THE STRANGE MECHANICAL STRUCTURE OF THE PROTON

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We know that the proton mechanical structure is strange,

but how **STRANGE** is it?

MOTIVATION

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

$$\langle p', \vec{s}\,' | T_a^{\mu\nu} | p, \vec{s} \rangle = \overline{u}(p', \vec{s}\,') \Bigg[A_a(t) \frac{P^\mu P^\nu}{m_N} + D_a(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu}\Delta^2}{4m_N} + \bar{C}_a(t)\, m_N\, g^{\mu\nu} + J_a(t) \frac{P^{\{\mu} i\sigma^{\nu\}\lambda}\Delta_\lambda}{m_N} - S_a(t) \frac{P^{[\mu} i\sigma^{\nu]\lambda}\Delta_\lambda}{m_N} \Bigg] u(p, \vec{s}),$$

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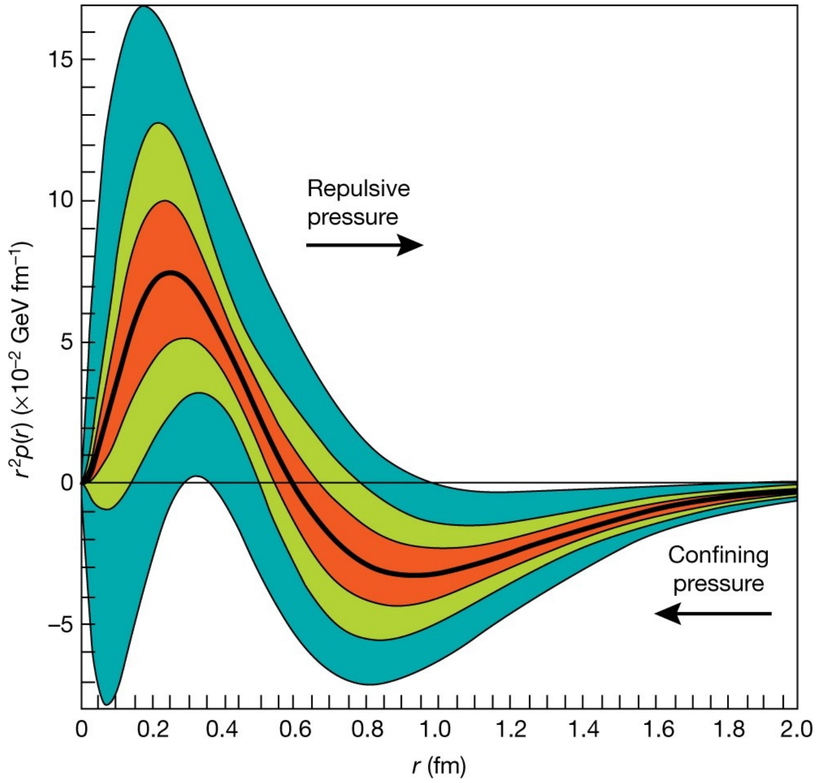
$$\left. + J_a(t)\,\frac{P^{\{\mu}i\sigma^{\nu\}\lambda}\Delta_\lambda}{m_N} - S_a(t)\,\frac{P^{[\mu}i\sigma^{\nu]\lambda}\Delta_\lambda}{m_N}\right]u(p, \vec{s}),$$

- D-term at zero momentum transfer represents a fundamental property of the proton, on par with charge, spin, and mass.

MOTIVATION

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

*only defined for the total D-term, not individual partonic components



HOW DO WE MEASURE IT?

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

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

- Different processes provide insights into the various partonic D-terms
- Only know total D-term once all the partonic components are known!

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

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

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

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

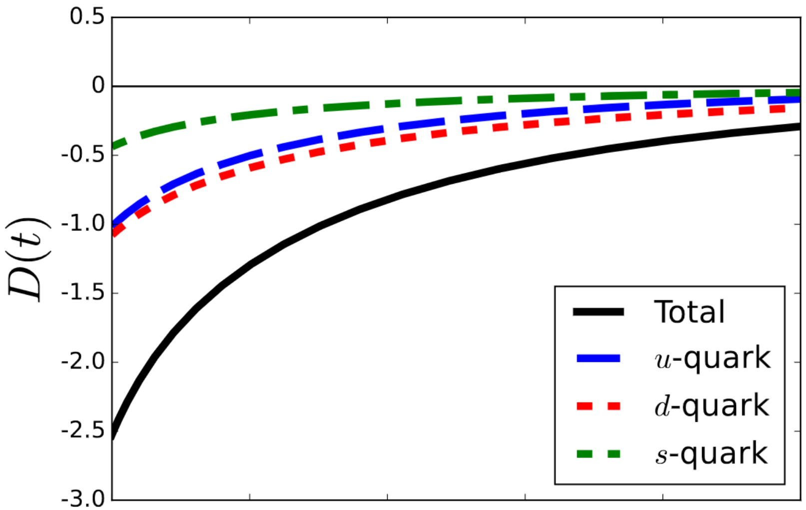
$$D(0) = D_g(0) + D_u(0) + D_d(0) + \underbrace{D_s(0)} + \ldots.$$

Strange quarks: Accessible via ?

WHO CARES ABOUT D_S?

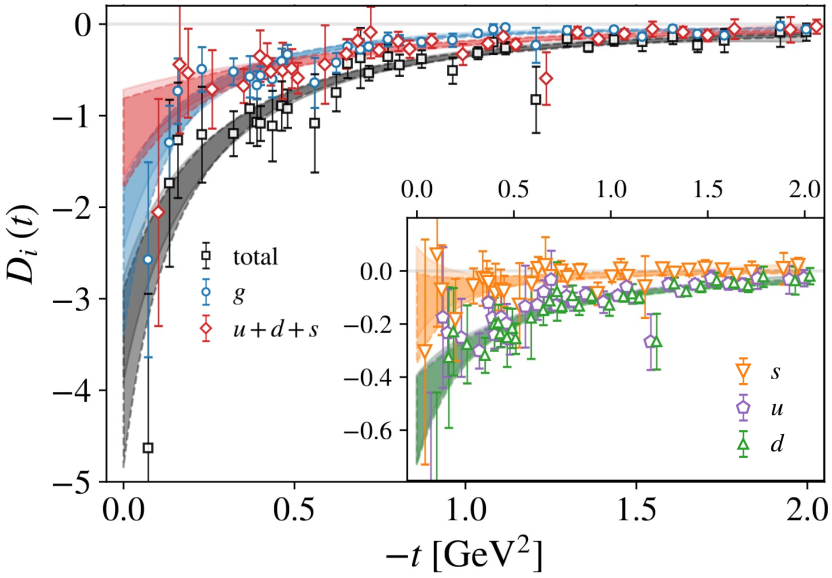
- At first glance, D_s should be small
- However, large-N_c predicts that the D-term is ”flavor-blind”, i.e. $D_u \sim D_d$ despite their different number densities
  - $D_u \sim D_d$ is supported by lattice results
- Extending this argument, could $D_u \sim D_d \sim D_s$?
- Calculation by Won et al. in the χQSM suggests that $D_u \sim D_d \sim 2D_s$

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



WHO CARES ABOUT D_S?

- On the other hand, the lattice results by Hackett et al. show that D_s is consistent with zero
- Uncertainties are still large, but the results do not exclude *positive* values of D_s
- $D_s > 0$ suggests the intriguing possibility that strange quarks exert forces in opposite direction to up & down quarks!

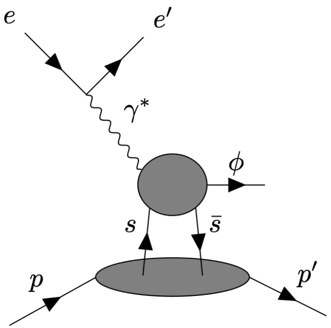


	Dipole	z-expansion
	D_i	D_i
u	−0.56(17)	−0.56(17)
d	−0.57(17)	−0.56(17)
s	−0.18(17)	−0.08(17)
$u+d+s$	−1.30(49)	−1.20(48)
g	−2.57(84)	−2.15(32)
Total	−3.87(97)	−3.35(58)

ACCESSING THE STRANGENESS D-TERM

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

- Recently, Hatta & Strikman proposed that *near-threshold electroproduction of ϕ mesons* could provide sensitivity to the strangeness D-term
  - Utilized a novel OPE framework that applies in the near-threshold region (unlike the collinear framework)



ArXiv:2102.12631

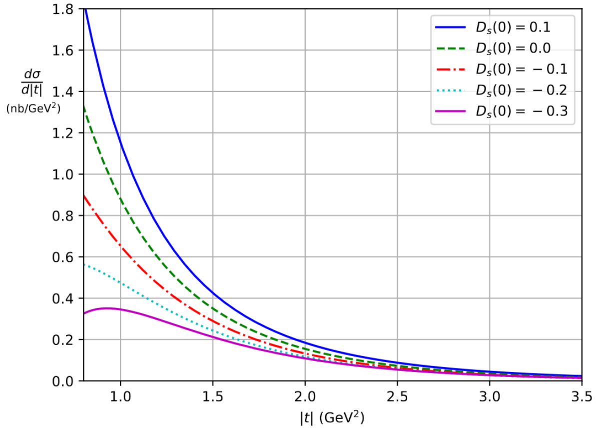
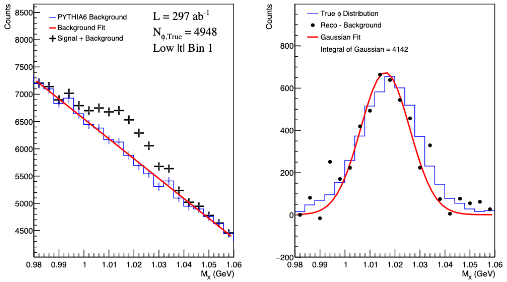


Figure 2: Theoretical predictions for $d\sigma/d|t|$ at $Q^2 = 3.4$ GeV^2 and $W = 2.2$ GeV with different assumptions for $D_s(0)$. In this kinematic range $t_{\min} \approx 0.7$ GeV^2. It can be seen that the introduction of a non-zero $D_s(0)$ has a large impact on the shape and size of the cross section.

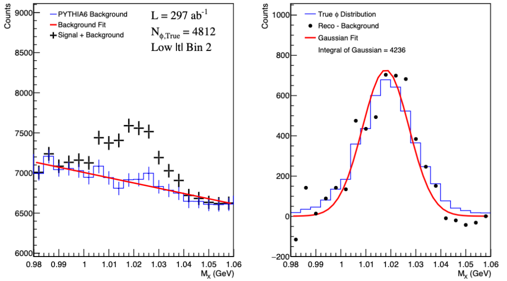
This is the only known process to access this potentially important piece of the sum rule!

HALL C LOI

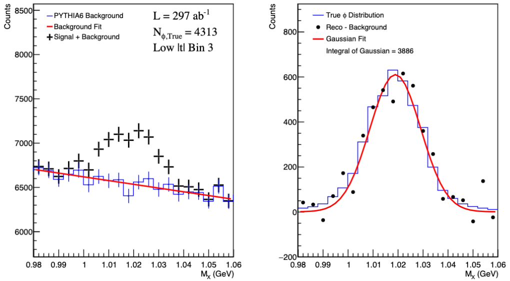
- To this end, we put a letter of intent to perform a measurement of exclusive ϕ production at Q^2 ~ 3.5 GeV^2 and W ~ 2.2 GeV^2
  - Cross section so near to the threshold is very small, need high luminosity!
- Reconstruct ϕ in the missing mass spectrum of H(e,e′p) reaction
- Use the excellent resolution of the Hall C spectrometers to pick out the ϕ peak above a large physics background
  - Background is irreducible unless additional particles can be detected
  - ~30 PAC days required to achieve reasonable precision on ϕ yield in multiple |t| bins



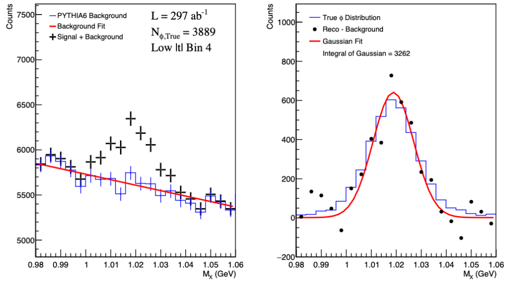
(a) $0.828 < |t| < 0.8905$ GeV^2



(b) $0.8905 < |t| < 0.953$ GeV^2



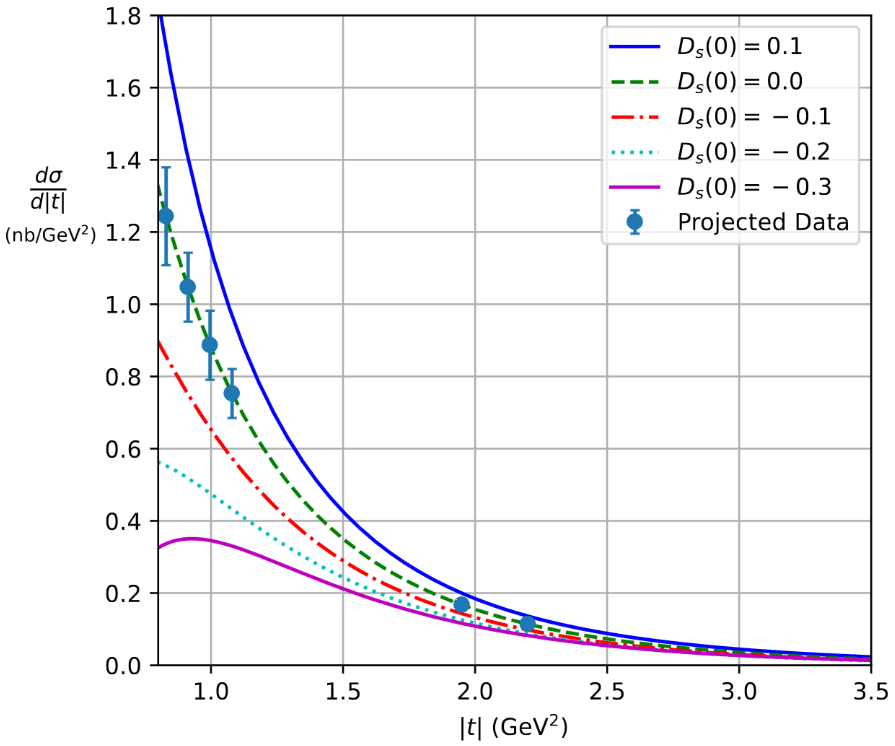
(c) $0.953 < |t| < 1.0155$ GeV^2

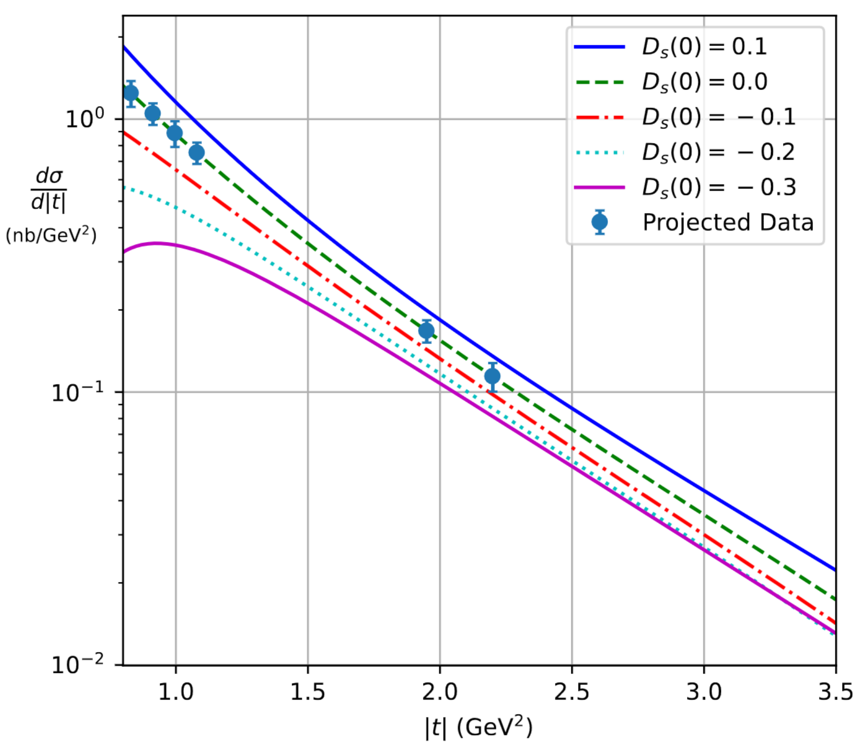


(d) $1.0155 < |t| < 1.078$ GeV^2

- Estimated cross section uncertainty per point is ~10%
- Largest uncertainty from background subtraction

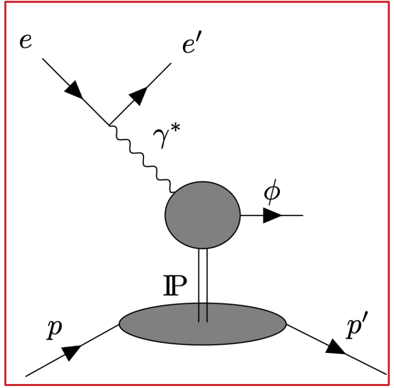
Projected results show good sensitivity to D_s, on par with the lattice precision!



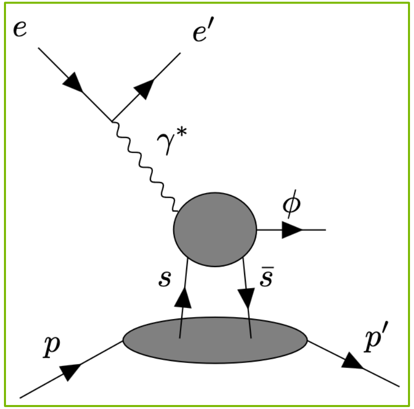


REALITY CHECK

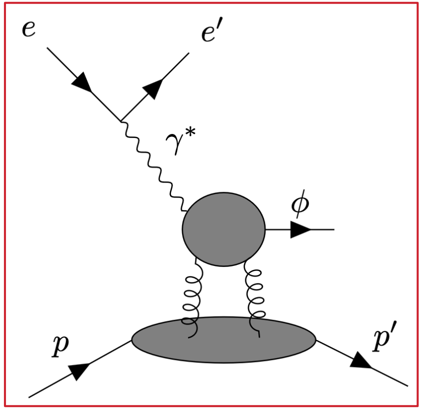
- The reality is (as always) that it’s not so simple!
- Other physics processes can contribute to ϕ electroproduction
  - This will dilute the sensitivity to the D-term
- **Needs more phenomenological input before we can really claim an extraction of D_s**
  - E.g. calculation of gluon exchange contribution within the same framework
- Additional caveats:
  - Calculation wants $Q^2 \gg |t|$
    - For $|t|$ ~ 1 GeV^2 is Q^2 ~ 3.5 GeV^2 high enough?
  - Non-linear behavior observed in the photoproduction cross section for $W < 2.4$ GeV, resonances?



Pomeron exchange (insensitive to D_s)



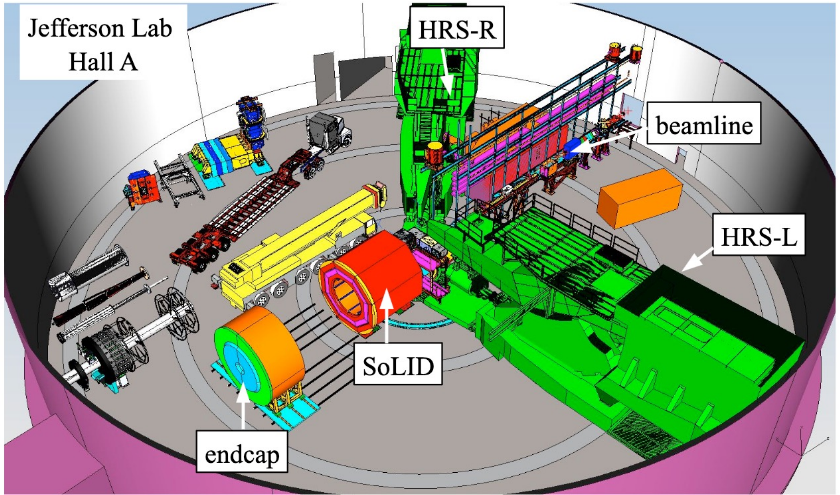
Strange exchange (sensitive to D_s)

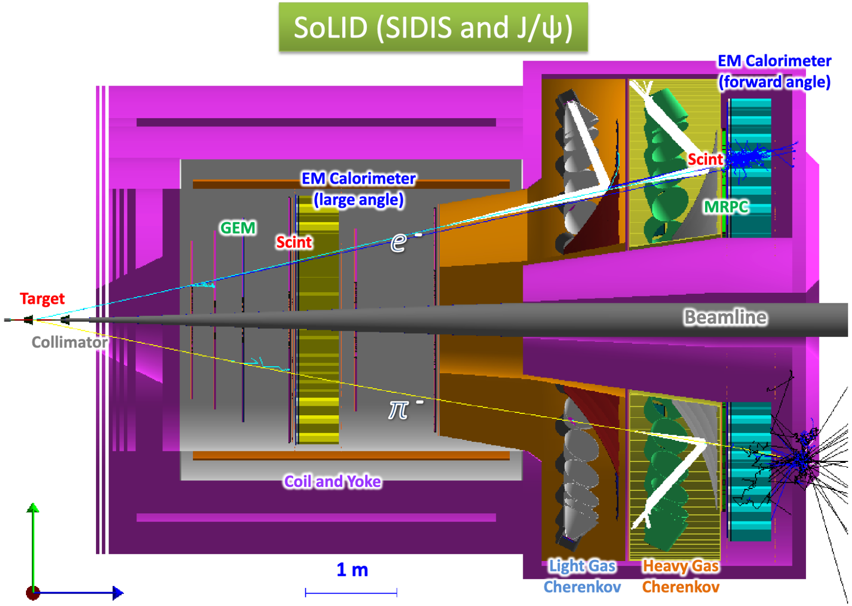


Two gluon exchange (insensitive to D_s)

NEXT STEPS: SOLID

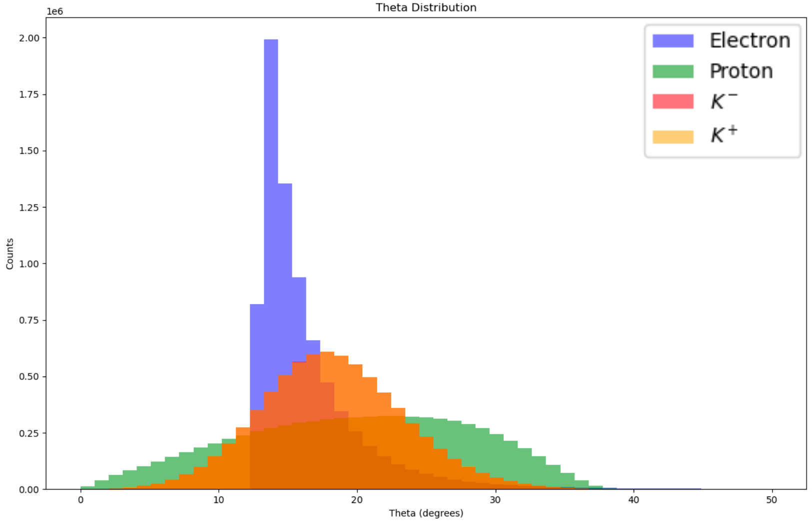
- Explore SoLID's capabilities to measure exclusive ϕ at higher Q^2
- Large acceptance
  - Means ϕ decay products can be measured directly
  - Background can be substantially reduced
  - More statistics & continuous kinematic coverage for multidimensional measurement

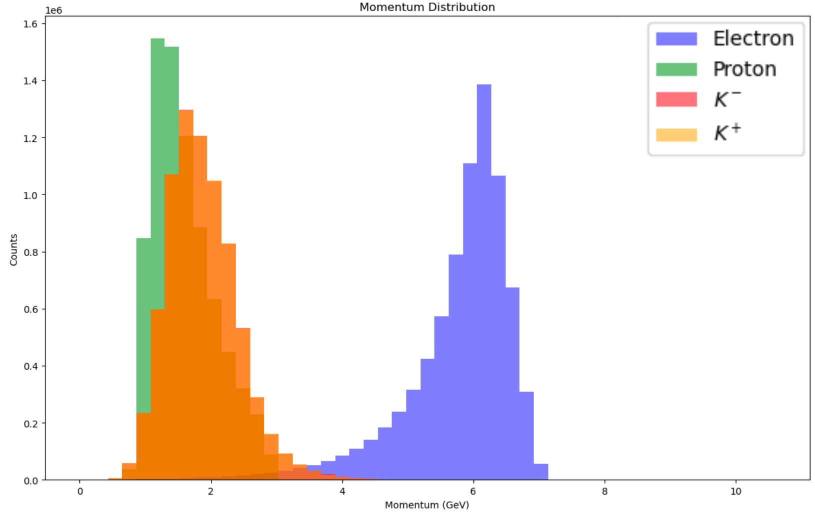




PARTICLE DISTRIBUTIONS

- Generated Kinematics:
  - $1.96 < W < 2.4$ GeV
  - $Q^2 > 3.5$ GeV^2
  - $|t| < 4$ GeV^2
- The most important region is low-t, where the proton momenta are low
- ϕ takes most of the momentum of the virtual photon
  - Produced roughly back-to-back to the scattered electron





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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$R_{\text{Trig.}}$ = ~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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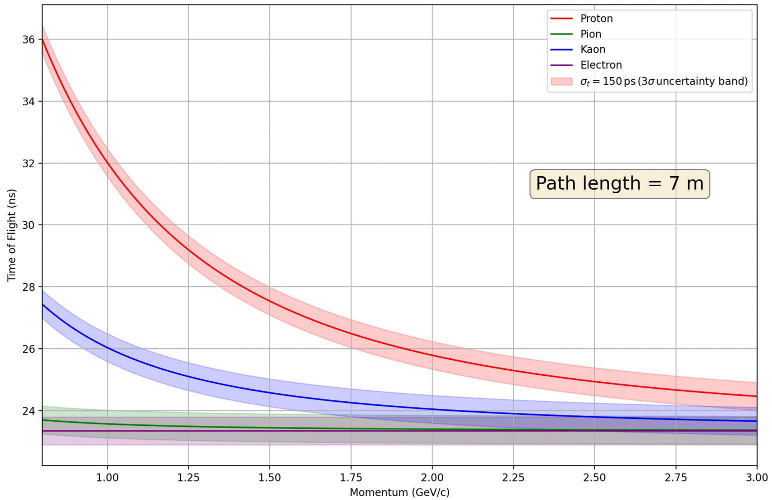
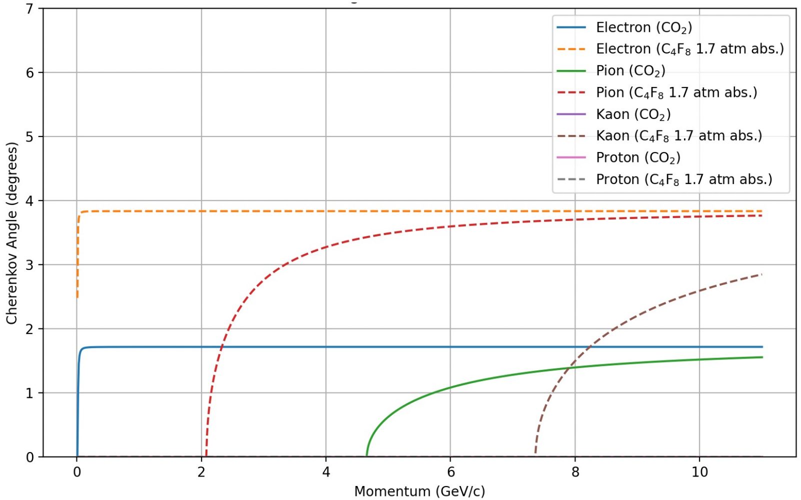
PID

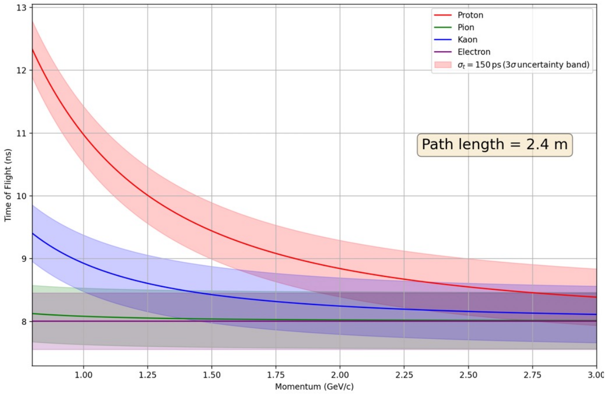
- Kaons from decay of ϕ should be PID'd to reduce background
- Range of $K^{+,-}$ momentum from ~1-4 GeV in forward detector
- HGC will provide π rejection above 2.5 GeV
- 150 ps TOF covers 3σ π/K up to ~2.5 GeV
  - MRPC would handle this better, reduce the reliance on HGC near its threshold
- Scattered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

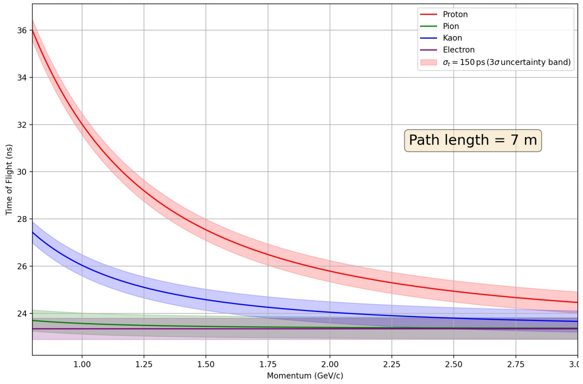


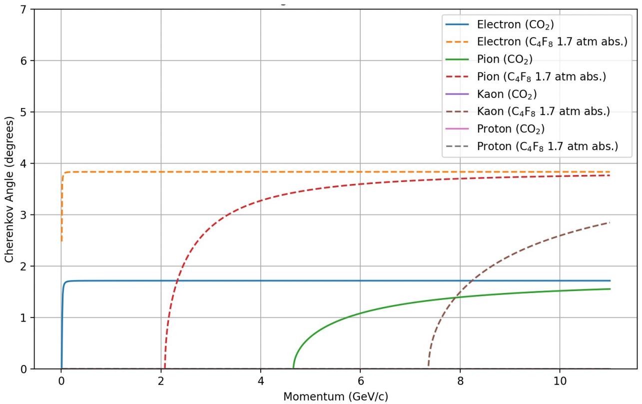


ANALYSIS STRATEGY

- 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



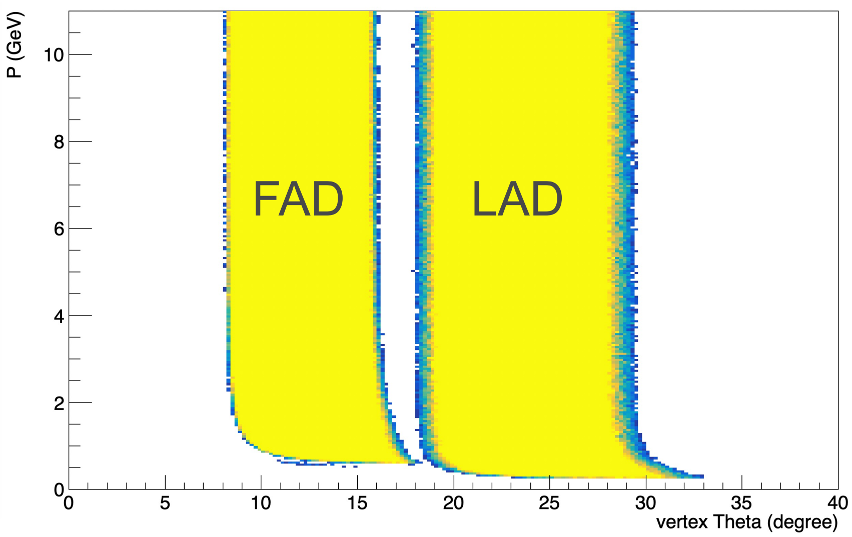




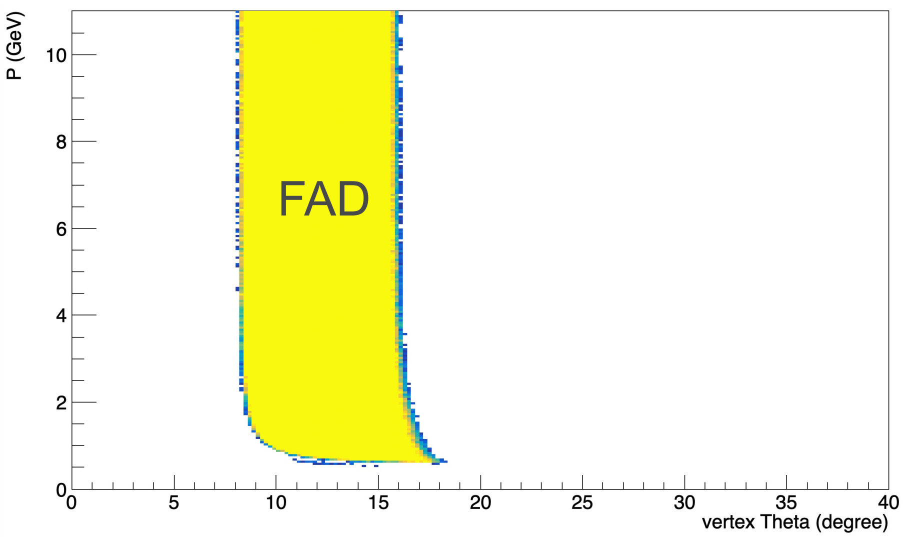
ACCEPTANCES & MOMENTUM SMEARING

- Utilize an approximate acceptance map for J/ψ setup
  - Scaled by a factor of 0.9 for projections
- Assume a 2% resolution on reconstructed momentum
- Ideally would use full detector simulation including PID

Protons + electrons



Kaons



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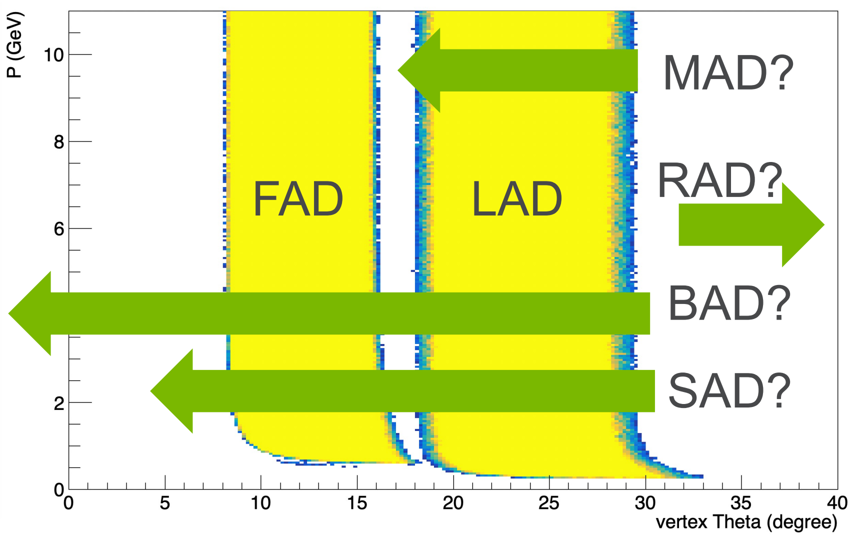

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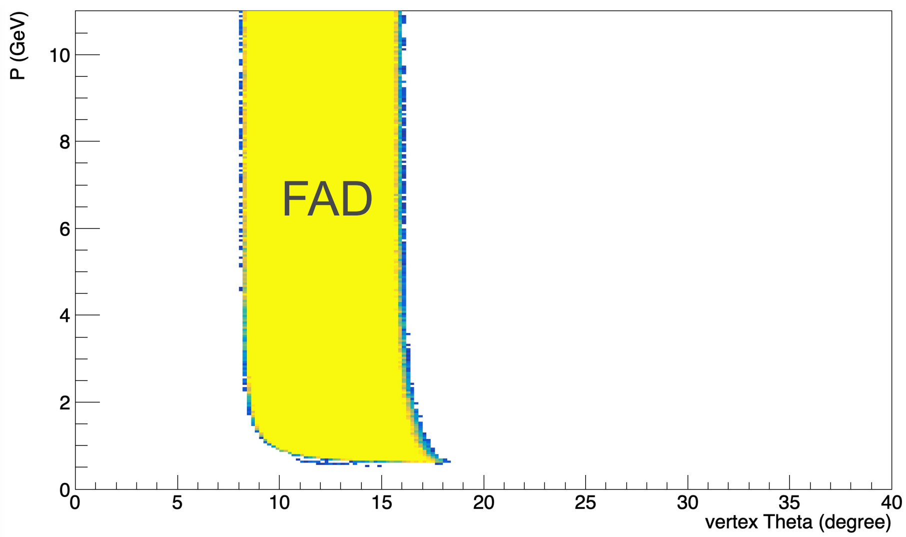
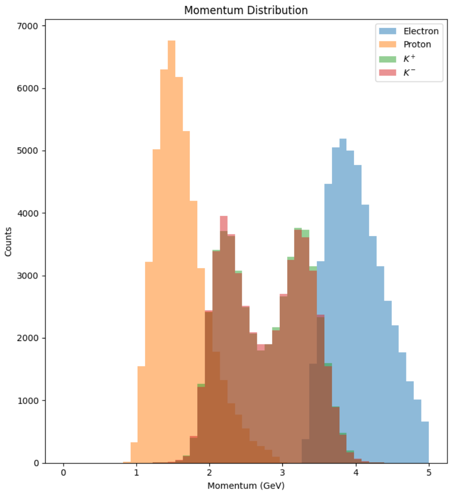
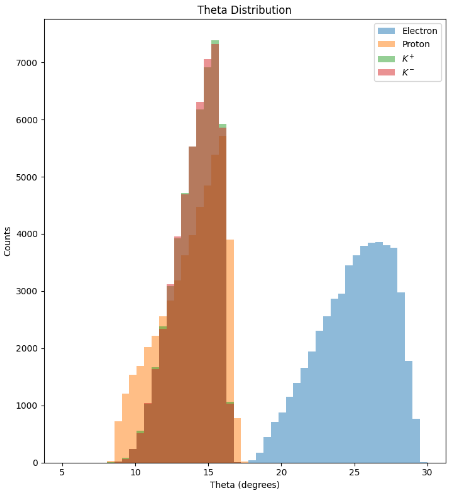


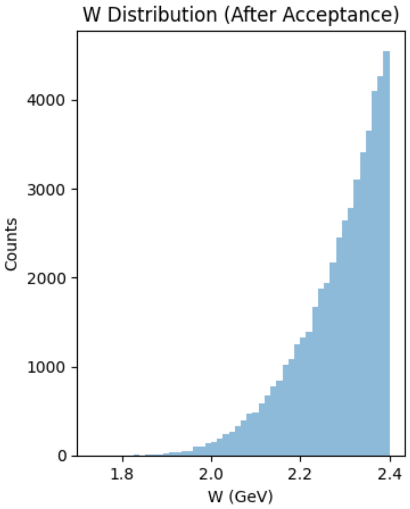
RECONSTRUCTED QUANTITIES

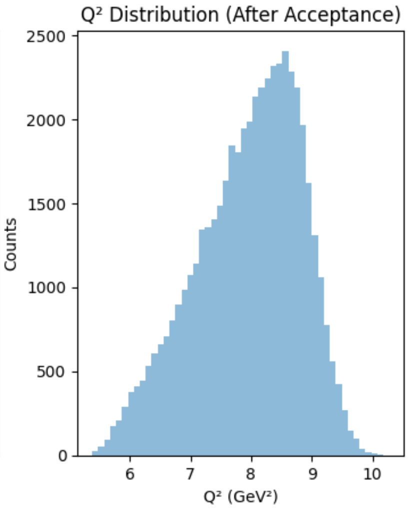
- 50 days at 10^{37} cm^{-2}/s
- Kinematics strongly constrained by requirement of being near-threshold
- Highest statistics at quite high Q^2
  – Ideal for comparison to OPE predictions!

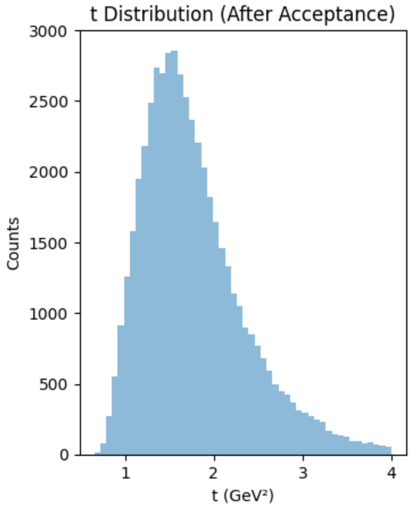




Sufficient statistics to measure multi-differentially in W, Q^2!



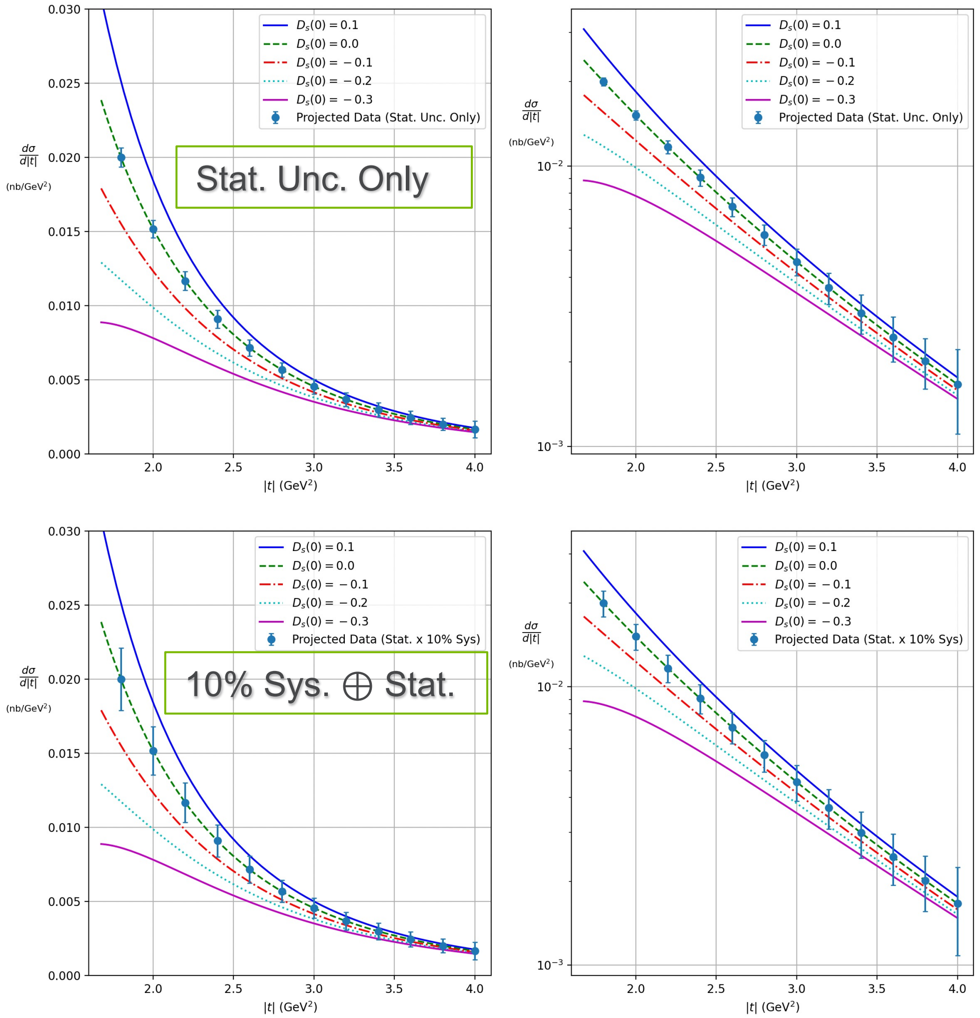




PROJECTIONS

- First look at some projections
  - Assume 50 days at 10^{37} cm^{-2}/s
  - ~43 ab^{-1}
  - Events generated according to CLAS12 model
  - $8 < Q^2 < 9$ GeV^2 (2-3x Hall C)
  - $2.2 < W < 2.4$ GeV
  - **This is only one bin of many!**

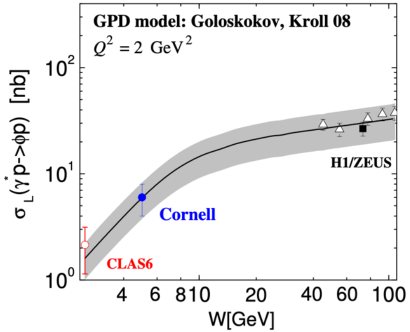
- Pessimistic assumption of 10% uncertainty in quadrature with statistical uncertainties
  - Even in the pessimistic scenario, exhibits good sensitivity to D_s!

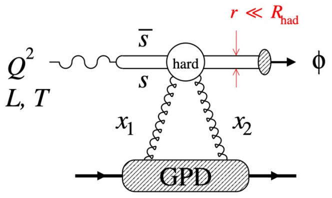


BEYOND D_S

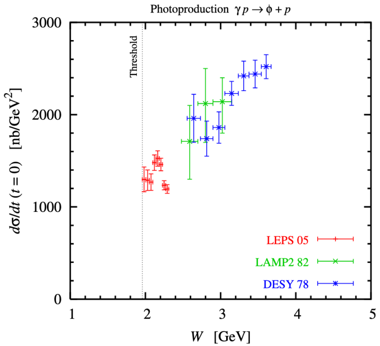
Proposal to Jefferson Lab PAC39
Exclusive Phi Meson Electroproduction with CLAS12

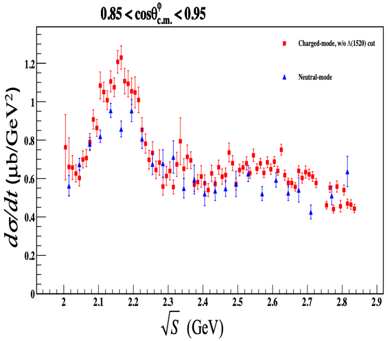
- To leading order, exclusive ϕ @ SoLID can access the same physics as ϕ @ CLAS12
- At large W the exclusive ϕ process is proposed to be sensitive to the gluon GPD at high-x
  - Much larger cross section
  - High precision attainable





- Investigate the non-monotonic behavior observed in ϕ photoproduction
  - Study how it evolves into the electroproduction regime
  - Needs continuous acceptance in W provided by SoLID

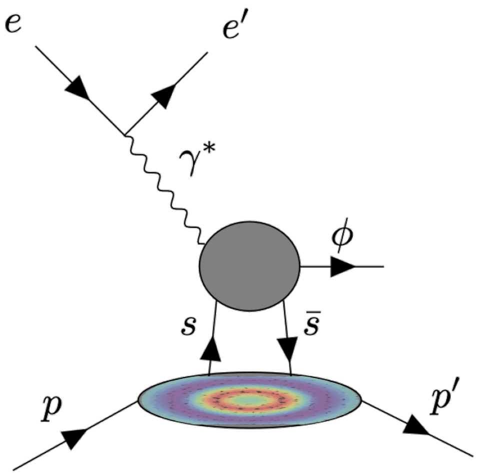


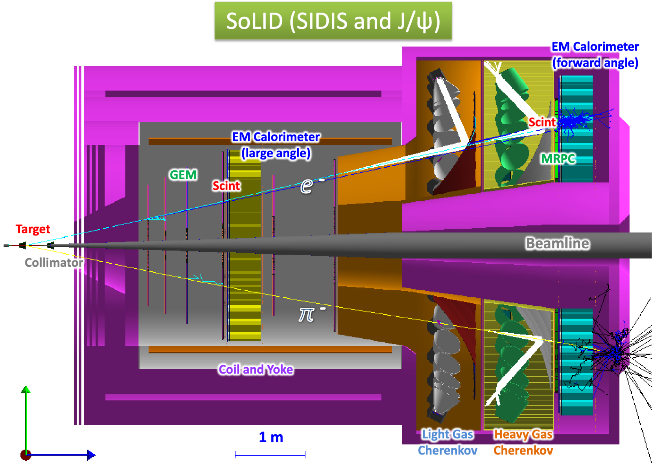


CONCLUSION

- If we ever want a complete experimental measurement of the total D-term of the proton, will need to measure the strangeness D-term
  - More theoretical & phenomenological input is needed!

- SoLID provides a unique opportunity to measure near-threshold exclusive ϕ electroproduction, the only known process sensitive to D_s
  - **Only SoLID** will have the luminosity & acceptance to perform a percent-level measurement of this cross section in the foreseeable future





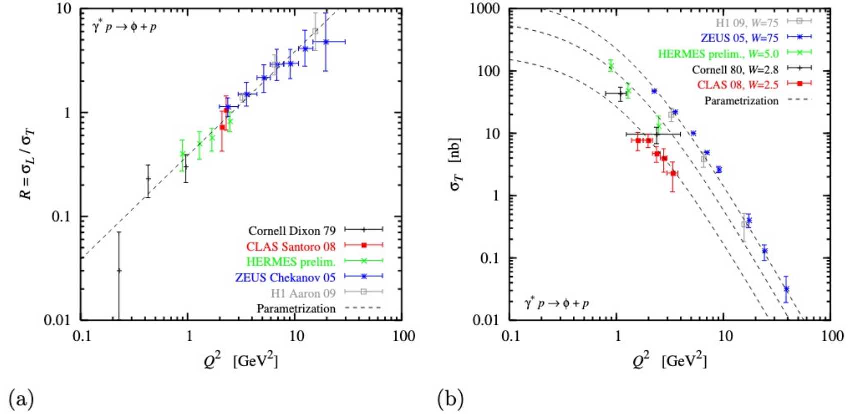
BACKUP

CROSS SECTION MODEL

- Utilize the parameterization of world data developed for CLAS12 exclusive ϕ proposal to PAC39

- Events generated according to these parameterizations using the lAger event generator

- t-dependence parameterized as a dipole



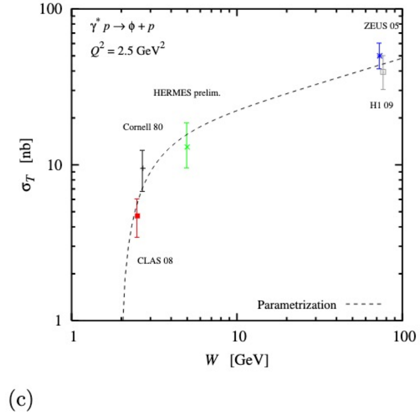


FIG. 12: (a) Ratio $R = \sigma_L/\sigma_T$ as function of Q^2, combining measurements at different W. (b) Transverse cross section σ_T as function of Q^2, for measurements at different W. (c) Transverse cross section σ_T as function of W, at $Q^2 = 2.5\,\mathrm{GeV}^2$. The curves represents the parametrization of Eqs. (41)–(50).

CROSS SECTION MODEL

The differential cross section is given by the general expression

$$\frac{d\sigma_{L,T}}{dt} = \frac{\sigma_{L,T}\,F(t)}{F_{\text{int}}} \quad (51)$$

$$F(0) = 1, \quad (52)$$

$$F_{\text{int}} \equiv \int_{t_{\max}}^{t_{\min}} dt\,F(t), \quad (53)$$

where different physical models are considered for the function $F(t)$ implementing the t–dependence.

1. Exponential t–dependence

$$F(t) = e^{Bt} \quad (54)$$

$$F_{\text{int}} = e^{Bt_{\min}}/B \quad (55)$$

The exponential slope B is parametrized as a function of W:

$$B(W) = B_0 + 4\alpha' \ln \frac{W}{\text{GeV}} \quad (56)$$

$$B_0 = 2.2\,\text{GeV}^{-2}, \quad (57)$$

$$\alpha' = 0.24. \quad (58)$$

2. Power–like t–dependence (dipole at amplitude level):

$$F(t) = \frac{m_g^8}{(m_g^2 - t)^4} \quad (59)$$

$$F_{\text{int}} = \frac{m_g^8}{3(m_g^2 - t_{\min})^3} \quad (60)$$

The mass parameter at $W \sim$ few GeV is chosen as

$$m_g^2 = 1.0\,\text{GeV}^2. \quad (61)$$

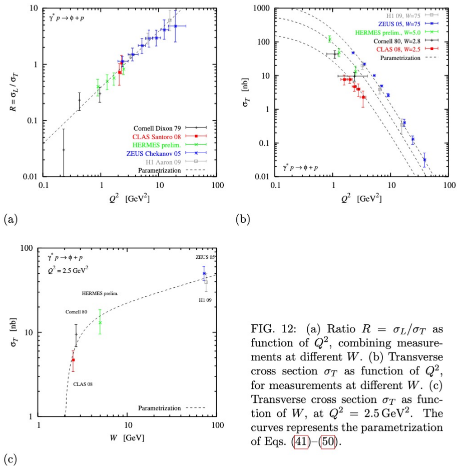


FIG. 12: (a) Ratio $R = \sigma_L/\sigma_T$ as function of Q^2, combining measurements at different W. (b) Transverse cross section σ_T as function of Q^2, for measurements at different W. (c) Transverse cross section σ_T as function of W, at $Q^2 = 2.5\,\text{GeV}^2$. The curves represents the parametrization of Eqs. (41)–(50).

The parametrization was cosntricted by fitting data on the transverse cross section $\sigma_T(W,Q^2)$ and the ratio $R = \sigma_L(W,Q^2)/\sigma_T(W,Q^2)$; the differential cross sections and their t–dependence were then parametrized according to different physical models for the t–dependence (exponential, dipole) [50]. The transverse cross section is parametrized as

$$\sigma_T(W,Q^2) = \frac{c_T(W)}{(1+Q^2/m_\phi^2)^{\nu_T}}, \quad (41)$$

$$\nu_T = 3.0 \quad (\text{independent of } W) \quad (42)$$

$$c_T(W) = \alpha_1 \left(1 - \frac{W_{\text{th}}^2}{W^2}\right)^{\alpha_2} \left(\frac{W}{\text{GeV}}\right)^{\alpha_3} \text{nb} \quad (43)$$

$$W_{\text{th}} = m_N + m_\phi = 1.96\,\text{GeV} \quad (44)$$

$$\alpha_1 = 400, \quad (45)$$

$$\alpha_2 = 1.0, \quad (46)$$

$$\alpha_3 = 0.32. \quad (47)$$

The longitudinal cross section is parametrized as

$$\sigma_L(W,Q^2) = R(W,Q^2)\,\sigma_T(W,Q^2) \quad (48)$$

$$R(W,Q^2) = \frac{c_R Q^2}{m_\phi^2}, \quad (49)$$

$$c_R = 0.4 \quad (\text{independent of } W) \quad (50)$$