jeffy lab

"Beam in 30 minutes or it's free"

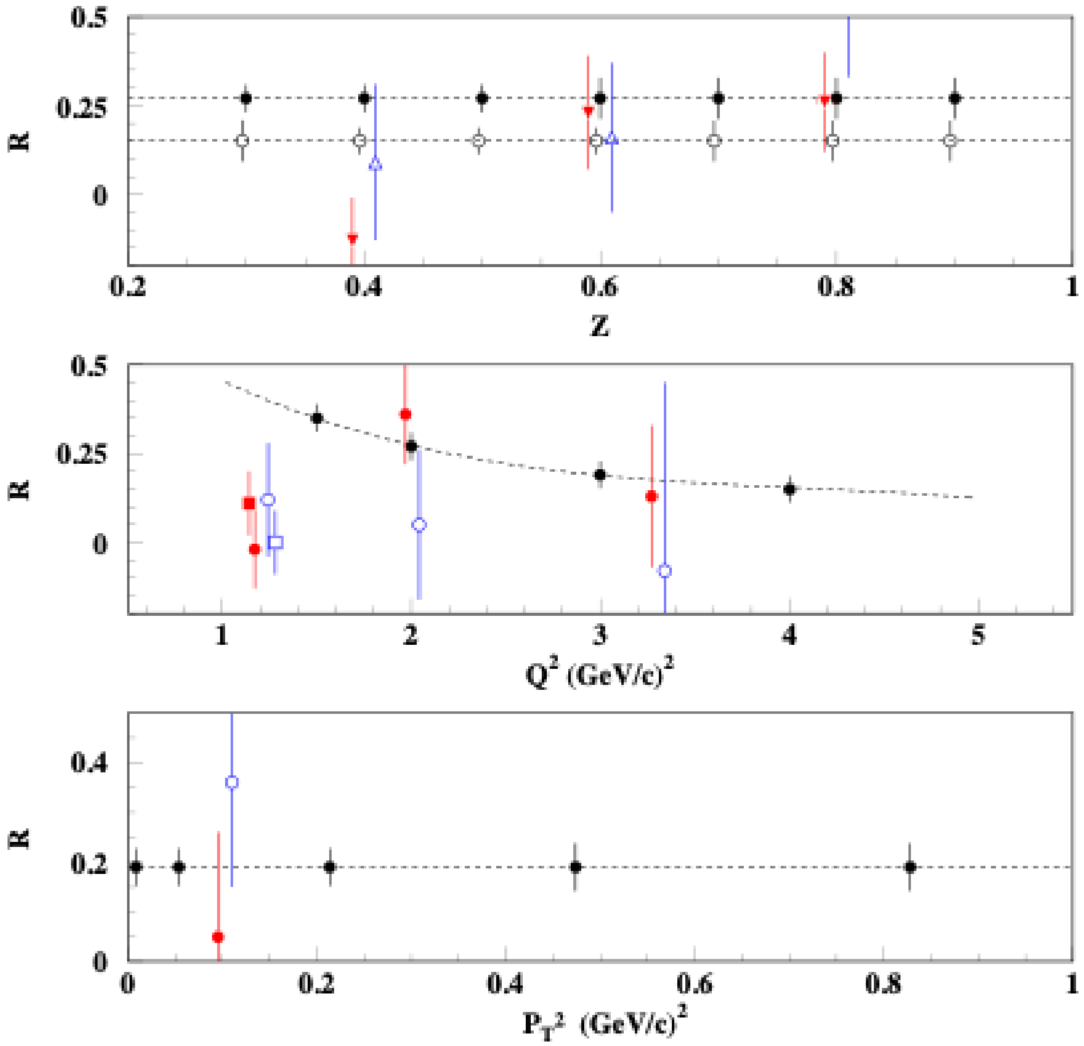
# *R-SIDIS Analysis*

February 3, 2025

Topics:

1. Analysis goals
2. Rosenbluth Separations
3. Extraction of cross sections
4. Other stuff

# R-SIDIS Measurement Goals



Extract $R=\sigma_L/\sigma_T$ in SIDIS
→ charged pions and kaons
→ H and D targets

Measure as a function of $x/Q^2$, z, and $P_T$

Compare R in SIDIS to DIS
Key questions:

1. How does R transition from low z to exclusive limit (z=1)?
2. Is R the same for pions and kaons?
3. What is the $P_T$ dependence?

# R-SIDIS Measurement Goals

Extract nuclear dependence of $R_{SIDIS}$

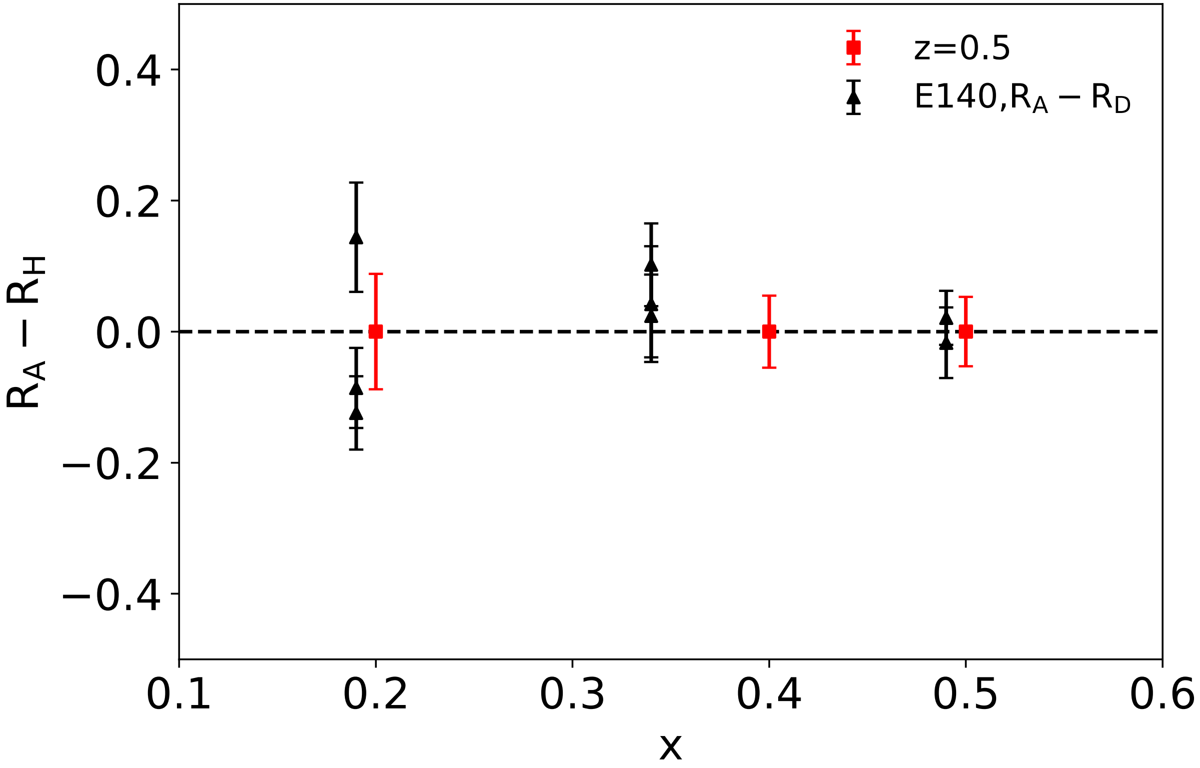
→ Approved experiment to measure nuclear dependence of R in inclusive DIS – related to EMC effect, anti-shadowing, etc.

→ Nuclear dependence of $R_{SIDIS}$ important for interpretation of hadron attenuation measurements, dilution extraction for polarized target experiments, possible interesting new physics

Exploratory measurement → $x/Q^2$ dependence, z dependence, $P_T$ dependence at subset of proton/deuteron measurements

▲ SLAC E140: Nuclear Dependence of R in DIS

🟥 E12-24-001: Nuclear Dependence of R in SIDIS (projected precision)



# Inclusive Electron Scattering cross section and kinematics

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 (E')^2}{Q^4}\left[W_2(\nu,Q^2)\cos^2\frac{\theta}{2} + 2W_1(\nu,Q^2)\sin^2\frac{\theta}{2}\right]$$

$$MW_1(n,Q^2) \circledR\ F_1(x)$$

$$nW_2(n,Q^2) \circledR\ F_2(x)$$

$$F_2(x) = \sum_i e_i^2 x q_i(x)$$

$Q^2$ = -(four-momentum transferred to struck nucleon)$^2$= $4E_e E'_e \sin^2\frac{\theta_e}{2}$

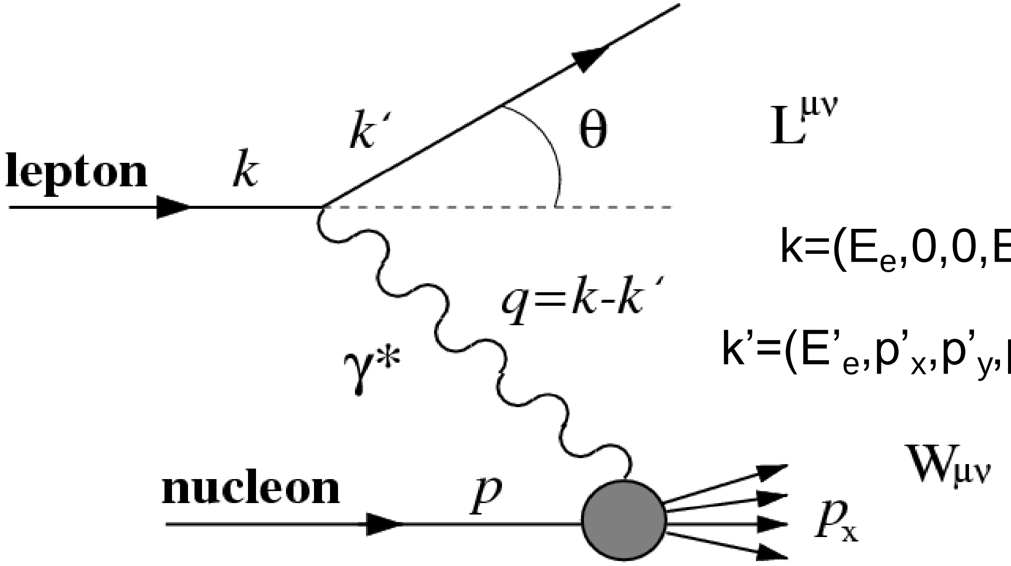
$$\nu = E_e - E'_e$$

$W^2$=total energy of virtual-photon + target in CM frame

$$= \nu^2 + M^2 + 2M\nu \ - q^2$$

$$x = \frac{Q^2}{2M\nu}$$

Bjorken scaling variable
→ Fraction of nucleon momentum carried by struck quark



$k=(E_e,0,0,E_e)$

$k'=(E'_e,p'_x,p'_y,p'_z)$

# (Inclusive) Rosenbluth (L-T) Separations

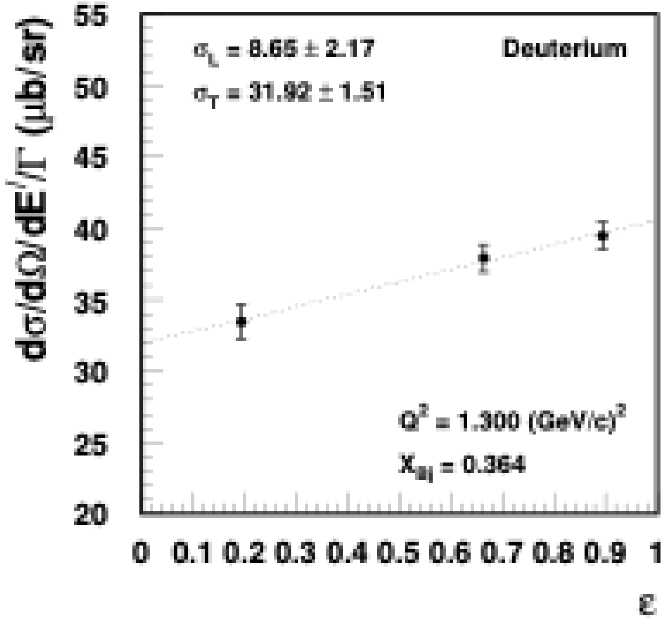
Inclusive cross section can be re-written:

$$\frac{d\sigma}{d\Omega dE} = \Gamma \left[\sigma_T(\nu, Q^2) + \epsilon \sigma_L(\nu, Q^2)\right]$$

$$\Gamma = \frac{\alpha}{2\pi^2}\frac{E'_e}{E_e}\frac{1}{Q^2}\frac{1}{1-\epsilon}K_{eq} \qquad K_{eq} = \frac{W^2 - M^2}{2M} \qquad \epsilon = \left[1 + 2\left(1 + \frac{Q^2}{4M^2x^2}\right)\tan^2\frac{\theta}{2}\right]^{-1}$$

Plot cross section at fixed $\nu$ (or x) and $Q^2$
→ Plot vs. $\varepsilon$ and fit line
→ Slope = $\sigma_L$, intercept $\sigma_T$

Vary $\varepsilon$ by making measurements at different beam energies (scattered electron momentum and angle will also change to keep x and $Q^2$ fixed)



Example from Vladas Tvaskis' thesis

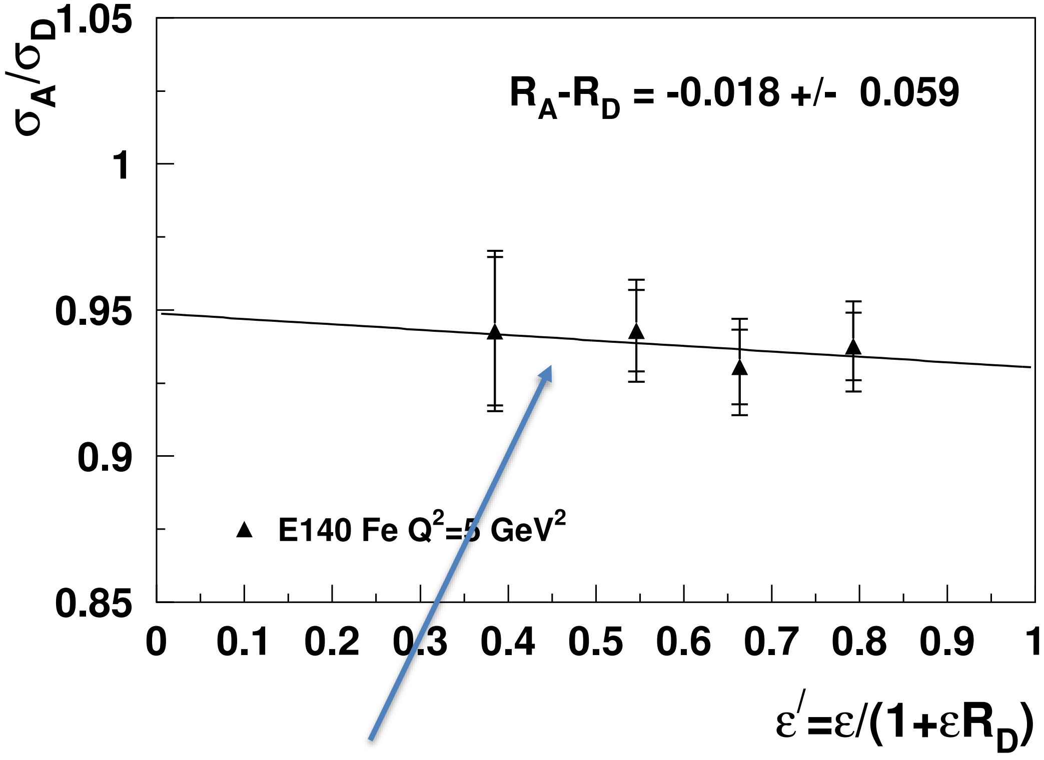
# Nuclear Dependence of R=$\sigma_L/\sigma_T$

Nuclear dependence of R can be extracted by looking epsilon dependence of target ratios

$$\frac{\sigma_A}{\sigma_H} = \frac{\sigma_A^T}{\sigma_H^T}[1 + \epsilon'(R_A - R_H)]$$

$$\epsilon' = \epsilon/(1 + \epsilon R_H)$$

Example: $R_A$-$R_D$ from SLAC E140 (inclusive DIS)



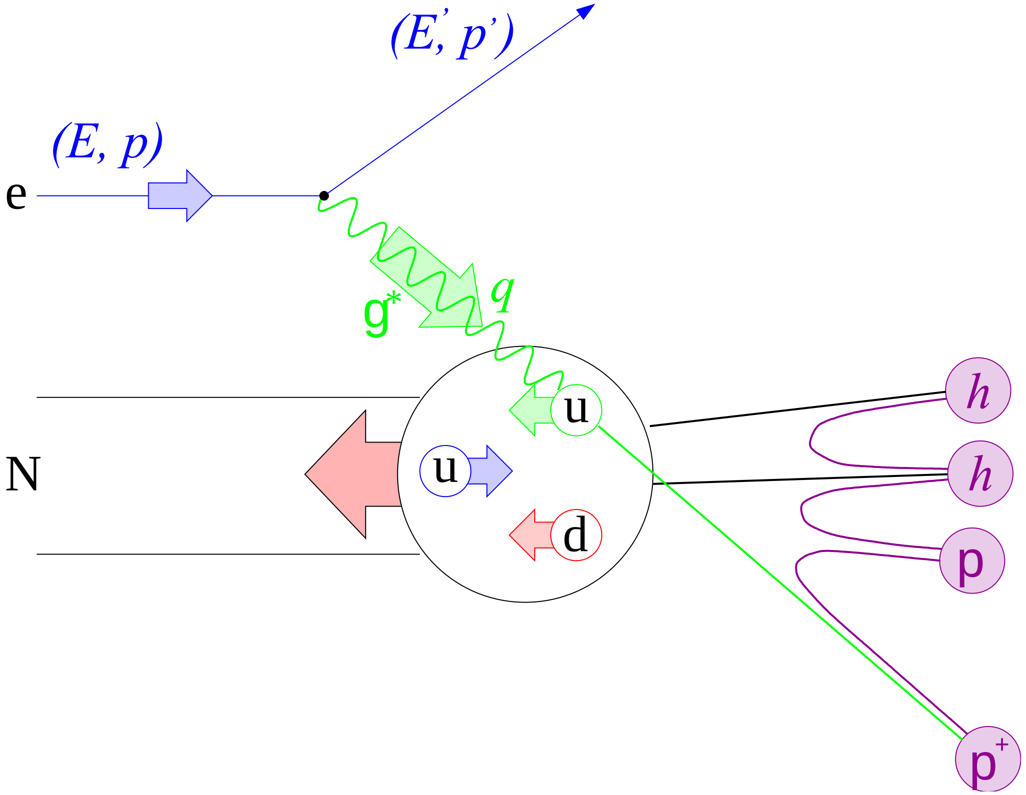
Slope = $R_A$-$R_D$

# Semi-inclusive DIS

SIDIS → production of one or more hadrons in DIS reaction

Simple picture:
1. Electron scatters from quark in nucleon
2. Quark is kicked out → subsequently hadronizes, ending up in bound state

In this simple picture, SIDIS can be used to "tag" the flavor of the struck quark in DIS process



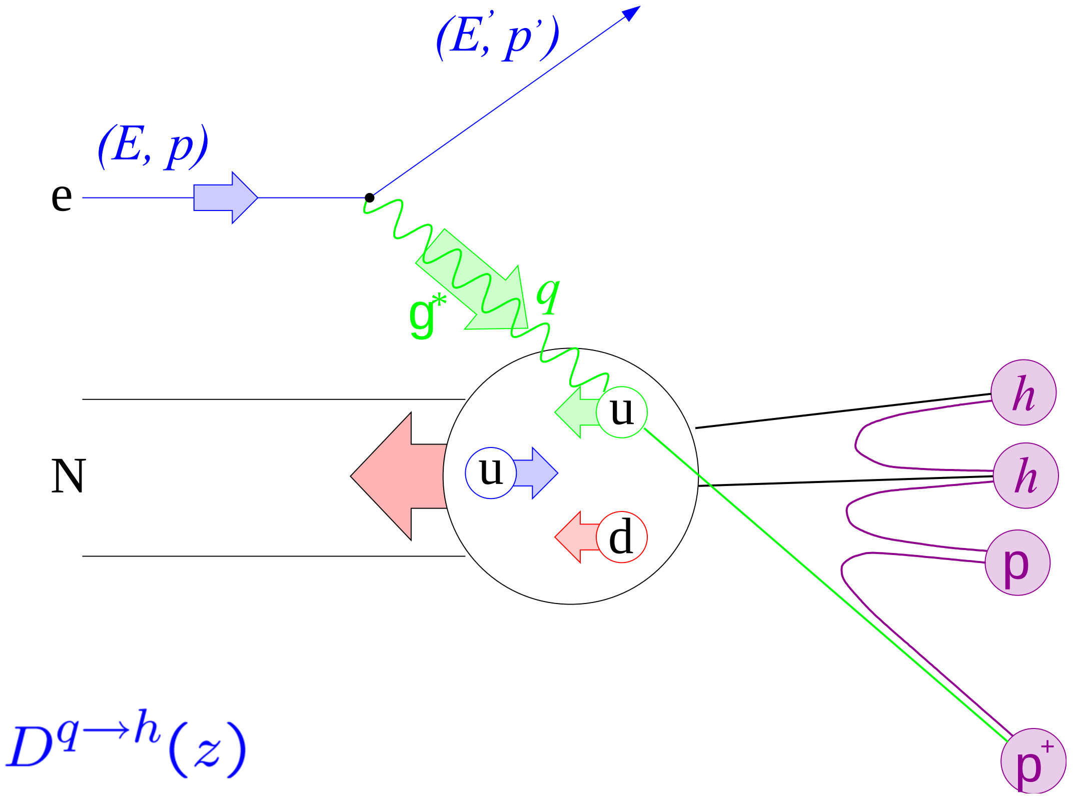
$$d\sigma^h \propto \sum f^{H\to q}(x)\,\mathrm{d}\sigma_q(y)\,D^{q\to h}(z)$$

Fragmentation function

# Semi-inclusive DIS

In principle SIDIS can also be used to gain information about spatial distributions of quarks in nucleons

→ This requires measurements/observation of transverse degrees of freedom



$$d\sigma^h \propto \sum f^{H\to q}(x)\,\mathbf{d}\sigma_q(y)\,D^{q\to h}(z)$$

$$\downarrow$$

$$d\sigma^h \propto \sum f^{H\to q}(x, k_T) \otimes \mathbf{d}\sigma_q(y) \otimes D^{q\to h}(z, p_\perp)$$

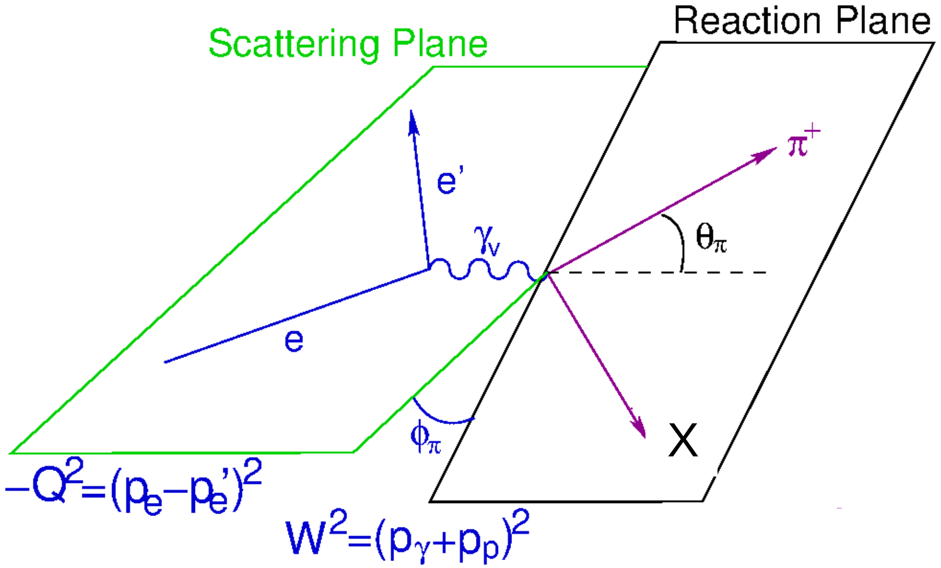
# SIDIS Cross Section(s)

Unpolarized cross section → requires 3 more degrees of freedom

$$\frac{d\sigma}{dE_e d\Omega_e dP_\pi d\Omega_\pi} = \Gamma\left[\frac{d\sigma_T}{dP_\pi d\Omega_\pi} + \epsilon\frac{d\sigma_L}{dP_\pi}d\Omega_\pi + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dP_\pi d\Omega_\pi}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dP_\pi d\Omega_\pi}\cos 2\phi\right]$$

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left[F_T + \epsilon F_L + \sqrt{2\epsilon(1+\epsilon)}\cos\phi F_{LT} + \epsilon\cos 2\phi F_{TT}\right]$$

Inclusive: structure functions depend just on x and $Q^2$
SIDIS: structure functions depend on x,$Q^2$, z, and $P_T$



$$z = \frac{q\cdot p}{q\cdot P} = \frac{E_h}{\nu} \qquad p_{||} = \frac{p\cdot q}{|q|} \qquad p_T = (p^2 - p_{||}^2)^{\frac{1}{2}}$$

$$\cos\phi = \frac{(-\vec{q}\times\vec{k})\cdot(-\vec{q}\times\vec{p_h})}{|\vec{q}\times\vec{k}||\vec{q}\times\vec{p_h}|}$$

# Rosenbluth separations for SIDIS

$$\frac{d\sigma}{dE_e d\Omega_e dP_\pi d\Omega_\pi} = \Gamma\left[\frac{d\sigma_T}{dP_\pi d\Omega_\pi} + \epsilon\frac{d\sigma_L}{dP_\pi}d\Omega_\pi + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dP_\pi d\Omega_\pi}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dP_\pi d\Omega_\pi}\cos 2\phi\right]$$

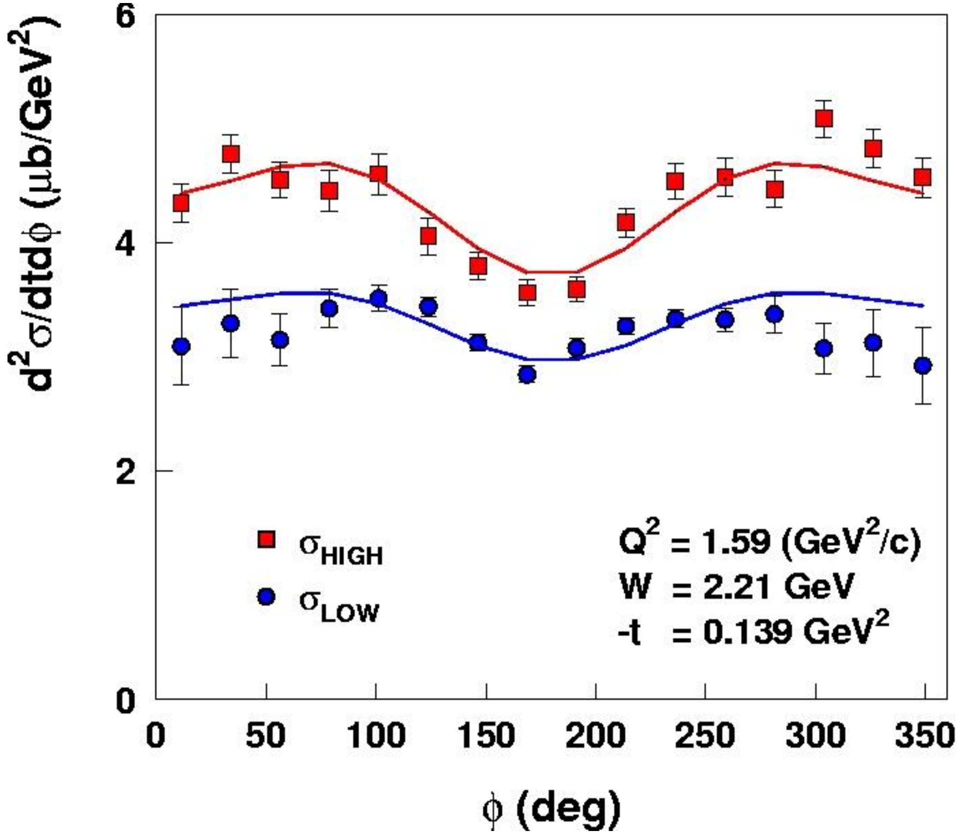
L-T separation for meson production more complicated due to phi dependent terms

We're most interested in $\sigma_L$ and $\sigma_T$

Need to extract cross section at fixed x, $Q^2$, z, and $P_T$ vs. $\phi$ at each beam energy ($\varepsilon$)

Two options:

1. Integrate over $\phi$ at each $\varepsilon$ → cross section reduces to $\sigma_L+\varepsilon\sigma_T$
2. Do multiparameter fit over all $\varepsilon$ settings → extract L, T, LT, TT terms simultaneously



Example from exclusive pion production (Tanja Horn)

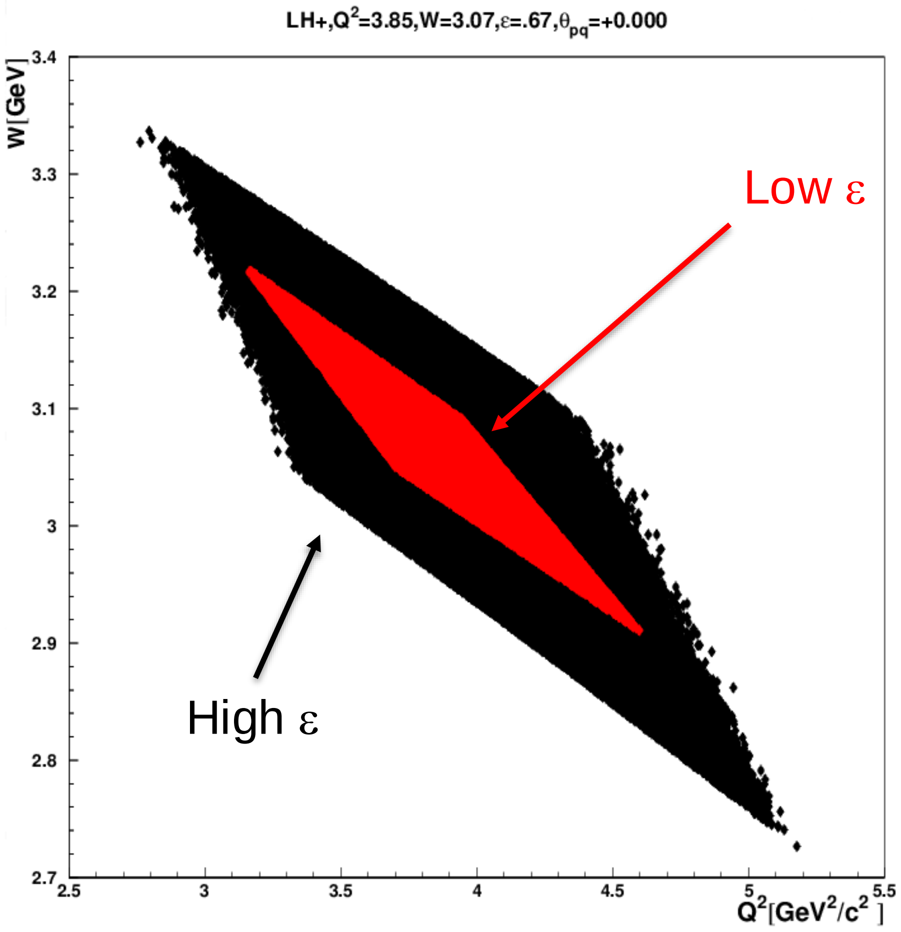
# Phase Space at high and low epsilon

Complication in L-T separations due to finite acceptance of spectrometers
→ Electron phase space ($x,Q^2$) or ($W,Q^2$)

Need to perform L-T separation at same x and $Q^2$
→ Integrating over different regions can results in different effective x and $Q^2$

2 options:

- Add so-called “diamond cuts” to acceptance → force $x/Q^2$ at coverage low and high $\varepsilon$ to be the same
  - Results in reduced statistics for high $\varepsilon$ data (or longer run times)
- “Bin-center” over full $x/Q^2$
  - Bin-centering at some level is required anyway
  - Can result in larger systematic uncertainties



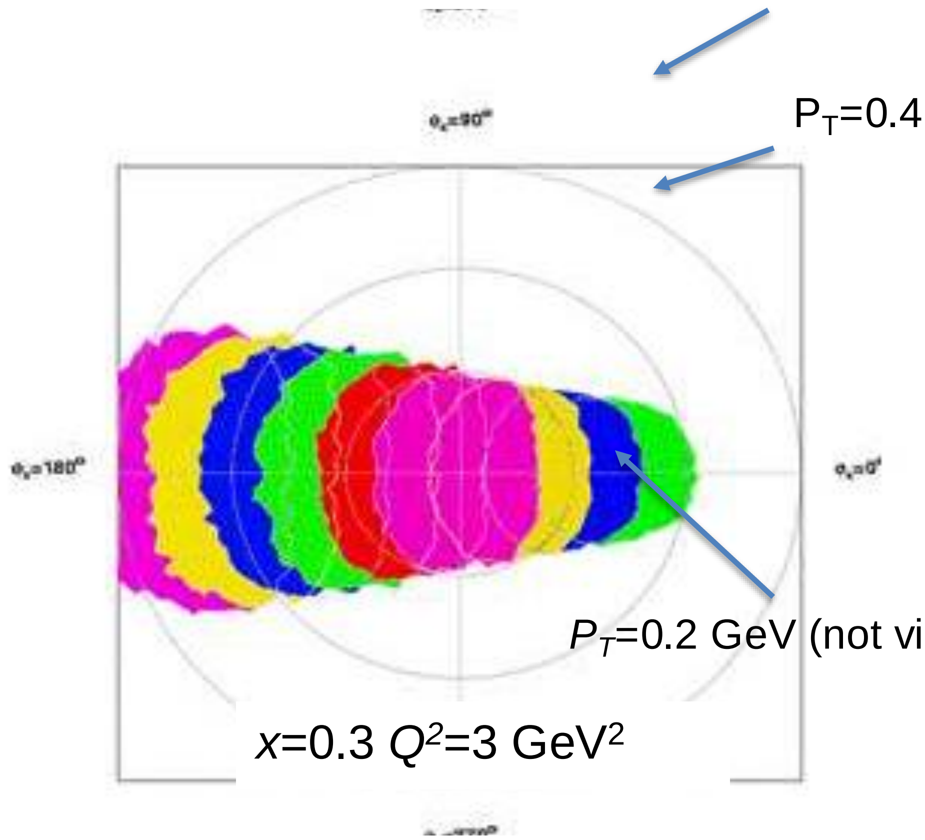
# $P_T$ range and $\phi$ dependence

$$\frac{d\sigma}{dE_e d\Omega_e dP_\pi d\Omega_\pi} = \Gamma \left[ \frac{d\sigma_T}{dP_\pi d\Omega_\pi} + \epsilon \frac{d\sigma_L}{dP_\pi} d\Omega_\pi + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{dP_\pi d\Omega_\pi} \cos\phi + \epsilon \frac{d\sigma_{TT}}{dP_\pi d\Omega_\pi} \cos 2\phi \right]$$

The $P_T$ range over which we can unambiguously extract $\sigma_L$ and $\sigma_T$ is limited by the spectrometer acceptance

→Can move the spectrometer left and right of the q-vector direction to cover $\phi$=0 and 180 degrees

→ Out-of-plane acceptance limits PT range near $\phi$=90 and 270 degrees



$P_T$=0.6 GeV

$P_T$=0.4 GeV

$P_T$=0.2 GeV (not visible)

$x$=0.3 $Q^2$=3 GeV$^2$

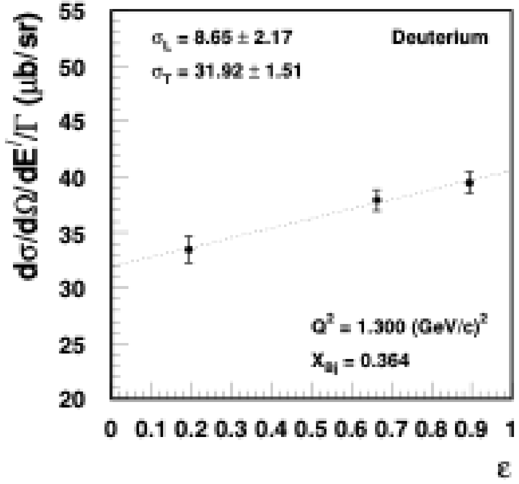
# Systematic Uncertainties

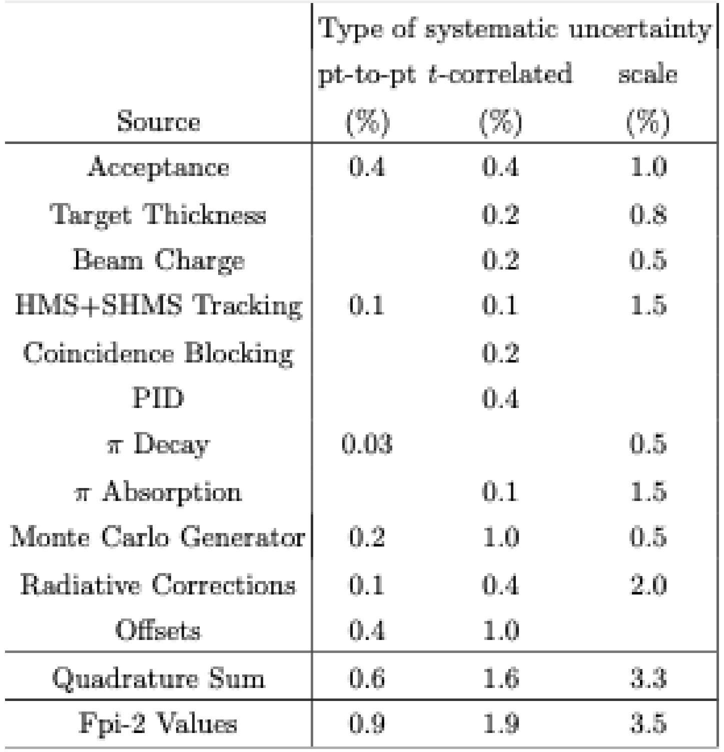
In general – there are 2 classes of systematic uncertainties

- Scale or normalization type systematic uncertainties
    - These uncertainties are in general independent of time and running condition
    - Example: target length → this will stay the same throughout run (unless damaged)
- Point-to-point or random systematic uncertainties
    - These uncertainties can vary with time, beam energy, spectrometer setting, etc.
    - Examples: acceptance (same region not populated at high and low epsilon) tracking efficiency (rate dependendent)

Point-to-point uncertainties are the most crucial to control

- Added in quadrature with statistical uncertainty at each epsilon → direct impact on slope, intercept
- Scale uncertainties will cancel when forming $\sigma_L/\sigma_T$ ratio

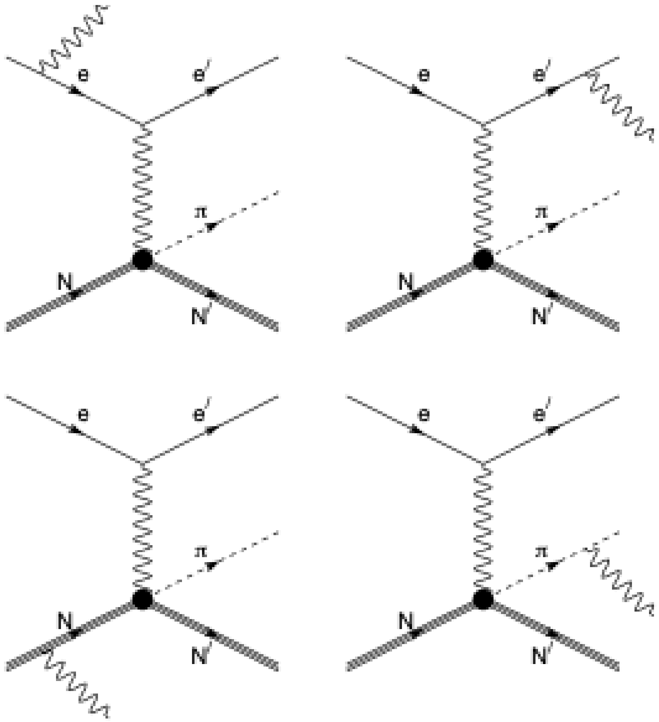




| | Type of systematic uncertainty | | |
|---|---|---|---|
| | pt-to-pt | $t$-correlated | scale |
| Source | (%) | (%) | (%) |
| Acceptance | 0.4 | 0.4 | 1.0 |
| Target Thickness | | 0.2 | 0.8 |
| Beam Charge | | 0.2 | 0.5 |
| HMS+SHMS Tracking | 0.1 | 0.1 | 1.5 |
| Coincidence Blocking | | 0.2 | |
| PID | | 0.4 | |
| $\pi$ Decay | 0.03 | | 0.5 |
| $\pi$ Absorption | | 0.1 | 1.5 |
| Monte Carlo Generator | 0.2 | 1.0 | 0.5 |
| Radiative Corrections | 0.1 | 0.4 | 2.0 |
| Offsets | 0.4 | 1.0 | |
| Quadrature Sum | 0.6 | 1.6 | 3.3 |
| Fpi-2 Values | 0.9 | 1.9 | 3.5 |

# Corrections and backgrounds

Radiative corrections → emissions of ”extra” photons by incoming/outgoing electrons, outgoing pion



Contributions:

→ SIDIS events from other kinematics can radiate into experimental acceptance → can also radiate out of acceptance

→ Events from exclusive processes can radiate into acceptance

→ For example: $H(e,e'\pi+)n$, $H(e,e'\pi+)\Delta^0$

Additional background possible from exclusive vector meson production → can decay into $\pi^+\pi^-$ pair

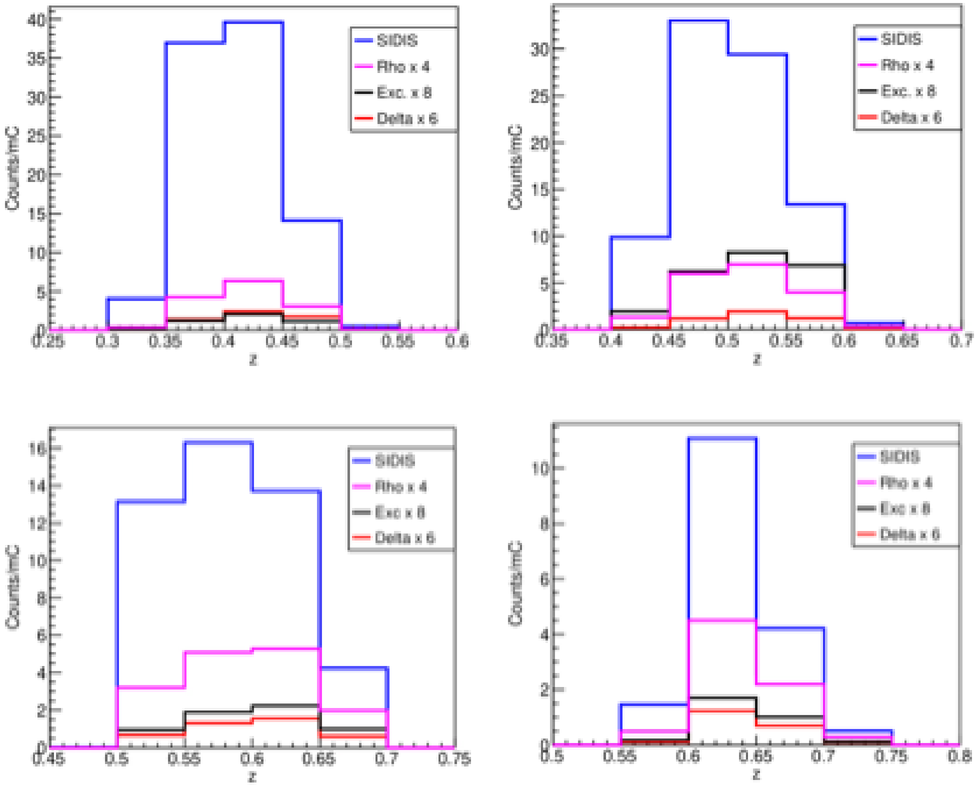
→ Dominate by diffractive $\rho^0$ production

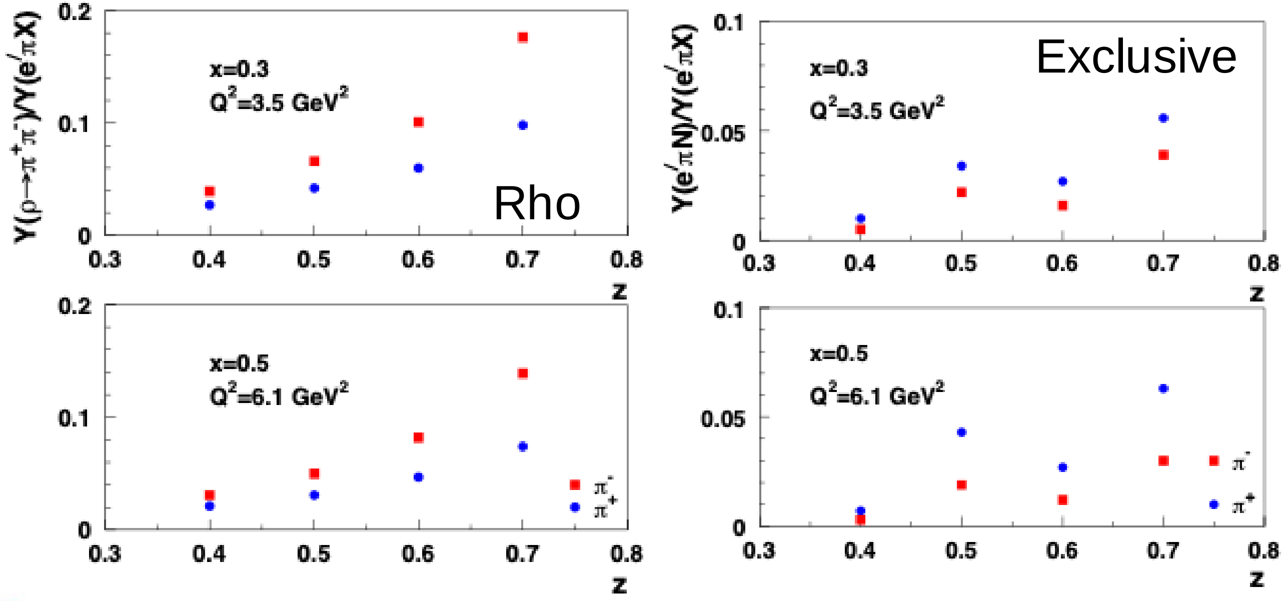
# Corrections and backgrounds

Example from Hem Bhatt’s thesis

→ Exclusive, and delta production estimates based on models that describe the Hall C 2018 SIDIS and world exclusive data

→ Rho model based on HERMES modifications to Pythia, with tweaks to improve agreement with JLab 6 GeV results





Estimates from E12-09-002 proposal

# Extraction of cross sections

$$\frac{d\sigma}{dE_e d\Omega_e dP_\pi d\Omega_\pi} \Rightarrow \frac{\text{\# of scattered electrons in } E_e,\Omega_e \text{ bin in coincidence with a pion in given } P_\pi,\ \Omega_\pi \text{ bin}}{\Delta E_e\ \Delta\Omega_e\ \Delta P_\pi\ \Delta\Omega_\pi\ (\text{\# of target protons/cm}^2)\ (\text{\# of incident electrons})}$$

In principle, can calculate cross section “by-hand”
→ # of events from output of analyzer hcana
→ Incident electrons from beam current measurements
→ Target particle from target density and thickness
→ Phase space from Monte Carlo simulation

Also need efficiency corrections:
→ Live times (computer and electronic)
→ Tracking efficiency
→ Detector efficiencies

Other corrections:
→ Radiative effects
→ Bin centering
→ Pion decay

# Bin centering

When determining cross section, what kinematics do we quote?

→ Events are integrated over non-zero phase-space in $(x,Q^2)$

Can we just average x and $Q^2$?

→ If cross section is linear in those variables over the bin size, this could be ok

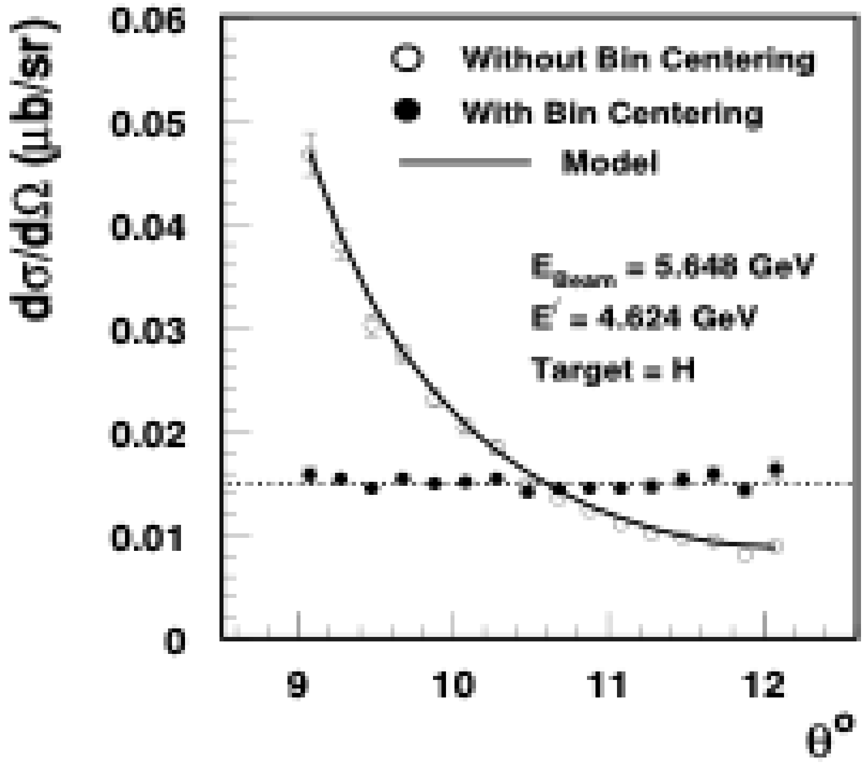
→ If cross section not linear – average cross section at average $(x,Q^2)$ is not the same as the cross section evaluated at average $(x,Q^2)$

Need to "bin-center" the data to quote cross-section at particular $(x,Q^2)$

→ This can be done by applying explicit weight to each event *OR*

→ Can be done implicitly by comparing data to cross-section weighted simulation

Inclusive example



Vladas Tavaskis' thesis

For coincidence reactions this is easier

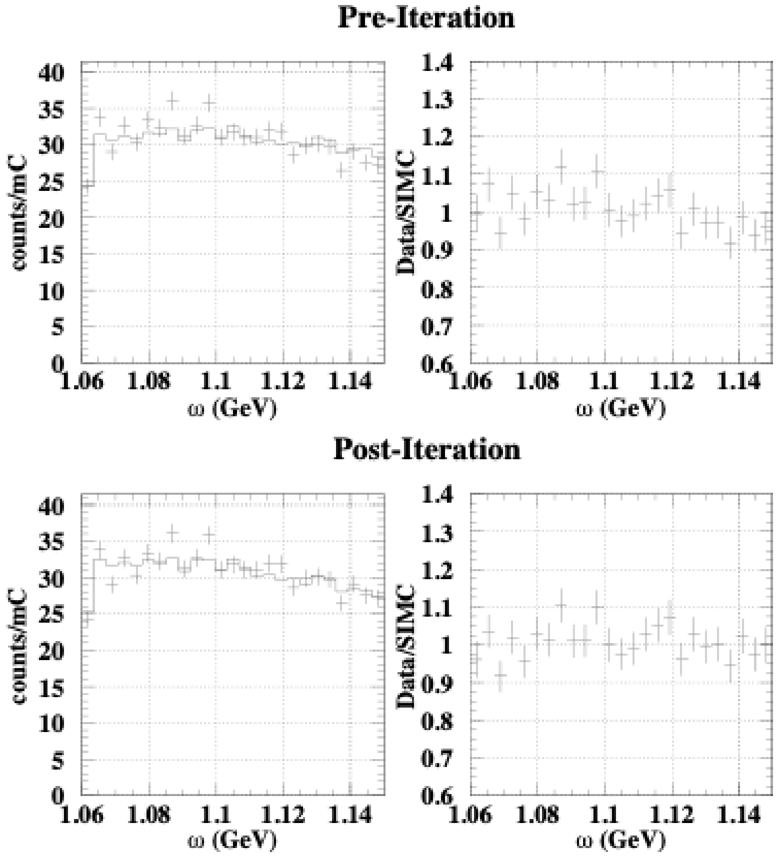
# Extraction of cross sections

Easiest technique is the ratio method:

$$\left[\frac{d\sigma(x_0,Q_0^2,z_0,P_{T0})}{dE_e d\Omega_e dP_\pi d\Omega_\pi}\right]_{exp} = \frac{Y_{DATA}}{Y_{MC}(\sigma_{model})}\left[\frac{d\sigma(x_0,Q_0^2,z_0,P_{T0})}{dE_e d\Omega_e dP_\pi d\Omega_\pi}\right]_{model}$$

Monte Carlo includes radiative effects, pion decay, multiple scattering, acceptance …

By using the ratio method is performing an "implicit" bin centering correction – but cross section model used in the MC must agree with the data → may require correction and iteration of the model cross section



# Extraction of cross sections - SIDIS

$$\left[\frac{d\sigma(x_0,Q_0^2,z_0,P_{T0})}{dE_e d\Omega_e dP_\pi d\Omega_\pi}\right]_{exp} = \frac{Y_{DATA}}{Y_{MC}(\sigma_{model})}\left[\frac{d\sigma(x_0,Q_0^2,z_0,P_{T0})}{dE_e d\Omega_e dP_\pi d\Omega_\pi}\right]_{model}$$

Need to decide how you want to bin/present data, e.g., show z-dependence at fixed $P_T$, $P_T$ dependence at fixed z, etc.

$Y_{data}$→ efficiency-corrected # of counts normalized to charge
→ counts from root trees, charge and efficiencies from report file output from hcana

$Y_{MC}$→ Monte Carlo yield from SIMC → cross section weighted, includes target thickness, RC, etc.

$\sigma_{model}$ → usually from stand-alone calculation. Difficult (although not impossible) to get cross section at particular point from simc. Crucial that stand-alone calculation matches model in simc exactly

# Extraction of cross sections - DIS

$$\left[\frac{d\sigma(x_0,Q_0^2)}{dE_e d\Omega_e}\right]_{exp} = \frac{Y_{DATA}}{Y_{MC}(\sigma_{model})}\left[\frac{d\sigma(x_0,Q_0^2)}{dE_e d\Omega_e}\right]_{model}$$

$Y_{data}$→ efficiency-corrected # of counts normalized to charge
→ counts from root trees, charge and efficiencies from report file output from hcana

$Y_{MC}$→ More complicated than simc. Radiative corrections come from stand-alone program (outputs tables). MC yield from single-arm Monte-Carlo + cross section weights from tables. Must write program to combine RC weights + single-arm MC events

$\sigma_{model}$ → from same tables as RC (but using cross section at vertex instead)

# Analysis to-do list:

- Standard data analysis stuff
  - Reference time and time window cuts
  - Detector and beamline calibrations
  - Determine target boiling corrections, check other efficiencies
  - Determination of kinematic offsets
  - Determination of charge normalized, efficiency-corrected data yields ← next week
  - Simulated yields ← 2 weeks
  - Monte Carlo model iteration
  - Extract cross sections/ratio → Rosenbluth separations ← today
  - Publish
- High-priority for early in experiment running
  - Online reference time and time window cuts
  - Online calibrations
  - Event counter (simple, fast) to ensure we are taking adequate statistics
  - Normalization checks – compare elastic and DIS yields to MC
  - Online target boiling checks
  - Optics checks (?)

# Preparations for next meeting

- Make sure you can access JLab computer systems remotely
  - Easiest to request access to linux VDI
  - https://jlab.servicenowservices.com/sp?sys_kb_id=dec16b0ddb7f0410ee4a3889fc961944&id=kb_article_view&sysparm_rank=1&sysparm_tsqueryId=db133dbc97e79a507d05bba6f053afcd
  - Submit request to helpdesk@jlab.org if you don't already have access
- Get 2-factor token → needed to access ifarm computers (another helpdesk request)
- Check if you are part of the c-rsidis group → type "groups" on ifarm
  - If not, email Hanjie Liu (hanjie@jlab.org) to request to be added
  - This will give you access to the rsidis group and work disks
- Learn about loading modules:
  - https://jlab.servicenowservices.com/scicomp?id=kb_article_view&sysparm_article=KB0014671
  - To access root on ifarm, you'll have to load the appropriate module
- If you like python, you can request access to the JLab instance of jupyterhub:
  - https://jupyterhub.jlab.org/
- RSIDIS elog: https://hallcweb.jlab.org/elogs/R-SIDIS+Experiment/