Recent COMPASS results on Transverse Spin Asymmetries in SIDIS

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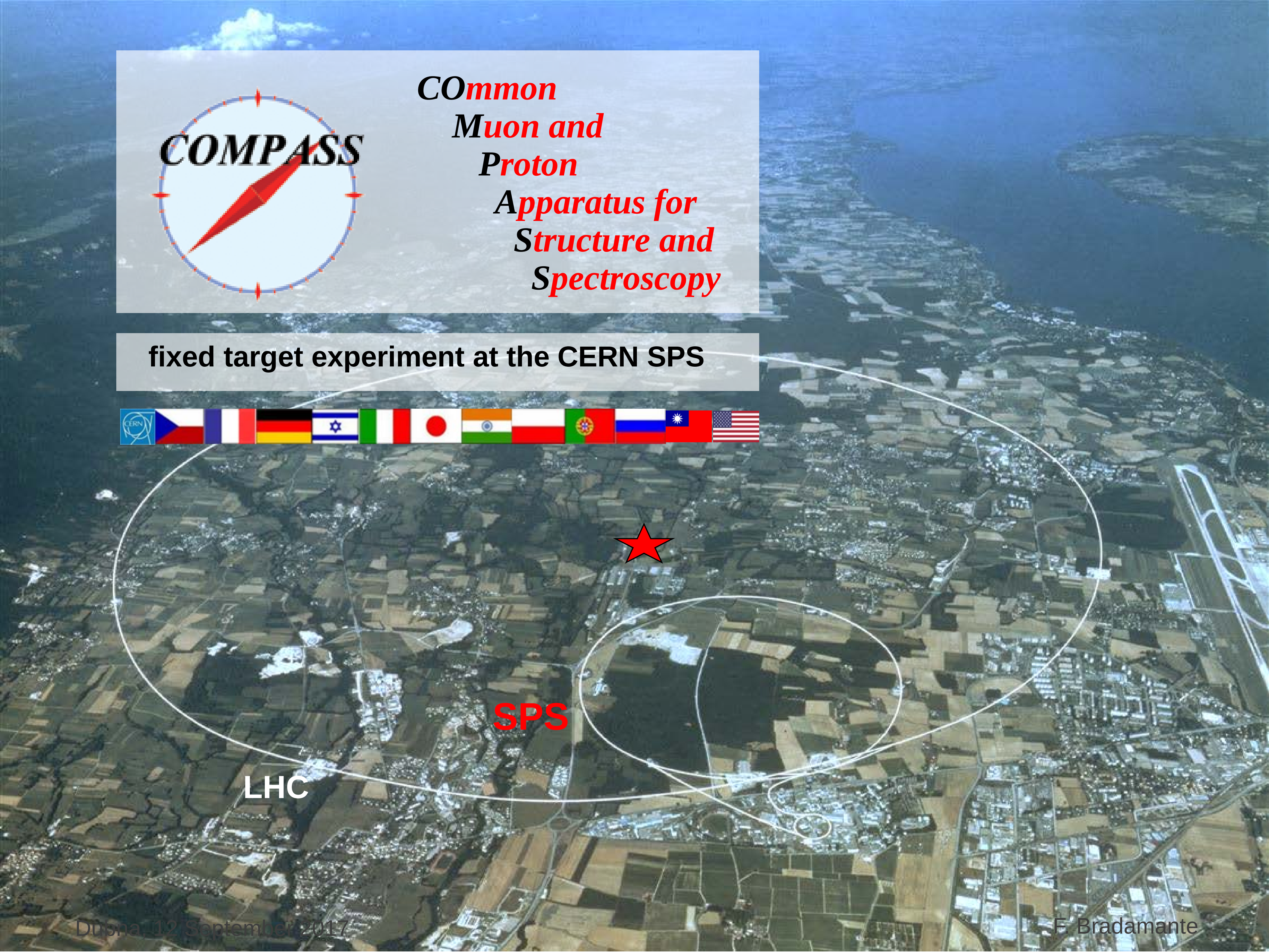
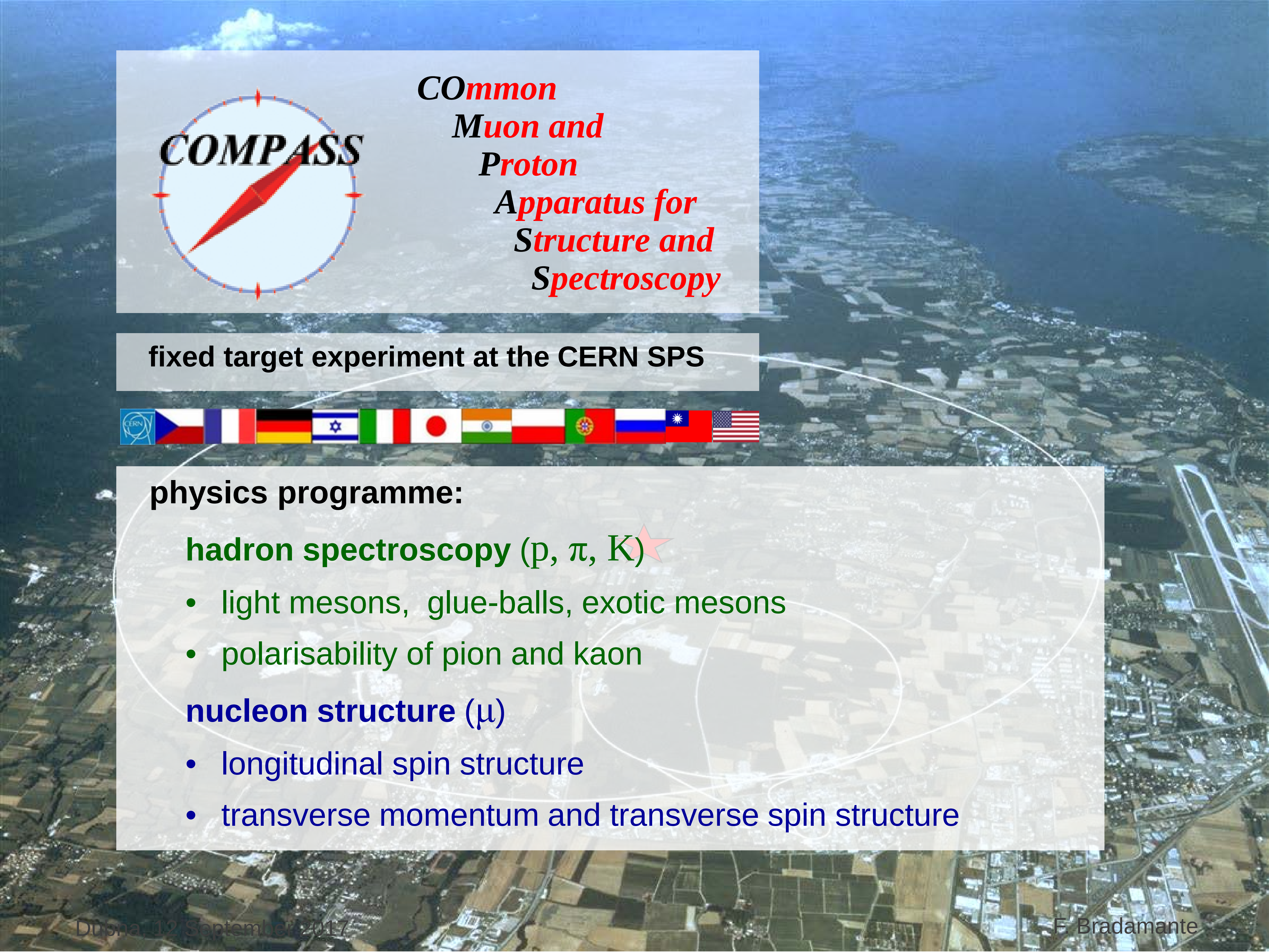
On behalf of the COMPASS Collaboration

COMPASS

***CO**mmon*
***M**uon and*
***P**roton*
***A**pparatus for*
***S**tructure and*
***S**pectroscopy*

fixed target experiment at the CERN SPS





COMPASS

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

fixed target experiment at the CERN SPS

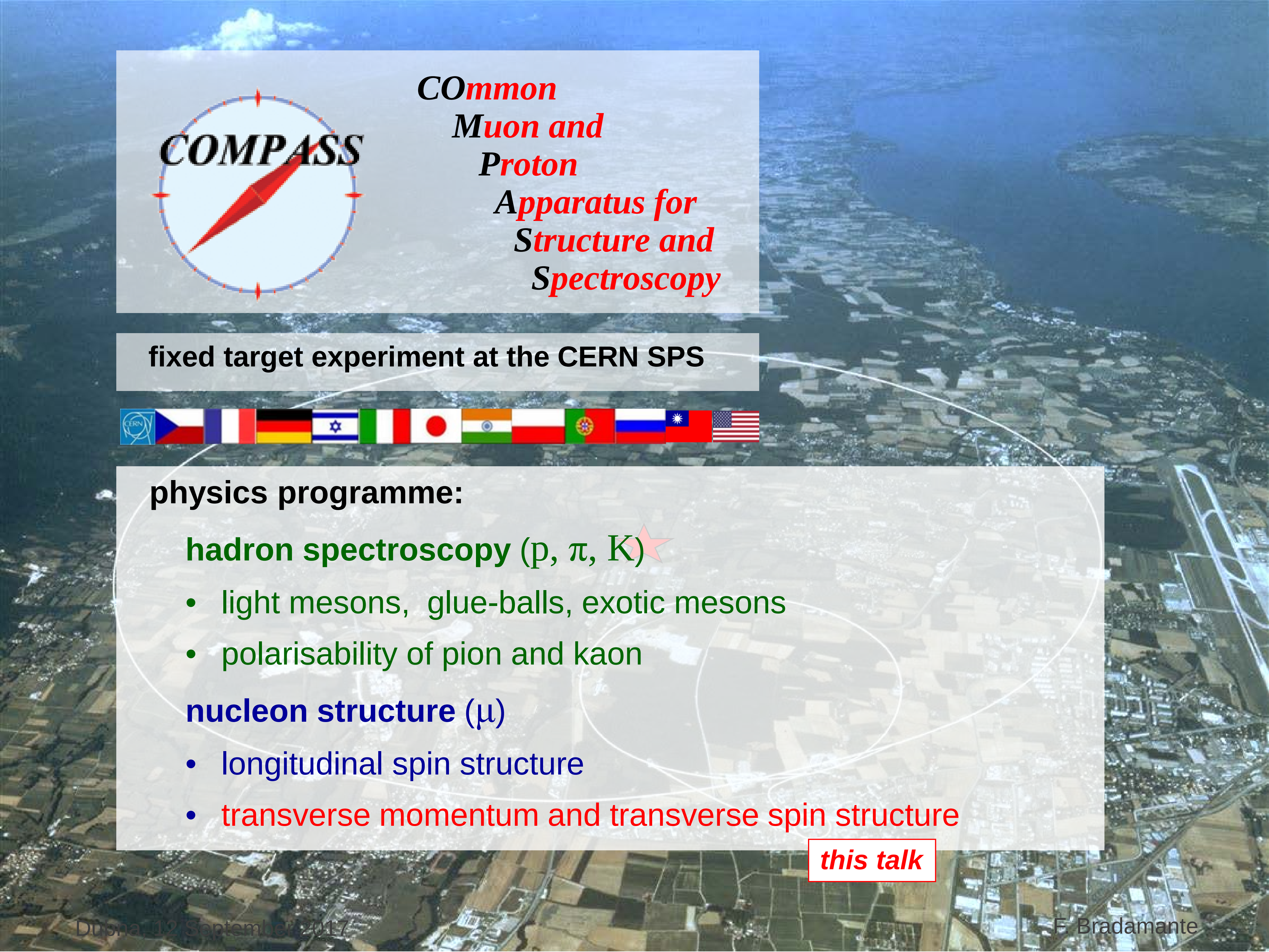
physics programme:

hadron spectroscopy (p, π, K)

- light mesons, glue-balls, exotic mesons
- polarisability of pion and kaon

nucleon structure (μ)

- longitudinal spin structure
- transverse momentum and transverse spin structure



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this talk

COMPASS spectrometer

designed to

- use high energy beams
- have large angular acceptance
- cover a broad kinematical range

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- **use high energy beams**
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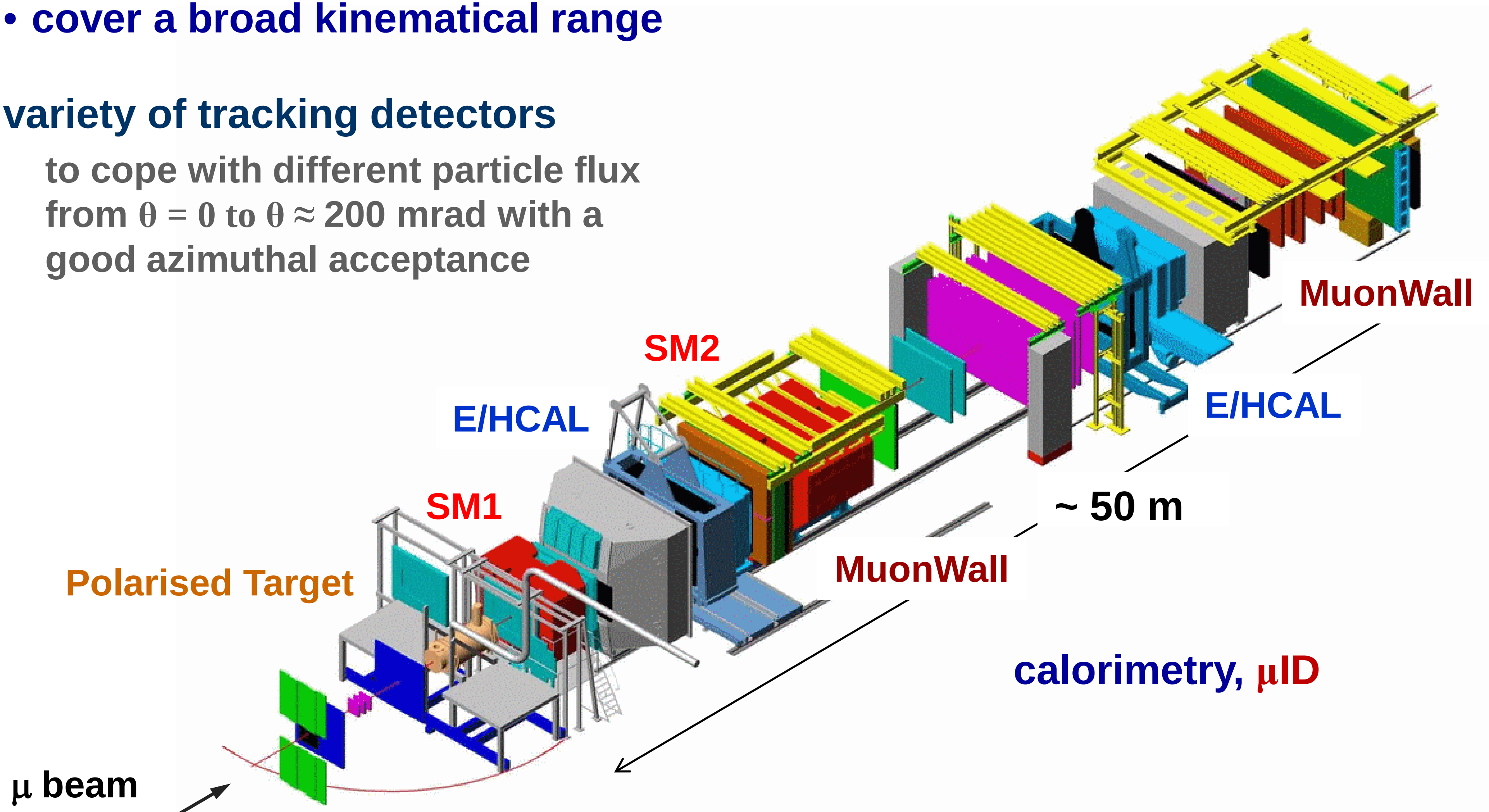
two stages spectrometer
- **Large Angle Spectrometer (SM1)**
- **Small Angle Spectrometer (SM2)**

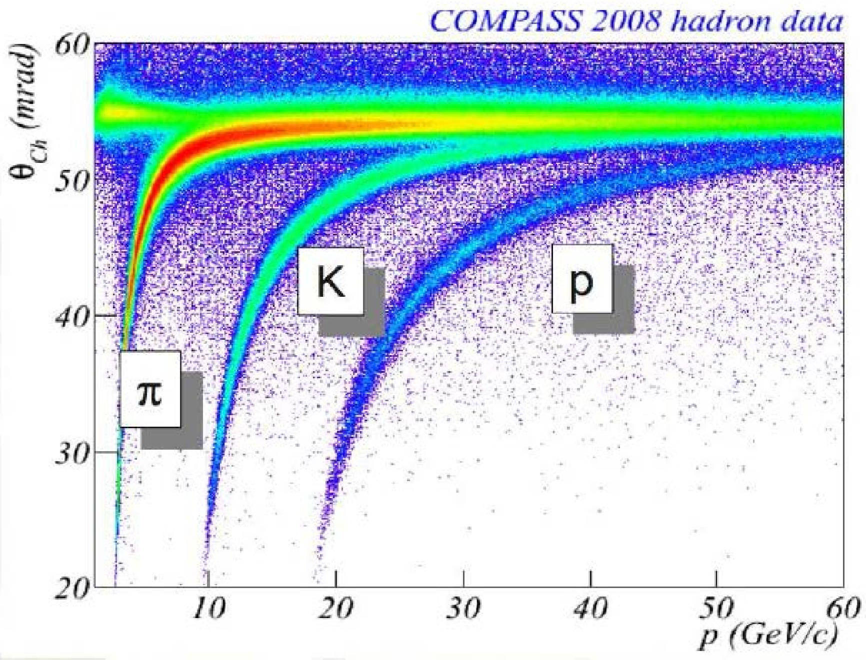
variety of tracking detectors

to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad with a good azimuthal acceptance



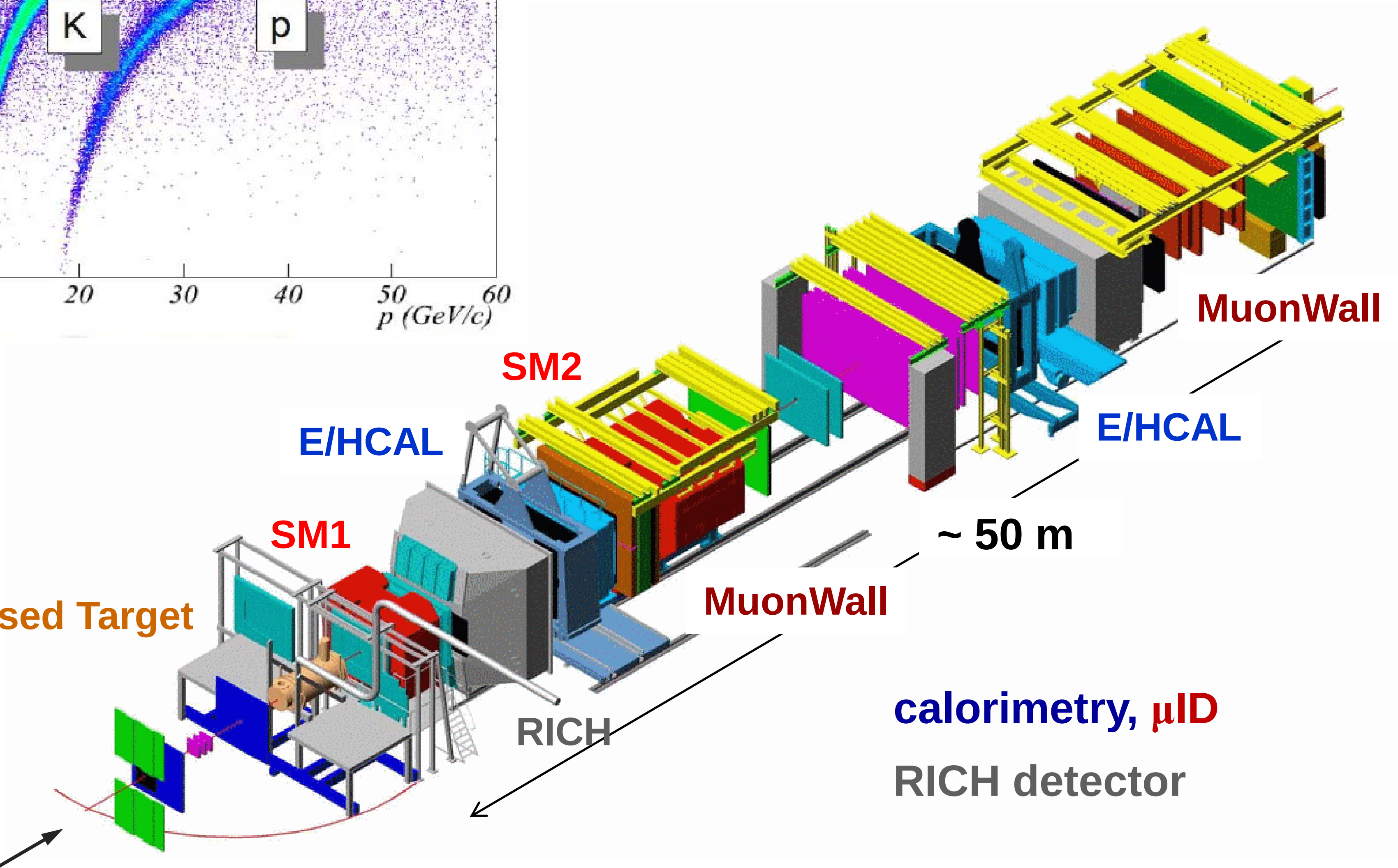
calorimetry, μID

COMPASS spectrometer



two stages spectrometer

- Large Angle Spectrometer (**SM1**)
- Small Angle Spectrometer (**SM2**)



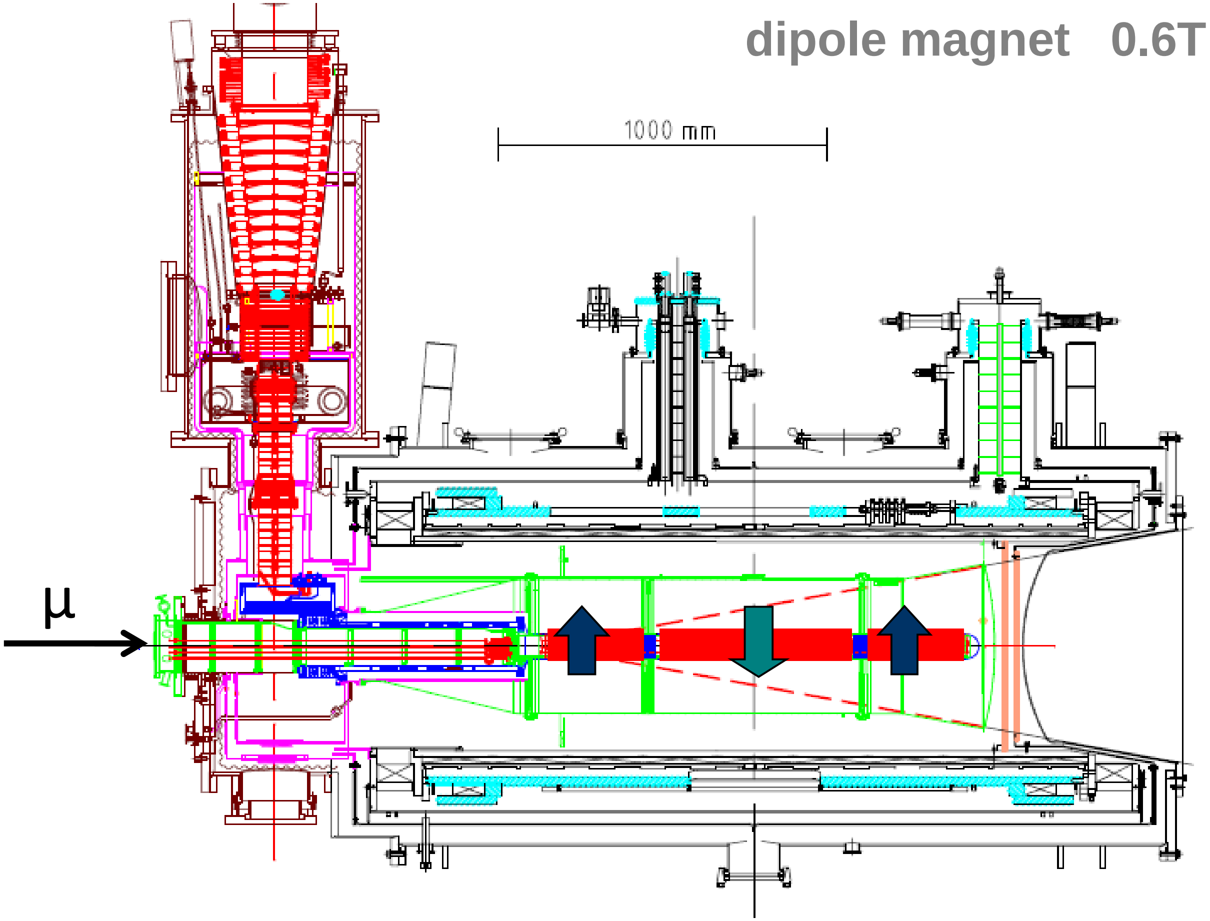
calorimetry, μID

RICH detector

the polarized target system (>2005)

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

solenoid	2.5T
dipole magnet	0.6T



acceptance > ± 180 mrad

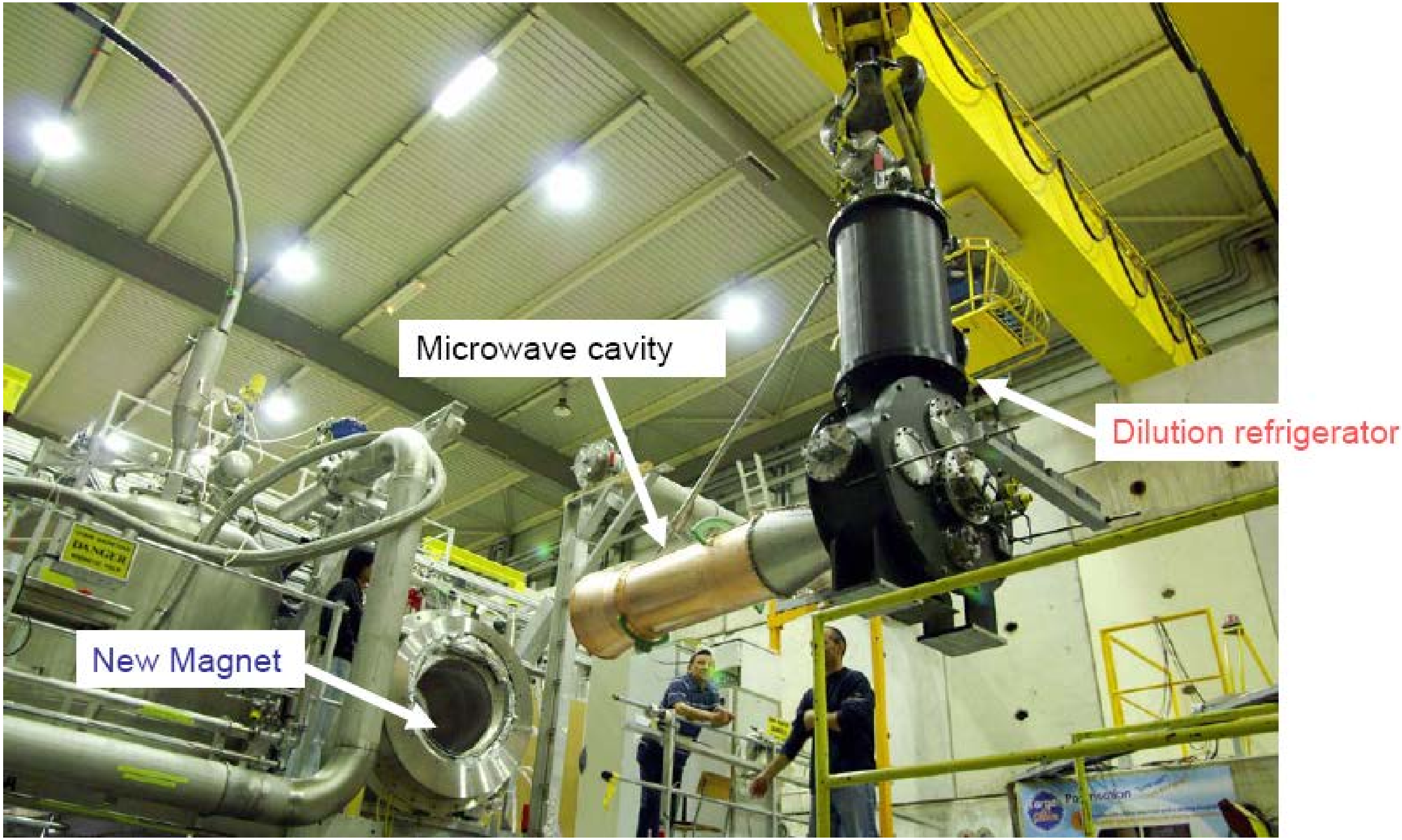
3 target cells
30, 60, and 30 cm long

opposite polarisation

	d (^{6}LiD)	p (NH_3)
polarization	50%	90%
dilution factor	40%	16%

no evidence for relevant nuclear effects *(160 GeV)*

the polarized target system



COMPASS data taking

COMPASS data taking

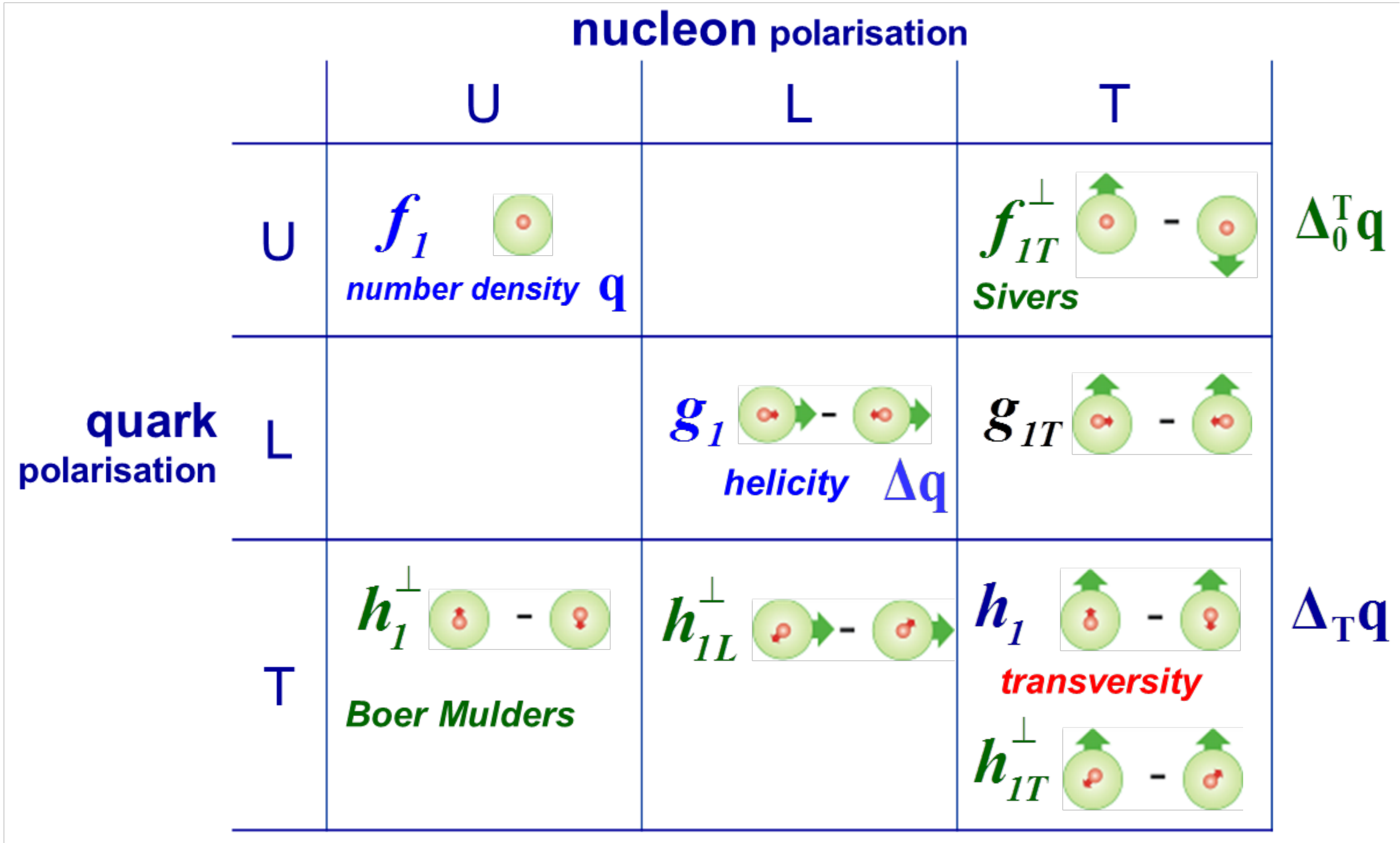
2002	**nucleon structure with**	**160 GeV μ**	**L&T**	**polarised deuteron target**
2003	**nucleon structure with**	**160 GeV μ**	**L&T**	**polarised deuteron target**
2004	**nucleon structure with**	**160 GeV μ**	**L&T**	**polarised deuteron target**
2005	*CERN accelerators shut down*			
2006	**nucleon structure with**	**160 GeV μ**	**L**	**polarised deuteron target**
2007	**nucleon structure with**	**160 GeV μ**	**L&T**	**polarised proton target**
2008	***hadron spectroscopy***			
2009	***hadron spectroscopy***			
2010	**nucleon structure with**	**160 GeV μ**	**T**	**polarised proton target**
2011	**nucleon structure with**	**190 GeV μ**	**L**	**polarised proton target**
2012	**Primakoff & DVCS / SIDIS test**			
2013	*CERN accelerators shut down*			
2014	Test beam Drell-Yan process with π beam and T polarised proton target			
2015	**Drell-Yan process with π beam and T polarised proton target**			
2016	**DVCS / SIDIS with μ beam and unpolarised proton target**			
2017	**DVCS / SIDIS with μ beam and unpolarised proton target**			
2018	**Drell-Yan process with π beam and T polarised proton target**			

MUON beam PROGRAM:

TRANSVERSITY and Transverse Momentum Dependent PDFs

the structure of the nucleon

taking into account the quark intrinsic transverse momentum k_T ,
at leading order other 6 TMD PDFs are needed for a full description
of the nucleon structure

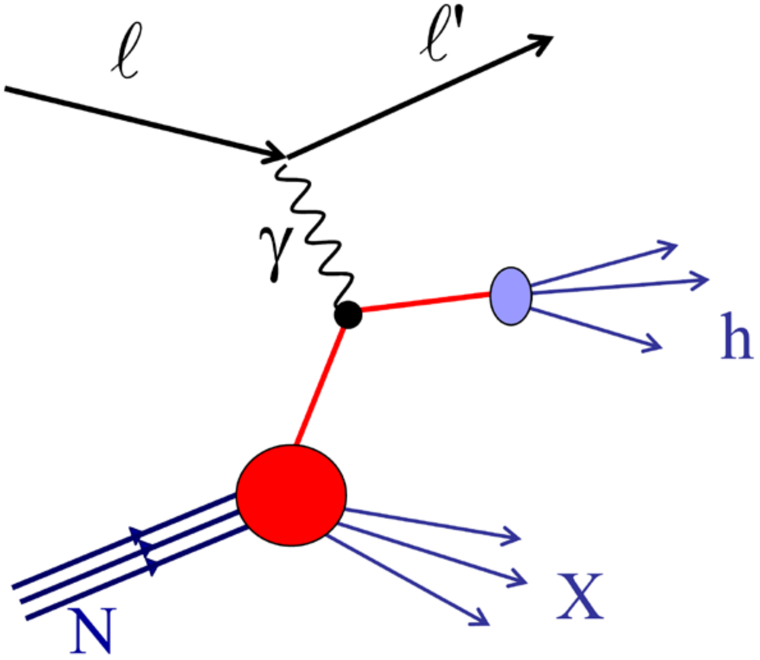


		nucleon polarisation			
		U	L	T	
quark polarisation	U	f_1 *number density* $\mathbf{q}$		$f_{1T}^{\perp}$ - *Sivers*	$\Delta_0^T \mathbf{q}$
	L		g_1 - *helicity* $\Delta \mathbf{q}$	g_{1T} -	
	T	$h_1^{\perp}$ - *Boer Mulders*	$h_{1L}^{\perp}$ -	h_1 - *transversity* $h_{1T}^{\perp}$ -	$\Delta_T \mathbf{q}$

SIDIS gives access to all of them

Semi-Inclusive Deep Inelastic Scattering

hard interaction of a lepton with a nucleon via virtual photon exchange

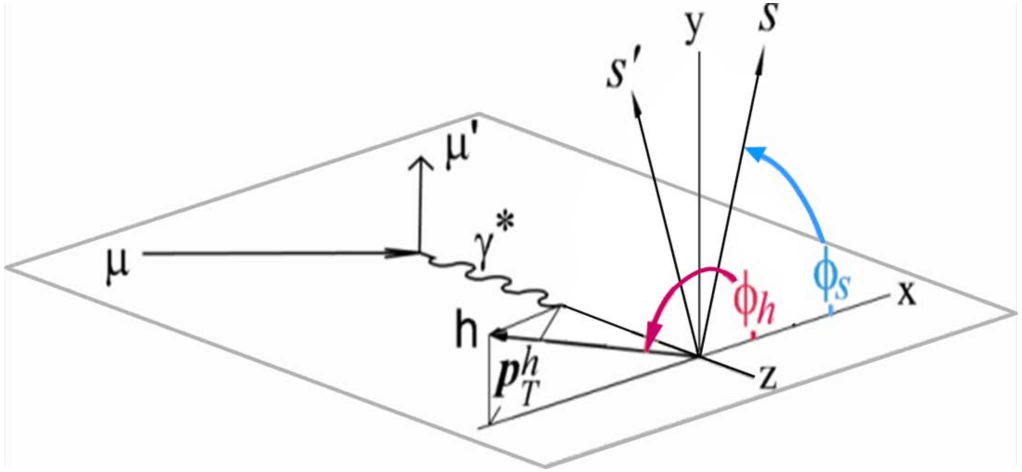


$$x = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot q}{P\cdot \ell} =_{LAB} \frac{E-E'}{E}$$

$$Q^2 = -q^2 \qquad W^2 = (P+q)^2$$

$$z = \frac{P\cdot P_h}{P\cdot q} =_{LAB} \frac{E_h}{E-E'}$$

$$\sigma^{lN\to lhX} \propto \sum_q f(x)\otimes\sigma^{lq\to lq}\otimes D_q^h(z)$$



Semi-Inclusive Deep Inelastic Scattering

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

unpol target

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$\longrightarrow$ **pol target**

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

$$+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$\uparrow$ **pol target**

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

18 structure functions

Semi-Inclusive Deep Inelastic Scattering

14 independent azimuthal modulations

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\cos\phi_h}\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\,\boxed{\cos(2\phi_h)}\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\sin\phi_h}\,F_{LU}^{\sin\phi_h}$$

$$+\,S_{\|}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_h}\,F_{UL}^{\sin\phi_h}+\varepsilon\,\boxed{\sin(2\phi_h)}\,F_{UL}^{\sin 2\phi_h}\right]+S_{\|}\lambda_e\left[\sqrt{1-\varepsilon^2}\;F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_h}\,F_{LL}^{\cos\phi_h}\right]$$

$$+\,|\boldsymbol{S}_\perp|\Big[\boxed{\sin(\phi_h-\phi_S)}\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)$$

$$+\,\varepsilon\,\boxed{\sin(\phi_h+\phi_S)}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\boxed{\sin(3\phi_h-\phi_S)}\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_S}\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin(2\phi_h-\phi_S)}\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\boxed{\cos(\phi_h-\phi_S)}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos(2\phi_h-\phi_S)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

Semi-Inclusive Deep Inelastic Scattering

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\cos\phi_h}\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\overset{h_1^\perp H_1^\perp}{\boxed{\cos(2\phi_h)}}\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\sin\phi_h}\,F_{LU}^{\sin\phi_h} \\
&\quad+S_\parallel\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_h}\,F_{UL}^{\sin\phi_h}+\varepsilon\overset{h_{1L}^\perp H_1^\perp}{\boxed{\sin(2\phi_h)}}\,F_{UL}^{\sin 2\phi_h}\Big]+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2} \\
&\quad+|\boldsymbol{S}_\perp|\Big[\boxed{\sin(\phi_h-\phi_S)}\overset{f_{1T}^\perp D_1}{\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) \\
&\qquad+\varepsilon\underset{h_1 H_1^\perp}{\boxed{\sin(\phi_h+\phi_S)}}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\overset{h_{1T}^\perp H_1^\perp}{\boxed{\sin(3\phi_h-\phi_S)}}\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_S}\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin(2\phi_h-\phi_S)}\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&\quad+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\boxed{\cos(\phi_h-\phi_S)}\overset{g_{1T} D_1}{F_{LT}^{\cos(\phi_h-\phi_S)}}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi_S} \\
&\qquad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos(2\phi_h-\phi_S)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

14 independent azimuthal modulations

amplitudes of the modulations
→ TMD PDFs

Semi-Inclusive Deep Inelastic Scattering

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\cos\phi_h}\,F_{UU}^{\cos\phi_h}$$

$h_1^\perp H_1^\perp$

$$+\,\varepsilon\,\boxed{\cos(2\phi_h)}\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\sin\phi_h}\,F_{LU}^{\sin\phi_h}$$

$h_{1L}^\perp H_1^\perp$

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_h}\,F_{UL}^{\sin\phi_h}+\varepsilon\,\boxed{\sin(2\phi_h)}\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}$$

$f_{1T}^\perp D_1$

$$+\,|\boldsymbol{S}_\perp|\Big[\boxed{\sin(\phi_h-\phi_S)}\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon$$

$$+\,\varepsilon\,\boxed{\sin(\phi_h+\phi_S)}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon$$

$h_1 H_1^\perp$

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_S}\,F_{UT}^{\sin\phi_S}+\sqrt{}$$

$$\Big]$$

$g_{1T} D_1$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\boxed{\cos(\phi_h-\phi_S)}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos(2\phi_h-\phi_S)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

14 independent azimuthal modulations

amplitudes of the modulations
→ TMD PDFs

SIDIS

- **allows to disentangle the effects related to the different TMD PDFs and to access all of them**
- **by identifying the final state hadrons and using different targets allows for flavour separation**

→ ***very powerful tool***

all the amplitudes (AA) have been measured in COMPASS

TMDs in unpolarised SIDIS

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{$$

$$F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\;\overset{k_T}{\boxed{\cos\phi_h}}\;F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\,\underset{h_1^\perp H_1^\perp}{\overset{k_T}{\boxed{\cos(2\phi_h)}}}\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\;\boxed{\sin\phi_h}\;F_{LU}^{\sin\phi_h}$$

$$+\ \ldots\ \Bigg\}$$

unpolarised SIDIS

Relevance for TMDs:

- the cross-section dependence on $\boldsymbol{p_{Th}}$ comes from:
  - intrinsic k_T of the quarks
  - $p_\perp$ generated in the quark fragmentation

$$\left\langle \boldsymbol{p_{Th}}^{\mathbf{2}} \right\rangle = \langle p_\perp{}^{\mathbf{2}} \rangle + \boldsymbol{z}^{\mathbf{2}} \langle k_{\boldsymbol{T}}{}^{\mathbf{2}} \rangle$$

- the azimuthal modulations in the unpolarized cross-sections comes from:
  - intrinsic k_T of the quarks
  - Boer-Mulders PDF

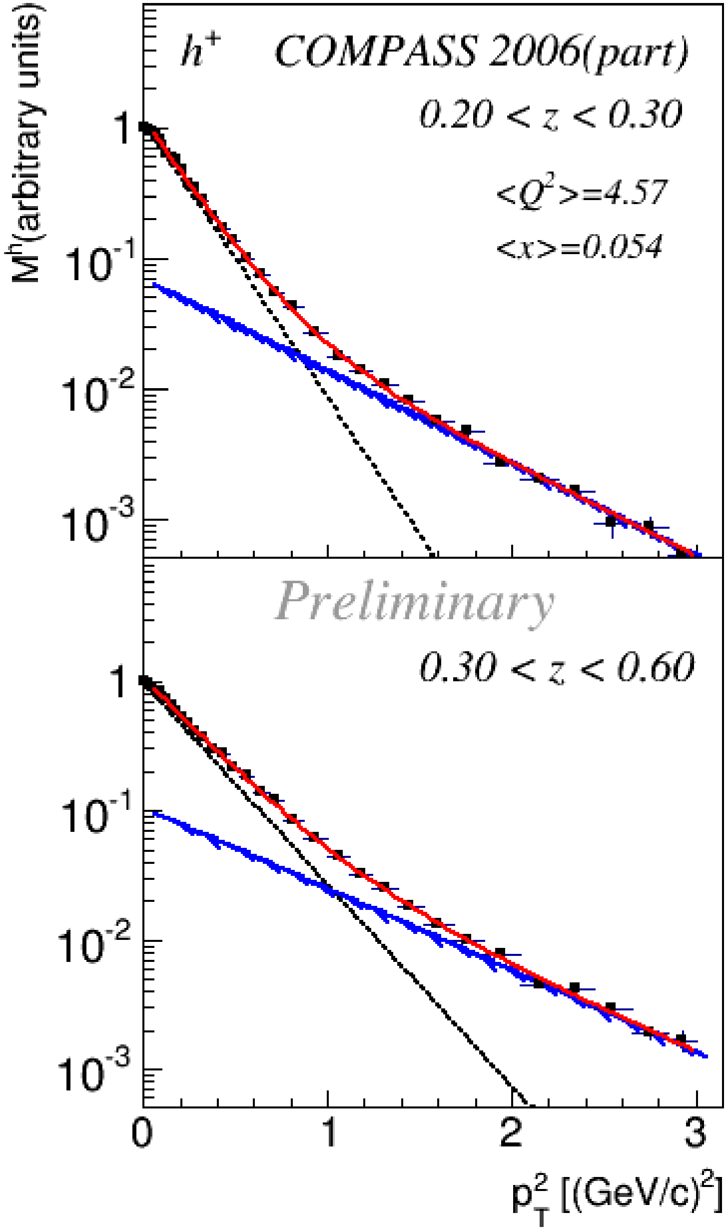
combined analysis should allow to disentangle the different effects

COMPASS

- has produced results on $^{\mathbf{6}}\boldsymbol{LiD}$ $(\sim\boldsymbol{d})$ from 2004/6 data
- will measure SIDIS on LH_2 in parallel with DVCS

unpolarised SIDIS – p_{Th} distributions

deuteron



Fit distributions with

- 1 exponential for $p_{Th}^2 \in [0.05, 0.68]$
- 2 exponentials for $p_{Th}^2 \in [0.05, 3]$

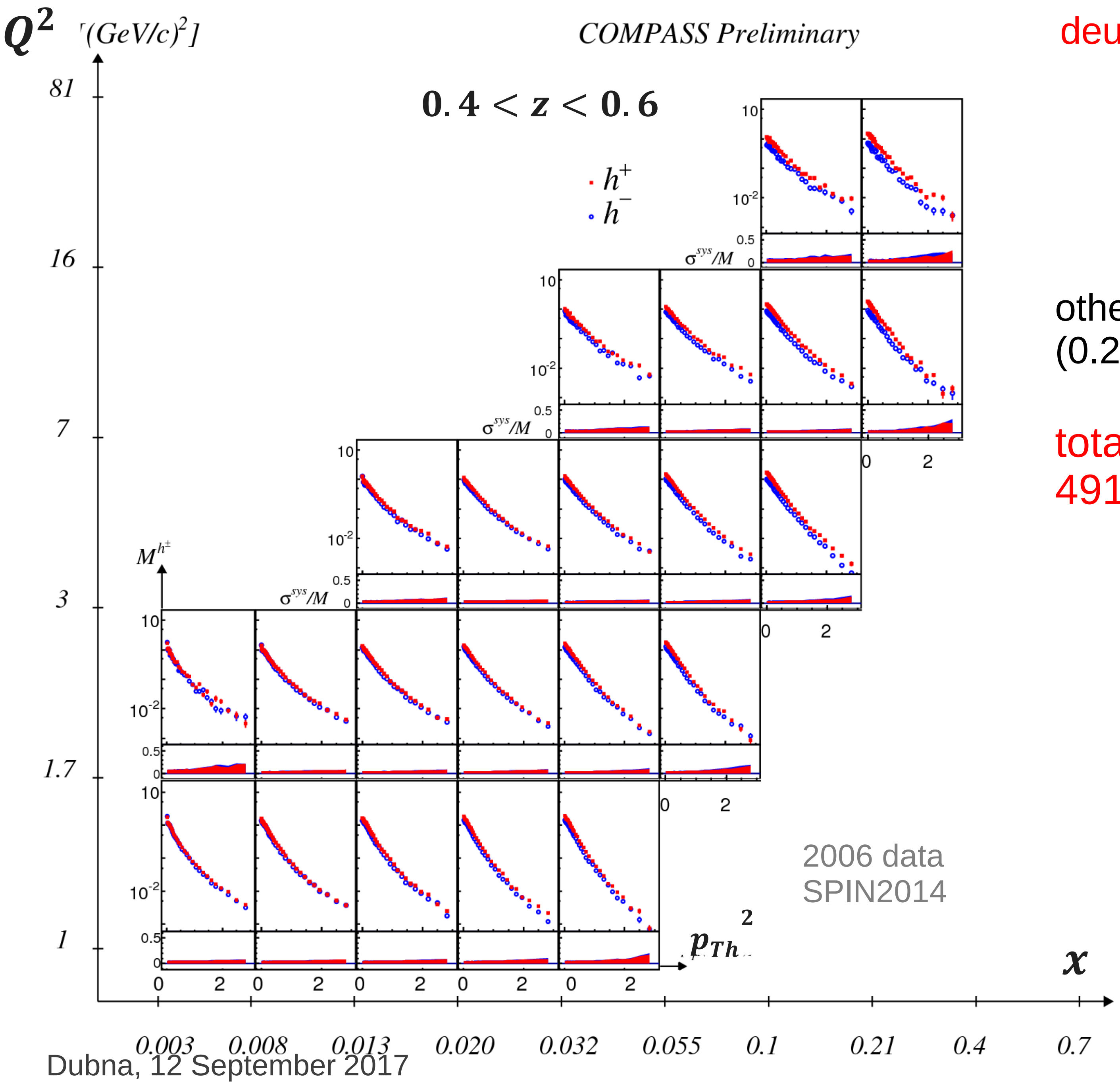
↓

needed to describe the shape of p_{Th}^2 the COMPASS data

Transversity 2014

unpolarised SIDIS – p_{Th} distributions

deuteron



other 3 z bins
(0.2-0.3, 0.3-0.4, 0.6-0.8)

total:
4918 data points

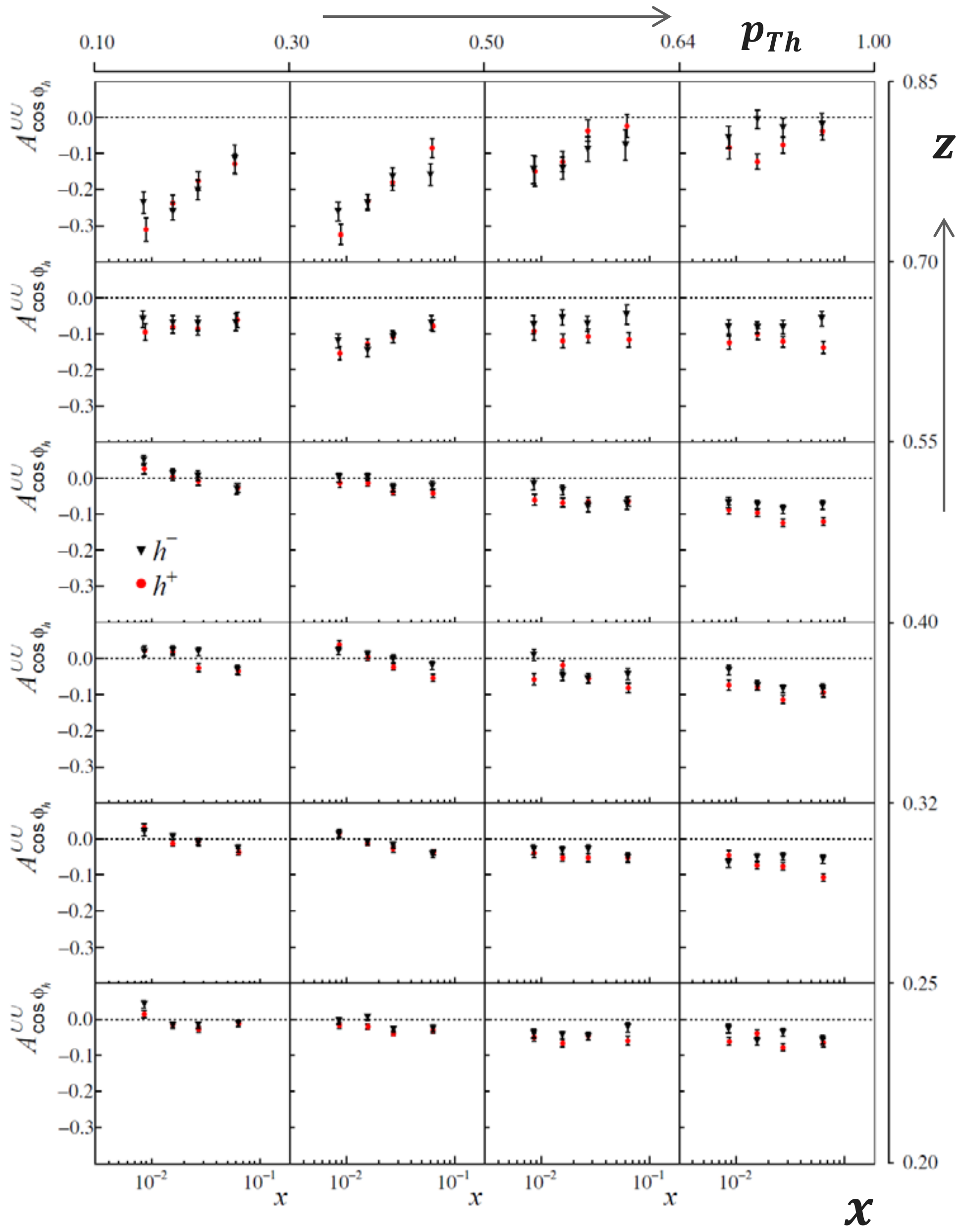
paper ready,
to be sent to PRD

2006 data
SPIN2014

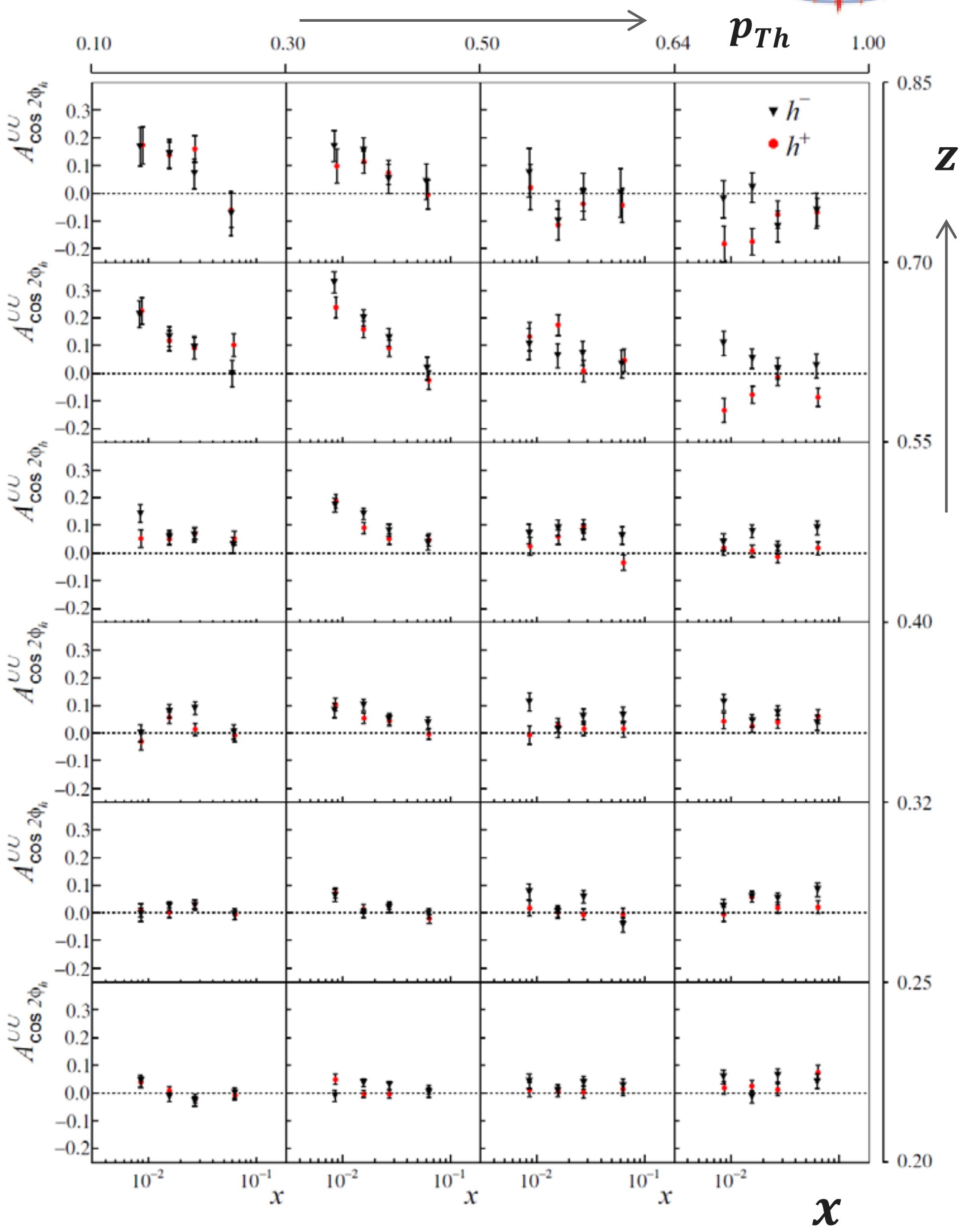
unpolarised SIDIS – azimuthal asymmetries

deuteron

cos ϕ_h



cos $2\phi_h$

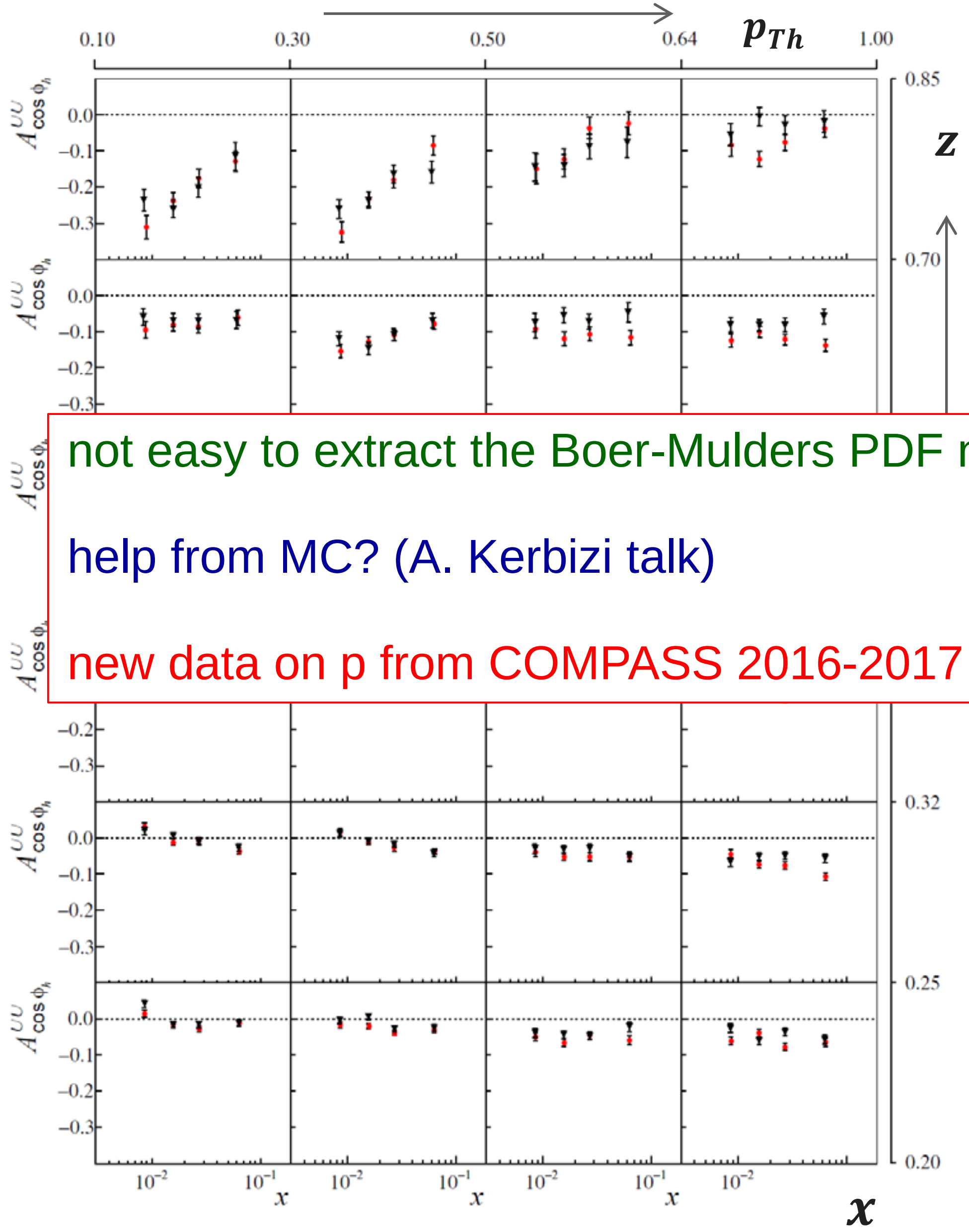


NPB 886 (2014) 1046

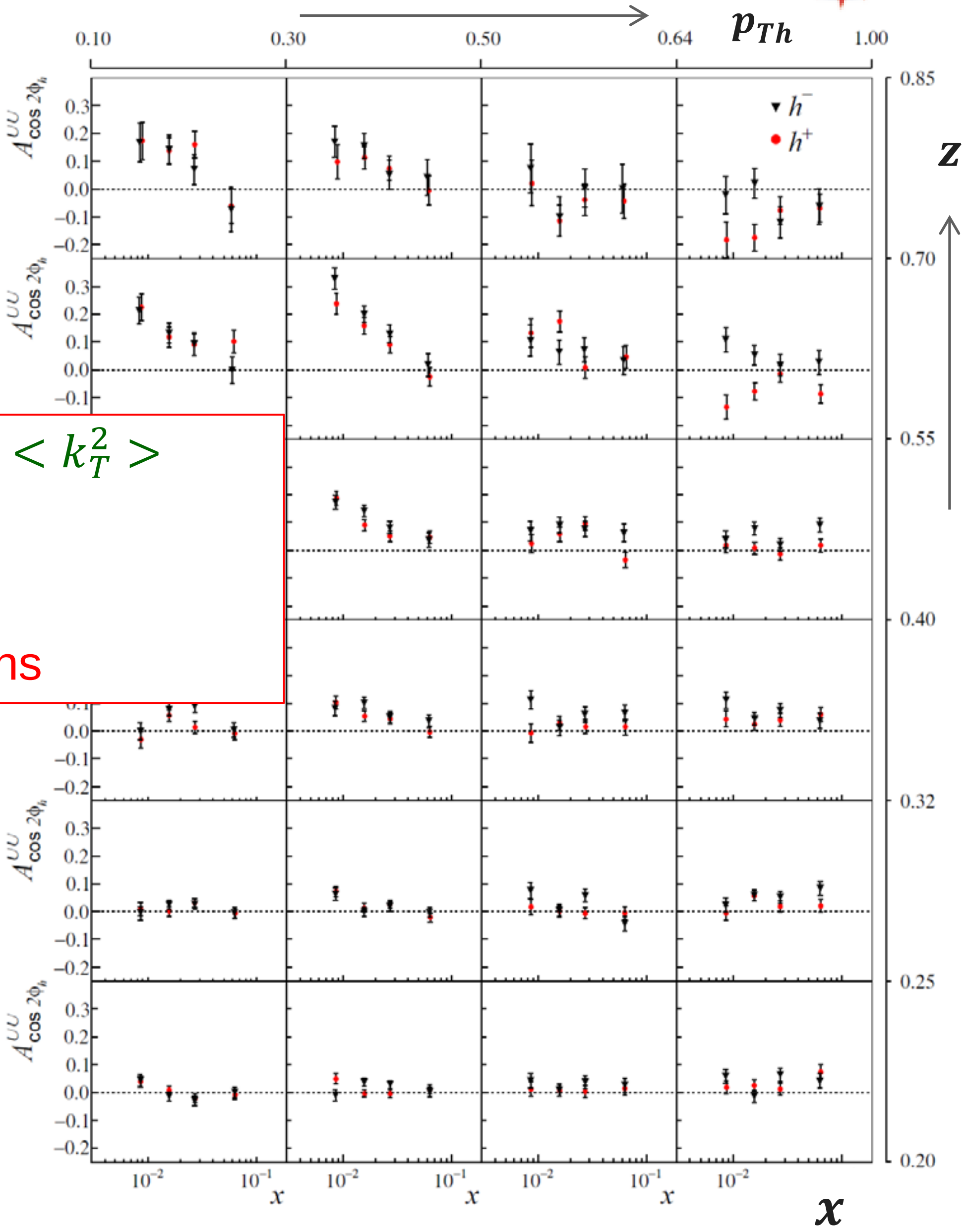
unpolarised SIDIS – azimuthal asymmetries

deuteron

cos ϕ_h



cos $2\phi_h$



not easy to extract the Boer-Mulders PDF nor $< k_T^2 >$

help from MC? (A. Kerbizi talk)

new data on p from COMPASS 2016-2017 runs

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TMDs in SIDIS off longitudinally polarised N

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{$$

$$\dots$$

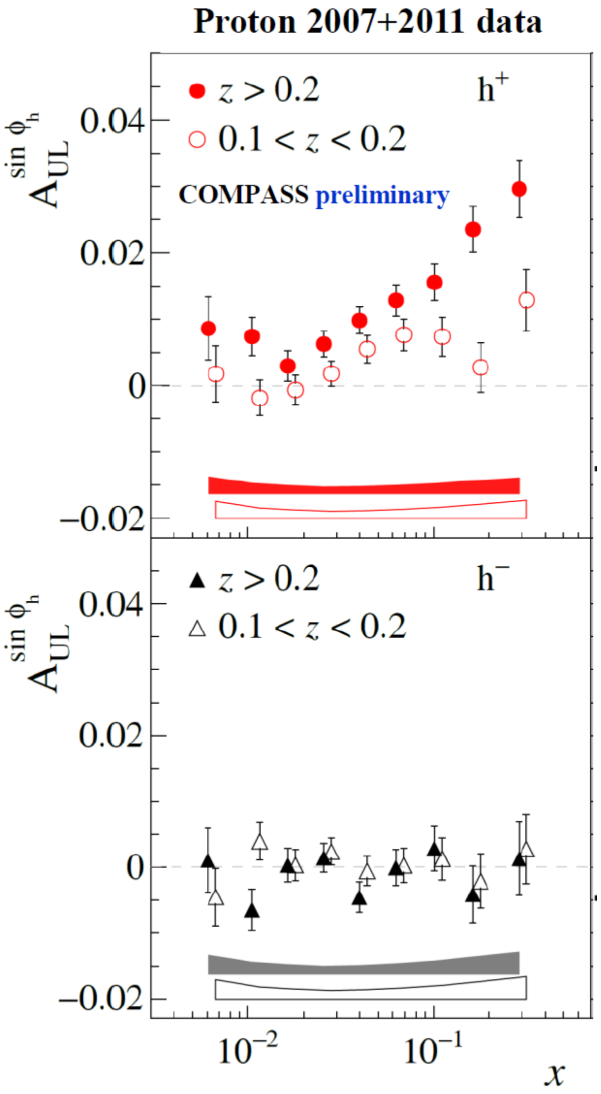
$$+\,S_{\|}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_h}\,F_{UL}^{\sin\phi_h} + \varepsilon\,\boxed{\sin(2\phi_h)}\,\overset{h_{1L}^{\perp}\,H_1^{\perp}}{F_{UL}^{\sin 2\phi_h}}\right]$$

$$+\,S_{\|}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_h}\,F_{LL}^{\cos\phi_h}\right]$$

$$+\ \dots\ \Bigg\}$$

SIDIS off longitudinally polarised p

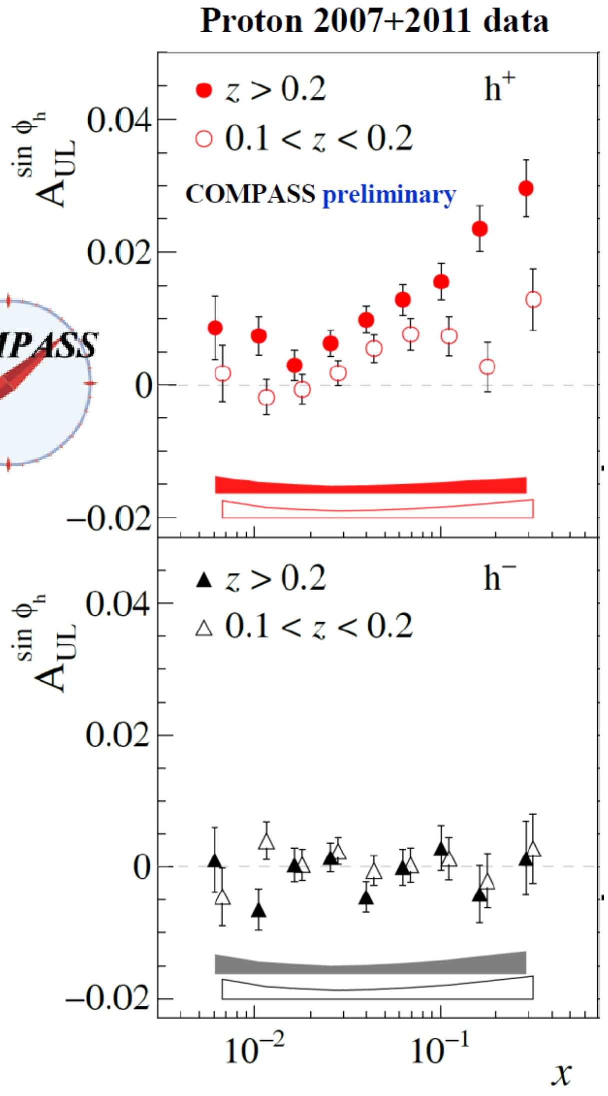
$$A_{UL}^{\sin\phi_h} = F_{UL}^{\sin\phi_h} / F_{UU}$$



SIDIS off longitudinally polarised p

$$A_{UL}^{\sin\phi_h} = F_{UL}^{\sin\phi_h}/F_{UU}$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M}\, g_{1L}^q\, \frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M}\, h_{1L}^{\perp q}\, \frac{\tilde{H}_q^h}{z}\right)\right\}$$

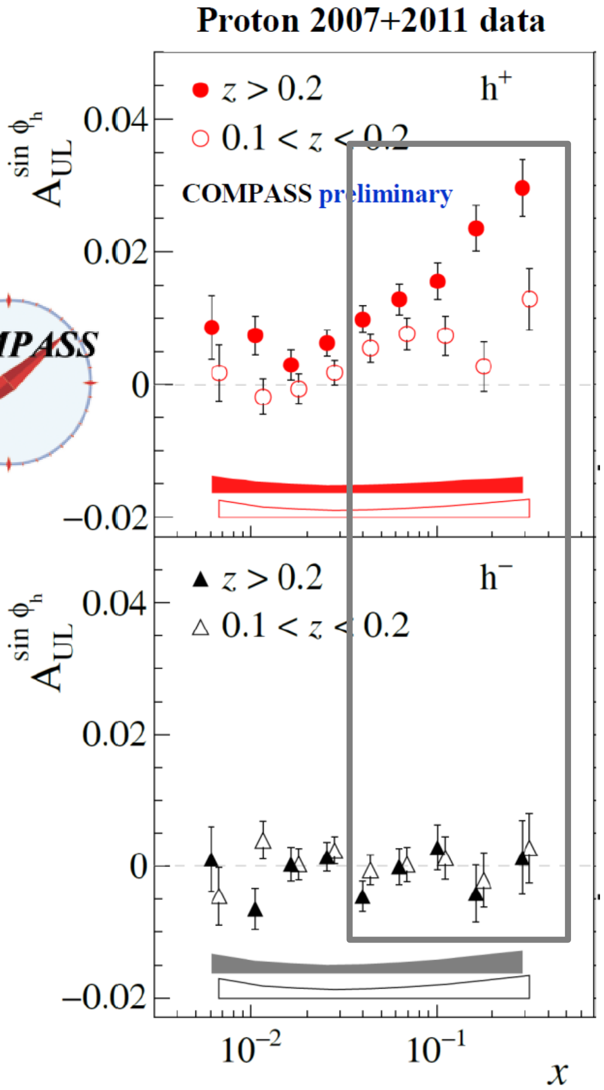


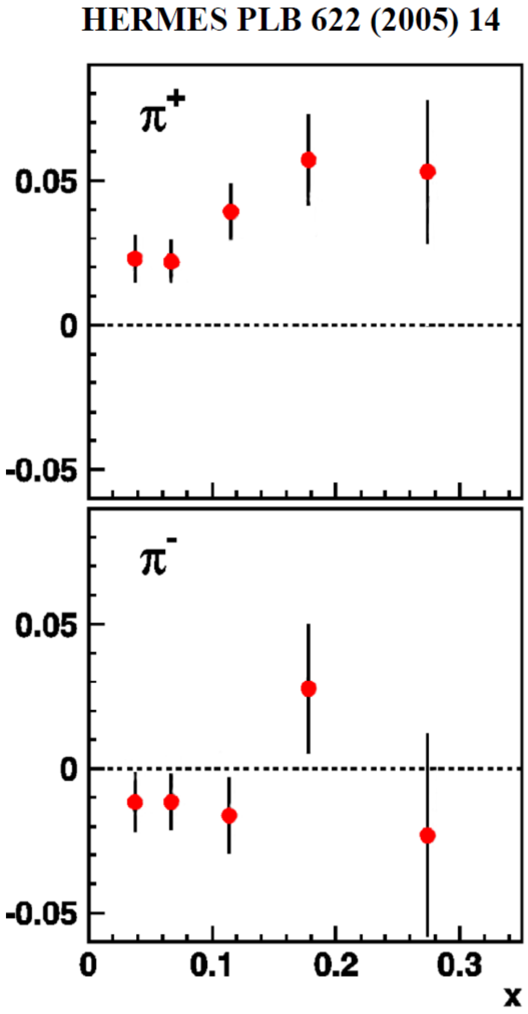
Q-suppressed,
different “twist” contributions

SIDIS off longitudinally polarised p

$$A_{UL}^{\sin\phi_h} = F_{UL}^{\sin\phi_h} / F_{UU}$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M}\, g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M}\, h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z}\right)\right\}$$





Q-suppressed,
different “twist” contributions

$$\sqrt{2\,\epsilon(1+\epsilon)}$$

SIDIS off transversely polarised N

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =\cdots \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{$$

$$+\,|\boldsymbol{S}_\perp|\Bigg[\overset{f_{1T}^{\perp}D_1}{\boxed{\sin(\phi_h-\phi_S)}}\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\,\varepsilon\,\underset{h_1 H_1^{\perp}}{\boxed{\sin(\phi_h+\phi_S)}}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\overset{h_{1T}^{\perp}H_1^{\perp}}{\boxed{\sin(3\phi_h-\phi_S)}}\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_S}\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin(2\phi_h-\phi_S)}\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\overset{g_{1T}D_1}{\boxed{\cos(\phi_h-\phi_S)}}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{\;\;\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos(2\phi_h-\phi_S)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},$$

Semi-Inclusive Deep Inelastic Scattering

MAJOR RESULT:
in the past 10 years 2 of these new PDF’s have been measured and shown to be different from zero

by COMPASS and HERMES

the transversity PDF

amplitude of the sine modulation in $\phi_h + \phi_s - \pi$

Collins asymmetry ~ $h_1 \otimes H_1^\perp$

the Sivers PDF

amplitude of the sine modulation in $\phi_h - \phi_s$

Sivers asymmetry ~ $f_{1T}^\perp \otimes D_1$

A STEP TOWARDS
THE 3-D STRUCTURE OF THE NUCLEON

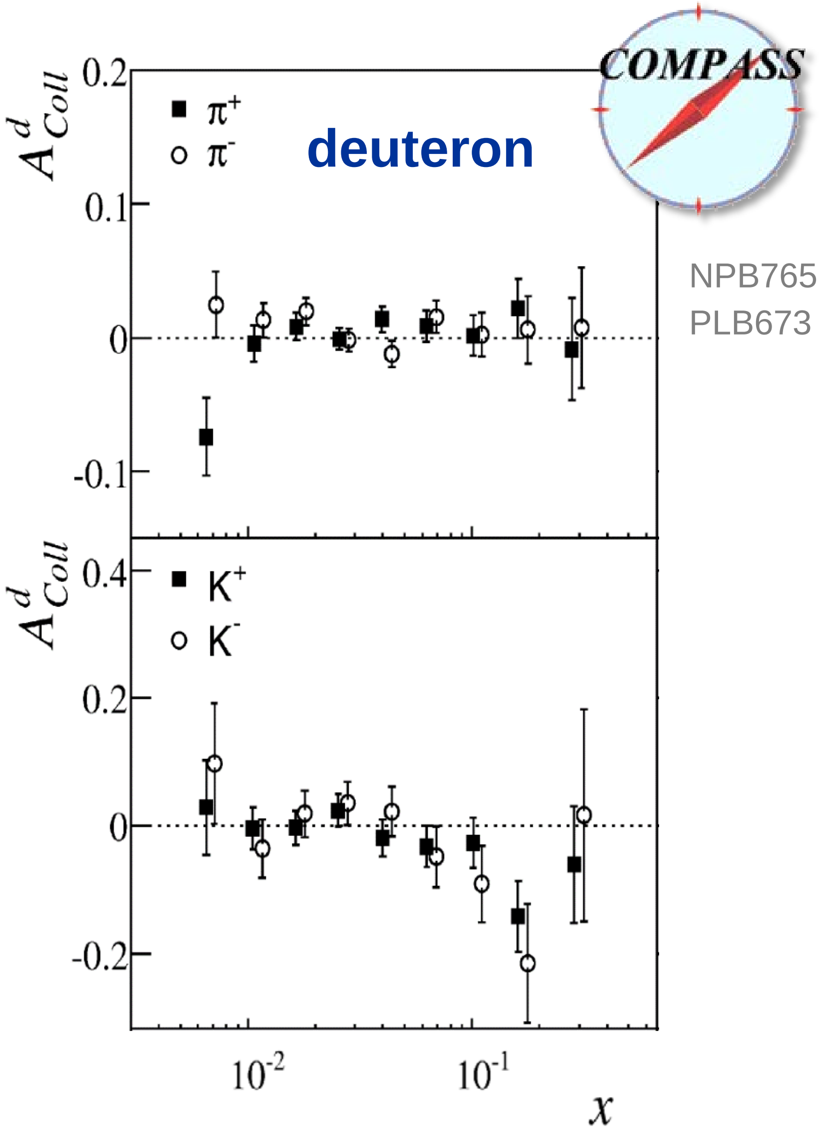
Collins asymmetry

Collins asymmetry

$\sim h_1 \otimes H_1^{\perp}$

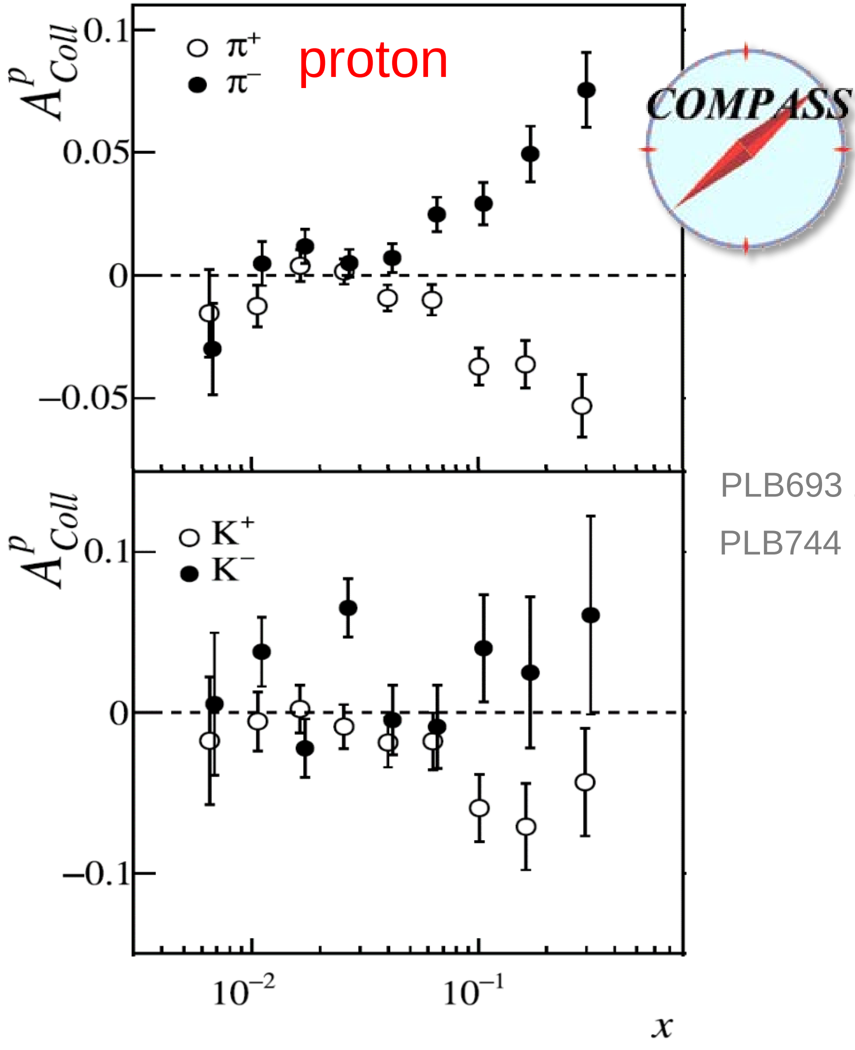
2004: first evidence for non-zero Collins asymmetry on p from HERMES

final COMPASS results



NPB765 2007

PLB673 2009



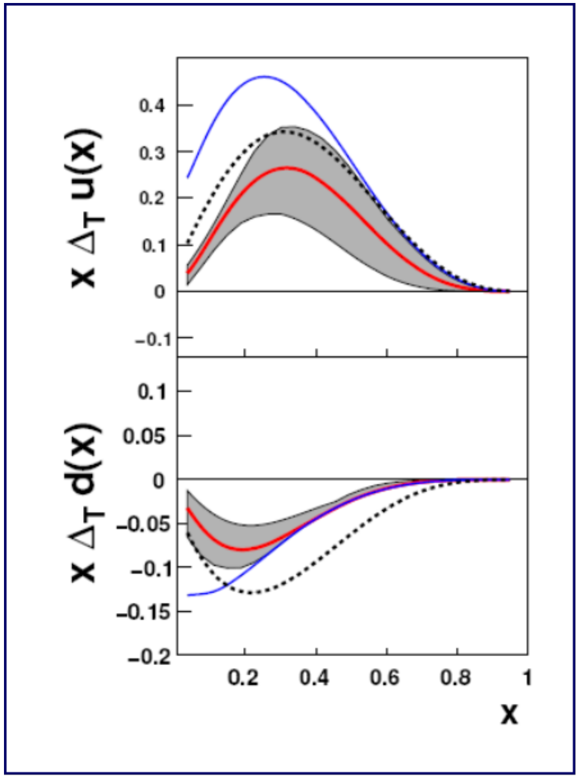
PLB693 2010

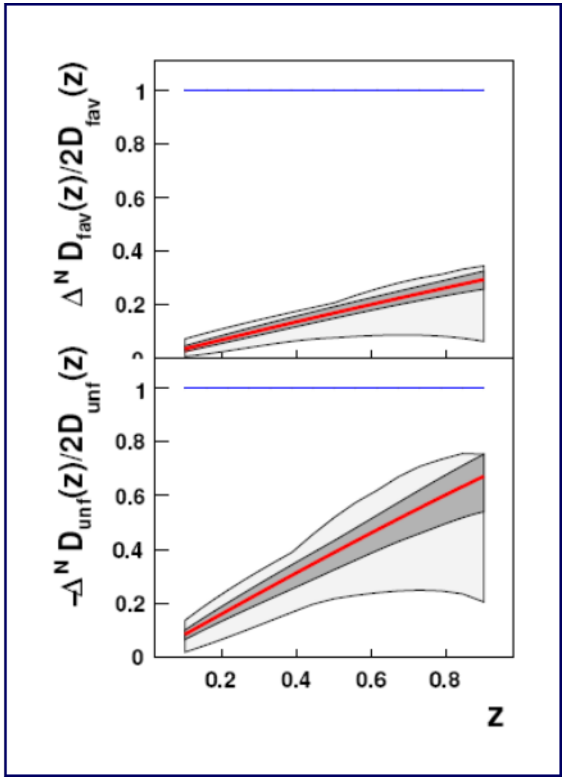
PLB744 2015

Transversity from SIDIS

M. Anselmino et al., Nucl. Phys. Proc. Suppl. 2009

fit to HERMES p, COMPASS d, Belle e+e- data





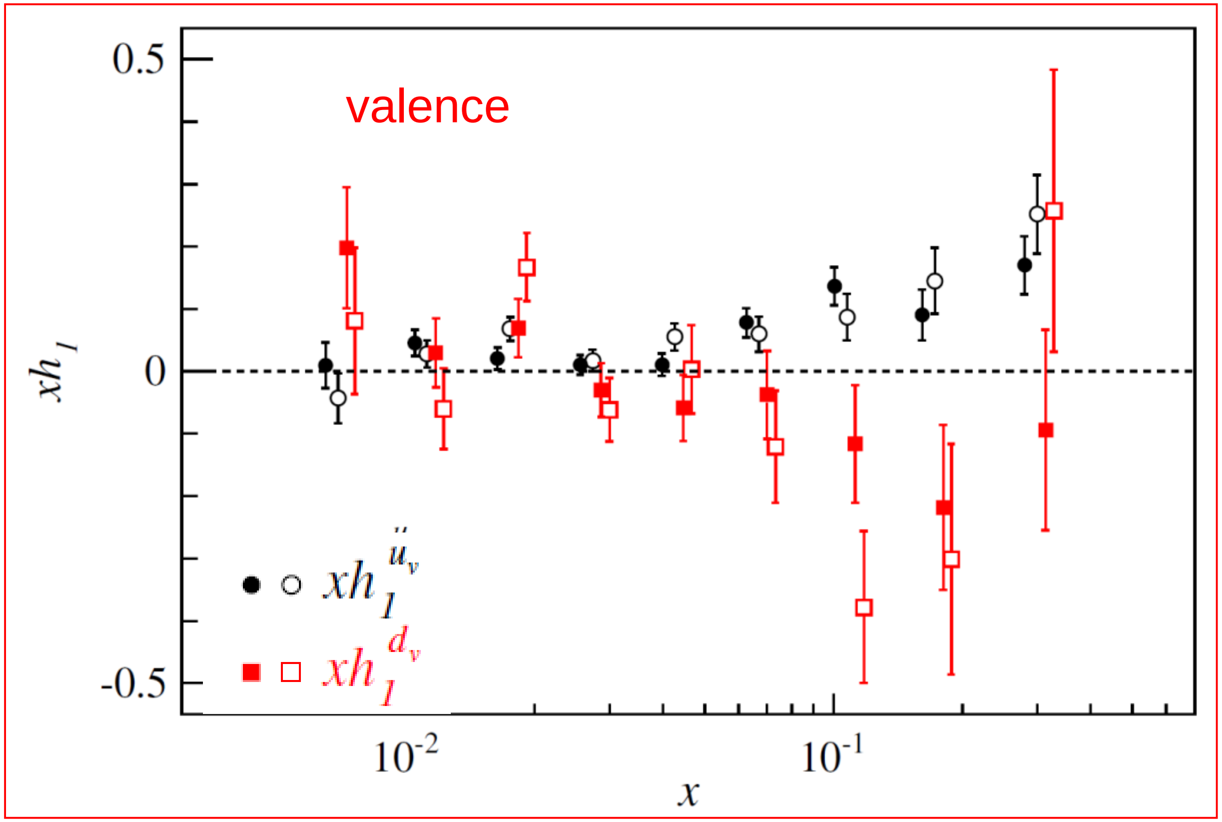
and many others …

Transversity from SIDIS

Collins and di-hadron asymmetries

point by point extraction

one can use directly the COMPASS p and d asymmetries,
and the Belle data to evaluate the analysing power
(with some “reasonable” assumptions)
advantage: no MC nor parametrisation is needed



open points: dihadron

closed points: Collins

large uncertainties
on the d distribution
due to the poor
deuteron/neutron
data

A. Martin F. B. V. Barone
PRD91 2015

Transversity from SIDIS

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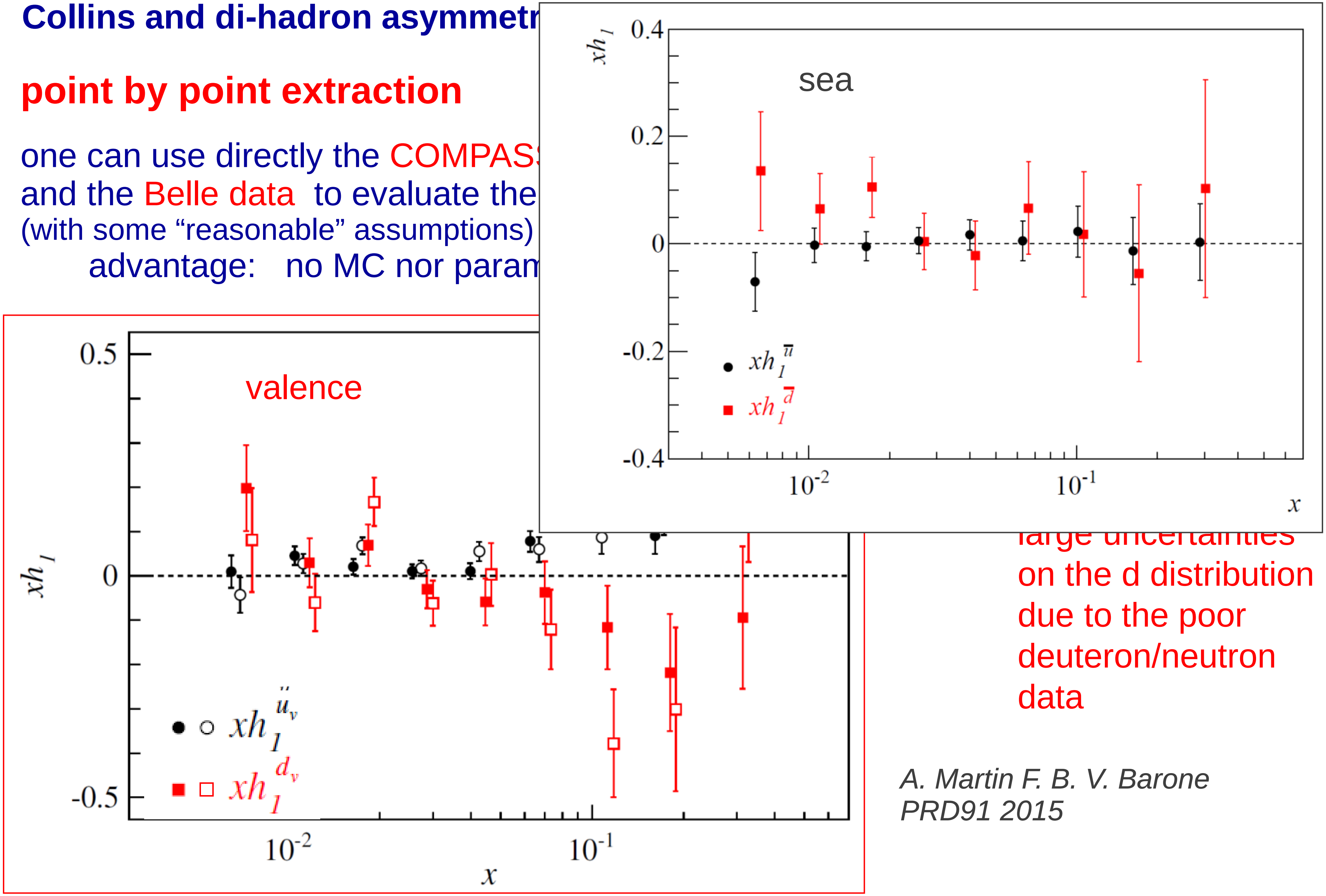


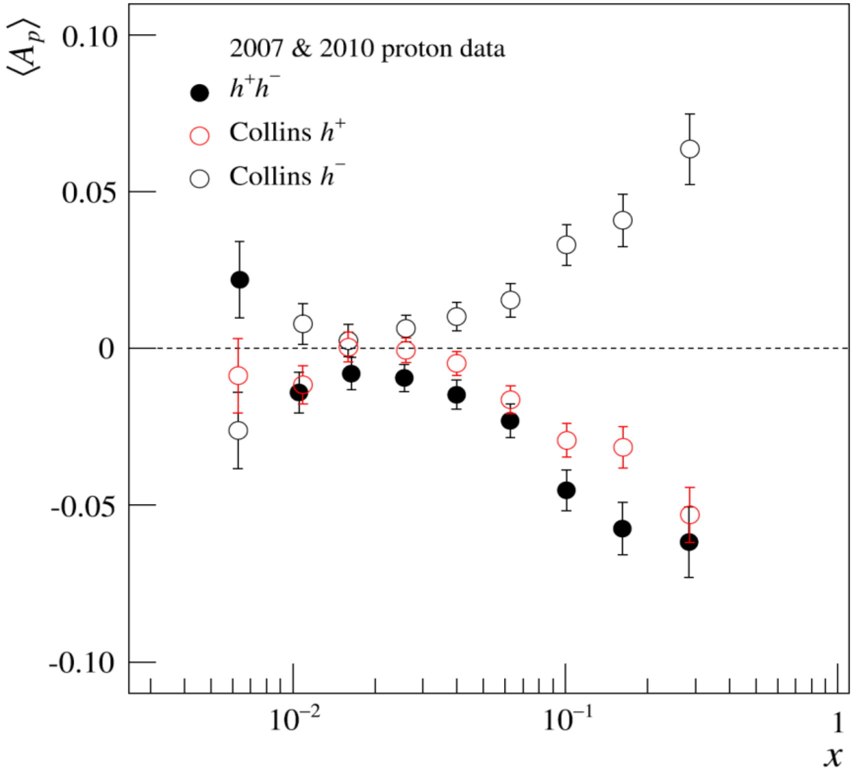
large uncertainties
on the d distribution
due to the poor
deuteron/neutron
data

A. Martin F. B. V. Barone
PRD91 2015

Transversity from SIDIS

not shown here

- di-hadron asymmetries   [PLB 713 (2012) 10, PLB 736 (2014) 124]
- interplay among transversity induced asymmetries
  [PLB 753 (2016) 406]

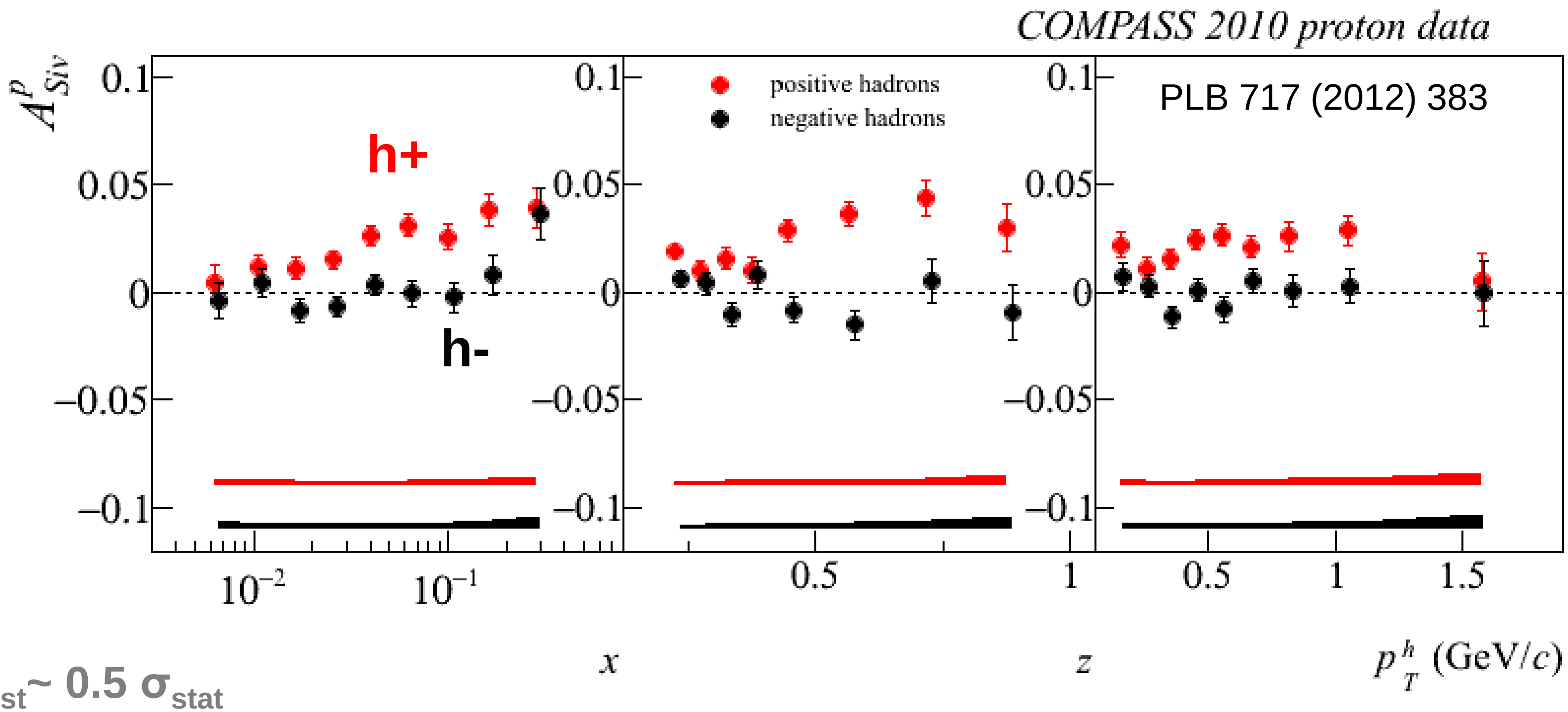


Sivers asymmetries

Sivers asymmetries on proton

charged hadrons

2010 data



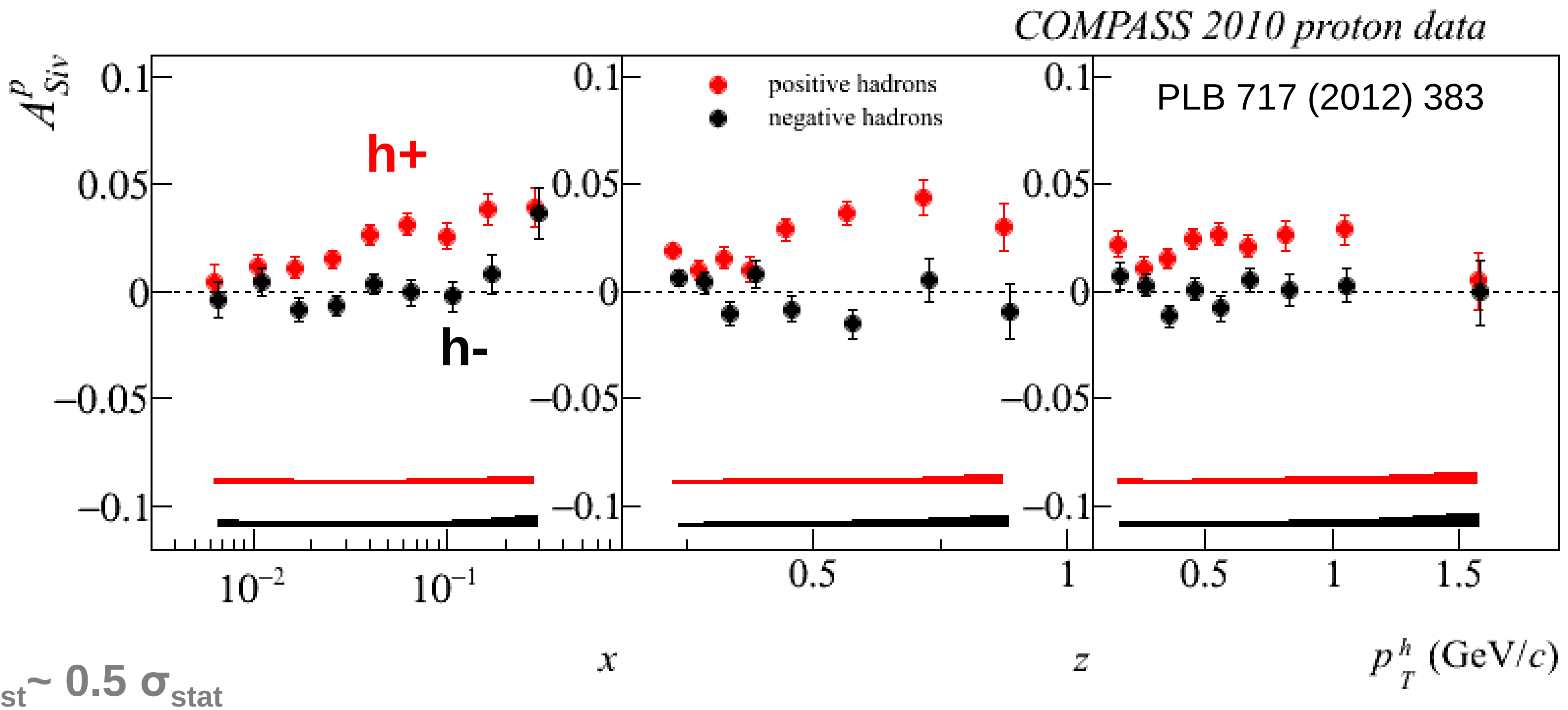
$\sigma_{syst} \sim 0.5\ \sigma_{stat}$

clear evidence for a positive signal for h^{+}, which extends to small x

Sivers asymmetries on proton

charged hadrons

2010 data



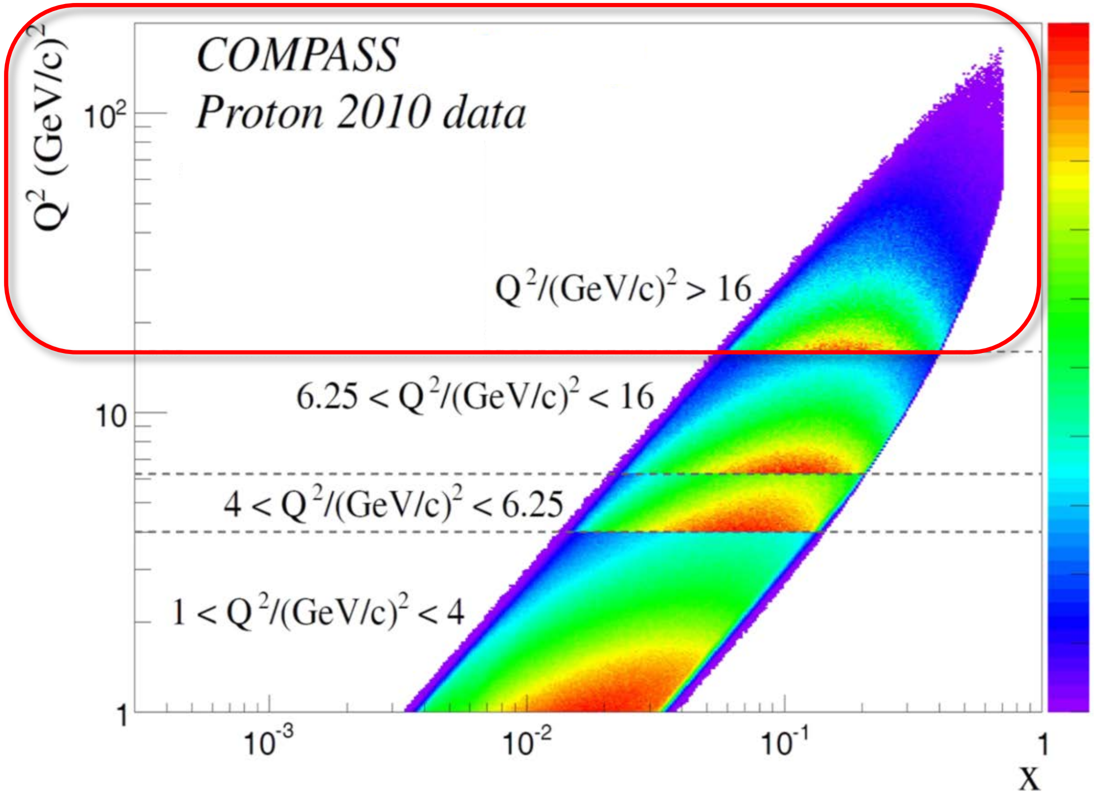
$\sigma_{syst} \sim 0.5\ \sigma_{stat}$

clear evidence for a positive signal for h^+, which extends to small x

d data compatible with zero but with large statistical uncertainties

Sivers asymmetries on proton

COMPASS has measured the SIDIS TSA in the four Q^2 ranges of the Drell-Yan measurement

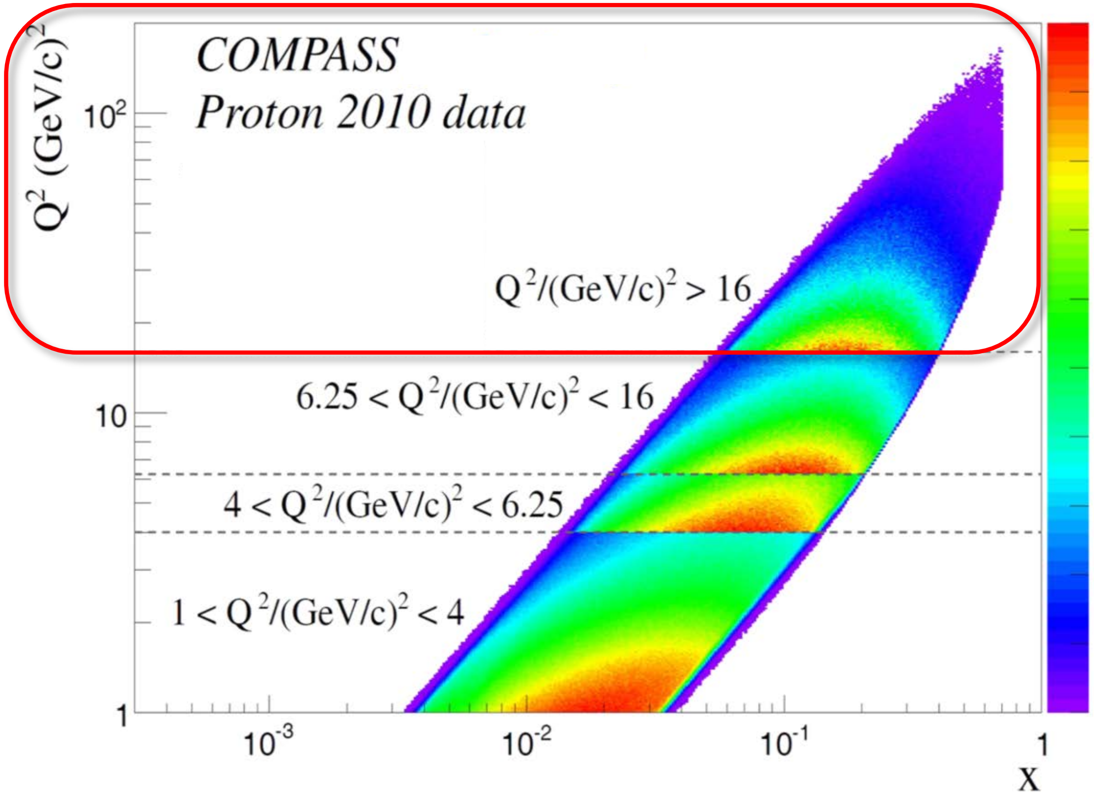


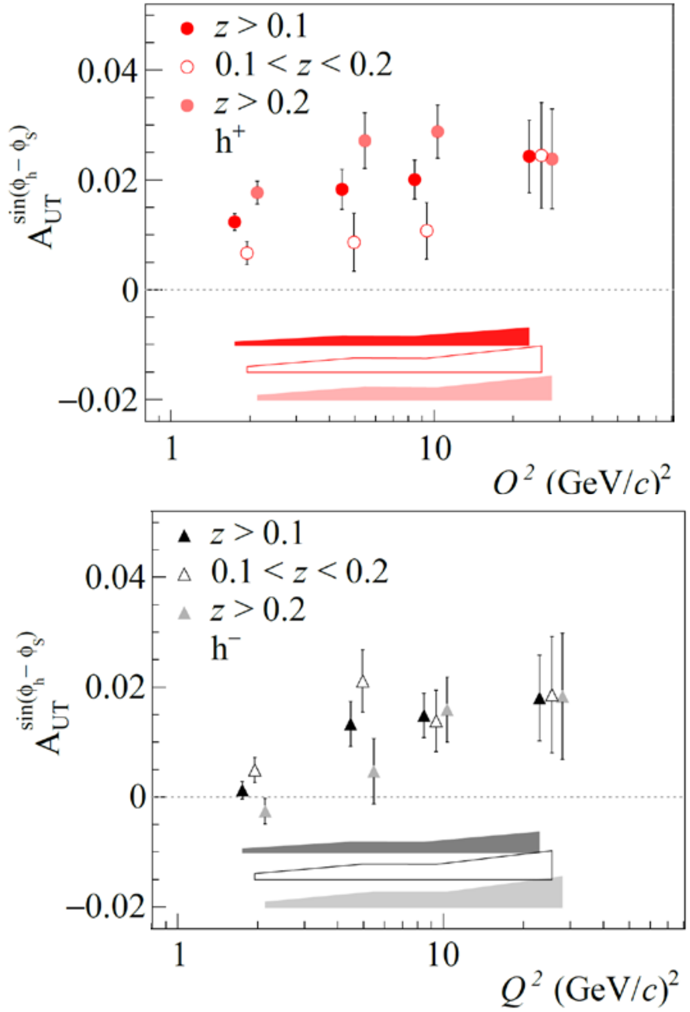
“golden” region for DY: Q^2 >16 GeV^2

Sivers asymmetries on proton

COMPASS has measured the SIDIS TSA in the four Q^2 ranges of the Drell-Yan measurement

PLB 770 (2017) 138





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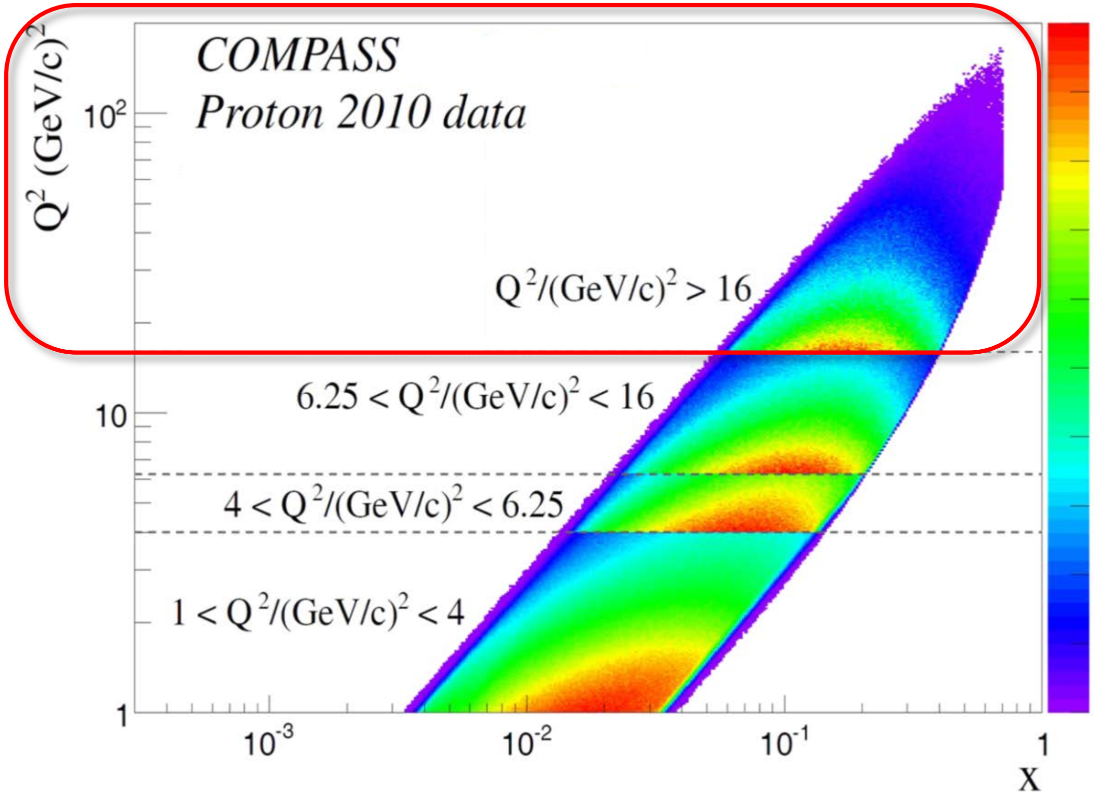
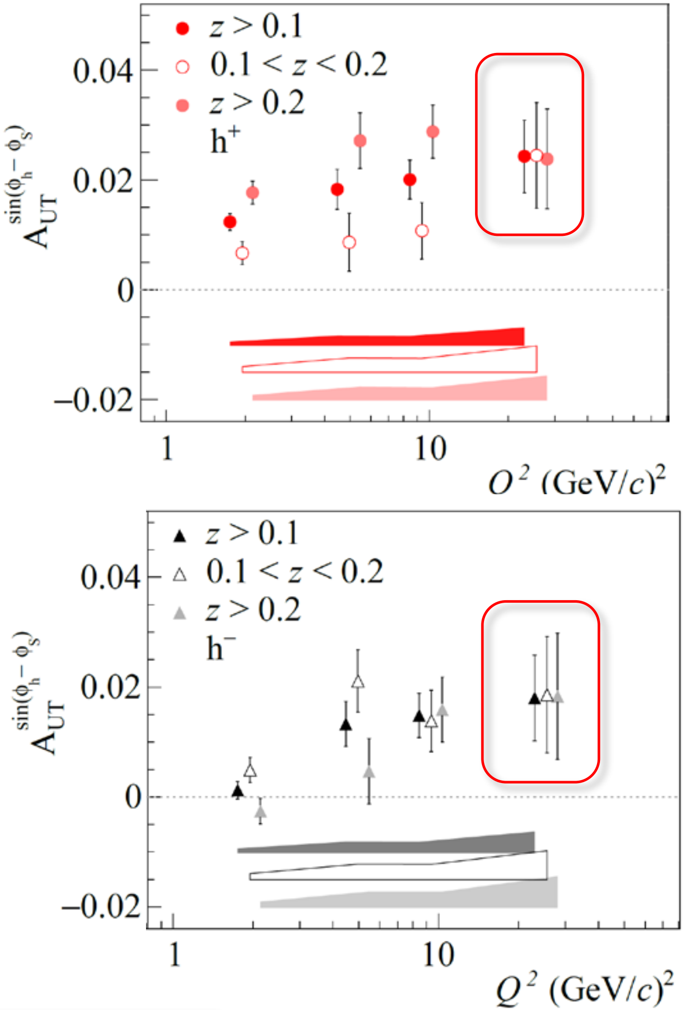
PLB 770 (2017) 138





"golden" region for DY: Q^2 >16 GeV^2

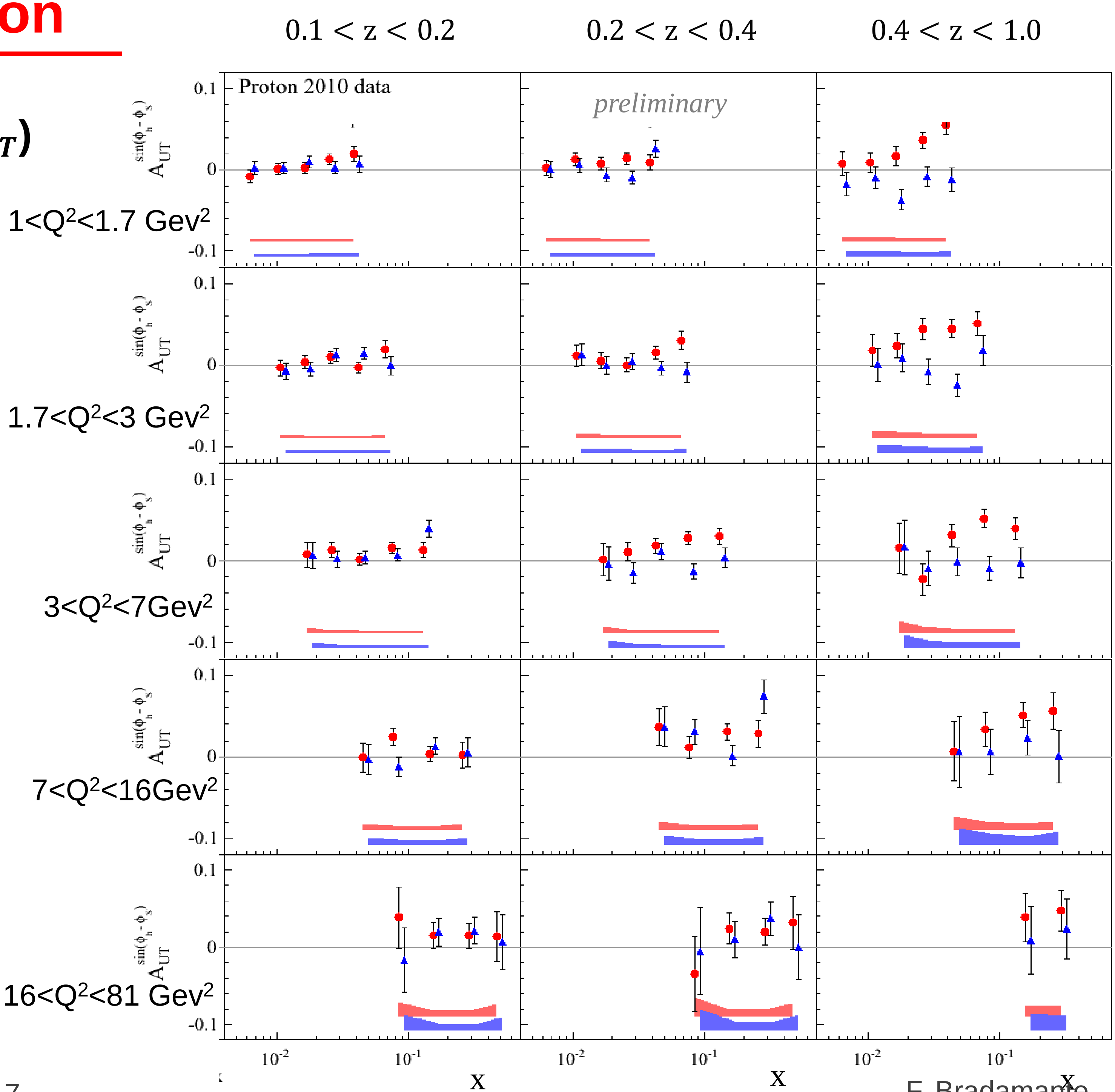
clearly positive
test of change of sign feasible

TSA on proton

multiD ($x, Q^2; z, P_T$) analysis

an example:
Sivers
asymmetry

$P_T > 0.1$ GeV/c



SPIN2014

Sivers asymmetries

not shown here: gluon Sivers

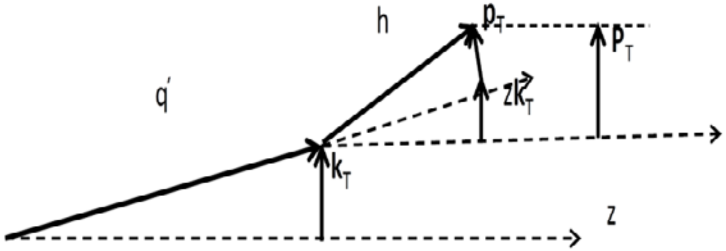
- J/Ψ asymmetry [J. Matousek, DSPIN-15]
- high p_T hadron pair asymmetry [K. Kurek, DSPIN-15, PLB 772 (2017) 854]

new:
weighted
Sivers asymmetries
in SIDIS

weighted Sivers asymmetries - why

“standard” Sivers asymmetry

$$A_{Siv}(x,z) = \frac{\sum_q e_q^2 x f_{1T}^{\perp q}(x) \otimes D_{1q}(z)}{\sum_q e_q^2 x f_1^q(x)\, D_{1q}(z)}$$



to evaluate the convolution, models are needed
e.g. Gaussian model

with several assumptions, one gets

$$A_{Siv,G}(x,z) \cong \frac{\pi M}{2\langle P_T\rangle} \frac{\sum_q e_q^2\, x f_{1T}^{\perp(1)q}(x)\, z D_{1q}(z)}{\sum_q e_q^2 x f_1^q(x)\, D_{1q}^h(z)}$$

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

weighted Sivers asymmetries

by weighting the spin dependent part of the cross-section with P_T
one can solve the convolution

there are two slightly different possibilities:

$$w = P_T/zM \qquad A_{Siv}^{w}(x,z) = 2\,\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) D_{1q}(z)}{\sum_q e_q^2 x f_1^q(x) D_{1q}(z)}$$

easier interpretation

$$w' = P_T/M \qquad A_{Siv}^{w'}(x,z) = 2\,\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x)\, zD_{1q}(z)}{\sum_q e_q^2 x f_1^q(x) D_{1q}(z)}$$

easier comparison with the “gaussian ansatz”

weighted Sivers asymmetries

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easier comparison with the “gaussian ansatz”

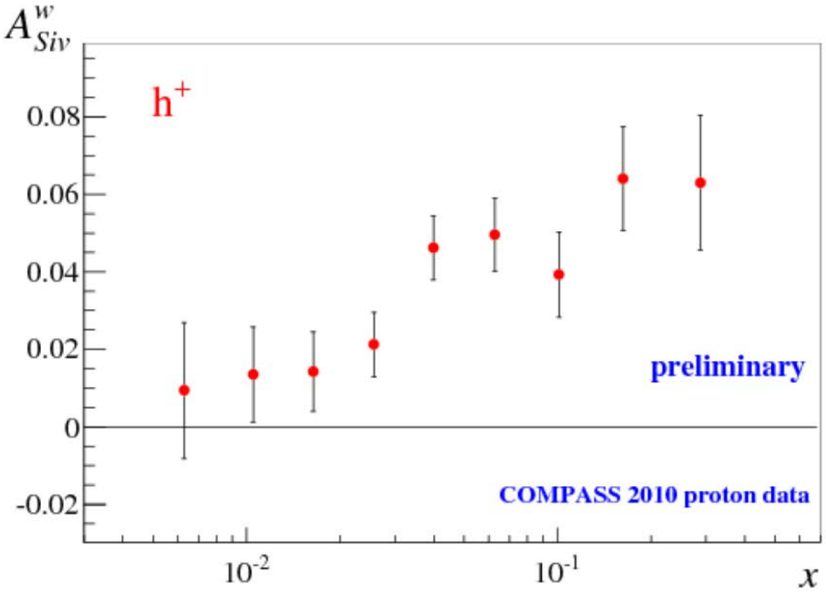
COMPASS has measured both, in bins of x and z

P_T/zM weighted Sivers asymmetry

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

$$w = P_T/zM$$

standard cuts
z>0.2
arXiv:1702.00621



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

P_T/zM weighted Sivers asymmetry

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

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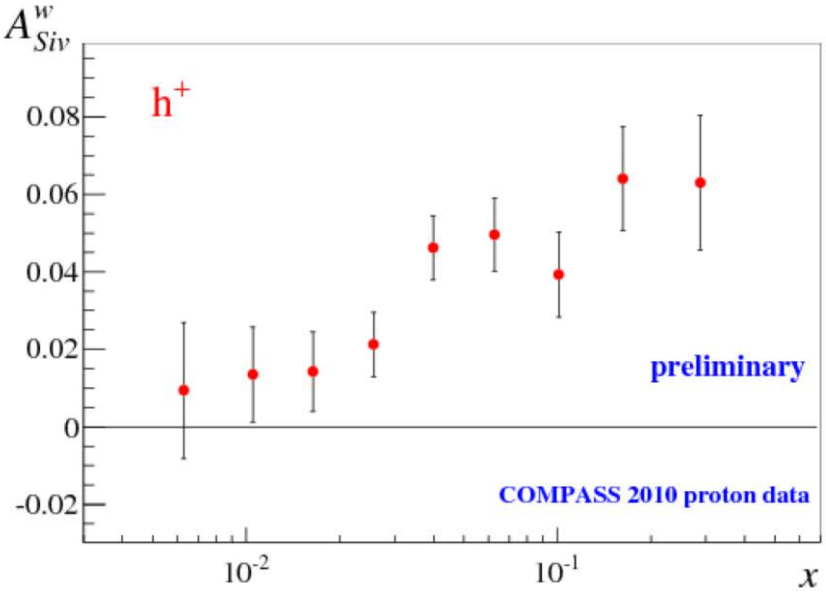
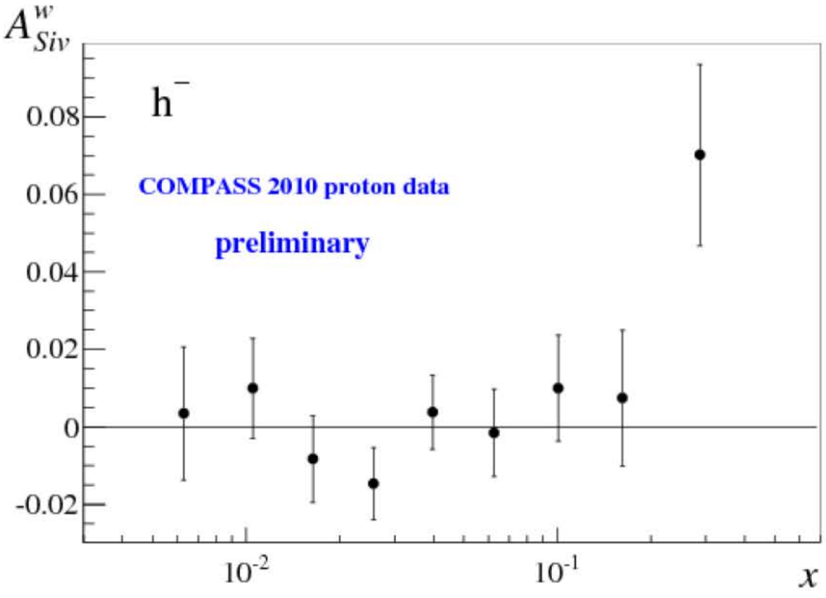




$$\sim 2\frac{f_{1T}^{\perp(1)u}(x)}{f_1^u(x)}$$

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

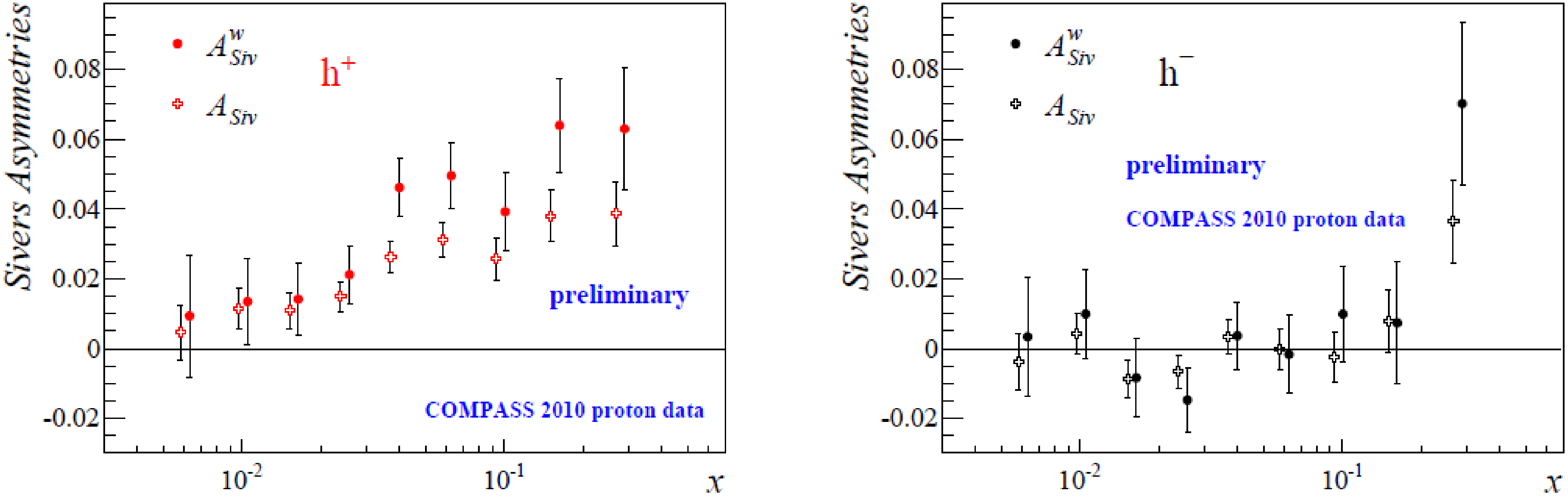
P_T/zM weighted Sivers asymmetry

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

$$w = P_T/zM$$

standard cuts
z>0.2
arXiv:1702.00621

comparison with the published “standard” asimmetries



open points: standard asymmetries, PLB 717 (2012) 383

P_T/zM weighted Sivers asymmetry

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

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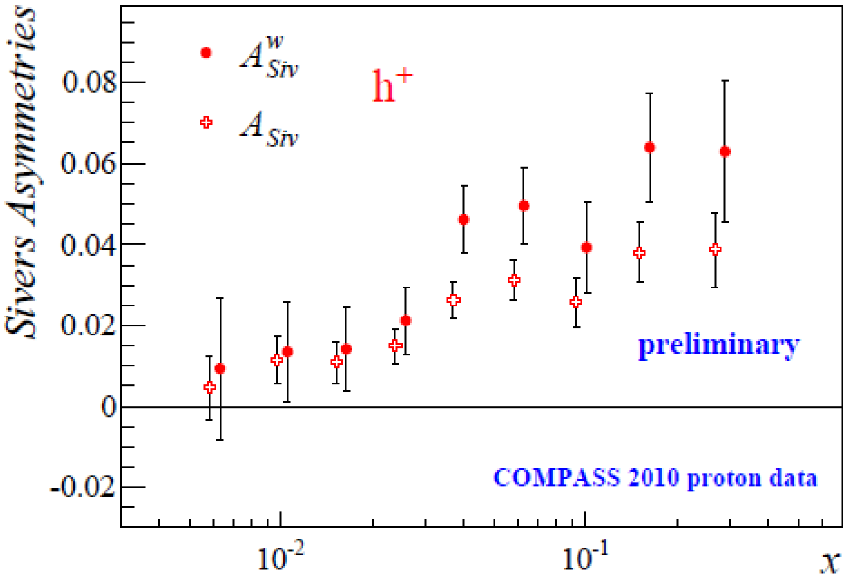

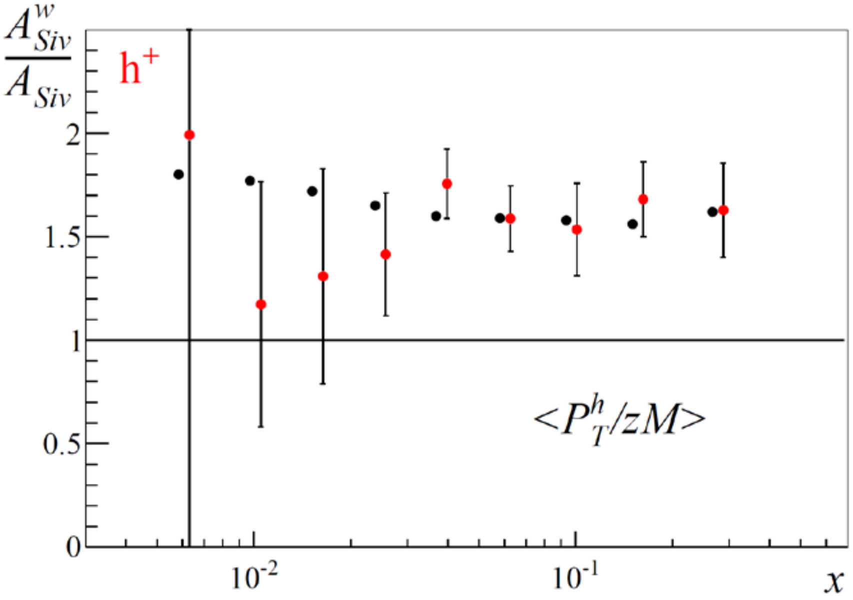

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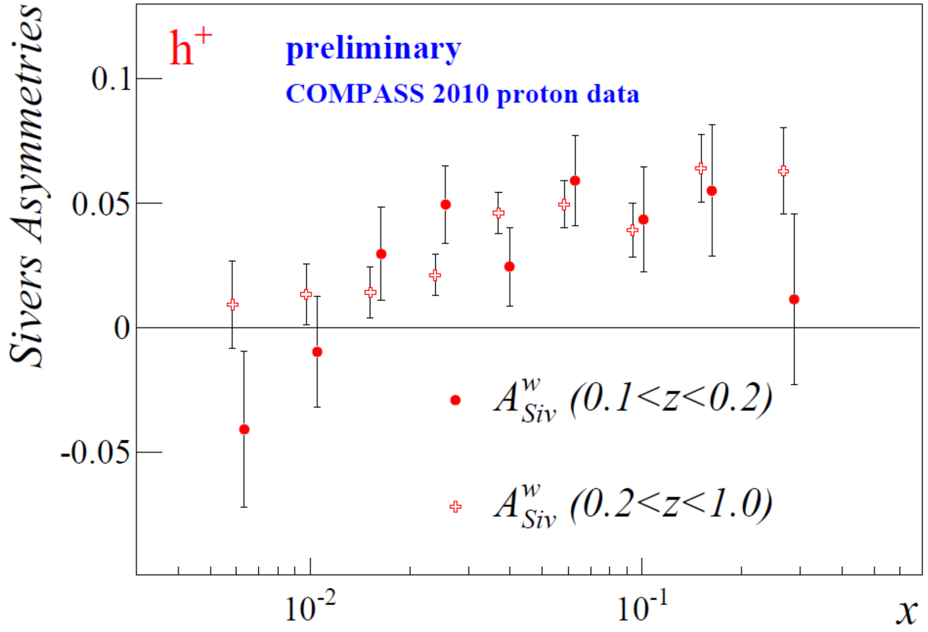
$w = P_T/zM$

standard cuts

arXiv:1702.00621

different *z* ranges



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

ok

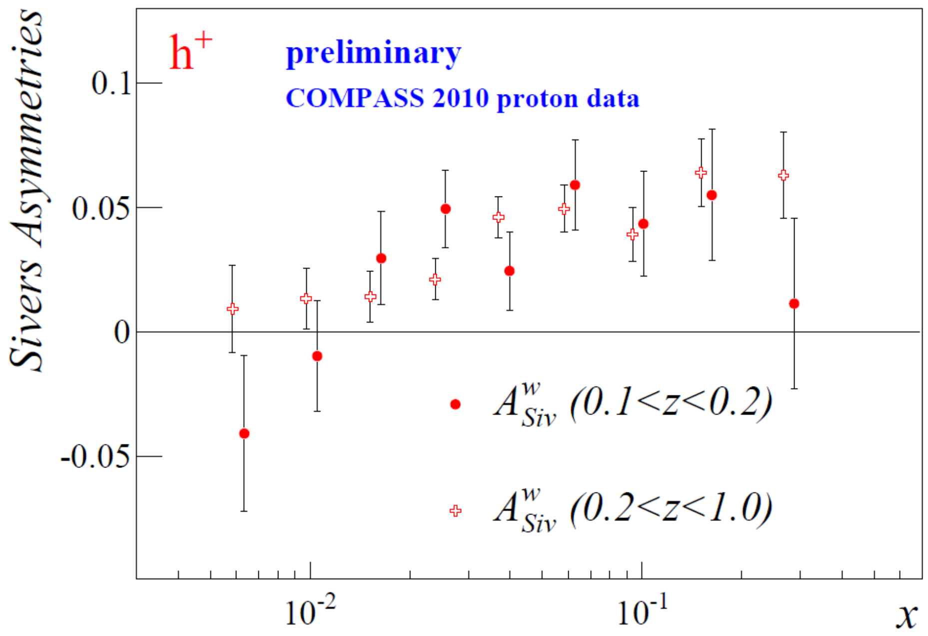
P_T/zM weighted Sivers asymmetry

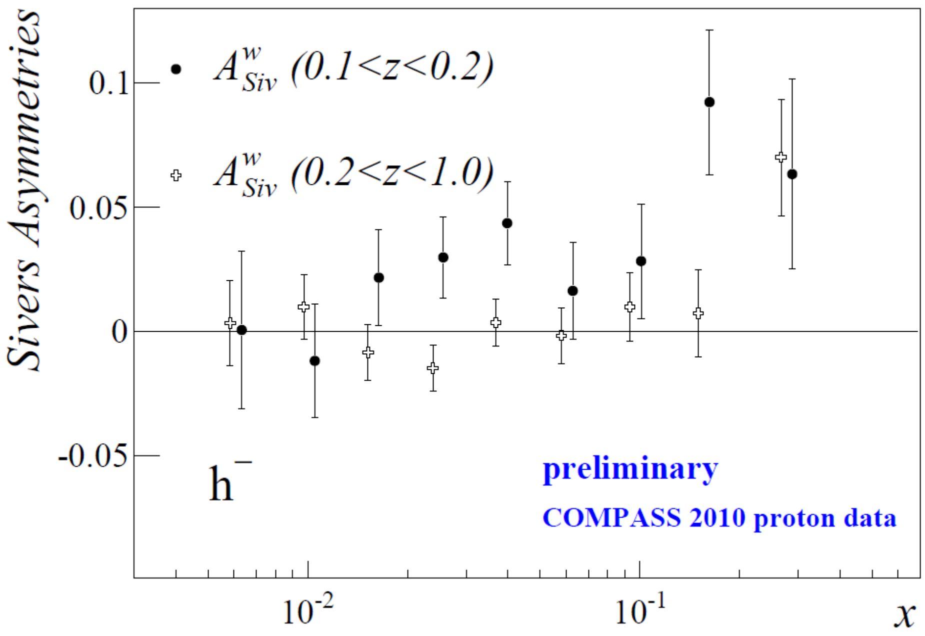
$$A_{Siv}^{w}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x)\int D_{1q}(z)dz}{\sum_q e_q^2 x f_1^q(x)\int D_{1q}(z)dz} \qquad w = P_T/zM$$

standard cuts

arXiv:1702.00621

different *z* ranges





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

ok

both $f_{1T}^{\perp(1)u}$ and $f_{1T}^{\perp(1)d}$ contribute
the relative contribution depends on z

$0.1 < z < 0.2 \qquad \boldsymbol{h^+ \sim h^-}$

P_T/zM weighted Sivers asymmetry

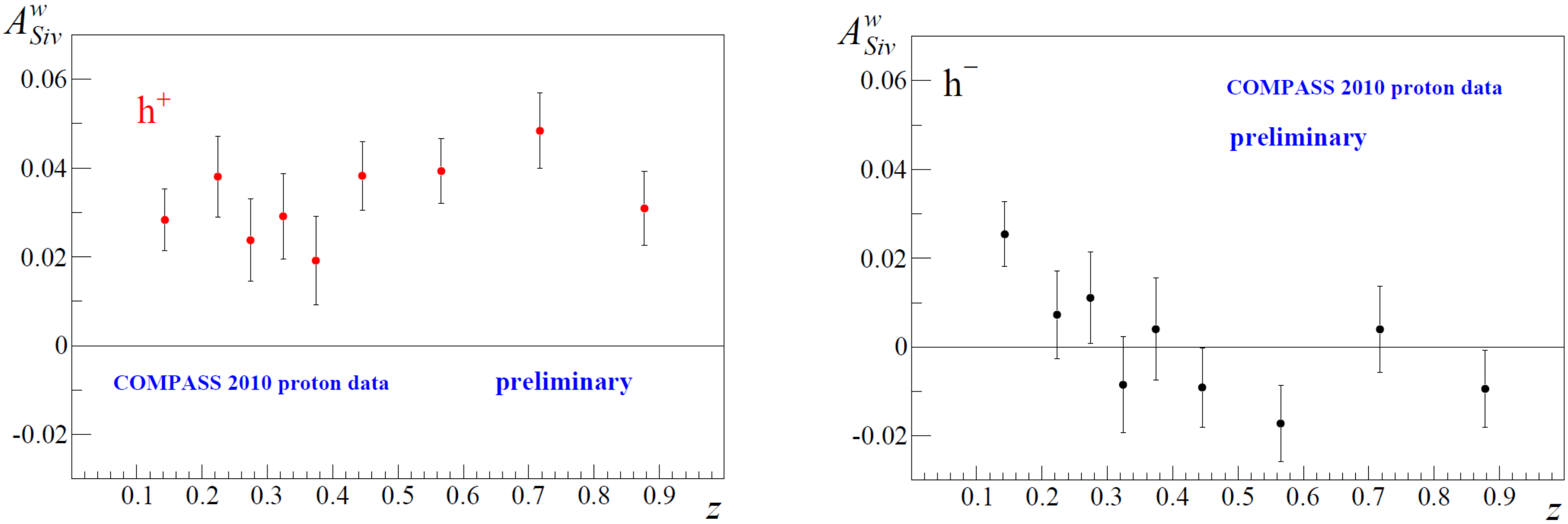
$$A^w_{Siv}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x)\int D_{1q}(z)dz}{\sum_q e_q^2 x f_1^q(x)\int D_{1q}(z)dz}$$

$w = P_T/zM$

standard cuts

arXiv:1702.00621

z dependence



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

ok

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

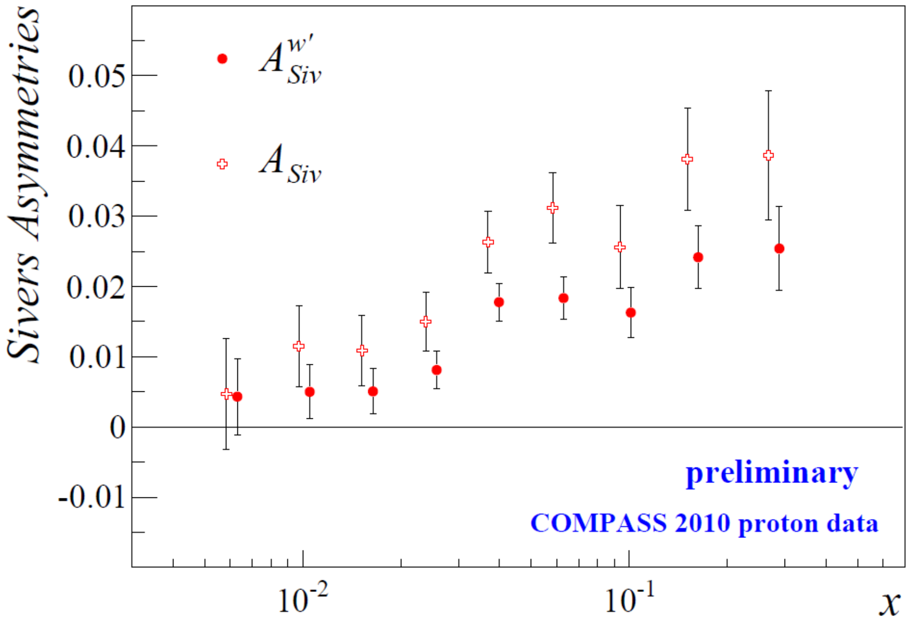
the relative contribution depends on z

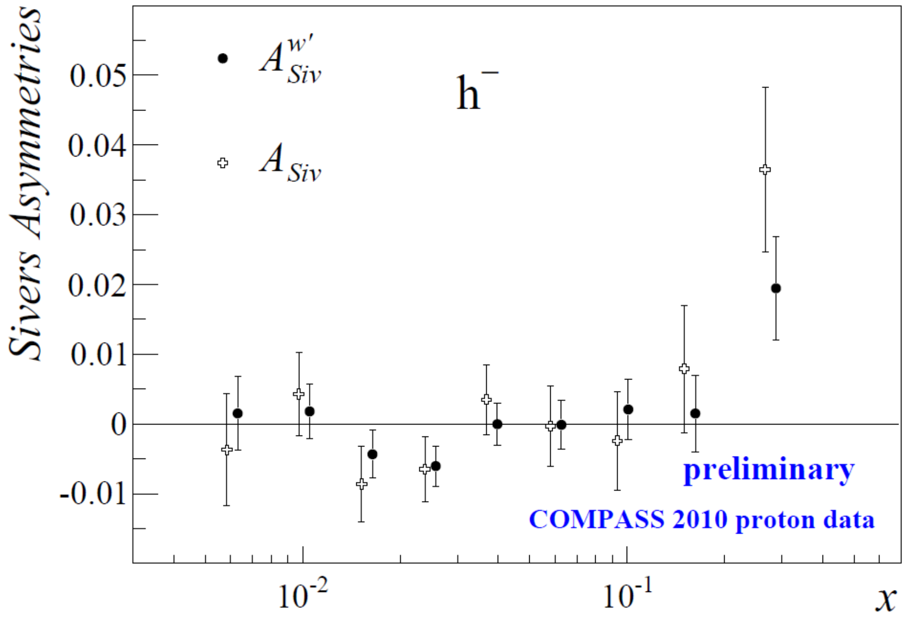
P_T/M weighted Sivers asymmetry

$$A_{Siv}^{w'}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x)\int zD_{1q}(z)dz}{\sum_q e_q^2 x f_1^q(x)\int D_{1q}(z)dz} \qquad w' = P_T/M$$

standard cuts
z>0.2

comparison with the published “standard” asymmetries'





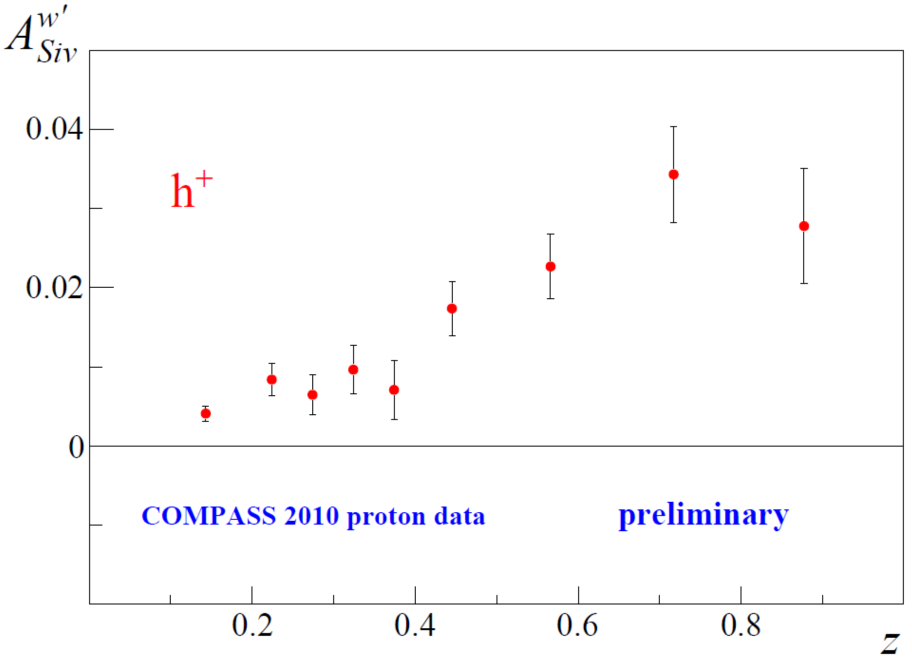
P_T/M weighted Sivers asymmetry

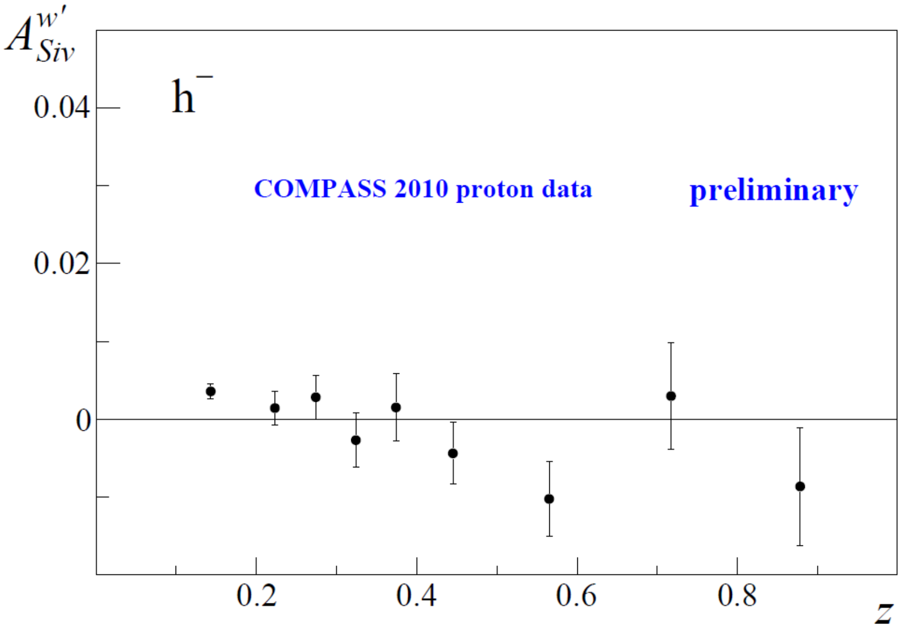
$$A_{Siv}^{w\prime}(z) = 2\frac{\sum_q e_q^2 \int C(x) f_{1T}^{\perp(1)q}(x)\,dx\;\; zD_{1q}(z)}{\sum_q e_q^2 \int C(x) f_1^q(x)dx\;\; D_{1q}(z)}$$

standard cuts

$w' = P_T/M$

z dependence





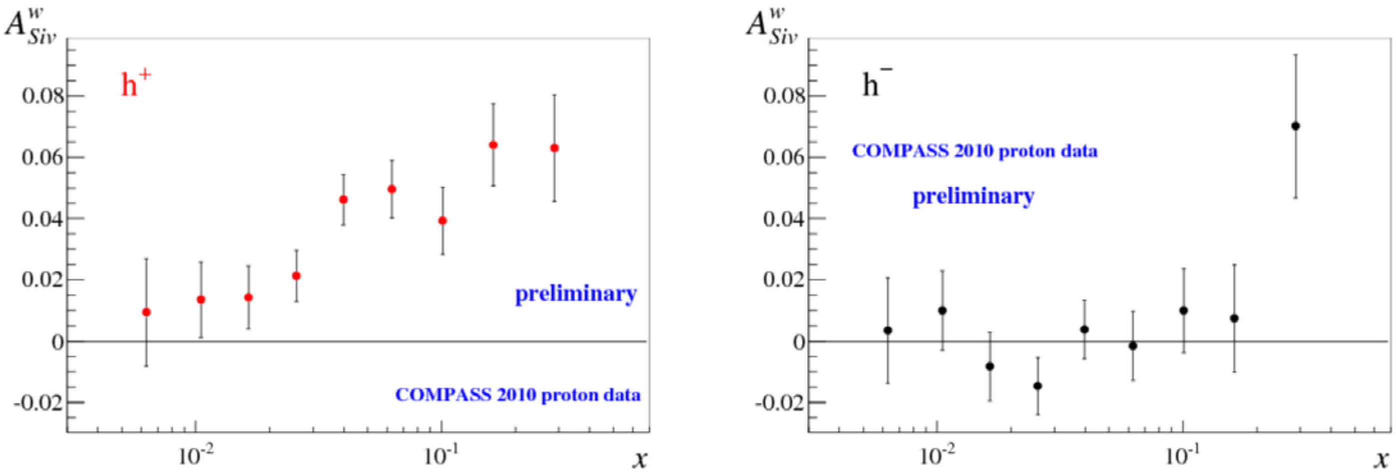
$$\sim 2z\frac{\int C(x) f_{1T}^{\perp(1)q}(x)\,dx}{\int C(x) f_1^q(x)dx}$$

ok

1st moment of the Sivers functions

from P_T/zM weighted Sivers asymmetry

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



z>0.2

used to extract the u- and d-quark Sivers functions (J. Matousek talk)

assumptions:

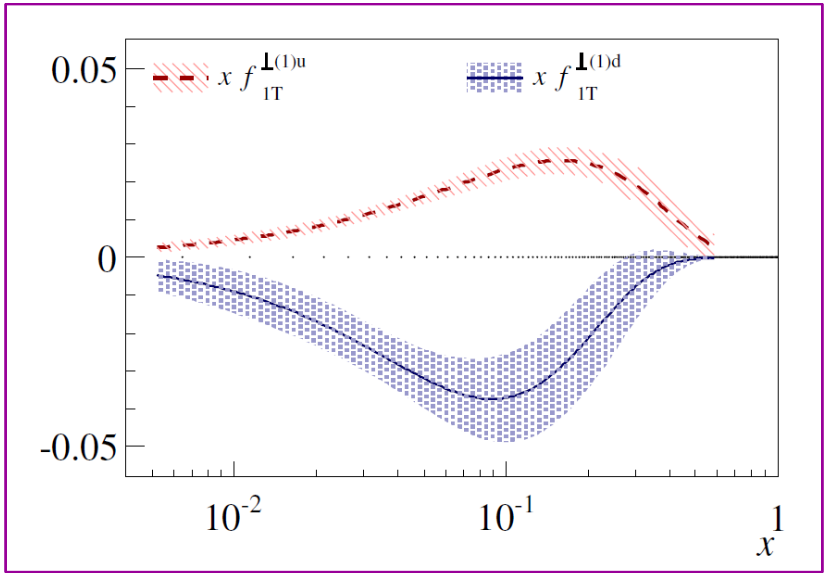
- **the Sivers functions of all the sea quarks are zero**

$$A^w_{Siv}(x) = 2\frac{x f_{1T}^{\perp(1)u_v}\int D_{1u}dz + x f_{1T}^{\perp(1)d_v}\int D_{1d}dz}{\sum_q e_q^2 x f_1^q(x)\int D_{1q}(z)dz}$$

- $f_{1T}^{\perp(1)\,q} = a_q\, x^{b_q}(1-x)^{c_q}$ **with** $q = u_v, d_v$

1^{st} moment of the Sivers functions

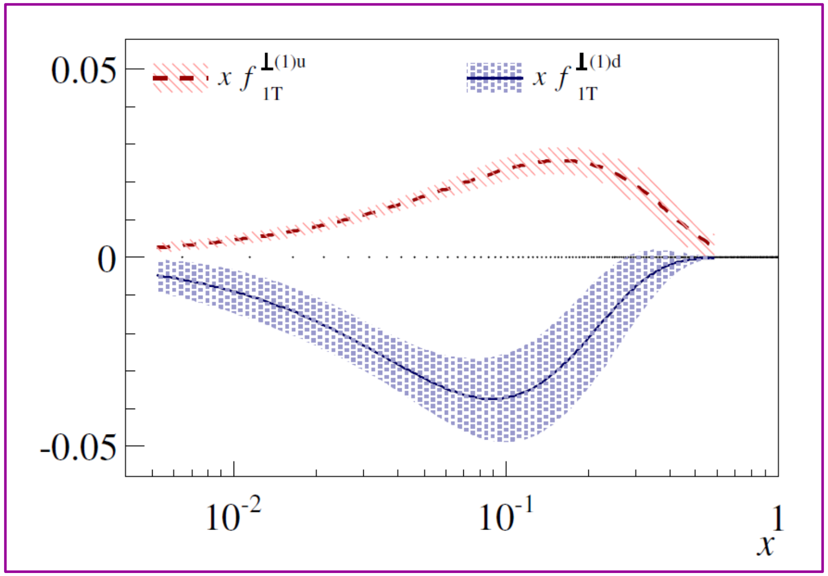
from P_T/zM weighted Sivers asymmetry



bands: 1 σ statistical errors only

1st moment of the Sivers functions

from P_T/zM weighted Sivers asymmetry



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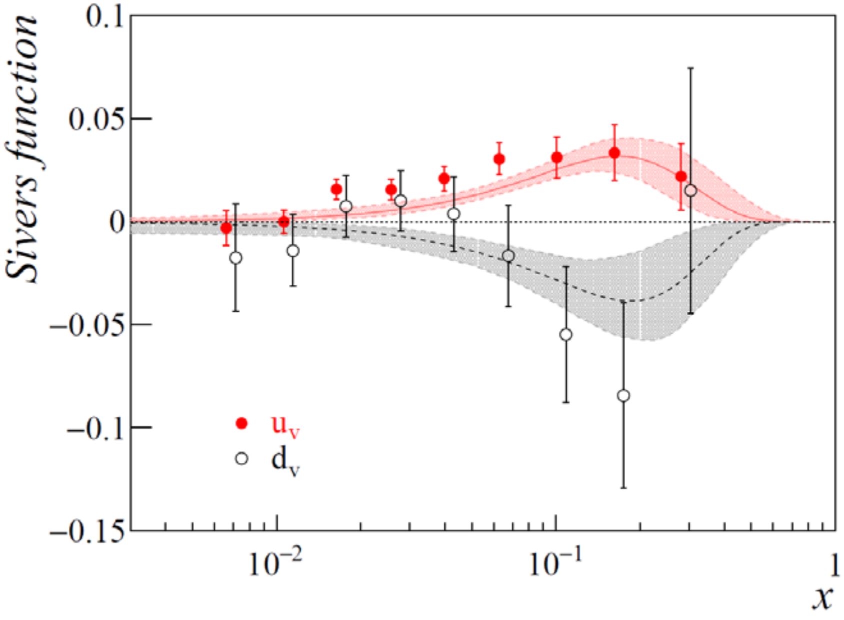


point by point extraction
COMPASS standard
Sivers asymmetries
p and d, pion and K
M B B 2017

curves: fit of COMPASS
and HERMES data,
Anselmino et al 2012

P_T weighted Sivers asymmetry

to summarise:

- **the results for the asymmetries for p look very interesting**
  in particular
  at first order no deviation from naïve expectation based on factorisation
- a first simple attempt to extract the **1st moment of the Siver functions** gives quite reasonable results
- **new d data needed also in this case to complete the exploratory COMPASS program**

measurement of the

transversity transmitted Λ polarisation

NEW!

Λ polarisation

the Λ polarisation can be measured from the angular distribution of the proton produced in the decay $\Lambda \rightarrow p\, \pi^-$

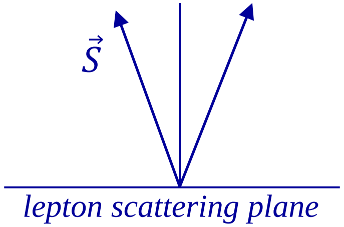
in the Λ c.m.s., the proton angular distribution is $\frac{dN}{d\cos\theta} \propto 1 + \alpha P_\Lambda \cos\theta$

where $\alpha = 0.642 \pm 0.013$ and

θ is the angle between the proton direction and the direction of the Λ polarisation

in SIDIS off transversely polarised nucleons, the Λ polarisation measured using the "reflected" direction of the nucleon spin can be written as

$$P_\Lambda = \frac{\sum_q e_q^2\, h_1^q\, H_1^{\Lambda/q}}{\sum_q e_q^2\, f_1^q\, D_1^{\Lambda/q}}$$



"transversity transmetted Λ polarisation"

the "transverse polarisation" is measured using as axis the normal to the lepton scattering plane

Λ polarisation

$$P_\Lambda = \frac{\sum_q e_q^2 \, h_1^q \, H_1^{\Lambda/q}}{\sum_q e_q^2 \, f_1^q \, D_1^{\Lambda/q}}$$

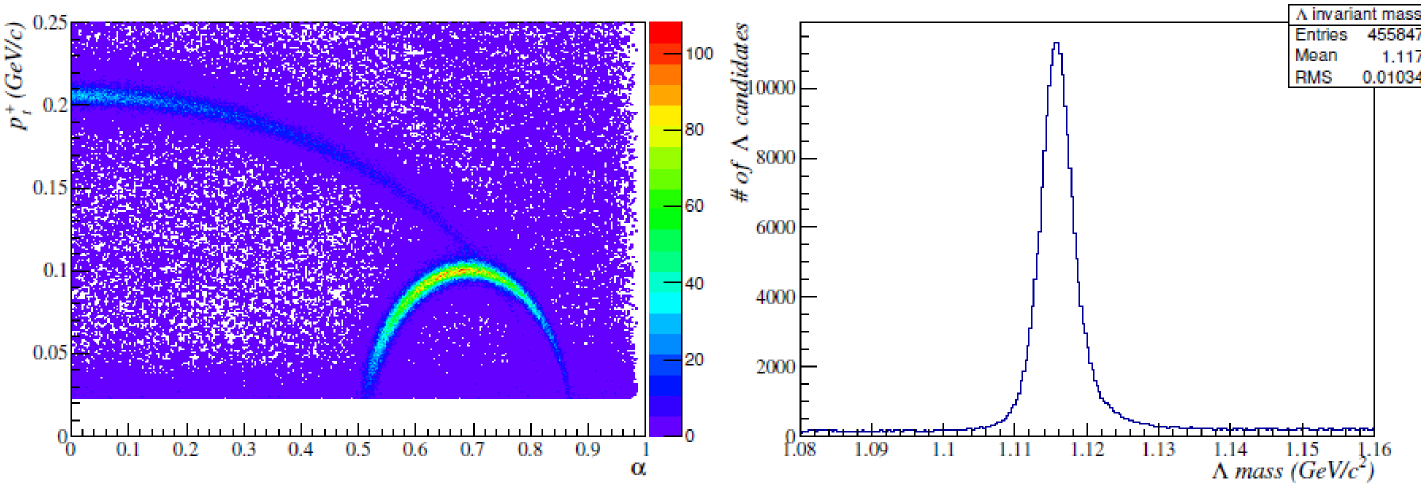
today transverity is somewhat known, while $\boldsymbol{H_1^{\Lambda/q}}$ is completely unknown

with different assumptions,
this measurement can give information either on $\boldsymbol{h_1^s}$ or on $\boldsymbol{H_1^{\Lambda/q}/D_1^{\Lambda/q}}$

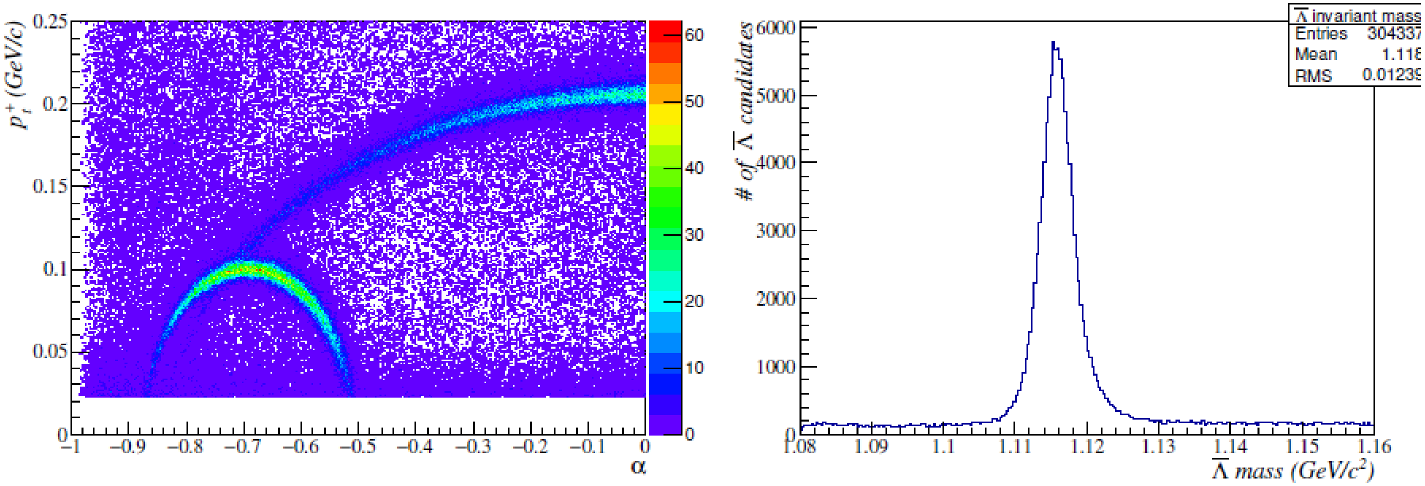
COMPASS has measured the Λ and $\bar{\Lambda}$ polarisation
from the complete proton data set (2007 and 2010)

$\Lambda/\bar{\Lambda}$ polarisation

$Q^2 > 1\ (\mathrm{GeV/c})^2$



~300k



~150k

$\Lambda/\bar{\Lambda}$ polarisation

the polarisation has been measured in x, z and P_T bins
from the complete p data set (2007 and 2010)

for all Λ and $\bar{\Lambda}$ candidates and

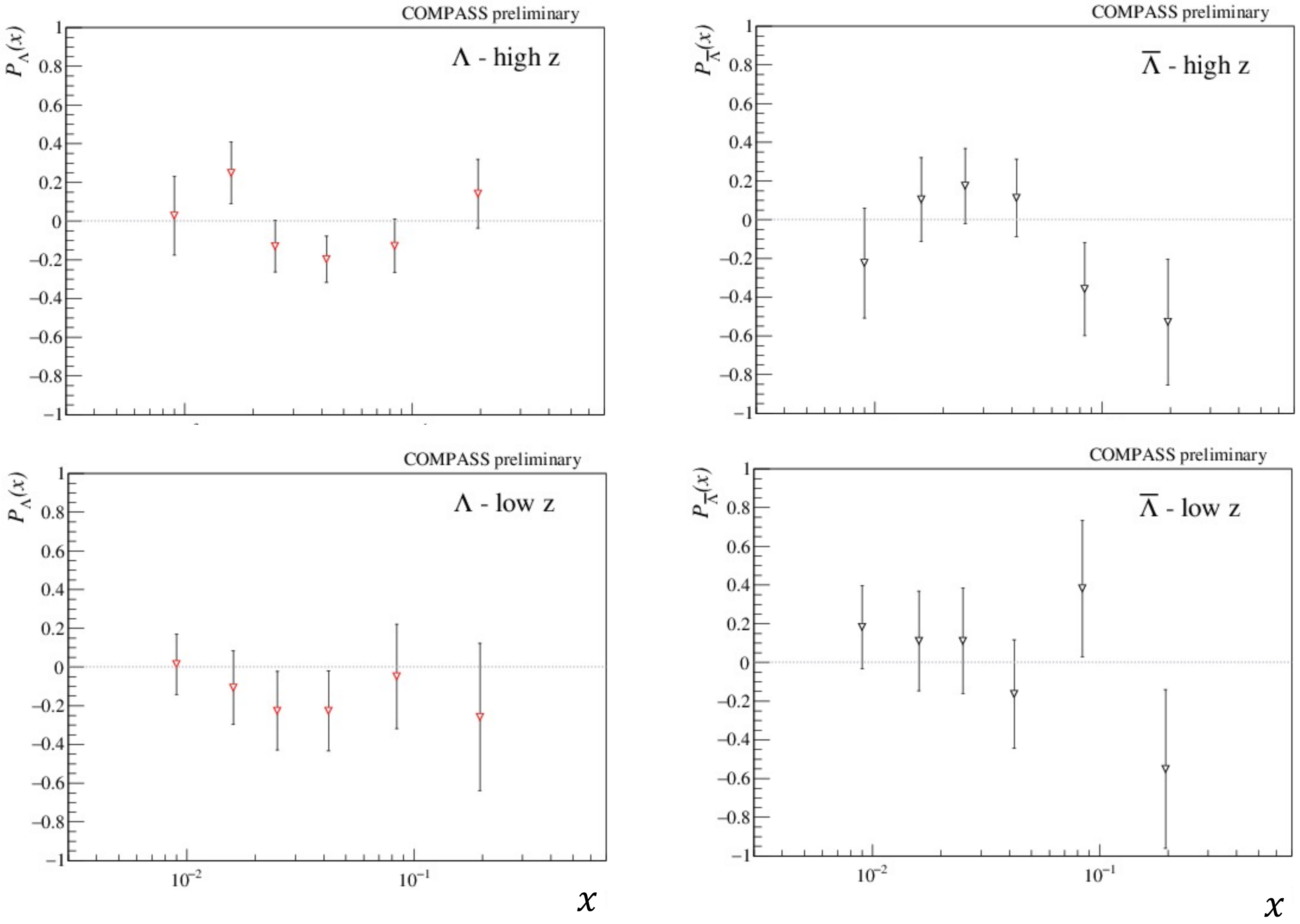
for

- $z > 0.2$ *and* $x_F > 0$ high z region
- $z > 0.2$ *or* $x_F > 0$ low z region

- $x > 0.032$ high x region
- $x < 0.032$ low x region

- $P_T > 0.5$ GeV/c high P_T region
- $P_T < 0.5$ GeV/c low P_T region

$\Lambda/\bar{\Lambda}$ polarisation



statistically limited

still the only existing measurement

interpretation work ongoing in COMPASS

COMPASS

Common Muon and Proton Apparatus for Structure and Spectroscopy

Long-Term plans

Dubna, 12 September 2017

F. Bradamante

1. **COMPASS QCD facility**
2. **Beyond 2020 Workshop (March 2016)**
3. **Long term plans**
    - RF separated beam
    - Spectroscopy
    - Drell-Yan
    - Exclusive measurements with muon and hadron beams
4. **Shorter term plans**
    - SIDIS
    - Drell-Yan
    - Astrophysics
5. **Summary**

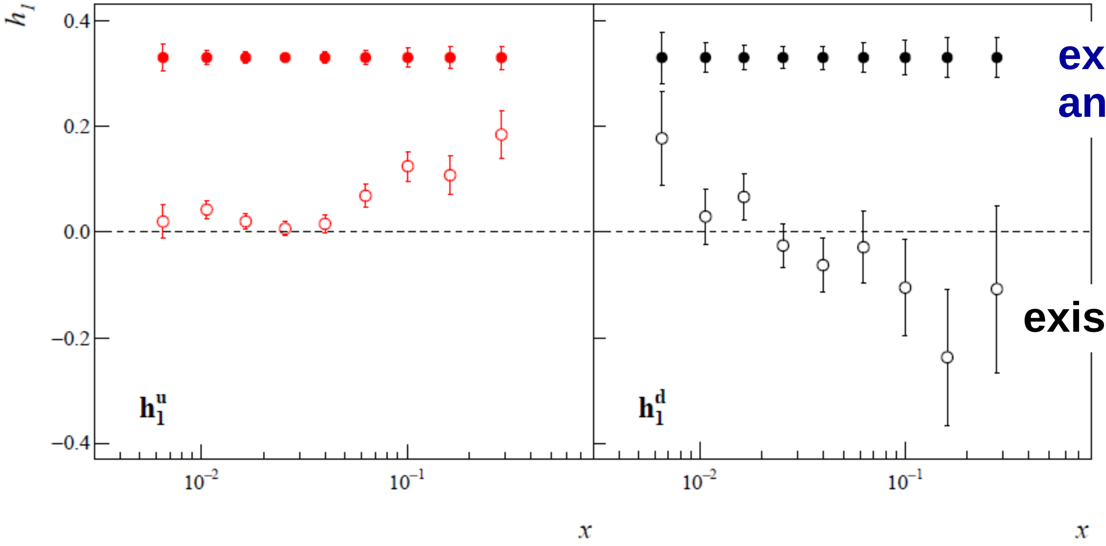
→ **LoI**

Oleg Denisov INFN(Torino)/CERN for the COMPASS Coll.

latest developments: a proposal for

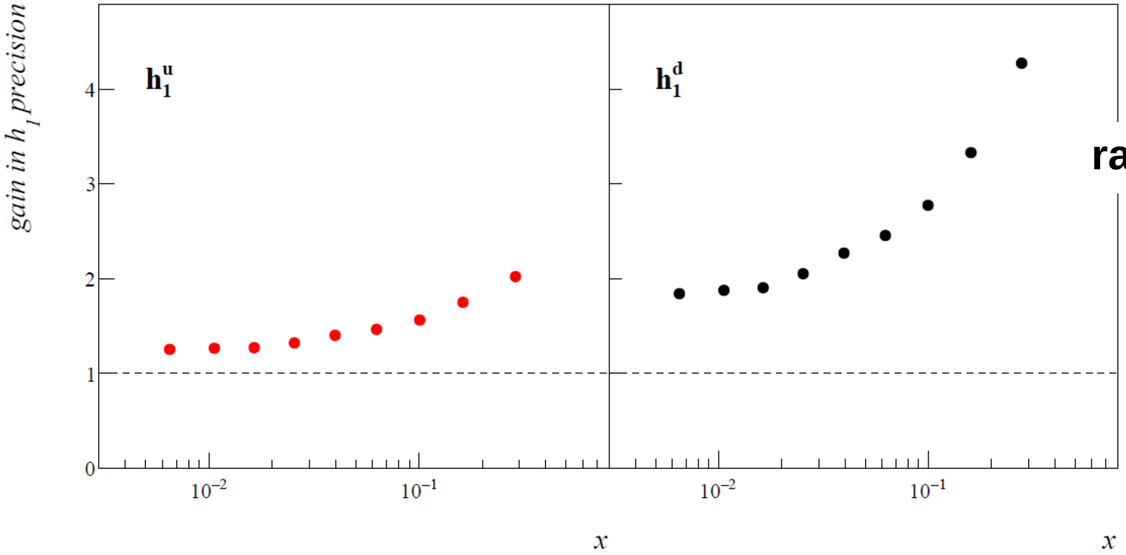
1. a one year measurement of SIDIS on transversely polarised deuteron

u and d quark
Transversity PDFs



existing p data
and 1y d data

existing data



ratio of errors

latest developments: a proposal for

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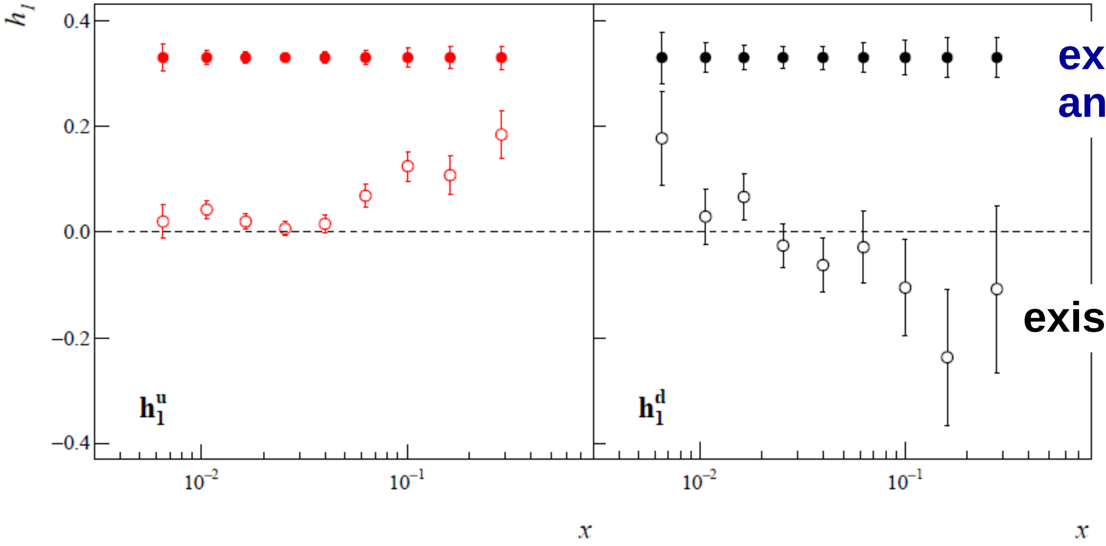
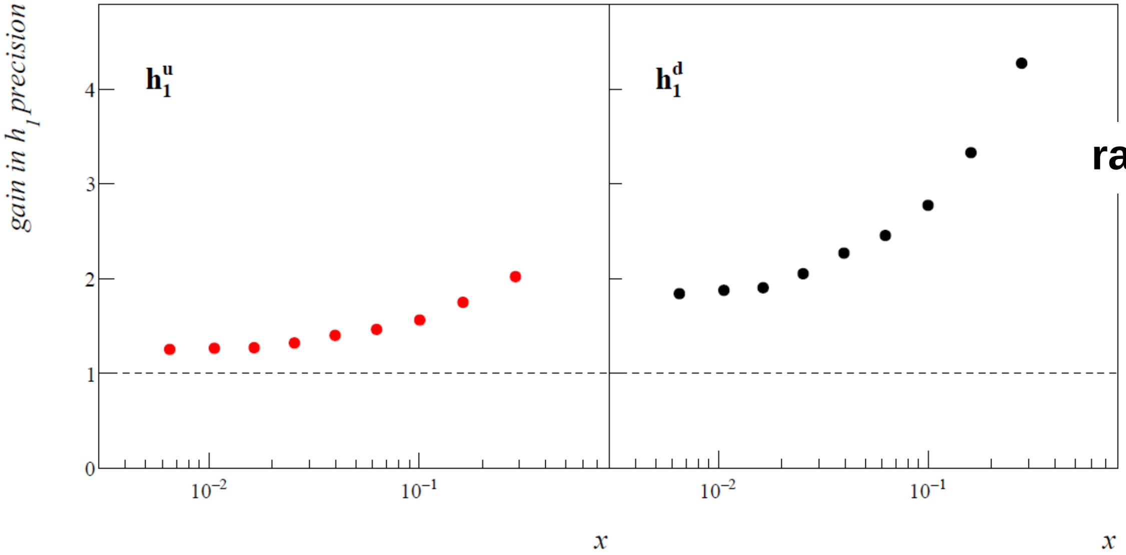


existing p data
and 1y d data

existing data

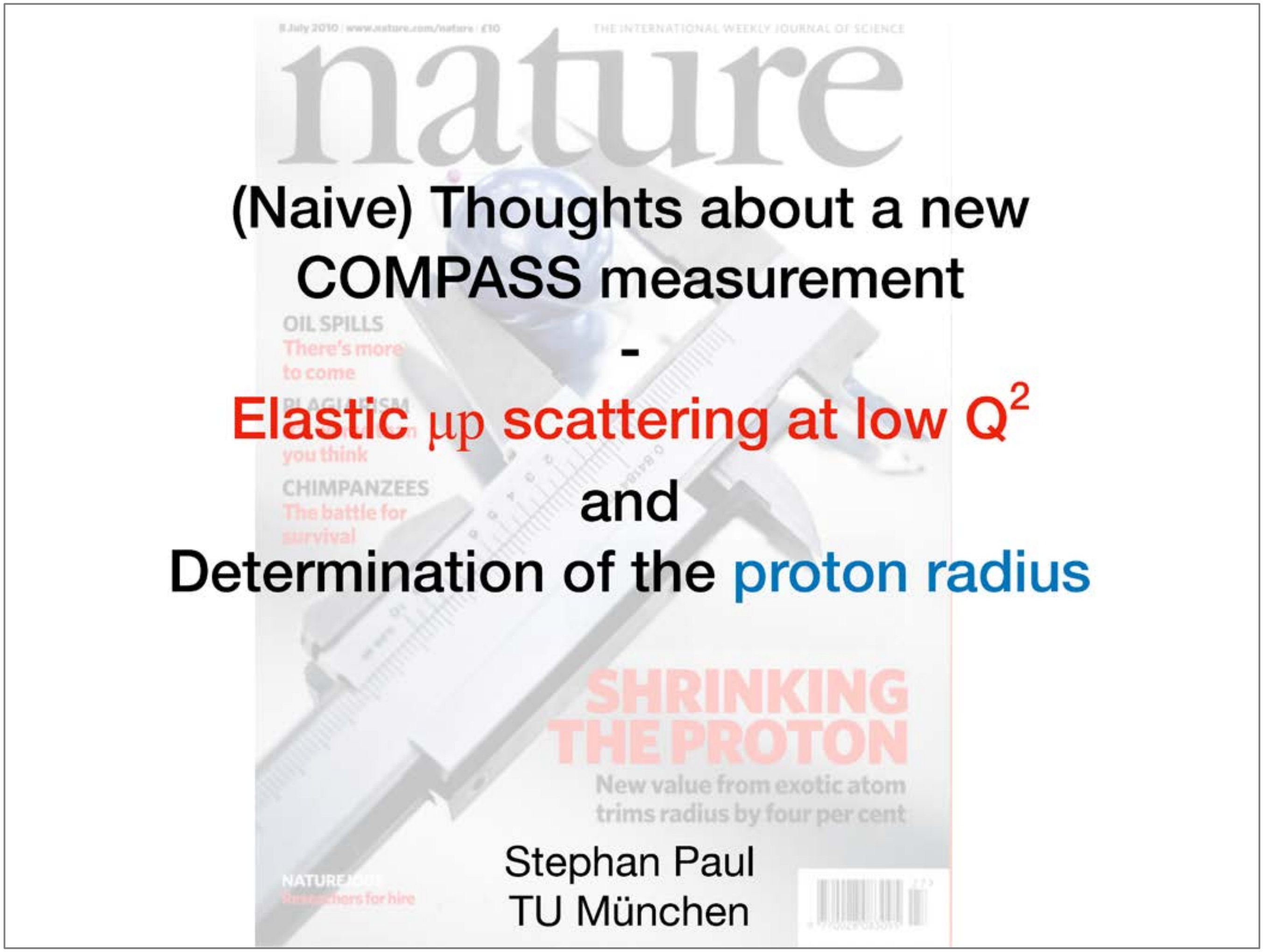
needed to complete
the COMPASS
transverse
spin program



ratio of errors

latest developments: a proposal for

2. a measurement of μp elastic scattering



(Naive) Thoughts about a new COMPASS measurement

-

Elastic μp scattering at low Q^2

and

Determination of the proton radius

Stephan Paul

TU München

in parallel with an LoI for the longer term projects