RECENT RESULTS AND FUTURE PLANS OF COMPASS

Andrea Bressan
University of Trieste and INFN

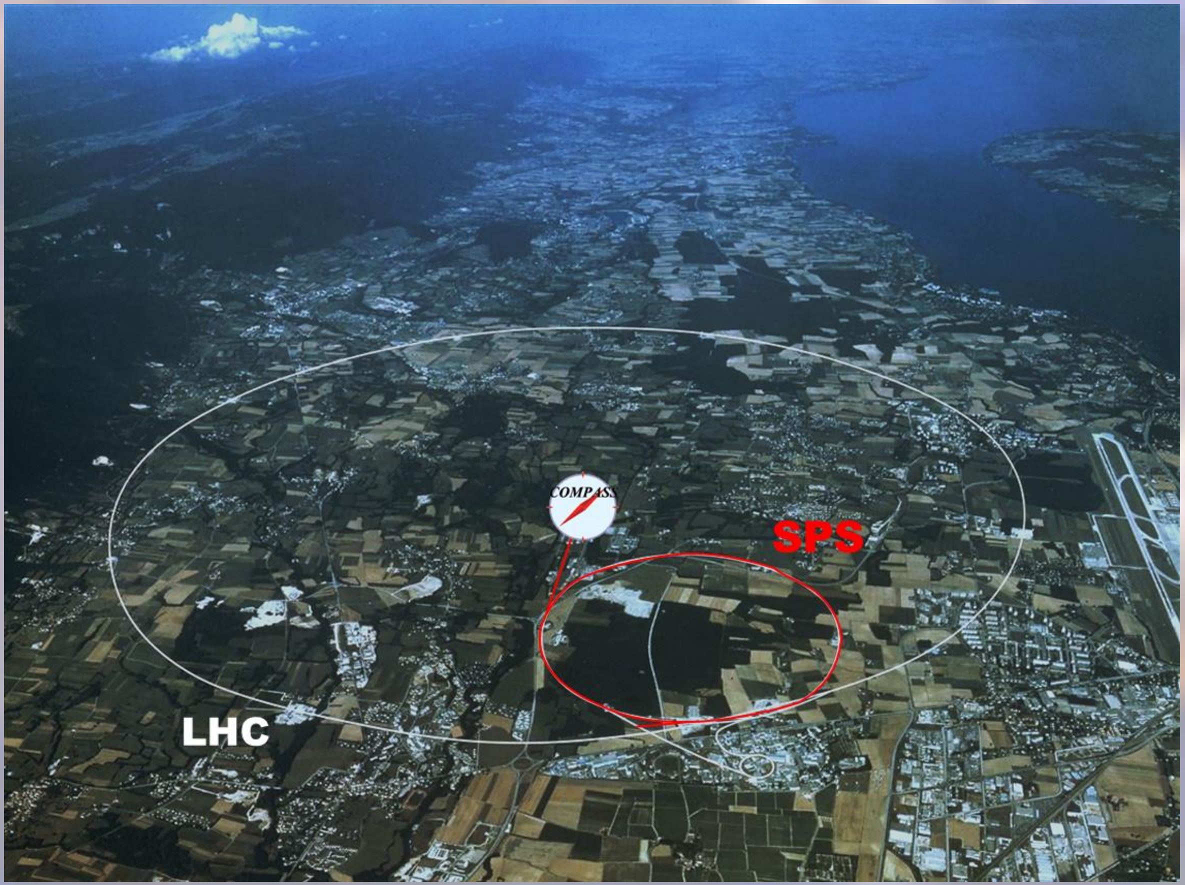
XCIX Congresso Nazionale SIF, Trieste 23-27 Settembre 2013

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

Collaboration
~ 250 physicists
from 24 Institutions
of 13 Countries

- **fixed target**
- **experiment**
- **at the CERN SPS**

data taking: since 2002



COMPASS-II Collaboration

Дубна (LPP and LNP),
Москва (INR, LPI, State University),
Протвино

CERN

Bochum, Bonn (ISKP & PI),
Erlangen,
Freiburg, Mainz,
München TU

Warsawa (NCBJ),
Warsawa (TU)
Warsawa (U)

Yamagata

USA (UIUC)

Praha (CU/CTU)
Liberec (TU)
Brno (ISI-ASCR)

Lisboa/Aveiro

Saclay

Calcutta (Matrivian)

Tel Aviv

Torino (University,INFN),
Trieste (University,INFN)

Taipei (AS)

COMPASS

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

two stages spectrometer

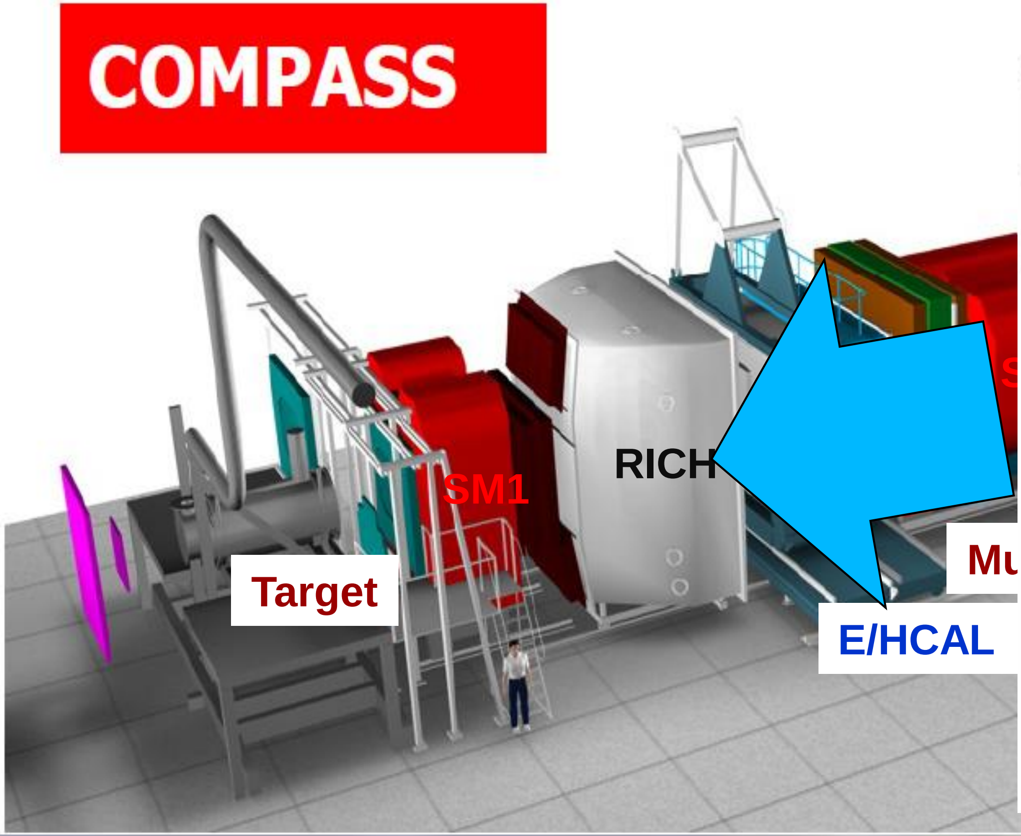
Large Angle Spectrometer (SM1)

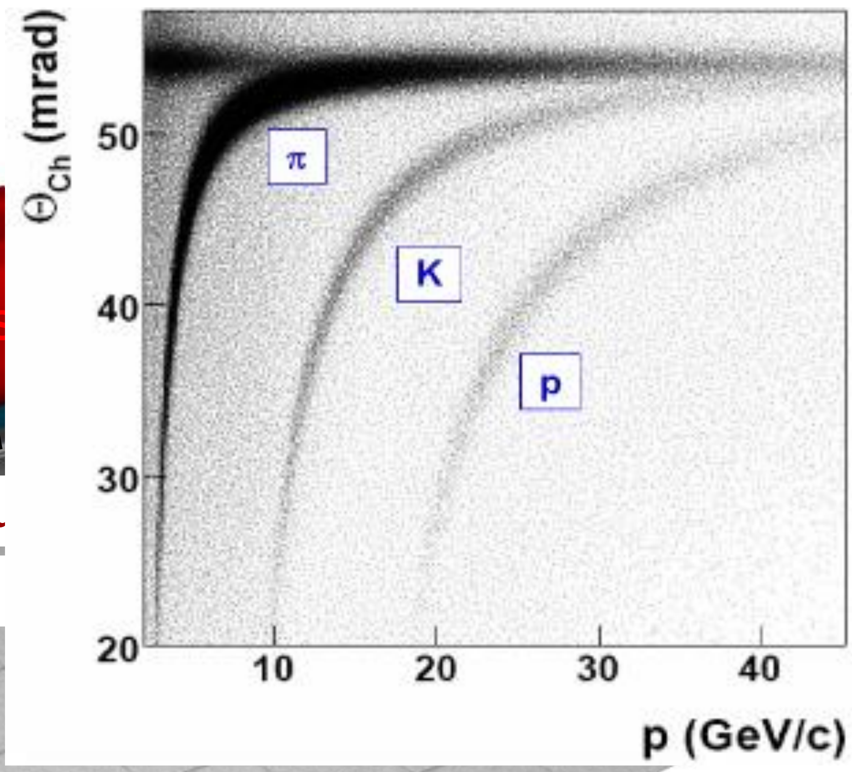
Small Angle Spectrometer (SM2)

radiator C_4F_{10}

threshold: π ~2 GeV/c

K ~ 10 GeV/c





COMPASS – some facts

- Located at CERN North Area beam line
  - Possible beams: μ^+, μ^-, π^+, π^-, K $\rightarrow$ Several physics programs

- Experiments with muon beam
- Experiments with hadron beams

COMPASS - I (2002 – 2011)

- Spin structure, Gluon polarization
- Flavor decomposition
- Transversity
- Transverse Momentum-dependent PDF

- Pion polarizability
- Diffractive and Central production
- Light meson spectroscopy
- Baryon spectroscopy

COMPASS - II (2012 – 2017)

- DVCS and HEMP
- Unpolarized SIDIS and TMDs

- Pion and Kaon polarizabilities
- Drell-Yan studies

COMPASS – some facts

- Located at CERN North Area beam line
  - Possible beams: μ^+, μ^-, π^+, π^-, K $\rightarrow$ Several physics programs

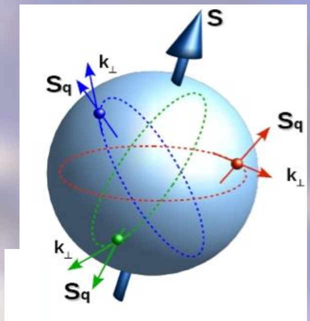
Experiments with muon beam	Experiments with hadron beams
COMPASS - I (2002 – 2011)	
Spin structure	Hadron spectroscopy
p, d polarized target (L & T)	Small LH_2 or nuclear targets
COMPASS - II (2012 – 2017)	
DVCS/Unpol SIDIS	Drell-Yan studies
Long LH_2 target	Polarized target (T)

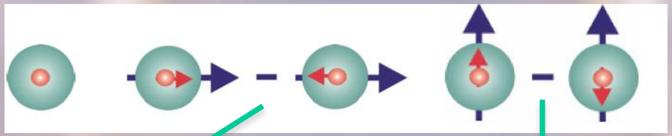
Reconfigurable target region - versatile experimental setup!

The spin of the nucleon

Three twist-2 quark DF's in collinear approximation ($\int dk_\perp$)

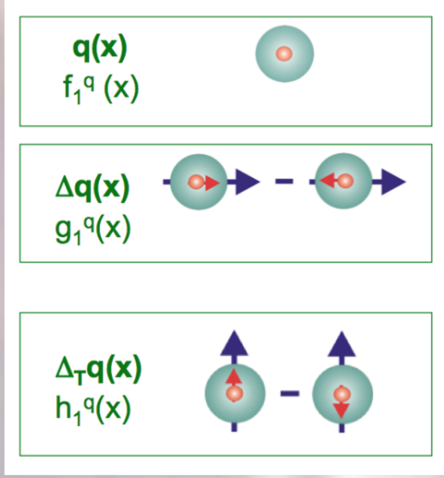
$$F^{Tw\text{-}2}_{Coll}(x) = \frac{1}{2}\left\{ q(x) + S_L \gamma_5 \Delta q(x) + S_T \gamma_5 \gamma^1 \Delta_T q(x) \right\} n^+$$





helicity

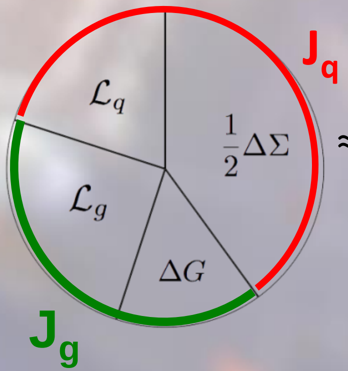
transversity



$$\frac{S_z^N}{\hbar} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$

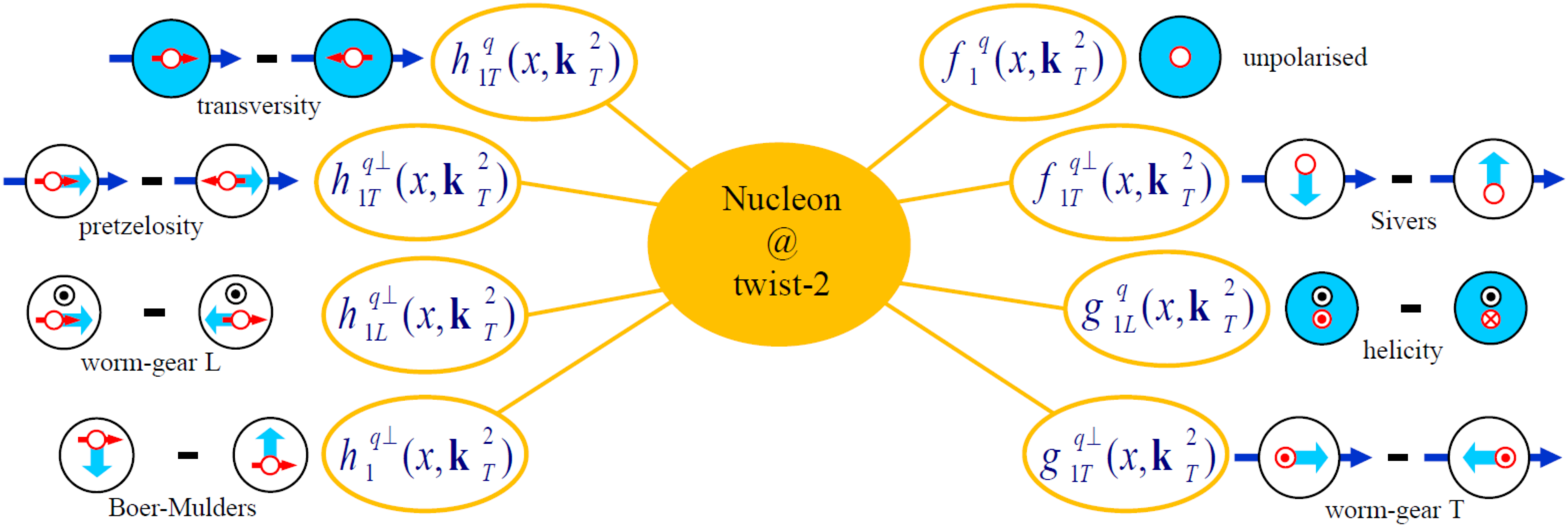
NR limit
[boost, rotat.]=0

➡ $\Delta_T q(x,Q^2) = \Delta q(x,Q2)$



≈30% : **Spin puzzle**

TMD Distribution Functions

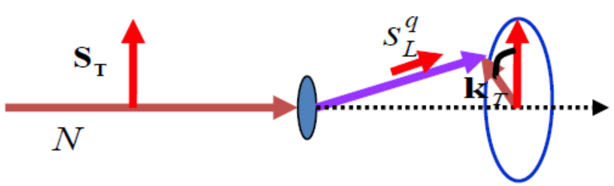


nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

Proton goes out of the screen. Photon goes into the screen



$\mathbf{k}_T$ – intrinsic transverse momentum of the quark

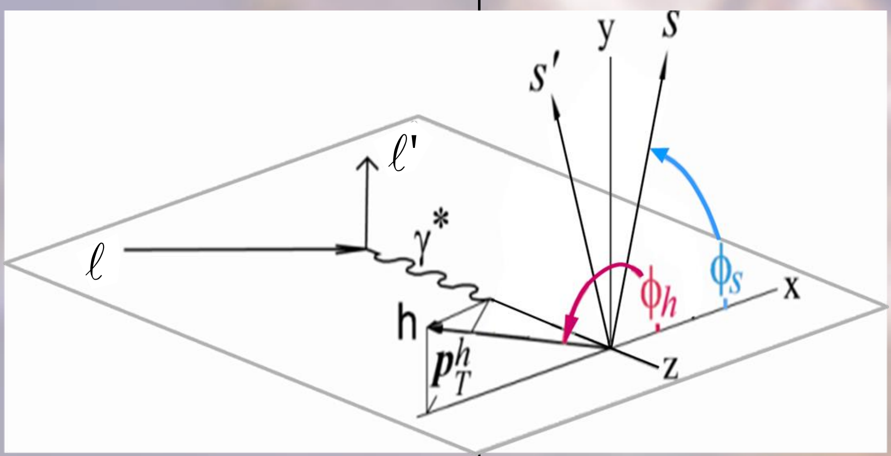
SIDIS x-Section

$$A_{U(L),T}^{w(\varphi_h,\varphi_S)} = \frac{F_{U(L),T}^{w(\varphi_h,\varphi_S)}}{F_{UU,T} + \varepsilon F_{UU,L}}$$

$$\varepsilon = \frac{1 - y - \frac{1}{4}y^2\gamma^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}y^2\gamma^2}, \quad \gamma = \frac{2xM}{Q}$$

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right] \times \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \times$$

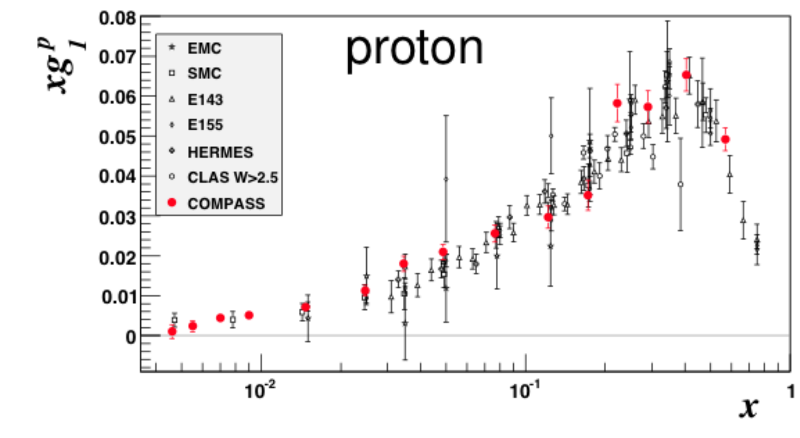
$$\left\{ \begin{array}{l}
1 + \cos\varphi_h \times \sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h} + \cos(2\varphi_h) \times \varepsilon A_{UU}^{\cos(2\varphi_h)} + \lambda \sin\varphi_h \times \sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h} + \\
S_L \left[\sin\varphi_h \times \sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\varphi_h} + \sin(2\varphi_h) \times \varepsilon A_{UL}^{\sin(2\varphi_h)} \right] + \\
S_L \lambda \left[\sqrt{1-\varepsilon^2}A_{LL} + \cos\varphi_h \sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h} \right] + \\
\mathbf{S}_T \left[\begin{array}{l}
\sin\varphi_S \times \left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right) + \\
\sin(\varphi_h - \varphi_S) \times \left(A_{UT}^{\sin(\varphi_h-\varphi_S)}\right) + \\
\sin(\varphi_h + \varphi_S) \times \left(\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}\right) + \\
\sin(2\varphi_h - \varphi_S) \times \left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}\right) + \\
\sin(3\varphi_h - \varphi_S) \times \left(\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)
\end{array} \right] + \\
\mathbf{S}_T \lambda \left[\begin{array}{l}
\cos\varphi_S \times \left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}\right) + \\
\cos(\varphi_h - \varphi_S) \times \left(\sqrt{(1-\varepsilon^2)}A_{UT}^{\cos(\varphi_h-\varphi_S)}\right) + \\
\cos(2\varphi_h - \varphi_S) \times \left(\sqrt{2\varepsilon(1-\varepsilon)}A_{UT}^{\cos(2\varphi_h-\varphi_S)}\right)
\end{array} \right]
\end{array} \right\}$$

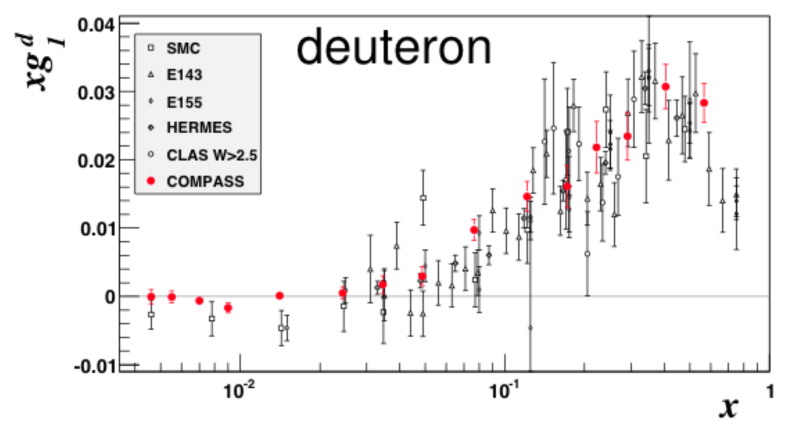


New A_1^p & g_1^p from 2011 200 GeV data

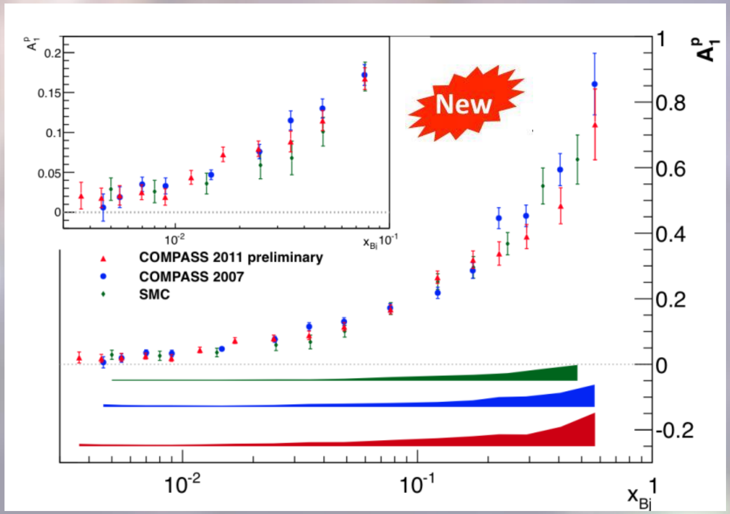
Phys. Lett. B 690 (2010) 466

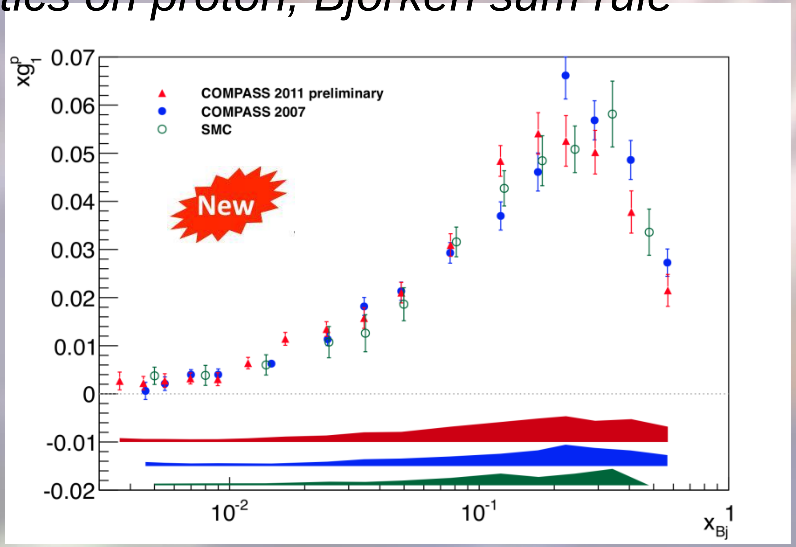
Phys. Lett. B 647 (2007) 8



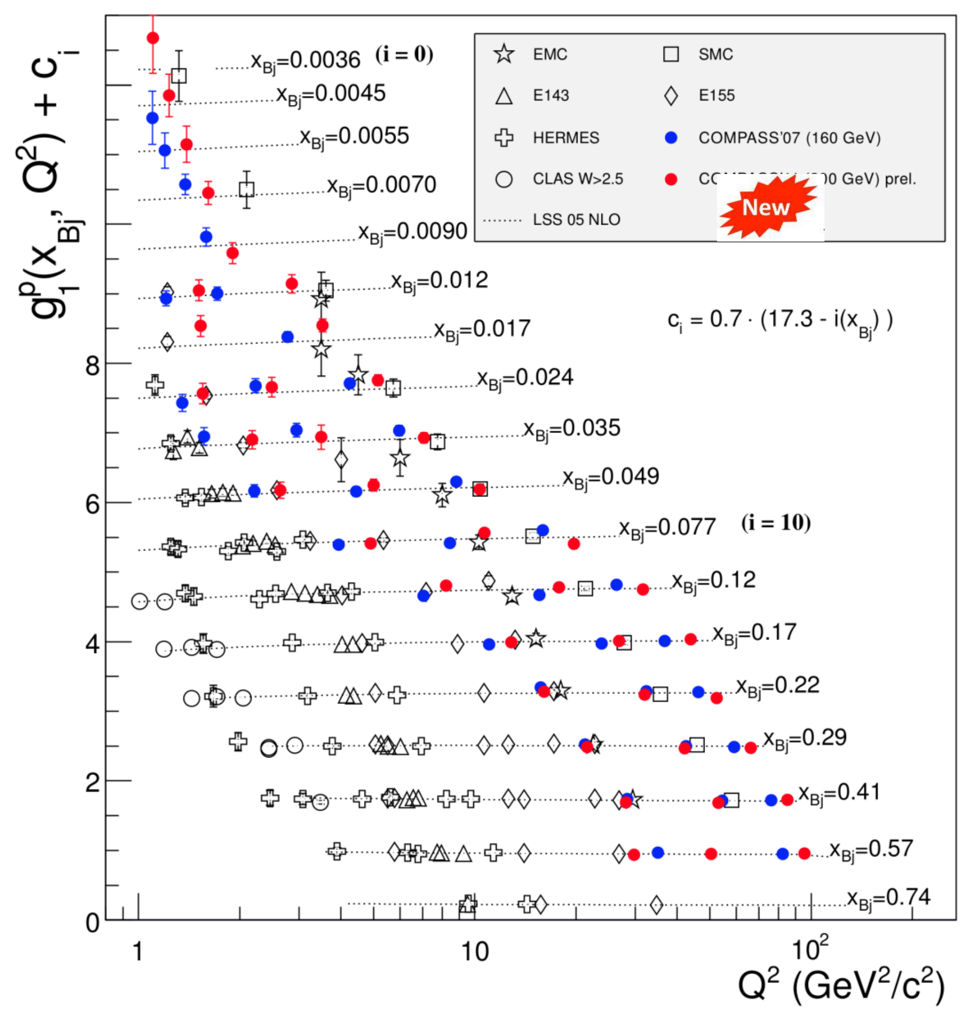


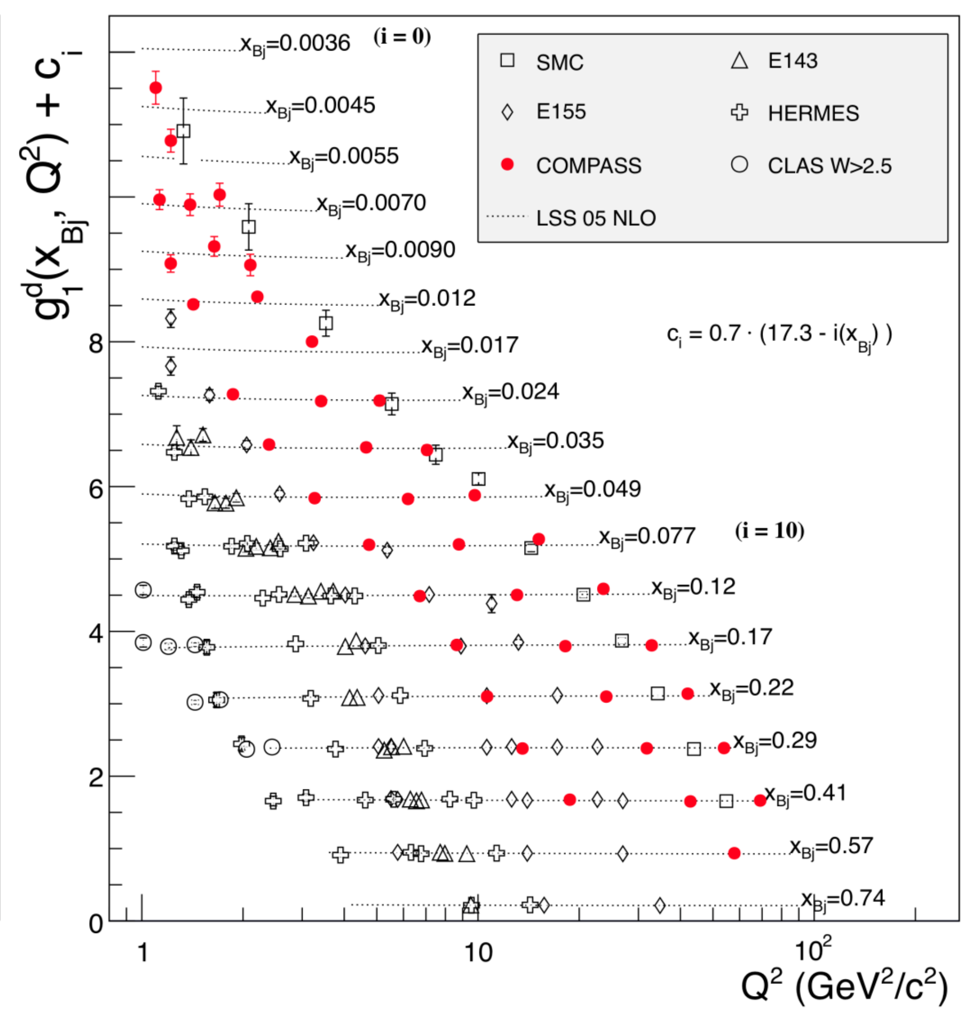
COMPASS new 2011 proton data: 200 GeV muon beam
→ lower x, higher Q^2, improve statistics on proton, Bjorken sum rule





New world data on $g_1^{p,d}(x,Q^2)$



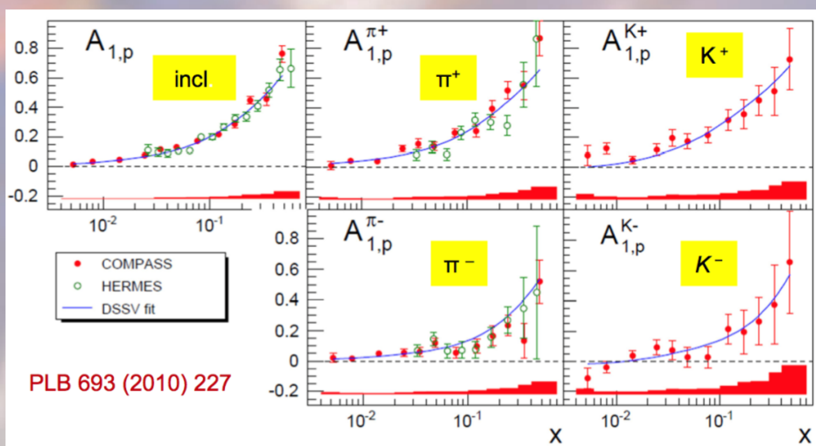


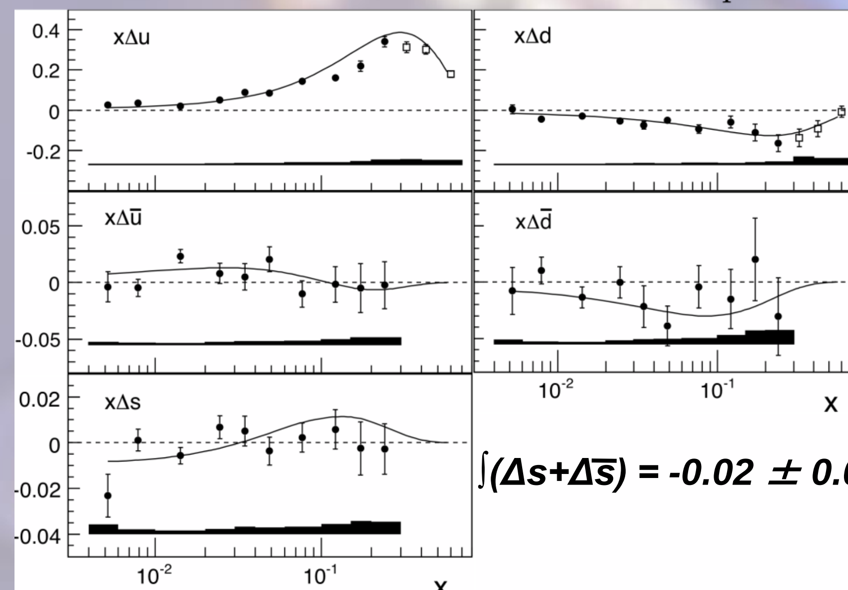
Polarized PDF from SIDIS

$$A_1^{h\,(p/d)}(x,z,Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}$$

- **Inputs needed for the extraction of $\Delta q(x, Q^2)$:**
  - Unpolarised PDFs ($q(x, Q^2)$) $\rightarrow$ MRST04
  - $D_q^h(z, Q^2) \rightarrow$ DSS parameterisation

PRL 101 (2008) 072001; PR D80 (2009) 034030





$\int(\Delta s+\Delta\bar{s}) = -0.02 \pm 0.02 \pm 0.02$

Soon: new 2011 data

Leading Order (LO) fit of the 10 asymmetries (5d+5p)

Determine 6 flavor separated PDFs $\Delta u,\ \Delta d,\ \Delta\bar{u},\ \Delta\bar{d},\ \Delta s$ and $\Delta\bar{s}$

Good agreement between COMPASS data and DSSV parametrization, but…

Strange sea polarization

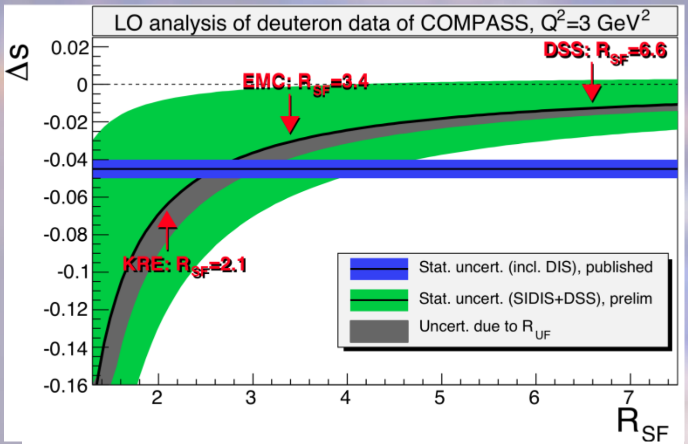
PLB 693(2010)227 (Compass)

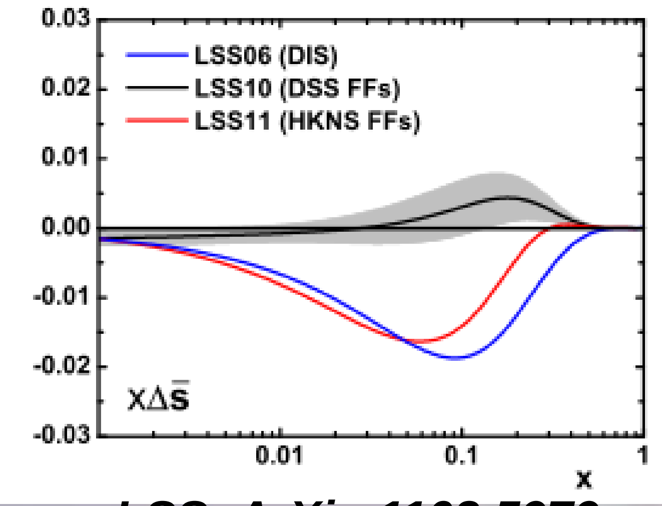
- $K^{\pm}$ asymmetries from deuteron data

$$\frac{\Delta s}{s} = A_1^{\mathrm{d}} + \left(A_1^{K^+ + K^-} - A_1^{\mathrm{d}}\right)\frac{Q/s+\alpha}{\alpha-0.8}$$

- $Q = u + \bar{u} + d + \bar{d}$, $\alpha = \frac{2R_{UF}+2R_{SF}}{3R_{UF}+2}$

- $R_{UF} = \frac{\int D_d^{K^+}(z)\mathrm{d}z}{\int D_u^{K^+}(z)\mathrm{d}z}$, $R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)\mathrm{d}z}{\int D_u^{K^+}(z)\mathrm{d}z}$





LSS: ArXiv:1103.5979

Large sensitivity of Δs to « strange to favoured » FF ratio

→ try to extract R_{SF} from Kaon multiplicities

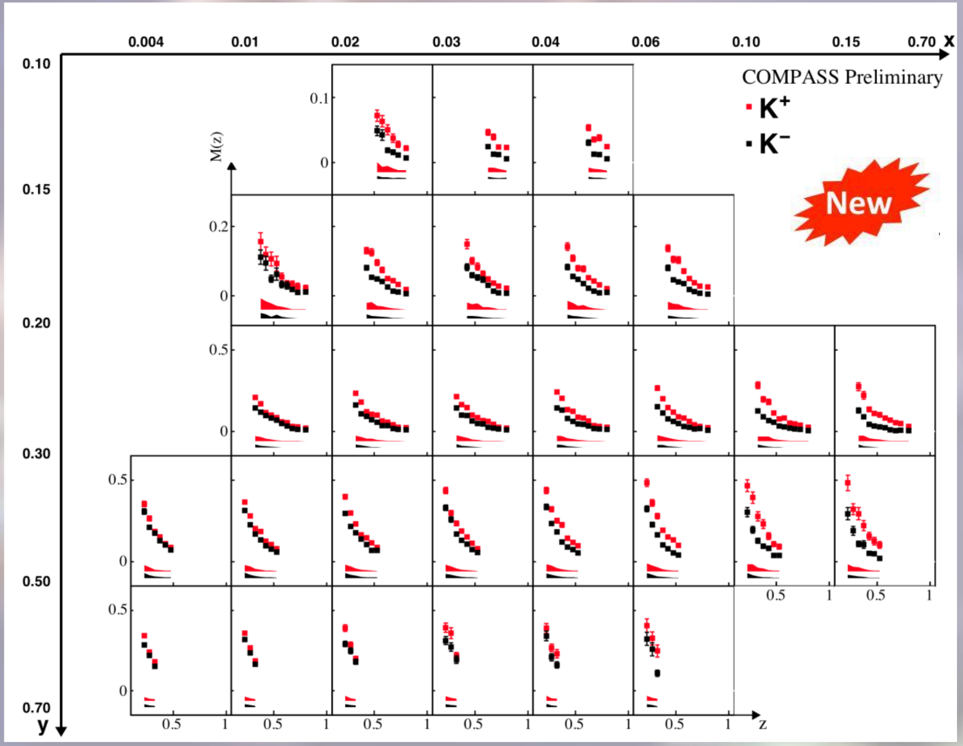
Hadron multiplicities

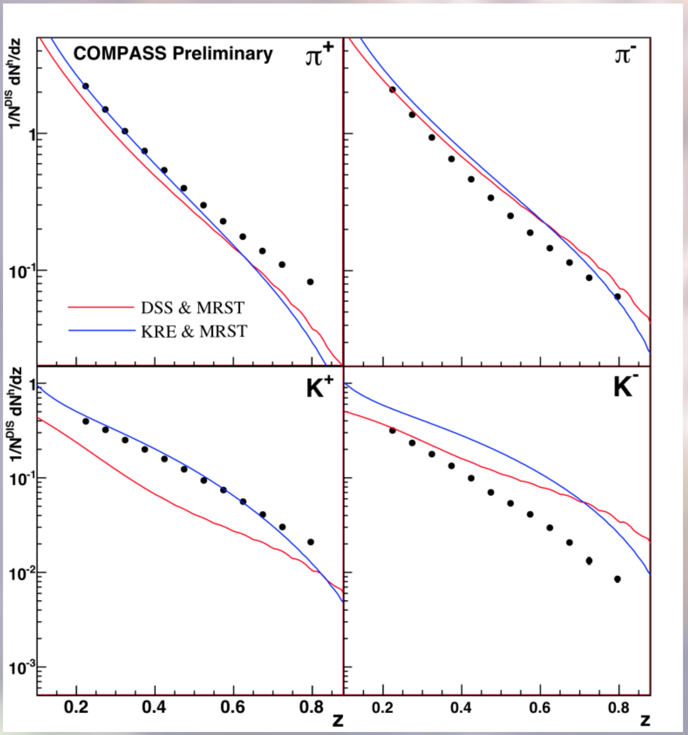
$$M^h(x,Q^2,z) = \frac{d^3\sigma^h/dxdQ^2dz}{d^2\sigma^{DIS}/dxdQ^2} = \frac{\sum_q e_q^2(q(x,Q^2)D_q^h(z) + \bar{q}(x,Q^2)D_{\bar{q}}^h(z))}{\sum_q e_q^2(q(x,Q^2) + \bar{q}(x,Q^2))}$$

h=π,K (identified by Ring Imaging Cerenkov)

➢*M^h depend on unpolarized PDF's:*

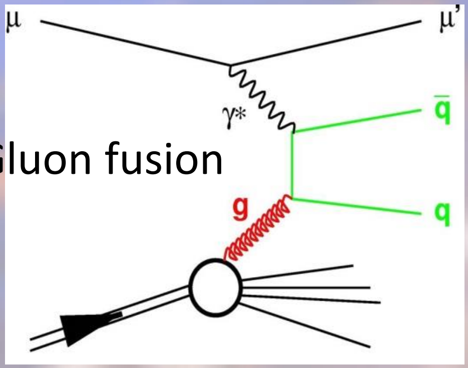
- *u(x),d(x) unpolarized PDF well known*
- *strange PDF s(x) less well known*





Gluon polarization via PGF: open charm

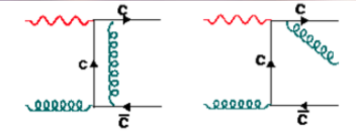
Photon-Gluon fusion

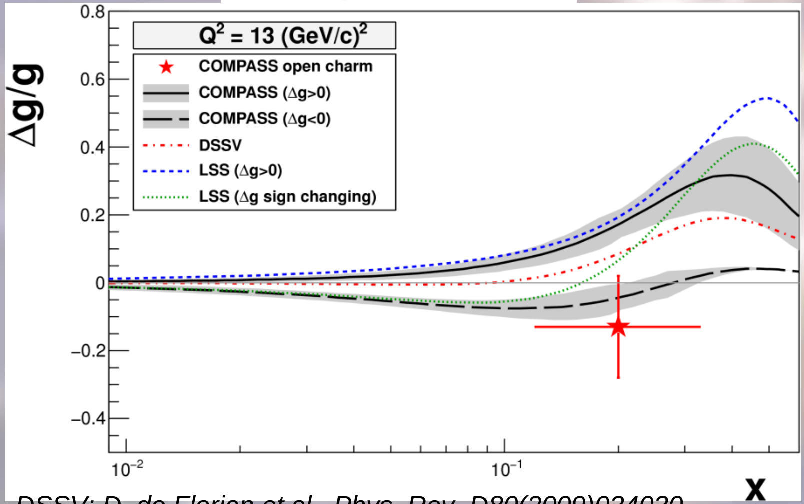


$$A_{LL}^{\mu N(LO)} = R^{PGF} a_{LL}^{PGF} \frac{\Delta g}{g}(x)$$

- **Open Charm production**
  - $\gamma^* g \rightarrow c\bar{c}$ ⇒ reconstruct D^0 mesons
  - Hard scale: M_c^2
  - No intrinsic charm in COMPASS kinematics
  - No physical background
  - Weakly Monte Carlo dependent
  - Low statistics

NLO





DSSV: D. de Florian et al., Phys. Rev. D80(2009)034030
LSS: E. Leader, A.V. Sidorov, D.B. Stamenov, arXiv 1010.5742(2010)

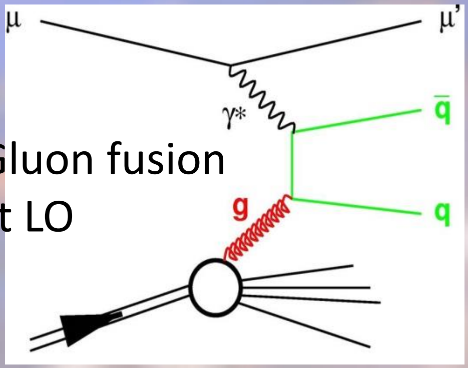
- First extraction of **ΔG at NLO**
- **Constrains ΔG at larger x**
- **Charm result can be included in global NLO fits:** model independent asymmetries $A_{LL}(p_T, E_D)$ available

PRD 87 (2013) 052018 New

ΔG/G(x=0.2) = -0.13 ± 0.15 ± 0.15

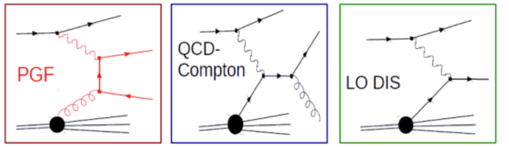
Gluon polarization via PGF: high p_T

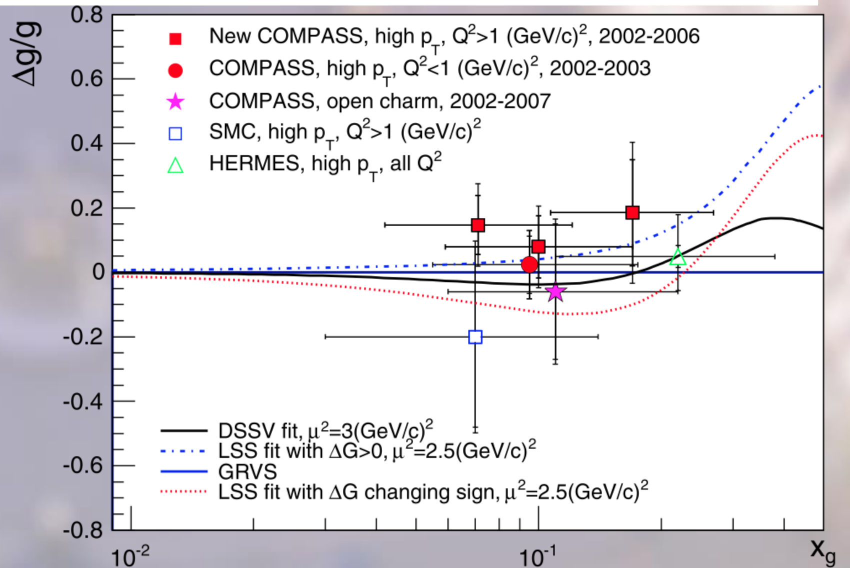
Photon-Gluon fusion at LO



$$A_{LL}^{\mu N(LO)} = R^{PGF} a_{LL}^{PGF} \frac{\Delta g}{g}(x) + ...$$

- **High-p_T hadron pairs**
  - $\gamma^* g \rightarrow q\bar{q}$ ⇒ reconstruct 2 jets or h^+h^-
  - Hard scale: Q^2 or Σp_T^2 [$Q^2 > 1$ or $Q^2 < 1$ $(GeV/c)^2$]
  - High statistics
  - Physical background
  - Strongly Monte Carlo dependent





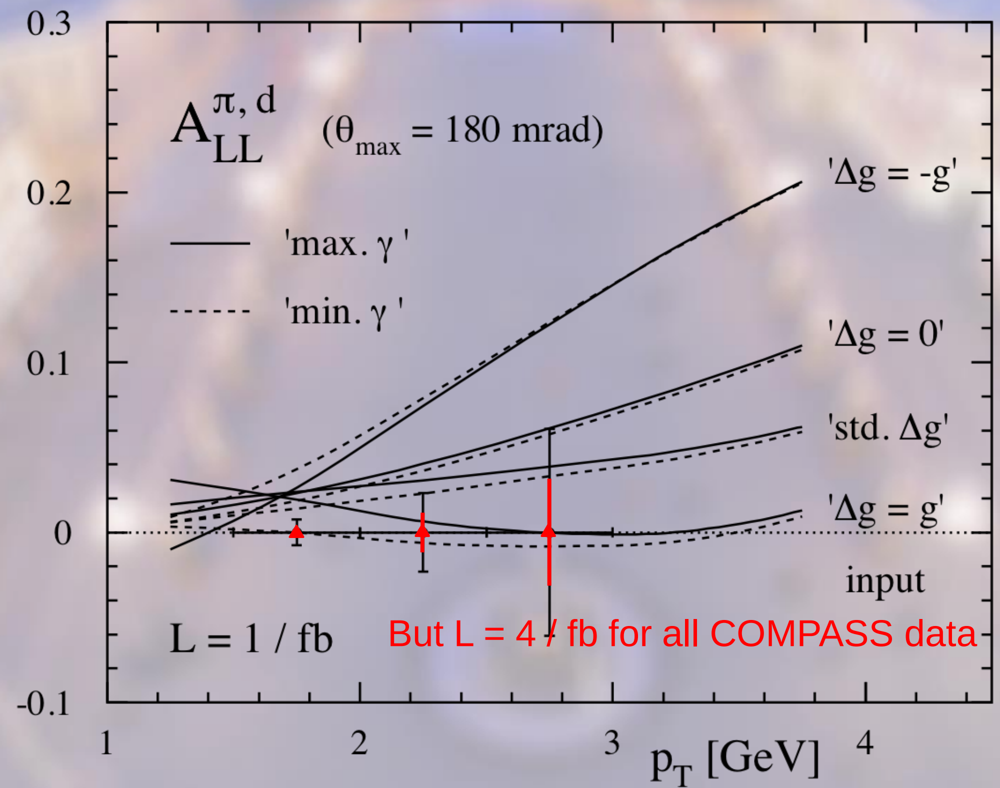
Phys. Lett. B 718 (2013) 922 New

Caveat:

- LO extractions of ΔG/G(x)
- Can not directly be compared to NLO fits
- Need for reliable NLO for high p_T in COMPASS c.m. energy range…
- $A_{LL}^{2h}/D(x,p_T)$ available for $Q^2>1$ data

$A_{LL}^{1h}(p_T)$:polarized hadron γ-production

Projections by Jäger et al. for COMPASS with 1 fb^{-1} (=1/4 COMPASS stat.)



Jäger, Stratmann & Vogelsang: ***EPJ C44 (2005) 533***

So far, only NLO pQCD for polarized case (no resum.)

In perspective: constraining ΔG by $A_{LL}^{1h}(p_T)$ (**working on**)

Collins and Sivers asym.

- T polarized target, SIDIS:
- Measure azimuthal asymmetries:

$\mu p^{\uparrow} \rightarrow \mu p h^{+/-}$

Collins: Outgoing hadron direction & quark transverse spin

Sivers: Nucleon spin & quark transverse momentum k_T

at LO:

Collins

$\Delta_T q$ transverse spin distr.

Collins fragmentation function, depends on spin

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q \otimes \Delta_T D_q^h}{\sum_q e_q^2 q \otimes D_q^h}$$

Sivers

TMD

Quark fragmentation function

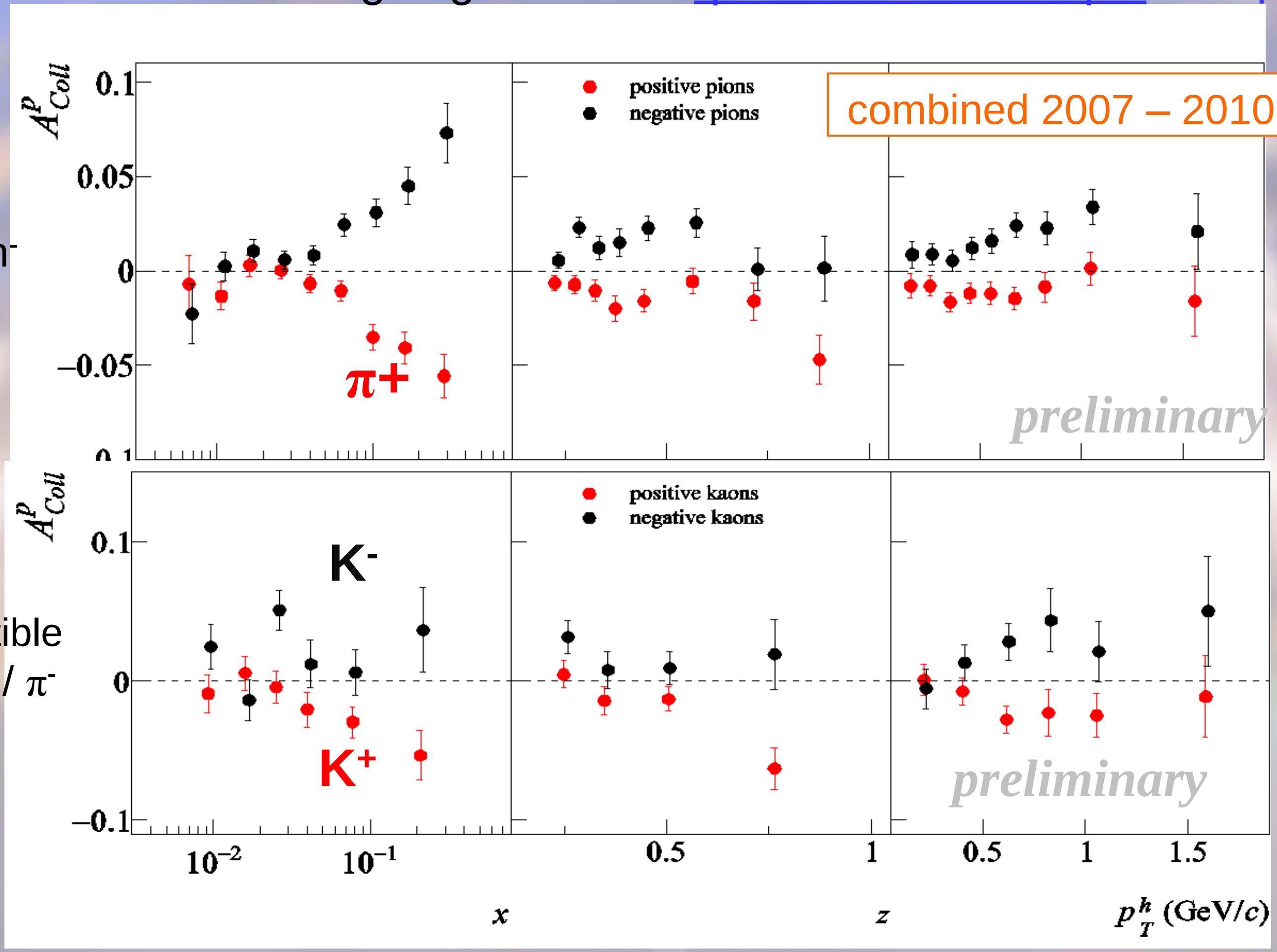
$$A_{Siv} = \frac{\sum_q e_q^2 f_{1Tq}^{\perp} \otimes D_q^h}{\sum_q e_q^2 q \otimes D_q^h}$$

note: **$\Delta_T q$** also measured using
''Two hadron'' fragmentation function

Collins Asymmetry on p - π, K id.

Correlation between outgoing hadron & quark transverse spin → $\Delta_T u$ & $\Delta_T d$

~ h^+ / h^-

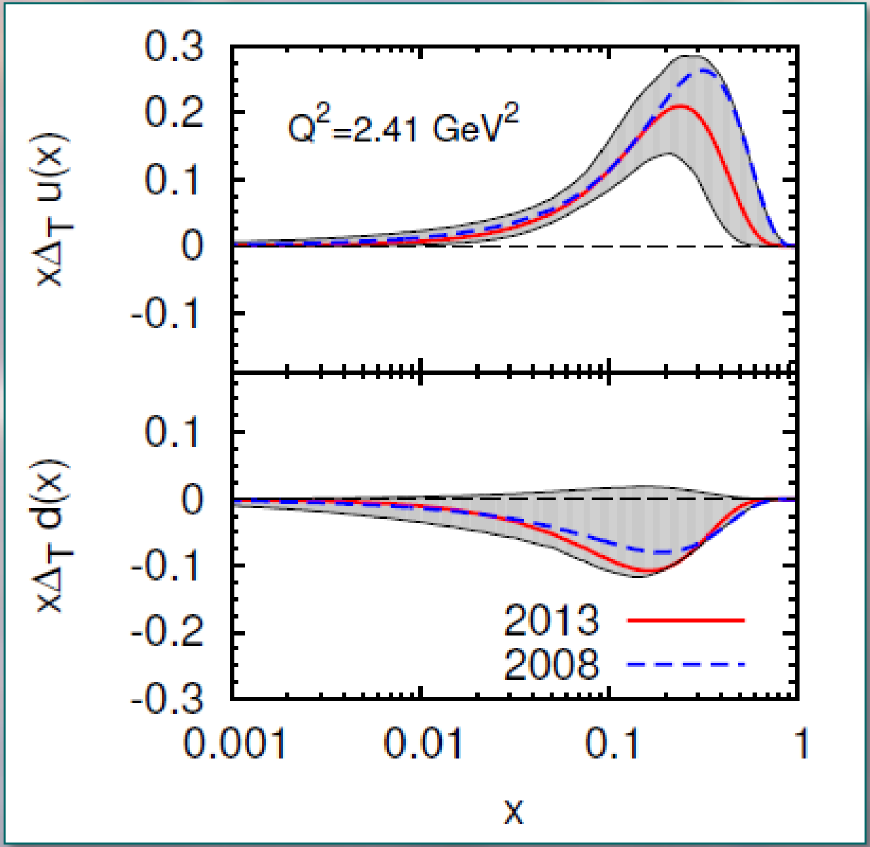


compatible with π^+ / π^-

- **Agreement HERMES/COMPASS (not shown)** → **no Q^2 dependence seen** (factor of ~3 inQ^2)
- **Now also produced in bins of z and y**

Transversity from Collins

Combined analyses of **HERMES, COMPASS** and **BELLE fragm.fct.** data



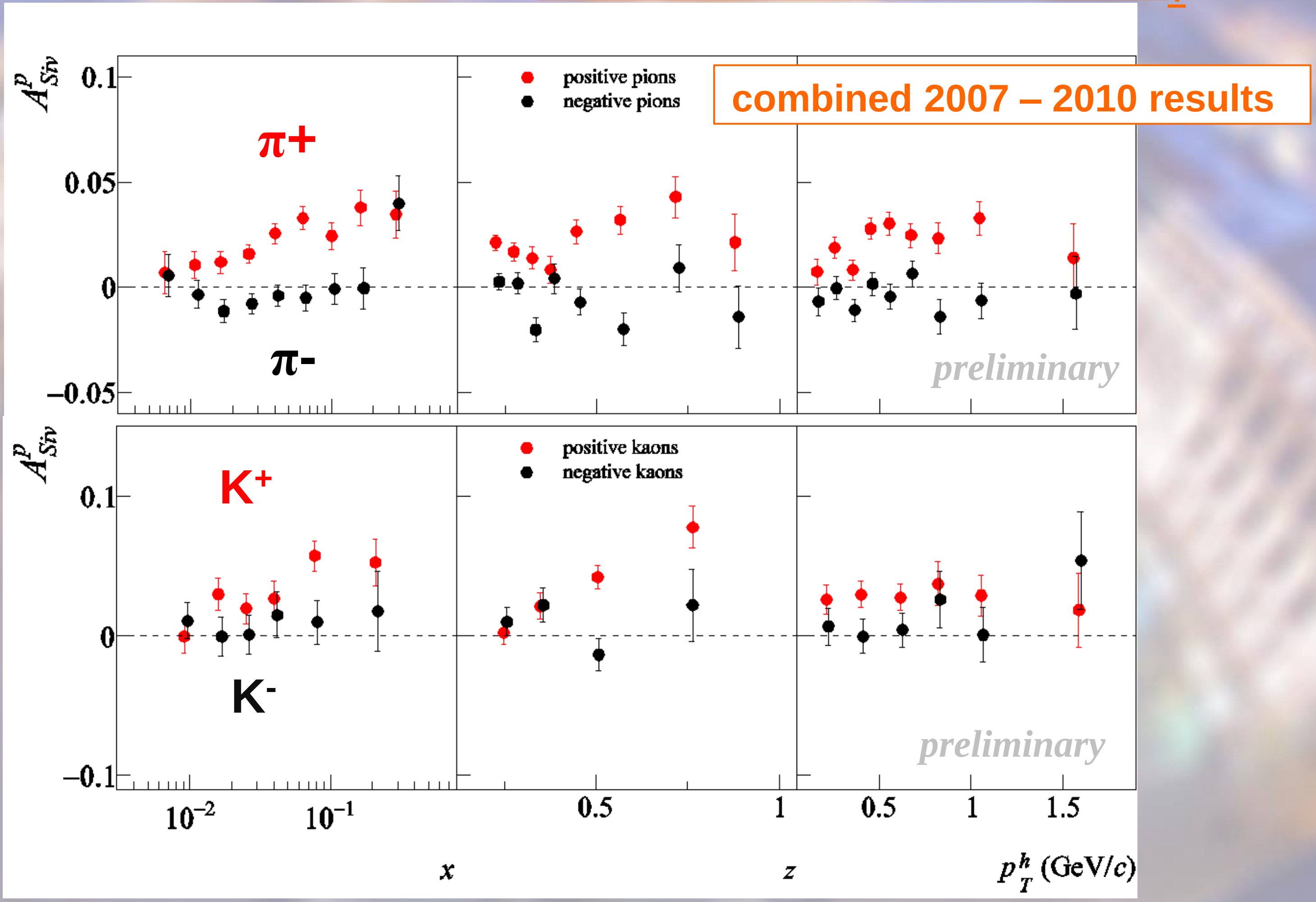
Anselmino et al. arXiv: 1303.3822

Sivers Asymmetry on p - π, K id.

Correlation between nucleon spin & quark transverse momentum k_T

~ h^+ / h^-

larger than for π^+

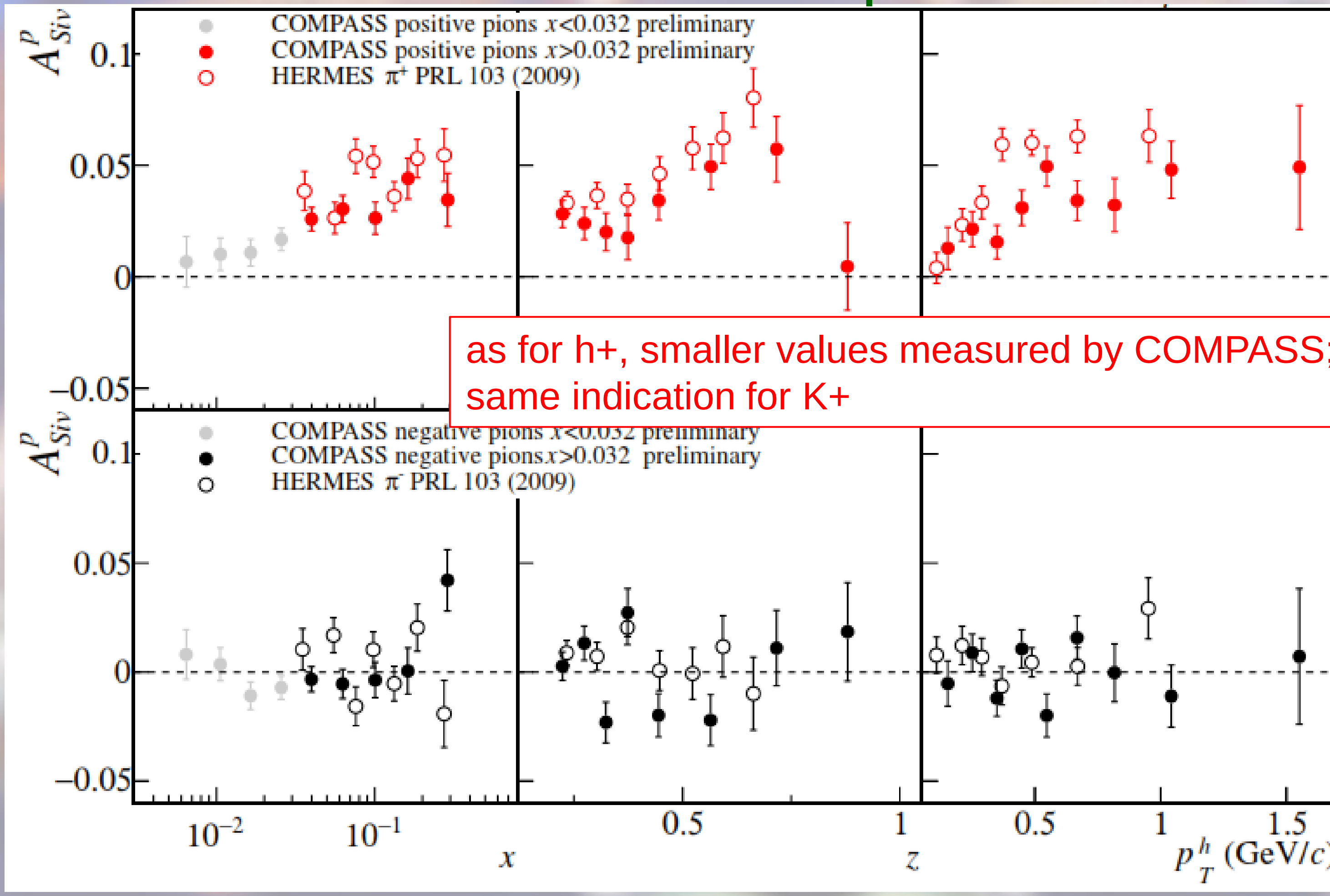


- In region of overlap, agreement with HERMES, but smaller strength
- Now also produced in separate bins of z and y.

Sivers asymmetry on p, x > 0.032

charged pions (and kaons), 2010 data

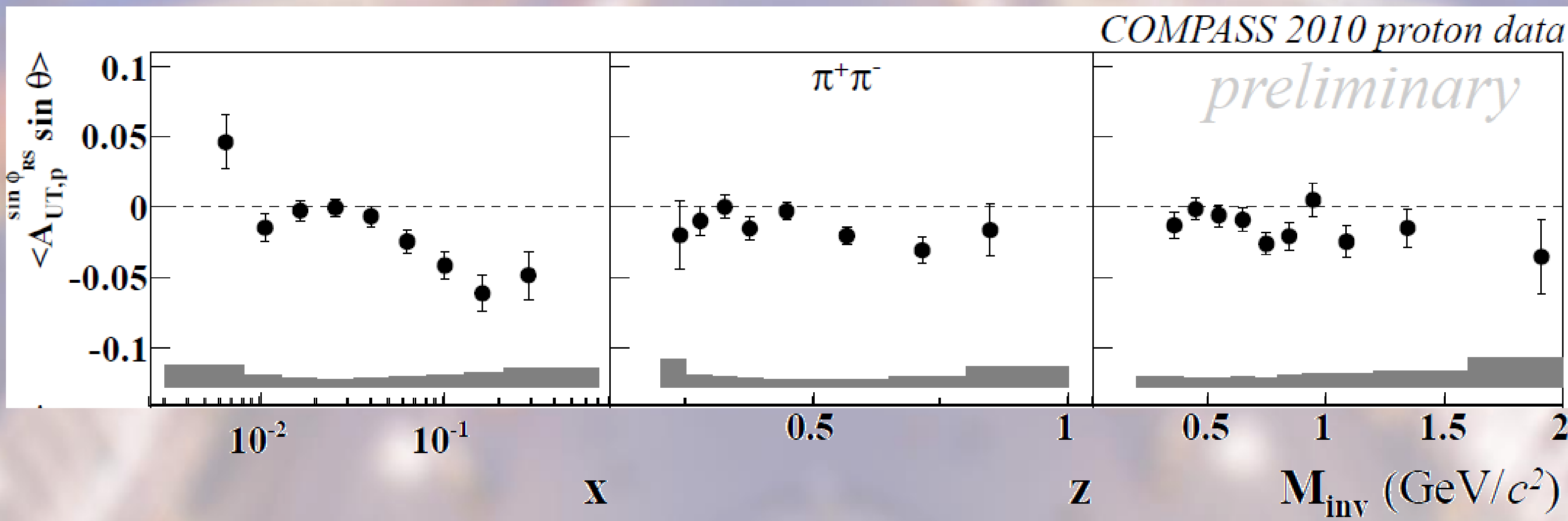
comparison with HERMES results



as for h+, smaller values measured by COMPASS;
same indication for K+

2-hadron asymmetries

Another access to transversity h_1

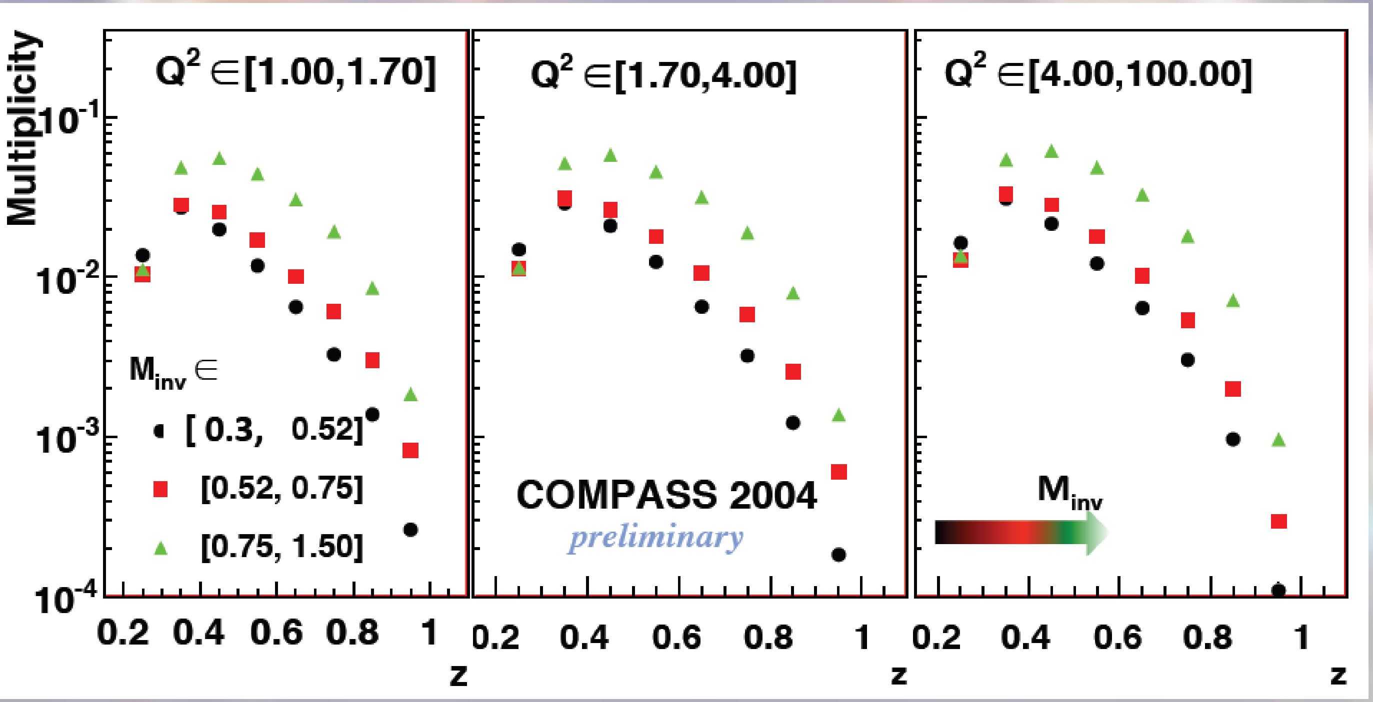


$$A_{RS} = \frac{1}{f \cdot P_T \cdot D} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{\angle}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, M_h^2)}$$

- h_1^u & h_1^d extraction
- Also measured for the first time for K^+K^- , π^+K^- and $K^+\pi^-$ pairs

2-h multiplicities

- First time measured in lp
- Needed for pol. PDF extraction; will complete e+ e- data



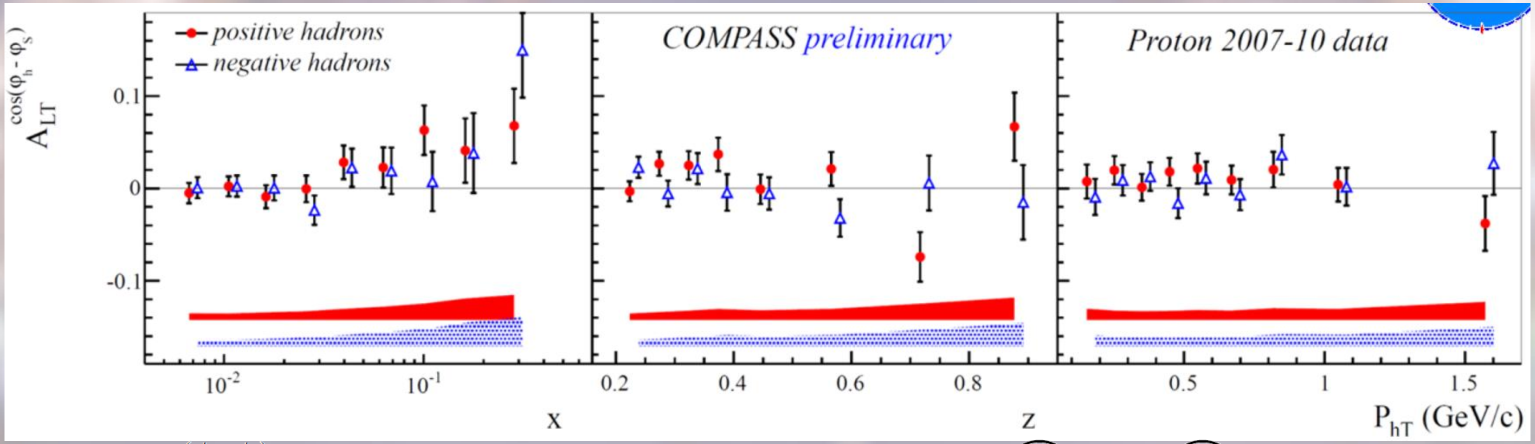
Other Transverse Target spin asymmetries

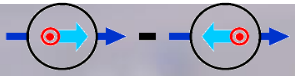
k_T effects → modulations in SIDIS cross-section

$\mu\, p^{\uparrow} \rightarrow \mu\, p\, h^{+/-}$

- **Major progress in TMD measurement**
- **Powerful tool to understand correlations**

$A_{LT}^{\cos(\varphi_h - \varphi_s)}$ shown as example



$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$, "Worm Gear" PDF g_{1T}^q : 

In agreement with HERMES prelim., and with theoretical predictions

Physics from hadron beam

Rich program on hadron spectroscopy at COMPASS,
search for exotic mesons
- Diffractive resonance production
- Central production

π, K, p beams - 190 GeV : large energy transfer spectrum t
Spectrometer : flat acceptance, ECALs/ HCALs, RICH id.
charged & neutral channels

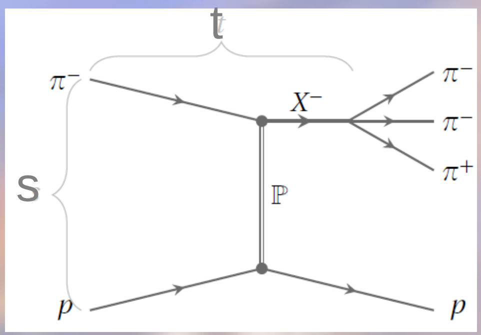
Huge statistics

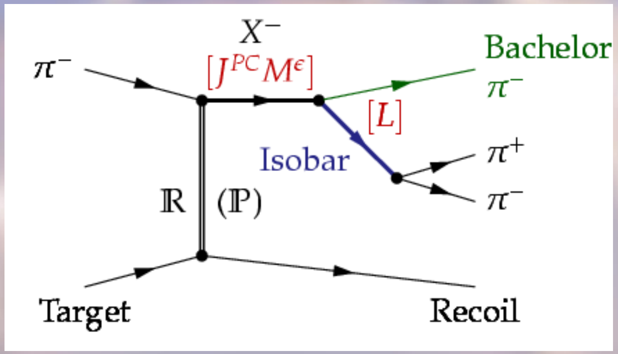
Major progress on analysis
Potential for discovery of small intensity new states

Selected results

- Diffractive processes $\pi^- p \rightarrow \pi^-\pi^+\pi^- p_{recoil}$
- Pion polarisability π^- Ni $\rightarrow$ π^- Ni γ - (2009 Primakoff)

Diffractive resonance production in $\pi^- p \rightarrow \pi^-\pi^+\pi^- p_{recoil}$





Isobar model

Partial waves :
J^{PC} M^ε [isobar] L

J^{PC}-exotic mesons

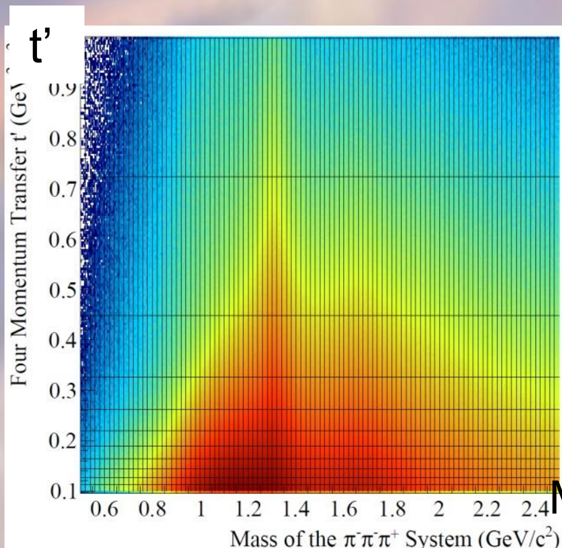
Study 2008 data, large statistics

Partial Wave Analysis (PWA):

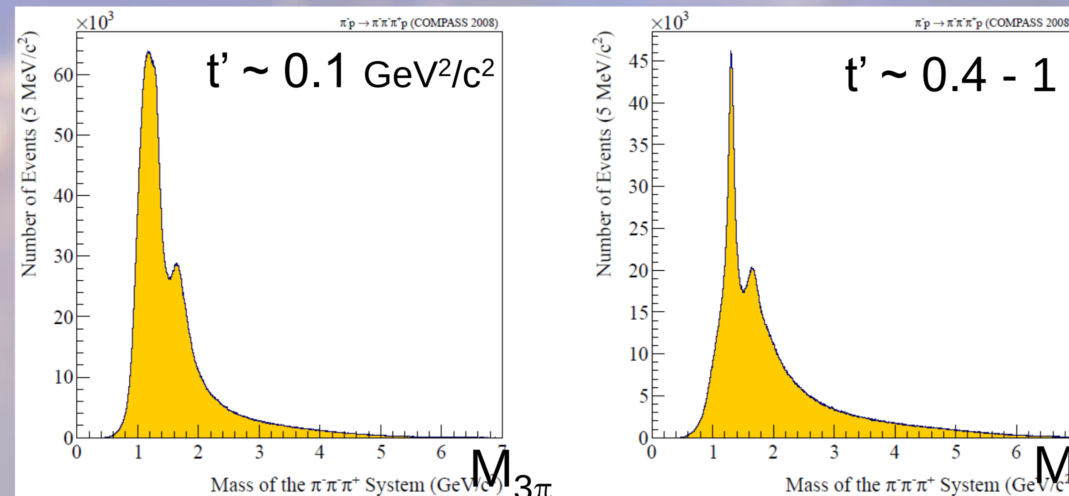
Step 1: In ($M_{3\pi}$, t') bins, 88 PW, (27 with thresholds)
Impose isobar description

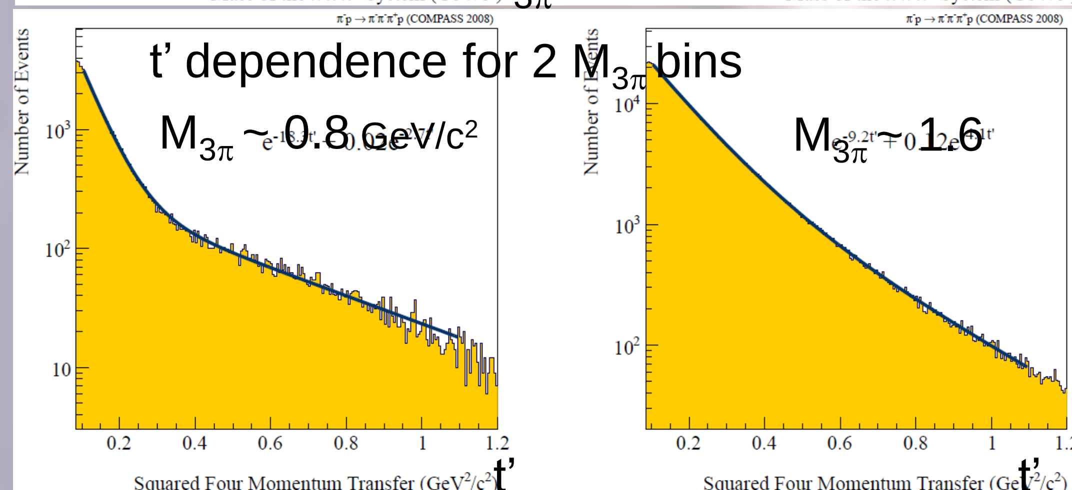
Step 2: $M_{3\pi}$ dependent fits on selected waves,
combined fit of t' bins
(same mass, width; different background and couplings)
Extract resonance parameters

Shape of mass in 2 t' bins



11 x 100 (t',$M_{3\pi}$) bins



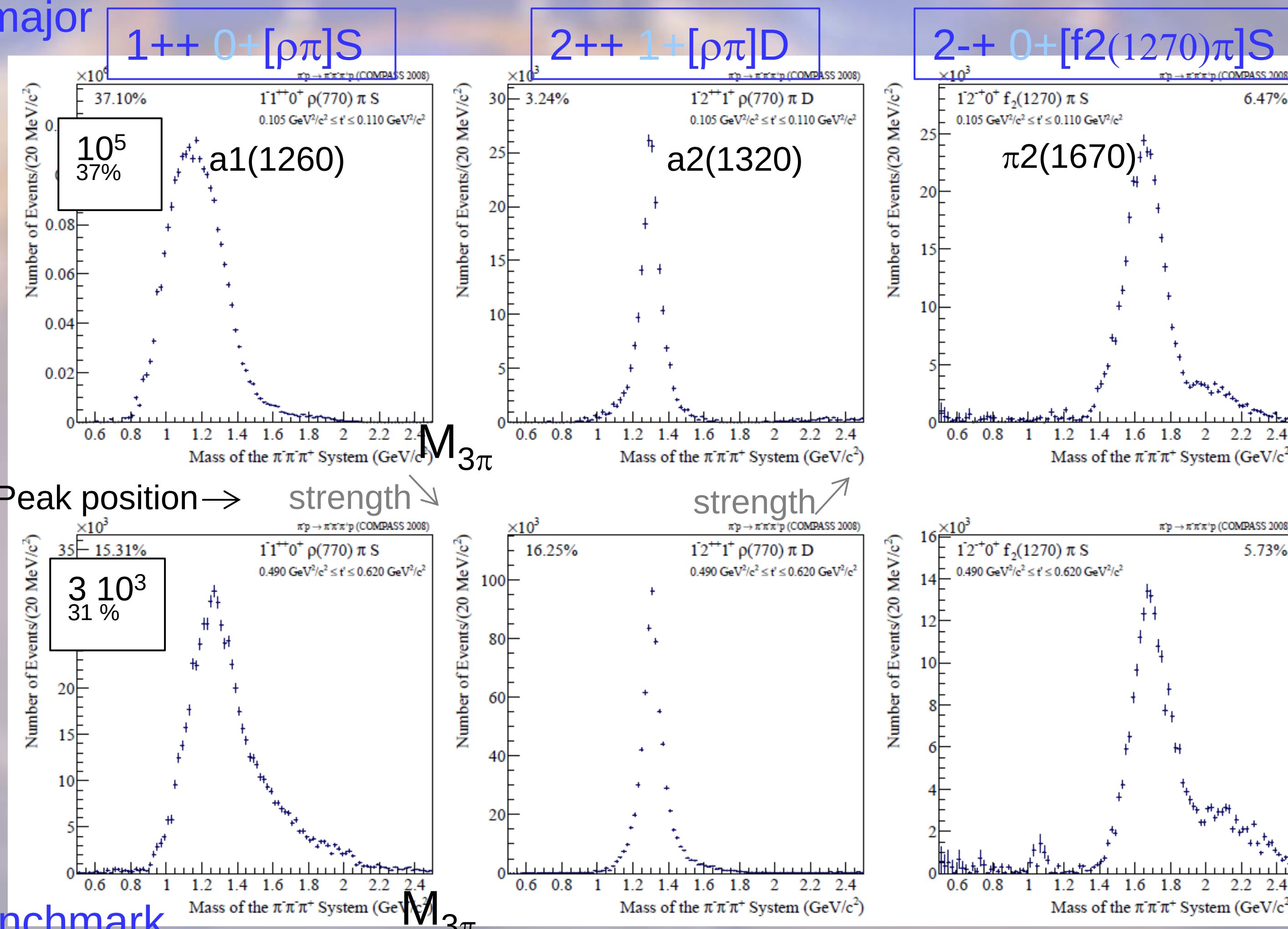


Step 1: PWA in (M, t') bins

Intensities for 3 major waves vs $M_{3\pi}$

t'~0.1 (GeV^2/c^2)
100 $M_{3\pi}$ bins

t'~0.5

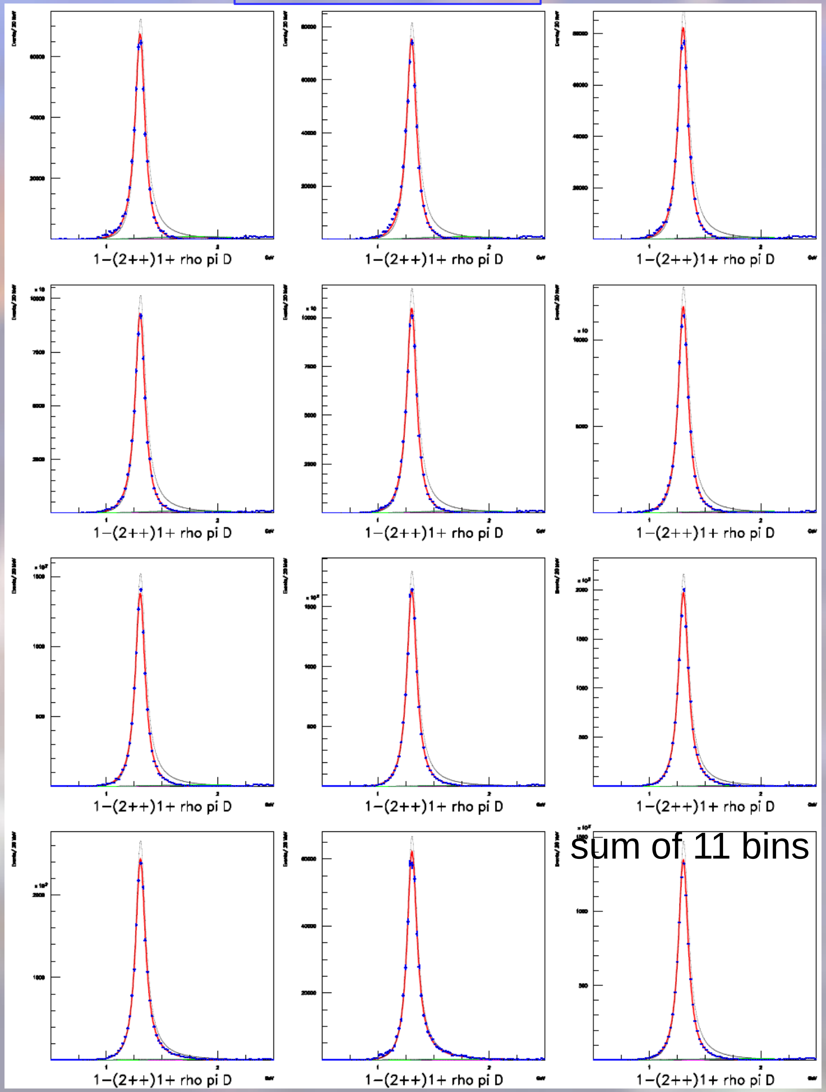


- a1 as benchmark
- Possibility of separation of resonant and non resonant content

high statistics & fine binning

Step 2 : PWA $M_{3\pi}$ dependent fit, ex: 2++

2++ 1+[ρπ]D

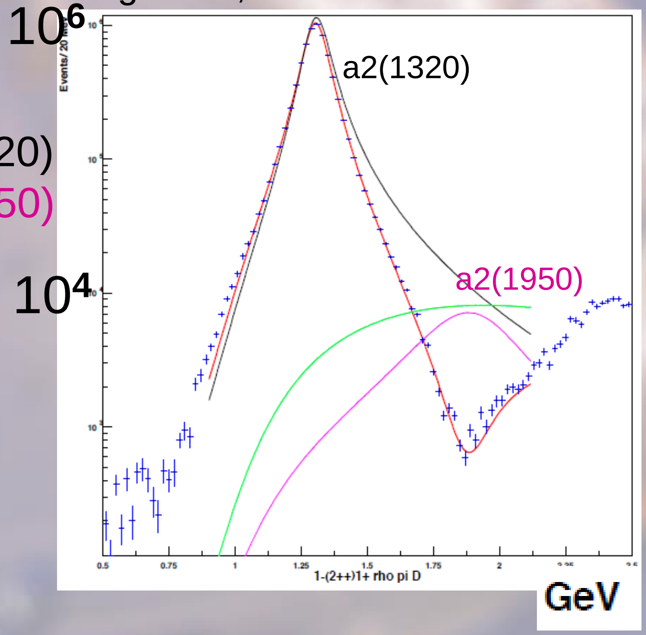


- Mass dependent fits for 5 selected waves, using a model for 3π resonance + bkgd.
- 11 t' bins

- data

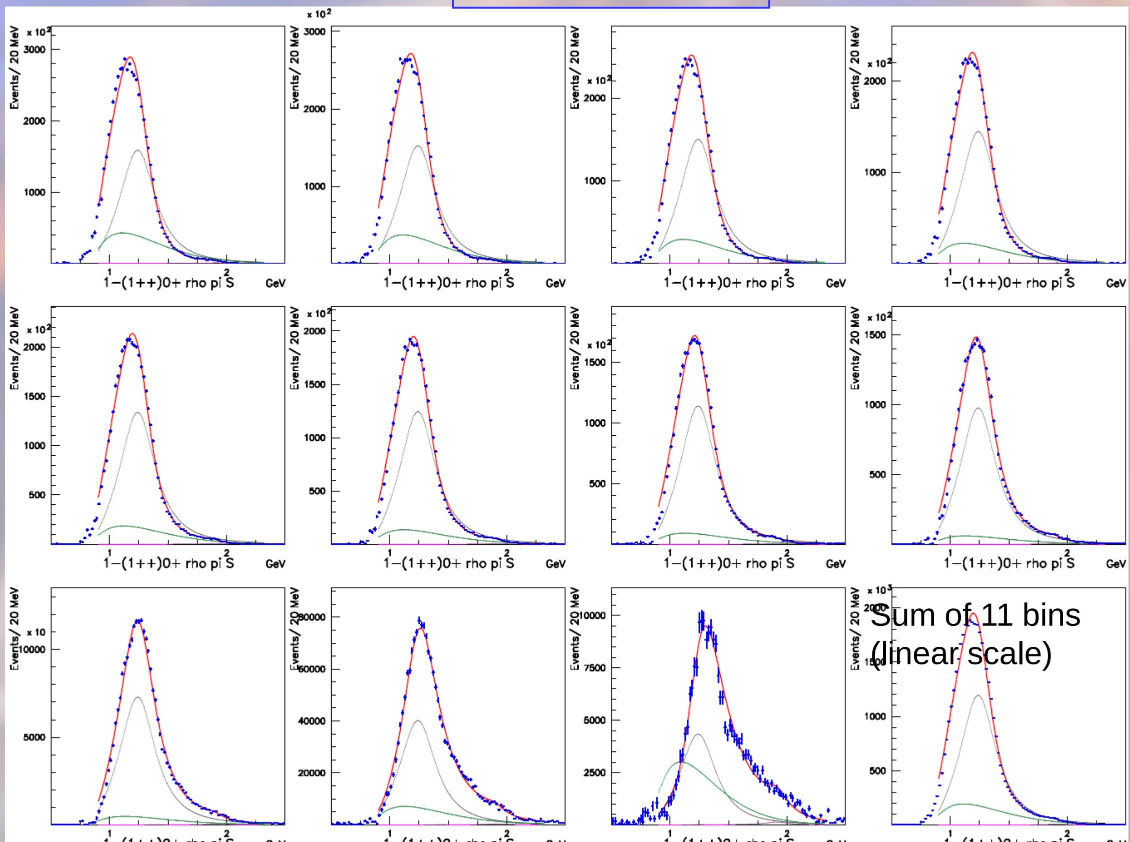
--- model :
BW-a2 (1320)
+ BW-a2 (1950)
+ Bkgd

log scale, sum of 11 bins



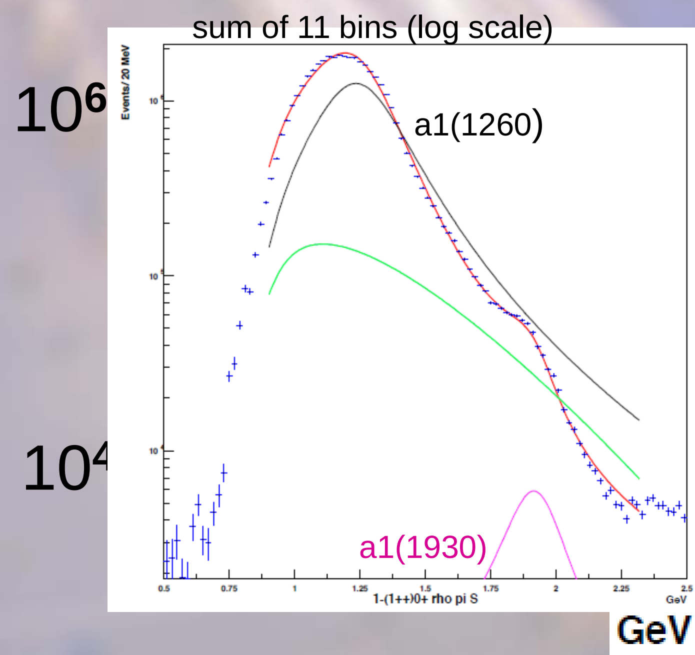
PWA $M_{3\pi}$ dependent fit, ex: 1++

1++ 0+[ρπ]S



- data

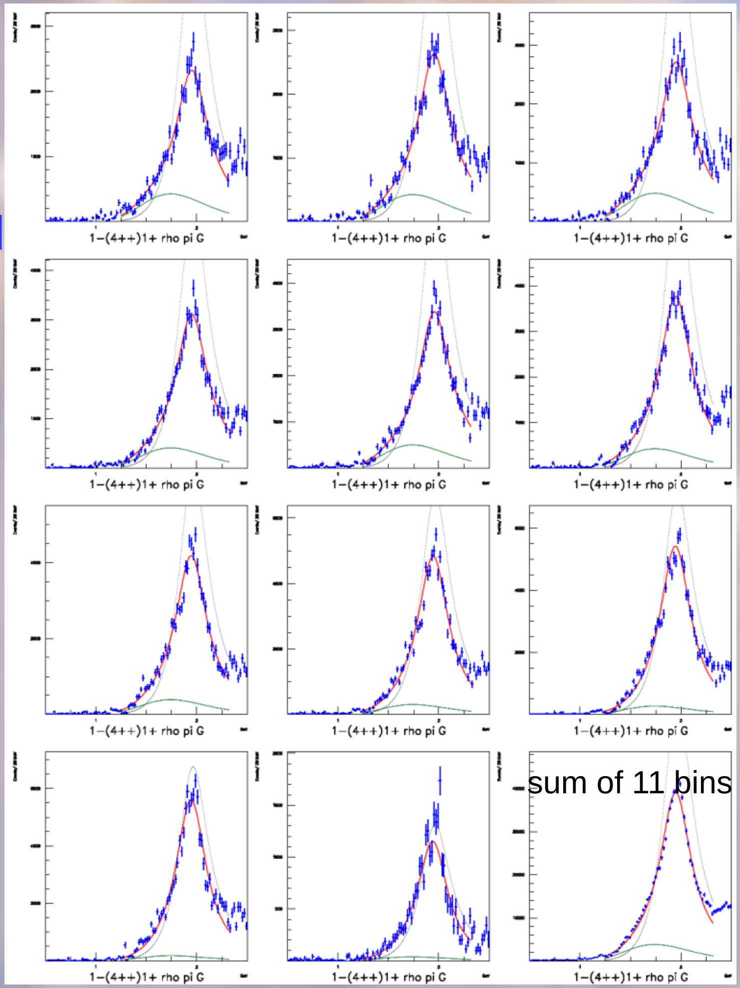
--- model :
BW-a1 (1260)
+ BW-a1 (1930)
+ Bckgd



PWA $M_{3\pi}$ dependent fit, ex: small wave 4++

4++ 1+[ρπ]G

<1% of total intensity,
a4(2040) well established



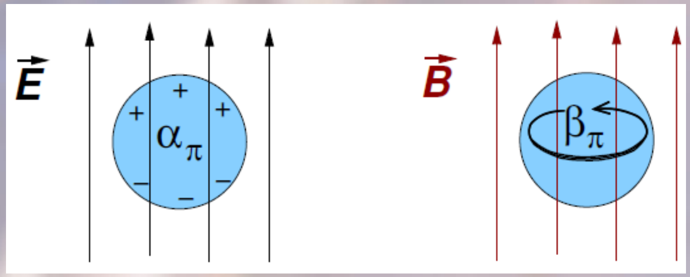
- data

--- model :
BW-a4 (2040)
+ Bckgd

Pion polarisabilities - Primakoff 2009 data

Polarisabilities: deviation from pointlike particle

electric (α) and magnetic (β)



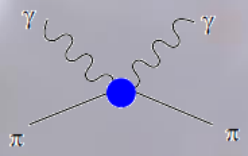
Predictions from Ch PT:

$$\alpha_\pi + \beta_\pi = (0.2 \pm 0.1) \cdot 10^{-4} \mathrm{fm}^3$$
$$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \cdot 10^{-4} \mathrm{fm}^3$$
$$\alpha_\pi = (2.9 \pm 0.5) \cdot 10^{-4} \mathrm{fm}^3$$

Experiments inconclusive:

$\alpha_\pi - \beta_\pi$ = 4 -14 . 10^{-4}

assuming ($\alpha_\pi + \beta_\pi$ =0)



At LO, Compton cross section is proportional to $\alpha_\pi - \beta_\pi$

$\pi\,\gamma \rightarrow \pi\,\gamma$ measured via $\pi\,Z \rightarrow \pi\,Z\;\gamma$

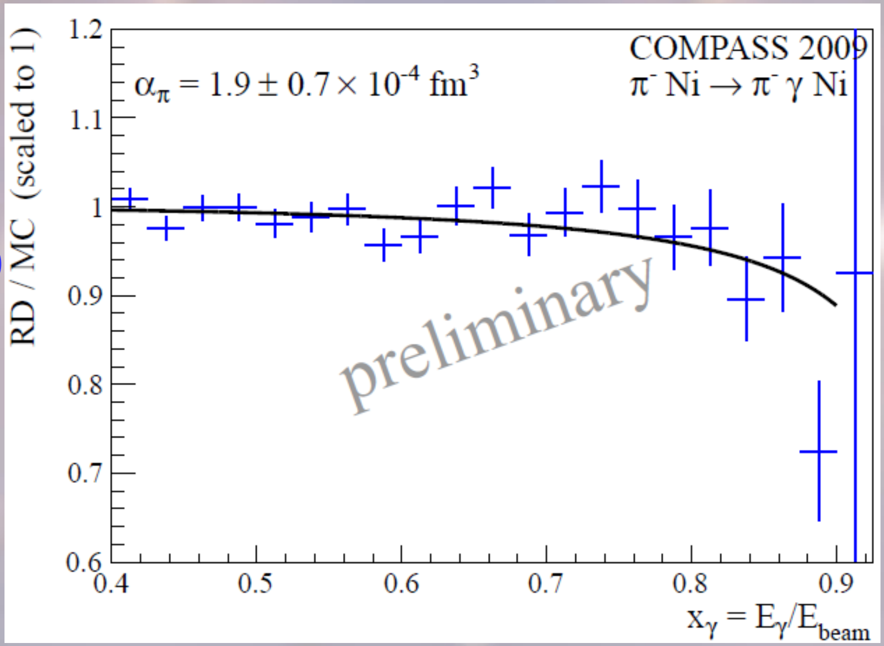
Pion polarisability - result

2009 data $\pi^- Ni \rightarrow \pi^- Ni\ \gamma$ exclusive reaction

- high resolution vertexing, precise calorimetry, calibrations, alignment
- precise MC description of spectrometer performance,

$\alpha_\pi - \beta_\pi$ extracted from comparison of data to MC(pointlike)

Ratio: data/MC (pointlike)



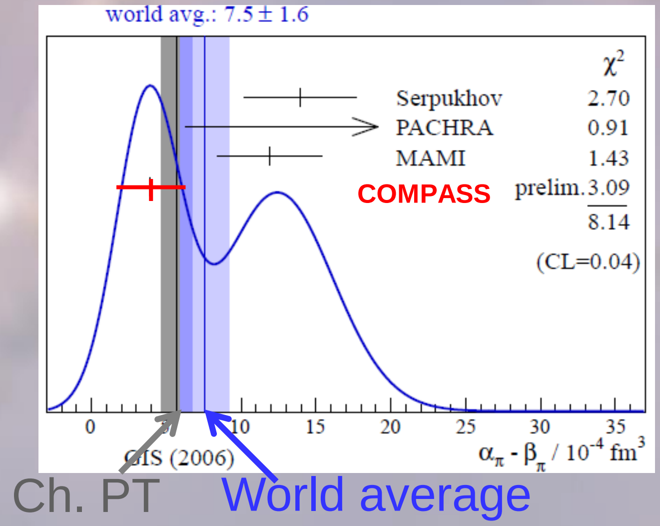
$\alpha_\pi - \beta_\pi = (3.7 \pm 1.4)\ \times 10^{-4}\ \text{fm}^3$

$\alpha_\pi\ = (1.9 \pm 0.7) \times 10^{-4}\ \text{fm}^3$ (assuming $\alpha_\pi + \beta_\pi = 0$)

Pion polarisability – result vs world data

COMPASS result :

in agreement with ChPT expectation,
does not confirm other dedicated measurements



2012 data: 5-6 times more statistics & extended kin range

FUTURE

COMPASS

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \left[\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}}\right]_{pt} + C.\frac{(s-m_\pi^2)}{s^2}\cdot\Big((1-\cos\theta_{cm})^2(\alpha_\pi-\beta_\pi) + (1+\cos\theta_{cm})^2(\alpha_\pi+\beta_\pi)\frac{s^2}{m_\pi^4} + (1-\cos\theta_{cm})^3(\alpha_2-\beta_2)\frac{(s-m_\pi^2)^2}{24s}\Big)$$

Polarisability effect with increasing s at backward or forward angle

2009 data

$\alpha_\pi - \beta_\pi$ (in 10^{-4} fm^3)=

$3.7 \pm 1.4_{stat} \pm 1.6_{syst}$

AGREEMT WITH CHPT

STILL PRELIMINARY

2012 data, 3 components

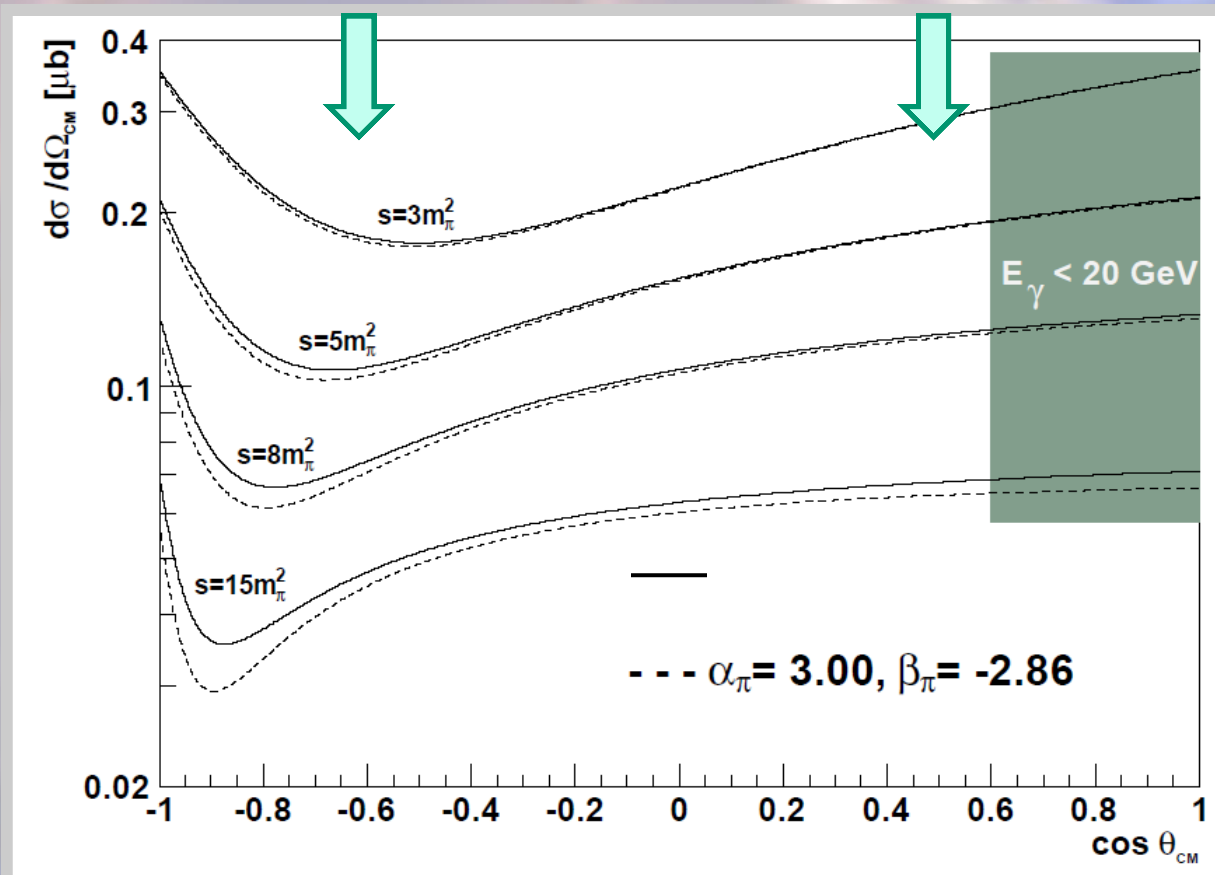
$(\alpha_\pi - \beta_\pi)$

$(\alpha_\pi + \beta_\pi)$

$(\alpha_2 - \beta_2)$

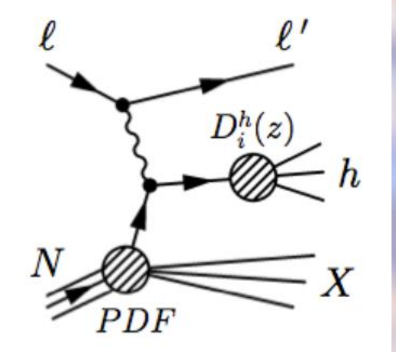
can be measured with an accuracy of 10%

and kaon polarizabilities



Semi-Inclusive Deep Inelastic Scattering

Semi-Inclusive DIS measurements • with polarized targets (2002-2011)
• with a pure proton target (with GPD program



Use of RICH detector and Calorimeters
Charge separation and identification K^+, K^-, K^0, π^+, π^-, π^0, Λ…

Major progress as compared to previous experiments
to strange PDFs: s(x) and Δs(x)

Hadron multiplicities at LO

$$\frac{dN^h(x,z,Q^2)}{dN^{DIS}} = \frac{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

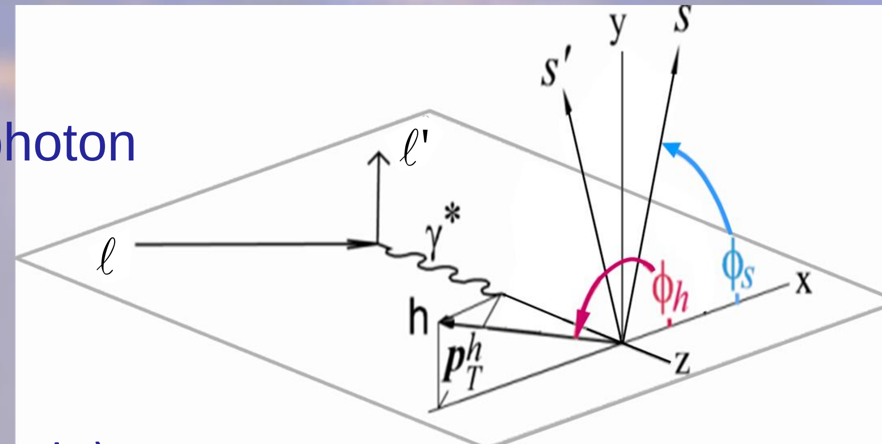
PDF
depend on x

quark Fragmentation Function
depend on z (fraction of energy of the outgoing hadron)

Final goal: extensive measurements *(x, z, Q^2, p_T^h)*
to provide inputs to NLO global analysis for both PDF and FF

TMDs

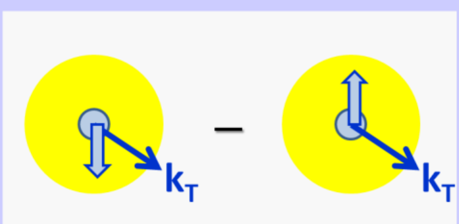
Asymmetries in the azimuthal angle ϕ_h
of the outgoing hadron around the virtual photon
can reveal quark transverse spin and
quark transverse momentum (k_T) effects
beyond the collinear approximation



At leading twist, not only $f_1(x, k_T)$, $g_{1L}(x, k_T)$, $h_1(x, k_T)$
but also 5 otherTransverse Momentum Dependent PDF (TMD (x, k_T))
which do not survive after integration on k_T

2 examples of TMDs

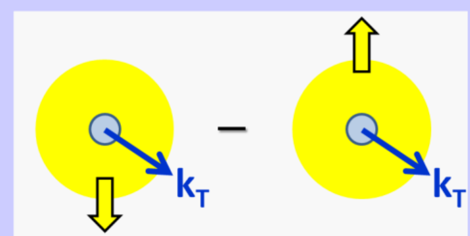
The **Boer-Mulders** function



correlates the quark k_T and
the quark transverse spin (unpol N)

Chiral-odd and T-odd

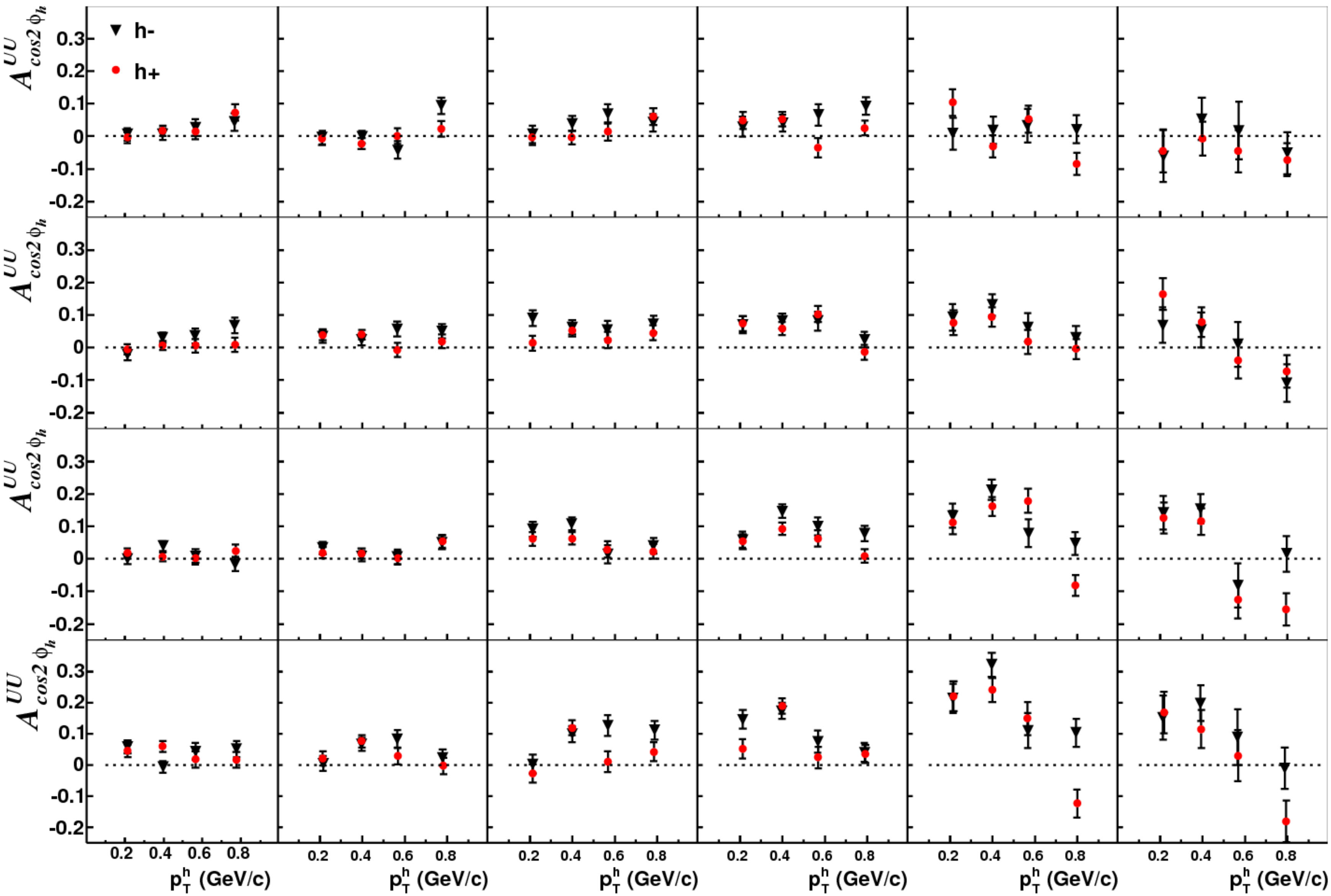
The **Sivers** function



correlates the quark k_T and
the nucleon spin (transv. Pol. N)

Chiral-even and T-odd

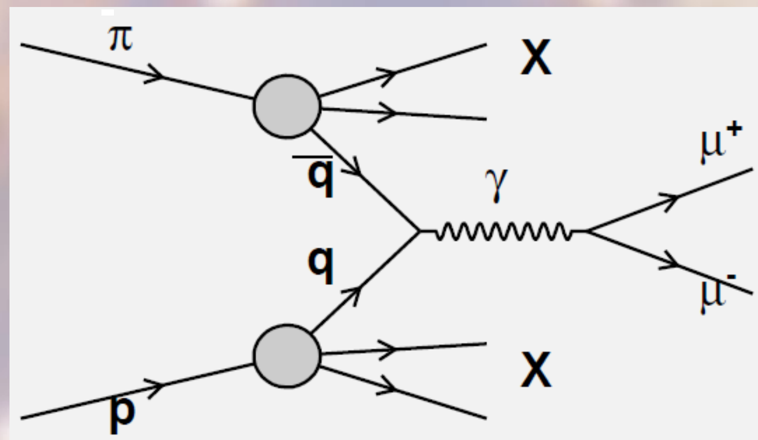
COMPASS ^{6}LiD (25% of 2004 data) preliminary



→many data collected and still to be collected in SIDIS with GPD program

After SIDIS, polarized Drell-Yan to study TMDs

Drell –Yan $\pi^- p^\uparrow \rightarrow \mu^+\mu^- X$



Cross sections:

In SIDIS: convolution of a TMD with a fragmentation function

In DY: convolution of 2 TMDs $\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f_{u|p}$

→ complementary information and universality test

The polarized Drell-Yan process in π⁻ p

$$\frac{d\sigma}{d^4q d\Omega} = \left[\frac{\alpha^2}{Fq^2}\left(F_{UU}^1 + F_{UU}^1\right)\left(1 + A_{UU}^1 \cos^2\theta\right)\right] \times$$

$$\left\{ \begin{array}{l} 1 + \cos\varphi \times D_{[\sin 2\theta]} A_{UU}^{\cos\varphi} + \cos(2\varphi) \times D_{[\sin^2\theta]} A_{UU}^{\cos(2\varphi_h)} + \\ S_L \left[\sin\varphi \times D_{[\sin 2\theta]} A_{UL}^{\sin\varphi} + \sin(2\varphi) \times D_{[\sin^2\theta]} A_{UL}^{\sin(2\varphi)} \right] + \\ \mathbf{S}_T \left[\begin{array}{l} \sin\varphi_S \times \left(D_{[1]} A_{UT}^{\sin\varphi_S} + D_{[\cos^2\theta]} \tilde{A}_{UT}^{\sin\varphi_S} \right) + \\ \sin(\varphi - \varphi_S) \times \left(D_{[\sin 2\theta]} A_{UT}^{\sin(\varphi-\varphi_S)} \right) + \\ \sin(\varphi + \varphi_S) \times \left(D_{[\sin 2\theta]} A_{UT}^{\sin(\varphi+\varphi_S)} \right) + \\ \sin(2\varphi - \varphi_S) \times \left(D_{[\sin^2\theta]} A_{UT}^{\sin(2\varphi-\varphi_S)} \right) + \\ \sin(2\varphi + \varphi_S) \times \left(D_{[\sin^2\theta]} A_{UU}^{\sin(2\varphi_h+\varphi_S)} \right) \end{array} \right] + \end{array} \right\}$$

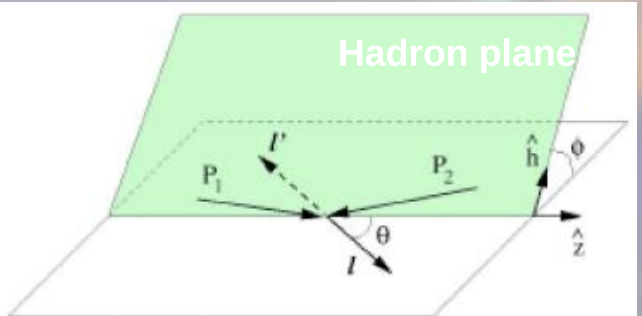
➔Access to TMDs for incoming pion ⊗ target nucleon
TMD as Transversity, Sivers, Boer-Mulders, pretzelosity

Collins-Soper frame (of virtual photon)

θ, φ lepton plane wrt hadron plane

target rest frame

φ_S target transverse spin vector /virtual photon

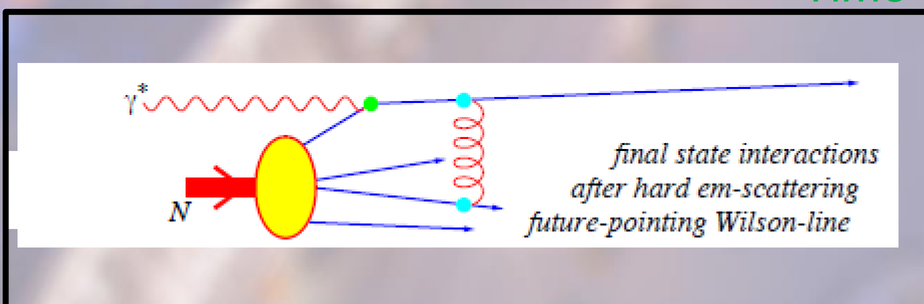


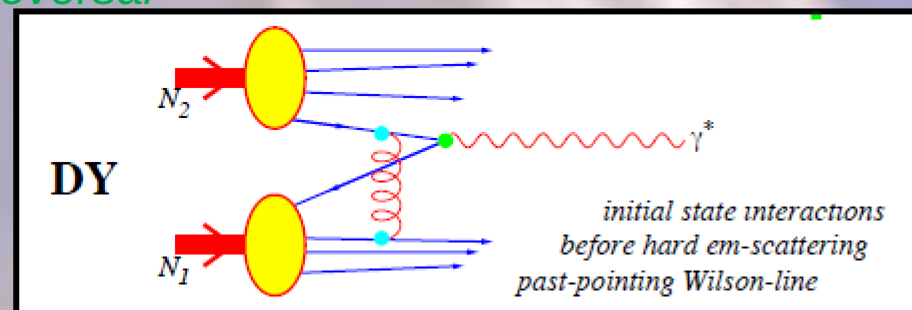
Experimental check of the change of sign of TMDs confronting Drell-Yan and SIDIS results

T-odd character of the Boer-Mulders and Sivers functions

In order not to be forced to vanish by time-reversal invariance
the SSA requires an interaction phase generated by
a rescattering of the struck parton in the field of the hadron remnant

Time reversal





these functions are process dependent, they change sign to provide the gauge invariance

Boer-Mulders

$$h_1^{\perp}(SIDIS) = -h_1^{\perp}(DY)$$

Sivers

$$f_{1T}^{\perp}(SIDIS) = -f_{1T}^{\perp}(DY)$$

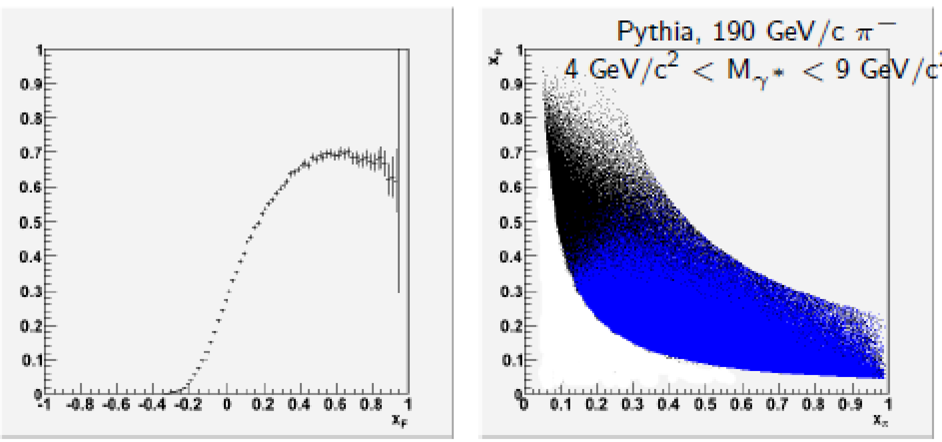
NEED EXPERIMENTAL VERIFICATION
SIGN + AMPLITUDE + SHAPE

TEST OF CONSISTENCY
OF THE APPROACH

Why DY $\pi p^{\uparrow}$ is very favourable at COMPASS?

σ^{DY} dominated by the annihilation of a valence anti-quark from the pion and a valence quark from the polarised proton

$$\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f_{u|p}$$



x_F acceptance plot

x_p vs x_π scatter plot: in black all generated events, in blue events in acceptance

Competitive experiments at

RHIC (STAR, PHENIX) collider $p^{\Uparrow} p$

Fermilab fixed target $p^{\Uparrow\Rightarrow} H$, $pH^{\Uparrow\Rightarrow}$

J-PARC fixed target $pp^{\Uparrow}$, $\pi p^{\Uparrow}$

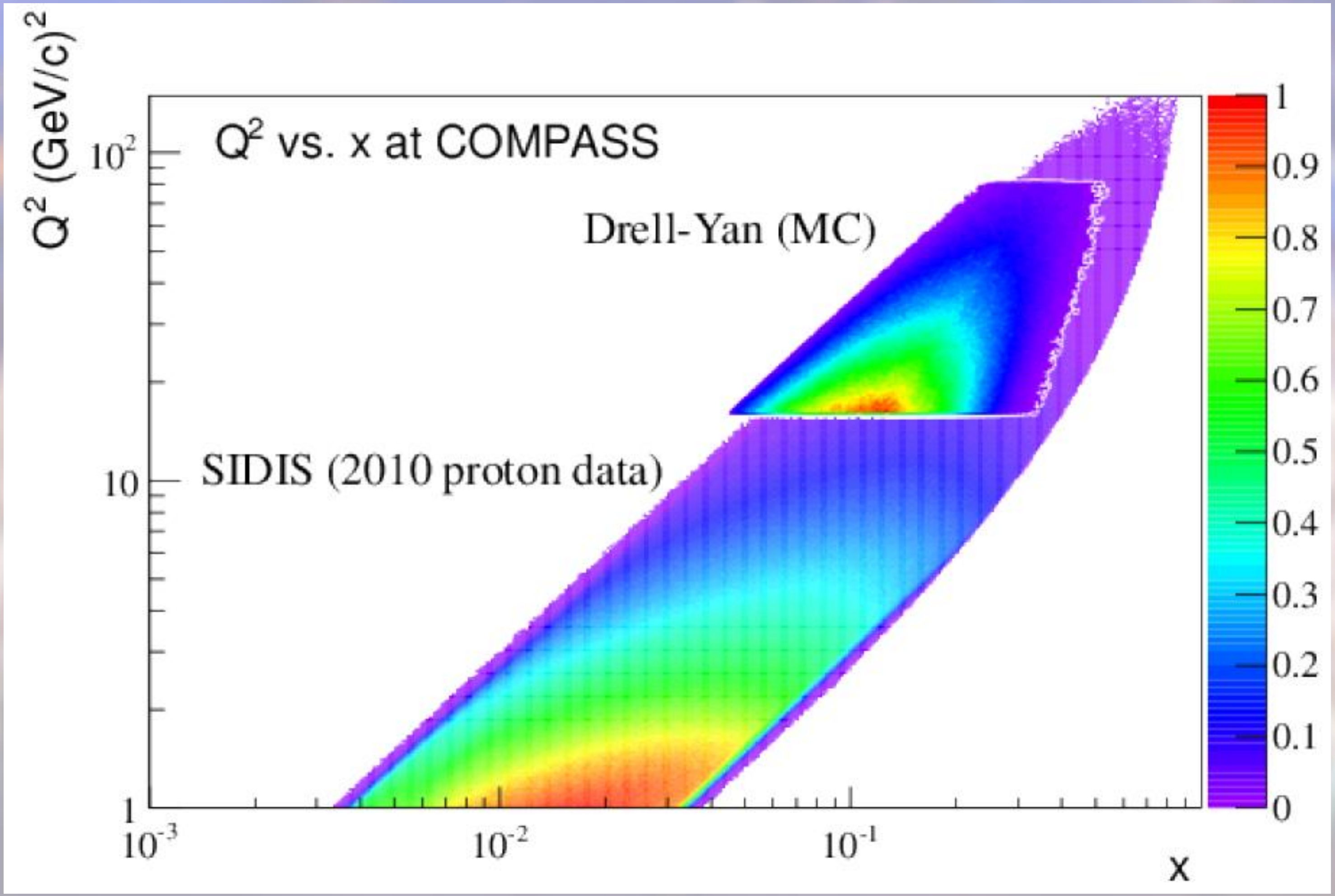
FAIR (PAX) collider $\bar{p}^{\Uparrow} p^{\Uparrow}$

NICA collider $p^{\Uparrow} p^{\Uparrow}$, $d^{\Uparrow} d^{\Uparrow}$

large acceptance of COMPASS
in the valence quark region for p and π
where SSA are expected to be larger

COMPASS has the chance to be the first experiment to collect single polarized DY

Q^2 vs x phase space at COMPASS



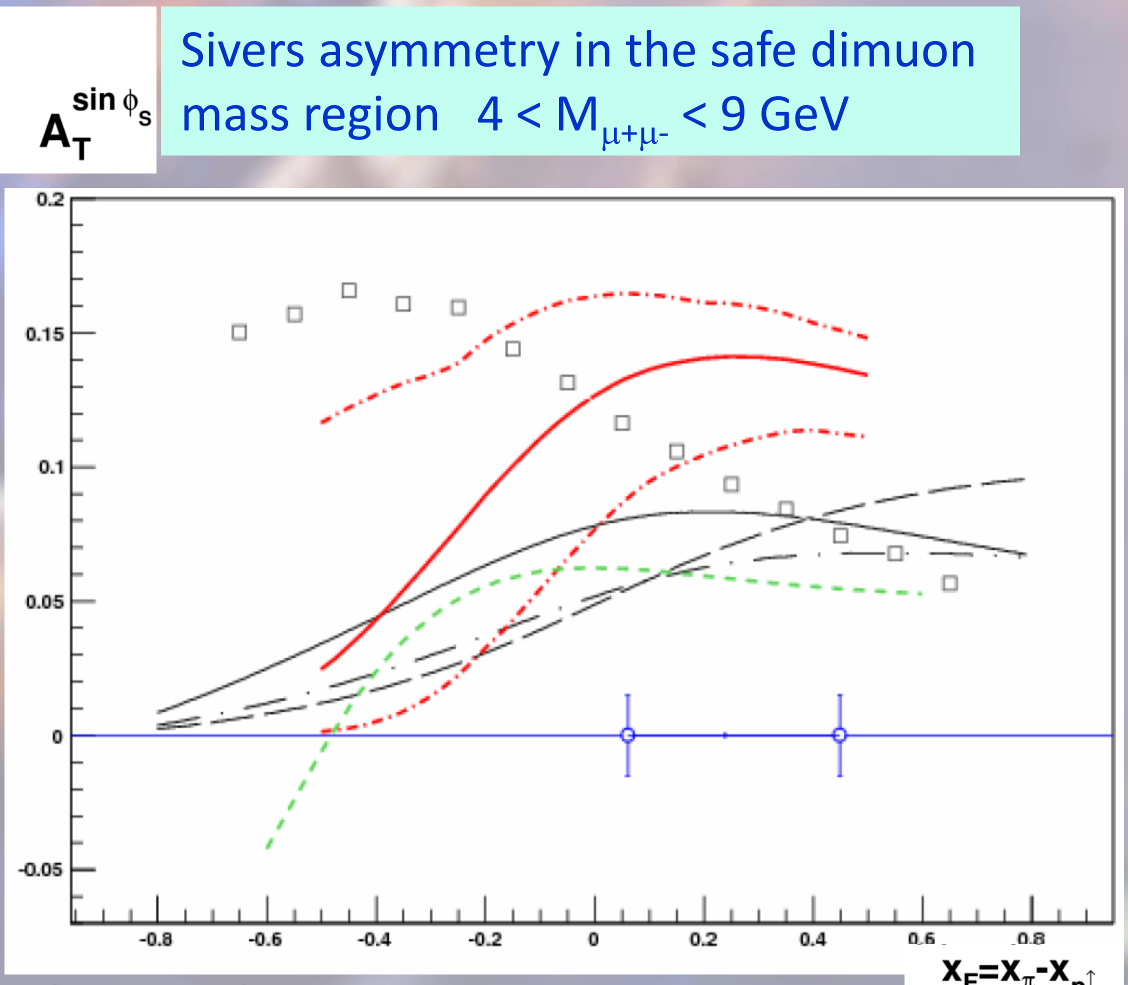
The phase spaces of the two processes overlap at COMPASS

→ Consistent extraction of TMD DPFs in the same region

Predictions for Drell-Yan at COMPASS

$$A_T^{\sin\phi_S}(x_a,x_b) = \frac{2}{f\,|S_T|}\frac{\int \mathrm{d}\phi_S \mathrm{d}\phi \frac{\mathrm{d}N(x_a,x_b,\phi,\phi_S)}{\mathrm{d}\phi\,\mathrm{d}\phi_S}\sin\phi_S}{N(x_a,x_b)}$$

Sivers asymmetry in the safe dimuon mass region $4 < M_{\mu+\mu-} < 9$ GeV



2 years of data

190 GeV pion beam

$6 \cdot 10^8$ π^-/spill (of 9.6s)

1.1 m transv. pol. NH_3 target

Lumi=$1.2\ 10^{32}$ $cm^{-2}s^{-1}$

Red solid and dod-dashed line

Anselmino et al., PRD79 (2009

Black solid and dashed:

Efremov et al., PLB612 (2005)

Black dot-dashed:

Collins et al., PRD73 (2006)

Squares:

Bianconi et al., PRD73 (2006)

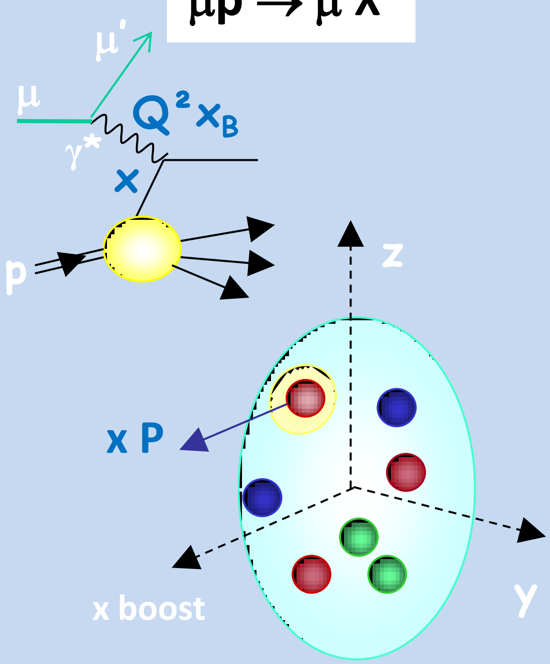
Green short-dashed:

Bacchetta et al., PRD78 (2008)

From inclusive to exclusive reactions (3D tomography)

Deep Inelastic Scattering

$\mu p \rightarrow \mu' X$

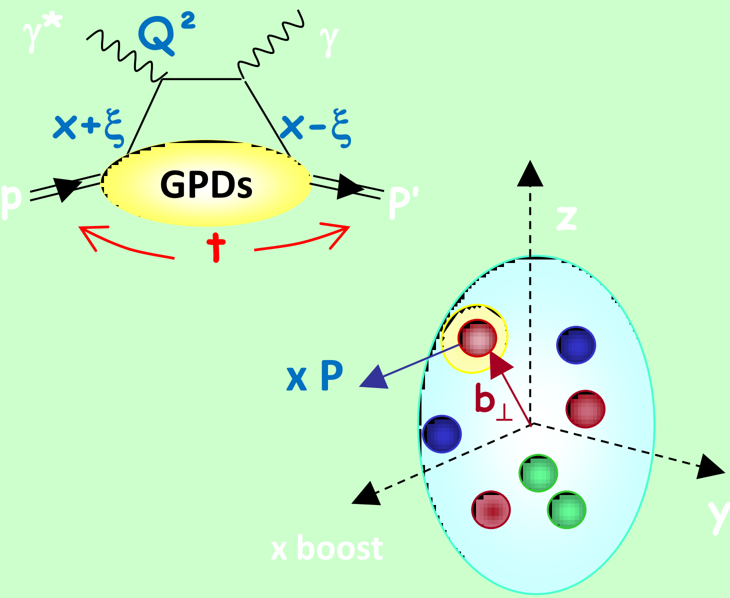


Distrib. de Partons q (x)

P_x

Deeply Virtual Compton Scattering

$\mu p \rightarrow \mu' p' \gamma$



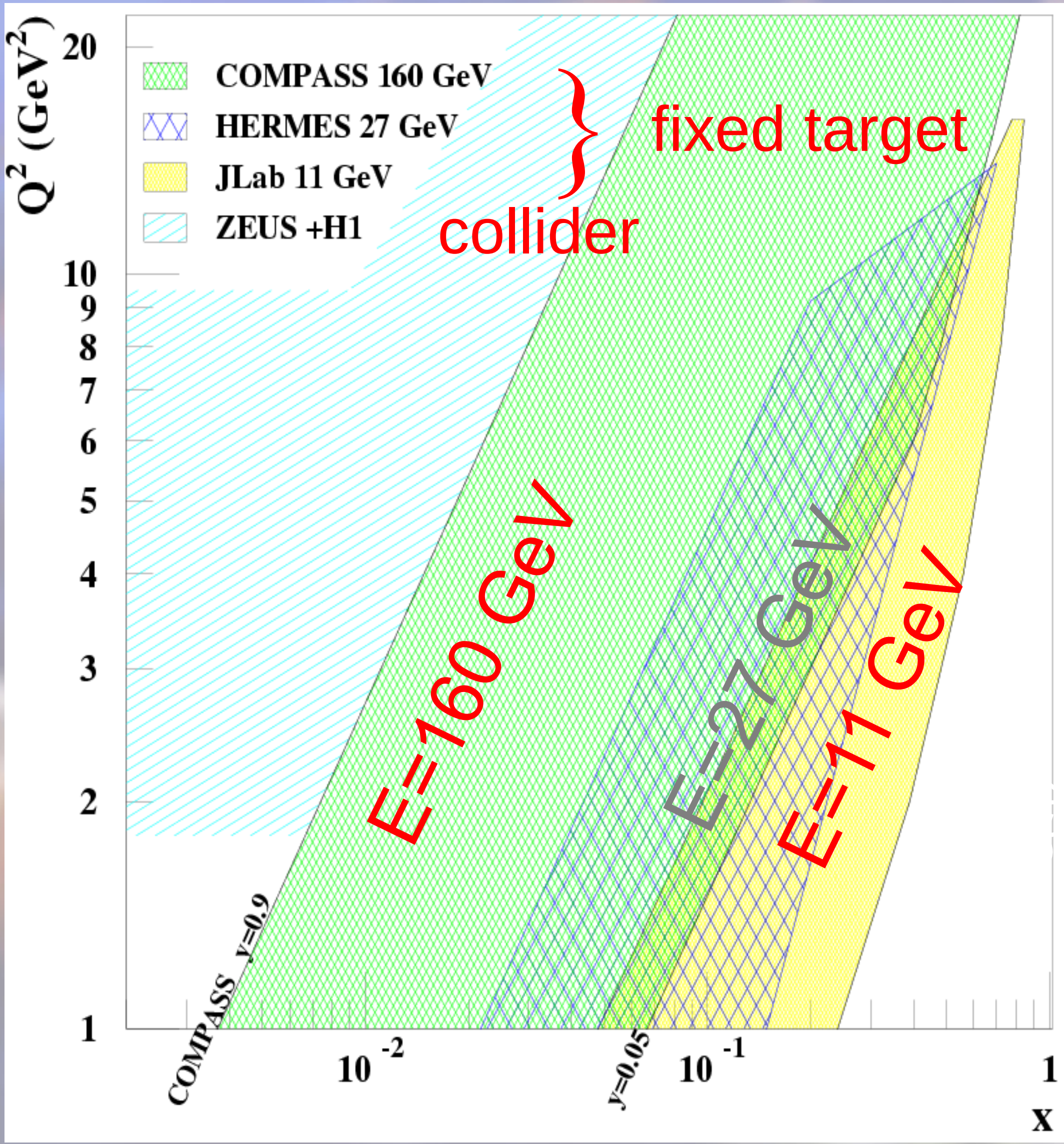
Generalized Partons Distrib. $H(x, \xi, t)$

$(P_x, b_\perp)$

Beyond collinear approximation -> Trans. Position ($b_\perp$) Dependent GPD in Excl. React.

-> as Trans. Momentum ($k_\perp$) Dep. PDF or TMD in SIDIS & DY

Kinematic domain (Q^2, x_B) for GPDs



COMPASS unique for GPDs

CERN High energy muon beam

- ✓ **100 - 190 GeV**
- ✓ **$\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ available**
- ✓ **80% Polarisation with opposite polarization**

✓ **4.6 10^8 μ^+**

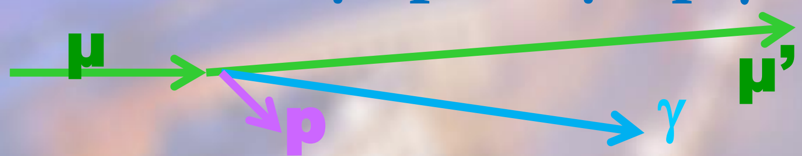
➔ **Lumi= 10^{32} cm^{-2} s^{-1} with 2.5m LH2 target**

- ➢ Explore the intermediate x_{Bj} region
- ➢ Uncovered region between ZEUS+H1 & HERMES **+ Jlab** before new colliders may be available

It's time to show the impact of COMPASS
=> goal of the 2012 DVCS pilot run

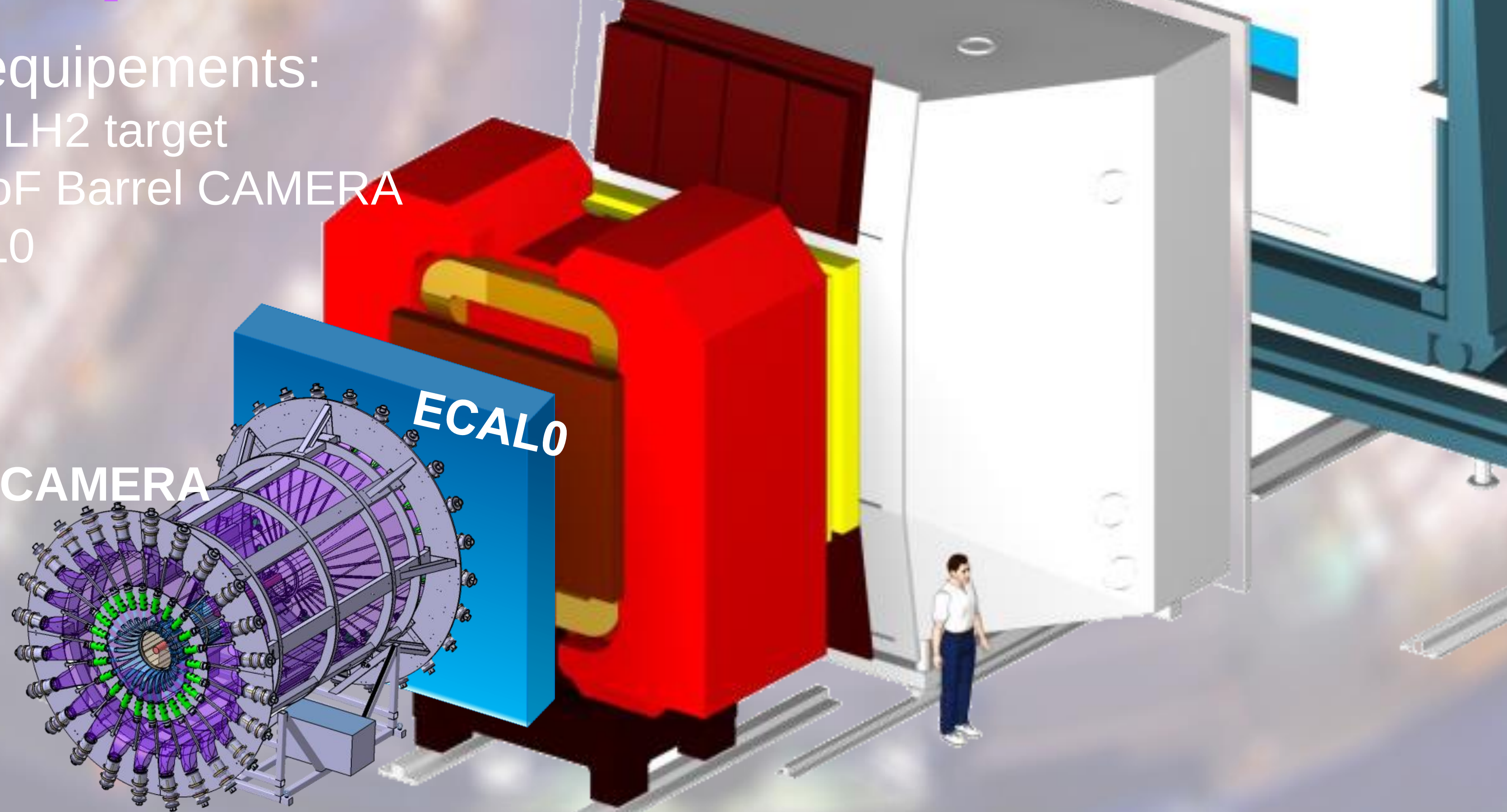
Upgrades of the COMPASS spectrometer

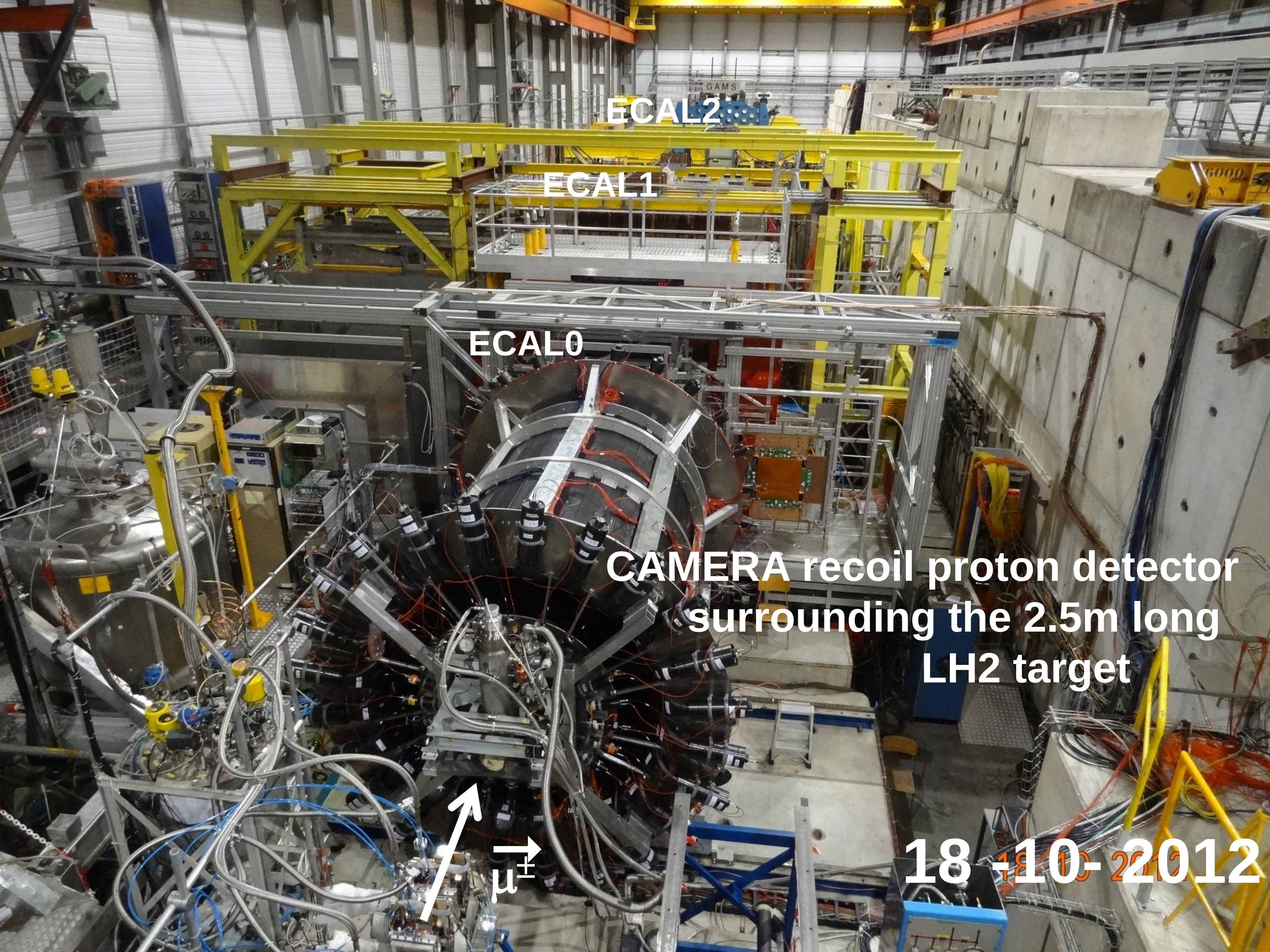
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$



New equipements:

- 2.5m LH2 target
- 4m ToF Barrel CAMERA
- ECAL0




GAMS
ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
$\vec{\mu}^{\pm}$
18-10-2012

Deeply Virtual Compton Scattering

$$d\sigma_{(\mu p\to\mu p\gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \cancel{P_\mu\, d\sigma^{DVCS}_{pol}}$$

$$+\ \cancel{e_\mu}\, a^{BH}\, \mathcal{R}e\, A^{DVCS} \qquad + e_\mu\, P_\mu\, a^{BH}\, \mathcal{I}m\, A^{DVCS}$$

Phase 1: the transverse imaging

with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam + unpolarized 2.5m long LH2 (proton) target

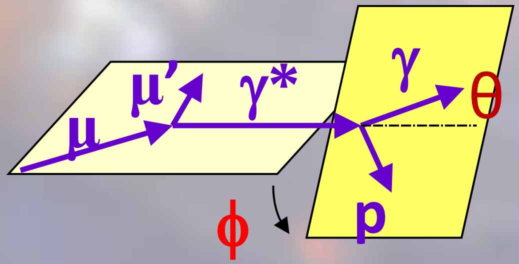
$$S_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + K \cdot s_1^{Int} \sin\varphi$$

Using $S_{CS,U}$ and BH subtraction

and integration over ϕ

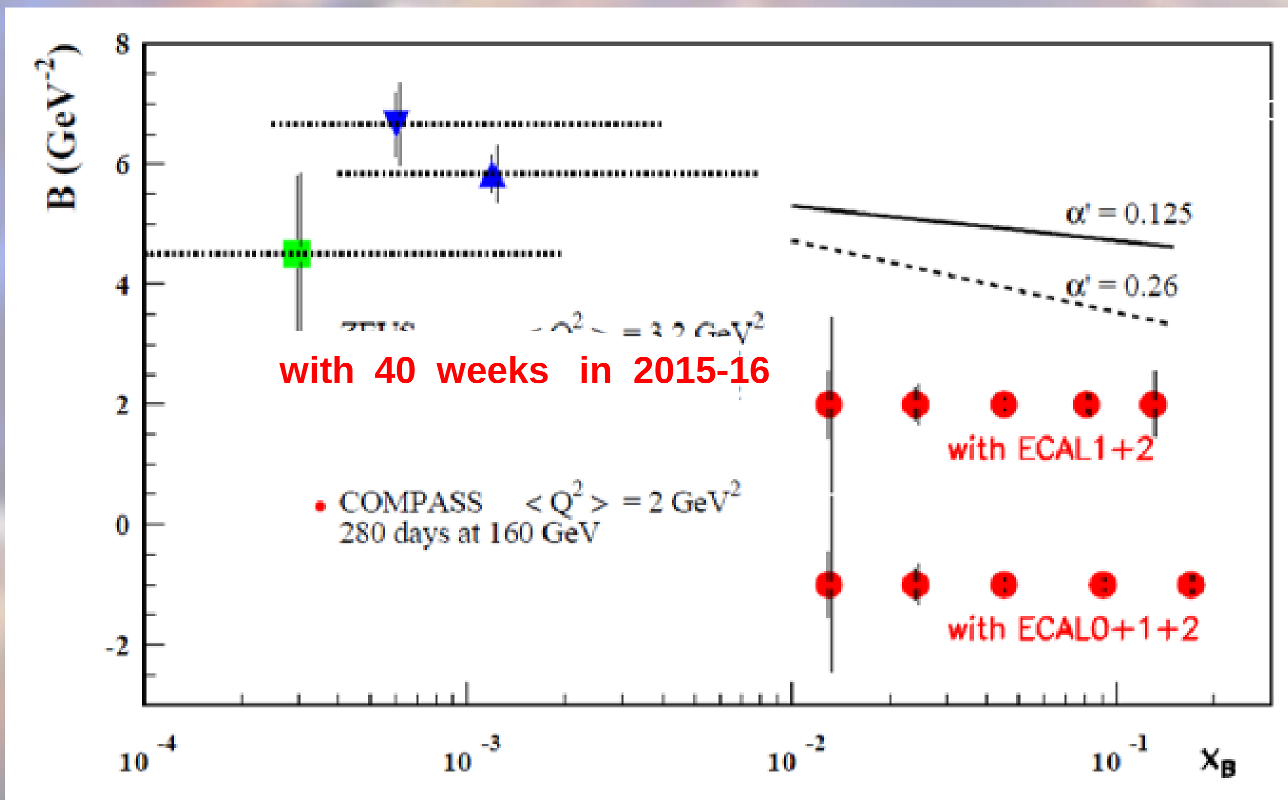
$\downarrow$

$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$



Transverse imaging

$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$



2 years of data
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%

ansatz at small x_B
inspired by
Regge Phenomenology:

$B(x_B) = b_0 + 2\,\boldsymbol{\alpha'}\,\ln(x_0/x_B)$

α' slope of Regge traject

Deeply Virtual Compton Scattering

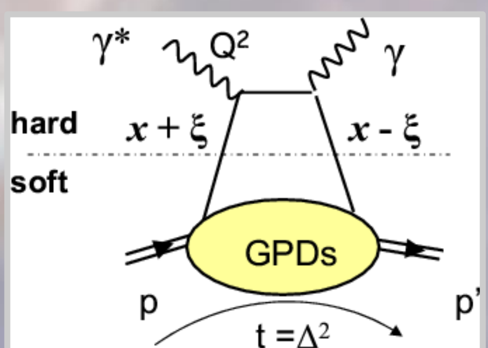
$$d\sigma_{(\mu p\to\mu p\gamma)} = \cancel{d\sigma^{BH}} + \cancel{d\sigma^{DVCS}_{unpol}} + P_\mu\, d\sigma^{DVCS}_{pol} + e_\mu\, a^{BH}\, \mathcal{R}e\, A^{DVCS} + \cancel{e_\mu P_\mu}\, a^{BH}\, \mathcal{I}m$$

Phase 1: DVCS experiment to constrain GPD H

with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam + unpolarized 2.5m long LH2 (proton) target

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int}\cos\phi \quad \text{and} \quad c_{0,1}^{Int} \sim \mathcal{R}e(F_1\mathcal{H})$$

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K\cdot s_1^{Int}\sin\varphi \quad \text{and} \quad s_1^{Int} \sim \mathcal{I}m(F_1\mathcal{H})$$



$\xi \sim x_B / (2-x_B)$

Note: dominance of H at COMPASS kinematics

$$\mathcal{I}m\,\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$$

$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, \frac{H(x,\xi,t)}{x-\xi} = \mathcal{P}\int dx\, \frac{H(x,x,t)}{x-\xi} + D(t)$$

Re part of the *Compton Form Factors* linked to the *D term*

Summary for GPD @ COMPASS

GPDs investigated with Hard Exclusive Photon and Meson Production

COMPASS-II 2016-17: with LH_2 target + RPD (phase 1) $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ 160 GeV

- ✓ the t-slope of the DVCS and HEMP cross section
  → transverse distribution of partons
- ✓ the Beam Charge and Spin Sum and Difference
  → $\mathcal{Re}\, T^{DVCS}$ and $\mathcal{Im}\, T^{DVCS}$ for the GPD H determination
- ✓ Vector Meson $\rho^0, \rho^+, \omega, \Phi$
- ✓ Pseudo-saclar π^0

Using the 2007-10 data: transv. polarized NH_3 target without RPD
In a future addendum > 2017: transv. polarised NH_3 target with RPD (phase 2)

- ✓ the Transverse Target Spin Asymm
  → GPD E and chiral-odd (transverse) GPDs

For the next 10 years, before any collider is available, and complementary to Jlab 12 GeV, COMPASS@CERN can be a major player in QCD physics using its unique high energy (~200 GeV) hadron and polarised positive and negative muon beams


Thank You

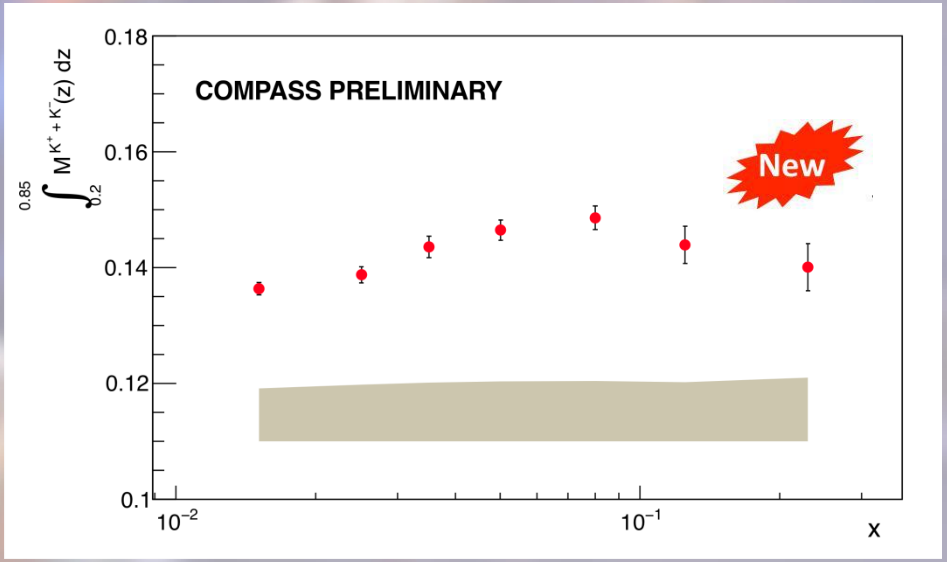
Sensitivity of M^K to strange FF D_s^K

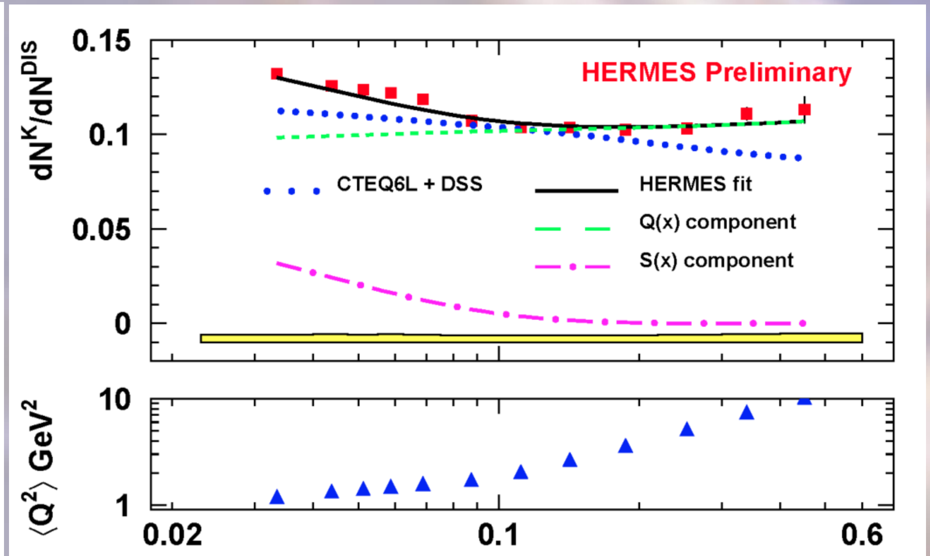
$$\int_{0.2}^{0.85} M^{K^+ + K^-}(x,z)dz = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz}{5Q(x)+2S(x)}$$

$\longrightarrow$ $2S(x) << 5Q(x)$

$$\int_{0.2}^{0.85} M^{K^+ + K^-}(x,z)dz = \frac{1}{5}\left(\int D_Q^K(z)dz + \frac{S(x)}{Q(x)}\int D_S^K(z)dz\right)$$

Directly related to strange PDF and FF of strange quark into K





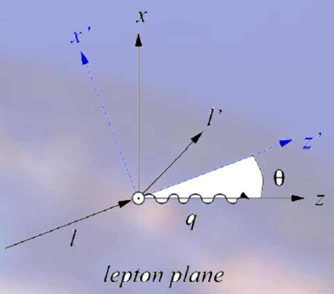
Arxiv 1212. 5407

Small x dependence → small $D_s^K(z)$, R_{SF} or $S(x)$

solves tension for Δs between DIS & SIDIS ?

New tension with HERMES?
more work needed (higher twist…)

SIDIS x-Section

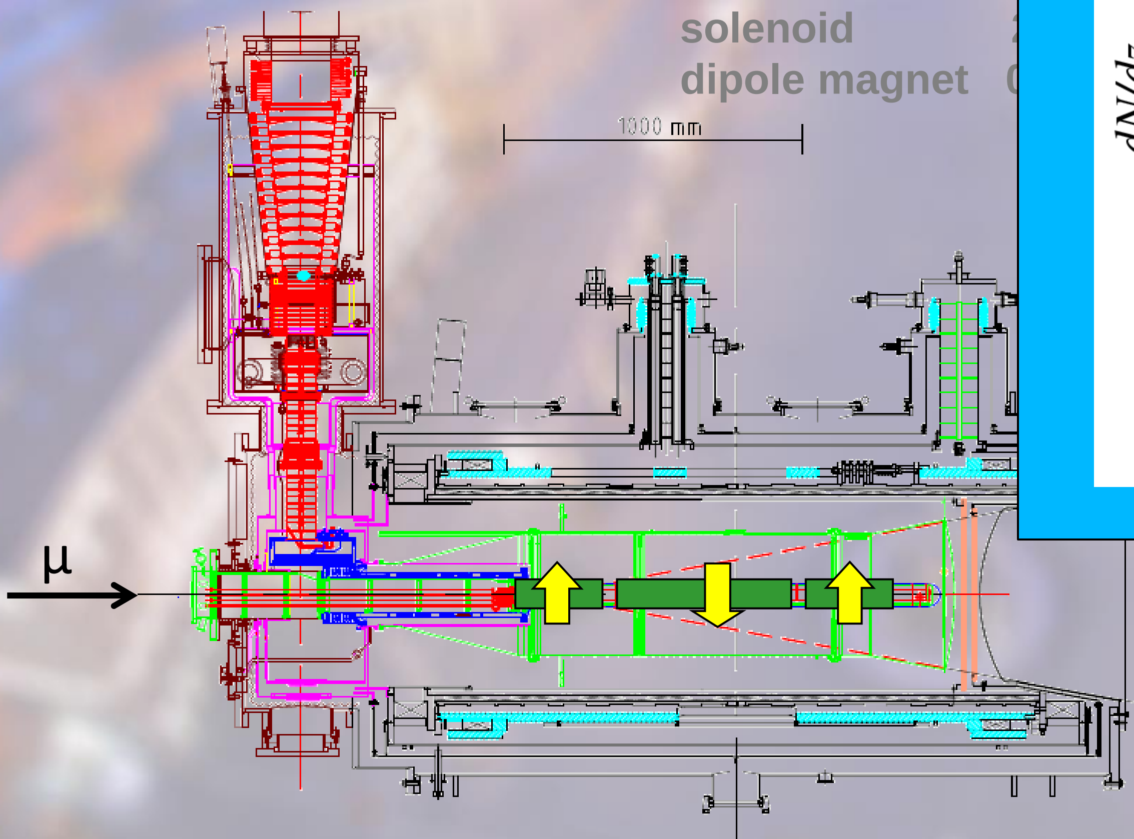


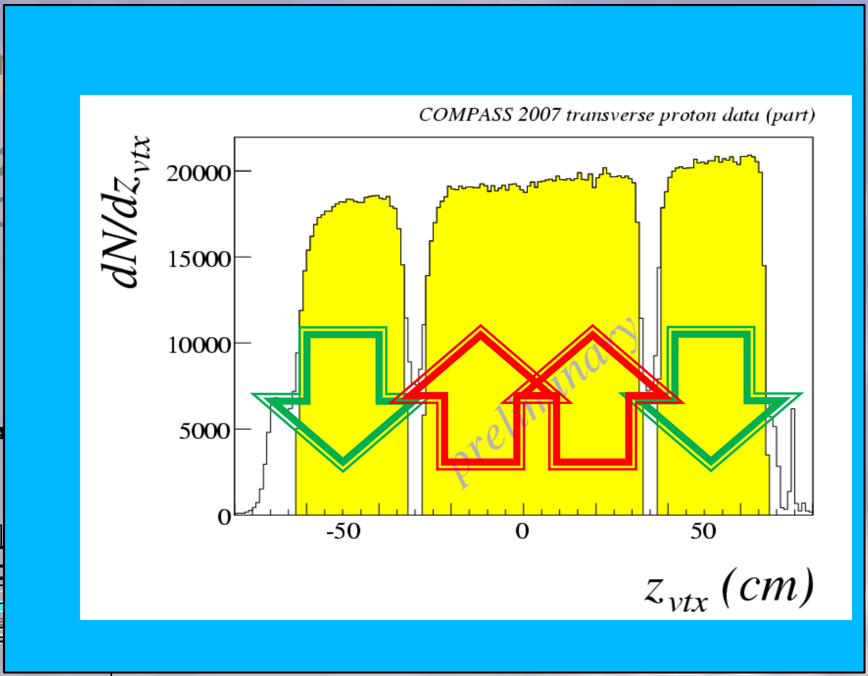
$$
\begin{aligned}
\frac{d\sigma}{dxdydzdP_{h\perp}^{2}d\varphi_h d\varphi_S} &= \left[\frac{\cos\theta}{1-\sin^2\theta\sin^2\varphi_S}\right]\left[\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times \\
&\Bigg\{ 1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}+\cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)}+\lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h}+ \\
&\frac{\mathbf{P}_T}{\sqrt{1-\sin^2\theta\sin^2\varphi_S}}\Bigg[\sin\varphi_S\times\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+ \\
&\quad \sin(\varphi_h-\varphi_S)\times\left(\cos\theta A_{UT}^{\sin(\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin 2\varphi_h}\right)+ \\
&\quad \sin(\varphi_h+\varphi_S)\times\left(\cos\theta\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin 2\varphi_h}\right)+ \\
&\quad \sin(2\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin 2\varphi_h}\right)+ \\
&\quad \sin(3\varphi_h-\varphi_S)\times\left(\cos\theta\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right) \\
&\quad \sin(2\varphi_h+\varphi_S)\times\left(\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin 2\varphi_h}\right)+\Bigg]+ \\
&\frac{\mathbf{P}_T\lambda}{\sqrt{1-\sin^2\theta\sin^2\varphi_S}}\Bigg[\cos\varphi_S\times\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}+\sin\theta\sqrt{(1-\varepsilon^2)}A_{LL}\right)+ \\
&\quad \cos(\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{(1-\varepsilon^2)}A_{UT}^{\cos(\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h}\right)+ \\
&\quad \cos(2\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{UT}^{\cos(2\varphi_h-\varphi_S)}\right)+ \\
&\quad \cos(\varphi_h+\varphi_S)\times\left(\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h}\right)\Bigg]\Bigg\}
\end{aligned}
$$

the polarized target system (>2005)

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

solenoid
dipole magnet





opposite polarisation

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

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

Predictions for Drell-Yan at COMPASS

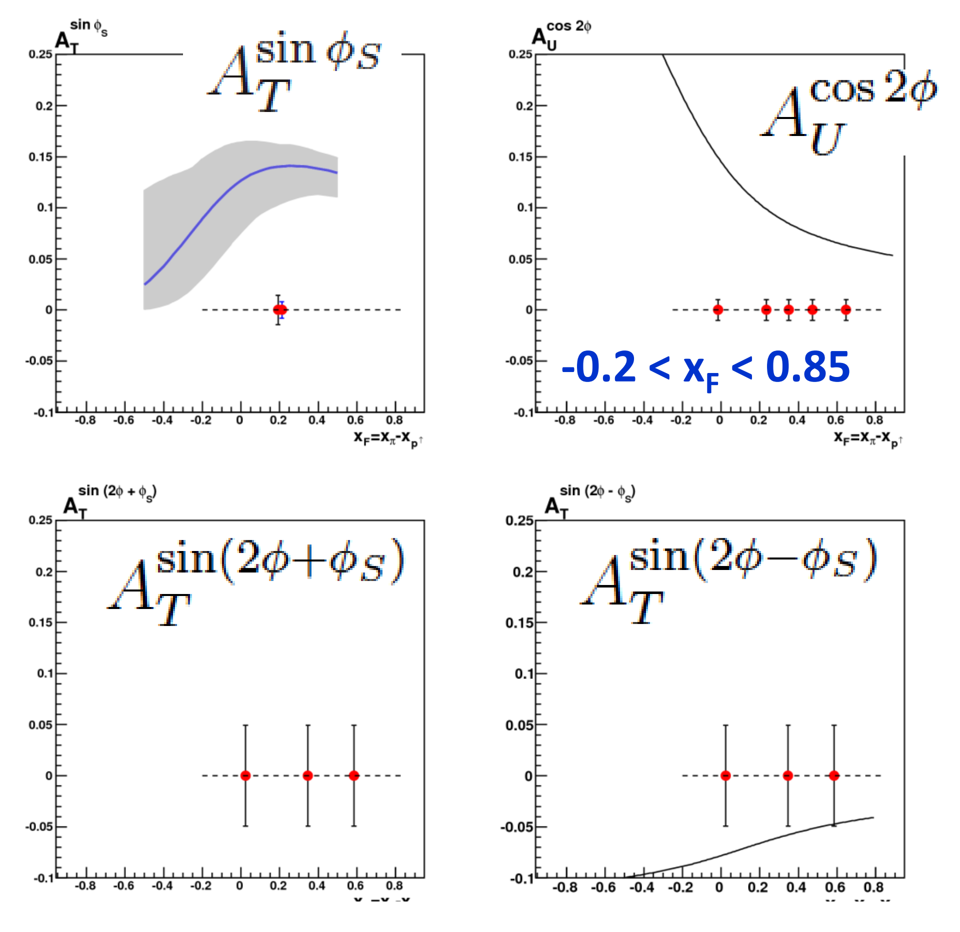
$4. \leq M_{\mu\mu} \leq 9.\ \mathrm{GeV}/c^2$

Sivers

M. Anselmino et al, Phys. Rev. D 79, 054010 (2009)

Boer-Mulders

B. Zhang et al, Phys. Rev. D 77, 054011 (2008)



BM ⊗ pretz.

BM ⊗ transv.

A. N. Sissakian, Phys. Part. Nucl. 41, 64-100 (2010)

The first ever polarised Drell-Yan experiment sensitive to TMDs