Transverse target-spin asymmetries for production of pions and kaons in semi-inclusive deep-inelastic scattering

Andy Miller
on behalf of the
HERMES Collaboration

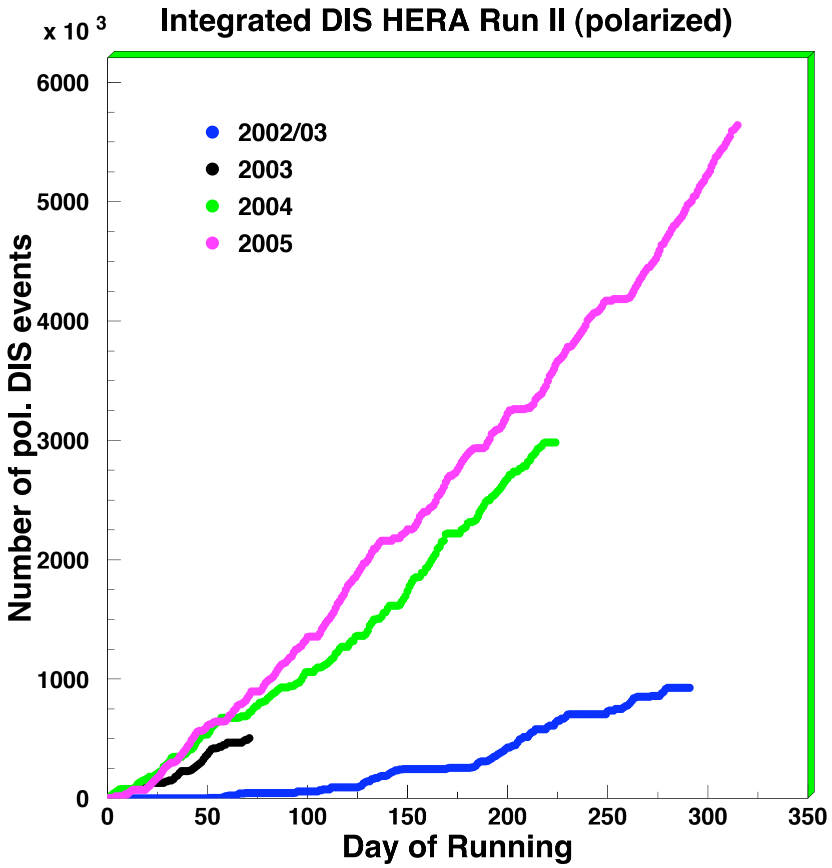
hermes

Thanks to all my Hermes colleagues whose pretty slides I hacked!

Trento
June 11, 2007

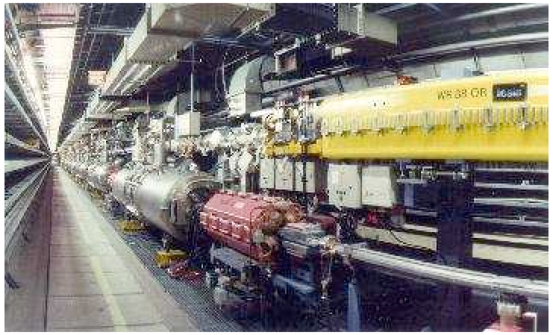
What's on the menu?

- Preliminary Collins and Sivers asymmetries from the complete 2002-2005 HERMES data set with a transversely polarized hydrogen target
- Some technical issues about how we extract the results
- An invitation for advice about how we might present such results in publications
- An invitation for advice about where we might deploy our analysis resources in future

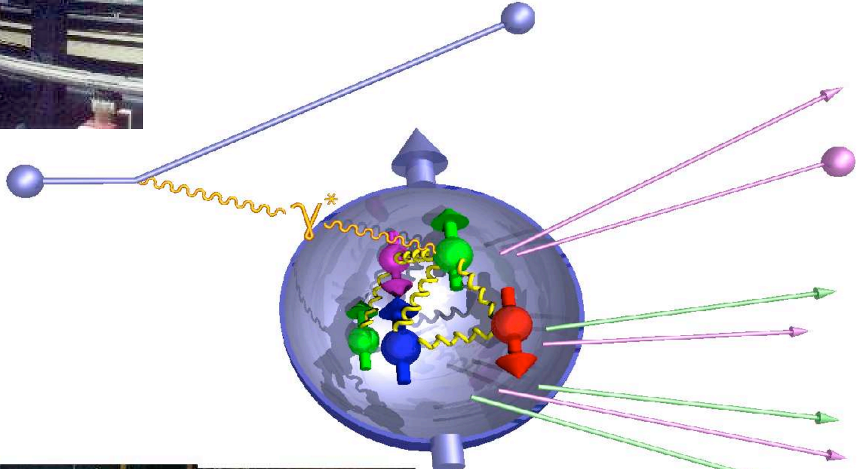


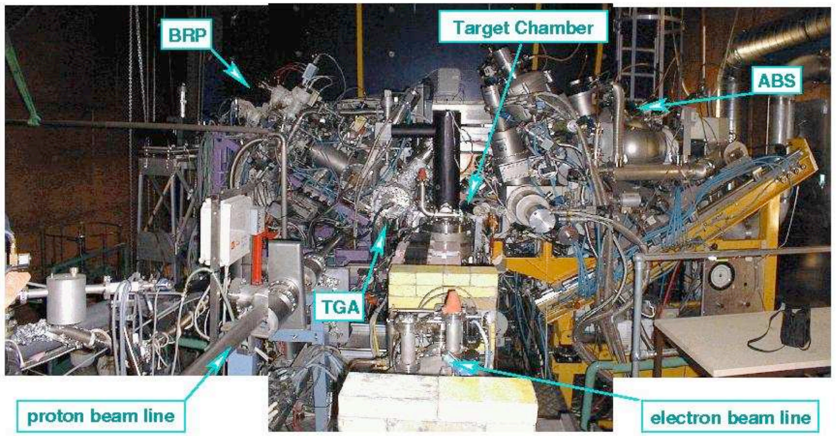
The HERMES Experiment at HERA

27.5 GeV HERA positron beam



HERMES Spectrometer





2002-2005

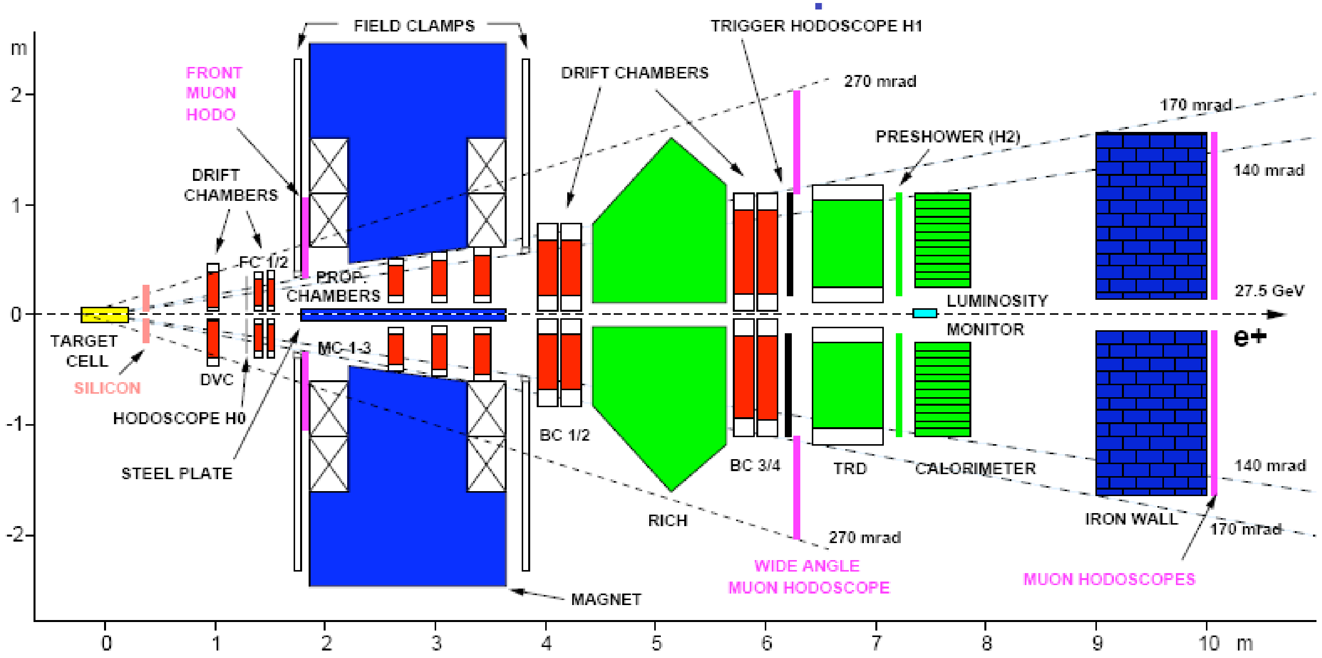
Transversely polarized atomic hydrogen (P ≈ 80%)

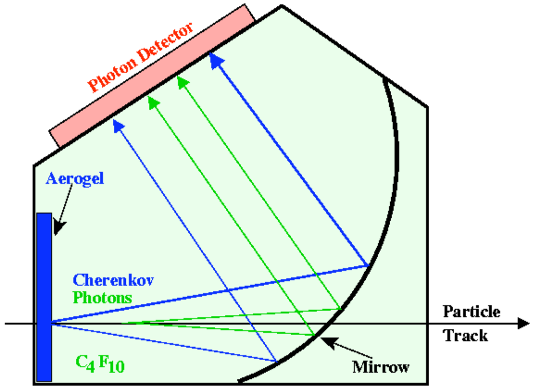
Rapid spin flipping!

The HERMES Spectrometer

Angular acceptance: $40\ mrad < |\theta_y| < 140\ mrad \quad |\theta_x| < 170\ mrad$

Resolution: $\delta p \leq 2.6\%\ ; \quad \delta\vartheta \leq 1\ mrad$





Dual radiator RICH

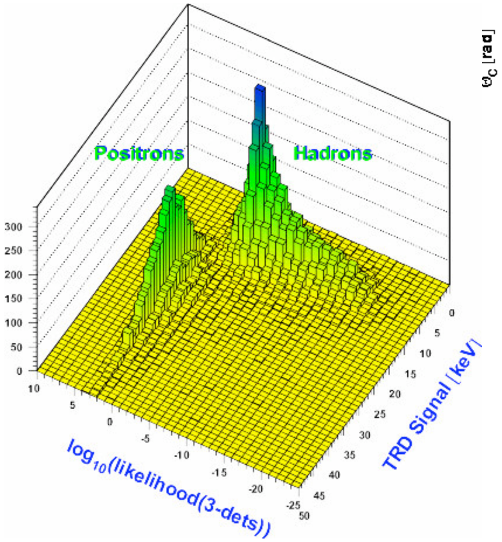
Particle Identification:

TRD, Calorimeter, preshower, RICH:

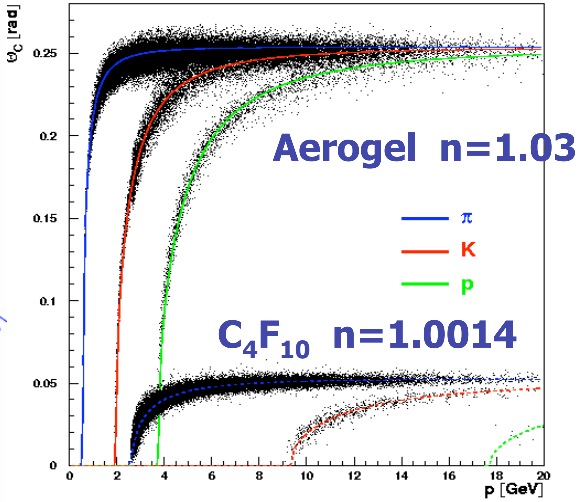
lepton-hadron > 98%

RICH:

Hadron: π ~ 98%, K ~ 88% , P ~ 85%



hadron separation



Extraction of Azimuthal Amplitudes (I)

Unbinned Maximum-Likelihood fit of several amplitudes together

Accounting for the full kinematic dependence of the amplitudes, the Probability Density Function (PDF) of events is defined as:

Target polarization dist^n $-1<P<1$ Acceptance Azimuthally averaged x-section

$$\begin{aligned}F(\langle\sin(\phi+\phi_S)\rangle^h_{UT},\langle\sin(\phi-\phi_S)\rangle^h_{UT},P,x,y,z,P_t,\phi,\phi_S) &= \rho(P)\,\varepsilon(x,y,z,P_t,\phi,\phi_S)\,\underline{\sigma}_{UU}(x,y,z,P_t)\times \\ &\Big\{1+2\langle\cos\phi\rangle^h_{UU}(x,y,z,P_t)\cos\phi+2\langle\cos2\phi\rangle^h_{UU}(x,y,z,P_t)\cos(2\phi) \\ &+P\Big[2\langle\sin(\phi+\phi_S)\rangle^h_{UT}(x,y,z,P_t)\sin(\phi+\phi_S)+2\langle\sin(\phi-\phi_S)\rangle^h_{UT}(x,y,z,P_t)\sin(\phi-\phi_S)\Big]\Big\}\end{aligned}$$

Collins Sivers

The Likelihood is then defined as:

Event weights for particle ID

$$\mathcal{L}(\langle\sin(\phi+\phi_S)\rangle^h_{UT},\langle\sin(\phi-\phi_S)\rangle^h_{UT}) = \prod_{i=1}^{N} F(\langle\sin(\phi+\phi_S)\rangle^h_{UT},\langle\sin(\phi-\phi_S)\rangle^h_{UT},P_i,x_i,y_i,z_i,P_{ti},\phi_i,\phi_{Si})^{W_i}$$

Two major conveniences:

- The normalization of the PDF is automatically independent of the fitted parameters, if the total event sample is unpolarized: $\int \mathrm{d}P\, P\rho(P) = 0$
- Acceptance ε and azimuthally averaged cross section $\underline{\sigma}_{UU}$ do not depend on the fitted parameters ⇨ they can be omitted in calculation of the likelihood

However, integrating PDF over 3 kinematic variables involves an approximation

Extraction of Azimuthal Amplitudes (II)

After integrating over 3 kinematic variables, and binning in a fourth, the complete PDF is:

$$\begin{aligned} F(\langle \sin(\phi+\phi_S)\rangle^h_{UT}, \langle \sin(\phi-\phi_S)\rangle^h_{UT}, P, \phi, \phi_S) &= \rho(P)\, \varepsilon(\phi,\phi_S)\, \underline{\sigma}_{UU} \times \\ &\Big\{ 1 + 2\langle \cos\phi\rangle^h_{UU} \cos\phi + 2\langle \cos 2\phi\rangle^h_{UU} \cos(2\phi) \\ &\quad + P\Big[2\langle \sin(\phi+\phi_S)\rangle^h_{UT} \sin(\phi+\phi_S) + 2\langle \sin(\phi-\phi_S)\rangle^h_{UT} \sin(\phi-\phi_S) \\ &\quad +2\langle \sin(3\phi-\phi_S)\rangle^h_{UT} \sin(3\phi-\phi_S) + 2\langle \sin(2\phi-\phi_S)\rangle^h_{UT} \sin(2\phi-\phi_S) + 2\langle \sin\phi_S\rangle^h_{UT} \sin\phi_S \Big] \Big\} \end{aligned}$$

and the Likelihood is

$$\mathcal{L}(\langle \sin(\phi+\phi_S)\rangle^h_{UT}, \langle \sin(\phi-\phi_S)\rangle^h_{UT}) = \prod_{i=1}^{N} F(\langle \sin(\phi+\phi_S)\rangle^h_{UT}, \langle \sin(\phi-\phi_S)\rangle^h_{UT}, P_i, \phi_i, \phi_{Si})^{W_i}$$

- The “stationary approximation” employed in the kinematic integration were studied in Monte Carlo, and assigned as a systematic uncertainty (more later...)
- Approximate values for the $\cos(n\phi)$ amplitudes were extracted from data and used in the fit; the difference was assigned as a systematic uncertainty
- The addition of the three last terms had negligible influence on the Collins and Sivers amplitudes, and those three amplitudes are consistent with zero

Our statistical treatment is completely standard

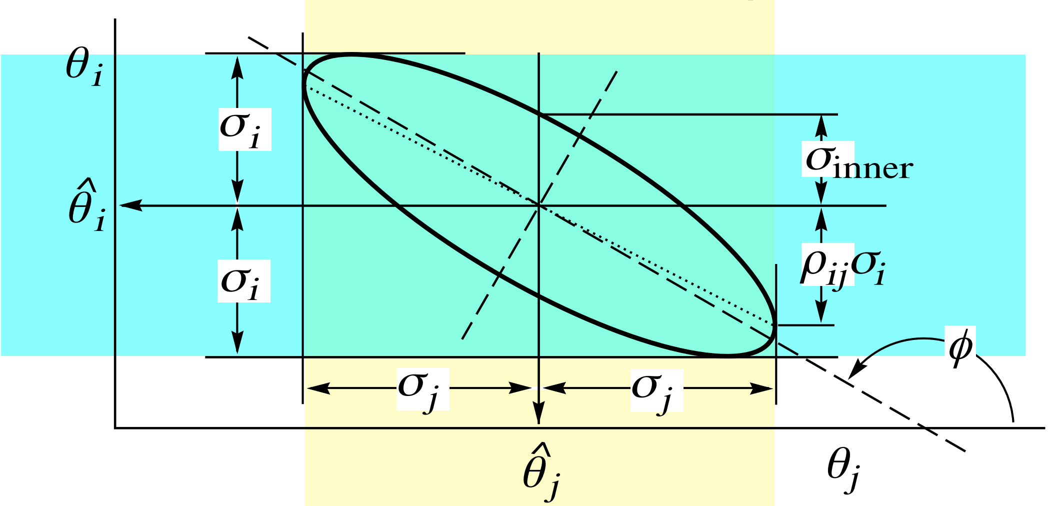
and according to the Particle Data Group

The definition of statistical uncertainty is not "a matter of taste":
It is defined in terms of the fundamental concept of **repeatability**

Definition:
The statistical uncertainty in any single parameter from a fit is the standard deviation of the distribution in that parameter obtained by fitting a large number of statistically independent such data sets (from e.g. a simulation)

We have used numerical simulations to demonstrate that our uncertainties for azimuthal amplitudes from our Maximum Likelihood fits satisfy this definition.

A likelihood contour for two parameters



- Each 1σ uncertainty corresponds to 68% probability content of one band or the other
- Correlations between the parameters are fully accounted for by the covariance matrix

Why do we need to define our uncertainty?

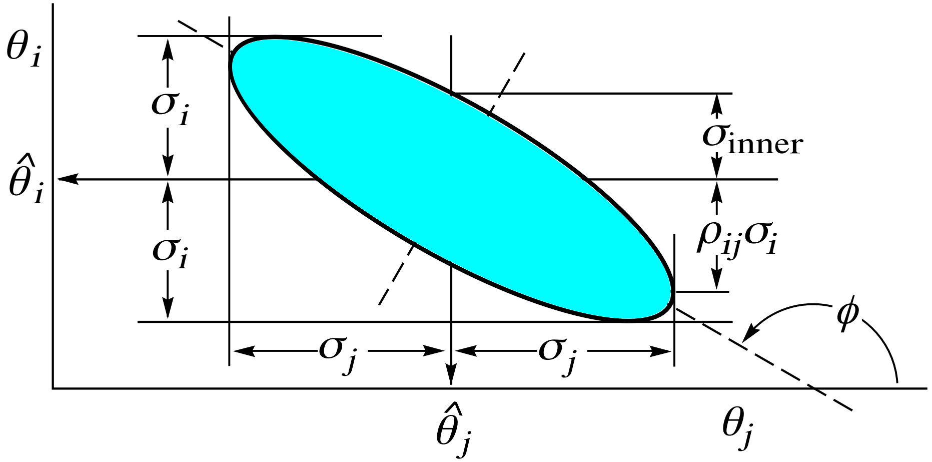
Some groups fitting experimental data use a different approach

e.g. two groups doing NLO QCD fits to g_1 data

They require the **ellipse** to contain 68% probability, which requires a larger ellipse

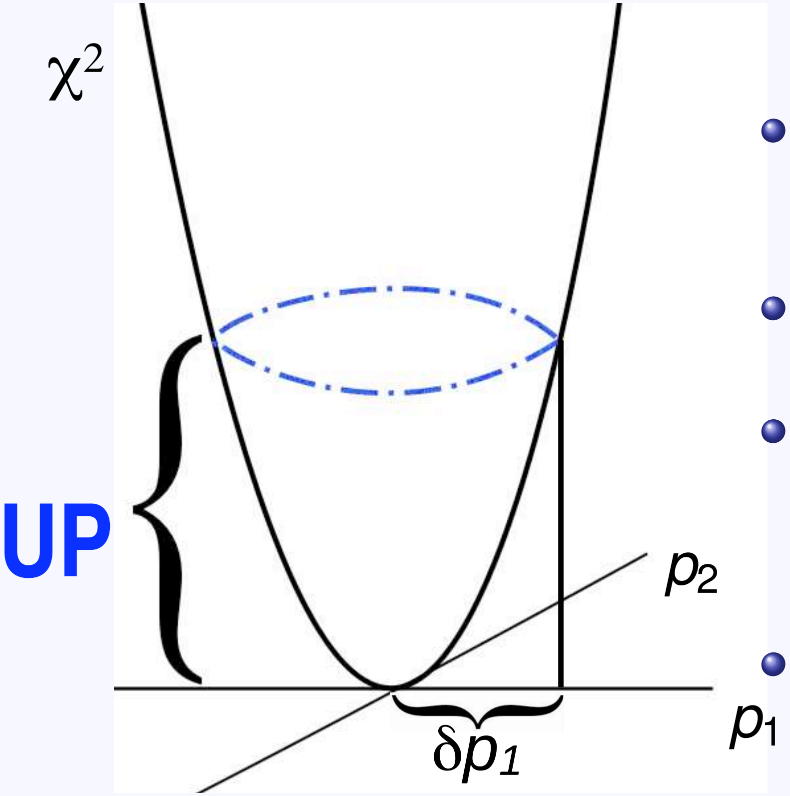
Consequence: the uncertainty of each parameter depends on the total number of parameters, even if they're uncorrelated, while that total is often a matter of taste

A likelihood contour for two parameters



Assuming the χ^2 surface is paraboloidal, they do this by increasing the MINUIT parameter "UP" to the number of parameters

The uncertainties scale as $\sqrt{\text{UP}}$



- The *UP value* is the parameter in MINUIT by which uncertainties for parameters are defined.
- UP=1 defines a 1σ uncertainty for single parameters.
- UP≈ npar corresponds to the 1σ uncertainty for the npar parameters to be simultaneously located inside the hypercontour.
- UP large: compensation for unknown systematic effects.

Lepton-beam or virtual-photon asymmetries?

Sivers lepton-beam asymmetry:

$$2\left\langle \sin(\phi+\phi_S)\right\rangle_{UT}^{h}(\bar{x},\bar{z}) \simeq \frac{\sum_q e_q^2 \int \mathrm{d}x\,\mathrm{d}y\, \frac{B(y)}{xy^2}\, \delta q(x) \int \mathrm{d}z\, H_1^{\perp(1)}(z)[q\to h]}{\sum_q e_q^2 \int \mathrm{d}x\,\mathrm{d}y\, \frac{A(x,y)}{xy^2}\, q(x) \int \mathrm{d}z\, D_1(z)[q\to h]}$$

Collins lepton-beam asymmetry:

$$2\left\langle \sin(\phi-\phi_S)\right\rangle_{UT}^{h}(\bar{x},\bar{z}) \simeq -\frac{\sum_q e_q^2 \int \mathrm{d}x\,\mathrm{d}y\, \frac{A(x,y)}{xy^2}\, f_{1T}^{\perp(1)}(x) \int \mathrm{d}z\, D_1(z)[q\to h]}{\sum_q e_q^2 \int \mathrm{d}x\,\mathrm{d}y\, \frac{A(x,y)}{xy^2}\, q(x) \int \mathrm{d}z\, D_1(z)[q\to h]}$$

$$B(y) \equiv (1-y) \qquad A(x,y) \equiv \frac{y^2}{2} + (1-y)\frac{1+R(x,y)}{1+\gamma(x,y)^2}$$

$$R(x,y) \equiv \frac{\sigma_L(x,y)}{\sigma_T(x,y)} \qquad \gamma(x,y)^2 \equiv \frac{Q^2}{\nu^2}$$

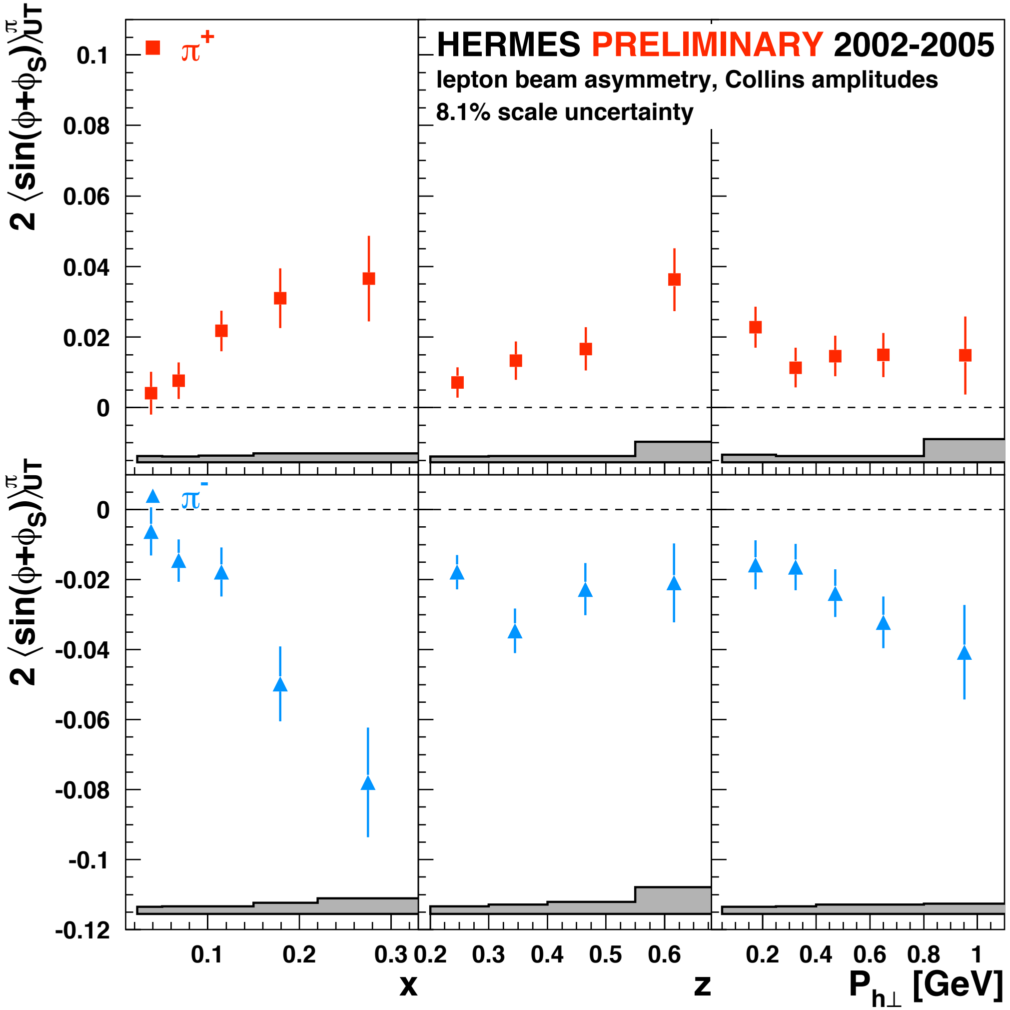
Up to now, most analyses have factorized the integrals by neglecting the y dependences of pdfs and fragmentation functions

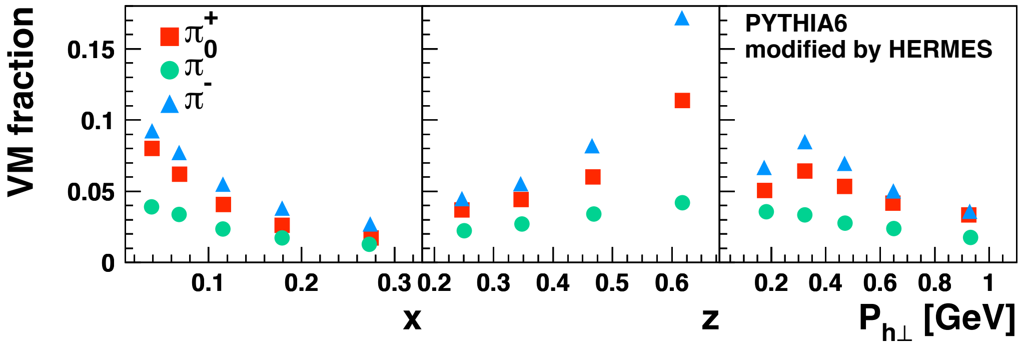
In any case, the above integrals involve the acceptance, and maybe be inconvenient for those interpreting the results

We can easily account for *A* and *B* as event weights to provide VPAs

However, we would have to simulate R$_{\mathrm{SIDIS}}$

The Collins asymmetries for charged pions

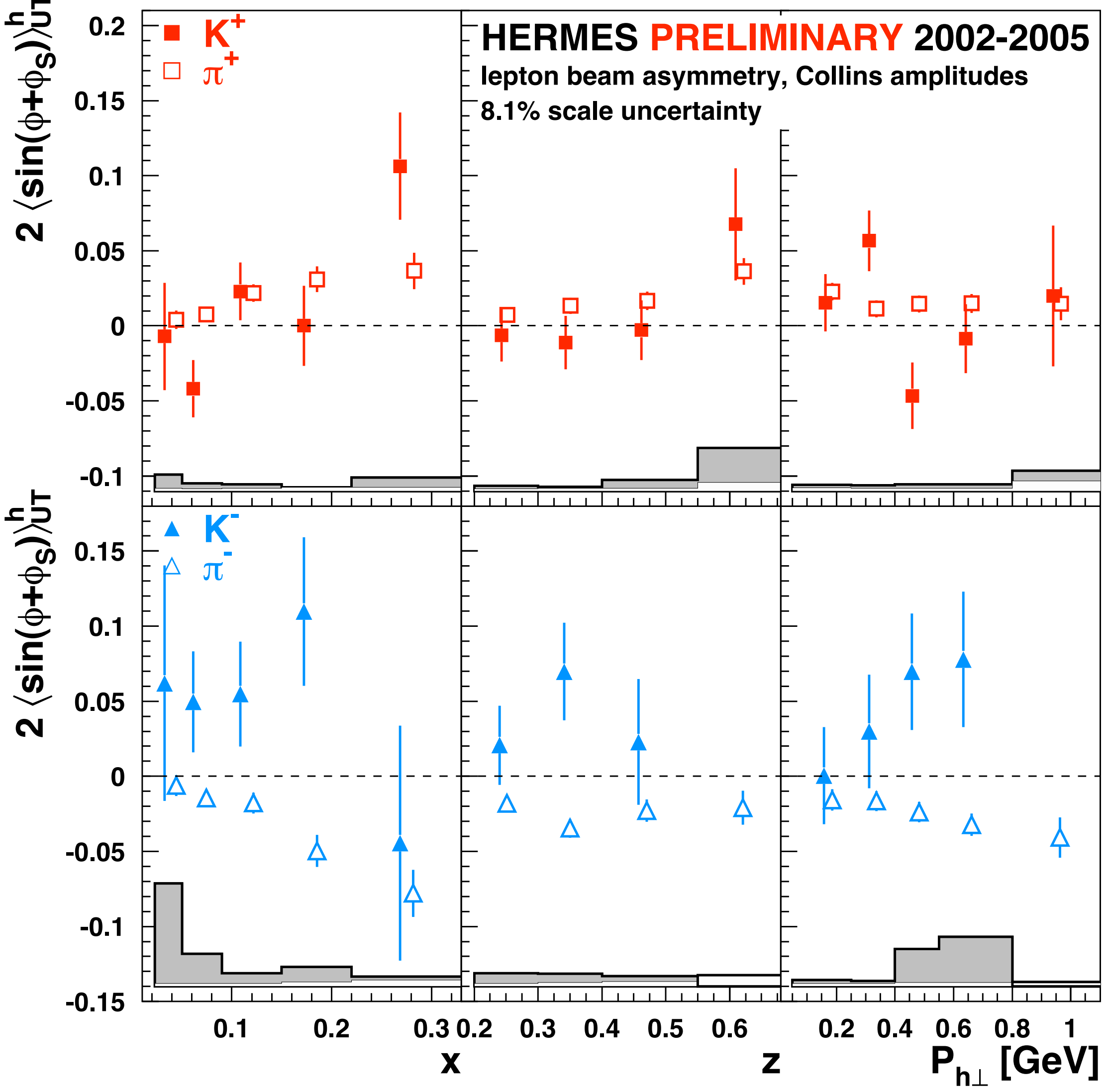




- π^+ asymmetries are positive -- no surprise: u-quark dominance and expect $\delta u>0$ since $\Delta u>0$
- Larger negative π^-asymmetries were a surprise -- now understood to signify the disfavoured Collins function is large with opposite sign
- “Contamination” by decay of exclusively produced vector mesons is not completely negligible (2-16%)
- Systematic uncertainty (gray bands) account for effects of acceptance, smearing, and $\cos\varphi$ and $\cos 2\varphi$ in the spin-averaged denominator of the asymmetry

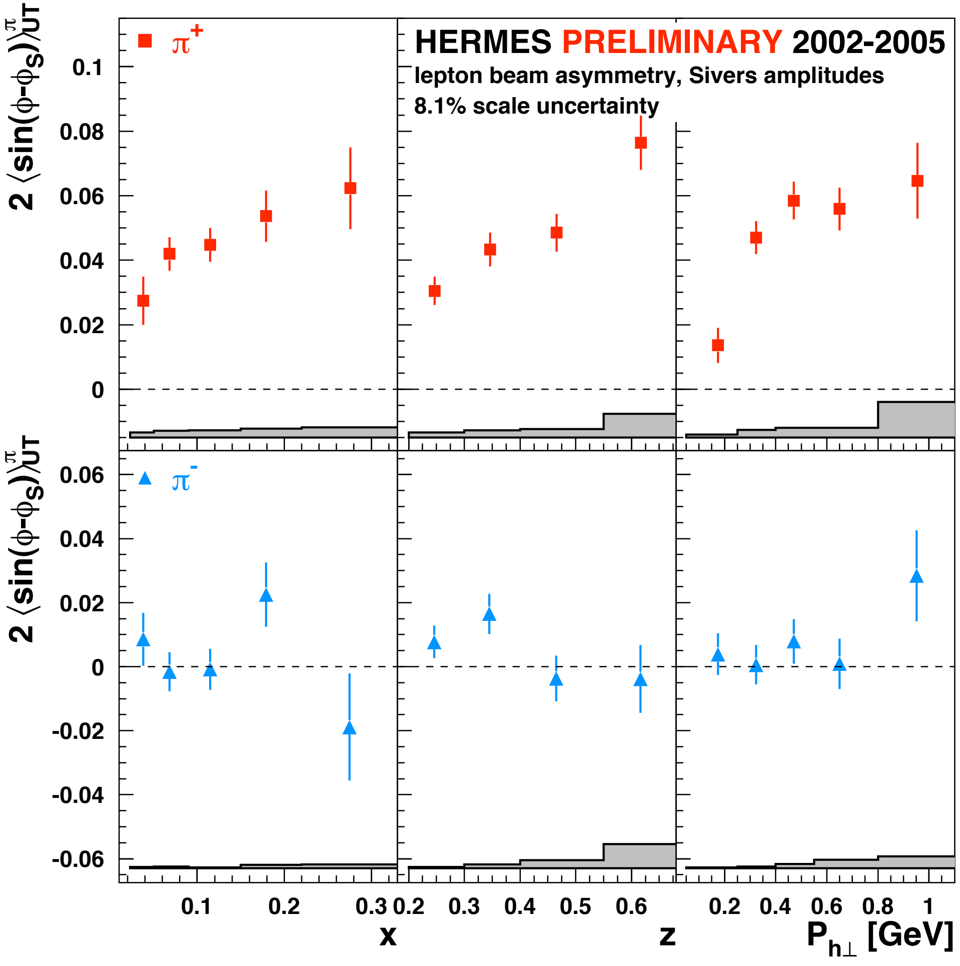
The Collins asymmetries for charged kaons

compared to charged pions



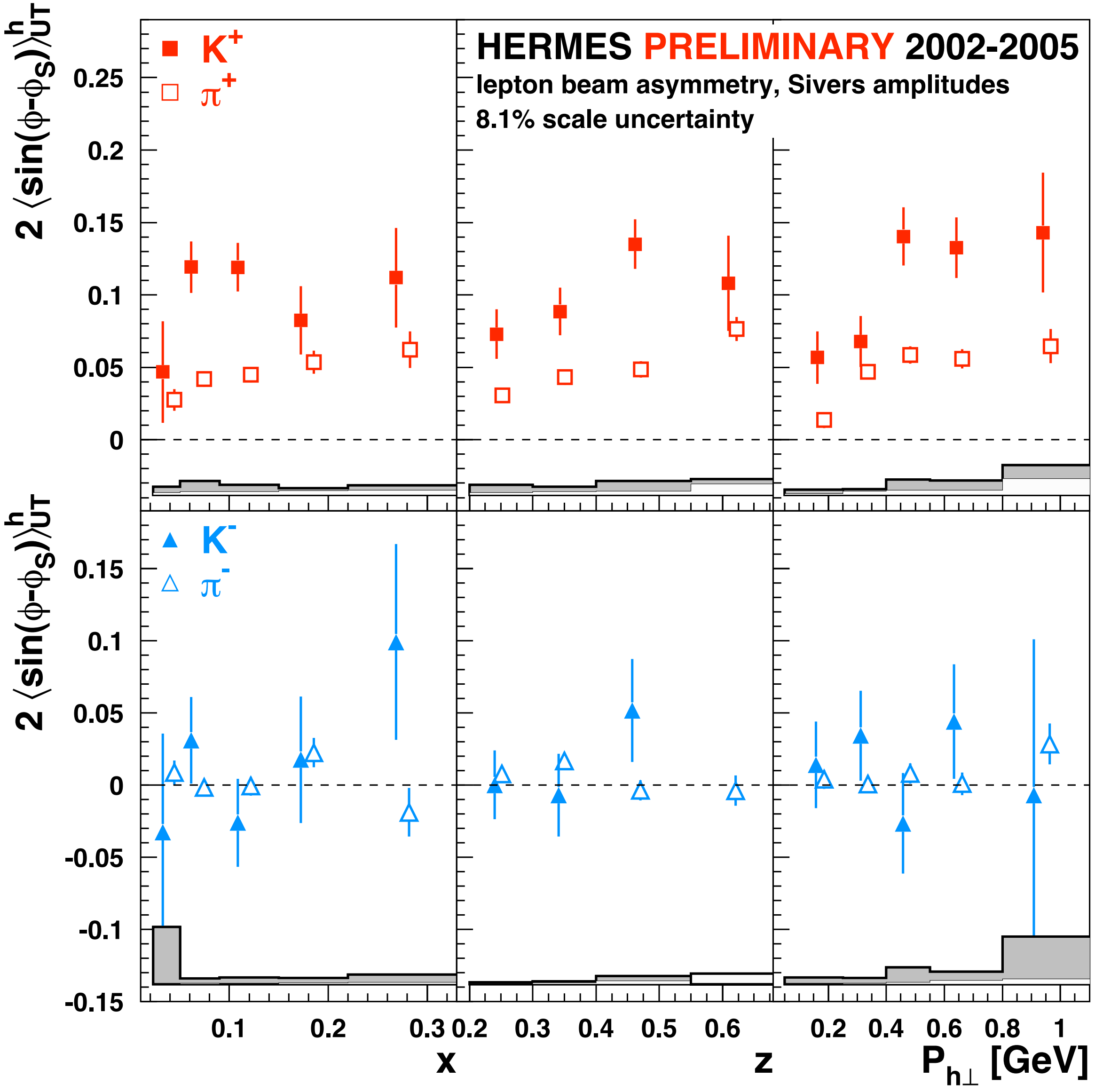
- K^+ amplitudes consistent with π^+ as expected from u-quark dominance
- K^- may have the opposite sign from π^- (K^- is an all-sea object)

The Sivers asymmetries for charged pions



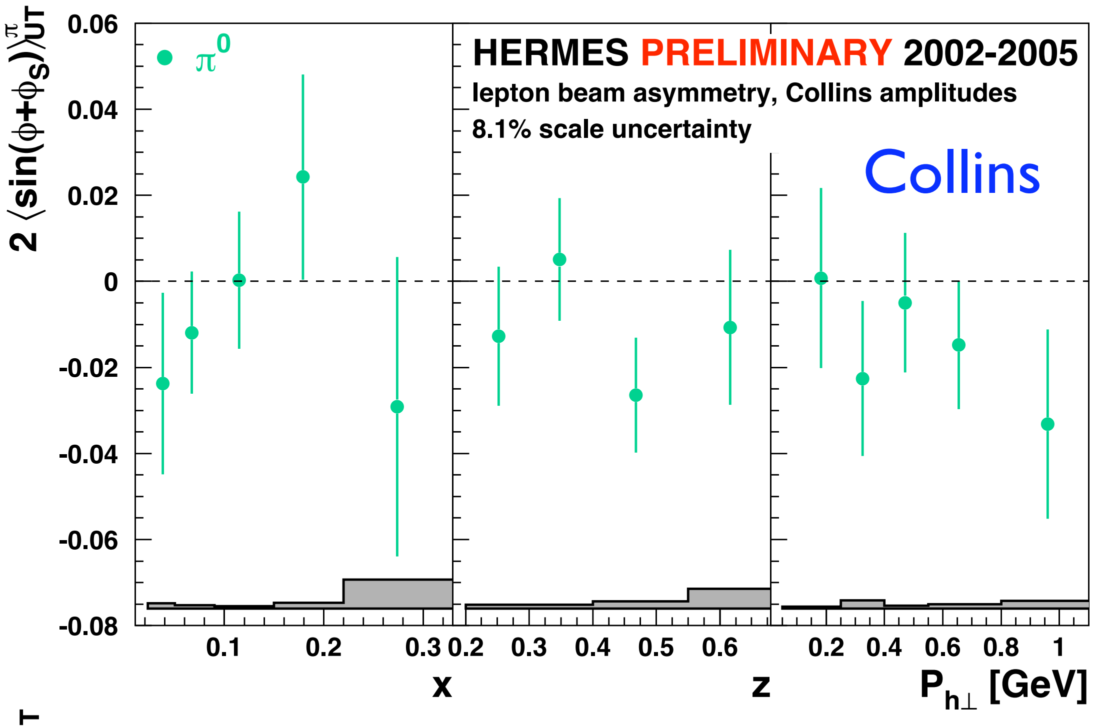
- π^+ asymmetries are substantial and positive
- First unambiguous evidence for a non-zero T-odd distribution function in DIS
- A signature for quark orbital angular momentum
- The implied negative sign of the u-quark Sivers function (in the Trento Convention) is consistent with Burkhardt's "Chromodynamic Lensing" picture!

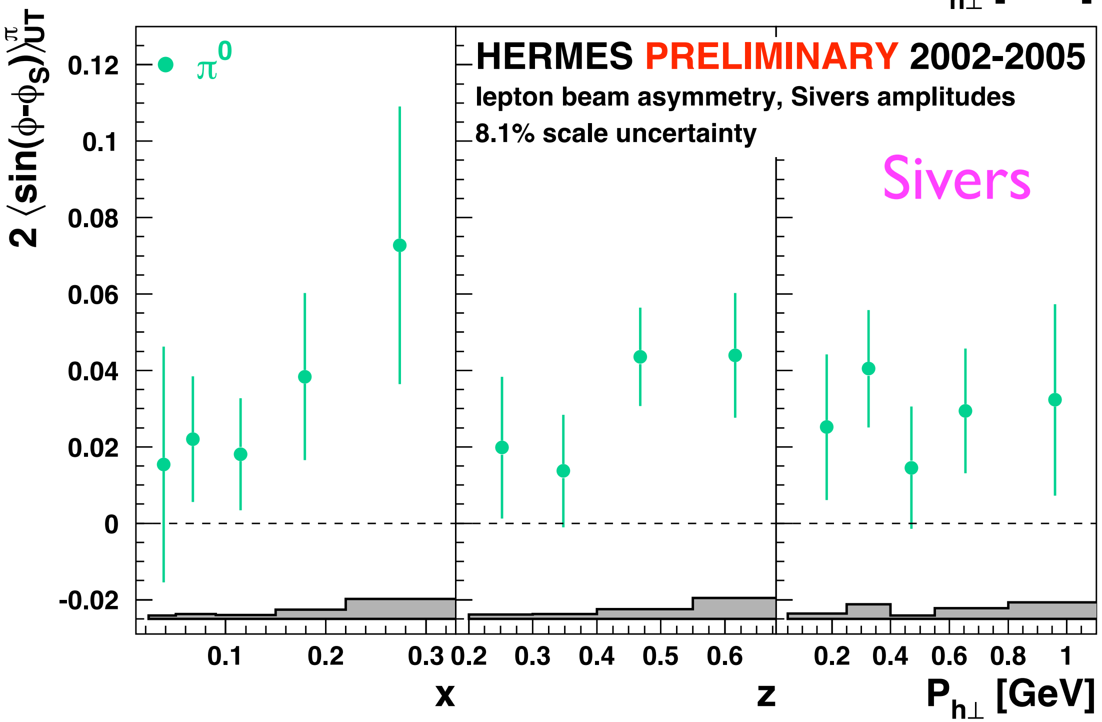
Comparing Sivers charged kaons with pions



- K^+ amplitude is now confirmed to be 2.3±0.3 times larger than for π^+, averaged over acceptance
- Conflicts with usual expectations based on u-quark dominance
- Suggests substantial magnitudes of the Sivers function for the sea quarks
- Both K^- and π^- amplitudes are consistent with zero

Neutral pions



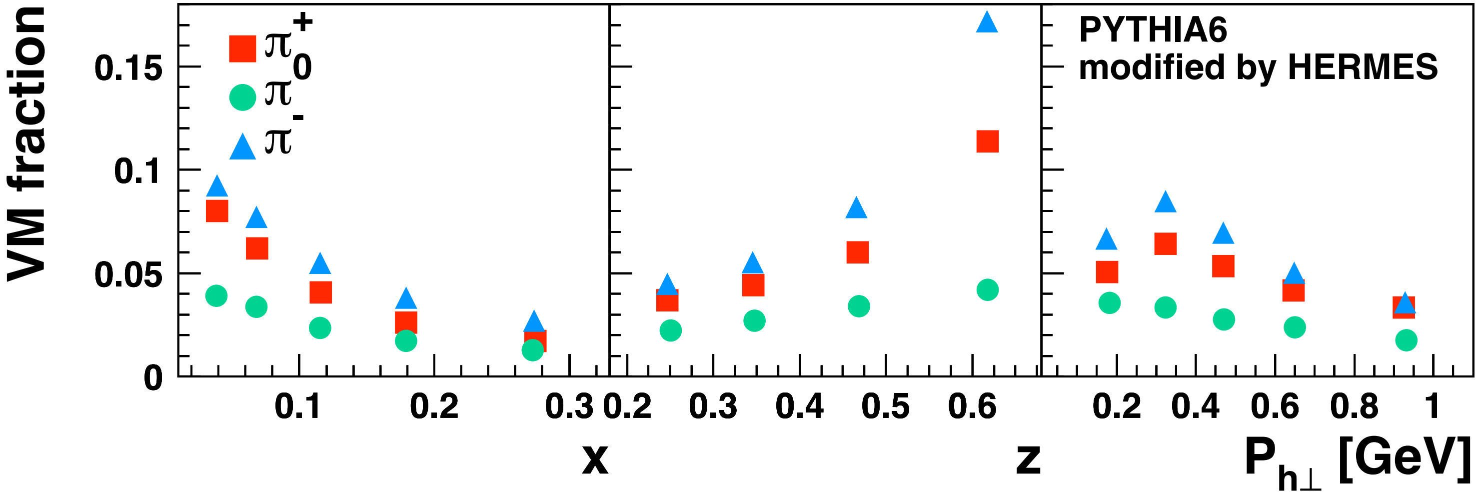


The results for the three pion charge states are consistent with isospin symmetry

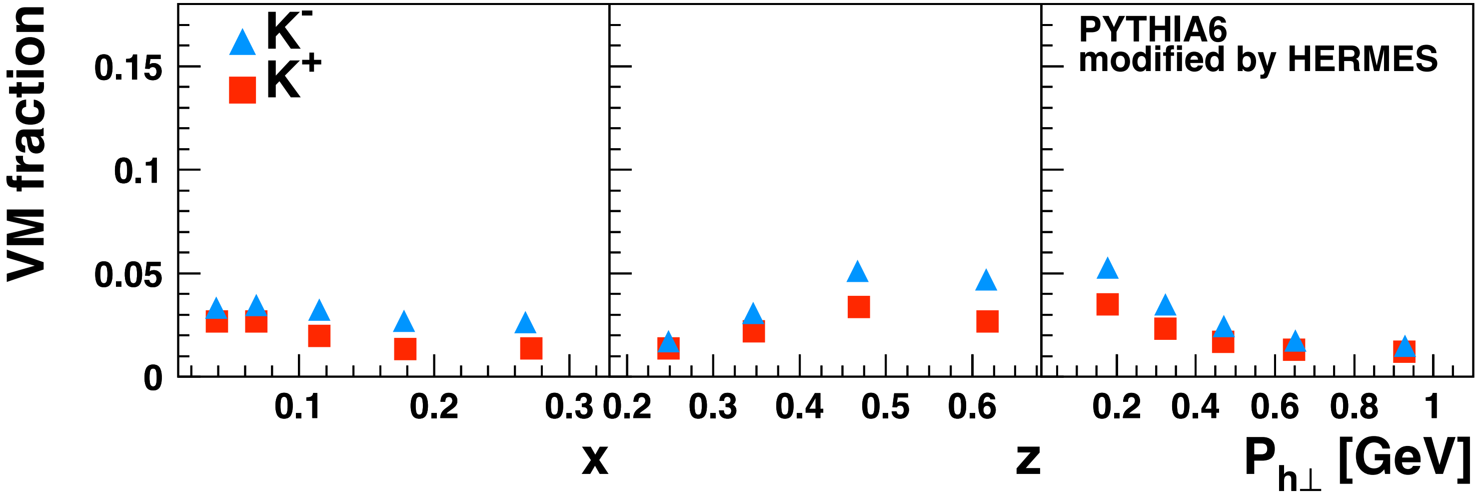
"Contamination" by decay of vector mesons

Fractional yield contributions from Pythia simulation:

for pions



for kaons



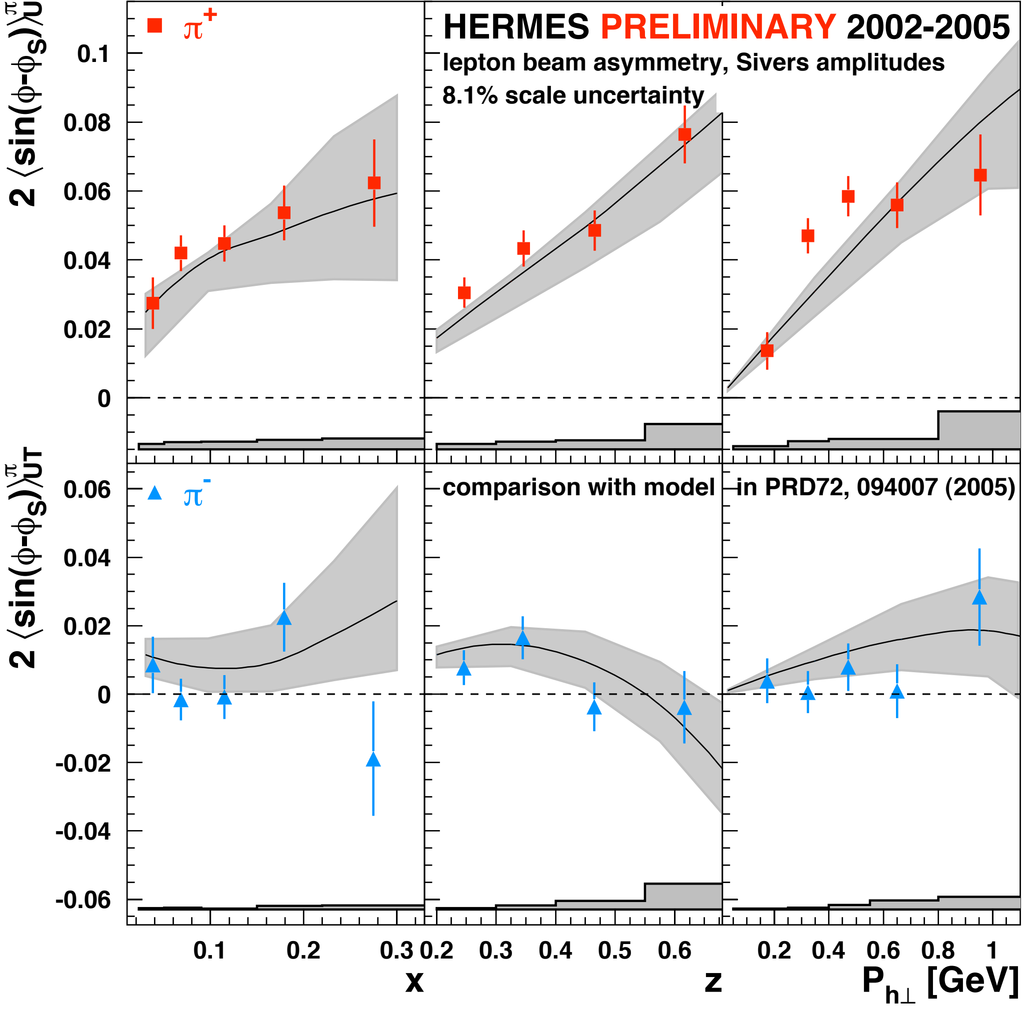
TTSA of VM prod$^{\underline{n}}$ and decay distribution not yet available for a correction

Sivers: a fit of Hermes, Compass pion data

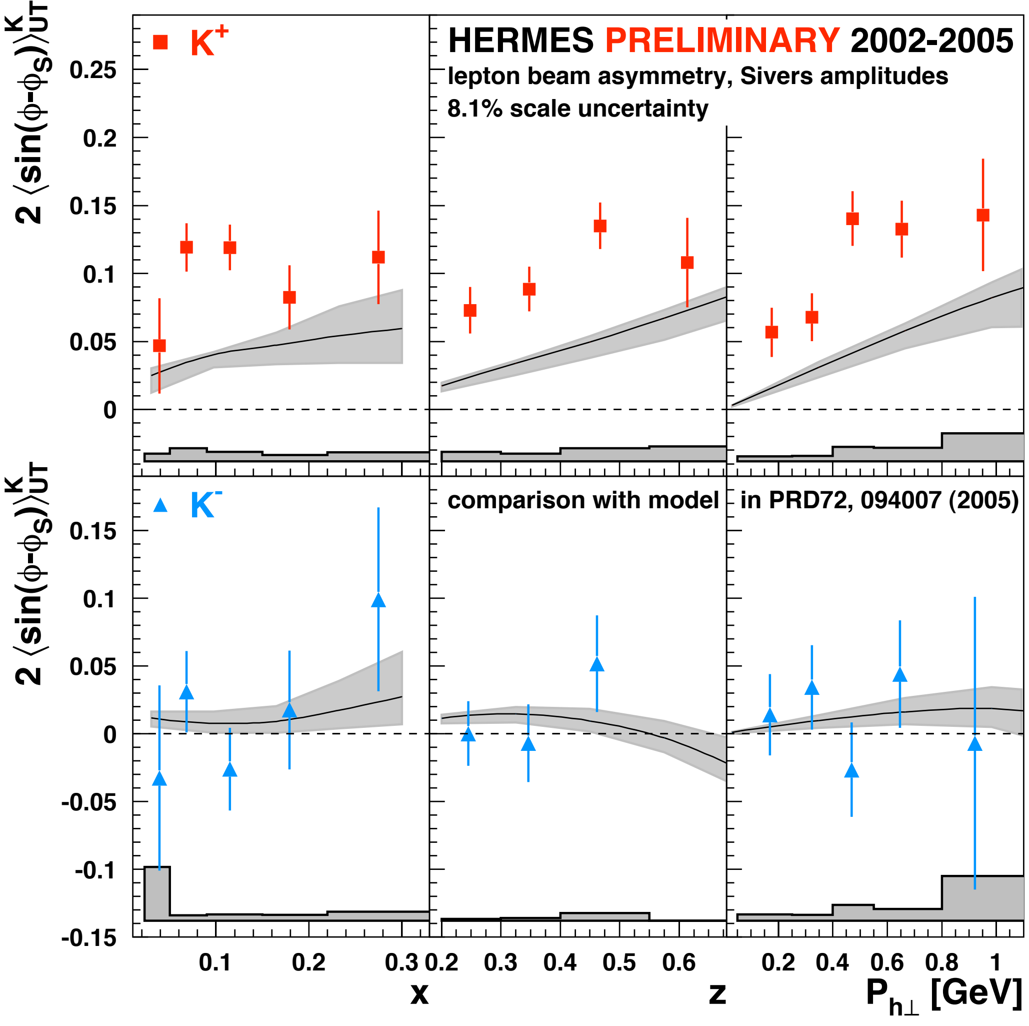
Anselmino et al., Phys. Rev. D72, 094007 using Kretzer fragmentation functions

Using Gaussian widths for intrinsic p_T, fragmentation k_T fitted to unpol. cosφ data

Pions don't constrain sea quarks



Predictions for kaons

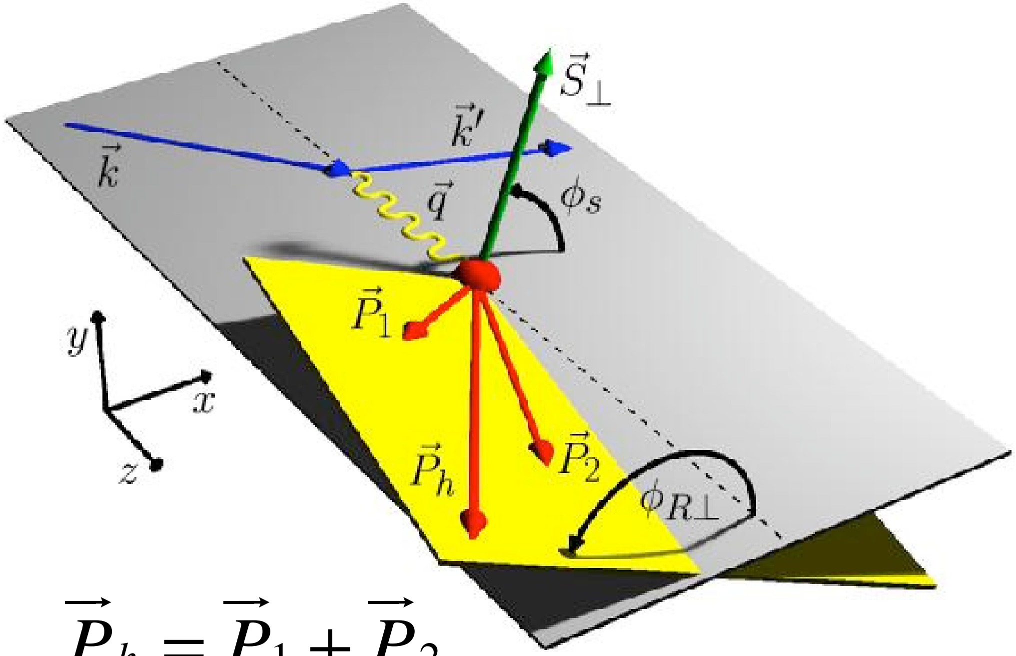


New kaon data suggest sea contributions may be significant

Alternative probe for Transversity: 2-hadrons

$$A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \qquad \propto |\mathbf{S}_{\perp}| \sin(\phi_{R\perp} + \phi_S) \frac{\sum_q e_q^2 \; h_1^q H_1^{\sphericalangle,sp}}{\sum_q e_q^2 \; f_1^q D_1^q}$$

$$H_1^{\sphericalangle,sp}(z, M_h^2) =$$ interference fragmentation between pion pair in s-wave and p-wave



$$\vec{P}_h = \vec{P}_1 + \vec{P}_2$$

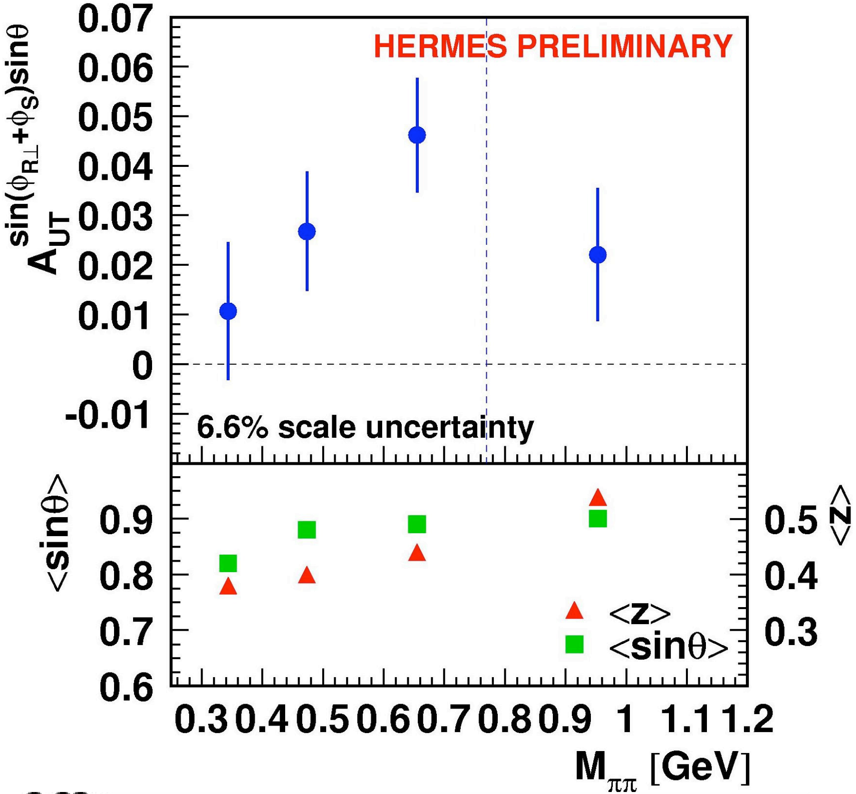
Advantages:

- direct product of transversity and fragmentation function (no convolution)
- easier to calculate Q^2 evolution

Disadvantages:

- less statistics
- cross section depends on 9 variables (sensitive to detector acceptance effects)

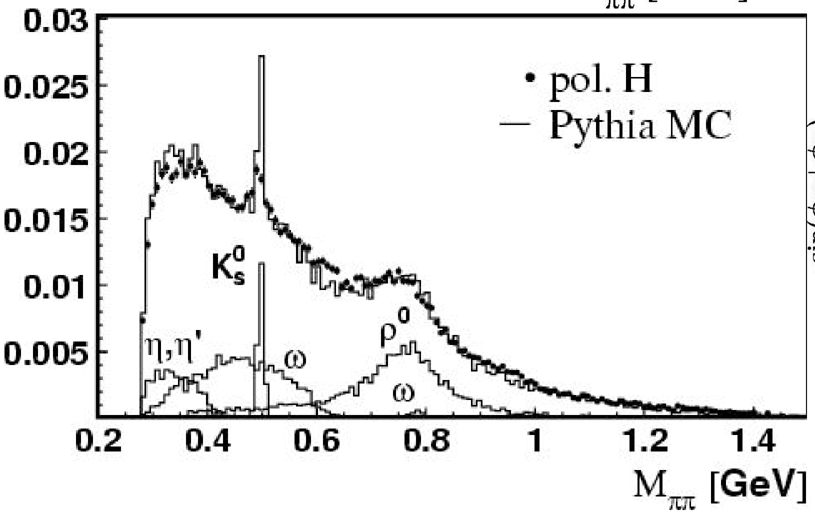
2-hadron asymmetries for 2002-2004



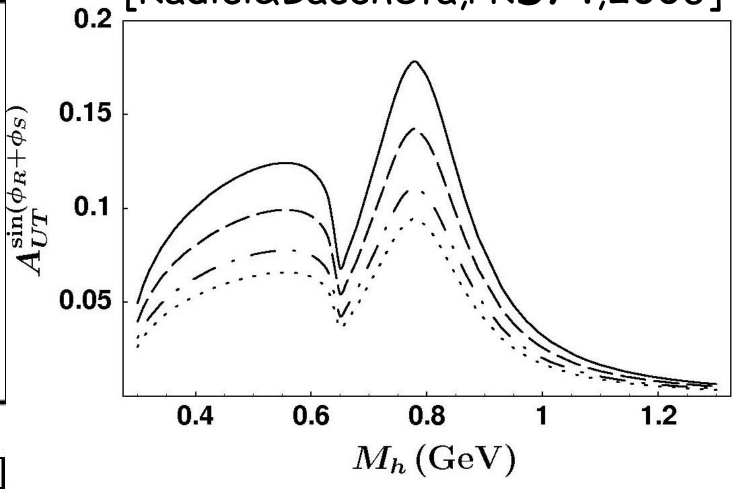
- significantly non-zero amplitudes (2002-2004):
  2-hadron fragmentation probes transversity!
- result disfavors model of Jaffe et al. for $H_1^{\sphericalangle,sp}$
- model of Bacchetta & Radici:
  - overestimates amplitudes
  - consistent with mass dependence
- MC studies: nonlinear mass dependence of amplitude

→ [0%,+44%] (rel.) systematic uncertainty (detector acceptance effect)

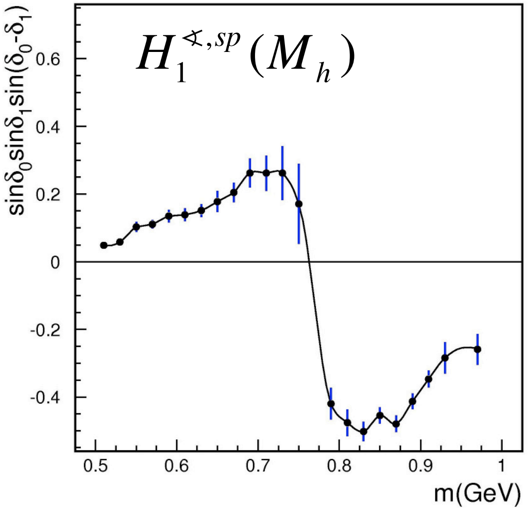
- BELLE intends to measure 2-hadron FF's



[Radici&Baccheta,PRD**74**,2006]



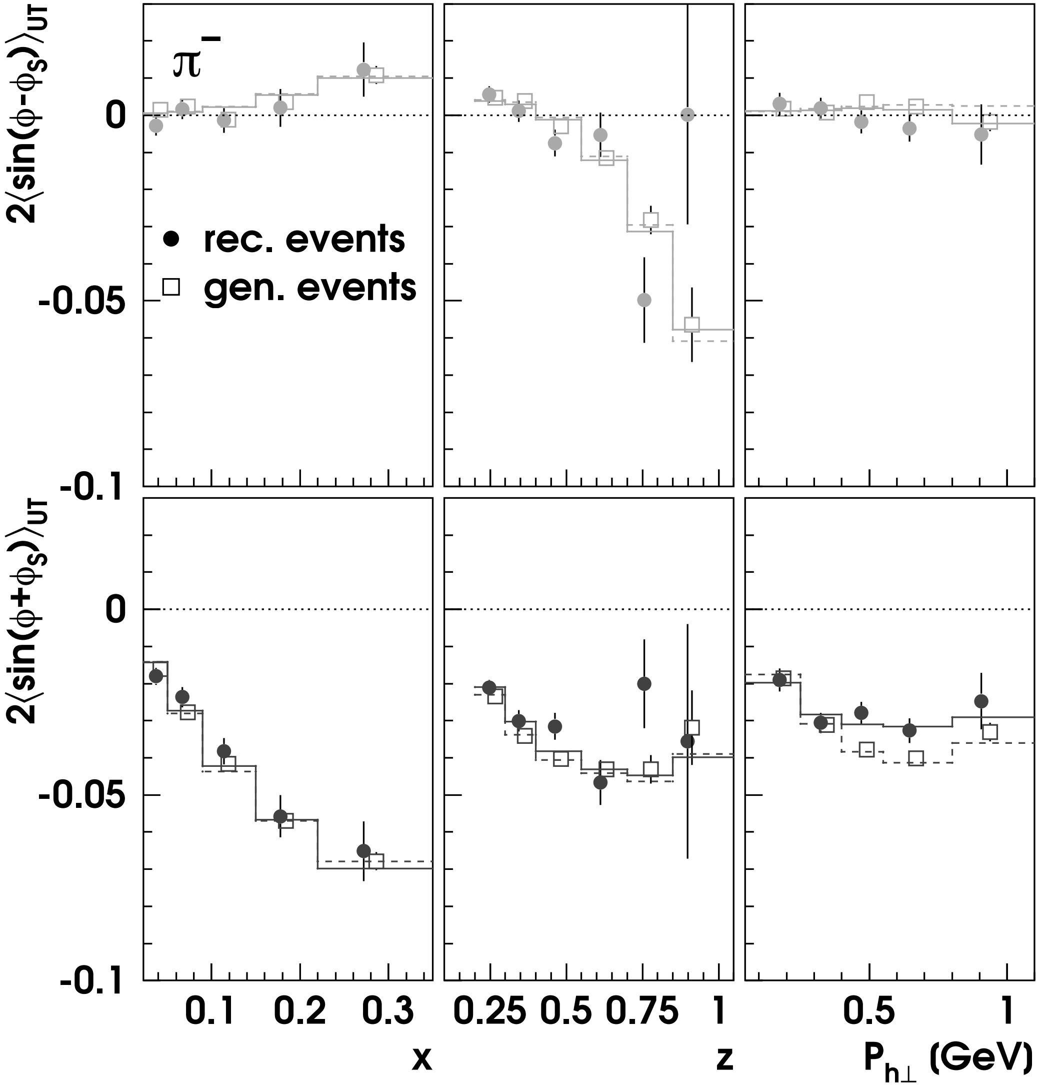
[Jaffe et al,PRL**80**,1998]



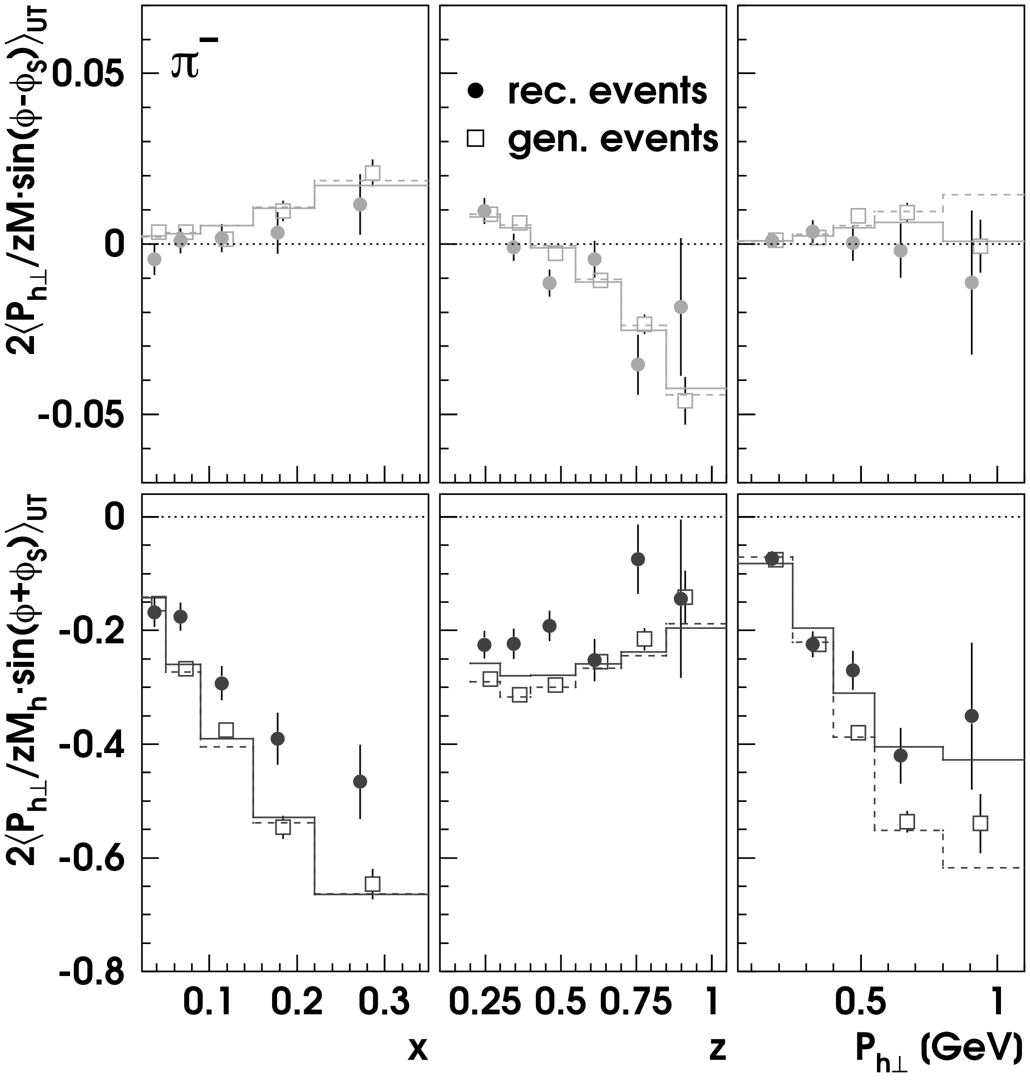
Why haven't we release P_T-weighted asymmetries?

MC Study of acceptance effects

Unweighted amplitudes



P_T-weighted amplitudes

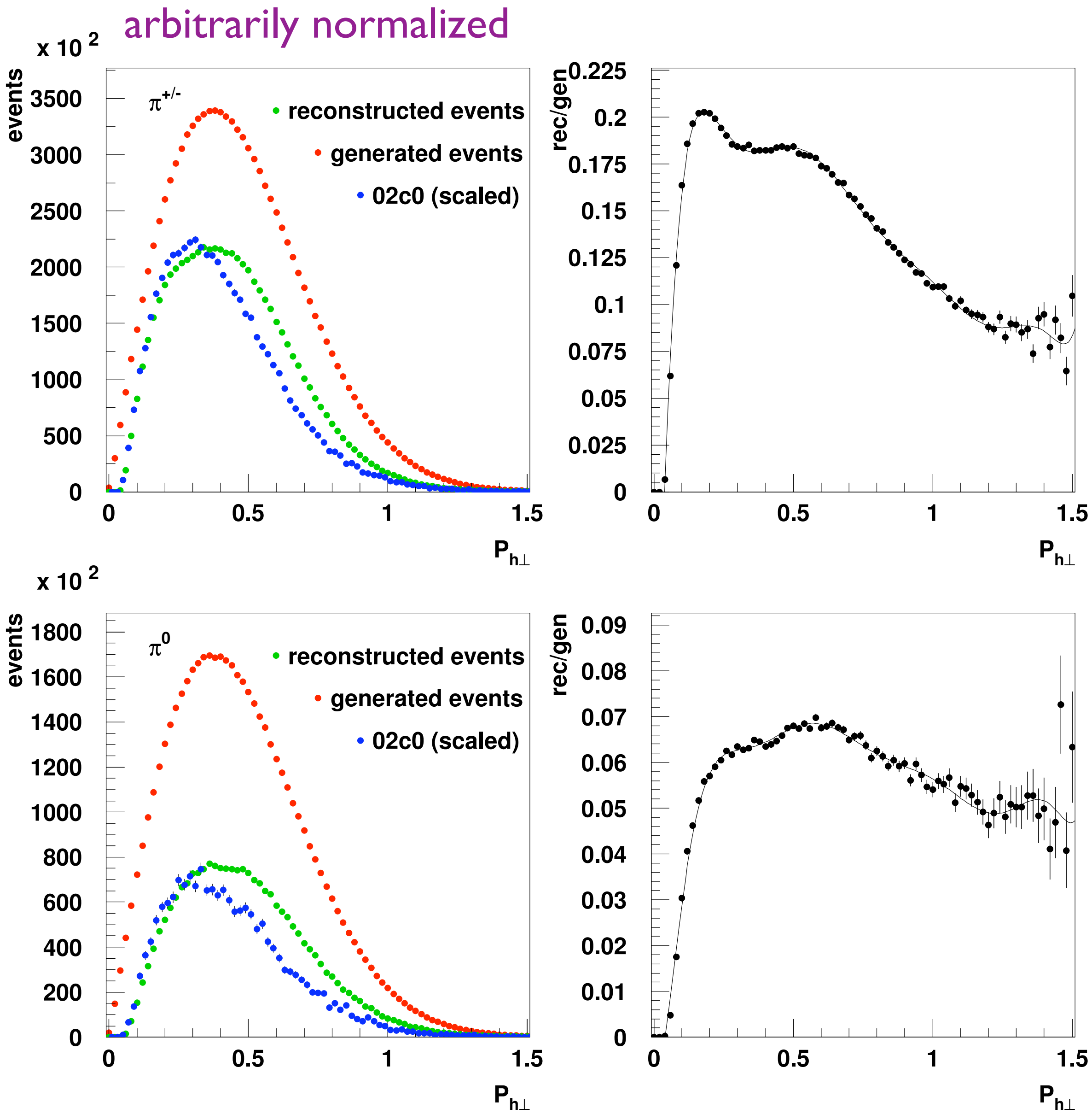


(Please ignore the curves.)

Thanks to Uli Elschenbroich!

MC: Acceptance Depends strongly on P_T

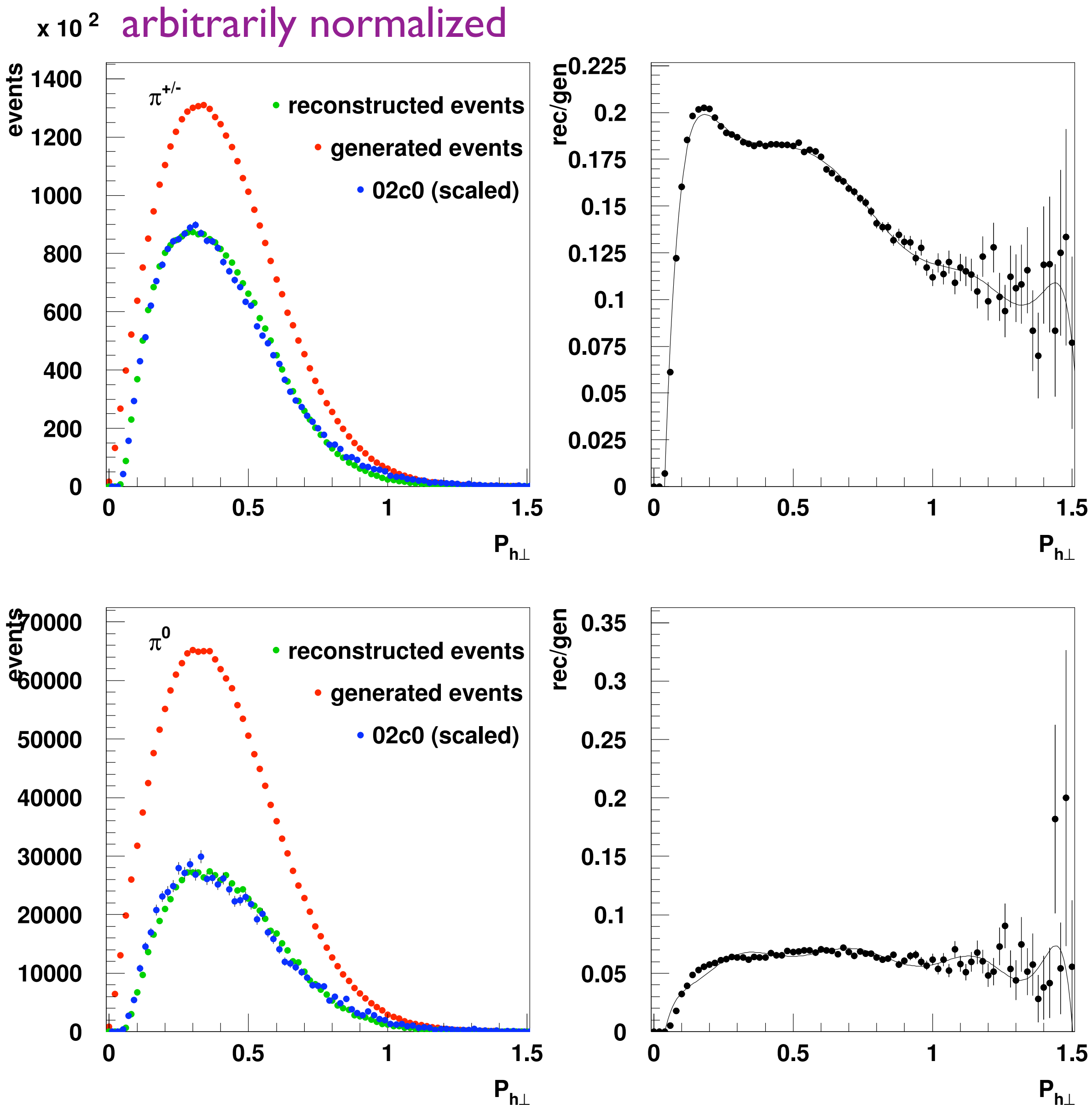
$P_{h\perp}$ Distribution



- also reconstructed events scaled
- $\langle p_T \rangle$ = 0.44 and $\langle K_T \rangle$ = 0.44 constant

MC: Acceptance Depends strongly on P_T

$P_{h\perp}$ Distribution



- also reconstructed events scaled
- $\langle p_T \rangle$ = 0.38 and $\langle K_T \rangle$ = 0.38 constant

Solutions under study

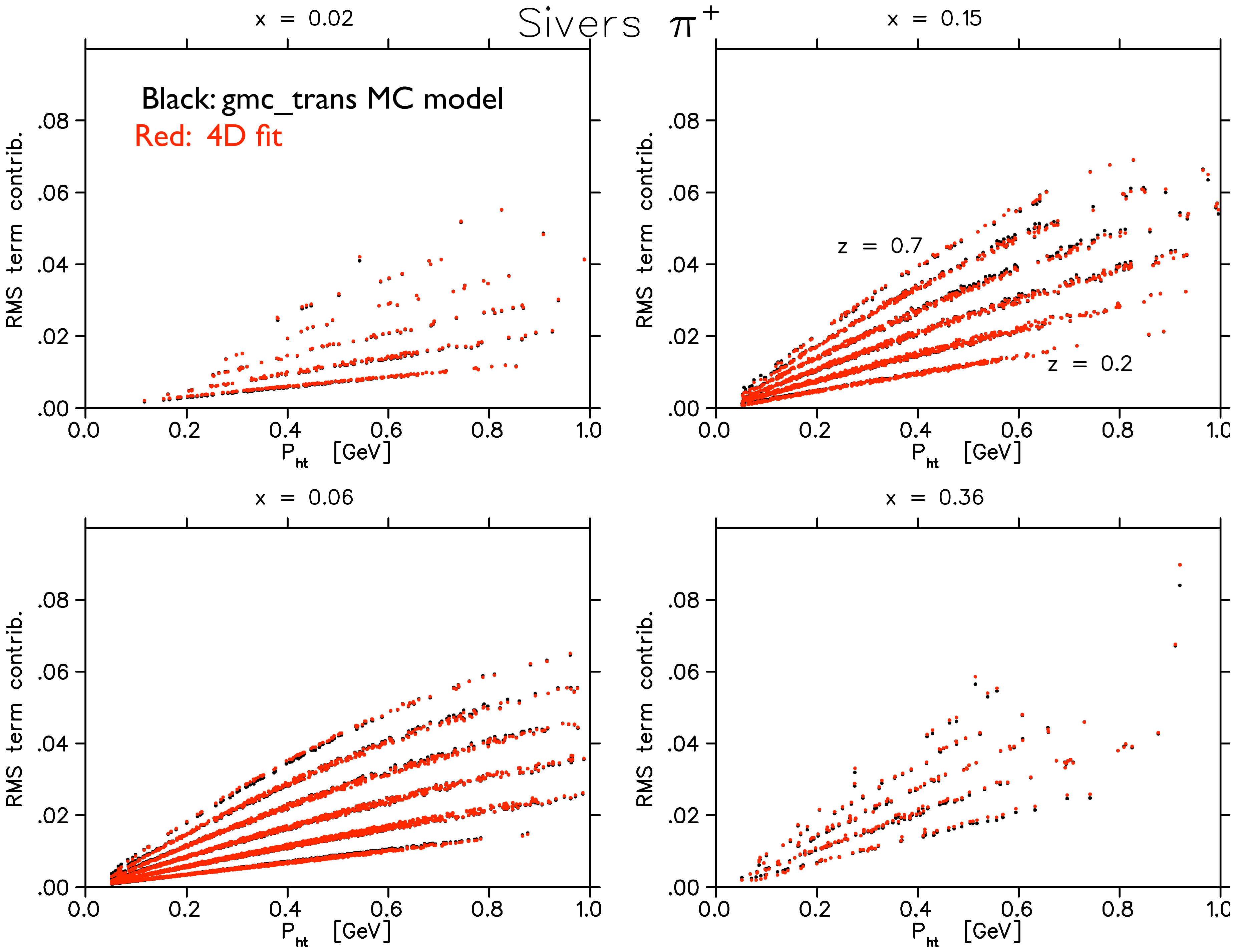
- Multi-dimensional unfolding based on a Monte Carlo smearing matrix
  ⇨ might work in 5D for the Boer-Mulders function, not 6D for TTSAs
  - Has the advantage that radiative effects are included
- Fit the multi-dimensional kinematic dependence of the azimuthal amplitudes

  ⇨ Quantify ignorance of full kinematic dependence, propagate to result

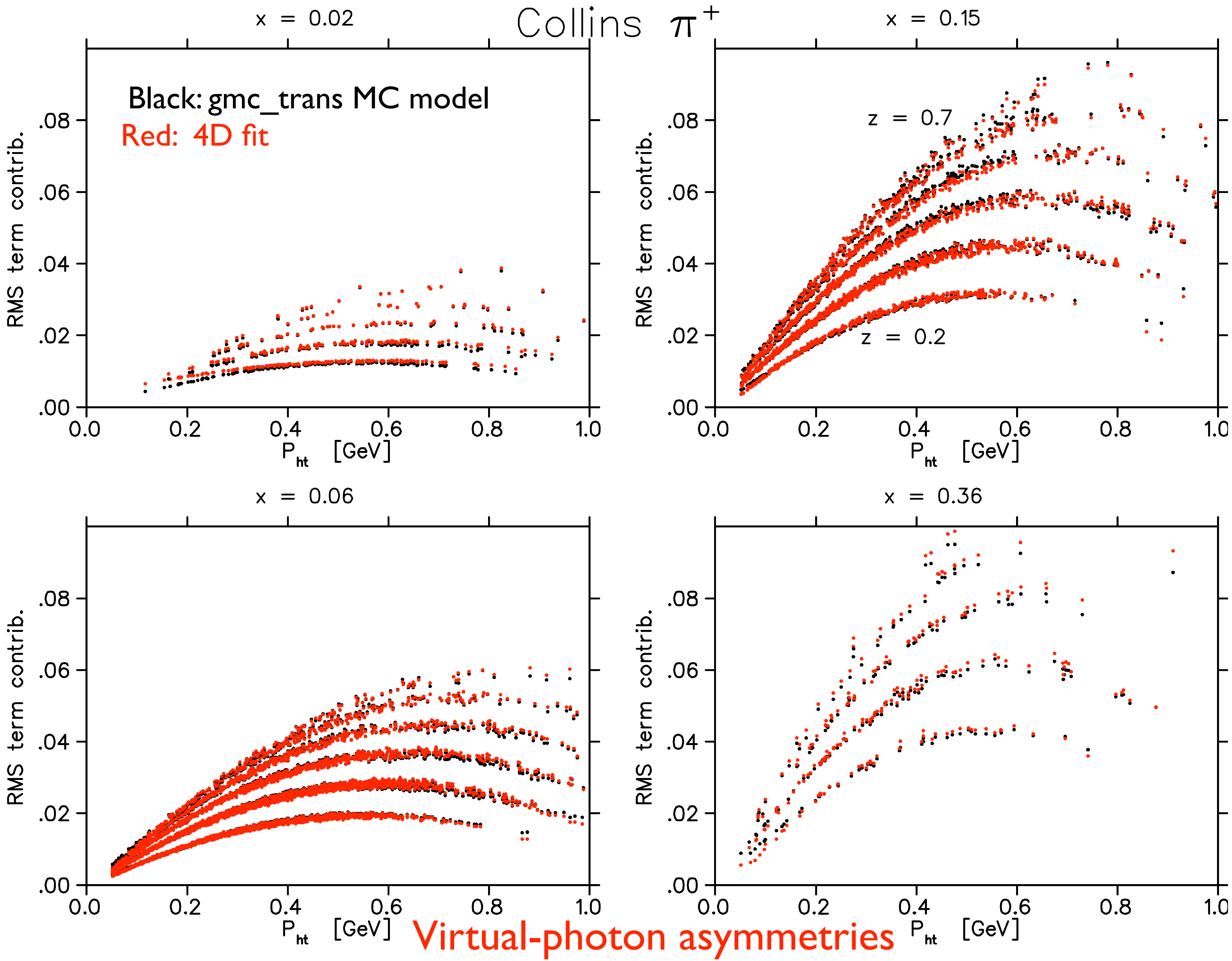
  ⇨ fit the full kinematic dependence on (x,y,z,P_t) using some set of 4D orthogonal functions, then fold result with known $\sigma_{UU}(x,y,z,P_t)$

  ⇨ This has been shown to work while analyzing MC data, but...
  - Problem: What to use for $\sigma_{UU}(x,y,z,P_t)$?
    ⇨ Measured multiplicities? They don't contain, e.g. , z-P_T correlations
    ⇨ Monte Carlo tuned to data?

44-parameter 4D fit to fully differential MC model



44-parameter 4D fit to fully differential MC model



Virtual-photon asymmetries

Analyses underway or under consideration

- 2005 data for 2-hadron asymmetries
- P_t-weighted Collins and Sivers asymmetries
    - Requires many-parameter kinematic fit plus model for $\underline{\sigma}_{UU}$
- The Boer-Mulders function via $\langle\cos(2\phi)\rangle$
    - Requires 5D unfolding
- $\langle\cos(\phi-\phi_S)\rangle_{LT}$ providing access to twist-2 function $g_{1T}{}^{\perp}$
- Inclusive pion photoproduction A_{UT} ("E704 Effect")

Express your preferences...

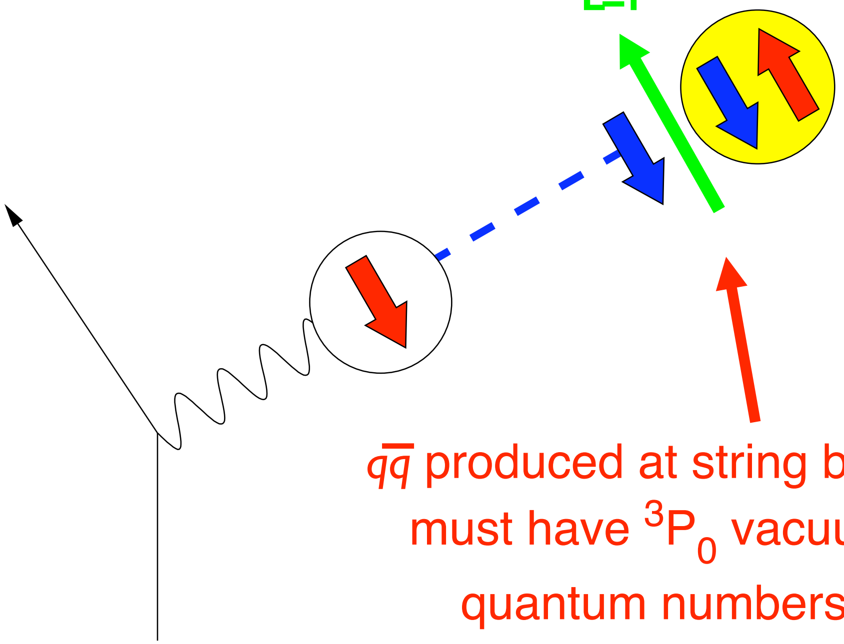
Summary

- The precision of these data for identified hadrons is now adequate for the quantitative extraction of the flavour dependence of both Transversity and the Sivers function
- There is evidence for substantial magnitudes of the Sivers function for sea quarks

Special thanks to the prime movers for this analysis:
Ulrike Elschenbroich
Markus Diefenthaler
Luciano Pappalardo
Gunar Schnell
Paul van der Nat

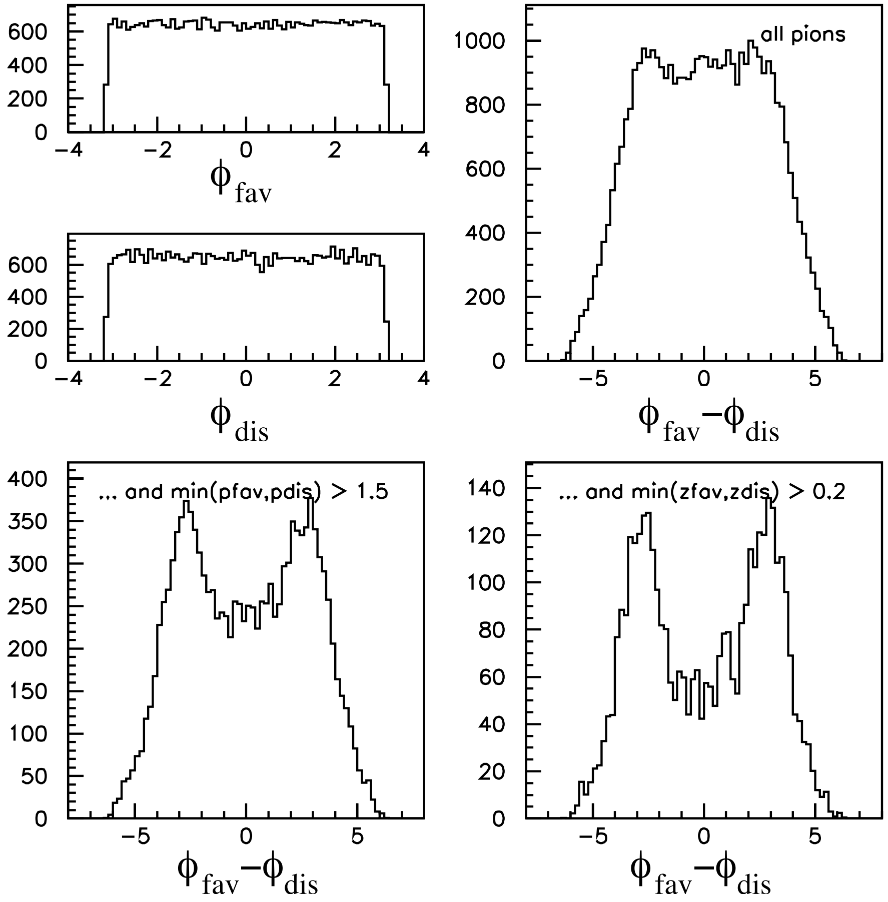
Quark polarimetry with the Collins effect

String fragmentation model



$q\bar{q}$ produced at string break
must have $^3P_0$ vacuum
quantum numbers

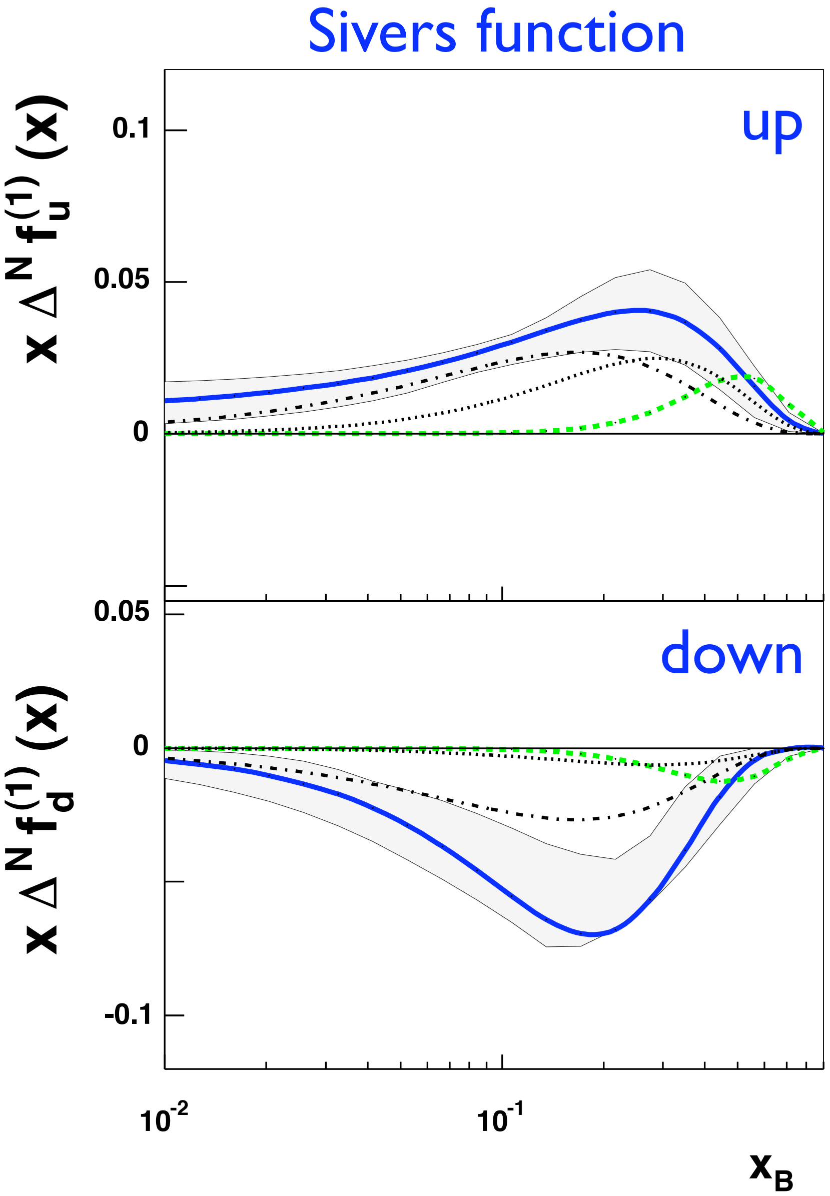
JETSET simulation



Transverse momentum conservation ⇒ any correlation of favoured pion $P_{\pi\perp}$ with any spin will be opposite for disfavoured pions

Sivers: a fit of Hermes, Compass pion SSA data

Anselmino et al., Phys. Rev. D72, 094007



- Their result for d-quarks at least as large in magnitude as for u-quarks
- Dot-dashed: fit to Hermes data under large-Nc limit constraint $f_{1T}^{\perp u} = -f_{1T}^{\perp d}$

  Efremov et al., Phys. Lett. B612, 233, 2005
- Green-dashed: fit to inclusive pion SSA's

  D'Alesio et al., Phys. Rev. D70, 074009, 2004
- Dotted: MIT Bag Model

  Feng Yuan, Phys. Lett. B575, 45, 2003