12-GeV era Hall C SIDIS experiments

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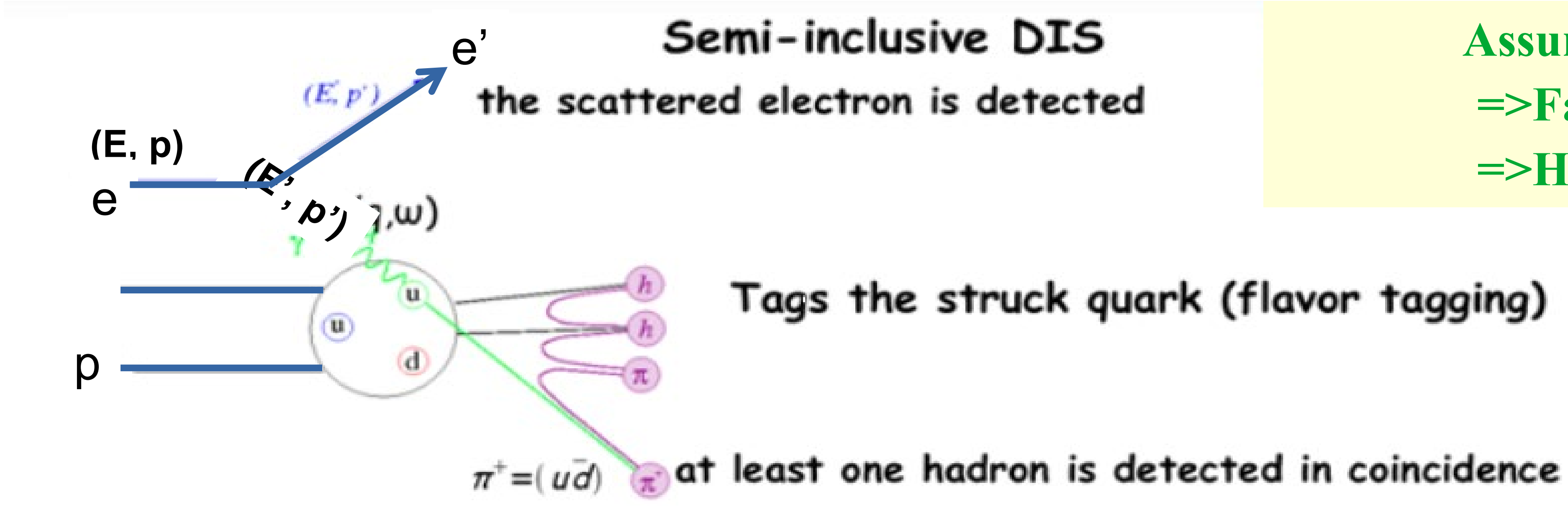
Analysis from three Hall C experiments in 2018-2019

- 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)

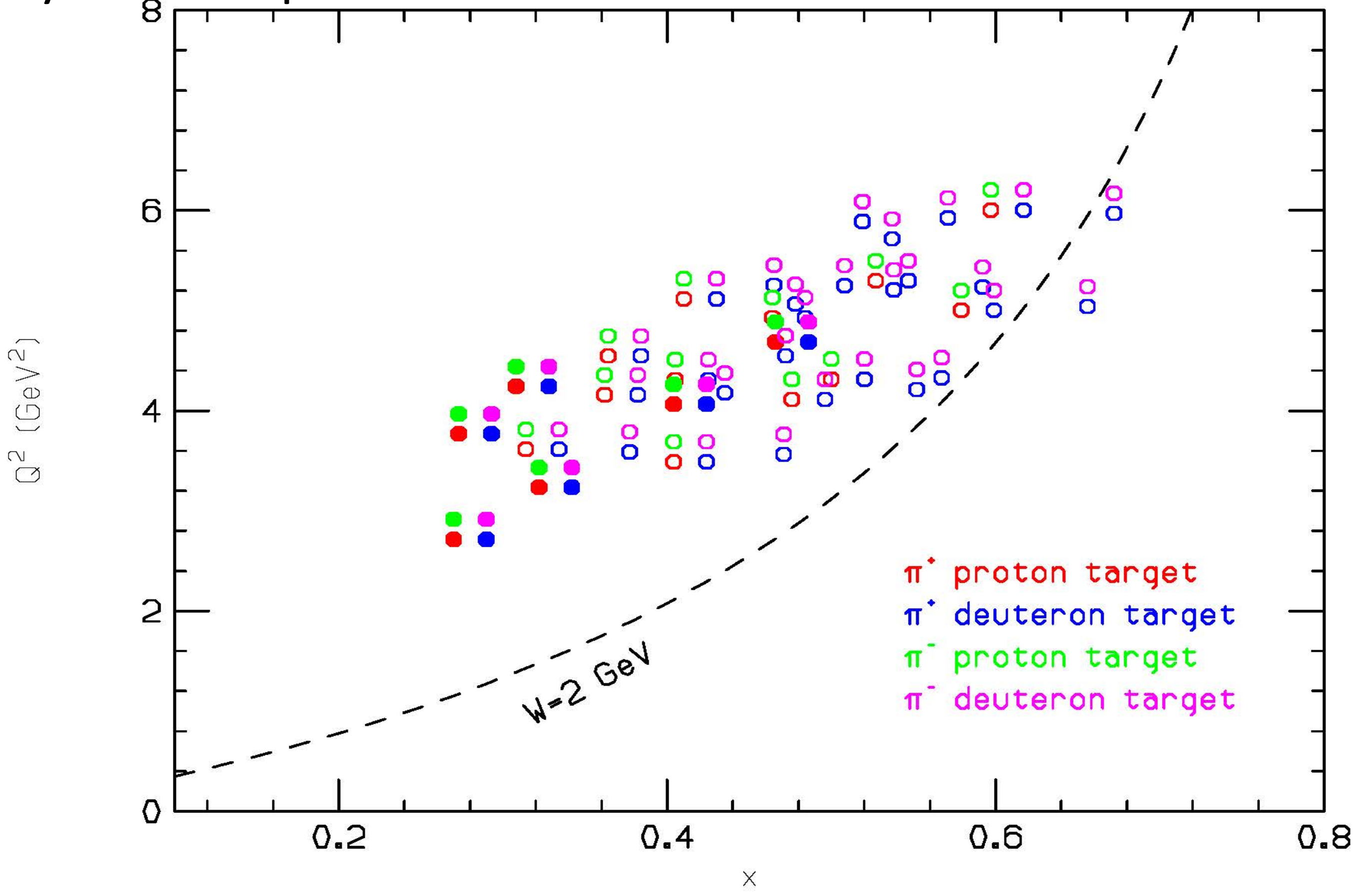
Kinematic coverage in (x,Q^2)

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

CLAS coverage extends to lower x and lower Q^2

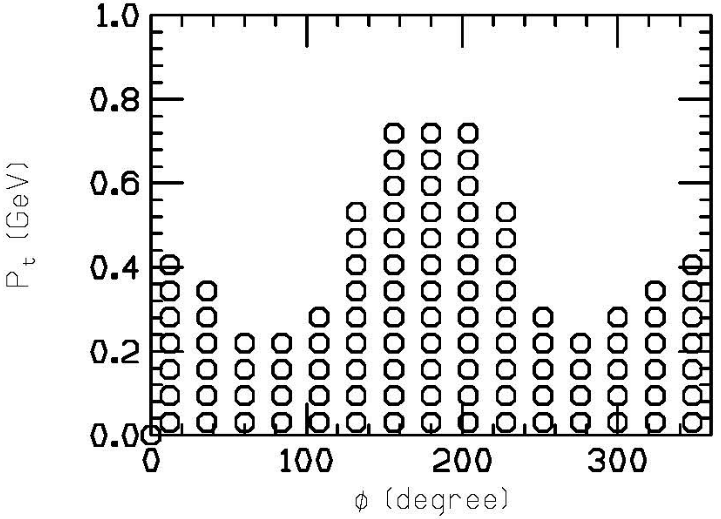
each circle has 10,000 to 1000,000 events

Dominated by valance quark distributions

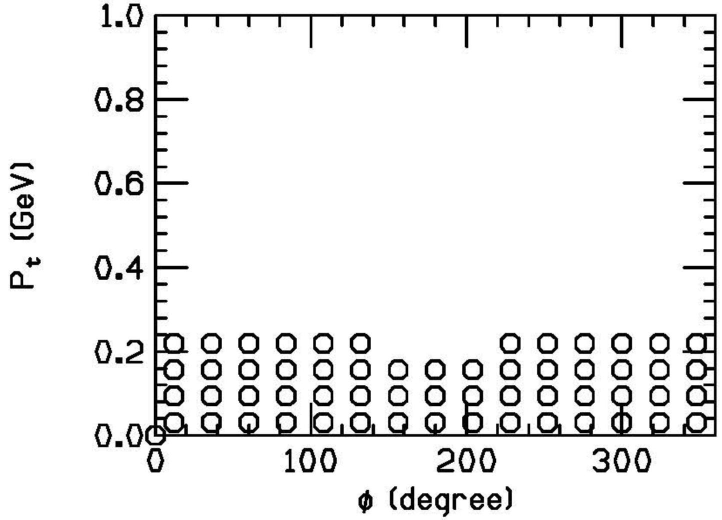


Kinematic coverage in P_t and ϕ

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

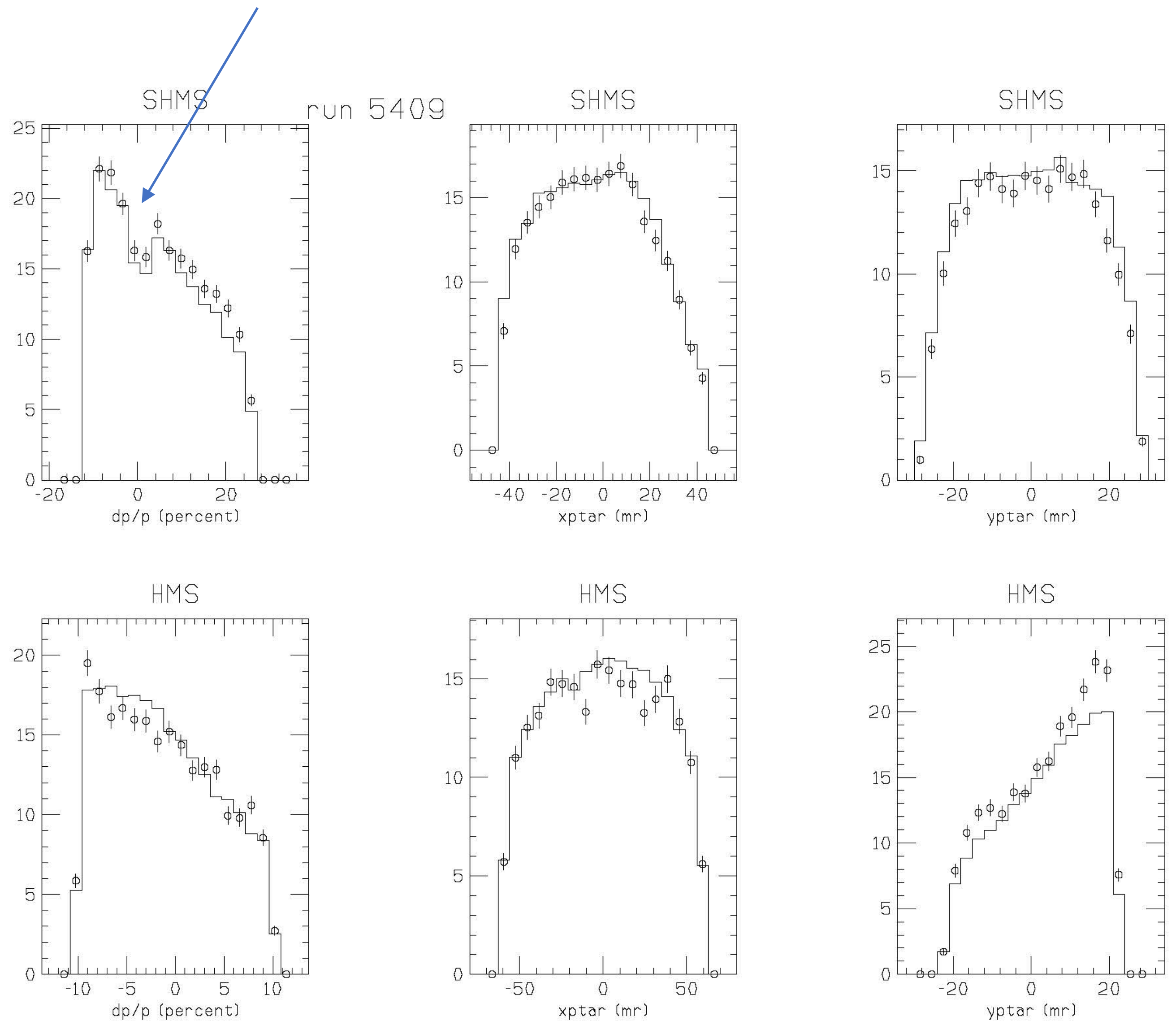
For each bin:

- 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

Incorporation of HG Cherenkov Efficiency into SIMC



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:

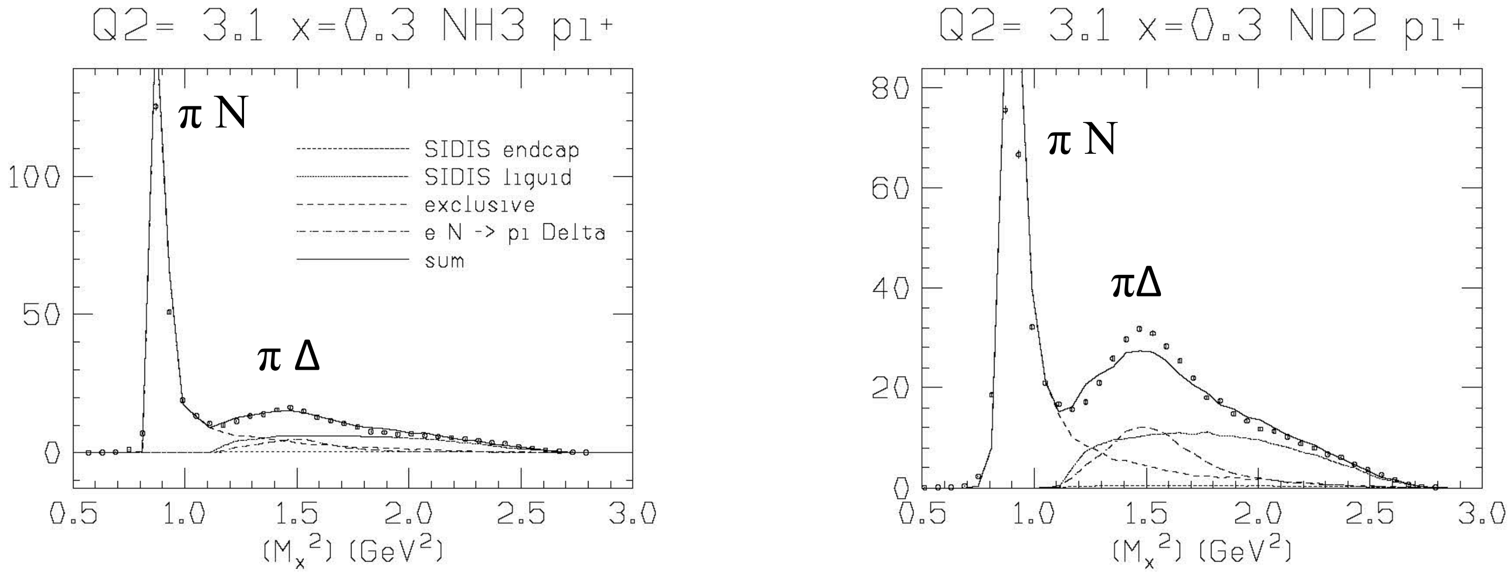
a) SIDIS model assuming factorization, excluding b), c), and d). Run with rad. Corr. On/off.

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

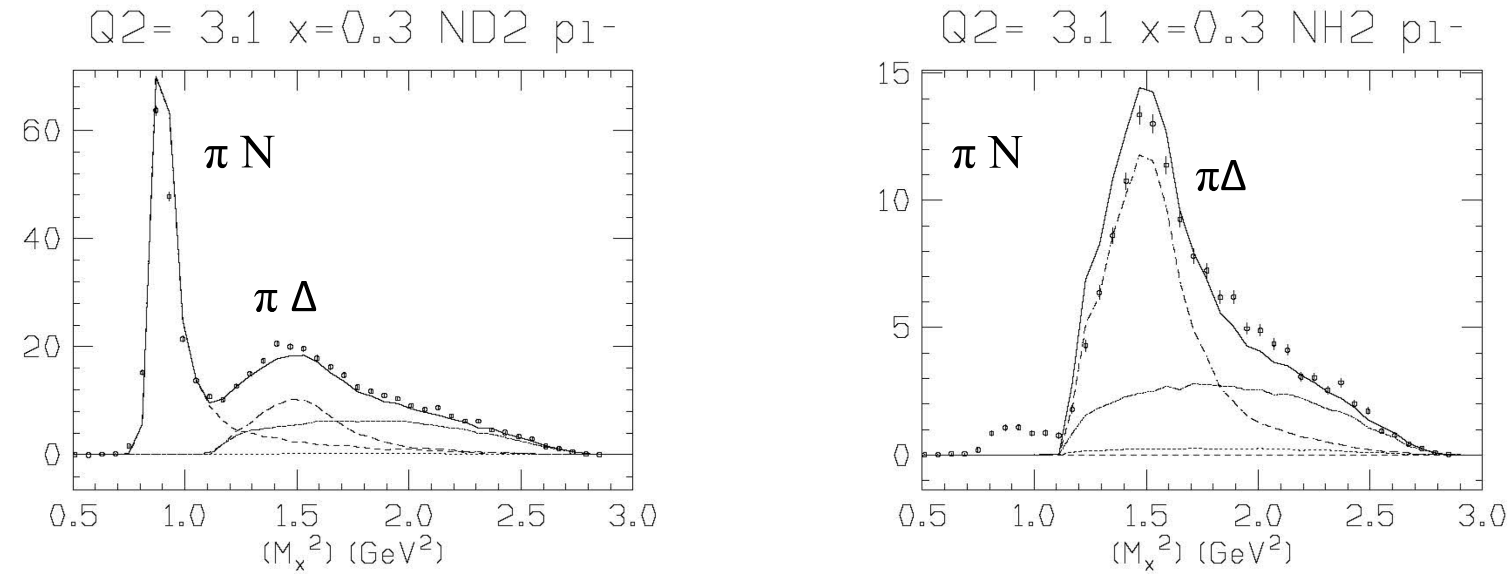
c) Quasti-excluisive production ($e\,N \rightarrow e\,\pi\,\Delta$)

d) Rho production with one pion detected from rho decay (not used in present analysis)

Modeling of high-z region in SIMC



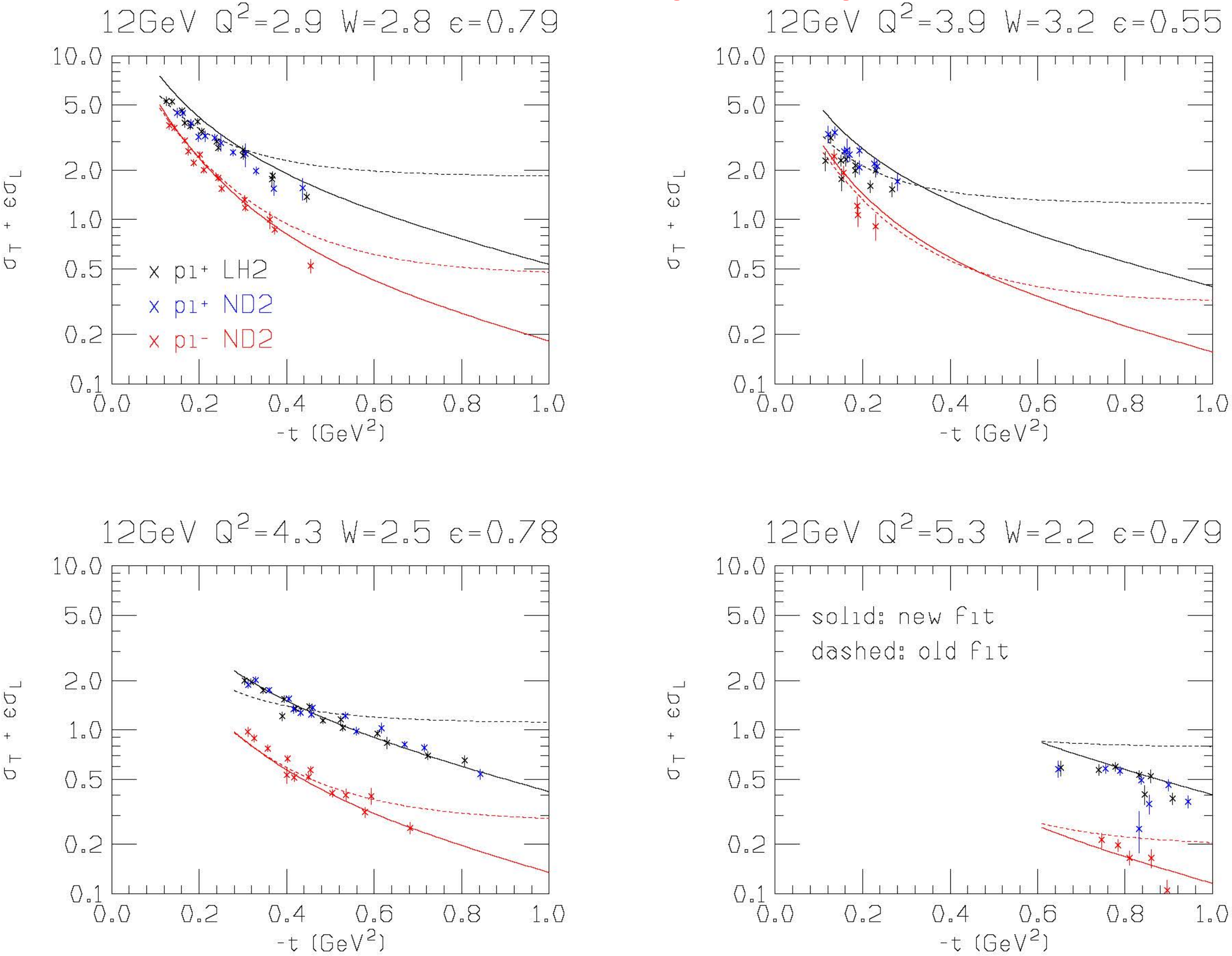
Z= 1 z=0.75 Z=1 z=0.75



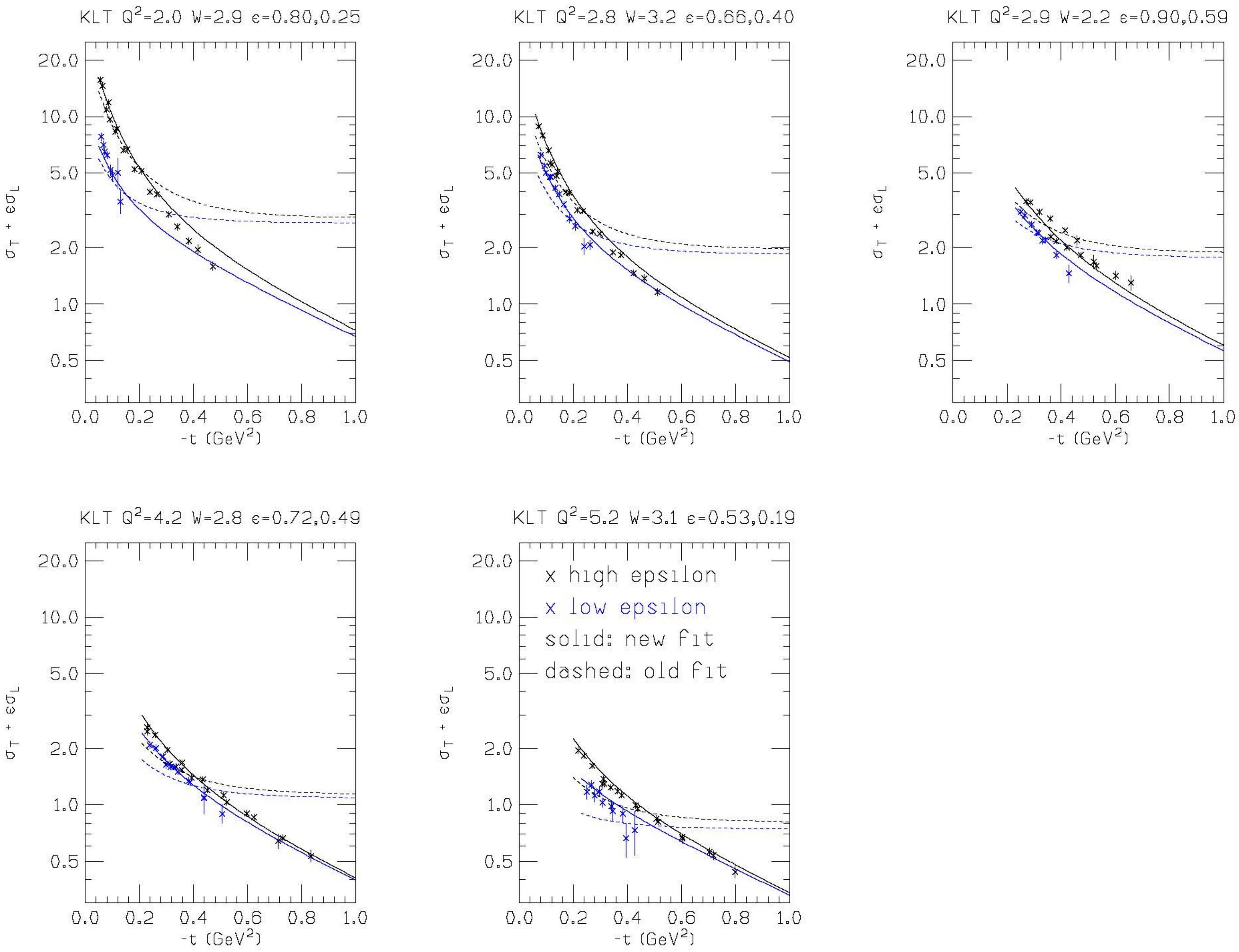
Improvements to SIMC: Exclusive pion production

- Previous fit (parm3000 works sort of o.k. for exclusive pion cross sections from all 3 experiments., but up to 60% discrepancies at some settings.
- Extracted exclusive cross sections for both pi+ and pi- from all three experiments. The KLT experiment has only pi+, but two values of beam energy, so that longitudinal and transverse components can be separated. Total of 4000 data points in bins of Q2, W, t, phi*.
- Added case for pi- in HMS, e- in SHMS. Total 1000 more data points.
- Included data from Fpi-I and Fpi-II experiments (150 points)
- Included data from DESY (6 data points).
- Used MINUIT to fit 17 parameters each for pi+ and pi- for a new fit (param2021). No longer assume sigL(pi-) = sigL(pi+)

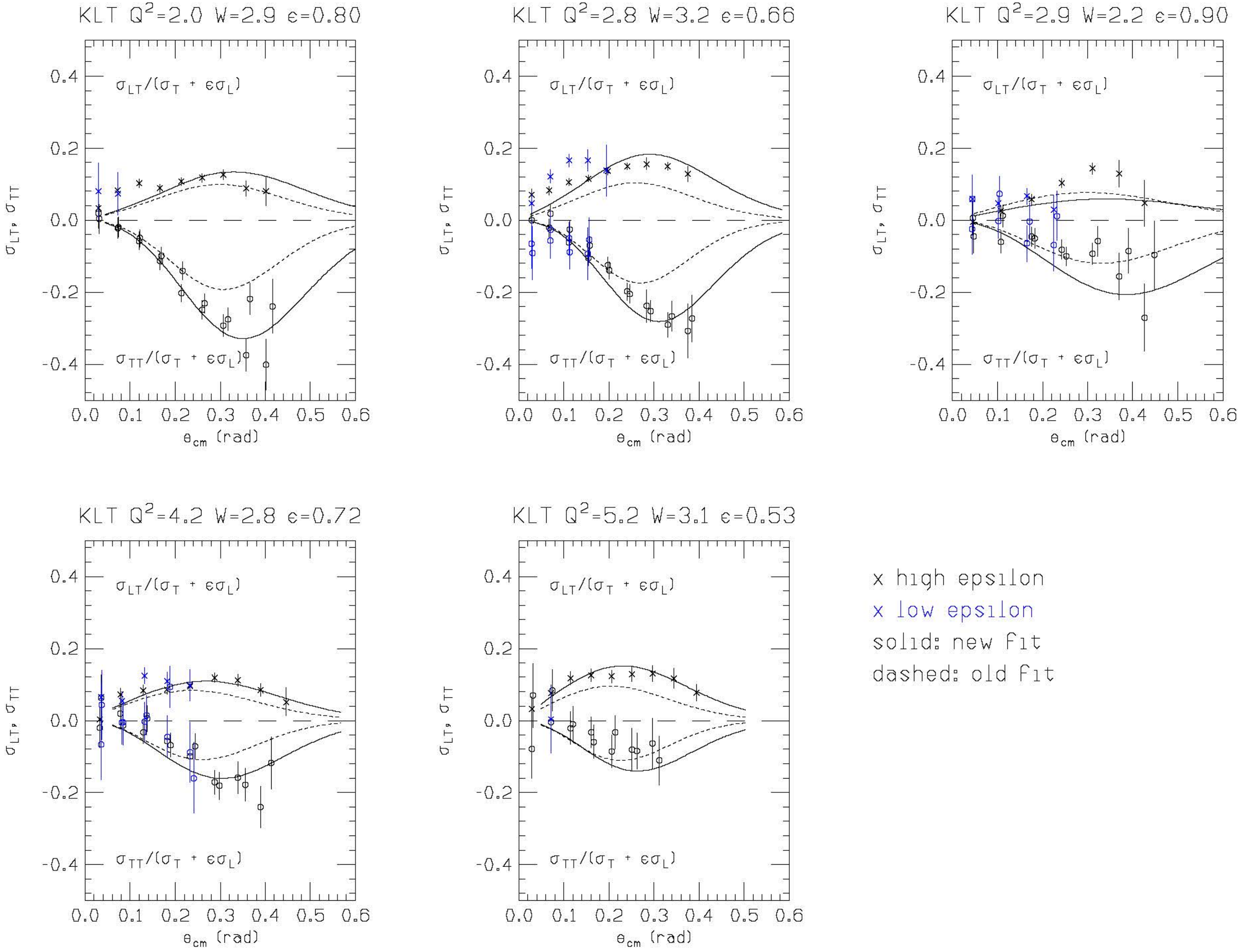
New fit to exclusive pion production



New fit to exclusive pion production



New fit to exclusive pion production



Improvements to SIMC: Exclusive pion production

- New fit is up to 60% lower at high t, a bit higher at small t as far as sig_T + epsislon * sig_T is concerned
- Sig_LT is generally a bit larger than param_3000 fit
- Sigma_TT is significantly larger
- New fit is called param_2021

Improvements to SIMC: pi-Delta final state

Changed shape of Delta(1232) from old method which generated long tails to new method using Breit-Wigner distribution

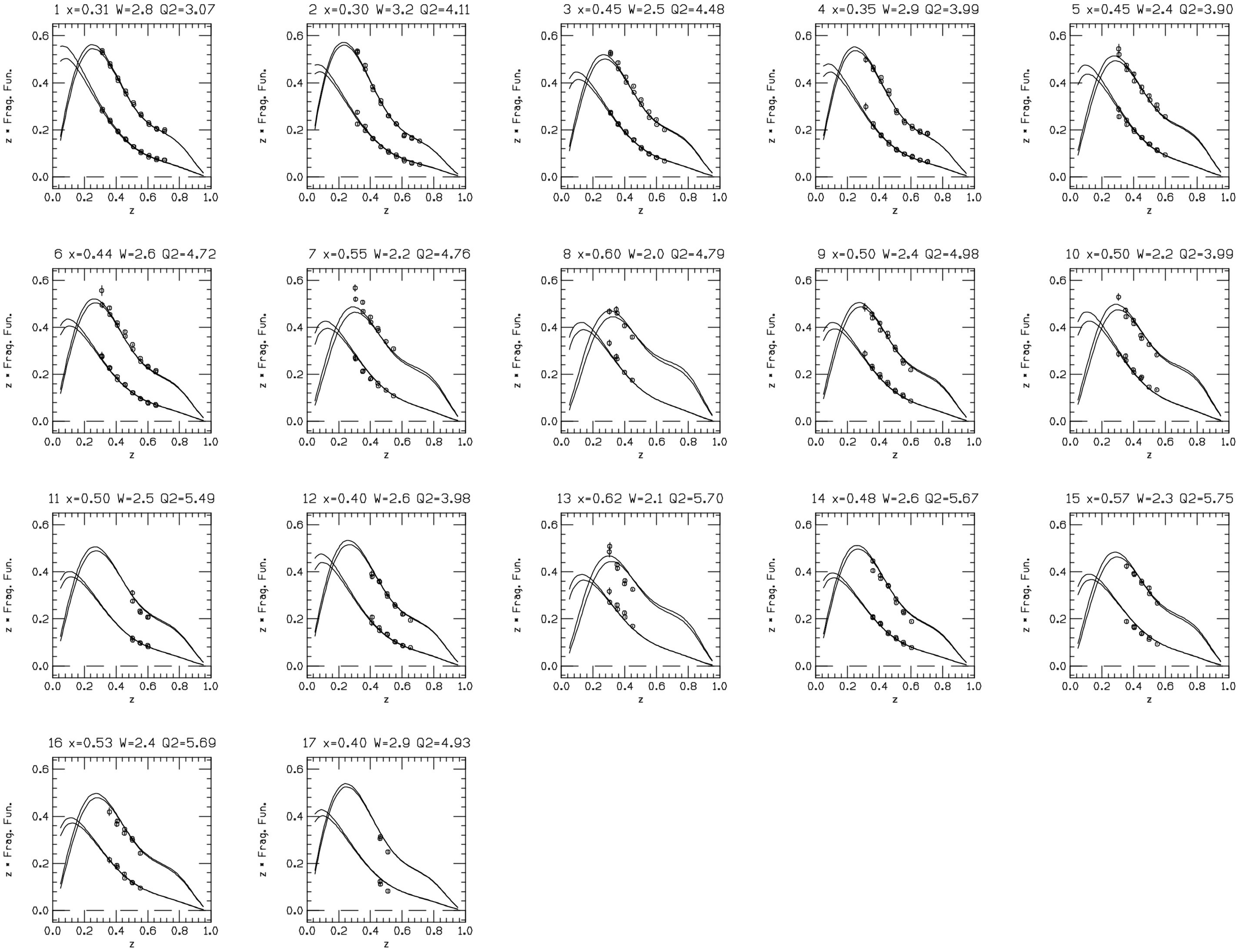
Fit missing mass spectra with Delta shape and non-resonant shape, as function of t and phi* for each kinematic setting.

Included e- in SHMS in the study

On average (within factor of 2), pi-Delta can be described by factor scaling the corresponding exclusive channel
Pi+ Delta0 -> 0.5 times pi+ n final state (Cletsh-Gordon 0.25)
Pi+ Delta- -> 0.8 times pi+ n (CG 0.75)
Pi- Delta++ -> 1.0 times pi- p (CG 1.2)
Pi- Delta+ -> 1.0 times pi- p (CG 0.5)

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 $p_{t,}$.
Found that using an empirical target mass-corrected variable z-prime works better than using normal value of z.
The cos(phi) and cos(2phi) terms are zero in my model.
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
0.0
0.2
0.4
0.6
0.8
1.0

Fits to cos(ϕ), cos(2ϕ), and constant

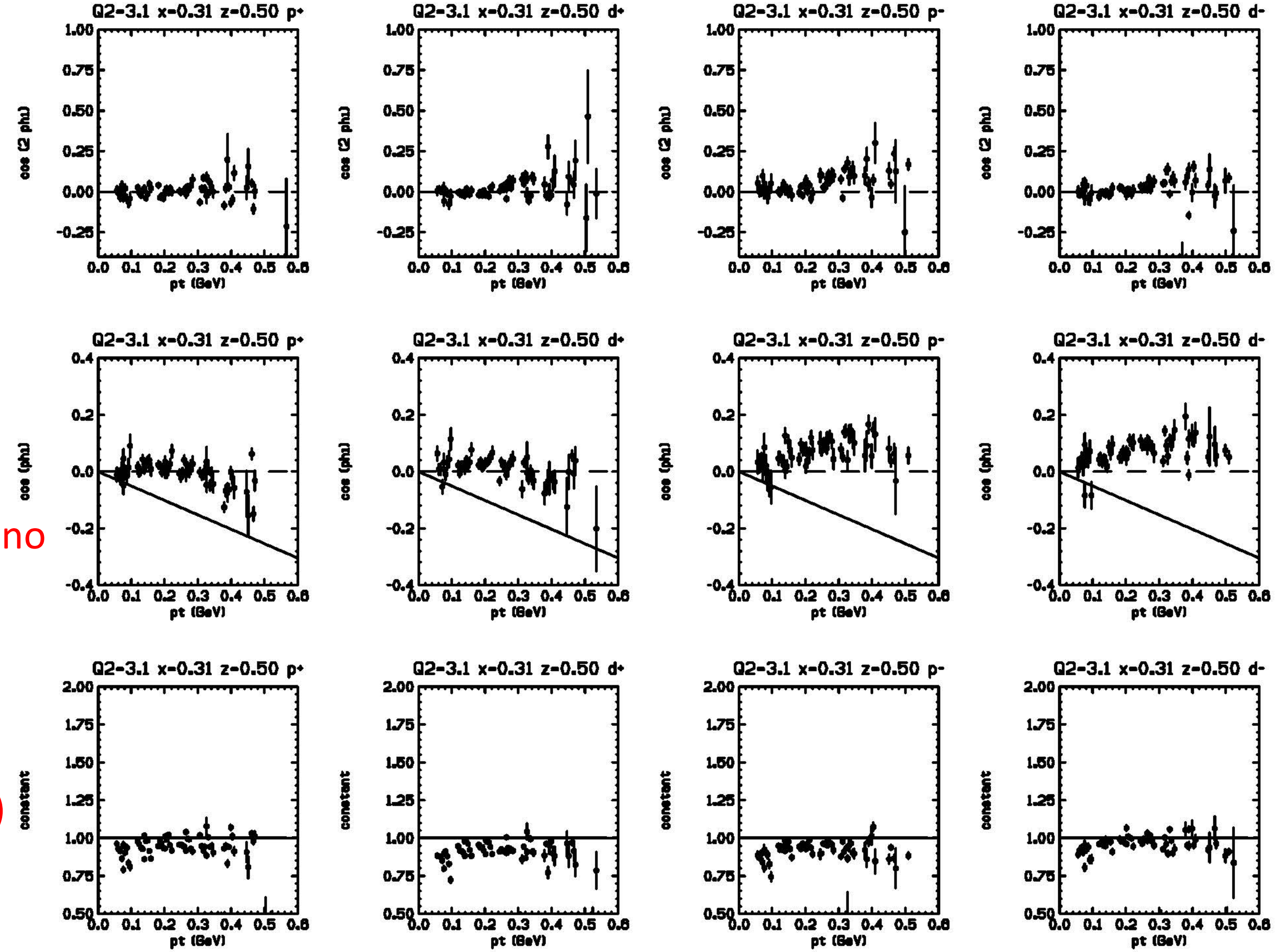
For 0.4 < z < 0 .6 VERY PRELIMINARY

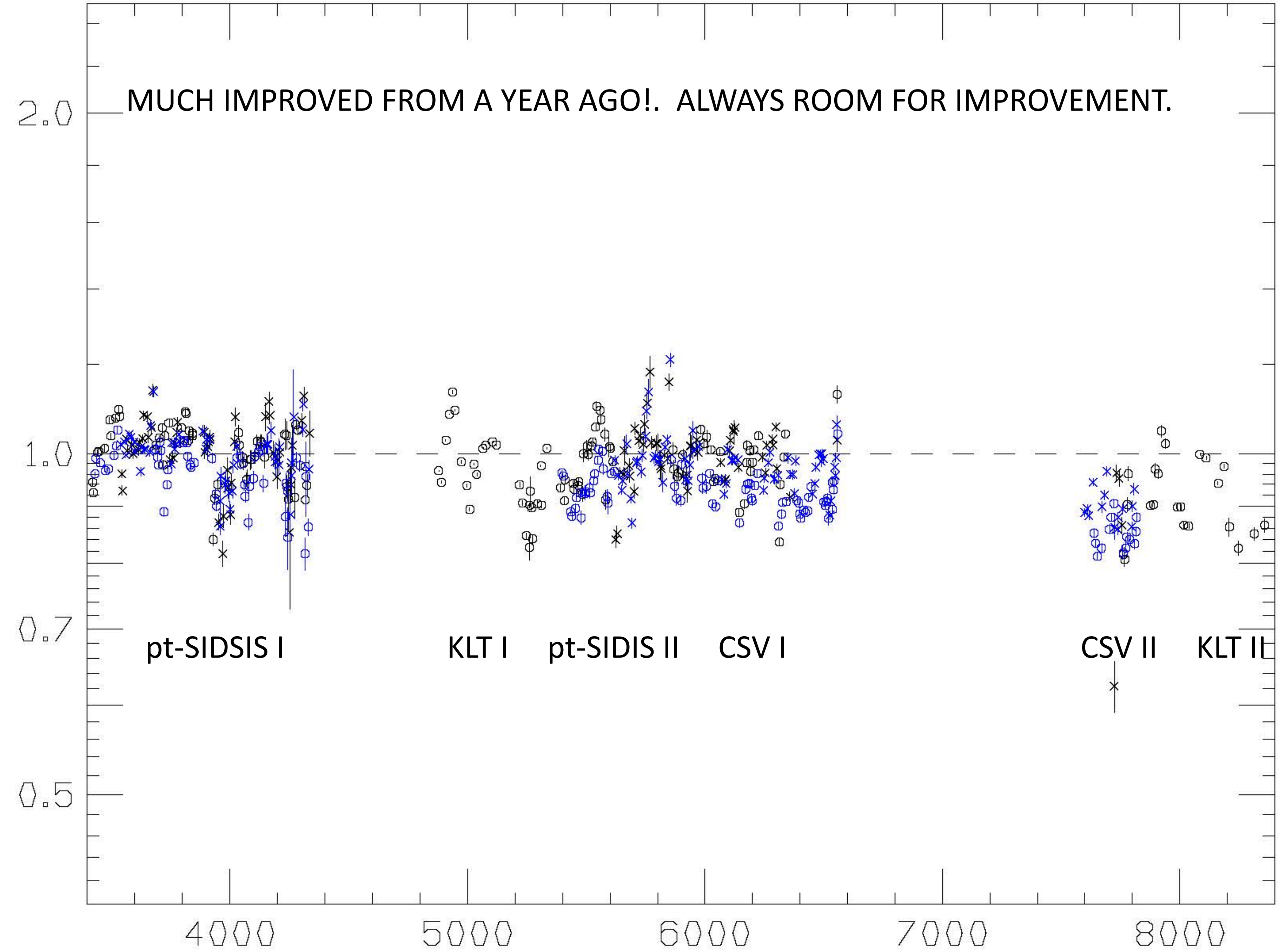
cos(2ϕ)

cos(ϕ)

Curves from Anselmino
For Cahn term

Constant (
relative to SIMC)





MUCH IMPROVED FROM A YEAR AGO!. ALWAYS ROOM FOR IMPROVEMENT.
2.0
1.0
0.7
0.5
pt-SIDSIS I
KLT I
pt-SIDIS II
CSV I
CSV II
KLT II
4000
5000
6000
7000
8000

Fits to cos(ϕ), cos(2ϕ), and constant

- Similar results at other (x,Q^2) bins
- Within Anselmino framework, best fit more or less <k_t^2>=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

- Fix a few small problems in exclusive pion cross sections. Publish results from td-SIDIS and CSV-SIDIS. Publish fit. Help with publication of KLT results.
- Improve fit to exclusive Delta(1234) production. Publish cross sections and fit. Anybody know of any existing data?
- Finalize pion SIDIS cross sections and publish.
- 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

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 $O(k_\perp/Q)$:

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

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

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.