TMD physics with e.m. probes at COMPASS

INFN

Andrea Bressan

University of Trieste and INFN

(on behalf of the COMPASS Collaboration)

INT-18-3-Probing Nucleons and Nuclei in High Energy Collisions
Symposium – 22-26 October, UW, SEATTLE

COMPASS data taking

muon beam	deuteron (^{6}LiD) PT	2002 2003 2004	80% L/20% T target polarisation
		2006	L target polarisation
	proton (NH_3) PT	2007	50% L /50% T target polarisation
Hadron	LH target	2008 2009	
muon beam	proton (NH_3) PT	2010	T target polarisation
		2011	L target polarisation
Hadron	Ni target	2012	Primakoff
muon beam	LH2 target	2012	Pilot DVCS & unpol. SIDIS
Hadron	Proton (NH3) DT PT	2014 2015 2018	Pilot DY run DY run DY run
muon beam	LH2 target	2016 2017	DVCS & unpol. SIDIS

Muon beam: SIDIS setup

- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer

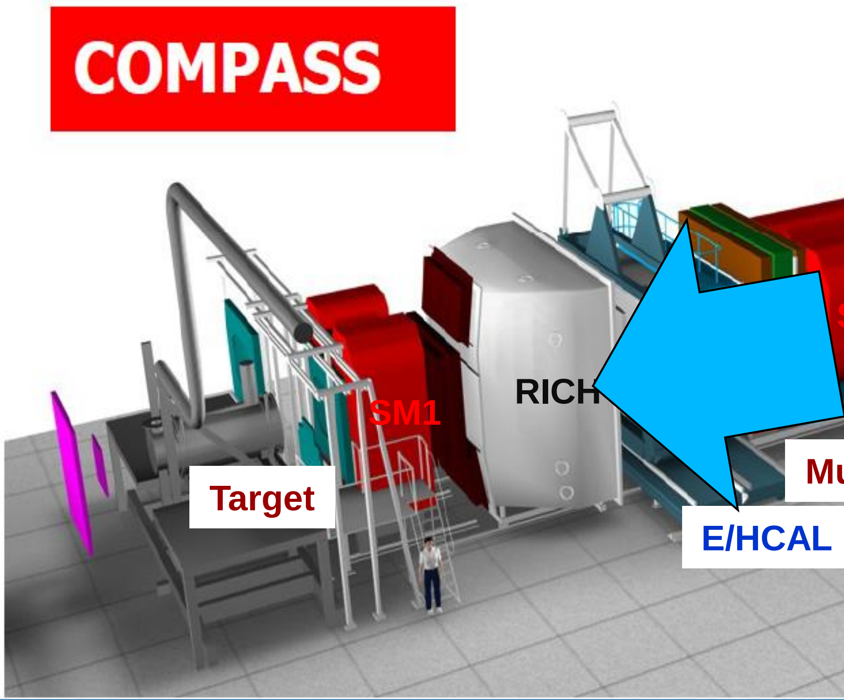
Large Angle Spectrometer (SM1)

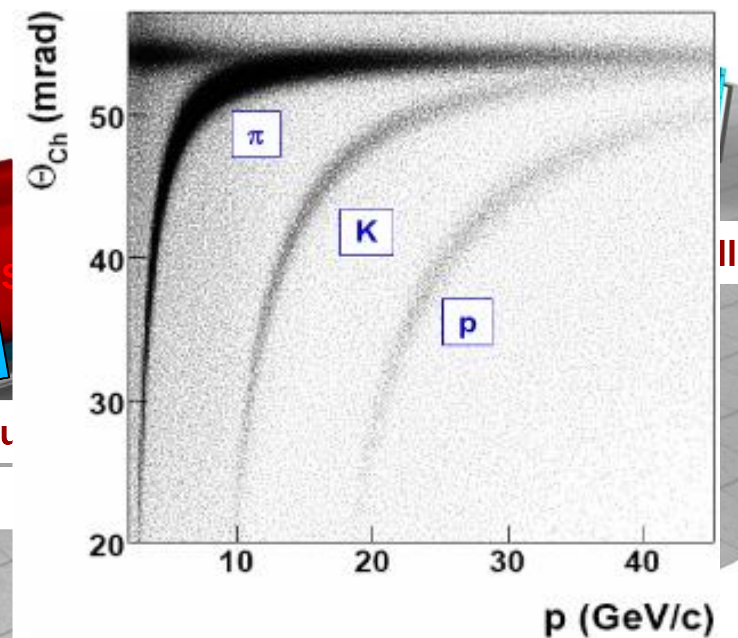
Small Angle Spectrometer (SM2)

radiator C_4F_{10}

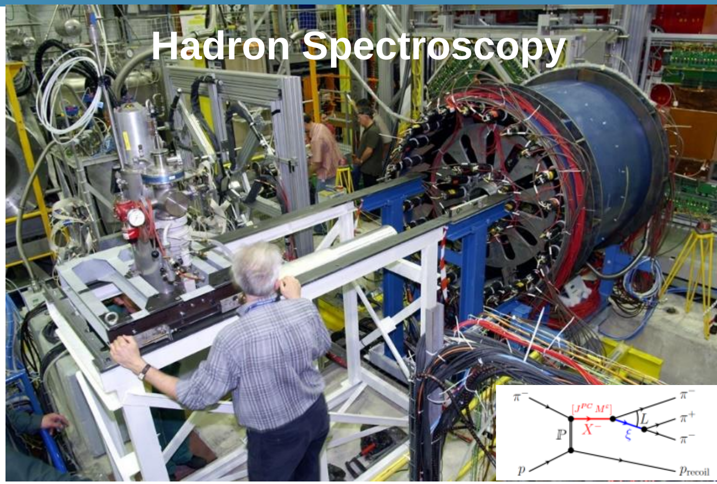
threshold: π ~2 GeV/c

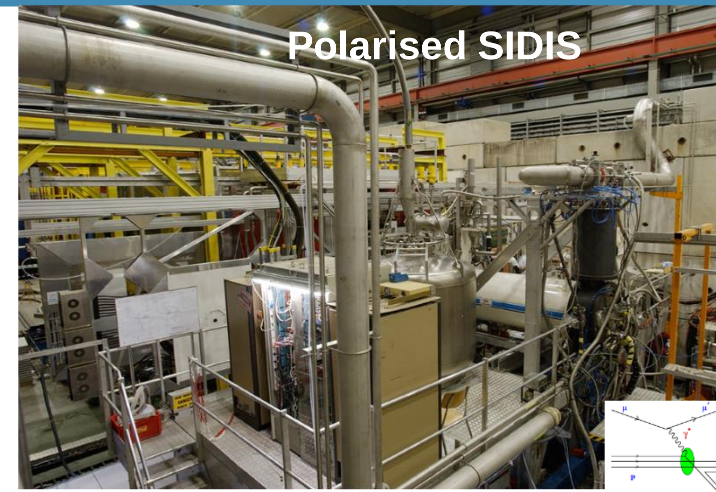
K ~ 10 GeV/c



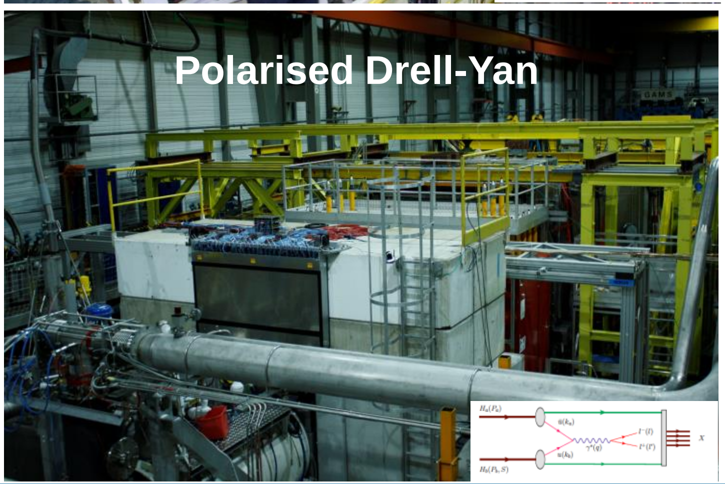


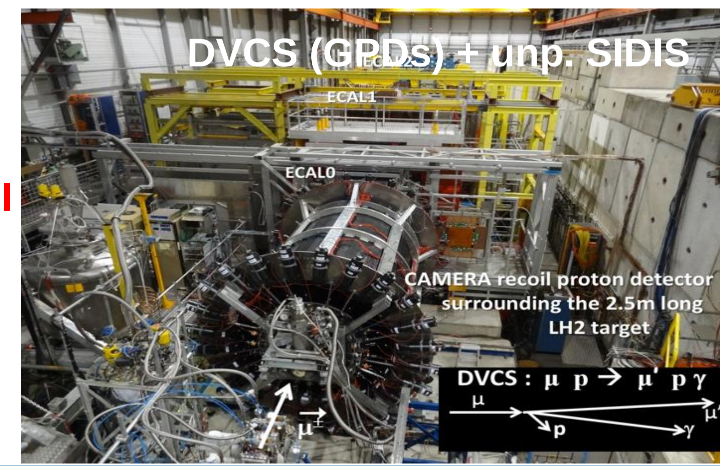
COMPASS target area





COMPASS-I
1997-2011



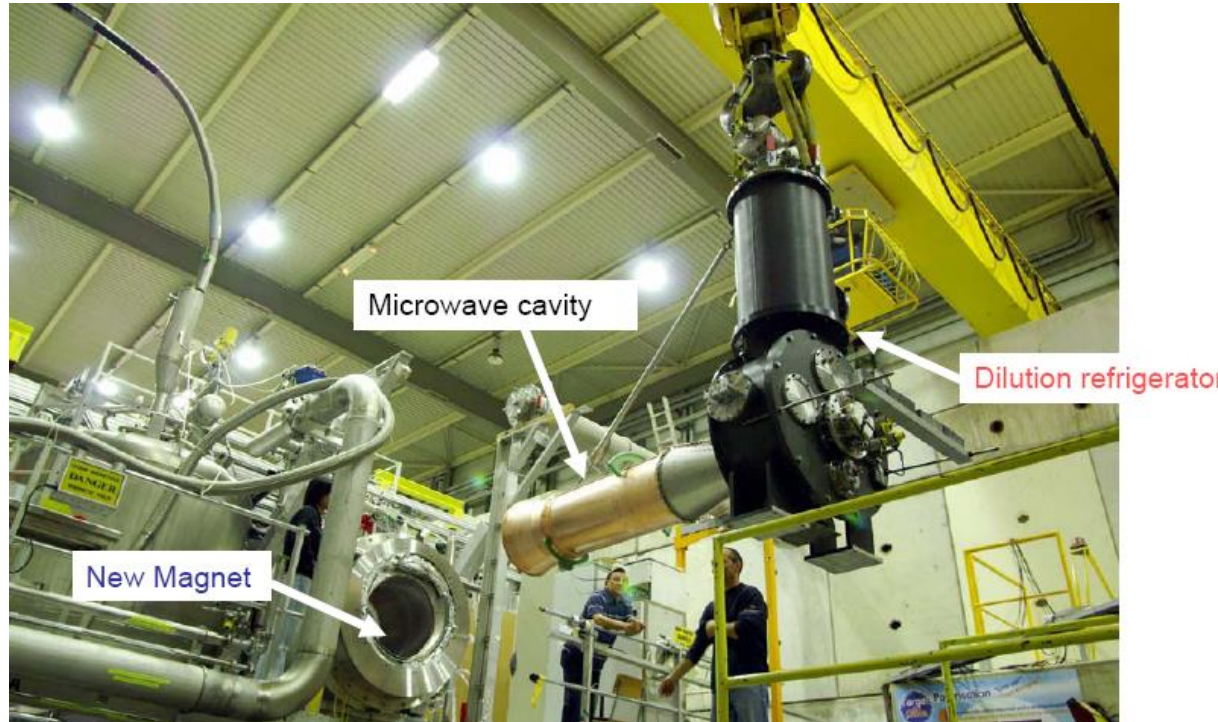


COMPASS-II
2012-2020

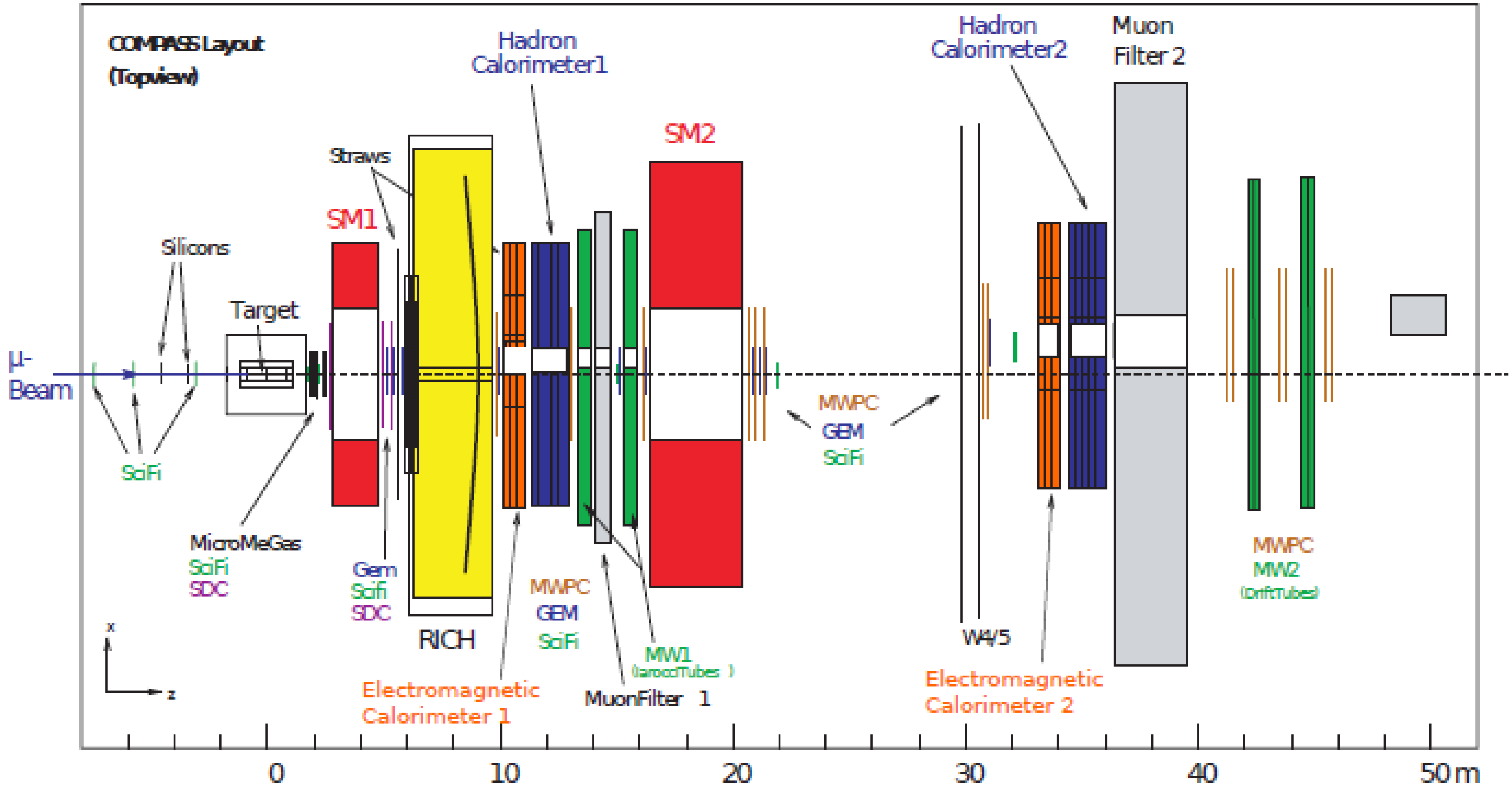
Operations on the target area

Targets

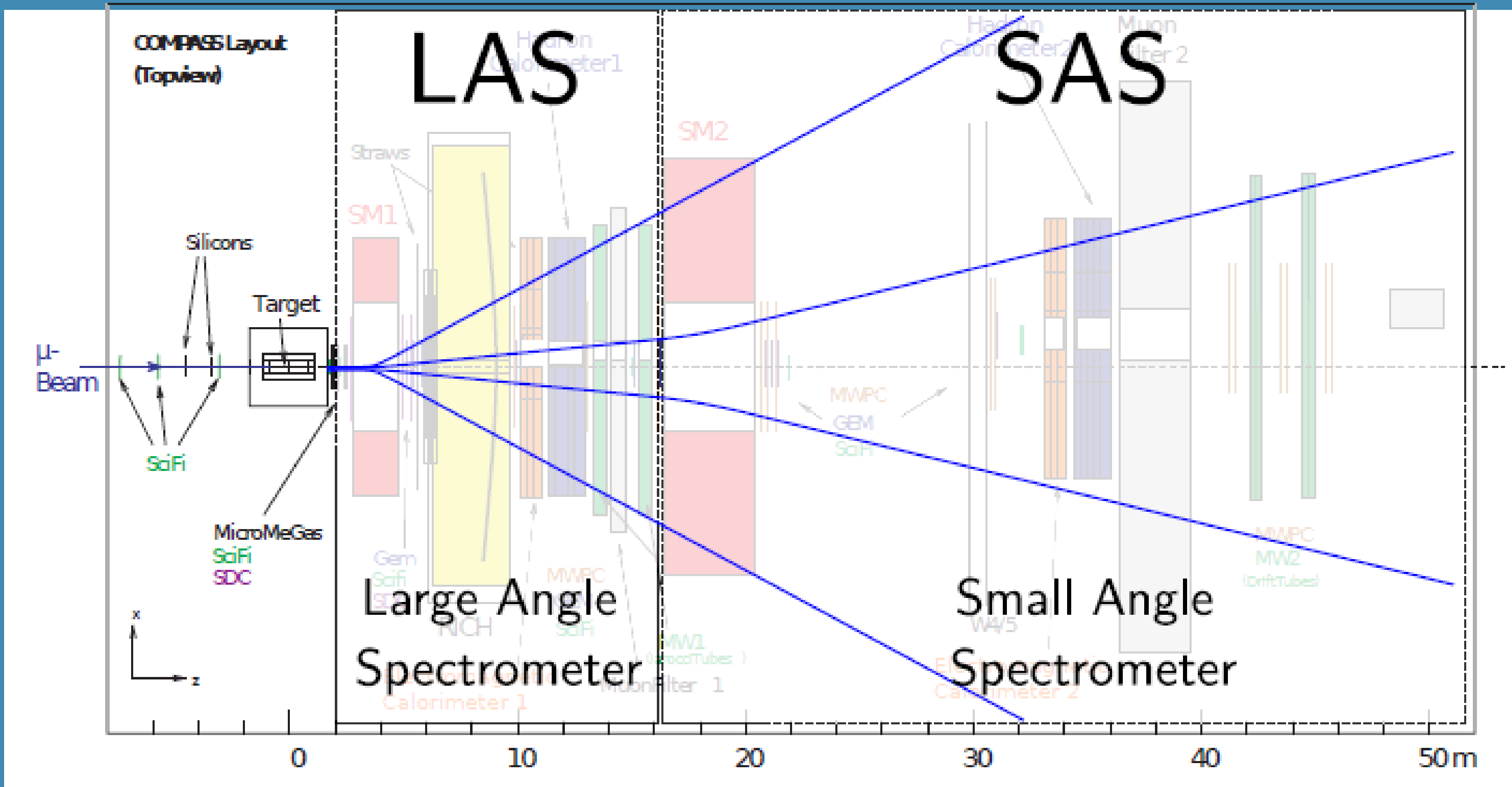

27 09 2012


Microwave cavity
Dilution refrigerator
New Magnet

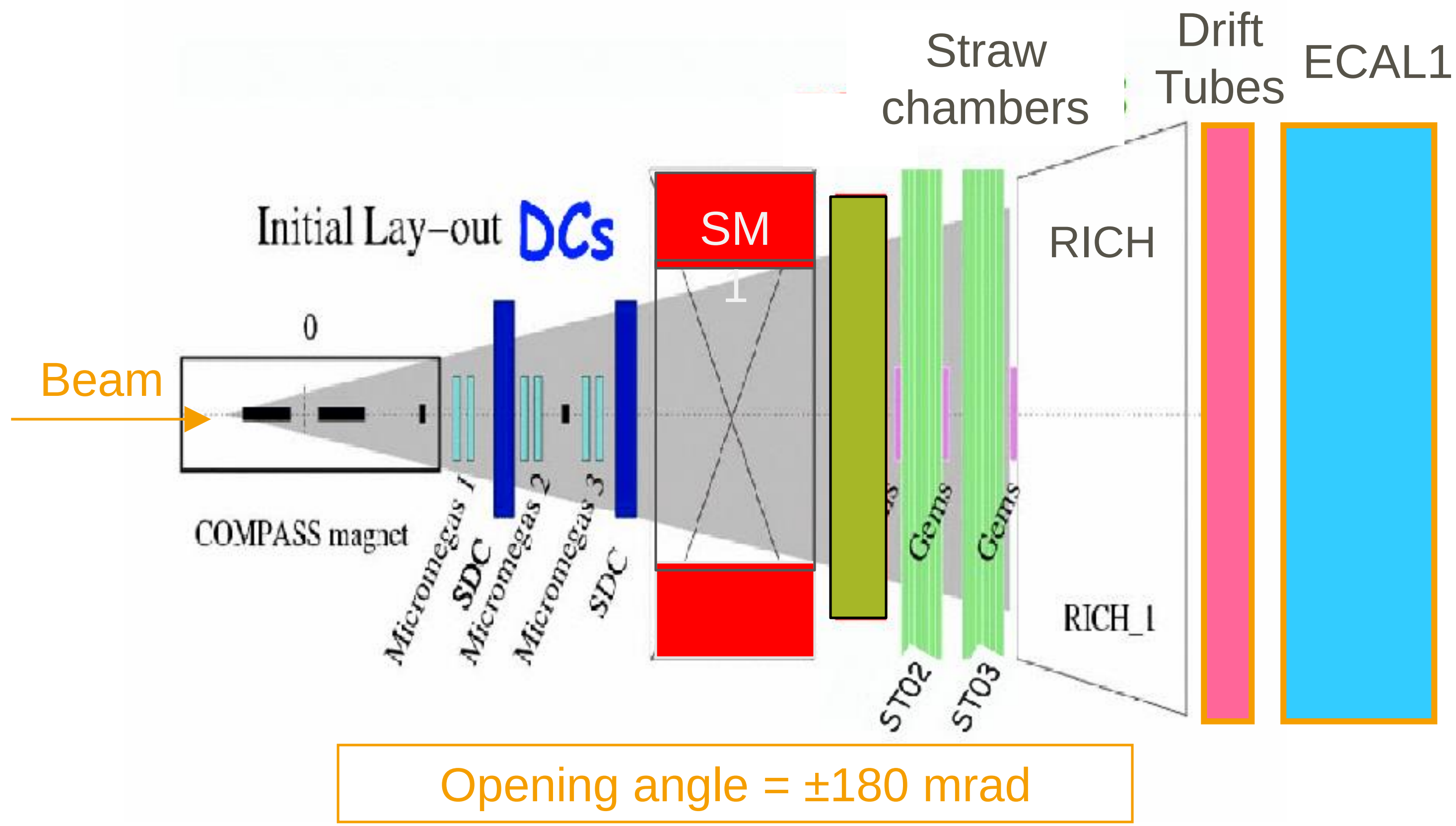
Spectrometer top view



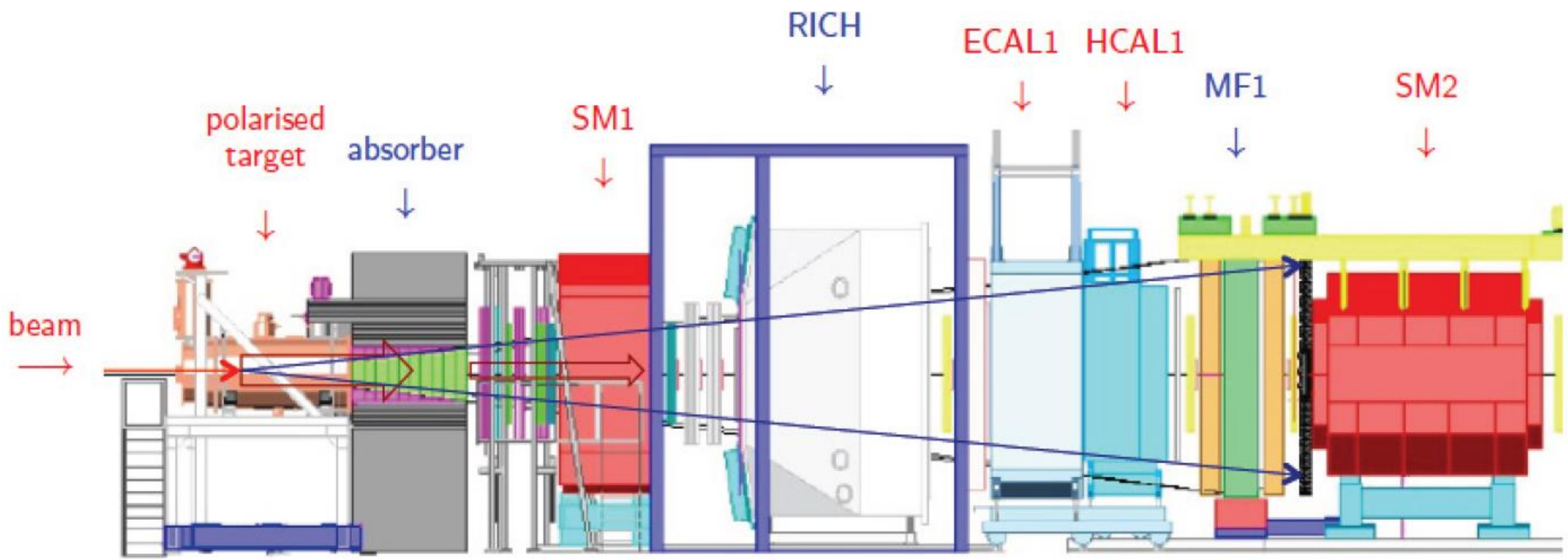
Two stage spectrometer



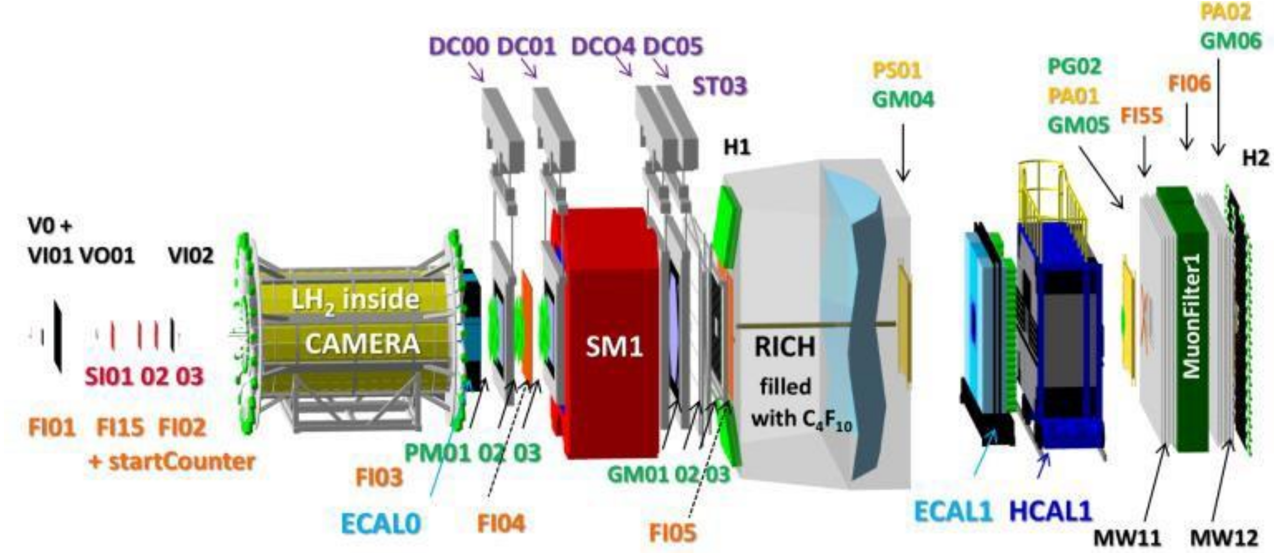
Large Angle Spectrometer

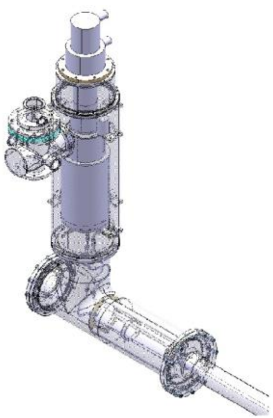


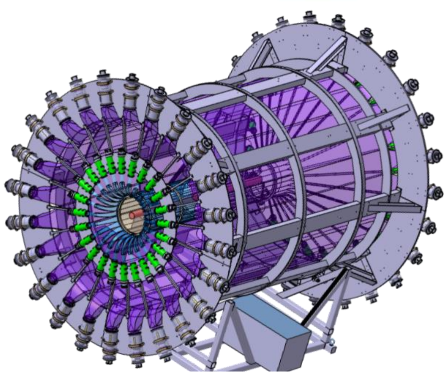
Hadron beam: Drell-Yan setup

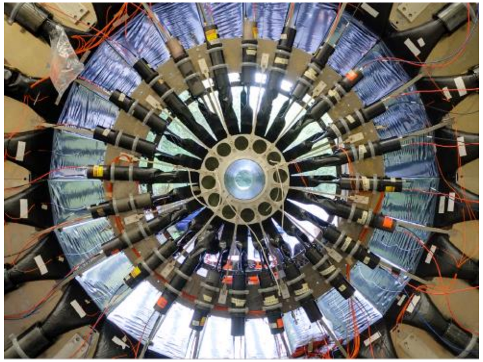


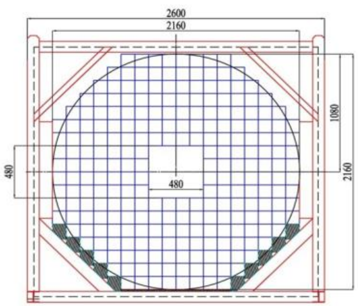
Muon beam – DVCS setup



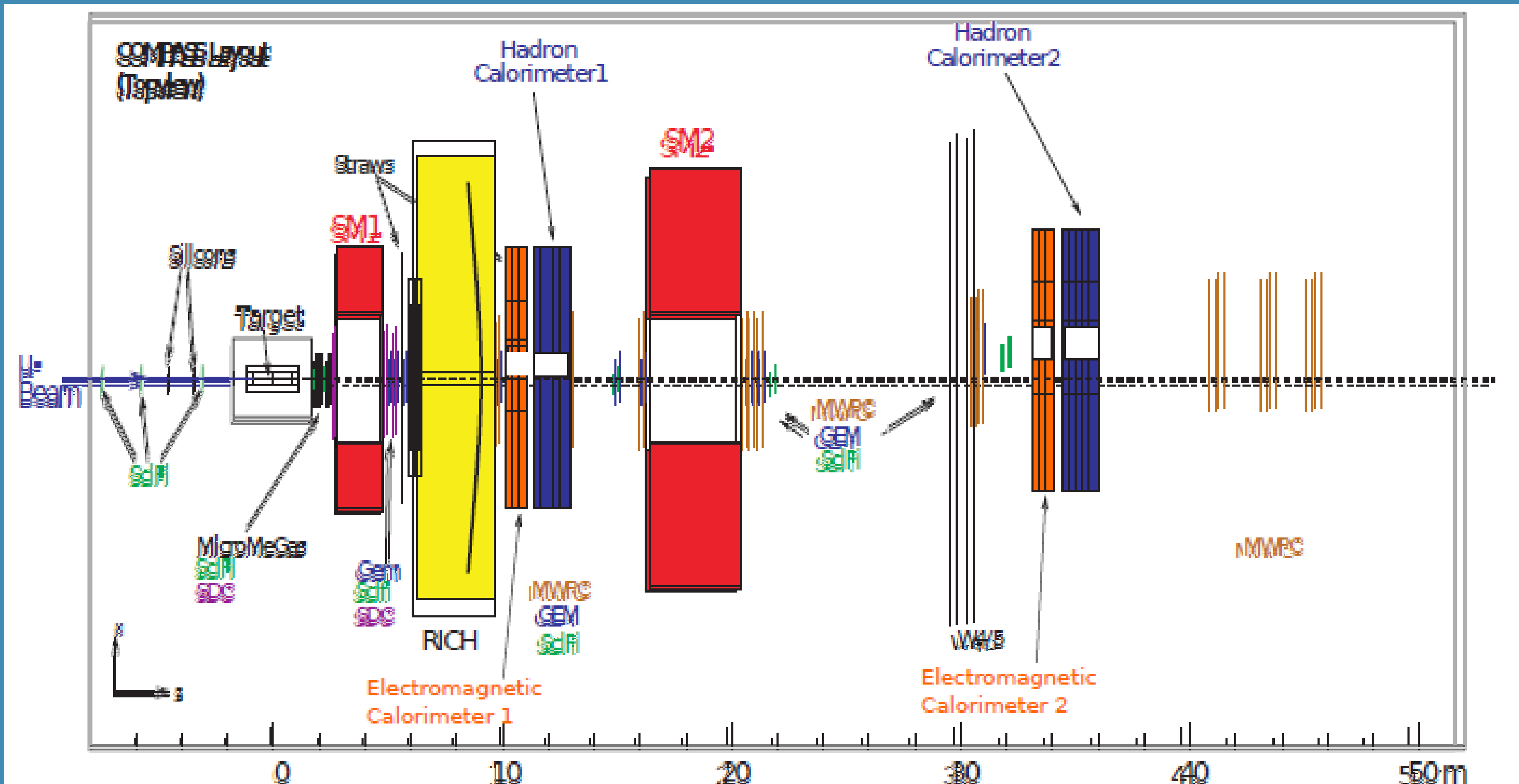




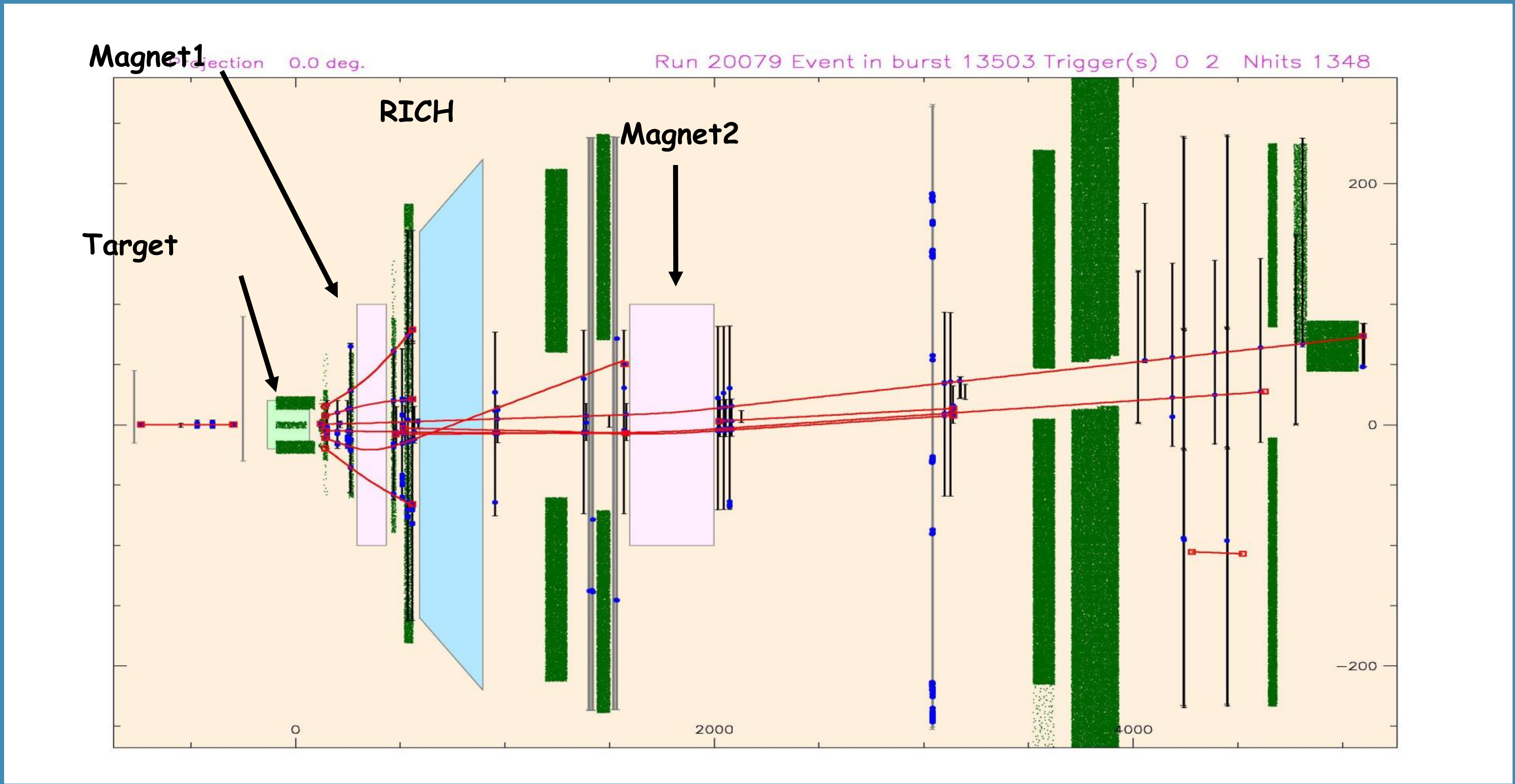




Spectrometer elements

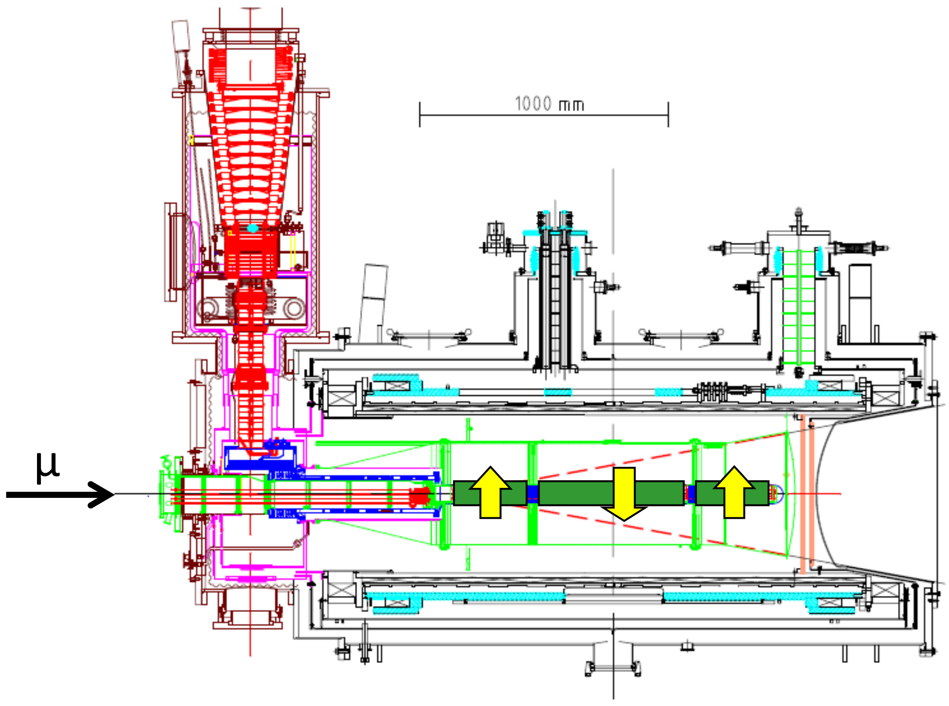


Spectrometer: momentum determination

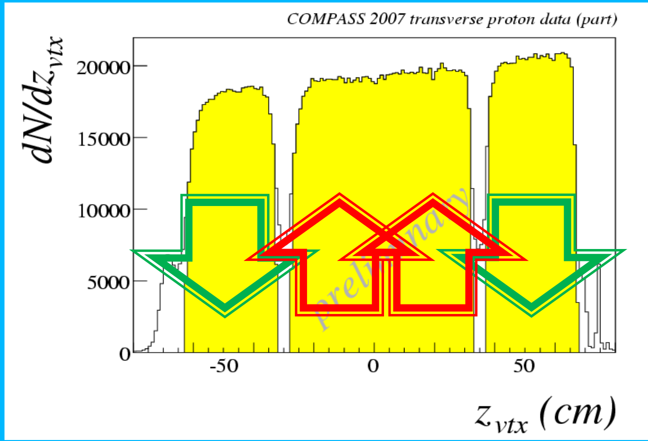


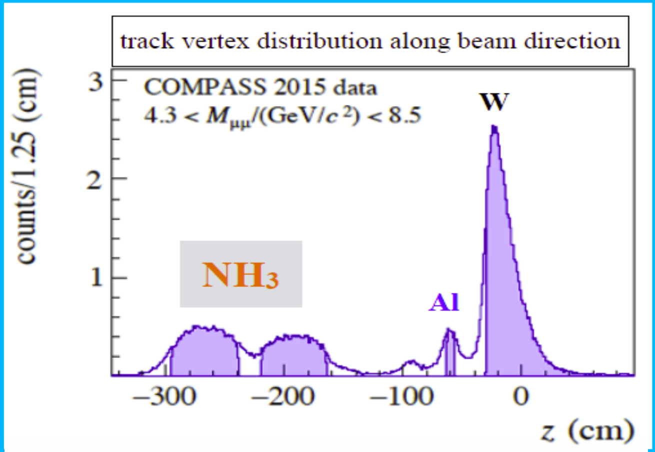
the polarized target system (>2005)

^{3}He – ^{4}He dilution refrigerator (T~50mK)

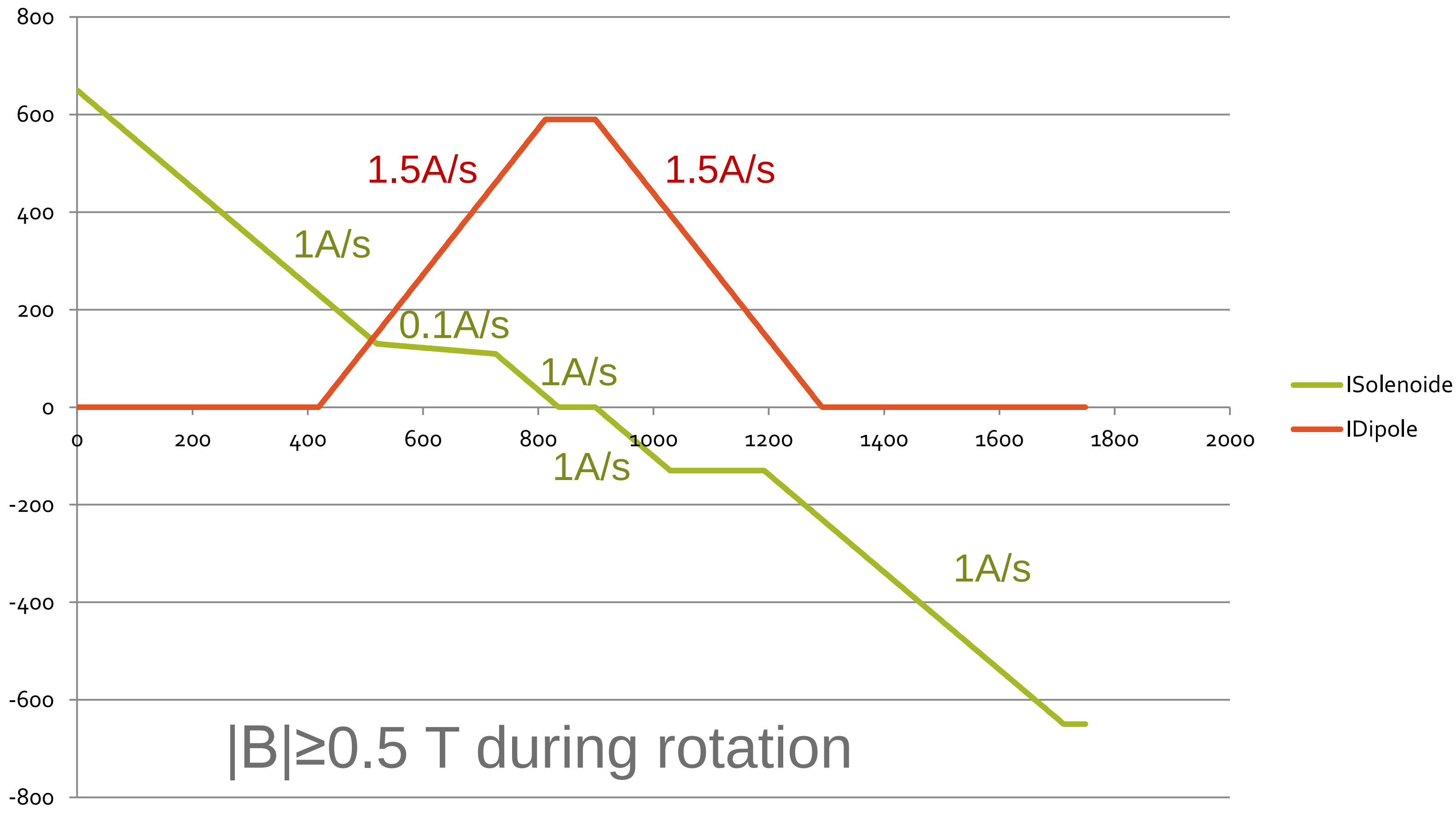


solenoid 2.5T
dipole magnet 0.6T

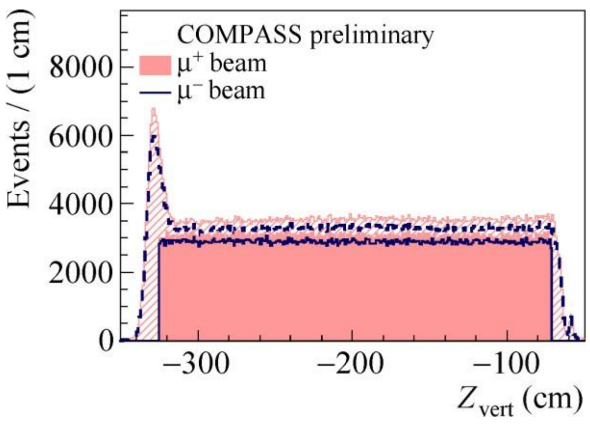


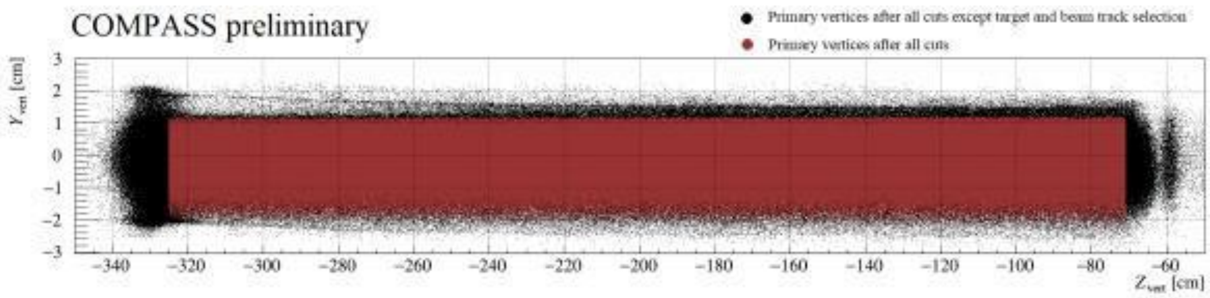


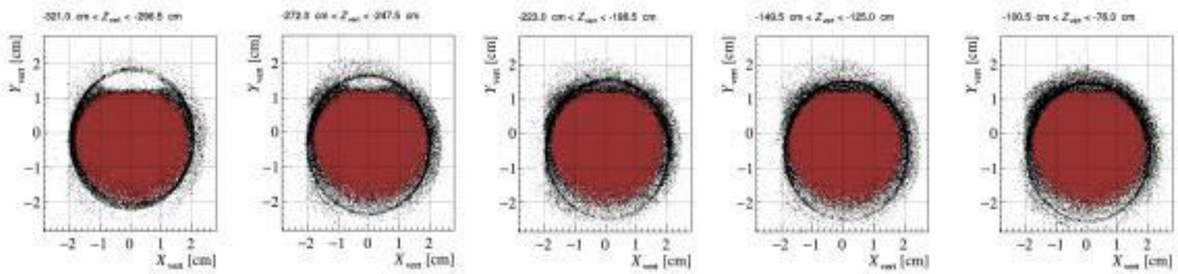
Typical cycle of a "field rotation"

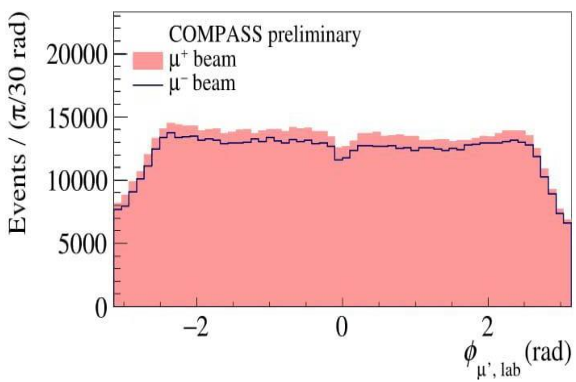


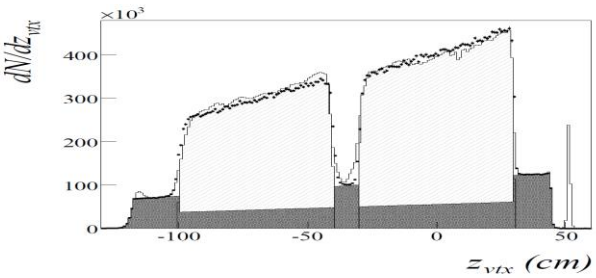
Vertex determination





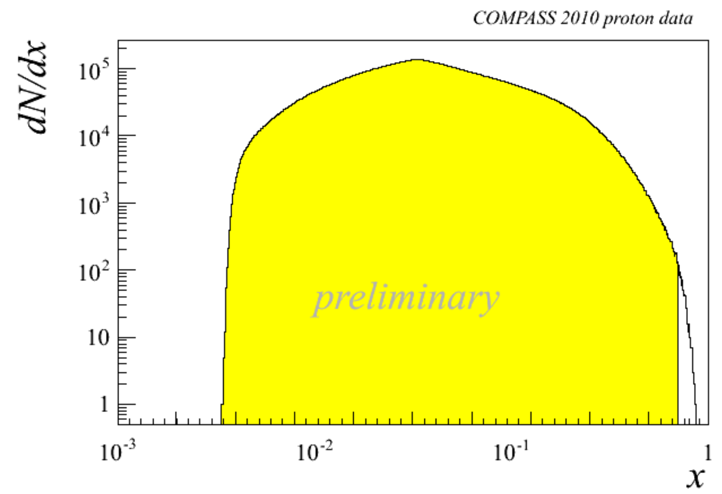


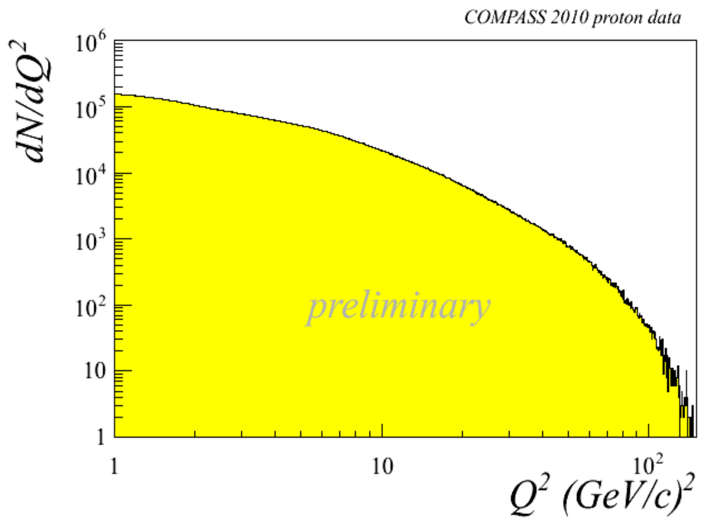


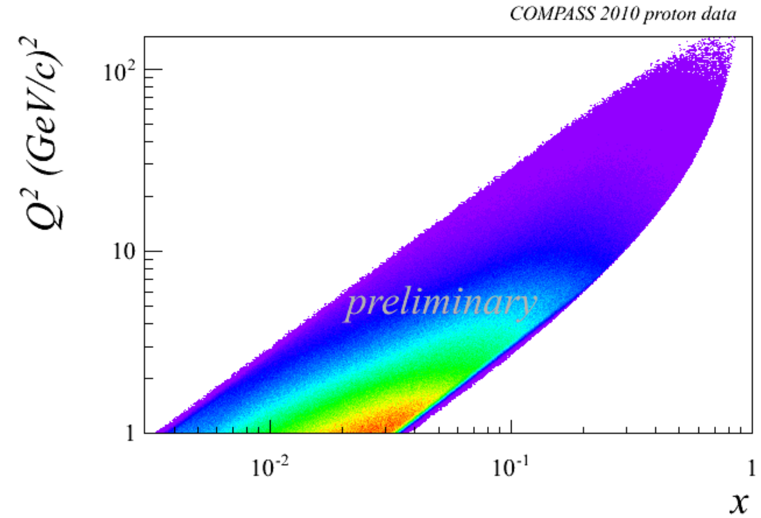


Kinematic distributions

DIS cuts: $Q^2 > 1\ (GeV/c)^2$
$0.1 < y < 0.9$
$W > 5\ GeV/c^2$



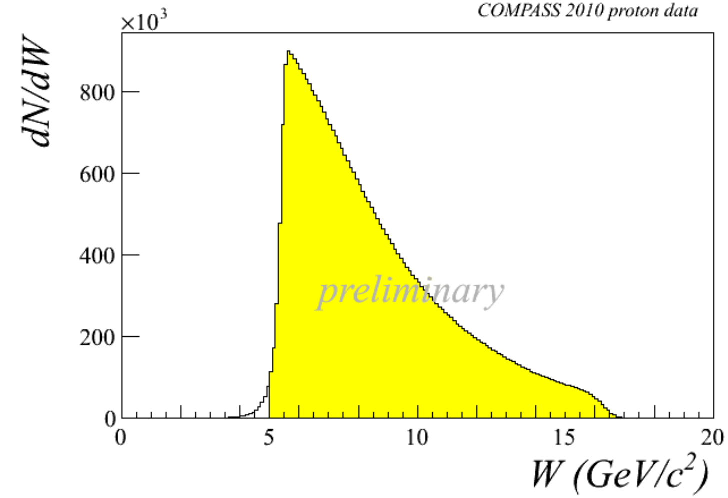


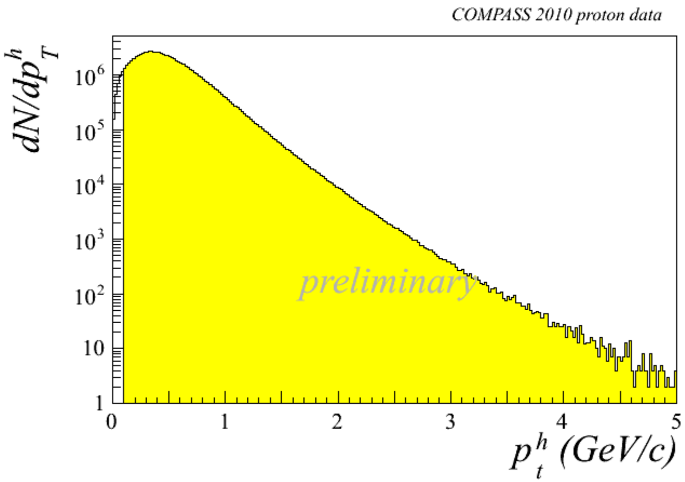


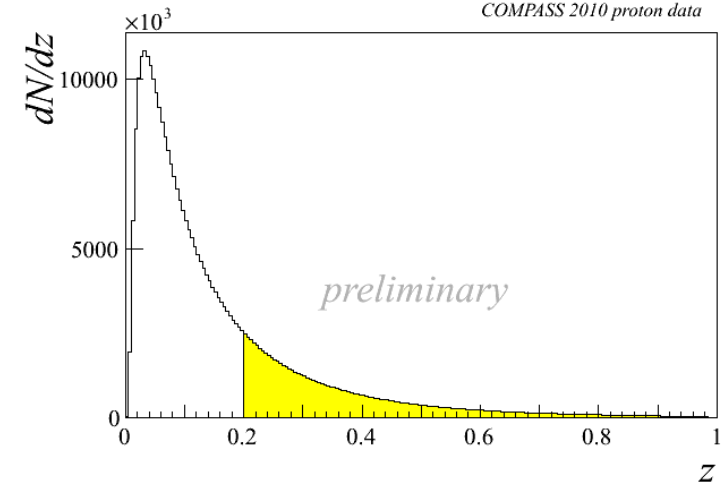
Kinematic distributions - 2

DIS cuts: $Q^2 > 1\ (\text{GeV}/c)^2$
$0.1 < y < 0.9$
$W > 5\ \text{GeV}/c^2$

hadron selection: $P_{hT} > 0.1$ GeV/c,
z>0.2



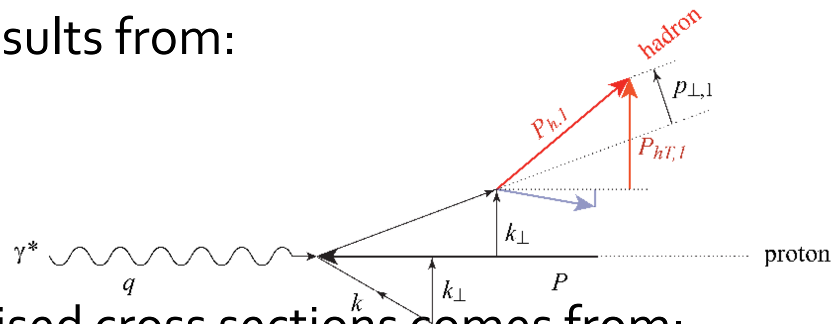




Selected COMPASS results on TMD effects

Importance of unpolarized SIDIS

- The cross section dependence from P_{hT} results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation



- The azimuthal modulations in the unpolarised cross sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

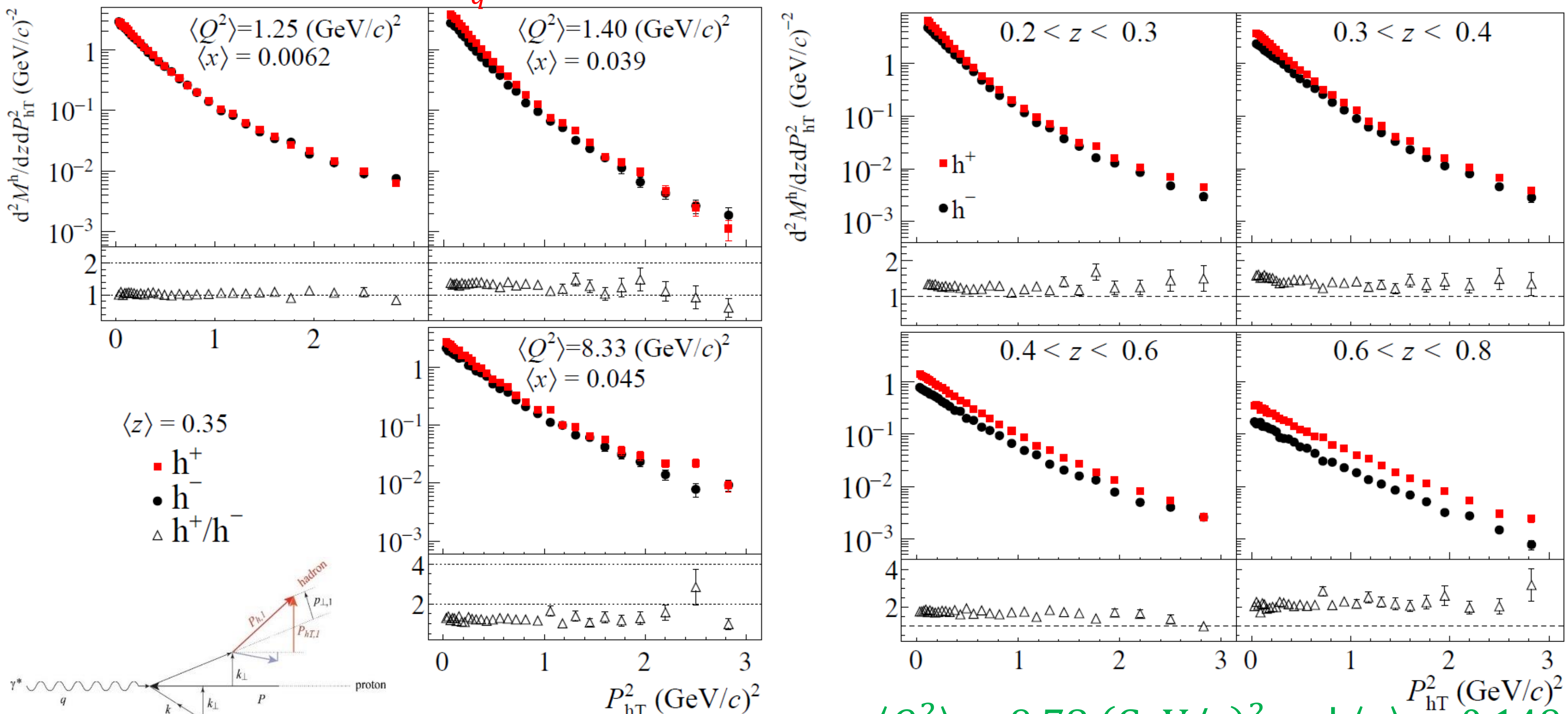
- Difficult measurements were one has to correct for the apparatus acceptance

- COMPASS and HERMES have
  - results on ^6LiD $(\sim d)$ and d and on p (Hermes only)
  - No COMPASS measurements on p since on NH_3 $(\sim p)$ nuclear effects may be important

- ⇒COMPASS-II, measurements on LH_2 in parallel with DVCS

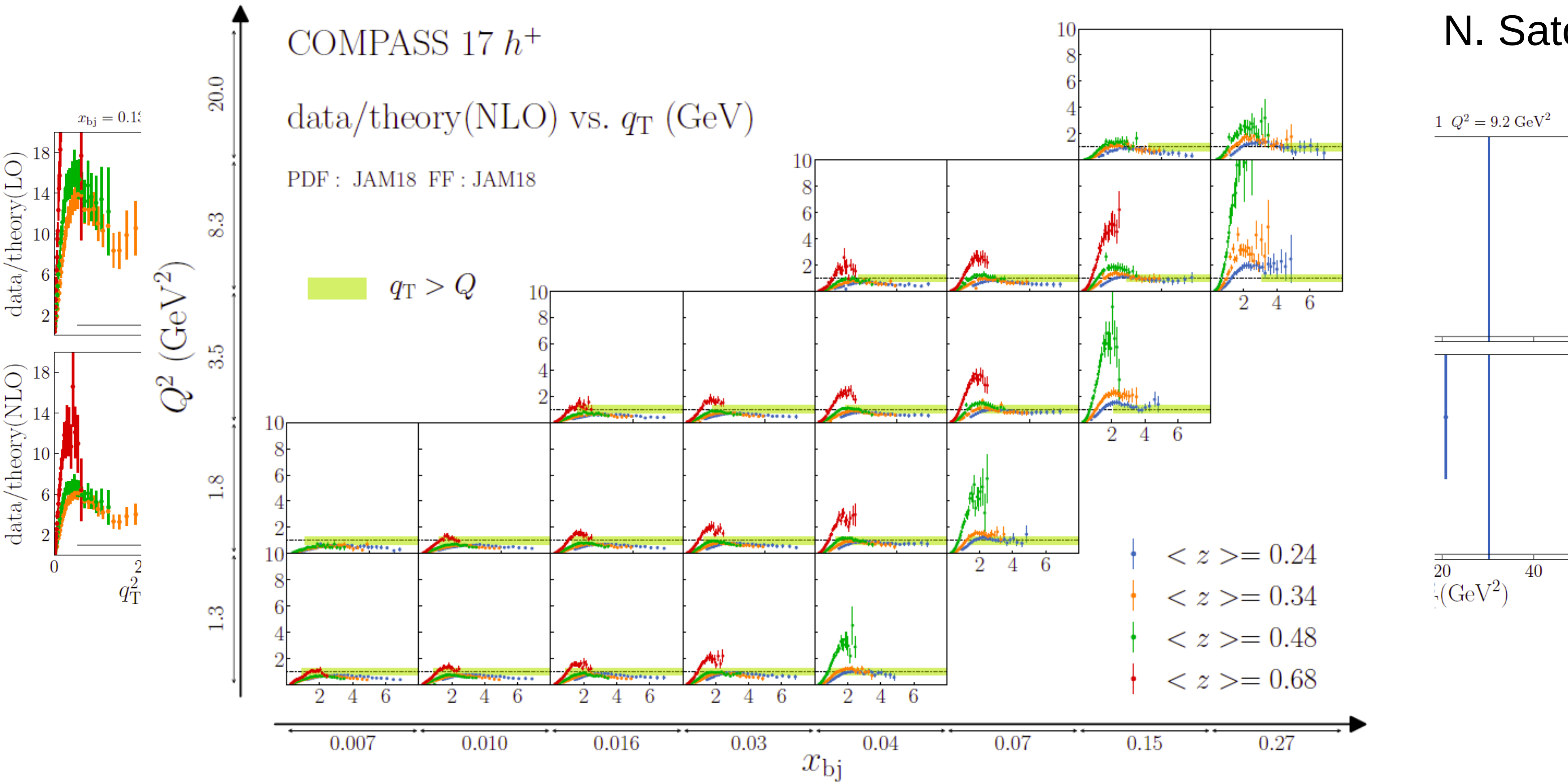
Positive vs Negative charged hadrons

$$F_{UU}^{h}(x,z,P_{hT}^2;\,Q^2) = x\sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta(\vec{p}_\perp + z\vec{k}_\perp - \vec{P}_{hT})\; f_1^q(x,k_\perp^2;Q^2) D_1^{q\to h}(z,p_\perp^2;Q^2)$$



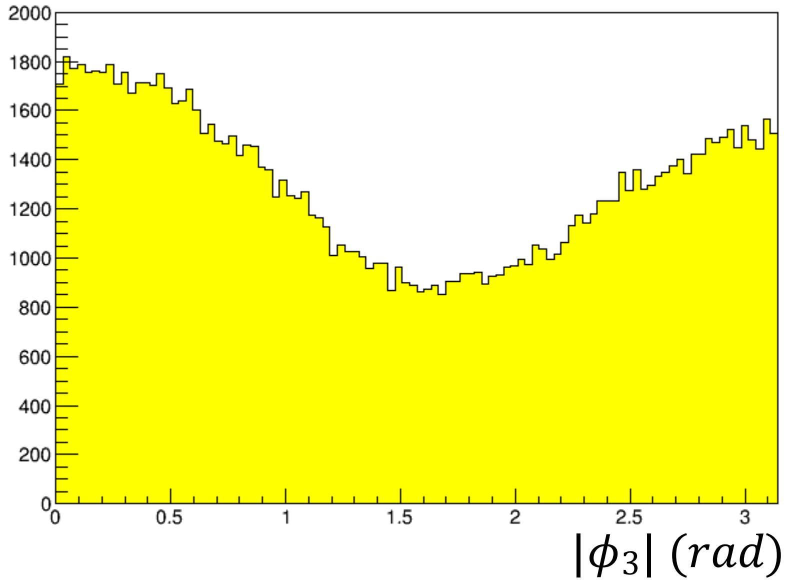
$\langle Q^2\rangle = 9.78\ (\mathrm{GeV}/c)^2$ and $\langle x\rangle = 0.149$

The matching problem ($q_T/Q > 1$ region)

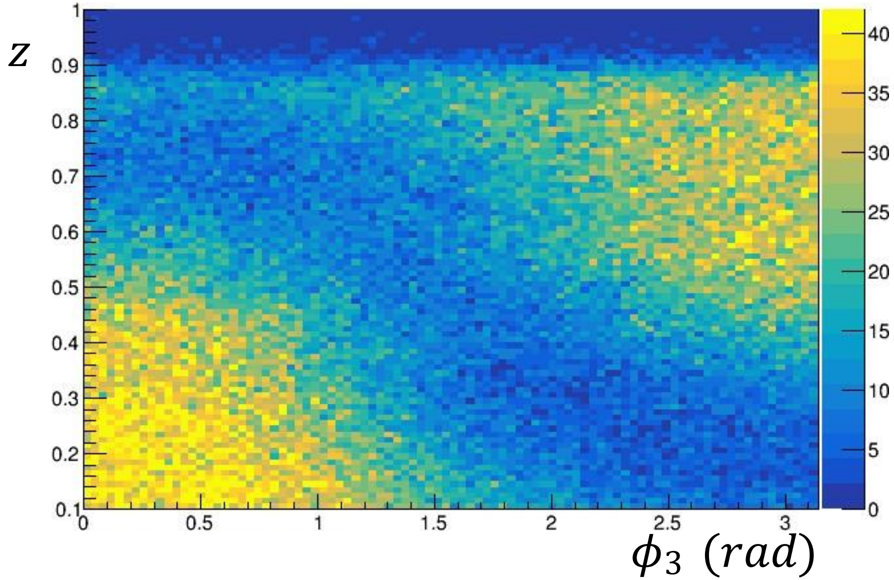


N. Sato

Azimuthal distributions in exclusive events



$|\phi_3|$ distribution for h+ in exclusive events

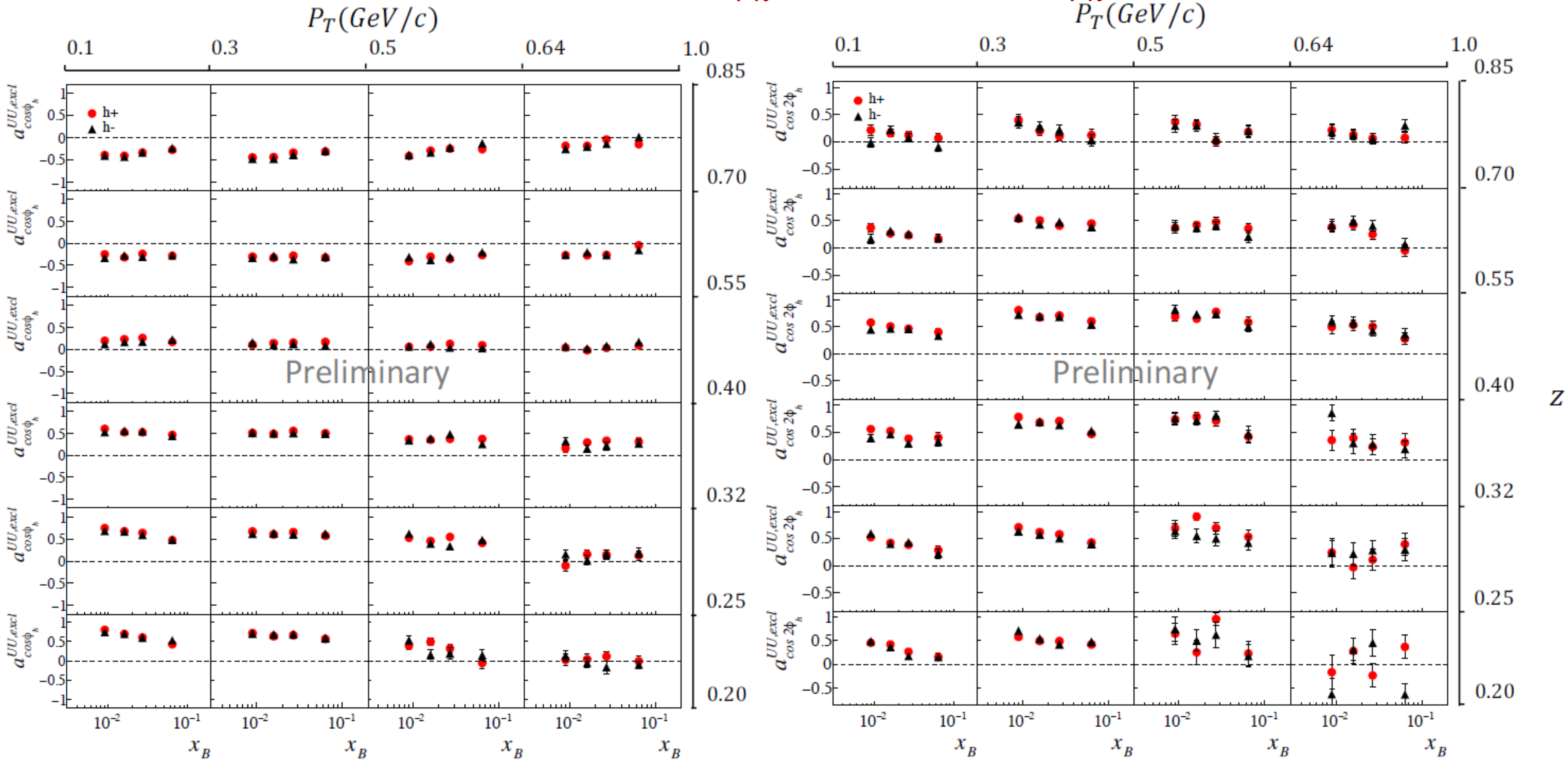


Correlation between z and $|\phi_3|$ for h^+ in exclusive events

- **$|\phi_h|$ distributions show very large modulations**
- **Strong correlation between z and $|\phi_h|$**

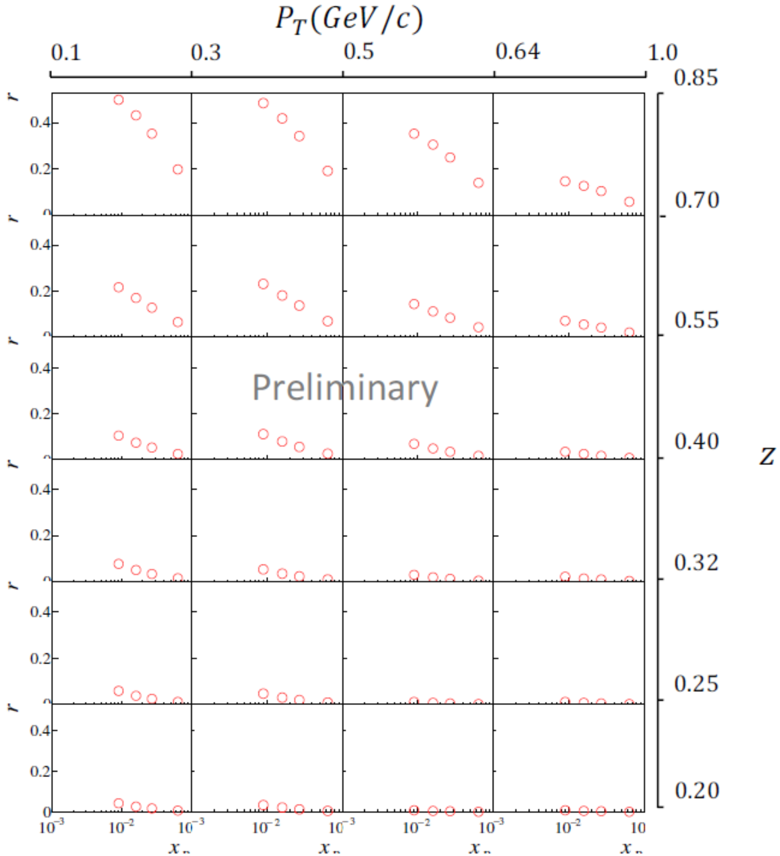
Modulations in the azimuthal distributions

$$N_{excl}(\phi_h) = N_0\left[1 + a^{UU\,excl}_{\cos\phi_h}\cos\phi_h + a^{UU\,excl}_{\cos 2\phi_h}\cos 2\phi_h\right]$$

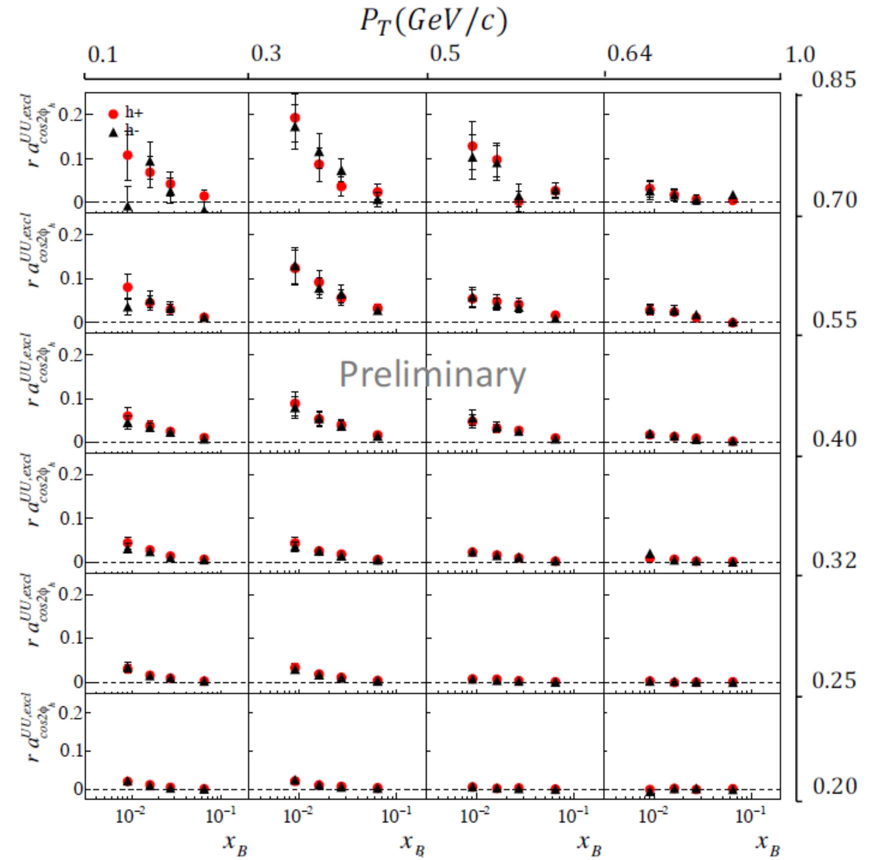


Subtraction from the measured asymmetries

$$r = N_h^{excl} / (N_h^{excl} + N_h^{SIDIS})$$



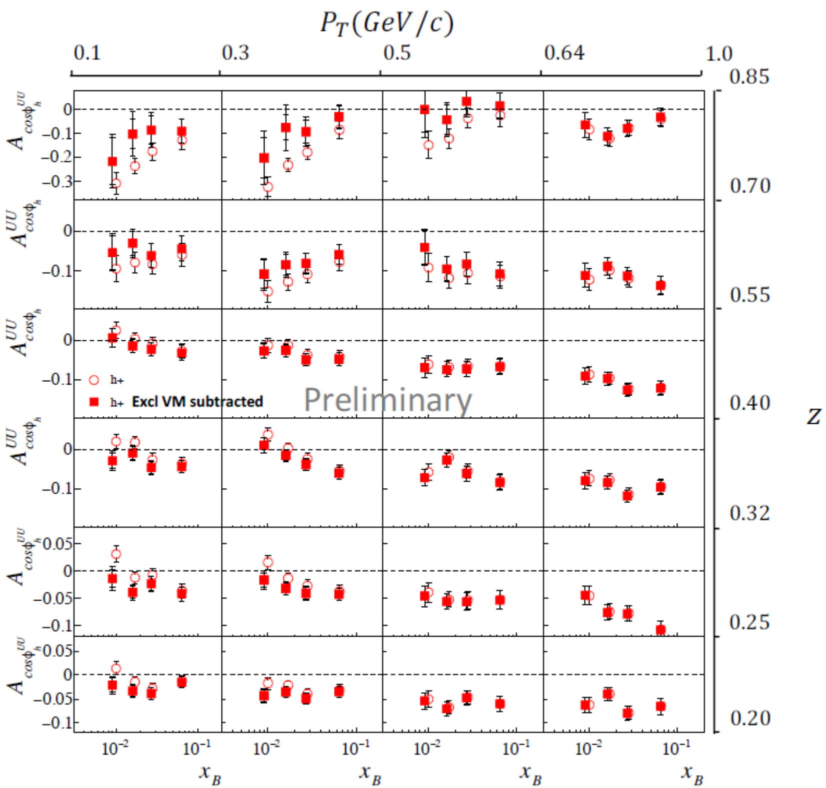
$$r a_{\cos\phi_h}^{UU\ excl}$$

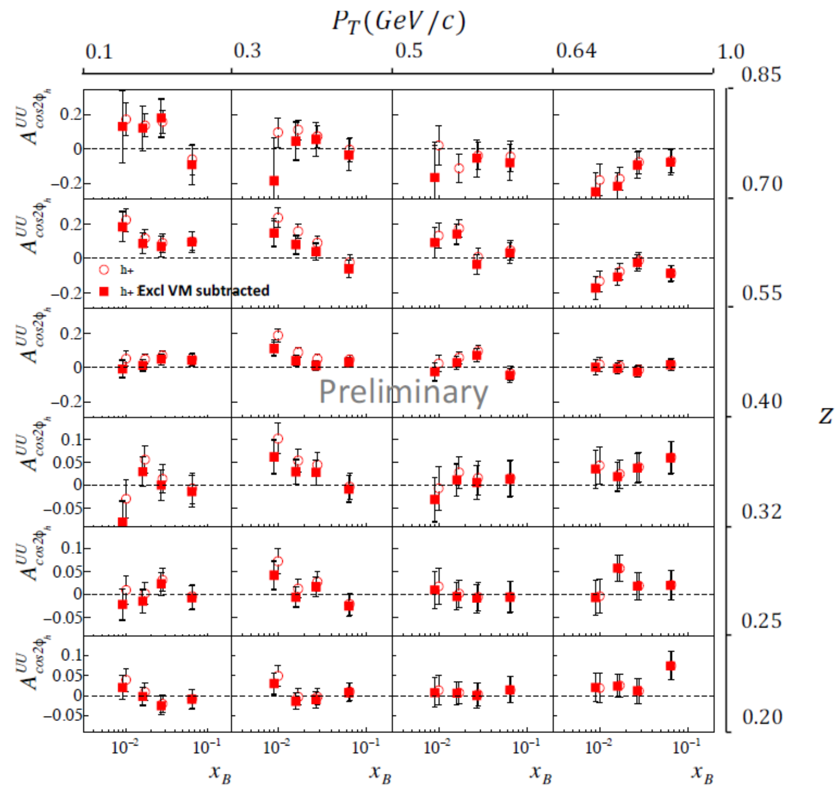


Subtracted results

$$A^{UU}_{\cos\phi_h} \rightarrow \frac{1}{1-r}\left(A^{UU}_{\cos\phi_h} - r a^{UU\,excl}_{\cos\phi_h}\right)$$

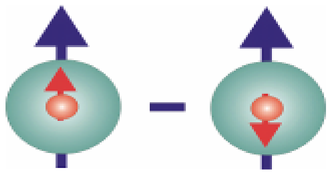
$$A^{UU}_{\cos 2\phi_h} \rightarrow \frac{1}{1-r}\left(A^{UU}_{\cos 2\phi_h} - r a^{UU\,excl}_{\cos 2\phi_h}\right)$$





Transversity PDF

$$h_1^q(\mathbf{x}) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$$



$q = u_v, d_v, q_{sea}$

quark with **spin** parallel to the nucleon spin in a transversely polarised nucleon

- probes the relativistic nature of quark dynamics
- no contribution from the gluons → simple Q^2 evolution
- Positivity: Soffer bound……………... $2|h_1^q| \leq f_1^q + g_1^q$ *Soffer, PRL 74 (1995)*
- first moments: tensor charge………. $\delta q(Q^2) = \int_0^1 dx\left[h_1^q(x) - h_1^{\bar{q}}(x)\right]$
- is chiral-odd: decouples from inclusive DIS *Bakker, Leader, Trueman, PRD 70 (04)*

Transversity

is chiral-odd:

observable effects are given only by the product of h_1^q (x) and an other chiral-odd function

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

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

"Collins" asymmetry

"Collins" Fragmentation Function

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

"two-hadron" asymmetry

"Interference" Fragmentation Function

$\ell N^{\uparrow} \rightarrow \ell' \, \Lambda \, X$

Λ polarisation

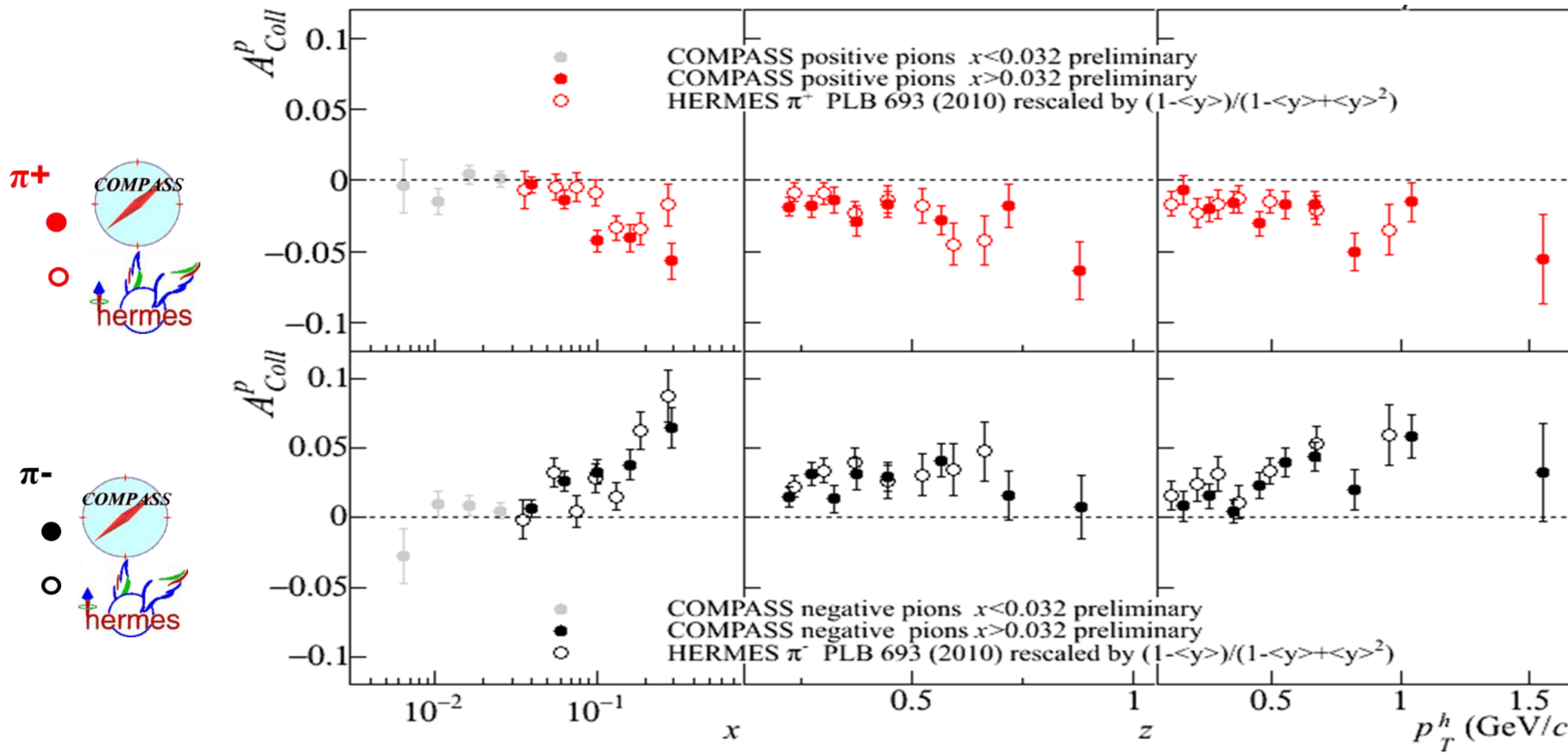
Fragmentation Function of q↑→Λ

Collins asymmetry on proton

x > 0.032 region

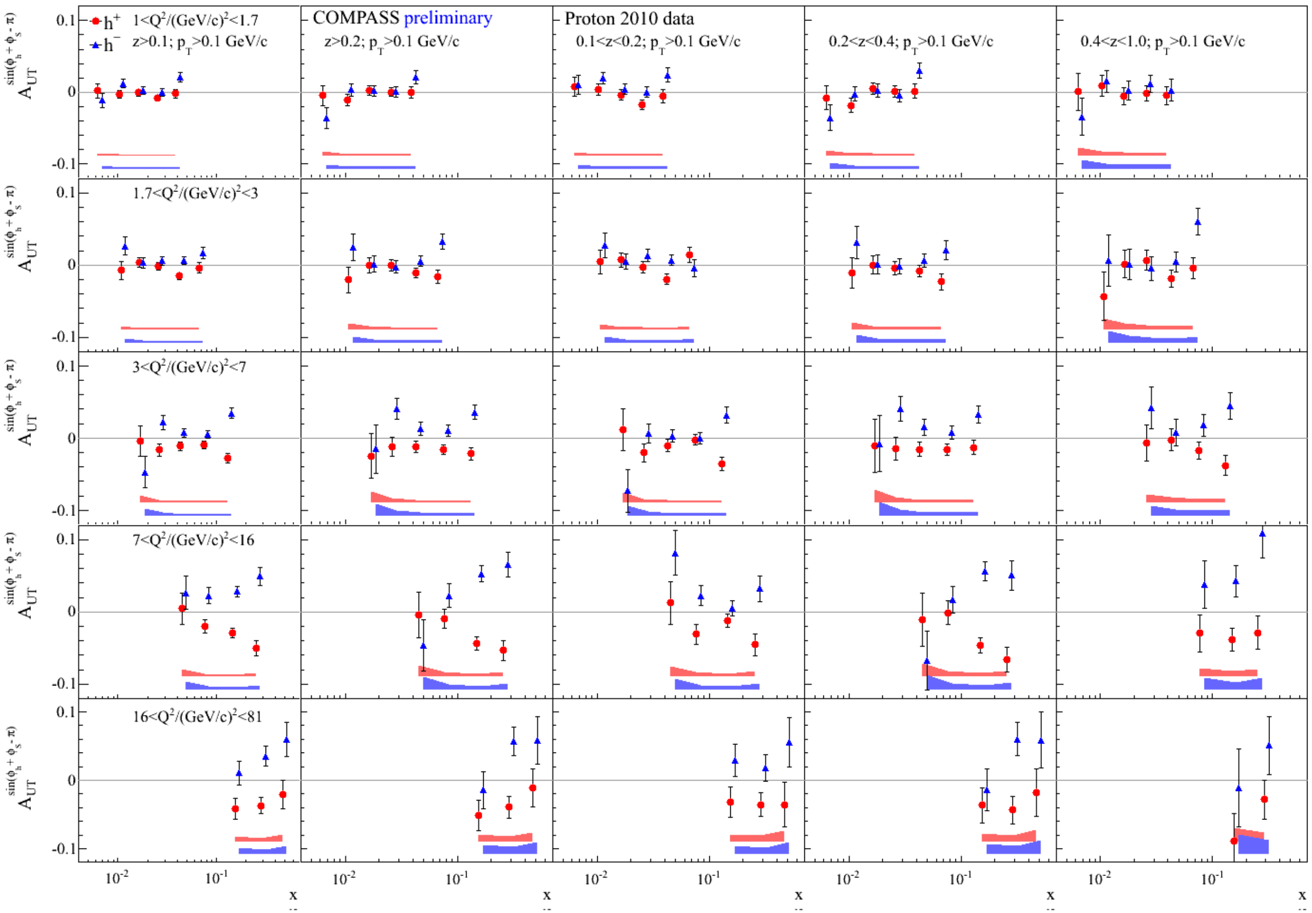
charged pions

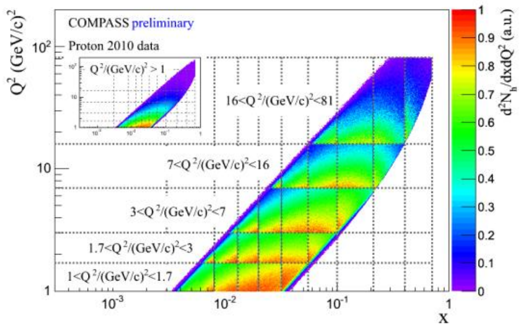
COMPASS and HERMES results



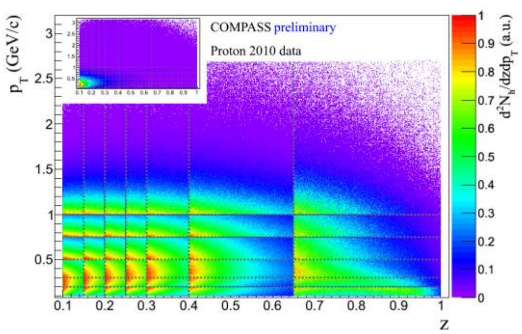
Collins asymmetry on proton. Multidimensional

Extraction of TSAs with a Multi-D $(x{:}\,Q^2{:}\,z{:}\,p_T)$ approach



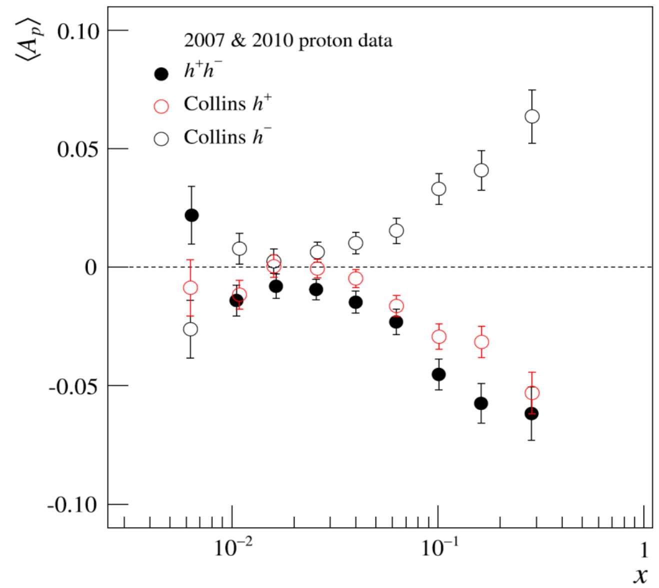


One dense plot out of many



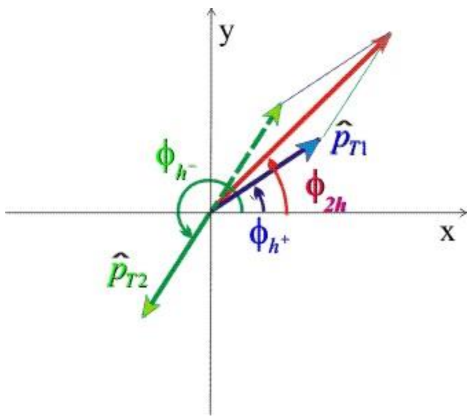
Interplay among dihadron and single hadron asymmetries

- Collins asymmetry for h+ and for h-
  "mirror symmetry"
- dihadron asymmetry
  only somewhat larger than h+ Collins



hints for a common origin
of the Collins FF and DiFF

Como 2013, DSpin2013, PLB736 (2014) 124

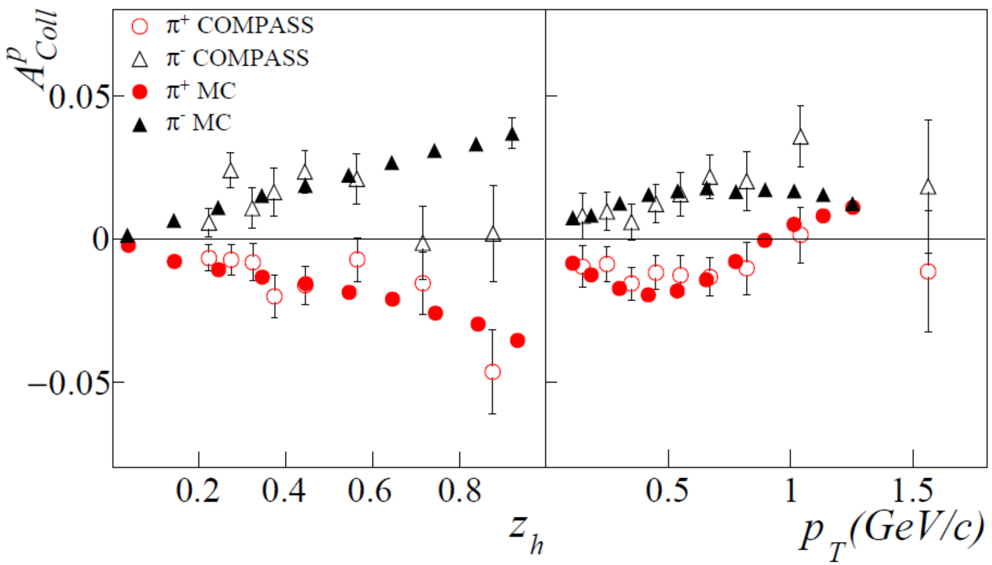


look at
the $\Delta\phi = \phi_1 - \phi_2$
dependence of the asymmetries

COMPASS

A^p_{Coll} on proton and $^3P_0$ model for FF

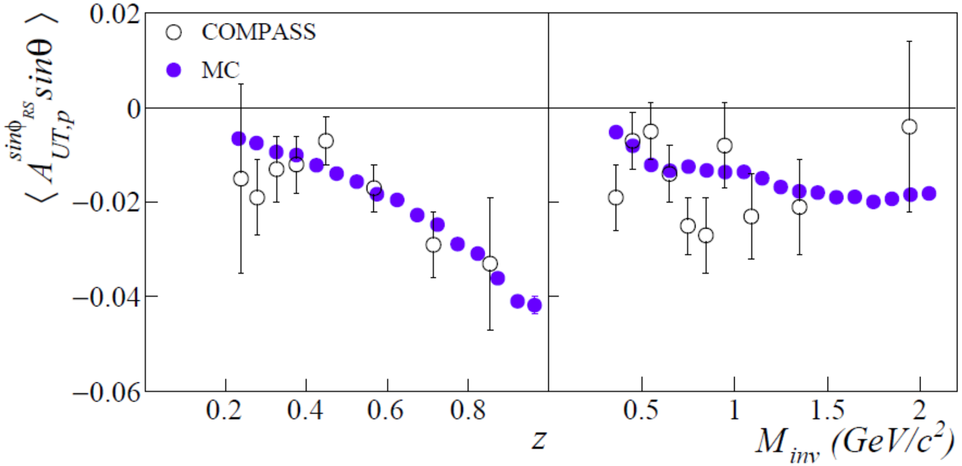
Albi Kerbizi @ DSPIN17 http://theor.jinr.ru/~spin/2017/
Phys. Rev. D 97, 074010 (2018)/arXiv:1802.00962

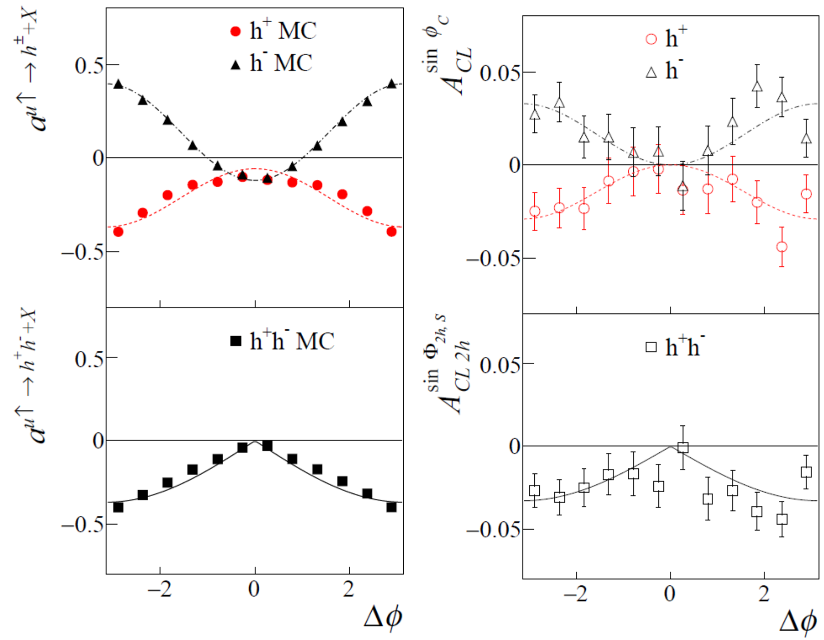


- The curves are fits of the Monte Carlo data, scaled by $\lambda \sim \langle h_1^u / f_1^u \rangle \sim 0.055$
- Agreement with the measured Collins asymmetry is quite satisfactory

2h asymmetries on p and $^3P_0$ model for FF

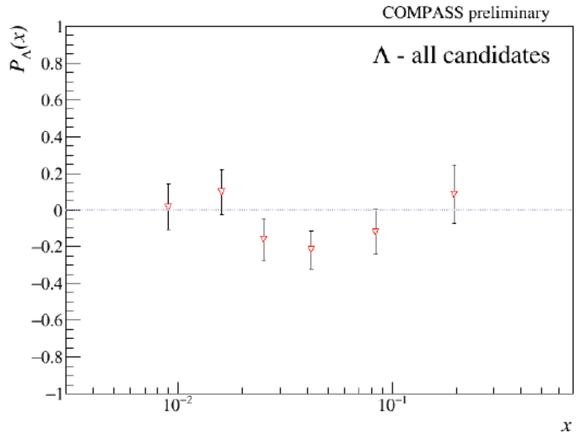
$$A_{UT}^{\sin(\phi_R+\phi_S-\pi)} = \frac{\sum_q e_q^2 h_1^q(x) H_{q\to h_1h_2}^{\measuredangle}\left(z,\mathcal{M}_{h_1h_2}^2\right)}{\sum_q e_q^2 q(x) D_q^{h_1h_2}\left(z,\mathcal{M}_{h_1h_2}^2\right)}$$

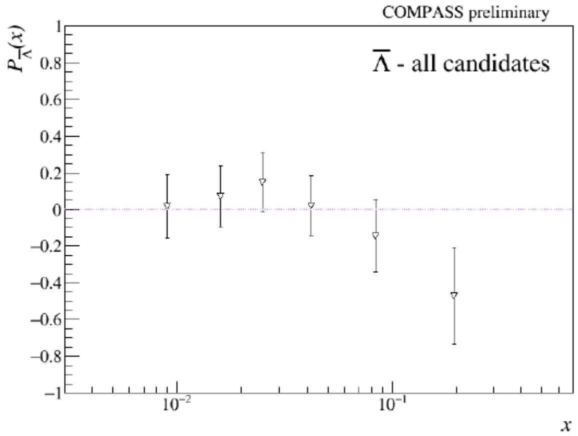




$a_P^{u\uparrow\to h^+h^-X} = \langle\sin(\phi_R+\phi_S-\pi)\rangle$ and $\vec{R} = \frac{z_2\vec{P}_{h1}-z_1\vec{P}_{h2}}{z_1+z_2}$ and as before $\lambda\sim\langle h_1^u/f_1^u\rangle\sim 0.055$

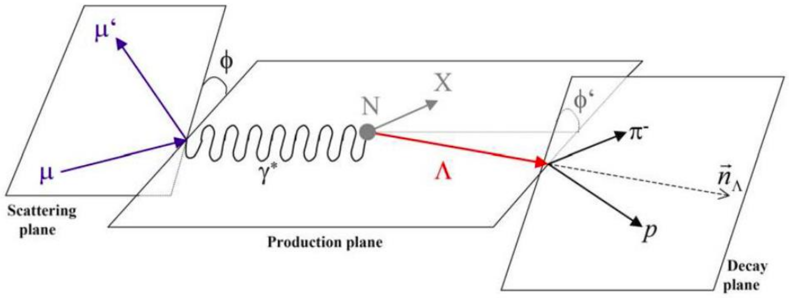
Λ transverse spin transfer from COMPASS





$$P_{\Lambda(\bar{\Lambda})}(x,z) = \frac{\sum_q e_q^2 h_1^q(x)\, H_1^{\Lambda(\bar{\Lambda})}(z)}{\sum_q e_q^2 f_1^q(x)\, D_1^{\Lambda(\bar{\Lambda})}(z)}$$

$$\frac{dN}{d\cos\theta^*} \propto A\left(1 + \alpha P_{\Lambda(\bar{\Lambda})}\cos\theta^*\right)$$



Sivers Asymmetry

Sivers: correlates nucleon spin & quark transverse momentum k_T /T-ODD

at LO:

$$A_{Siv} = \frac{\sum_q e_q^2 f^{\perp}_{1Tq} \otimes D_q^h}{\sum_q e_q^2 q \otimes D_q^h}$$

$$\mu p^{\uparrow} \rightarrow \mu X h^{\pm}$$

The Sivers PDF	
1992	Sivers proposes $f_{1T}^{\perp}$
1993	J. Collins proofs $f_{1T}^{\perp} = 0$ for T invariance
2002	S. Brodsky, Hwang and Schmidt demonstrate that $f_{1Tq}^{\perp}$ may be $\neq 0$ due to FSI
2002	J. Collins shows that $(f_{1T}^{\perp})_{DY} = -(f_{1T}^{\perp})_{SIDIS}$
2004	HERMES on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$
2004	COMPASS on d: $A_{Siv}^{\pi^+} = 0$ and $A_{Siv}^{\pi^-} = 0$
2008	COMPASS on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$

Sivers Asymmetry

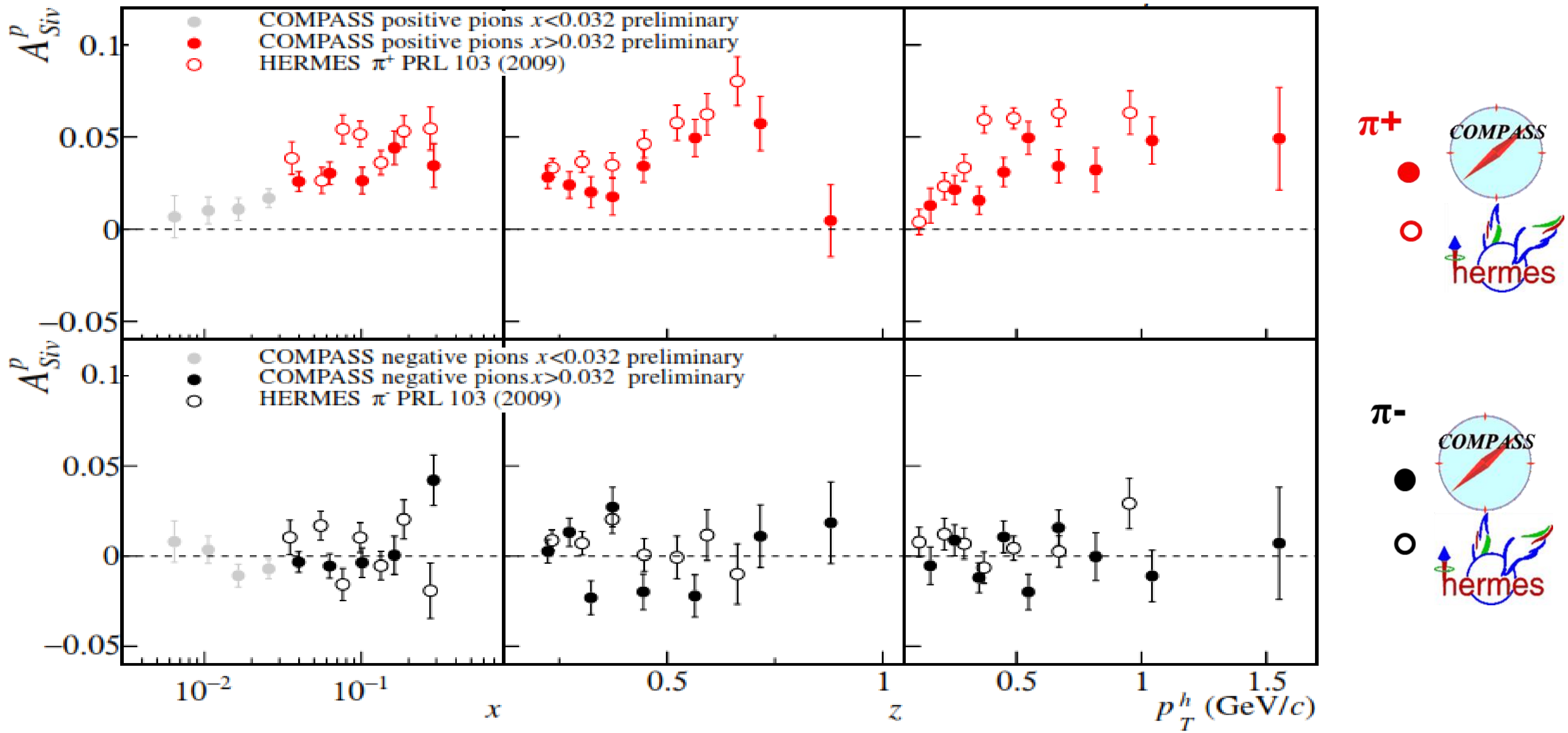
$$A_{Siv}(x,z) = \frac{F_{UT}^{\sin\Phi_{Siv}}(x,z)}{F_{UU}(x,z)} = \frac{\sum_q e_q^2 x f_{1T}^{\perp q}(x, k_\perp^2) \otimes D_{1q}^h(z, \ p_\perp^2)}{\sum_q e_q^2 x f_1^q(x, \ k_\perp^2) \otimes D_{1q}^h(z, \ p_\perp^2)}$$

- To evaluate it we need to solve the convolutions (i.e. make hypothesis on the transverse momenta dependences of the TMDs)
- Gaussian ansatz: $f_{1T}^{\perp q}(x) \frac{e^{-k_\perp^2/\langle k_\perp^2 \rangle_S}}{\pi \langle k_\perp^2 \rangle_S}$ $\quad D_{1q}^h(z) \frac{e^{-p_\perp^2/\langle p_\perp^2 \rangle}}{\pi \langle p_\perp^2 \rangle}$
- Leading to: $A_{Siv,G}(x,z) = \frac{\sqrt{\pi} M}{\sqrt{z^2 \langle k_T^2 \rangle_S + \langle p_T^2 \rangle}} \frac{\sum_q e_q^2 \, x f_{1T}^{\perp(1)q}(x) z D_{1q}^h(z)}{\sum_q e_q^2 x f_1^q(x) D_{1q}^h(z)}$ with $f_{1T}^{\perp(1)q}(x)$

$= \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x, k_T^2)$

Sivers asymmetry on p

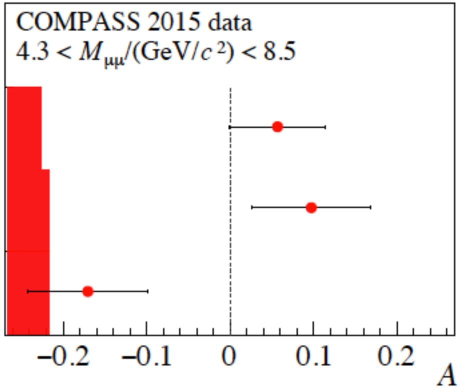
charged pions (and kaons), HERMES and COMPASS



Transverse Spin Asymmetry in Drell-Yan

190 GeV/c π^- beam, transversely polarized NH_3 target

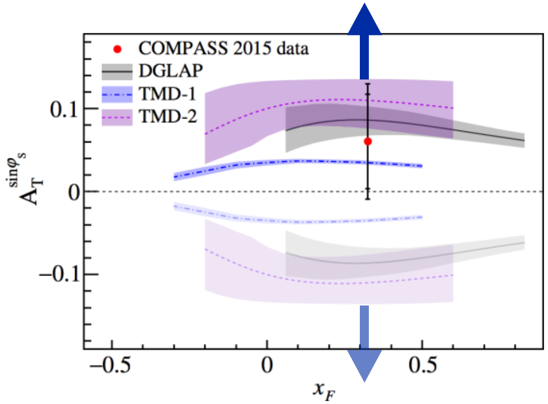
$$f_{1T,\mathrm{DY}}^{\perp} = -f_{1T,\mathrm{SIDIS}}^{\perp}$$



(Sivers)$_p$ ⊗ $(f_1)_\pi$

(Pretzelosity)$_p$ ⊗ (BM)$_\pi$

(Transversity)$_p$ ⊗ (BM)$_\pi$



PRL119, 112002 (2017).

The weighted Sivers asymmetry

- If we weight the spin dependent part of the cross-section

$$F_{UT}^{\sin\Phi_{Siv}}(x,z) = \Sigma_q\, e_q^2 \int d^2\vec{P}_T P_T F_q(x,z,P_T^2)$$

- with $w = P_T/zM$, i.e.

$$F_{UT}^{\sin\Phi_{Siv},w}(x,z) = \Sigma_q\, e_q^2 \int d^2\vec{P}_T \frac{P_T^2}{zM} F_q(x,z,P_T^2) = 2\,\Sigma_q\, e_q^2 x f_{1T}^{\perp(1)q}(x) D_{1q}^h(z)$$

and $F_q(x,z,P_T^2) = \int d^2\vec{k}_T \int d^2\vec{p}_T\, \delta^2(\vec{P}_T - z\vec{k}_T - \vec{p}_T) \frac{\vec{P}_T \cdot \vec{k}_T}{MP_T^2} x f_{1T}^{\perp q}(x,k_T^2)\, D_{1q}(z,p_T^2)$

- we have no longer a convolution but a product of two integrals and we can write

$$A_{Siv}^{w}(x,z) = \frac{F_{UT}^{\sin\Phi_{Siv},w}(x,z)}{F_{UU}(x,z)} = 2\frac{\Sigma_q\, e_q^2 x f_{1T}^{\perp(1)q}(x) D_{1q}^h(z)}{\Sigma_q\, e_q^2 x f_1^q(x) D_{1q}^h(z)}$$

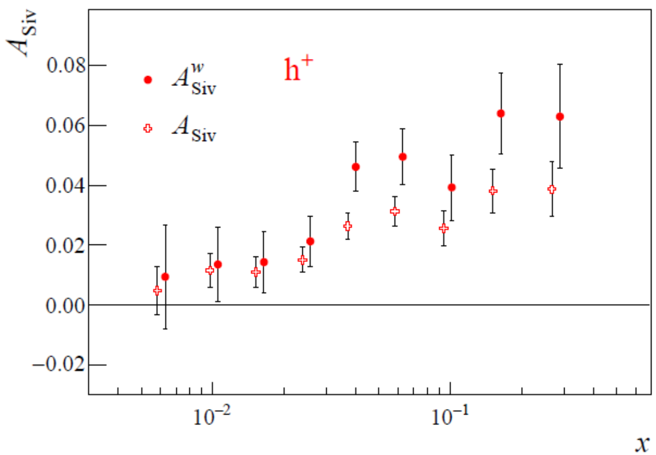
with $f_{1T}^{\perp(1)q}(x) = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x,k_T^2)$

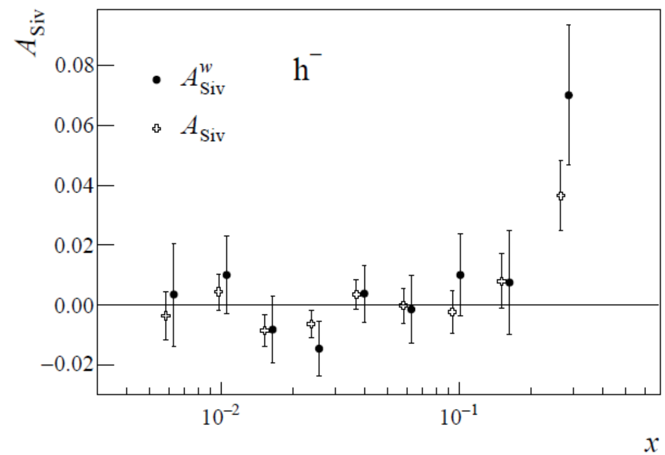
The weighted Sivers asymmetry

$$A^{w}_{Siv}(x) = 2\,\frac{\sum_q e_q^2\, x f_{1T}^{\perp(1)q}(x) \int D_{1q}^h(z)dz}{\sum_q e_q^2\, x f_1^q(x) \int D_{1q}^h(z)dz}$$

$w = P_T/zM$

standard cuts
z>0.2





$$\sim 2\,\frac{f_{1T}^{\perp(1)u}(x)}{f_1^u(x)}$$

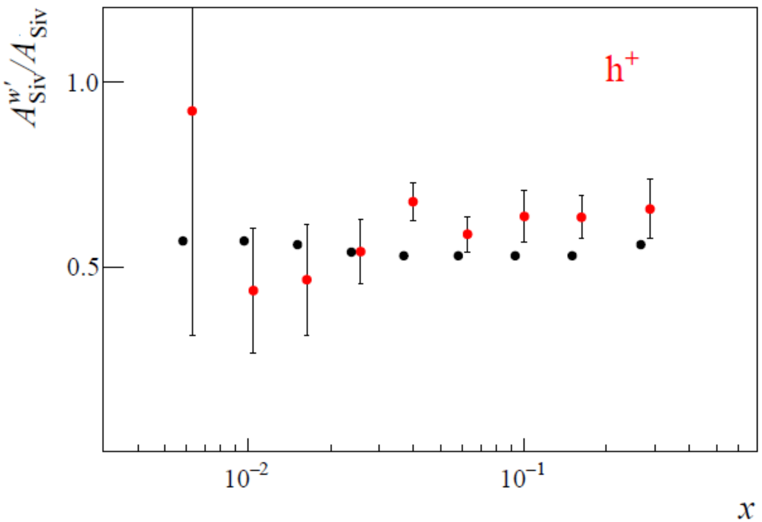
both $f_{1T}^{\perp(1)u}$ and $f_{1T}^{\perp(1)d}$ contribute

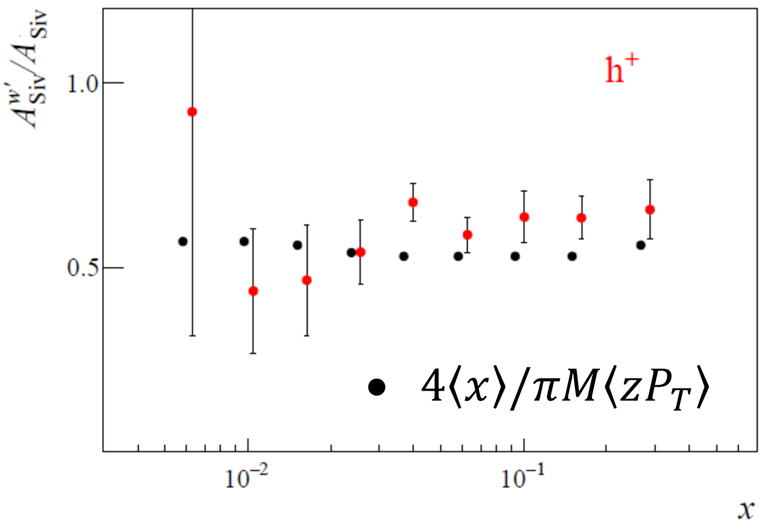
The weighted Sivers asymmetry

$$A_{Siv}^{w}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) \int D_{1q}^h(z)dz}{\sum_q e_q^2 x f_1^q(x) \int D_{1q}^h(z)dz}$$

$w = P_T/zM$

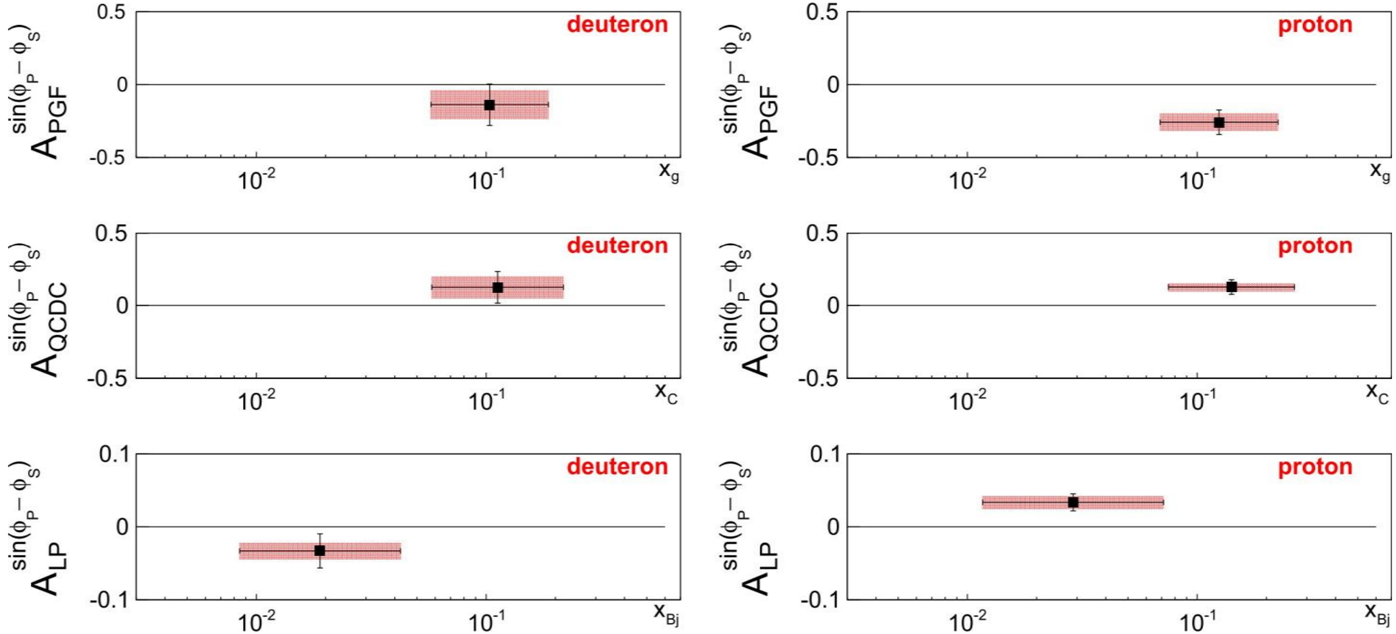
standard cuts
z>0.2





The ratio between weighted and unweighted Sivers asymmetries follows the average of $4\langle x\rangle/\pi M\langle zP_T\rangle$ of the unpolarised sample

Sivers Asymmetry for Gluon from SIDIS



$$A_{PGF}^{Siv,d} = -0.14 \pm 0.15(\text{stat.}) \pm 0.10(\text{syst.})$$
$$\langle x_g \rangle = 0.13$$

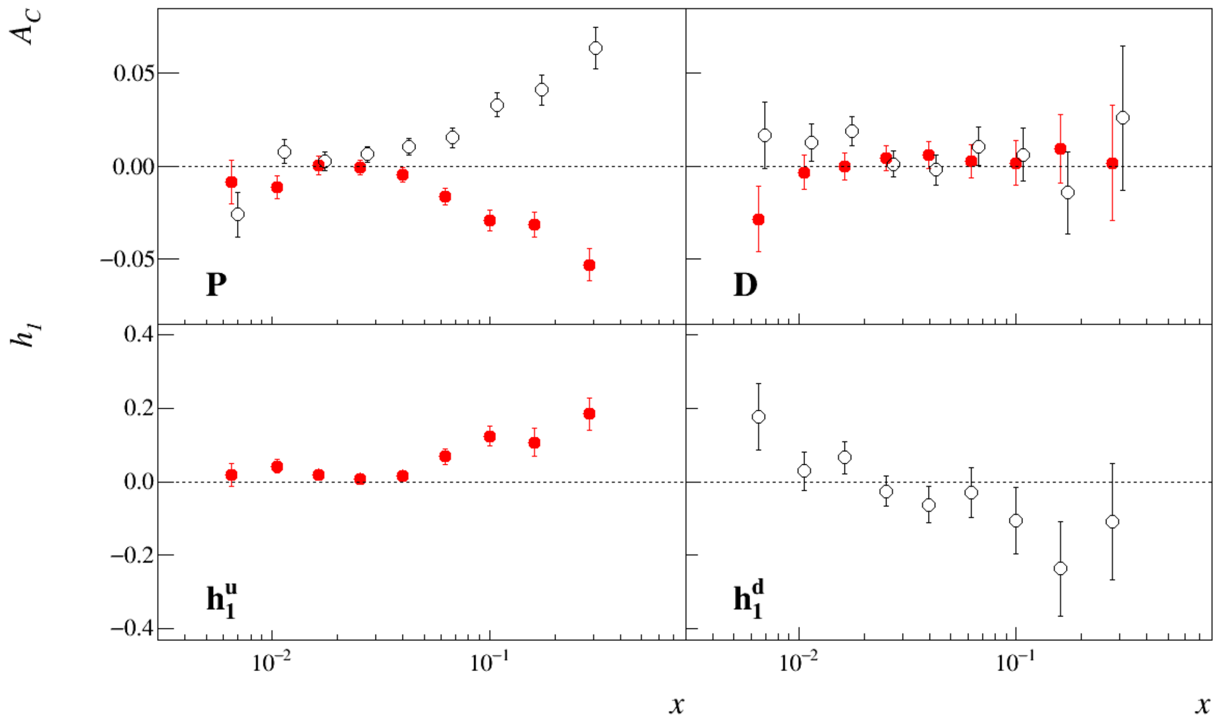
$$A_{PGF}^{Siv,p} = -0.26 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.})$$
$$\langle x_g \rangle = 0.15$$

C. Adolph et al. (COMPASS Collaboration), Phys. Lett. B 772, 854 (2017).

FUTURE

2021 Deuteron run

- Benchmark: h_1 extraction from Collins asymmetries

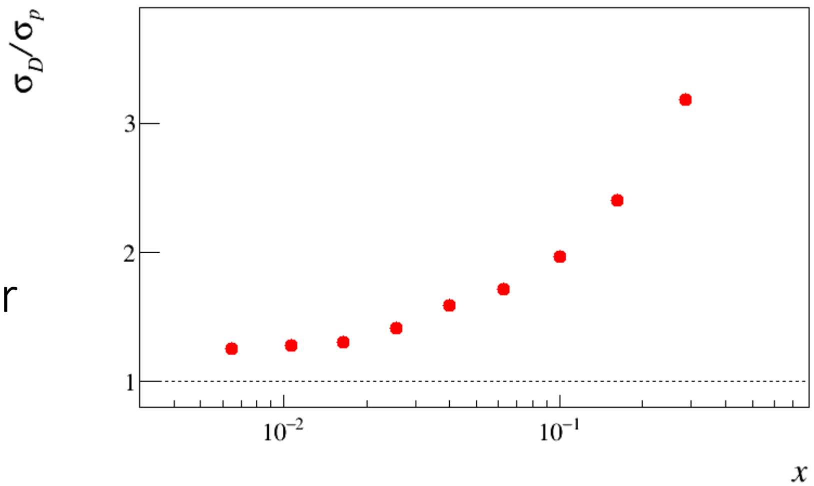


Transversity extracted as in PRD 91(2015) 014034

From ^{6}LiD ('02 – '04) to NH_3('07 – '10)

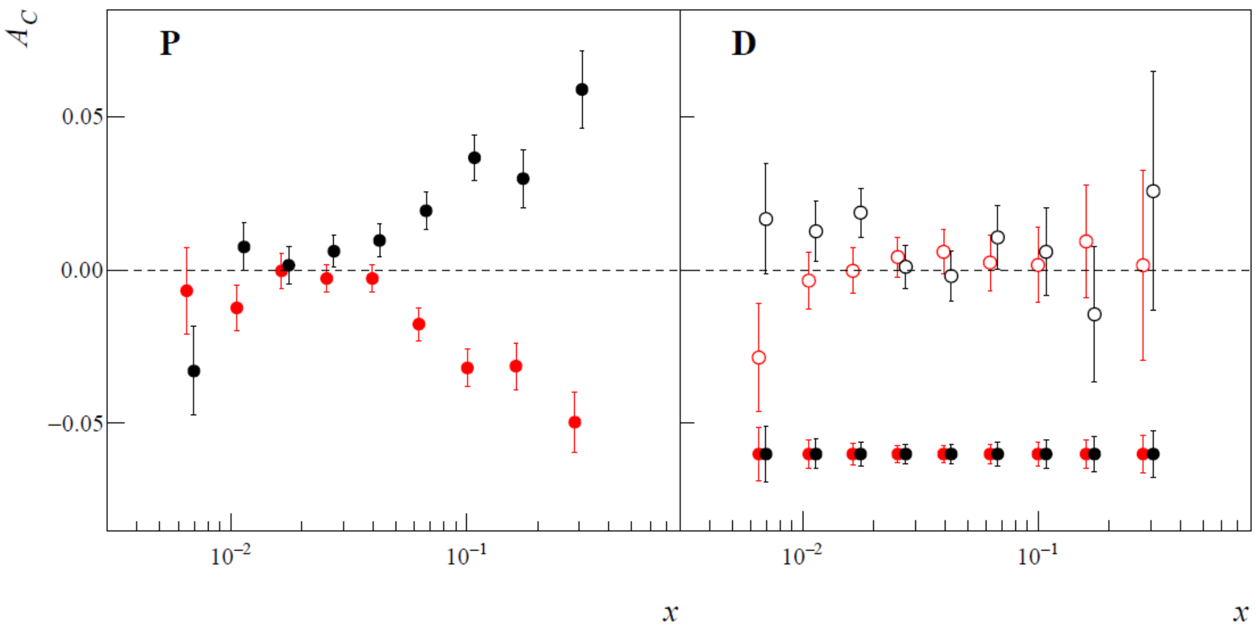
- Many improvements from 2004 data taking:
  - New 3 cells target / 1.3 gain due to larger diameter
  - New superconducting magnet / Factor 2.5 increase of acceptance at large x
  - New large x trigger with LAST / Factor 2 increase at large x
  - + larger integrated luminosity (partially lost given the less favorable figure of merit $\frac{f_p P_{pT}}{f_D P_{DT}} = 0.6$)

ALL IN ALL A TOTAL FACTOR OF >10



2021 Deuteron Run

- COMPASS proposed to CERN to run a full year with the transversely polarized deuteron target and this proposal has been approved



From Collins asymmetries to transversity

- Following Physical Review D 91, 014034 (2015), in the valence region

$$xh_1^u = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\left(xf_p^+ A_p^+ - xf_p^- A_p^-\right) + \frac{1}{3}\left(xf_d^+ A_d^+ - xf_d^- A_d^-\right)\right]$$

$$xh_1^d = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\frac{4}{3}\left(xf_d^+ A_d^+ - xf_d^- A_d^-\right) - \left(xf_p^+ A_p^+ - xf_p^- A_p^-\right)\right]$$

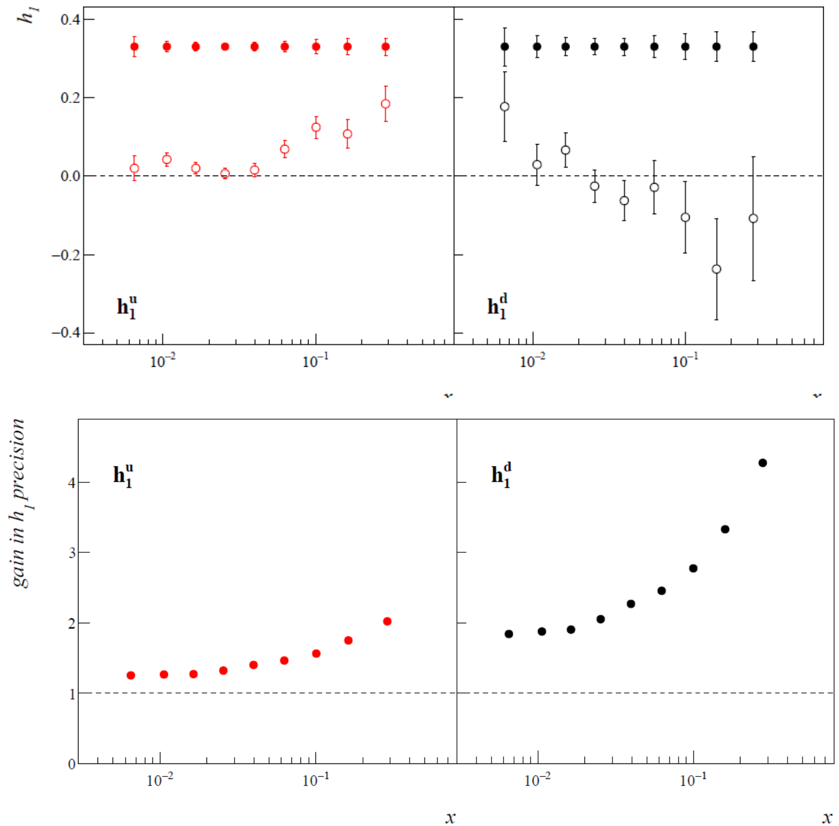
With $\tilde{a}_P^h$ and $\tilde{\alpha}$ constants

π^+ in p: $f_p^+ = 4\left(f_1^u + \frac{\widetilde{D}_{unf}}{\widetilde{D}_f} f_1^{\bar{u}}\right) + \left(\frac{\widetilde{D}_{unf}}{\widetilde{D}_f} f_1^d + f_1^{\bar{d}}\right) + \frac{\widetilde{D}_{unf}}{\widetilde{D}_f}\left(f_1^s + f_1^{\bar{s}}\right)$

π^- in p: $f_p^+ = 4\left(\frac{\widetilde{D}_{unf}}{\widetilde{D}_f} f_1^u + f_1^{\bar{u}}\right) + \left(f_1^d + \frac{\widetilde{D}_{unf}}{\widetilde{D}_f} f_1^{\bar{d}}\right) + \frac{\widetilde{D}_{unf}}{\widetilde{D}_f}\left(f_1^s + f_1^{\bar{s}}\right)$

New deuteron data

- 1 full year (same as 2010). We also gain from $\frac{f_p P_{pT}}{f_D P_{DT}} = \frac{0.155\times0.8}{0.40\times0.5} = 0.6$



projected

present

Transversity extracted as in PRD 91(2015) 014034

New QCD facility at CERN M2

https://arxiv.org/abs/1808.00848

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

August 3, 2018

Letter of Intent:

A New QCD facility at the M2 beam line of the CERN SPS

O.Yu. Denisov
on behalf of the working group:
"A New QCD Facility at the M2 beam line of the CERN SPS"*

Contents

*The final author list of the LoI will be finished in October 2018. Please send e-mail to NQF-M2@cern.ch for questions and requests.

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware Additions
μp elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pr. H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified PT magnet
Input for DMS	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	LHe target
$\overline{p}$-induced Spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectr.: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex det.
Primakoff (RF)	Kaon polarisi-bility & pion life time	$\sim$100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

Longitudinally polarized target results

Year	Obs.	
2006	$A_{LL}^{2h}(Q^2 < 0)$	$\Delta g/g$
2007	$g_1^d(x)$,	$\Gamma_1^d, \Delta\Sigma$
2008	$A_{1,d}^{h^+ - h^-}$	$\Delta u_v + \Delta d_v$
2009	$A_{1,d}, A_{1,d}^{\pi^\pm}, A_{1,d}^{K^\pm}$	$\Delta u_v + \Delta d_v, \Delta\bar{u} + \Delta\bar{d}, \Delta s (= \Delta\bar{s})$
2010	$g_1^p(x)$,	$\Gamma_1^{NS}, \lvert g_A/g_V \rvert$
2010	$A_{1,d}, A_{1,d}^{\pi^\pm}, A_{1,d}^{K^\pm}, A_{1,p}, A_{1,p}^{\pi^\pm}, A_{1,p}^{K^\pm}$	$\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta\bar{d}, \Delta s, \Delta\bar{s}$
2010	$\sin\phi$, $\sin 2\phi$, $\sin 3\phi$, $\cos\phi$ asyms	$h_L, f_L^\perp, h_1, f_{1T}^\perp, h_{1L}^\perp, h_{1T}^\perp, h_{1L}^\perp, g_L^\perp, g_{1T}$
2013	A_{LL}^{2h}	$\Delta g/g$
2013	$A_D^{\gamma N}$	$\Delta g/g$ in LO and NLO
2015	$g_1^p(x)$	$\Gamma_1^{NS}, \Delta\Sigma, \Delta u + \Delta\bar{u} \cdots$
2015	A_{LL}^p	NLO QCD fits for $\Delta g/g$
2017	$g_1^d(x)$	Final result + BJ sum rule
2018	$A_1^p(x)$ and $g_1^p(x)$	Small x and Q^2

Transversely polarized target results

Year	Obs	
2005	$A^h_{Siv,d}, A^h_{Col,d}$	First ^{6}LiD data
2006	$A^h_{Siv,d}, A^h_{Col,d}$	Full ^{6}LiD statistics
2009	$A^{\pi^\pm,K^\pm,K^0_S}_{Siv,d}, A^{\pi^\pm,K^\pm,K^0_S}_{Col,d}$	Full ^{6}LiD statistics
2010	$A^h_{Siv,p}, A^h_{Col,p}$	2007 NH_3 data
2012	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full ^{6}LiD
2012	$A^h_{Siv,p}, A^h_{Col,p}$	Full NH_3statistics
2012	$A^{sin(\phi_\rho-\phi_S)}_{UT,d}, A^{sin(\phi_\rho-\phi_S)}_{UT,p}$	Exclusive ρ^0
2013	$A^{(\phi_\rho,\phi_S)}_{UT,d}, A^{(\phi_\rho,\phi_S)}_{UT,p}$	Exclusive ρ^0, all asyms.
2014	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full ^{6}LiD and NH_3
2014	$A^{\pi^\pm,K^\pm,K^0_S}_{Siv,d}, A^{\pi^\pm,K^\pm,K^0_S}_{Col,d}$	Full NH_3 statistics
2015	Interplay $A^{sin\phi_{RS}}_{UT,p}$ vs $A^h_{Col,p}$	Full NH_3 statistics
2017	$A^{sin\phi}_{DY}$	Sivers in DY
	$A^{w,h}_{Siv,p}$	P_T weighted Sivers

Unpolarised target results

Year	Obs	
2013	$dn^h/(dN^\mu dz\, dp_T^2)$	Unpolarized multiplicities on d, 2004
2014	$A_{UU,d}^{\cos\phi_h}, A_{UU,d}^{\cos 2\phi_h}, A_{LU,d}^{\sin\phi_h}$	2004, part
2016	$dn^\pi/(dN^\mu dz)$	Unpolarized multiplicities on d, 2006
2016	$dn^h/(dN^\mu dz\, dp_T^2)$	Unpolarized multiplicities on d, 2006
2016	$dn^K/(dN^\mu dz)$	Unpolarized multiplicities on d, 2006
2018	dn^{K^+}/dn^{K^-}	Multiplicity ratio at high z
2018	$\sqrt{\langle r_\perp^2\rangle}$	Transverse p extension at $\langle x\rangle = 0.056$


Thank you

SIDIS access to TMDs

Factorisation (Collins & Soper, Ji, Ma, Yuan, Qiu & Vogelsang, Collins & Metz...)

$\sigma(\ell p \to \ell' h X) \sim q(x) \otimes \hat{\sigma}^{\gamma q \to q} \otimes D_q^h(z)$

chiral odd

T odd

Nucleon polarization (columns) / Parton polarization (rows)

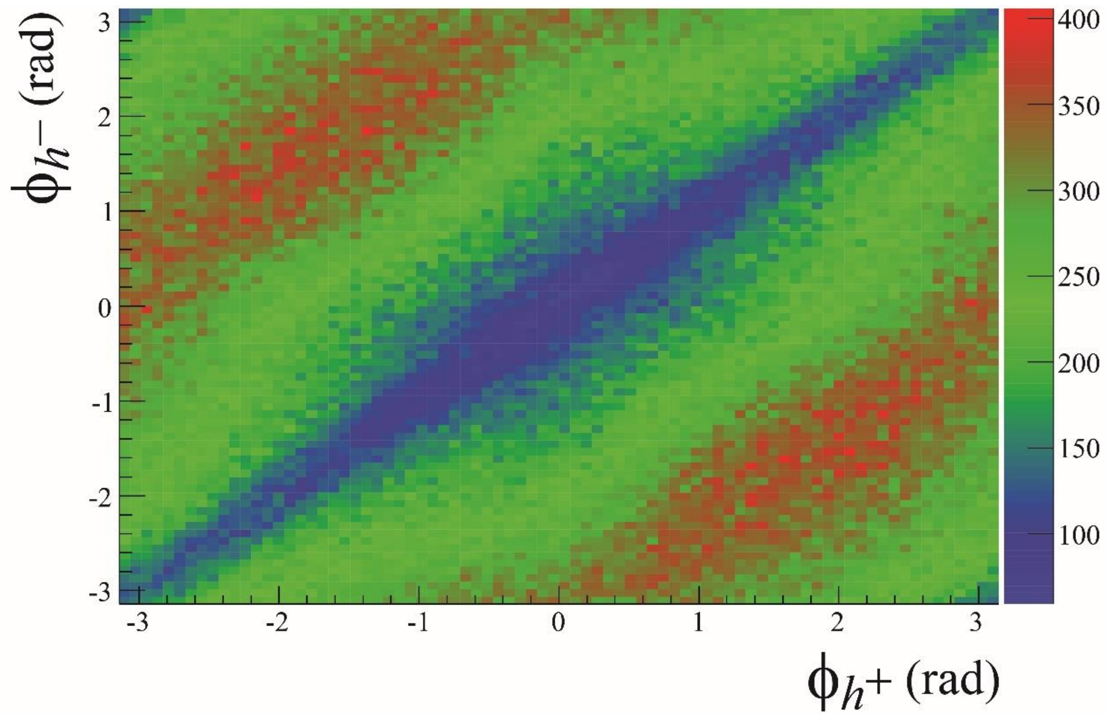
	U	T	L
U	f_1	$f_{1T}^\perp$	
T	$h_1^\perp$	$h_1, h_{1T}^\perp$	$h_{1L}^\perp$
L		g_{1T}	g_{1L}

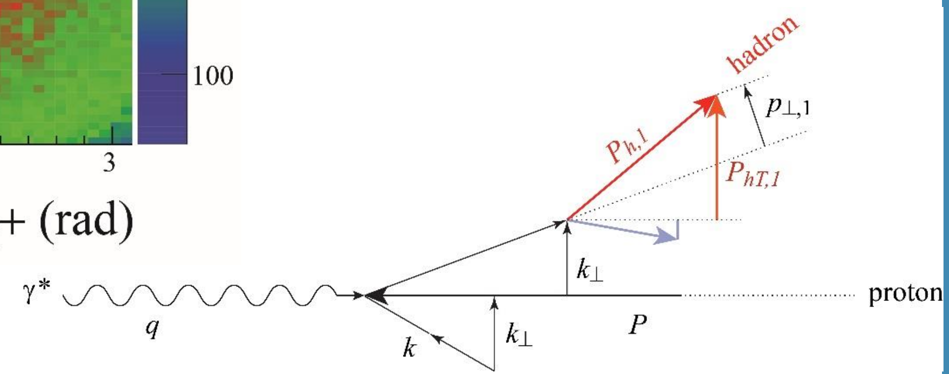
Hadron polarization (columns) / Parton polarization (rows)

	U	T	L
U	D_1	$D_{1T}^\perp$	
T	$H_1^\perp$	H_1 , $H_{1T}^\perp$	$H_{1T}^\perp$
L		G_{1T}	G_{1L}

- NOT directly accessible
- Their extractions require measurements of x-sections and asymmetries in **a large kinematic domain of** x, Q^2, z, P_{hT}

Is correlation having an impact?

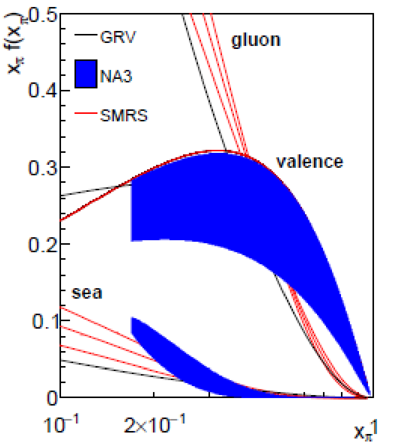


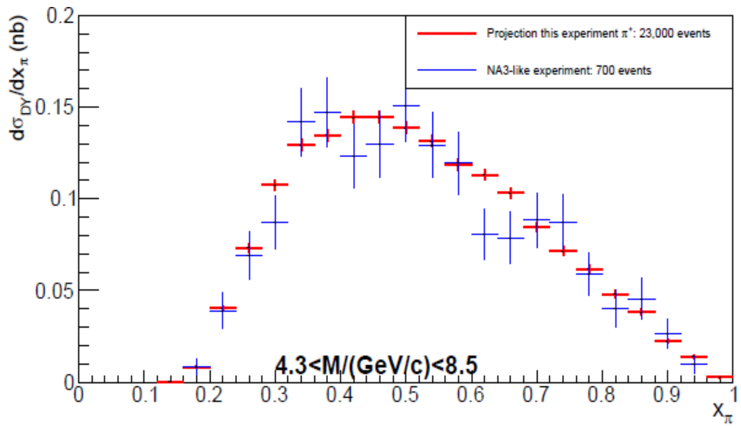


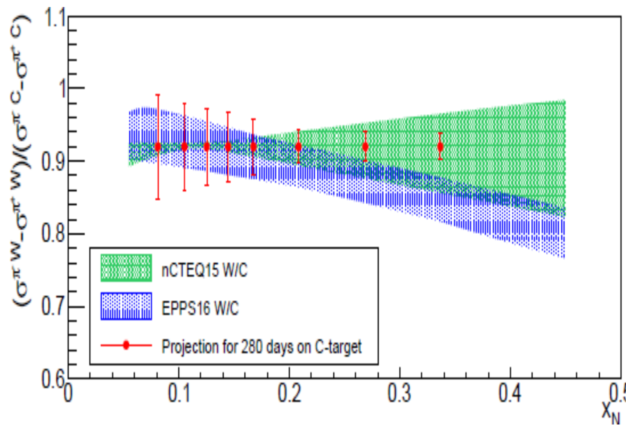
hadron physics with hadron beams

- New Drell-Yan experiment with 190 GeV π± beams and C, W targets
  - Determine pion valence and sea quark distributions (both π beams charges) Study direct photons and charmonium ==⇒ gluons in π
  - Study flavour dependent nuclear effects (2 beam charges, 2 targets: C, W)
- Important: good beam charge balance and PID in beams

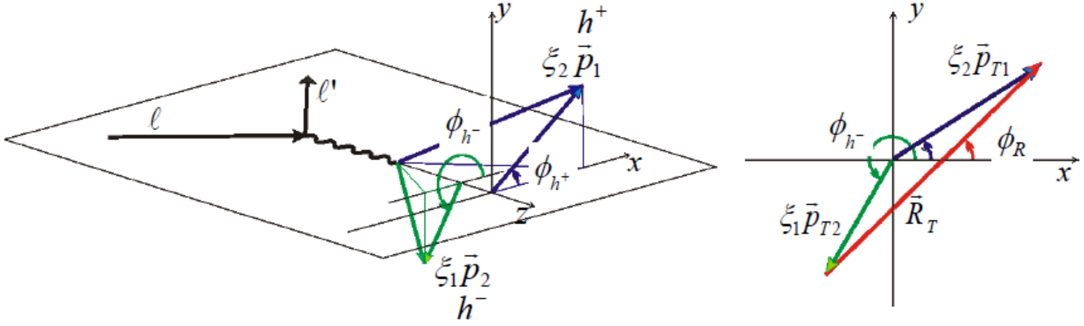
projections: 2× 140 days; π+ : π− time 10:1; C, W targets





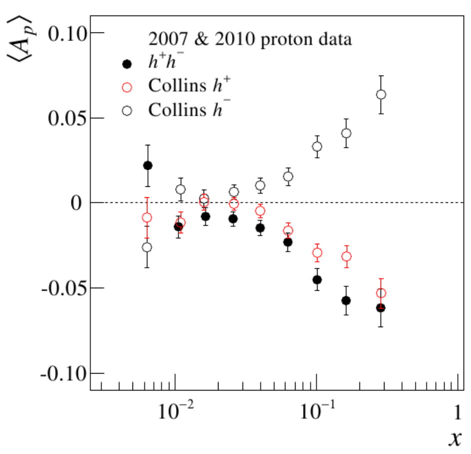


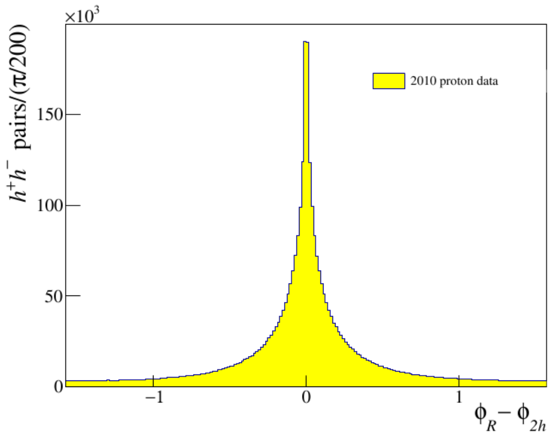
Hadron correlations

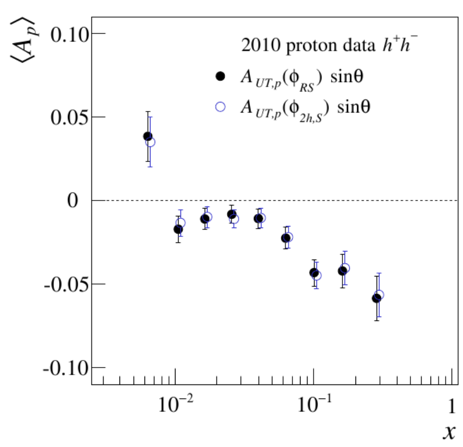


Interplay between Collins and IFF asymmetries

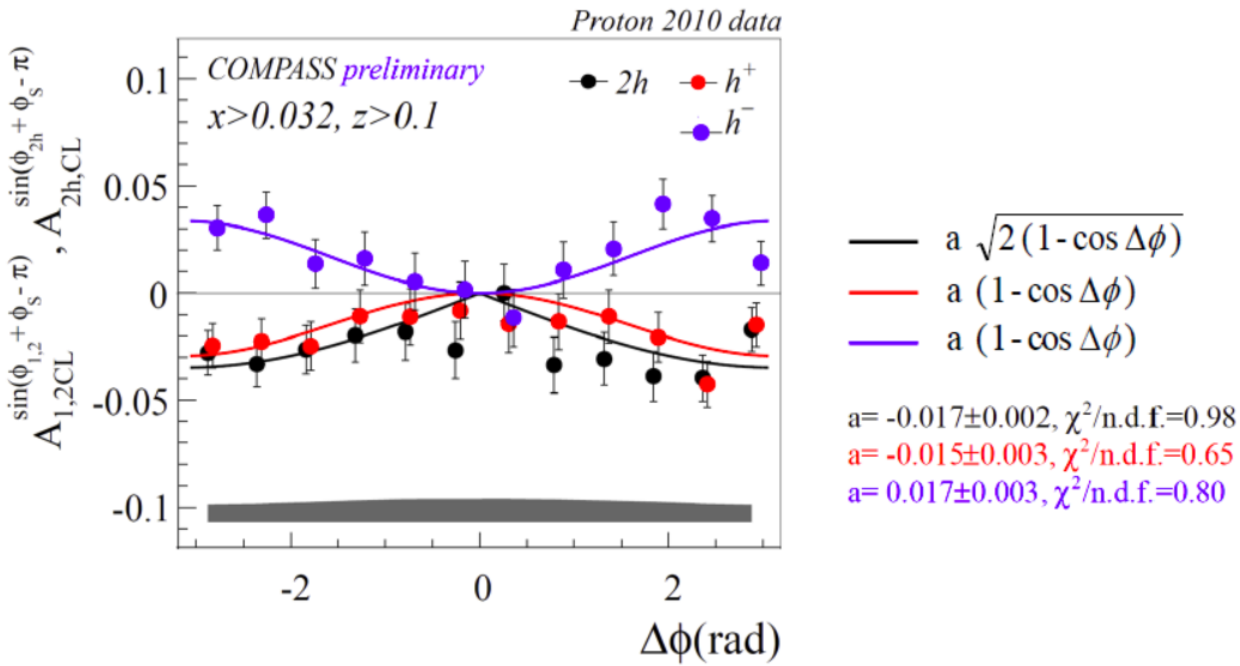
common hadron sample for Collins and 2h analysis







Asymmetries for $x > 0.032$ vs $\Delta\phi = \phi_{h^+} - \phi_{h^-}$



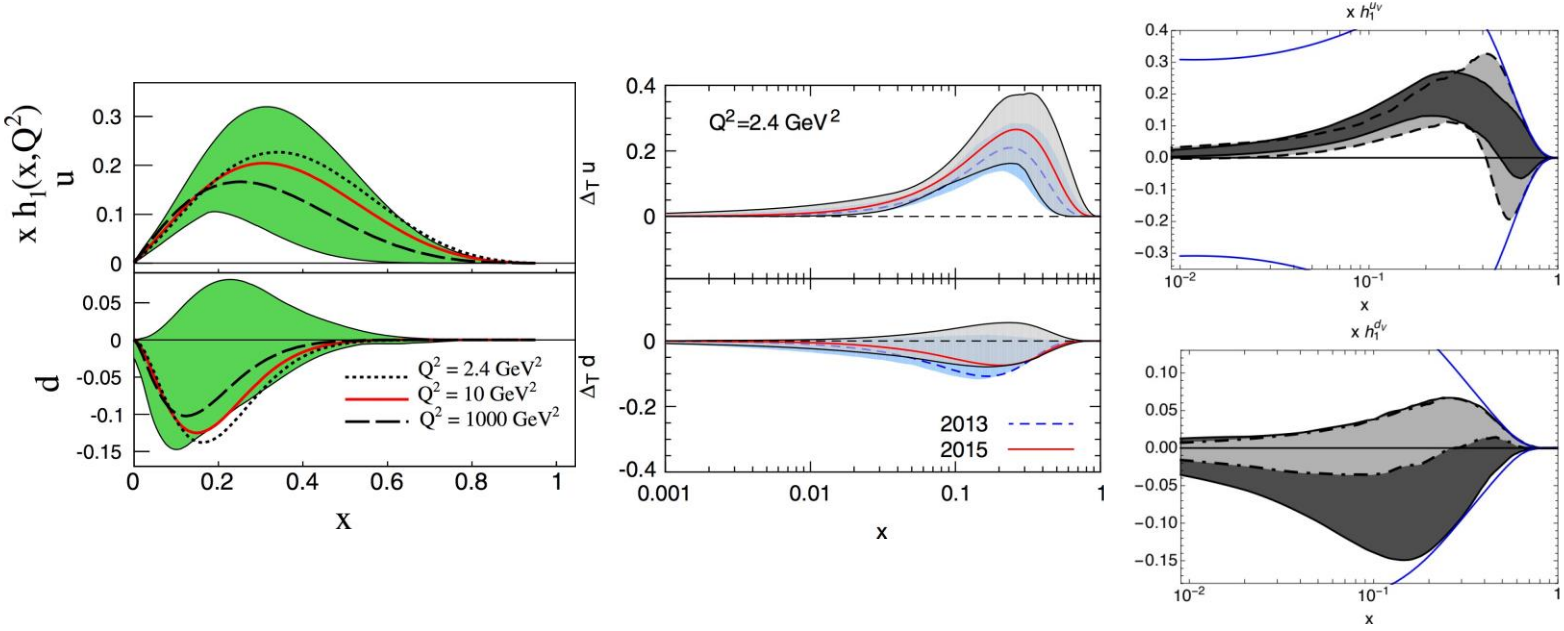
$$a = \frac{\sigma_{1C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)}$$

$$= -\frac{\sigma_{2C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)}$$

ratio of the integrals compatible with $4/\pi$

Hints for a common origin of 1h and 2h mechanisms

Global Analysis: Transversity



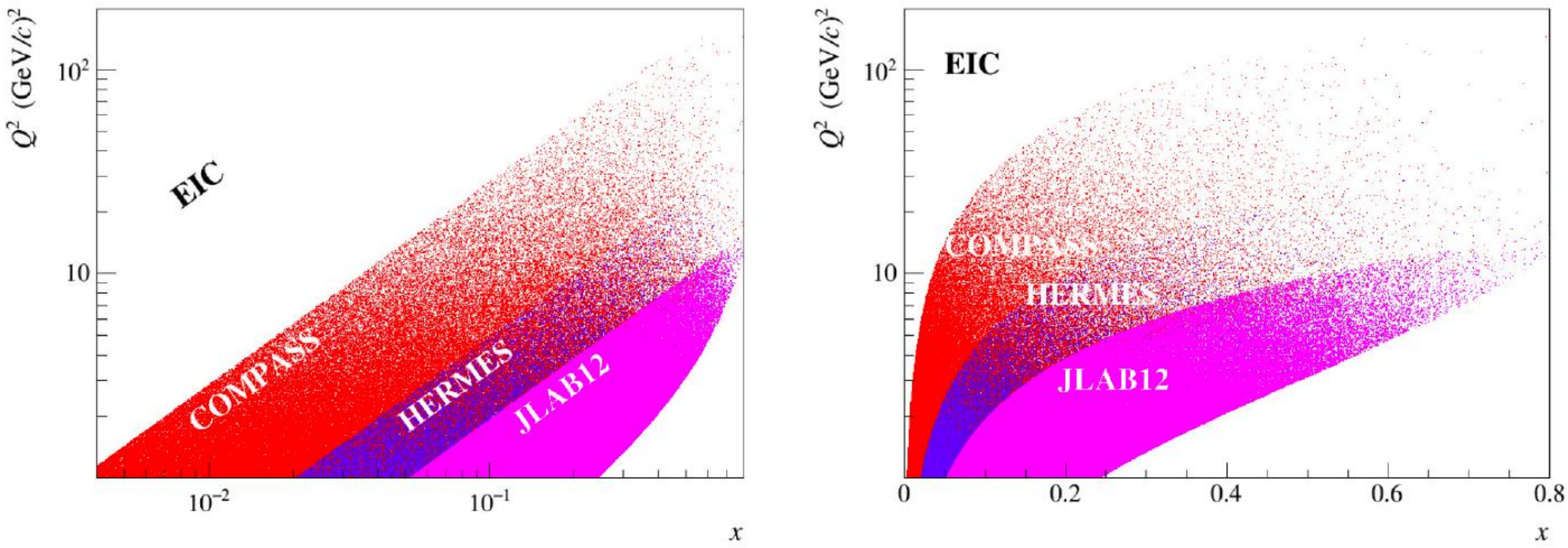
Z.-B. Kang et al., Phys. Rev. D 93, 014009 (2016).

M. Anselmino et al., Phys. Rev. D 92, 114023 (2015).

M. Radici and A. Bacchetta, arXiv: 1802.05212[hep-ph]

20

Kinematic coverage



Unpolarised Azimuthal Modulation

When looking at the content of the structure functions/modulations in terms of TMD PDFs for the $\cos\phi_h$ and $\cos 2\phi_h$ we can write:

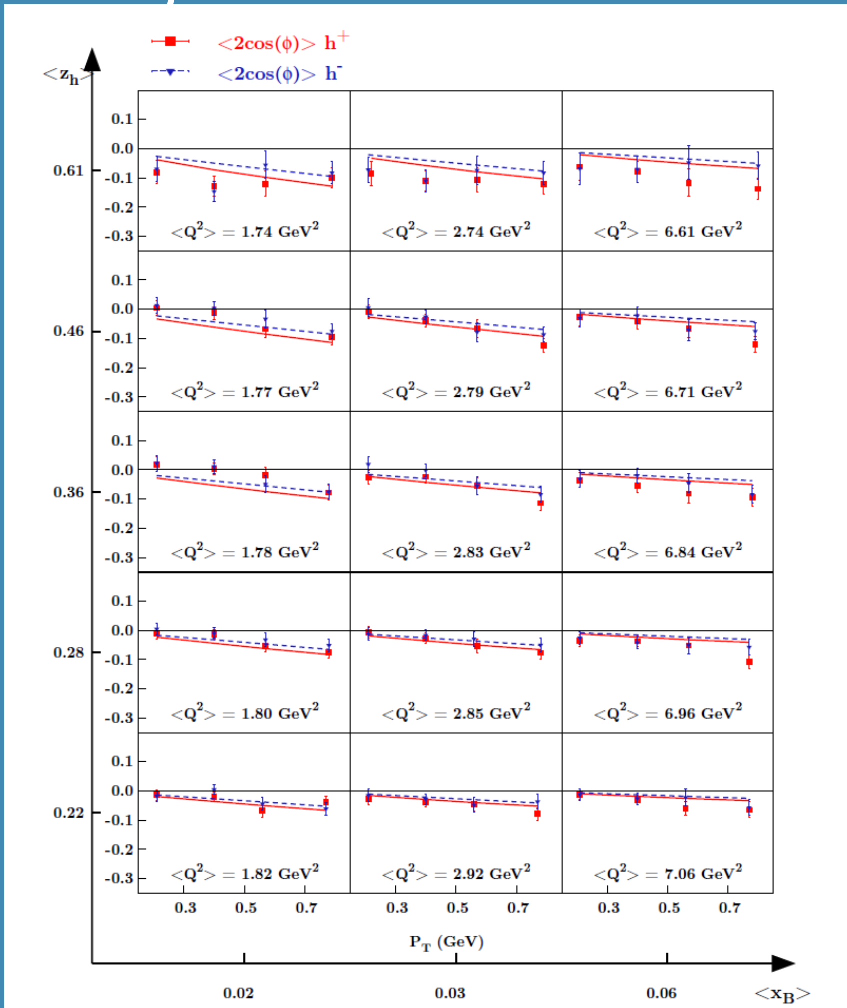
$$F_{UU}^{\cos\phi_h} = -\frac{2M}{Q} C\left[\frac{\hat{h}\cdot\vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp}{M}\frac{\vec{P}_{hT} - z(\hat{h}\cdot\vec{k}_\perp)}{zM_h M} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

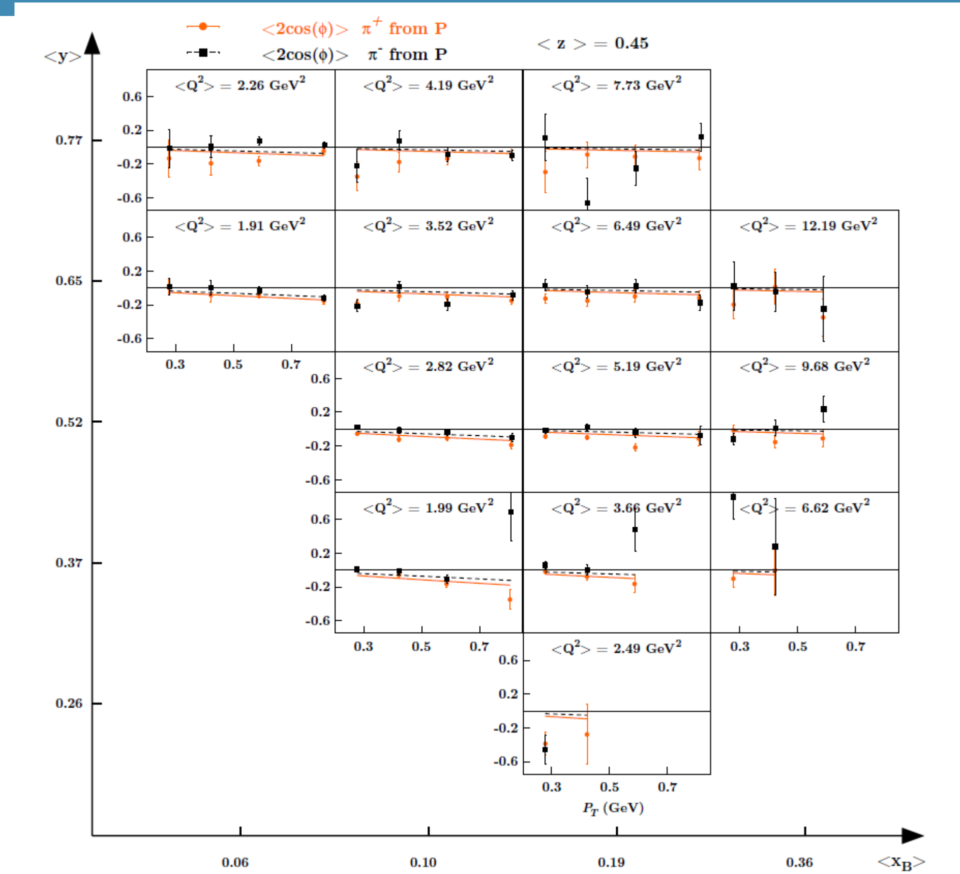
$$F_{UU}^{\cos 2\phi_h} = C\left[\frac{(\hat{h}\cdot\vec{k}_\perp)(\hat{h}\cdot\vec{p}_\perp) - \vec{p}_\perp\cdot\vec{k}_\perp}{MM_h} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

In the $\cos 2\phi_h$ Cahn effects enters only at twist4

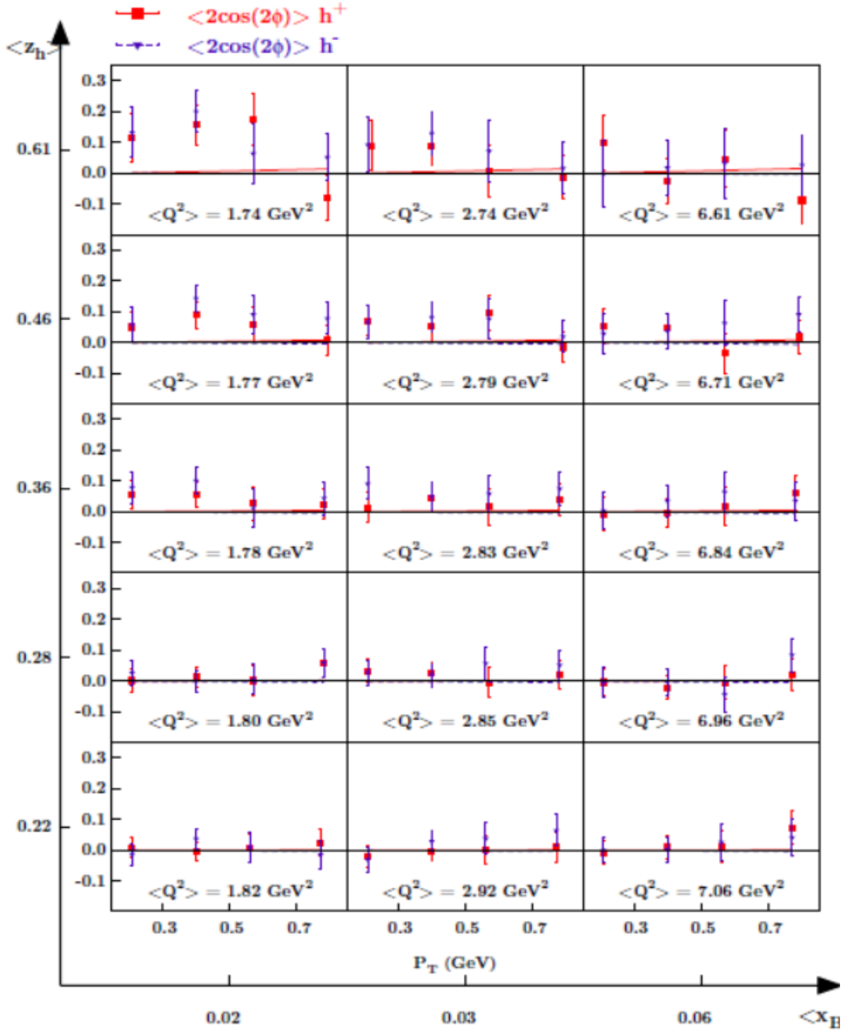
$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C\left[\left\{2\left(\hat{h}\cdot\vec{k}_\perp\right)^2 - k_\perp^2\right\} f_1 D_1\right]$$

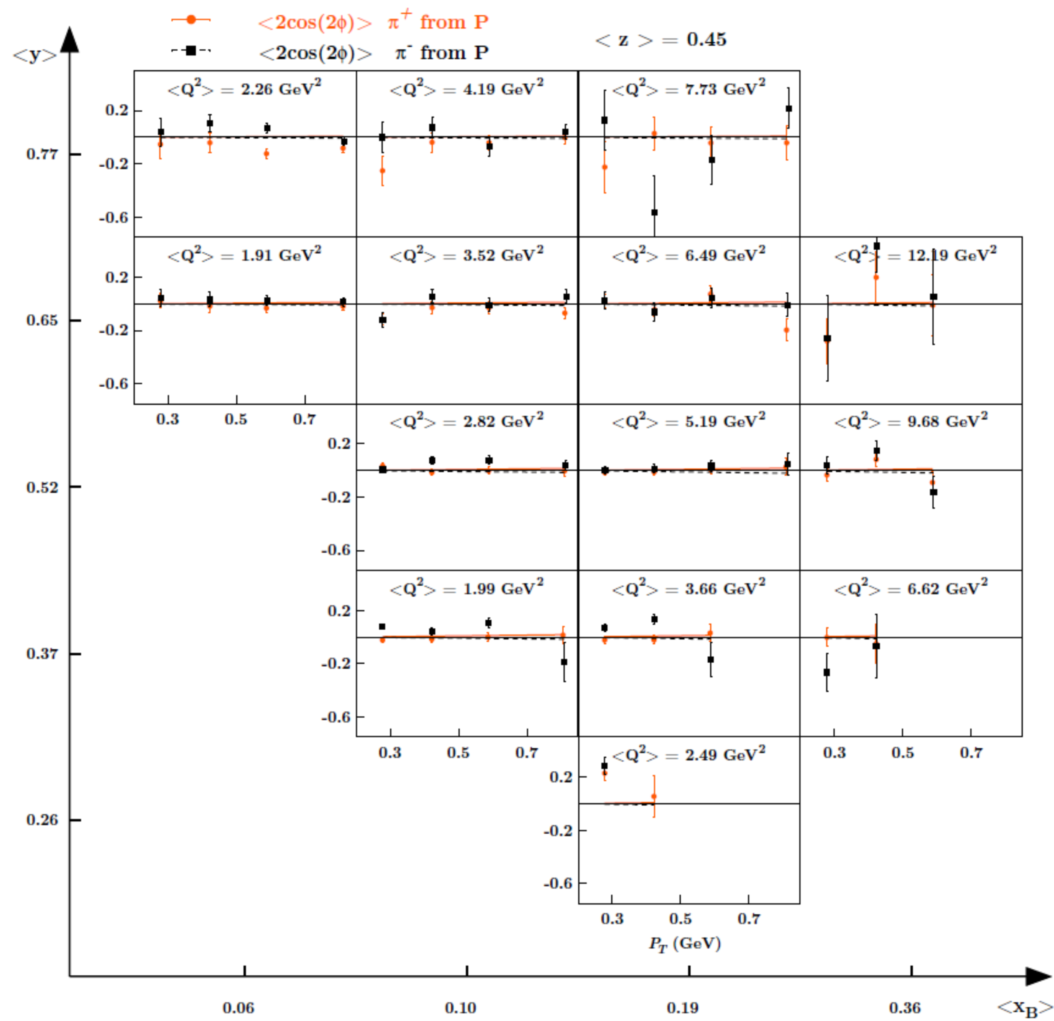
cos ϕ modulation



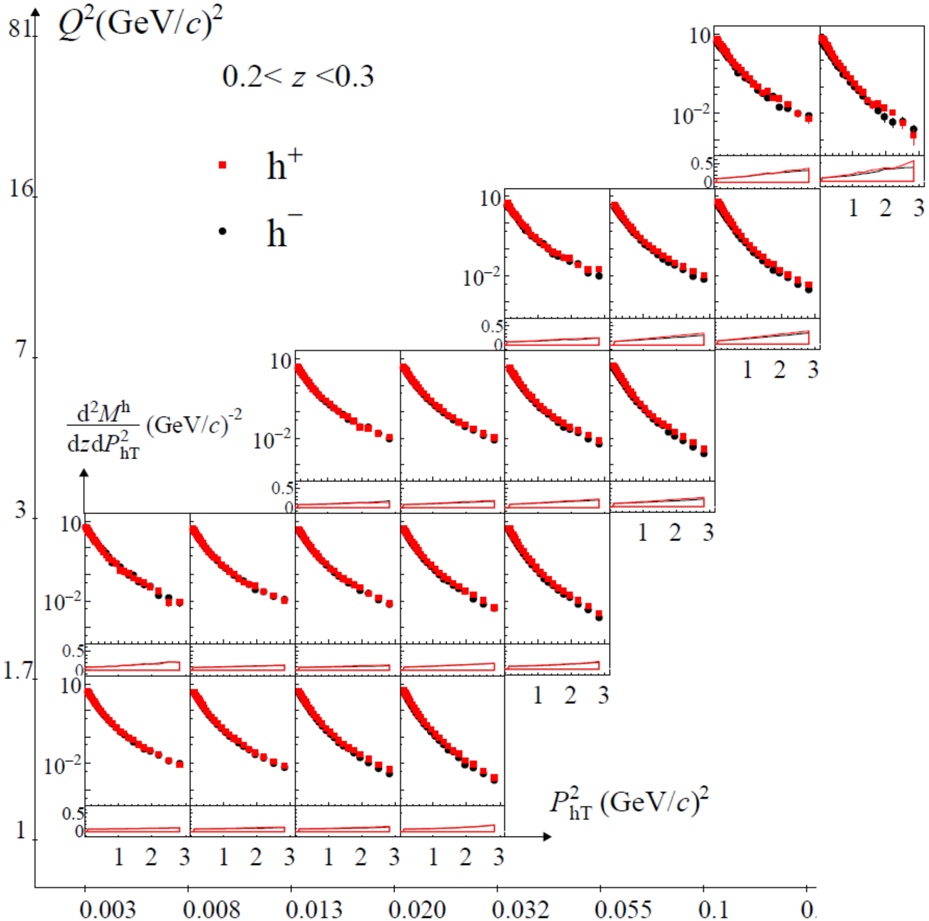


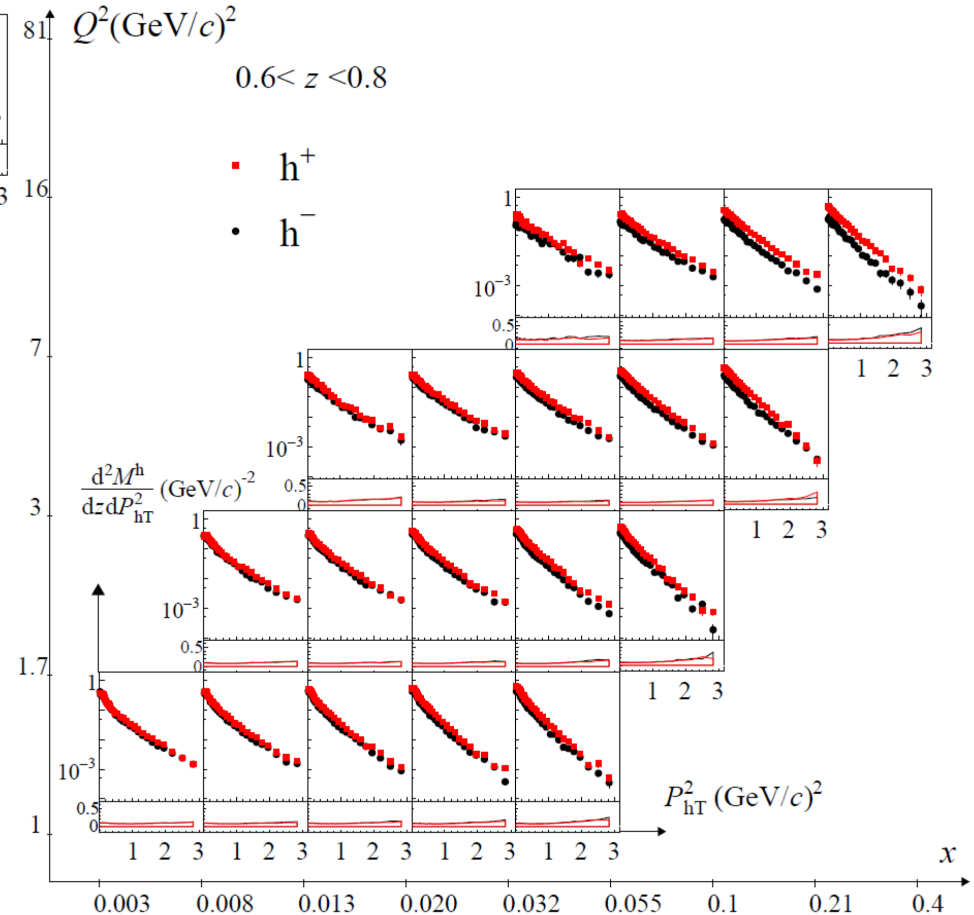
Boer-Mulders in $\cos 2\phi$ and in $\cos \phi$



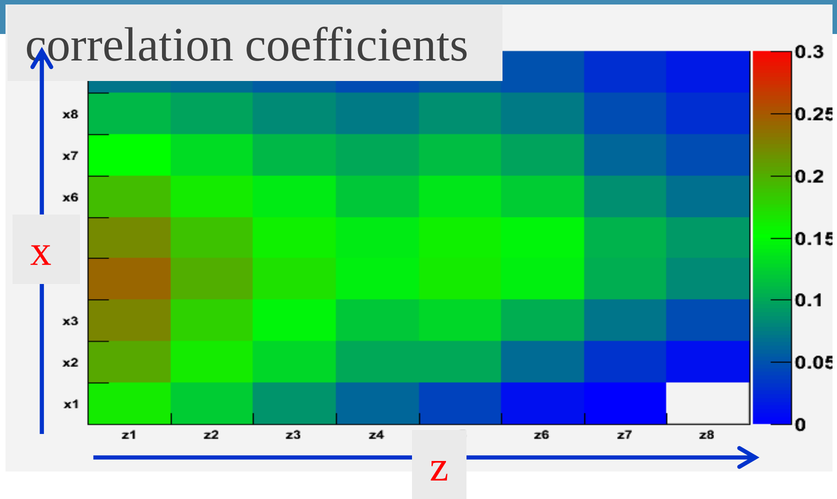


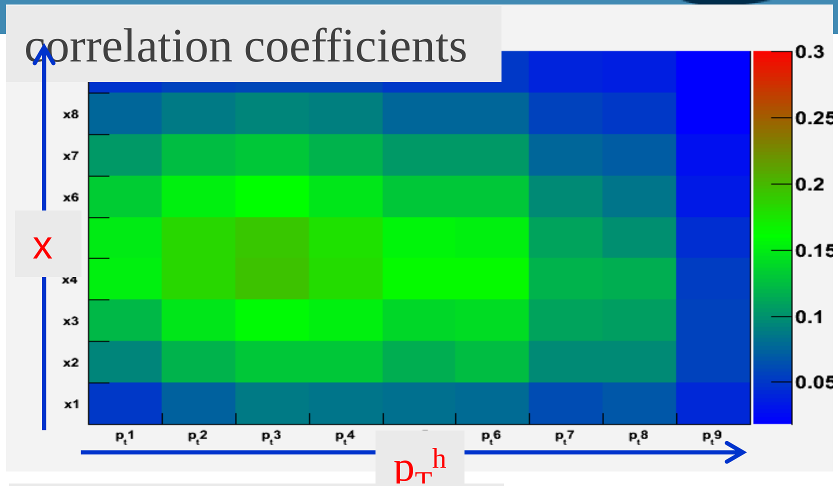
Importance of unpolarized SIDIS

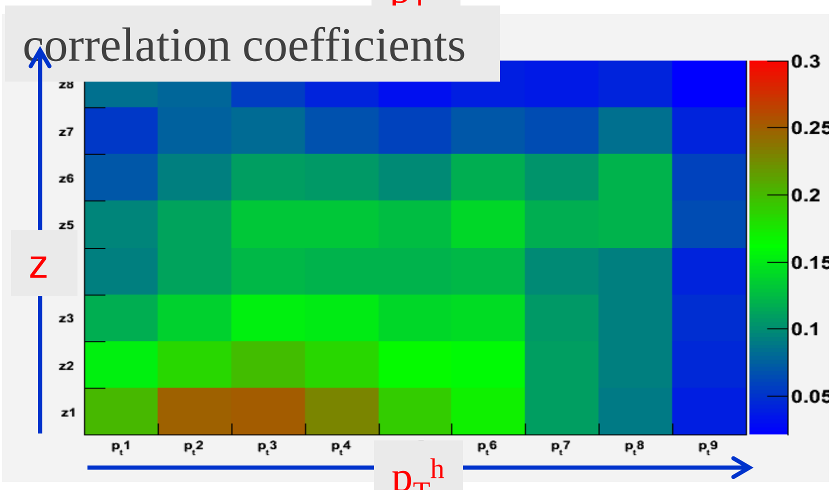




Statistical correlations







charged pions

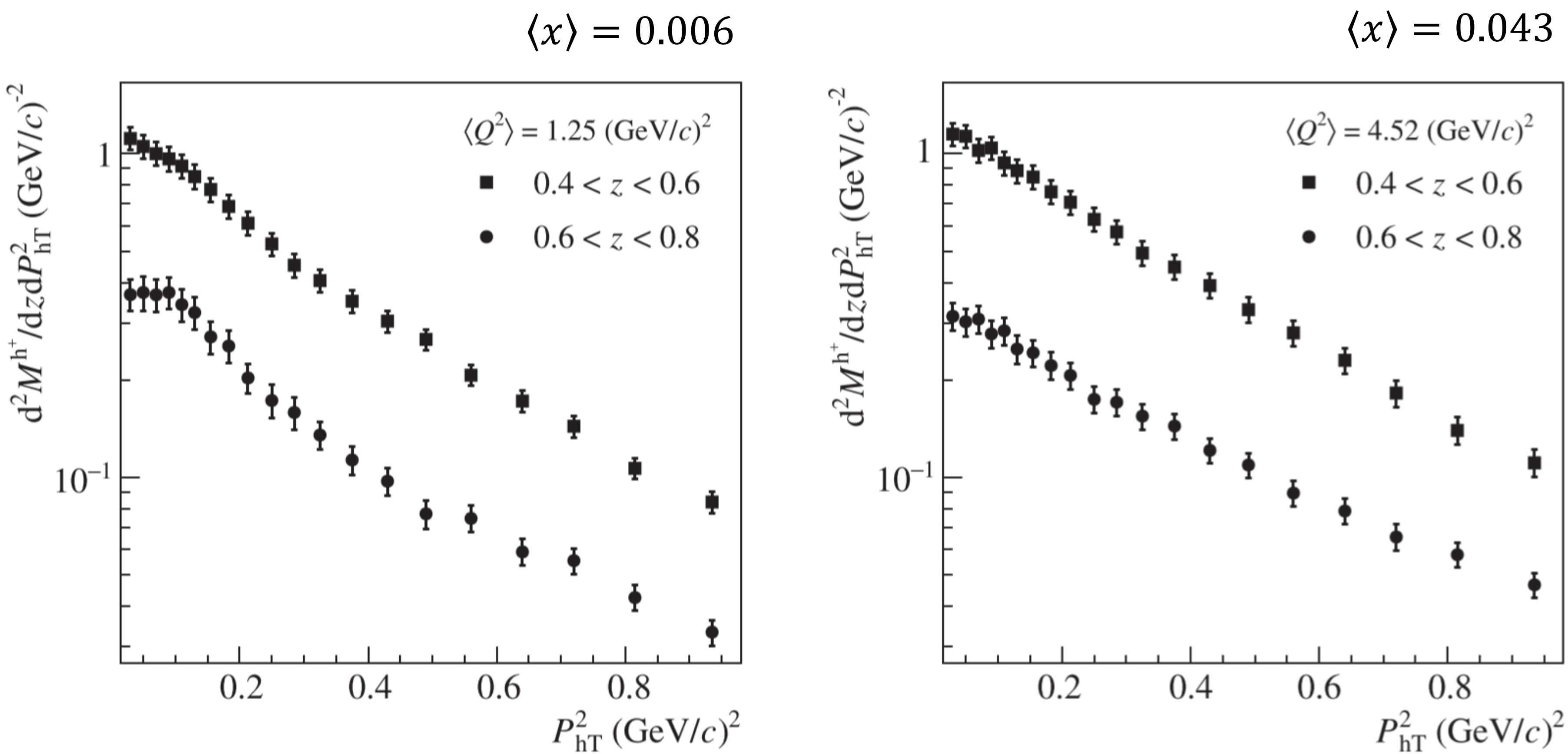
also available for

charged hadrons

charged kaons

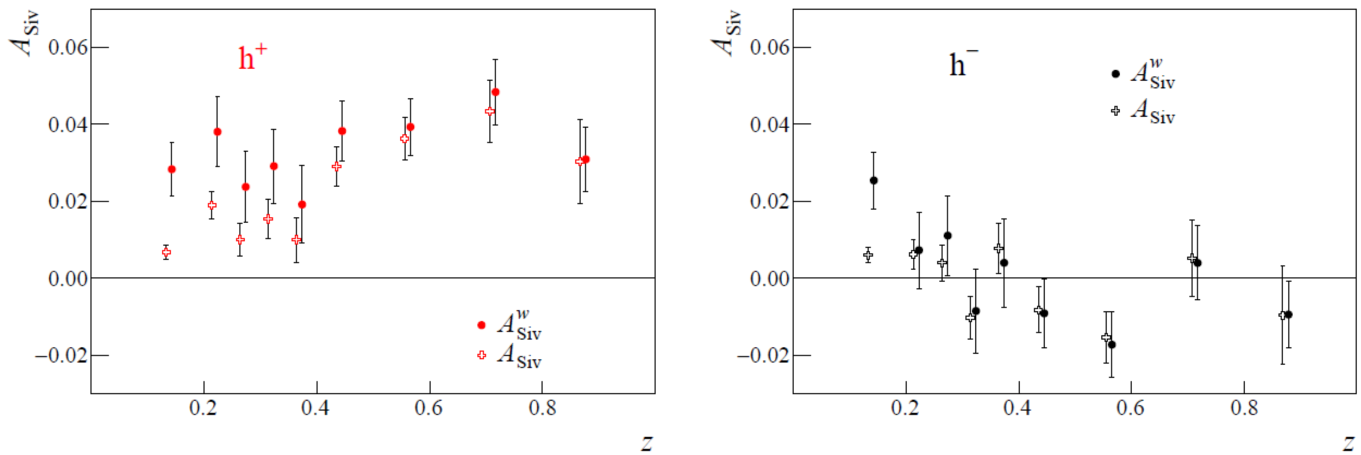
have to be taken into account

Low P_{hT} behavior



The weighted Sivers asymmetry

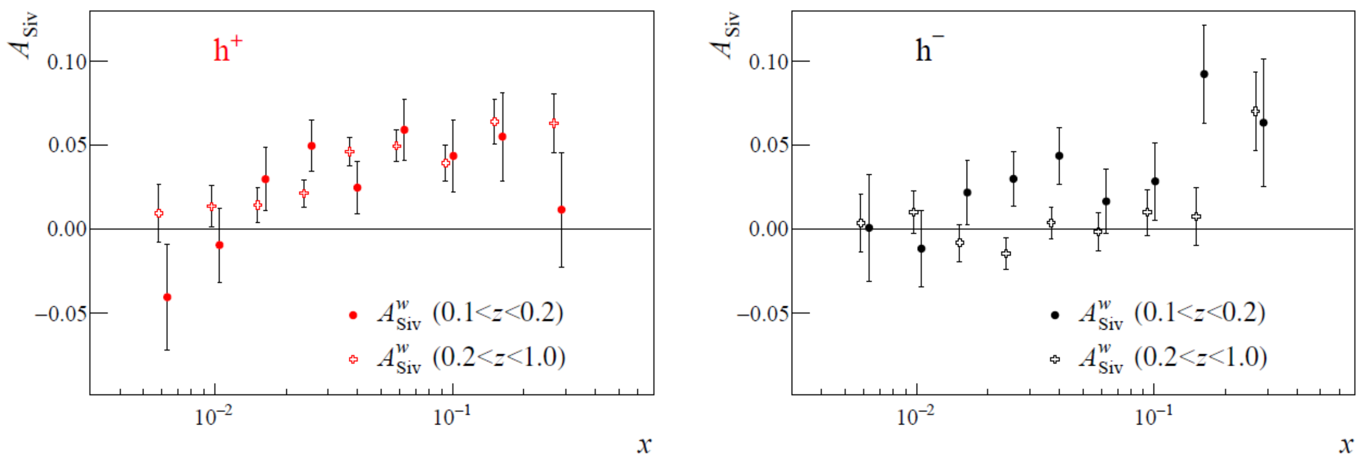
1. weight $w = P_T/zM$ $A^w_{Siv}(z)$ $0.1 < z < 1.0$



$$2\frac{\int C(x)x f_{1T}^{\perp(1)u}(x)dx}{\int C(x)x f_1^u(x)dx}$$

The weighted Sivers asymmetry

1. weight $w = P_T/zM$ $A^w_{Siv}(z)$ $0.1 < z < 1.0$



For $0.1 < z < 0.2$ the asymmetries for h^+ and h^- show the same behavior

TMD PDFs

- The theoretical expression of TMDs has a more complicated structure of the gauge link, connecting two space-time points with a transverse separation

$$f_{q/N}(x, k_\perp) = \frac{1}{8\pi}\int dr^- \frac{dr_\perp^2}{(2\pi)^2} e^{-iMxr^-/2+ik_\perp\cdot r_\perp}$$

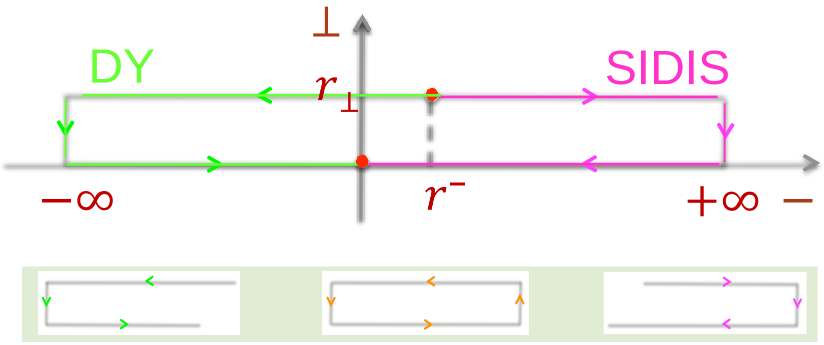
$$\langle N(P)|\bar{q}(r^-, r_\perp)\gamma^+ W[r^-, r_\perp; 0] q(0)|N(P)\rangle|_{r^+\sim 1/\nu\to 0}$$

- The Wilson line W is no longer on the light-cone axis and may introduce a **process dependence**

Parity and Time reversal invariance ⇒

$$\left(f_{1Tq}^{\perp}\right)_{DY} = -\left(f_{1Tq}^{\perp}\right)_{SIDIS}$$

Most critical test to TMD approach to SSA



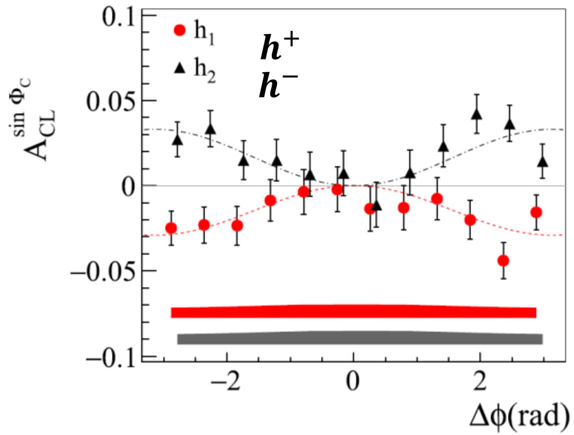
Interplay among dihadron and single hadron asymmetries

PLB 753 (2016) 406

analitically

$$A_{CL1}^{\sin \Phi_C} = a_1 + a_2 \cos \Delta\phi$$
$$A_{CL2}^{\sin \Phi_C} = a_2 + a_1 \cos \Delta\phi$$

mirror symmetry



agreement with data if $a_1 = -a_2 = a$

$$A_{CL\,2h}^{\sin \Phi_{2h,S}} = a\sqrt{2(1-\cos\Delta\phi)}$$

ratio of the $\Delta\phi$ integrated 2h and 1h asymmetries: $4/\pi$

slightly larger than h^+

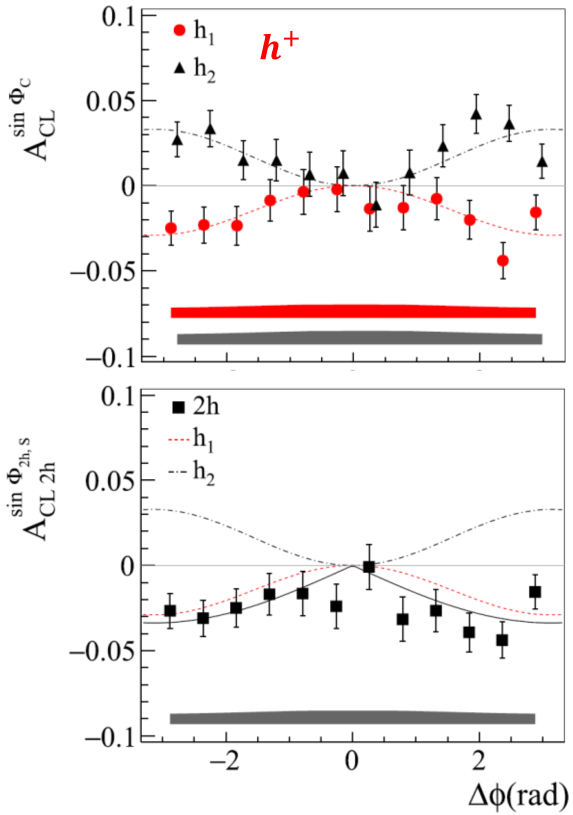
Interplay among dihadron and single hadron asymmetries

PLB 753 (2016) 406

analytically

$$A_{CL1}^{\sin\Phi_C} = a_1 + a_2\cos\Delta\phi$$
$$A_{CL2}^{\sin\Phi_C} = a_2 + a_1\cos\Delta\phi$$

mirror symmetry



agreement with data if

$$A_{CL\,2h}^{\sin\Phi_{2h,S}} = a\sqrt{2(1-\cos\Delta\phi)}$$

agreement with data

a very simple relationships among the asymmetries in the “2h sample”

they are driven by the same elementary mechanism.

ratio of the $\Delta\phi$ integrated 2h and 1h asymmetries: $4/\pi$

slightly larger than h^+