THE MECHANICAL STRUCTURE OF THE PROTON AT SOLID

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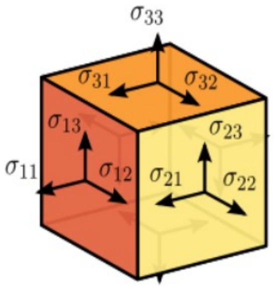
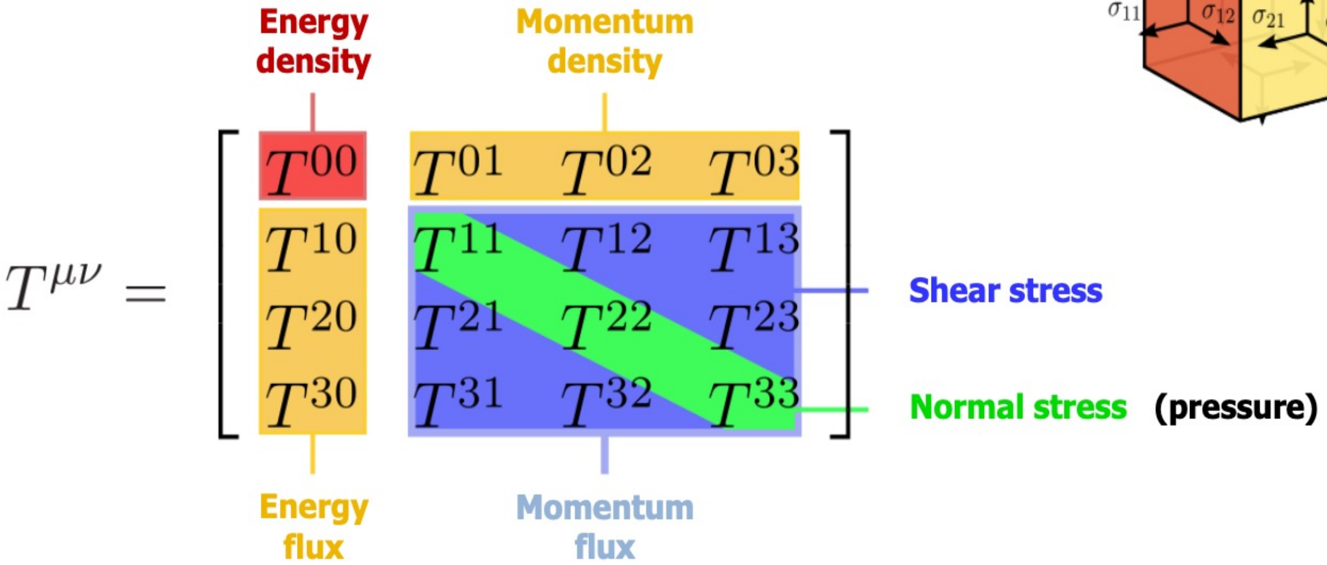
PROTON MECHANICAL STRUCTURE

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





GRAVITATIONAL FORM FACTORS

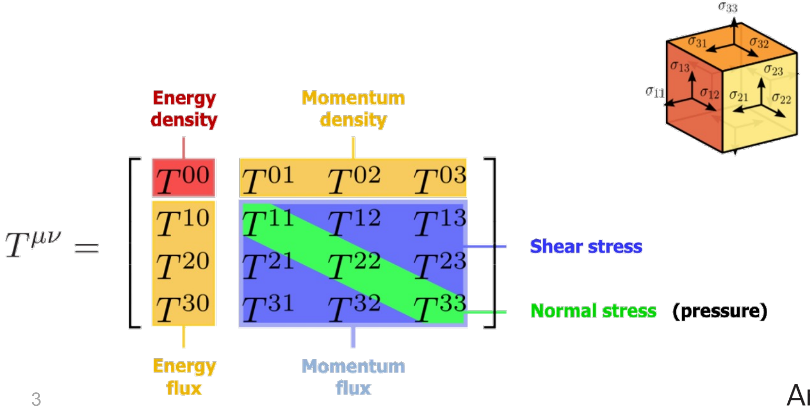
- Proton gravitational form factors (GFFs) encode information about the matrix elements of the QCD energy-momentum tensor

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

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

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

EMT Matrix Elements



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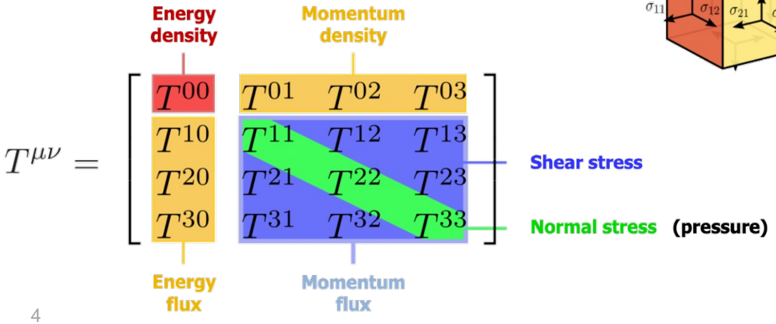
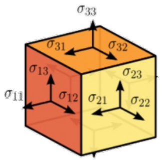
Form factors

Fourier transforms of spatial distributions





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Form factors

Fourier transforms of spatial distributions

“Gravitational”

Describing the energy-momentum tensor

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

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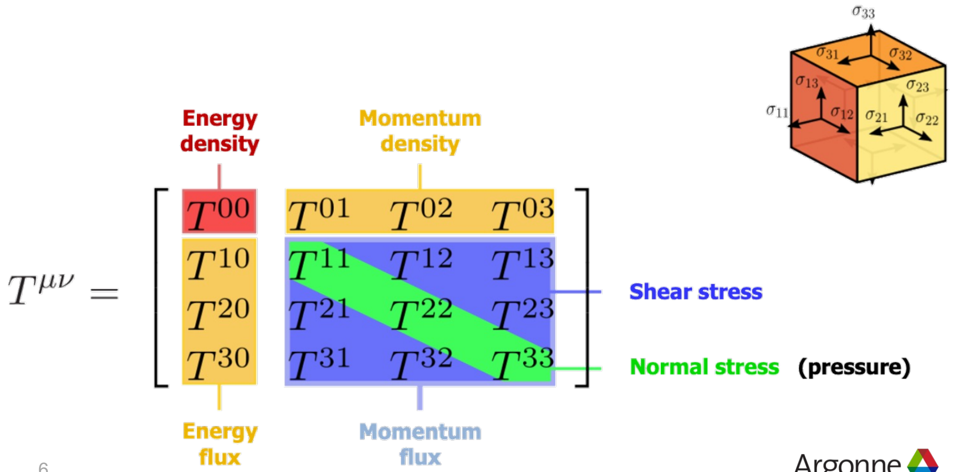
D-term

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

On par with spin, charge, mass!



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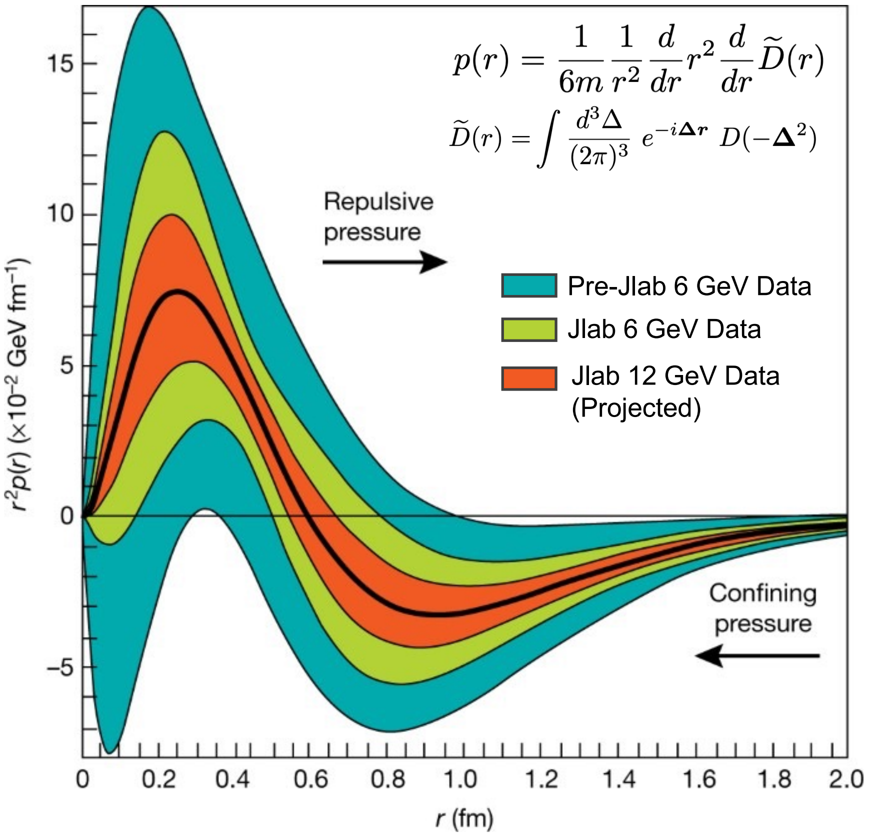
***D*-term**

Often called the last global unknown property of the proton!

em:	$\partial_\mu J^\mu_{\text{em}} = 0$	$\langle N' \| J^\mu_{\text{em}} \| N \rangle$	$\longrightarrow$	$Q = 1.602176487(40) \times 10^{-19}\text{C}$ $\mu = 2.792847356(23)\mu_N$
weak:	PCAC	$\langle N' \| J^\mu_{\text{weak}} \| N \rangle$	$\longrightarrow$	$g_A = 1.2694(28)$ $g_p = 8.06(55)$
gravity:	$\partial_\mu T^{\mu\nu}_{\text{grav}} = 0$	$\langle N' \| T^{\mu\nu}_{\text{grav}} \| N \rangle$	$\longrightarrow$	$m = 938.272013(23)\,\text{MeV}/c^2$ $J = \frac{1}{2}$ $\boldsymbol{D} = \boldsymbol{?}$

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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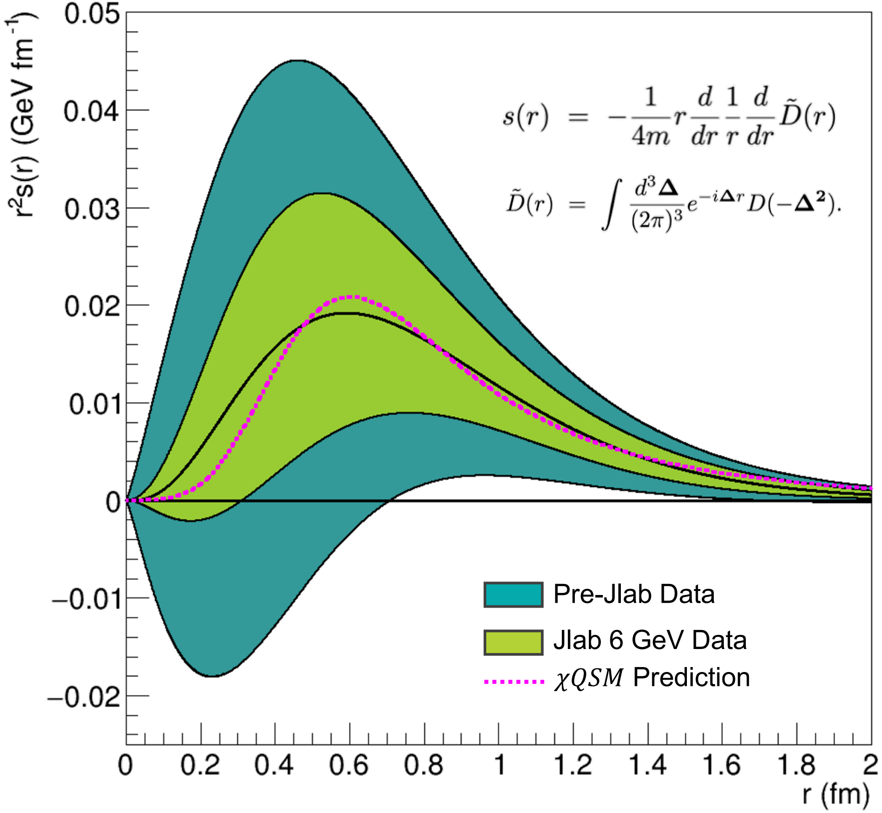

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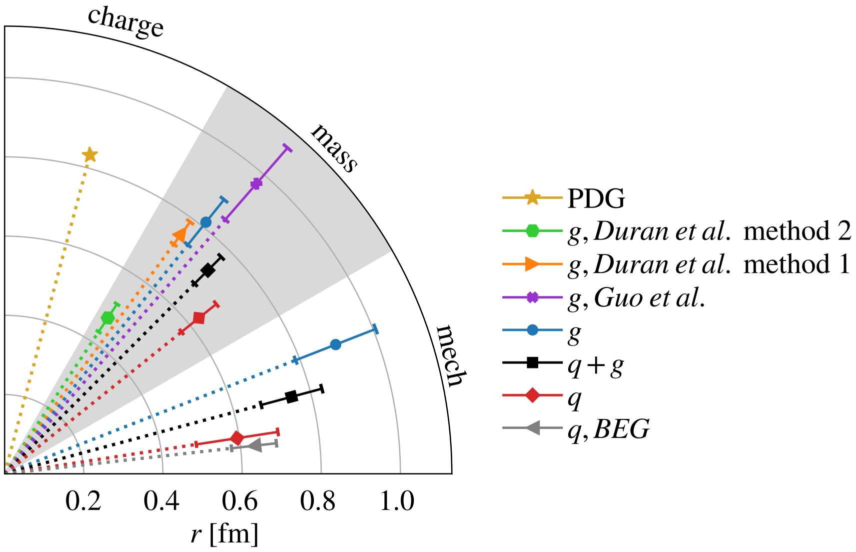
$$\langle r^2 \rangle_{\text{mech}} = \frac{\int d^3r\ r^2\ \left[\frac{2}{3}s(r) + p(r)\right]}{\int d^3r\ \left[\frac{2}{3}s(r) + p(r)\right]} = \frac{6D}{\int_{-\infty}^{0} dt\ D(t)}$$



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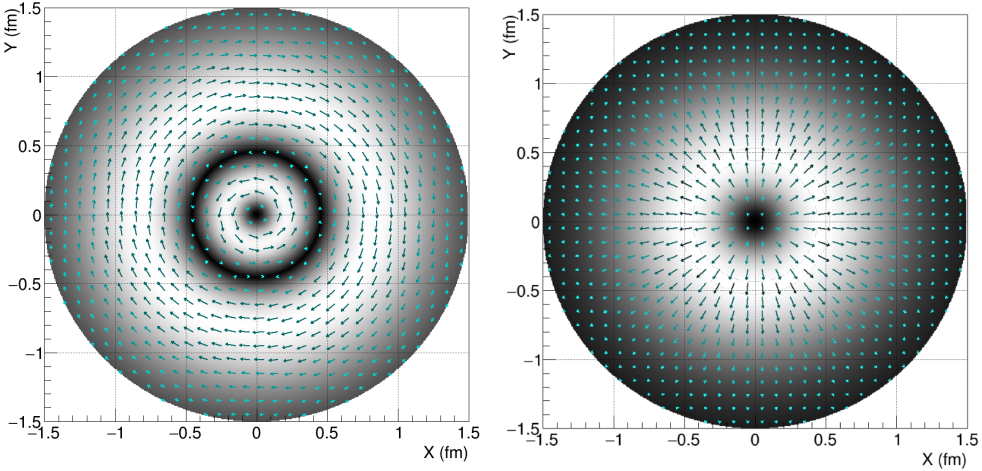
  - **Tangential & normal force distributions**



Tangential force

Normal force

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

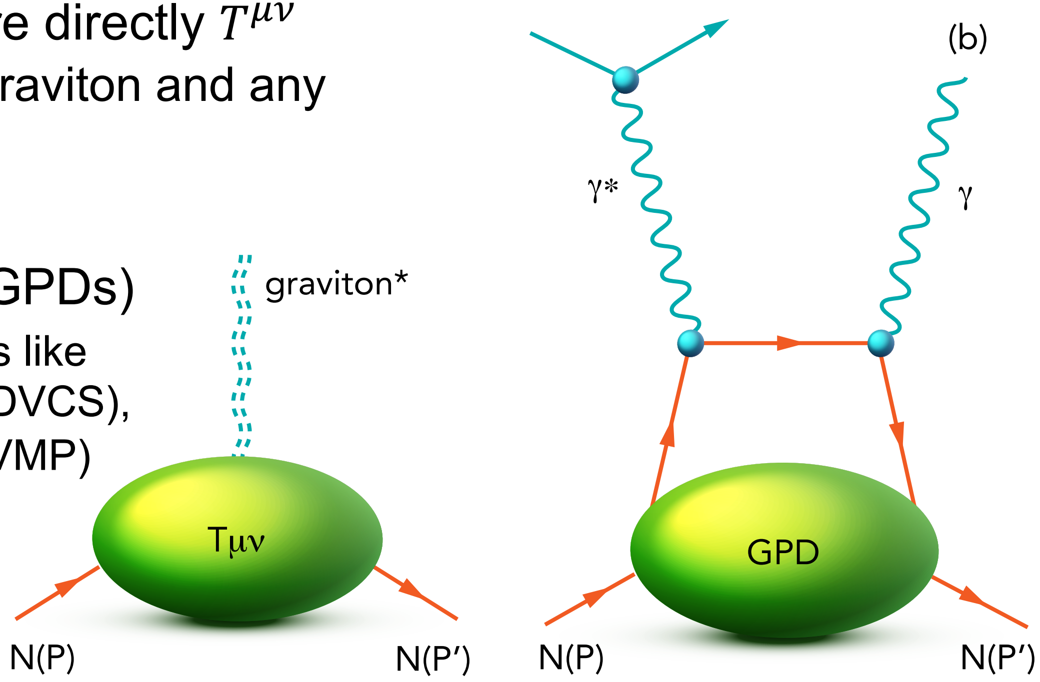
$$\frac{dF_r}{dS_r} = \frac{2}{3}s(r) + p(r)$$

HOW DO WE MEASURE THIS STUFF?

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

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

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



Graviton exchange $\approx$ Deeply Virtual Compton Scattering

HOW DO WE MEASURE THIS?

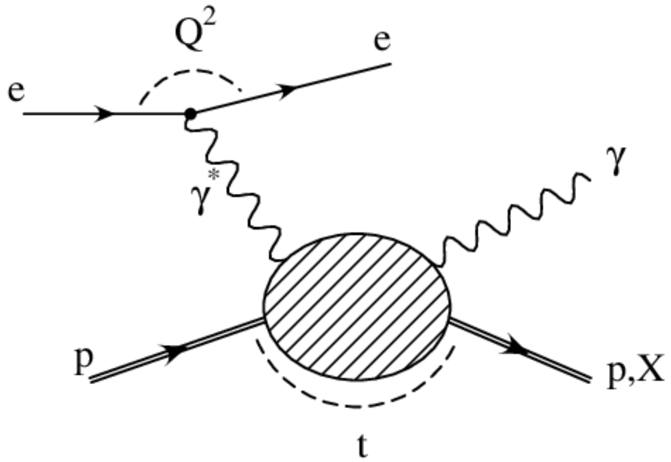
The total D-term is related to the partonic D-terms by a sum rule:

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

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

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

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



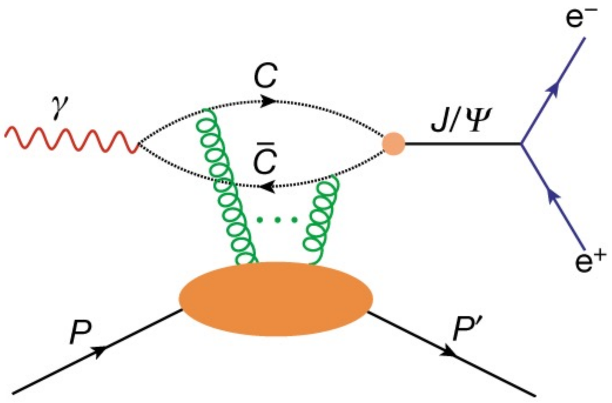
The pressure distribution inside the proton

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

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

SoLID J/ψ!

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



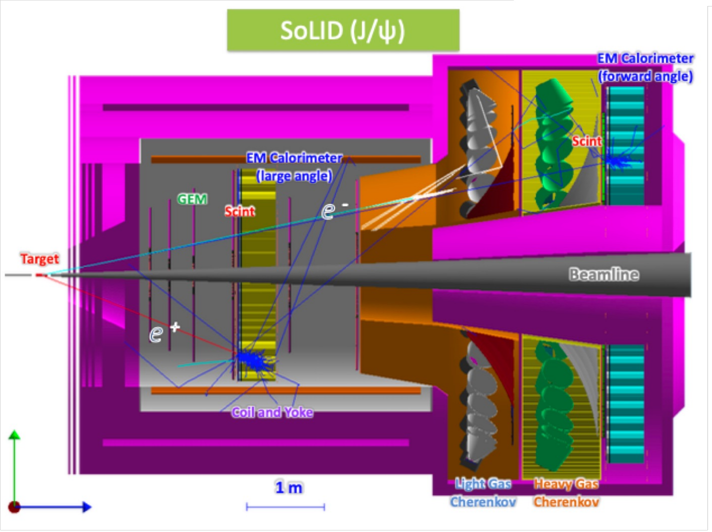
Determining the Proton's Gluonic Gravitational Form Factors

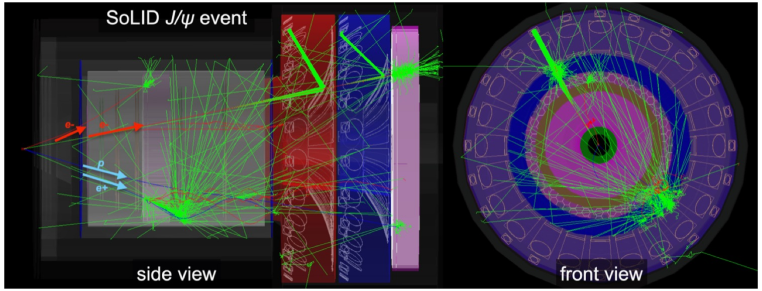
B. Duran[3,1], Z.-E. Meziani[1,3**], S. Joosten[1], M. K. Jones[2], S. Prasad[1], C. Peng[1], W. Armstrong[1], H. Atac[3], E. Chudakov[2], H. Bhatt[5], D. Bhetuwal[5], M. Boer[11], A. Camsonne[2], J.-P. Chen[2], M. M. Dalton[2], N. Deokar[3], M. Diefenthaler[2], J. Dunne[5], L. El Fassi[5], E. Fuchey[9], 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]

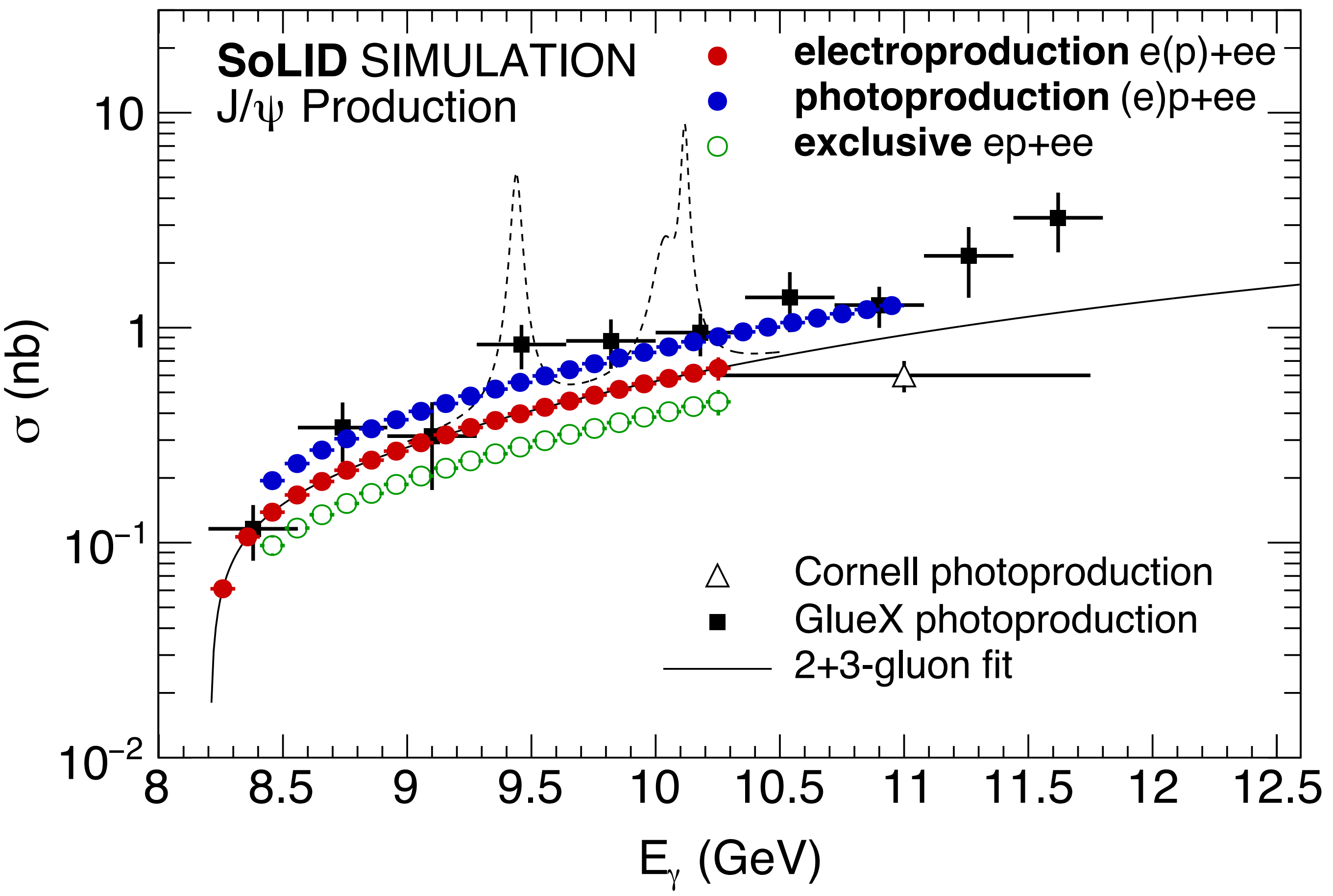
THE SOLID-J/Ψ EXPERIMENT

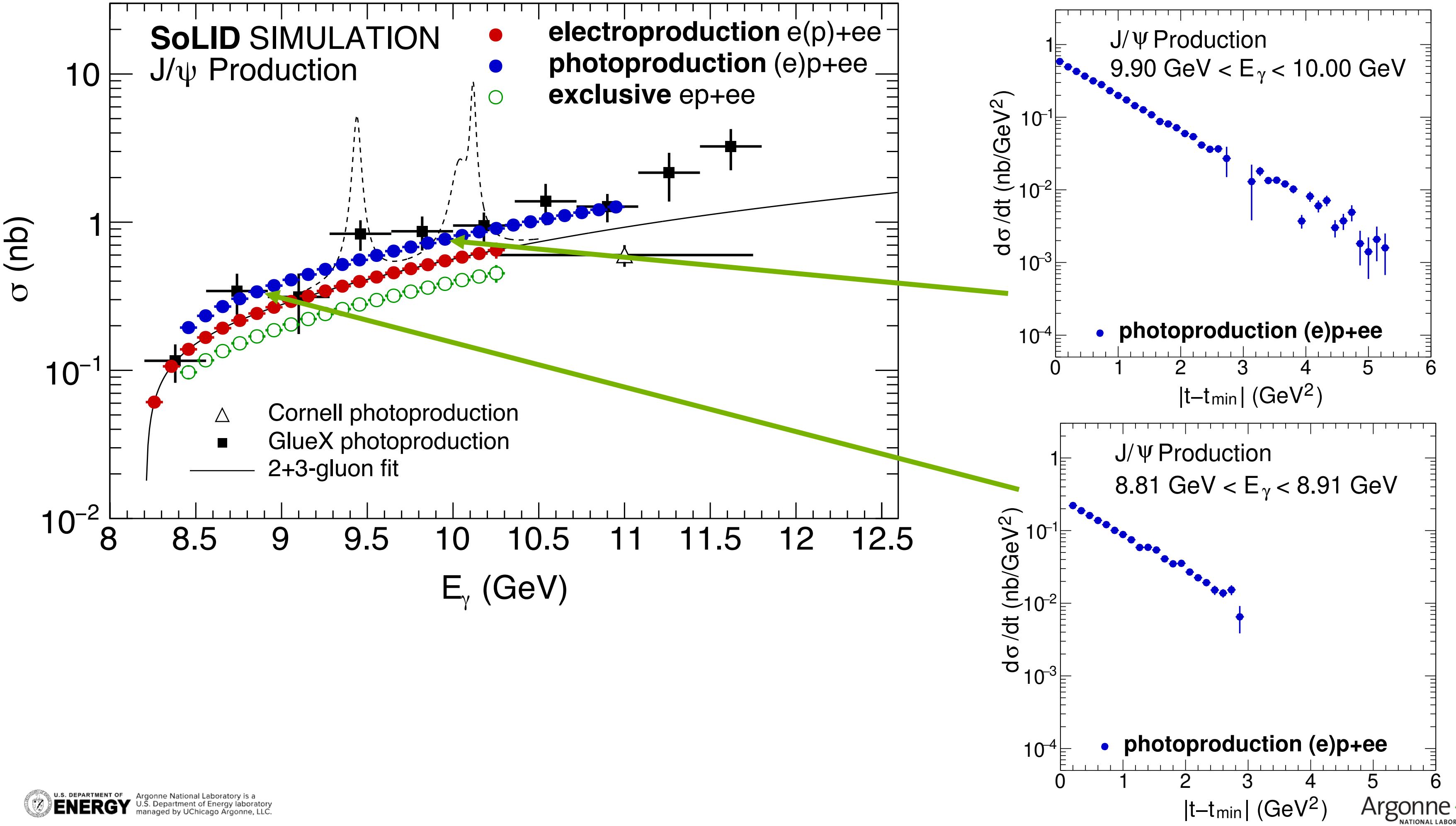
Ultimate factory for near-threshold J/ψ

- General purpose large-acceptance spectrometer
- 50+10 days of 3μA beam on a 15cm long LH2 target (10^{37}/cm^2/s)
- **Ultra-high luminosity**: 43.2ab^{-1}
- **Open 2-particle trigger,** covering J/ψ production in four channels:
  Electroproduction (e,e$^-$e$^+$), photoproduction (p,e$^-$ e$^+$),
  inclusive (e$^-$e$^+$), exclusive (ep,e$^-$e$^+$)
- The electoproduction channel provides for a modest lever-arm in Q^2 near threshold






SoLID SIMULATION
J/ψ Production
electroproduction e(p)+ee
photoproduction (e)p+ee
exclusive ep+ee
Cornell photoproduction
GlueX photoproduction
2+3-gluon fit
σ (nb)
10
1
10^−1
10^−2
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
E_γ (GeV)


SoLID SIMULATION
J/ψ Production
electroproduction e(p)+ee
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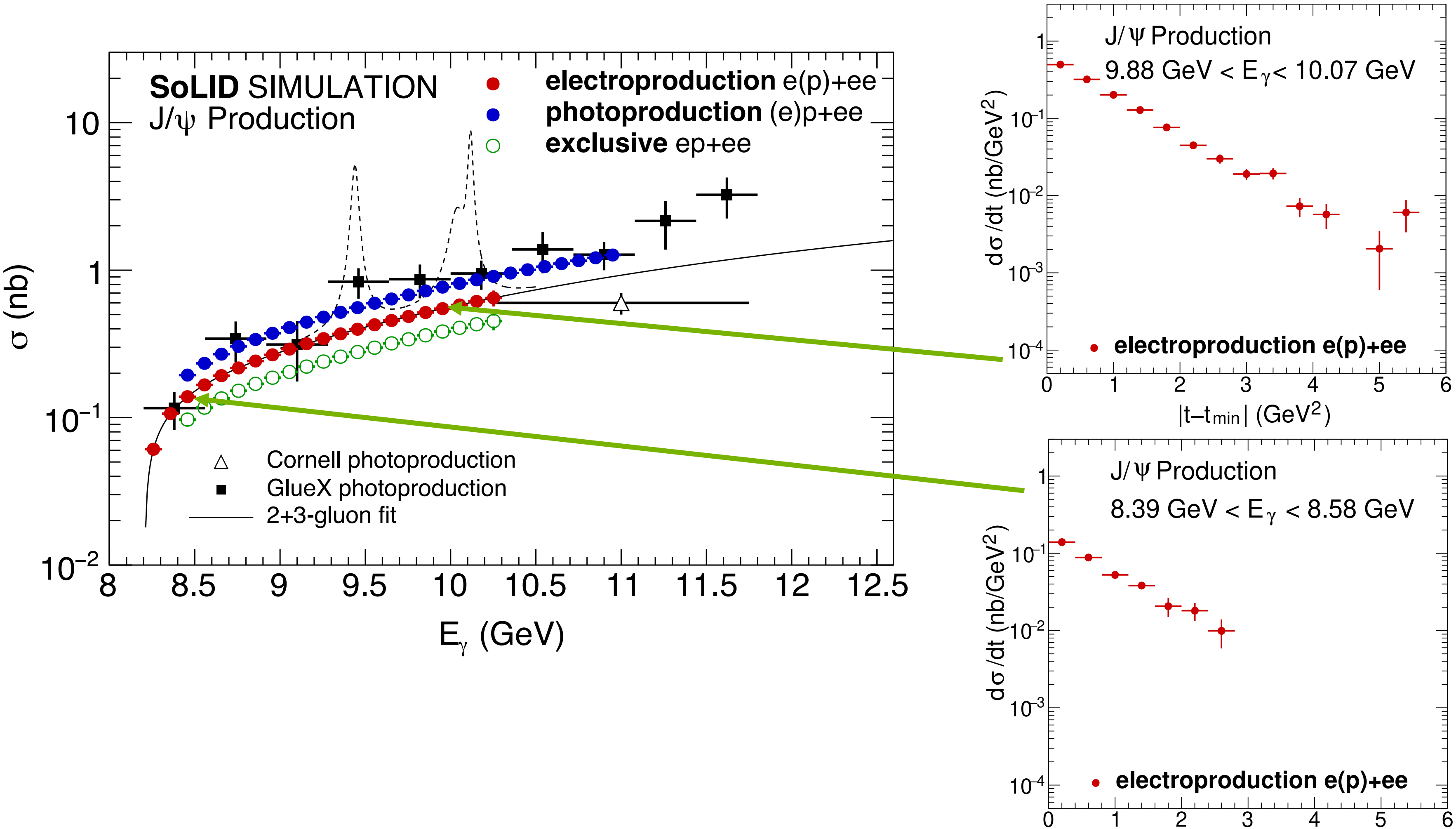
2+3-gluon fit
σ (nb)
Eγ (GeV)
10
1
10−1
10−2
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
J/Ψ Production
9.90 GeV < Eγ < 10.00 GeV
photoproduction (e)p+ee
dσ /dt (nb/GeV²)
|t−tmin| (GeV²)
J/Ψ Production
8.81 GeV < Eγ < 8.91 GeV
photoproduction (e)p+ee
dσ /dt (nb/GeV²)
|t−tmin| (GeV²)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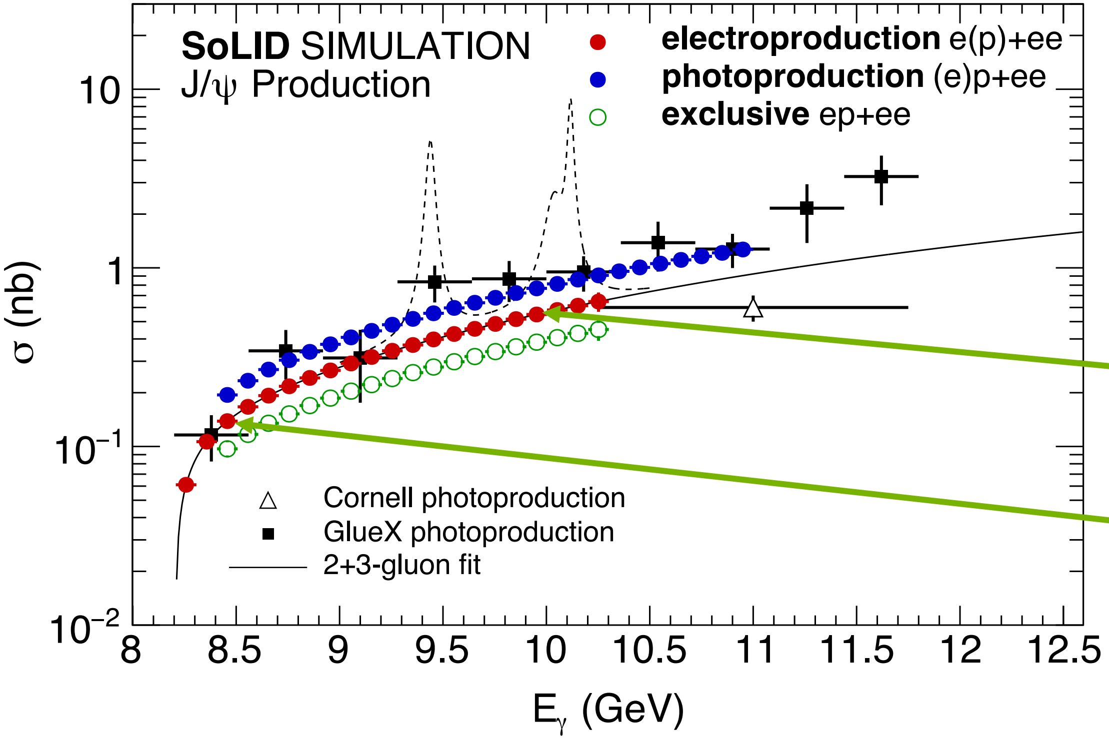
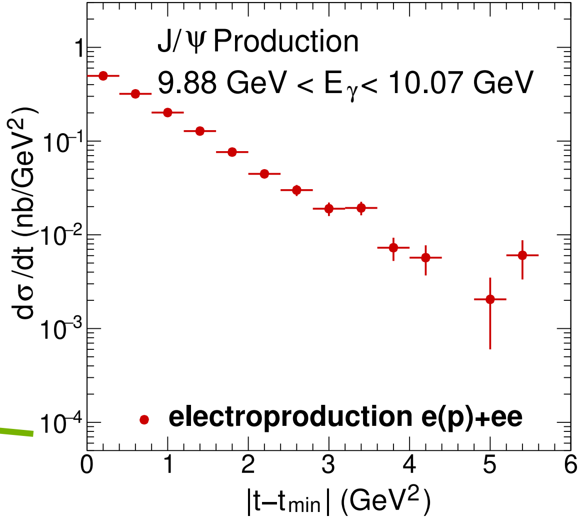
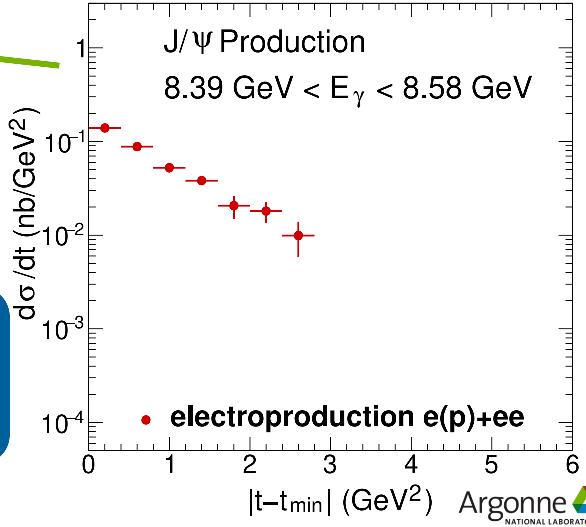
electroproduction e(p)+ee
photoproduction (e)p+ee
exclusive ep+ee
Cornell photoproduction
GlueX photoproduction
2+3-gluon fit
σ (nb)
E_γ (GeV)
J/ψ Production
9.88 GeV < E_γ < 10.07 GeV
electroproduction e(p)+ee
dσ/dt (nb/GeV²)
|t−t_min| (GeV²)
J/ψ Production
8.39 GeV < E_γ < 8.58 GeV
electroproduction e(p)+ee
dσ/dt (nb/GeV²)
|t−t_min| (GeV²)



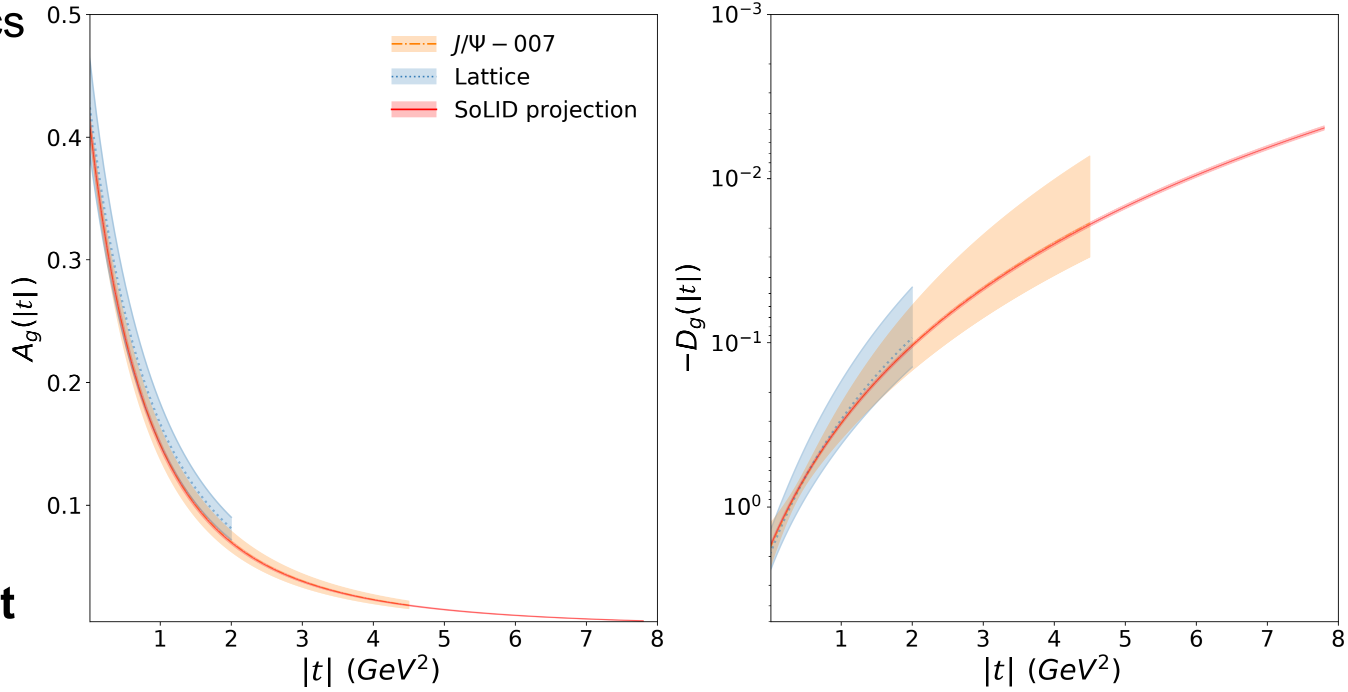




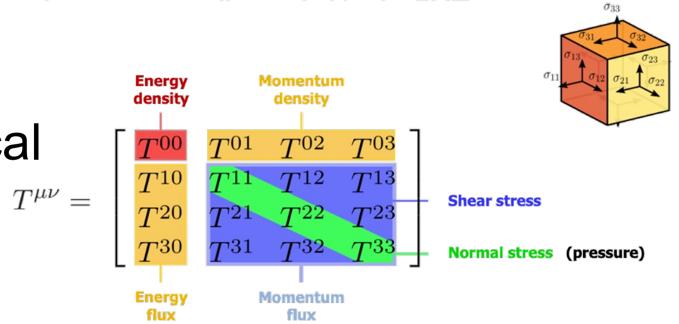
Highly multi-dimensional measurement!

GLUON GFFS

- Extremely high statistics enables precise extraction of D_g, A_g
- No longer limited by poor experimental precision!
  - More food for thought for theorists
- **SoLID will let us take full advantage of what CEBAF can offer!**



$\bar{c}$ CAVEAT

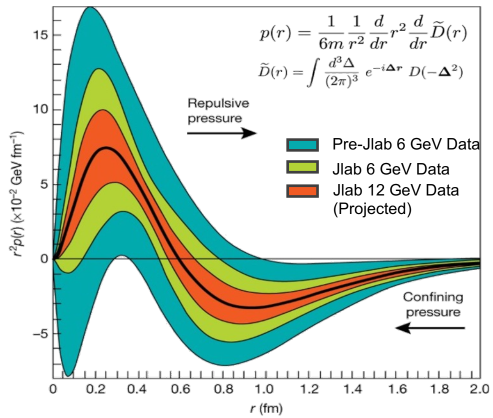


- $\bar{c}$ form factor contributes to many of the mechanical structure quantities, not only the D-term
  - $\bar{c}$ currently inaccessible by experiment

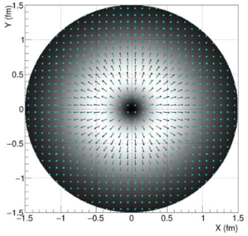
$$\langle p', s' | \hat{T}^a_{\mu\nu}(x) | p, s \rangle = \bar{u}' \left[A^a(t) \frac{\gamma_{\{\mu} P_{\nu\}}}{2} + B^a(t) \frac{i P_{\{\mu} \sigma_{\nu\}\rho} \Delta^\rho}{4m} + D^a(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu} \Delta^2}{4m} + m \, \bar{c}^a(t) \, g_{\mu\nu} \right] u \, e^{i(p'-p)x}$$

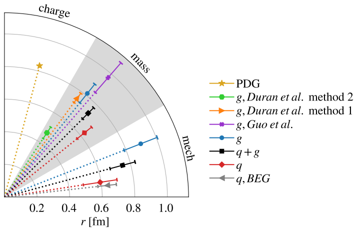
$$t = (p - p')^2 = \Delta^2 \qquad \Delta = p' - p = q - q' \qquad P = \frac{p + p'}{2}$$

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



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





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

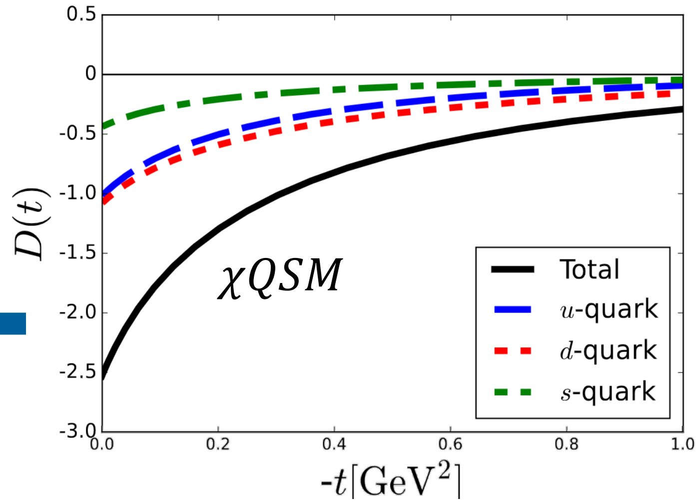
$$D(0) = D_g(0) + D_u(0) + D_d(0) + D_s(0) + \ldots .$$

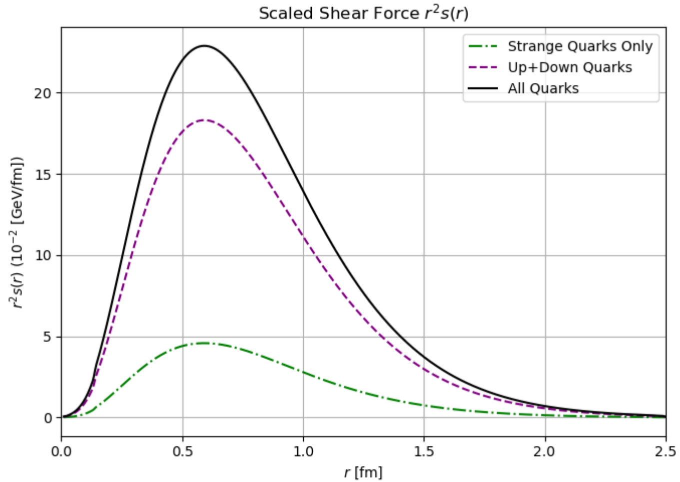
Strange quarks: Can we just neglect them…?

THEORY PREDICTIONS

ArXiv: 2307.00740

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





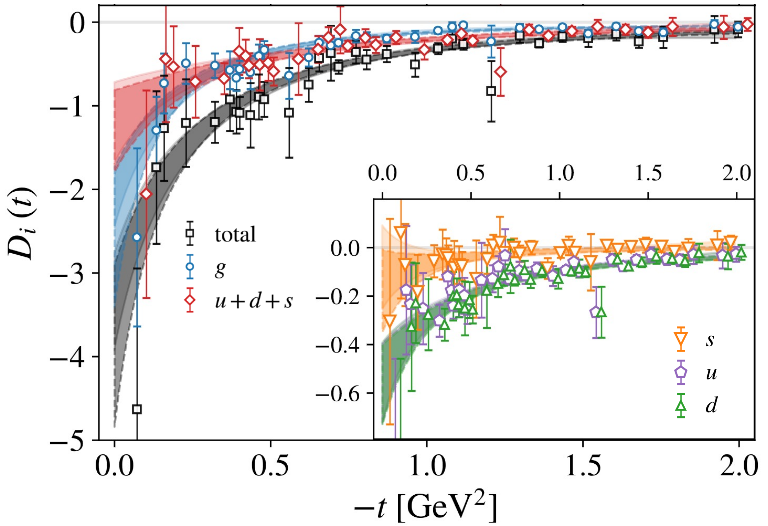
This would make D_s a non-negligible contributor to the total D-term, and thus **necessary for a full extraction of many of the mechanical properties of the proton!**

THEORY PREDICTIONS

- On the other hand, lattice results of Hackett et al. predict D_s consistent with zero
  - Uncertainties are still large, but the results do not exclude *positive* values of D_s

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

- $D_s > 0$ would mean that strange quarks feel forces in opposite direction to up & down quarks!
  - The pop-sci articles write themselves…



	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)

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

But how…?

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

But how…?

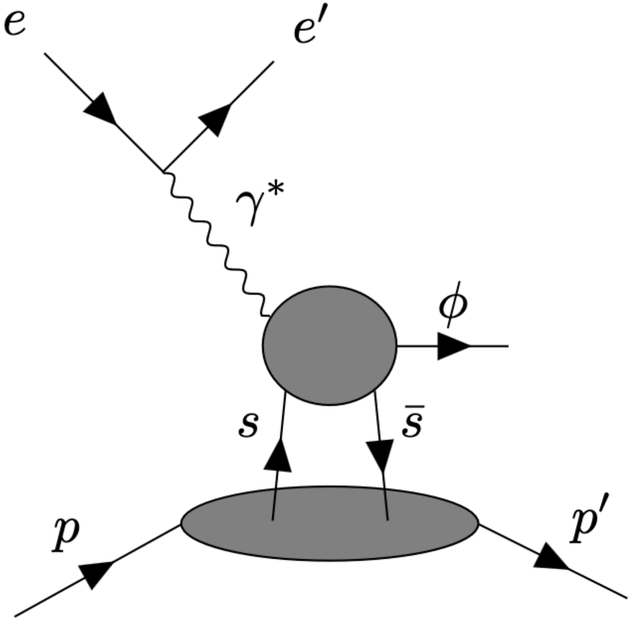
SoLID ϕ!

ACCESSING THE STRANGENESS D-TERM

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

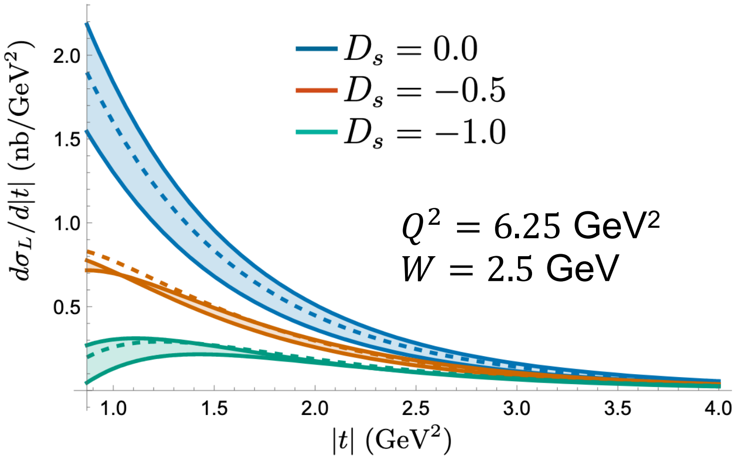
- Recently, it was proposed that *near-threshold electroproduction of ϕ mesons* could provide sensitivity to the strangeness D-term
  - ϕ meson is very nearly a pure $s\bar{s}$ state
  - Expected to couple strongly to strangeness in the proton

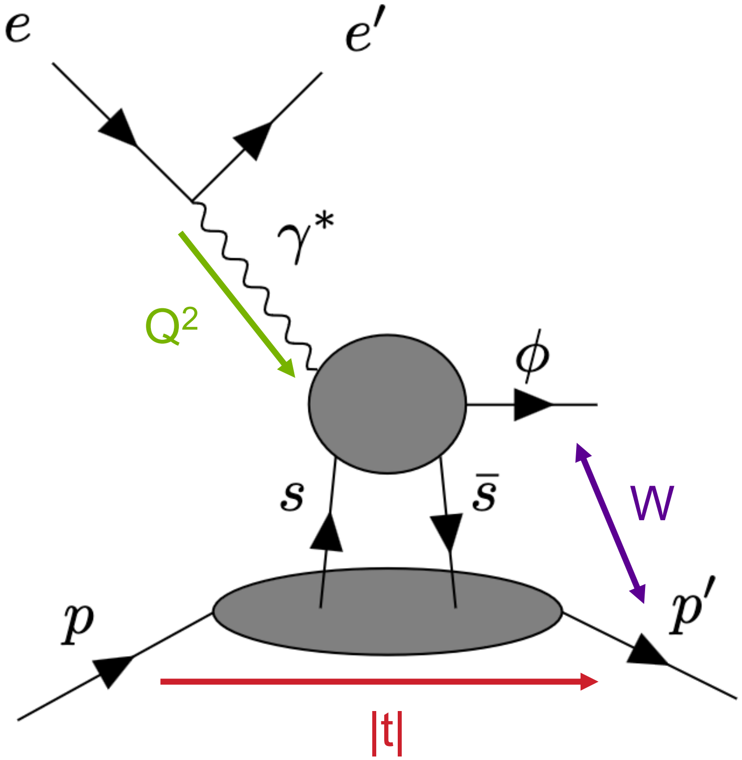
- Never measured in the required kinematic region!



DEEP NEAR-THRESHOLD ϕ KINEMATICS

- Deep = high momentum transfer = **high Q^2**
- Near-threshold = invariant mass of final-state hadrons **$W \sim M_\phi + M_p$** ~ 1.96 GeV
- Small momentum transfer to proton = **Low-|t|**
  - Strong sensitivity to strangeness D-term!





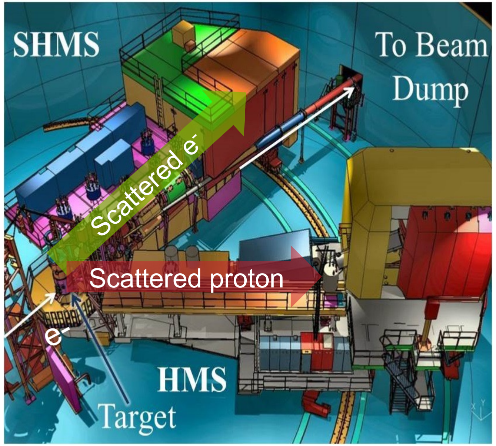
ϕ-meson lepto-production near threshold and the strangeness D-term

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

THE STRANGENESS D-TERM IN HALL C

2501.01582

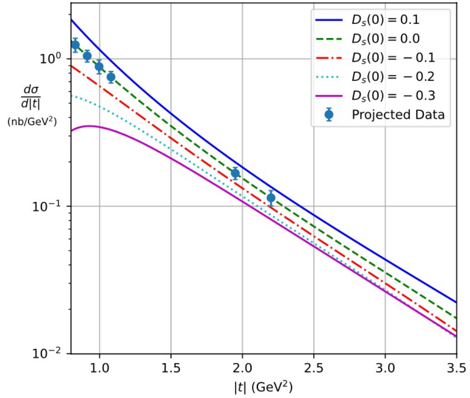
- **Proposed Measurement:** Exclusive ϕ meson electroproduction near threshold in Hall C at Jefferson Lab (2024 LOI)
  - — Measure the |t|-dependence of the electroproduction cross-section using the reaction H(e, e′p)ϕ at Q^2 ~ 3.5 and W ~ 2.2
  - — Uses the missing mass technique with standard Hall C spectrometers to identify exclusive events
    - No hit from $\phi \rightarrow KK$ BR, but large DIS background!



- **Theoretical Challenges:**

Two points highlighted by the PAC:

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



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

THE STRANGENESS D-TERM IN HALL C

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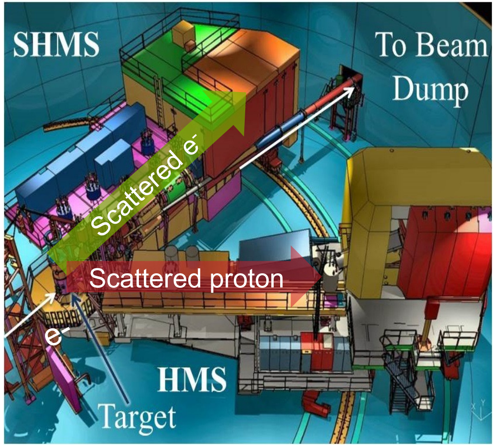

- **Theoretical Challenges:**

Two points highlighted by the PAC:

Jobs for theorists…

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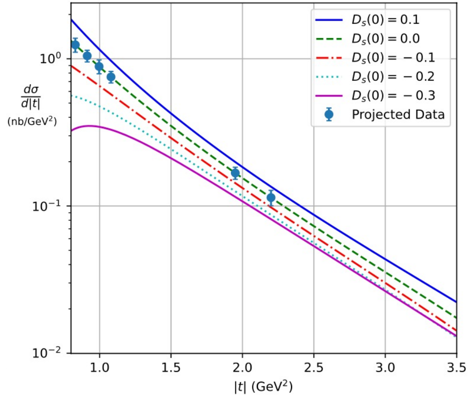


Hall C Phi Collaboration, "Studying the Strangeness D-Term in Hall C via Exclusive ϕ Electroproduction," JLab PAC 52 LOI (2024)

THEORY PREDICTIONS

Hatta, HK, Passek, Schoenleber (To be submitted)

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

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

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

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

"Threshold Approximation" – Keep only j = 1

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

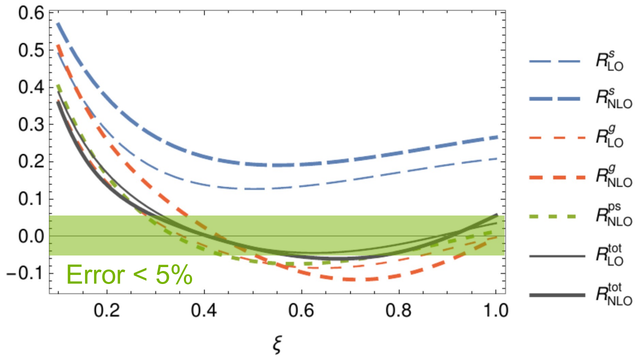
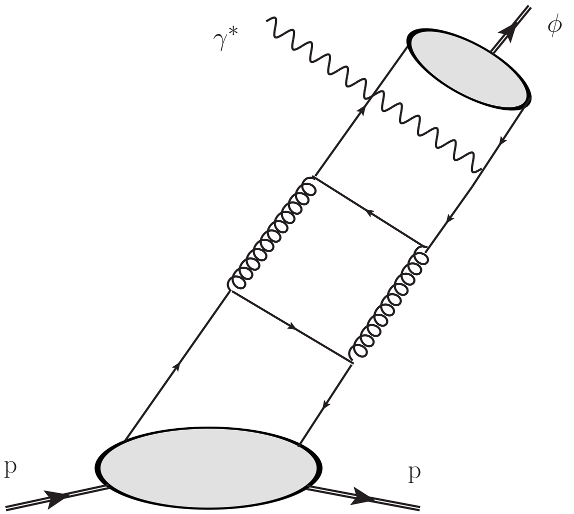


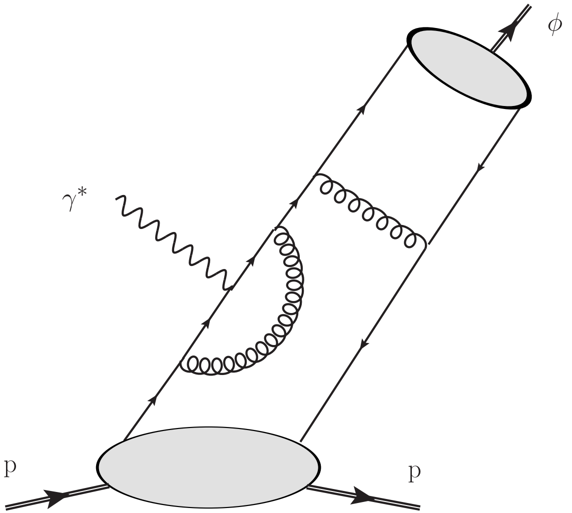
FIG. 4: Relative error for the amplitude $\mathcal{H}$ from truncating the conformal partial wave expansion after the first term. Plotted quantities are defined in (40). The subscript denotes whether the leading order (LO) or next-to-leading order (NLO) coefficient function has been used. In this and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

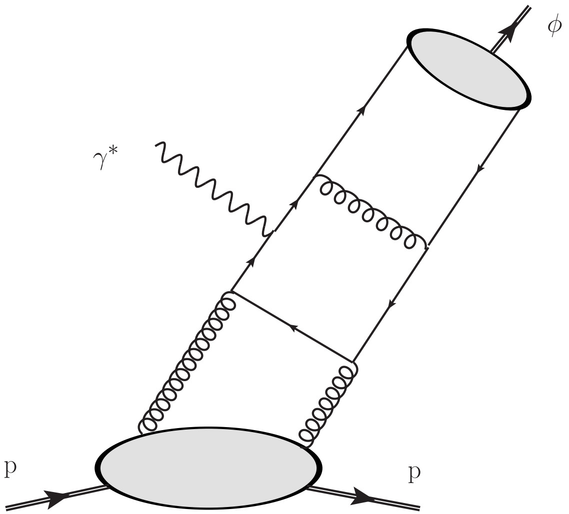
THEORY PREDICTIONS

Hatta, HK, Passek, Schoenleber (To be submitted)

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







Hatta, HK, Passek, Schoenleber (To be submitted)

These predictions are valid for $\xi \gtrsim 0.4$ and $Q^2 \gtrsim 3|t|$

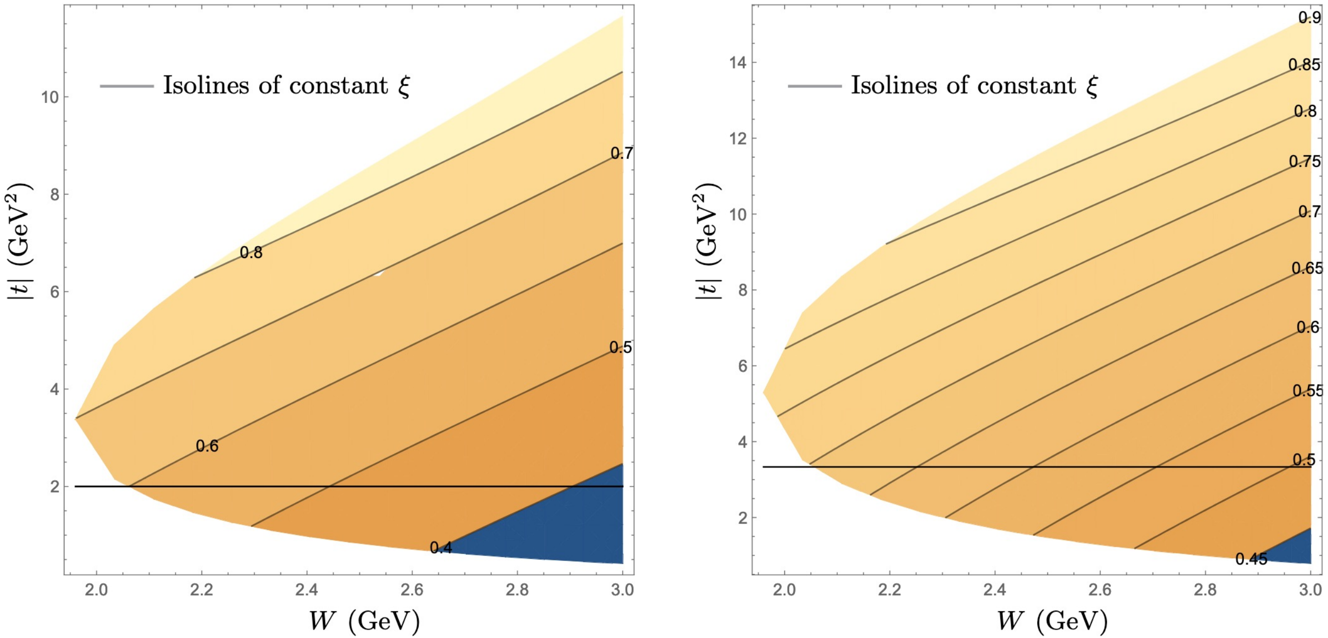
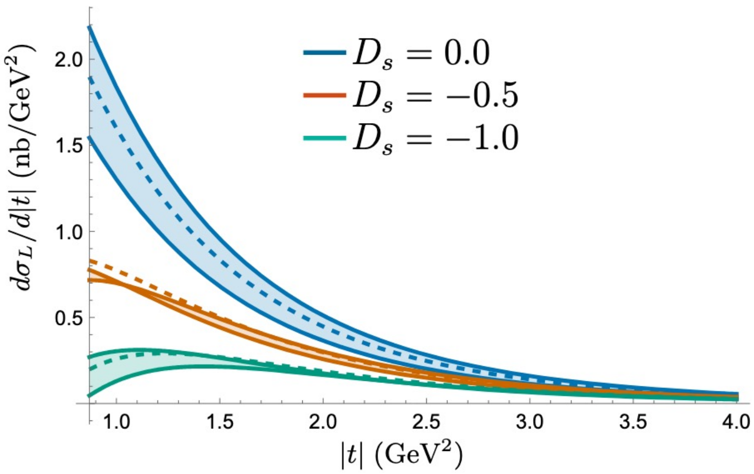


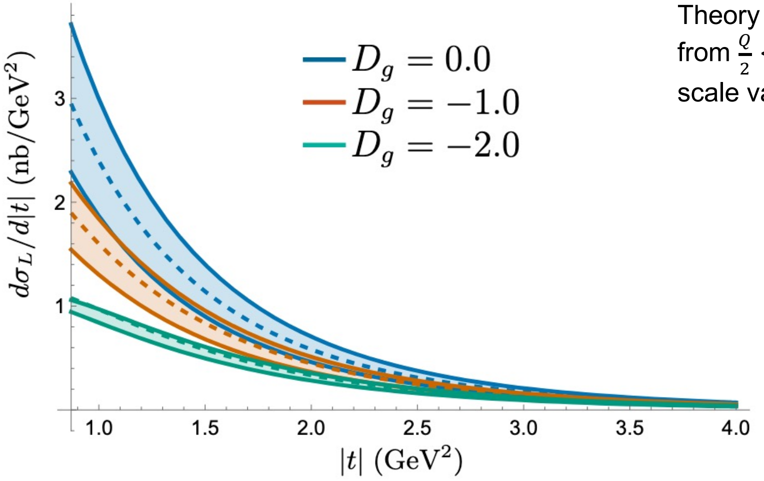
FIG. 1: Contour plots of ξ in the $(W, |t|)$ plane at $Q^2 = 6$ GeV^2 (left) and $Q^2 = 10$ GeV^2 (right). The horizontal line is at $|t| = \frac{Q^2}{3}$.

Challenging to satisfy! Need high Q^2 & $W < 3$

THEORY PREDICTIONS

Hatta, HK, Passek, Schoenleber (To be submitted)





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

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

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

THEORY PREDICTIONS

Hatta, HK, Passek, Schoenleber (To be submitted)

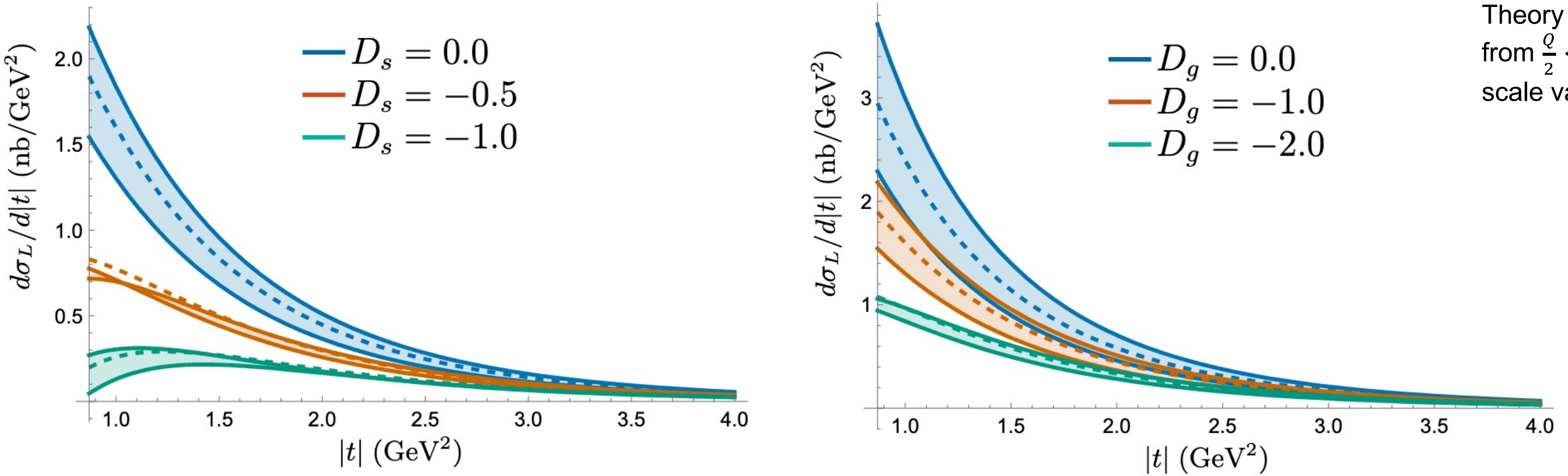
$$\mathcal{H}(\xi,t) \approx \frac{2\kappa}{\xi^2}\frac{15}{2}\Bigg[\left\{\alpha_s(\mu)+\frac{\alpha_s^2(\mu)}{2\pi}\left(25.7309-2n_f+\left(-\frac{131}{18}+\frac{n_f}{3}\right)\ln\frac{Q^2}{\mu^2}\right)\right\}(A_s(t,\mu)+\xi^2 D_s(t,\mu))$$
$$+\frac{\alpha_s^2}{2\pi}\left(-2.3889+\frac{2}{3}\ln\frac{Q^2}{\mu^2}\right)\sum_q(A_q+\xi^2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

$\xi \sim 0.5$

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

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

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



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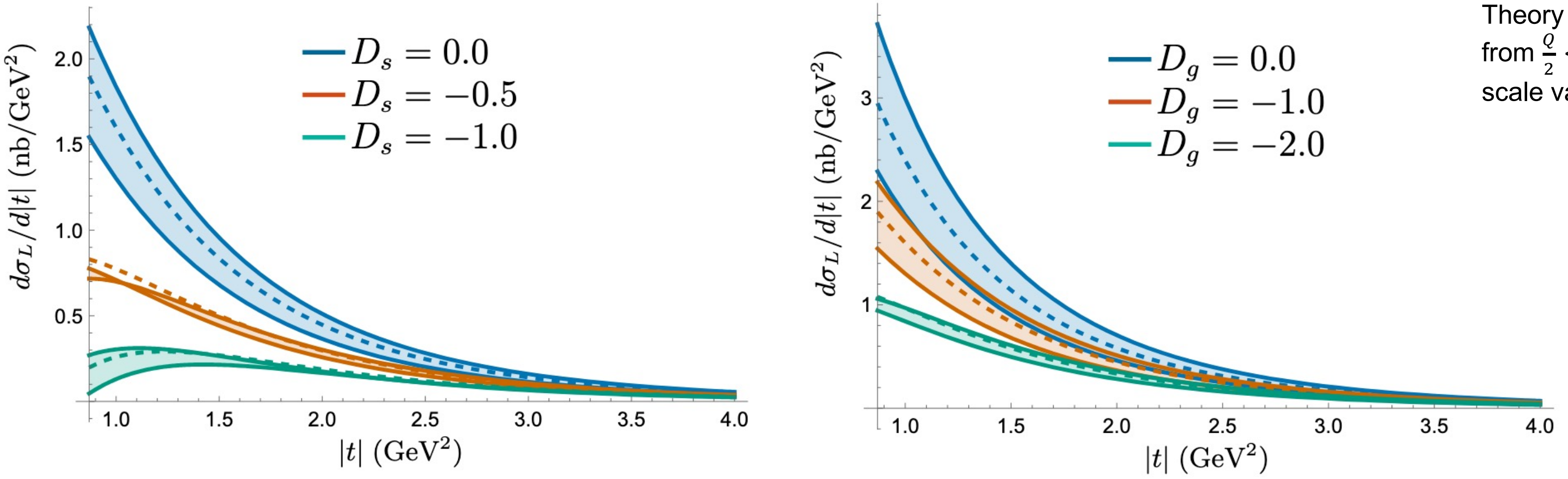
THEORY PREDICTIONS

Hatta, HK, Passek, Schoenleber (To be submitted)

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

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

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



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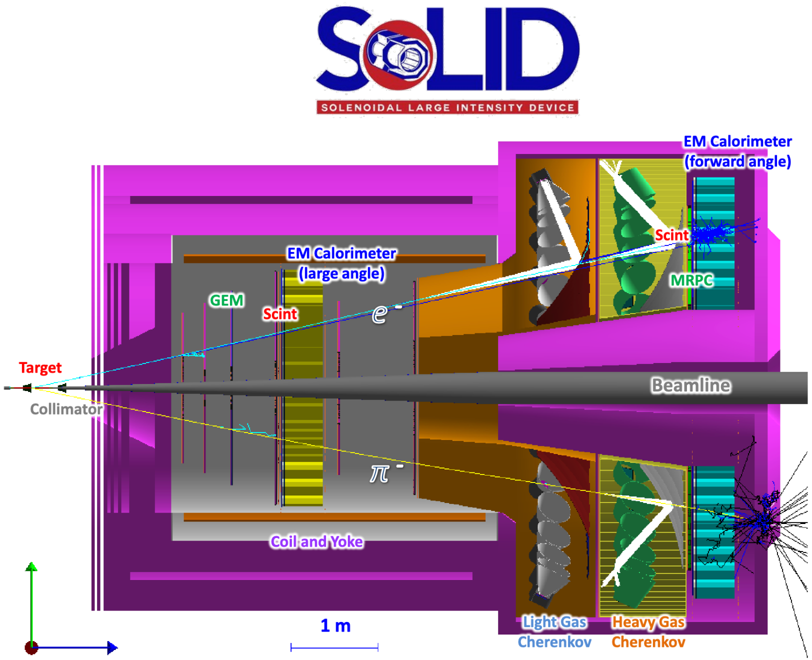
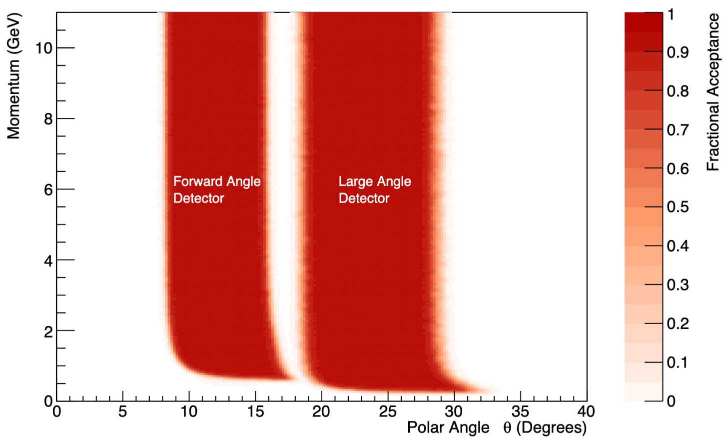
EXCLUSIVE ϕ IN SOLID

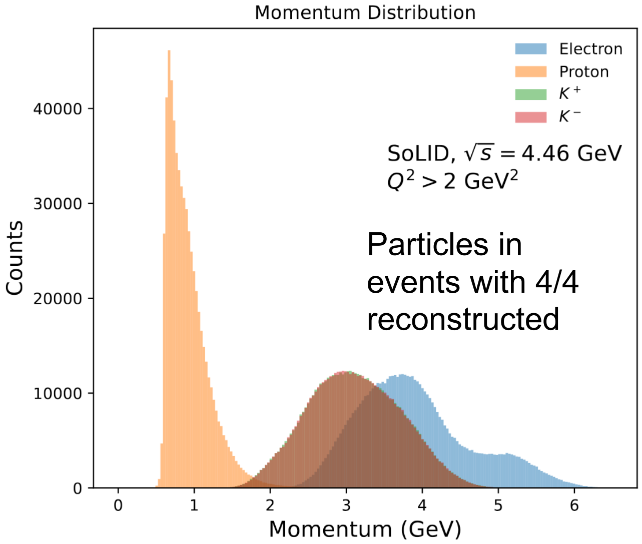
- Large acceptance & luminosity!
  - ϕ decay products can be measured directly
    - Fully exclusive, low background
    - Measure R to extract σ_L
  - PID from ToF, Cherenkovs
  - High statistics & continuous kinematic coverage for multidimensional measurement

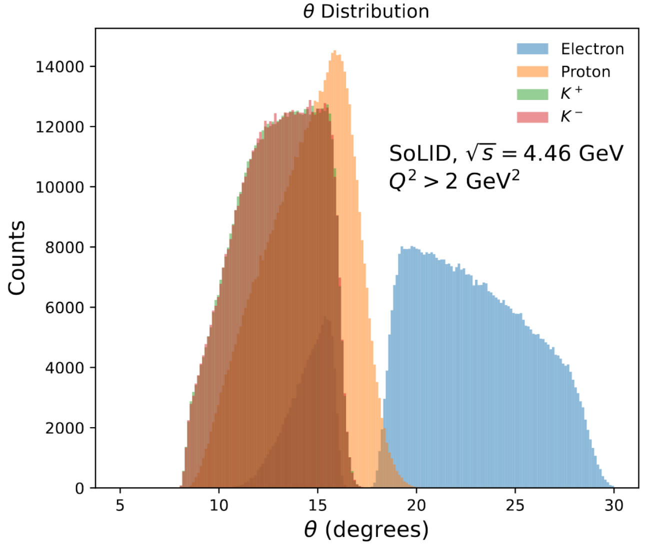


PROJECTIONS

- First look at 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



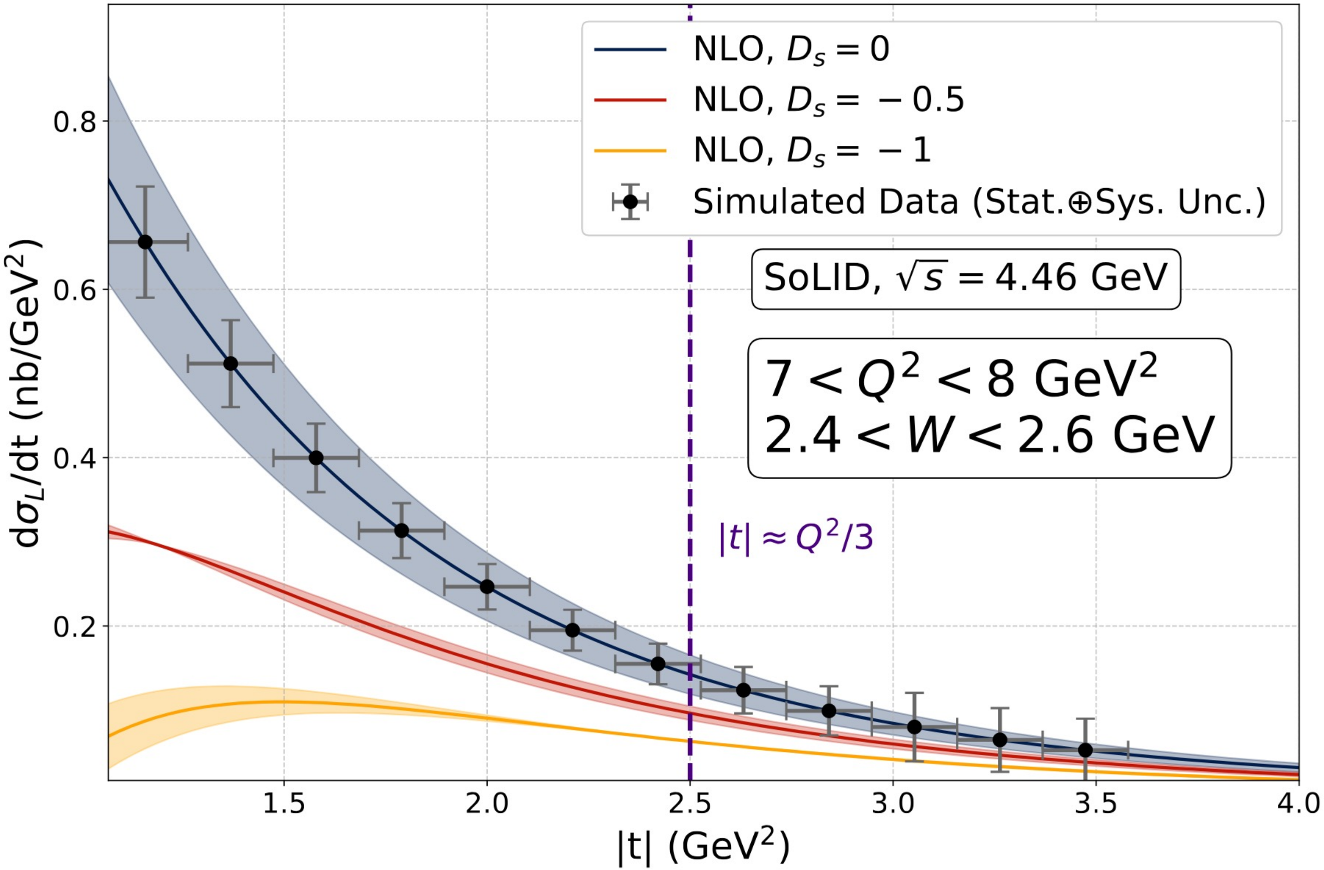


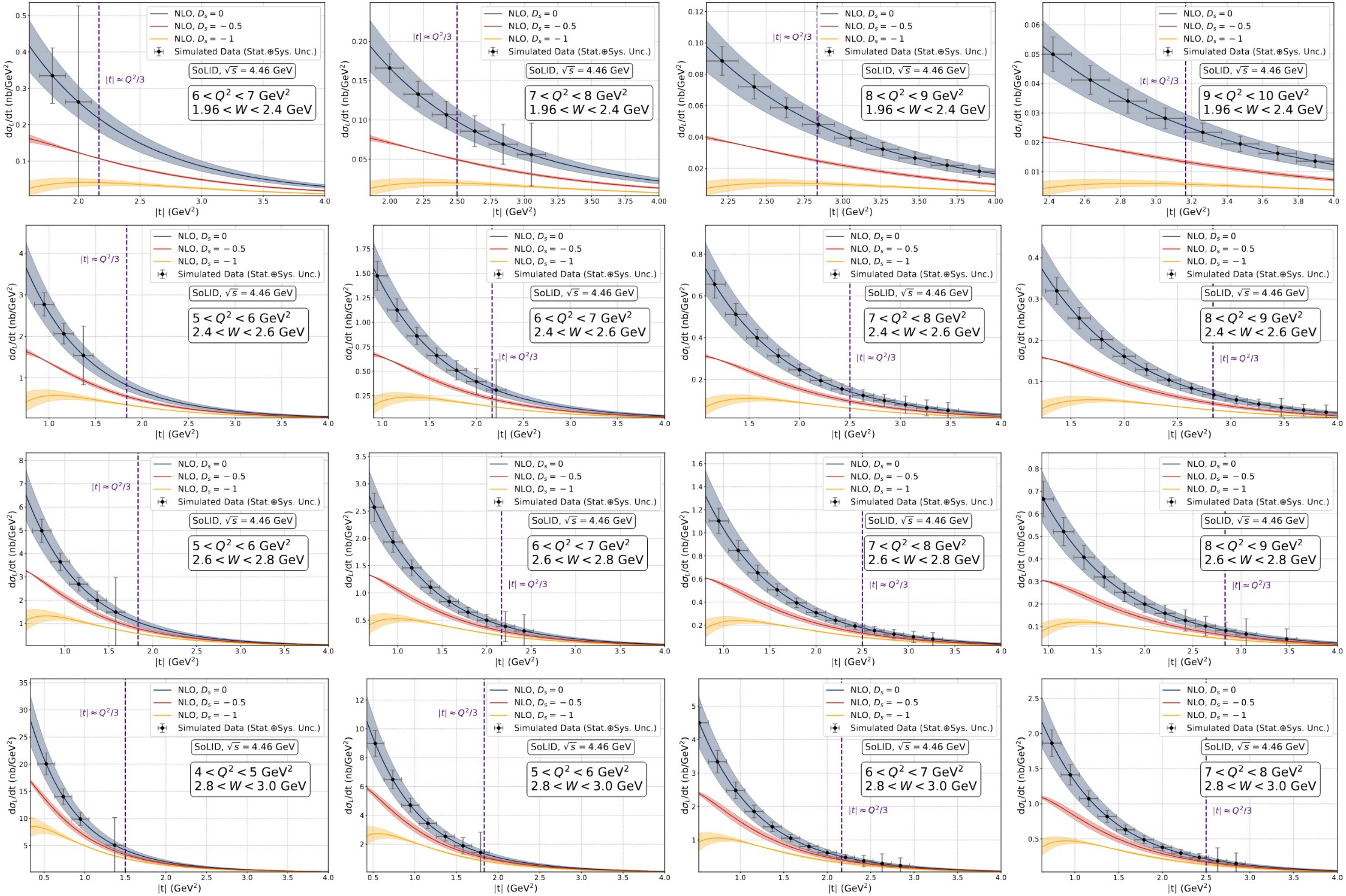


Particle momenta nicely suited for the SoLID PID systems!

PROJECTIONS

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




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
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$7 < Q^2 < 8$ 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
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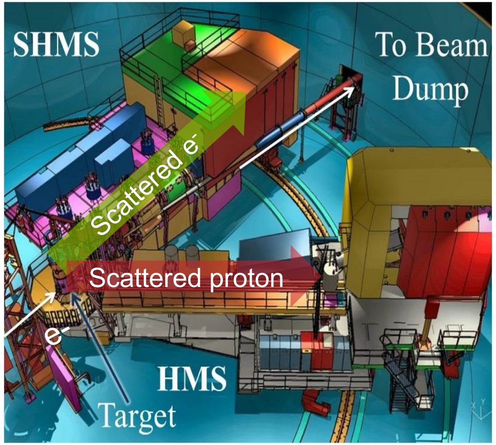
$7 < Q^2 < 8$ GeV^2 $2.6 < W < 2.8$ GeV
$8 < Q^2 < 9$ GeV^2 $2.6 < W < 2.8$ GeV
$4 < Q^2 < 5$ GeV^2 $2.8 < W < 3.0$ GeV
$5 < Q^2 < 6$ GeV^2 $2.8 < W < 3.0$ GeV
$6 < Q^2 < 7$ GeV^2 $2.8 < W < 3.0$ GeV
$7 < Q^2 < 8$ GeV^2 $2.8 < W < 3.0$ GeV

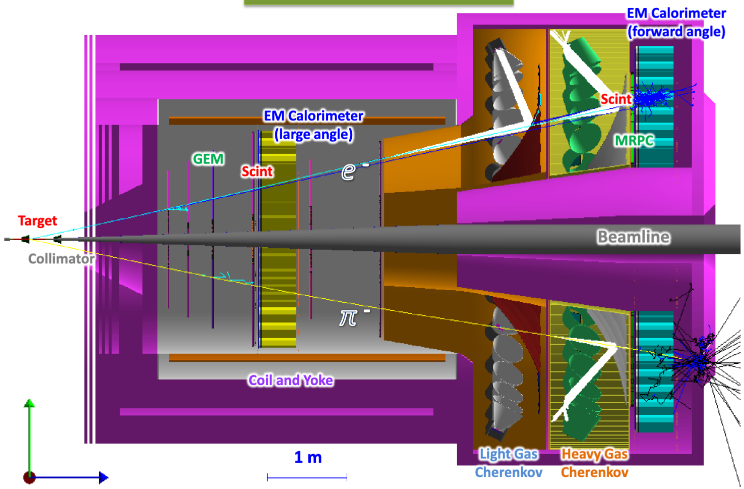
CONCLUSION

- QCD EMT framework provides new insights into the structure of hadrons
  - In particular, D-term accesses a new & exciting set of measurable quantities
- If we ever want a complete experimental measurement of the total D-term of the proton, **will need to measure the strangeness D-term**
  - Can be done at CEBAF, with the right tools

SoLID provides the opportunity to measure D_g and eventually D_s, bringing us into the **precision era of proton mechanical structure!**



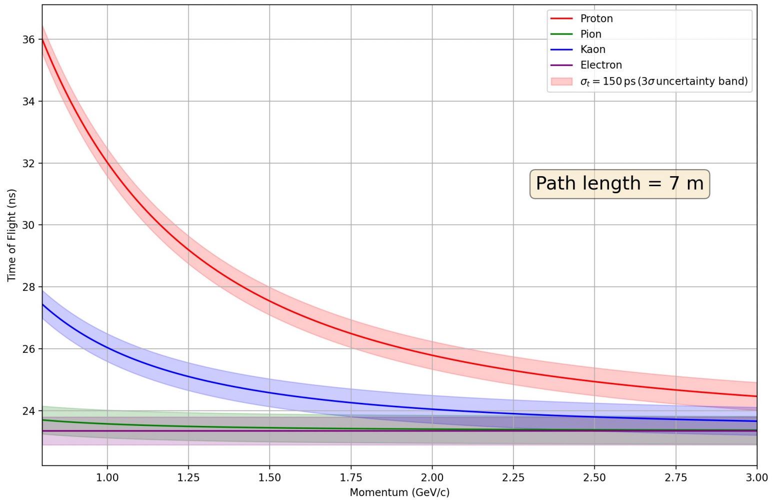
SoLID (SIDIS and J/ψ)

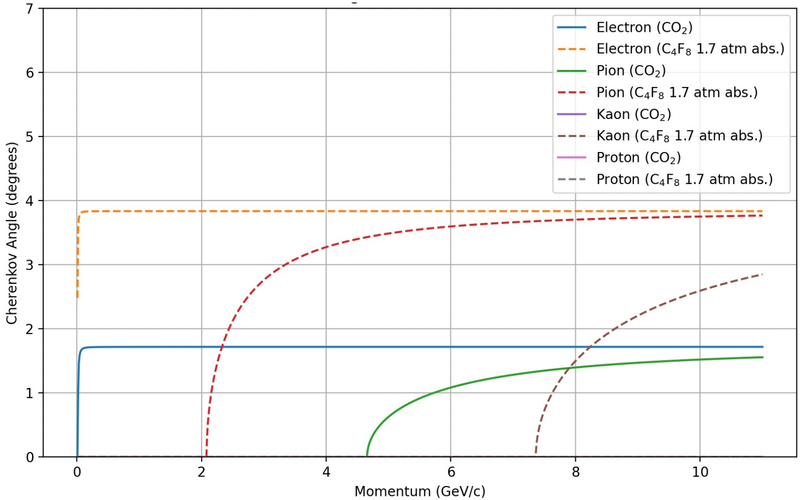


Let me know if you're interested in collaborating!

PID

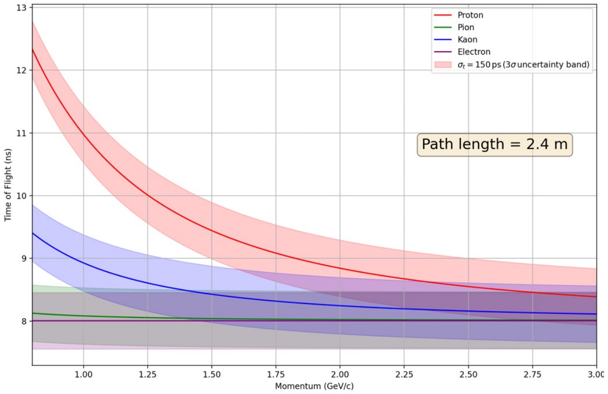
- Kaons from decay of ϕ should be PID'd to reduce background
- Range of $K^{+,-}$ momentum from ~1-4 GeV in forward detector
- HGC will provide π rejection above 2.5 GeV
- 150 ps TOF covers 3σ π/K up to ~2.5 GeV
  - MRPC would handle this better, reduce the reliance on HGC near its threshold
- Scattered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

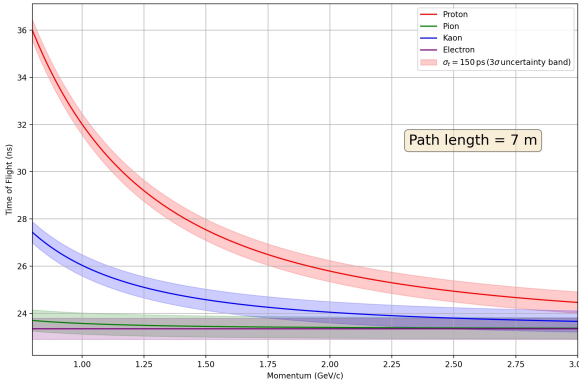


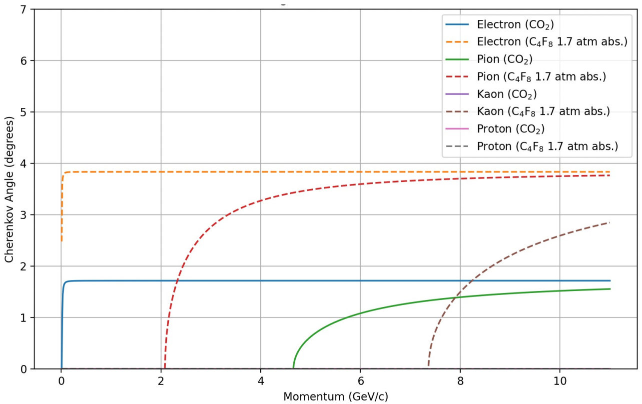


ANALYSIS STRATEGY

- 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







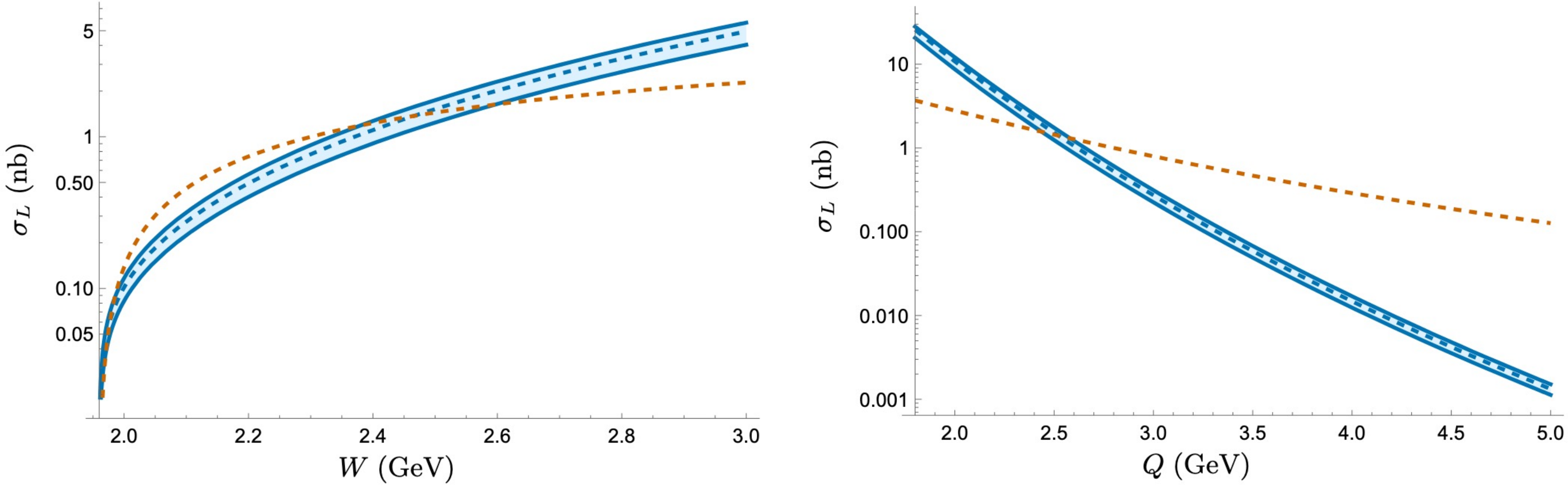


FIG. 8: NLO longitudinal cross section integrated over t with $D_s = 0$ and $D_g = -1$ as a function of W at fixed $Q = 2.5$ GeV (left), and as a function of Q at fixed $W = 2.5$ GeV (right). The red dashed curve is the CLAS parametrization (56).

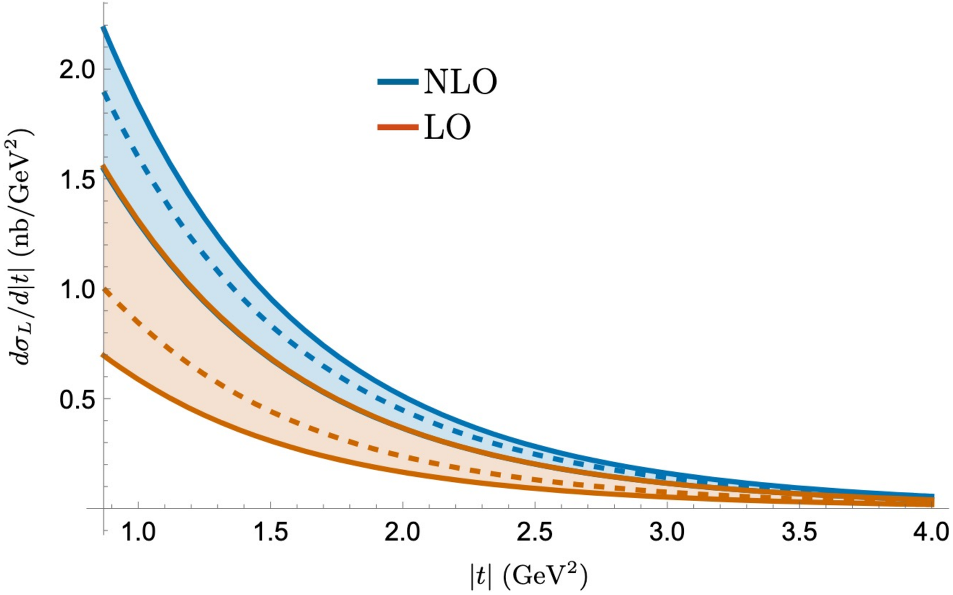


FIG. 6: Differential $\gamma^* p$ cross section in units of nb/GeV^2 at $W = Q = 2.5$ GeV, $D_g = -1$, and $D_s = 0$ as a function of $|t|$. The orange and blue bands represent the LO and NLO cross sections, respectively, with the renormalization scale varied in the range $Q/2 < \mu < 2Q$.