Semi-inclusive Deep Inelastic Scattering with 22 GeV electrons in Hall C

- Introduction
- SIDIS Framework
- Kinematic Space
- Closing Opinions

Thanks to Rolf Ent, Thia Keppel, and Dave Gaskell for critical help in the preparation of this talk!

SIDIS at 22 GeV in Hall C

- At January 2023 workshop on 22 GeV physics opportunities, Dave Gaskell and I took a look at SIDIS kinematics with *existing* Hall C spectrometers.

- To fully explore SIDIS physics, you need full azimuthal coverage and excellent PID, such as CLAS12 and SoLID (see Dave's talk from Monday)

- Hall C spectrometers bring (at least) three critical capabilities:
    1) Precise measurement of absolute cross sections
    2) Rosenbluth separation of L/T cross sections
    3) High luminosity for small cross sections (*e.g.*, high p_T)

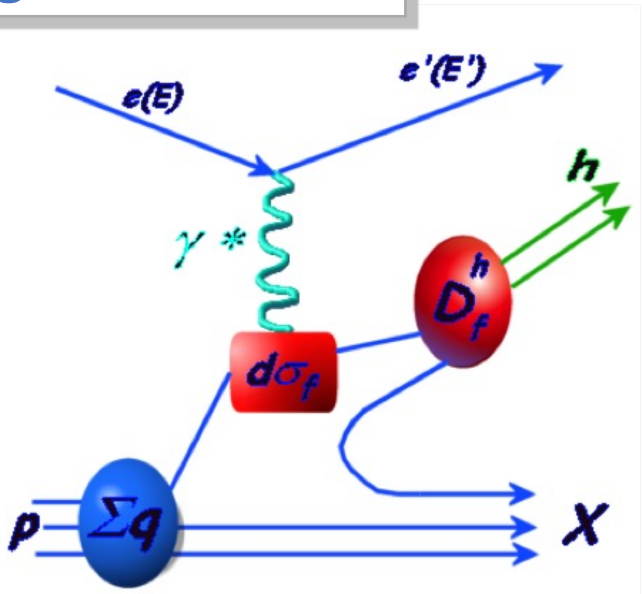
Do parton distributions and fragmentation functions factorize at Jefferson Lab energies?

Flavor Decomposition of SIDIS

$$\frac{1}{\sigma_{(e,e')}}\frac{d\sigma}{dz}(ep \rightarrow hX) = \frac{\sum_q e_q^2 f_q(x) D_q^h(z)}{\sum_q e_q^2(x) f_q(x)}$$

$f_q(x)$ *: parton distribution function*

$D_q^h(z)$ *: fragmentation function*



$z = E_h/\nu$

- Leading-Order (LO) QCD
- after integration over $p_{h\perp}$ and ϕ_h
- NLO: gluon radiation mixes
  x and z dependences
- Target-Mass corrections at large z
- ln(1-z) corrections at large z

$M_x^2 = W'^2 \sim M^2 + Q^2\,(1/x - 1)(1 - z)$

With p_T and k_T dependences, some kind of convolution is necessary to obtain final $P_{h\perp}$

What do we gain at 22 GeV?

- Larger W^2 -> Higher final state multiplicities (factorization)
  but at 6 and 12 GeV we already see factorization at mid-x
- Larger Mx^2 -> Can explore higher z and p_T
- Higher Q^2 -> Decrease in higher twist effects
- In general, many of the complications at 12 GeV are expected to be smaller as you move to the ideal high energy limit. With comprehensive measurements at 12 and 22 GeV we probe the transition
- Measurements of R_{SIDIS} at higher energy!

The SIDIS cross section …

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

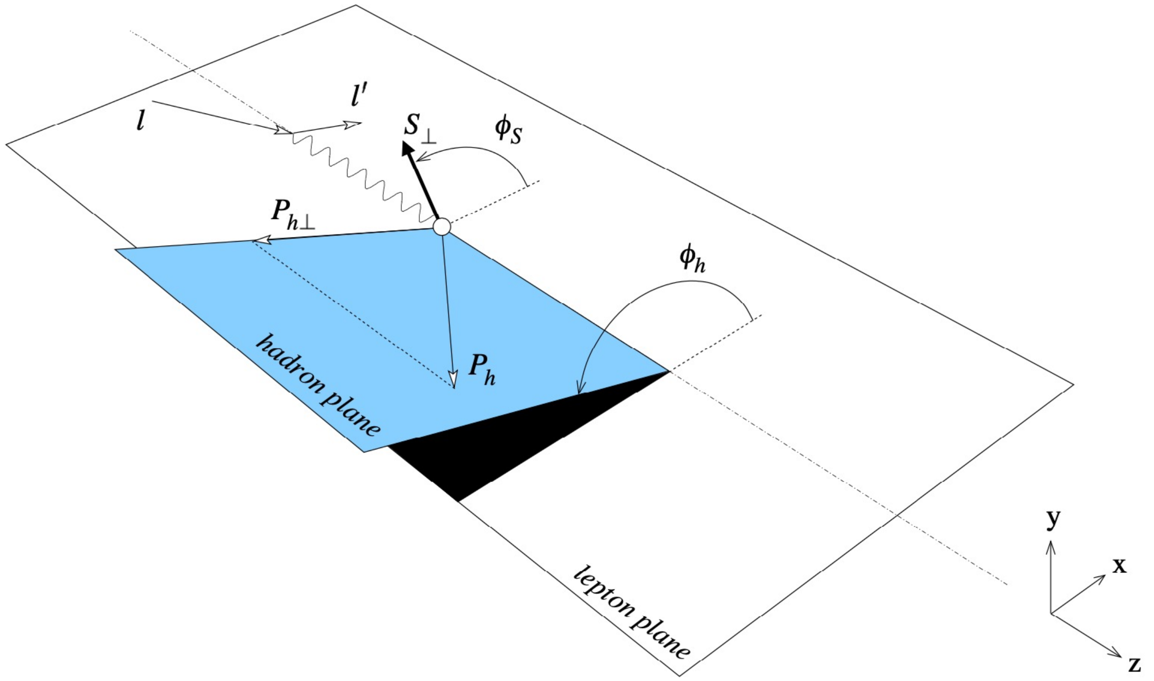
$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$



Taken from A. Bacchetta et al., JHEP02, 093 (2007)

SIDIS Differential Cross Section for unpolarized targets

Measurement of 6-fold differential cross section with *unpolarized* target has "only" five structure functions

$$\frac{d\sigma}{dx\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}(1+\frac{\gamma^2}{2x}) \Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LU}^{\sin\phi_h} \Big\}$$

Virtual Photon Polarization: ϵ

Electron helicity: λ_e

Hadron azimuthal angle: ϕ_h

Structure functions depend on x, Q^2, p_T!

Focus on R; what is it?

Inclusive DIS: $$\frac{d^2\sigma}{d\Omega_e dE'} = \sigma_{Mott}\{W_2(Q^2,W^2) + 2W_1(Q^2,W^2)tan^2(\theta/2)\},$$

$$F_1(x,Q^2) = MW_1(\nu,Q^2)\ ,$$
$$F_2(x,Q^2) = \nu W_2(\nu,Q^2)\ .$$

$$F_2(x) = 2xF_1(x) = x\sum_q e_q^2\,(q(x)+\bar{q}(x))$$

Inclusive DIS in terms of L and T cross sections: $$\frac{1}{\Gamma}\frac{d^2\sigma}{d\Omega dE'} = \sigma_T + \varepsilon\sigma_L$$

$$\Gamma = \frac{\alpha}{2\pi^2 Q^2}\frac{E'}{E}\frac{1}{1-\varepsilon}$$

$$\varepsilon = \left[1 + 2\left(1+\frac{\nu^2}{Q^2}\right)\tan^2\left(\frac{\theta}{2}\right)\right]^{-1}$$

What is R?

$$F_1(x,Q^2) = \frac{Q^2}{4\pi^2\alpha}\frac{(1-x)}{2x}\sigma_T$$

Purely Transverse: Sensitive to single parton densities

$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2\alpha}\frac{1}{1+\frac{Q^2}{\nu^2}}(1-x)(\sigma_L+\sigma_T)$$

Mixture of L and T

Define Pure L and ratio R:

$$F_L(x,Q^2) = \frac{Q^2}{4\pi^2\alpha}(1-x)\sigma_L$$

$$R(x,Q^2) = \frac{\sigma_L}{\sigma_T} = \frac{F_L}{2xF_1}$$

$R = \sigma_L/\sigma_T$ is a basic aspect of the photon-parton interaction

- First DIS evidence that quarks had spin ½ (R→0 as $Q^2 \to \infty$)

- At moderate fixed x, falls as $1/Q^2$

- At moderate finite Q^2, non-zero and sensitive to indirect gluon effects and higher twist

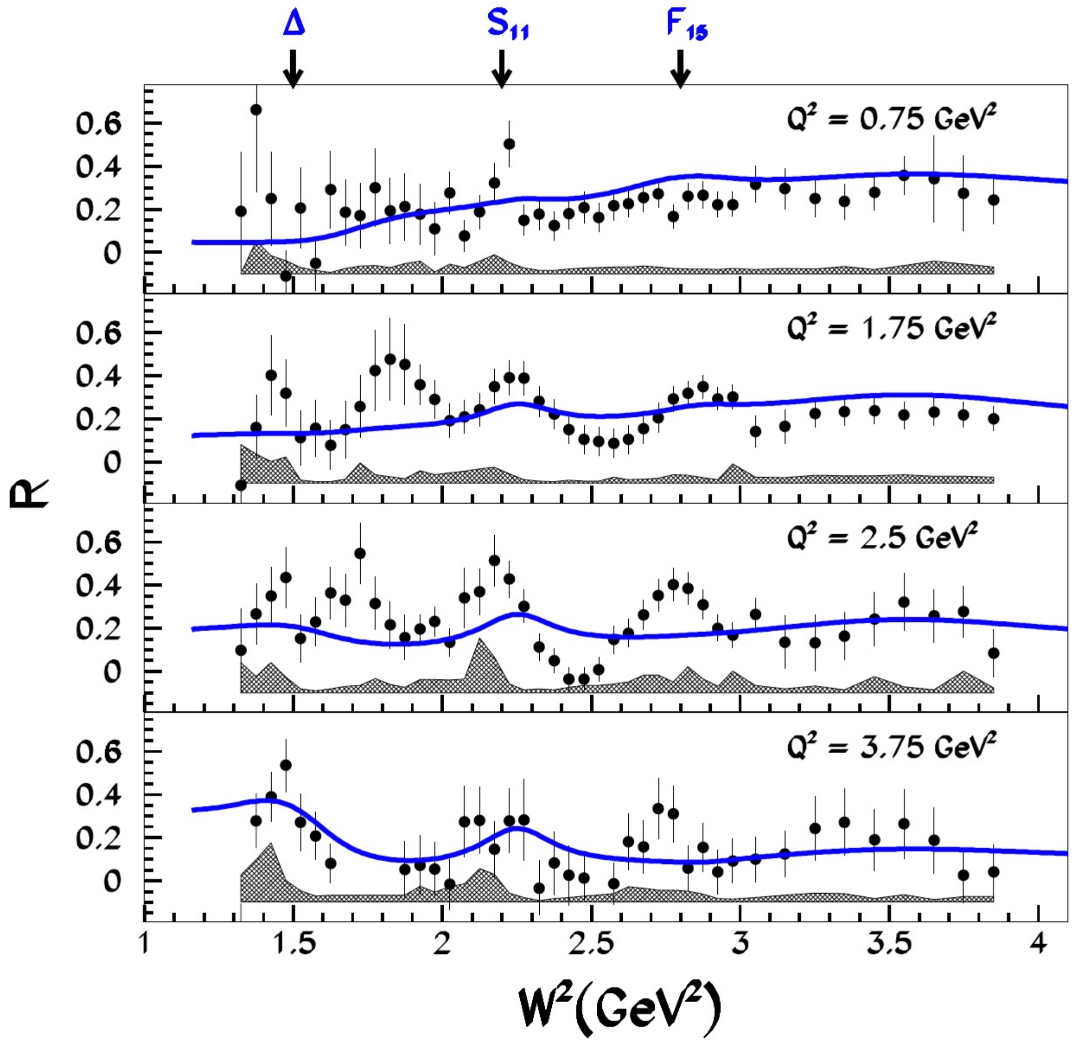
- In naïve quark model*, sensitive to intrinsic transverse momentum k_T:

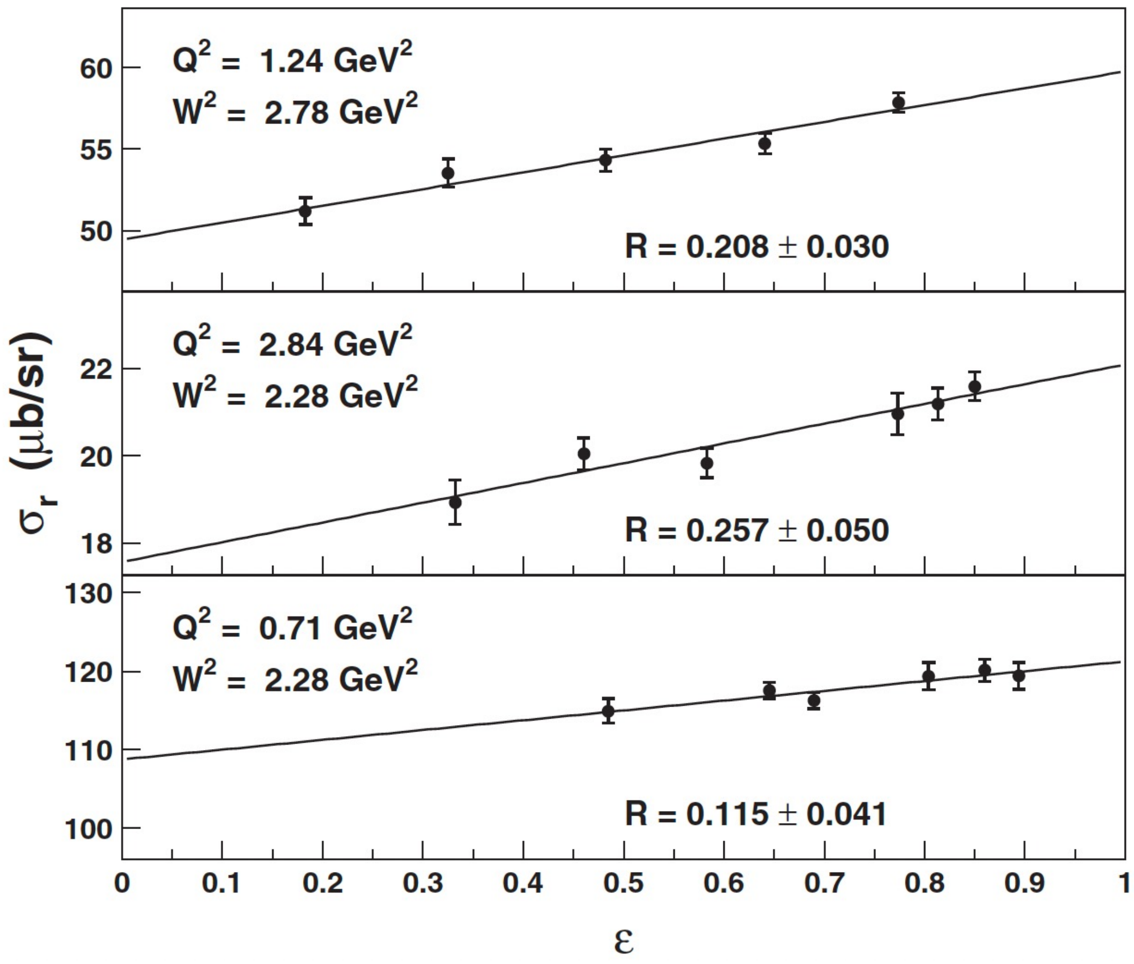
$$R = 4(M^2x^2 - \langle k_t^2 \rangle)/(Q^2 + 2\langle k_t^2 \rangle)$$

Connected to TMDs!

* R.C.Hwa, S. Matsuda, R.G. Roberts, Z. Physik C, Particles and Fields 1, 279 (1979).

What is R in Inclusive DIS?





Taken from Y. Liang et al., PRC 105, 065205 (2022)

What is R in Semi Inclusive DIS?

Without polarized beam and target

$$F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}\,.$$

$$\sigma = \Gamma(\,\sigma_T + \varepsilon\sigma_L + [\varepsilon(\varepsilon+1)/2]^{1/2}\cos(\phi)\sigma_{LT} + \varepsilon\cos(2\phi)\sigma_{TT}\,)$$

In addition to x and Q^2, can depend on z and p_T

Almost no experimental knowledge of R in SIDIS!!!

Hall C will explore this soon!

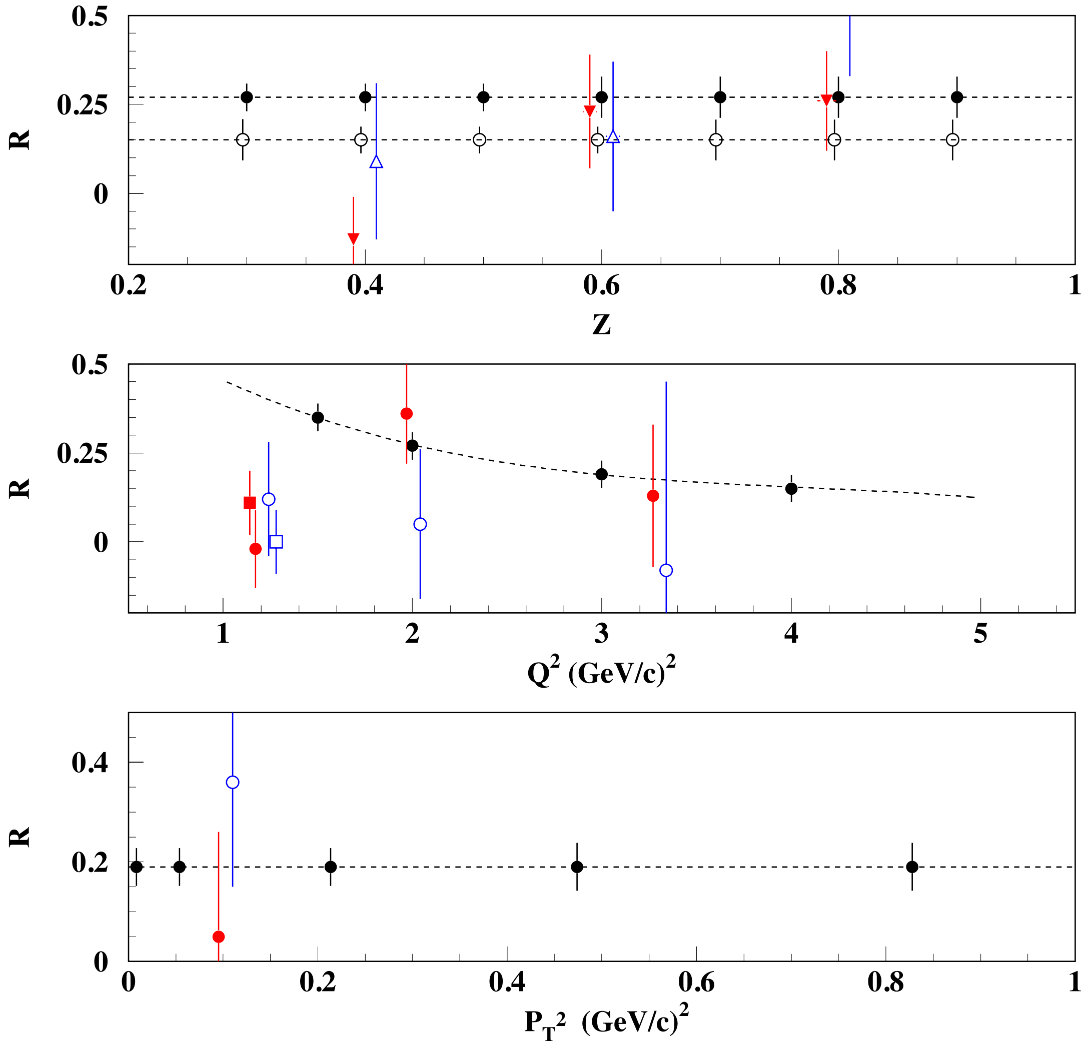
E12-06-104, *Spokespersons:* P. Bosted, R. Ent, E. Kinney, and H. Mkrtchyan

- This experiment will make precise measurements of R in charged π and K SIDIS on H and D targets as a function of Q^2, fractional hadron momentum *z*, and hadron transverse momentum p_T

- Standard technique to measure R: Vary the virtual photon polarization ε by using different incident beam energies and electron scattering angles, while keeping the Q^2, *x, z,* and p_T constant. Will use the two magnetic spectrometers in Hall C.

Scheduled to run 2025!

Previous compared to proposed



Projections for E12-06-104 vs existing Cornell Data (projections assume R_{SIDIS} = R_{DIS})

Comparable 1.6% systematic uncertainties not indicated

Projections: Solid Black H, Open Black D π

Cornell:

Top panel: solid red (open blue) π^+ (π^-) on LH_2

Middle : solid red (open blue) dots are π^+ (π^-) on LH_2

solid red (open blue) squares are π^+ (π^-) on LD_2

Bottom : solid red (open blue) dots are for π^+ (π^-) on LH_2

- We will be able to test many common assumptions used in SIDIS analyses:

$$R_{SIDIS} = R_{DIS}?$$

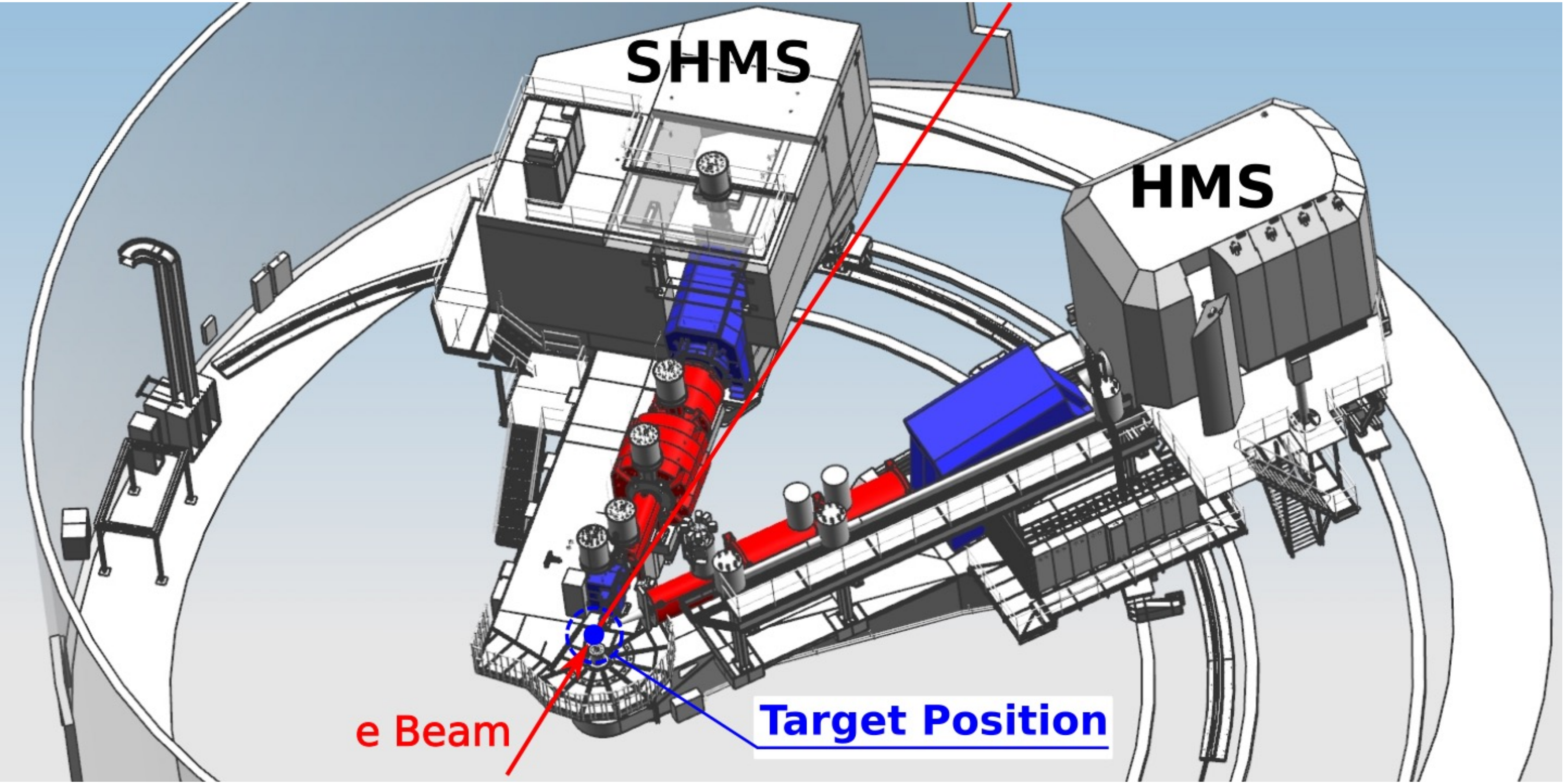
$$R^{\pi^+}_{SIDIS} = R^{\pi^-}_{SIDIS}? \qquad R^{H}_{SIDIS} = R^{D}_{SIDIS}? \qquad R^{\pi^+}_{SIDIS} = R^{K^+}_{SIDIS}? \qquad R^{K^+}_{SIDIS} = R^{K^-}_{SIDIS}?$$

- Important for determining spin structure function g_1^h (need term $(1 + \varepsilon R)$ to get g_1^h/F_1^h from $A_\parallel^h$)

- At low z, expect DIS Q^2 behavior ($\sim 1/Q^2$), but as z→ 1, expect Deep-Exclusive Q^2 behavior ($\sim Q^2$)

- Completely unknown p_T behavior, which might impact on TMD analyses

Hall C Spectrometers



Existing Hall C Spectrometers

SHMS:

Scattering angle down to 6.6º
Momentum up to 11 GeV/c

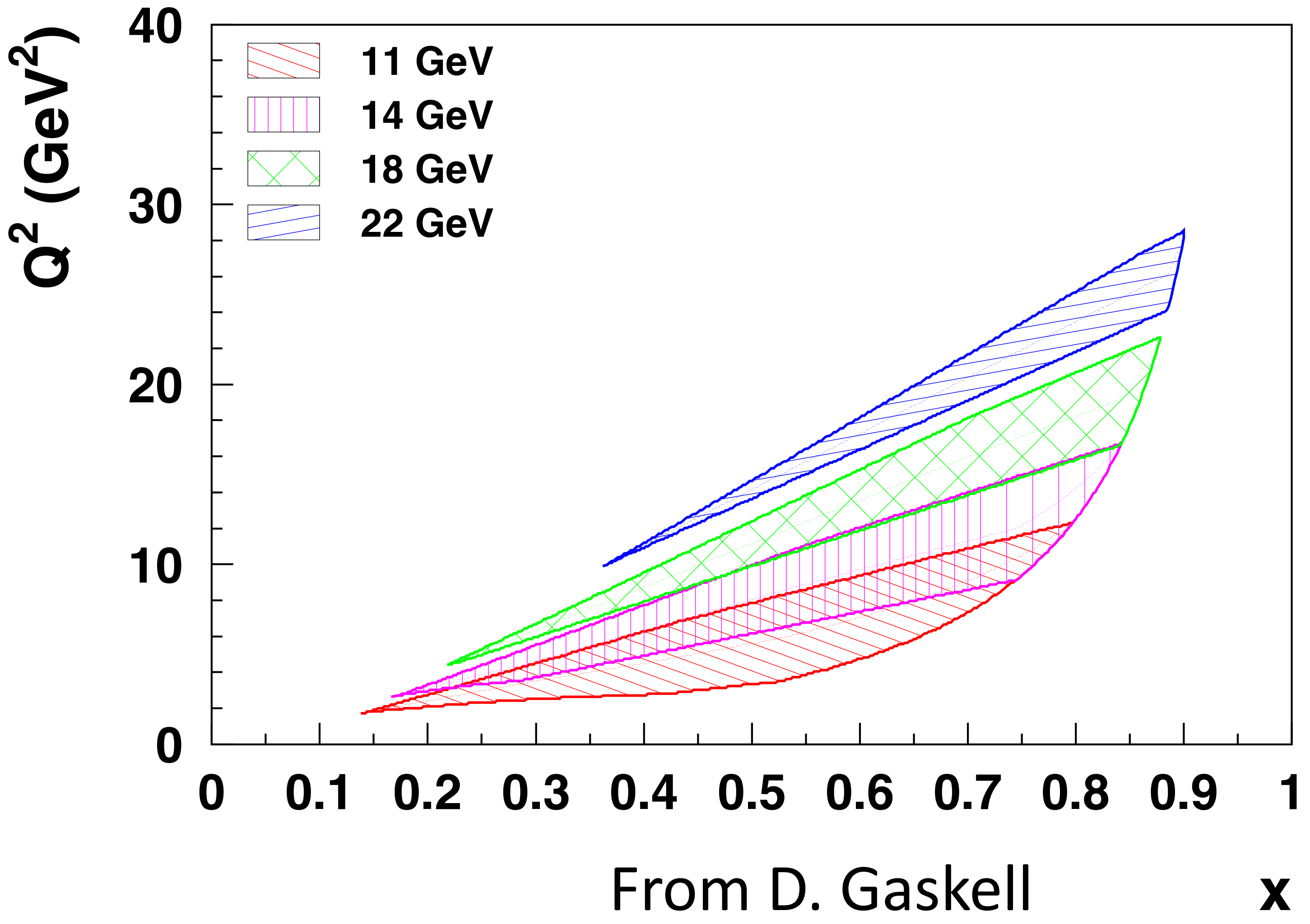
HMS:

Scattering angle down to 13.5º (e^-detection)
Momentum up to 6 GeV/c

Angular separation HMS-SHMS > 17.5º)

***Small scattering angle coverage and higher momentum needed to match higher beam energy

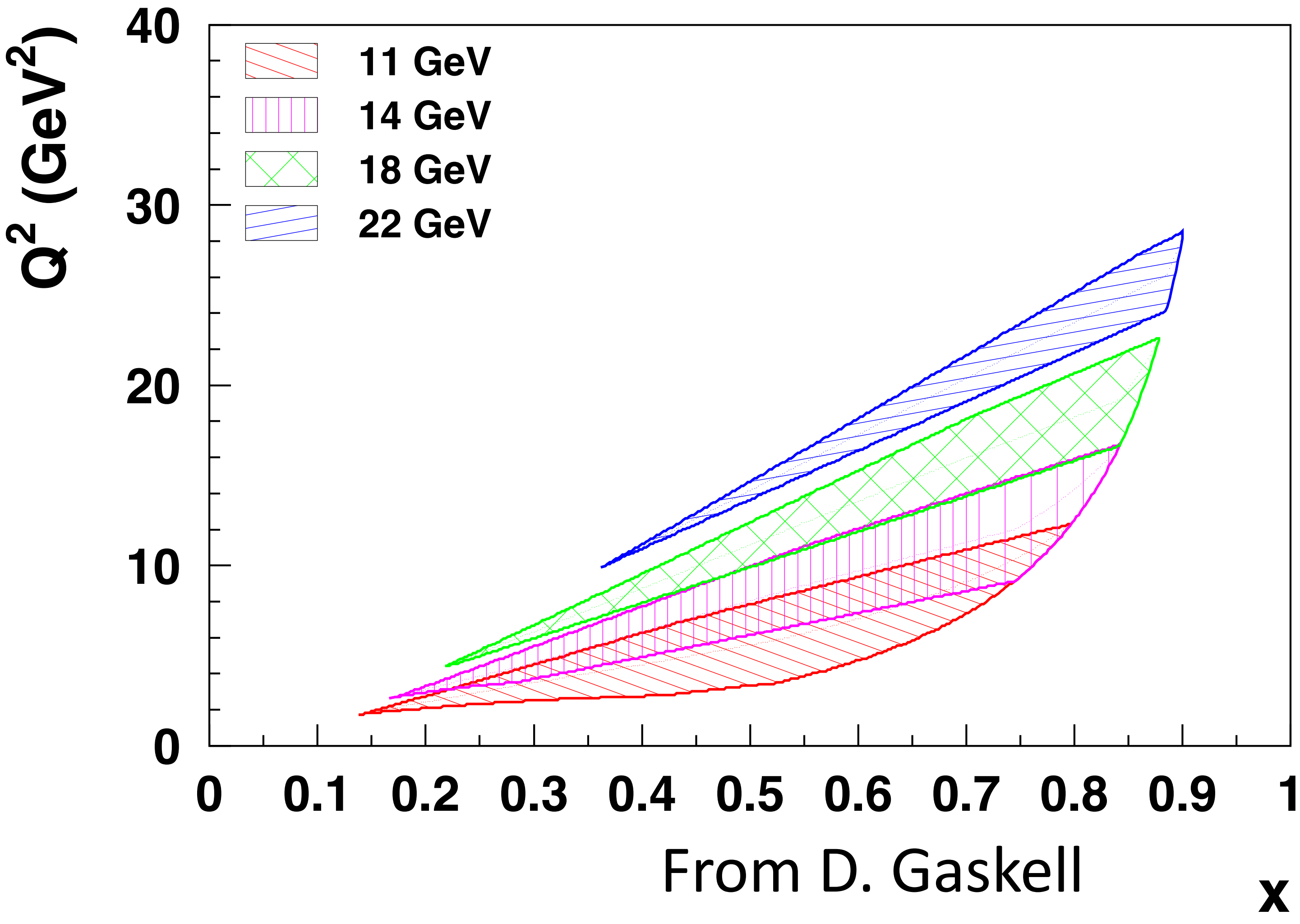
What can we do at 22 GeV to measure R?



From D. Gaskell

Kinematic ranges accessible in Hall C with existing HMS and SHMS spectrometers and that can achieve two ε values separated by 0.2 with a minimum ε of 0.1

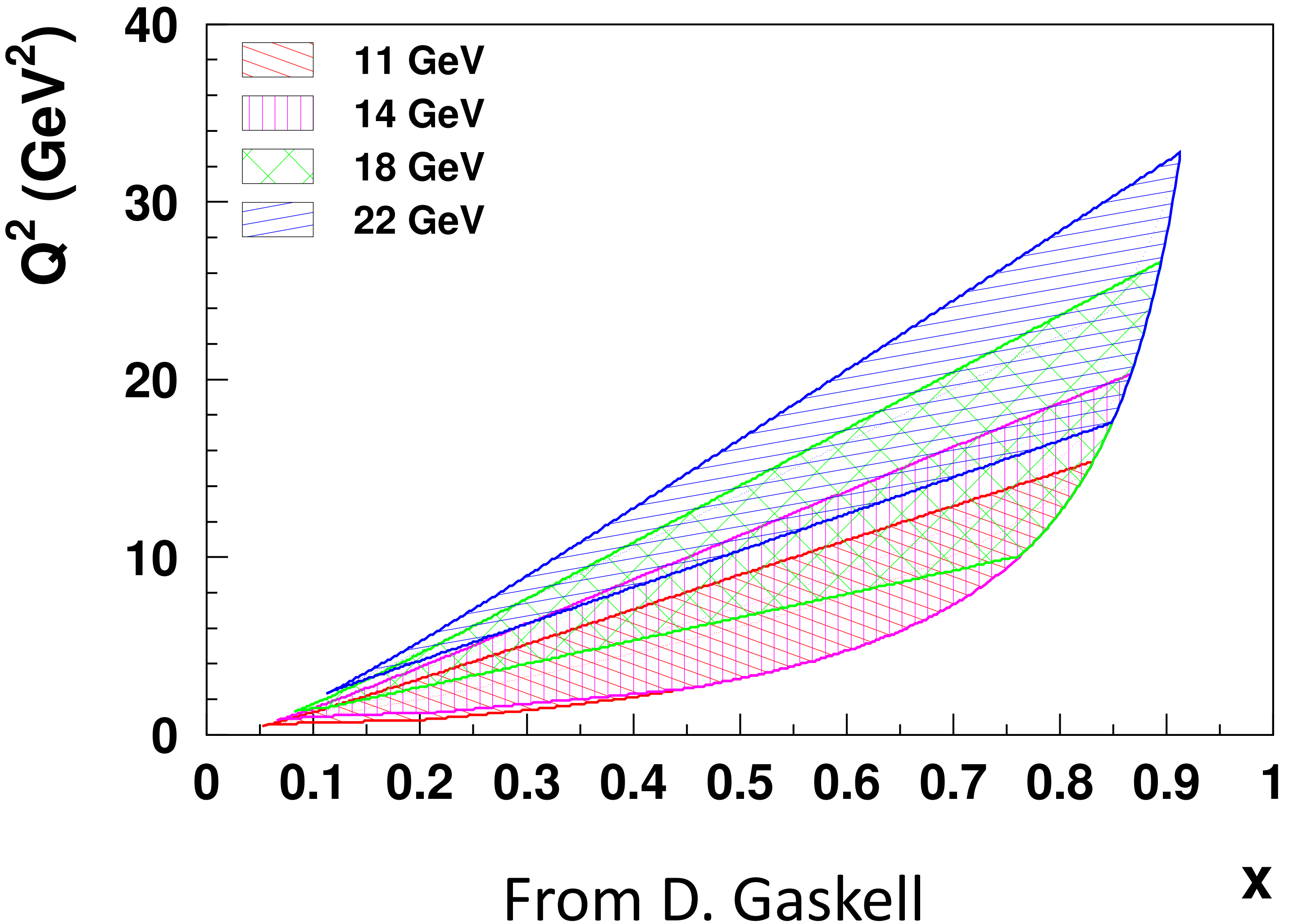
What can we do at 22 GeV?



From D. Gaskell

- Explore R and σ_L at higher x and Q^2
- Combine with 11 GeV results. Can we see approach to constituent (dressed) parton behavior?
- Need to simulate!
- Effect of upgrade to HMS under study

Upgraded HMS (θmin=5°, Pmax =11 GeV/c)



From D. Gaskell

Hall C Jefferson Lab at 22 GeV!

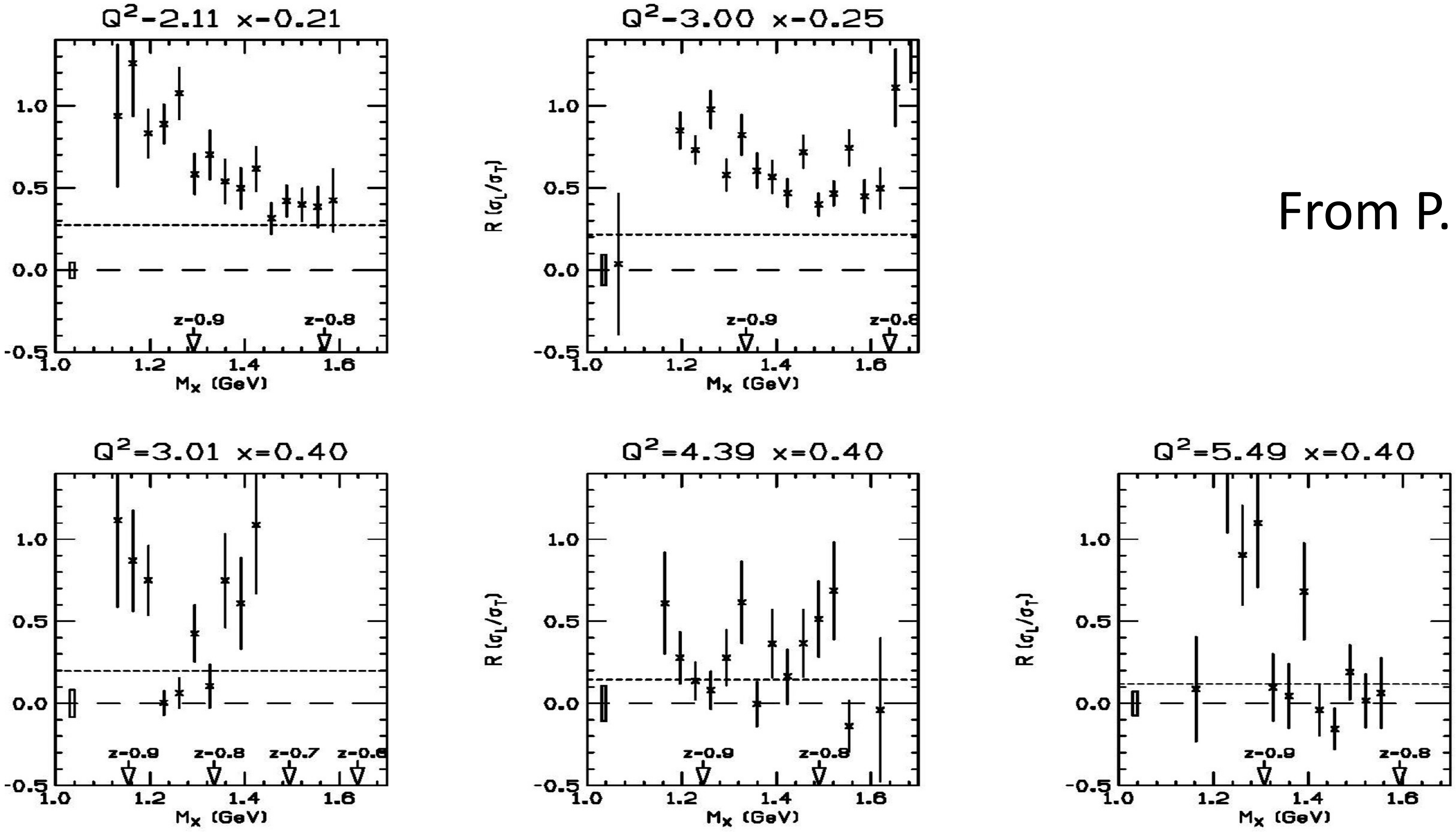
- R is a fundamental measurement of hadron structure
  - *Critical to precise determination of pdfs and TMDs*
  - *Longitudinal cross section explores "non-perturbative" structure beyond simple quark model*

- Very difficult to access at high energy colliders due to small range of ε, whereas Jefferson has luminosity and ε range to carry out timely and precise measurements!

- Combination with CLAS or SOLID style detector makes a very strong program to understand "realistic" SIDIS and hence QCD!

Backup Slide

Preliminary SIDIS Results from Hall C!!!



From P. Bosted