Measurements of Exclusive ϕ Production in Hall C at Jefferson Lab

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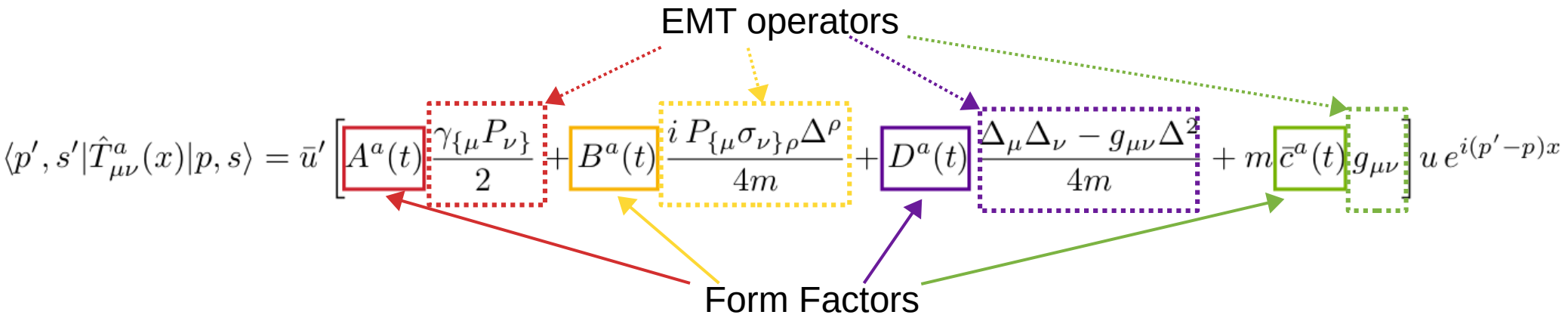
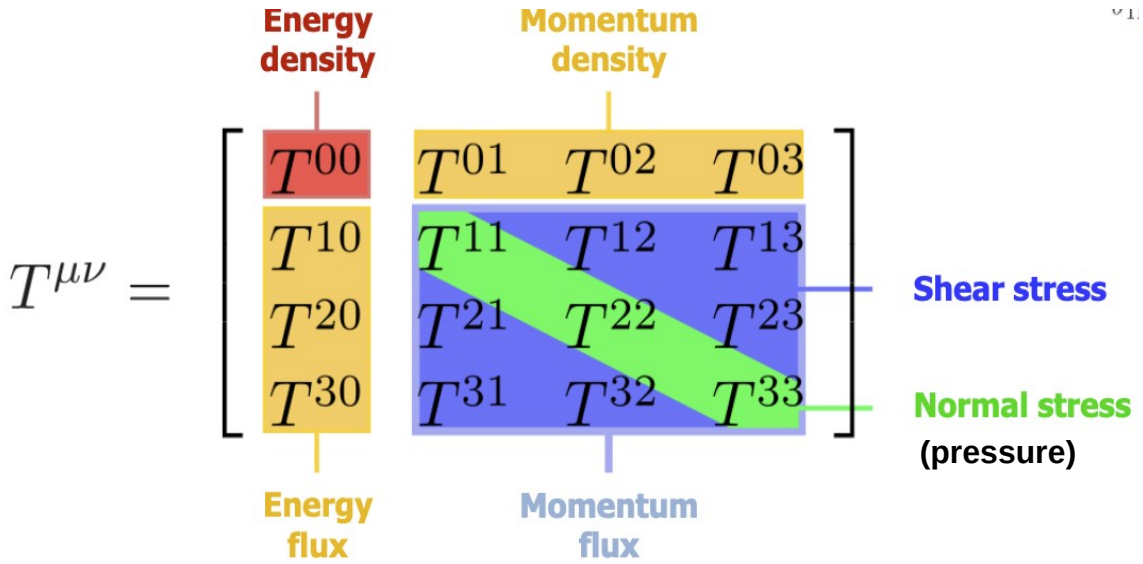
Towards Improved Hadron Femtography with Exclusive Reactions Workshop V
Charlottesville, July 20th, 2026

Jefferson Lab

Exclusive ϕ Electroproduction
Gravitational Form Factors

- Proton mechanical structure defined via the QCD Energy-Momentum Tensor
- Gravitational Form Factors: information about matrix elements of the QCD EMT





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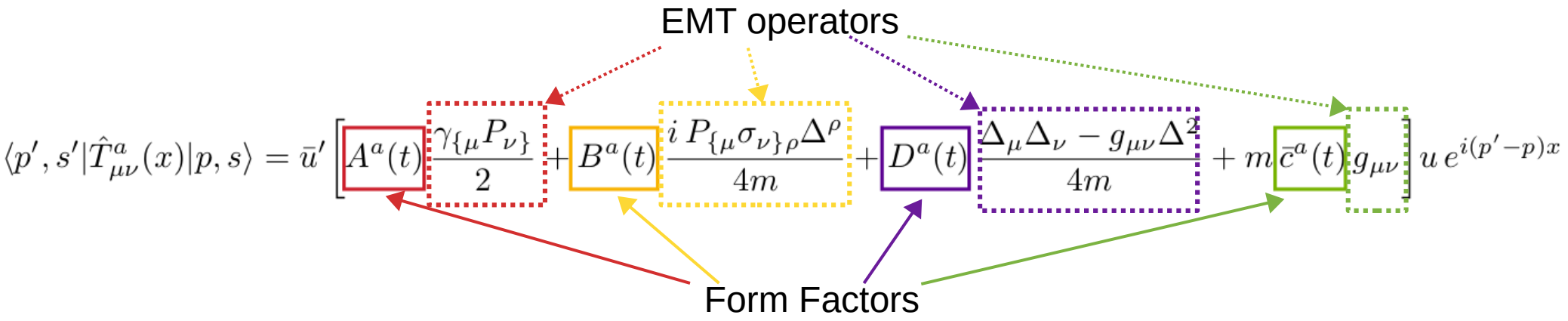

- A(t=0), B(t=0), $\bar{c}(t=0)$ well constrained experimentally, $D(t=0)$ / D-term isn't;
- D-term provides access to fondamental mechanical properties of the proton

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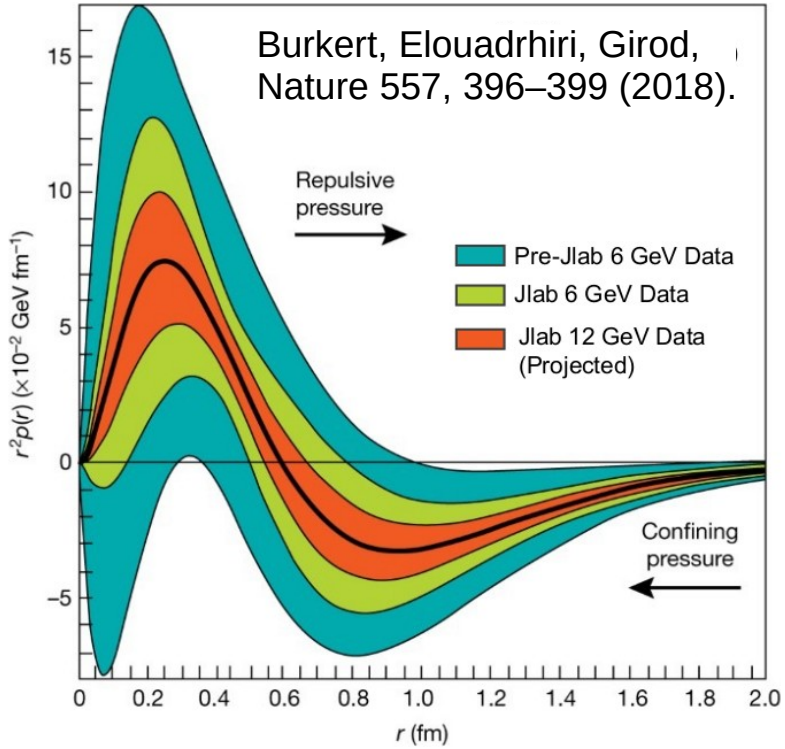
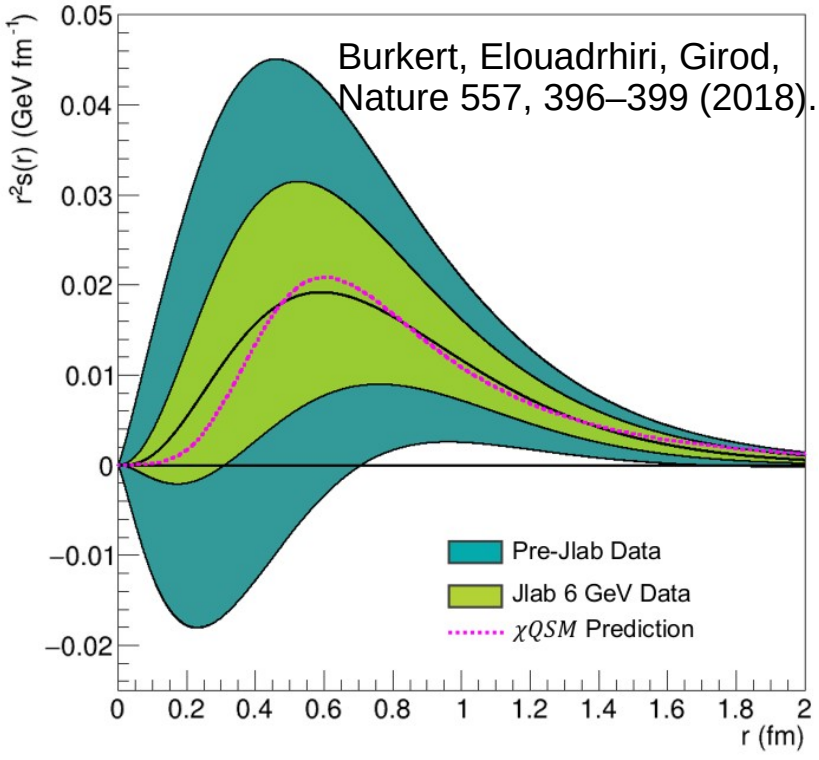
- Gravitational Form Factors: information about matrix elements of the QCD EMT
  - $A(t=0)$, $B(t=0)$, $\bar{c}(t=0)$ well constrained experimentally, $D(t=0)$ / D-term isn't;
  - D-term provides access to fondamental mechanical properties of the proton:
    - Pressure, Shear force, tangential, normal forces
    - Existing estimations : DVCS with u, d, contributions to D-term



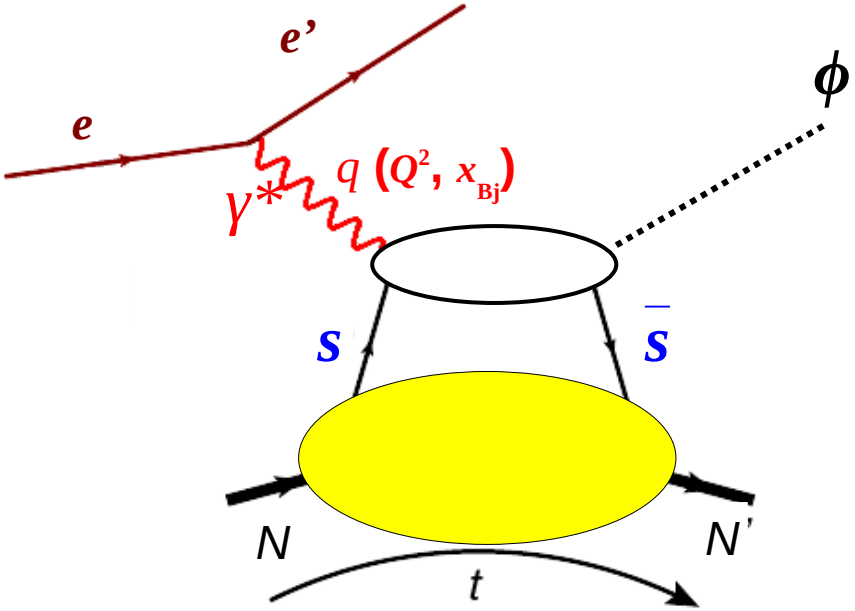


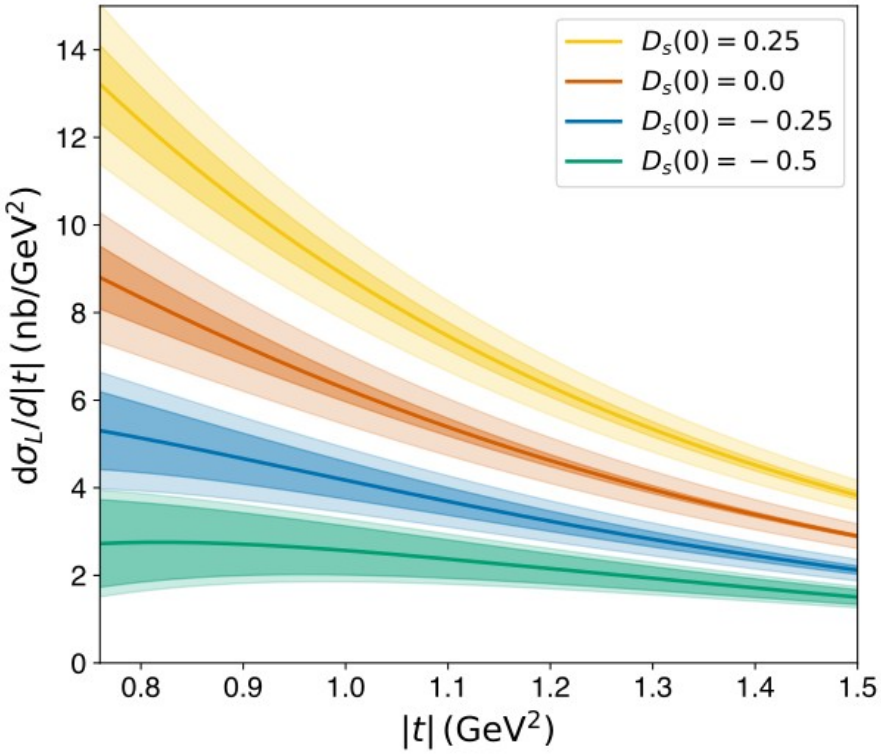
Exclusive ϕ Electroproduction
Gravitational Form Factors

- ϕ measurements provides contributions to D-term (s, ...) not accessible via DVCS

  Hatta, Klest et al, Progress of Theoretical and Experimental Physics, (2025)

  https://doi.org/10.1093/ptep/ptaf076





Exclusive ϕ Electroproduction
Gravitational Form Factors

- ϕ measurements provides contributions to D-term (s, ...) not accessible via DVCS

- S.Goloskokov, P.Kroll, EurPhysJ C 50, 829–842 (2007)
  - In DVES kinematics (well above threshold) σ_L dominated by gluon GPDs
  - Important contributions from σ_T in JLab kinematics

- Hatta, Klest et al, Progress of Theoretical and Experimental Physics, (2025)

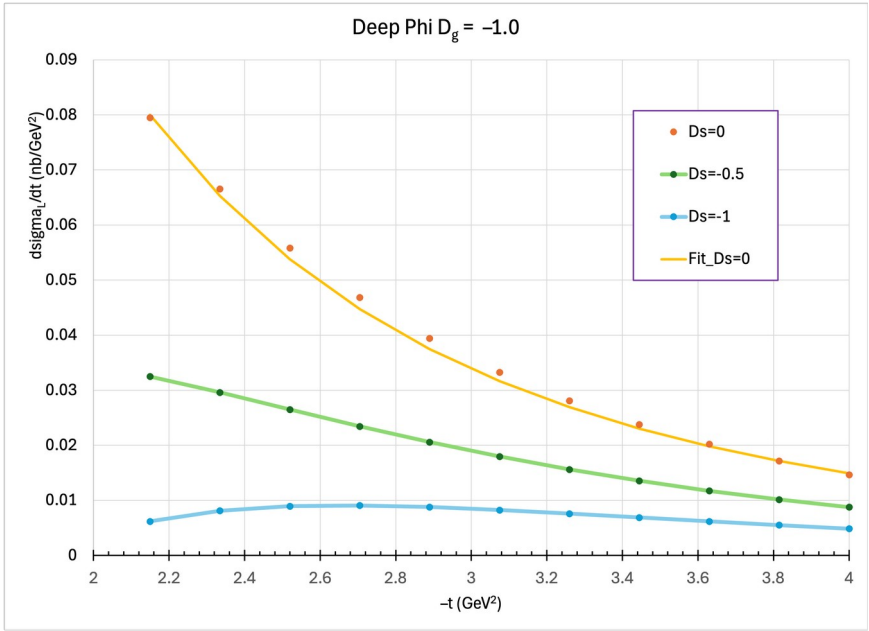
https://doi.org/10.1093/ptep/ptaf076

  - Near threshold,

Contributions of gluon +

strange D-terms to σ_L,

Q^2 = 9 GeV^2 , W = 2.2 GeV

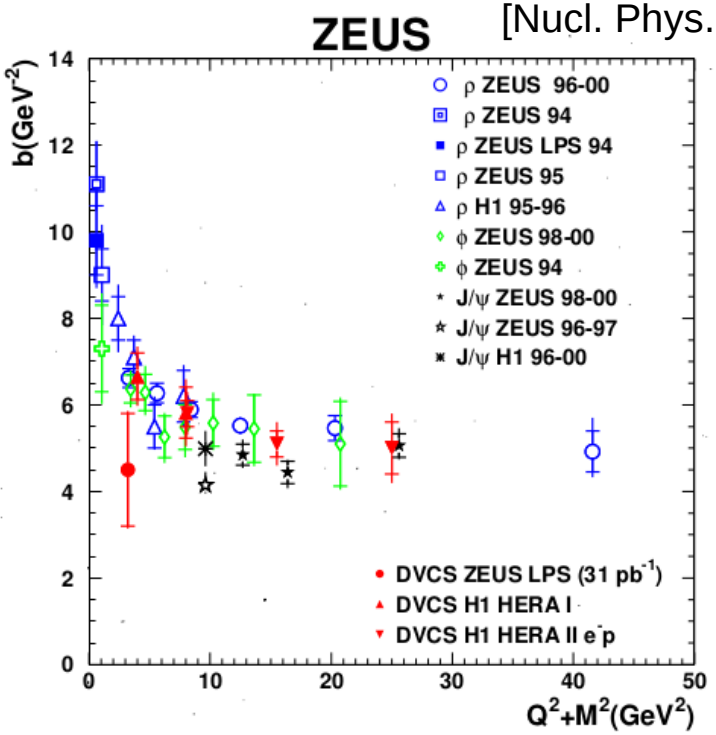


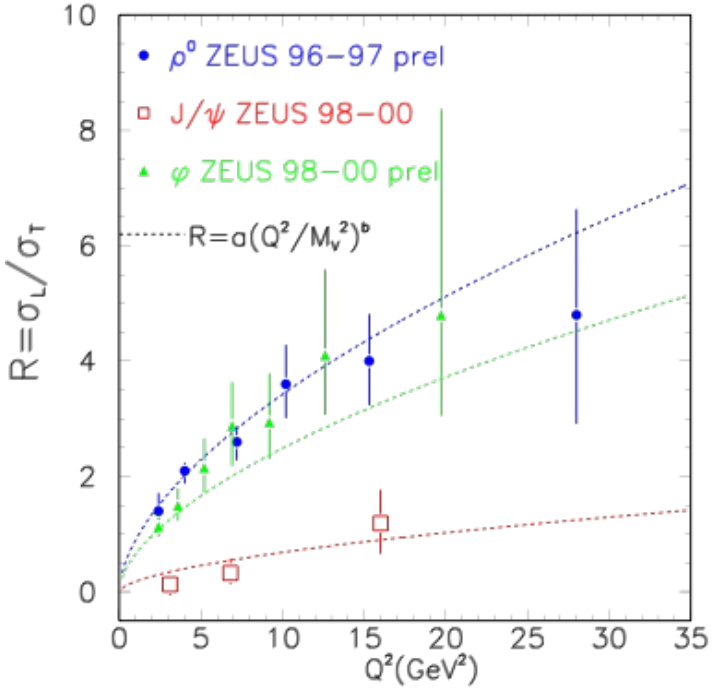
Exclusive ϕ Electroproduction

"Universality" of Vector meson processes at higher Q^2, lower x_{Bj}

- Hera measurements:
  - universal scaling of vector mesons at high Q^2, low x_{Bj}
  - ϕ, J/ψ, subject to comparable dynamics at similar perturbative scale
  - *can be compared at Jefferson Lab kinematics* (high x_{Bj}) to near-threshold J/ψ

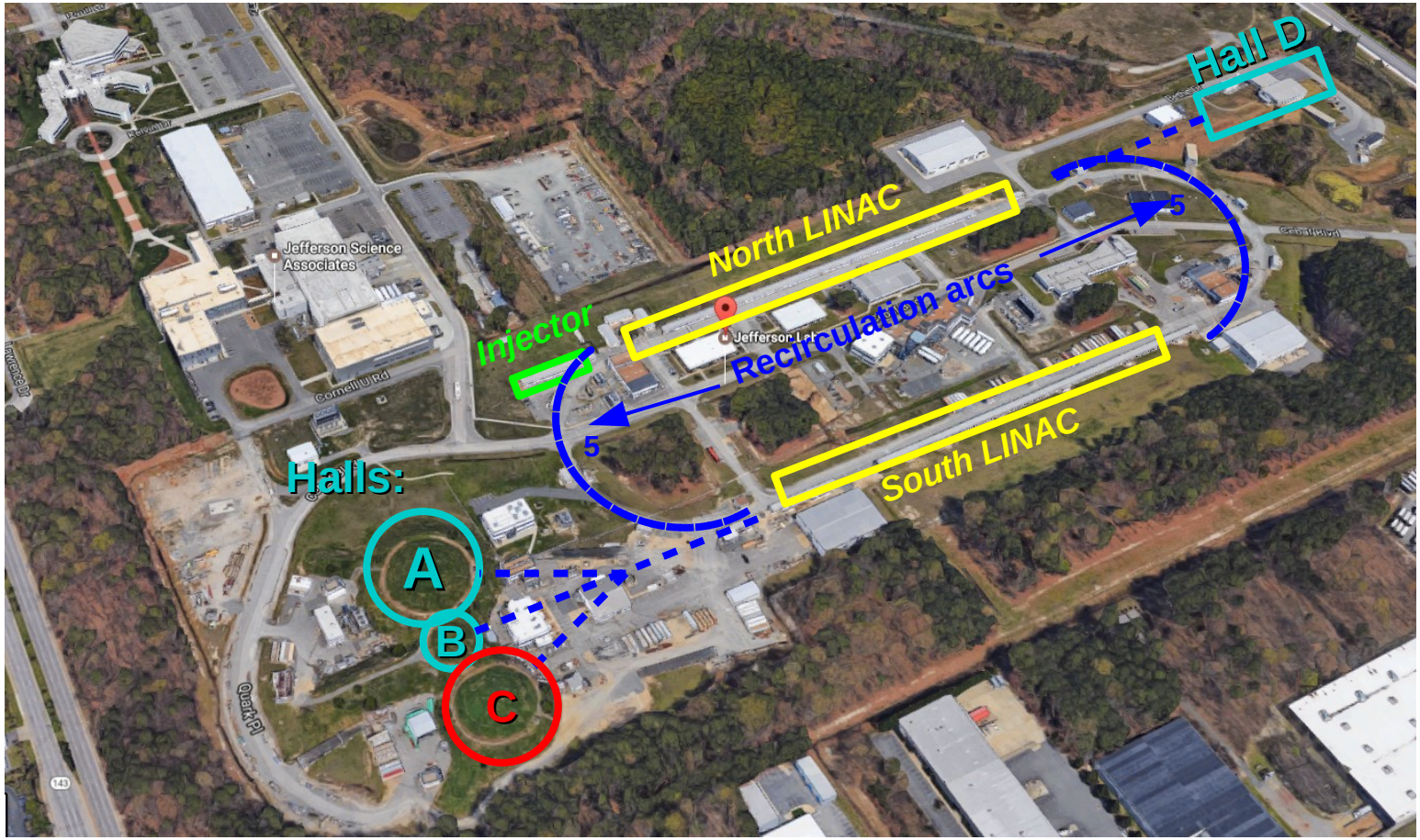
[Nucl. Phys. B Proc. Suppl., 146:92–101, 2005]





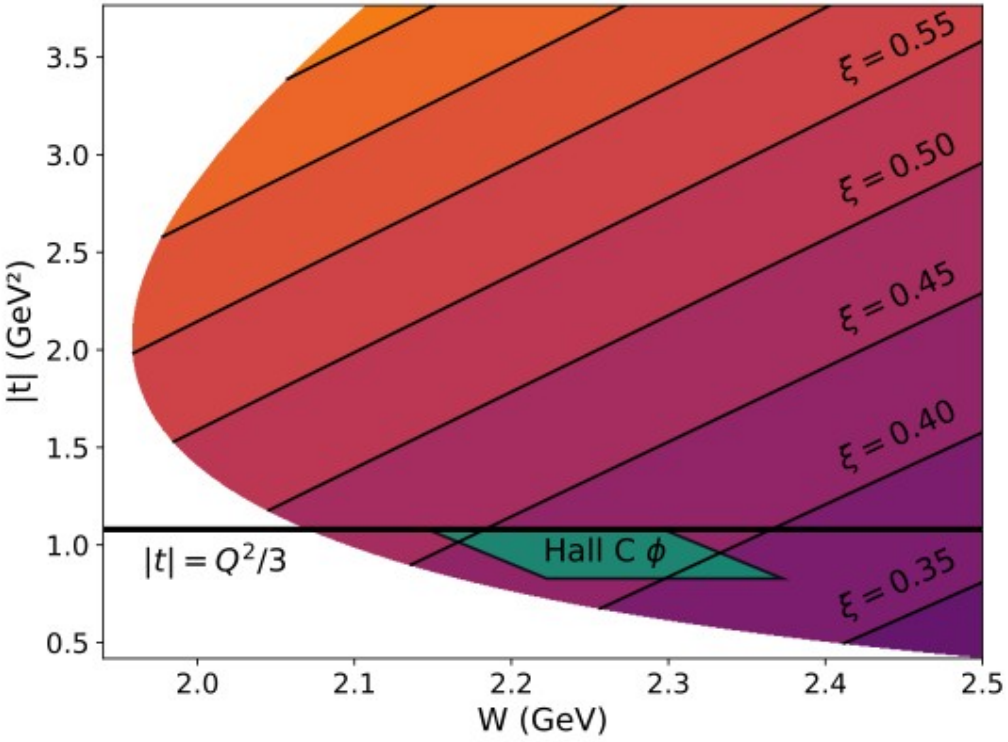
Jefferson Lab

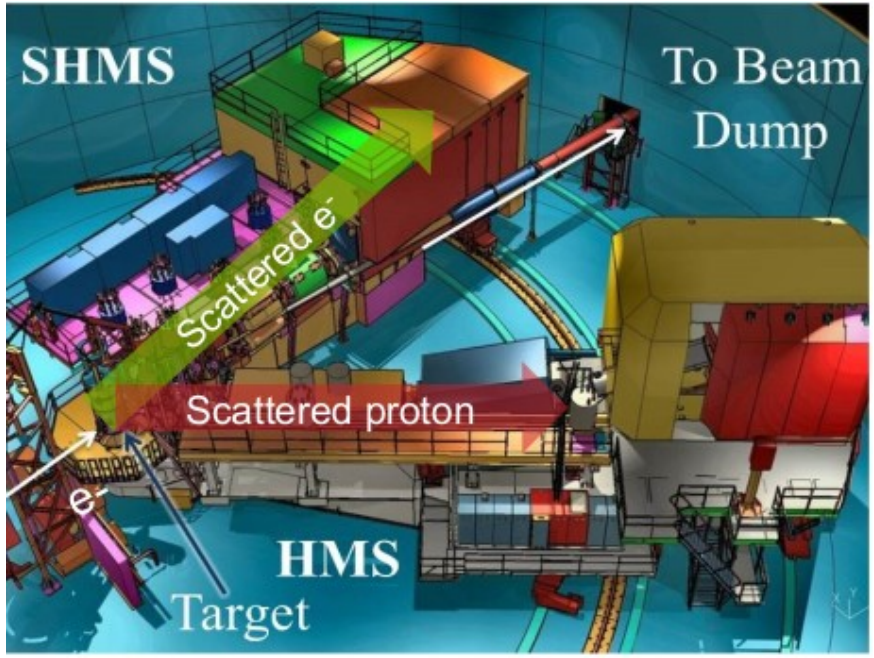
- High intensity, continuous wave electron beam machine
  - E_{max} = 11 GeV (for electrons)
  - I_{max} ~ 75 uA, polarization > 80 %



Proposed Measurements at Jefferson Lab
Exclusive-ϕ Experiment with HMS/SHMS

- Deep-ϕ measurement E12-25-007 (H. Klest, S. Joosten, H. Szumila-Vance)
  - Goal : measure strangeness contribution of D-term
  - kinematic constraints: $|t| < Q^2/3$, $W \sim W_{\phi th}$, $\xi > 0.4$.
  - Measurement of $\mathrm{H}(e, e'_{\mathrm{SMHS}} p_{\mathrm{MHS}})\phi$ at Q^2 = 3.4 GeV^2
    - SHMS @ 13º, 6.7 GeV/c
    - HMS @ 32º, 1.1 GeV/c





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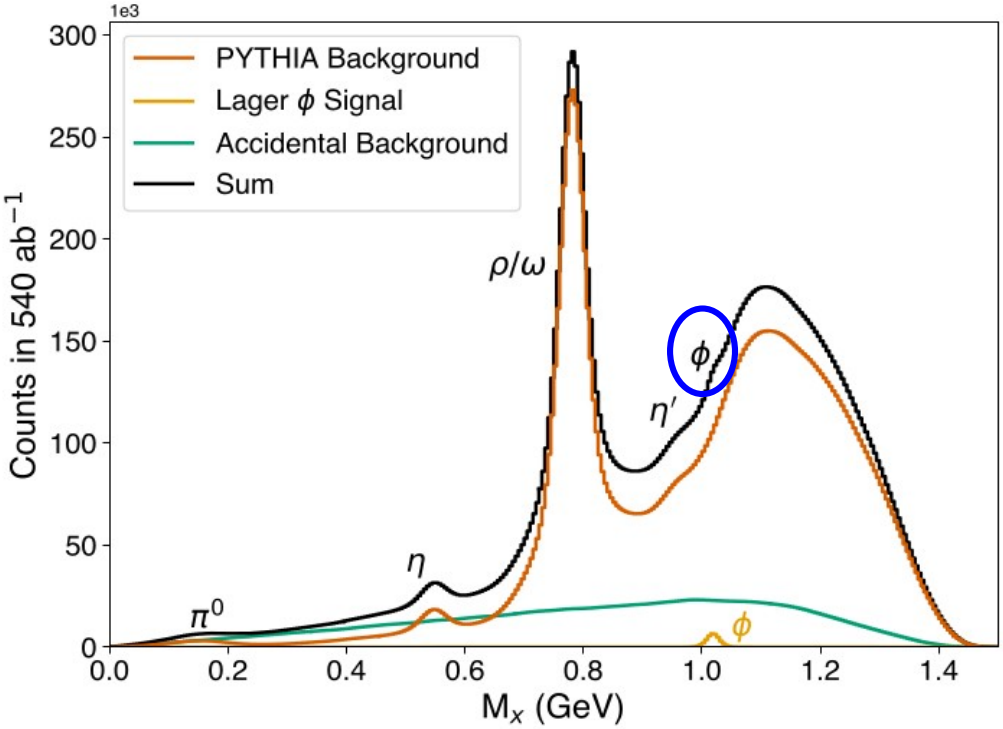
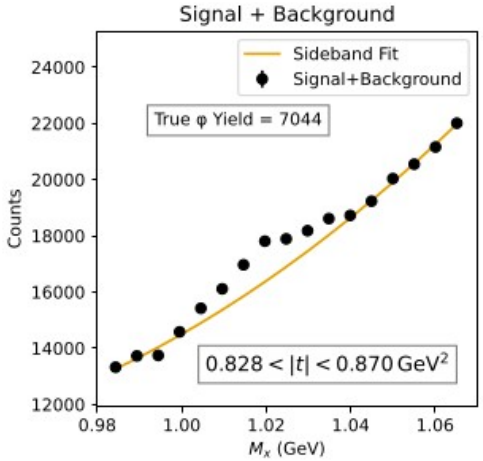
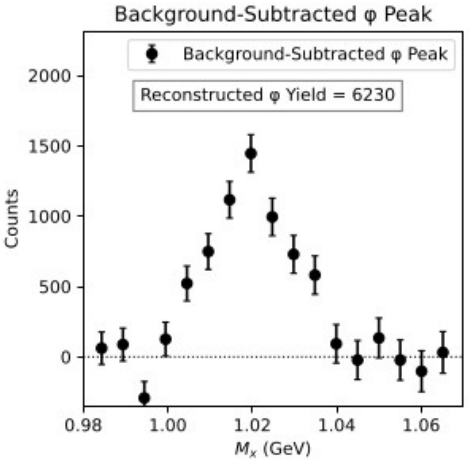
  - Measurement of $H(e, e'_{SMHS}p_{MHS})\phi$ at Q^2 = 3.4 GeV^2
  - ϕ atop a huge DIS background (DIS ~ Q^{-4}, ϕ ~ $Q^{-9.5}$)
  - ϕ reconstruction demonstrated







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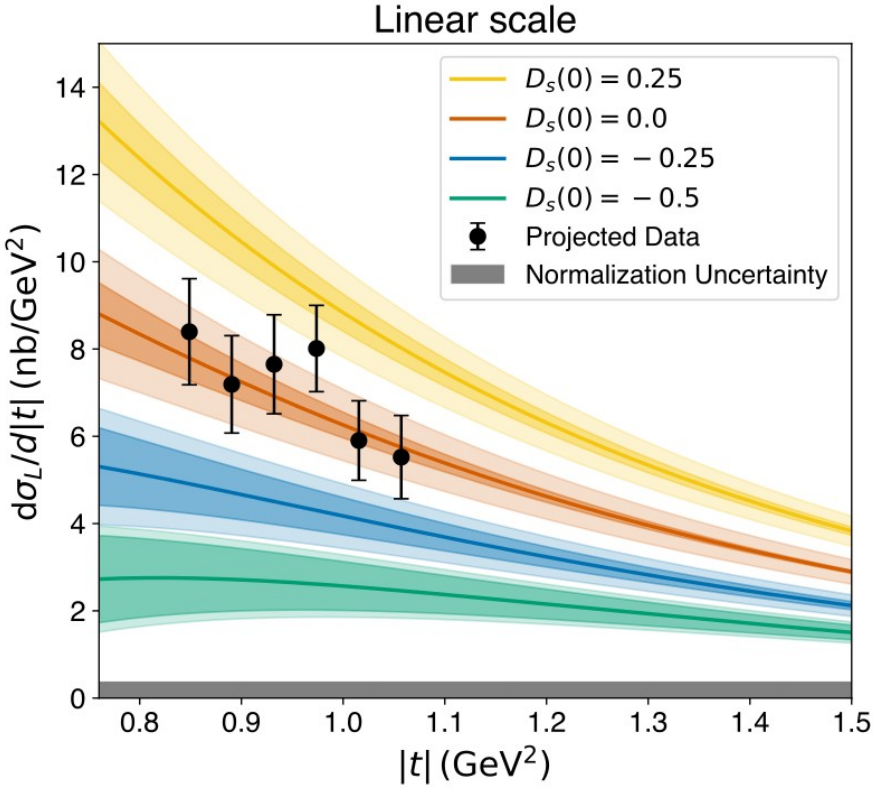
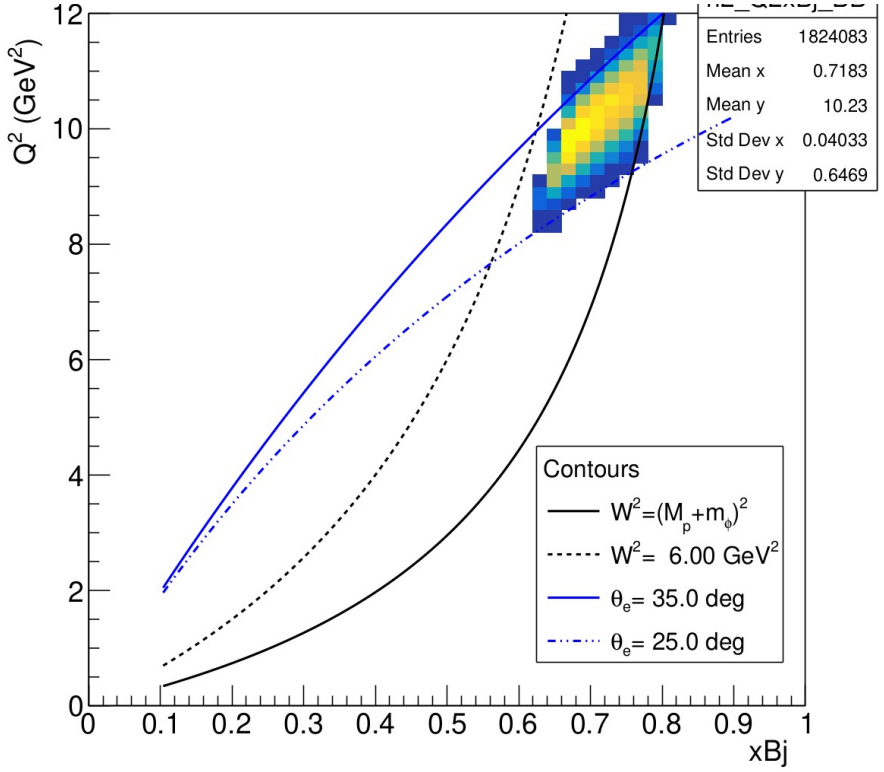
  - Measurement of $\mathrm{H}(e, e'_{\mathrm{SMHS}} p_{\mathrm{MHS}})\phi$ at Q^2 = 3.4 GeV^2
  - Projections for 32 days at 75 μA on 10 cm LH_2 target
  - Cross-section sensitive to D-term strangeness contribution
  - Approved by PAC53 with grade A-



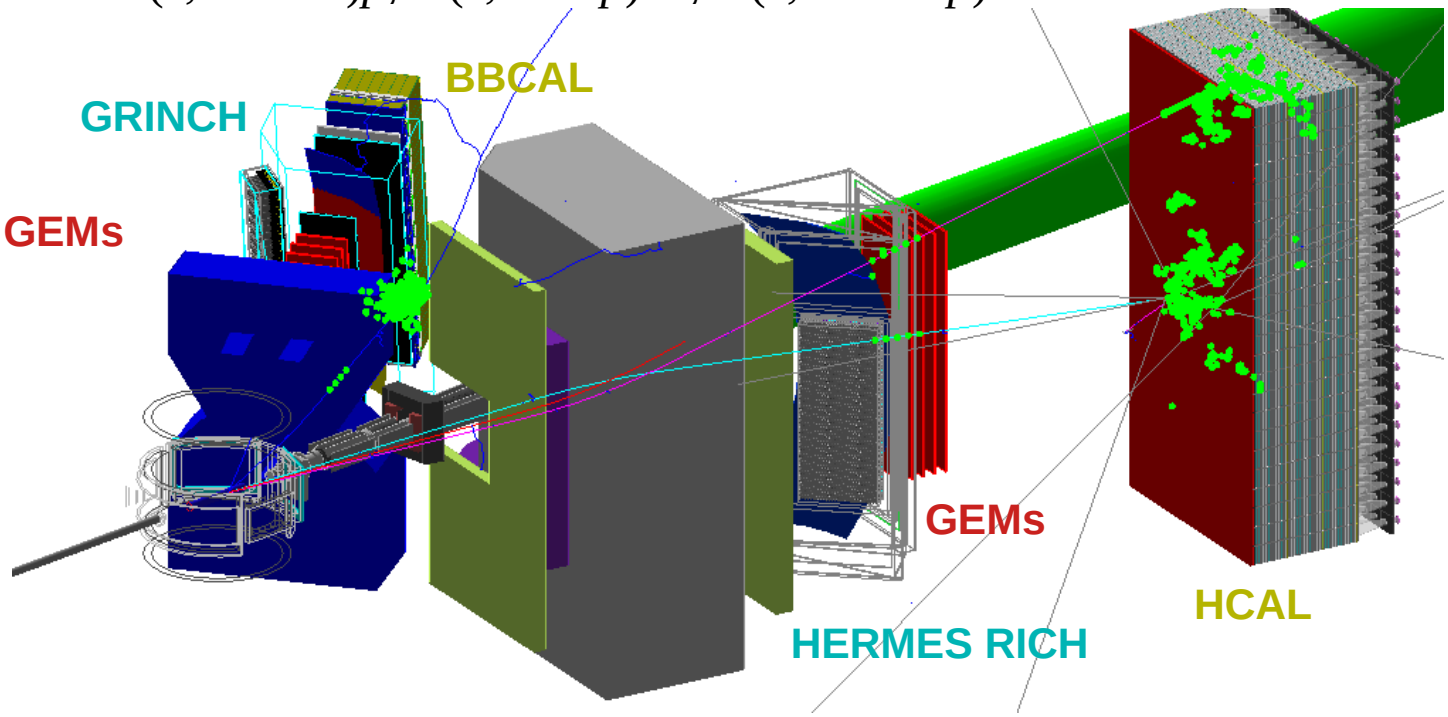
Proposed Measurements at Jefferson Lab
Deepest-ϕ Experiment with SBS

- Measurement of $ep \rightarrow e'p'(\phi \rightarrow K^+K^-)$ near threshold at Q^2 = 9 GeV^2
  - goal: measure $R = \sigma_L/\sigma_T$, absolute σ_L, σ_T + 16 Spin Density Matrix Elements
  - Kinematics 8 GeV2 < Q^2 < 12 GeV2, $(m_p+m_\phi)^2 < W^2 < 6$ GeV^2, t_0-t < 1 GeV^2
  - Perturbative scale $Q^2+M_\phi^{\,2} \geq 10$ GeV^2 ~ J/ψ at threshold $Q^2+M_{J/\psi}^{\,2} \geq 9.6$ GeV^2
- LOI submitted to PAC 54: **LOI12-26-008** (C. Hyde, EF)



Deepest-ϕ Experiment with SBS
Experimental Setup

- LOI12-26-008 Measurement of $ep \rightarrow e'p'(\phi \rightarrow K^+K^-)$ near threshold at Q^2 = 9 GeV^2
  - e' measured with BB at 30 degrees;
  - p', K^+, K^- measured with SBS at 14 degrees:
    - Near threshold p', ϕ ~co-linear
    - Large Q^2, ϕ boosted forward, K^+K^- in small decay cone => SBS
    - H$(e, e'K^+K^-)p$, H$(e, e'K^{\pm}p)K^{\pm}$, H$(e, e'K^+K^-p)$



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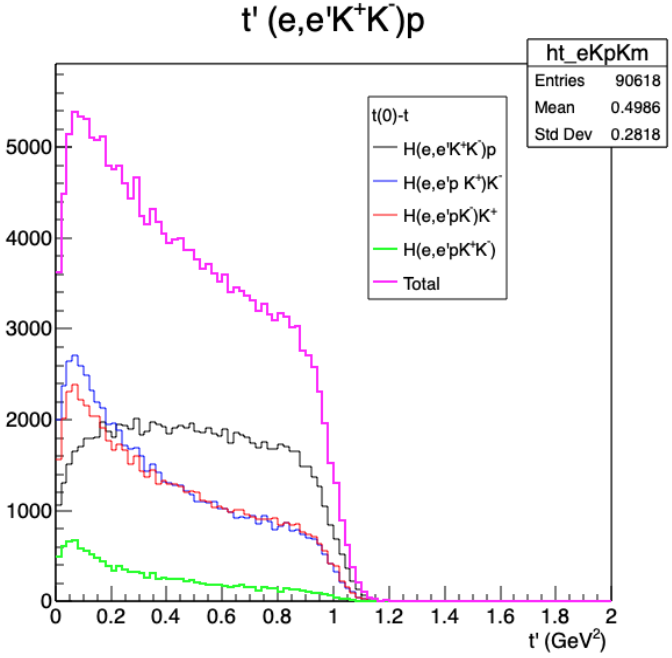
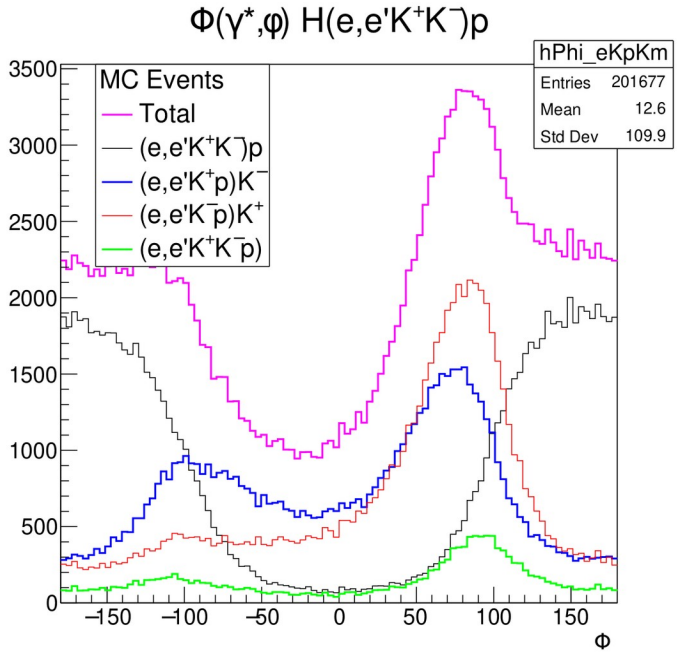
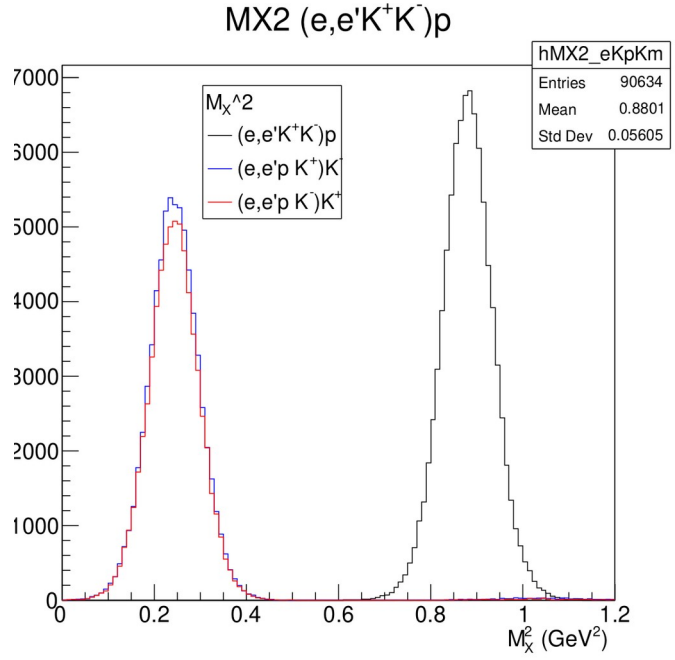
  - Acceptance for hadronic final state:
- MC smearing of tracks in BigBite, SBS
  - Resolution $\delta p/p$ = 1% $\delta\theta$ = 1.5 mrad







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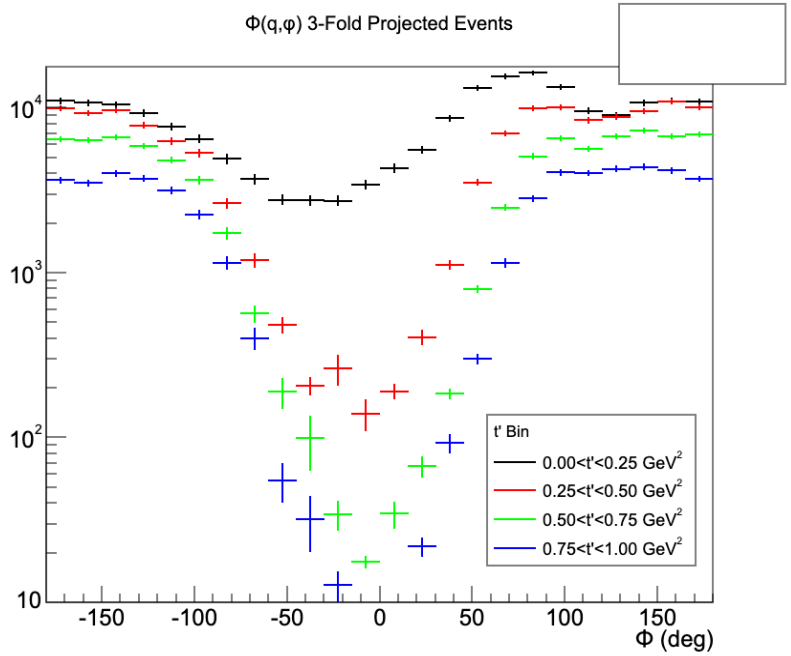
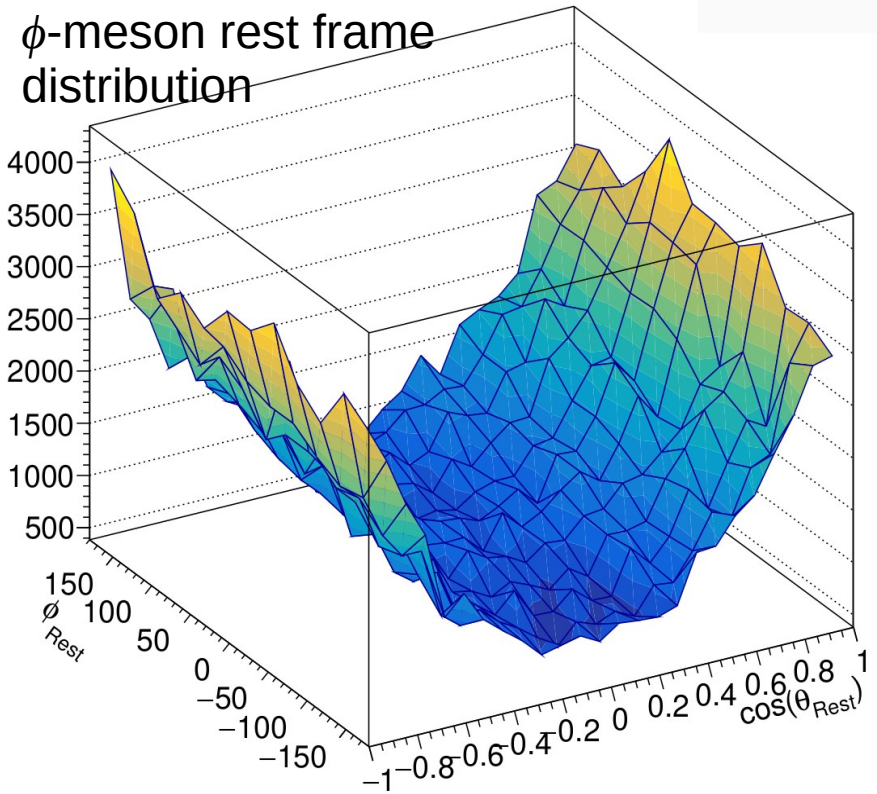
  - Projections: 40 days with 20 μA on 20cm LH_2
- Extraction of 16 SDME from harmonics in $\Phi_{\gamma^*\phi}$, $\theta_{\phi \rightarrow KK}$, $\varphi_{\phi \rightarrow KK}$
  - 9 SDME vanish in s-Channel Helicity Conservation => test of SCHC

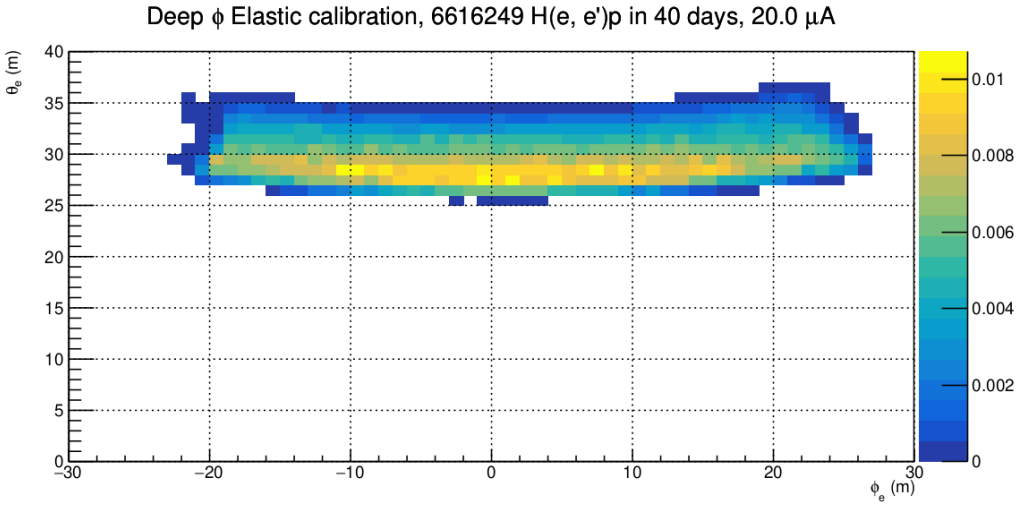


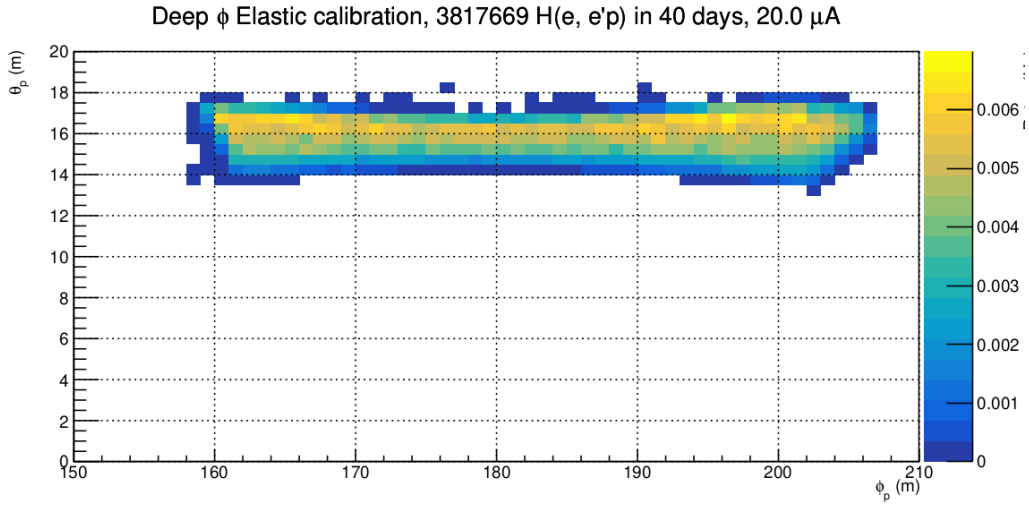
ϕ-meson rest frame distribution

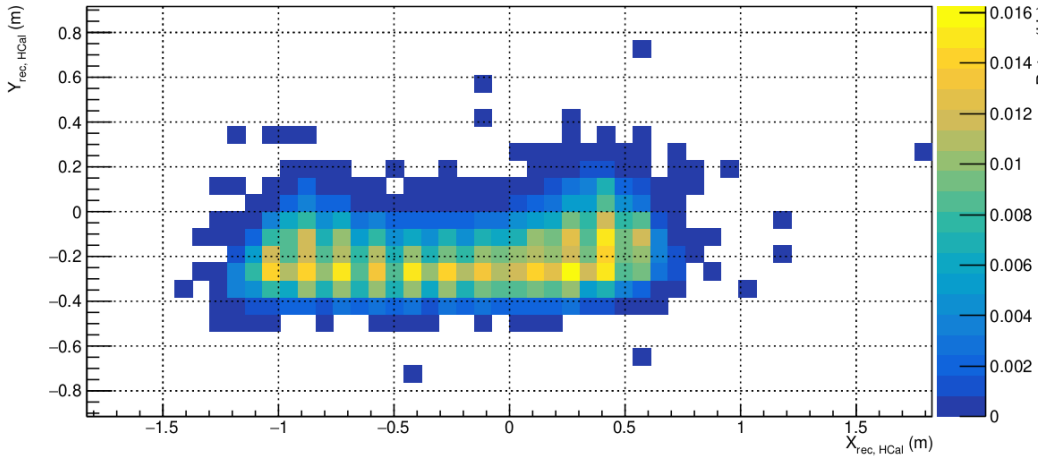


Deepest-ϕ Experiment with SBS
Experimental Challenges

- Measurement of absolute σ_L, σ_T might be challenging with SBS
  - $R = \sigma_L/\sigma_T$, SDME "only" requires knowledge of relative efficiency variation
  - Absolute efficiency can be estimated with elastics ep recorded during run;







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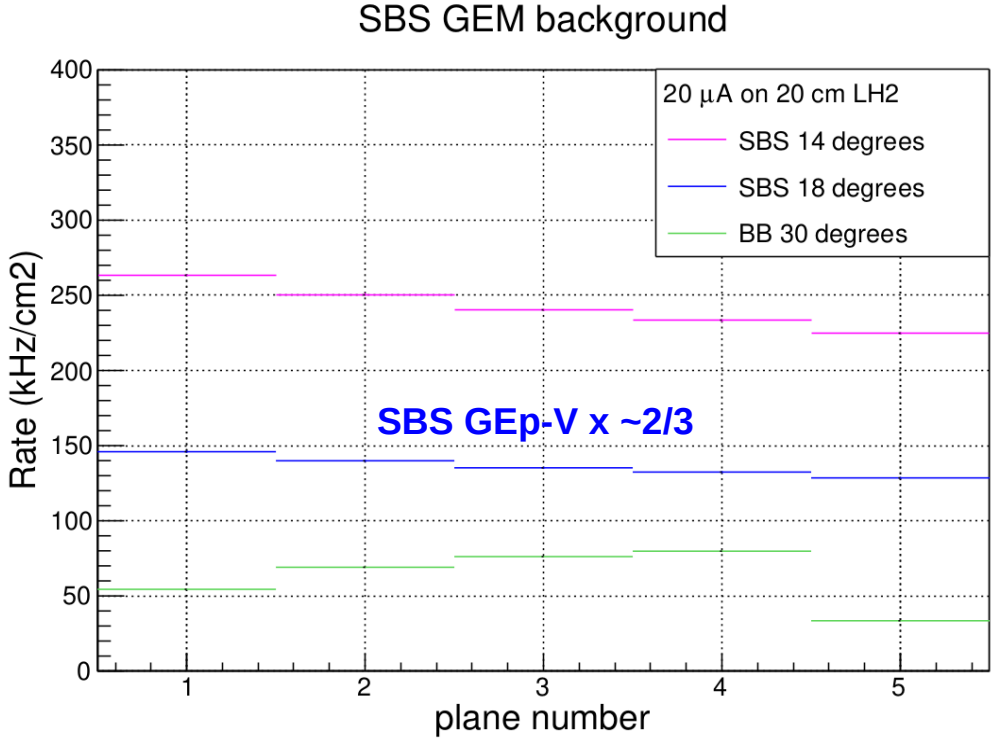
- Measurement of absolute σ_L, σ_T might be challenging with SBS
  - $R = \sigma_L/\sigma_T$, SDME "only" requires knowledge of relative efficiency variation
  - Absolute efficiency can be estimated with elastics ep recorded during run;
- Beam background conditions in trackers similar to SBS Gep-V
  - Tracking in SBS-GEP-V is extremely challenging
  - Major hardware developments shall be needed



SBS GEp-V 18º, 20μA, 30cm LH2

Deepest-ϕ Experiment with SBS
Path to Full Proposal

- PAC recommendations:

"The physics case is interesting. The PAC recommends the proponents to proceed to a full proposal after the raised issues are carefully considered. When moving to the proposal stage, the proponents will need to show that the sixteen ϕ spin-density matrix elements can be measured with sufficient precision in the respective bins considering detector acceptance effects."

- Other tasks for full proposal: semi-inclusive K^+, K^- estimated with Pythia
  - accidental $\mathrm{H}(e, e' K^+ K^-)\mathrm{X}$, $\mathrm{H}(e, e' K^\pm p)\mathrm{X}$ at exclusive limit;
  - need evaluate accidentals factoring $\pi^\pm$ misidentified as $K^\pm$ by HERMES RICH

Summary

- Deeply Virtual ϕ Exclusive measurement
  - measure strangeness component of GFFs D-term
  - at high perturbative scales ≥ 10 GeV^2:
    - ♦ “universal” process expected for vector mesons i.e. similar to J/ψ
    - ♦ process also sensitive to gluons.

- Deep-ϕ E12-25-007 with HMS/SHMS
  - good sensitivity to strangeness contribution to D-term
  - *approved by PAC53, could run next year!*

- Deepest-ϕ LOI12-26-008 with SBS
  - Perturbative scale similar to J/ψ at threshold
  - ambitious goal to measure $R = \sigma_L/\sigma_T$ + all SDME, test SCHC
  - encouraged by PAC54, focus on demonstrating feasibility

Back up

Deepest-ϕ Experiment with SBS
Experimental Setup

- Measurement of $ep \rightarrow e'p'(\phi \rightarrow K^+K^-)$ near threshold at Q^2 = 9 GeV^2
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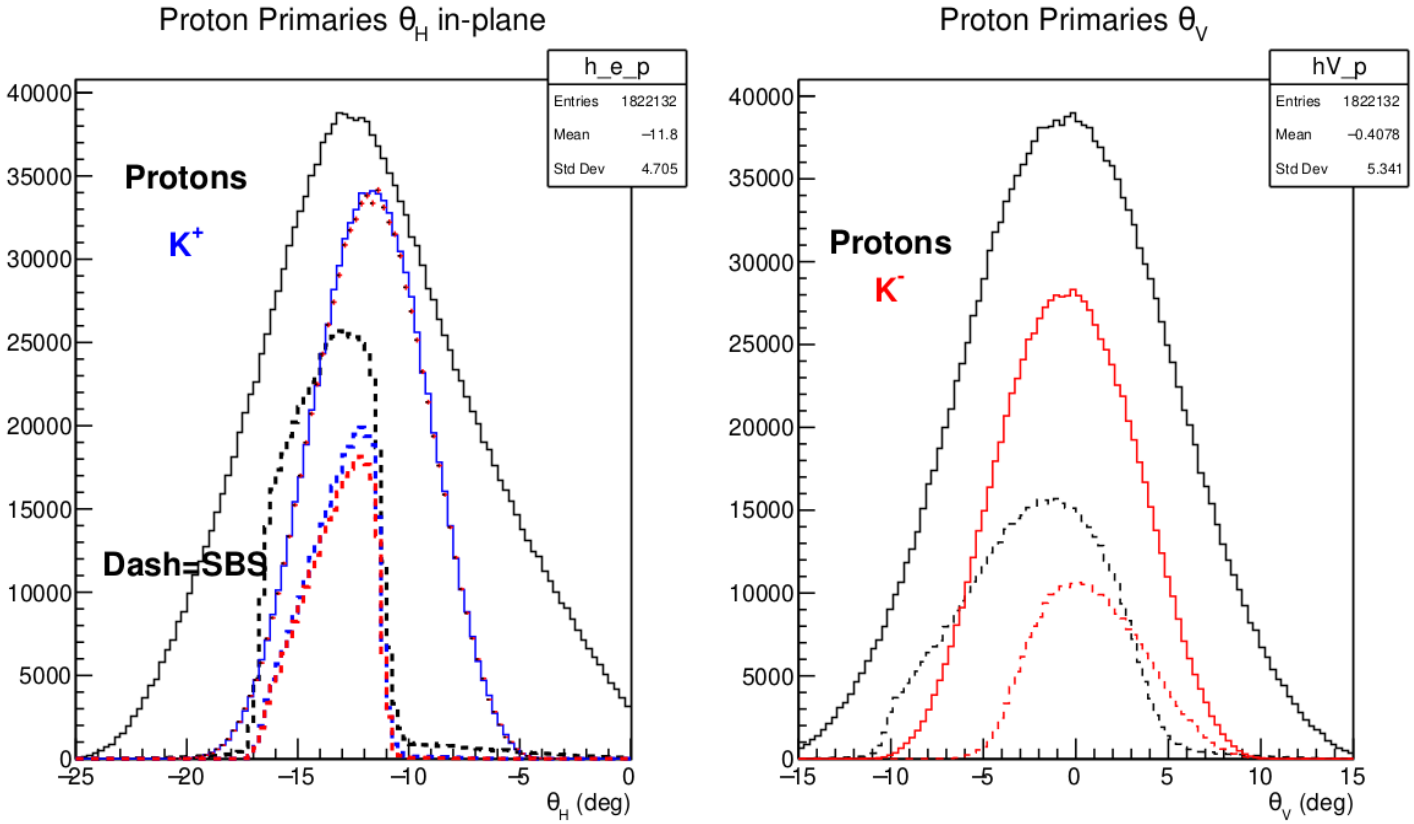
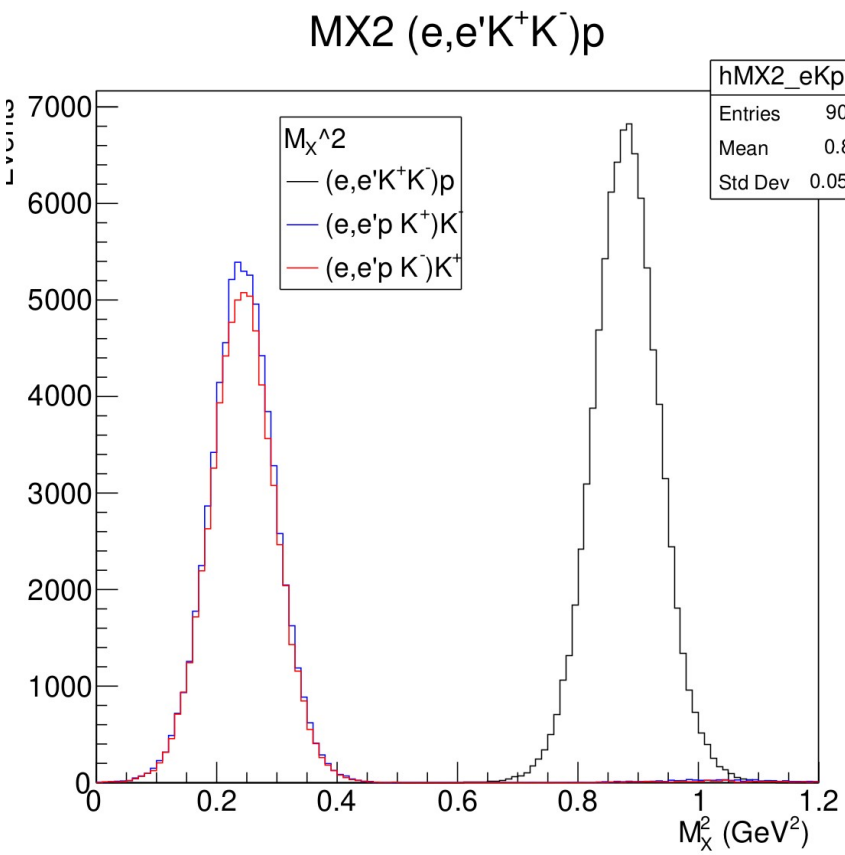
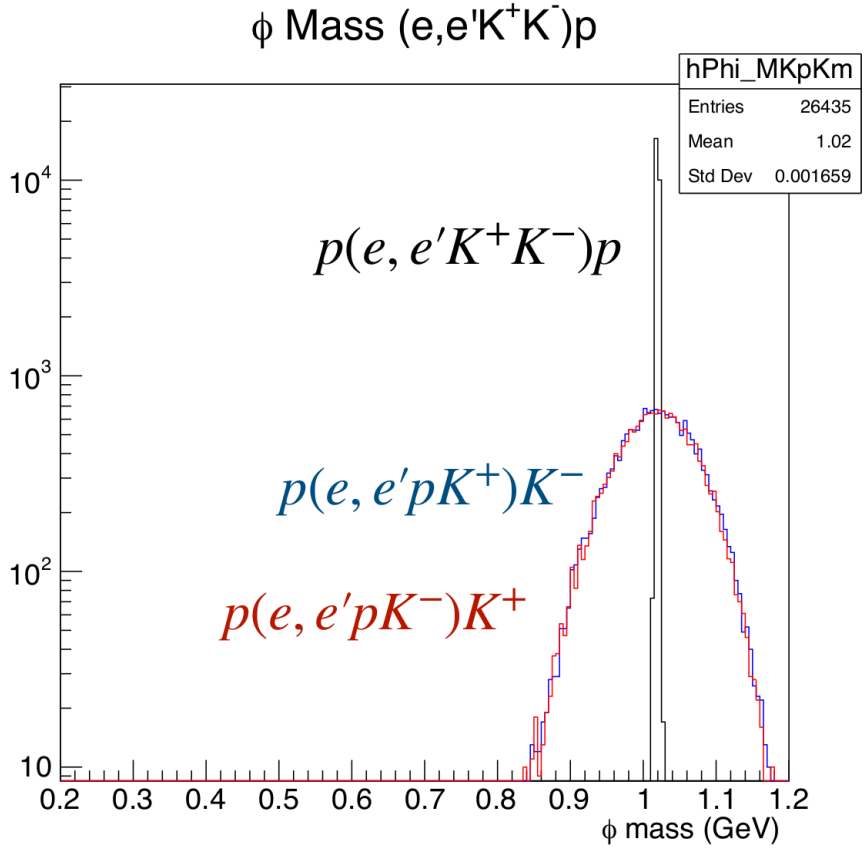
  - Acceptance for hadronic final state:



Deepest-ϕ Experiment with SBS
Experimental Resolutions

- MC smearing of tracks in BigBite, SBS
  - Resolution $\delta p/p$ = 1% $\delta\theta$ = 1.5 mrad





Deep-ϕ
SDME

$$
\begin{aligned}
W(\Phi,\theta,\phi) = & \frac{3/(4\pi)}{1+\epsilon R} \\
& \left\{ \frac{1}{3} + \left(\rho^0_{00} - \frac{1}{3}\right)\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) - \sqrt{2}\Re\left[\rho^0_{10}\right]\sin(2\theta)\cos\phi - \rho^0_{1,-1}\sin^2\theta\cos(2\phi) \right. \\
& - \epsilon\cos(2\Phi)\left[\rho^1_{11}\sin^2\theta + \rho^1_{00}\cos^2\theta - \sqrt{2}\Re\left[\rho^1_{10}\right]\sin(2\theta)\cos\phi - \rho^1_{1-1}\sin^2\theta\cos(2\phi)\right] \\
& - \epsilon\sin(2\Phi)\left[\sqrt{2}\Im\left[\rho^2_{10}\right]\sin(2\theta)\sin\phi + \Im\left[\rho^2_{1-1}\right]\sin^2\theta\sin(2\phi)\right] + \\
& \epsilon R\left[\frac{1}{2}\left(1-\rho^4_{00}\right) + \frac{1}{2}\left(3\rho^4_{00}-1\right)\cos^2\theta - \sqrt{2}\Re\rho^4_{10}\sin(2\theta)\cos\phi - \rho^4_{1-1}\sin^2\cos(2\phi)\right] \\
& + \sqrt{2\epsilon R(1+\epsilon)}\cos\Phi \\
& \qquad \left[\rho^5_{11}\sin^2\theta + \rho^5_{00}\cos^2\theta + \sqrt{2}\Re\left[\rho^5_{10}\right]\sin(2\theta)\cos\phi - \rho^5_{1-1}\sin^2\theta\cos(2\phi)\right] \\
& \left. \sqrt{2\epsilon R(1+\epsilon)}\sin\Phi\left[\sqrt{2}\Im\left[\rho^6_{10}\right]\sin(2\theta)\sin(\phi) + \Im\left[\rho^6_{1-1}\right]\sin^2\theta\sin(2\phi)\right]\right\}
\end{aligned}
$$