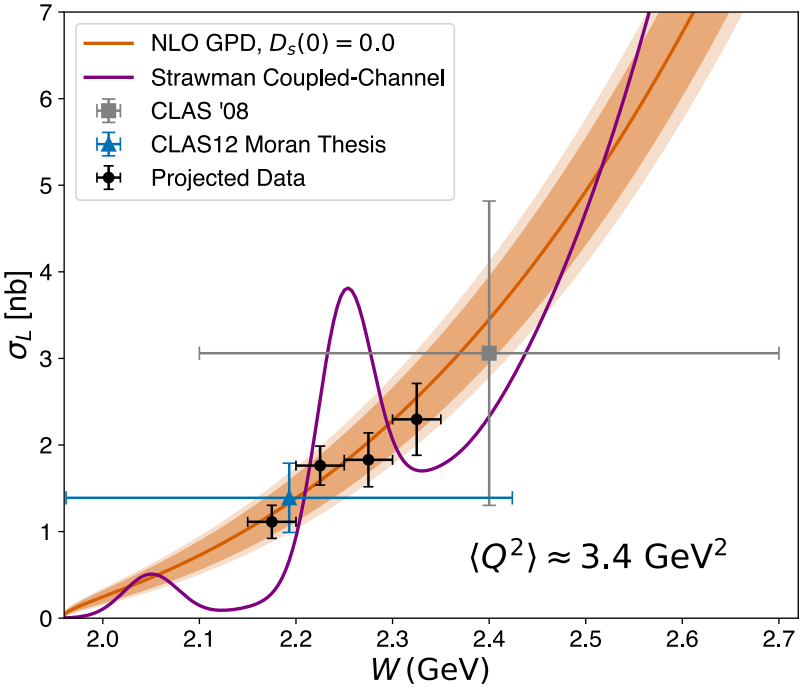
Can validate or invalidate collinear factorization at these kinematics with our data!



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

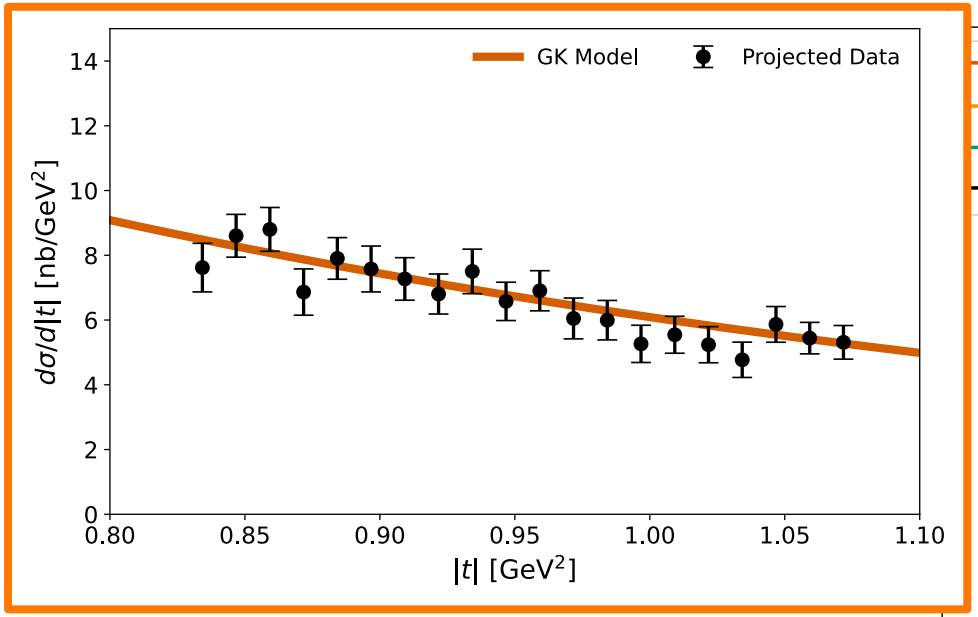
TESTING THE THEORY

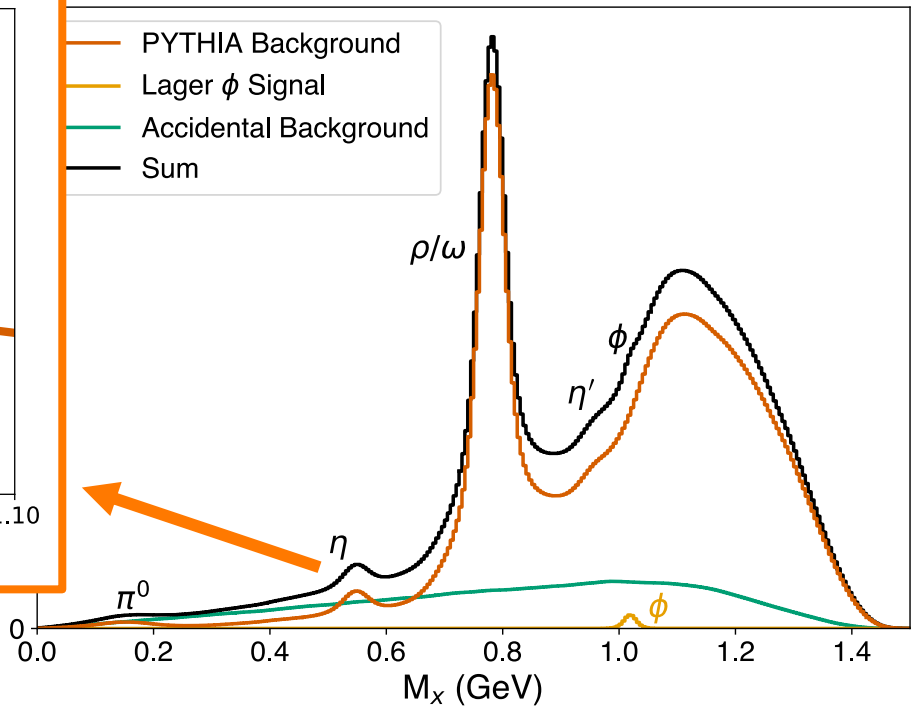
- The prediction of Hatta et al. “**agrees**” with CLAS data and preliminary results from CLAS12
  - **Data uncertainties are very large!**
- Almost any model can describe the existing data due to poor precision & large bins
- The speculation surrounding this topic is precisely why these **data are sorely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

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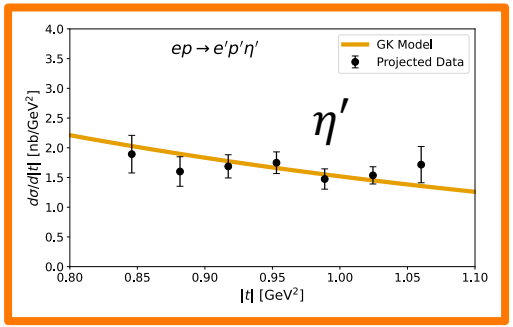
[1] Eides, Frankfurt, Strikman - **Hard Exclusive Electroproduction of Pseudoscalar Mesons and QCD axial anomaly**

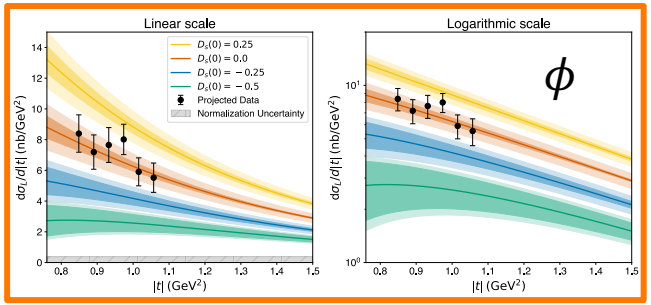
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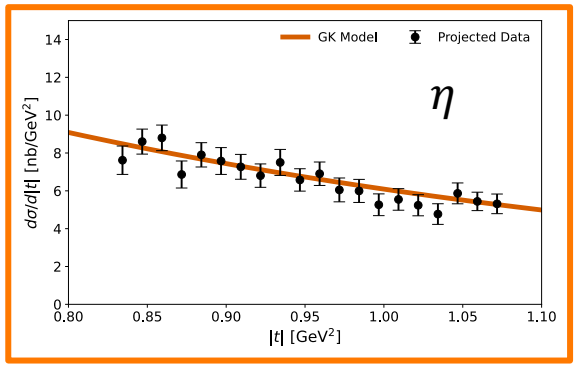
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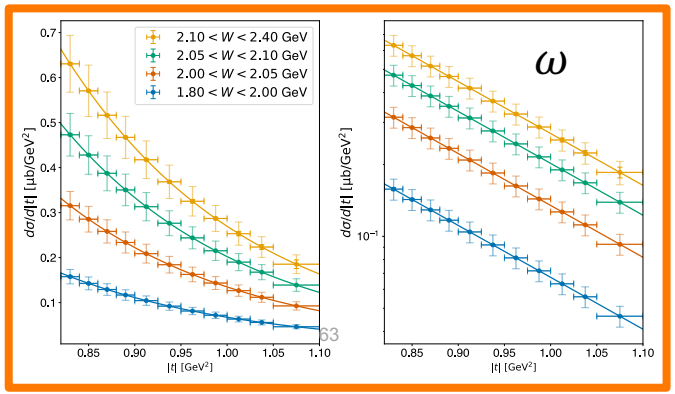
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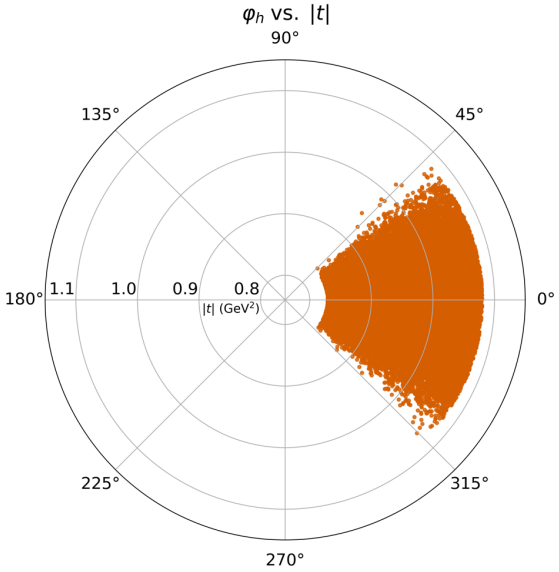
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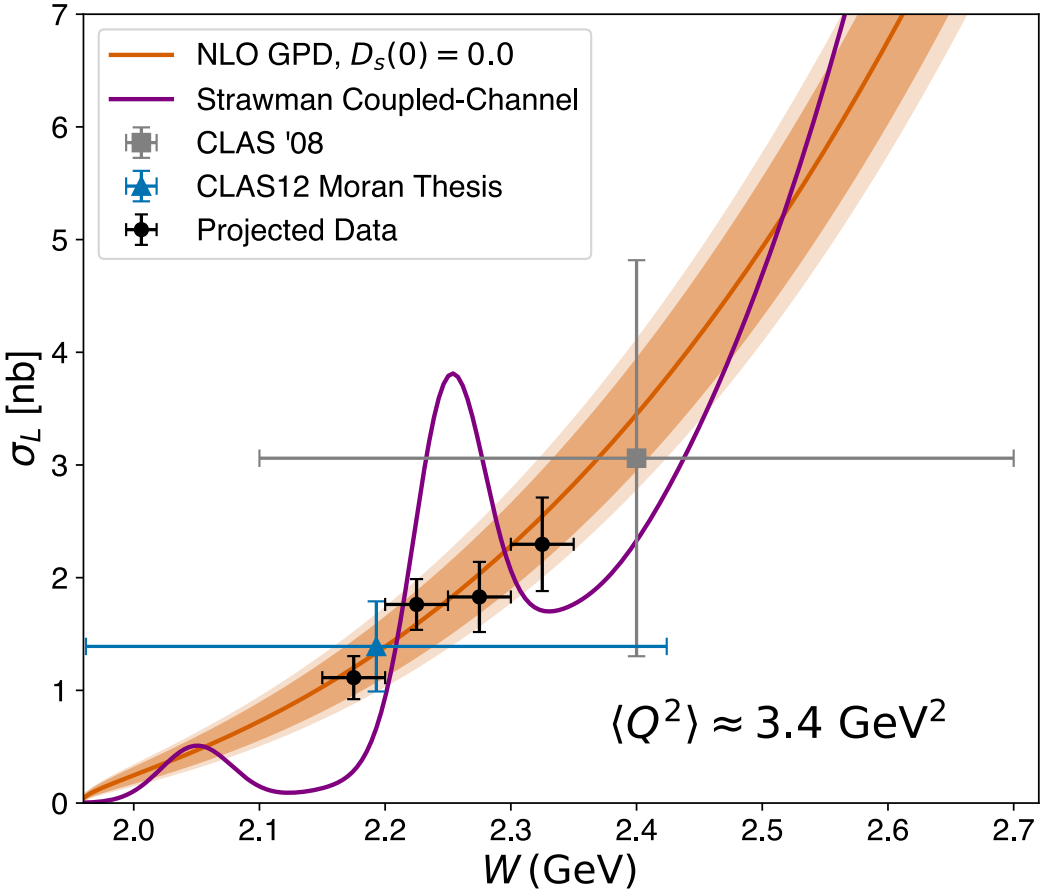








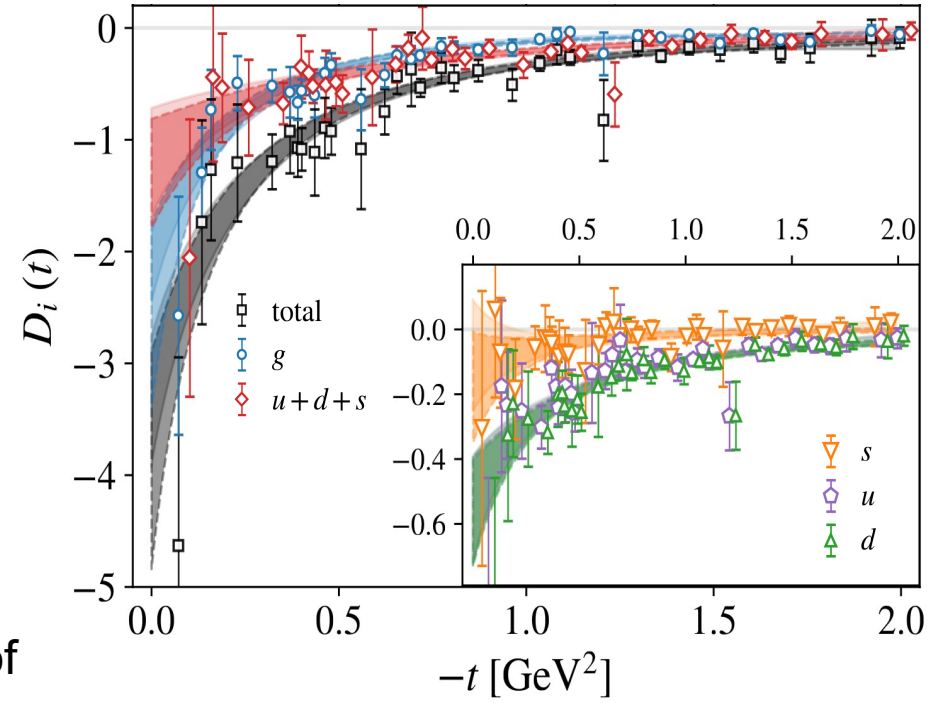
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Data Source	$\langle W \rangle$ (GeV)	Data σ_L	GPD σ_L
CLAS '08 data	2.40	3.06 ± 1.76	3.44 ± 0.66
CLAS12 Moran thesis data	2.19	1.39 ± 0.30	1.28 ± 0.33

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

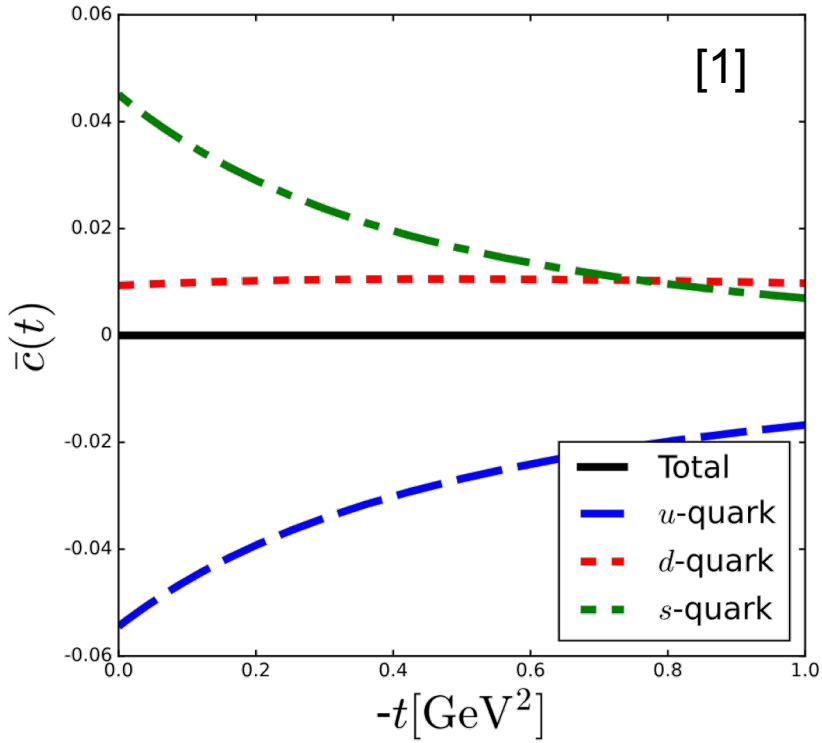
$\bar{c}$ CAVEAT

- $\bar{c}$ 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!**

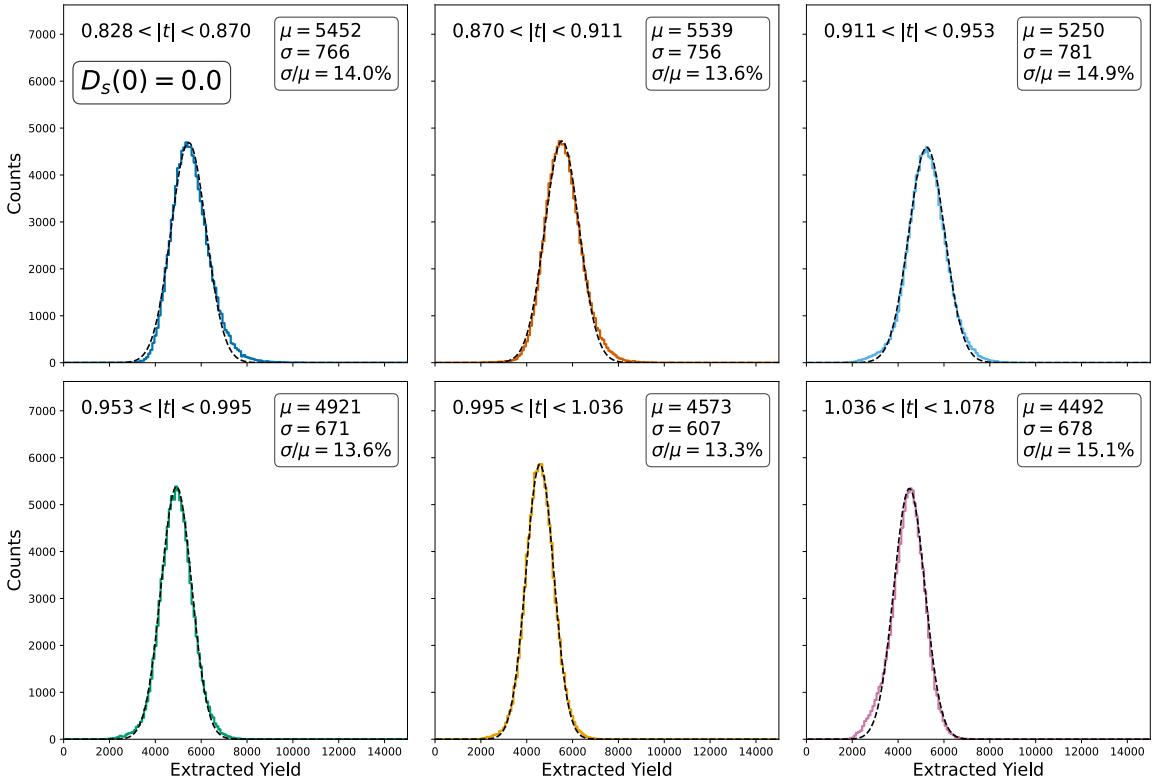


This caveat means that to extract the full set of mechanical properties, ***all* partonic D-term contributions must be known!**

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

SIGNAL EXTRACTION

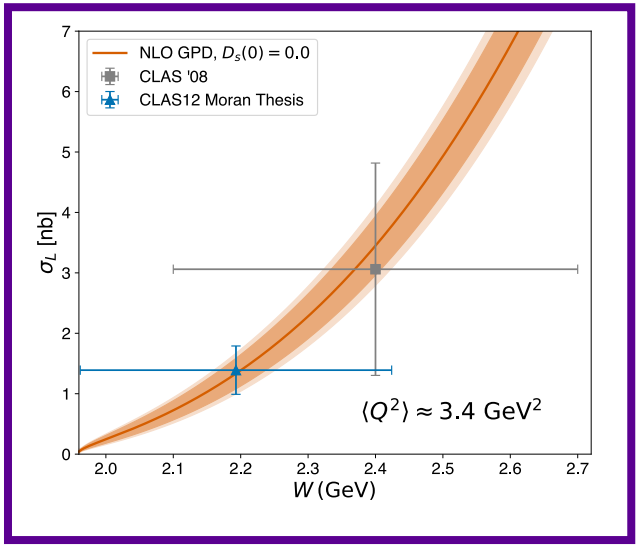
- Perform the background generation, fitting, and sideband background subtraction on pseudodata 100000 times
- Results of pseudoexperiments shown for 6 bins in $|t|$
  - Can bin less finely if cross section is smaller than predicted

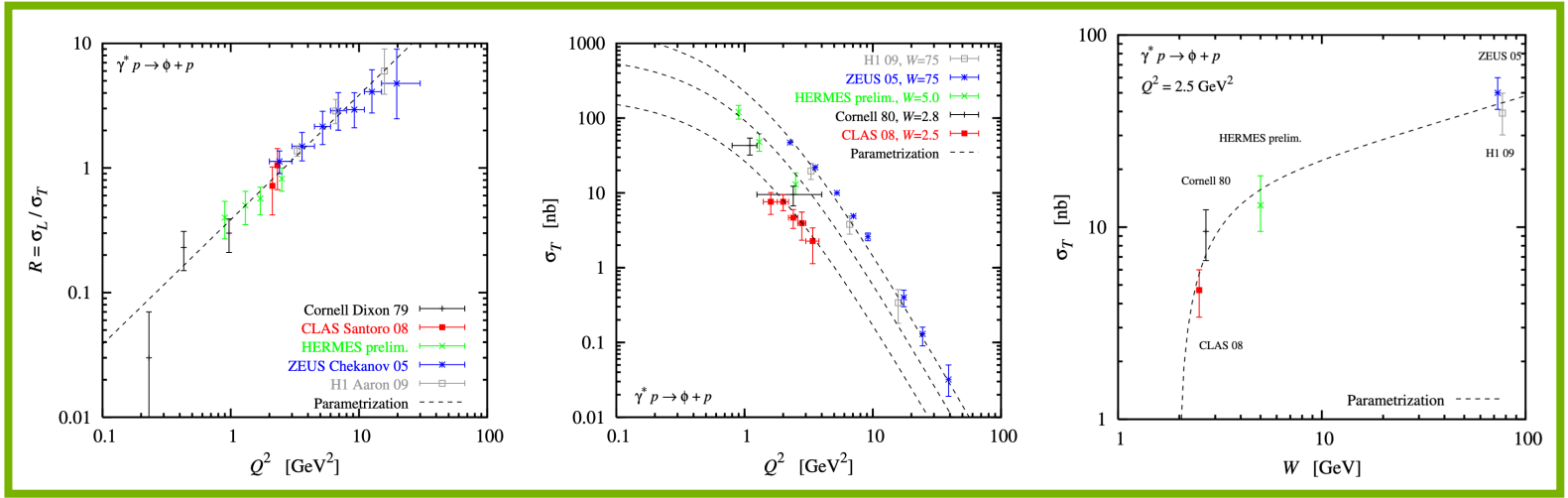


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CROSS SECTION PROJECTIONS

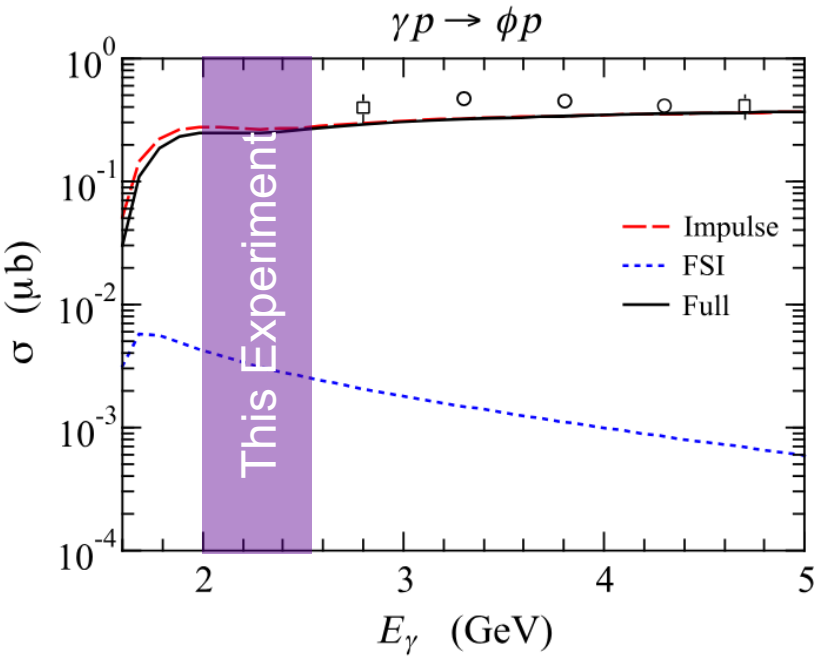
- ϕ Cross section conservatively estimated as the smaller of two predictions in our projections
  - **NLO GPD prediction**
  - **Model based on existing world data developed for CLAS12**



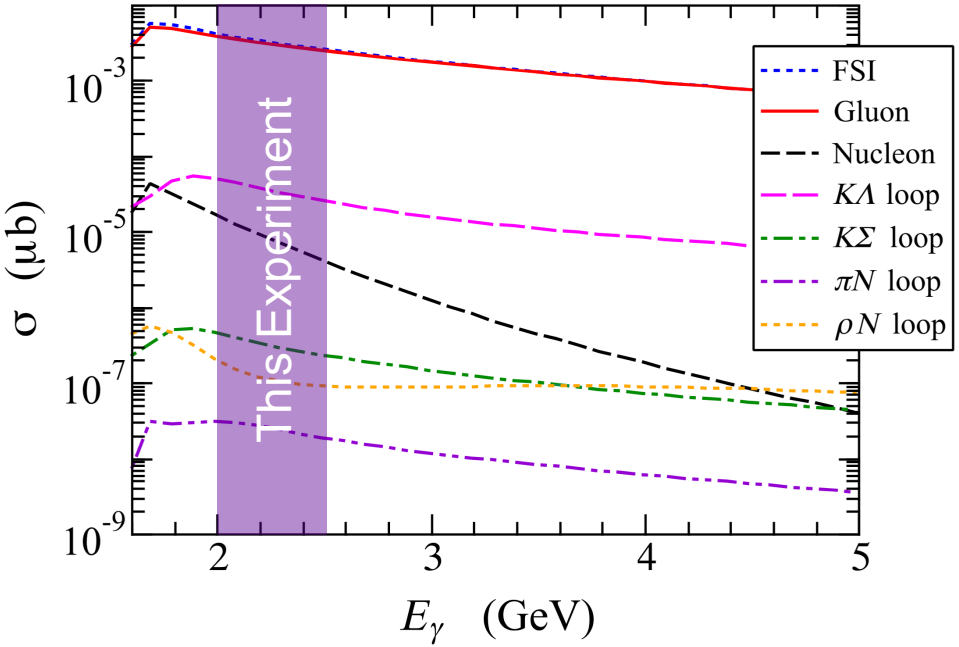


FINAL-STATE INTERACTIONS

- 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

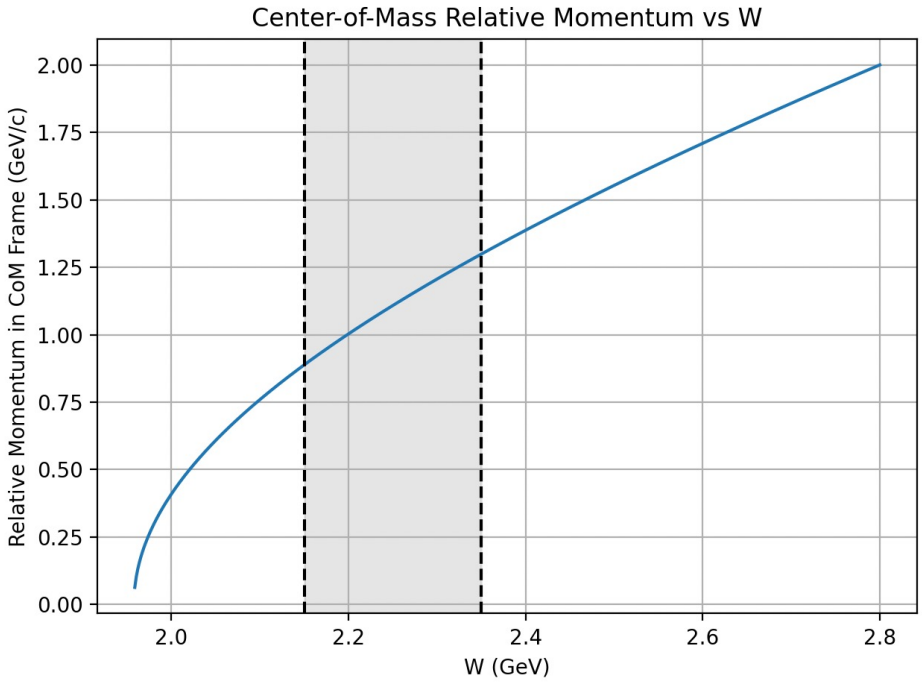
[1] - Mamo, Zahed: **Electroproduction of heavy vector mesons using holographic QCD: from near threshold to high energy regimes**

“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!**

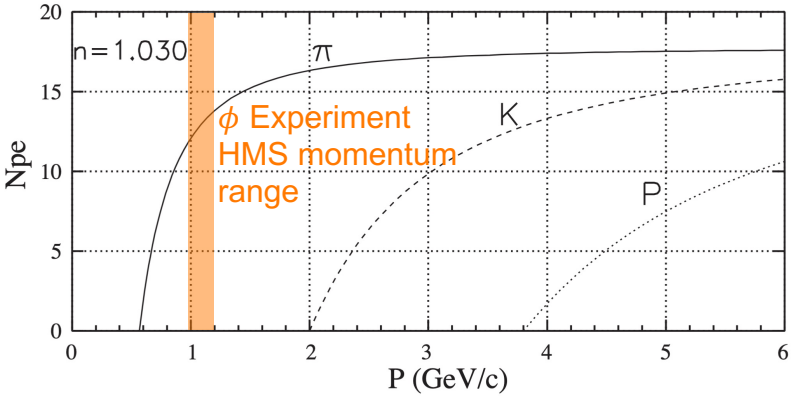


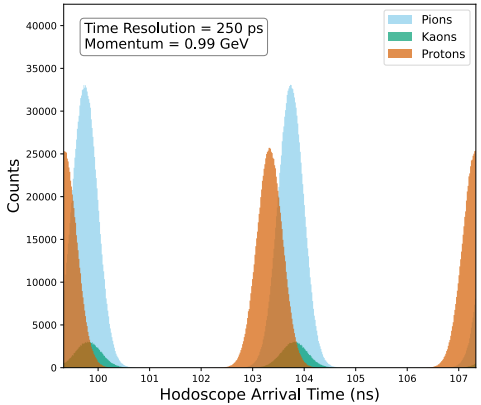
Total momentum between the ϕ and proton in the center-of-mass frame

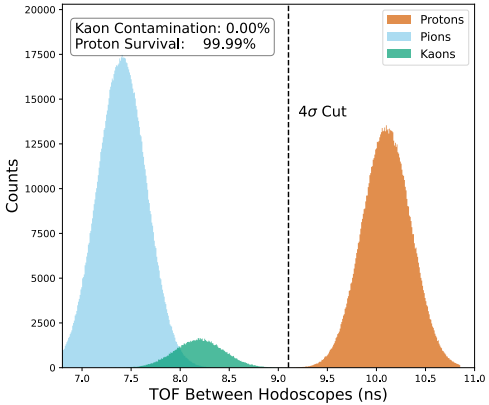
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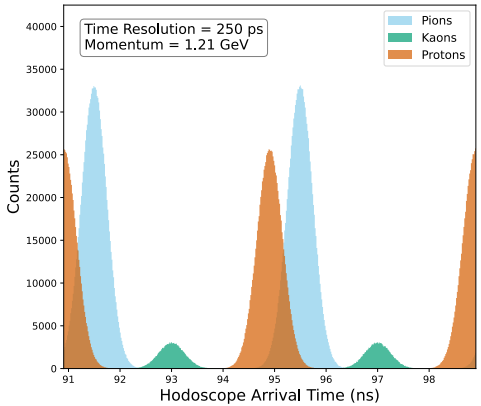
CAN WE DO *U*-CHANNEL?

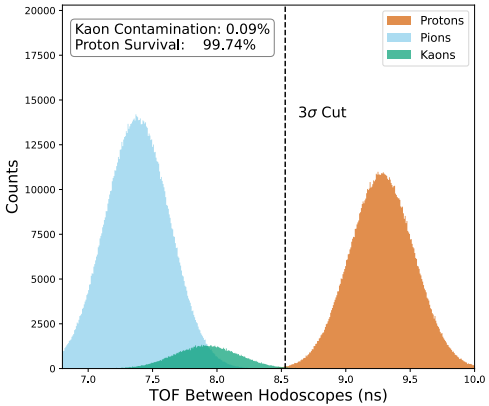
- u-channel: baryon takes most of the virtual photon momentum
- Instead of $H(e,e'P)X$, can we do $H(e,e'K)$X or $H(e,e'\pi)$X with our dataset?
  - HMS Aerogel would likely be able to cover π/K separation
    - Kaons are below Cherenkov threshold, pions reasonably far above it











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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]

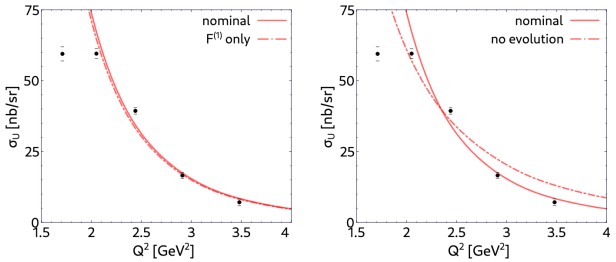
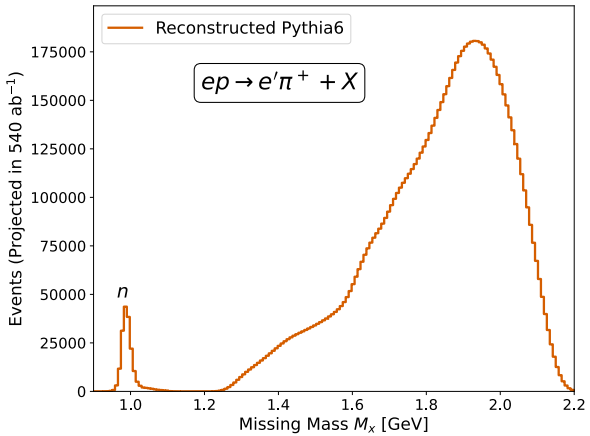
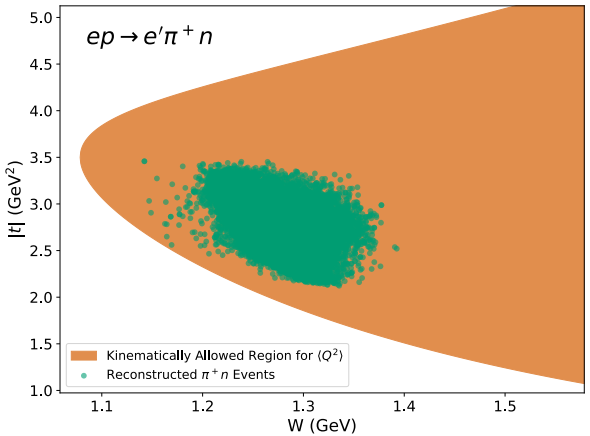
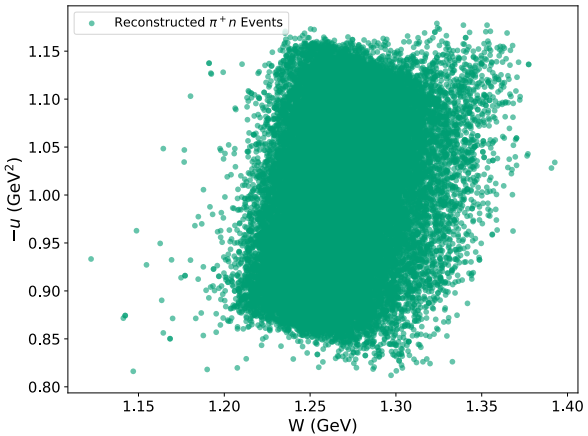


FIG. 5: CLAS data for the unseparated cross-section $\frac{d\sigma_U}{d\Omega^*_\pi}$ of the $\gamma^* p \to \pi^+ n$ reaction at backward angles [8], with $W = 2.2\,\text{GeV}$ and $u = -0.5\,\text{GeV}^2$. The solid curves represent the corresponding results obtained using the default version of our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



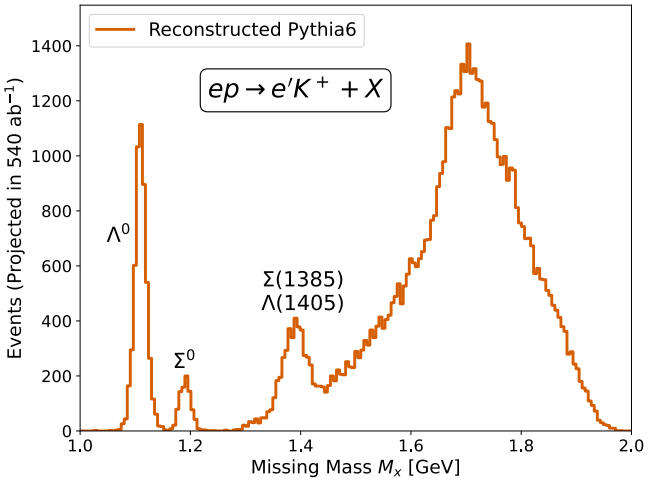




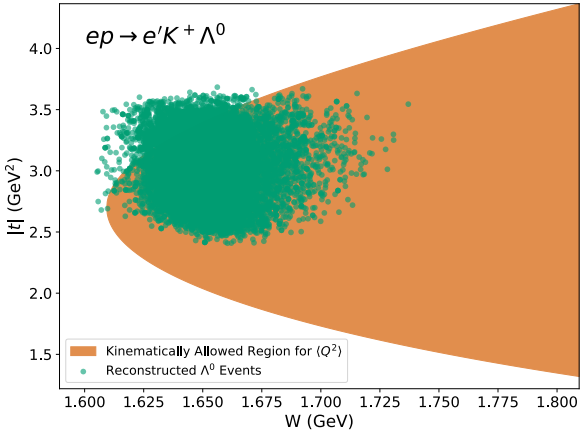
[1] Pire et al. - **Toward an advanced phenomenology of πN transition distribution amplitudes**

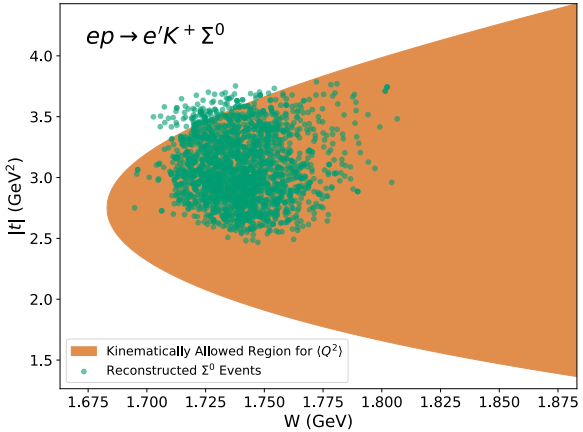
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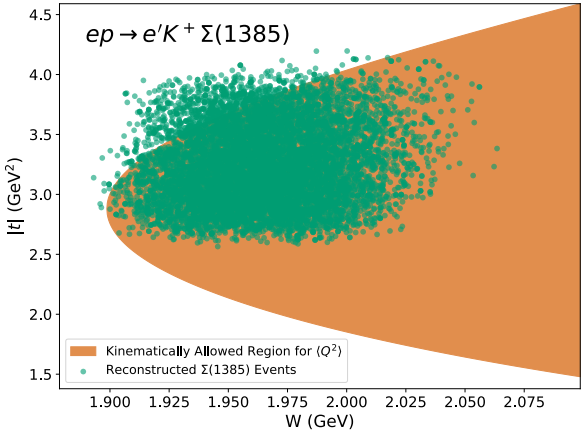
WE CAN DO *U*-CHANNEL!



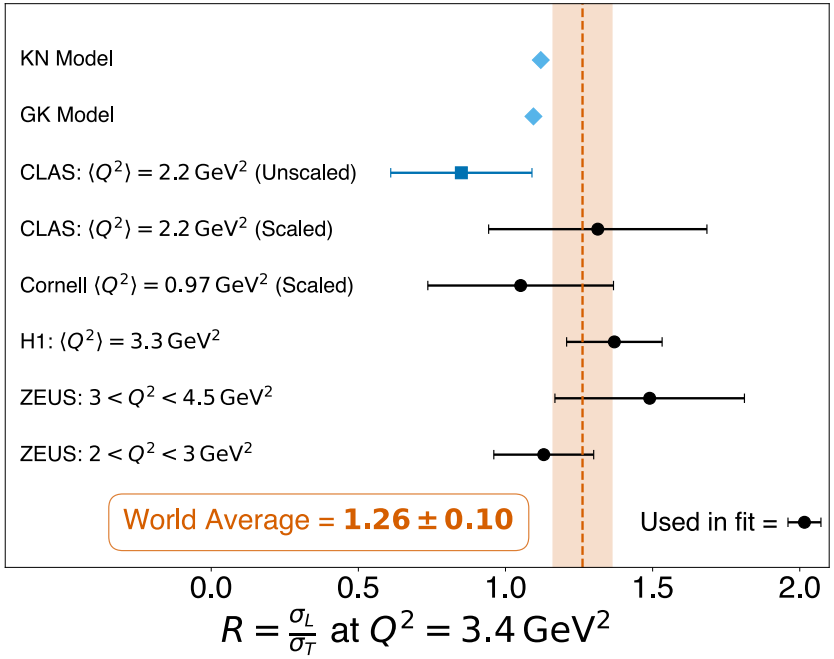
- Near-threshold, u-channel hyperon production is accessible **if K^+ can be efficiently ID'd**
- **Likely requires refurbishment of HMS aerogel**
- Note, PYTHIA6 resonance region cross sections are unreliable (especially in u-channel)
  - However, SIMC acceptance is correct, so these hyperons are well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



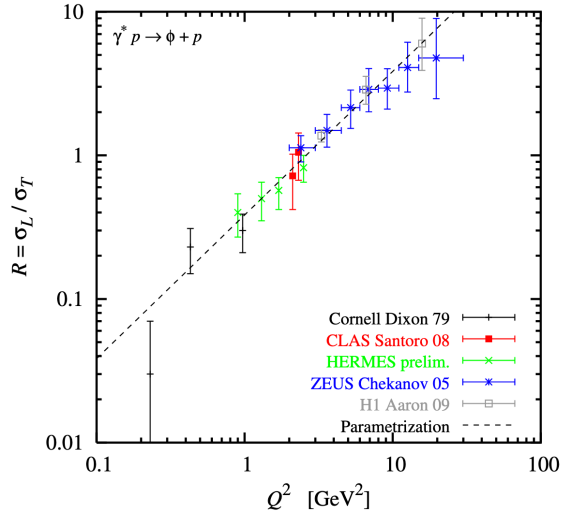




GETTING $d\sigma_L/d|t|$



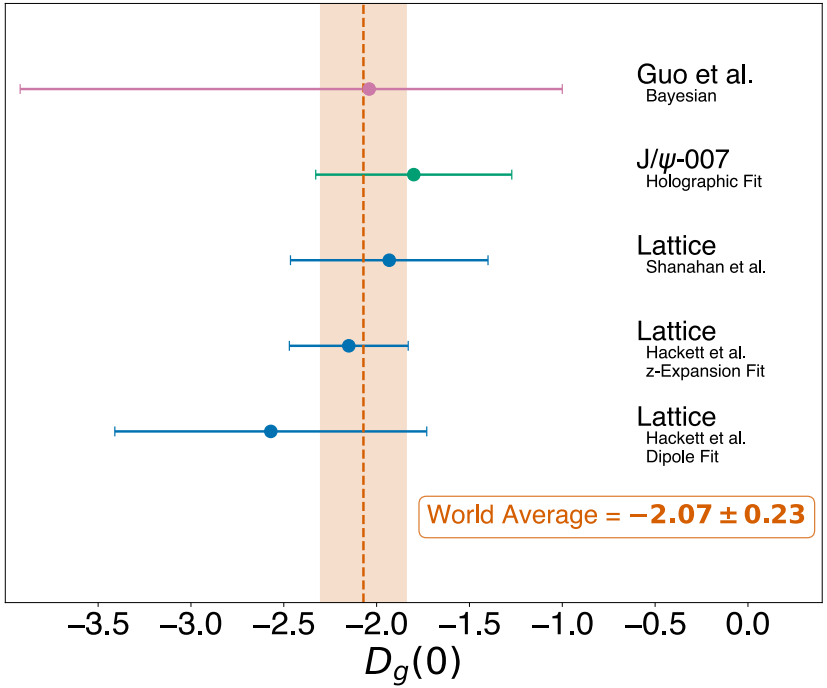
- With $d\sigma_e/d|t|$, need R to get $d\sigma_L/d|t|$
  - Fit the world data to get an idea (and uncertainty) on this quantity within our phase space ($Q^2 \sim 3.4$ GeV²)
- World data suggests $R(Q^2)$ **not** $R(Q^2, W, |t|)$



- Use CLAS12 parameterization to scale nearby world datapoints

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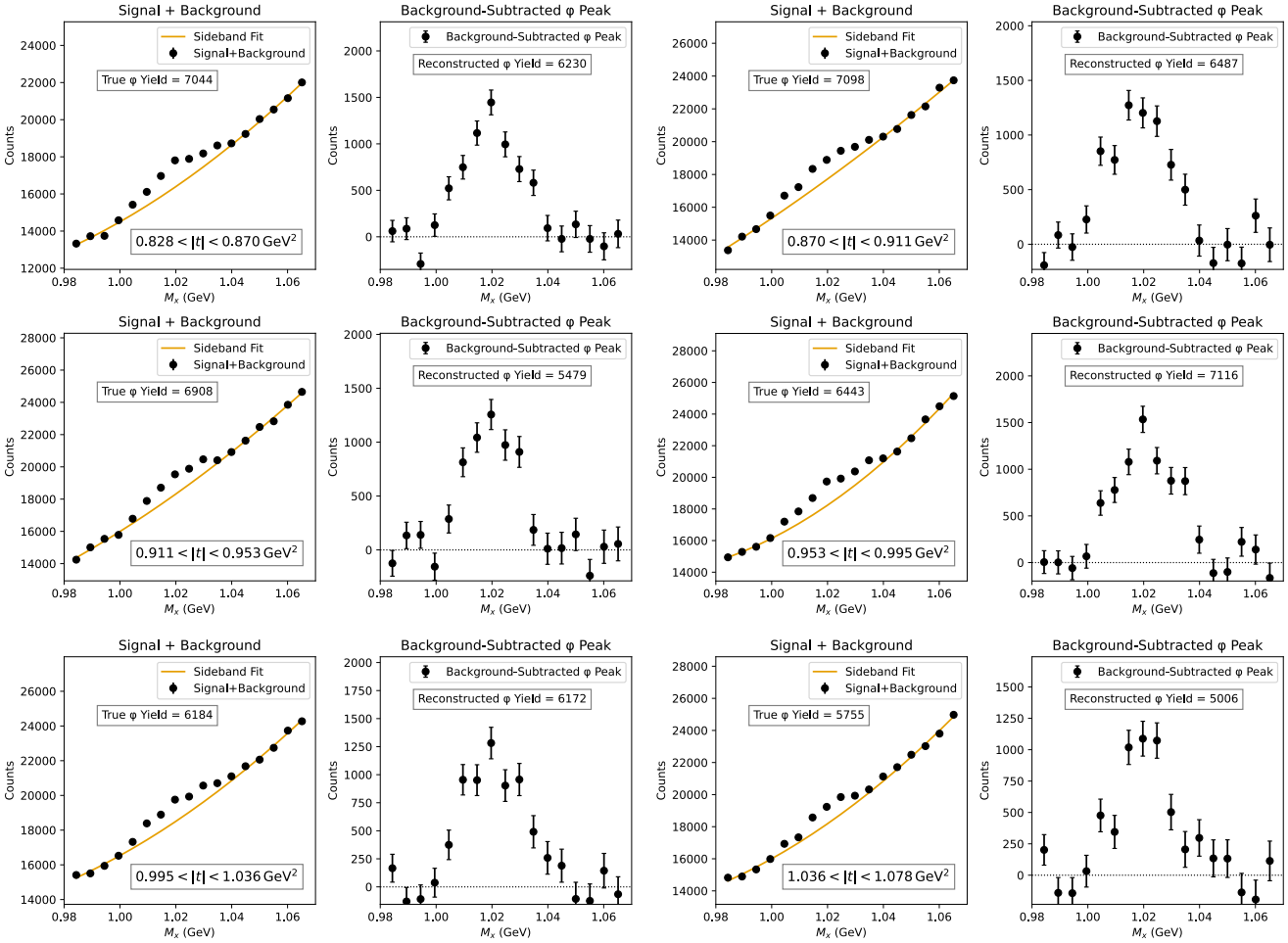
GETTING D_g



- 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!**

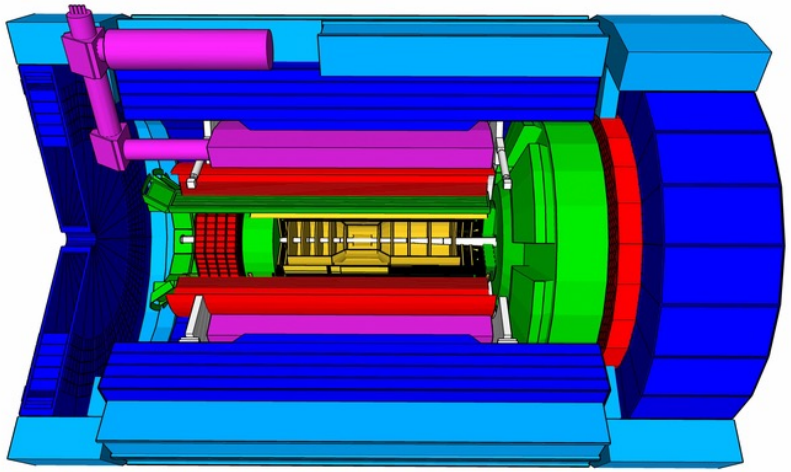
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WHAT ABOUT THE EIC?

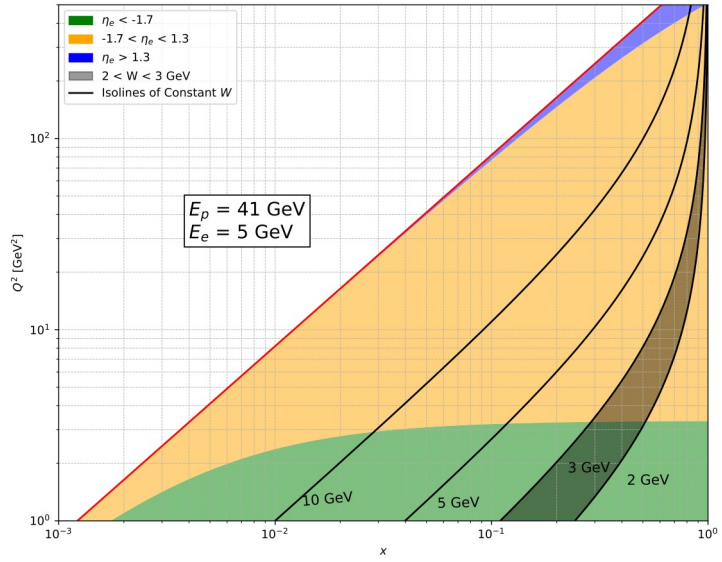
- **Large acceptance detector!**
  - Means ϕ decay products can be **measured directly**, fully exclusive
  - Use the dual-radiator RICH for PID of kaons at relatively small angles
  - **Background** can be **substantially reduced**

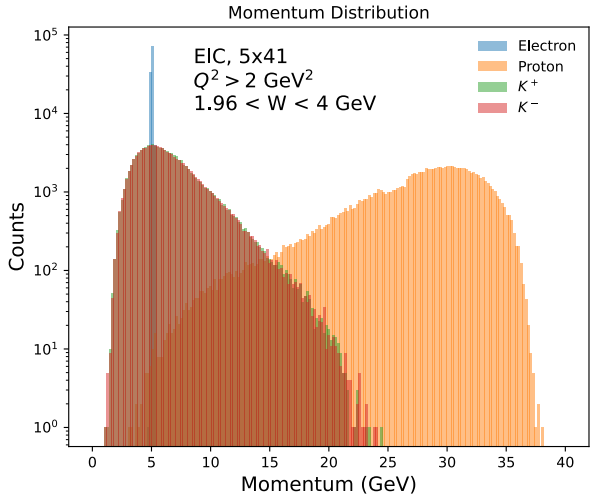


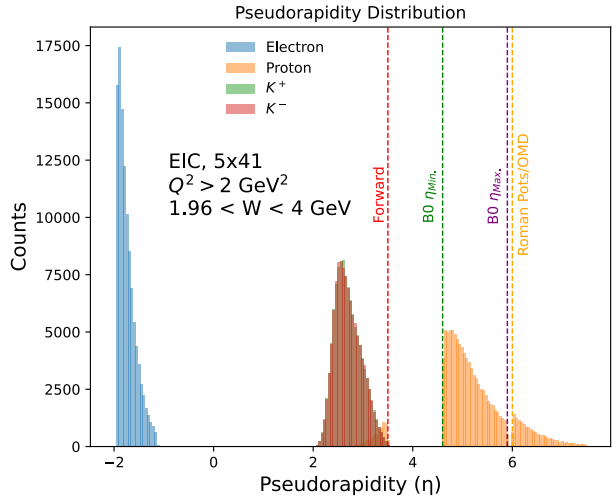
- How well can we do? Can we access $\boldsymbol{D_s}$ at the EIC?

PROJECTIONS

- 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!







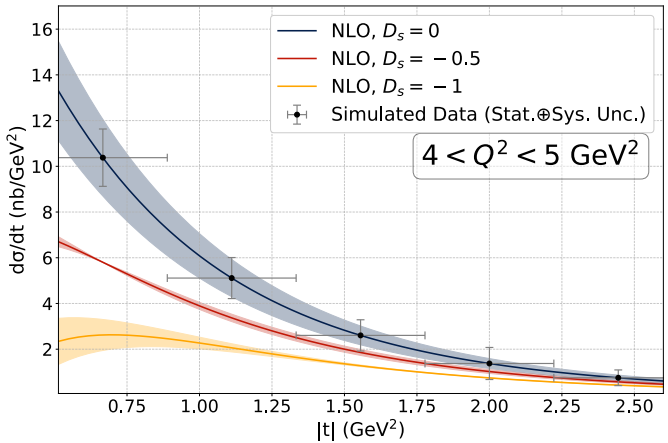
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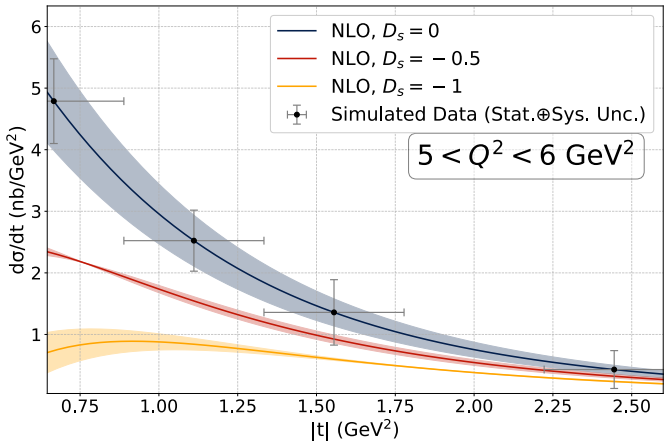
PROJECTIONS

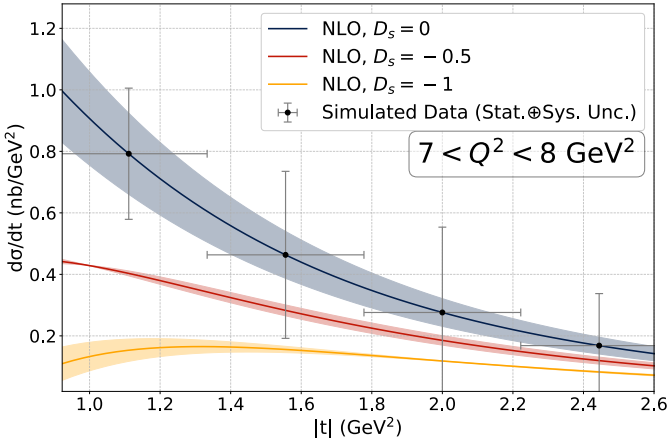
EIC 5x41 Projections for $\frac{d\sigma_L}{d|t|}$ at **2.4 < W < 2.8 GeV**

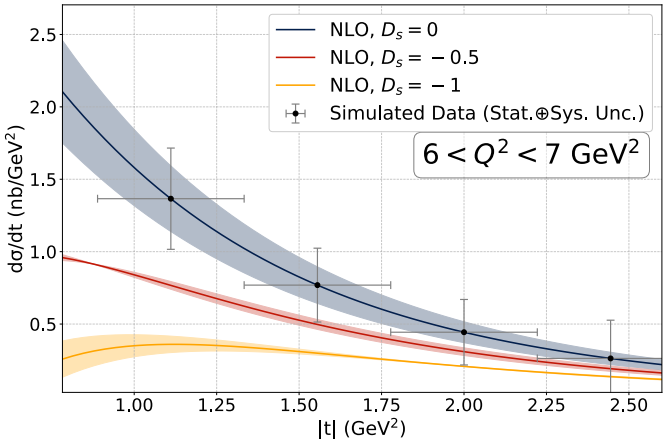
- Assume 10 fb^{-1} (5x41)
  - Two years (40 weeks) of running at the design luminosity
- Full exclusivity
  - e$^-$, K$^\pm$, p all measured in the detector

Limited by statistics & forward acceptance









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SOLID ANALYSIS STRATEGY

- How much information we need to reconstruct these exclusive ϕ events?

- Option 1: Fully exclusive reconstruction
  - Require $e + p + K^+ + K^-$ (or $e + p + h^+ + h^-$)

- Option 2: One missed particle
  - $e + p + K$ or $e + 2K$
  - Use missing mass to reconstruct the remaining particle
  - Resolution on M_x is not great

- Option 3: Full missing mass
  - Only reconstruct $e + p$
  - Background is overwhelming & resolution not good enough to pick out a ϕ peak

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Assume this technique for all that follows

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TRIGGER STRATEGY

- Cannot use J/ψ or TCS triggers
- $\mathrm{H}(e, e'p)$ channel isn't enough to reconstruct a ϕ on its own
  - Don't lose anything by requiring a triple coincidence in the trigger
- Trigger on electron at large angle + two charged hadrons at forward angles
  - Detected $e + p + K^+ + K^-$ rate from signal ϕ events is ~10 Hz
  - Large angle electron trigger threshold of 3 GeV
    - Going from 2.5 to 3 GeV reduces photon rate by a factor of 4.4 with respect to the J/ψ number of ~400 kHz

$$R_{\text{Trig.}} = \left(R_{\pi,FA} + R_{p,FA} + R_{\gamma,FA}\right) * \left(R_{\pi,FA} + R_{p,FA} + R_{\gamma,FA}\right) * T_{Window} * \left(R_{e,LA} + R_{\gamma,LA} + R_{h,LA}\right) * T_{Window}$$

Where R is the rate of triggers

Process	Rate Forward angle 11 GeV	Rate Large angle 11 GeV
single e^-	340 kHz	35.0 kHz
high energy photon	7.5 MHz	0.4 MHz
single π^+	11.0 MHz	0.25 MHz
single π^-	7 MHz	0.18 MHz
single proton	3.3 MHz	0.19 MHz

Table 2: Single rates for charged particles and high-energy photons detected at forward and large angles with an 11 GeV beam. The high energy photon cut-off is 0.7 (2.5) GeV at forward (large) angle.

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$R_{Trig.}$ = ~80 kHz

- Rate is high, should be reduced if we want to run in parallel with existing proposals
- Streaming RO? TOF in trigger? Track trigger?

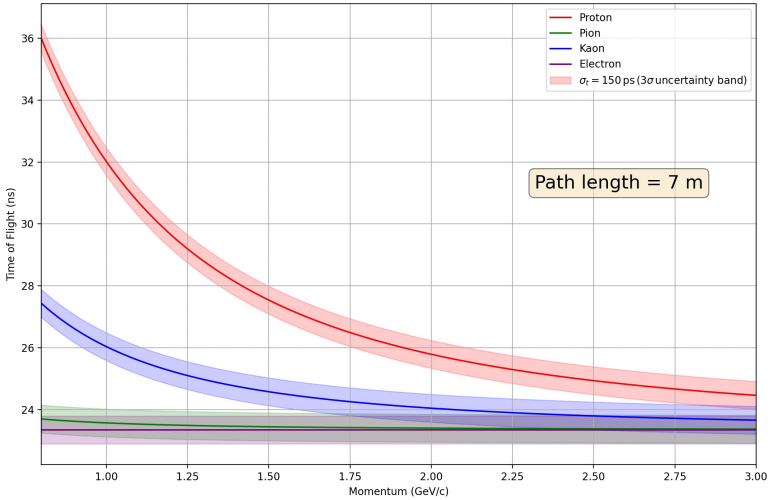
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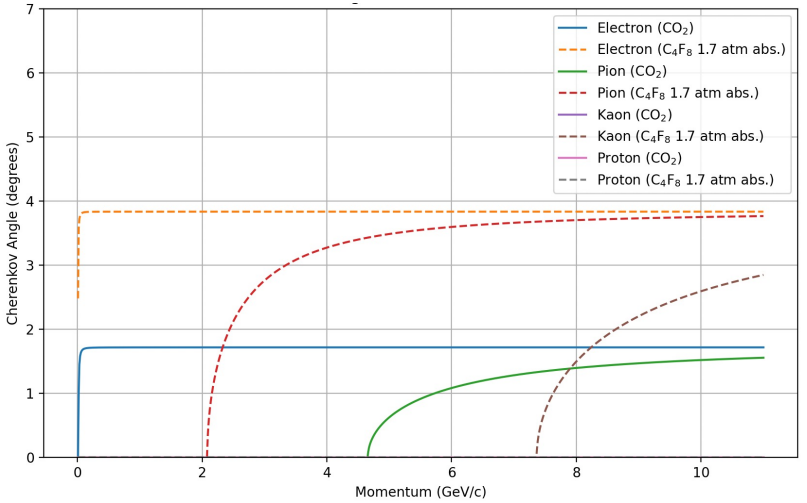
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PID

- Kaons from decay of ϕ should be PID'd to reduce background
- Range of $K^{+,-}$ momentum from ~1-4 GeV in forward detector
- HGC will provide π rejection above 2.5 GeV
- 150 ps TOF covers 3σ π/K up to ~2.5 GeV
  - MRPC would handle this better, reduce the reliance on HGC near its threshold
- Scattered proton is low momentum, typically 1-2 GeV
  - TOF should be able to handle it

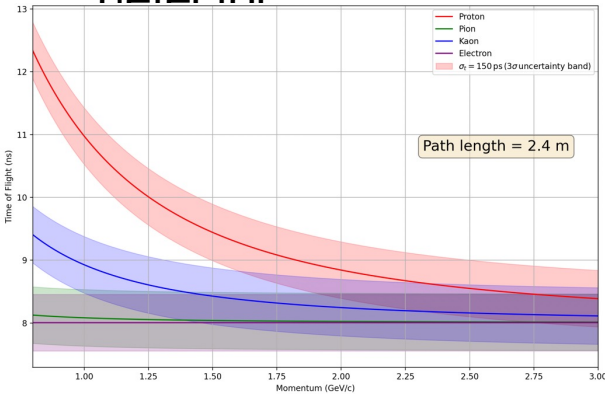


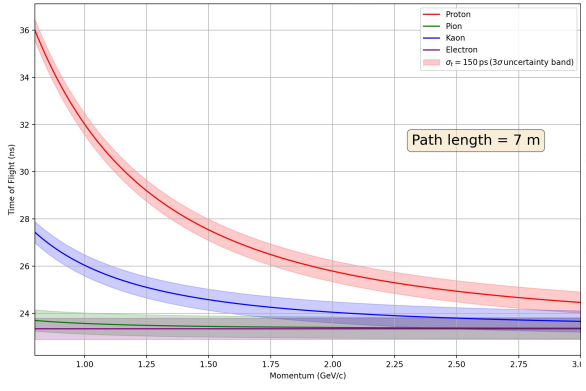


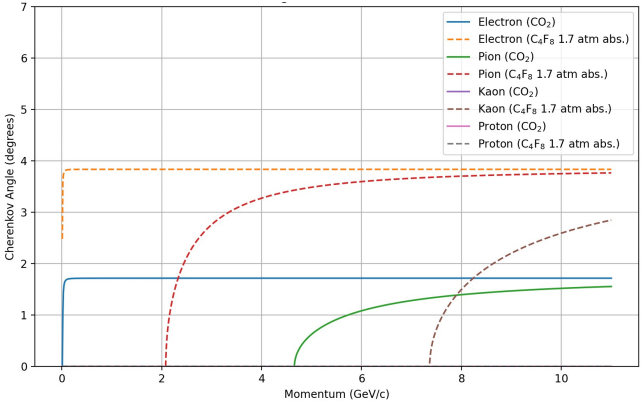
ANALYSIS STRATEGY

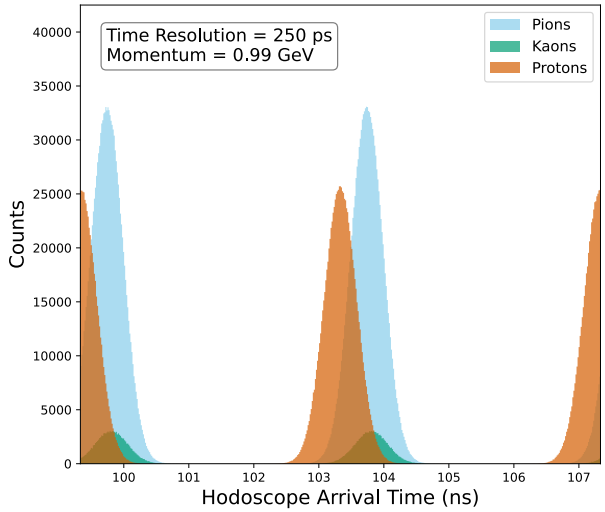
- Kaons:
  - — Forward detector has superior PID
    - Longer TOF baseline + Cherenkovs to reject fast pions
    - **MRPC would handle PID over whole momentum range**
    - SPD TOF could handle it up to where the HGC turns on
  - — Require kaons to be in forward detector

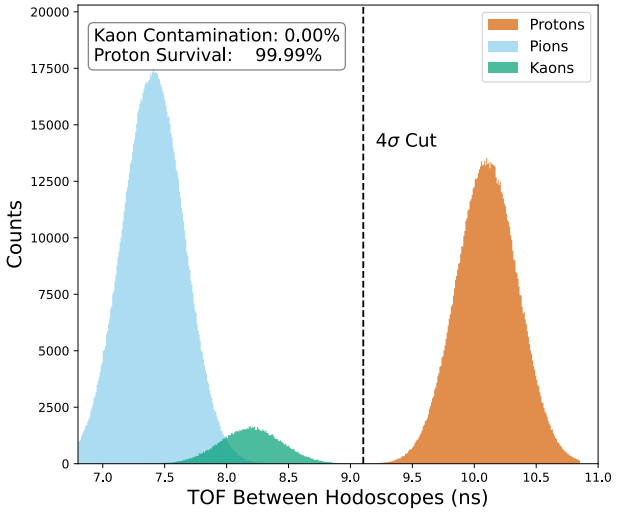
- Protons:
  - – Large-angle detector can PID protons up to ~ 2 GeV with SPD TOF
  - – Allow protons in forward or large angle detectors
- Electrons:
  - – Acceptance for fully exclusive reconstruction is best when electron is at large angle
  - – Require electron in large angle

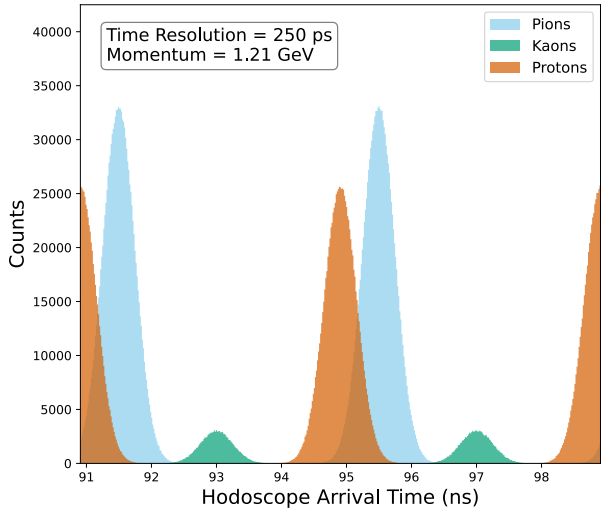


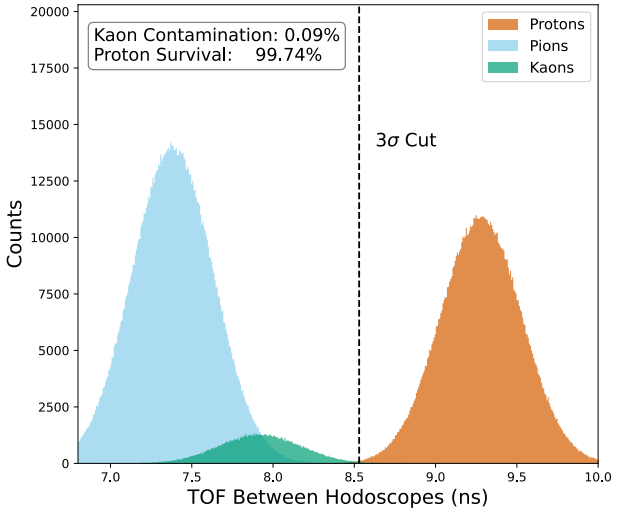












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