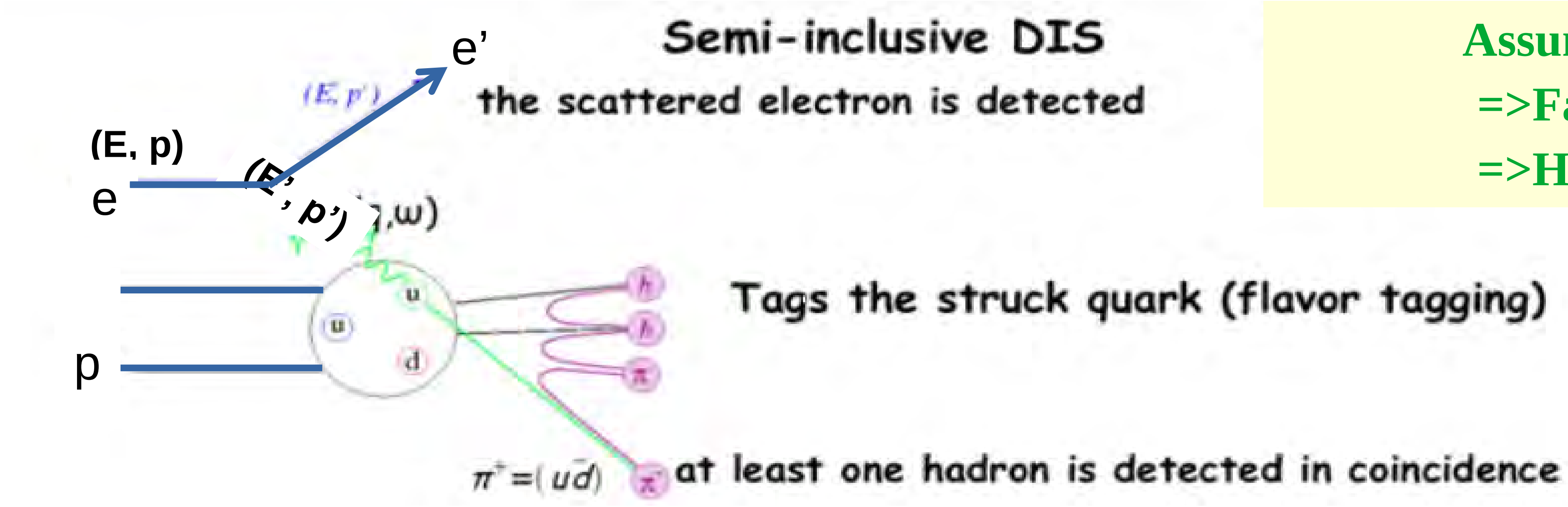
12-GeV era Hall C SIDIS experiments

Presenter: P. Bosted with help from Hem Bhatt

Analysis from three Hall C experiments in 2018-2019

- Pt-SIDIS wide range of Pt for six (x,Q^2) settings with detection of SIDIS π^+ and π^- from proton, deuteron, and aluminum, for $0.3<z<0.9$. No graduate student at present. Mostly being analyzed by myself.
- CSV-SIDIS: 26 more settings in (x,Q^2) for π^+ and p and π^- from deuteron (and some proton) but limited Pt coverage, again $0.3<z<0.9$. Graduate students Hem Bhatt and Shuo Jia.
- Kaon-LT: inelastic π^+ and K^+ on proton target useful for measuring SIDIS at high z , including the ratio $\mathrm{R} = \sigma_L/\sigma_T$

Semi-Inclusive Deep Inelastic Scattering (SIDIS)



Assumptions:

=>**Factorization**

=>**Hadronization**

u => π^+
d => π^-

We can use SIDIS and the formalism of Londergan et. al. to extract the CSV of quark distributions
Londergan, Pang and Thomas PRD54, 3154 (1996)

Few kinematic quantities :

x = $Q^2 / 2M_p\nu$: Fraction of proton's momentum carried by the quark (Bjorken x)

M_p = mass of proton

ν = energy Transfer in lab frame (E - E')

Q^2 = 4 momentum transfer squared = $4EE'\sin^2(\theta/2)$

z = fraction of energy transfer carried by outgoing hadron (pion) = E_h/ν $= \sqrt{(m^2_\pi + p^2_\pi)} / \nu$

Experiments overview

- HMS spectrometer detects electrons at scattering angles from 13 to 49 degrees, momenta from 1 to 6 GeV . Twenty-eight distinct settings: each divided into two (x,Q^2) bins. Solid angle 4 msr. Also detects π^- and K^-.
- SSMS detects particles on opposite side of the beam line. At angles from 6 to 30 degrees, momenta from 2 to 7 GeV.
- Beam energy mostly 10.6 GeV, beam currents 2 to 70 μA
- Targets are 10 cm liquid hydrogen and deuterium, and "dummy' to measure aluminum endcap contributions.
- Trigger was time coincidence between two spectrometers. Typical rate about 3000 Hz.
- Only one hadron per event (unlike open detectors such as CLAS)

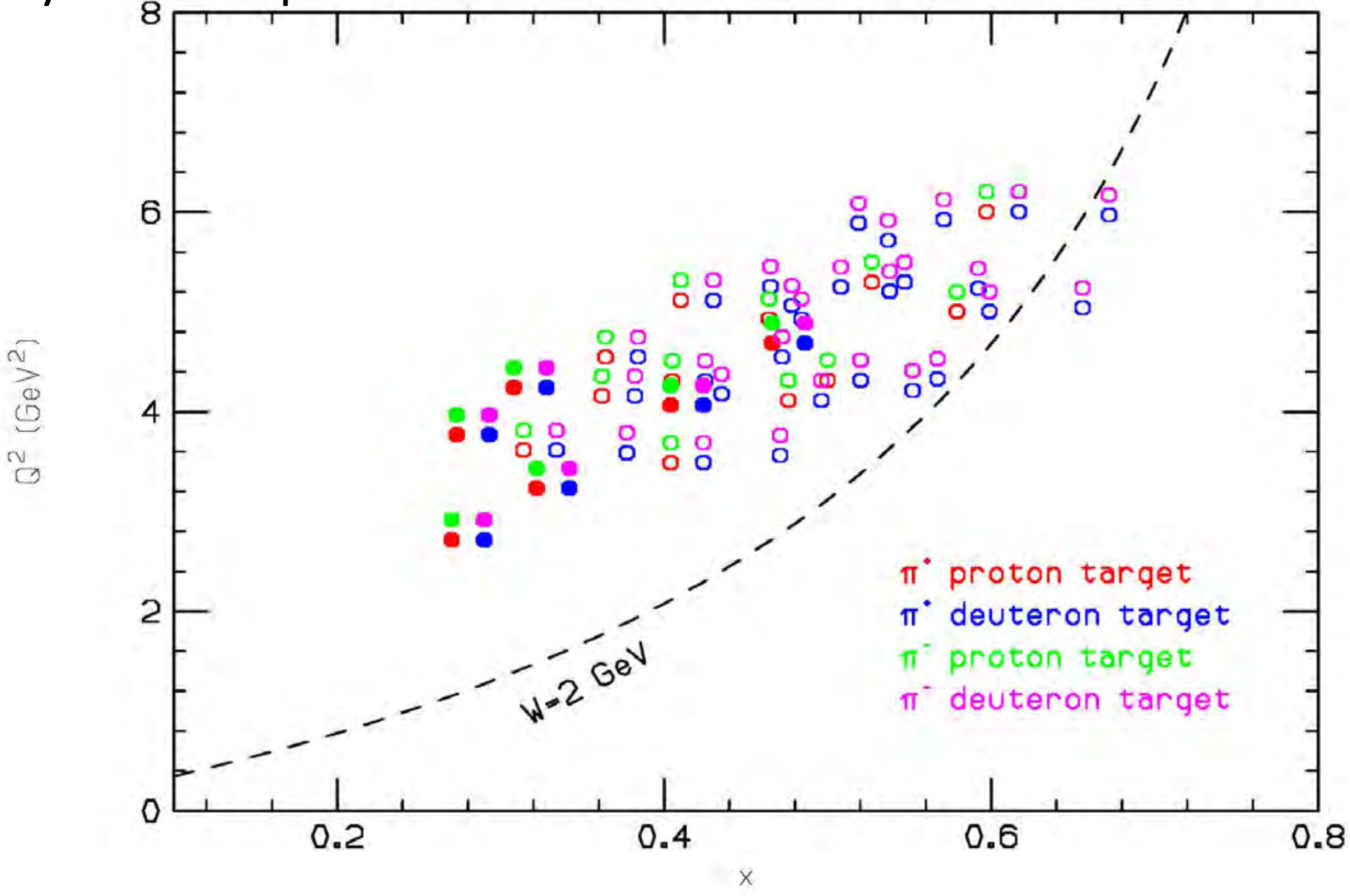
Kinematic coverage in (x,Q^2)

Solid circles are from t-SIDIS, open circles CSV SIDIS

CLAS coverage extends to lower x and lower Q^2

each circle has 10,000 to 1000,000 events

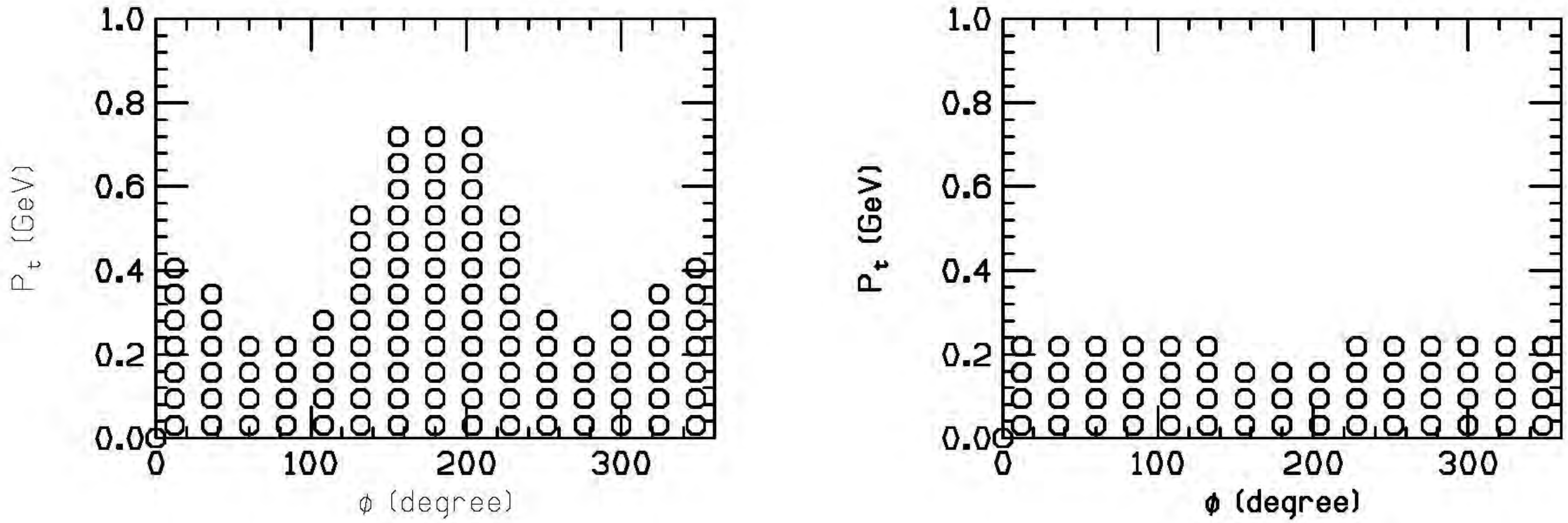
Dominated by valance quark distributions



Kinematic coverage in P_t and ϕ

Typica pt-SIDIS setting
at z=0.5

Typica CSV-SIDIS setting
at z=0.5



Additional kinematic coverage provided by electron in SHMS and pion in HMS (only for negative pions)

Data Analysis Tasks Completed (more or less)

- Determination of beam energy and position
- Calibration of beam current monitors
- Beam current correction to liquid target density
- Computer dead time correction
- Debugging and improvements to tracking code
- Electronic dead time correction
- Corrections for multiple trigger signals
- Calibration of spectrometer optics
- Determination of fiducial volume where spectrometer matched to calibration data and Monte Carlo code (SIMC)
- Calibration of all spectrometer detectors
- Mapping of detector efficiencies and purity.
- Processing of raw data into tracked particles with corresponding detector response

Binning
For each of 56 (x,Q^2) settings
With separate files for π, K

- 6 target/polity bins (p+, d+, Al+, p-, d-, Al-)
- 20 bins in z from 0.1 1 to 1 (bin 1 for excl. bin 2 for Delta)
- 15 bins in phi from 0 to 360 degrees
- 16 bins in Pt from 0 to 1 GeV

For each bin:

- 3 choices of PID/efficiency
- Monte Carlo predicted rate for 4 processes

Typically 500 bins with >50 counts for pt-SIDIS, 100 for CSV-SIDIS, kLT

Bins used individually in global fitting

Aceeptence and radiative corrections using Monte Carlo SIMC

=> Models beam characteristics

⇒ Models target

⇒ Transports particles through spectrometer and detectors

=> Includes multiple scattering, ionization energy loss, particle decay

⇒ Includes Bremstrahlung radiation of incoming and outgoing electron

⇒ “Internal” radiation in equivalent radiator approximation

⇒ Four separate reactions are simulated:

a) SIDIS model assuming factorization, excluding b), c), and d). Run with rad. Corr. On/off.

b) Exclusive pion production ($e\ N \rightarrow e\ \pi\ N$)

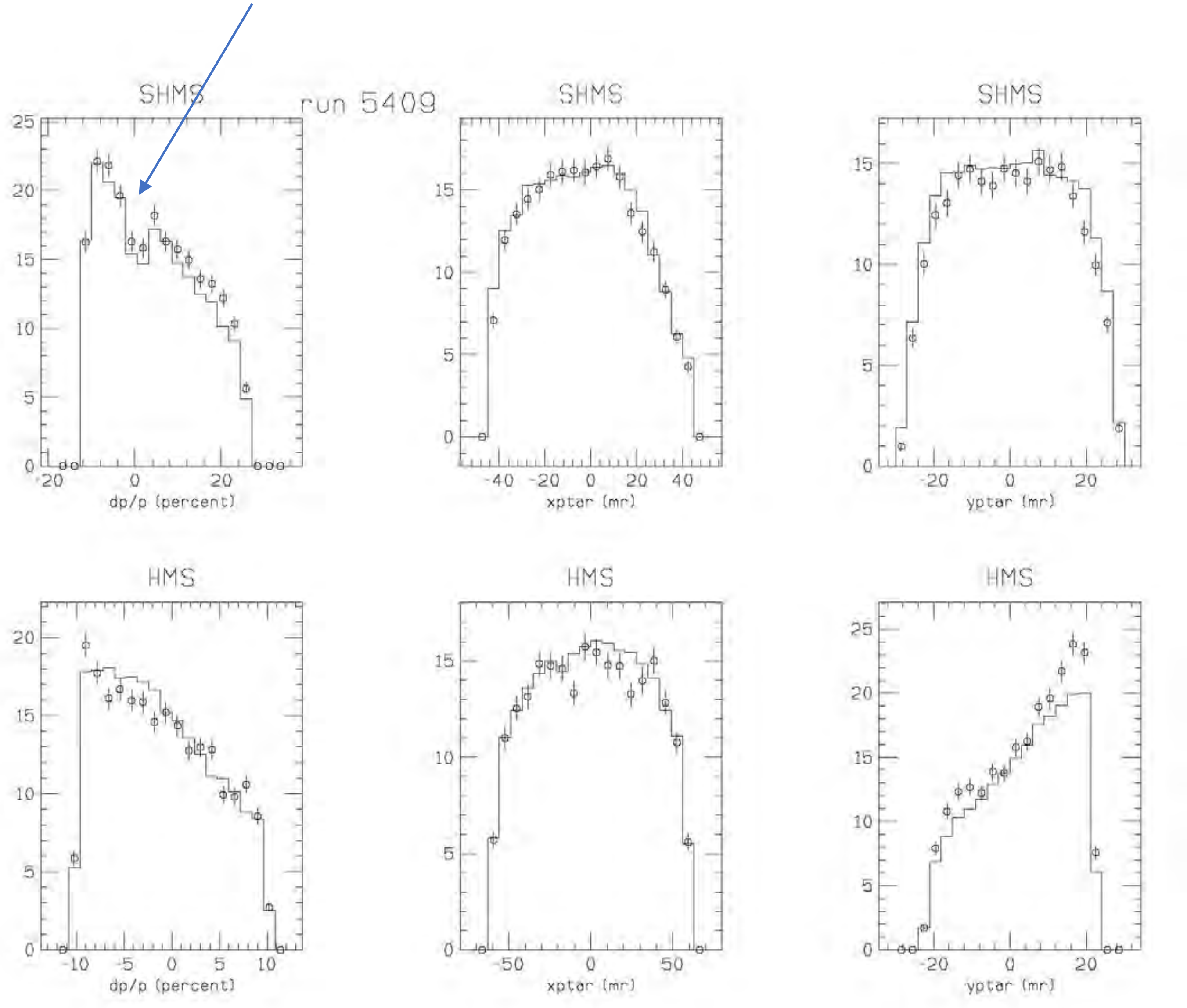
c) Quasti-excluisive production ($e\ N \rightarrow e\ \pi\ \Delta$)

d) Dirffractive rho production with one pion detected from rho decay

Improvements to SIMC

- Better random number generator
- Checked that parm3000 works sort of o.k. for exclusive pion cross sections from all 3 experiments., but up to 60% discrepancies at some settings. New param2021 in progress.
- Found that param3000 is too big in resonance region: changed to use a look-up table from MAID (resonance region is accessed in radiative corrections)
- Made rough fit to our data on e p -> e π^- Delta^{++} reaction since no fit available from anyone else. Also modeled smaller cross sections e p -> e pi+ Delta0, e n-> e pi+ Delta-, e n-> e pi- Delta+
- Made two iterations of fitting the SIDIS data and re-running SIMC. Model has converged to give good agreement in almost all kinematic settings.

Incorporation of HG Cherenkov Efficiency into SIMC



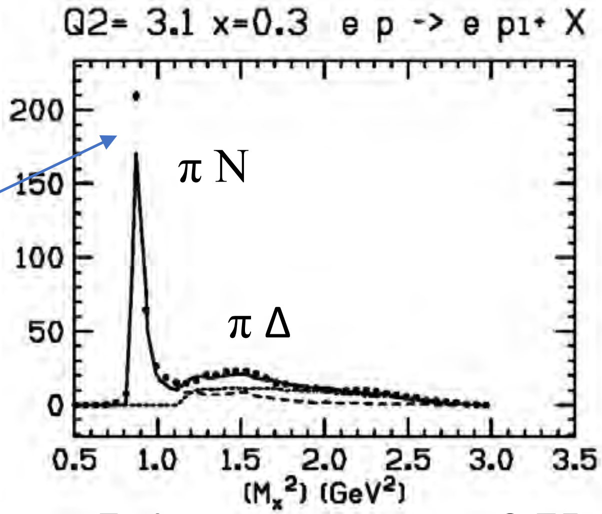
Modeling of high-z region in SIMC

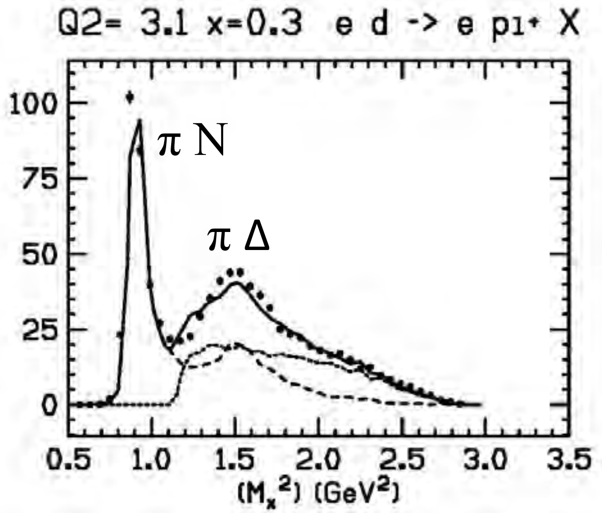
Dashed curves: pi N and pi Delta

Dotted curves: SIDIS model at high z

Solid curve: sum

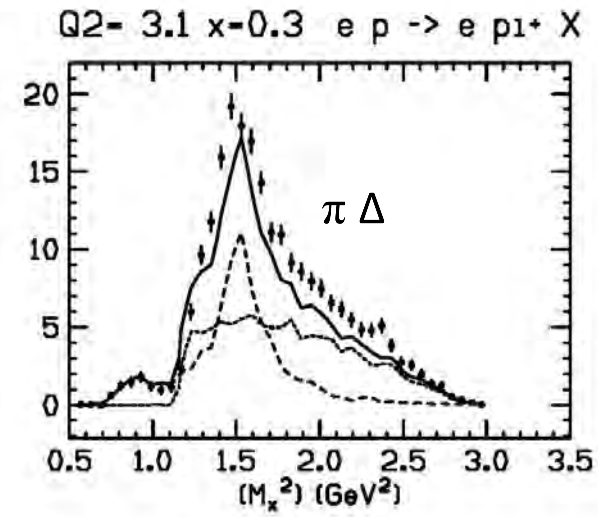
Note discrepancy: new
lft in progress

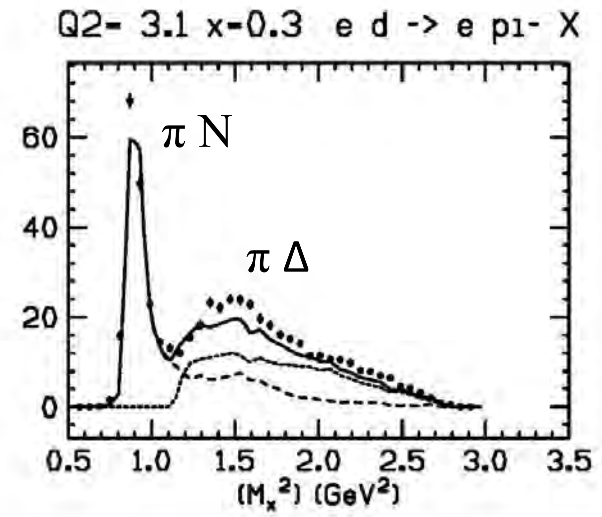




Z=1 z=0.75

Z=1 z=0.75





Formalism for P_t and co(ϕ) dependance

Cfrom Anselmino et al. 2005

In this way the $\mathbf{k}_\perp$ integration in Eq. (1) can be performed analytically, leading to the result, valid up to $O(k_\perp/Q)$:

$$\frac{d^5\sigma^{\ell p\to\ell hX}}{dx_B\,dQ^2\,dz_h\,d^2\mathbf{P}_T} \simeq \sum_q \frac{2\pi\alpha^2 e_q^2}{Q^4} f_q(x_B)\,D_q^h(z_h)\Bigg[1+(1-y)^2 - 4\,\frac{(2-y)\sqrt{1-y}\,\langle k_\perp^2\rangle\,z_h P_T}{\langle P_T^2\rangle\,Q}\cos\phi_h\Bigg]\frac{1}{\pi\langle P_T^2\rangle}\,e^{-P_T^2/\langle P_T^2\rangle}, \tag{2}$$

where $\langle P_T^2\rangle = \langle p_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle$. The term proportional to $\cos\phi_h$ describes the Cahn effect [1].

By fitting the data [10] on unpolarized SIDIS we obtain the following values of the parameters: $\langle k_\perp^2\rangle = 0.25\ (\mathrm{GeV}/c)^2$, $\langle p_\perp^2\rangle = 0.20\ (\mathrm{GeV}/c)^2$. The results are shown in Fig. 1.

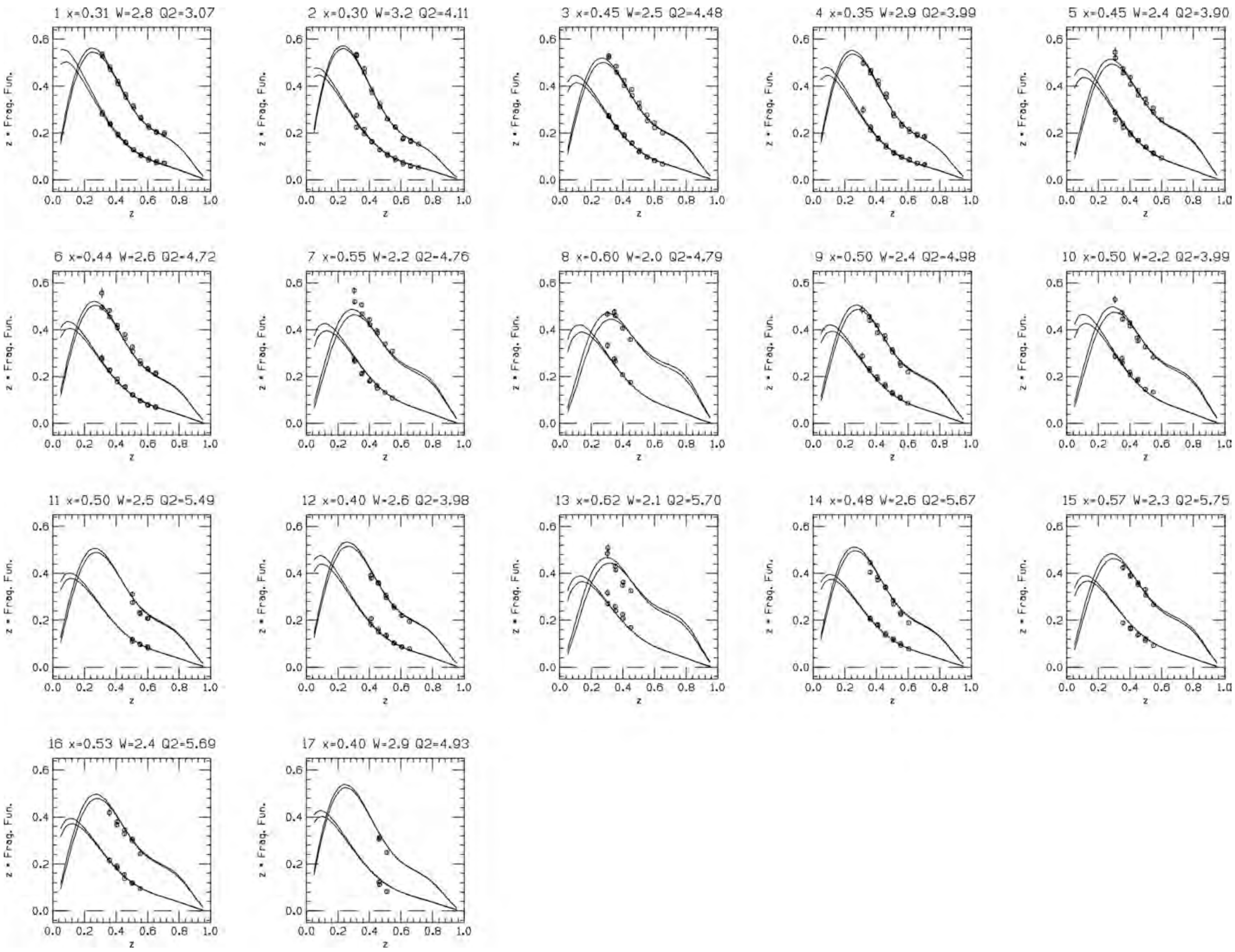
I find $<k_t^2>=0.10$ and $<p_t^2>0.20$ works better (see next page).

Same $<k_t^2>$ for u and d quarks, same $<P_{perp}^2>$ for favored, unfavored FF

Modeling of SIDIS in SIMC

Model assumes factorization: product of electron scattering (x,Q^2, epsilon) times fragmentation functions that give multiplicity (mainly a function of z, but added terms depending on Q^2 and W). Extracted favored and unfavored fragmentation functions for each kinematic setting from simultaneous fit to $\pi^+$and π^- cross sections from deuteron and proton targets (when available). Only used p_t settings with complete ϕ^* coverage. Used 12 parameters each for favored and unfavored FF, and two parameters to describe the exponential slope versus $p_{t,}$ as on previous page. Found that using an empirical target mass-corrected variable z-prime works better than using normal value of z.

Fit compared to data is shown on next page. By and large, there is a big improvement compared to using older models.

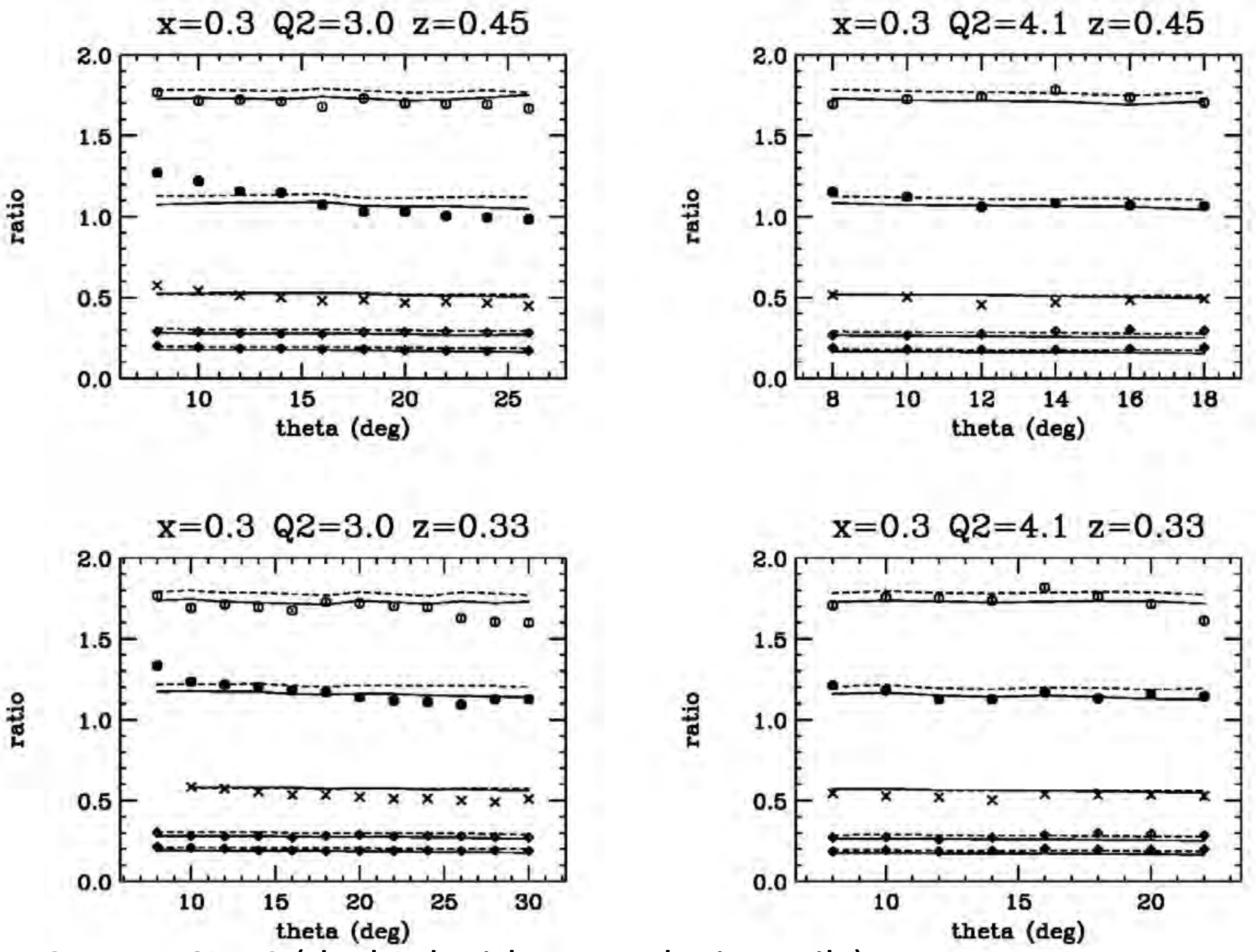

1 x=0.31 W=2.8 Q2=3.07
2 x=0.30 W=3.2 Q2=4.11
3 x=0.45 W=2.5 Q2=4.48
4 x=0.35 W=2.9 Q2=3.99
5 x=0.45 W=2.4 Q2=3.90
6 x=0.44 W=2.6 Q2=4.72
7 x=0.55 W=2.2 Q2=4.76
8 x=0.60 W=2.0 Q2=4.79
9 x=0.50 W=2.4 Q2=4.98
10 x=0.50 W=2.2 Q2=3.99
11 x=0.50 W=2.5 Q2=5.49
12 x=0.40 W=2.6 Q2=3.98
13 x=0.62 W=2.1 Q2=5.70
14 x=0.48 W=2.6 Q2=5.67
15 x=0.57 W=2.3 Q2=5.75
16 x=0.53 W=2.4 Q2=5.69
17 x=0.40 W=2.9 Q2=4.93
z * Frag. Fun.
z

Overview of p_t-scan ratios

- Scans in P_t at two of three (x,Q^2) and two large z bins
- Plots show ratios of specified data to data to data for π^+ on proton
- Curves are predicted ratios from SIMC. Solid is with exclusive tails, dashed in without exclusive tails
- Larger SHMS angle is larger P_t
- Results averaged over ϕ^*
- SIMC used same P_t slopes for all cases
- Results show that pt-slope is about the same for π^+ and π^- and proton and deuteron.

Ratios to Hydrogen π+ 15- November-2020

$^2H(\pi+)$
$^2H(\pi-)$
$^1H(\pi-)$
$Al(\pi+)$
$Al(\pi-)$



$^2H(\pi+)$
$^2H(\pi-)$
$^1H(\pi-)$
$Al(\pi+)$
$Al(\pi-)$

Curves: SIMC (dashed without exclusive tails)

Fits to cos(ϕ), cos(2ϕ), and constant

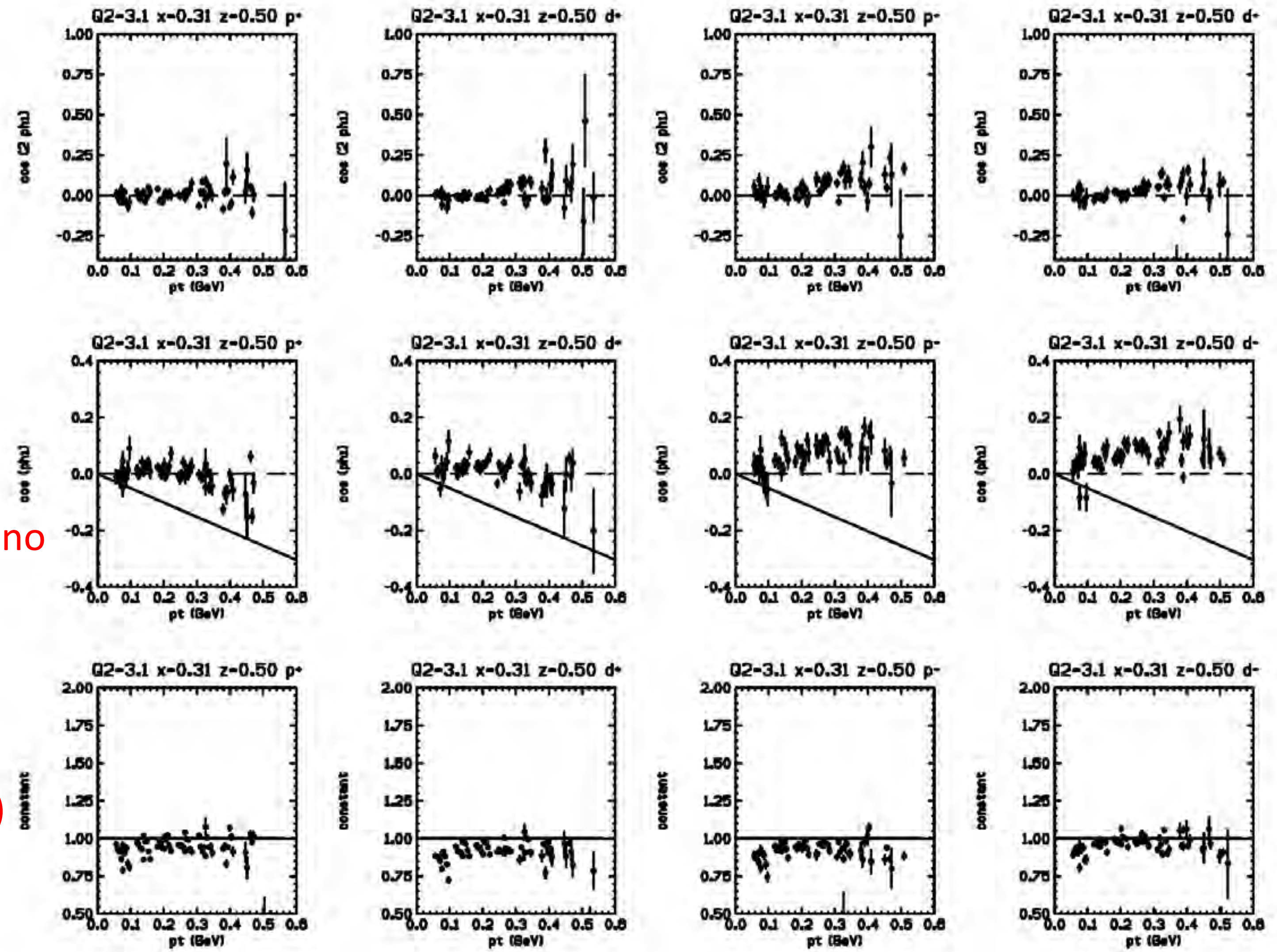
For 0.4 < z < 0 .6 VERY PRELIMINARY

cos(2ϕ)

cos(ϕ)

Curves from Anselmino
For Cahn term

Constant (
relative to SIMC)



Fits to cos(ϕ), cos(2ϕ), and constant

- Similar results at other (x,Q^2) bins
- Within Anselmino framework, best fit more or less $\langle k_t^2 \rangle = 0$, if just considering Cahn cos(phi) term. Why is cos(ϕ) for π^- somewhat greater than zero?
- Similar results have been found in Hall C (6 GeV), CLAS, and HERMES for cos(phi) term.
- What other terms might contribute, aside from small positive contributions as in the paper for Brandenburg et al. (SLAC 1995)
- Note: CLAS with 6 GeV electrons also finds small cos(ϕ) compared to Cahn (Osipenko et al.)

Interpretation of data

- Target-mass corrections of cos(ϕ), cos(2ϕ) terms?
- Dynamic higher twist corrections
- R = sigL / sigT ?
- Include diffractive rho events in our fragmentation function extractions, or try to treat them separately (or both)
- How reliably can we extract charge symmetry violations from the data (i.e. is valance d in neutron not same as u in proton?
- How reliably can we extract average transverse momentum of u and d quarks from data, as in Anselmino framework?
- How to treat fragmentation from sea quarks (u, d, s)
- Role of photon-gluon contributions in our kinematics?
- Influence of maximum allowed P_t on P_t distributions (as discussed in CLAS 6 GeV paper.

To-do list

- Improve fit to exclusive pion cross sections (including the five (Q2, W) epsilon-separated pi+ values from KLT experiment)
- Improve fit to exclusive Delta(1234) production
- Both of these will benefit from analysis of electron in SHMS, pi- in HMS (in progress).
- Put new F2 DIS model into SIDIS model.
- Then re-do fit to SIDIS datal and do one final iteration on the radiative corrections. Publish pion SIDIS results
- Start study of SIDIS kaons, especially from KLT experiment because pt-SIDIS and CSV have low statistical accuracy.
- Extend SHMS dp/p coverage to as low as possible (for KLT SIDIS). Extract R at high z from KLT data for pi+ and K+ .
- Extract the beam SSA for exclusive and SIDIS