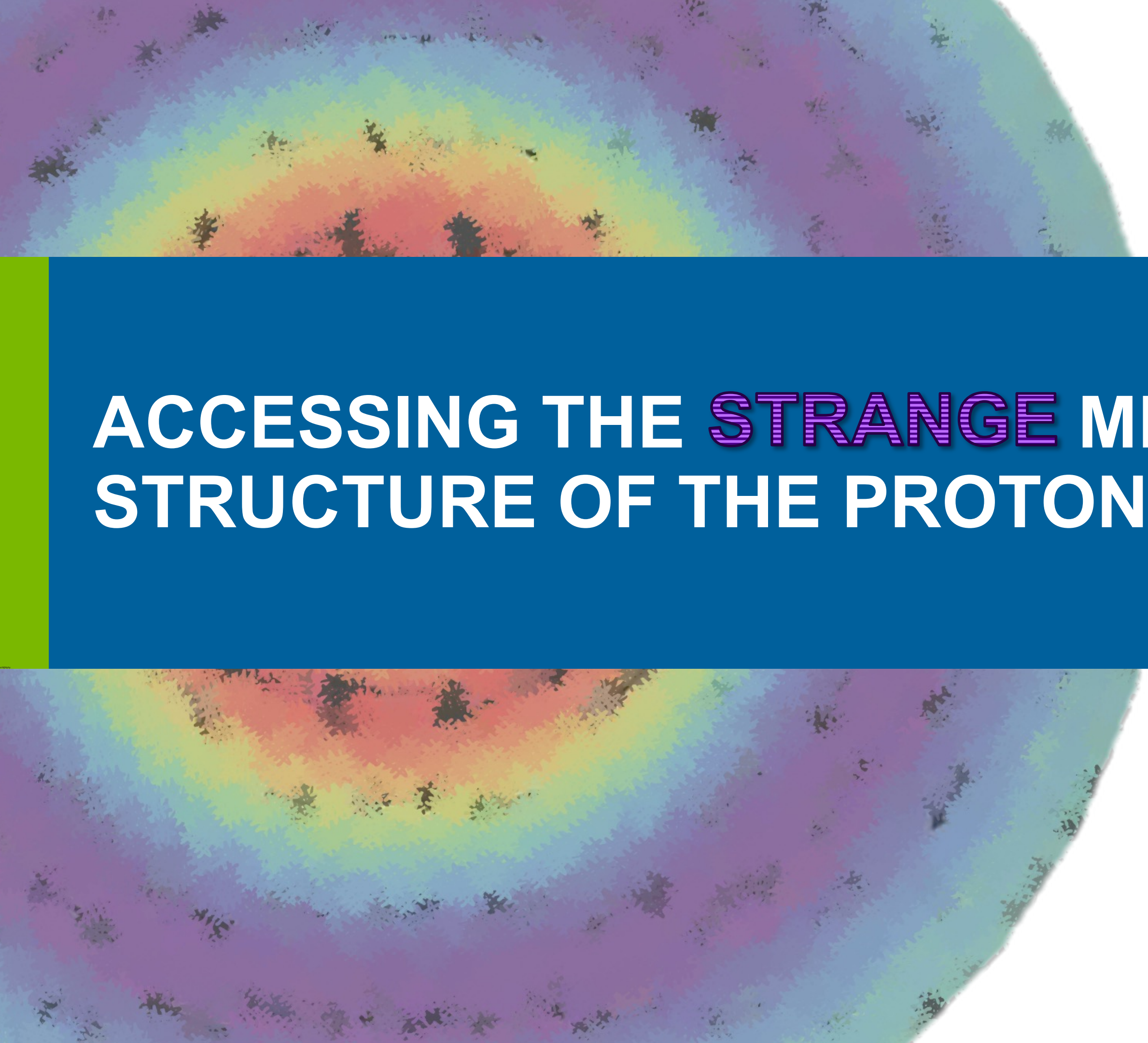


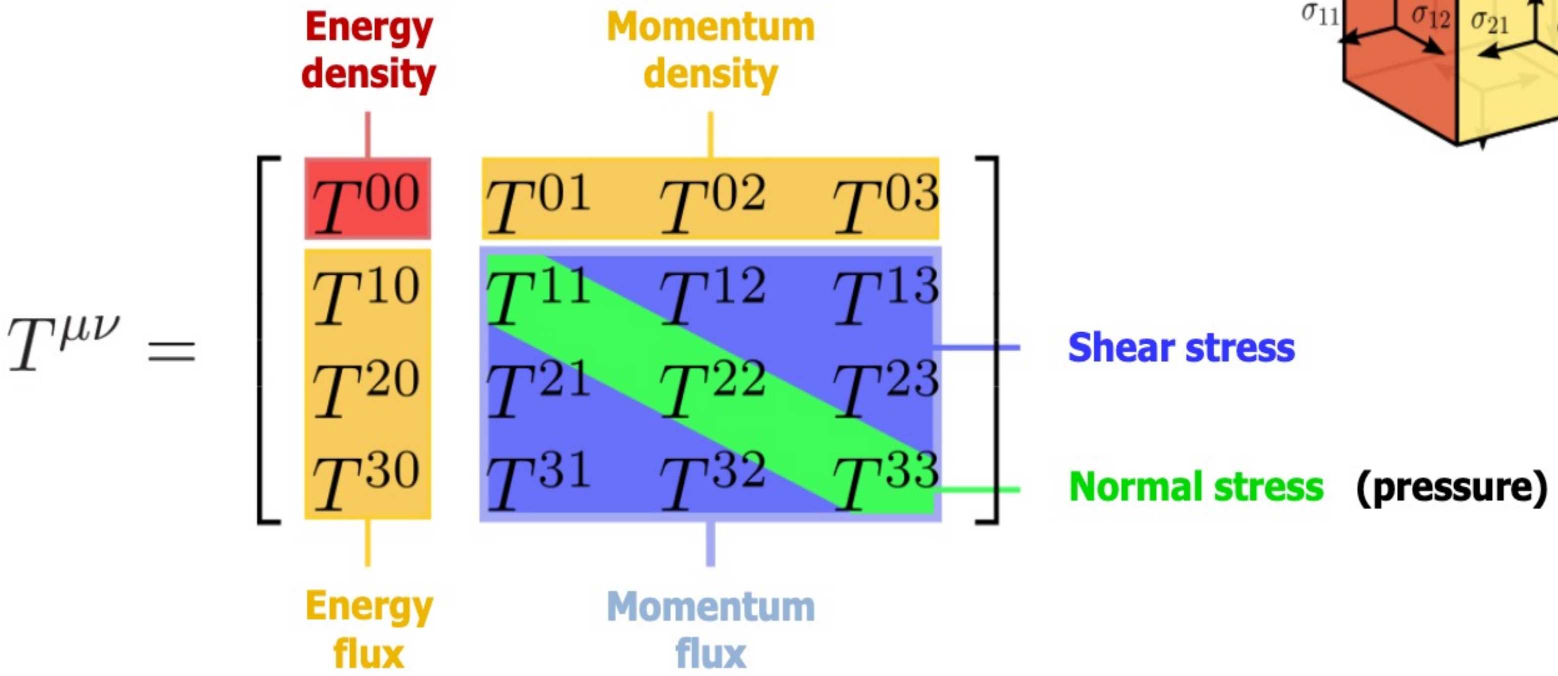
Argonne
NATIONAL LABORATORY

ACCESSING THE STRANGE MECHANICAL STRUCTURE OF THE PROTON AT THE EIC

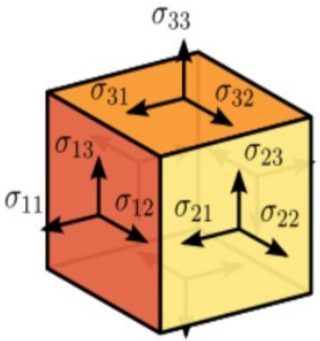
HENRY KLEST

EICUG EC Workshop
July 2024

ENERGY MOMENTUM TENSOR



$$T^{\mu\nu} = \begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$



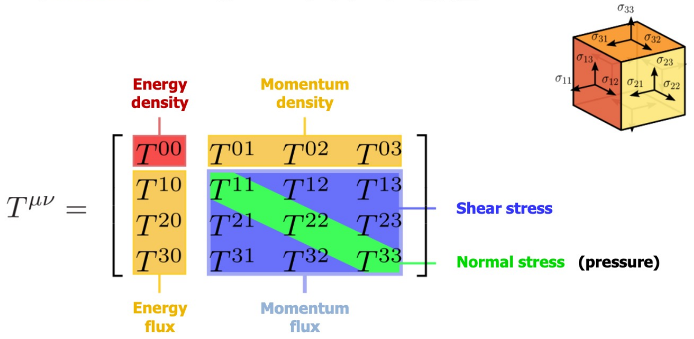
MOTIVATION

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

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

This messy equation is just an informed parameterization of the terms in the QCD EMT

Spiritually similar to e.g. the Wolfenstein parameterization of the CKM matrix



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

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

Form factors

Fourier transforms of *t* distributions

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Form factors

Fourier transforms of *t* distributions

“Gravitational”

Describing the energy-momentum tensor

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

MOTIVATION

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

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

D-term at zero momentum transfer (*t* = 0) represents a fundamental property of the proton, on par with charge, spin, and mass!

em:	$\partial_\mu J^\mu_{\text{em}} = 0$	$\langle N' \vert J^\mu_{\text{em}} \vert N\rangle$	$\longrightarrow$	$G_E(t),\ G_M(t)$	$\longrightarrow$	$Q,\ \mu,$	$\dots$
weak:	PCAC	$\langle N' \vert J^\mu_{\text{weak}} \vert N\rangle$	$\longrightarrow$	$G_A(t),\ G_P(t)$	$\longrightarrow$	$g_A,\ g_p,$	$\dots$
gravity:	$\partial_\mu T^{\mu\nu}_{\text{grav}} = 0$	$\langle N' \vert T^{\mu\nu}_{\text{grav}} \vert N\rangle$	$\longrightarrow$	$A(t),\ B(t),\ D(t)$	$\longrightarrow$	$M,\ J,\ D,$	$\dots$

global properties:

$Q_p = 1.602176487(40) \times 10^{-19}\text{C}$

$\mu_p = 2.792847356(23)\mu_N$

$g_A = 1.2694(28)$

$g_P = 8.06(0.55)$

$M_p = 938.272013(23)\ \text{MeV}$

$J_p = \frac{1}{2}$

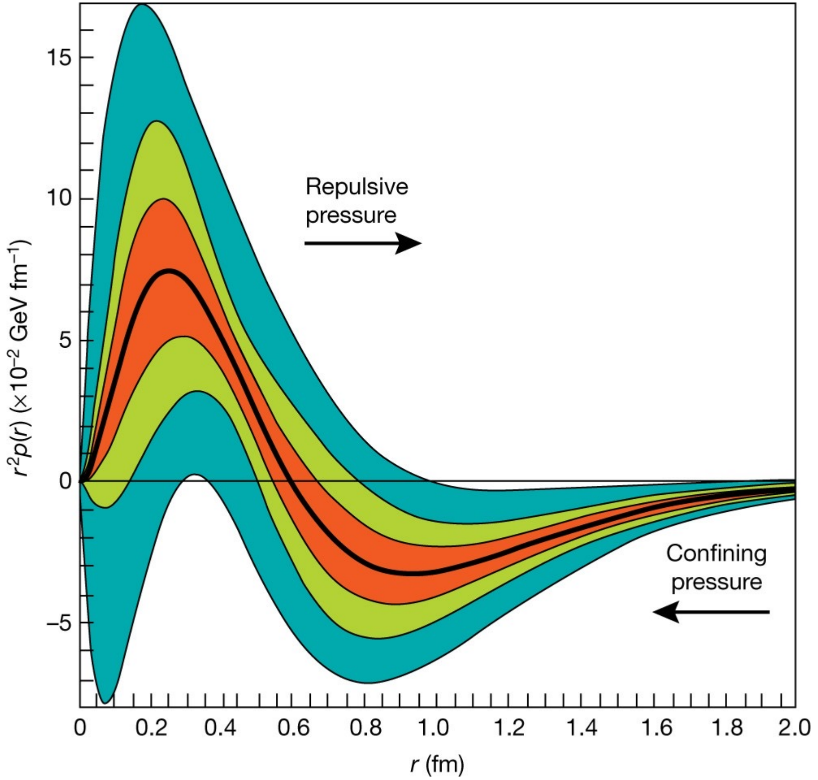
$D = ?$

Slide of P. Schweitzer

MOTIVATION

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

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



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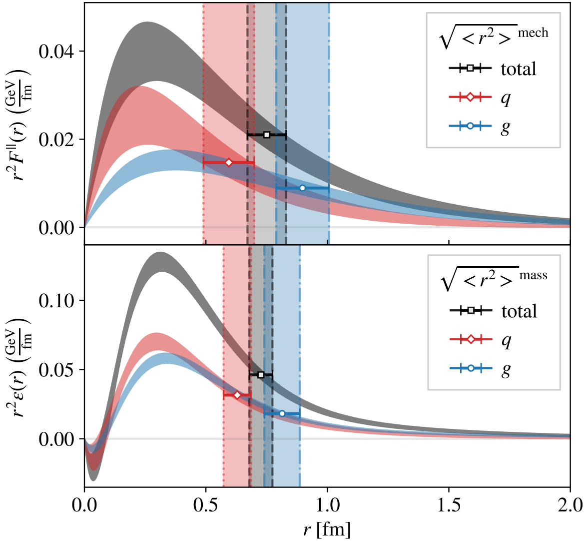
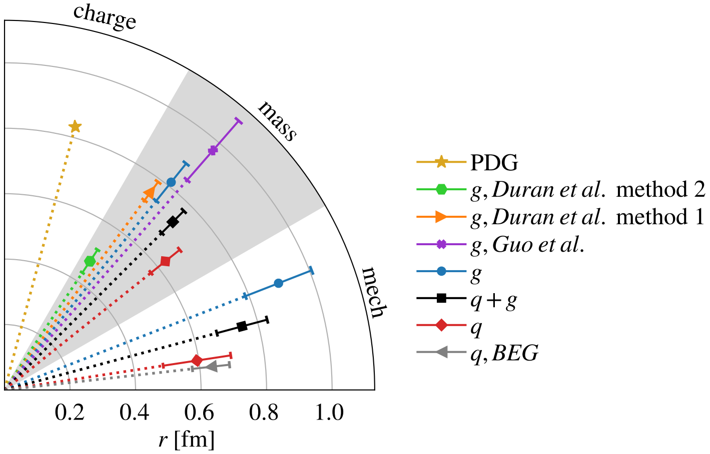




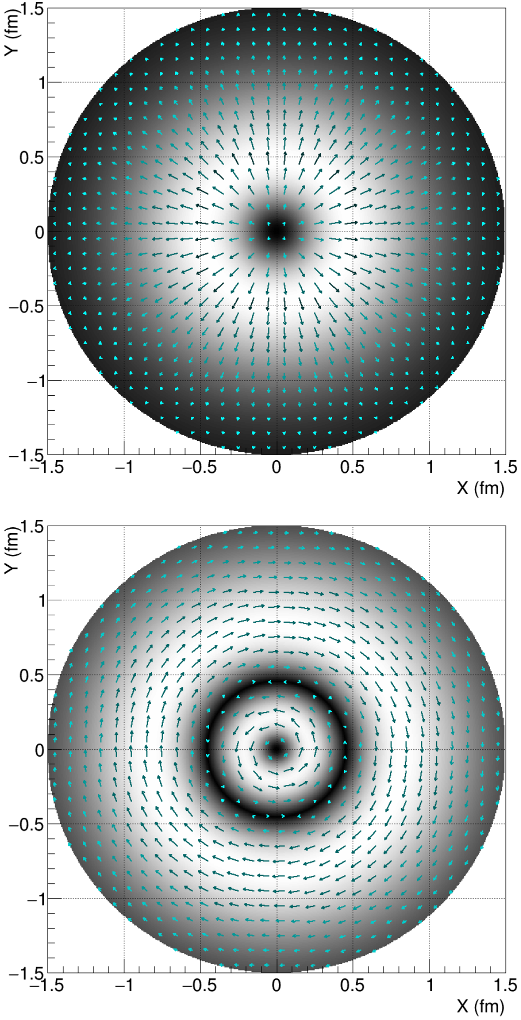
MOTIVATION

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

$$s(r) = -\frac{1}{4m} r \frac{d}{dr} \frac{1}{r} \frac{d}{dr} \tilde{D}(r)$$

$$p(r) = \frac{1}{6m} \frac{1}{r^2} \frac{d}{dr} r^2 \frac{d}{dr} \tilde{D}(r)$$

$$\tilde{D}(r) = \int \frac{d^3\boldsymbol{\Delta}}{(2\pi)^3} e^{-i\boldsymbol{\Delta} r} D(-\boldsymbol{\Delta}^2).$$



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

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

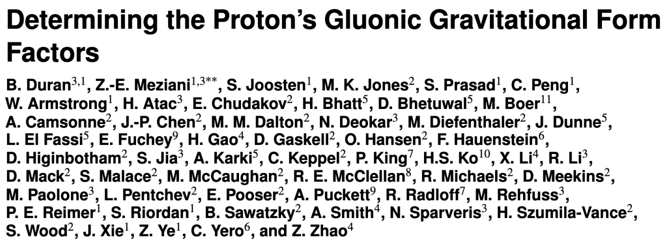
Up & down quarks: Accessible via DVCS cross section & beam-spin asymmetries

The pressure distribution inside the proton

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

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

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



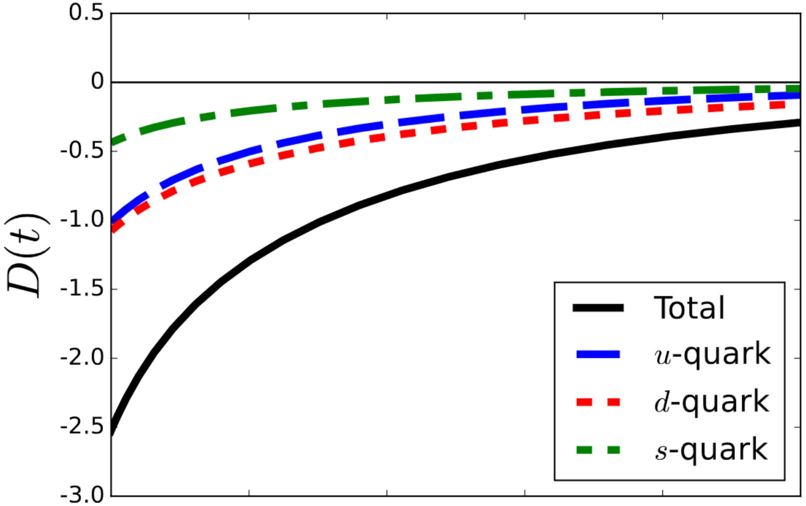
Determining the Proton's Gluonic Gravitational Form Factors

B. Duran[3,1], Z.-E. Meziani[1,3], S. Joosten[1], M. K. Jones[2], S. Prasad[1], C. Peng[1], W. Armstrong[1], H. Atac[3], E. Chudakov[2], H. Bhatt[5], D. Bhetuwal[5], M. Boer[11], A. Camsonne[2], J.-P. Chen[2], M. M. Dalton[2], N. Deokar[3], M. Diefenthaler[2], J. Dunne[5], L. El Fassi[5], E. Fuchey[9], H. Gao[4], D. Gaskell[2], O. Hansen[2], F. Hauenstein[6], D. Higinbotham[2], S. Jia[3], A. Karki[5], C. Keppel[2], P. King[7], H.S. Ko[10], X. Li[4], R. Li[3], D. Mack[2], S. Malace[2], M. McCaughan[2], R. E. McClellan[8], R. Michaels[2], D. Meekins[2], M. Paolone[3], L. Pentchev[2], E. Pooser[2], A. Puckett[9], R. Radloff[7], M. Rehfuss[3], P. E. Reimer[1], S. Riordan[1], B. Sawatzky[2], A. Smith[4], N. Sparveris[3], H. Szumila-Vance[2], S. Wood[2], J. Xie[1], Z. Ye[1], C. Yero[6], and Z. Zhao[4]**

$$D(0) = D_g(0) + D_u(0) + D_d(0) + \underbrace{D_s(0)}_{\text{Strange quarks: Accessible via ?}} + \ldots .$$

WHO CARES ABOUT D_S?

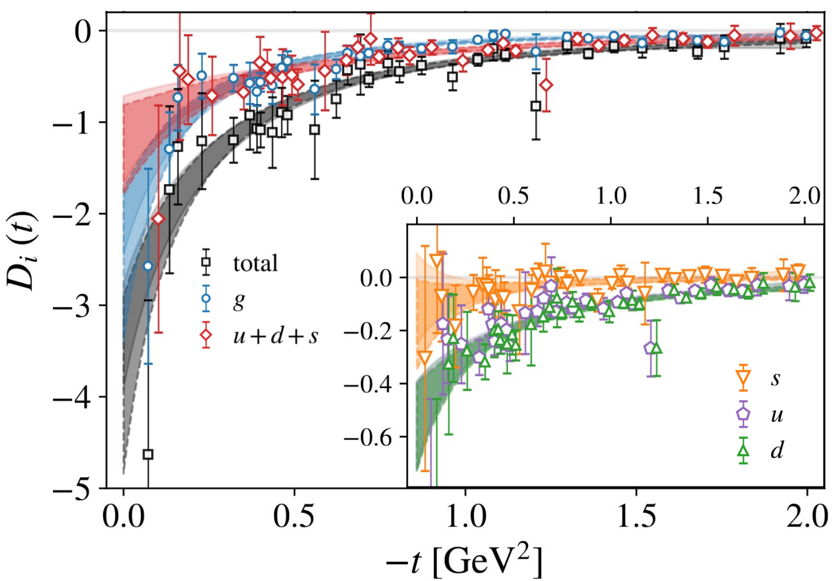
- Naively, D_s should be small
- However, large-N_c theory predicts that the D-term is ”flavor-blind”, i.e. $D_u \sim D_d$ despite their different number densities
  - $D_u \sim D_d$ is supported by lattice results
- Extending this argument, could $D_u \sim D_d \sim D_s$?
- Calculation by Won et al.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

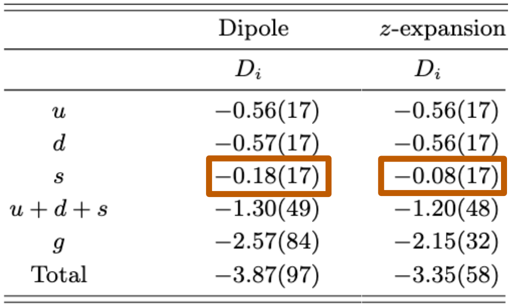


This would make D_s a non-negligible contributor to the total D-term, and thus necessary for a full extraction of many of the mechanical properties of the proton!

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 the **opposite direction** as up & down quarks!





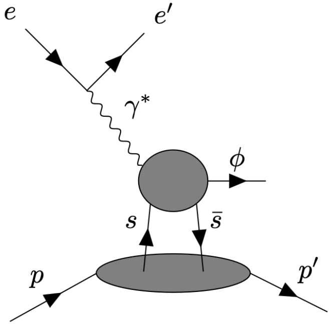
	Dipole	z-expansion
	D_i	D_i
u	−0.56(17)	−0.56(17)
d	−0.57(17)	−0.56(17)
s	−0.18(17)	−0.08(17)
$u+d+s$	−1.30(49)	−1.20(48)
g	−2.57(84)	−2.15(32)
Total	−3.87(97)	−3.35(58)

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)

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



ArXiv:2102.12631

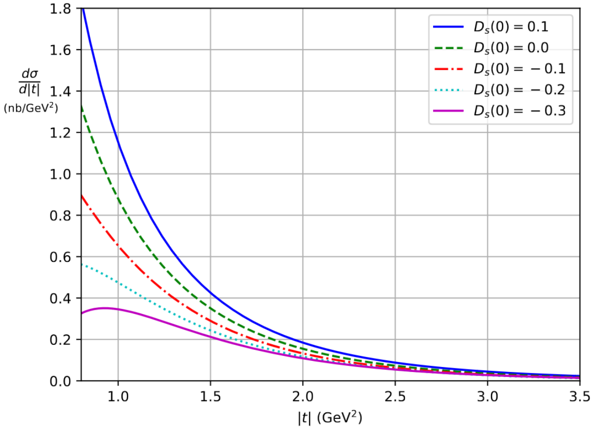
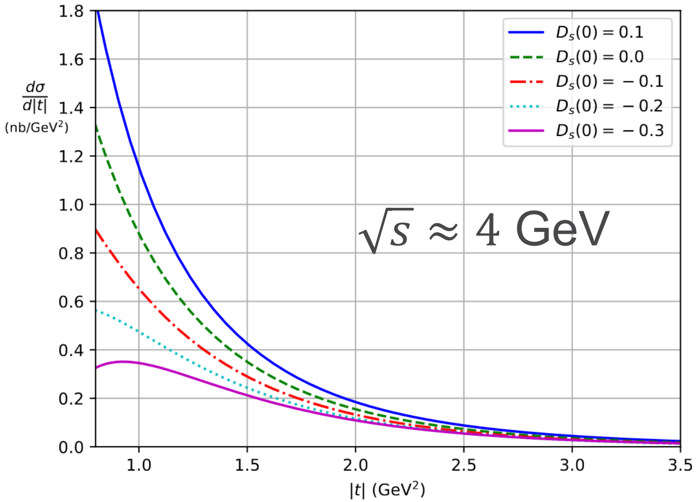


Figure 2: Theoretical predictions for $d\sigma/d|t|$ at $Q^2 = 3.4$ GeV^2 and $W = 2.2$ GeV with different assumptions for $D_s(0)$. In this kinematic range $t_{\min} \approx 0.7$ GeV^2. It can be seen that the introduction of a non-zero $D_s(0)$ has a large impact on the shape and size of the cross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

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|**
  - Most sensitive to strangeness D-term



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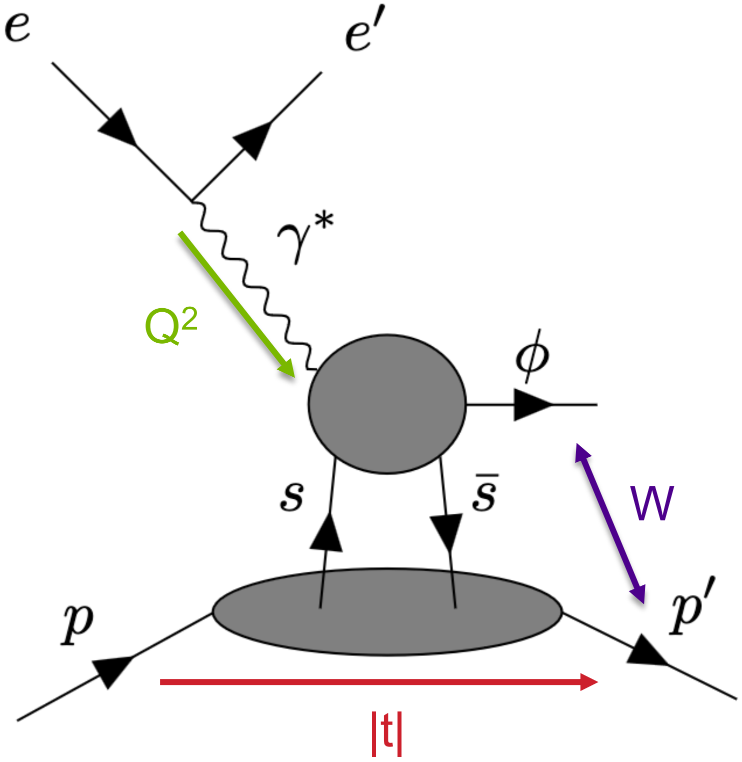
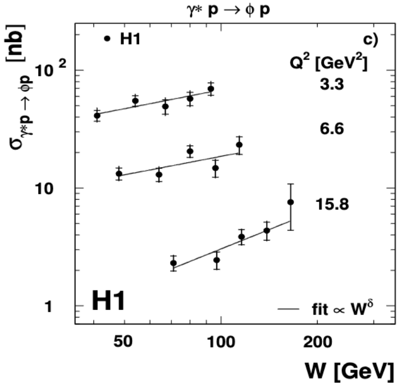


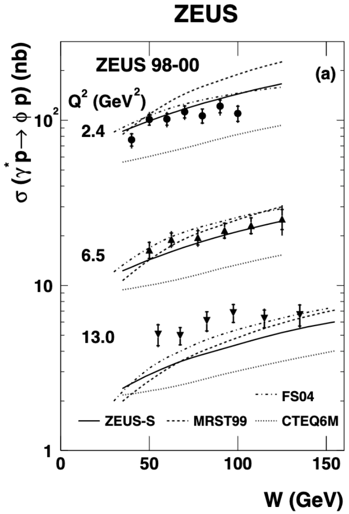
NEAR-THRESHOLD ϕ AT EIC?

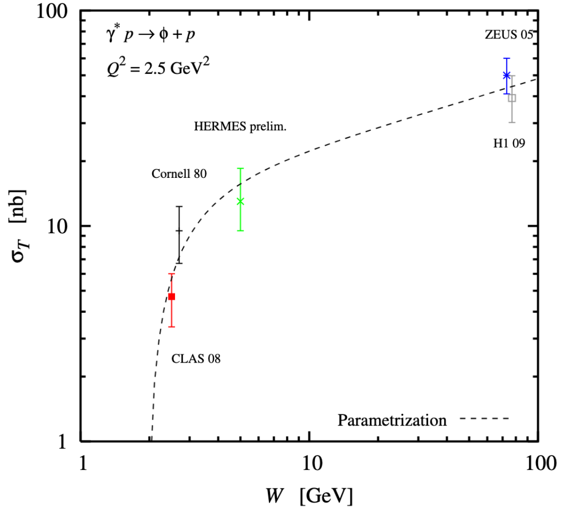
- Explore EIC’s capabilities to measure exclusive ϕ near-threshold

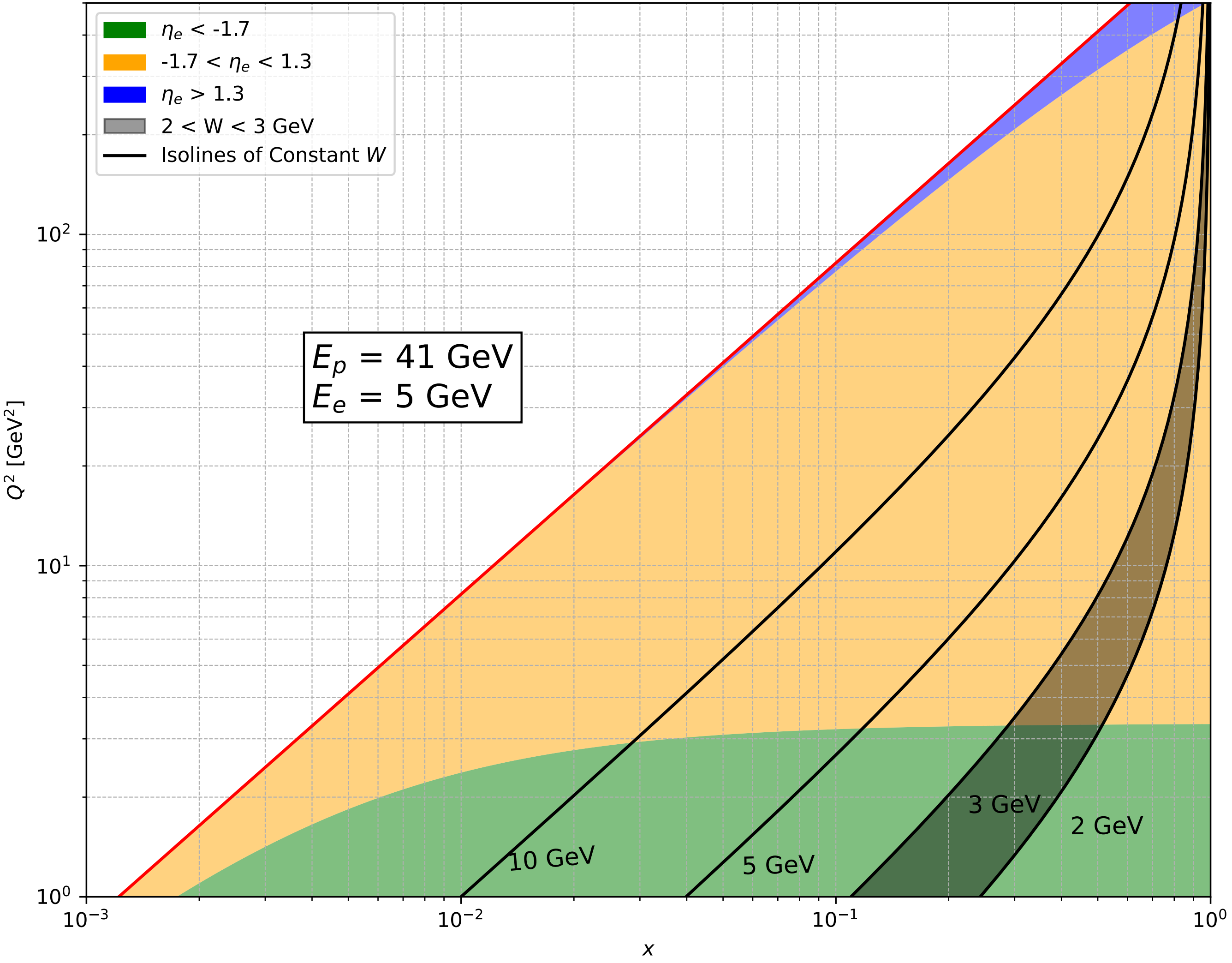
- Near-threshold reactions are hard at colliders
  - This reaction wasn’t measurable for H1 or ZEUS
  - Near-threshold implies that the invariant mass of the proton + produced particles is small
  - Requires acceptance for particles near the beam

- Several aspects make the EIC superior to HERA for these measurements
  - Ability to go to lower proton beam energies, enabling measurement of ϕ decay in central region
  - High luminosity to measure small cross sections
  - Better far forward acceptance



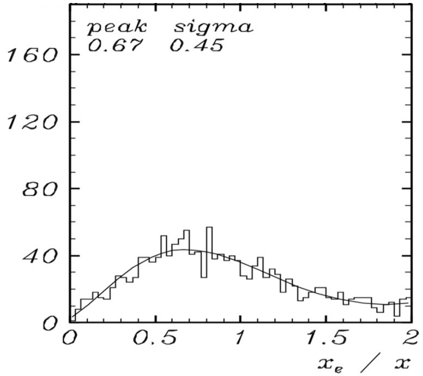




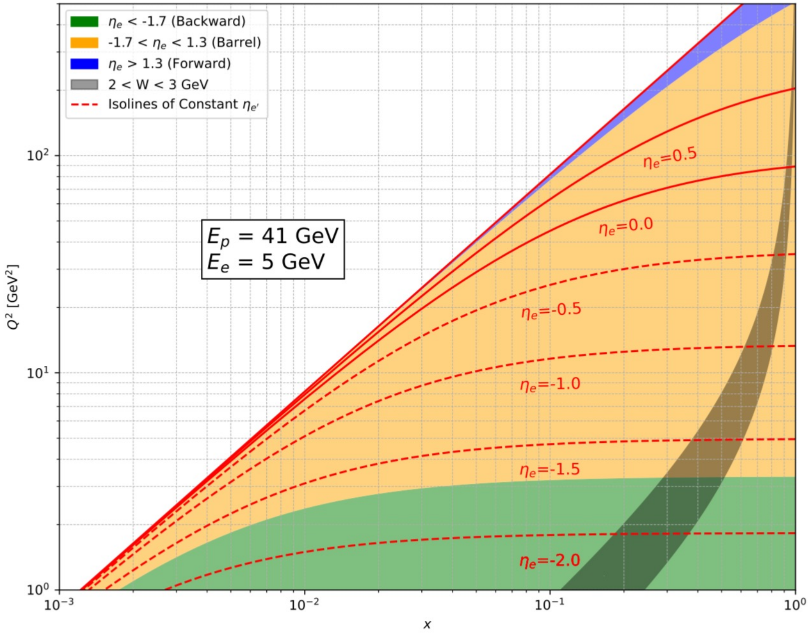


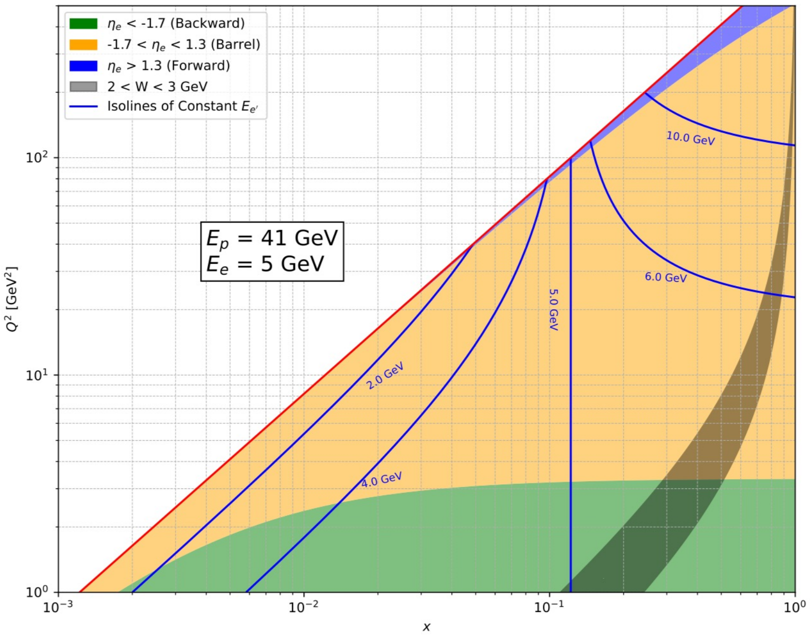
$\eta_e < -1.7$
$-1.7 < \eta_e < 1.3$
$\eta_e > 1.3$
2 < W < 3 GeV
Isolines of Constant W
E_p = 41 GeV
E_e = 5 GeV
10 GeV
5 GeV
3 GeV
2 GeV
Q^2 [GeV^2]
10^0
10^1
10^2
x
10^{-3}
10^{-2}
10^{-1}
10^0

ASIDE: KINEMATICS



- Near-threshold kinematics for ϕ production sits at high x, low y
- Scattered electron is well contained in central detector
  - **However, this is the dreaded low y kinematic region!**
  - Near the kinematic peak of $E_{e'} = E_{e,beam}$, tiny mis-measurements of $E_{e'}$ have a huge impact on where the kinematics are reconstructed (x in particular)
  - The only way out is to use information from the hadronic final state to reconstruct the kinematics, e.g. double-angle method, Σ method





EIC ANALYSIS STRATEGY

- How much information do we need to reconstruct these exclusive ϕ events?
- Option 1: Full missing mass
  - Only reconstruct $e + p$
  - Severe backgrounds

- Option 2: One missed particle
  - $e + p + K$ or $e + K^{+} + K^{-}$
  - Use missing mass technique to reconstruct the remaining particle
  - Resolution on M_x is not great, expect non-trivial background

- Option 3: Fully exclusive reconstruction
  - Require $e + p + K^{+} + K^{-}$

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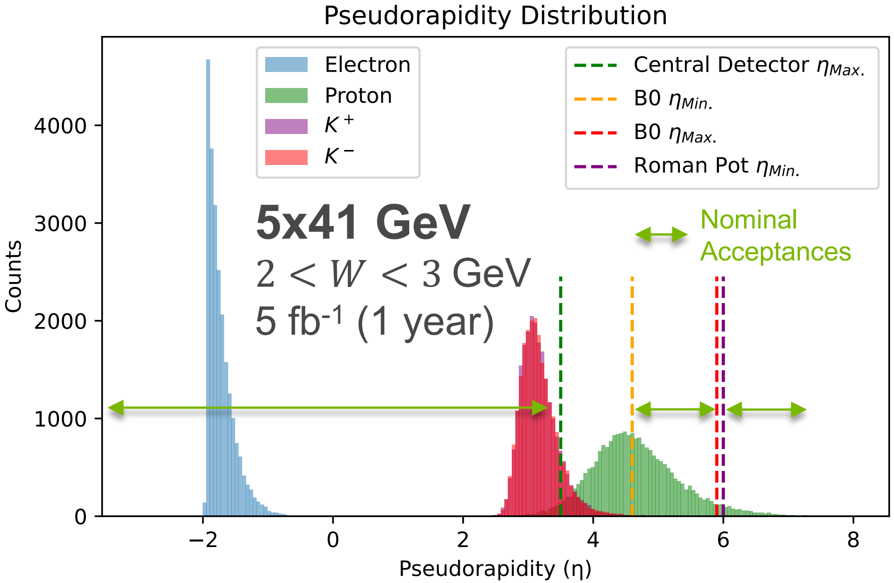
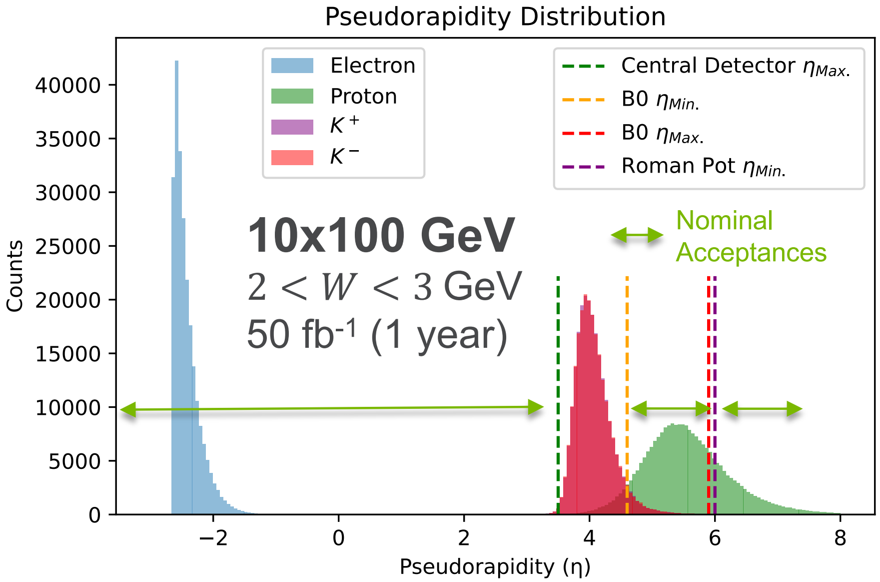
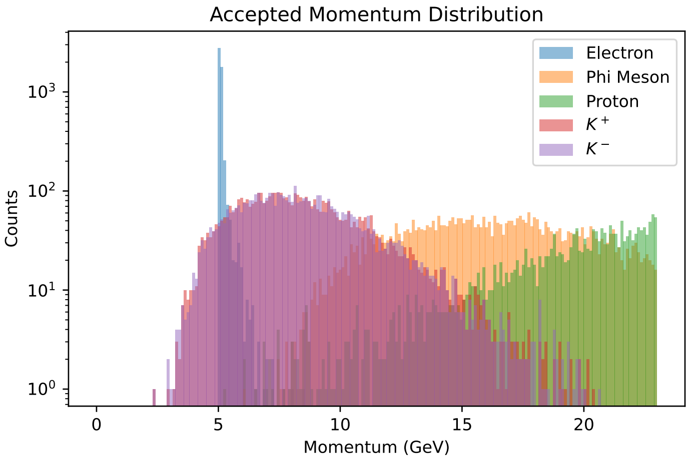
Assume only this technique in this talk

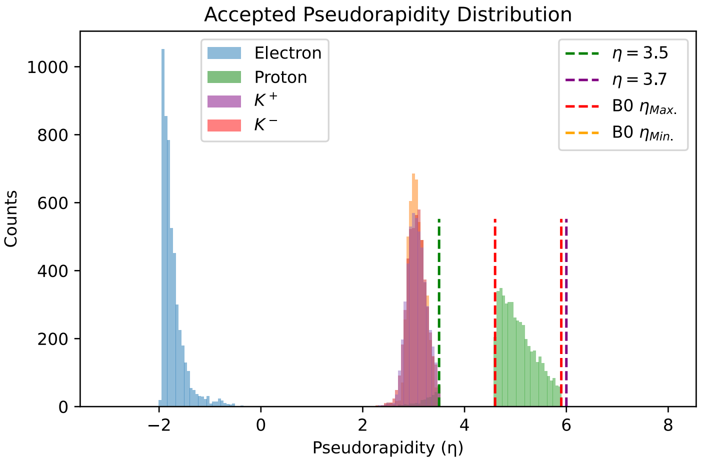
EIC SIMULATION SETUP

- 5 fb^{-1} of 5 GeV e^- on 41 GeV p data
  - $Q^2 > 2$ GeV^2
  - 1 year of data taking
  - Use lAger event generator
  - Cross section model based on a parameterization of all existing world data, developed for CLAS12
- Only the 5x41 energy setting allows the kaons from the ϕ decay to make it into the central detector acceptance
  - Boost from proton beam is too large even for 100 GeV proton beam energy



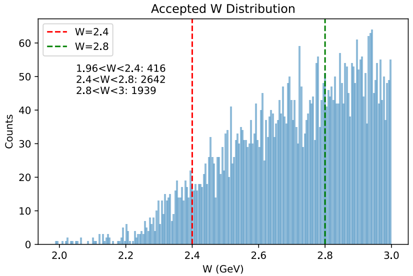


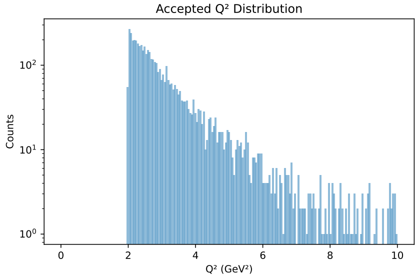


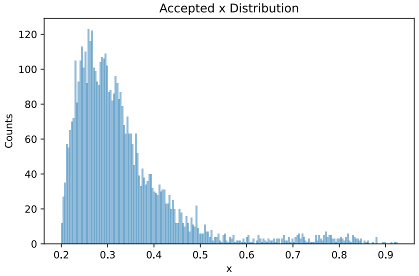


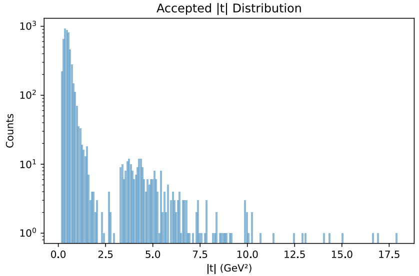
- Pessimistically assume 50% B0 acceptance & 0% RP & OMD acceptance
  - Fairly few detectable events send proton to RPs or OMDs for $Q^2 > 2$ GeV^2
  - $|t|$ distribution is steep!

- Statistics seem reasonable in this case!



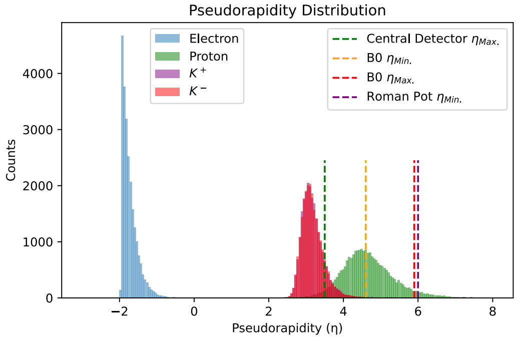




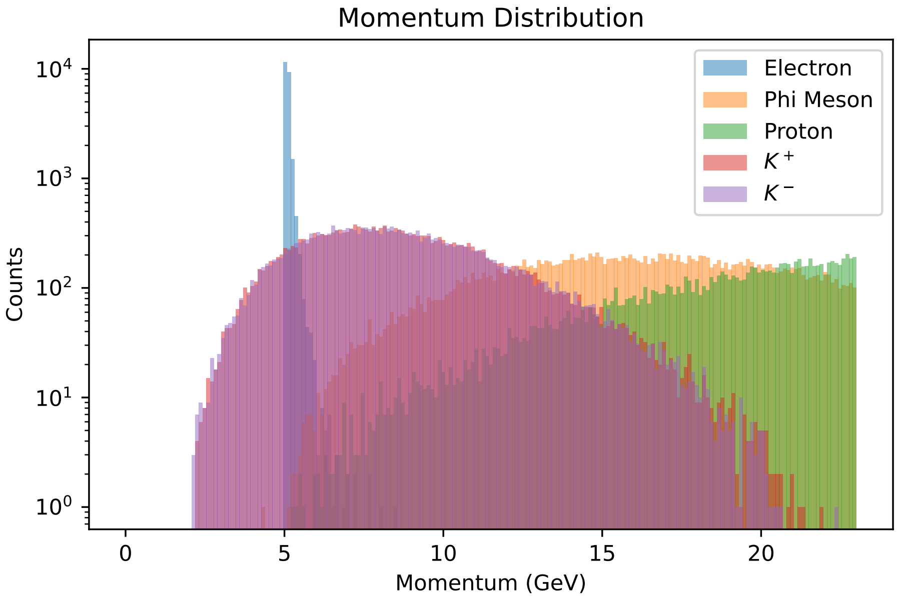


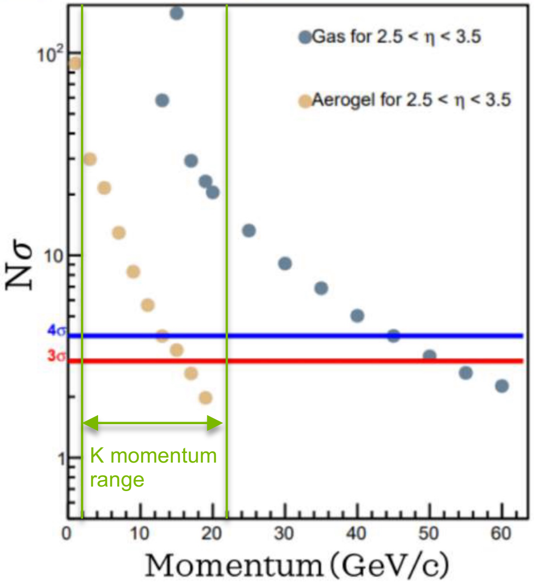
PID

- Kaon momenta range from a few GeV to ~20 GeV
- dRICH can separate pions from kaons consistently in this momentum & pseudorapidity range
  - Kaons begin to radiate in aerogel (n = 1.026) around 2.5 GeV
  - Kaons in C_2F_6 produce rings above 15 GeV



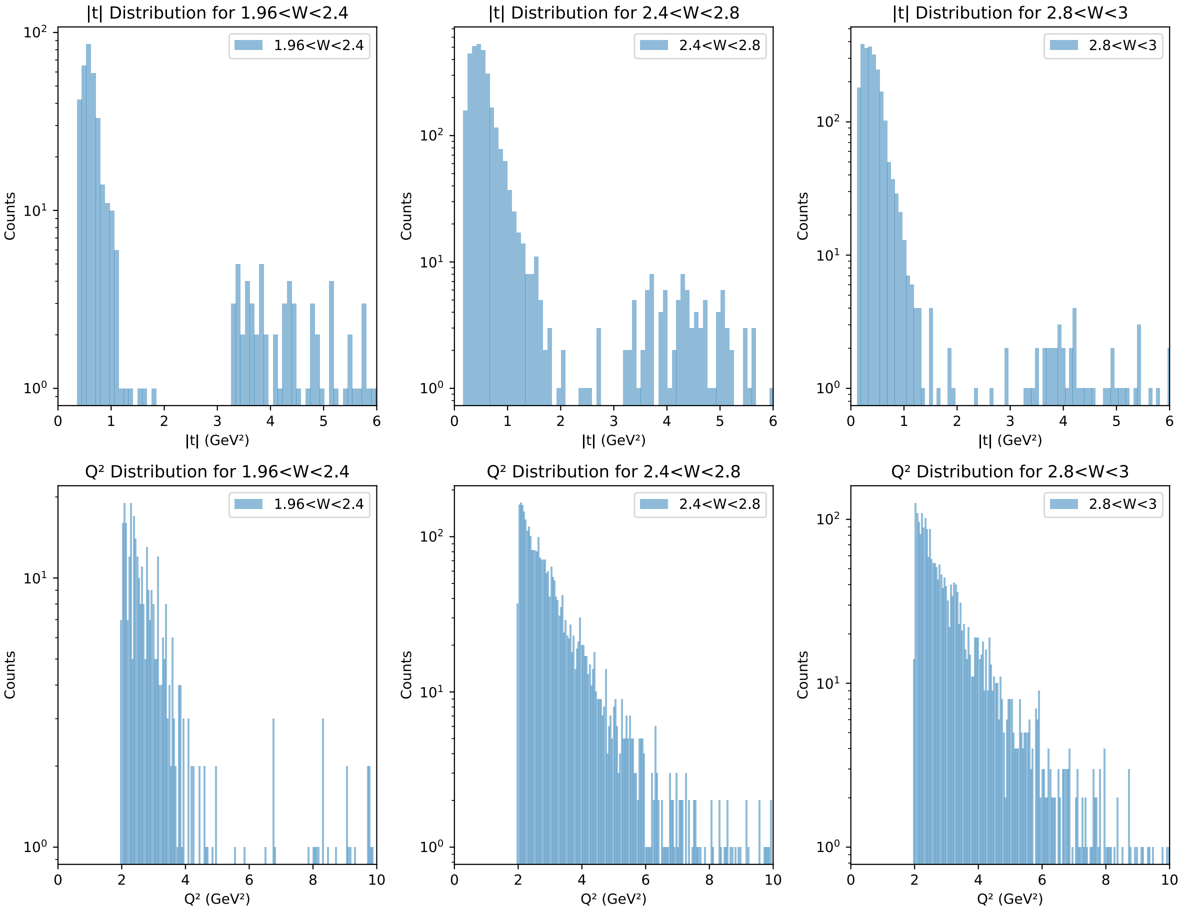
Expect greater than 4σ separation power for all kaons from this process!





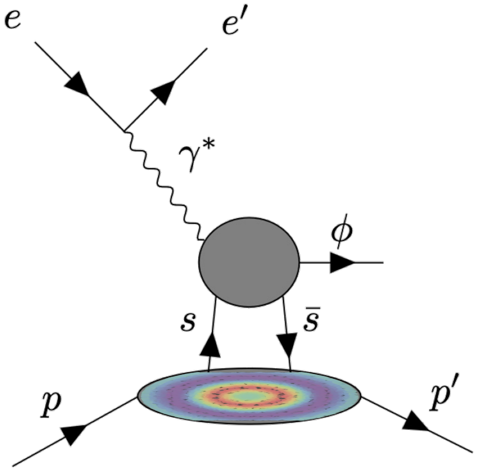
Accepted |t|-distributions

- Multi-differential measurement possible!
  - E.g. 3 different bins in *W*
- Evolution of cross section with *W* is important to rule out contamination from baryonic resonances decaying to $\phi + p$
- Measurement likely to be statistics limited
  - Integrated luminosity greater than 5 fb^{-1} would improve the situation
  - Let's run more than one year of 5x41 ☺



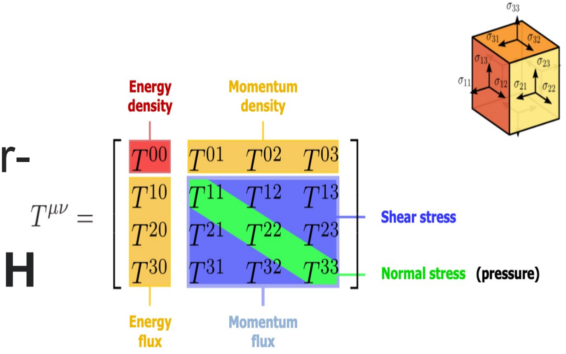
CONCLUSION

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

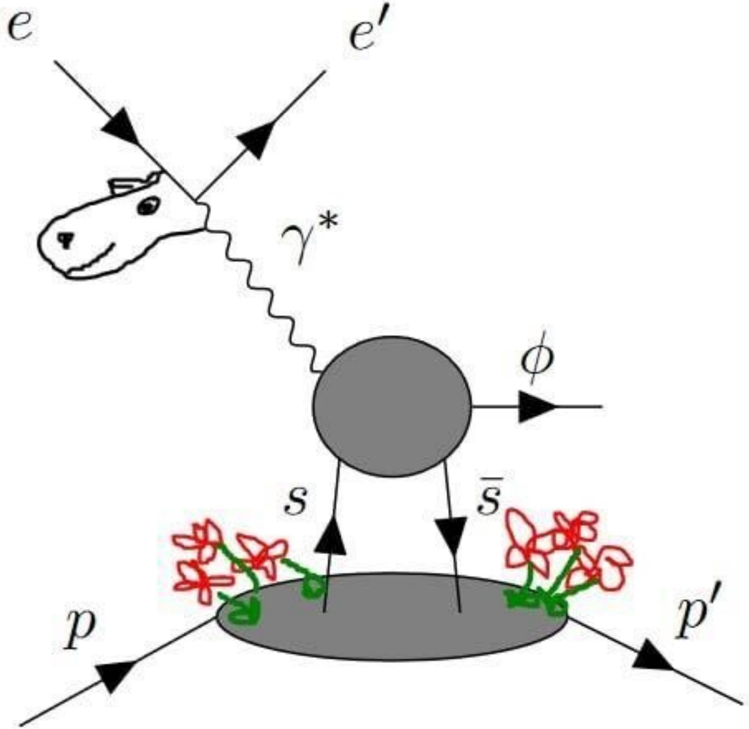


- Deep exclusive ϕ production offers the opportunity to learn about the forces exerted by strange quarks inside the proton!

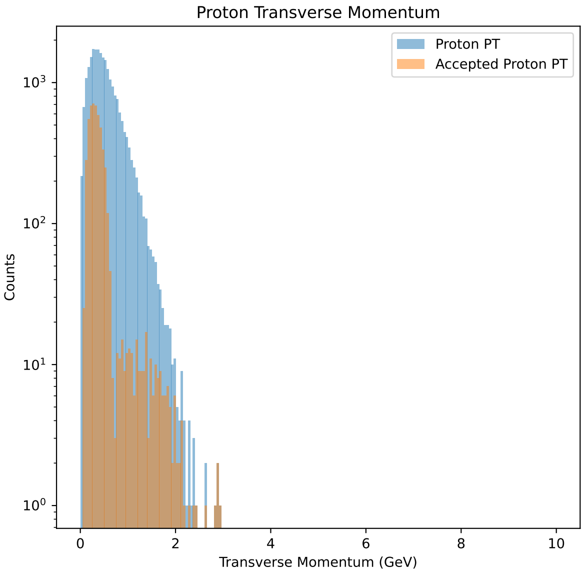
- EIC 5x41 energy configuration **can** provide access to near-threshold ϕ electroproduction!
  - **Sensitive to high η acceptance for tracking & dRICH**

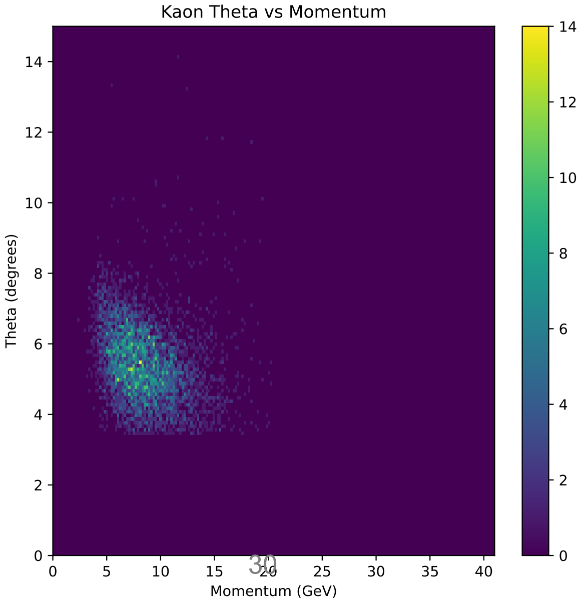


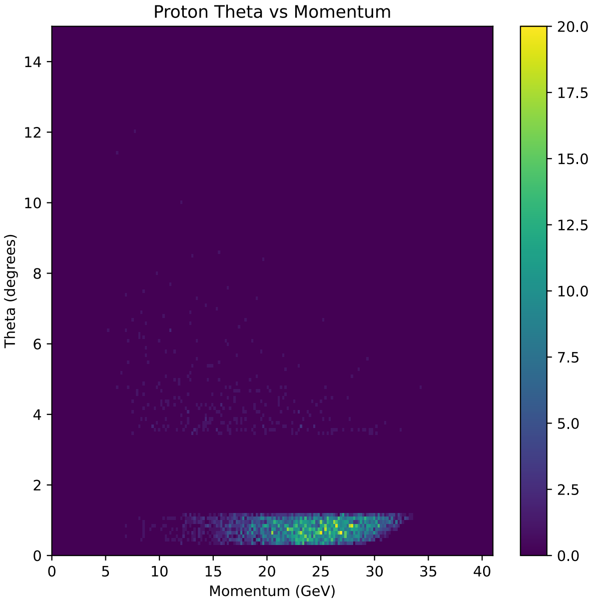
BACKUP



Accepted particle distributions

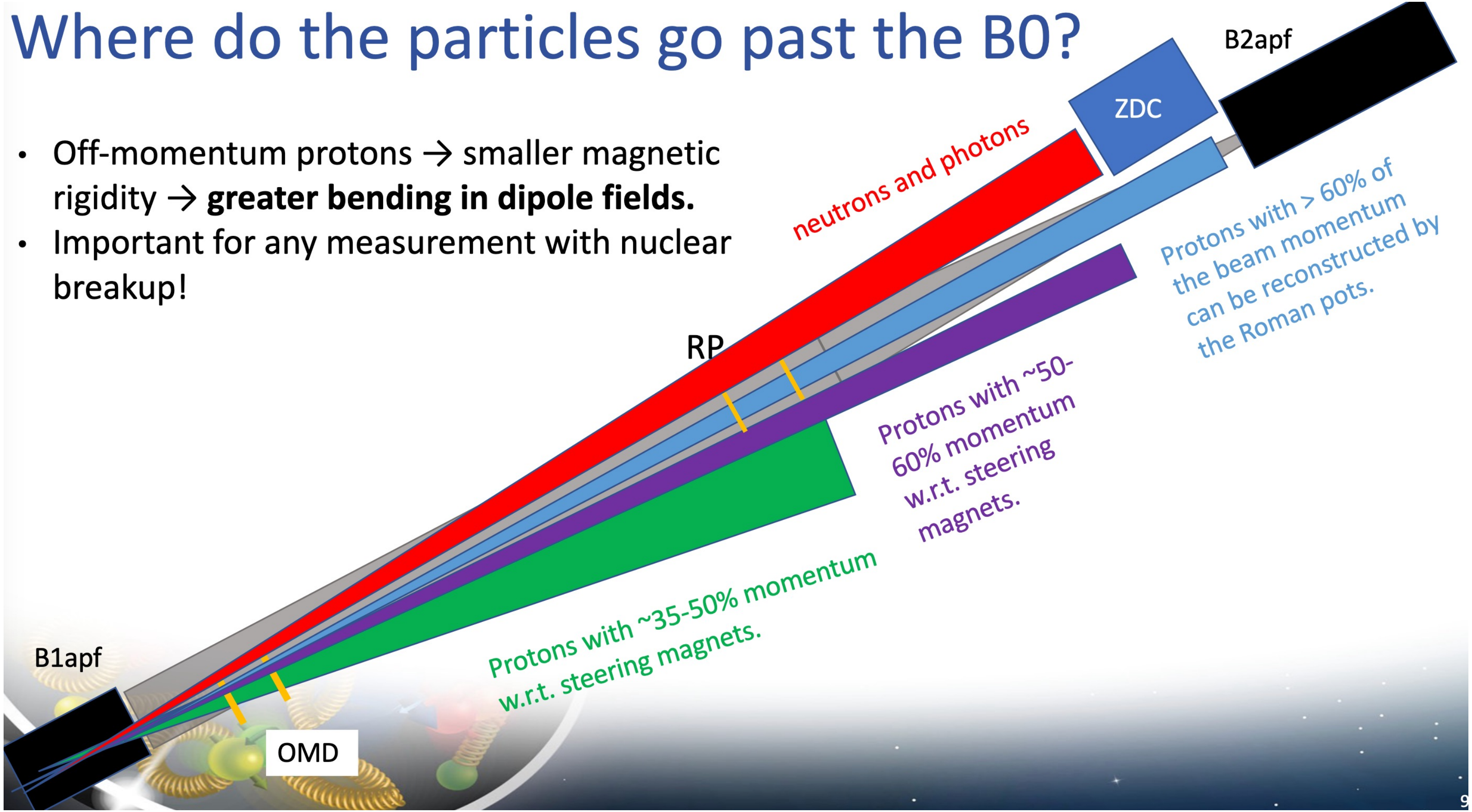


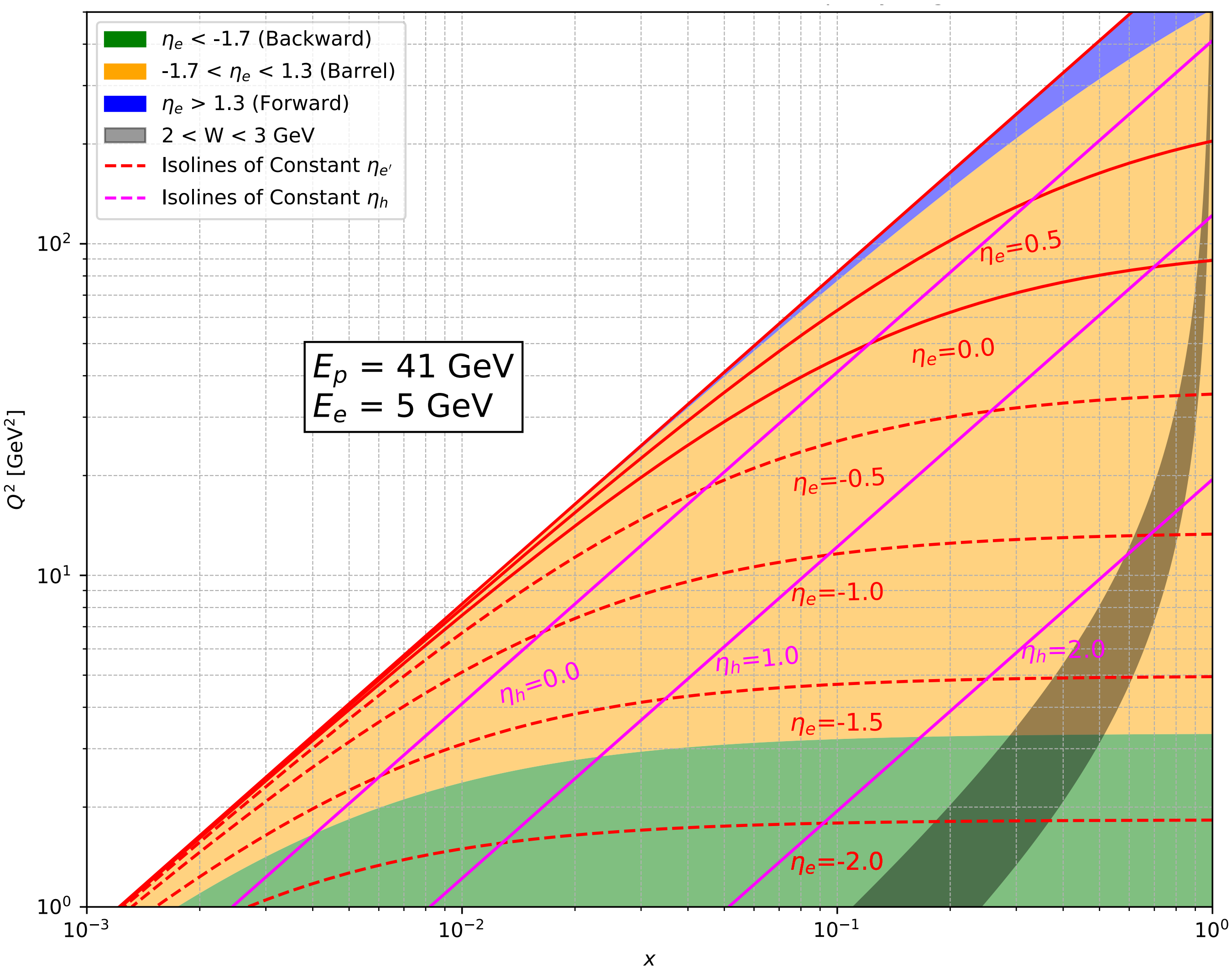




Where do the particles go past the B0?

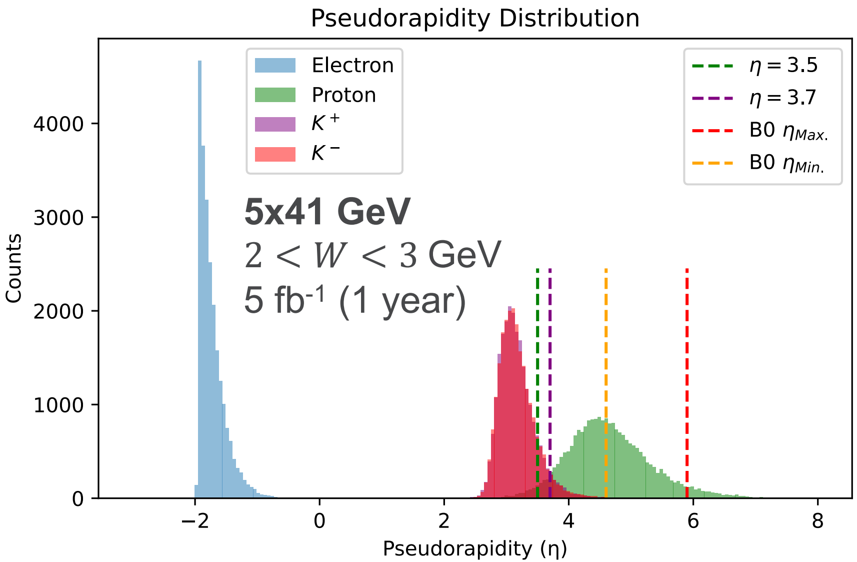
- Off-momentum protons → smaller magnetic rigidity → **greater bending in dipole fields.**
- Important for any measurement with nuclear breakup!

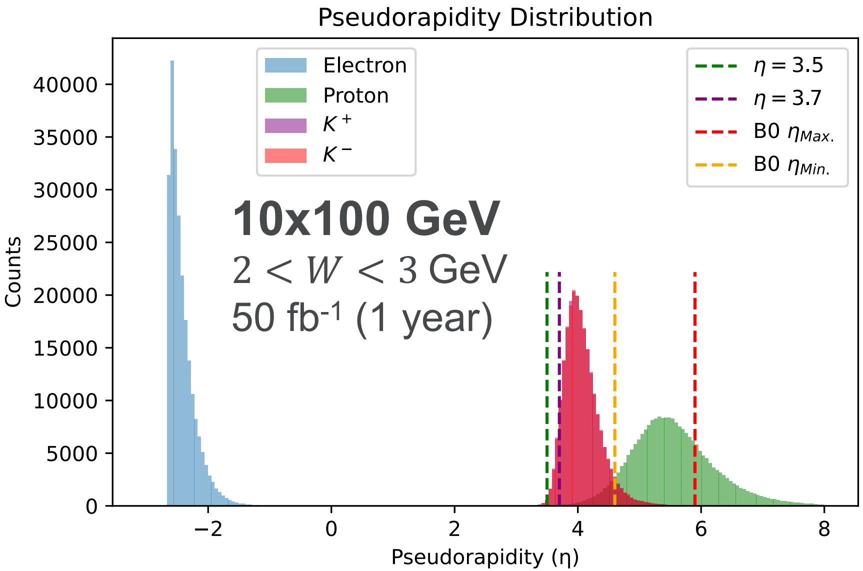


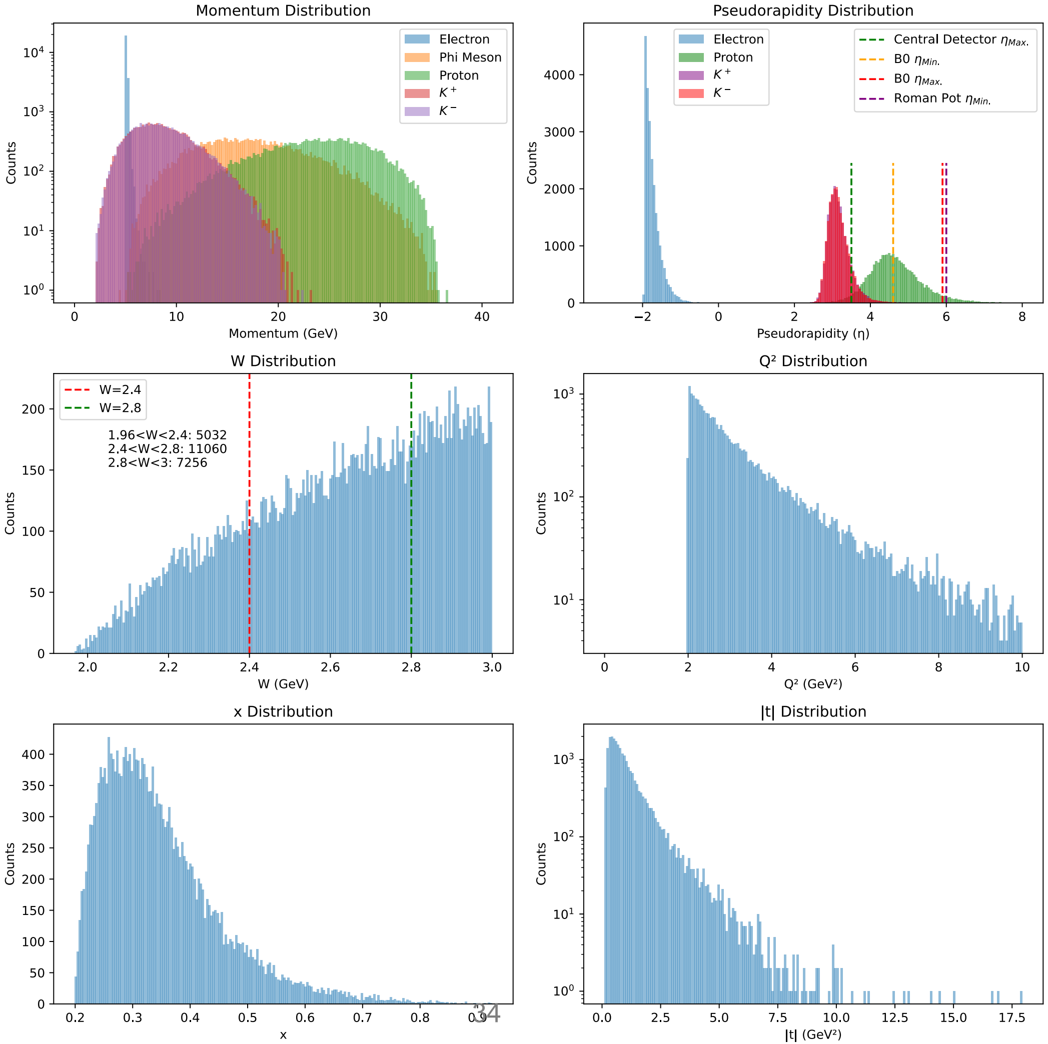

η_e < -1.7 (Backward)
-1.7 < η_e < 1.3 (Barrel)
η_e > 1.3 (Forward)
2 < W < 3 GeV
Isolines of Constant $\eta_{e'}$
Isolines of Constant η_h
E_p = 41 GeV
E_e = 5 GeV
η_e=0.5
η_e=0.0
η_e=-0.5
η_e=-1.0
η_e=-1.5
η_e=-2.0
η_h=0.0
η_h=1.0
η_h=2.0
10^2
10^1
10^0
Q^2 [GeV^2]
10^{-3}
10^{-2}
10^{-1}
10^0
x

PSEUDORAPIDITY ACCEPTANCE

- If the η range of the dRICH PID extends even to η = 3.7, could potentially reconstruct this final state also in the 10x100 energy configuration
  - **Note y-axes!** 10x more integrated luminosity available in 10x100
  - Possible that the tail of the 10x100 statistics could provide a better measurement than the whole 5x41 dataset

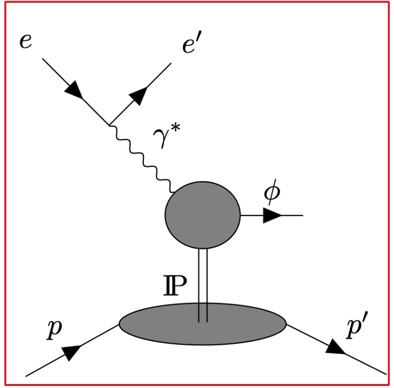




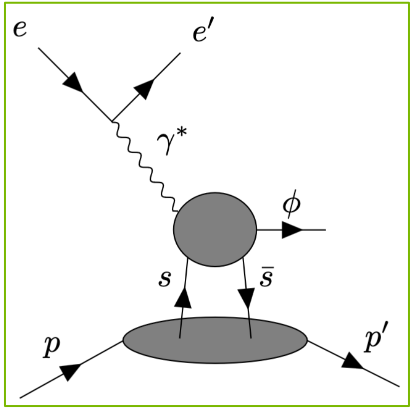

Momentum Distribution
Electron
Phi Meson
Proton
K^+
K^-
Counts
Momentum (GeV)
Pseudorapidity Distribution
Electron
Proton
K^+
K^-
Central Detector $\eta_{Max.}$
B0 $\eta_{Min.}$
B0 $\eta_{Max.}$
Roman Pot $\eta_{Min.}$
Counts
Pseudorapidity (η)
W Distribution
W=2.4
W=2.8
1.96<W<2.4: 5032
2.4<W<2.8: 11060
2.8<W<3: 7256
Counts
W (GeV)
Q² Distribution
Counts
Q² (GeV²)
x Distribution
Counts
x
|t| Distribution
Counts
|t| (GeV²)

REALITY CHECK

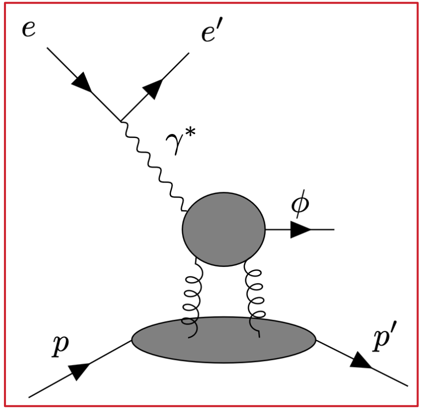
- The reality is (as always) that it’s not so simple!
- Other physics processes can contribute to ϕ electroproduction
  - This will dilute the sensitivity to the D-term
- **Needs more phenomenological input before we can really claim an extraction of D_s**
  - E.g. calculation of gluon exchange contribution 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)

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

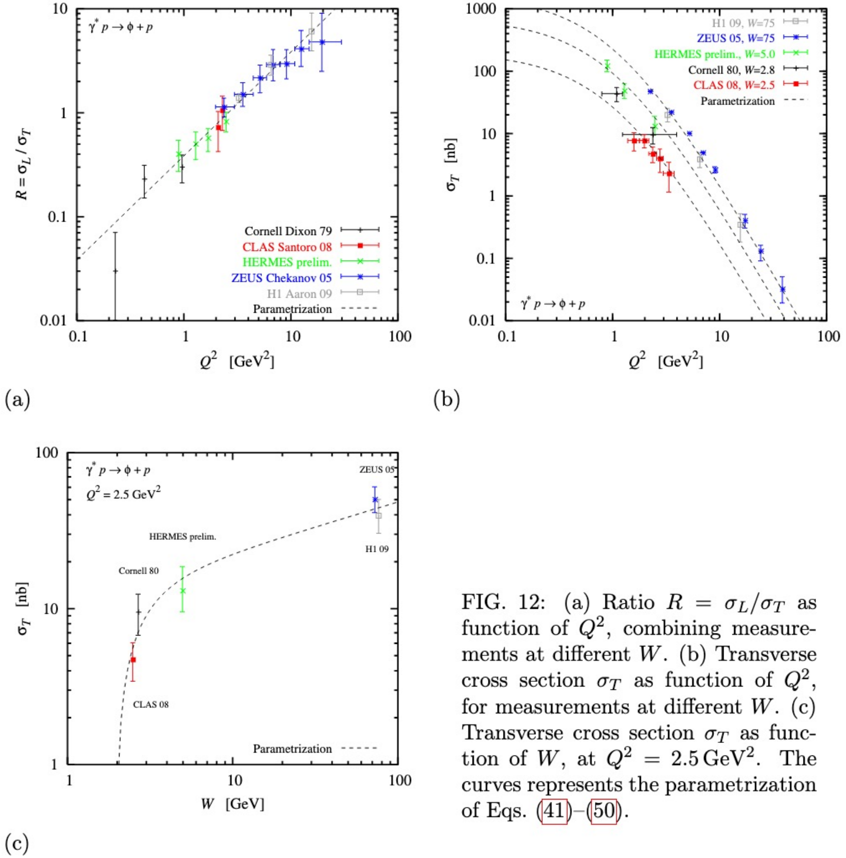


FIG. 12: (a) Ratio $R = \sigma_L/\sigma_T$ as function of Q^2, combining measurements at different W. (b) Transverse cross section σ_T as function of Q^2, for measurements at different W. (c) Transverse cross section σ_T as function of W, at $Q^2 = 2.5\,\mathrm{GeV}^2$. The curves represents the parametrization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

CROSS SECTION MODEL

The differential cross section is given by the general expression

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

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

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

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

1. Exponential t–dependence

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

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

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

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

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

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

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

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

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

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

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

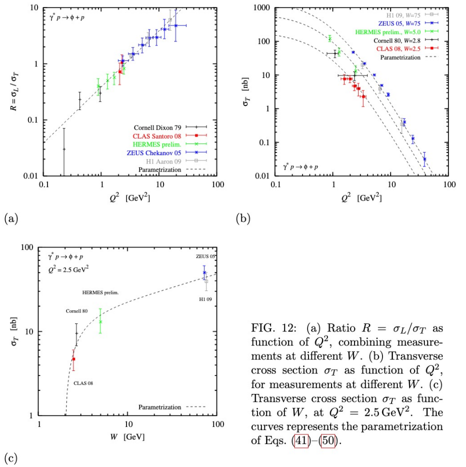


FIG. 12: (a) Ratio $R = \sigma_L/\sigma_T$ as function of Q^2, combining measurements at different W. (b) Transverse cross section σ_T as function of Q^2, for measurements at different W. (c) Transverse cross section σ_T as function of W, at $Q^2 = 2.5\,\text{GeV}^2$. The curves represents the parametrization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

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

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

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

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

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

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

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

The longitudinal cross section is parametrized as

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

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

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