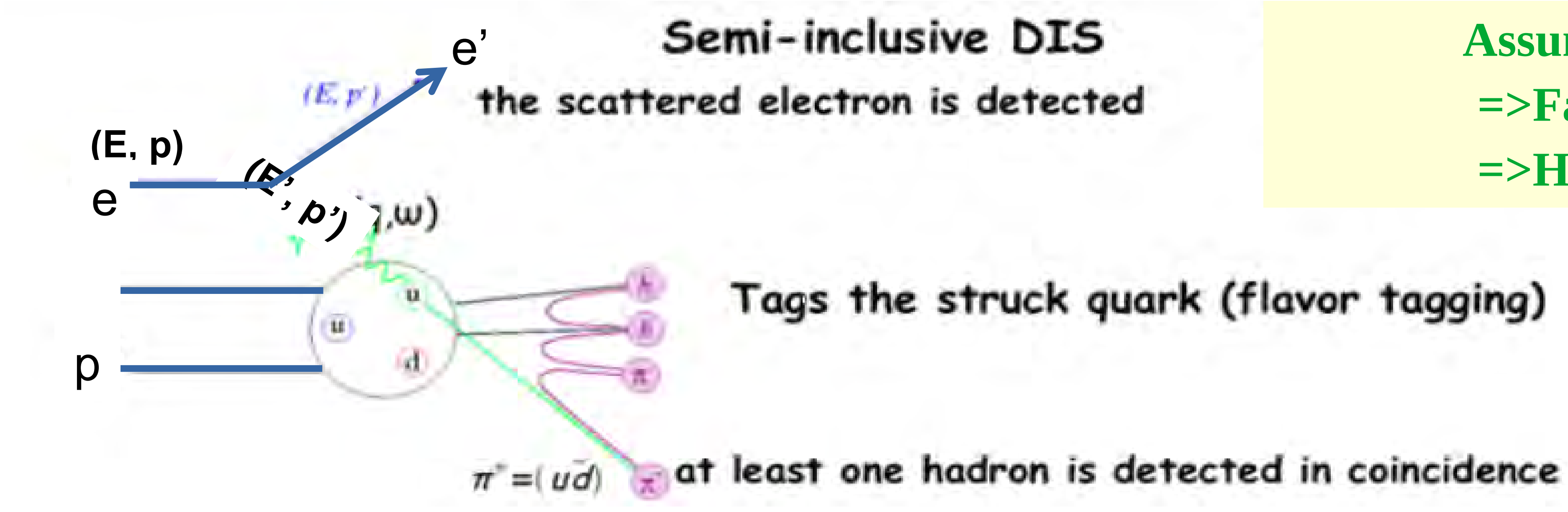
12-GeV era Hall C SIDIS experiments

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.
- 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 pi+ on proton target useful for measuring at high z the ratio $\mathrm{R} = \sigma_L/\sigma_T$ (not discussed further in this talk)

Semi-Inclusive Deep Inelastic Scattering (SIDIS)



Semi-inclusive DIS

the scattered electron is detected

Tags the struck quark (flavor tagging)

at least one hadron is detected in coincidence

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)

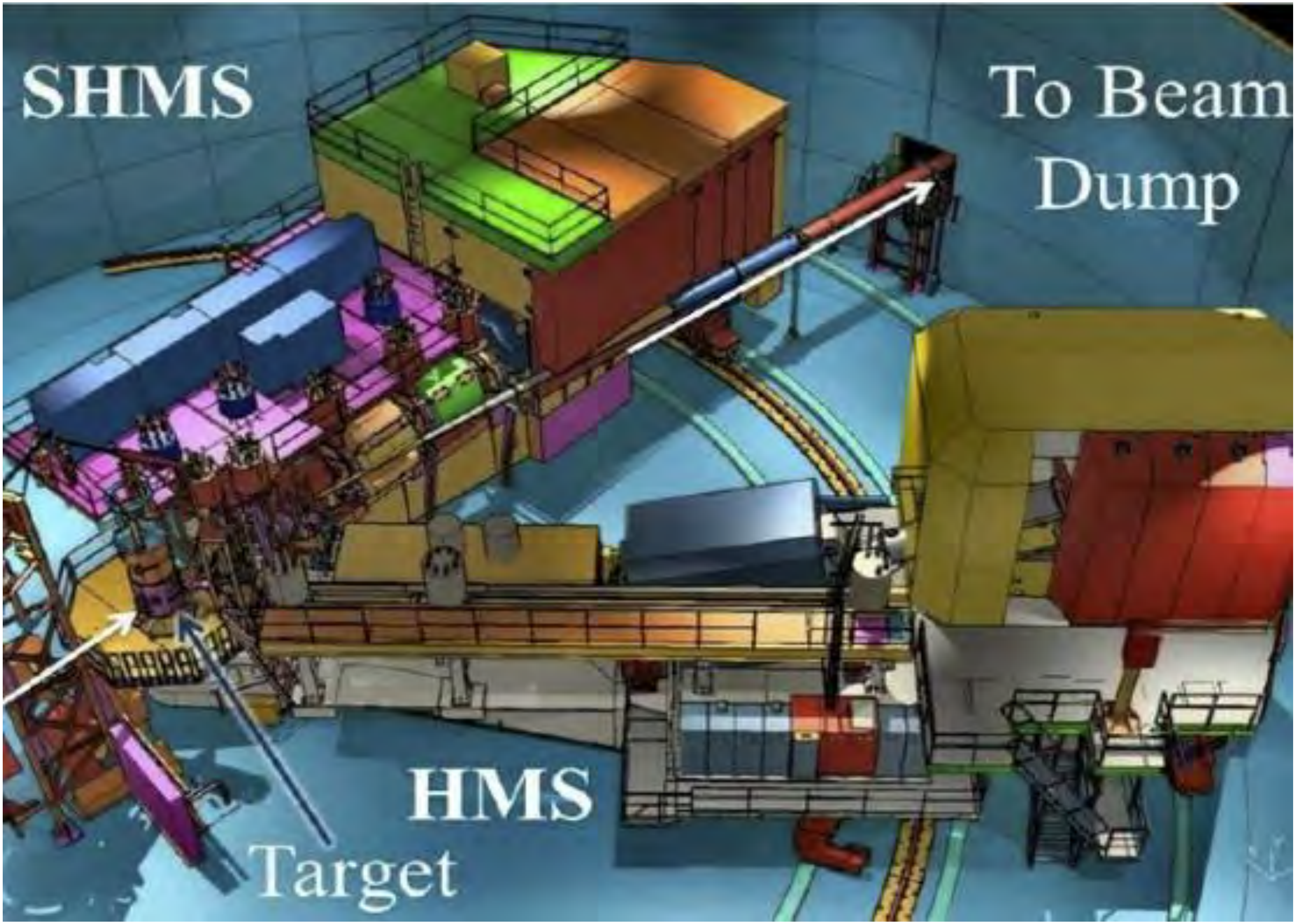
Few kinematic quantities :

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 $= \sqrt{(m^2_\pi + p^2_\pi)} / \nu$

Experiment overview

- HMS spectrometer detects electrons at scattering angles from 13 to 30 degrees, momenta from 4 to 6 GeV . Sixteen distinct setting: each divided into two (x,Q^2) bins. Solid angle 4 msr.
- 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 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)

Jefferson Lab HallC



Super High Momentum Spectrometer(SHMS):

Magnets: HB, Q1, Q2, Q3, Dipole

Characteristics:

Momentum Range: 2-11 GeV/c
Momentum Acceptance: -10% to +22 %
Momentum resolution: dP/P < 0.2
Scattering angle: 5.5 to 40 degrees
Solid Angle Acceptance: > 4 mSr
Beam Capacity: upto 90 μA

High Momentum Spectrometer (HMS):

Magnets: Q1, q2, Q3, Dipole

Characteristics:
Momentum Range 0.5-7.5 GeV/c
Momentum Acceptance -10% to +10 %
Momentum Resolution: dP/P < 0.1 %
Scattering angle = 12.5 to 90 degrees
Solid Angle Acceptance > 6 mSr
Beam Capacity upto 90 μA

Detector Hut: HMS and SHMS:
Drift Chambers
Hodoscopes
Cerenkovs
Calorimeter

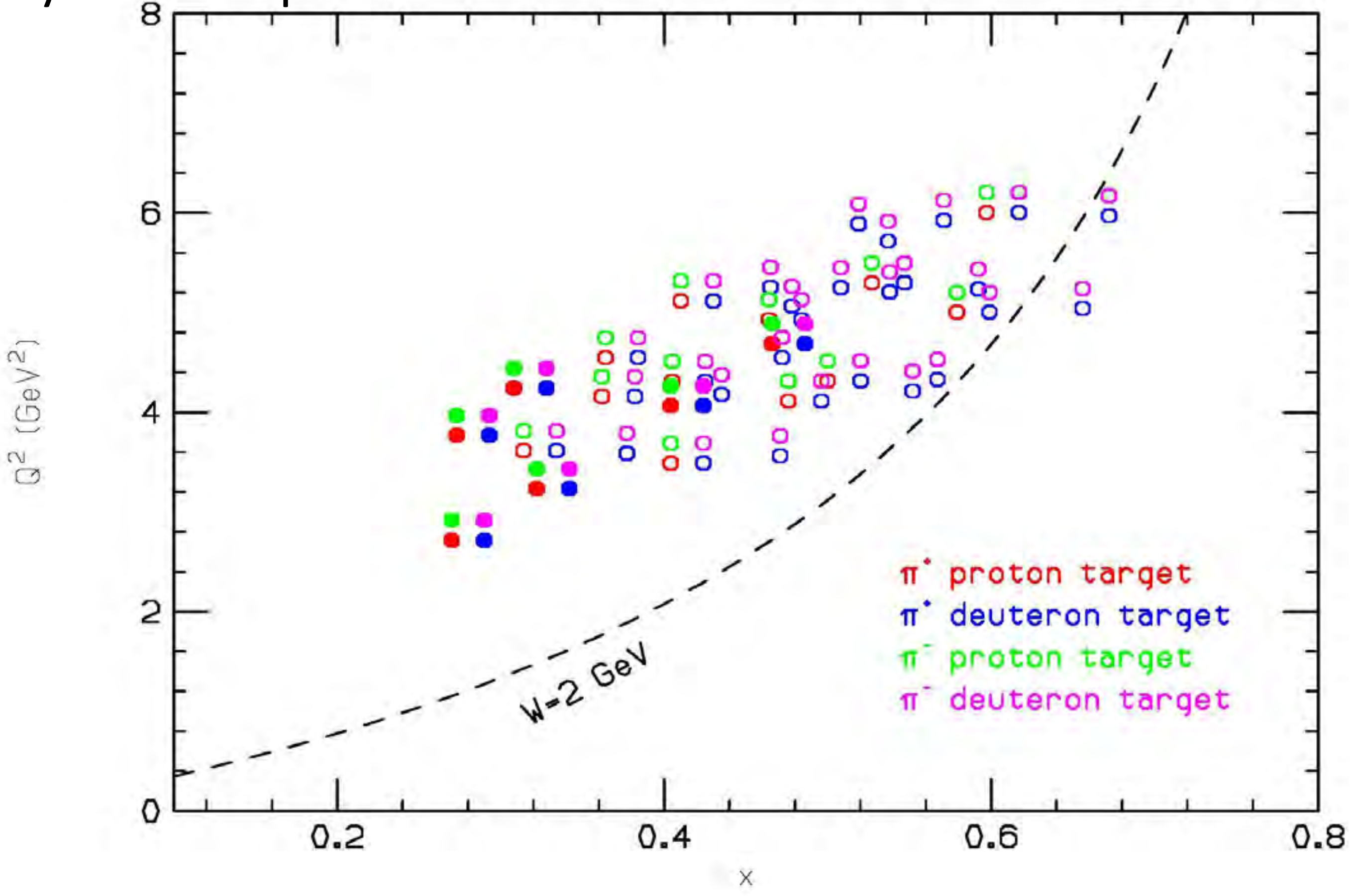
Kinematic coverage in (x,Q^2)

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

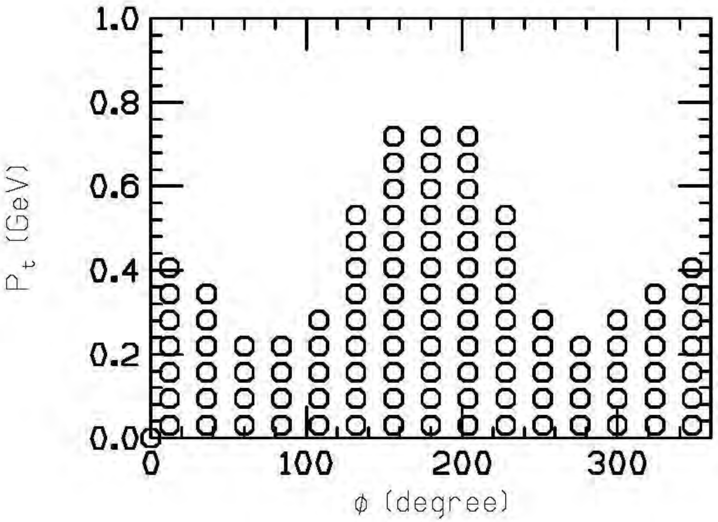
Dominated by valance quark distributions



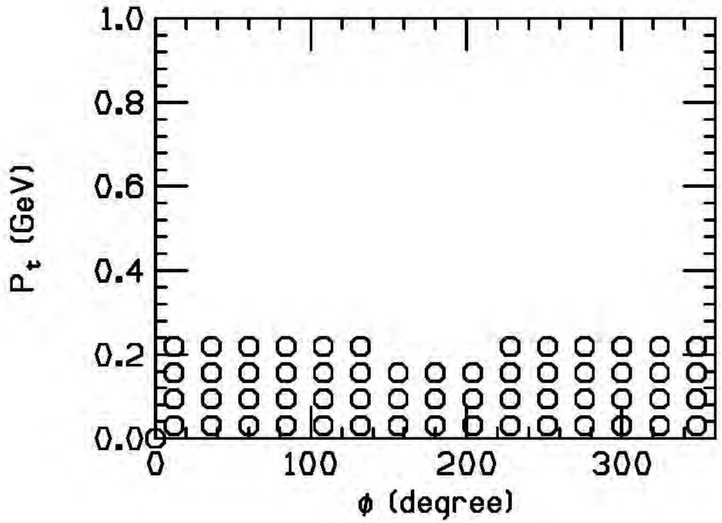
Kinematic coverage in P_t and ϕ

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

Typica pt-SIDIS setting
at z=0.5



Typica CSV-SIDIS setting
at z=0.5



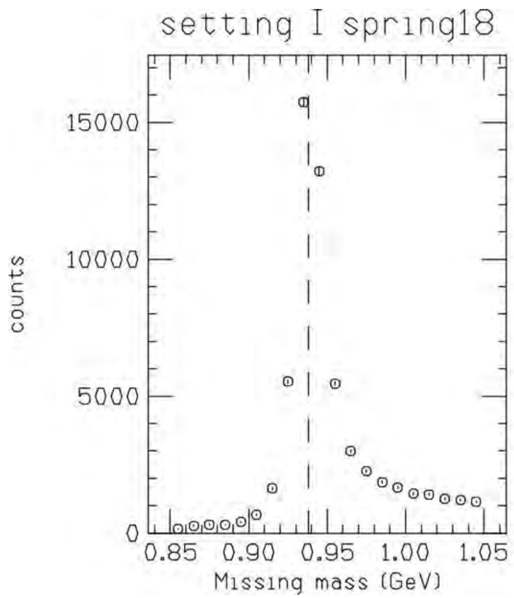
Additional kinematic coverage provided by electron in SHMS and pion in HMS (only for negative pions)

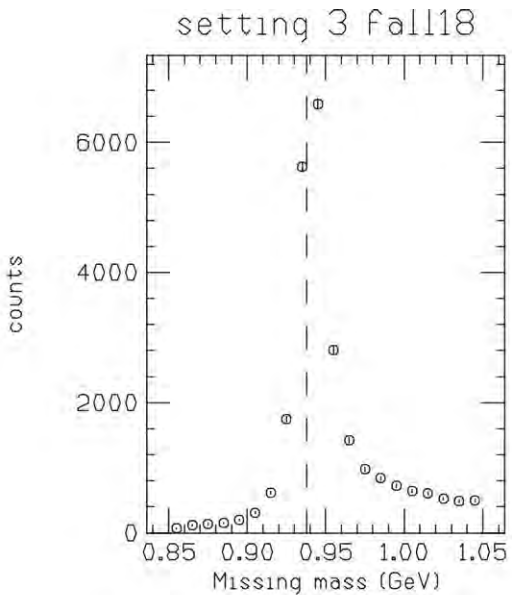
Data Analysis Tasks Completed (more or less)

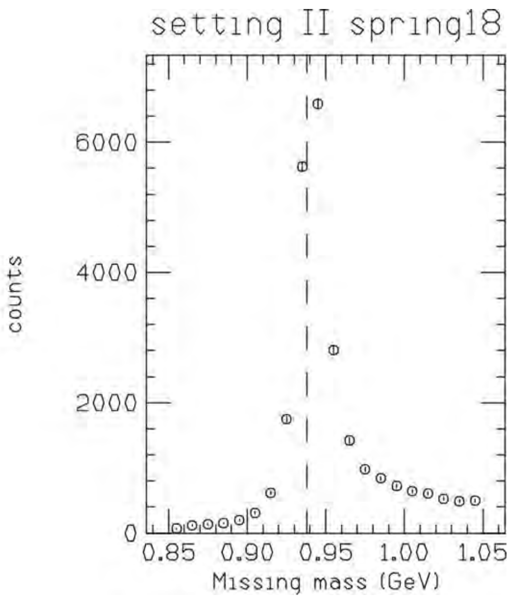
- Determination of beam energy and position
- Calibration of beam current monitors
- Beam current correction to liquid target density
- Computer dead time correction
- Debugging and improvements to tracking code
- Electronic dead time correction
- Corrections for multiple trigger signals
- Calibration 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
- Processing of raw data into tracked particles with corresponding detector response

Improvements to optics

- New SHMS matrix elements from Mark Jones
- Corrections of 0.9944 to 1 for HMS central momentum based on fit from Holly plus missing mass from exclusive pion production from our own data (all three experiments)
- Correction to HMS vertical offset of 2.7 mr based on fit from Carlos as well as making SIDIS cos(ϕ) distributions even in phi.



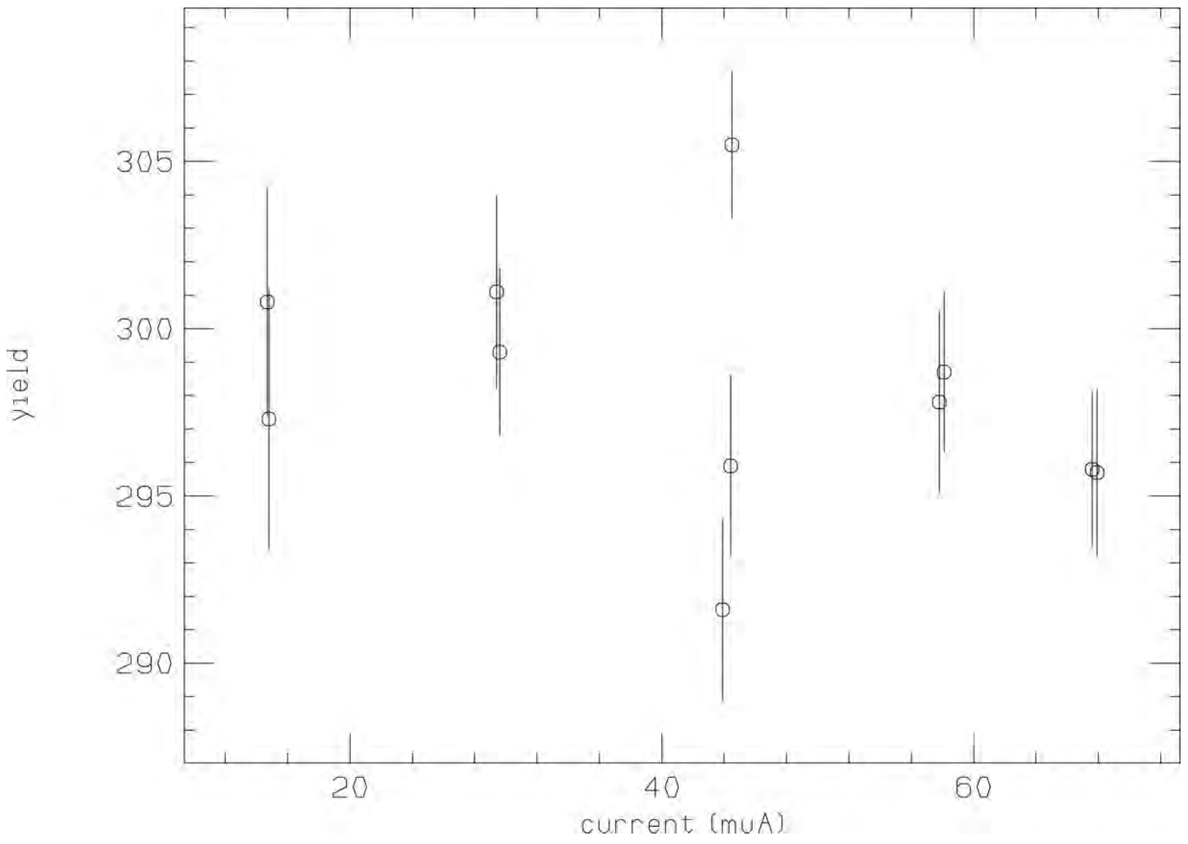




Improvements to data analysis

Using new code and parameters, find:

- Corrected yields no longer depend on beam current, while previously there were up to 20% changes.
- Yields from setting repeated in Fall18 now agree with yields from Spring18 (which has considerably larger effective dead time corrections)



Clean Particle Identification: SHMS

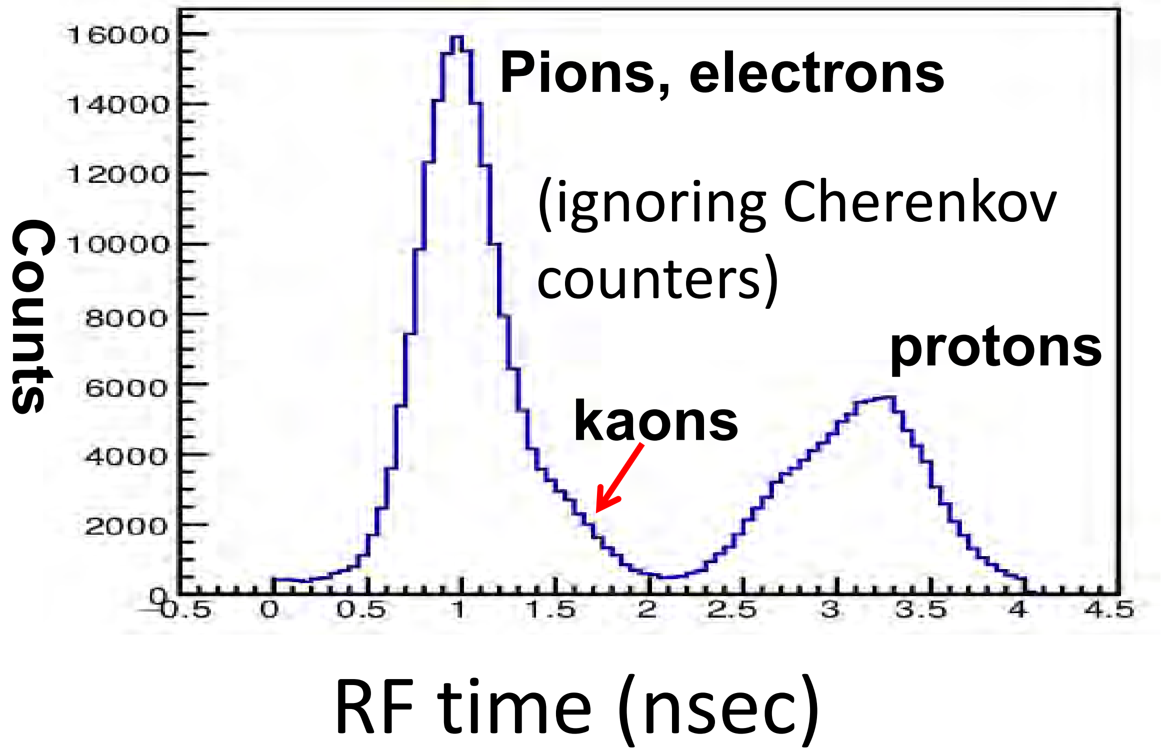
RF Time = time of flight between the target and hodoscope (~ 20 m apart) for beam buckets arriving at the target every 4.008 ns. An offset is added to align the pions at 1.0

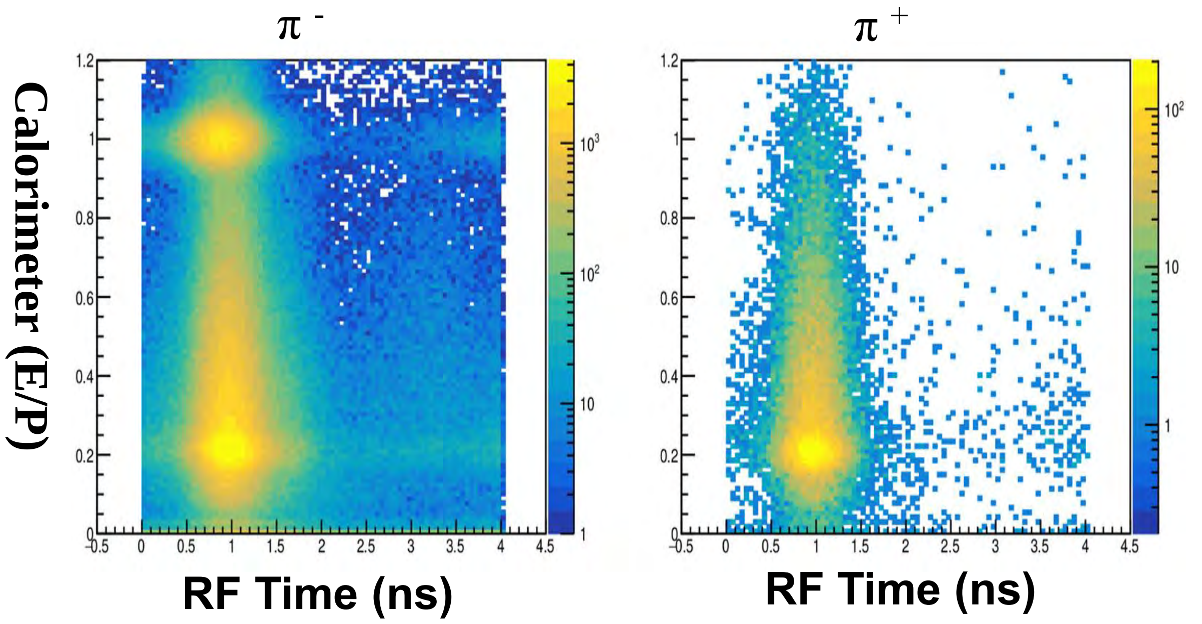
RF Timing Signal: To separate pions from kaons or protons

Calorimeter : To separate pions from electrons or positrons

Aerogel Cherenkov : To separate pions from protons and kaons (P<3 GeV)

Heavy Gas Cherenkov : To separate pions from kaons (P>3 GeV)





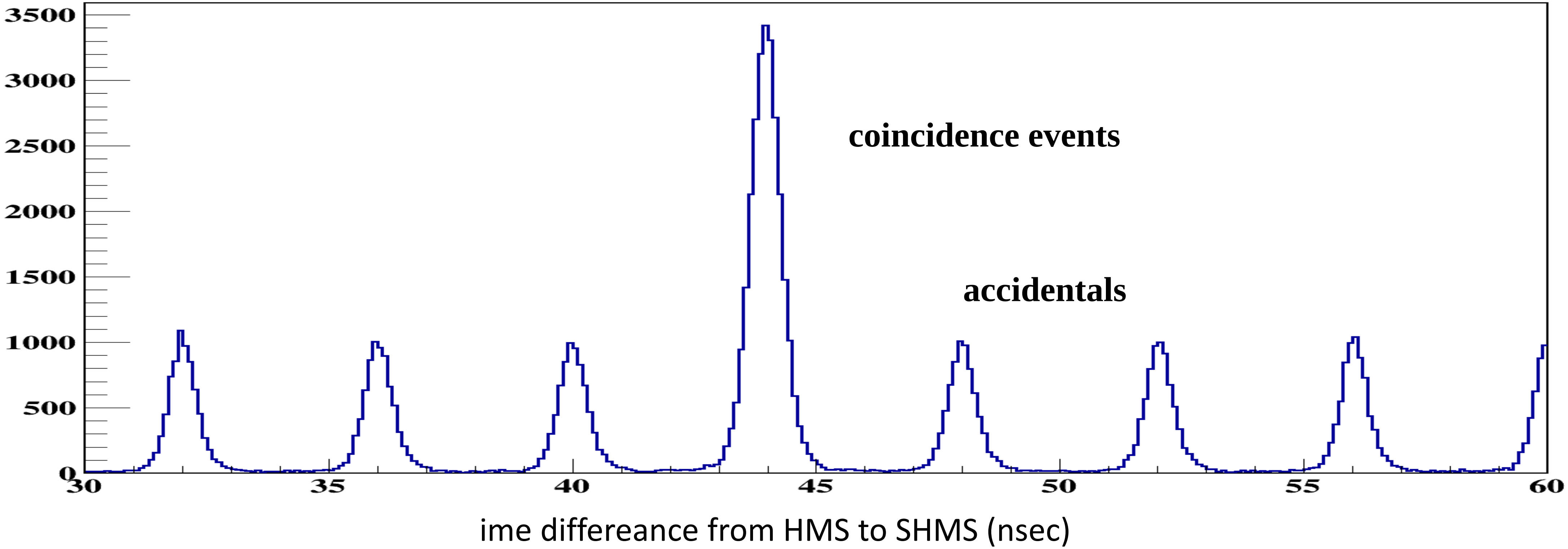
Calorimeter E/P vs RF Time (ns)

Paricle Identification: HMS

Calorimeter : To separate electrons from all hadronic background

Gas Cherenkov : To separate pions and electrons (P<4.5GeV)

Accidental coincidences correction



Binning

For each of 36 (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 to 1 (alternate: z')
- 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

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)

b) Exclusive pion production (e N → e π N)

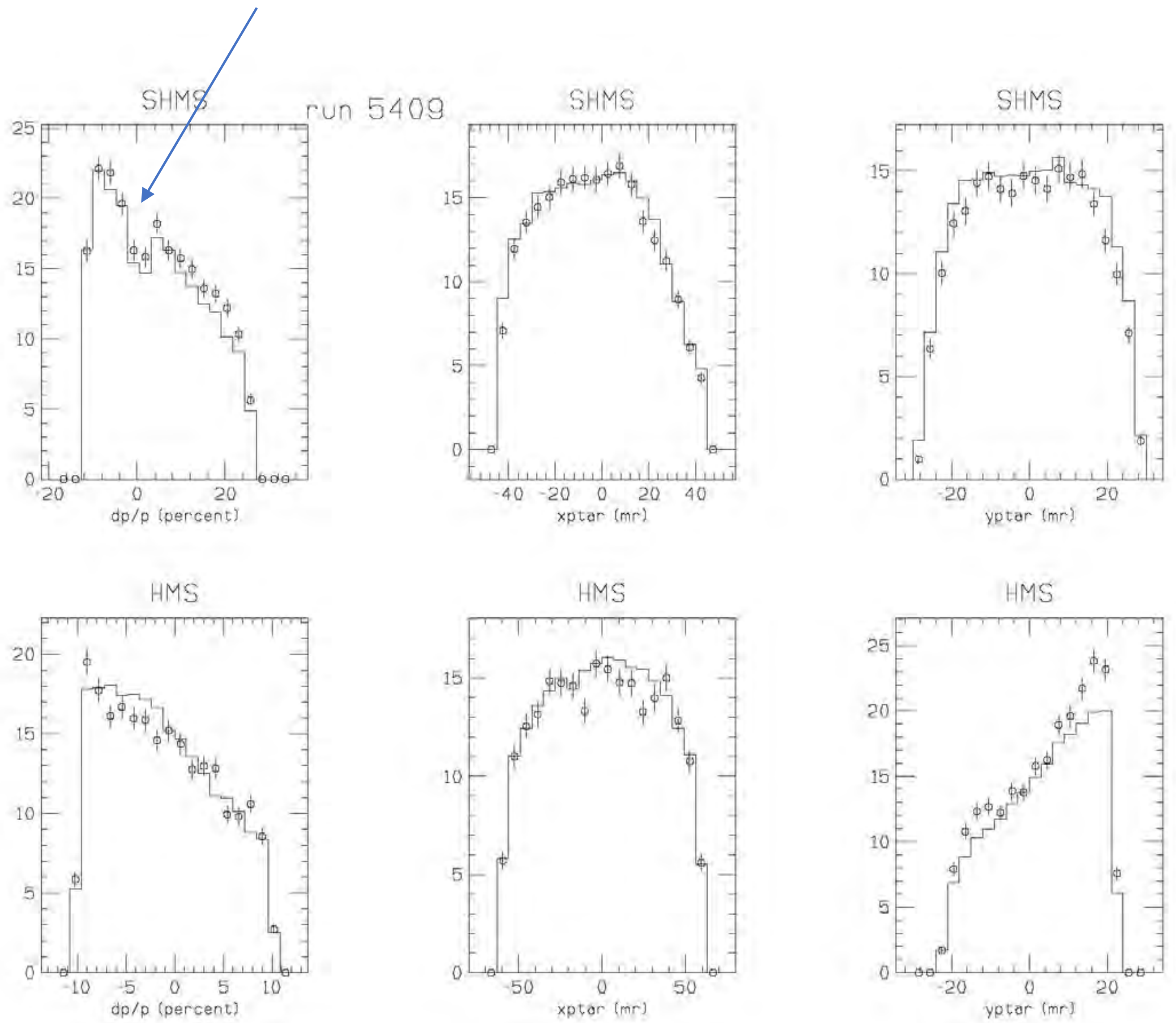
c) Quasti-excluisive production (e N → e π Δ)

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

Improvements to SIMC

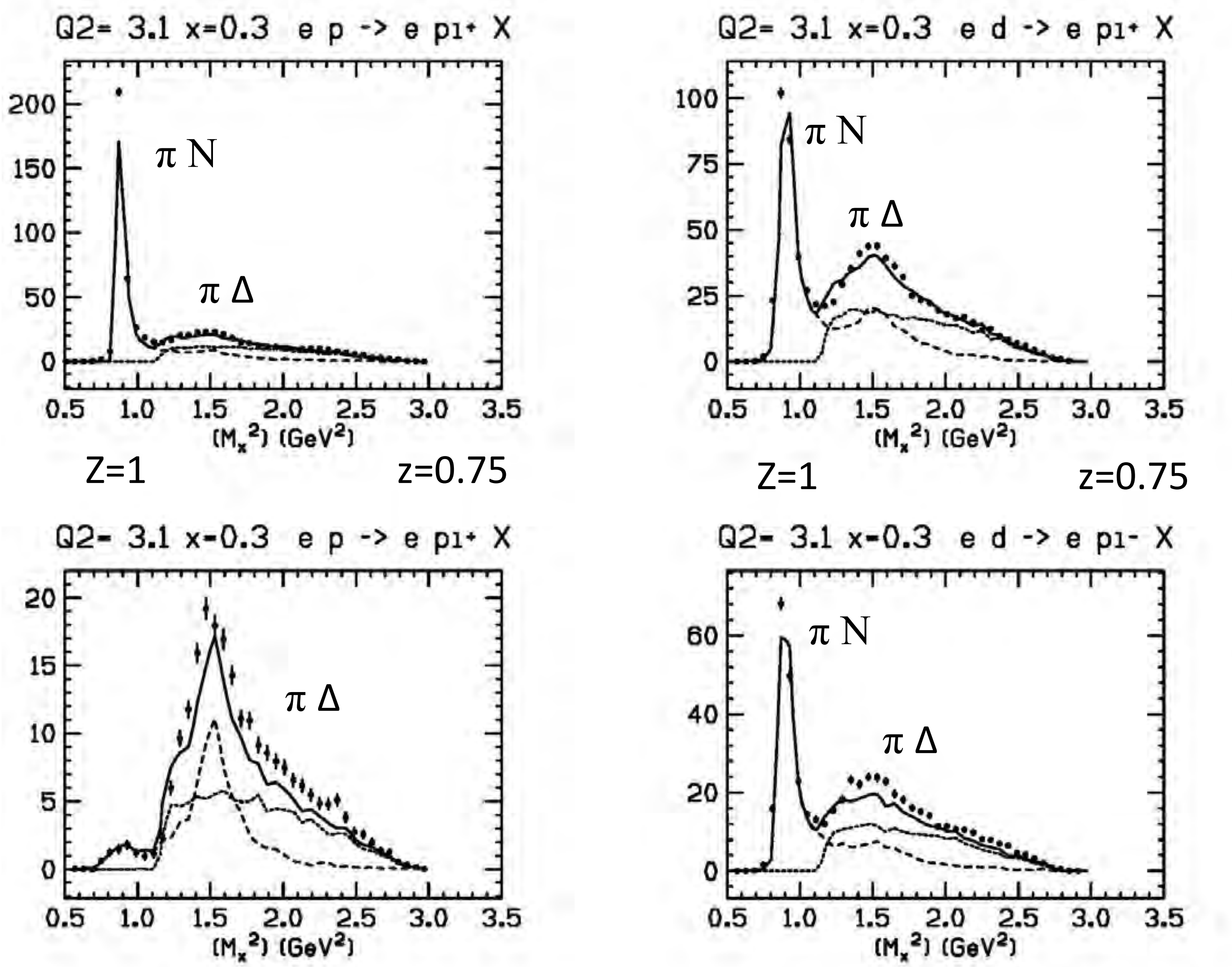
- Better random number generator
- Checked that parm03 works well for exclusive pion cross sections from all 3 experiments
- Found that param03 is too big in resonance region: changed to use a look-up table from MAID (resonance region is accessed in radiative corrections)
- Made rough fit to our data on e p -> e pi- 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+
- Added two more options for fragmentation functions. In SIDIS.
- Made code that generates SIMC outputs for every data run for SIDIS (with and without radiation), exclusive tails , SIDIS endcap contributions, and diffractive rho production .

Incorporation of Cherenkov Efficiency into SIMC



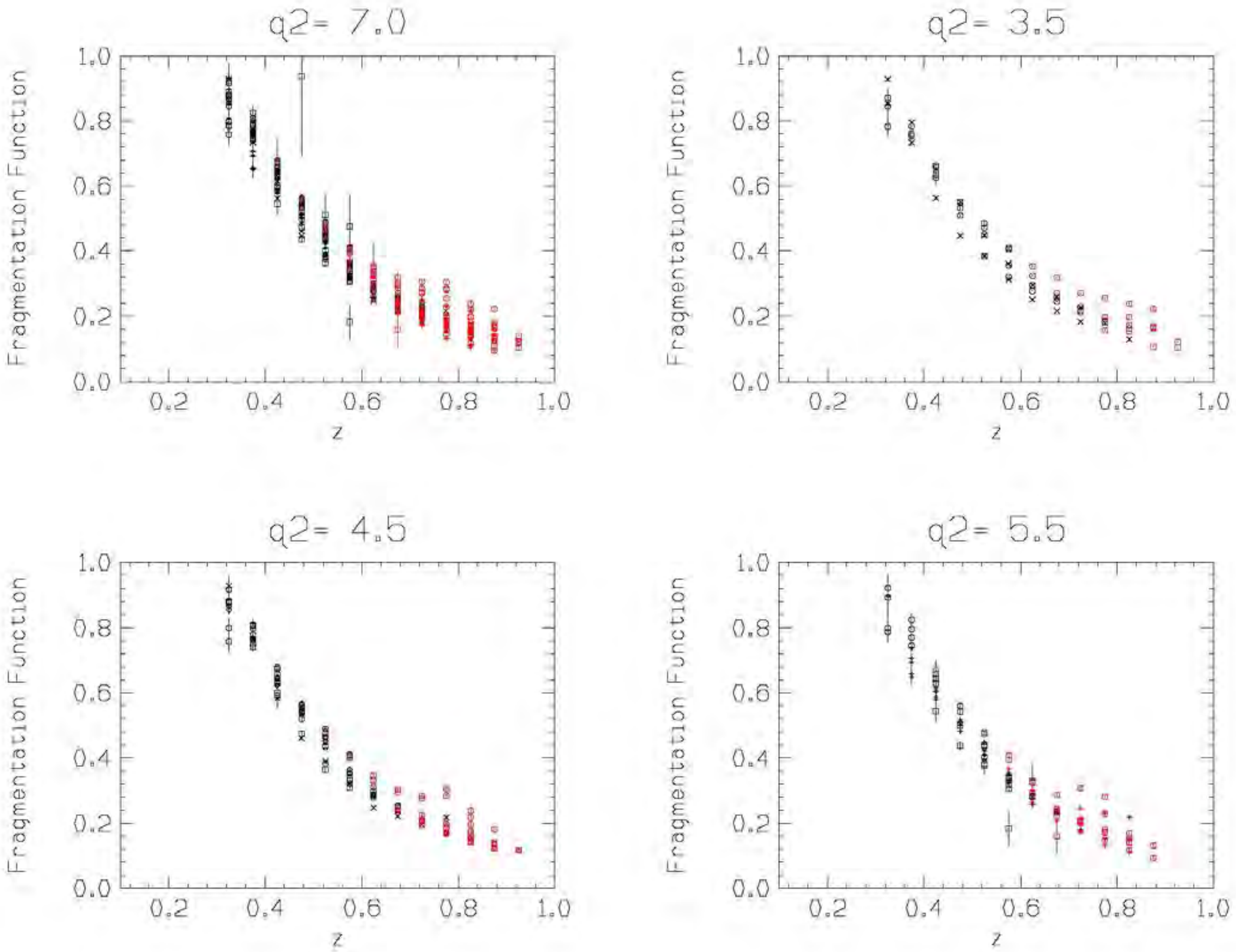
Modeling of high-z region in SIMC

Dotted curves: pi N and pi Delta Dotted curves: SIDIS model at high z Solid curve: sum



Modeling of SIDIS in SIMC

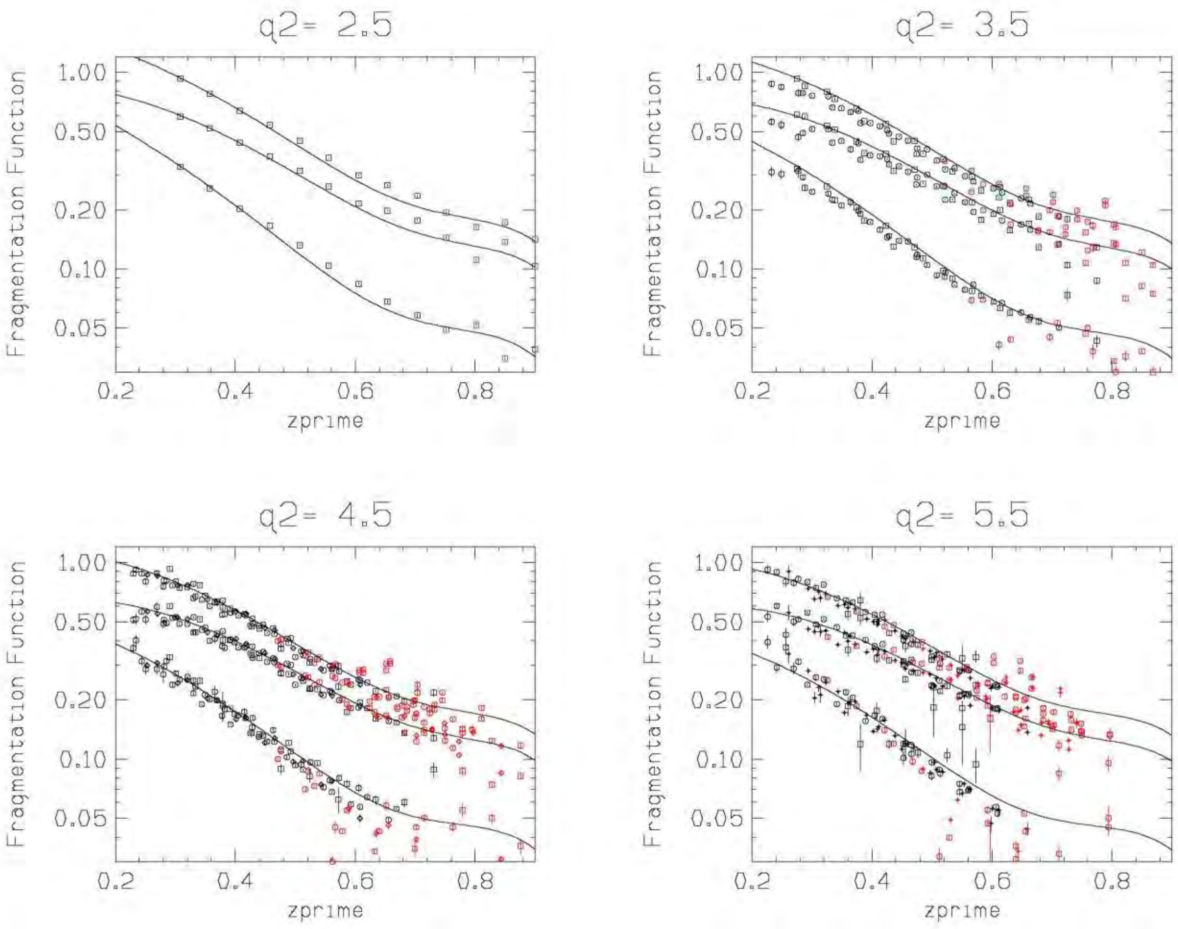
Fit all data for sum of favored and unfavored fragmentation function assuming depends on z. Big spread in results: poor chi2/d.f.



Red points: M_x<1.55 GeV

Modeling of SIDIS in SIMC

Fit all our Hall C data for favored, unfavored, and sum fragmentation functions, this time as a function of z' (basically light cone parallel momentum as defined in paper of Accardi, Hobbs, and Melnichouk). Works really well!



Red points: M_x<1.55 GeV

Lower points: unfavored
Mid-upper points: favored
Top points: sum

Overview of pt-scan ratios

- Scans in P_t at two of three (x,Q^2) and two large z bins
- Plots show ratios of data to data for pi+ on proton
- Curves are predicted ratios from SIMC. Solid is with exclusive tails, dashed in without exclusive tails
- Larger SHMS angle is igger Pt
- Results averaged over ϕ*
- SIMC used same P_t slopes for all cases [i.e. $\exp(-3.8\ P_t^2)$]

Ratios to Hydrogen π+ 15- November-2020

^{2}H(π+)

^{2}H(π-)

^{1}H(π-)

Al(π+)

Al(π-)

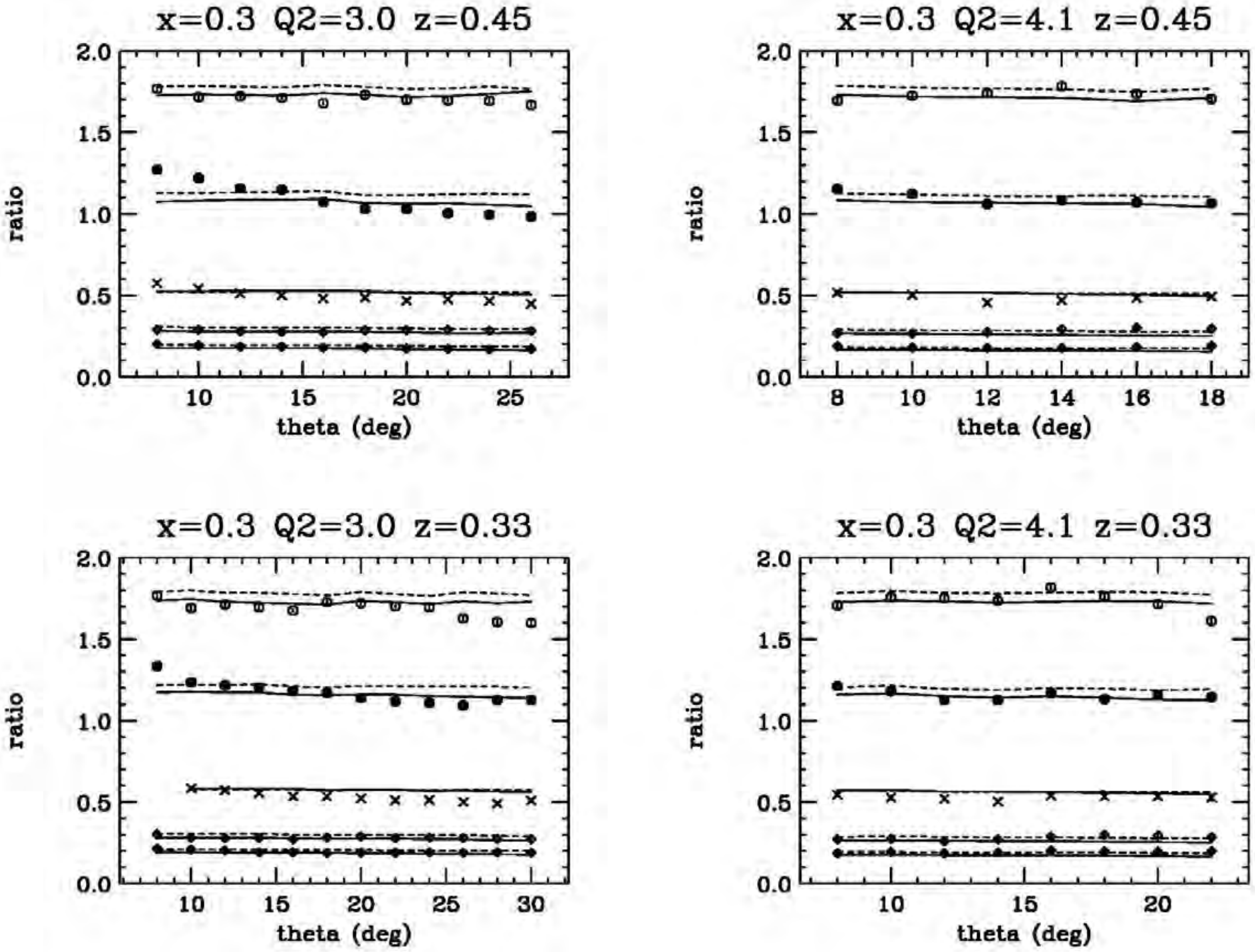
^{2}H(π+)

^{2}H(π-)

^{1}H(π-)

Al(π+)

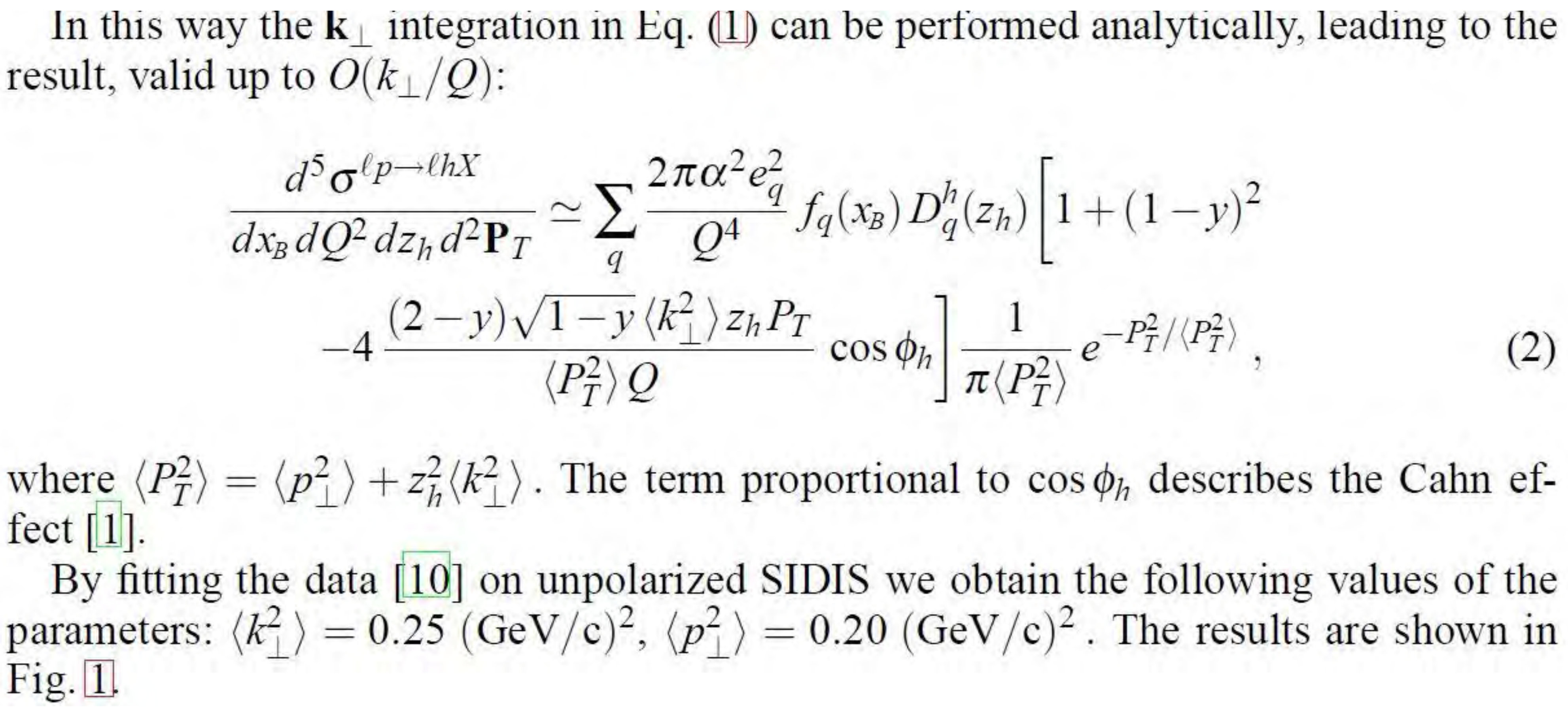
Al(π-)



Curves: SIMC (dashed without exclusive tails)

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].

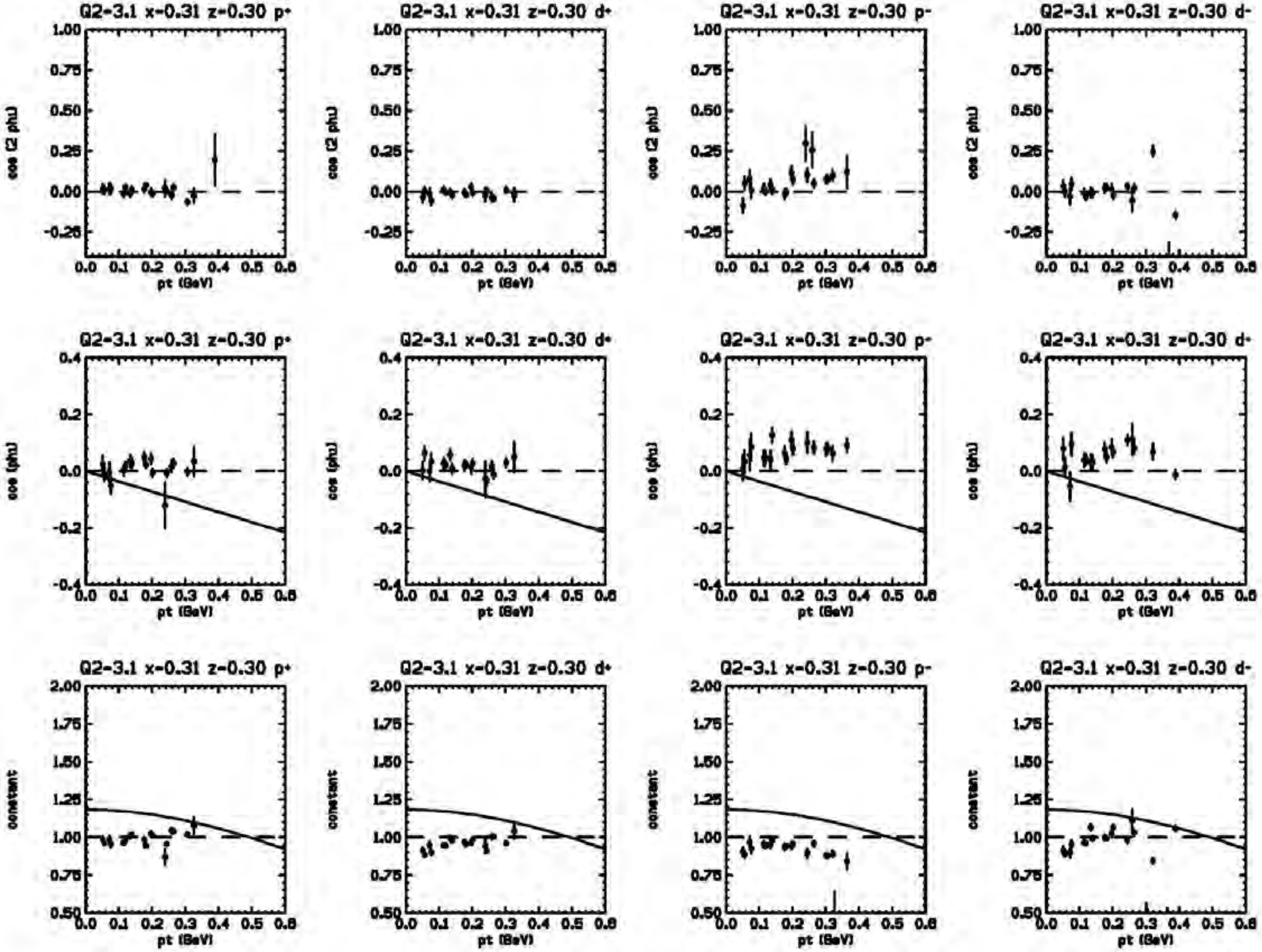
By fitting the data [10] on unpolarized SIDIS we obtain the following values of the parameters: $\langle k_\perp^2\rangle = 0.25$ (GeV/c)^2, $\langle p_\perp^2\rangle = 0.20$ (GeV/c)^2. The results are shown in Fig. 1.

Curves on next page use these value.

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

Fits to cos(ϕ), cos(2ϕ), and constant

For 0.2 < z < 0 .4 one kinematic setting, VERY PRELIMINARY

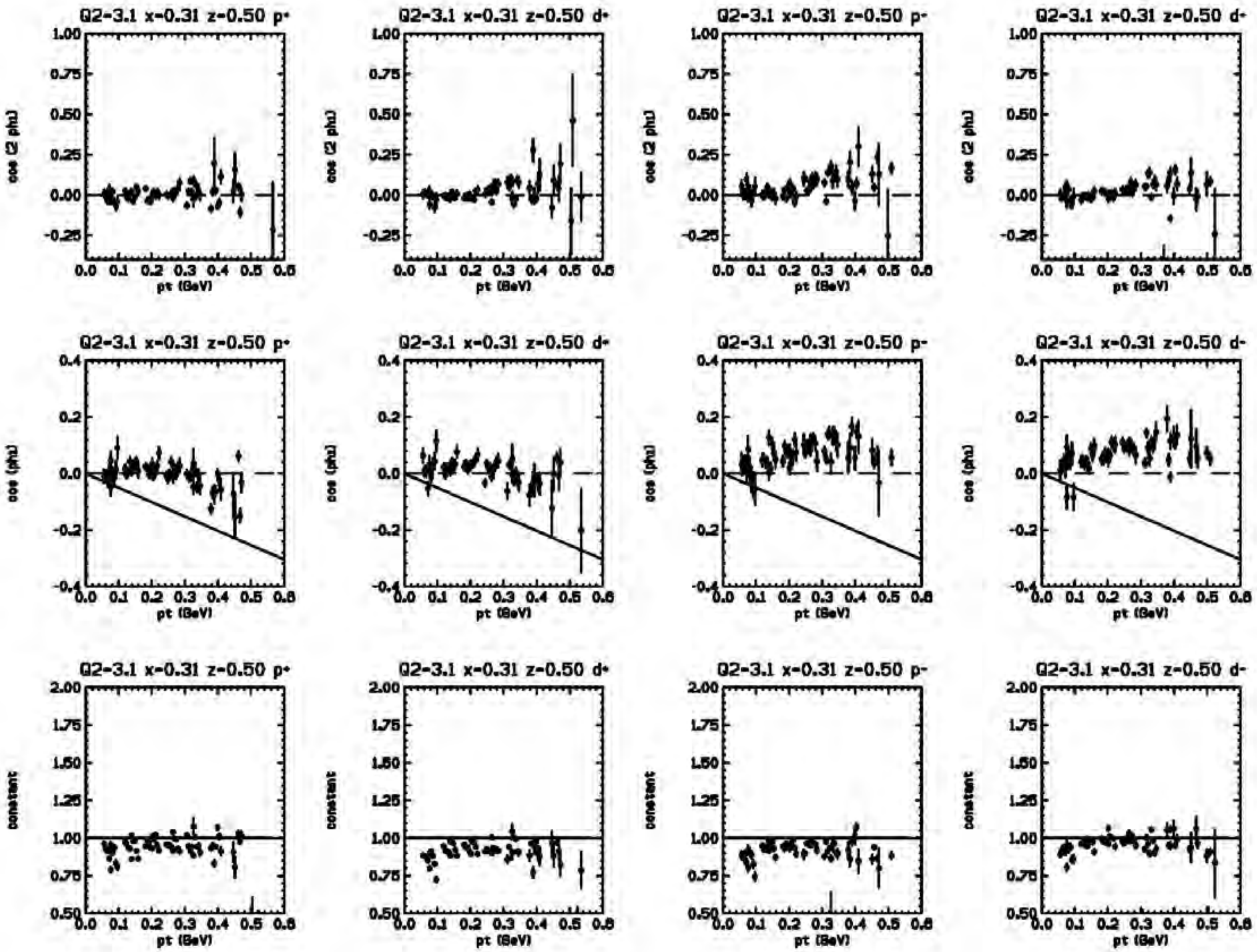


ROWS: (L to R) π^+ p, π^+ d, π^- p, $\pi^{\square}$ d

COLUMNS: top is 2<cos(2ϕ)>
middle is 2<cos(ϕ)>
bottom is Constant term

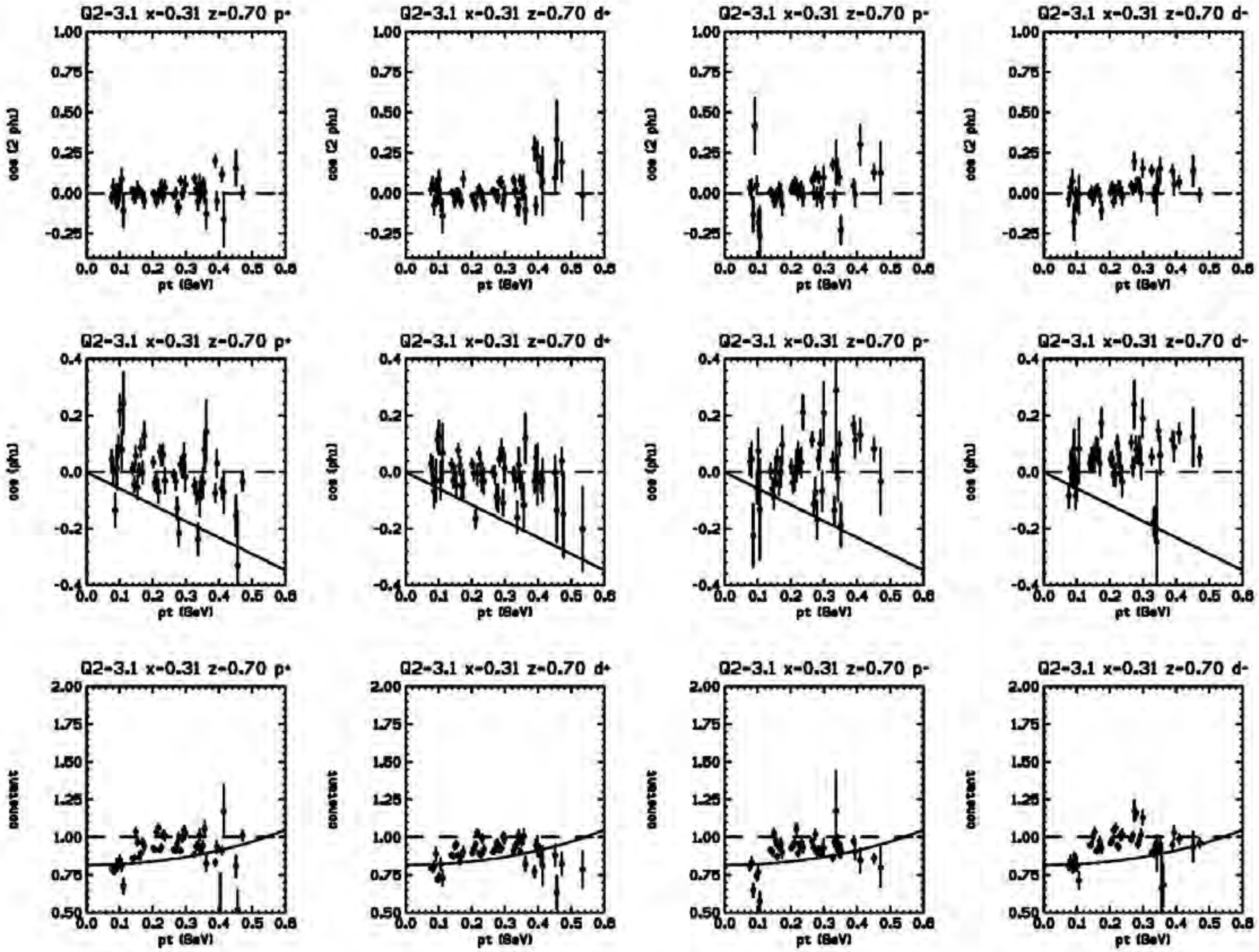
Fits to cos(ϕ), cos(2ϕ), and constant

For 0.4 < z < 0 .6 VERY PRELIMINARY



Fits to cos(ϕ), cos(2ϕ), and constant

For 0.6 < z < 0 .8 VERY PRELIMINARY



Fits to cos(ϕ), cos(2ϕ), and constant

- Similar results at other (x,Q^2) bins
- Within Anselmino framework, best fit more or less $<k_t^2>=0$!!
- Why is cos(ϕ) for π^- somewhat greater than zero?
- 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.)

To-do list

- Refine PID and efficiencies for pions
- Re-do luminosity corrections
- Study ratio of K/π. At first glance, not competitive with CLAS due to long length of SHMS. (most kaons decay away)
- Study SIDIS protons? Any theoretical interest in this?
- Beam SSA for pions. Limited to $P_t<0.3$ GeV.
- Extract R at high z from KLT data.
- Extract the beam SSA (Carlos has started on this).

Compared to HERMES and CLAS12

- High statistical precision, true multi-dimensional binning
- Small systematic errors on cross sections
- Very small systematic errors on ratios of p/d, π^+ / π^-
- Only valence region studied (x>0.25, Q^2>3 GeV^2)
- Only charged pions (no π^0)
- Full ϕ^* coverage only for P_t<0.3 GeV. Limited ϕ^* coverage out to 0.75 GeV.
- Good momentum and angle resolution in spectrometers leads to good resolution in P_t, and ϕ^* : bin migration effects minor.
- Cannot measure diffractive rho directly, only 1 pion at a time
- No polarized p or d targets planned in Hall C

Interpretation of data

- Target-mass corrections of $\cos(\phi)$, $\cos(2\phi)$ 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.