TMD physics at COMPASS present and future

Franco Bradamante

on behalf of the COMPASS Collaboration

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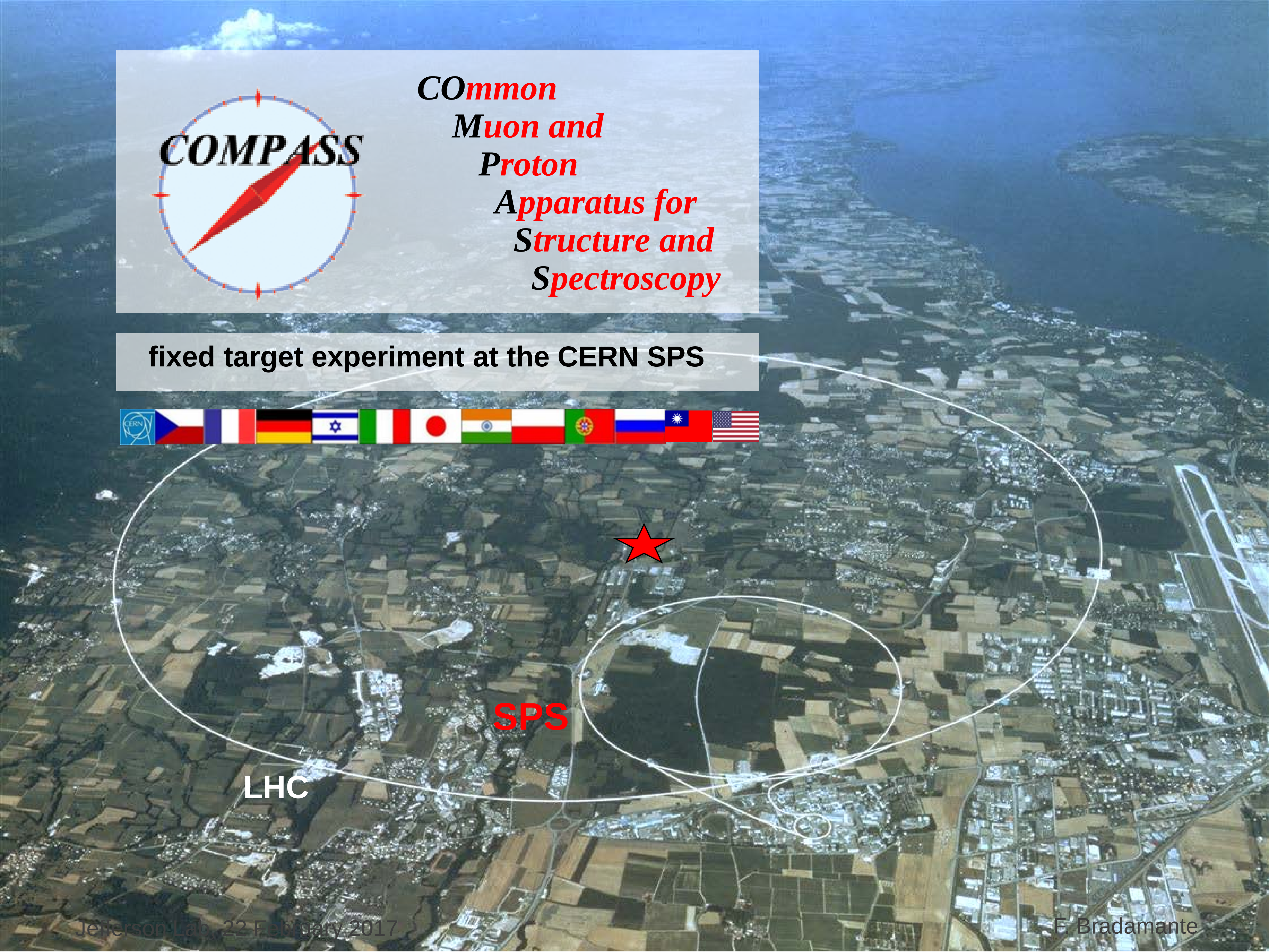
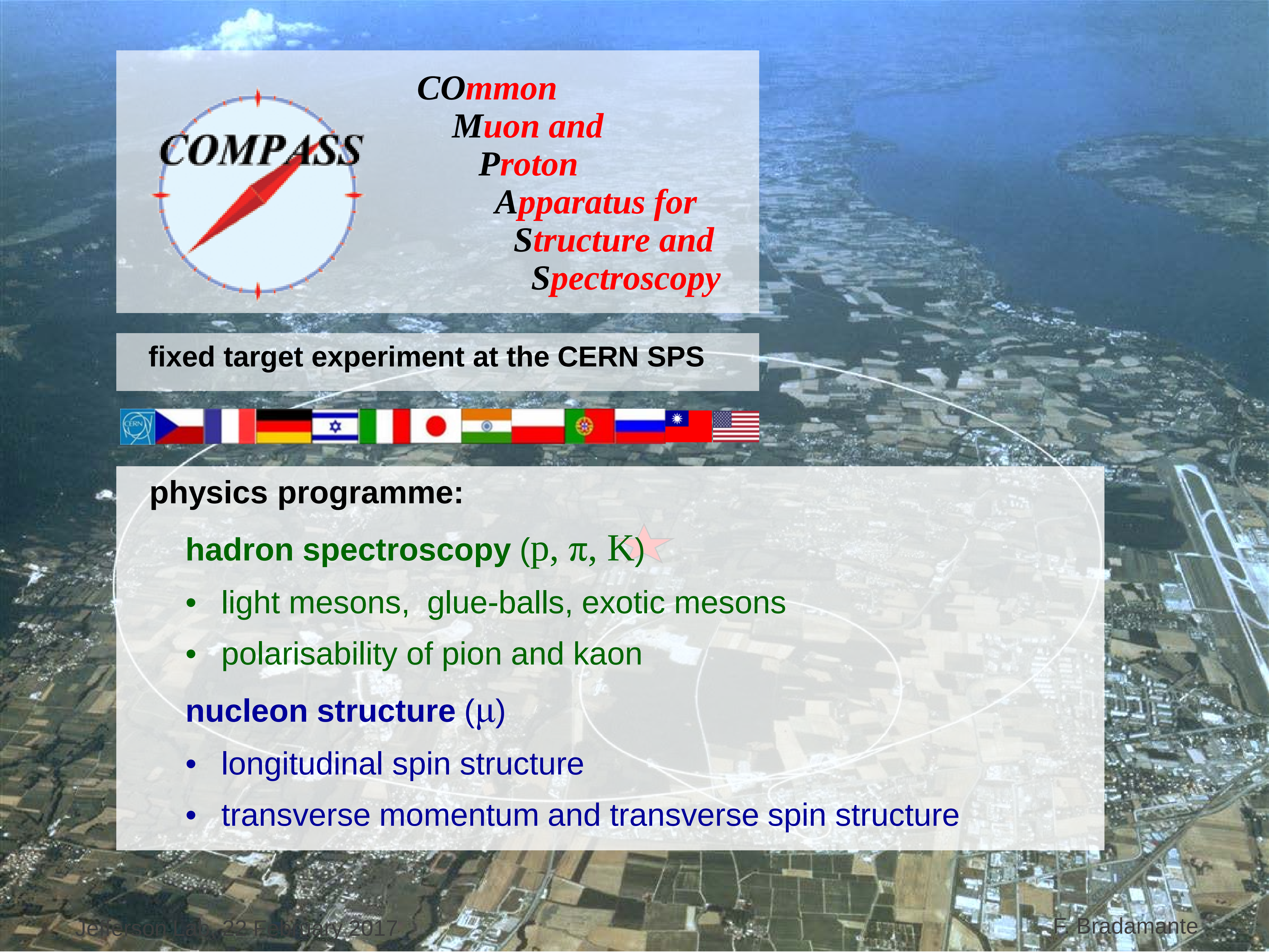


COMPASS

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

fixed target experiment at the CERN SPS



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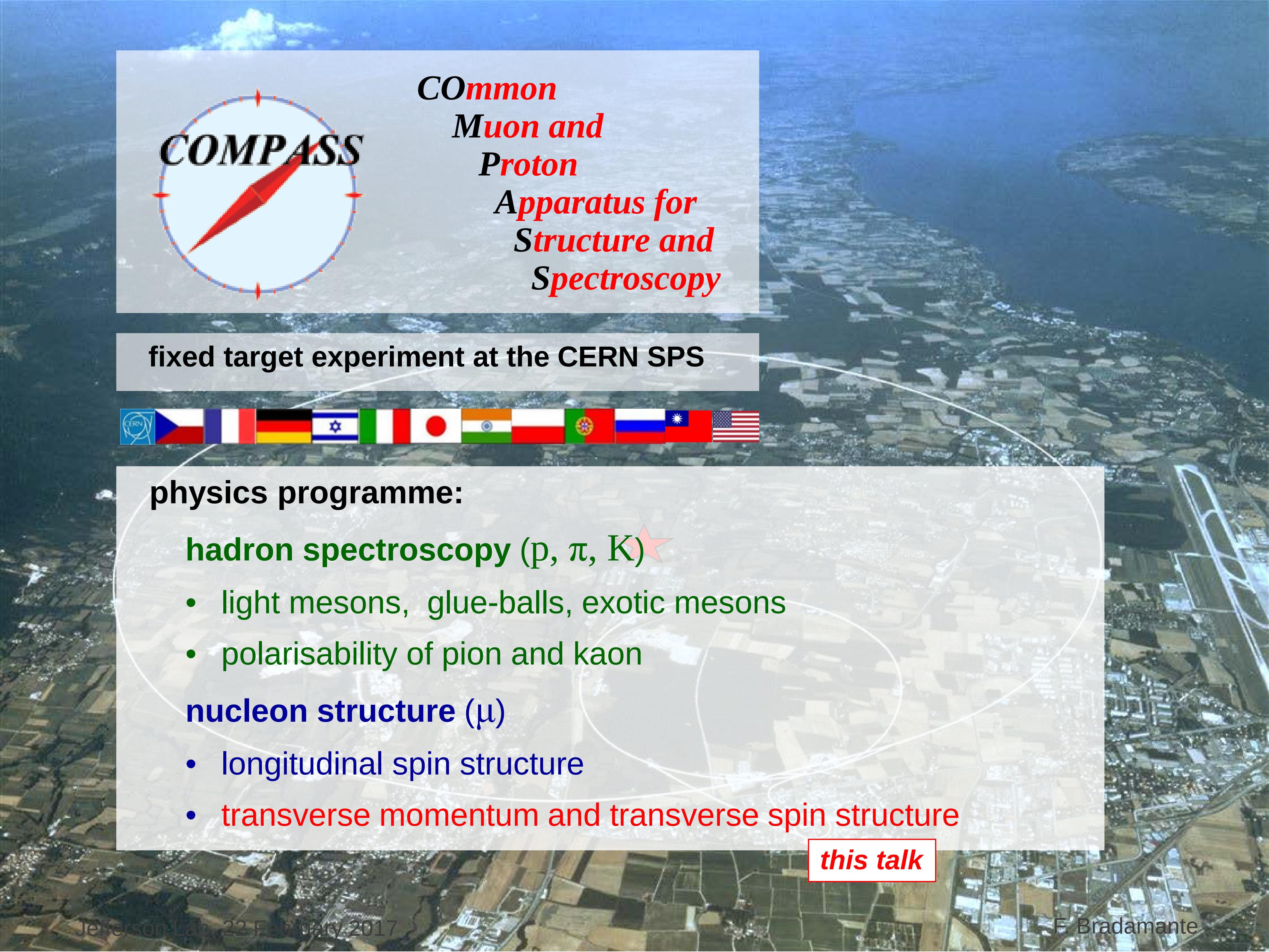
physics programme:

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



COMPASS

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Muon and
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Apparatus for
Structure and
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this talk

COMPASS spectrometer

designed to

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

COMPASS spectrometer

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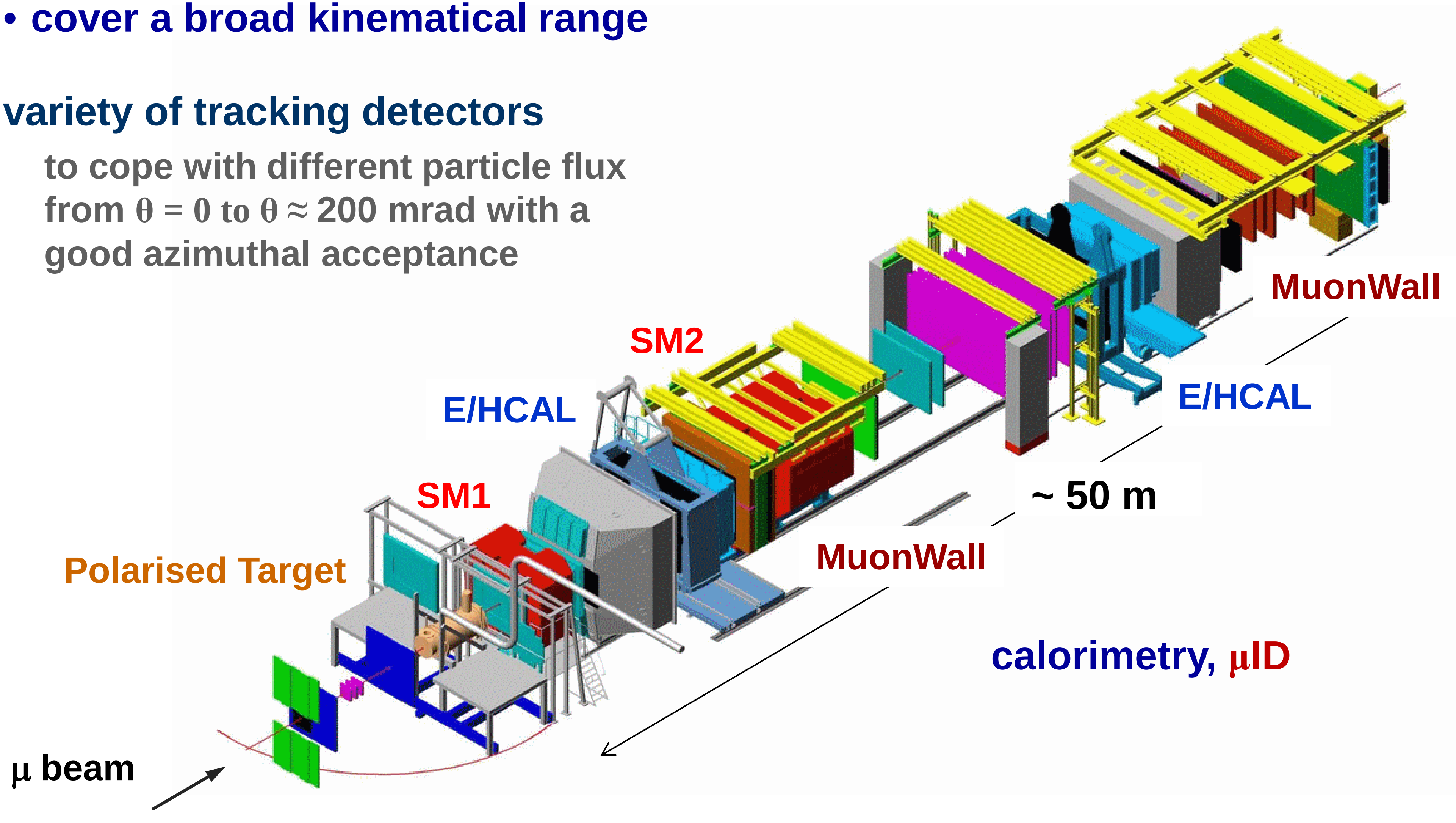
- **use high energy beams**
- **have large angular acceptance**
- **cover a broad kinematical range**

variety of tracking detectors

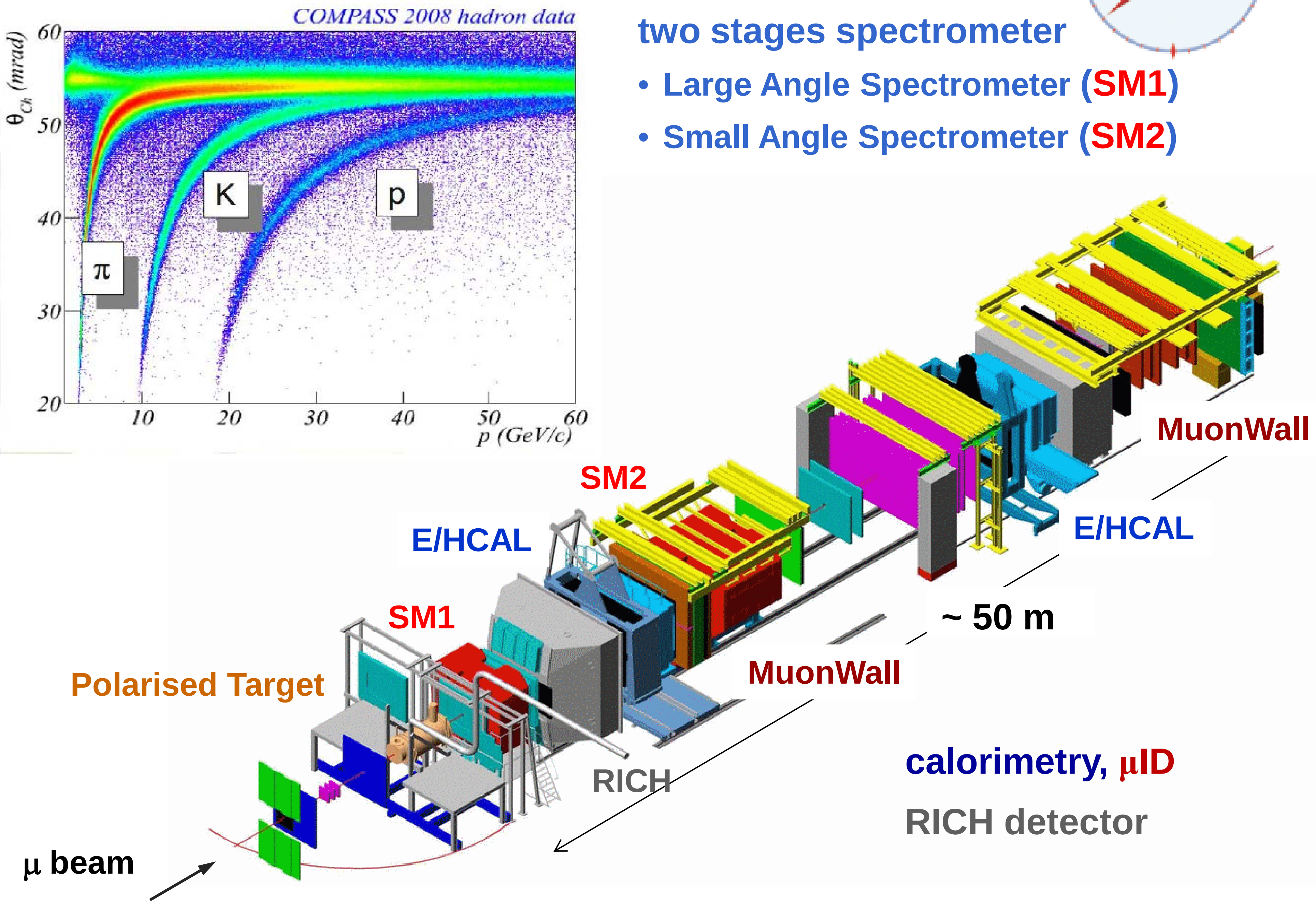
to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad with a good azimuthal acceptance

two stages spectrometer

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



COMPASS spectrometer



two stages spectrometer

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

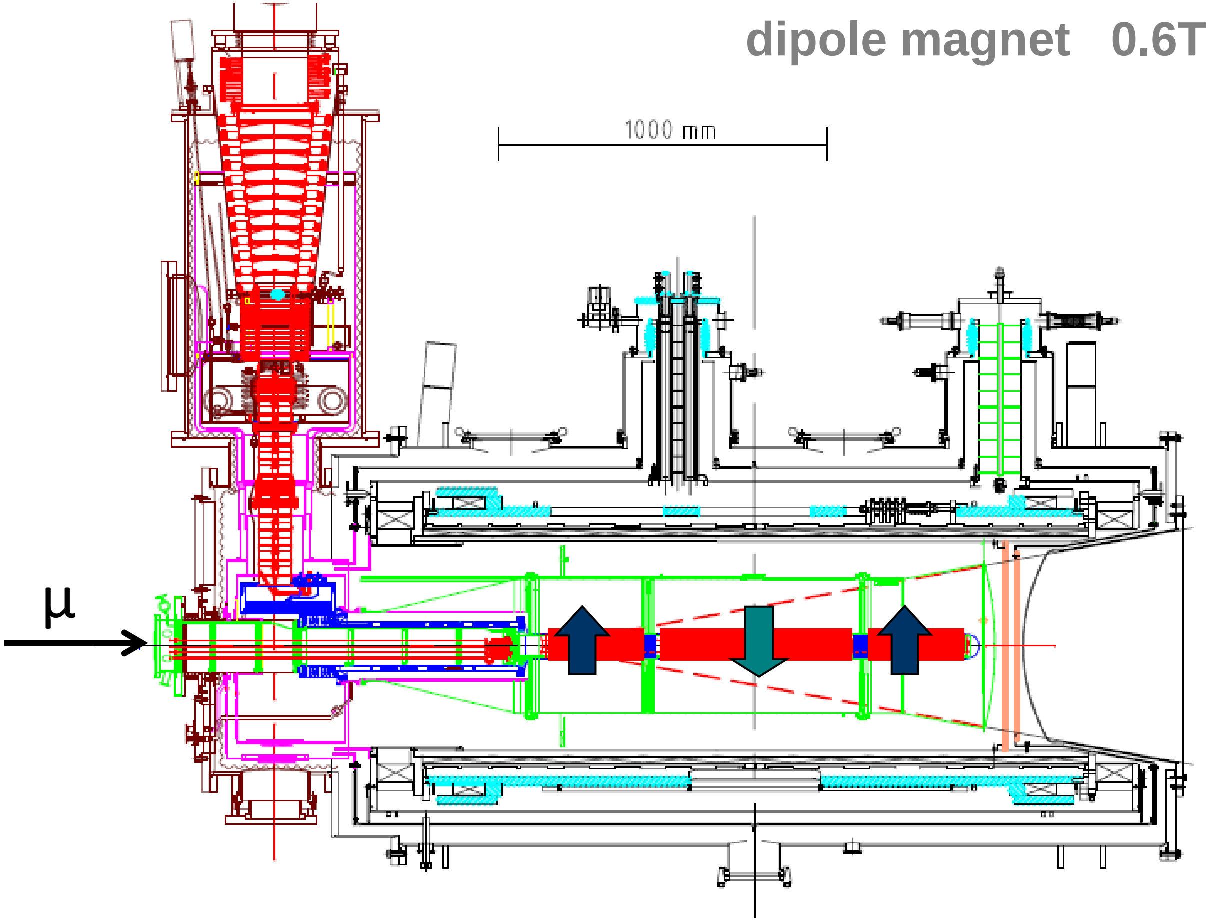
calorimetry, μID

RICH detector

the polarized target system (>2005)

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

solenoid 2.5T
dipole magnet 0.6T



acceptance > ± 180 mrad

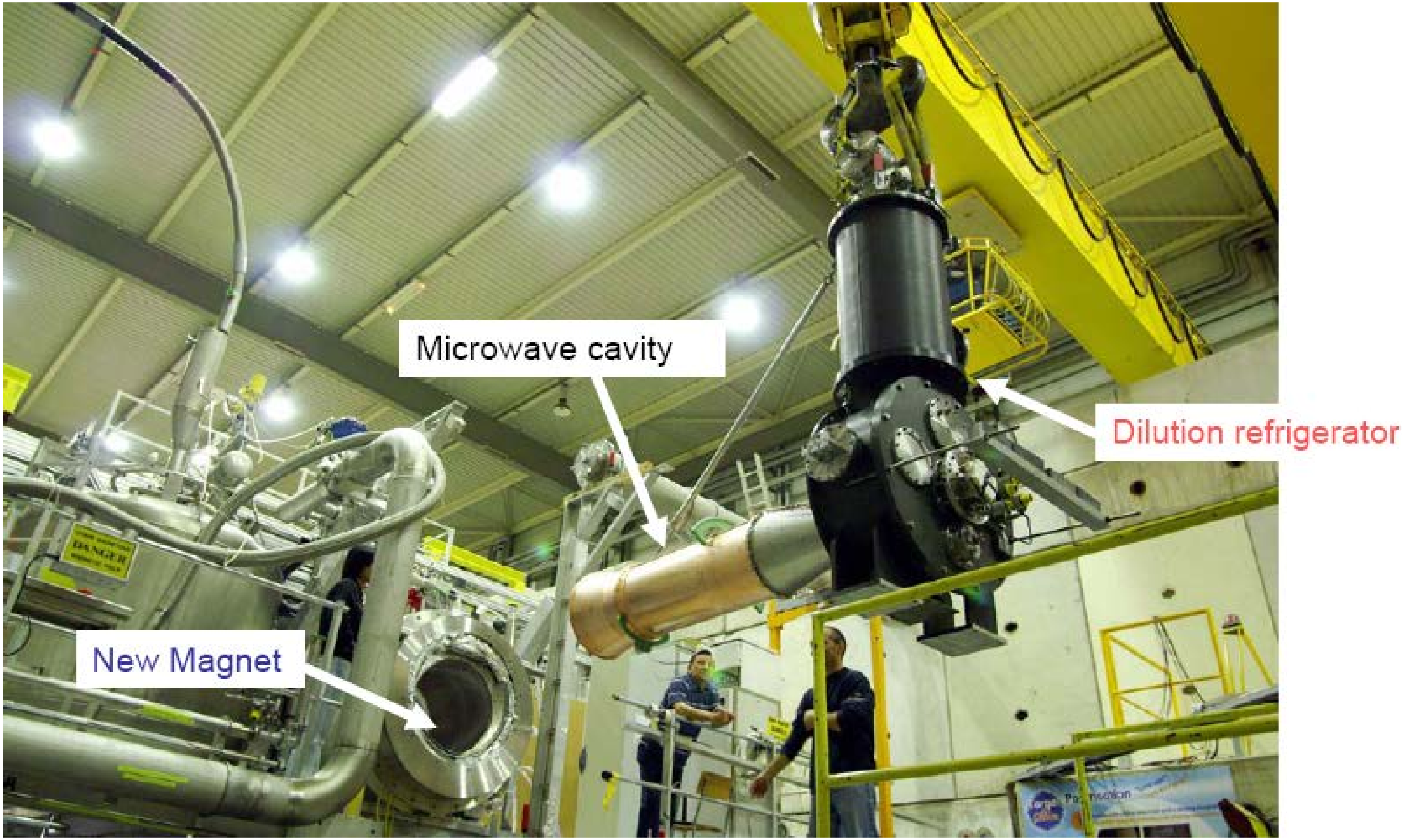
3 target cells
30, 60, and 30 cm long

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**			

COMPASS data taking

2002	**nucleon structure with**	**160 GeV μ**	**L&T**	**polarised deuteron target**
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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**			

SPECTROSCOPY

high energy hadron beams

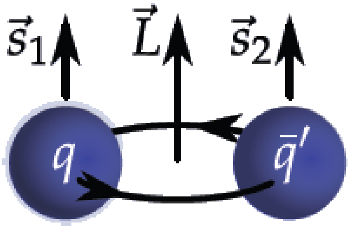
SPECTROSCOPY

Mesons

quantum numbers in CQM

$$S = 0, 1; \quad \vec{J} = \vec{L} + \vec{S}; \quad P = (-1)^{L+1}; \quad C = (-1)^{L+S}$$

forbidden (exotic QN's)

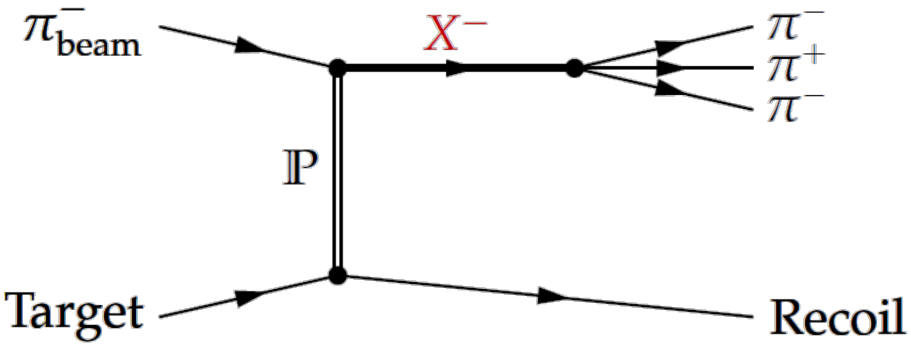


$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$$

more states in QCD:

hybrids $|q\bar{q}g\rangle$, glueballs $|gg\rangle$, multiquark states $|q^2\bar{q}^2\rangle$

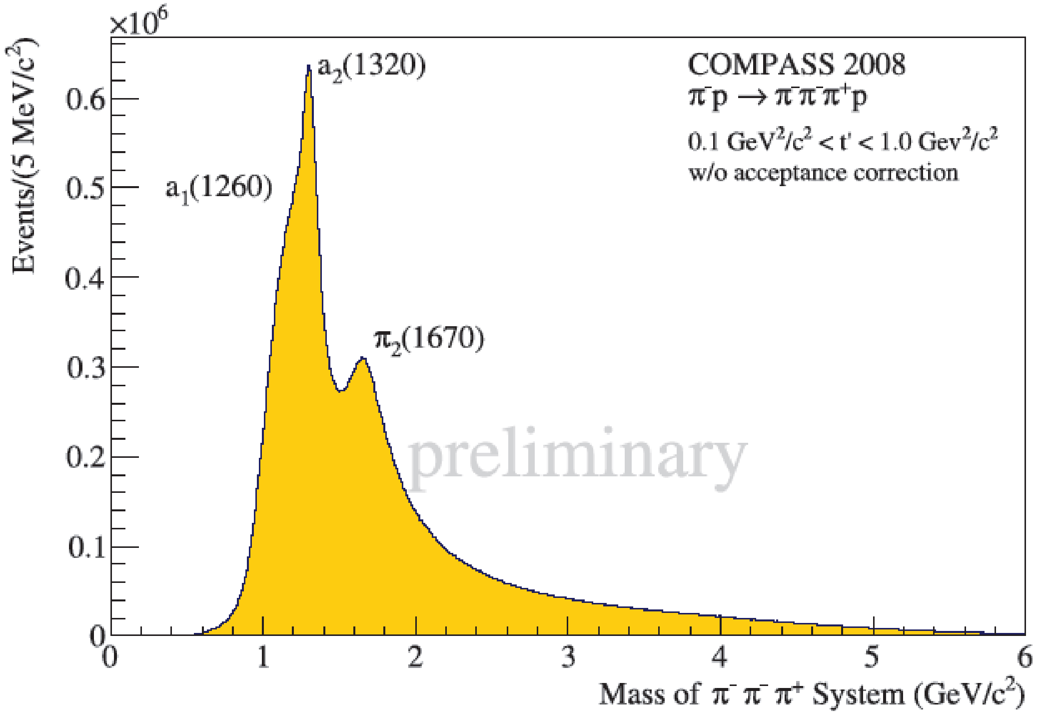
Diffractive dissociation:

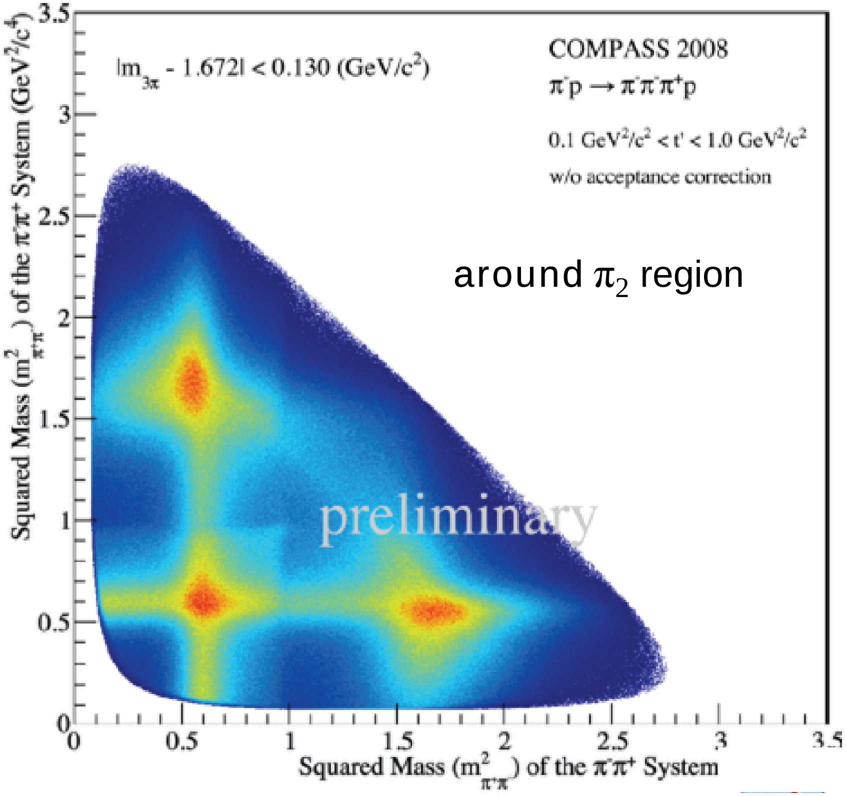


SPECTROSCOPY

$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

sample with $96 \cdot 10^6$ events

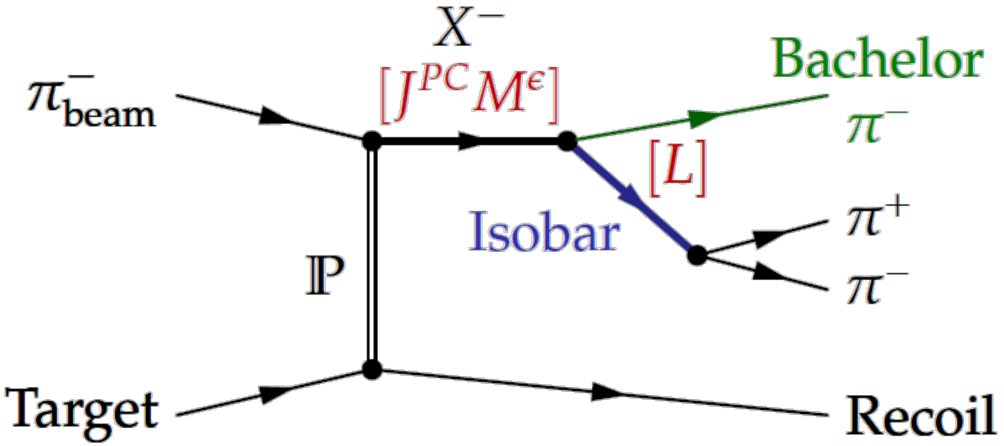




around π_2 region

SPECTROSCOPY

$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$



- **Isobar model:**

X decay is chain of successive two-body decays

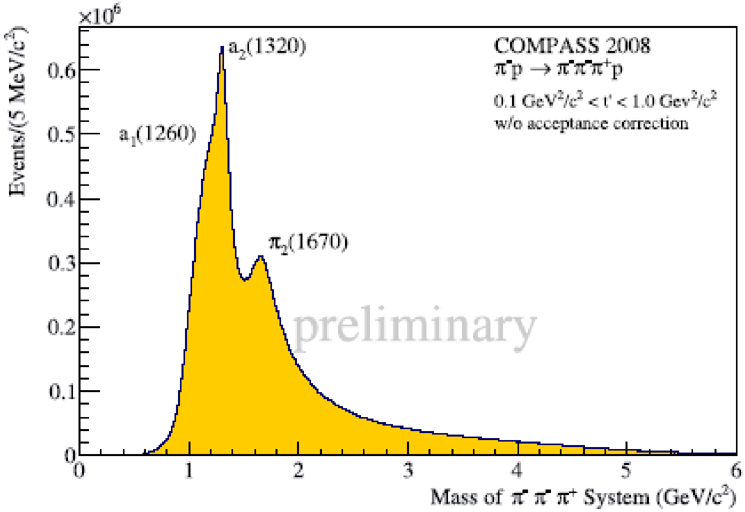
- **Analysis:**
  - Partial Wave Analysis (PWA) in mass bins with up to 88 waves
  - fit of spin-density matrix for major waves with Breit-Wigner

SPECTROSCOPY

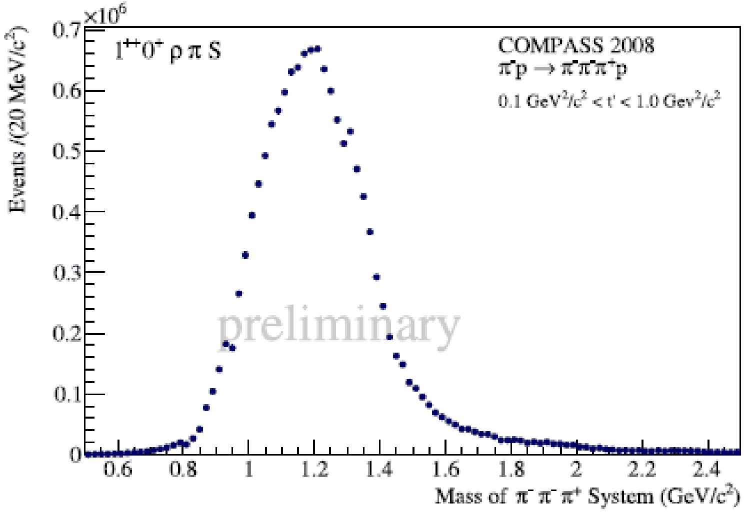
$\pi^- p \to \pi^-\pi^+\pi^- p$

Major waves

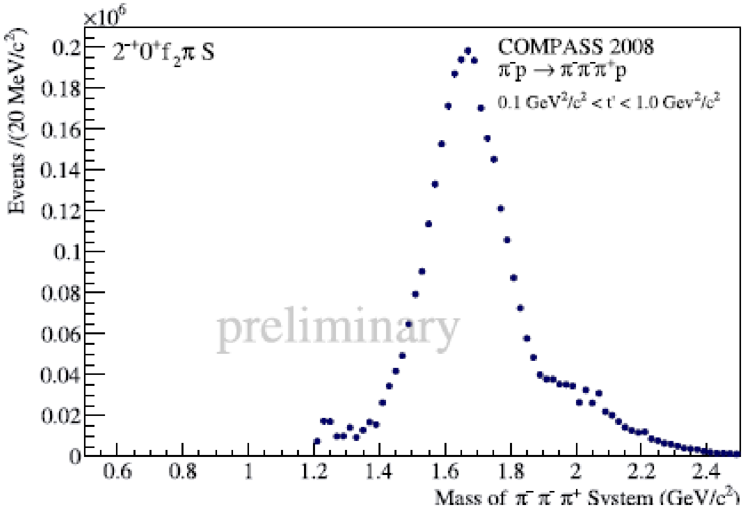
$\pi^-\pi^+\pi^-$ invariant mass spectrum



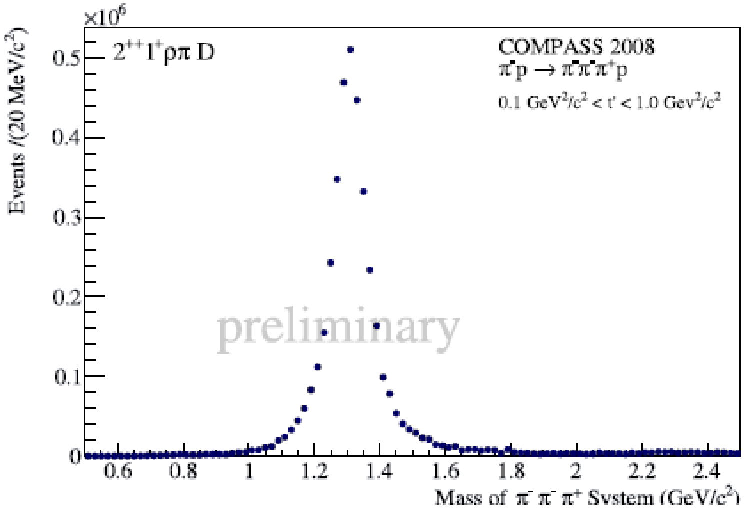
$1^{++}\,0^{+}\,[\rho\pi]S : a_1(1260)$



$2^{-+}\,0^{+}\,[f_2\pi]S : \pi_2(1670)$



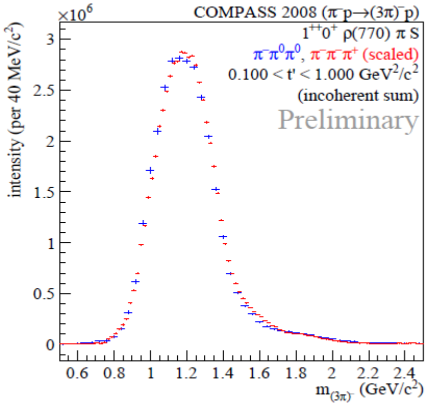
$2^{++}\,1^{+}\,[\rho\pi]D : a_2(1320)$



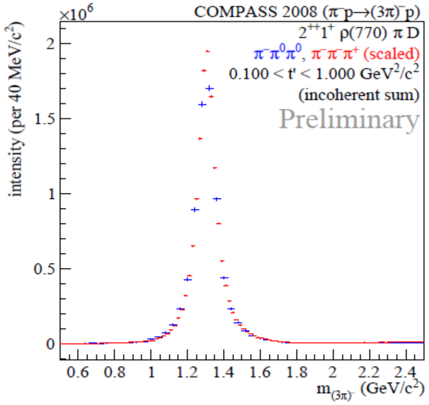
SPECTROSCOPY

charged $\pi^-\pi^+\pi^-$ and mixed $\pi^-\pi^0\pi^0$ final states

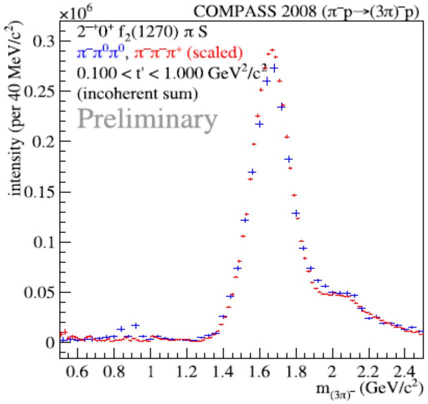
Major waves



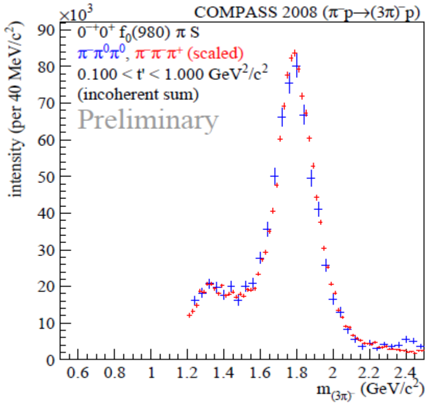
(a) $1^{++}\,0^+\,\rho\pi\,S$ wave with the $a_1(1260)$ peak.



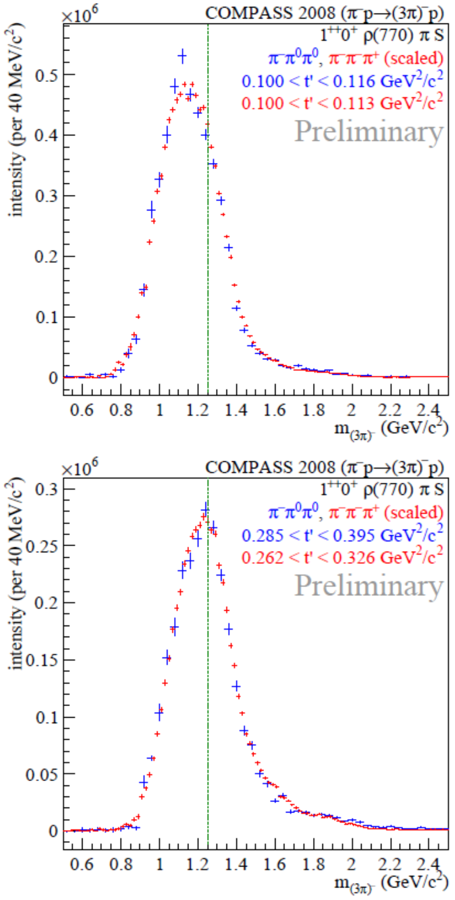
(b) $2^{++}\,1^+\,\rho\pi\,D$ wave with the $a_2(1320)$ peak.



(c) $2^{-+}\,0^+\,f_2(1270)\,\pi\,S$ wave with the $\pi_2(1670)$ peak.



(d) $0^{-+}\,0^+\,f_0(980)\,\pi\,D$ wave with the $\pi(1800)$ peak.



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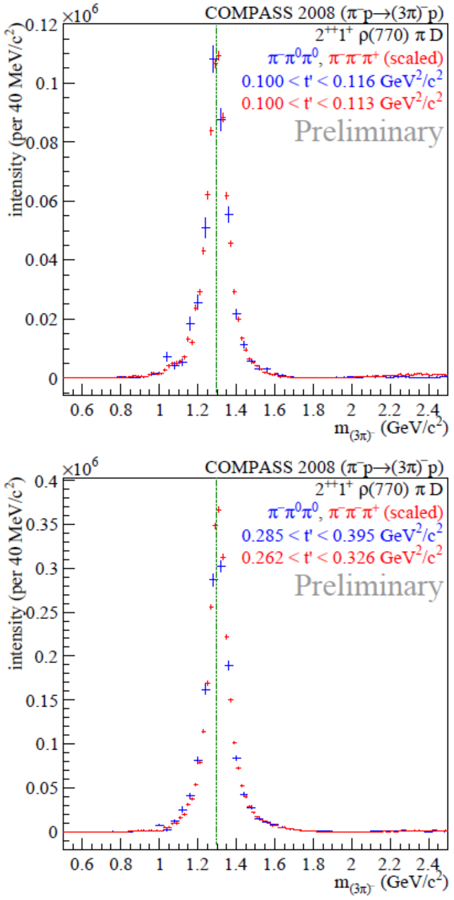


(b) $2^{++}\,1^+\,\rho\pi\,D$ wave with the $a_2(1320)$ peak.

good agreement

SPECTROSCOPY

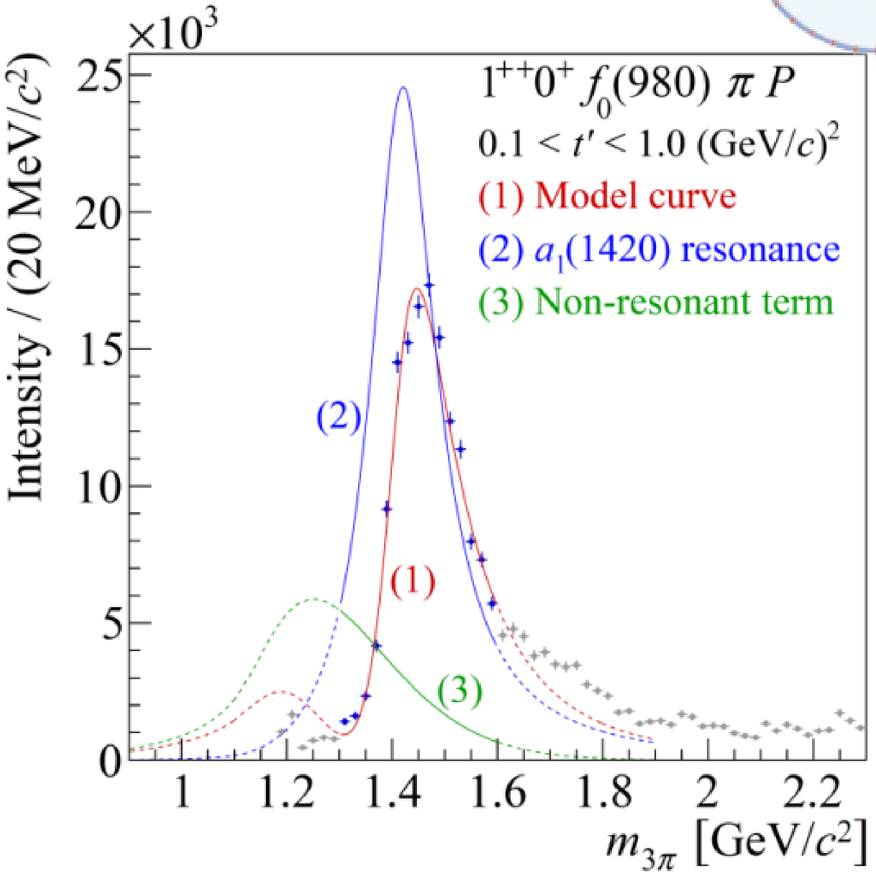
- **Observation of a new narrow axial-vector meson $a_1(1420)$**

PRL 115 (2015) 082001

***3π* data sample**

~ 50·10^6 exclusive events

factor 10 to 100
compared to
previous experiment



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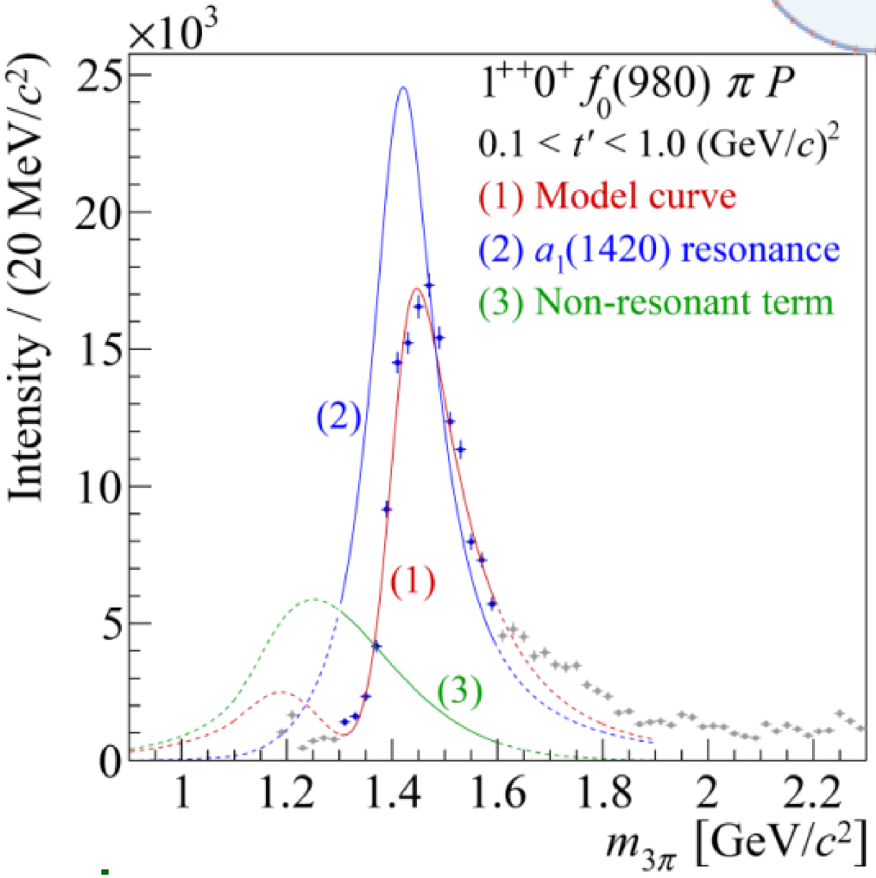

- **long paper:**

  Resonance Production and $\pi\pi$ S-wave in

  $\pi^- + p \rightarrow \pi^-\pi^-\pi^+ + p_{recoil}$ at 190 GeV/c

  arXiv:1509.00992 accepted for publication in PRD

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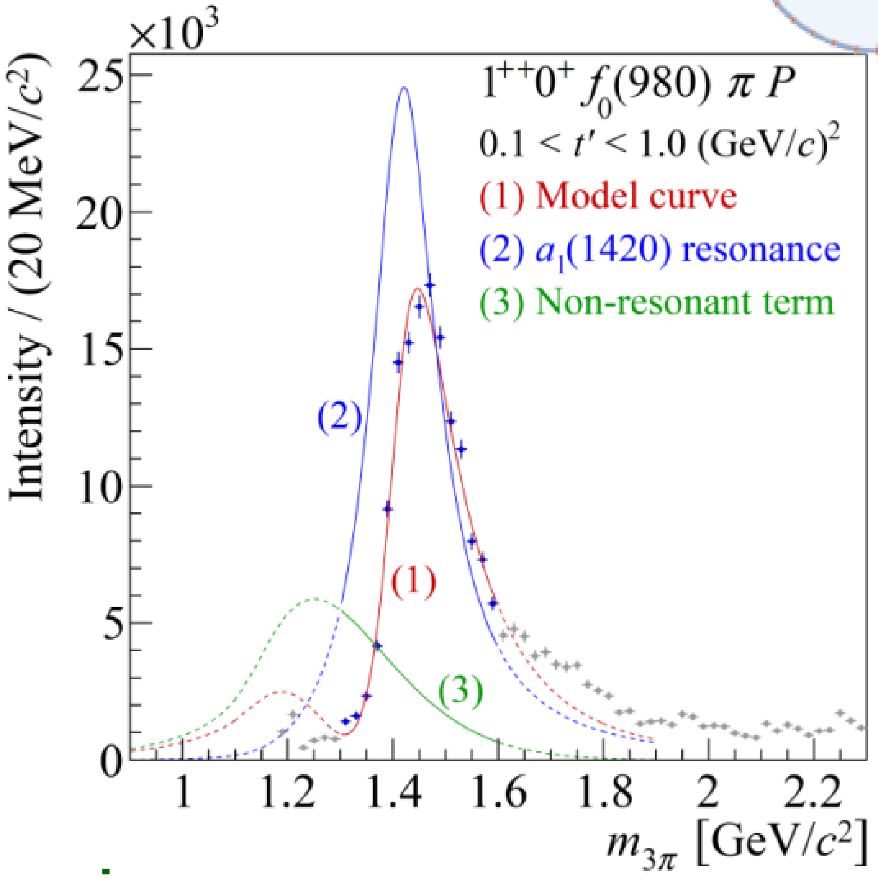

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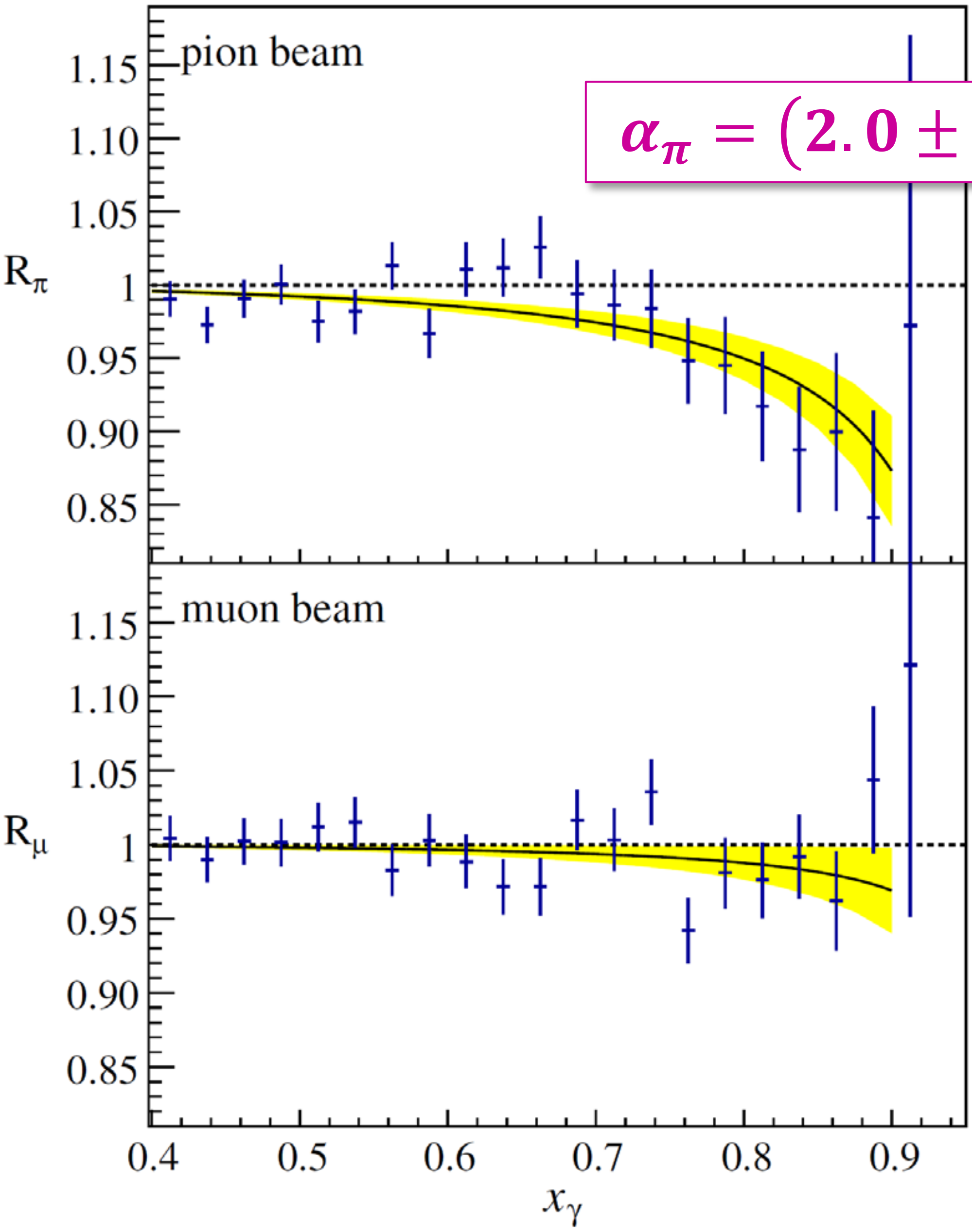
- **COMPASS in Phase Initiative**

Pion polarisability: results

PRL 114 (2015) 062002



$$\boxed{\alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \cdot 10^{-4}\,\text{fm}^3}$$

assuming $\alpha_\pi = -\beta_\pi$

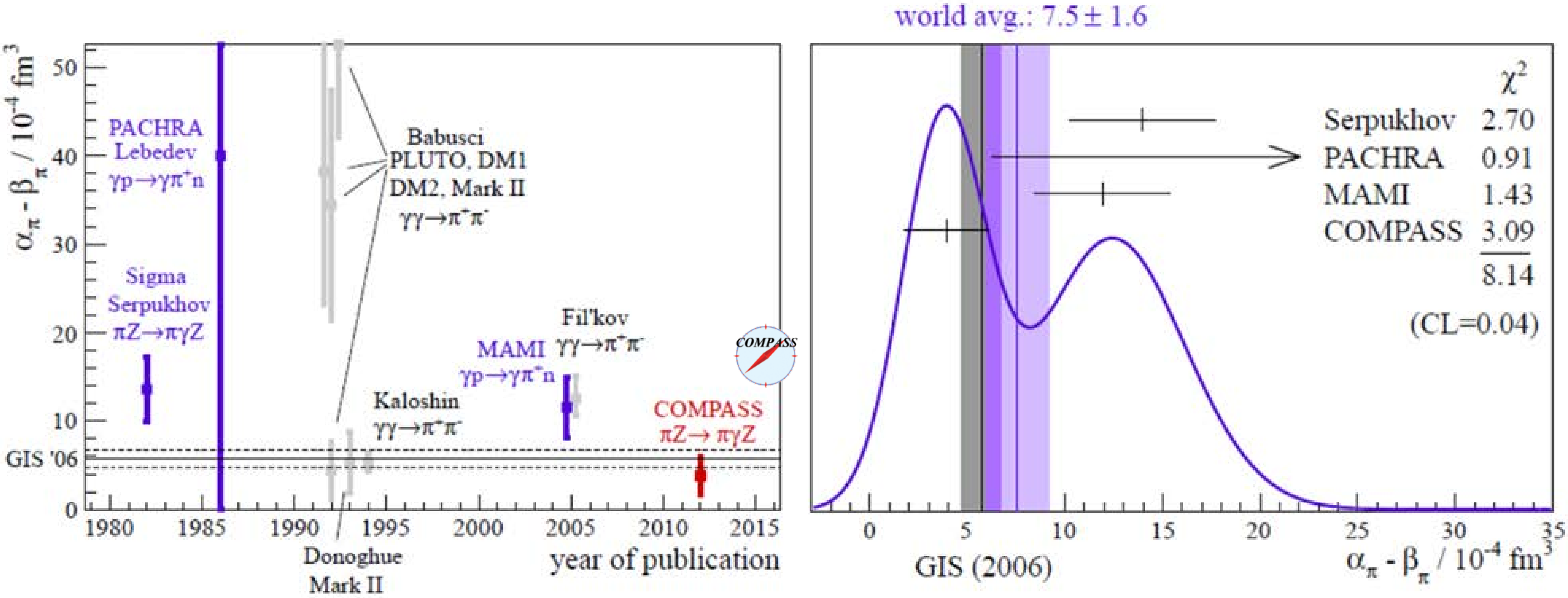
“false polarizability” from muon data

$$(0.5 \pm 0.5_{\text{stat}}) \cdot 10^{-4}\ \ \text{fm}^3$$

Source of uncertainty	Estimated magnitude $[10^{-4}\ \text{fm}^3]$ CL=68%
Determination of tracking detector efficiency	0.5
Treatment of radiative corrections	0.3
Subtraction of π^0 background	0.2
Strong interaction background	0.2
Pion-electron elastic scattering	0.2
Contribution of muons in the beam	0.05
Quadratic sum	0.7

Pion polarisability: results

world data including COMPASS

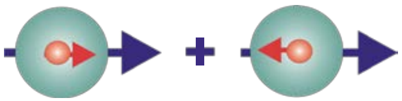
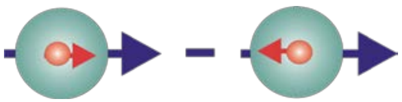


the COMPASS result is in significant tension with the earlier measurements

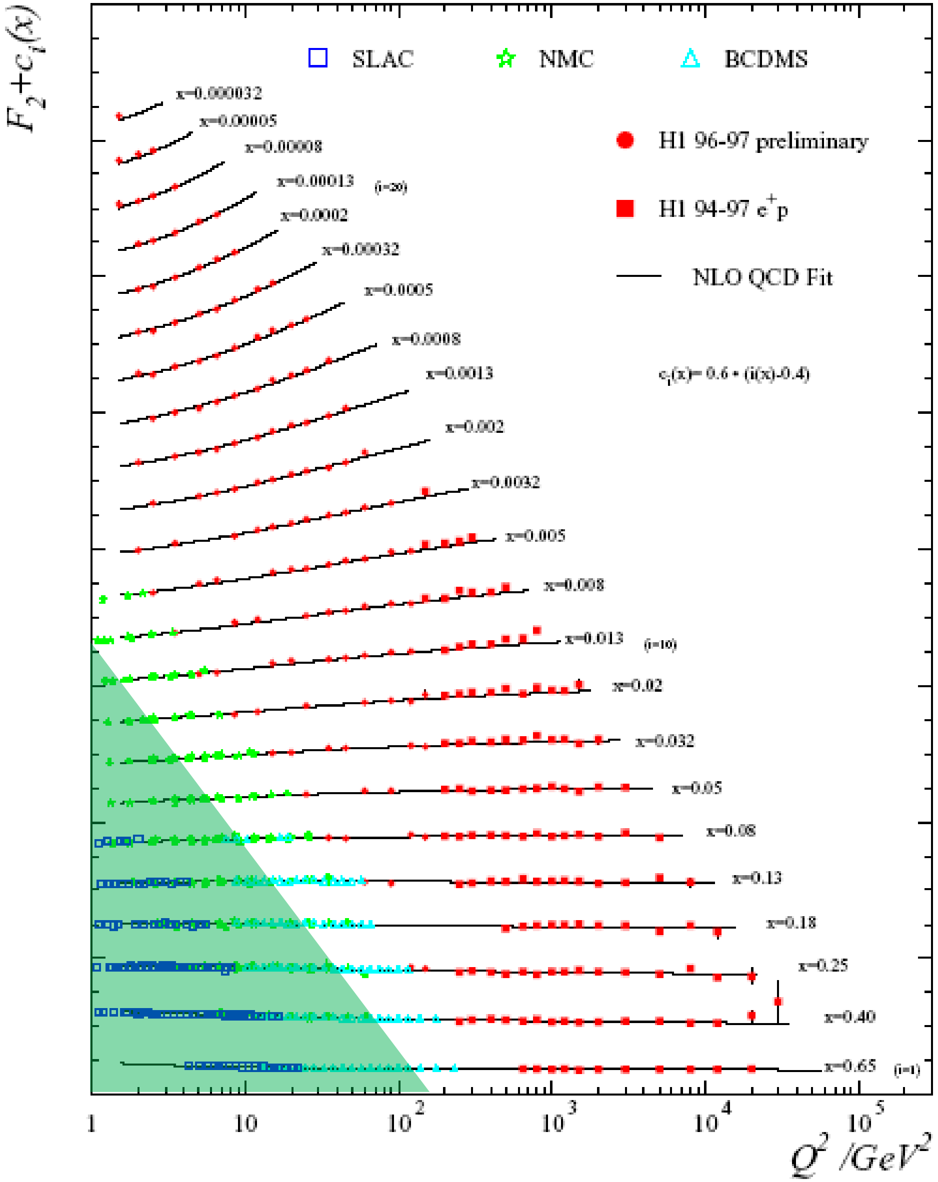
the expectation from ChPT is confirmed within the uncertainties

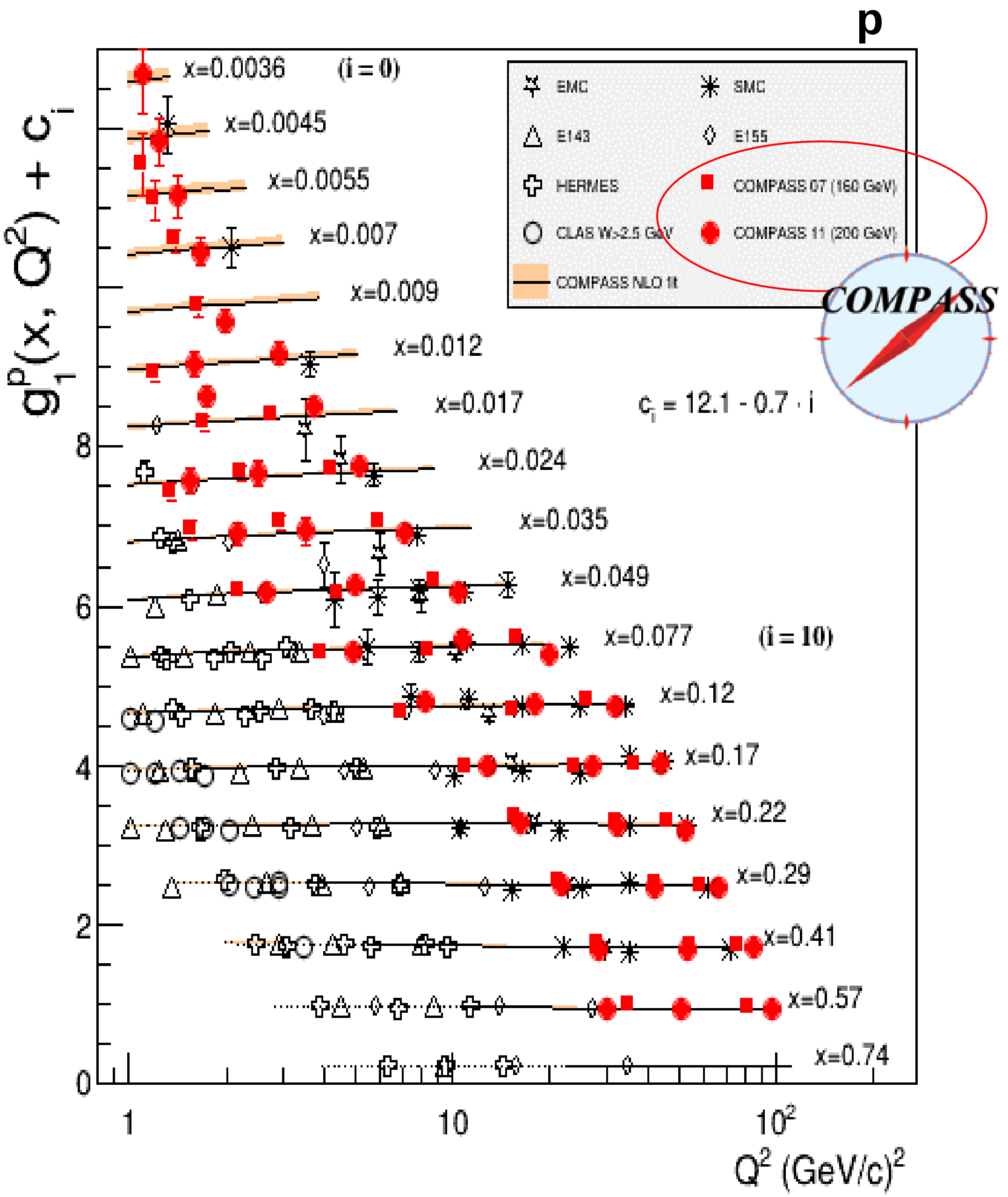
MUON beam PROGRAM:

COLLINEAR
NUCLEON STRUCTURE

$F_2(x, Q^2)$  $g_1(x, Q^2)$ 

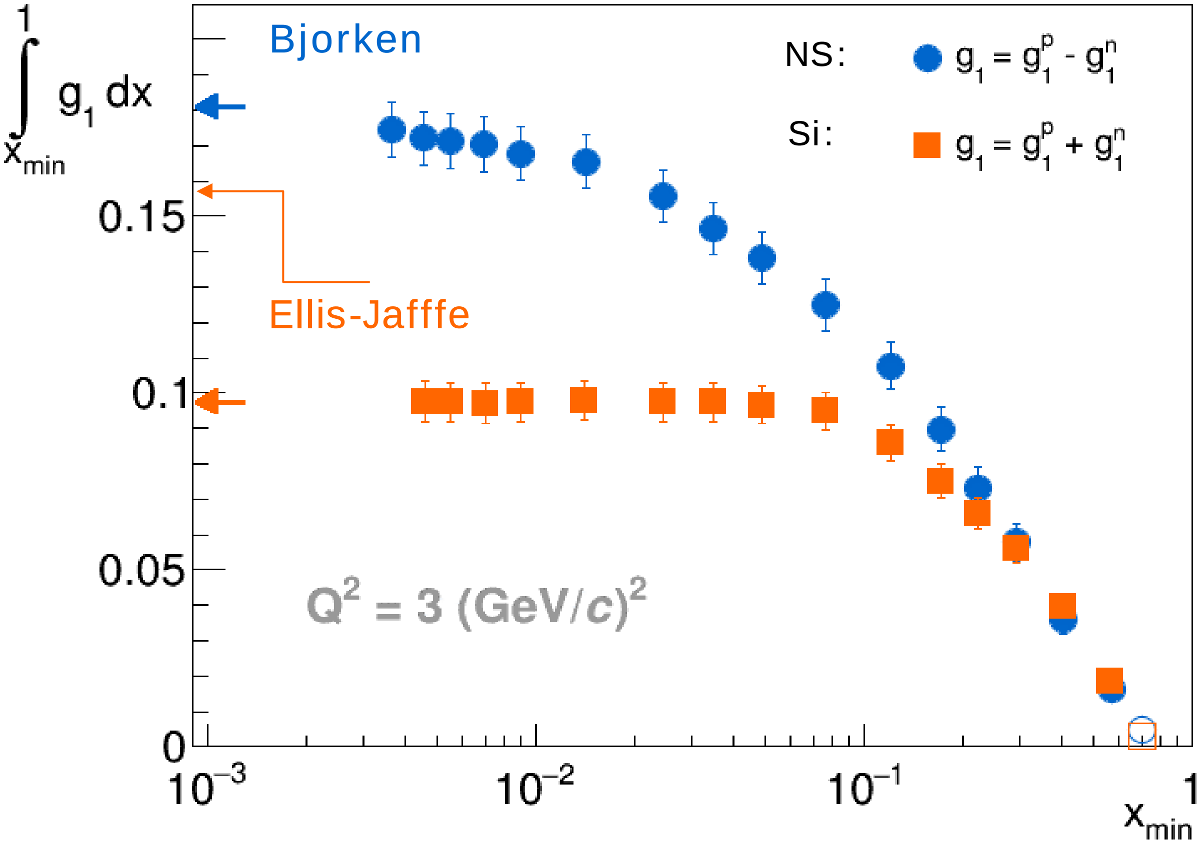
+
−


$F_2+c_i(x)$
SLAC
NMC
BCDMS
H1 96-97 preliminary
H1 94-97 e^+p
NLO QCD Fit
$c_i(x)= 0.6 \cdot (i(x)-0.4)$
x=0.000032
x=0.00005
x=0.00008
x=0.00013 (i=20)
x=0.0002
x=0.00032
x=0.0005
x=0.0008
x=0.0013
x=0.002
x=0.0032
x=0.005
x=0.008
x=0.013 (i=10)
x=0.02
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.40
x=0.65 (i=1)
1
10
10^2
10^3
10^4
10^5
$Q^2\ /GeV^2$


p
$g_1^p(x, Q^2) + c_i$
x=0.0036 (i = 0)
x=0.0045
x=0.0055
x=0.007
x=0.009
x=0.012
x=0.017
x=0.024
x=0.035
x=0.049
x=0.077 (i = 10)
x=0.12
x=0.17
x=0.22
x=0.29
x=0.41
x=0.57
x=0.74
$c_i = 12.1 - 0.7 \cdot i$
EMC
SMC
E143
E155
HERMES
COMPASS 07 (160 GeV)
CLAS W>2.5 GeV
COMPASS 11 (200 GeV)
COMPASS NLO fit
COMPASS
0
2
4
6
8
1
10
10^2
$Q^2\ (GeV/c)^2$

Sum Rules

PLB 753 (2016) 18



$$\Gamma_1^{NS}(Q^2) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$

Bjorken sum rule verified to 9%

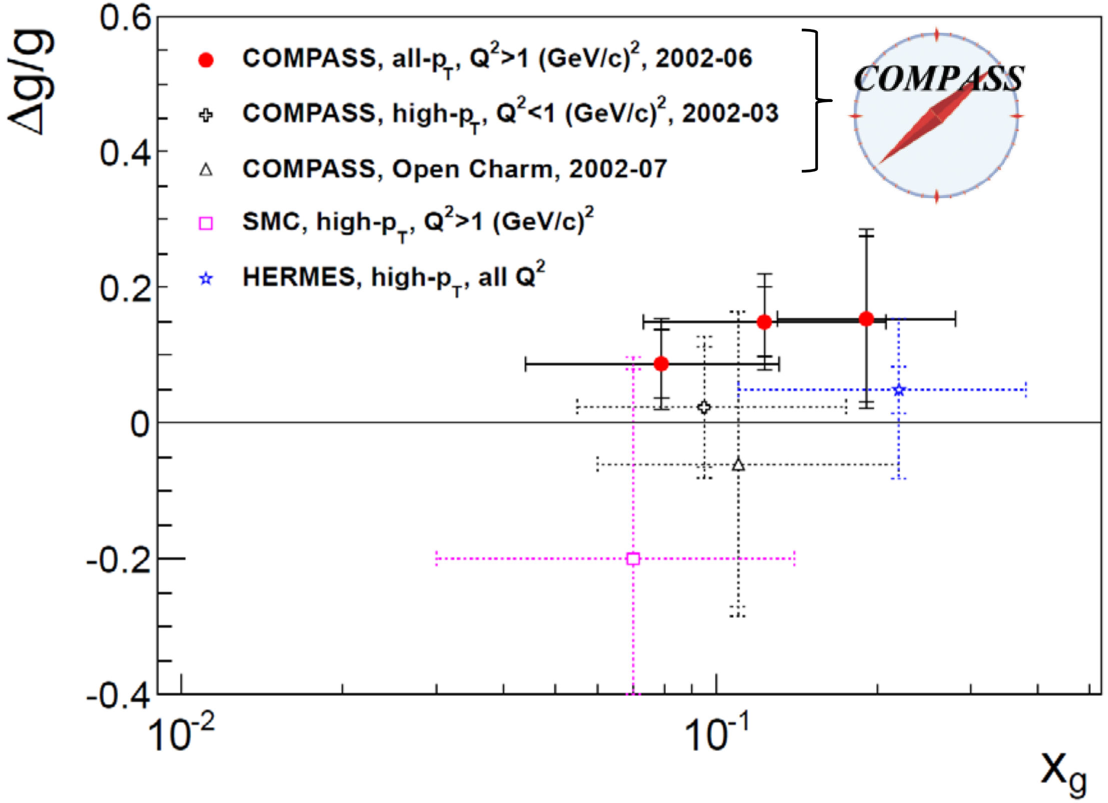
- BJ SR: major contribution from small *x*
- EJ SR: no contribution at small *x*

hep-ex/1612.00620

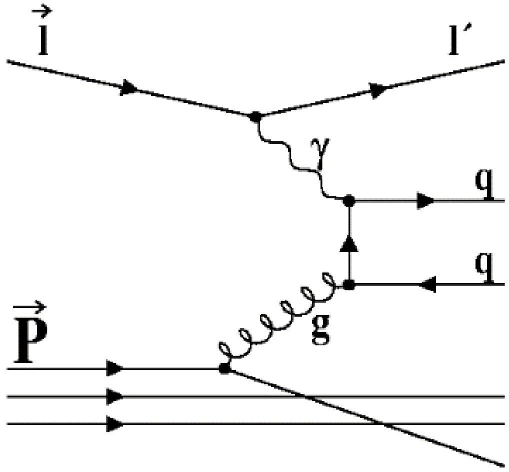
COMPASS data only: $|g_A/g_V| = 1.29 \pm 0.05\ \text{(stat.)}\ \pm 0.10\ \text{(syst.)}$

from neutron β decay: $|g_A/g_V| = 1.2723 \pm 0.0023$

$\Delta g/g$ from PGF (LO)



arXiv:1512.05053 [hep-ex]



gluon polarisation is much smaller than thought in the 1990s by many theorists (around $2\hbar$, even up to $6\hbar$, axial anomaly);

various methods confirmed by polarised *pp* at RHIC;

Δg still can make a substantial contribution to nucleon spin;

hadron multiplicities

- **Hadron multiplicity**

$$\frac{\mathrm{d}M^{\mathrm{h}}(x,z,Q^2)}{\mathrm{d}z} = \frac{\mathrm{d}\sigma^{\mathrm{h}}(x,z,Q^2)/\mathrm{d}x\mathrm{d}z\mathrm{d}Q^2}{\sigma^{\mathrm{DIS}}(x,Q^2)/\mathrm{d}x\mathrm{d}Q^2}$$

- **Factorsation Ansatz**

$$\sigma^{\mathrm{h}} \sim \sum \sigma_{\mathrm{hard}} \otimes \mathrm{PDF} \otimes \mathrm{FF}$$

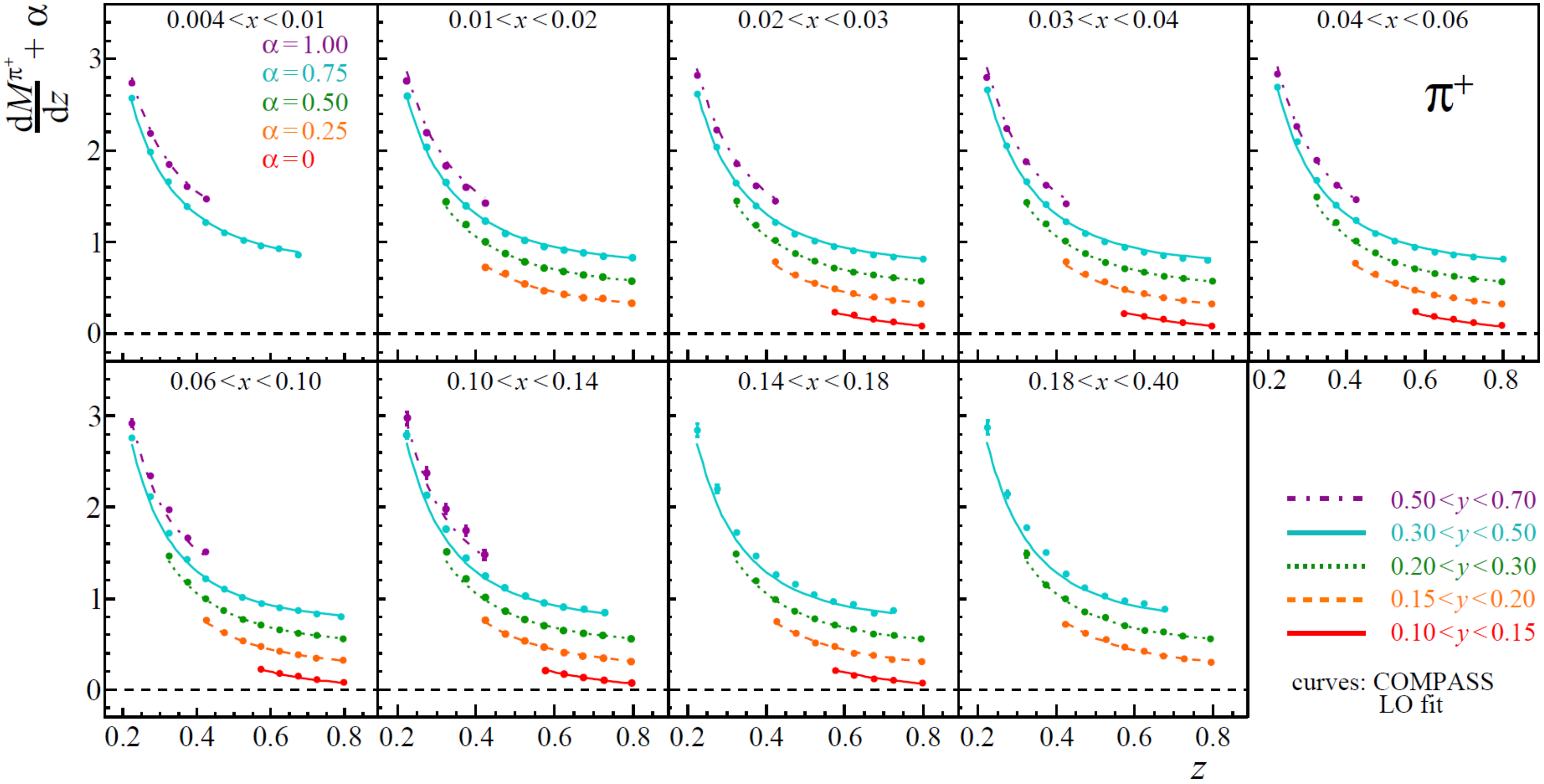
- with PDF: $q(x, Q^2)$ and fragmentation functions (FF): $D_q^{\mathrm{h}}(z, Q^2)$

Multiplicities in LO pQCD:

$$\frac{\mathrm{d}M^{\mathrm{h}}(x,z,Q^2)}{\mathrm{d}z} = \frac{\sum_q e_q^2 q(x,Q^2) D_q^{\mathrm{h}}(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

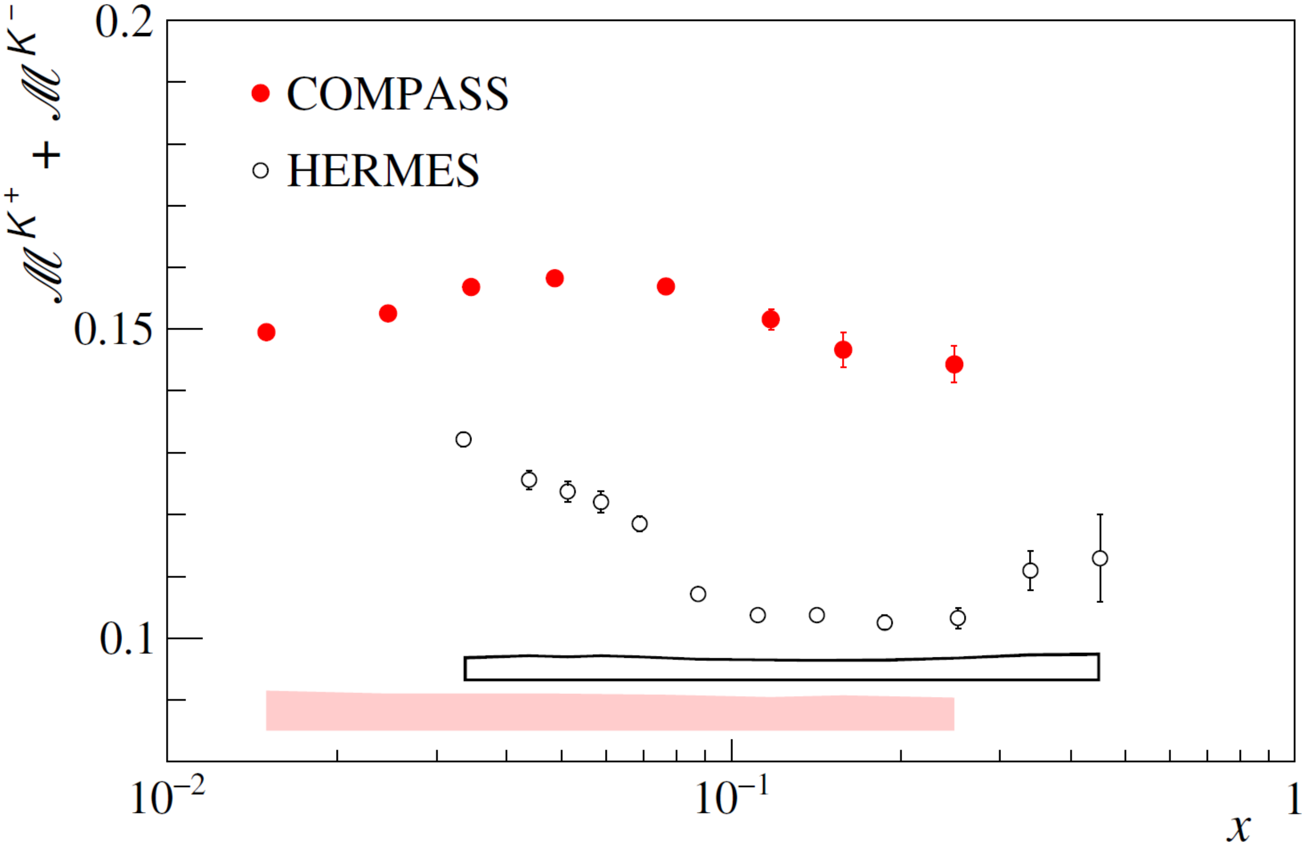
pion multiplicities

PLB 764 (2017) 001



- 317 kinematic bins (arXiv:1604.02695)
- practically no y dependence, strong z dependence
- curves: COMPASS LO pQCD fit

kaon multiplicities



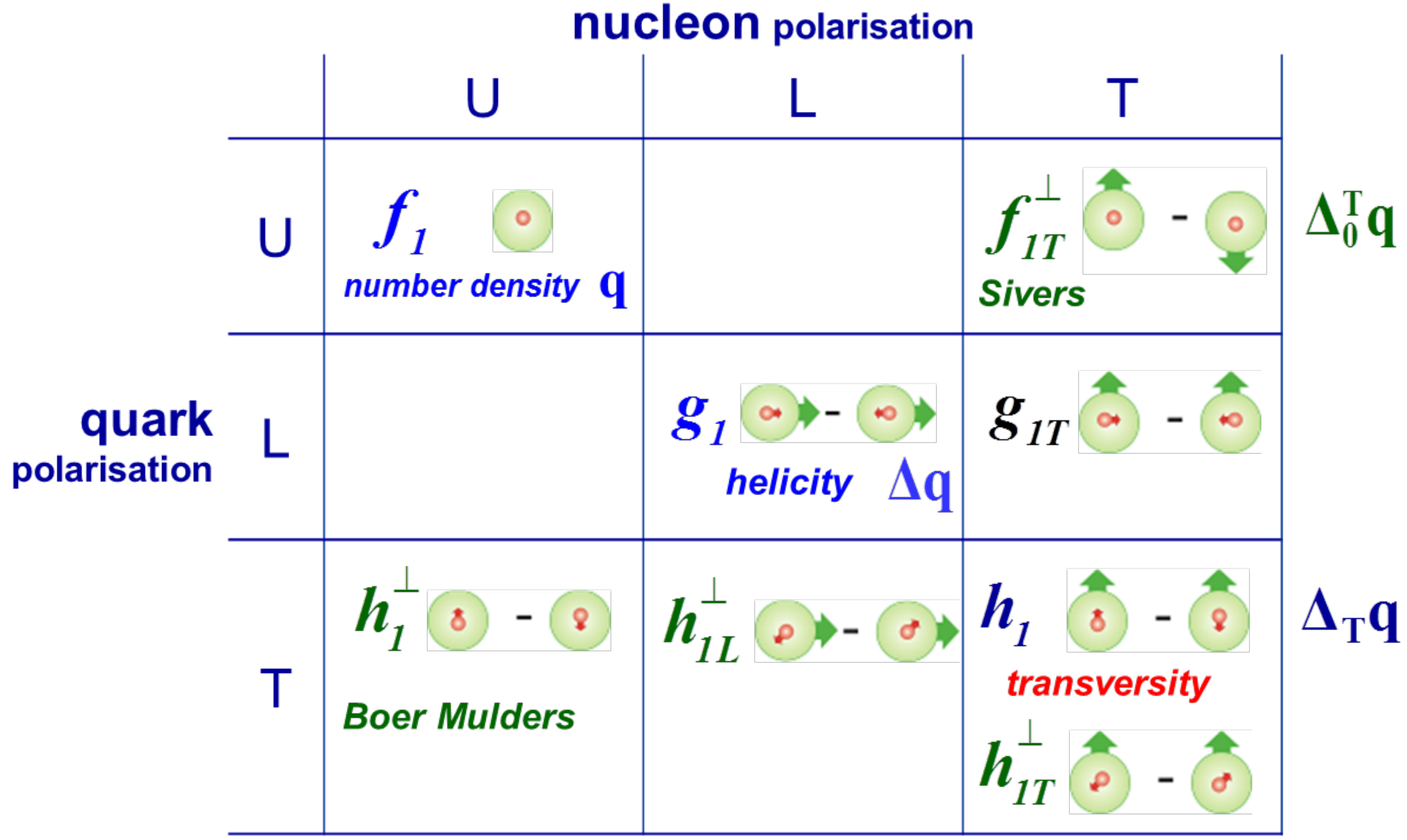
hep-ex/1608.06760, acc. PLB

MUON beam PROGRAM:

TRANSVERSITY and TMD 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

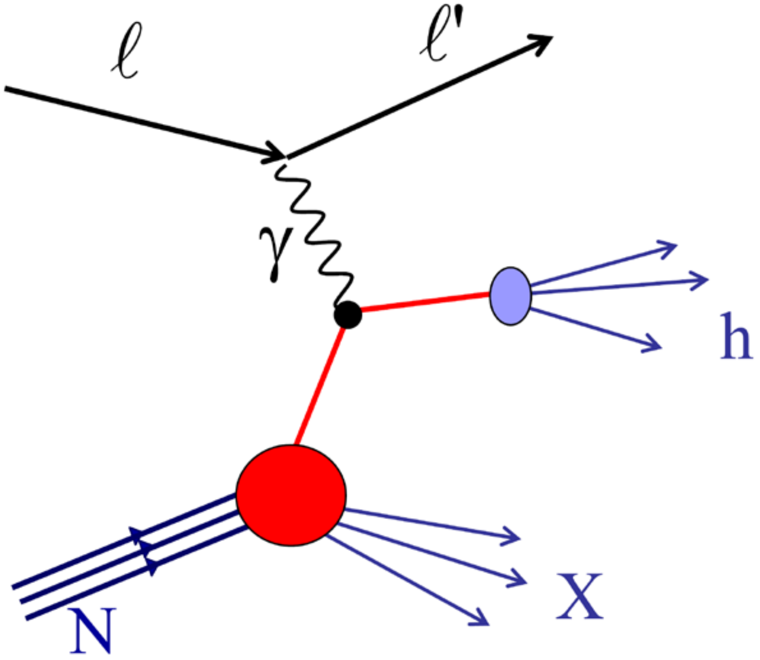


		nucleon polarisation			
		U	L	T	
quark polarisation	U	f_1 *number density* q		$f_{1T}^{\perp}$ *Sivers*	$\Delta_0^T q$
	L		g_1 *helicity* Δq	g_{1T}	
	T	$h_1^{\perp}$ *Boer Mulders*	$h_{1L}^{\perp}$	h_1 *transversity* $h_{1T}^{\perp}$	$\Delta_T q$

SIDIS gives access to all of them

Semi-Inclusive Deep Inelastic Scattering

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

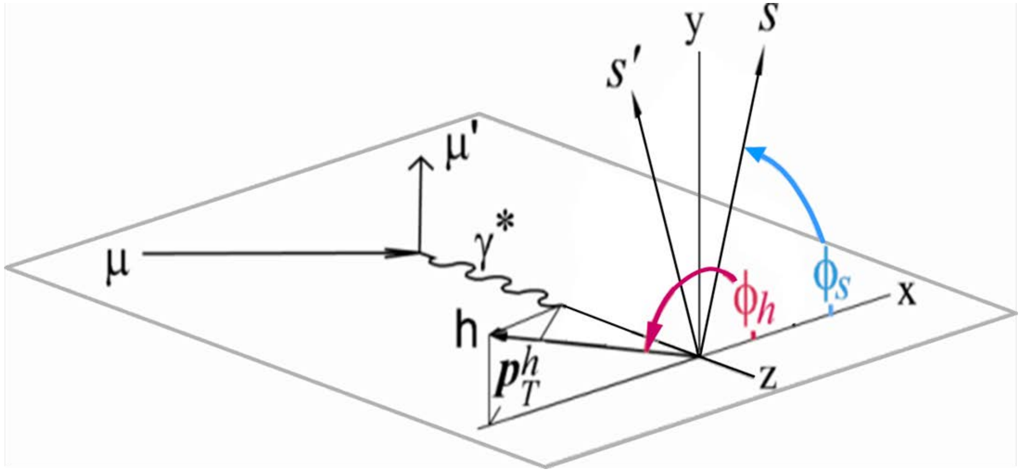


$$x = \frac{Q^2}{2P \cdot q} \qquad y = \frac{P \cdot q}{P \cdot \ell} =_{LAB} \frac{E - E'}{E}$$

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

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

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



Semi-Inclusive Deep Inelastic Scattering

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

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

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

unpol target

→ pol target

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

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

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

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

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

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

↑ pol target

18 structure functions

Semi-Inclusive Deep Inelastic Scattering

14 independent azimuthal modulations

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

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

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

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

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

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

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

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

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

Semi-Inclusive Deep Inelastic Scattering

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$$+\,S_\parallel\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\;\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\,\overset{h_{1L}^\perp H_1^\perp}{\boxed{\sin(2\phi_h)}}\,F_{UL}^{\sin 2\phi_h}\Big]+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}$$

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

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

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

14 independent azimuthal modulations

amplitudes of the modulations
→ TMD PDFs

Semi-Inclusive Deep Inelastic Scattering

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$h_1^\perp H_1^\perp$

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

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

$h_1 H_1^\perp$

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

$$\Big]$$

$g_{1T} D_1$

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

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

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

some SIDIS results on

TRANSVERSITY and TMD PDFs

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 $\sim h_1 \otimes H_1^\perp$

the Sivers PDF

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

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

A STEP TOWARDS
THE 3-D STRUCTURE OF THE NUCLEON

Semi-Inclusive Deep Inelastic Scattering

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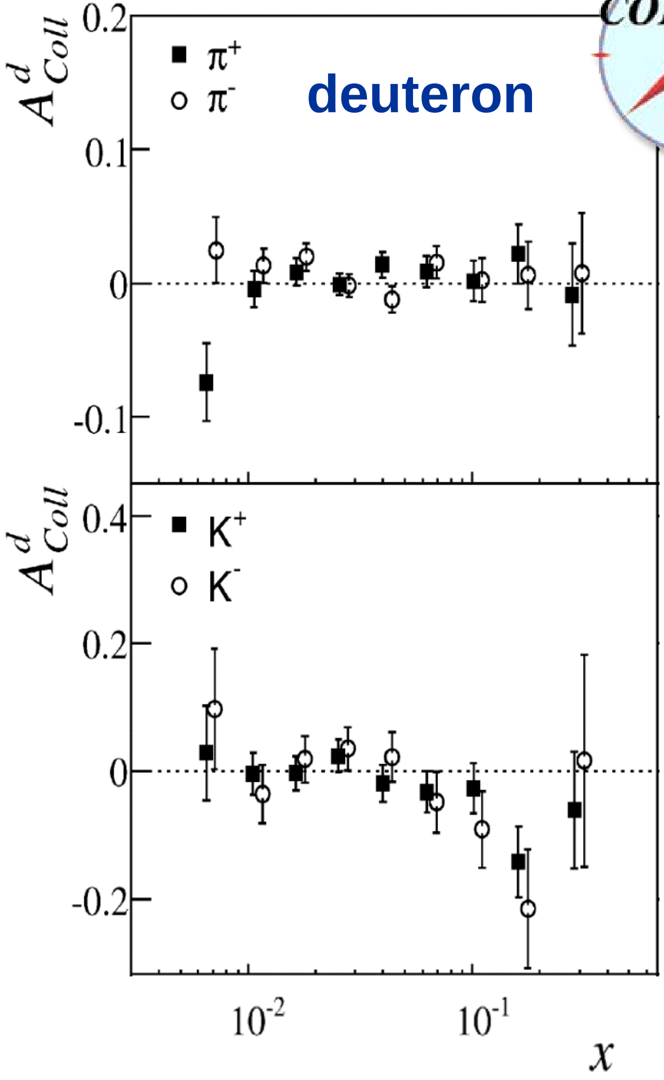
A STEP TOWARDS
THE 3-D STRUCTURE OF THE NUCLEON

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

Collins asymmetry

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

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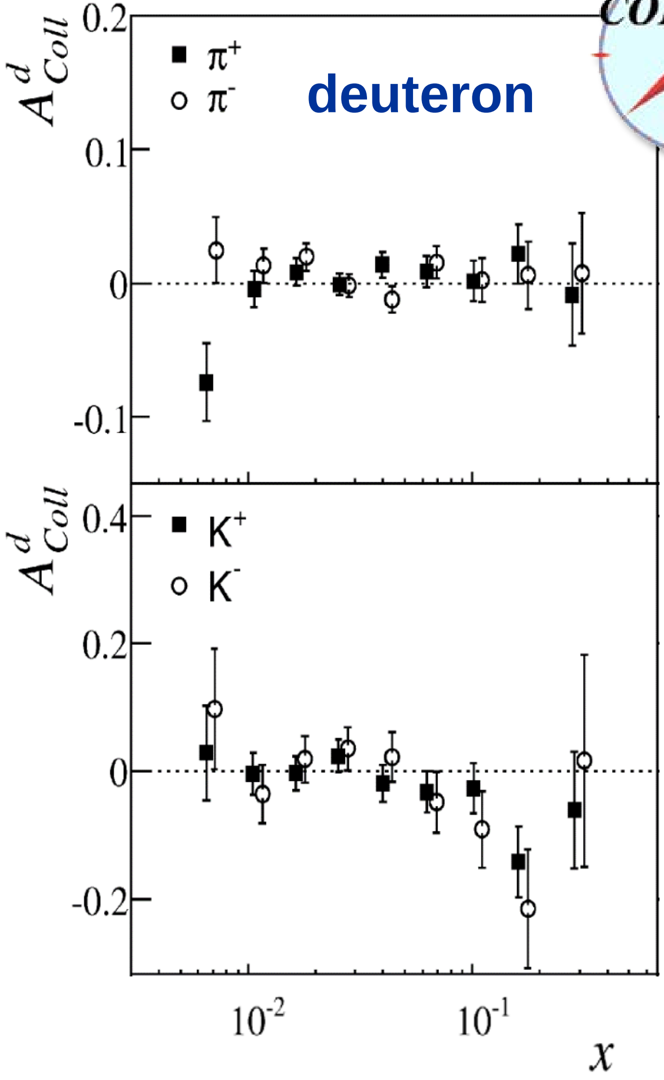
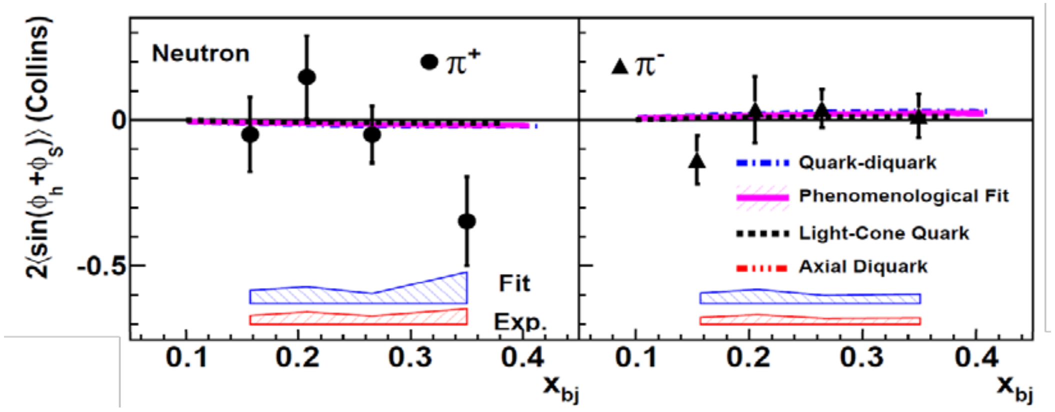


NPB765 2007
PLB673 2009

neutron

Hall A PRL107, 2011



Collins asymmetry

$\sim h_1 \otimes H_1^\perp$

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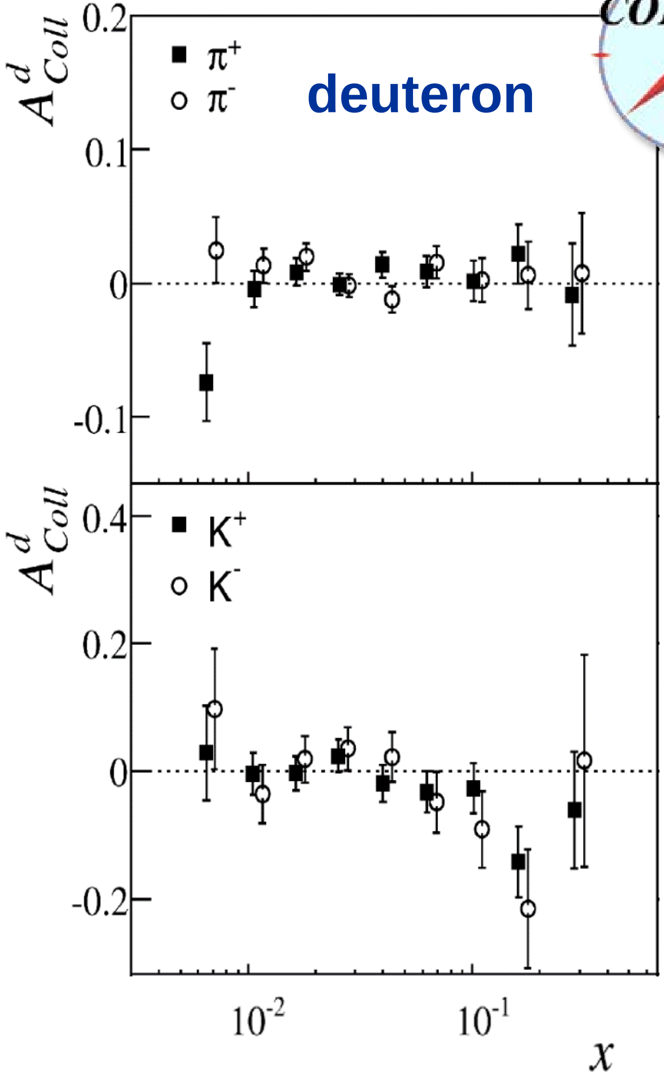

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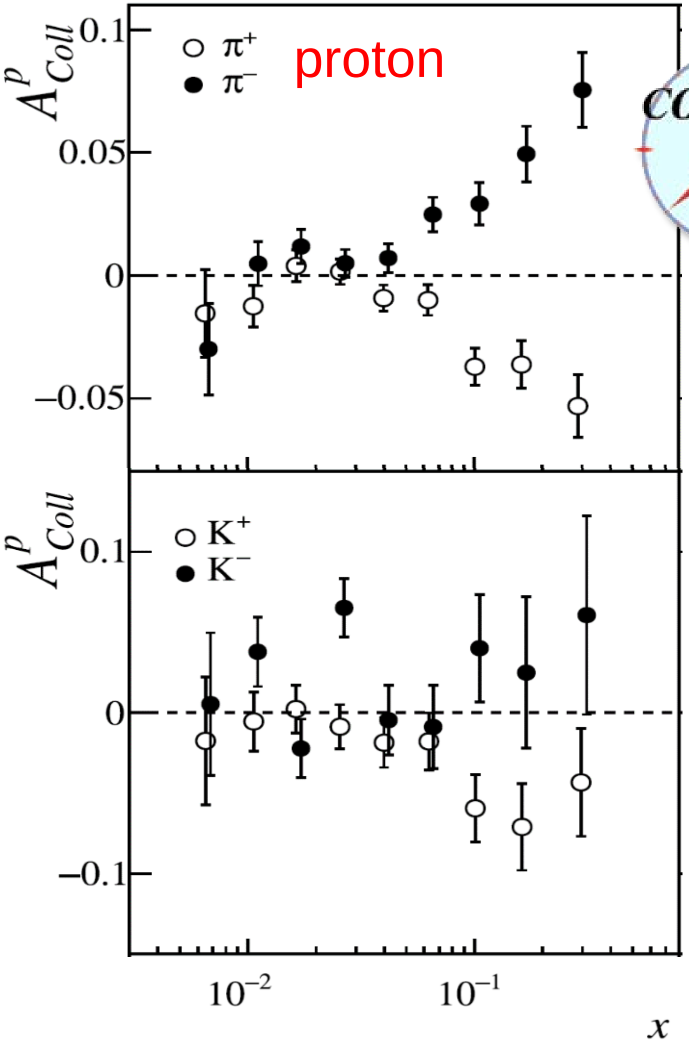


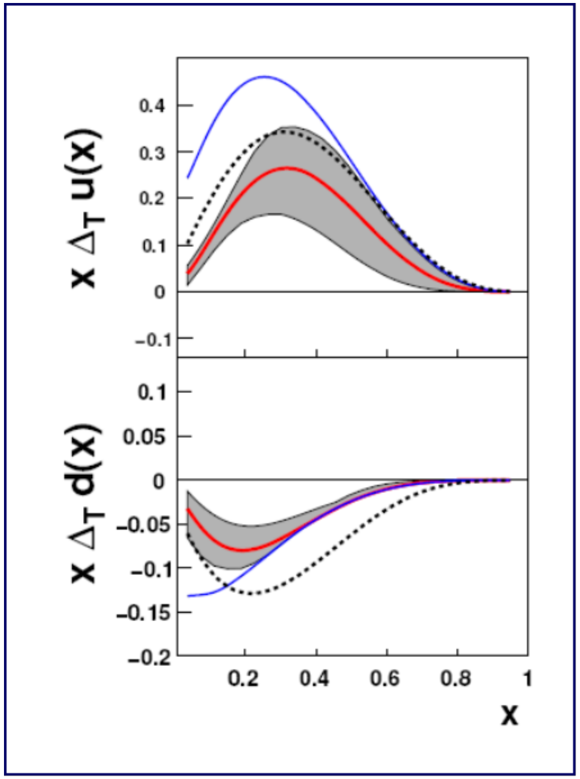
PLB693 2010

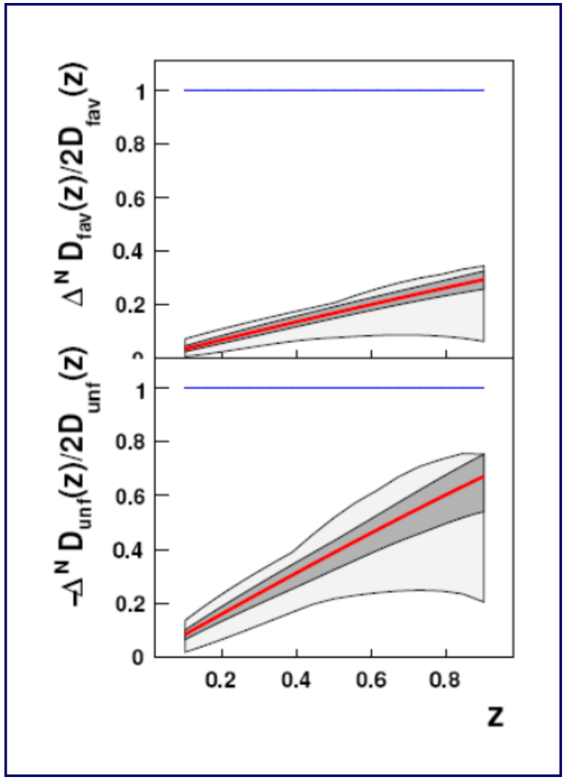
PLB744 2015

transversity from SIDIS

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

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





dihadron asymmetry

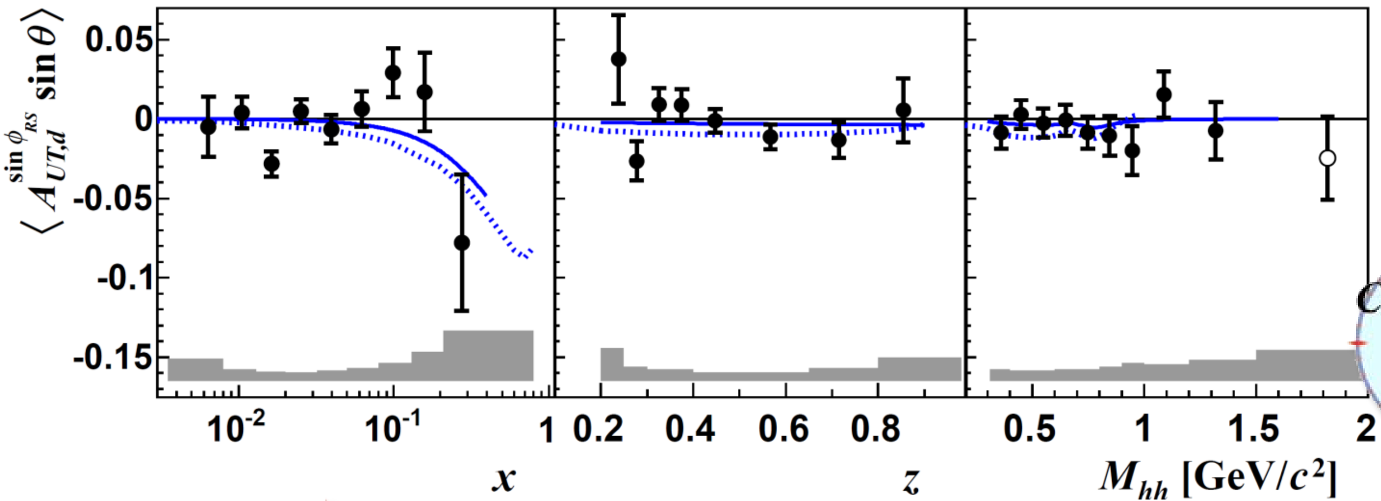
$\sim h_1 H_1^{\angle}$

dihadron asymmetry

~ $h_1 H_1^{\angle}$

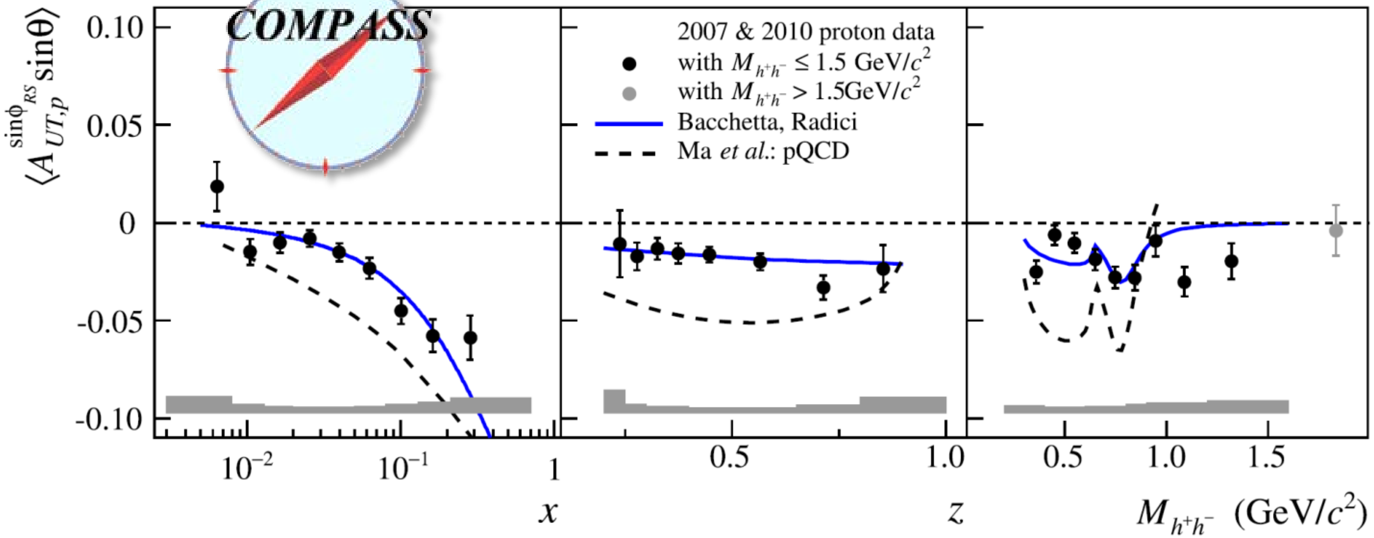
2008: first evidence for non-zero di-h FF on p from HERMES, low statistics

final COMPASS results



deuteron:

compatible with zero



proton:

same sign and shape

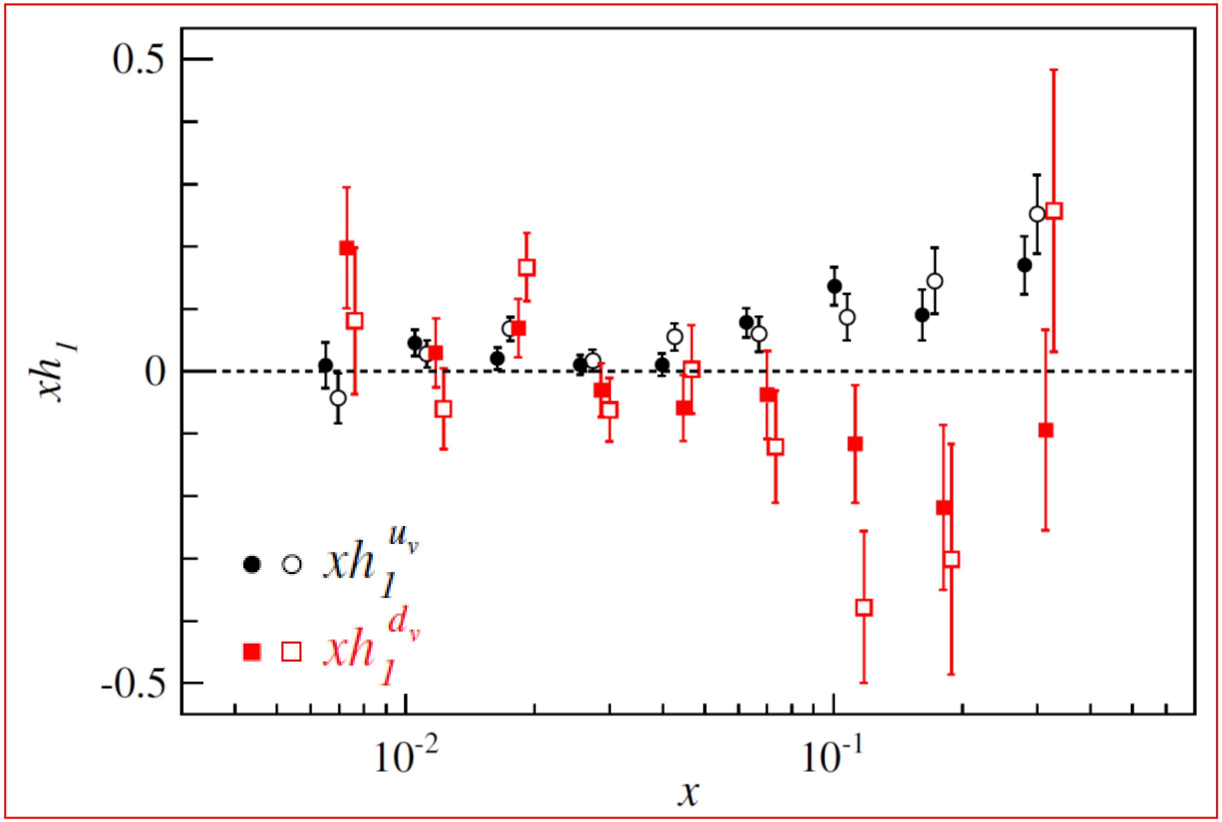
slightly higher
than Collins asymmetry
for h^+

PLB 713 2012, PLB736 2014

Transversity from 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 Monte Carlo nor parametrisation is needed



open points: dihadron

closed points: Collins

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

Transversity from Collins and di-hadron asymmetries

point by point extraction

one can use directly the COMP
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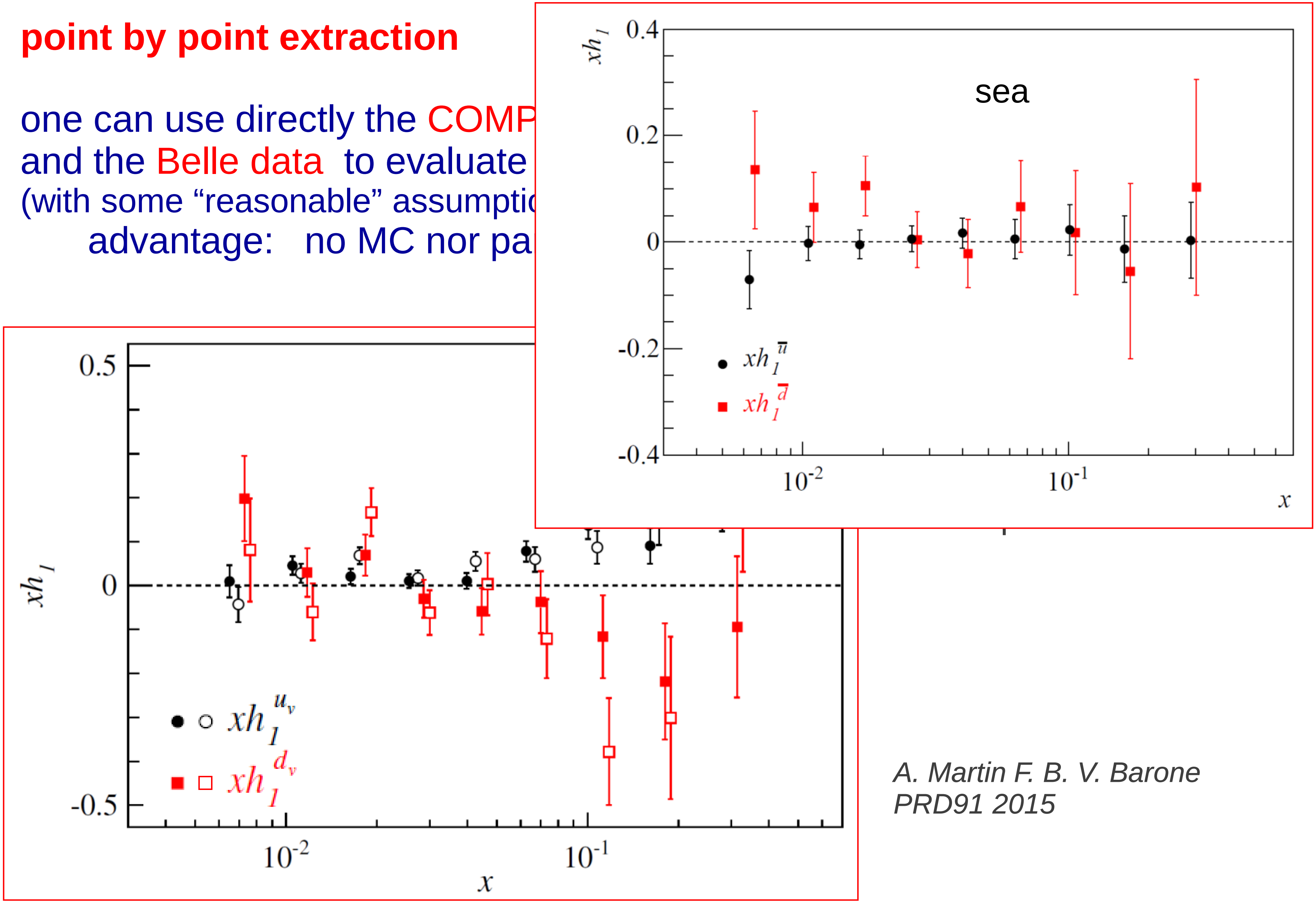


A. Martin F. B. V. Barone
PRD91 2015

interplay among dihadron and single hadron asymmetries

interplay among dihadron and single hadron asymmetries

- Collins asymmetry for h+ and for h-

  “mirror symmetry”

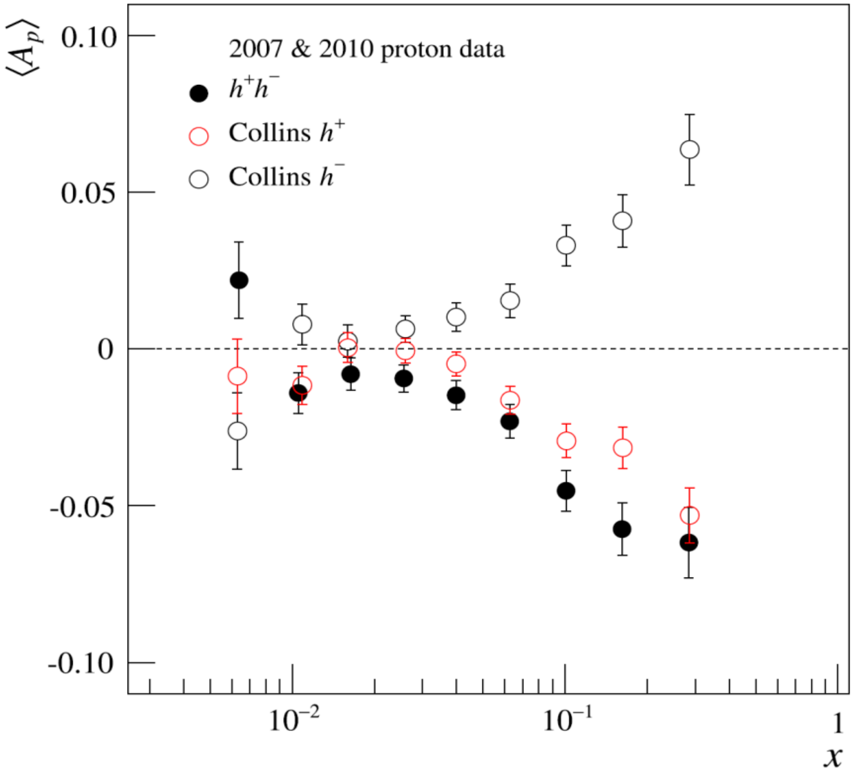
- dihadron asymmetry

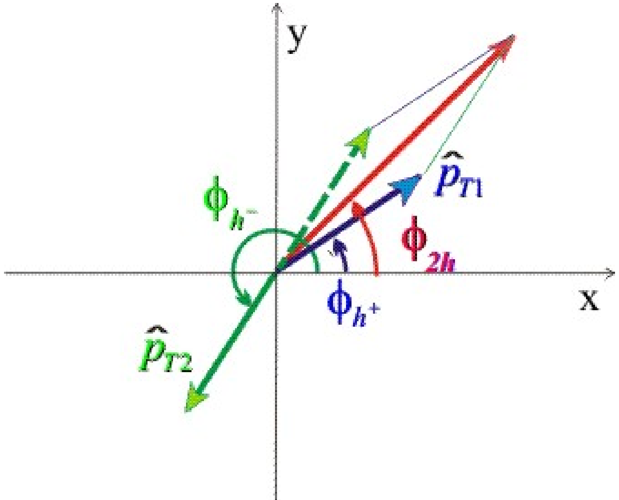
  only somewhat larger than h+ Collins

- meaning of the relevant angles

hints for a common origin
of the Collins FF and DiFF

Como 2013, DSpin2013, PLB736 (2014) 124





interplay among dihadron and single hadron asymmetries

- Collins asymmetry for h+ and for h-
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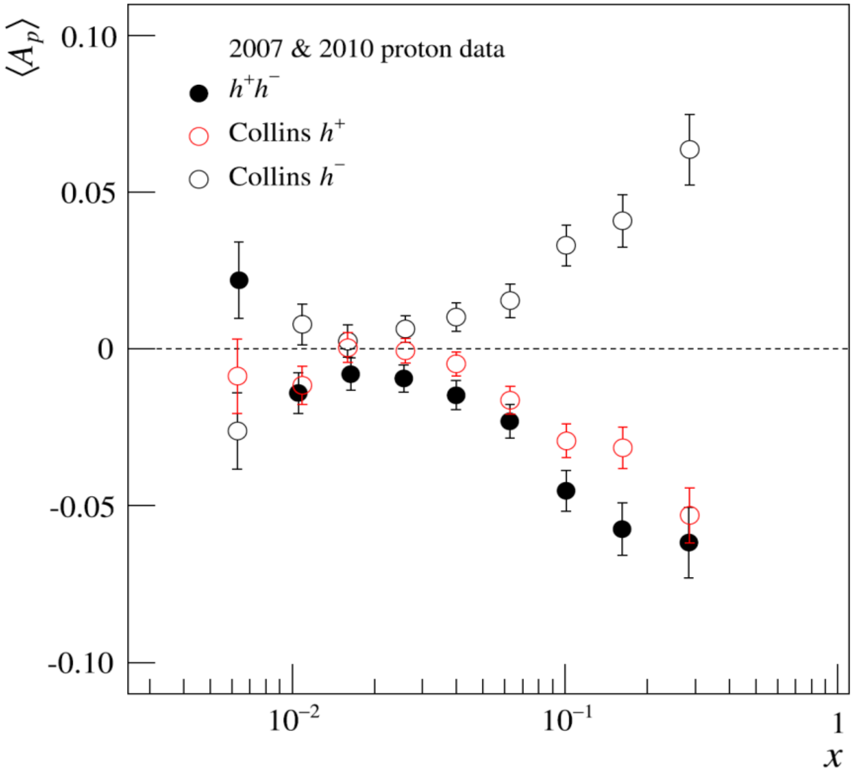

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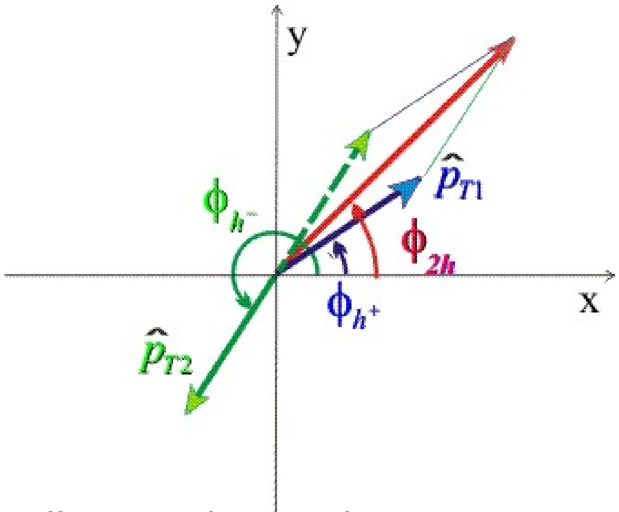
Como 2013, DSpin2013, PLB736 (2014) 124



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

one of the COMPASS studies on
final state hadron correlations

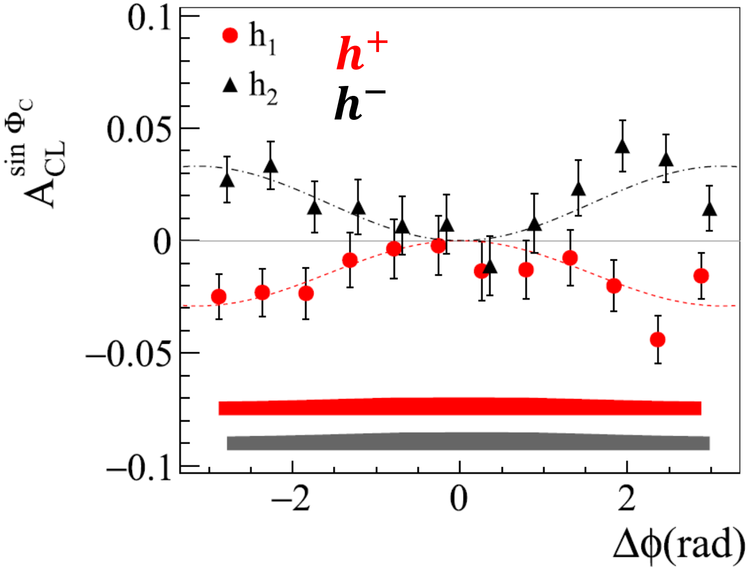
interplay among dihadron and single hadron asymmetries

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 $a_1 = -a_2 = a$

interplay among dihadron and single hadron asymmetries

PLB 753 (2016) 406

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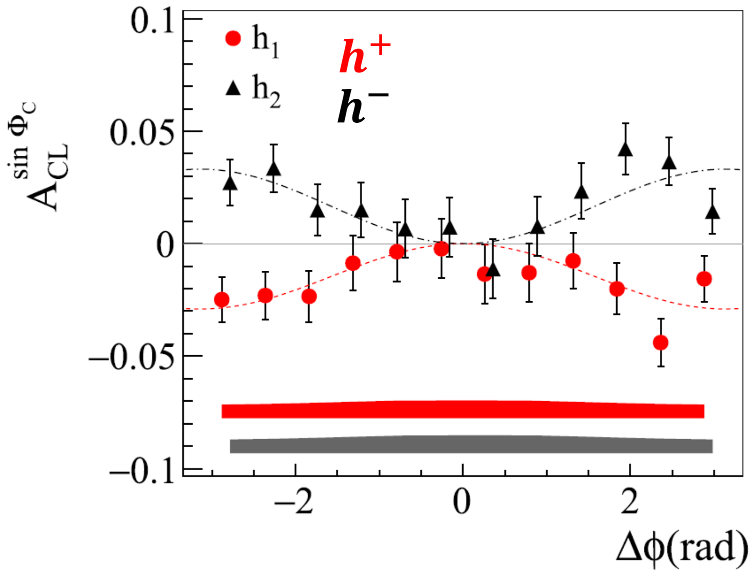

agreement with data if $a_1 = -a_2 = a$

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

ratio of the $\Delta\phi$ integrated 2h and 1h asymmetries: 4/π
slightly larger than h+

interplay among dihadron and single hadron asymmetries

PLB 753 (2016) 406

analitically

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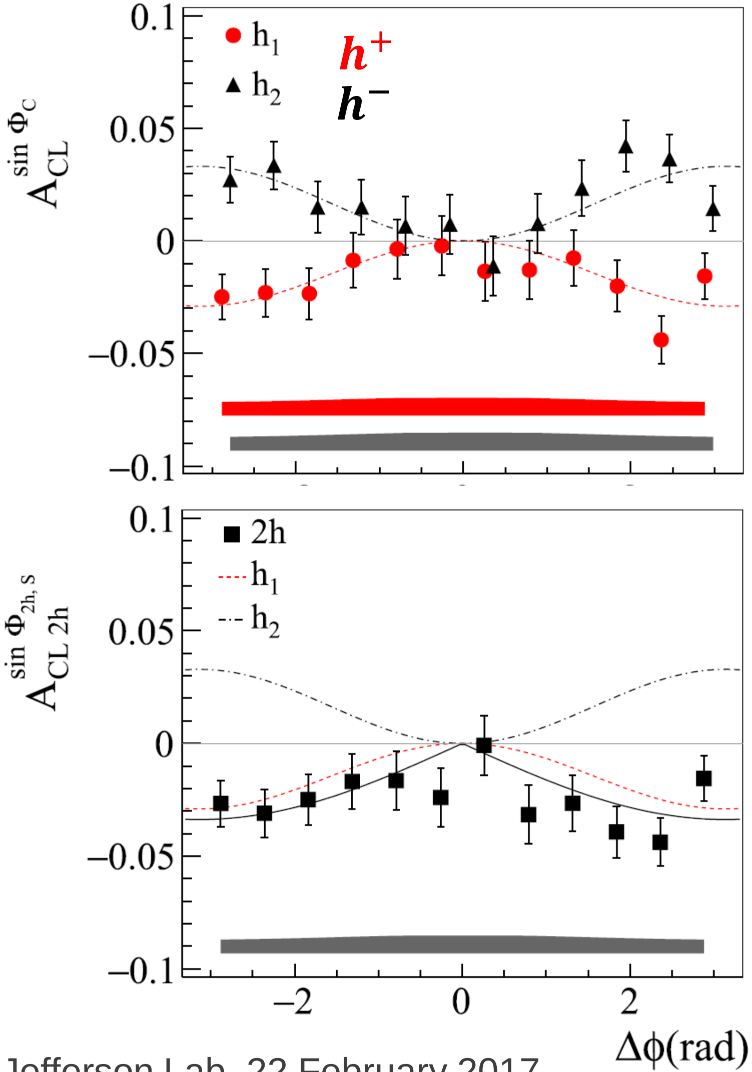


agreement with data if $a_1 = -a_2 = a$

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

agreement with data

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

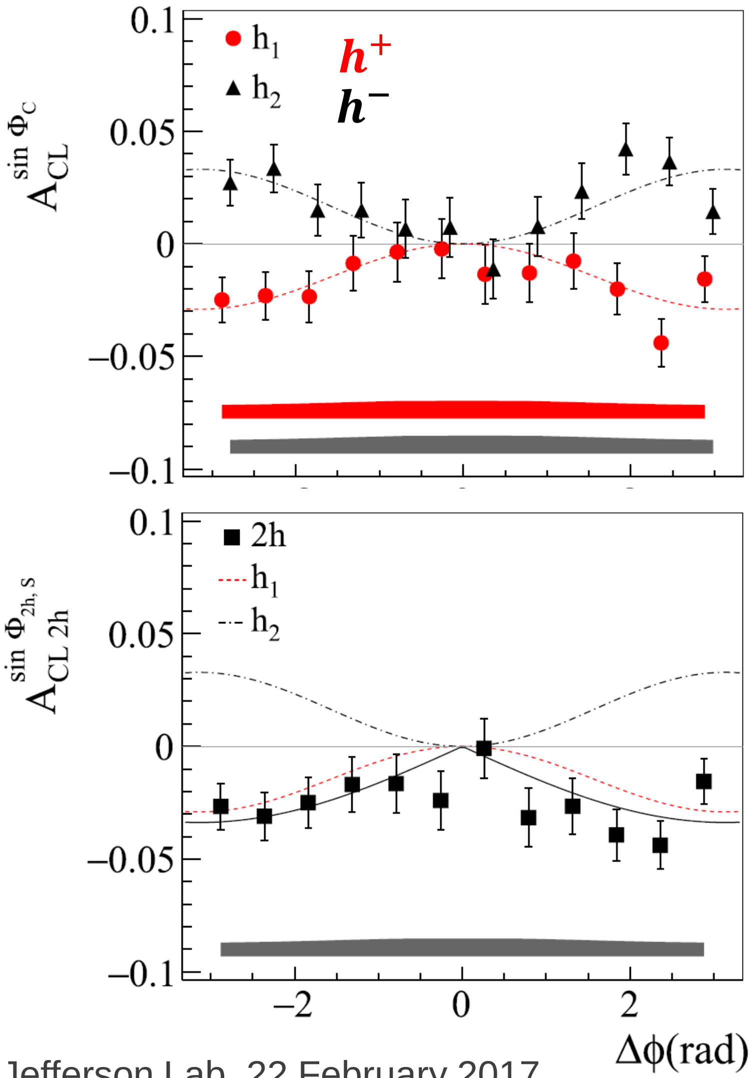
they are driven by the same elementary mechanism.

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

slightly larger than h^+

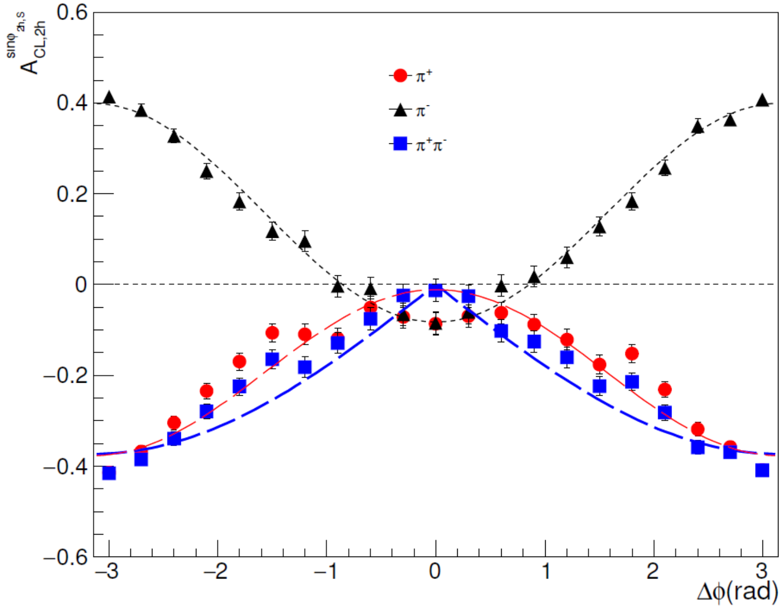
interplay among dihadron and single hadron asymmetries

new: first results from a **Monte Carlo code** for transversely polarized quark jet based on the string fragmentation and including, for the first time, the $^3P_0$ mechanism – only one free parameter for spin effects



results in good qualitative agreement with 1h and 2h asymmetries at COMPASS and Belle, and with Δϕ dependence

A. Kerbiziet al, SPIN2016

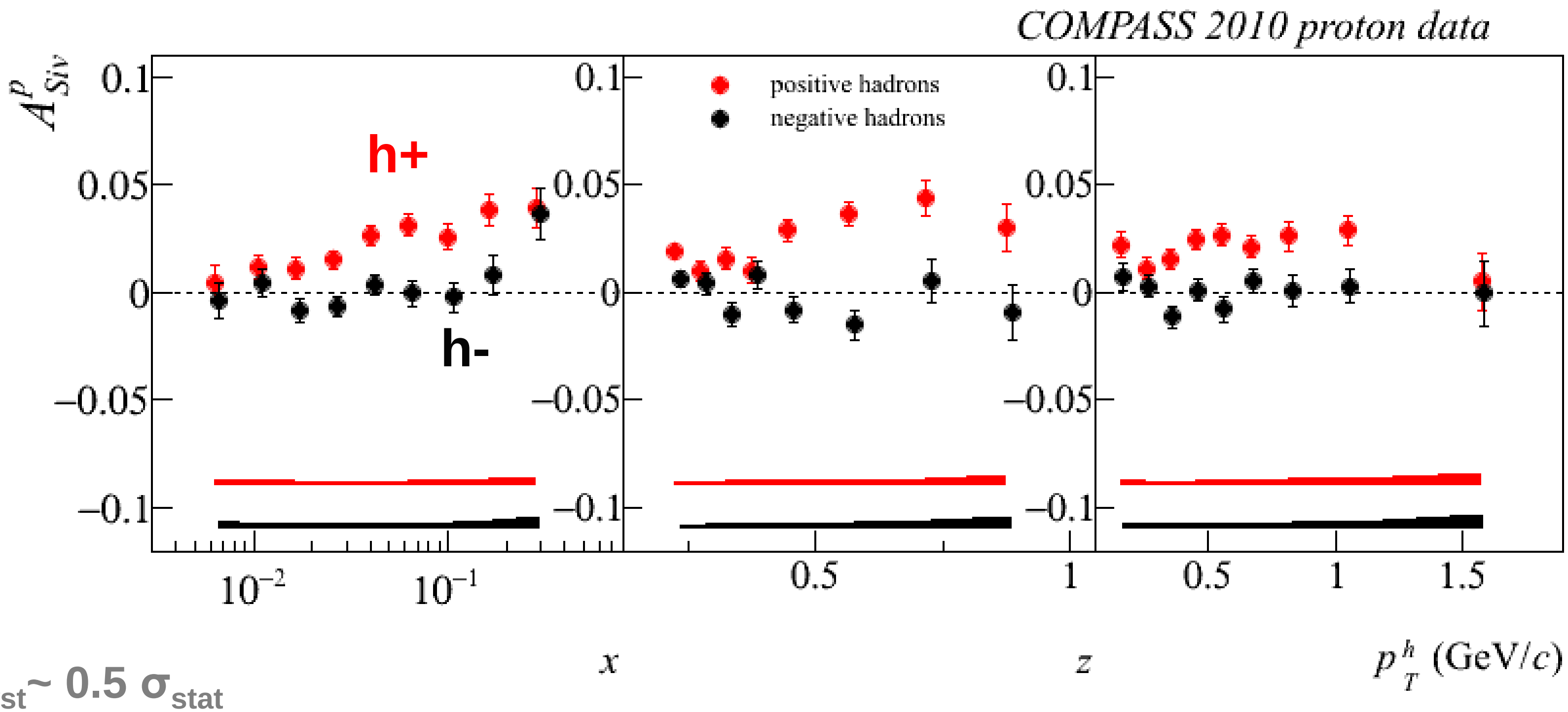


Sivers asymmetry

Sivers asymmetry on proton

charged hadrons

2010 data



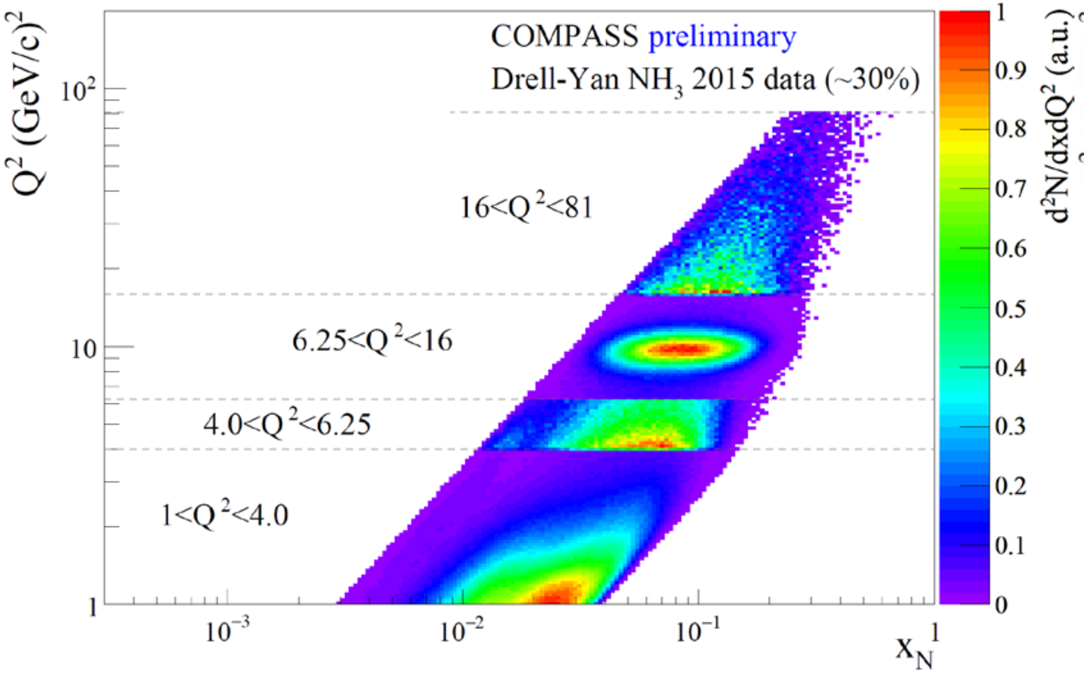
$\sigma_{syst} \sim 0.5\ \sigma_{stat}$

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

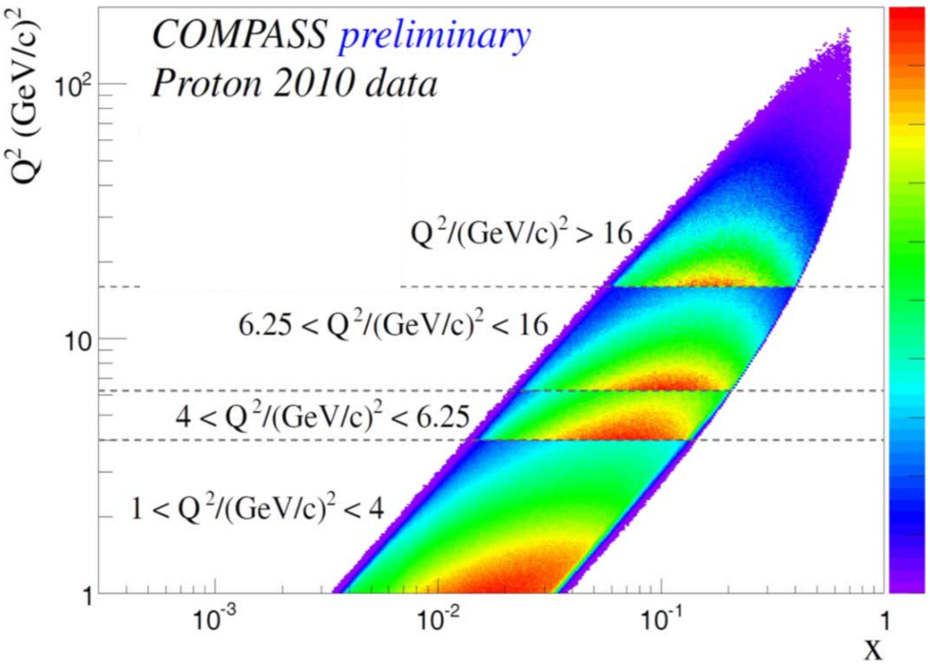
Sivers asymmetry on proton

COMPASS has measured the TSA in the 4 Q^2 ranges of the Drell-Yan experiment

Drell-Yan
190 GeV pion beam



SIDIS
160 muon beam



Sivers asymmetry on proton

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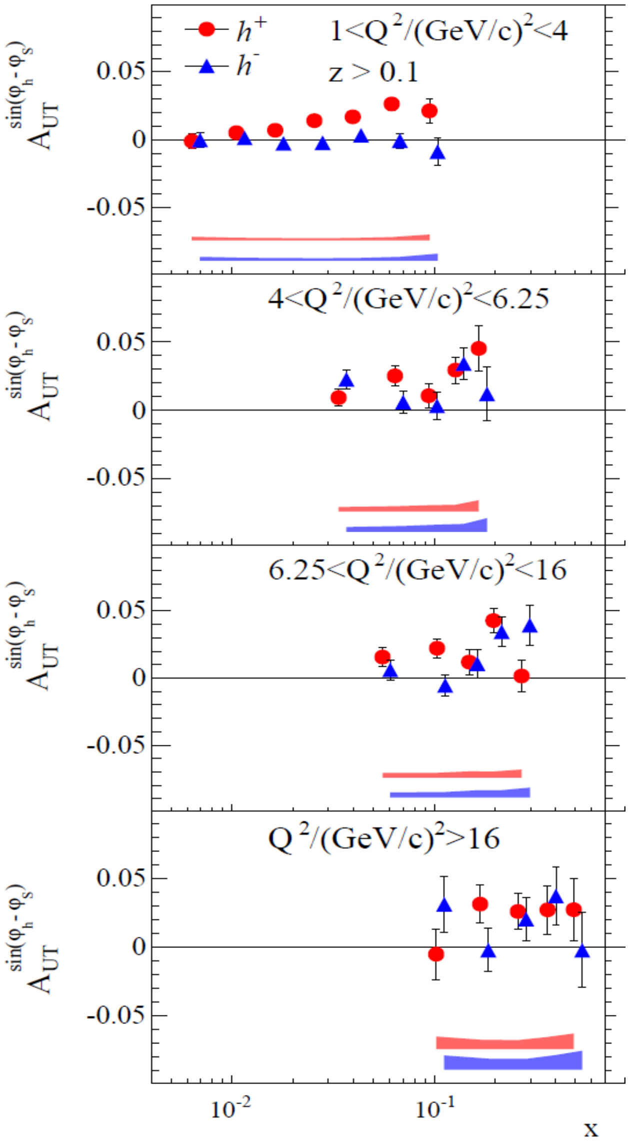
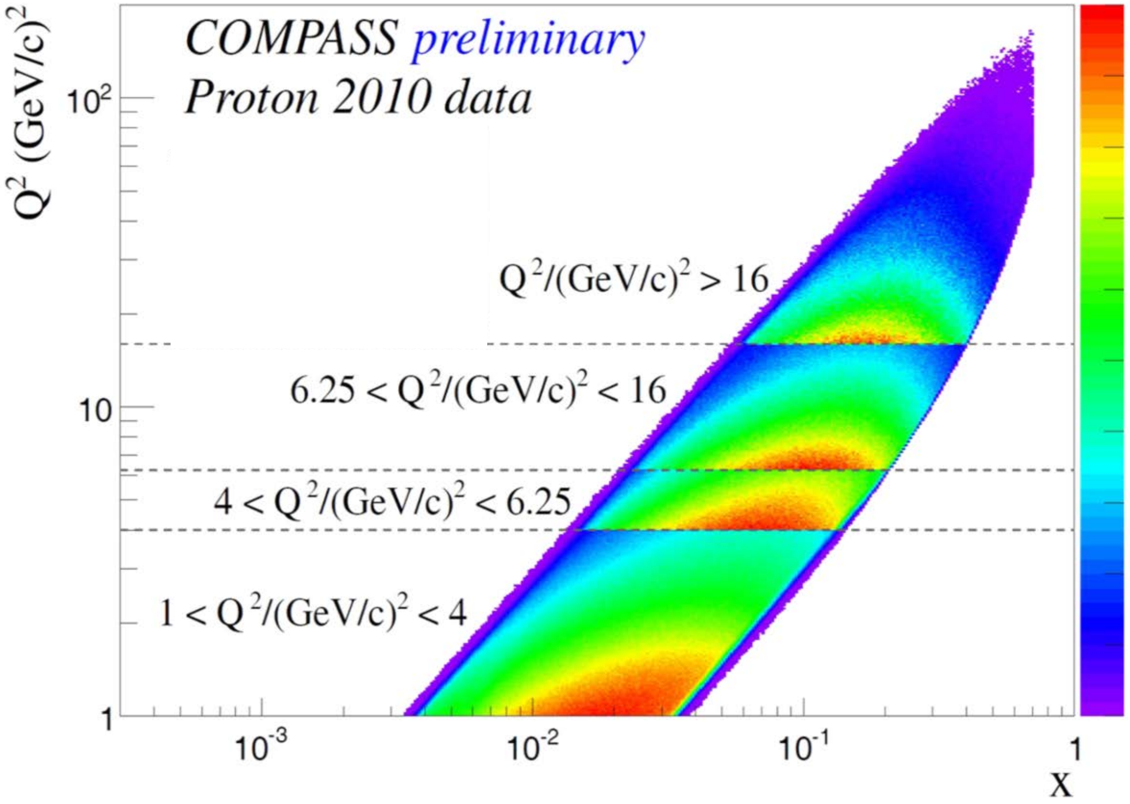




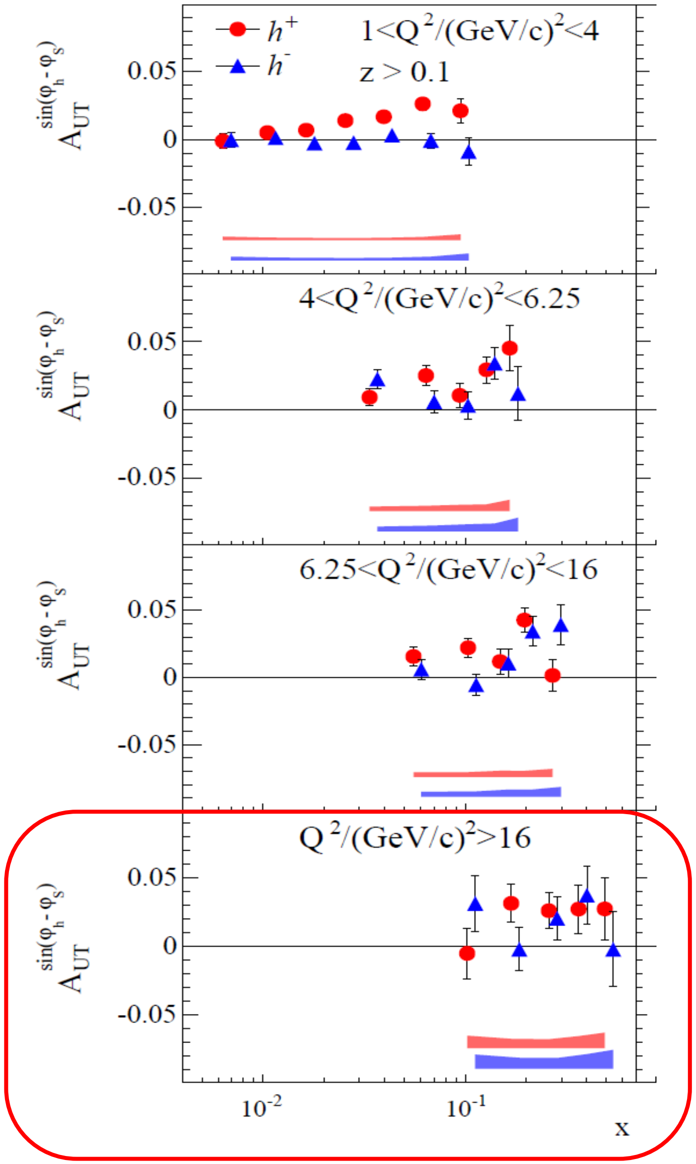
Transversity 2014

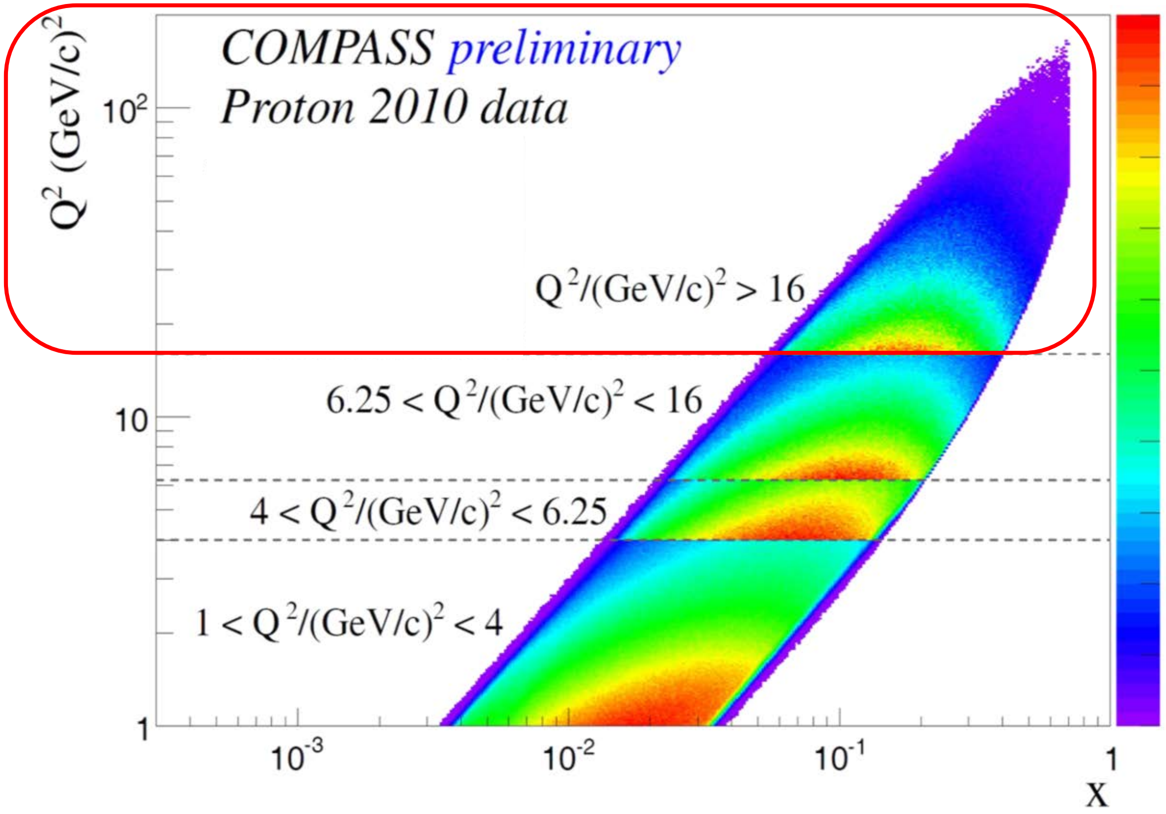
hep-ex/1609.07374, PLB

Sivers asymmetry on proton

COMPASS has measured the TSA in the 4 Q^2 ranges of the Drell-Yan experiment

“golden” region: Q^2 >16 GeV^2





clearly positive
test of change of sign feasible

F. Bradamante

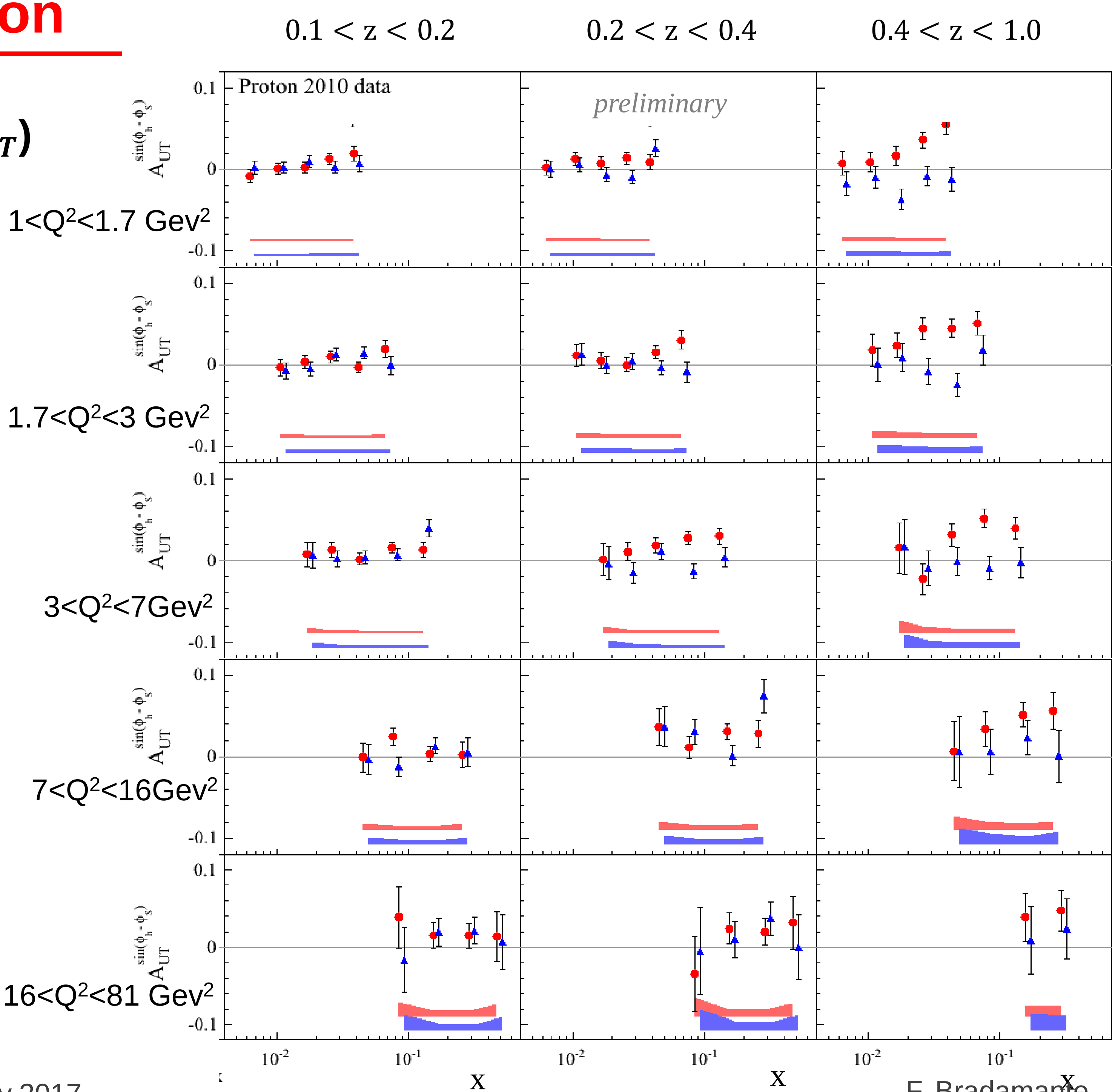
TSA on proton

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

an example:
Sivers
asymmetry

$P_T > 0.1$ GeV/c

SPIN2014

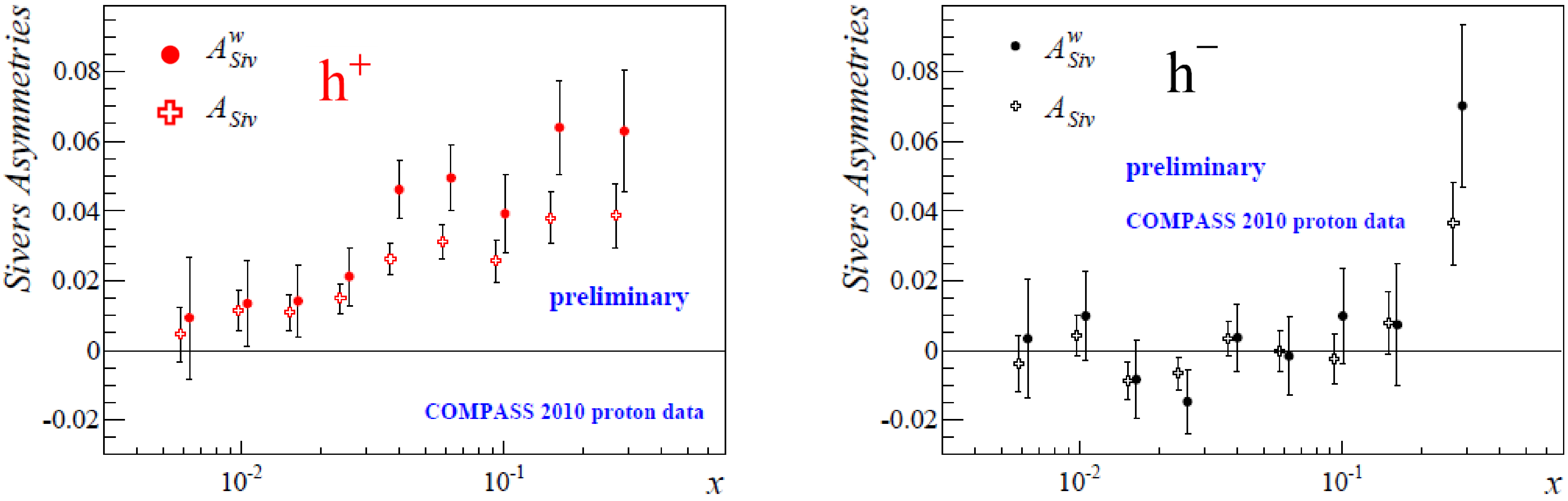


the weighted Sivers asymmetry

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

the weighted Sivers asymmetry

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

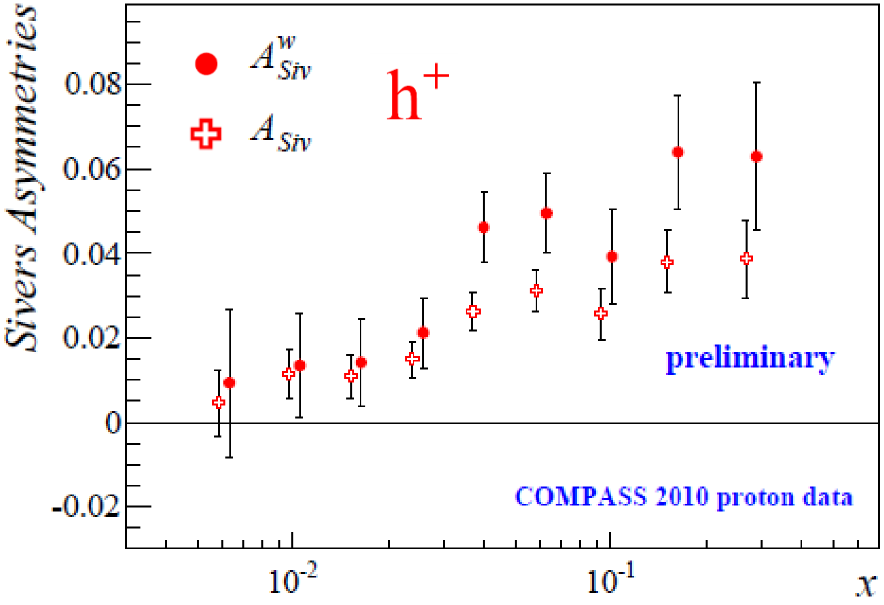


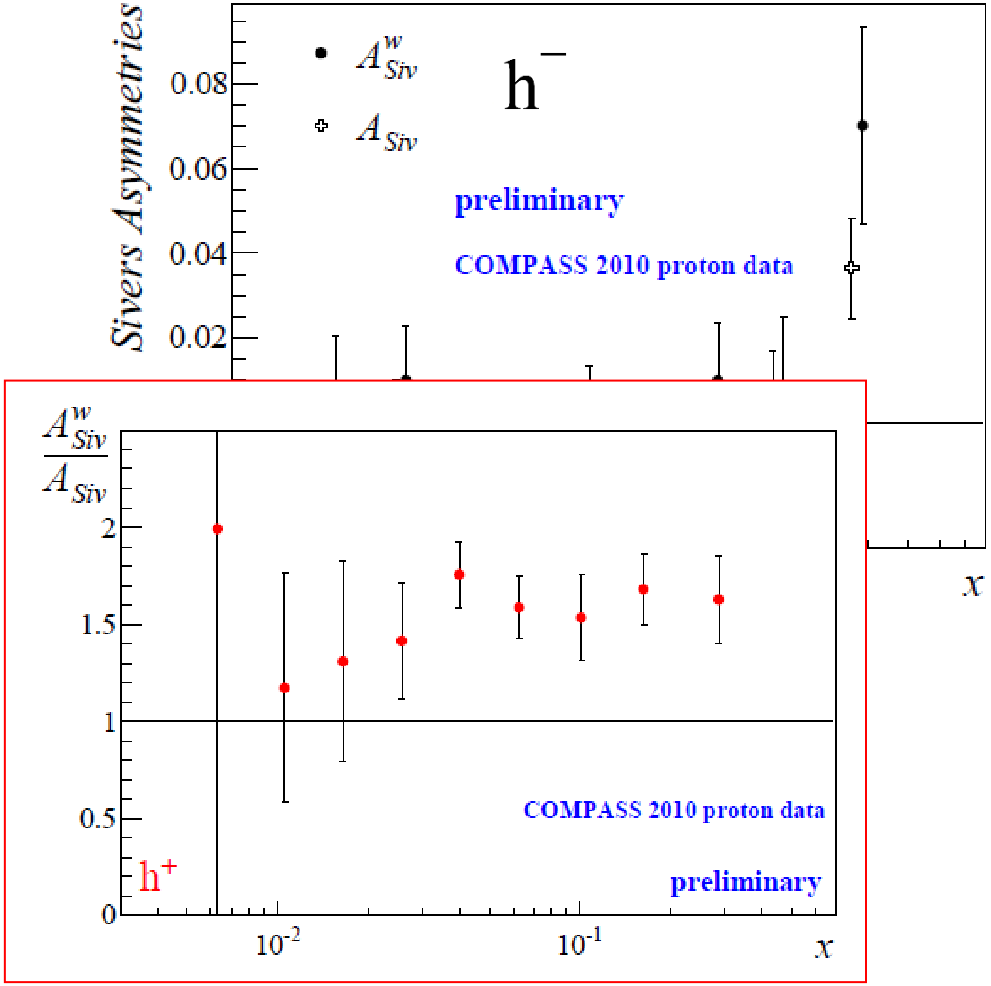
$A^w_{Siv}(x)$ SPIN2016,arXiv:1702.00621

$A^w_{Siv}(x)$ PLB717 (2012) 383

the weighted Sivers asymmetry

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





$A_{Siv}^{w}(x)$ SPIN2016,arXiv:1702.00621
$A_{Siv}^{w}(x)$ PLB717 (2012) 383

unpolarised SIDIS

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

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

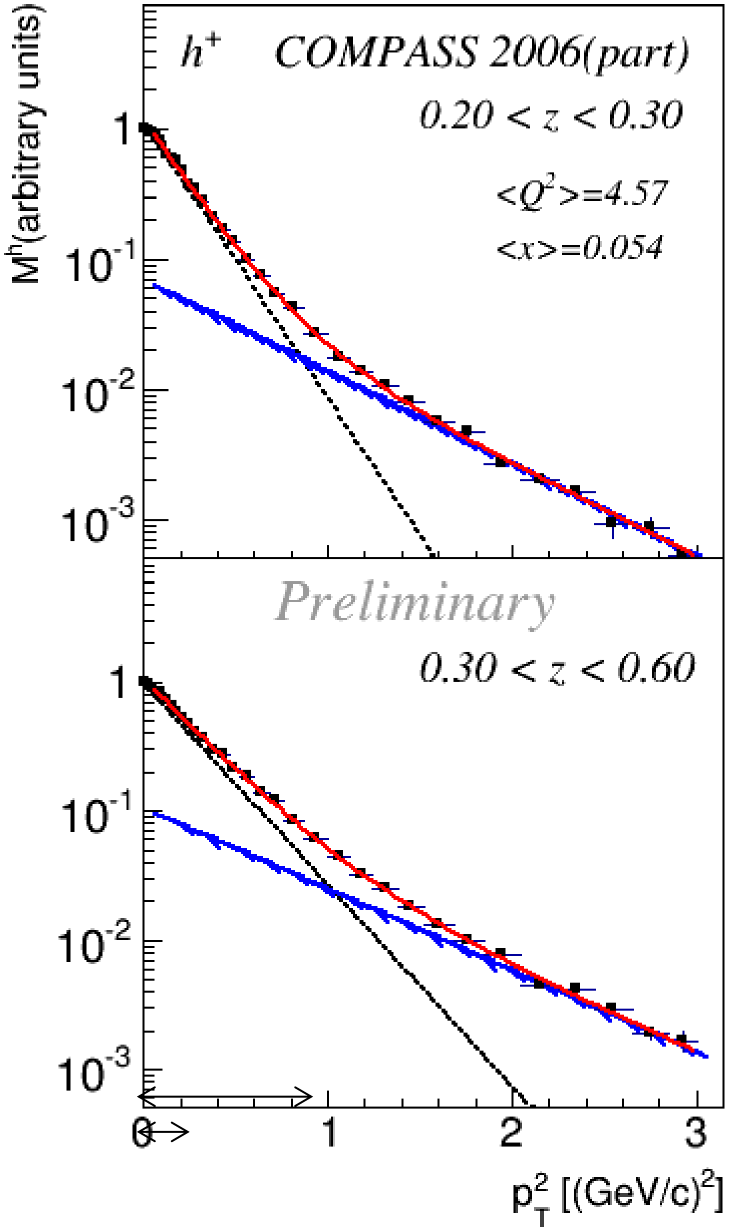
- the azimuthal modulations in the unpolarized cross-sections comes from:
    - intrinsic k_T of the quarks
    - Boer-Mulders PDF

combined analysis should allow to disentangle the different effects

COMPASS

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

unpolarised SIDIS – p_{Th} distributions



Transversity 2014

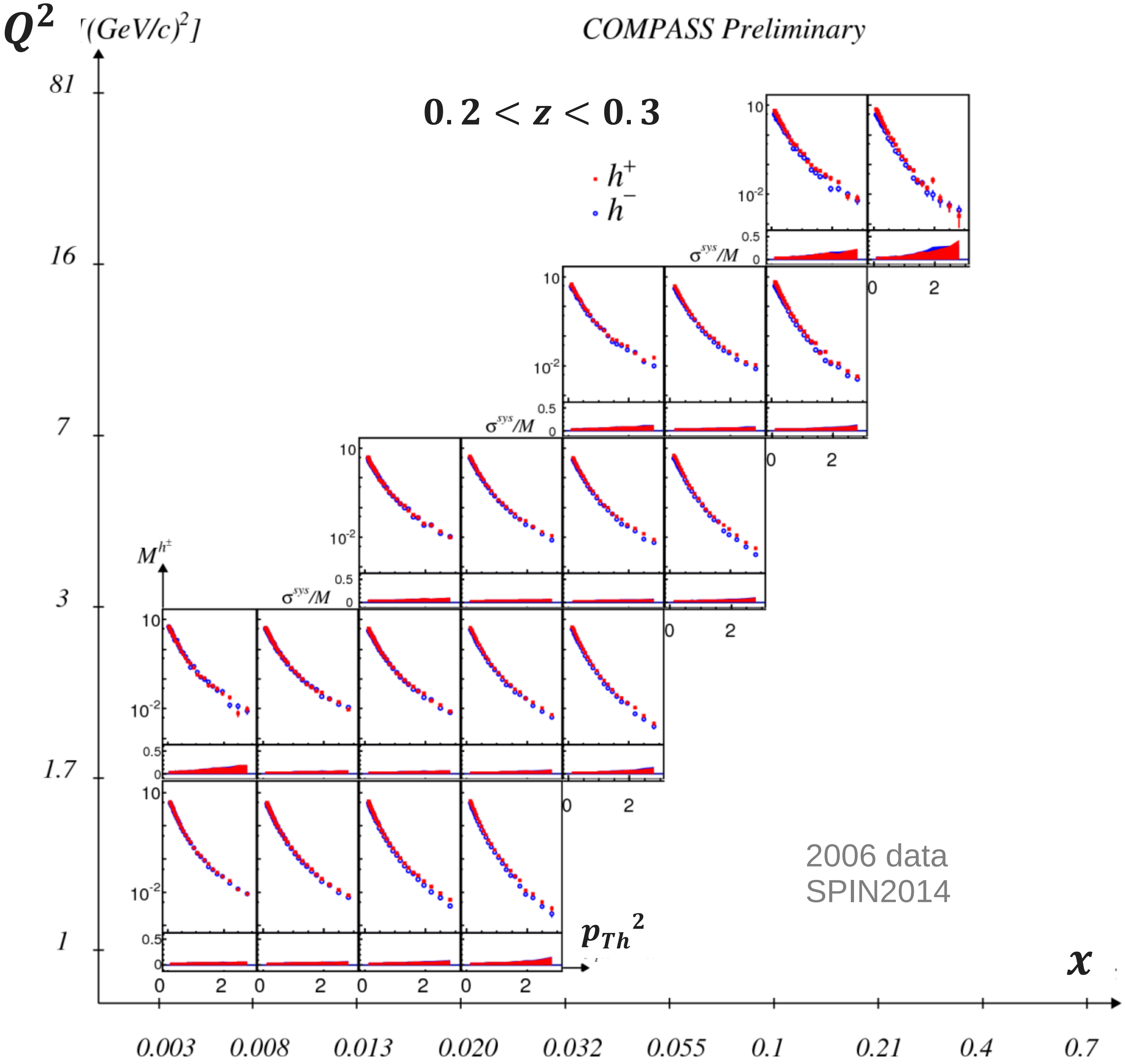
Fit distributions with

- 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

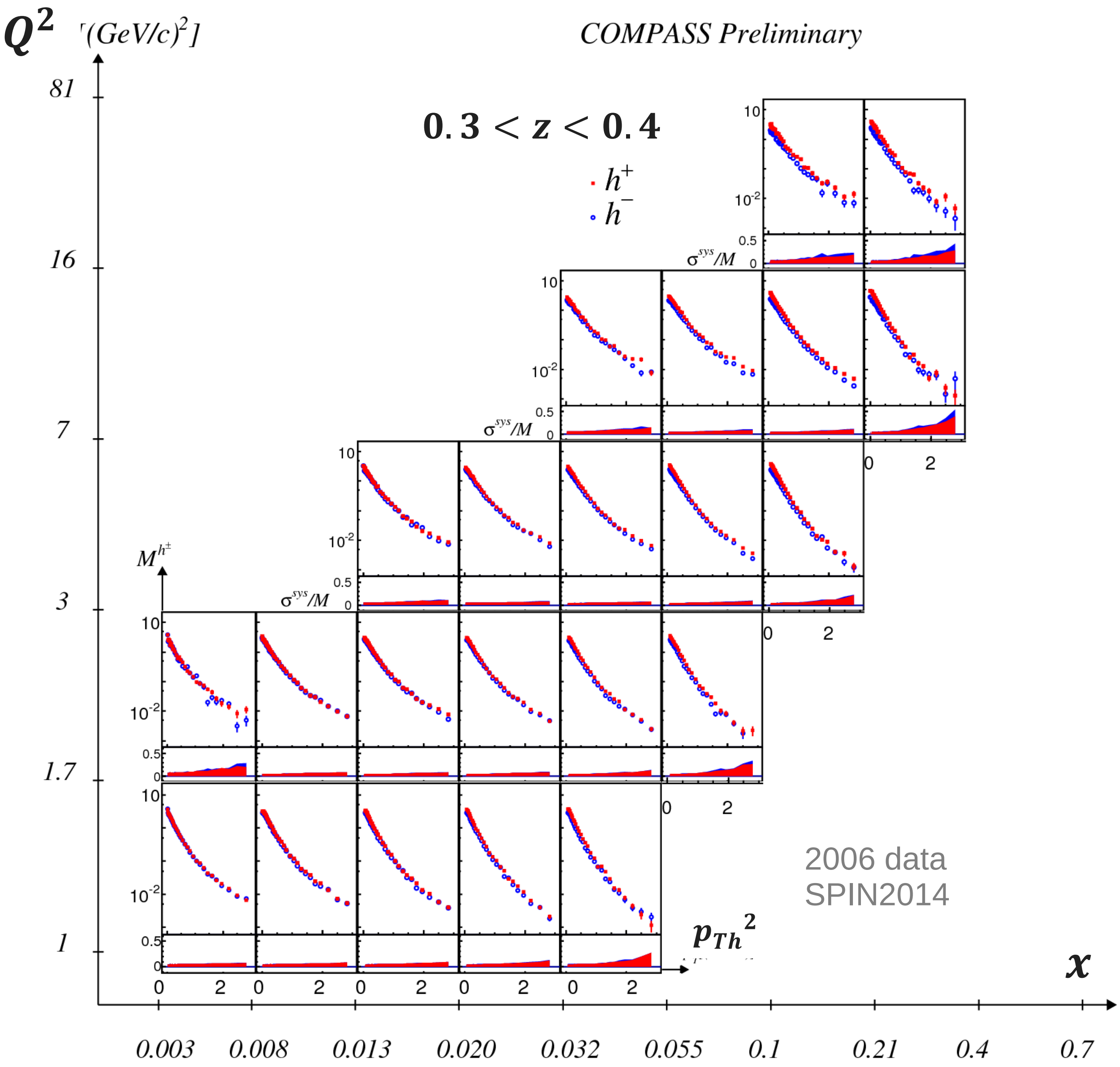
unpolarised SIDIS – p_{Th} distributions



2006 data
SPIN2014

F. Bradamante

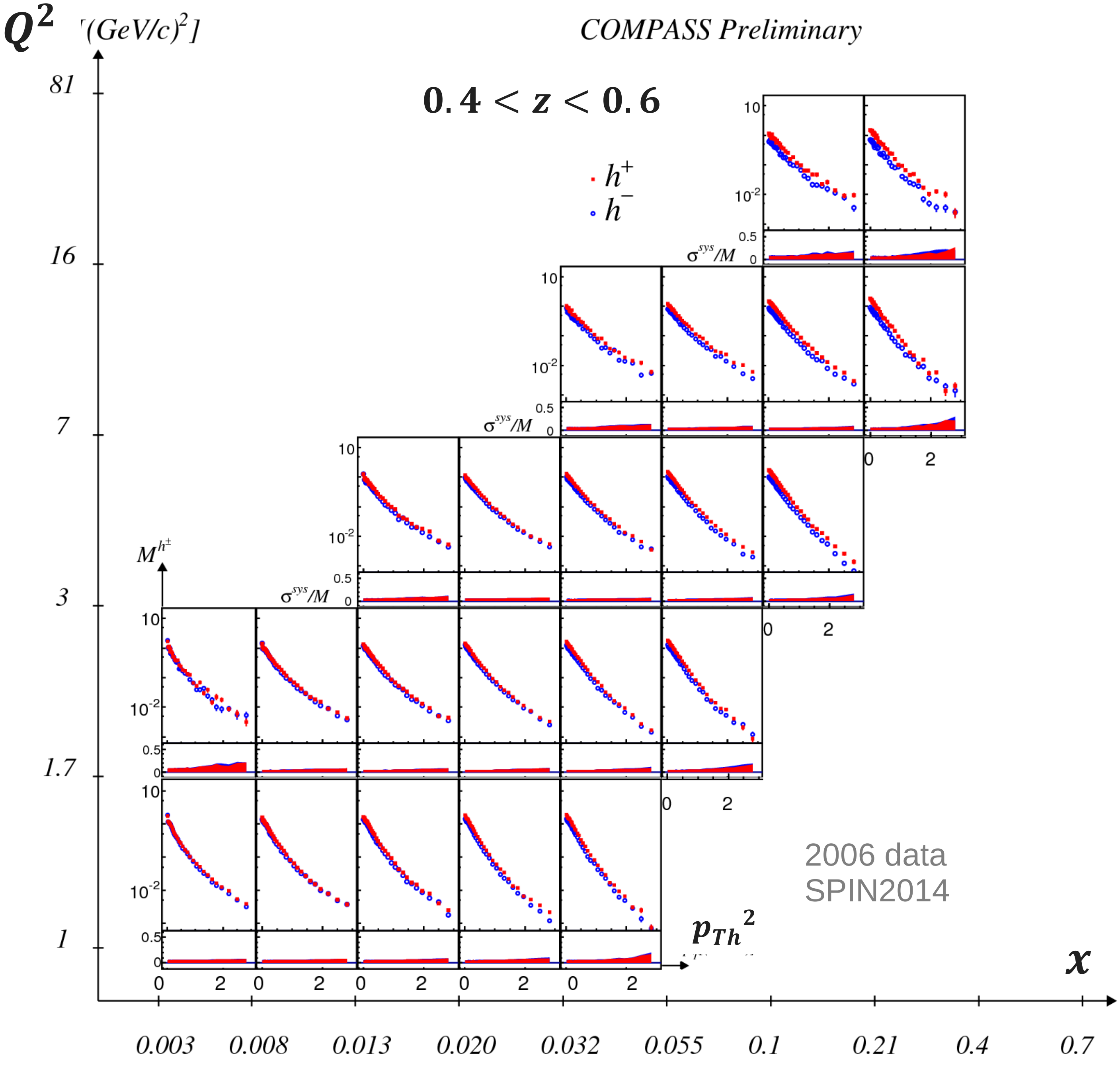
unpolarised SIDIS – p_{Th} distributions



2006 data
SPIN2014

F. Bradamante

unpolarised SIDIS – p_{Th} distributions



2006 data
SPIN2014

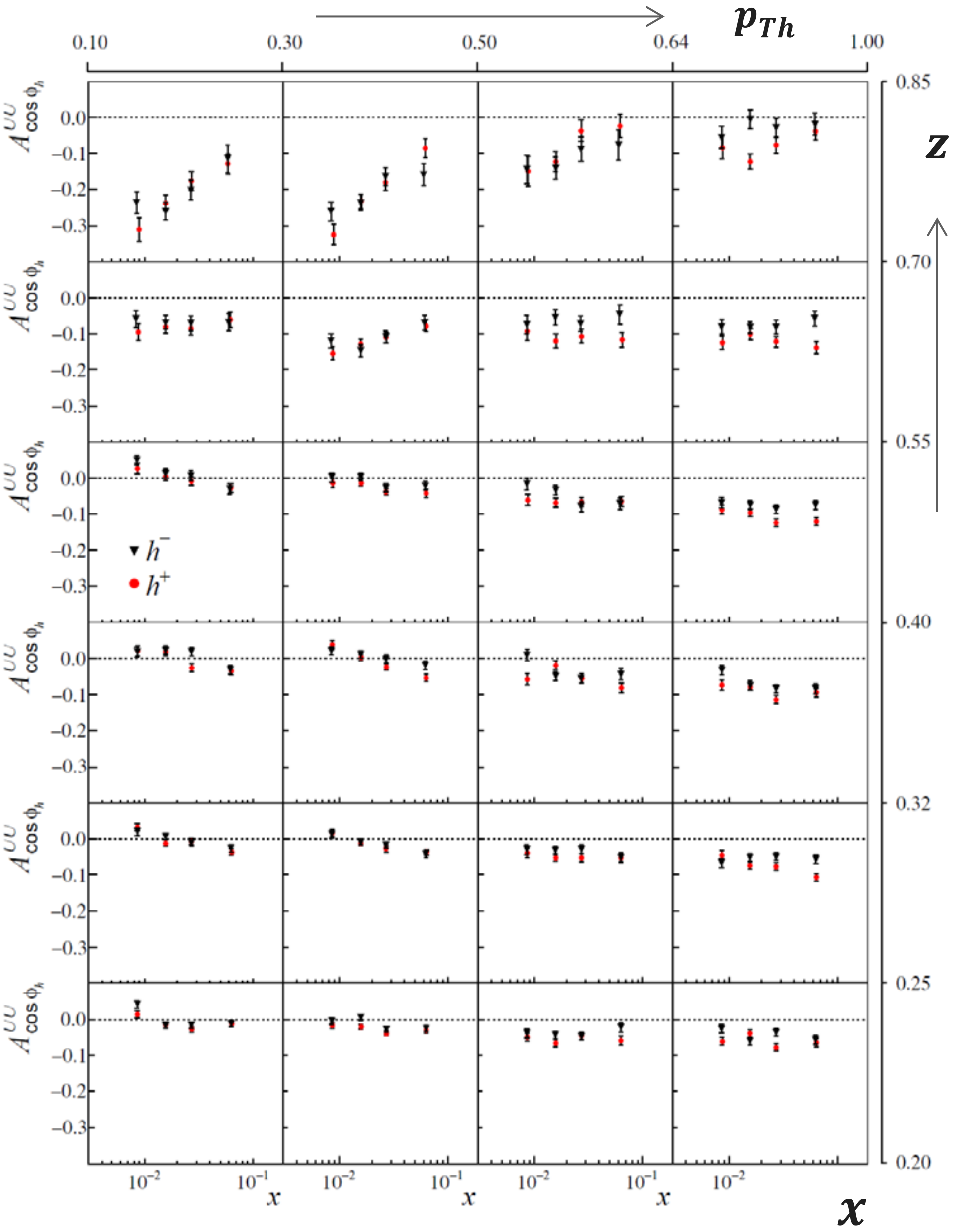
total:
4918 data points

F. Bradamante

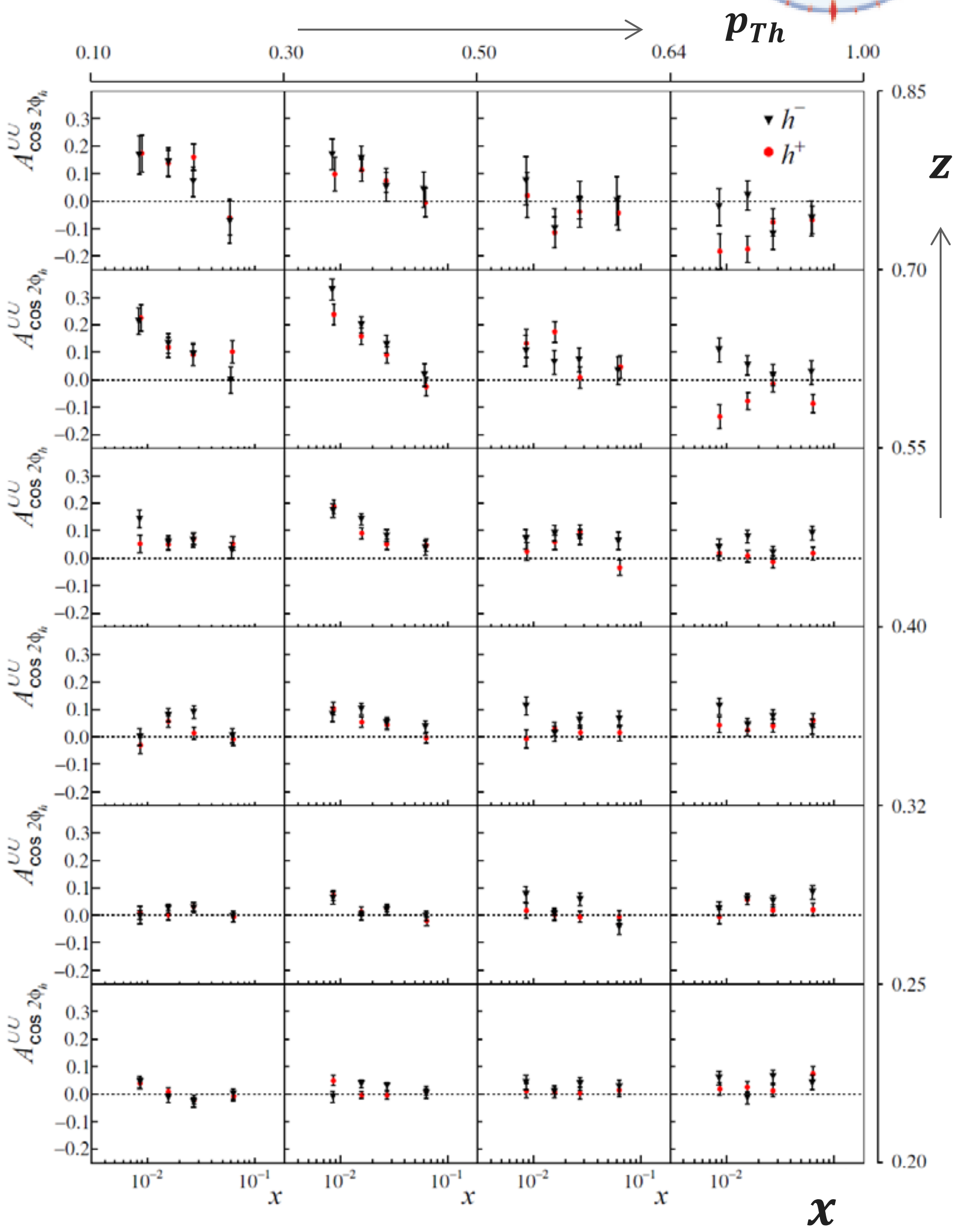
unpolarised SIDIS - azimuthal modulations

COMPASS

$\cos\phi_h$



$\cos 2\phi_h$



NPB 886 (2014) 1046

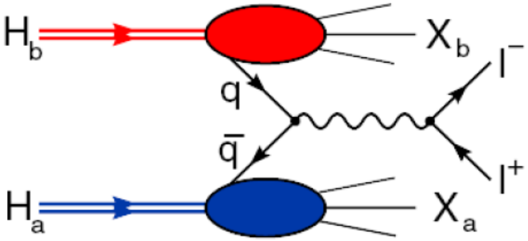
Drell-Yan at COMPASS

DRELL-YAN PROCESS

COMPLEMENTARY APPROACH TO SIDIS

COMPASS is measuring for the FIRST TIME

the Drell-Yan process $\pi^- p \to \mu^+ \mu^- X$
on a transversely polarized proton target



Single-polarised DY cross-section

LO QCD parton model: general expression of the DY cross-section

$$\begin{aligned}
\frac{d\sigma^{LO}}{d^4q\,d\Omega} &= \frac{\alpha_{em}^2}{F\,q^2}\hat{\sigma}_U^{LO}\Big\{\Big(1+D^{LO}_{[\sin^2\theta]}\,A_U^{\cos 2\phi}\cos 2\phi\Big) \\
&+ S_L D^{LO}_{[\sin^2\theta]}\,A_L^{\sin 2\phi}\sin 2\phi \\
&+ |\vec{S}_T|\Big[A_T^{\sin\phi_S}\sin\phi_S + D^{LO}_{[\sin^2\theta]}\Big(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S) \\
&+ A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\Big)\Big]\Big\}\,,
\end{aligned}$$

Single-polarised DY cross-section

LO QCD parton model: general expression of the DY cross-section

$h_1^\perp$ Boer-Mulders of the π

$h_1^\perp$ **Boer-Mulders of the p**

$$\frac{d\sigma^{LO}}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{F\,q^2}\hat{\sigma}_U^{LO}\Big\{\Big(1 + D^{LO}_{[\sin^2\theta]}\,A_U^{\cos 2\phi}\cos 2\phi\Big)$$

$$+ \quad S_L D^{LO}_{[\sin^2\theta]}\,A_L^{\sin 2\phi}\sin 2\phi$$

$$+ \quad |\vec{S}_T|\Big[A_T^{\sin\phi_S}\sin\phi_S + D^{LO}_{[\sin^2\theta]}\Big(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)$$

$$+ \quad A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\Big)\Big]\Big\}\,,$$

f_1 of the π

$f_{1T}^\perp$ **Sivers of the p**

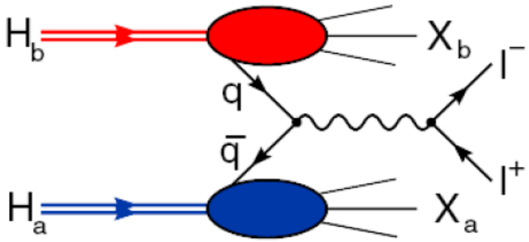
$h_1^\perp$ Boer-Mulders of the π

h_1 **transversity of the p**

$h_1^\perp$ Boer-Mulders of the π

$h_{1T}^\perp$ **pretzelosity of the p**

Drell-Yan

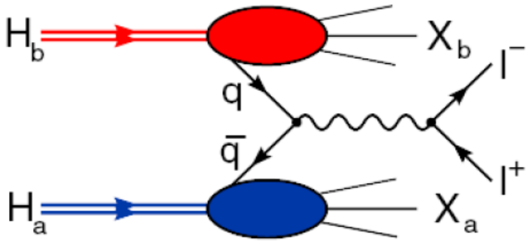


2015 run:

190 GeV π^- beam

transversely polarised proton (NH3) target

Drell-Yan



2015 run:

190 GeV π^- beam

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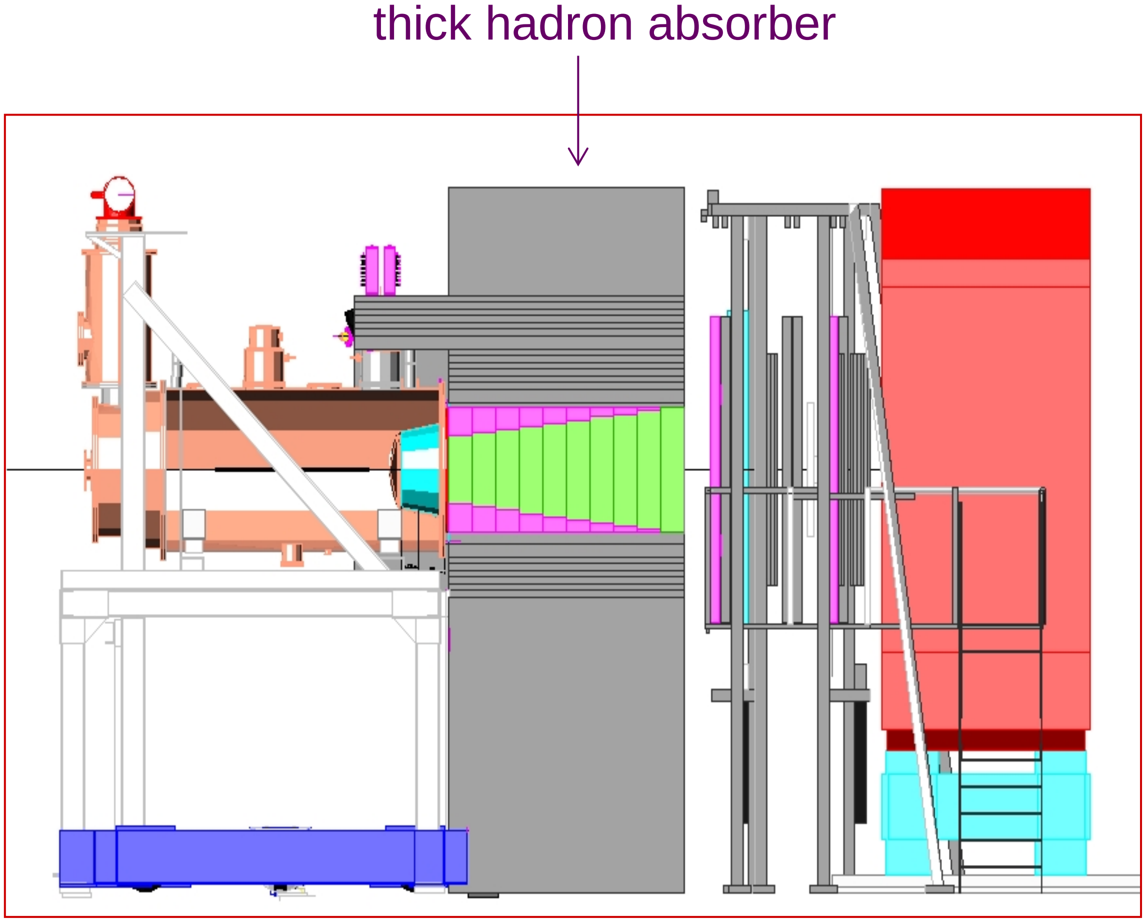
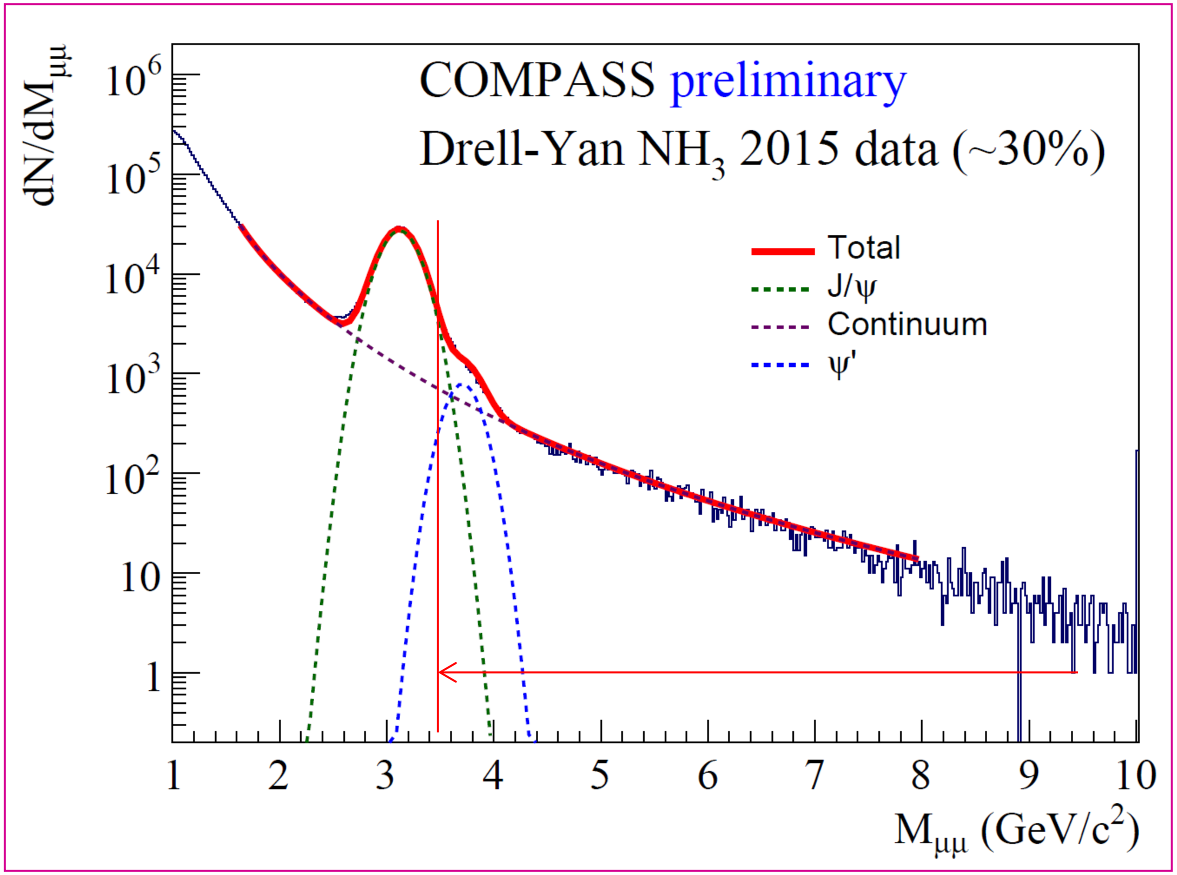


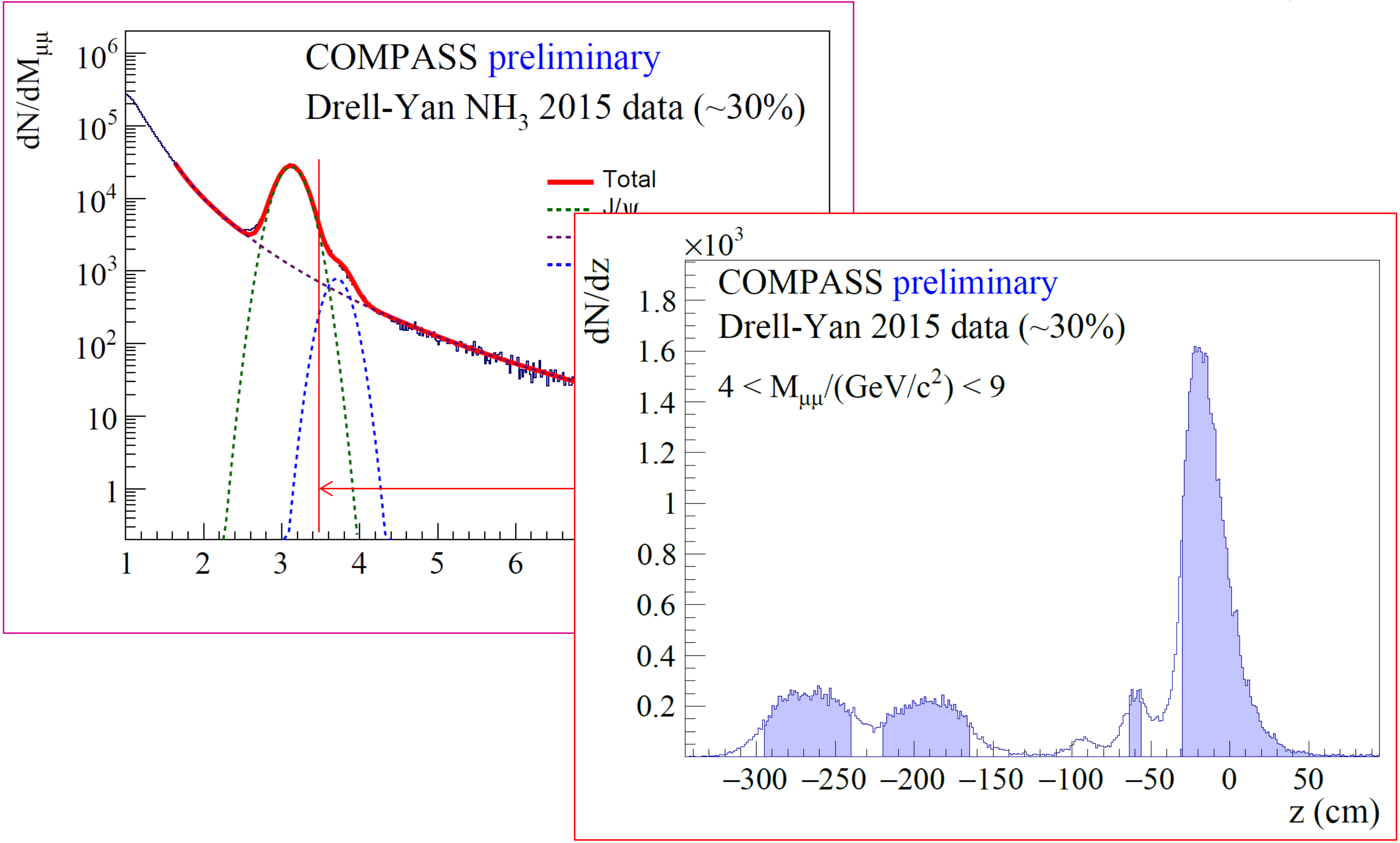
Drell-Yan

190 GeV π^- beam, transversely polarised proton (NH3) target



Drell-Yan

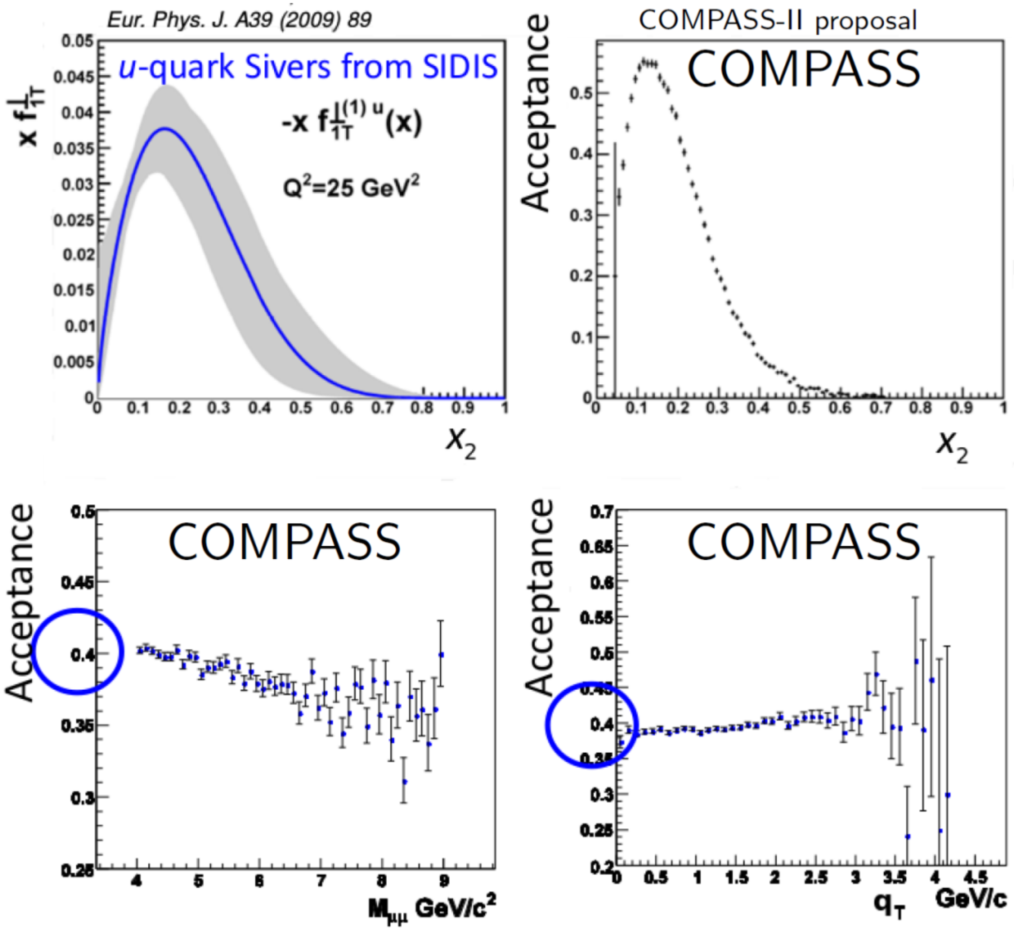
190 GeV π^- beam, transversely polarised proton (NH3) target



Drell-Yan

190 GeV π^- beam, transversely polarised proton (NH3) target

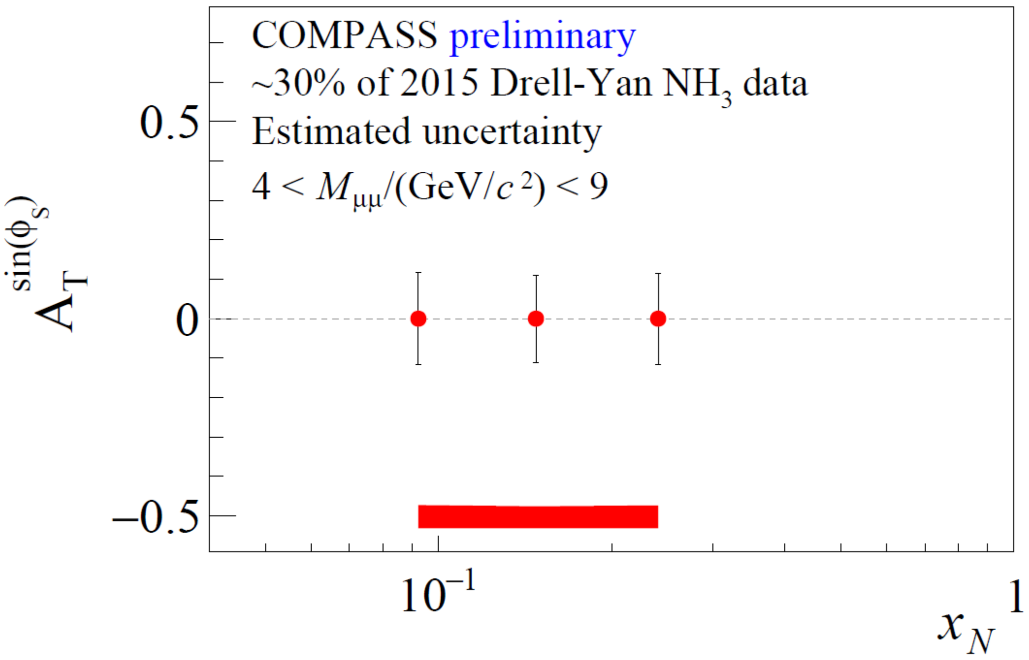
- COMPASS acceptance high where $f_{1T}^{\perp}$ is expected to be large
- High acceptance: 40% to be compared to previous experiments $\leqslant$ 10% (*e.g.* NA10, NA50 at CERN, E615 at FNAL)
- Acceptance flat in q_T



Drell-Yan

190 GeV π^- beam, transversely polarised proton (NH3) target

30% of 2015 data



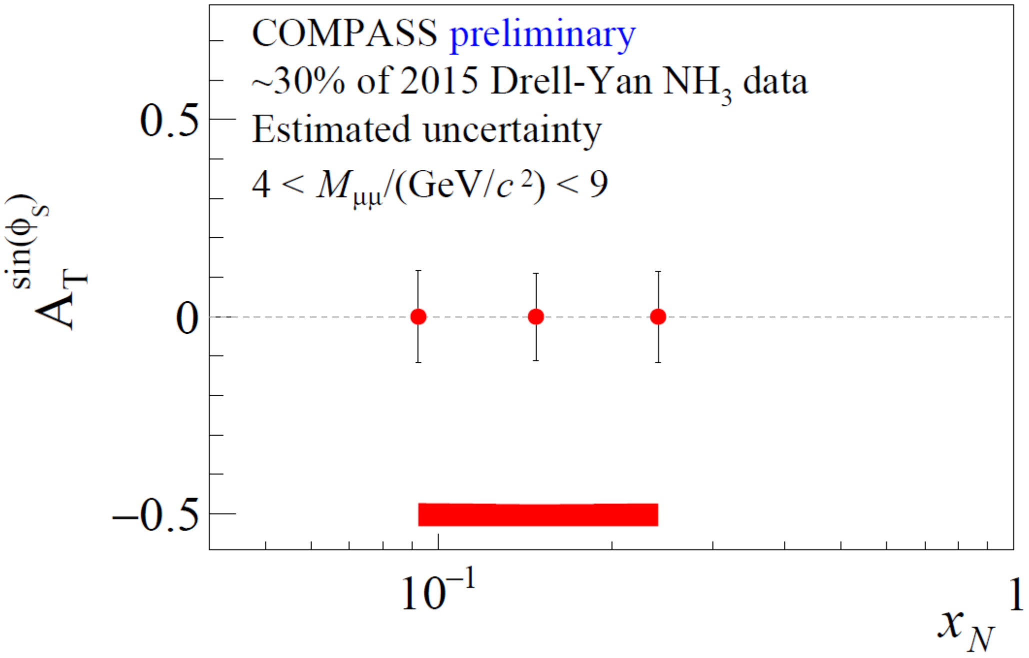
data analysis ongoing

results at DIS 2017

Drell-Yan

190 GeV π^- beam, transversely polarised proton (NH3) target

30% of 2015 data



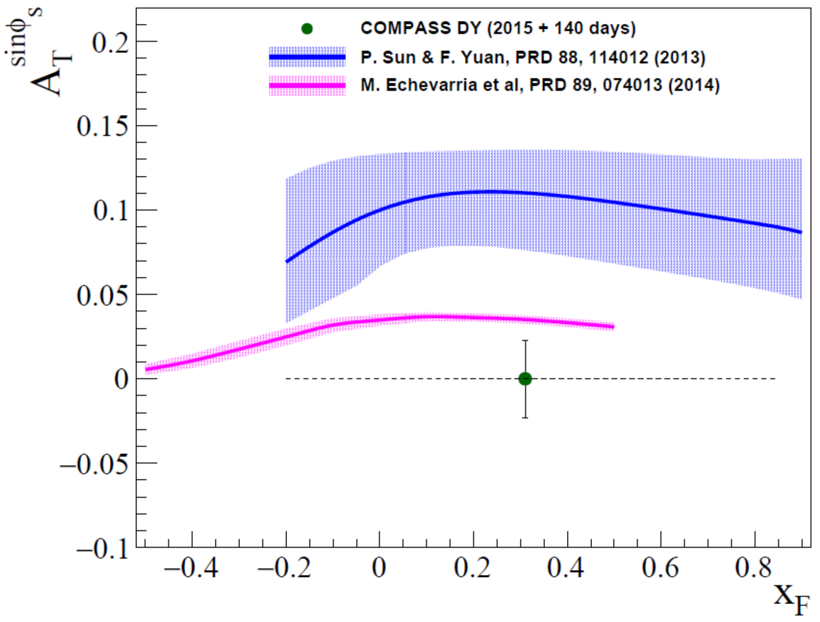
data analysis ongoing

results at DIS 2017

new run: 2018

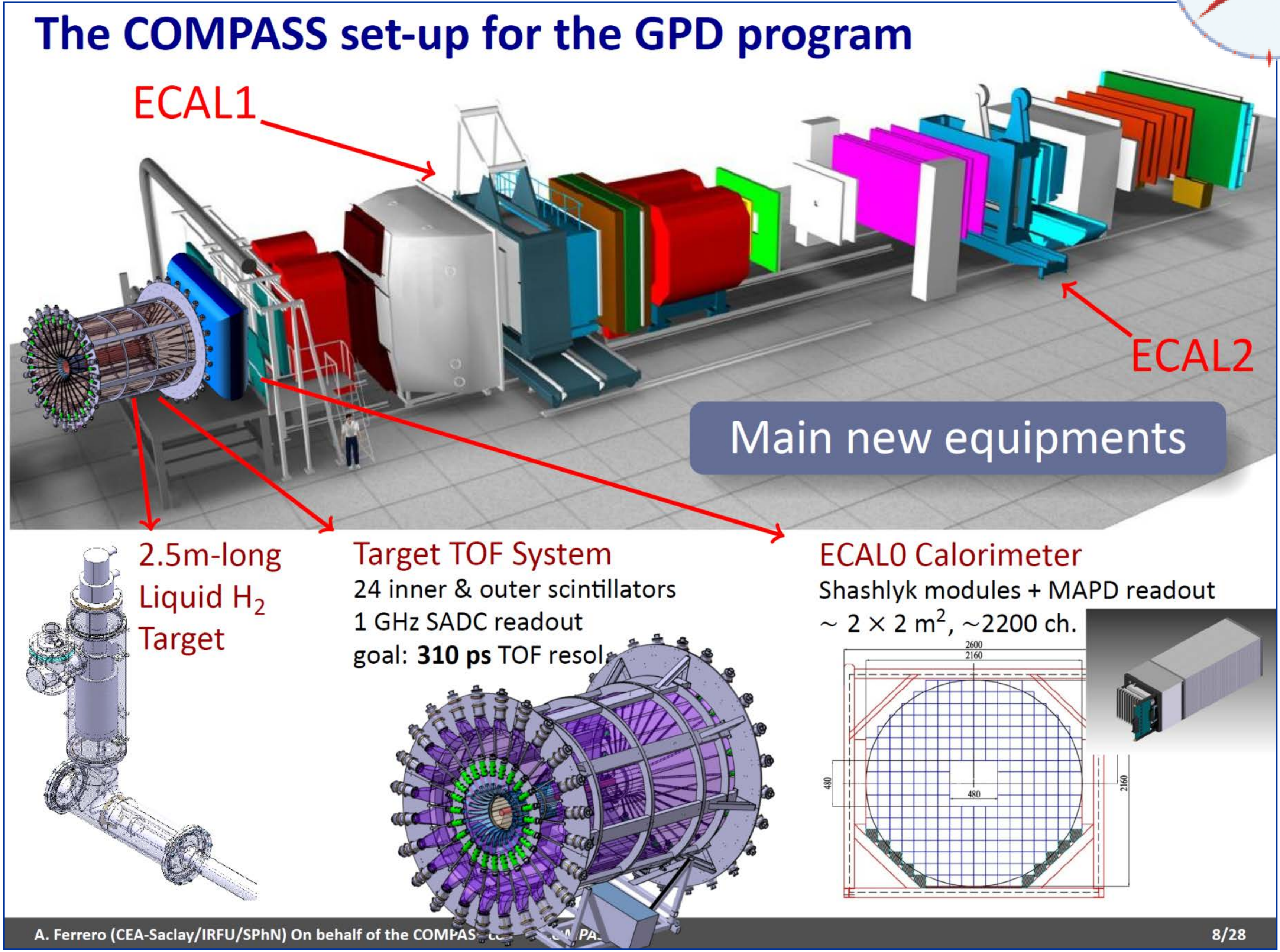
projected uncertainty

2015+2018



DVCS

DVCS



The COMPASS set-up for the GPD program

ECAL1

ECAL2

Main new equipments

2.5m-long Liquid H_2 Target

Target TOF System

24 inner & outer scintillators

1 GHz SADC readout

goal: **310 ps** TOF resol.

ECAL0 Calorimeter

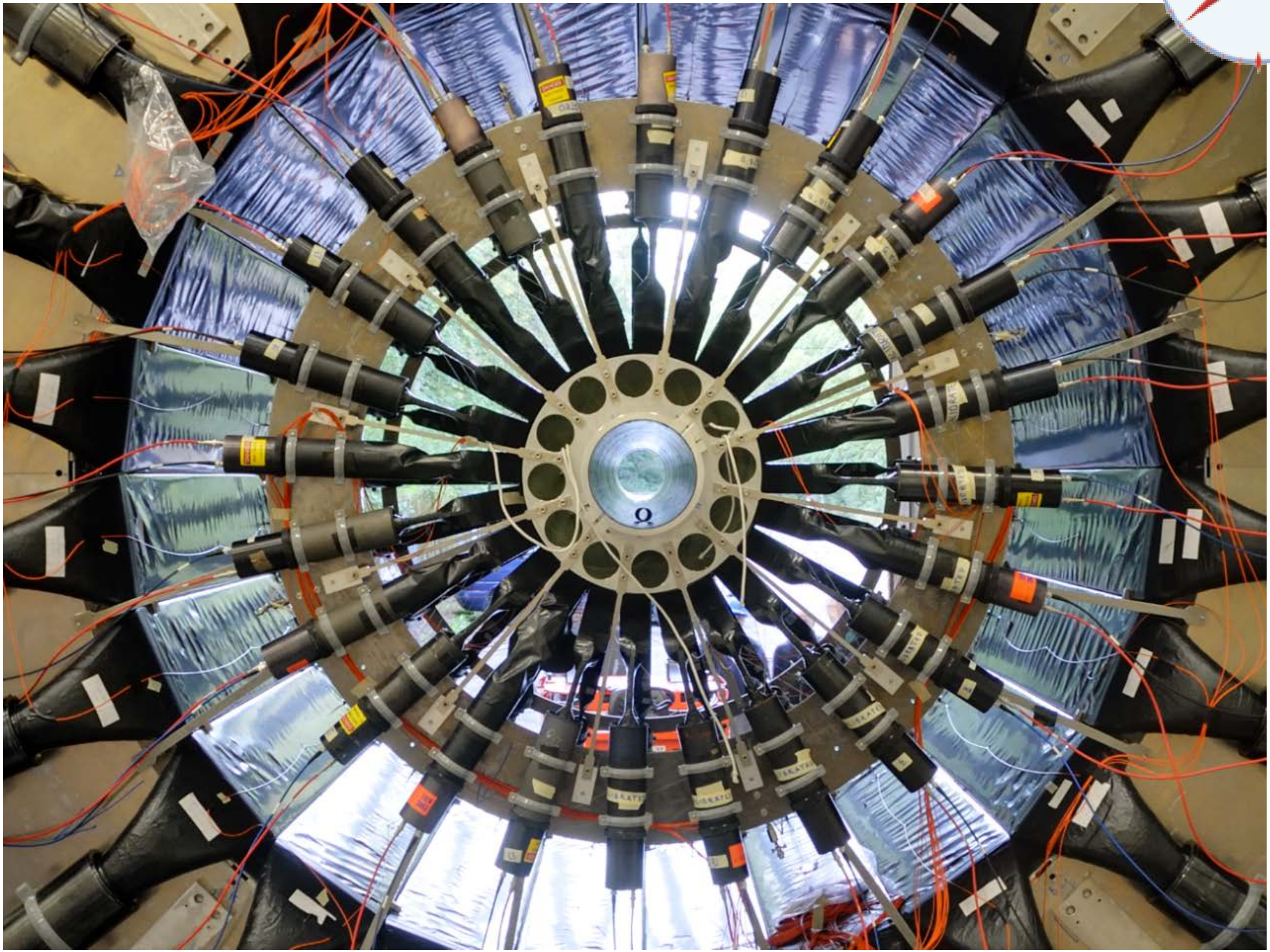
Shashlyk modules + MAPD readout

$\sim 2 \times 2$ m^2, ~2200 ch.

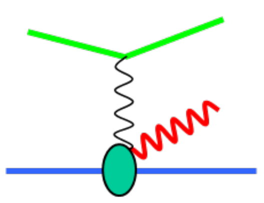
A. Ferrero (CEA-Saclay/IRFU/SPhN) On behalf of the COMPASS

8/28

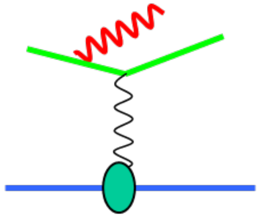
Camera detector for exclusivity



DVCS vs BH 2012 data

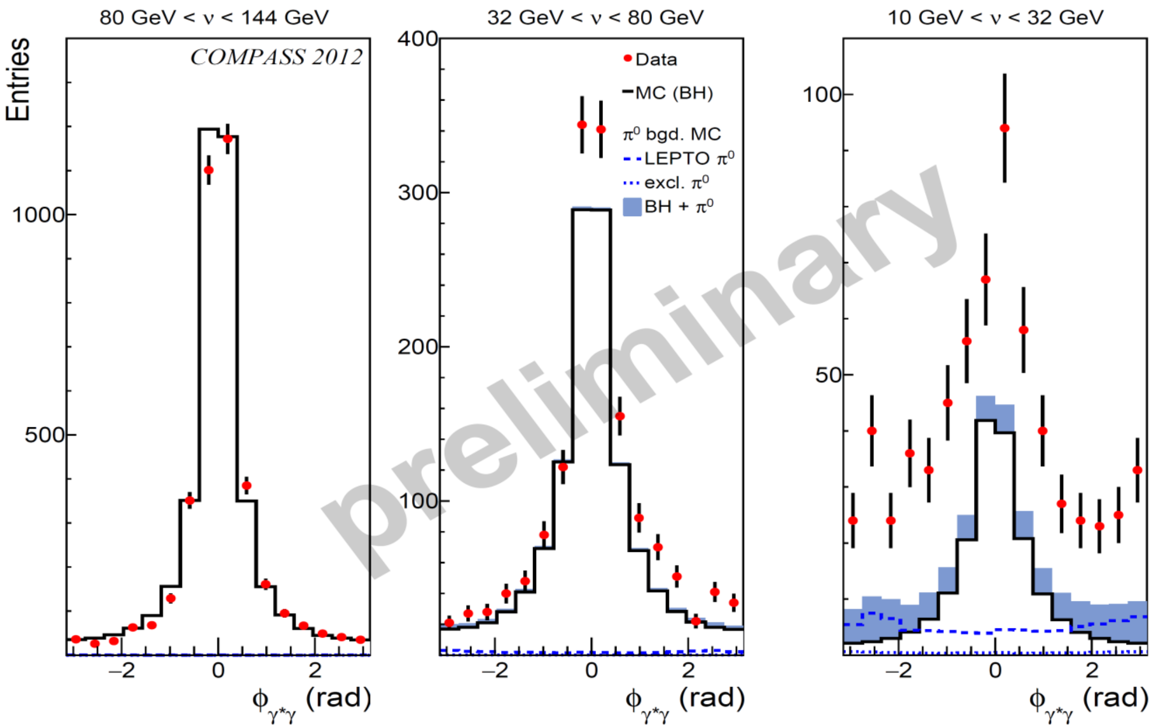


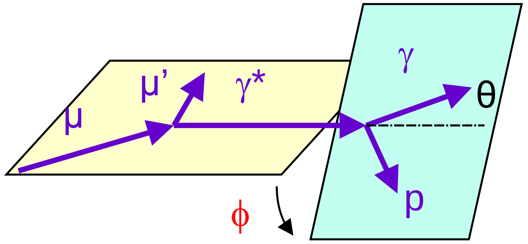
Deep VCS



Bethe-Heitler

- dominant BH process at small x_{BJ} clearly visible
- shape of ϕ distribution reproduced well by MC
- first estimates of π^0 background contributing at large x_{BJ}
- at large x_{BJ} an excess of events wrt BH + background

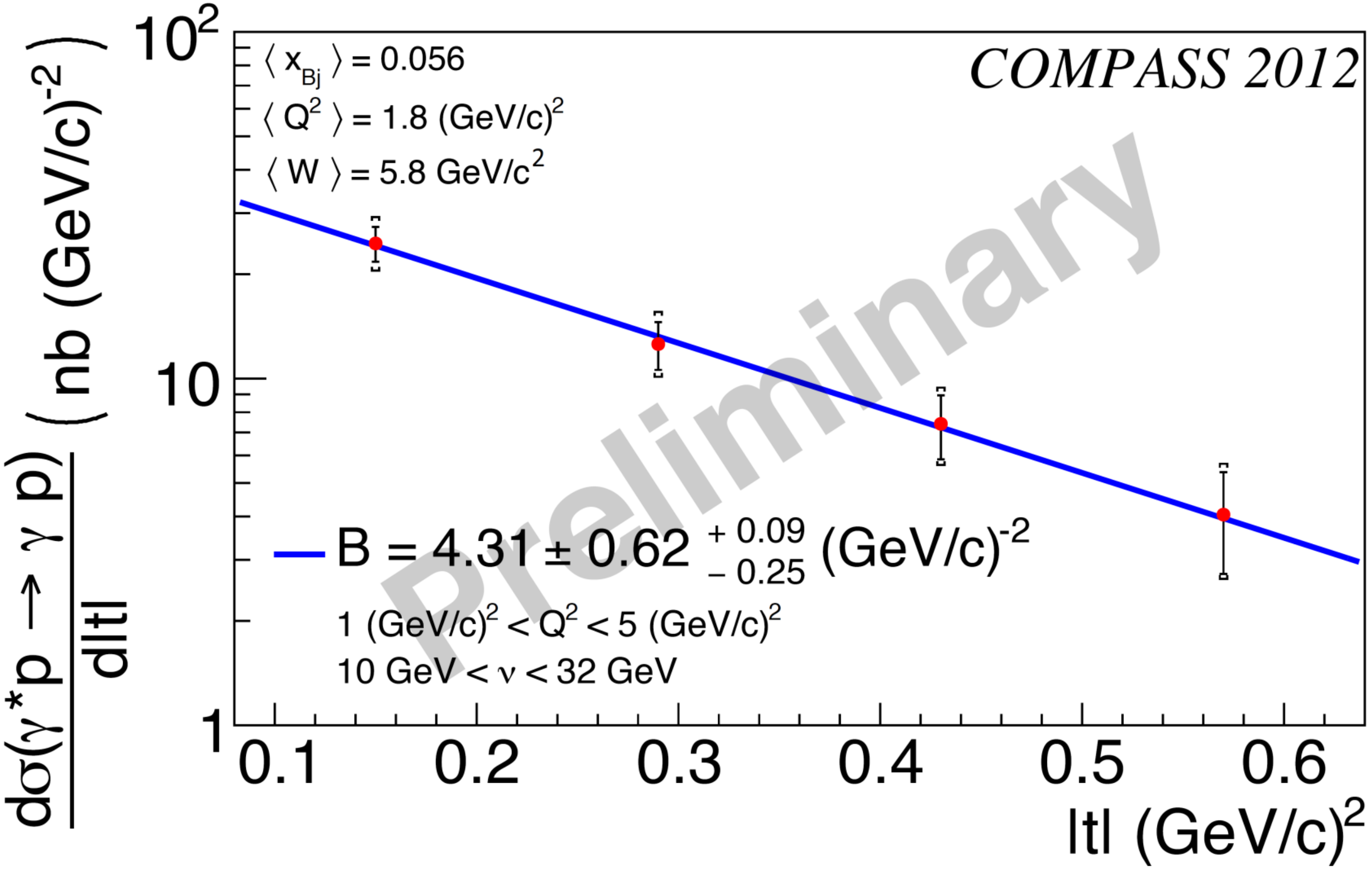




DVCS 2012 data

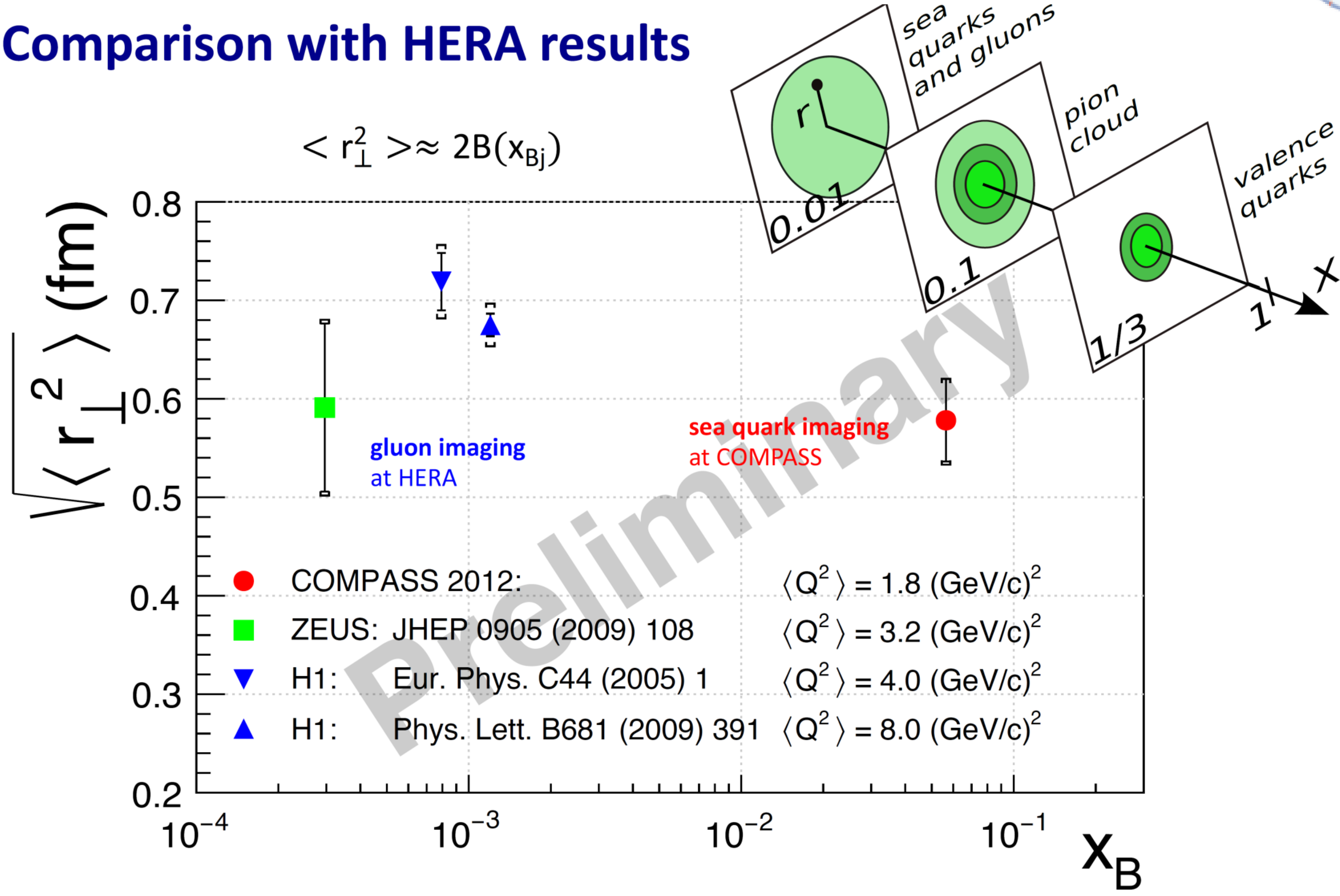
DVCS x-section and t-slope extraction

Kinematically constrained
vertex fit applied



DVCS 2012 data

Comparison with HERA results



COMPASS

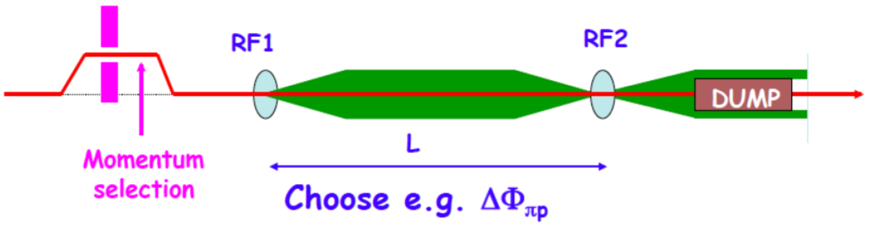
Common Muon and Proton Apparatus for Structure and Spectroscopy

Long-Term plans

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**

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

RF separated antiproton/kaon beam



$\Delta\Phi = 2\pi\,(L\ f\ /\ c)\,(\beta_1^{-1} - \beta_2^{-1})$ with $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$

“Normal” h^- beam composition:
~97% (π) ~2.5%(K) ~0.5% (pbar)

Assumptions:

- 8 x 10^7 antiprotons for 10^{13} ppp (10 seconds) (optimistic estimate by Lau Gatignon);
  - we assume here 4 x 10^{13} protons.

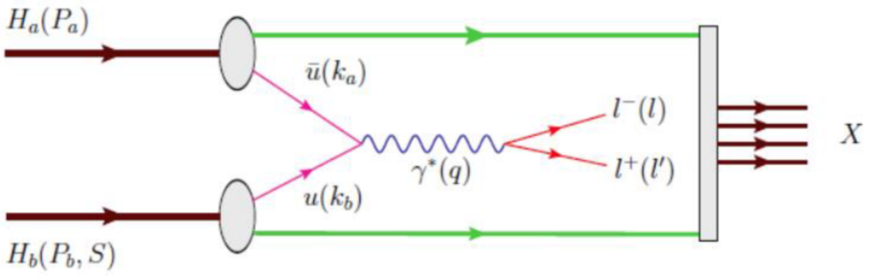
Antiprotons RF separated beam: 3.2 x 10^7 /s - Gain is a factor of 50 compared to the standard h^- beam for Drell-Yan experiment (~1% of h^- beam 6x10^7 /s dominated by π^-)

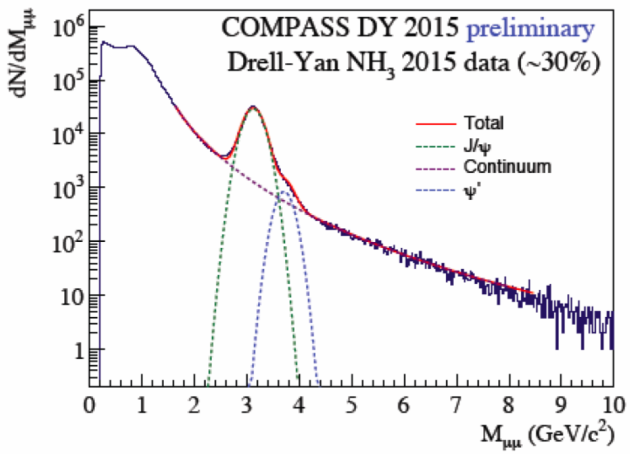
Using the same assumption for RF separated kaon beam, possible kaon beam intensity is 8 x 10^6 /s - Gain is a factor of 80 compared to to the standard “spectroscopy” h^- beam

High intensity RF separated beam will provide unique opportunities for Hadron Spectroscopy and Drell-Yan physics

RF separated beam - Drell-Yan (iii)
antiproton-induced Drell-Yan

- Antiproton-induced polarised DY makes **TMD's extraction model independent**
- Allows to profit from good knowledge of proton PDFs (from SIDIS) and as alternative probe permits to test TMDs universality
- New data on all TMDs induced asymmetries in both High Mass and *J/Ψ* regions:
  1. Model independent Boer-Mulders (quark-spin – quark-k_T correl.) extraction (CPT equiv.)
  2. Model independent Transversity extraction
  3. Lam-Tung relation for antiprotons (QCD effects)
  4. Sivers asymmetry (nucleon-spin – quark-k_T correlations) with no uncertainty from pion PDFs
  5. Sivers function for gluons (*J/Ψ* regions)
  6. Flavour separated TMDs extraction
  7. EMC effects & flavour dependent EMC effects

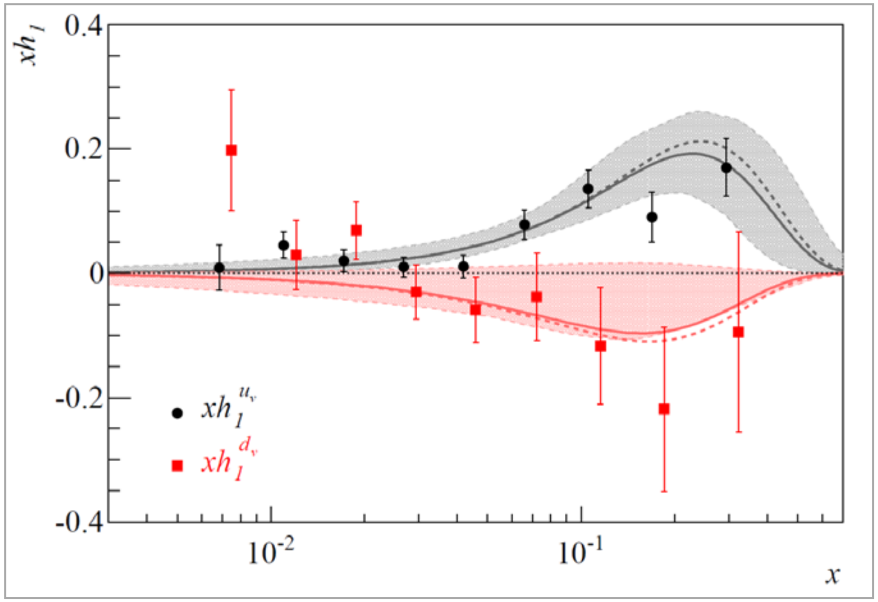




No competitors, unique data

SIDIS – transversely polarised Deuteron Target (^{6}LiD) Transversity/Sivers PDF extraction

- TMD PDFs and Transversity $h_1(x)$ are flavour dependent.
- Flavour separation ➔ data on both proton (NH_3) and deuteron (^{6}LiD) transversely polarised targets.
- Proton data set is factor of 4 compare to deuteron (see error bars for transversity $h_1(x)$ in the plot below)
-It is logical to increase the deuteron data set (so far the only data sets available are COMPASS (^{6}LiD) and CLAS (^{3}He) targets).



A. Martin, F.B., V. Barone PRD91 (2015) 014034

Competitors:
- No competitors in our kinematic range, Jlab will start by 2020

Conclusions

SIDIS gave and is giving fundamental contributions to the study of the transverse structure of the nucleon

Sivers, transversity, Collins functions different from zero

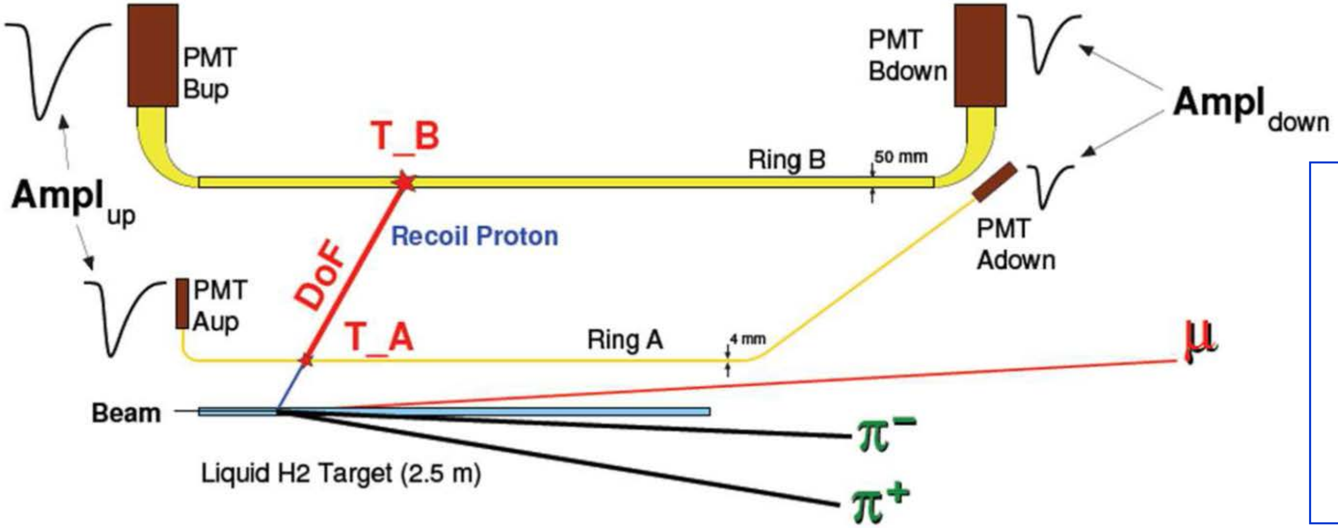
to progress further

- comparison with different processes, from Drell-Yan to pp hard scattering
- more from SIDIS
  - new precise measurements at new facilities with different energies
    JLab12, EIC
  - COMPASS can still do a lot in the “consolidation” phase
    from existing data
    Λ polarisation, weighted asymmetries, … new ideas and tests
    with new data
    LH2, hopefully in the future d↑
- more on fragmentation process
  - from e+e-, pp and SIDIS

still a long way, a lot to be learned, and a lot of fun!

SPARE

Camera detector for exclusivity

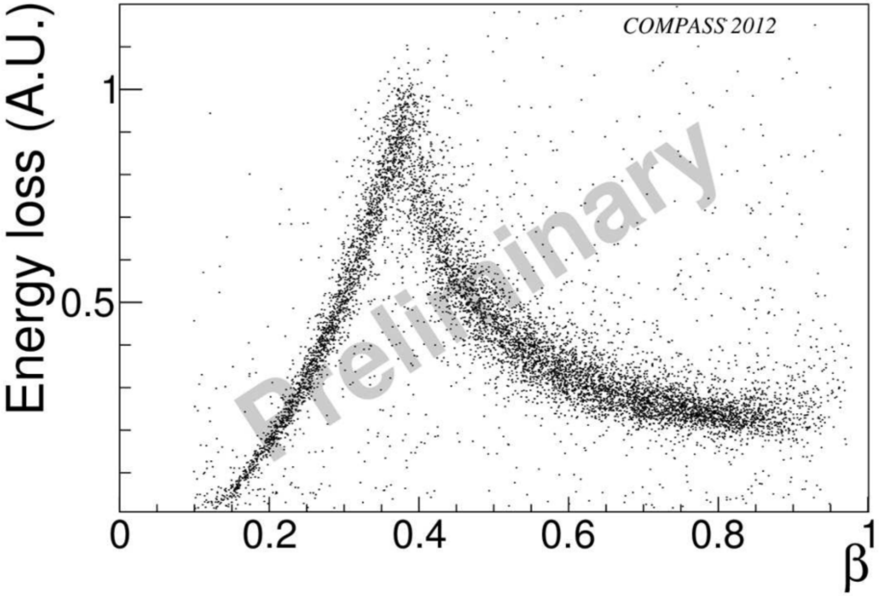


$E_{loss} \sim \sqrt{(Ampl_{up} \times Ampl_{down})}$

$z_{A,B} \sim (t_{up} - t_{down})_{A,B}$

$ToF = (t_{up} + t_{down})_{A,B}$

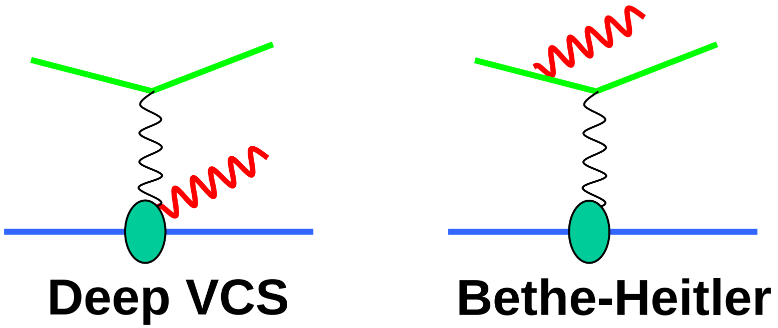
$\beta = DoF / ToF$



clear proton signature after exclusivity selection

DVCS–BH interference

- DVCS can be separated from BH and constrain the GPD *H* e.g. using different charge & spin (e_μ & P_μ) cross section combinations of the μ beam



  - at COMPASS μ± beams have opposite polarisation

$$d\sigma^{\mu p\to\mu p\gamma} = d\sigma^{BH} + d\sigma_0^{DVCS} + P_\mu d\Delta\sigma^{DVCS} + e_\mu \mathrm{Re}\, I + P_\mu e_\mu \mathrm{Im}\, I$$

Charge & Spin sum and difference:

$$\mathcal{S} = d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}} = 2(d\sigma^{BH} + d\sigma_0^{DVCS} + \mathrm{Im}\, I)$$

$$\mathcal{D} = d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}} = 2(d\sigma_0^{DVCS} + \mathrm{Re}\, I)$$

Im *I* and Re *I* are related to

$$H(x=\xi,\xi,t)$$

$$\mathcal{P}\int dx\, H(x,\xi,t)/(x-\xi)$$

RF separated beam – Hadron spectroscopy (ii)

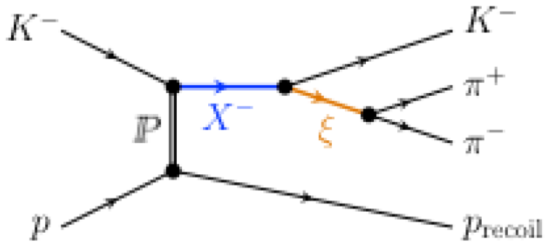
Light and Strange Meson Spectrum

RF separated kaon beam ~ 8×10^6 /s, beam momentum ~100 GeV

What can we contribute as COMPASS?

- State-of-the-art high-resolution spectrometer with full PID
- Advanced analysis techniques being developed in the light-quark sector

Method to be used: Kaon beam diffraction scattering on LH_2 and thin nuclear targets



- Goal: ~10 larger data sample than existing worldwide what would make possible to have similar to pion diffraction wave set: 88 waves in 11 t′ bins;
- COMPASS could rewrite PDG tables for strange mesons
- Extend studies of chiral dynamics to strange sector

No real competitors

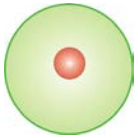
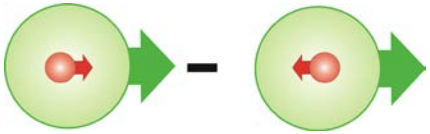
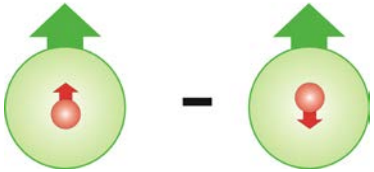
JParc - ~10^5 /s, low momenta kaons

JLab - ~10^4 /s, K^0 long beam, lower momenta

Unique opportunity

Collinear Nucleon Structure

The three ordinary PDFs

$\boldsymbol{f_1(x)}$		number	$q(x)$
$\boldsymbol{g_1(x)}$		helicity	$\Delta q(x)$
$\boldsymbol{h_1(x)}$		**transversity**	$\Delta_T q(x)$

- a chirally-odd distribution, hence not observable in DIS
- theoretically well known
- first exp. evidence in 2007

Beyond collinear pQCD…

- there are some phenomena involving transverse momenta (and transverse spin) which are not accounted for by a collinear pQCD description

- when the observed transverse momentum P_T is much smaller than the hard scale Q (two-scale process), one has to introduce the transverse-momentum dependent distributions (TMD PDFs)

- the TMD physics was prompted by the study of transverse spin phenomena but has also led to an improved QCD knowledge of ordinary, unpolarized, TMDs

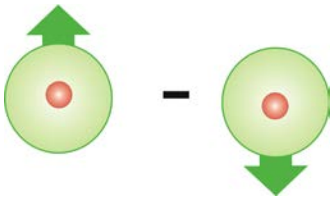
TMD PDFs

transverse spin couples to transverse momentum giving rise to a number of possible correlations

Sivers function

unpolarized quarks in a transversely polarized nucleon

$f_{1T}^{\perp}$



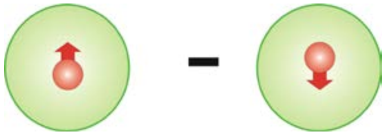
$$f_{q,p\uparrow}(x,\vec{p}_T) = f_1^q(x,p_T^2) - f_{1T}^{\perp q}(x,p_T^2)\,\frac{(\hat{P}\times\vec{k}_T)\cdot\vec{S}}{M}$$

→ single-spin **sin ($\phi - \phi_S$)** asymmetry

Boer-Mulders function:

transversely polarized quarks in an unpolarized nucleon

$h_1^{\perp}$



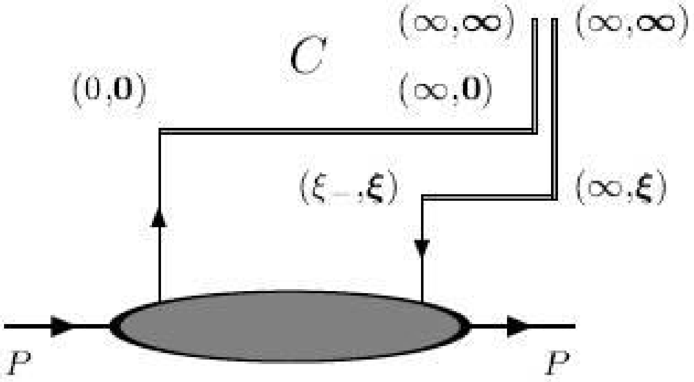
$$f_{q,p\uparrow}(x,\vec{p}_T) = \frac{1}{2}\left[f_1^q(x,p_T^2) - h_1^{\perp q}(x,p_T^2)\,\frac{(\hat{P}\times\vec{k}_T)\cdot\vec{S}_q}{M}\right]$$

→ **cos ϕ** and **cos 2ϕ** asymmetries

TMD PDFs

The gauge structure of TMDs:

$$F(x, \boldsymbol{k}_T) = \int \frac{d\xi^-}{2\pi} \int \frac{d^2\boldsymbol{\xi}_T}{(2\pi)^2} e^{ixP^+\xi^-} \, e^{-i\boldsymbol{k}_T \cdot \boldsymbol{\xi}_T} \, \langle P, S|\bar{\psi}(0)\, \mathcal{W}[0, \xi]\, \psi(\xi)|P, S\rangle|_{\xi^+=0}$$

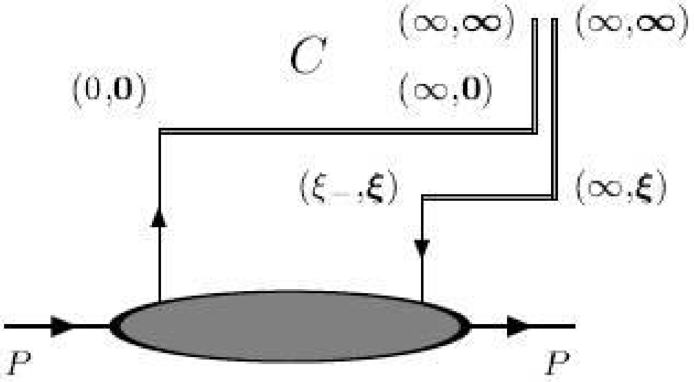


SIDIS : $\mathcal{W}[0, \xi] = \mathcal{W}^-[0, \infty]\, \mathcal{W}^T[0_T, \infty_T]\, \mathcal{W}^T[\infty_T, \xi_T]\, \mathcal{W}^-[\infty, \xi]$

TMD PDFs

The gauge structure of TMDs:

$$F(x, \boldsymbol{k}_T) = \int \frac{\mathrm{d}\xi^-}{2\pi} \int \frac{\mathrm{d}^2\boldsymbol{\xi}_T}{(2\pi)^2} \mathrm{e}^{\mathrm{i}xP^+\xi^-} \; \mathrm{e}^{-\mathrm{i}\boldsymbol{k}_T\cdot\boldsymbol{\xi}_T} \; \langle P, S|\bar{\psi}(0)\, \mathcal{W}[0,\xi]\, \psi(\xi)|P, S\rangle|_{\xi^+=0}$$



$$\text{SIDIS}: \mathcal{W}[0,\xi] = \mathcal{W}^-[0,\infty]\, \mathcal{W}^T[0_T,\infty_T]\, \mathcal{W}^T[\infty_T,\xi_T]\, \mathcal{W}^-[\infty,\xi]$$

the existence of Sivers and Boer-Mulders functions is a consequence of the gauge link structure, which also implies

T-odd TMD (SIDIS) = - TMD (DY)
a fundamental test of gauge invariance