Istituto Nazionale di Fisica Nucleare

Experimental overview of transversity

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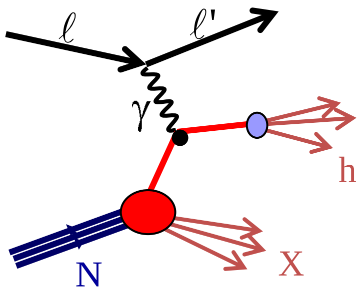
INFN Sezione di Trieste

IWHSS'12

International Workshop on Hadron Structure and Spectroscopy

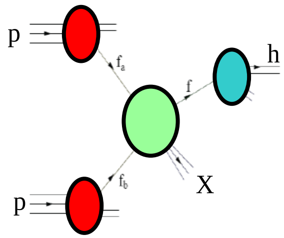
Lisbon, 16 - 18 April 2012

Study of transverse momentum dependent PDF



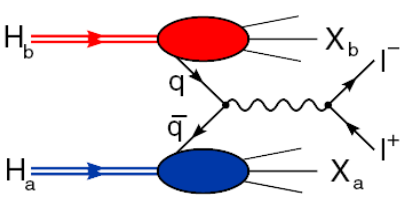
SIDIS off polarised targets

DESY (HERMES)
CERN (COMPASS)
JLab
future: ***eRHIC, EIC, ENC***



hard polarised pp scattering

RHIC / BNL



and projects for (polarised) Drell-Yan:

CERN (COMPASS)**,FNAL, JParc, RHIC, JINR, IHEP, GSI**

Accessing the transversity PDF

Transversity can be measured in SIDIS on a transversely polarised target via "quark polarimetry" :

$l\,N^{\uparrow} \rightarrow l'\,h\,X$ Collins asymmetry

$l\,N^{\uparrow} \rightarrow l'\,hh\,X$ Two hadron asymmetry

$l\,N^{\uparrow} \rightarrow l'\,\Lambda\,X$ Λ polarization

Accessing the transversity PDF

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$l\,N^{\uparrow} \rightarrow l'\,h\,X$	Collins asymmetry	Collins FF
$l\,N^{\uparrow} \rightarrow l'\,hh\,X$	Two hadron asymmetry	di-hadron FF
$l\,N^{\uparrow} \rightarrow l'\,\Lambda\,X$	Λ polarization	FF of $q^{\uparrow} \rightarrow \Lambda$

In all these processes, transversity appears together with an unknown fragmentation function

Accessing the transversity PDF

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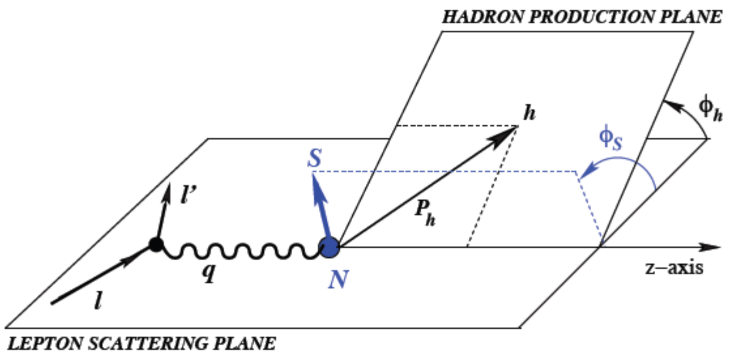
In all these processes, transversity appears together with an unknown fragmentation function

These FF can be detected in inclusive hadron production in e^+e^- annihilation.
→ special role of electron positron collider in the extraction of transversity

Accessing the transversity PDF: Collins mechanism

$l\, N^{\uparrow} \rightarrow l'\, h\, X$

amplitude of the $\sin(\phi_h + \phi_S - \pi)$ modulation in the azimuthal distribution of the final state hadrons



$$\mathbf{N}^{\pm}(\Phi_C) = N^0 \cdot (1 \pm A \sin \Phi_C)$$

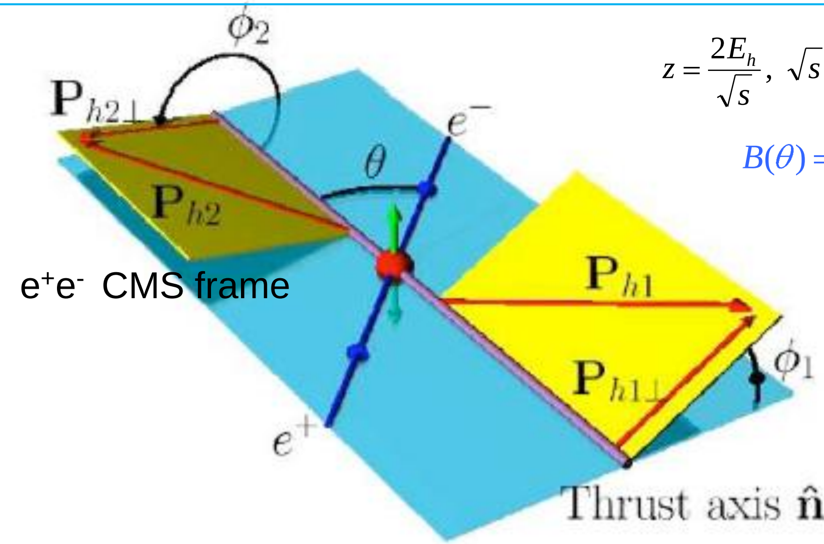
Transversity × Collins FF

$$\mathbf{A_{Coll}} = \frac{\mathbf{A}}{\mathbf{fP_T}} = \frac{\sum_q e_q^2 \Delta_T q H_1^{\perp q}}{\sum_q e_q^2 q D_1^q}$$

$e^+e^- \rightarrow h_1\, h_2\, X$

Quark spin direction unknown: measurement of Collins FF in one hemisphere is not possible

→ Measurement of azimuthal correlations for pion pairs around the jet axis in two-jet events; amplitude of $\cos(\phi_1 + \phi_2)$ modulation



$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52\ \text{GeV}$$

$$B(\theta) = \frac{\sin^2(\theta)}{1+\cos^2(\theta)}$$

Collins FF × Collins FF

$$\mathbf{A} \propto B(\theta) \frac{\sum_q e_q^2 H_1^{\perp q}(z_1) \cdot \overline{H}_1^{\perp q}(z_2)}{\sum_q e_q^2 D_1^q(z_1) \cdot \overline{D}_1^q(z_2)}$$

Accessing the transversity PDF: two hadron mechanism

$l N^{\uparrow} \rightarrow l' hh X$

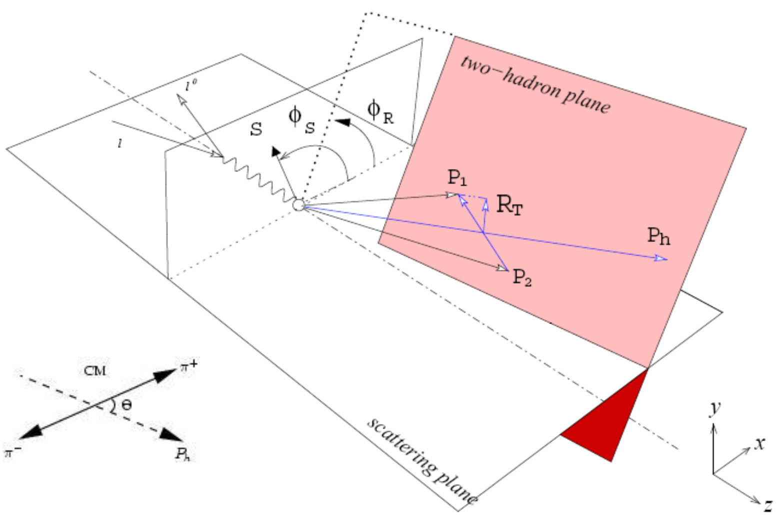
azimuthal asymmetry in the angle $\phi_{RS} = \phi_{R\perp} - \phi_{S}$,

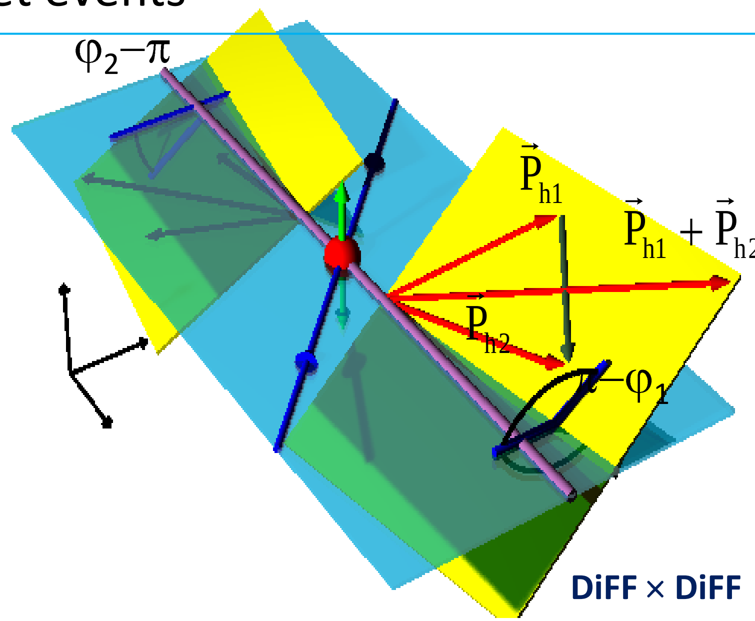
in which $\phi_{R\perp}$ is the angle of the plane defined by the two hadrons

$e^+e^- \rightarrow (h_1\ h_2)_{jet1}\ (h_1\ h_2)_{jet2}\ X$

quark spin direction unknown: measurement of di-hadron FF in one hemisphere is not possible

→Measurement of azimuthal correlations for di-pion pairs around the jet axis in two-jet events





Transversity × DiFF

$$A_{RS} = \frac{A}{fP_T} \propto \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{2h}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^{2h}(z, M_h^2)}$$

DiFF × DiFF

$$A \propto B(\theta) \frac{\sum_q e_q^2\, H_1^{2h}(z_1, m_1) \cdot \overline{H}_1^{2h}(z_2, m_2)}{\sum_q e_q^2\, D_1^{2h}(z_1, m_1) \cdot \overline{D}_1^{2h}(z_2, m_2)}$$

Experiments

From the experimental point of view…

SIDIS

Tools needed for the measurement:
- polarized targets
- large acceptance spectrometer with full particle identification : identification of scattered lepton and produced hadrons
- good coverage in azimuthal angle acceptance

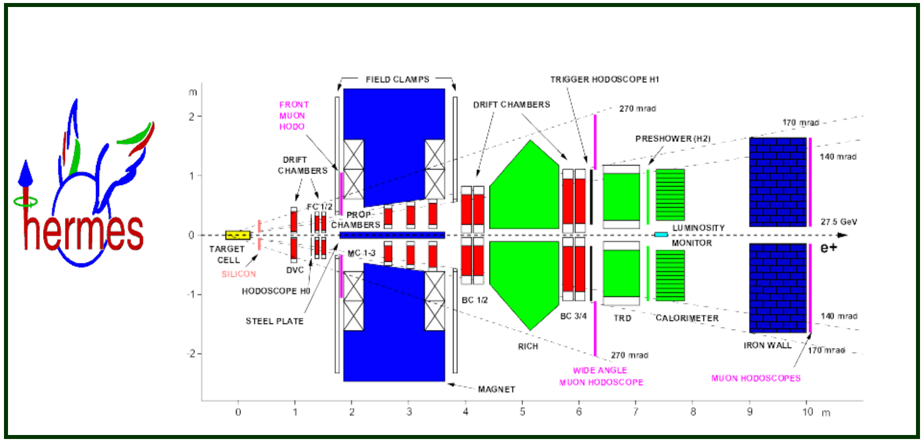
For a global interpretation of the measurements:
-different target materials
-cover large kinematical ranges
-measure on different hadrons

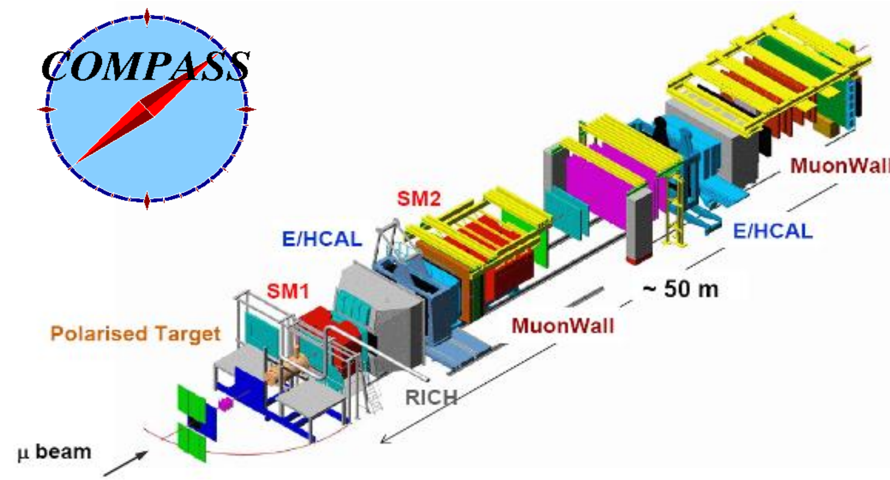
→ complementarity between different experiments is important

e^+e^- annihilation

- large data sample available → suitable to measure small asymmetries
- good particle ID (light quarks)
- good coverage in azimuthal angle acceptance

The SIDIS experiments





polarized (<60%) e^+/e^- beam of 27 GeV, both helicity states

Gaseous target, direct access to hydrogen/deuterium → dilution factor~1

Transverse measurement: p (long. p,d)

P_T~ 70-85%

fast spin-flip of target → same acceptance for the different polarization states

polarized (-80%) μ^+ of 160 GeV

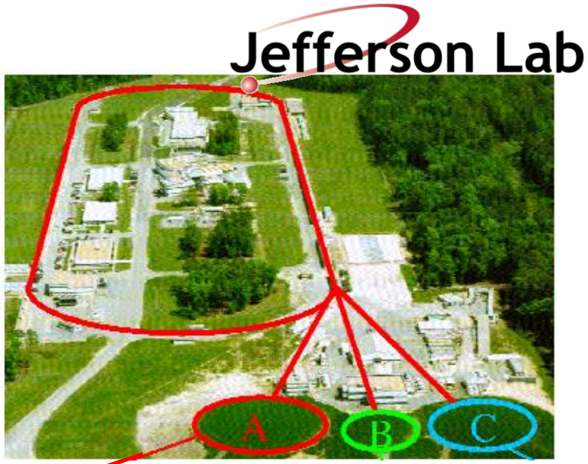
Solid state target, 120 cm long

^{6}LiD (d) P_T ~ 50% ; f ~ 0.40 both L and T

NH_3 (p) P_T ~ 80% ; f ~ 0.15 both L and T

nearby cells are oppositely polarised to take data simultaneously on the two orientations of the target→ Spin reversal in order of the hours/days

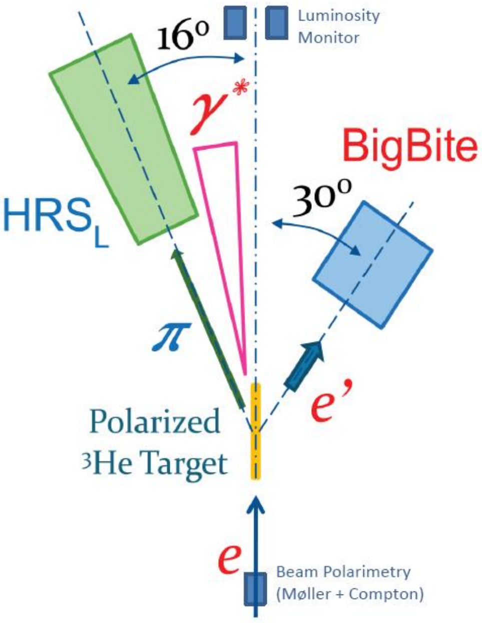
The SIDIS experiments



JLab E06-010

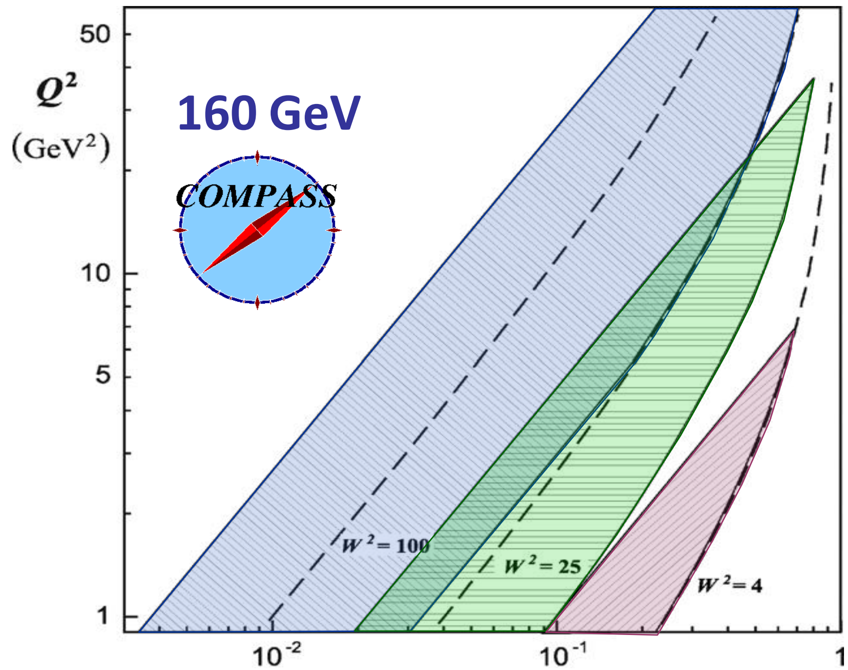
e- beam at ~6 GeV/c
40cm 3He gas target
transversely polarised,
different orientations possible

P_T~55% (n) f ~ 0.1-0.3
Spin flip every 20 minutes



Phase space of different experiments

Strong dependence of x, Q^2 and W, depending on the lepton beam energy.



hermes

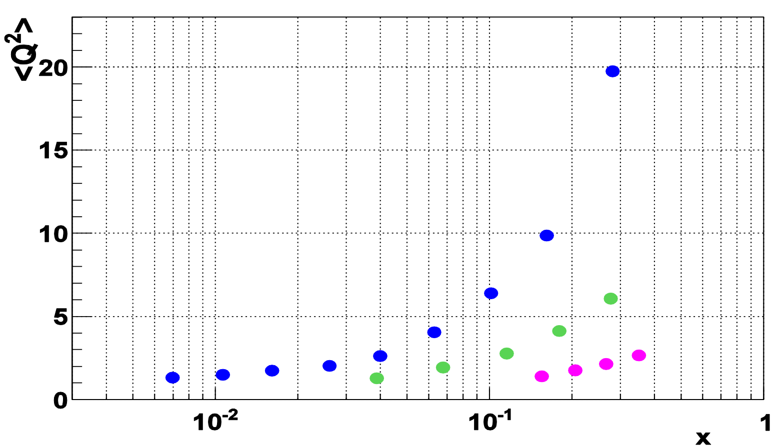
27.5 GeV

JLab 6 GeV

$0.004 < x < 0.3$, $25<W^2<200 GeV^2$

$0.023 < x < 0.4$, $10<W^2<50$

$0.14 < x < 0.48$, $4<W^2<10$



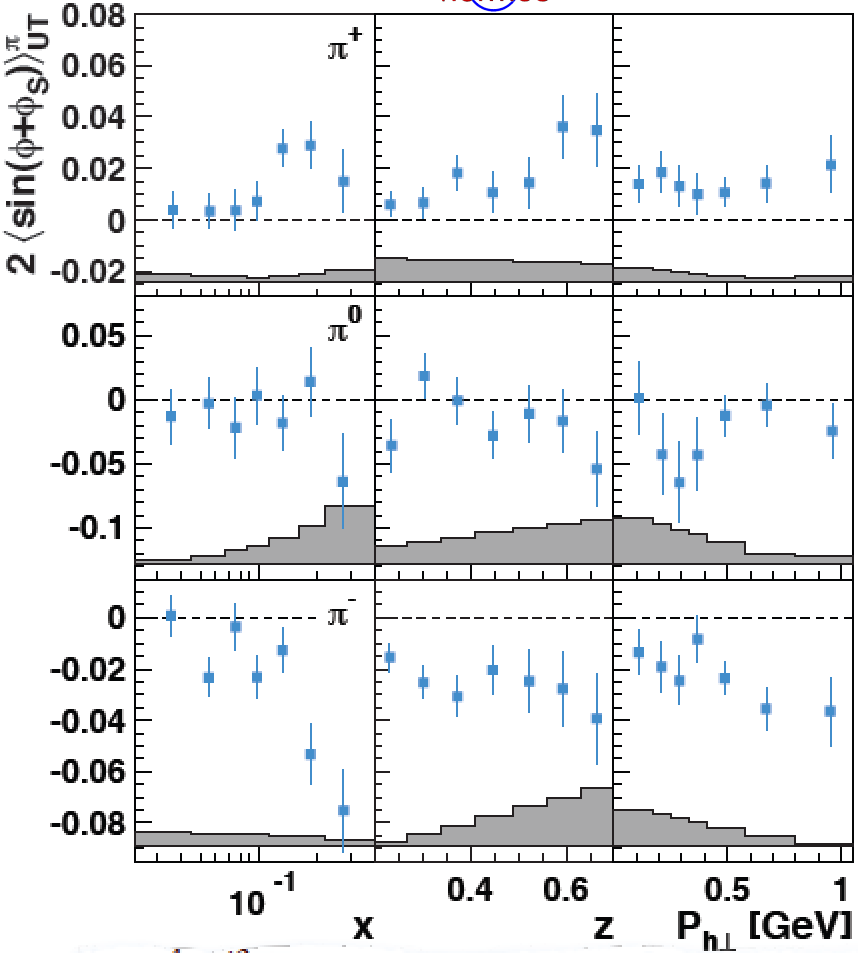
Phase space determined also by cuts

- $Q^2 > 1 (GeV/c)^2$
- y ($0.1<y<0.9/0.95$)
- low W to avoid resonance regions
- cut on momenta imposed by PID
- relative energy z of each hadron:
    - lower cut to avoid fragmentation region, usually z>0.1-0.2 (*depending on W)*
    - higher cut (z< 0.7, 0.85)

Results

Collins asymmetries, results on proton

PLB 693 (2010) 11



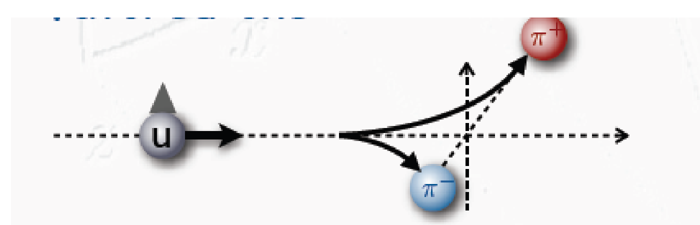
2005: First evidence that transversity PDF and Collins FF are different from zero

- Increase signal with x, valence region
- Increase also with z (agreement with Belle)
- clear signal for π^+ and π^- x>0.1

$$A_{\rm Coll}^{p,\pi^+} \sim e_u^2 h_1^u H_1^{\perp,{\rm fav}} + e_d^2 h_1^d H_1^{\perp,{\rm unf}}$$

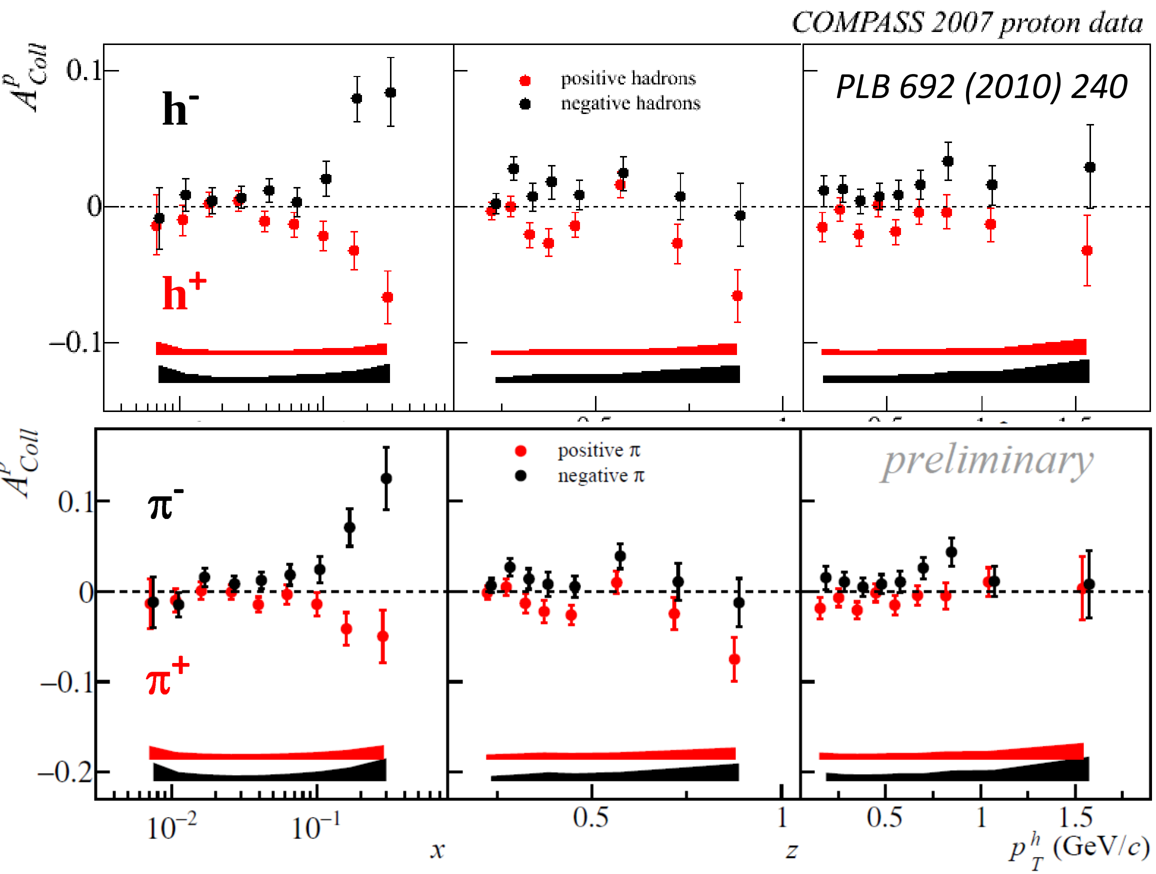
$$A_{\rm Coll}^{p,\pi^-} \sim e_u^2 h_1^u H_1^{\perp,{\rm unf}} + e_d^2 h_1^d H_1^{\perp,{\rm fav}}$$

→ $H_1^{unf} \sim -H_1^{fav}$



As predicted in recursive fragmentation model with quark spin [X.Artru, arXiv:1001.1061]

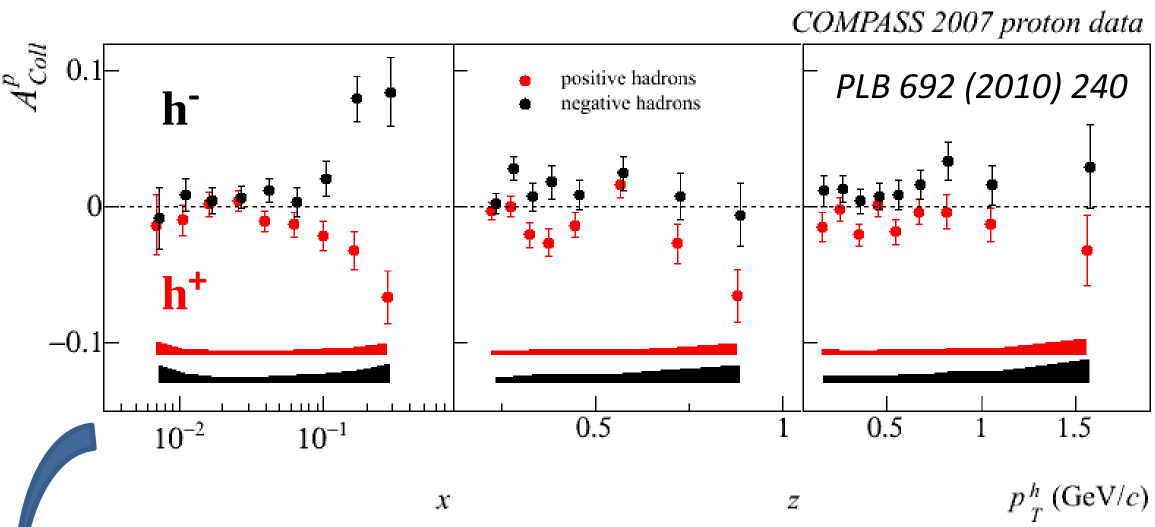
Collins asymmetries, results on proton



COMPASS results from 2007 proton run

- at small x, region not covered by HERMES asymmetries compatible with zero
- Strong signal in the valence region of opposite sign for π+ and π- agreement with HERMES

Collins asymmetries, results on proton



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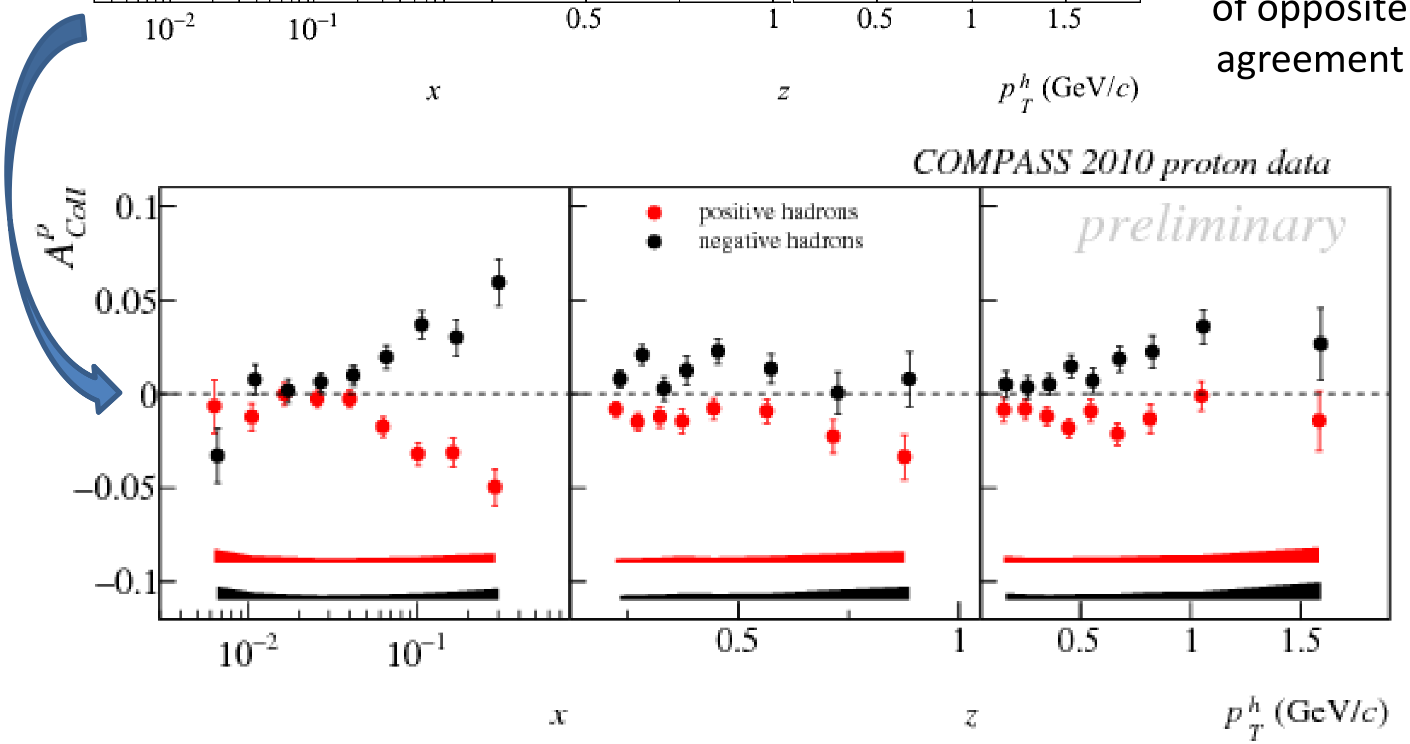
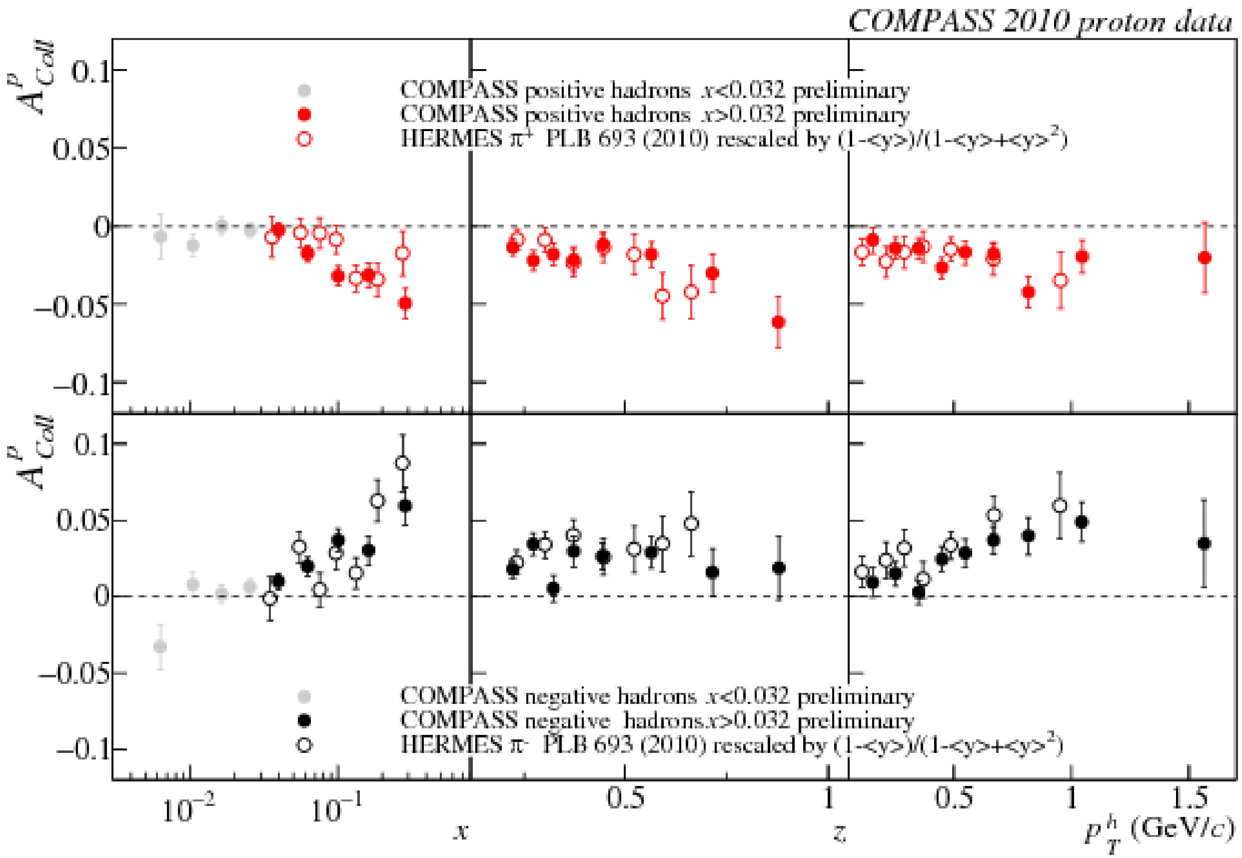


Recent result from the 2010 run, independent measurement: confirm the 2007 results with higher precision (factor ~2)

Collins asymmetries, results on proton

- Comparison between HERMES and COMPASS, taking into account the different conventions (sign, D_{nn})
- and limiting COMPASS range to the x>0.032 region, overlap with HERMES



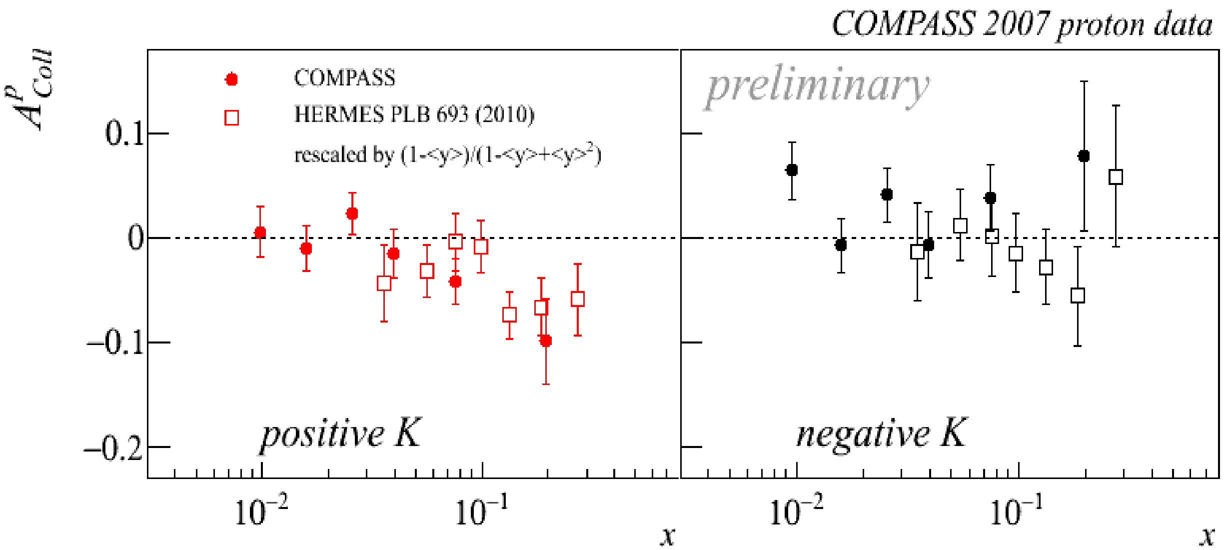
Good agreement :

- Non trivial result:

Q^2 COMPASS larger of HERMES's of a factor 2-3 in the last x bins

→weak Q^2 dependence of the Collins effect

Collins kaon asymmetries, results on proton

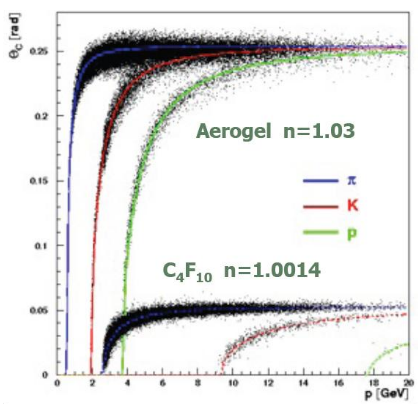


Results in agreement

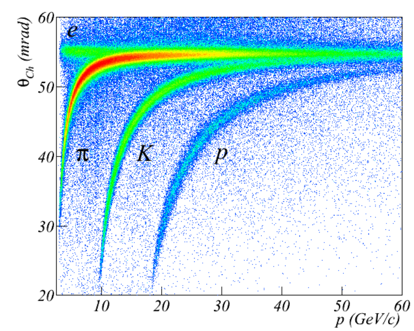
- K^- consistent with zero
- K^+ are similar to π^+, expected from u-dominance;

- K^+ signal slightly larger than π^+: role of sea quarks?

More precise K results from 2010 COMPASS data soon available



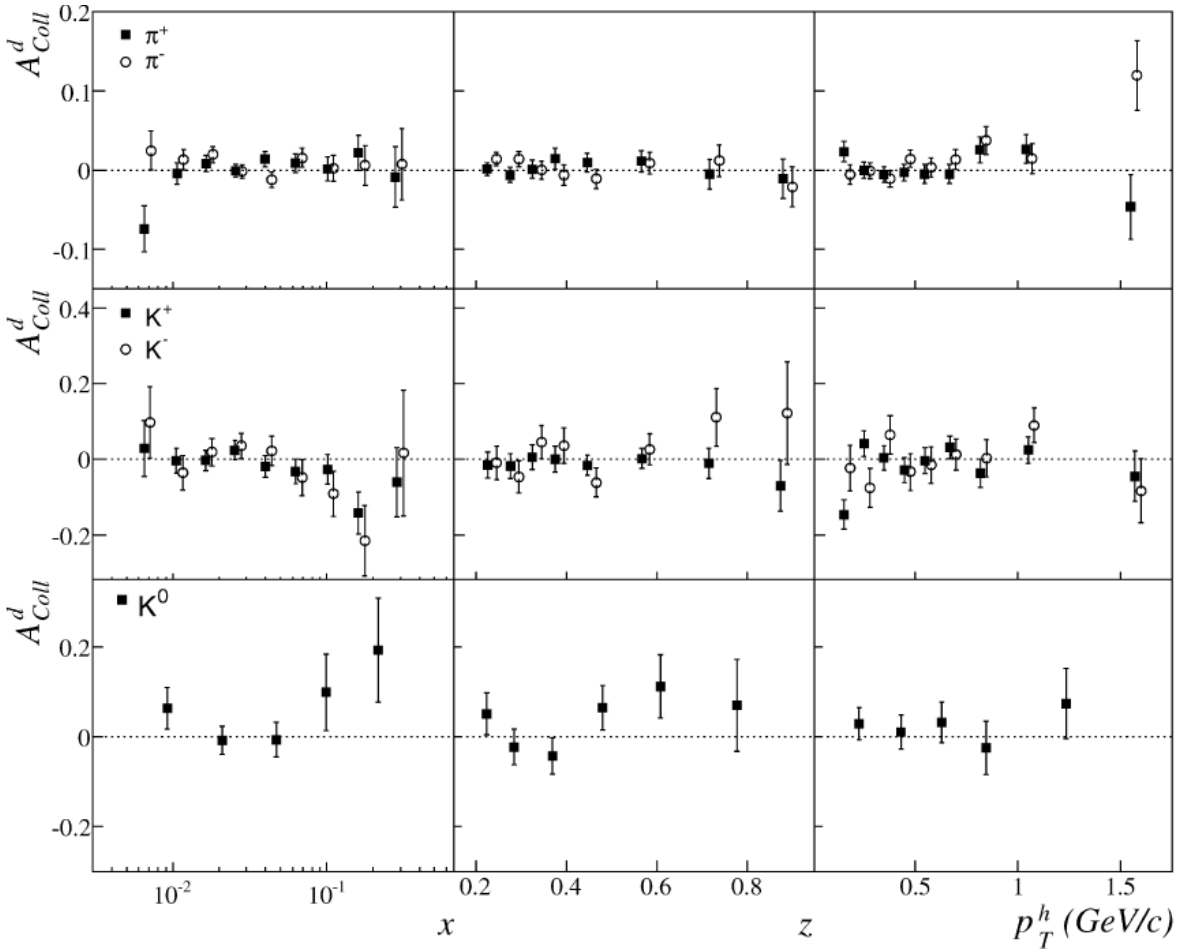
RICH PID K: 2-15 GeV



RICH PID K: 9-50 GeV

Collins asymmetries, results on deuterium

PLB 673(2009)127-135



$$A_d^{\pi+} = -\frac{(h_{1Tu} + h_{1Td}) \otimes (4H_{fav} + H_{unf})}{(u+d) \otimes (4D_{fav} + D_{unf})}$$

$$A_d^{\pi-} = -\frac{(h_{1Tu} + h_{1Td}) \otimes (H_{fav} + 4H_{unf})}{(u+d) \otimes (D_{fav} + 4D_{unf})}$$

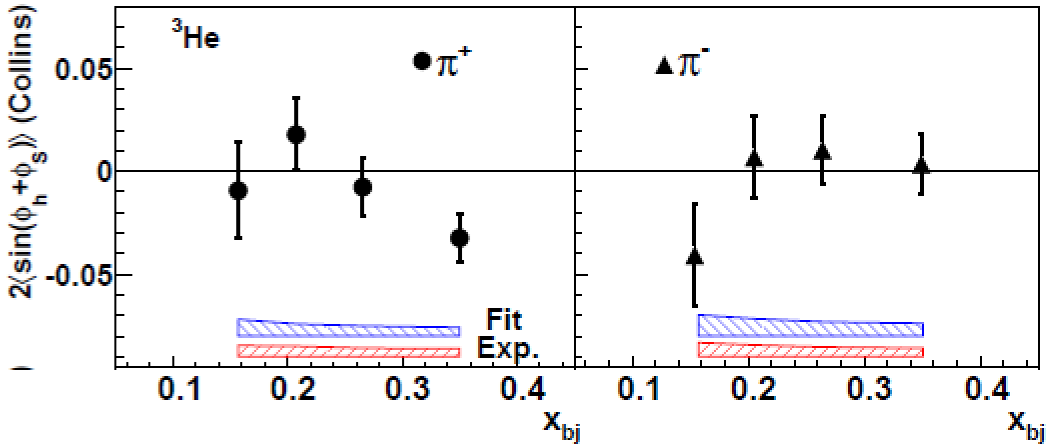
Some small effect expected even if $H^1_{unf} \sim -H^1_{fav}$
→ cancellation between $\Delta_T u$ (x) and $\Delta_T d$ (x)

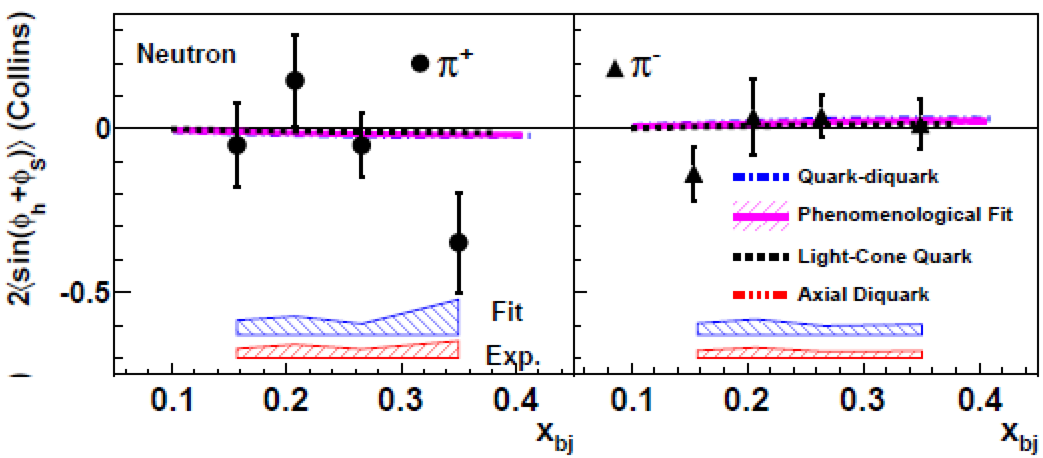
handle on $\Delta_T d$ (x)

Collins asymmetries, results on neutron

Another handle on $\Delta_T d(x)$ is provided by measurement on neutron

JLAB E06-010 Collaboration *PRL 107:072003,2011*



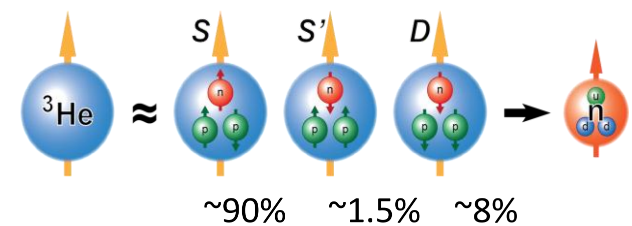


Consistent with zero except π^+ at x~0.34

Agreement with expectation from models and fit

Limited statistical precision

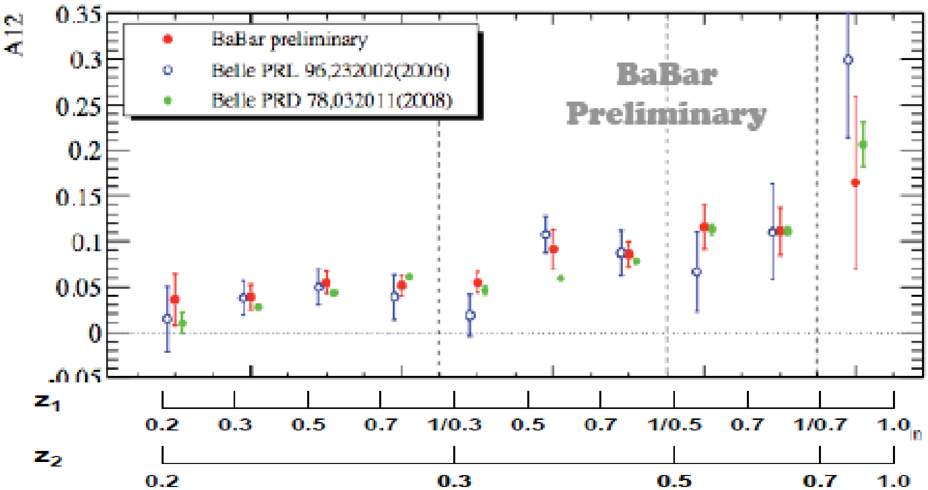
$$A^{C/S}_{^3\mathrm{He}} = P_n \cdot (1 - f_p) \cdot A^{C/S}_n + P_p f_p \cdot A^{C/S}_p$$



1st order 2p have spins anti-aligned → spin carried by the neutron

Collins effect in e^+e^- annihilation

2005: Belle measured sizeable asymmetries : Independent proof that Collins FF are different from zero



BaBar preliminary: $\mathcal{L}\approx$45 fb^{-1}

Belle Off-peak: $\mathcal{L}\approx$29 fb^{-1}

Belle full statistics (supersede previous results) $\mathcal{L}\approx$547 fb^{-1}

BABAR

I. Garzia, Transversity2011

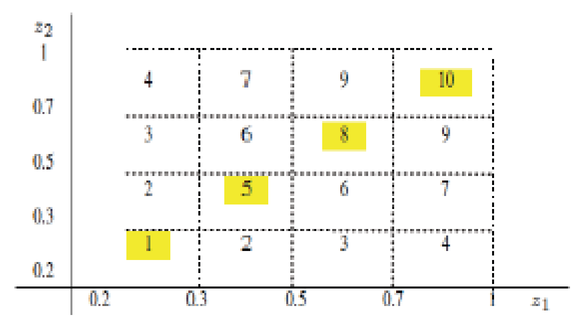
BELLE

Belle: 547 fb-1 data set, small statistical uncertainties;

Measured asymmetries rising with z.

Preliminary results from BaBar, 45 fb^{-1}

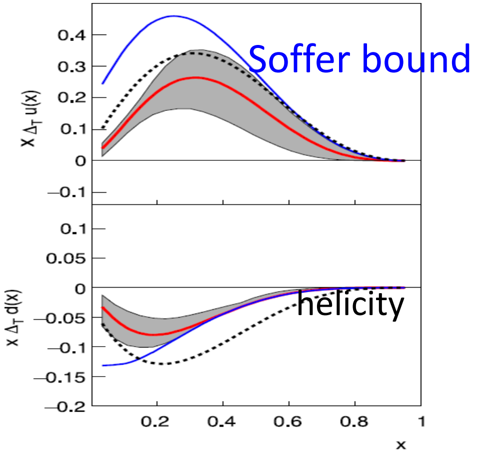
Asymmetries in good agreement



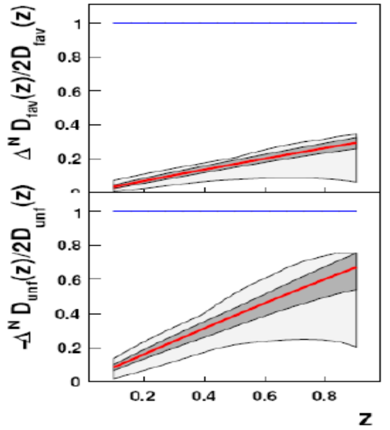
Collins asymmetries: summary

From 2005 onward, many new results for the Collins asymmetries at SIDIS experiments and e^+e^- colliders :
high statistical precision
and
covering large kinematical range

→ they can be used in a global fits to extract transversity PDF and Collins FF with improved precision

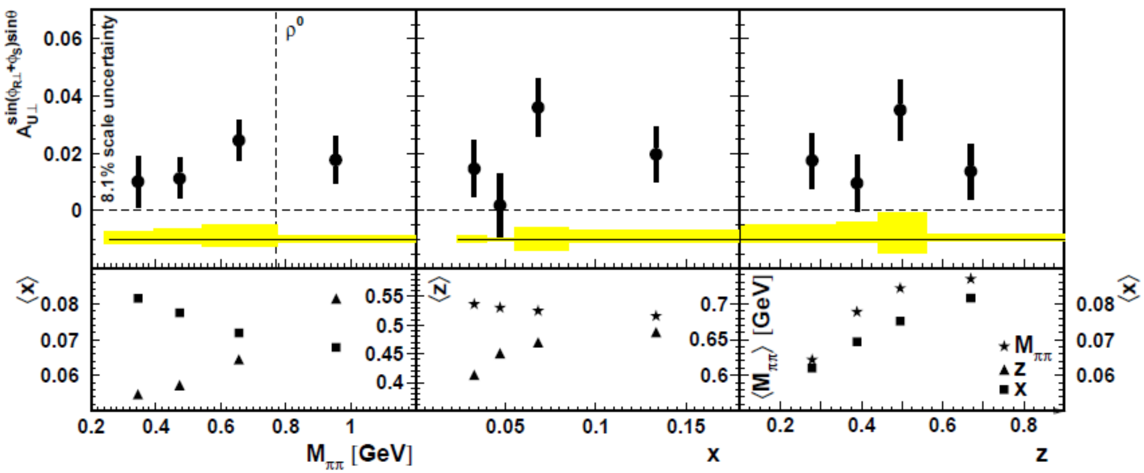


M. Anselmino et al.,
Nucl.Phys.Proc.Suppl.
191 (2009) 98



Two hadron asymmetries, proton

JHEP 0806 (2008) 017



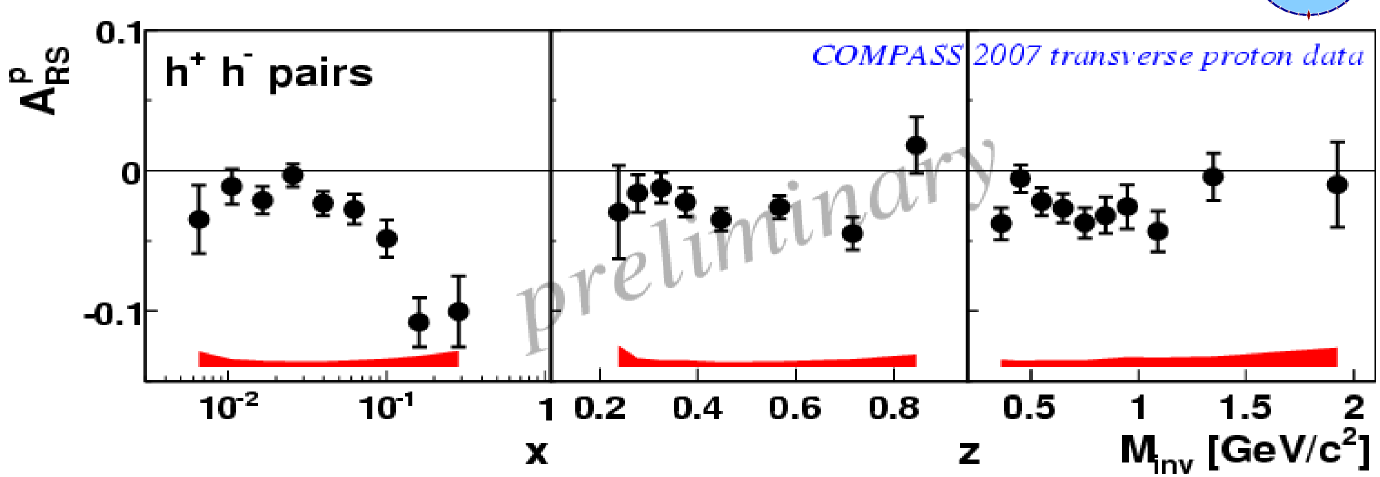
First evidence for a interference FF different from zero

Invariant mass dependence ruled out Jaffe model of a change sign to ρmass

Submitted to PLB

At small x, region not covered by HERMES asymmetries compatible with zero

large signal in the valence region

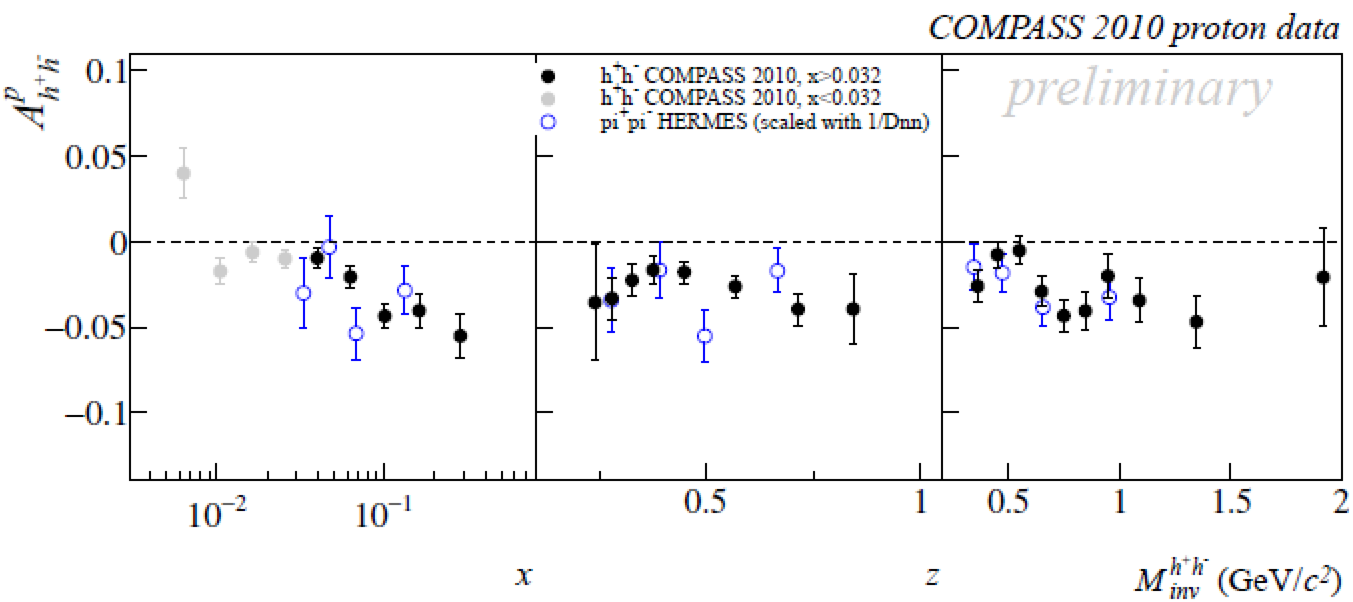


Two hadron asymmetries, proton

Results from 2010 run COMPASS available, here compared with HERMES

- Comparison between HERMES and COMPASS taking into account the different conventions (sign, D_{nn})
- and limiting COMPASS range to the x>0.032 region, overlap with HERMES

This selection makes the M_{inv} dependence more visible



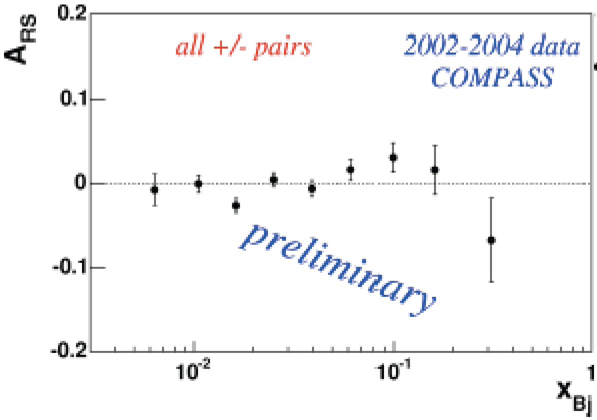
Good agreement

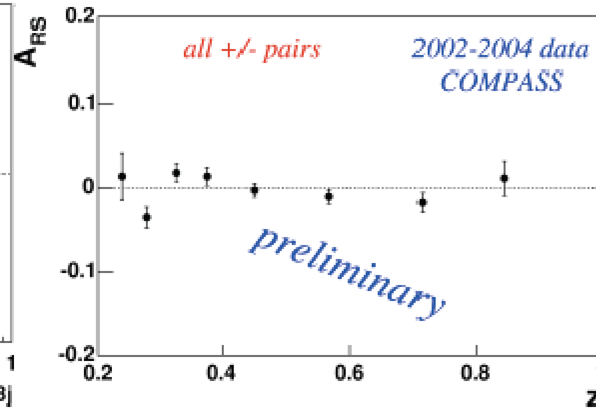
Broader range for COMPASS data in invariant mass

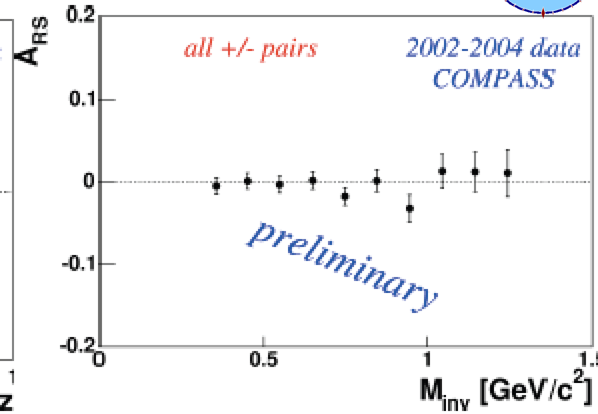
Two hadron asymmetries, deuterium

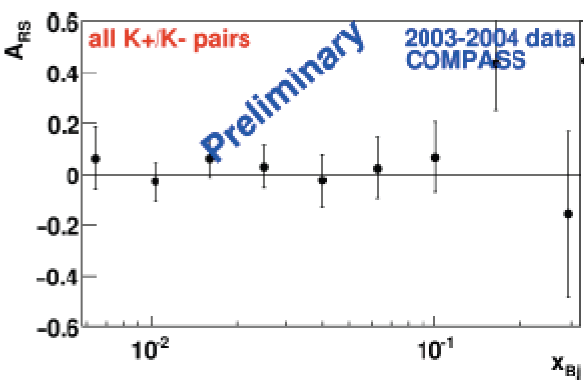
Compass measured also very small asymmetries on deuterium

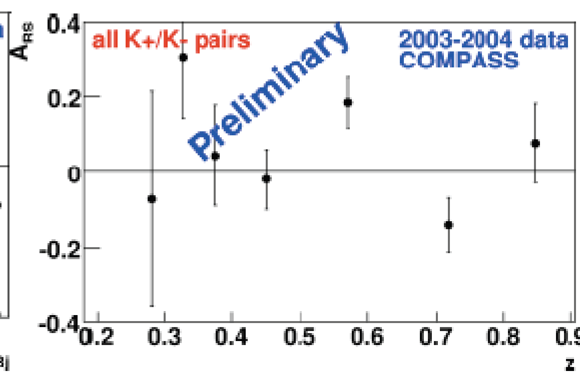
Submitted to PLB

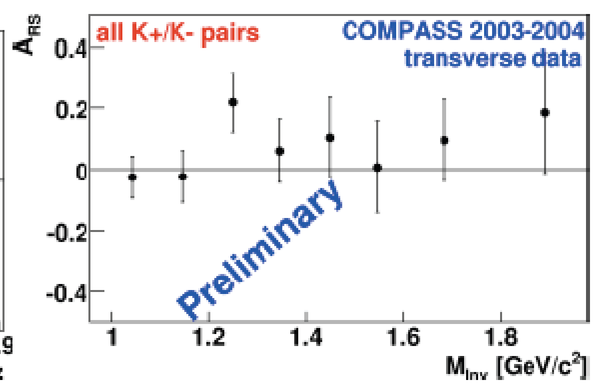








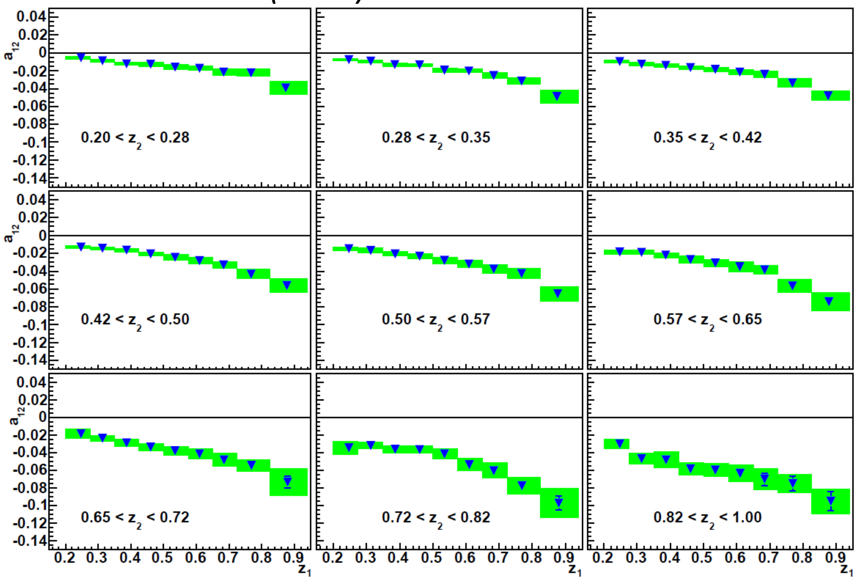




Also other hadron combination $\pi^+\pi^-$ $K^+\pi^-$ π^+K^- compatible with zero

Two hadron asymmetries in e^+e^- annihilation

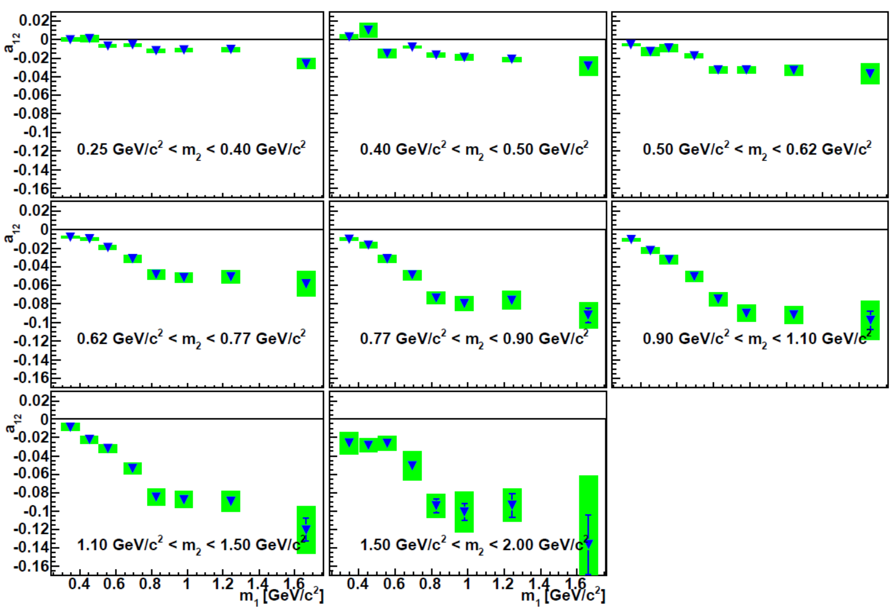
PRL107:072004(2011)



672fb^{-1}

Large asymmetries increasing with z

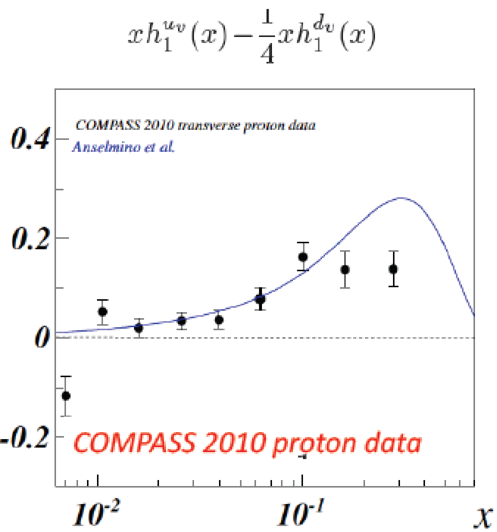
and

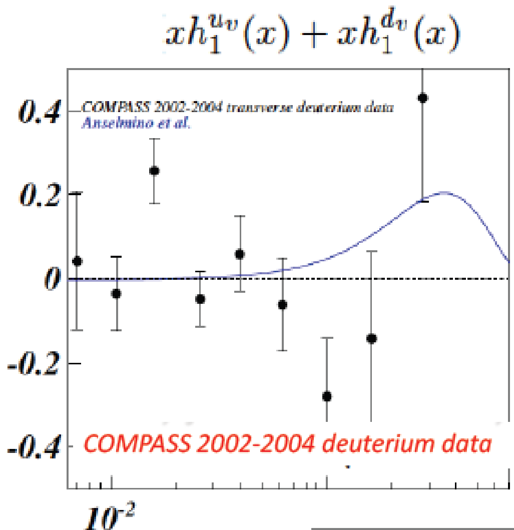


with invariant mass

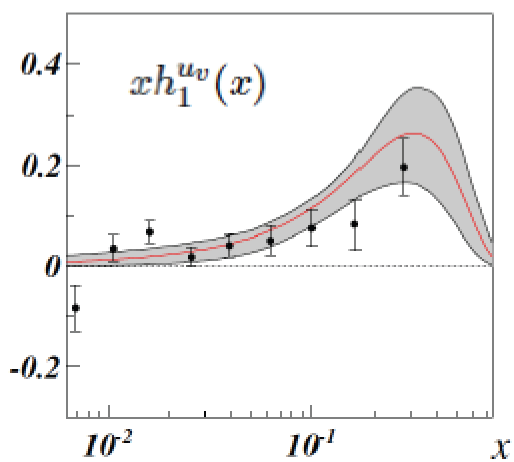
Extracting u and d transversity from COMPASS data

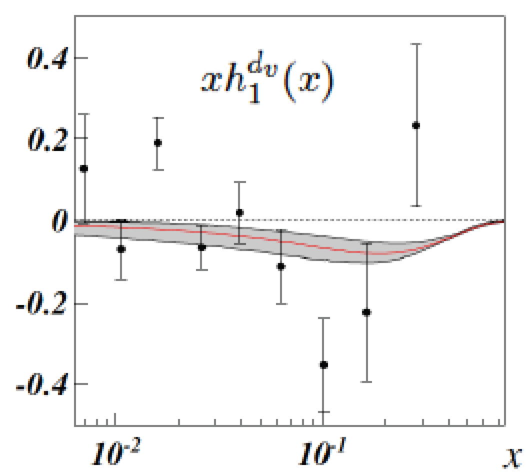
Extract information on DiFF from Belle data as in "*Bacchetta, Courtoy, Radici, PRL 107:012001,2011* "*;* u and d transversity PDF can be extracted using COMPASS deuterium and 2010 proton data





C.Elia PhD thesis,
Trieste
December 2011





Conclusions

- Big progress in few years in the field of transversity

- Several precise measurements that provide information on transversity and spin dependent FF are available:
  - SIDIS results, from experiments complementary on phase space and targets;
  - results from e^+e^- collider

First extraction of transversity for valence quarks ;
still, more data are useful to study its properties

More data to come, available in near future:

- COMPASS 2010 data: pions and kaons, study of asymmetries kinematical behavior
- Babar: Collins FF full statistics
- Belle Collins and DiFF with identifications , and unpolarized FF

Further results :

JLab 12 GeV/c (plan to measure Diff also) and on a longer time scale: ep collider

backup

$$D_{1,q}(z, M_{\pi\pi}, \cos\theta) \simeq D_{1,q}(z, M_{\pi\pi}) + D_{1,q}^{sp}(z, M_{\pi\pi})\cos\theta + D_{1,q}^{pp}(z, M_{\pi\pi})\frac{1}{4}(3\cos^2\theta - 1) \quad (3)$$

and

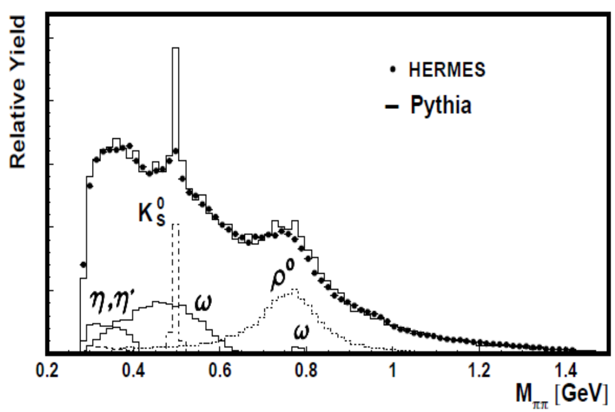
$$H_{1,q}^{\sphericalangle}(z, M_{\pi\pi}, \cos\theta) \simeq H_{1,q}^{\sphericalangle,sp}(z, M_{\pi\pi}) + H_{1,q}^{\sphericalangle,pp}(z, M_{\pi\pi})\cos\theta, \quad (4)$$

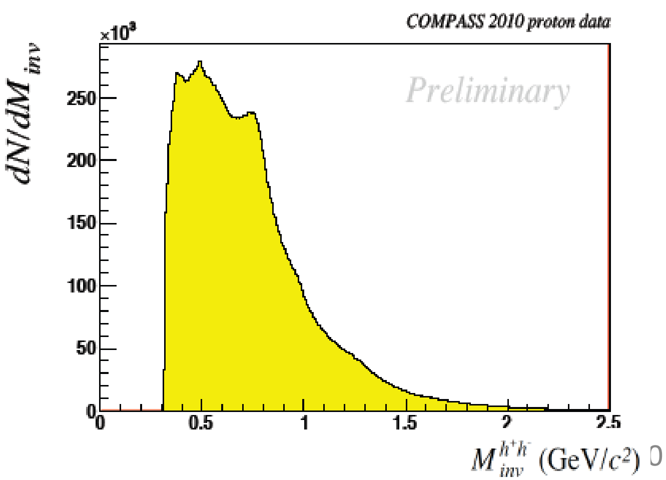
In compass, costheta~0, sensitive to Hsp;
Extract Asin(phi)*sin(theta)

In HERMES

$$A_{U\perp}(\phi_{R\perp} + \phi_S, \theta') = \sin(\phi_{R\perp} + \phi_S)\frac{a\sin\theta'}{1 + b\frac{1}{4}(3\cos^2\theta' - 1)},$$

$a \equiv A_{U\perp}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$ is a free parameter of the fit



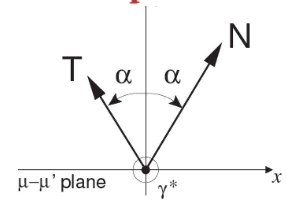


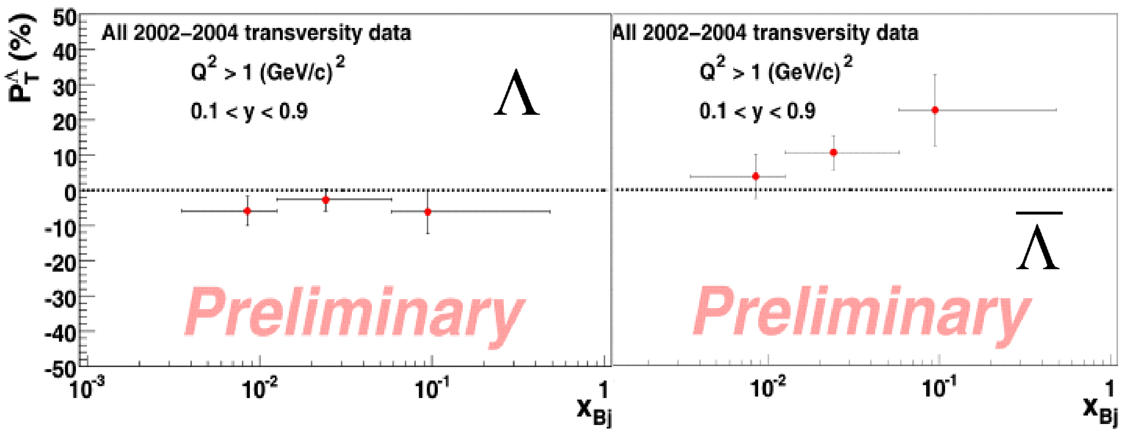
Λ polarisation

$\mu N^{\uparrow} \rightarrow \mu' \Lambda X$ $\mu N^{\uparrow} \rightarrow \mu' \bar{\Lambda} X$

$$P^{\Lambda}_{T,exp} = f P_N D(y) \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)}$$

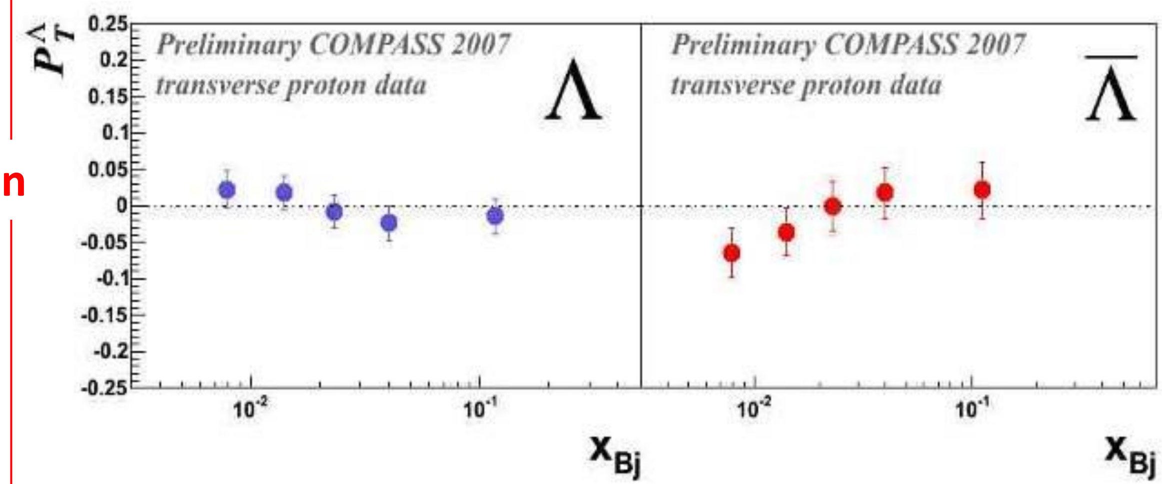
Λ polarization axis





deuteron

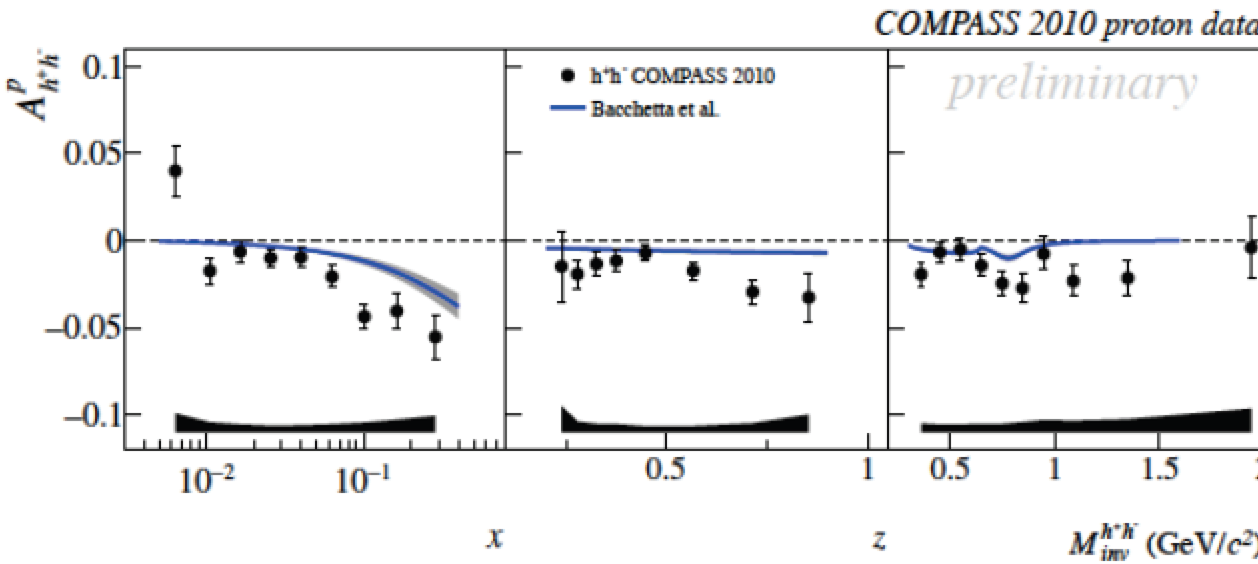
proton



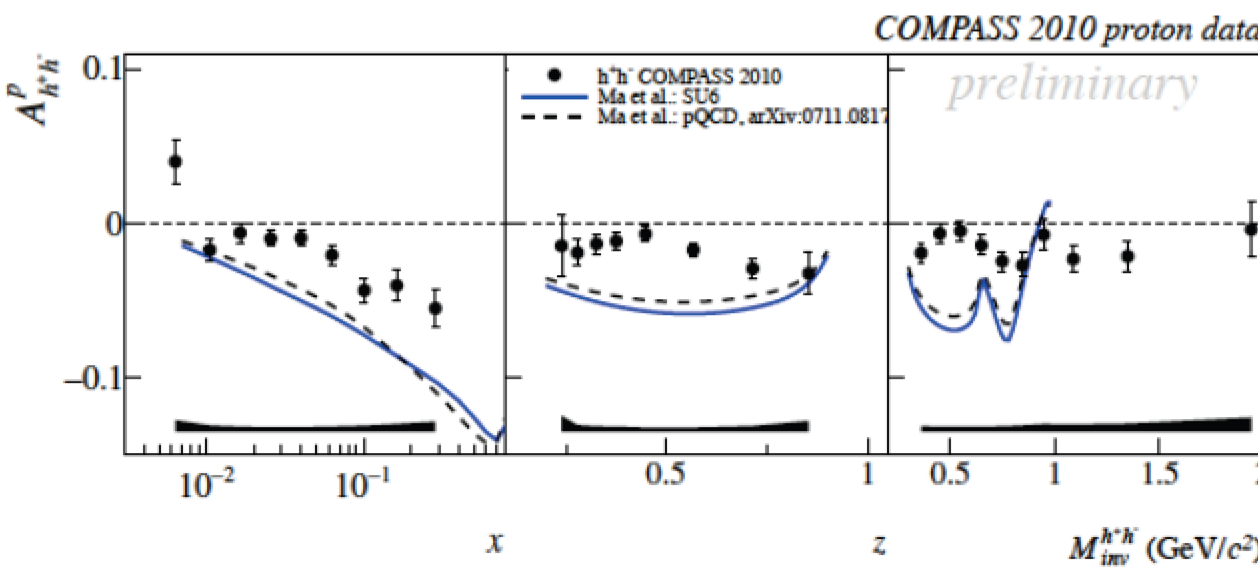
compatible with zero

more statistics is needed

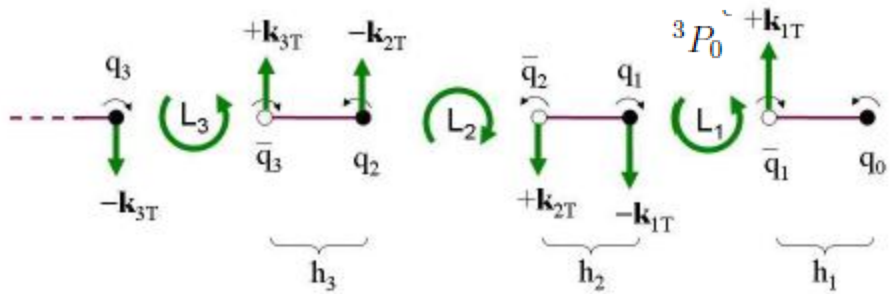
2010 proton data : comparison with model predictions



Bachetta & Radici



Ma et al.

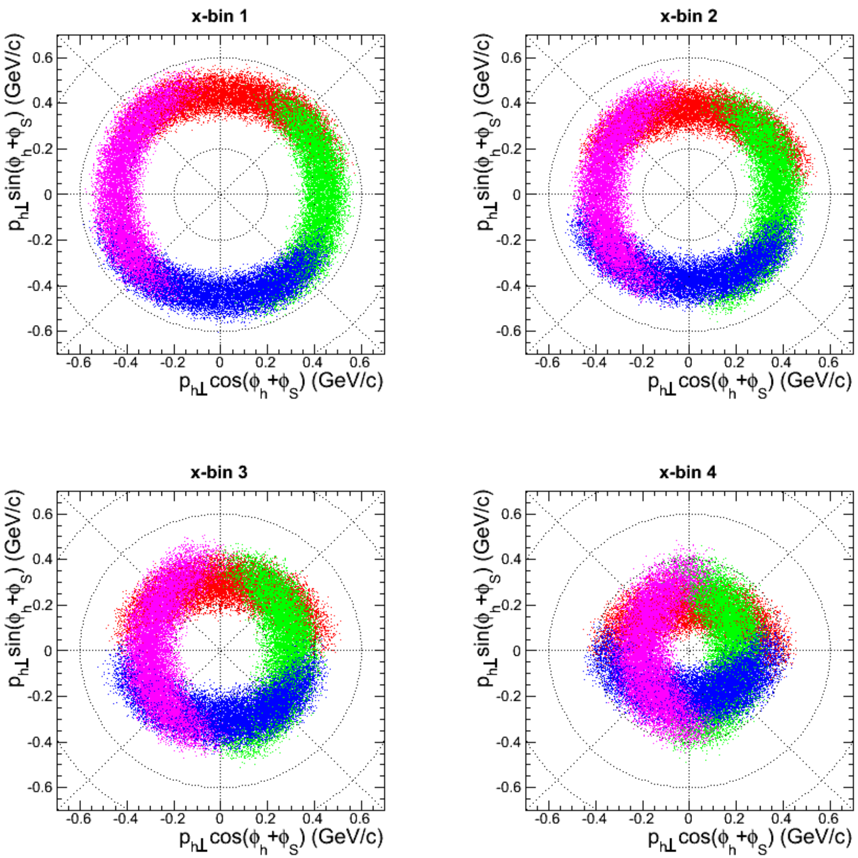


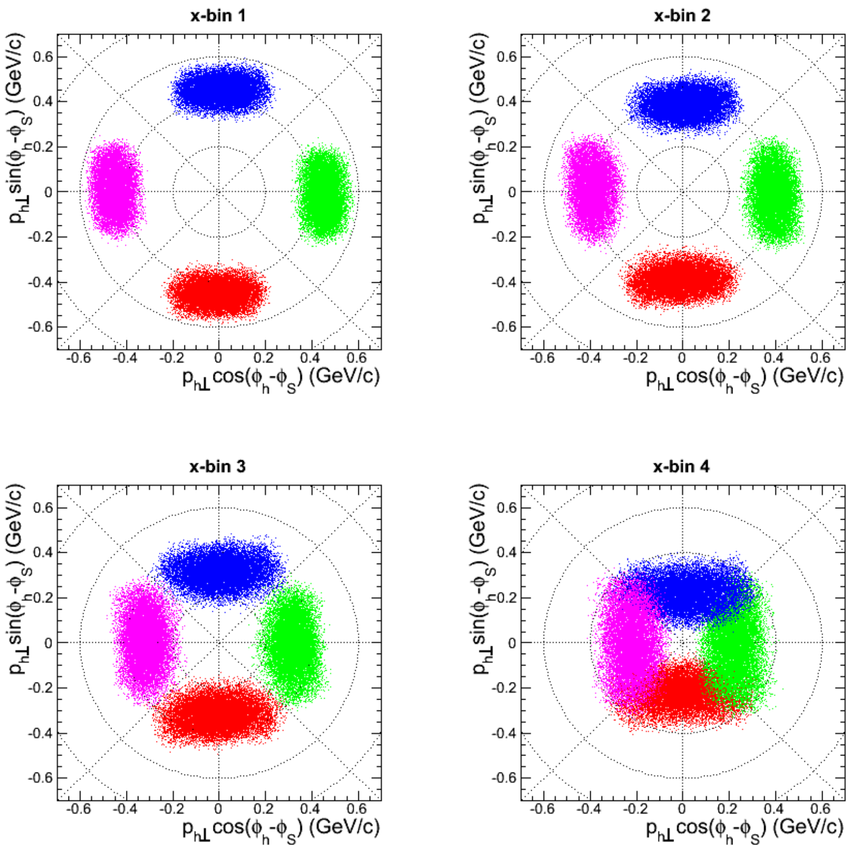
q_3
L_3
$+\mathbf{k}_{3T}$
$-\mathbf{k}_{2T}$
$\bar{q}_3$
q_2
$-\mathbf{k}_{3T}$
h_3
L_2
$\bar{q}_2$
q_1
$+\mathbf{k}_{2T}$
$-\mathbf{k}_{1T}$
h_2
$^3P_0$
L_1
$+\mathbf{k}_{1T}$
$\bar{q}_1$
q_0
h_1

Angular Coverage

color coded for each target spin direction: up, down, left and right.

Collins: $\phi_h + \phi_S$ Sivers and Worm-Gear: $\phi_h - \phi_S$



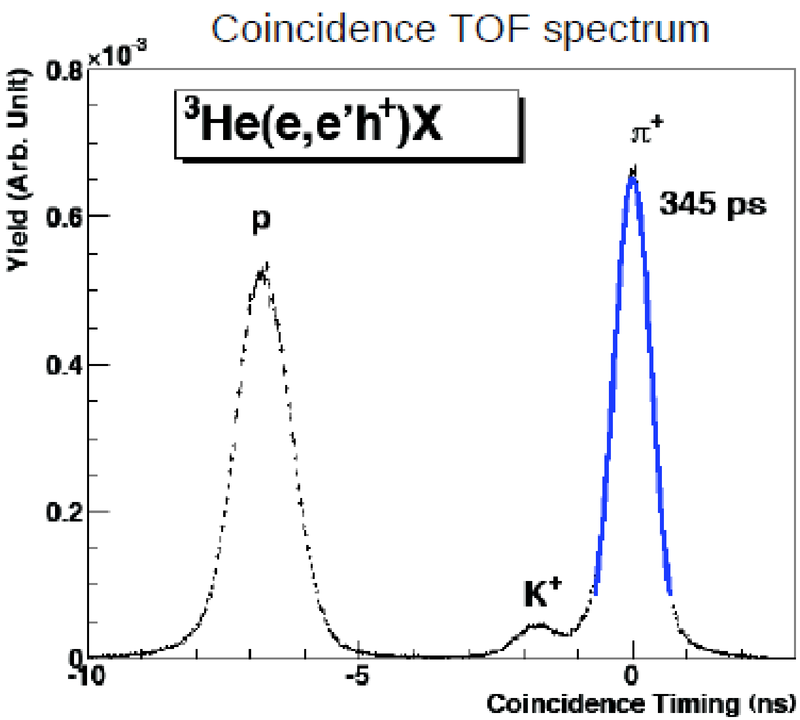


Target spin orientations: up-down and left-right (increases angular coverage)

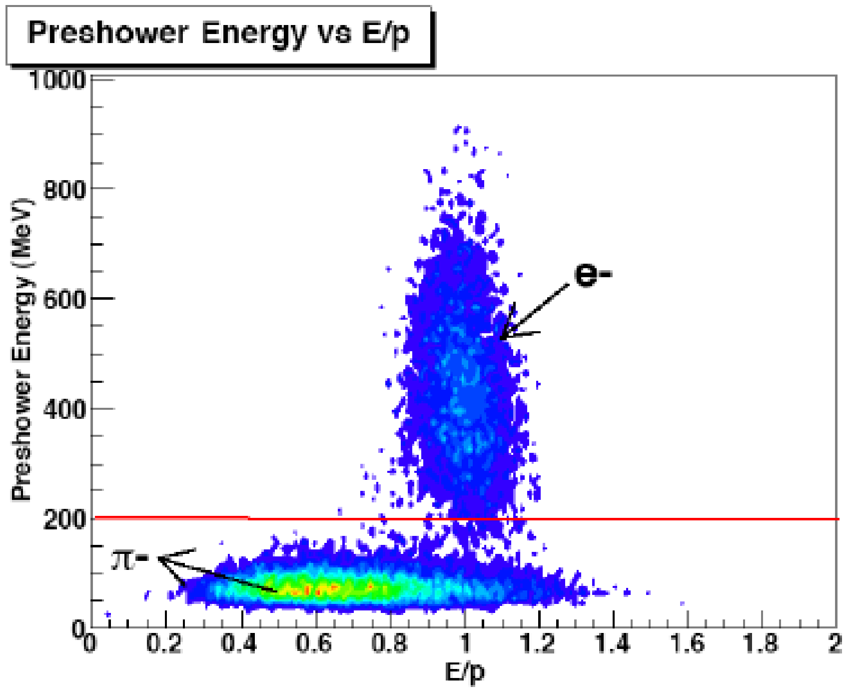
Jefferson Lab

Particle Identification

Hadron Identification from HRS

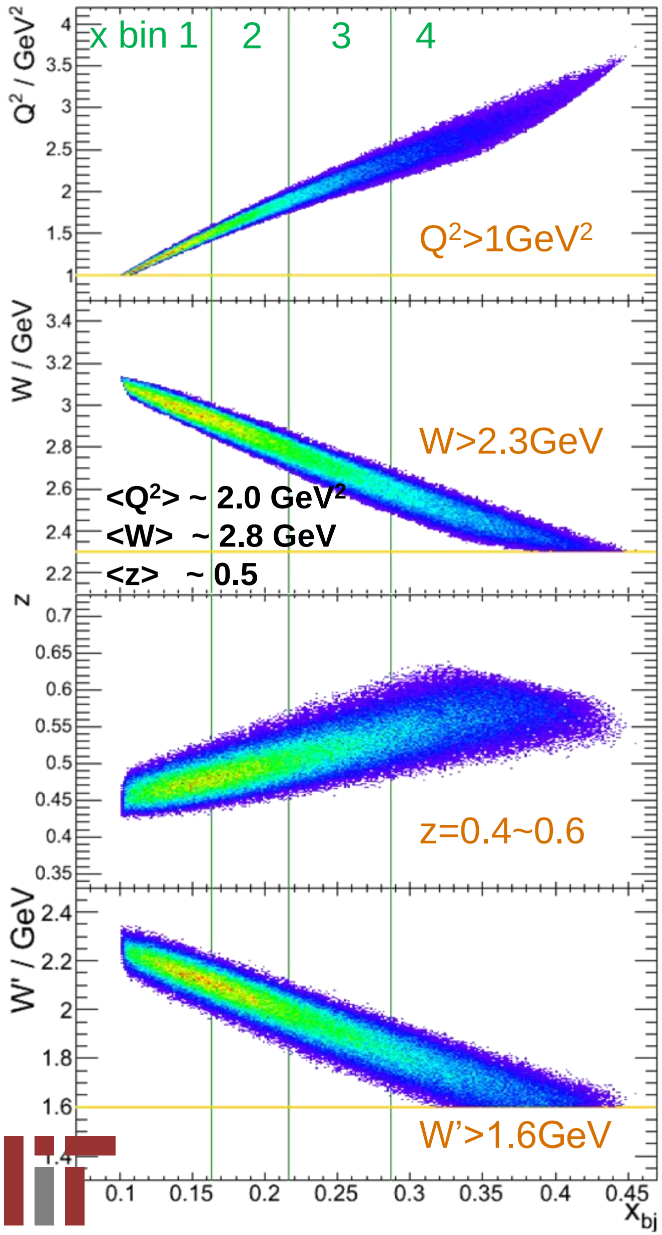


Electron Identification from BigBite



- Kaon and proton data can be separated by coincidence/TOF and the RICH detector: both provide K/π ~ 4σ separation
- Combined pion rejection 99.9%

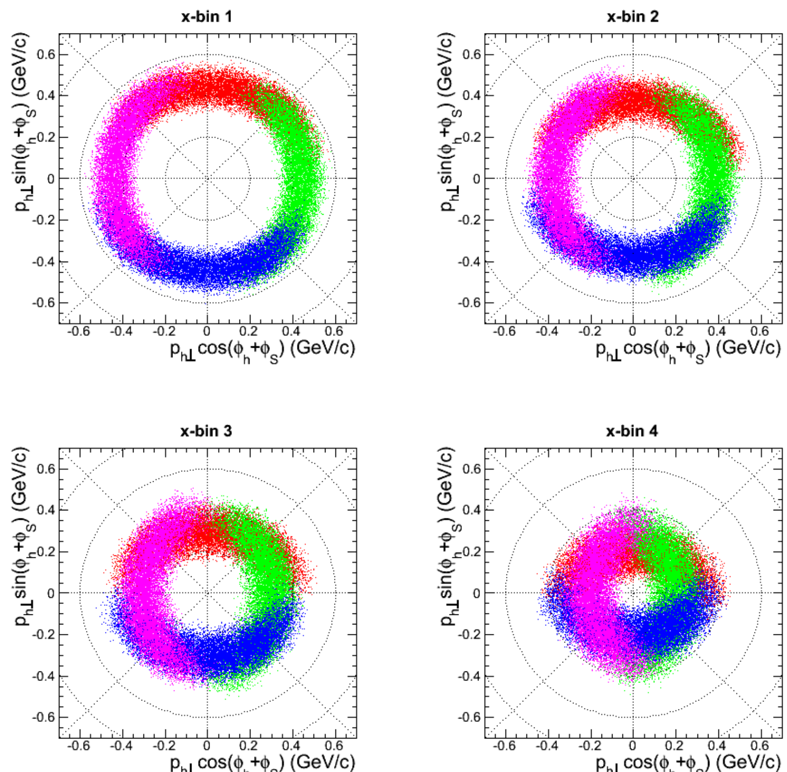
Kinematic Coverage



Angular Coverage

color coded for each target spin direction: up, down, left and right.

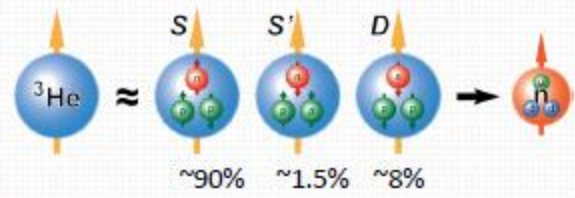
Collins: $\phi_h + \phi_S$

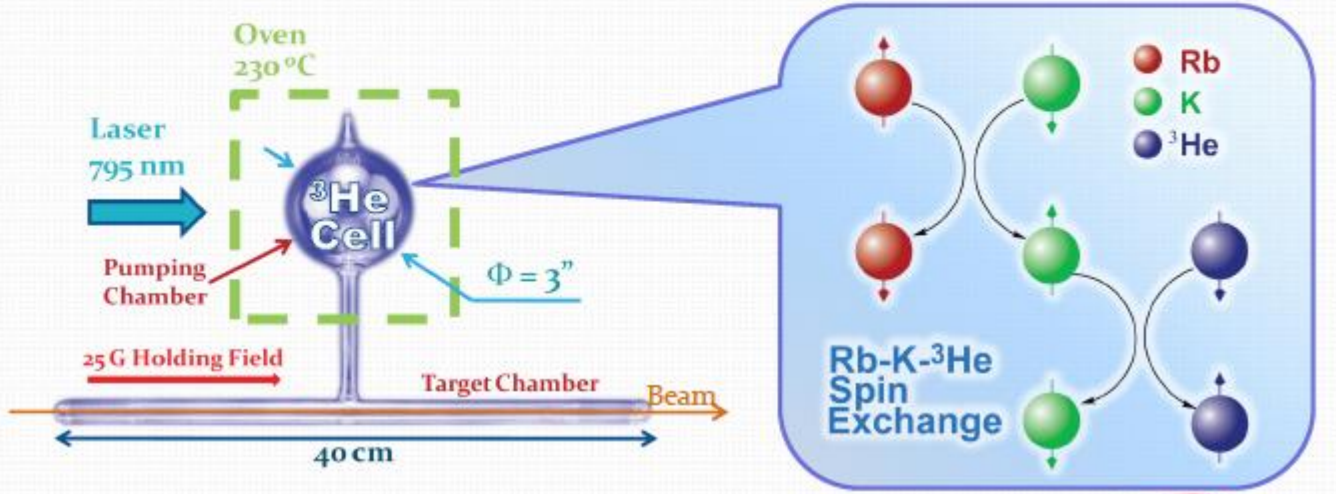


Target spin orientations: up-down and left-right (increases angular coverage)

Polarized ^3He Target

- Effectively a polarized neutron target
- Improved figure of merit
  - Rb+K hybrid mixture cell
  - Narrow bandwidth lasers
- Compact size: No cryogenic support needed





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Correction for N_2 Dilution

$$A_{raw} = f \cdot P_{^3\mathrm{He}} \cdot A_{^3\mathrm{He}}$$

$$f = \frac{N_{^3\mathrm{He}}\sigma_{^3\mathrm{He}}}{N_{^3\mathrm{He}}\sigma_{^3\mathrm{He}} + N_{\mathrm{N}_2}\sigma_{\mathrm{N}_2}}$$

Cross section ratios determined through reference cell N_2 and ^{3}He data.

x	$f_{\mathrm{N}_2}^{\pi^+}$	$f_{\mathrm{N}_2}^{\pi^-}$
0.137	0.911 ± 0.011	0.925 ± 0.009
0.189	0.908 ± 0.011	0.905 ± 0.011
0.249	0.909 ± 0.010	0.898 ± 0.012
0.336	0.915 ± 0.009	0.916 ± 0.010

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From ^{3}He to Neutron

$$g_1^{^3He} = P_n g_1^n + 2 P_p g_1^p$$

$$P_n = 0.86^{+0.036}_{-0.02} \quad and \; P_p = -0.028^{+0.009}_{-0.004}$$

$$A_{^3\mathrm{He}}^{C/S} = P_n \cdot (1 - f_p) \cdot A_n^{C/S} + \underline{P_p f_p \cdot A_p^{C/S}}$$

very small (< 0.003)

$$f_p = \frac{2\sigma_p}{\sigma_{^3\mathrm{He}}}$$

Cross section ratios determined through reference cell H_2 and ^{3}He data→MEASURED

x	$1 - f_p^{\pi^+}$	$1 - f_p^{\pi^-}$
0.156	0.212 ± 0.032 (0.027)	0.348 ± 0.032 (0.022)
0.206	0.144 ± 0.031 (0.029)	0.205 ± 0.037 (0.027)
0.265	0.171 ± 0.029 (0.028)	0.287 ± 0.036 (0.024)
0.349	0.107 ± 0.026 (0.030)	0.220 ± 0.032 (0.026)

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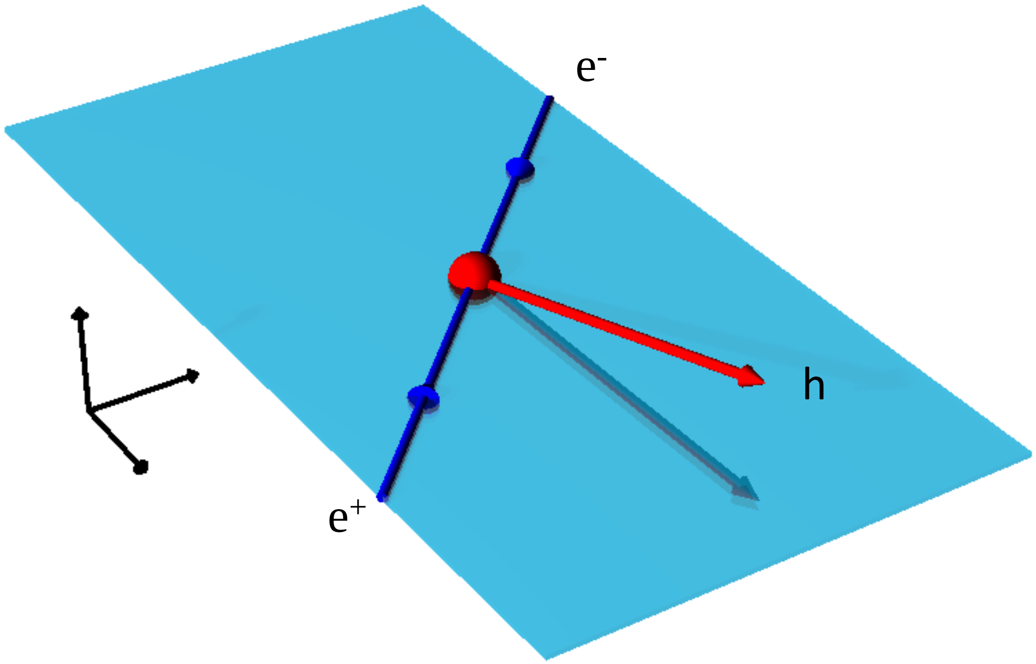
Fragmentation functions in e^+e^- annihilation

$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52\,\boldsymbol{GeV}$$

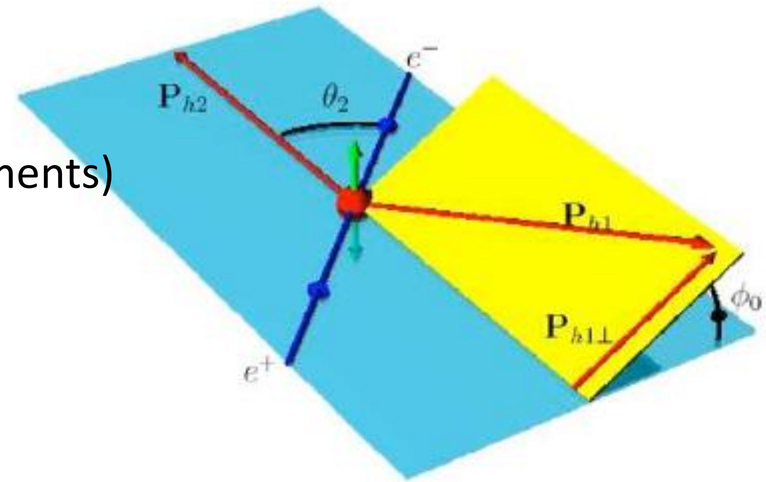


- Process: $e^+ e^- \rightarrow hX$
- At leading order sum of unpolarized fragmentation functions from quark and anti-quark side

LO $$F^h(z,s) = \frac{\sum_q e_q^2 [D_q^h(z) + D_{\bar{q}}^h(z)]}{\sum_q e_q^2}$$

NLO $$F^h(z,s) = \sum_i \int_z^1 \frac{dz'}{z'} C_i(s; z' \alpha_s) D_q^h(z)$$

Other method, does not require the
reconstruction of the thrust axis
(Useful for the sytematic control of the measurements)



qqbar is not accessible sperimentally → approximated by the thrust axis in 1st method:

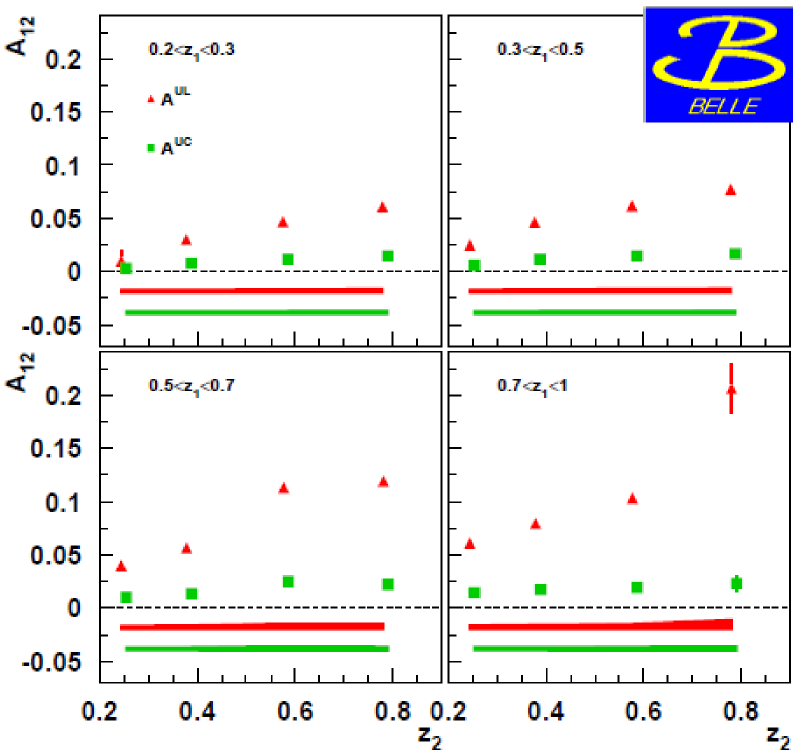
$$T = \max \frac{\sum_h |\boldsymbol{P}_h \cdot \hat{\boldsymbol{n}}|}{\sum_h |\boldsymbol{P}_h|},$$

$$A_{12}^{UL} = \left\langle \frac{\sin^2\theta}{1+\cos^2\theta} \right\rangle \frac{\pi\langle k_{tC}^2\rangle}{4M^2} \left[\frac{H_1^{fav}\overline{H}_2^{fav} + H_1^{dis}\overline{H}_2^{dis}}{D_1^{fav}\overline{D}_2^{fav} + D_1^{dis}\overline{D}_2^{dis}} - \frac{H_1^{fav}\overline{H}_2^{dis} + H_1^{dis}\overline{H}_2^{fav}}{D_1^{fav}\overline{D}_2^{dis} + D_1^{dis}\overline{D}_2^{fav}} \right]$$

$$A_{12}^{UC} = \left\langle \frac{\sin^2\theta}{1+\cos^2\theta} \right\rangle \frac{\pi\langle k_{tC}^2\rangle}{4M^2} \left[\frac{H_1^{fav}\overline{H}_2^{fav} + H_1^{dis}\overline{H}_2^{dis}}{D_1^{fav}\overline{D}_2^{fav} + D_1^{dis}\overline{D}_2^{dis}} - \frac{\left(H_1^{fav} + H_1^{dis}\right)\left(\overline{H}_2^{fav} + \overline{H}_2^{dis}\right)}{\left(D_1^{fav} + D_1^{dis}\right)\left(\overline{D}_2^{fav} + \overline{D}_2^{dis}\right)}$$

Collins effect in e^+e^- annihilation

PR D78:032011,2008

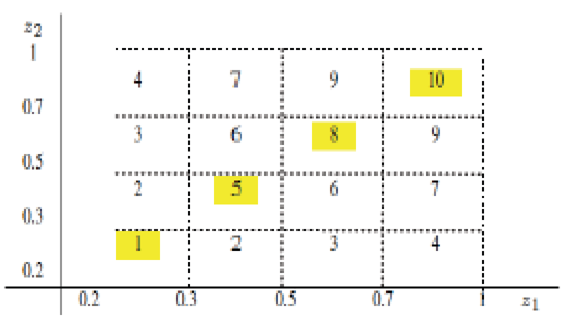


547 fb-1 data set, small statistical uncertainties;
Measured asymmetries rising with z,

Extraction of double ratios
unlike sign over like sign A^{UL} and
unlike over charged/neutral pairs A^{UC}
→gives different combinations of
favored and unfavored FF

The data do not allow to extract
the fav and unfav Collins FFs
→ Only from global fit

$$A_{12}^{UL} = \left\langle \frac{\sin^2\theta}{1+\cos^2\theta} \right\rangle \frac{\pi\langle k_{tC}^2\rangle}{4M^2} \left[\frac{H_1^{fav}\overline{H}_2^{fav} + H_1^{dis}\overline{H}_2^{dis}}{D_1^{fav}\overline{D}_2^{fav} + D_1^{dis}\overline{D}_2^{dis}} - \frac{H_1^{fav}\overline{H}_2^{dis} + H_1^{dis}\overline{H}_2^{fav}}{D_1^{fav}\overline{D}_2^{dis} + D_1^{dis}\overline{D}_2^{fav}} \right]$$



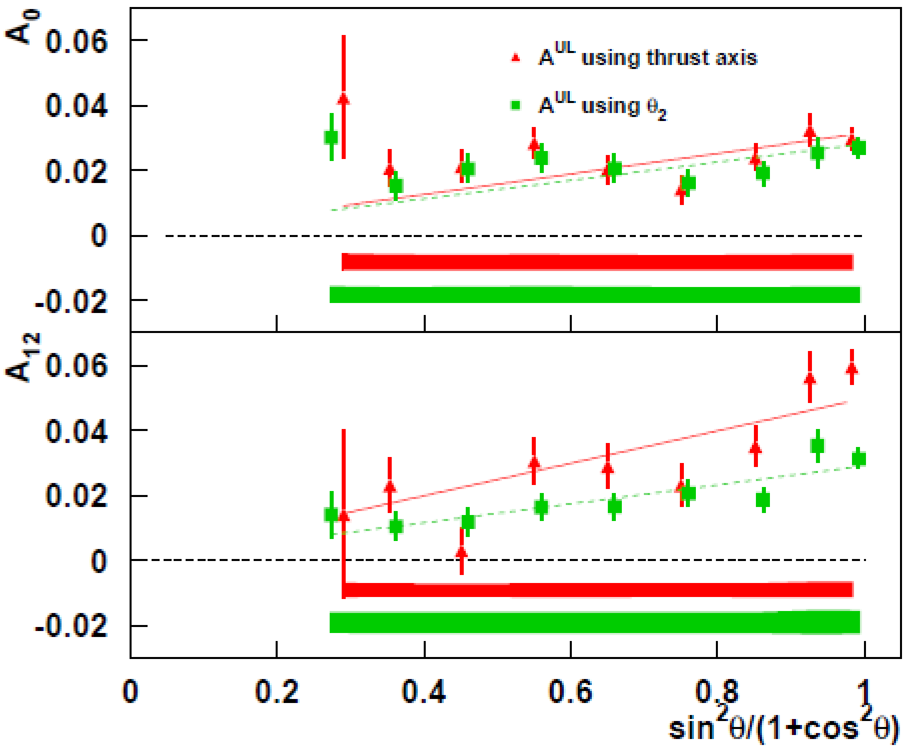
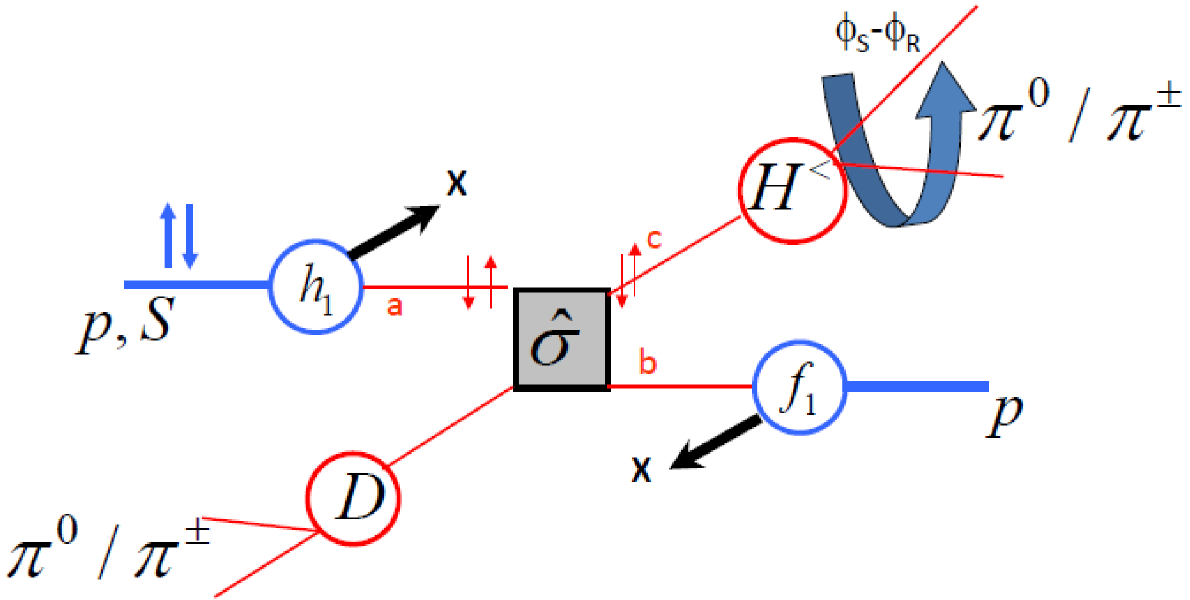


FIG. 19: Light quark (uds) A_0^{UL} (top) and A_{12}^{UL} (bottom) asymmetry parameters as a function of $\sin^2\theta/(1+\cos^2\theta)$, for θ_2 (squares) and for $\hat{n}_z$ (triangles). Linear fits are also displayed as dashed and continuous lines, respectively. The systematic error for θ_2 case is represented by the lower, that for $\hat{n}_z$ by the upper error band.

Transverse quark spins leads to a $\sin^2/1+\cos^2$ dependence of the asymmetries

More linear behavior in the A12 asym, explained by the fact that the thrust axis describes the original quark direction better than the second hadron polar angle (additional tranv mom relative to the quark axis)

Interference Fragmentation Function in p-p

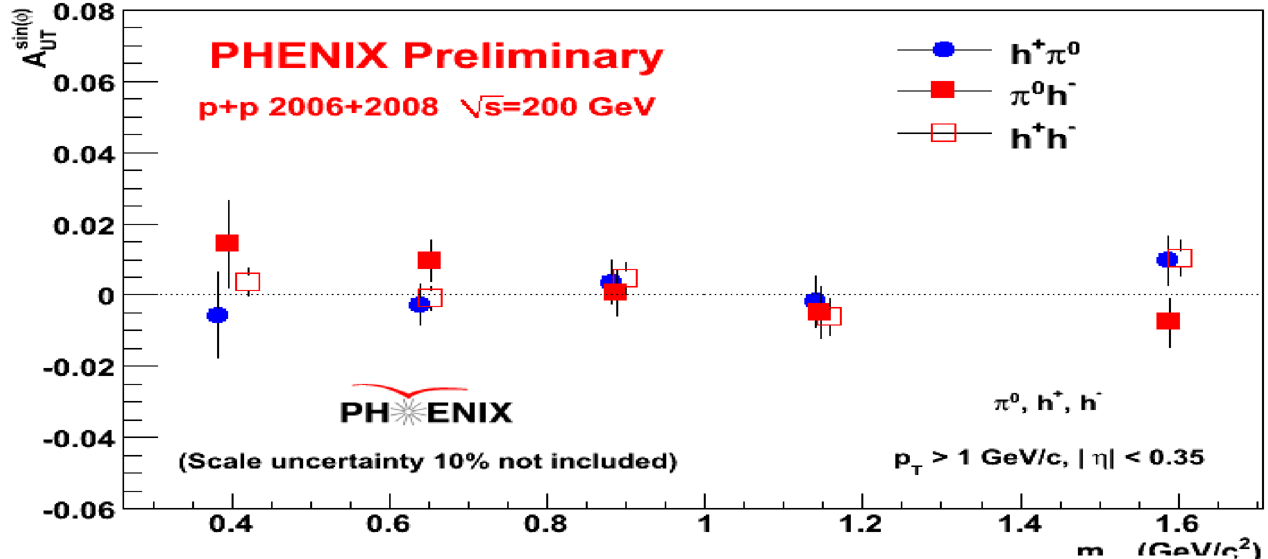


$$\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}(\phi_S - \phi_R) = A_{UT} \sin(\phi_S - \phi_R) \qquad A_{UT} \propto h_1 \otimes H_1^{<}$$

ϕ_S: Angle between polarisation vector and event plane
ϕ_R: Angle between two hadron plane and event plane

$A_{UT}^{\sin\phi}$ vs Invariant Mass of the Pair

First measurement of IFF in pp



These DiFF
are being measured
at Belle

Results and Projections
From run 12+13