Highlights from the COMPASS experiment

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for the Collaboration

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Plan

- COMPASS
- Helicity structure (quarks)
- Gluon polarisation
- Transverse spin-structure of the nucleon

- A glimpse a hadron spectroscopy
- Outlook

COMPASS: QCD structure of hadrons

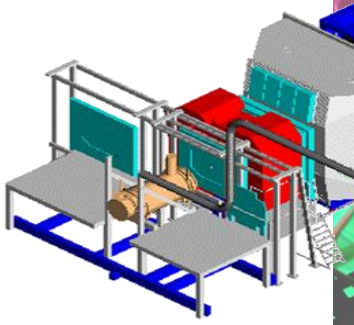
data taking since 2002

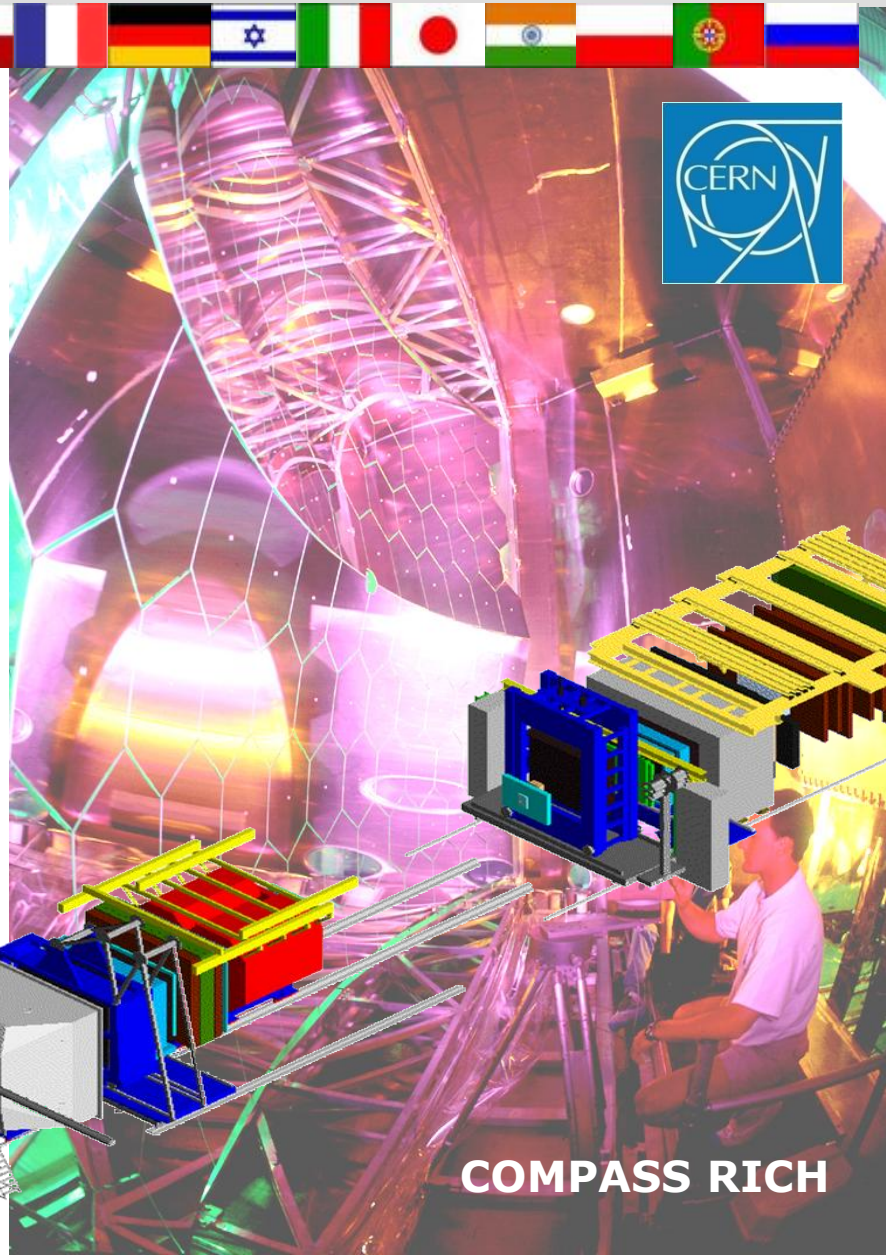
nucleon spin-structure

- helicity distributions of qluons and quarks
- transverse spin structure

hadron spectroscopy

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





COMPASS key figures (muon beam)

- Large solid polarised target
  - proton target (NH_3, 3 cells, e.g. +−+, ~85%, f ≅ 0.18)
  - deuteron target (^{6}LiD, 2 cells, e.g. +−, ~50%, f ≅ 0.4)
- Polarised muon beam
  - ~80% polarisation
  - 5 ×10^7 muons/s, duty factor 20 − 33 %
- Nominal luminosity
  - 5×10^{32} cm^{-2} s^{-1}
- Particle ID
  - RICH (π/K: 9–50 GeV/c), ECals, HCals, Muon walls
- DAQ
  - 250k channels
  - up to 30 kHz, several PByte/year (hadron runs)

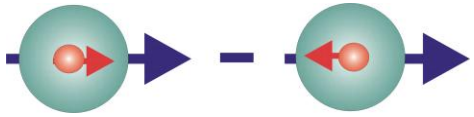
Parton Distribution Functions

Three twist-2 PDFs

q(x)
$f_1^q(x)$

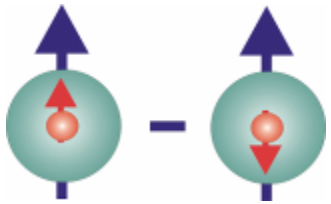
unpolarised PDF
quark with momentum *xP* in a nucleon
well known – unpolarised DIS

Δq(x)
$g_1^q(x)$



helicity PDF
quark with spin parallel to the nucleon spin in a longitudinally polarised nucleon
known – polarised DIS

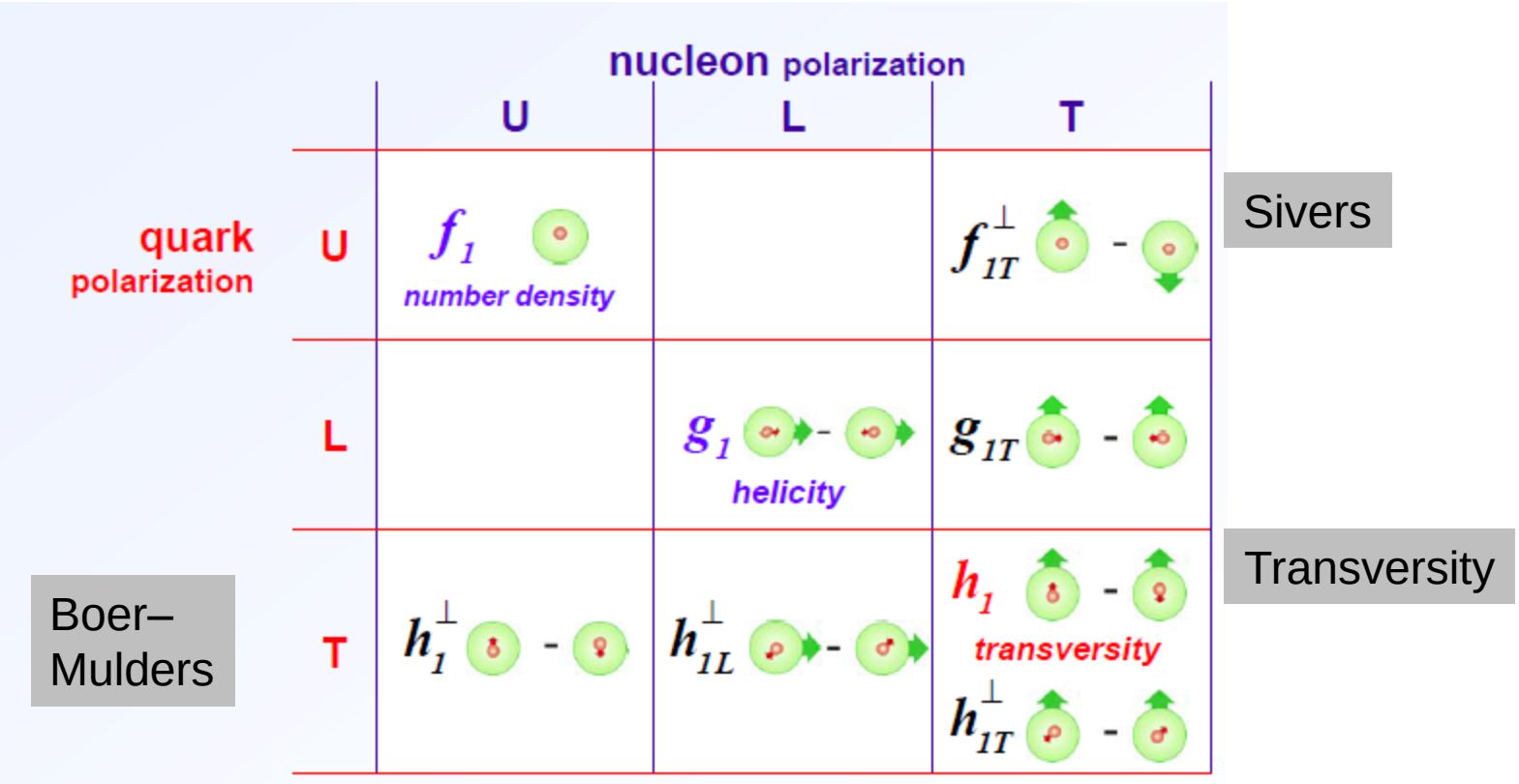
$\Delta_T q(x)$
$h_1^q(x)$



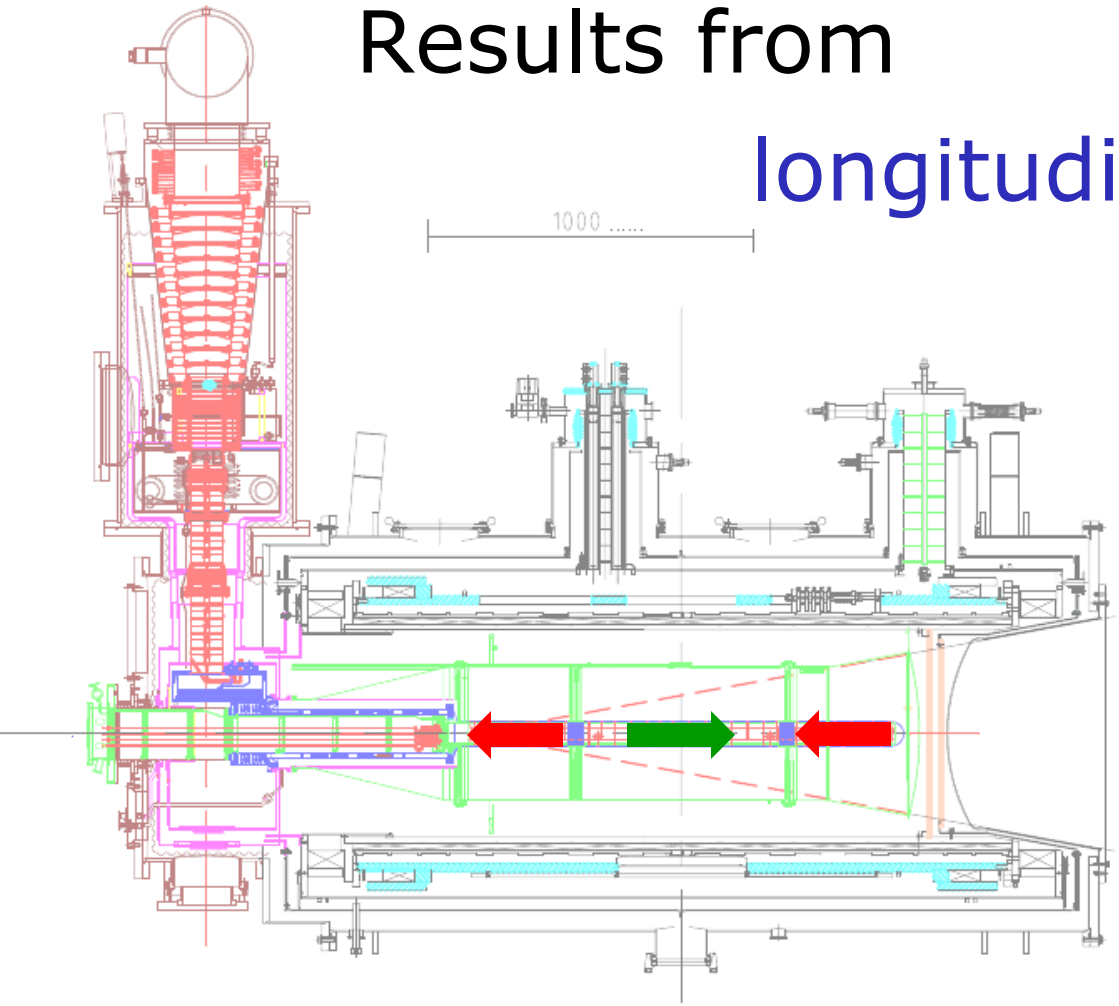
transversity PDF
quark with spin parallel to the nucleon spin in a transversely polarised nucleon
chiral odd, poorly known

TMD parton distributions

- 8 intrinsic transverse momentum dependent PDFs at LO
- Asymmetries with different angular dependences on hadron and spin azimuthal angles, Φ_h and Φ_s



Results from longitudinal polarisation



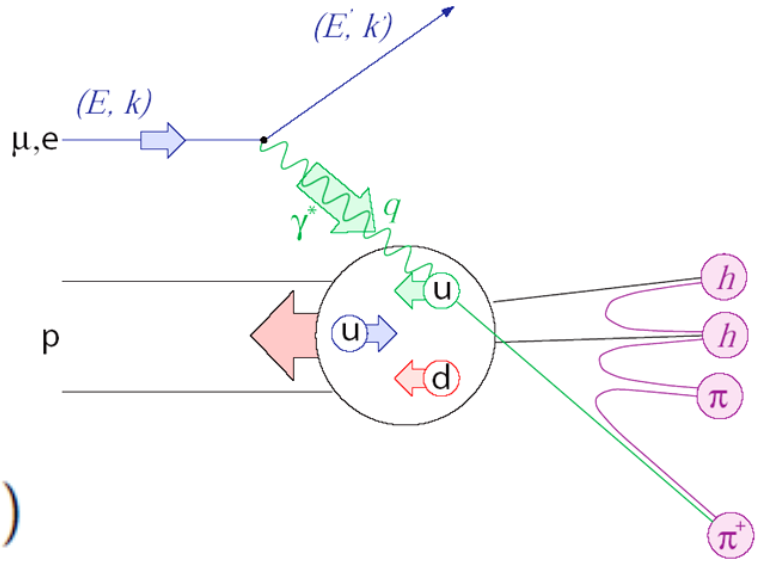
Longitudinal asymmetries

Semi-inclusive asymmetries

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

with

$$\Delta q(x,Q^2) = q^+(x,Q^2) - q^-(x,Q^2)$$

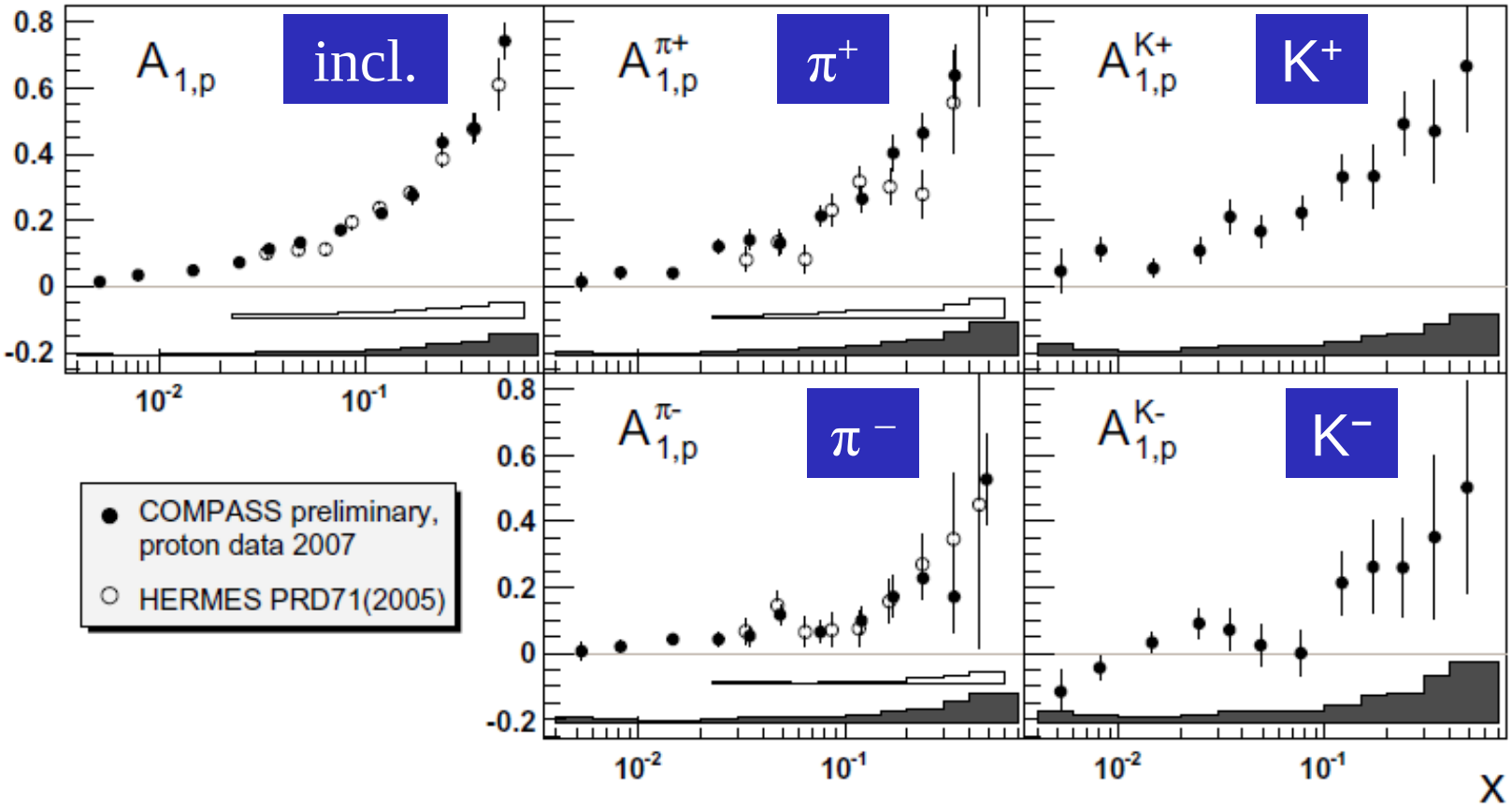


Inclusive asymmetry

$$A_1 = g_1/F_1; \quad g_1(x,Q^2) = \frac{1}{2}\sum e_q^2 \Delta q(x,Q^2)$$

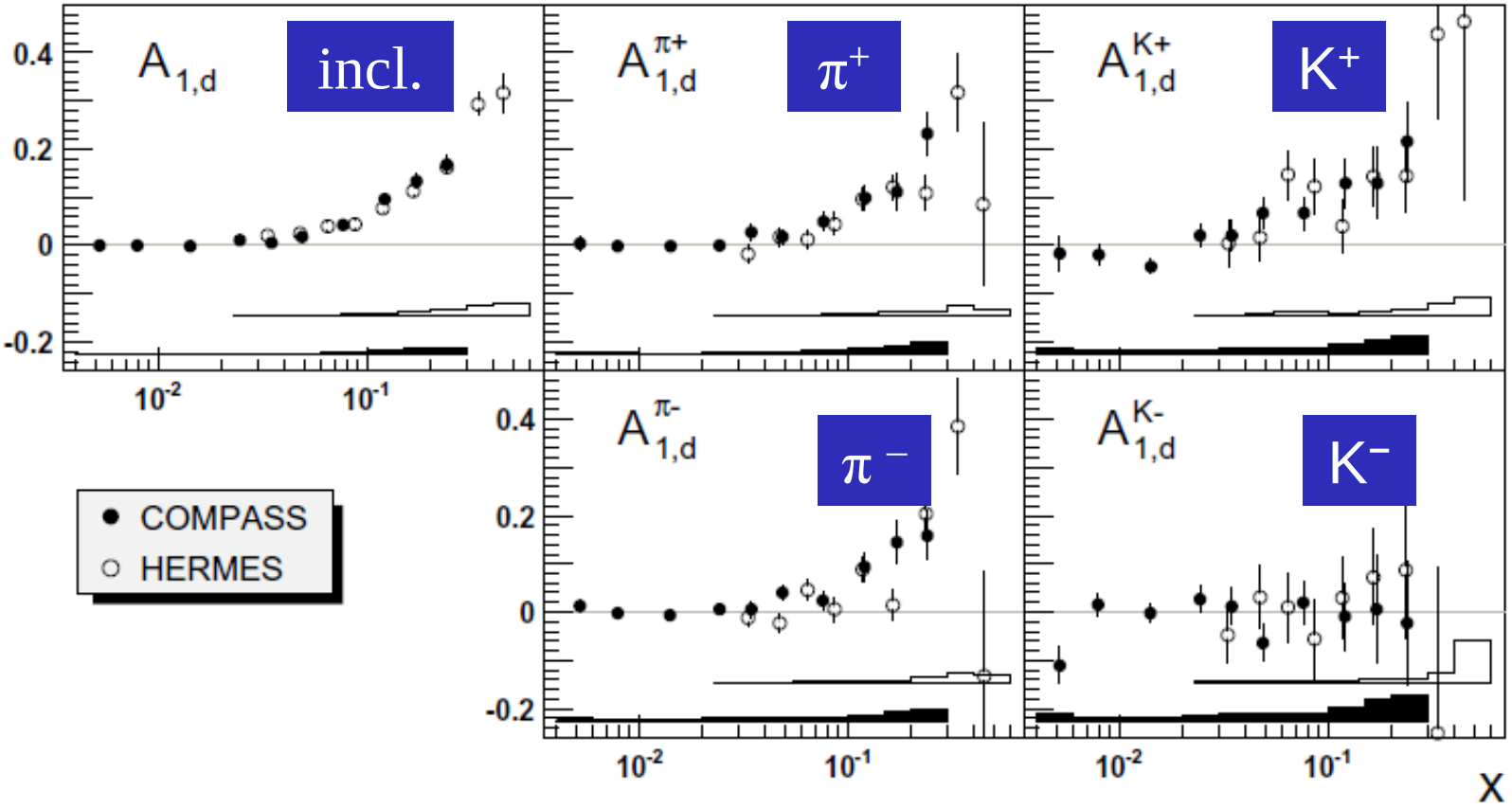
Incl. & semi-incl. asymmetries

- proton, first measurement of A^K, preliminary **new**



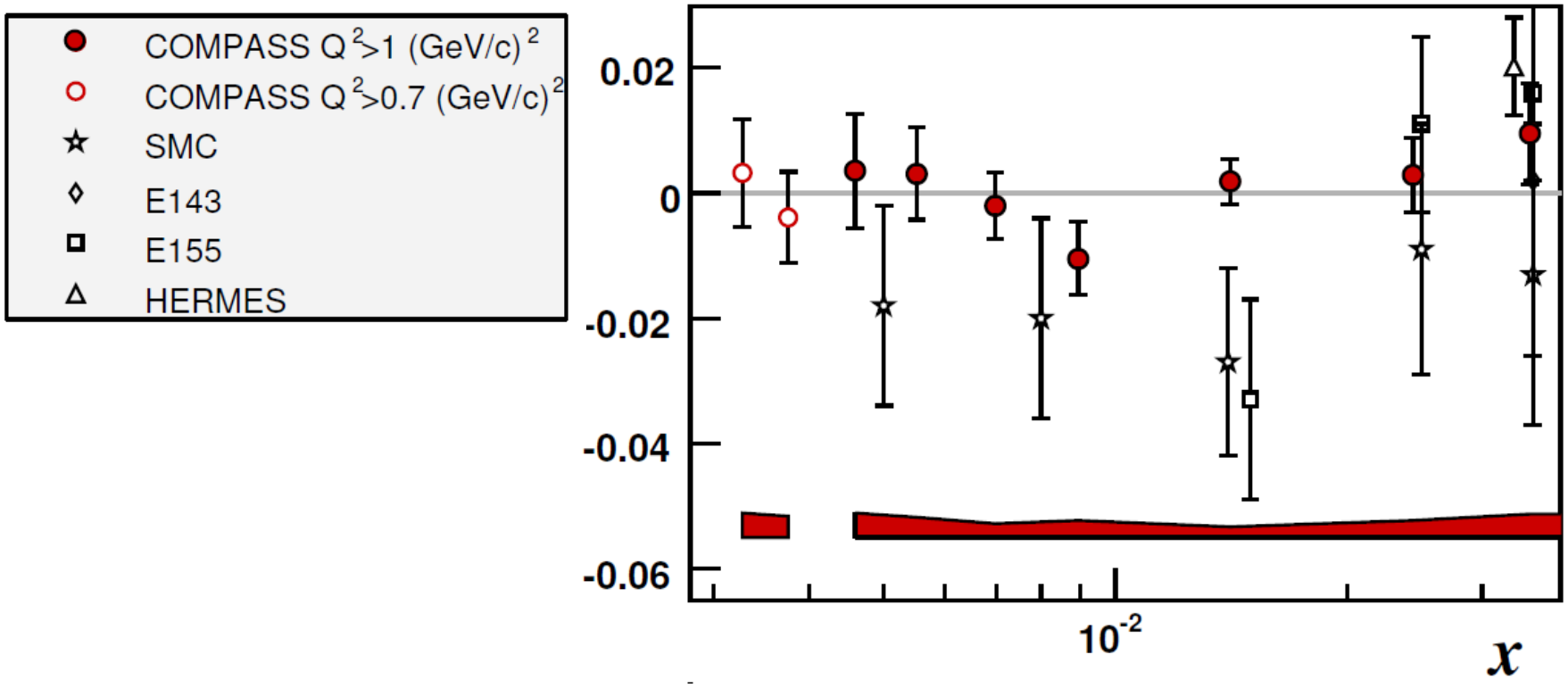
Incl. & semi-incl. asymmetries

- deuteron



Incl. deuteron asymmetry

- most precise measurement for $x<0.03$ and $Q^2 > 1$ GeV^2



Structure function $g_1(x,Q^2)$

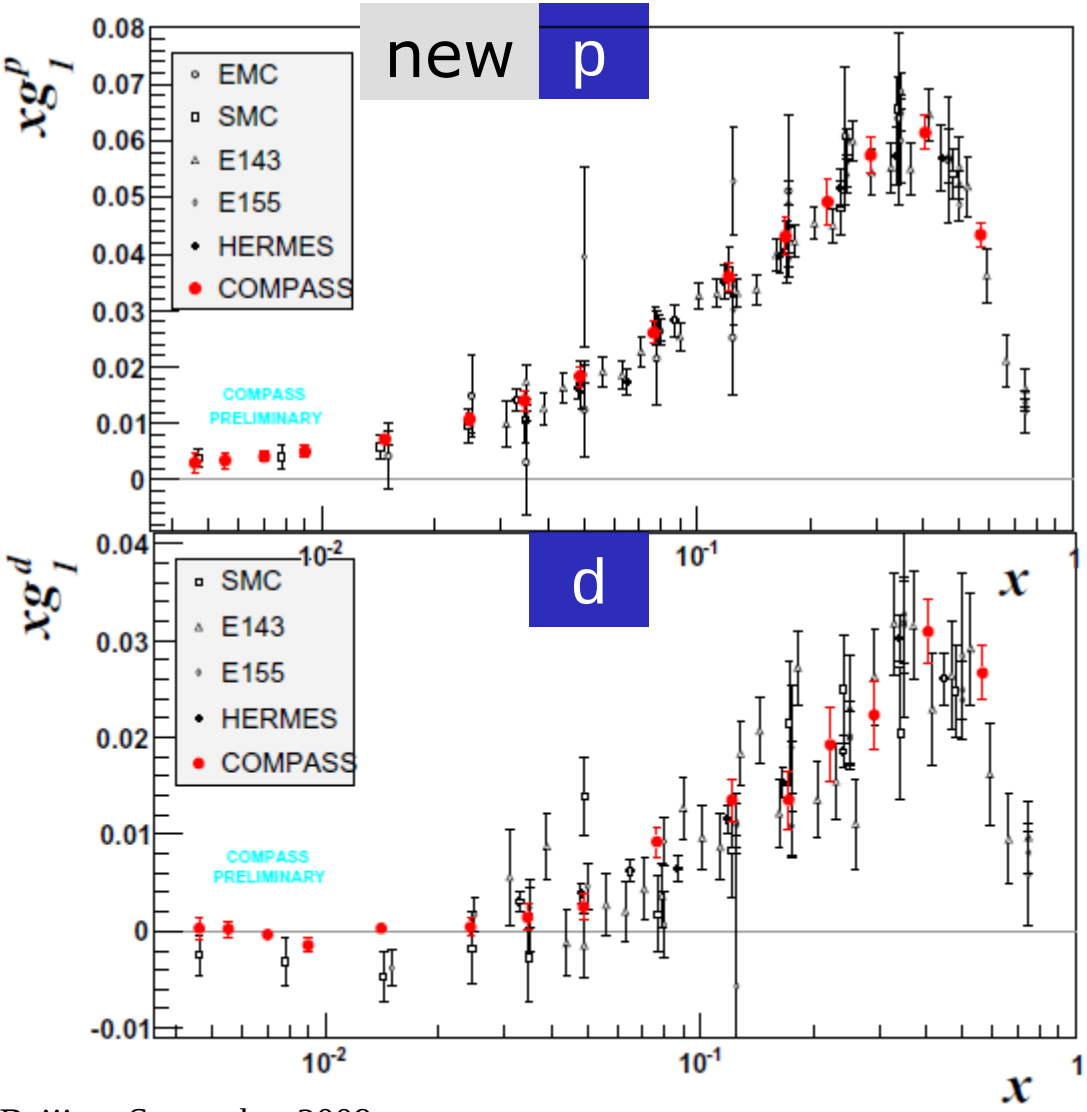
- very precise data
- only data below
  $x < 0.01$ ($Q^2 > 1$)

- deuteron data:

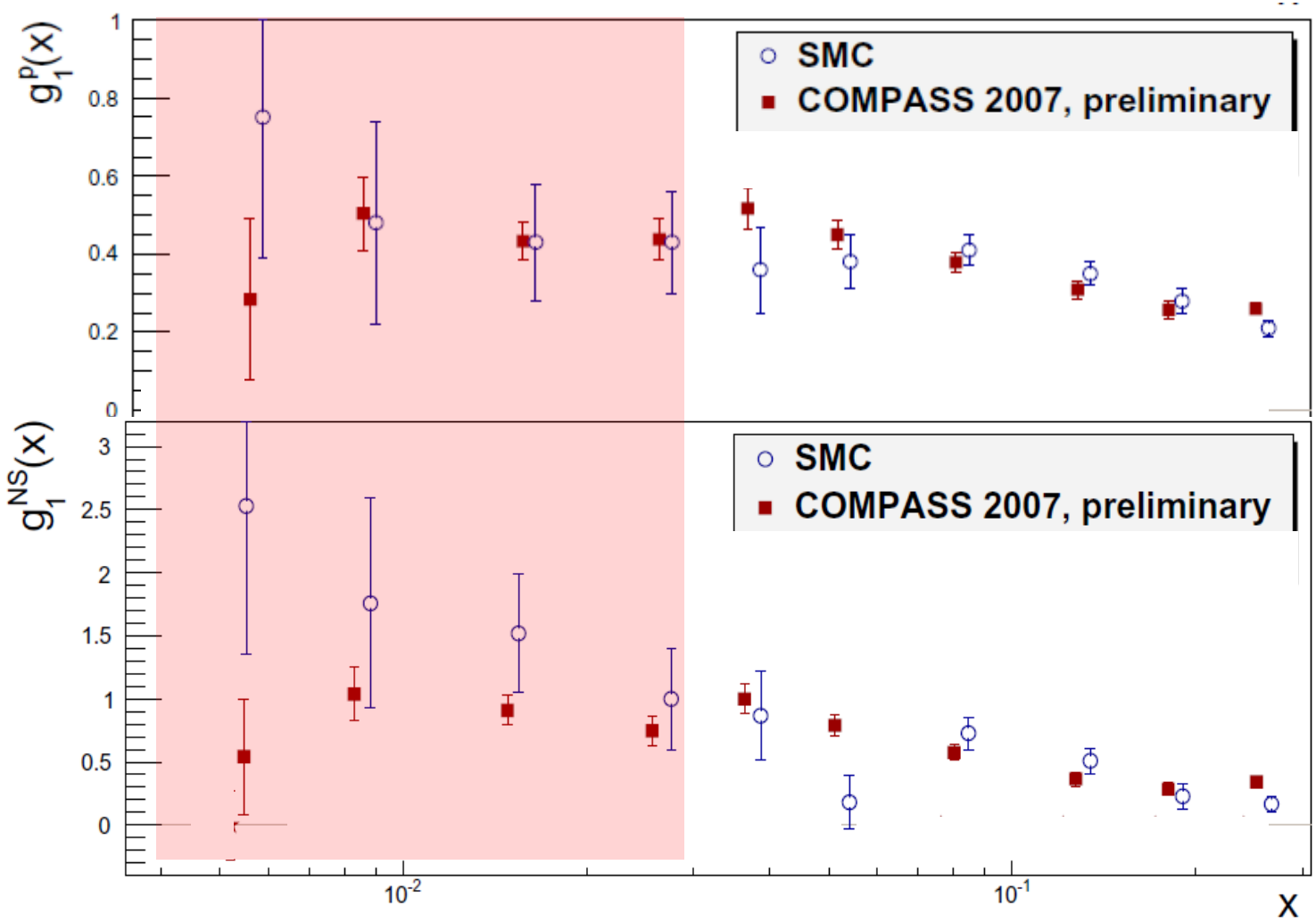
$a_0 = 0.33 \pm 0.03 \pm 0.05$

$\Delta s + \Delta s = -0.08 \pm 0.01 \pm 0.02$

(evol. to $Q^2=\infty$)



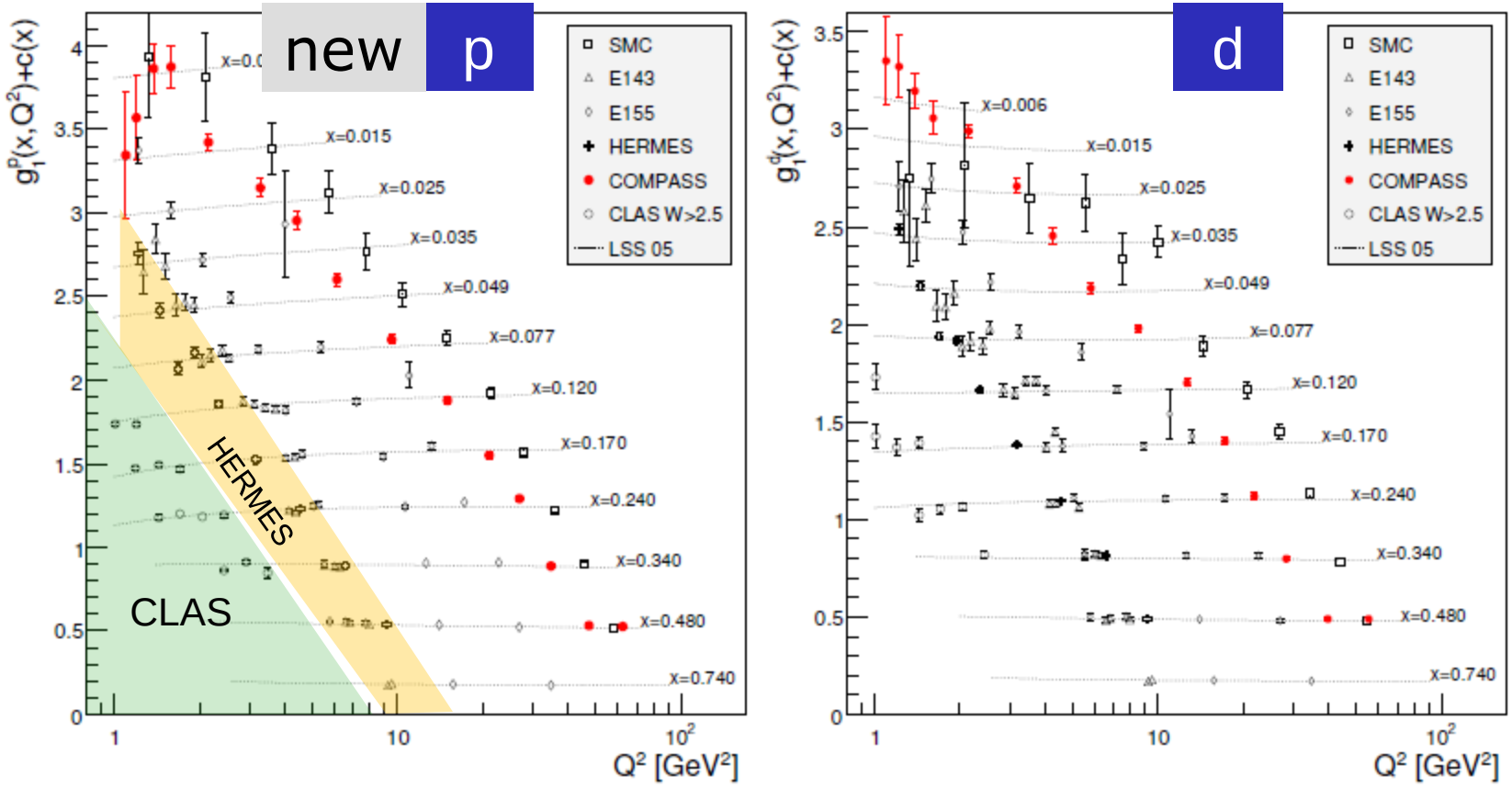
g_1 proton and g_1^{NS}



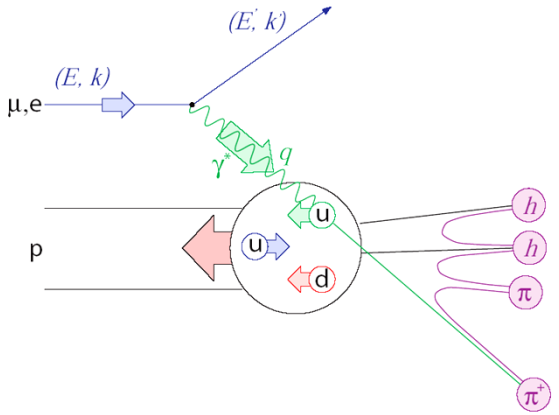
new

proton & deuteron $g_1(x,Q^2)$

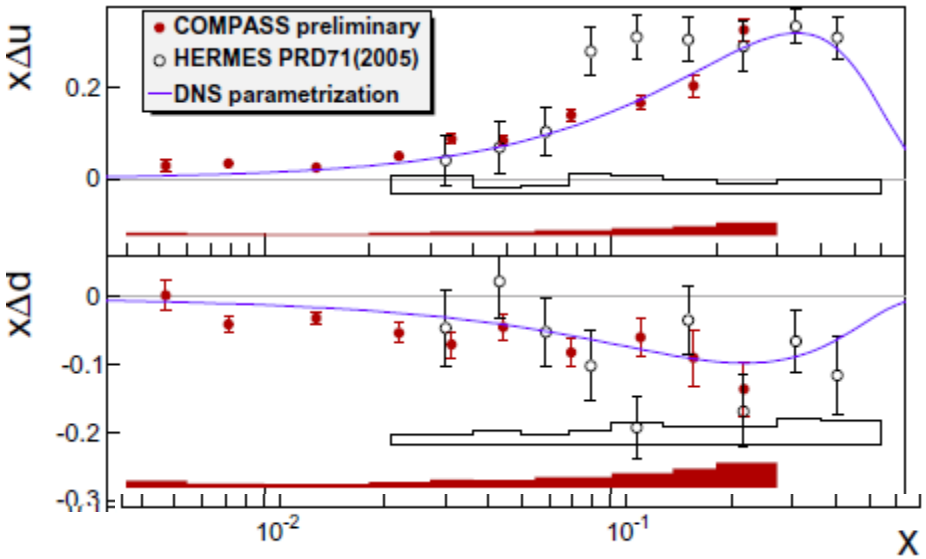
- unique kinematic domain
- important for global QCD analyses

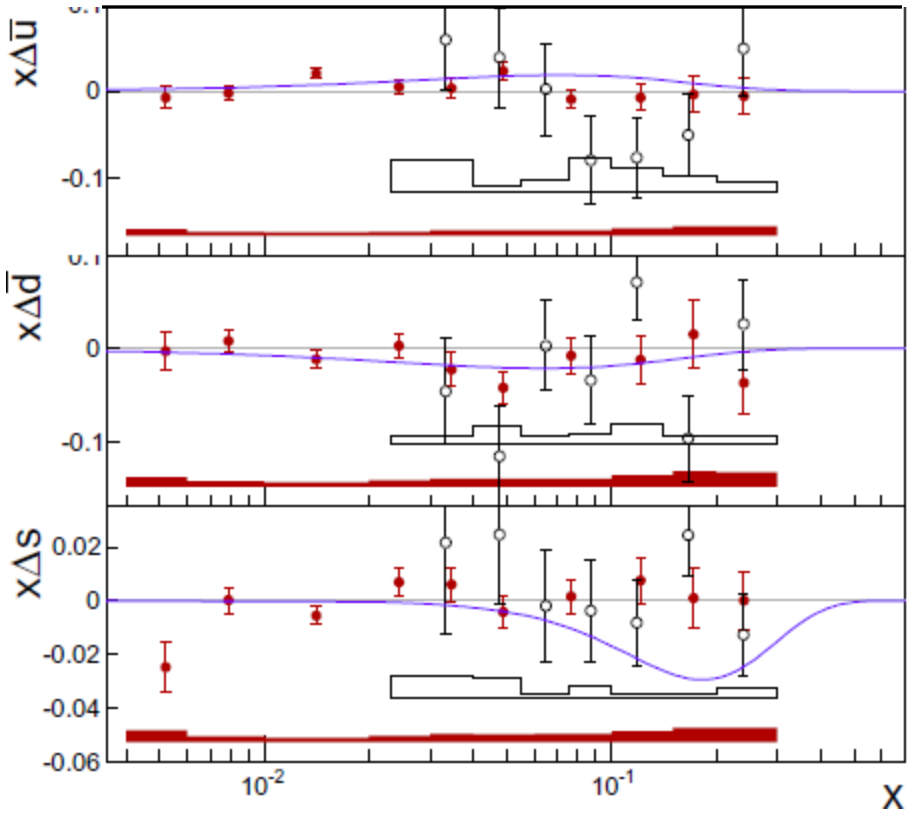


The role of quark flavours



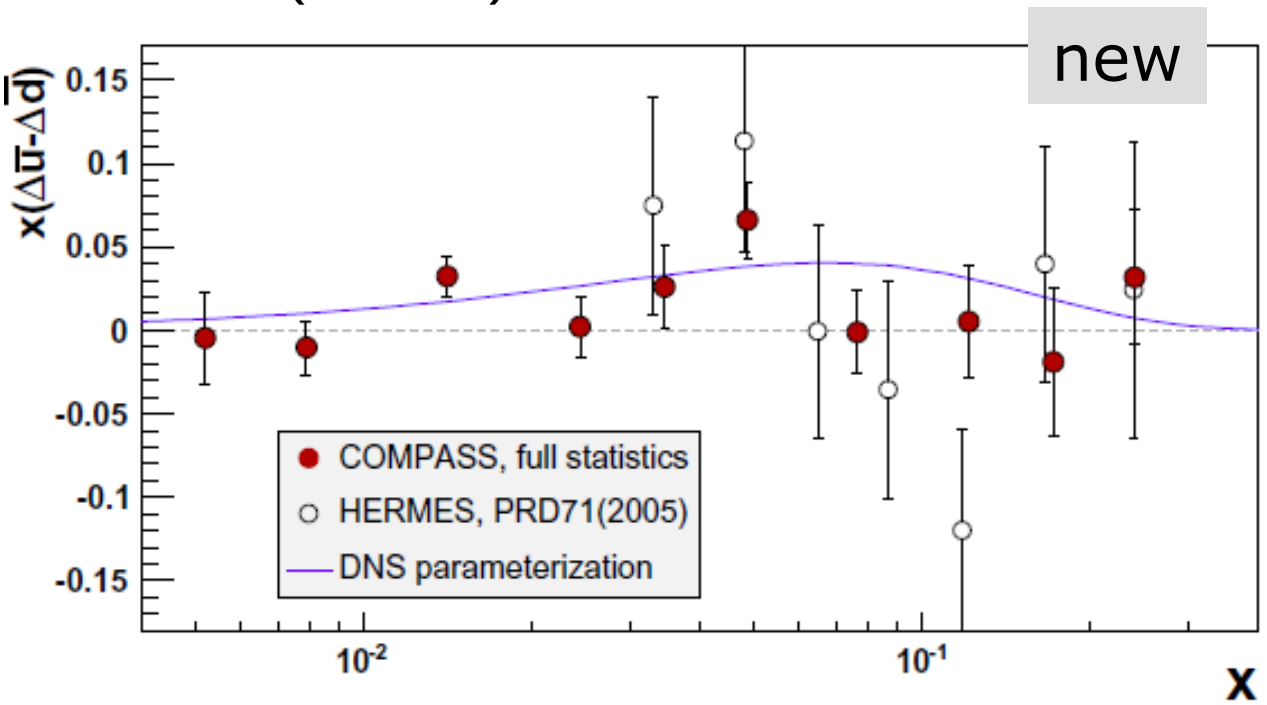
LO analysis, preliminary **new**





Flavour asymmetry? $\Delta\bar{u} - \Delta\bar{d}$

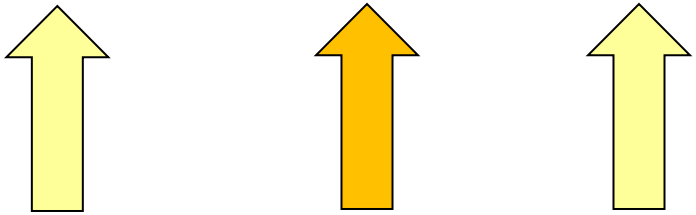
- considerable asymmetry in the unpolarised case
- model predicts naturally asymmetry for pol. case
- only small effect (if at all)



Angular momentum of the nucleon

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

quarks gluons orbital

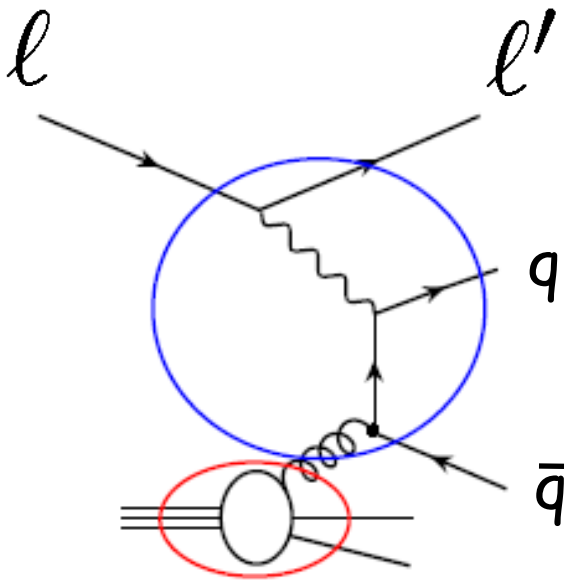


small ~0.15 unknown

poorly known

Hadron production in DIS via PGF

Principle: Gluon polarisation enters via photon-gluon fusion (PGF)



$$A_{\parallel} = R_{pgf} \langle \hat{a}_{pdf} \rangle \left\langle \frac{\Delta g}{g} \right\rangle$$

- measure $A_{\parallel}$
- calculate R_{pgf}, $\langle \hat{a}_{pgf} \rangle$ and background by Monte Carlo

Δg/g from open charm

cleanest process

- little physics background (LO, QCDC)

observe asymmetry in D meson production

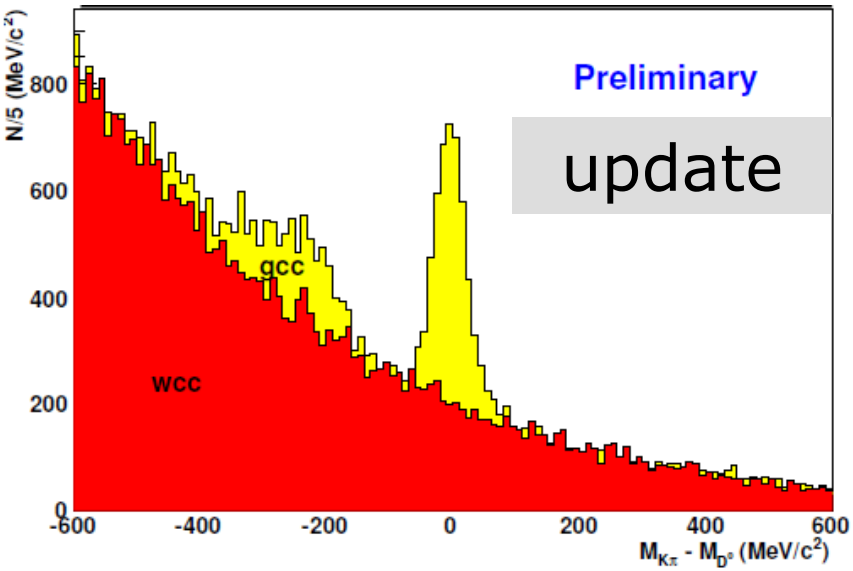
- statistics limited
- only one *D* meson via $D \to \pi K$ (BR ~ 4%)
- combinatorial background large
- drastically reduced when looking to *D** decay in coincidence with slow pion

$$D^* \to D^0 + \pi_S \to K + \pi + \pi_S$$

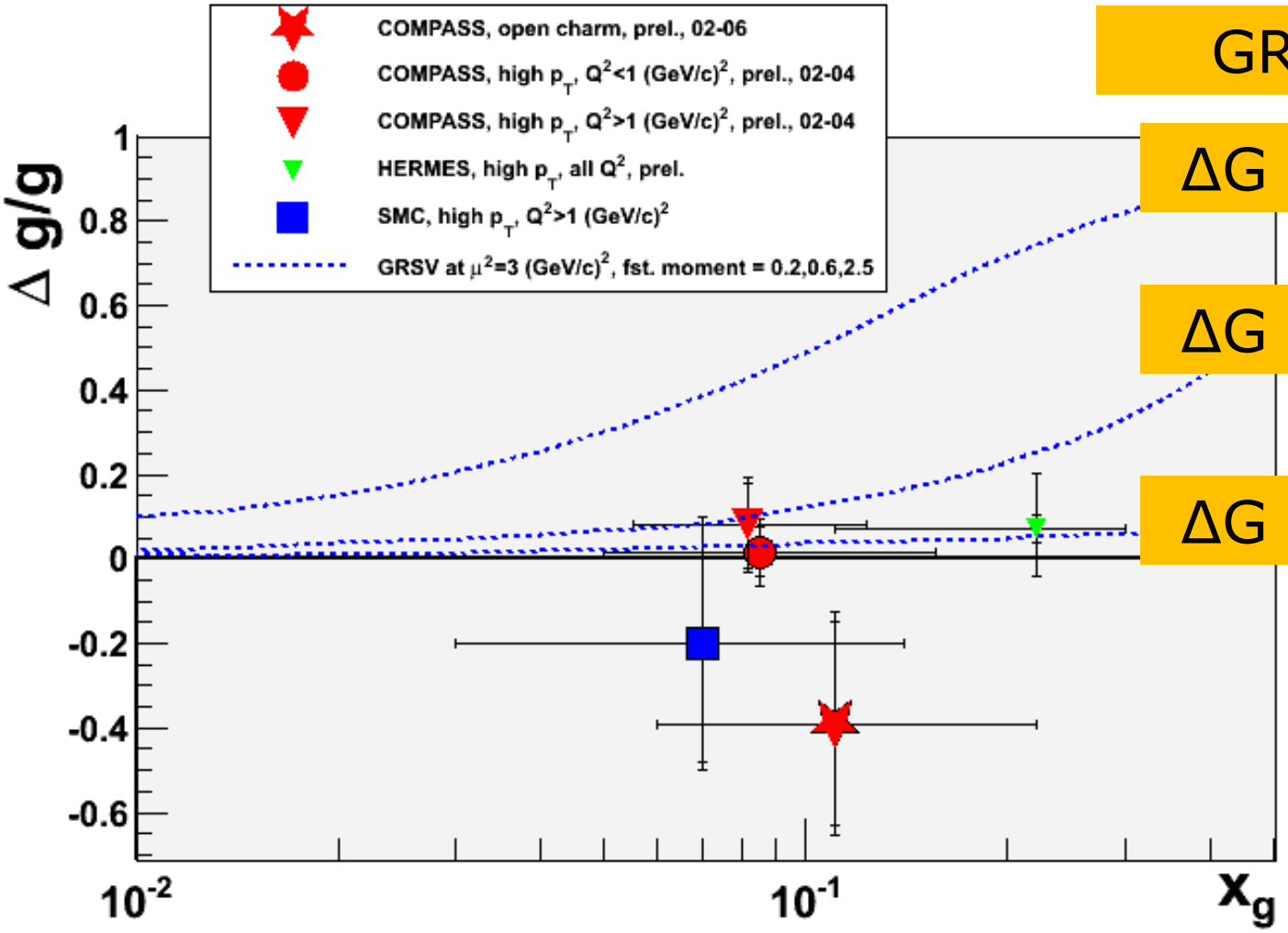
Update on open charm

- 2002–2006 deuteron data
- new channels in D* sample
  - sub-threshold kaons
  - 3-body decay with non-observed π^0

$$D^0 \to K\pi(\pi^0)$$



- old $\langle \Delta g/g \rangle_x = -0.49 \pm 0.27\,(\text{stat.}) \pm 0.11\,(\text{syst.})$
- new $\langle \Delta g/g \rangle_x = -0.39 \pm 0.24\,(\text{stat.})$



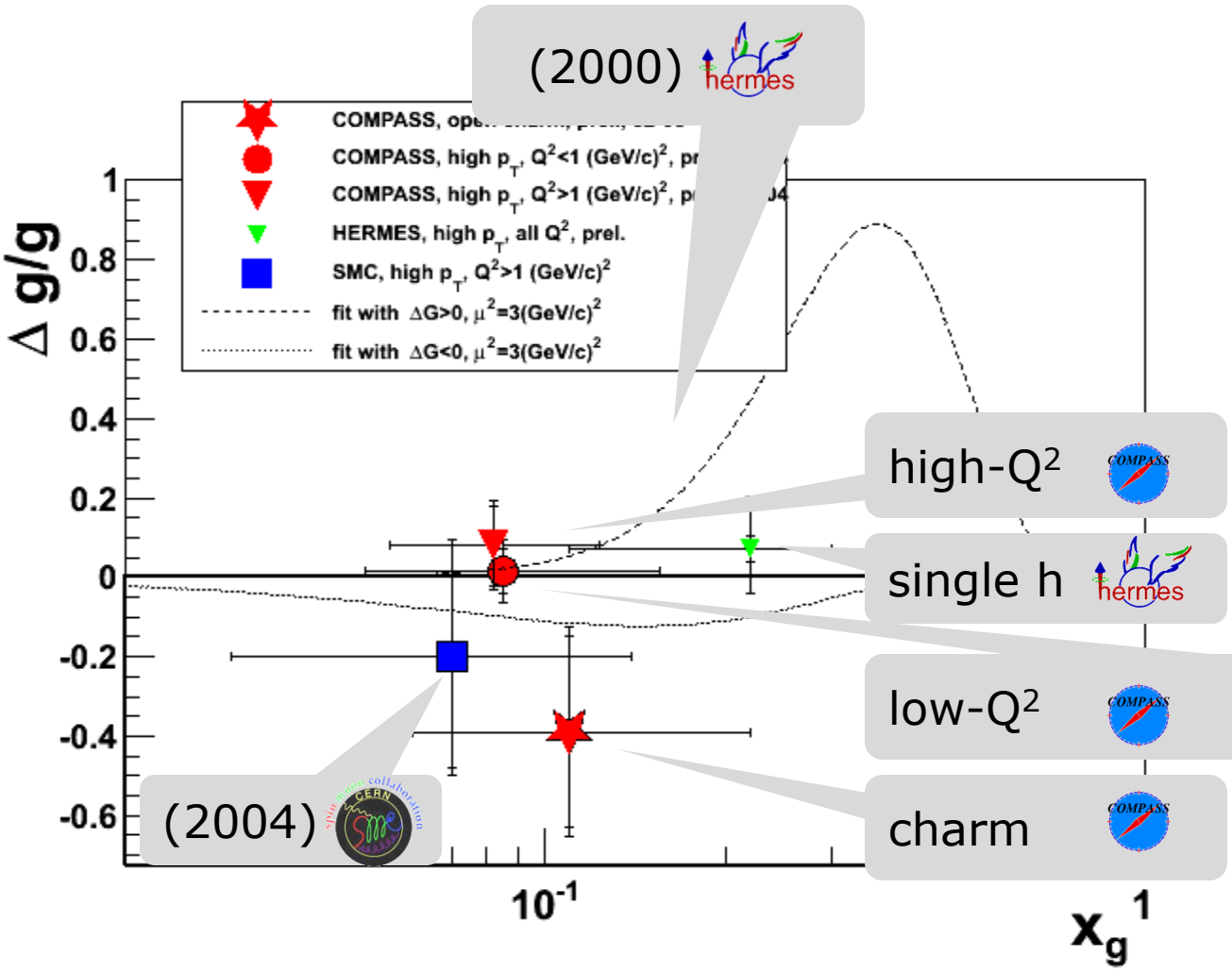
GRSV

ΔG = 2.5

ΔG = 0.6

ΔG = 0.2

Δg/g from hadron pairs (LO)



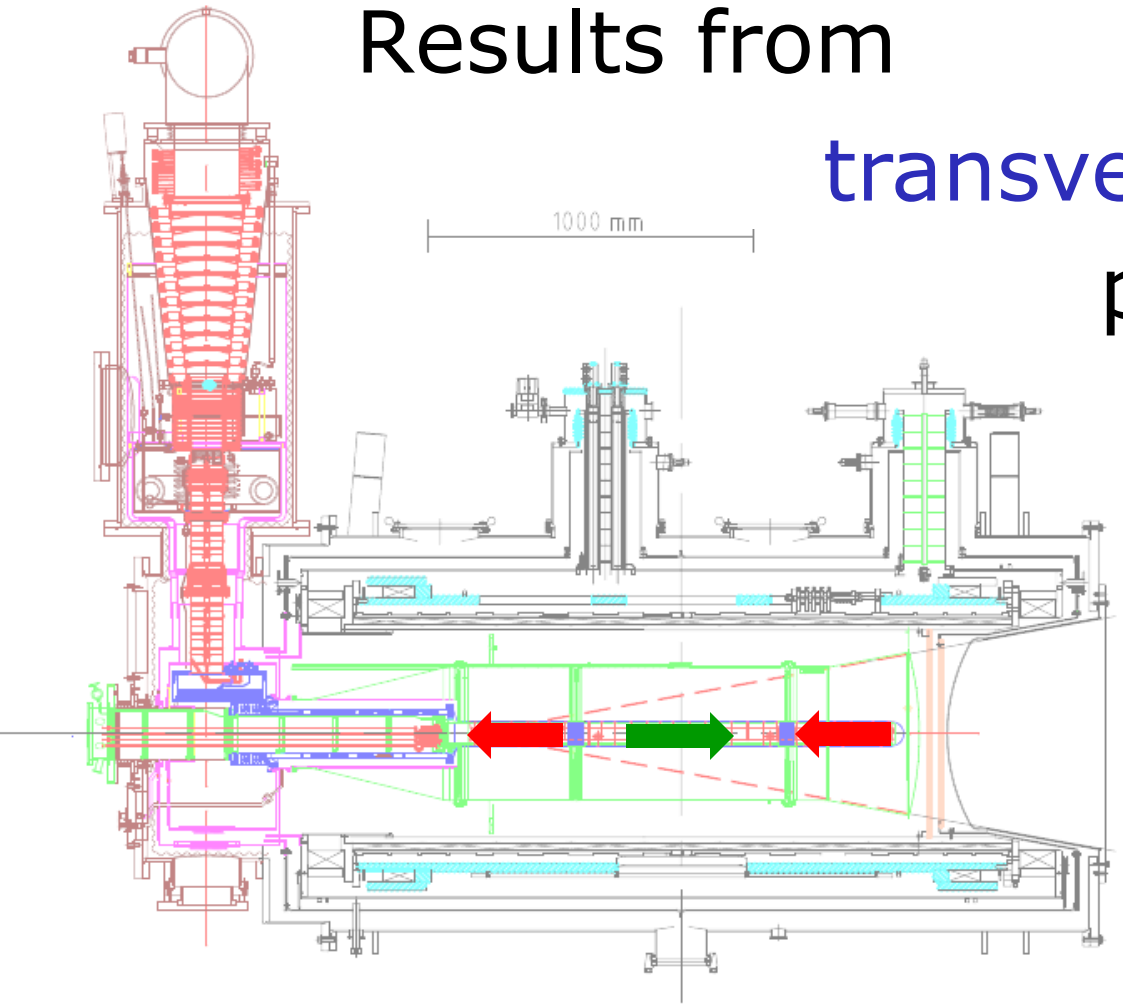
- LO data points at different scales 1 – 13 GeV²
- NLO fits to g_1 at 3 GeV²

Δg/g is small around x ≅ 0.1

PLB 633 (2006) 25-32

confirmed by RHIC

Results from transverse polarisation



Transversity PDF $\Delta_T^0 D_q^h$ or h_1

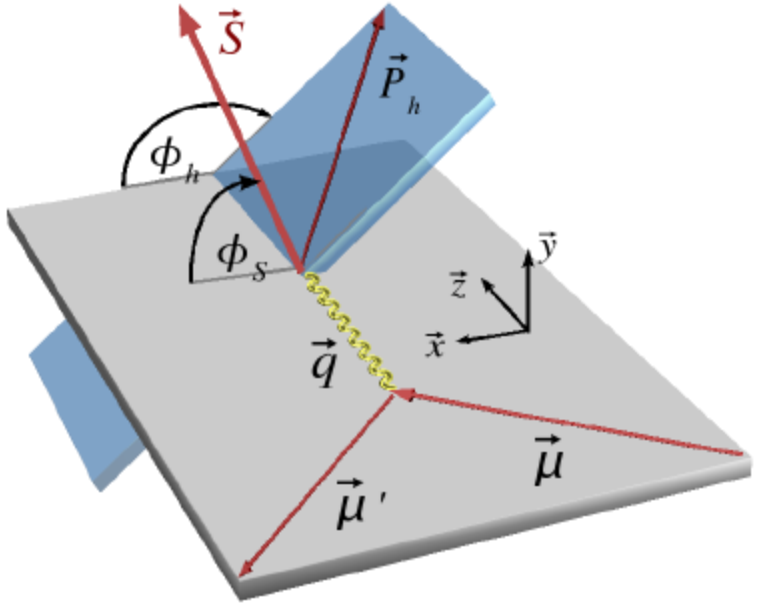
Couple $\Delta_T q$ to chiral odd Collins FF $\Delta_T^0 D_q^h$

$$A_{Coll} = \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 q(x) D_q^h(z, p_T^h)}$$

Azimuthal cross-section asymmetry:

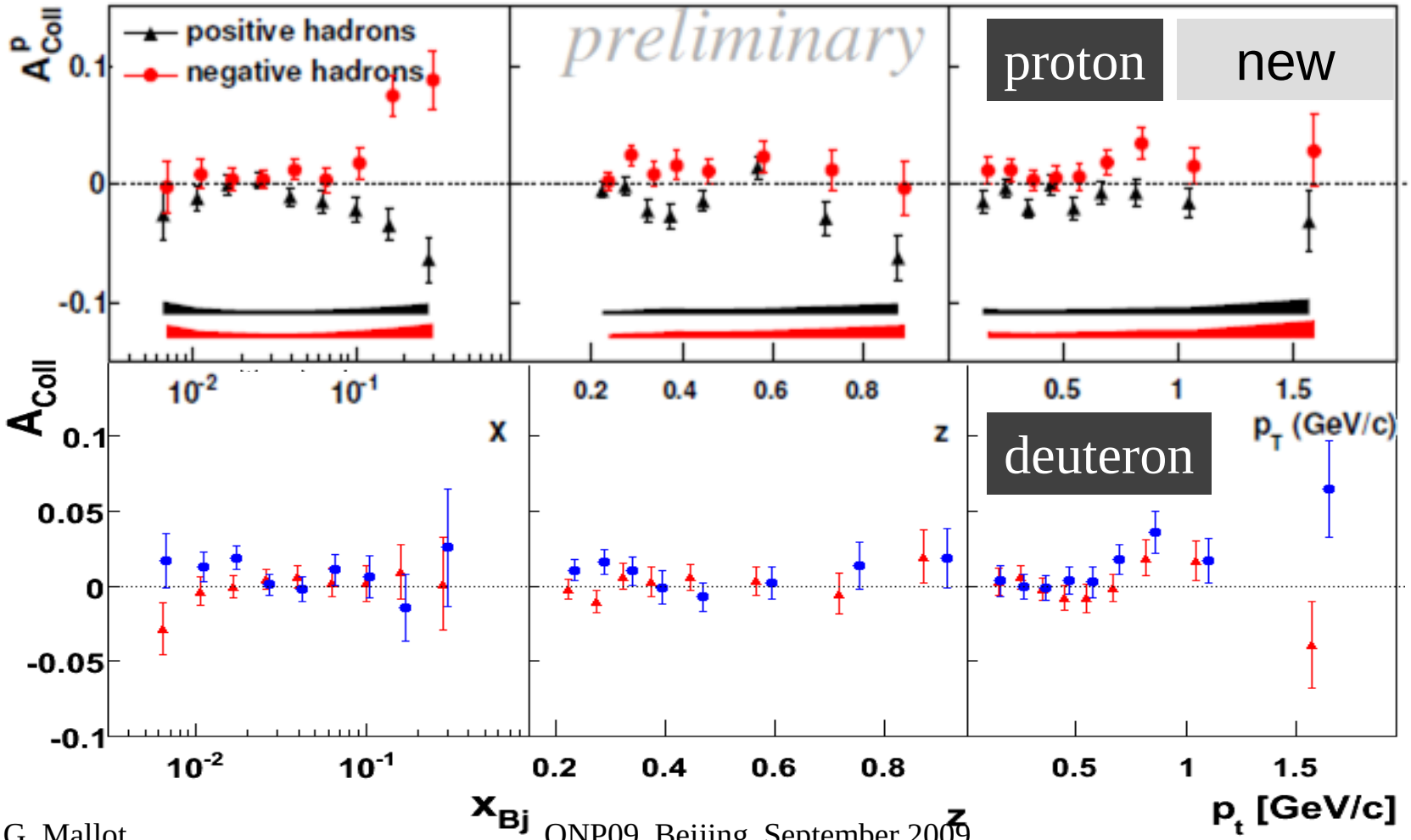
$$\frac{\Delta\sigma}{\sigma} \propto A_{Coll} \sin \Phi_C$$

$$\Phi_C = \phi_h - \phi_s - \pi$$



Collins Asymmetries

new: full 2007 proton data set (statistics tripled)



h^+

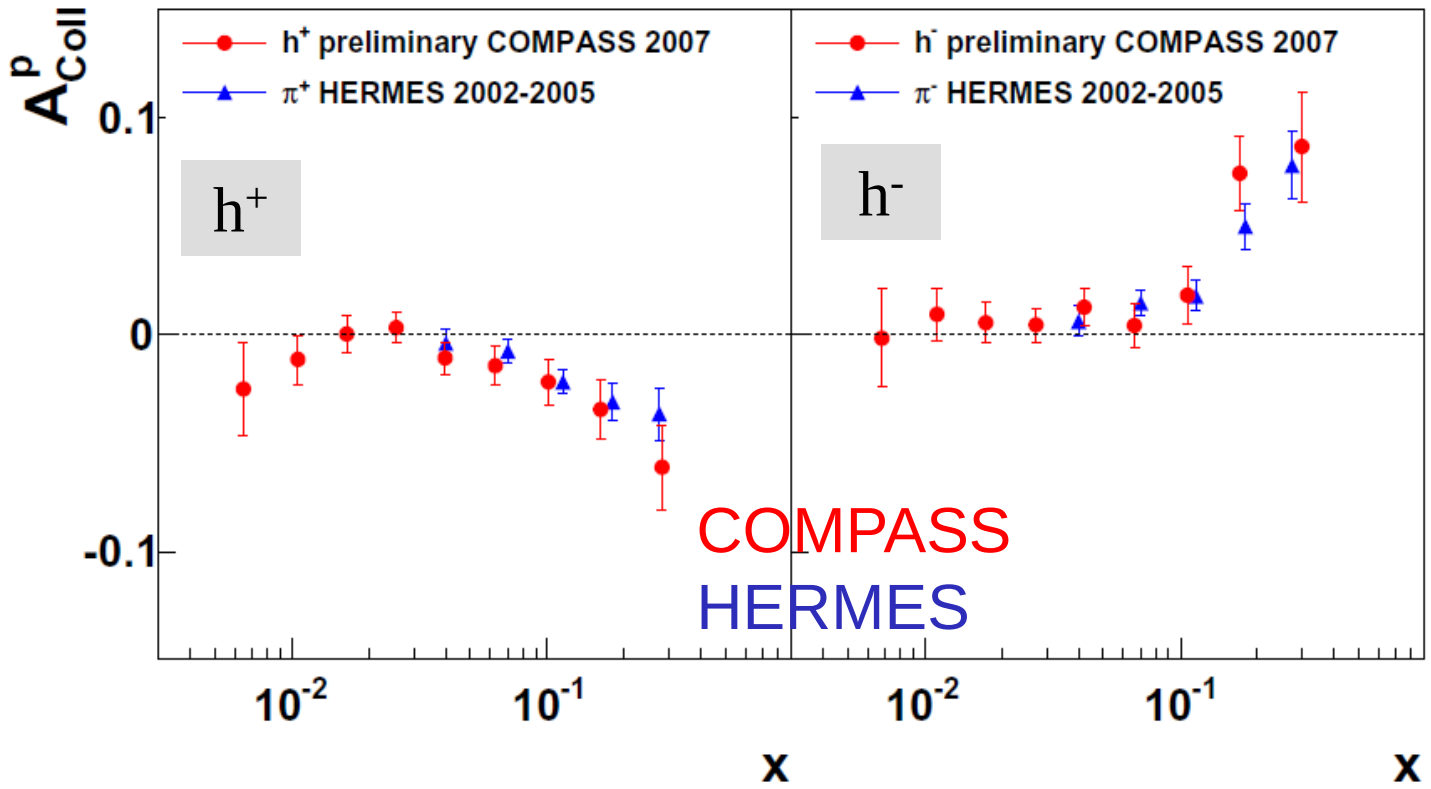
h^-

h^+

h^-

Comparison to HERMES

proton



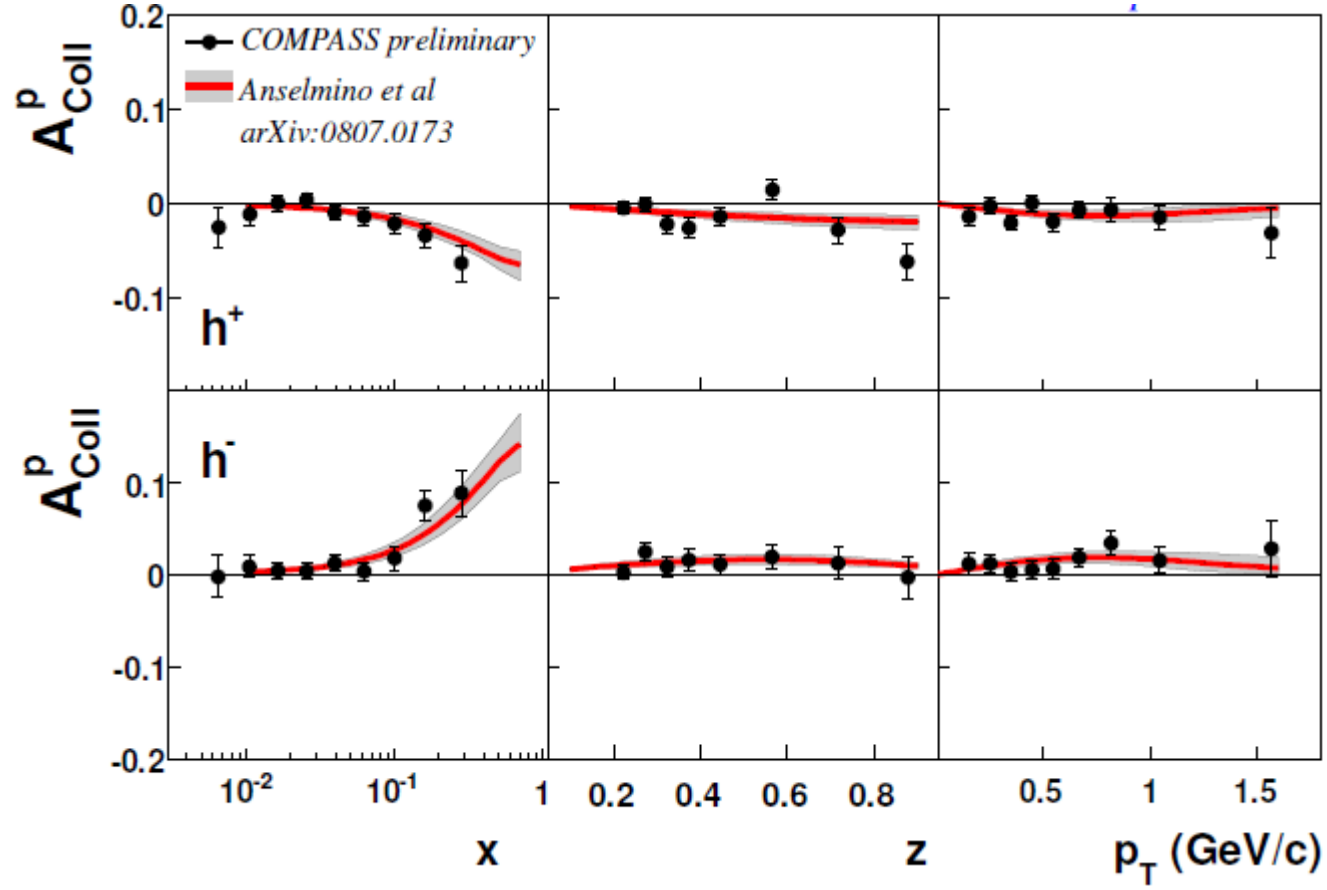
sign change and $D_{nn} \cong y$ applied for HERMES data

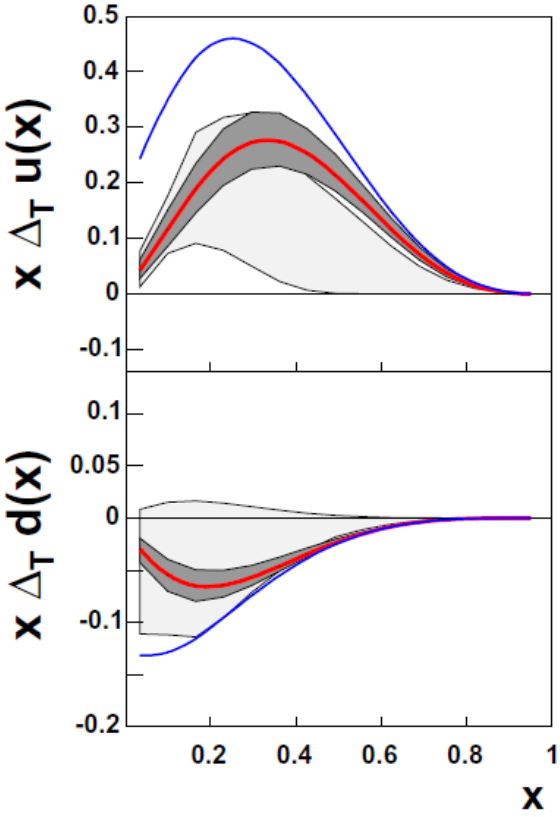
- large asymmetry ~10%
- good agreement in common *x* range
- zero deuteron result important ⇒ opposite sign of u and d quark transversity PDF

Global Fit

Fit to COMPASS *d*, HERMES, BELLE (FF, e^+e^-)

in good agreement with new proton data





Transversity PDF $\Delta_T q(x)$

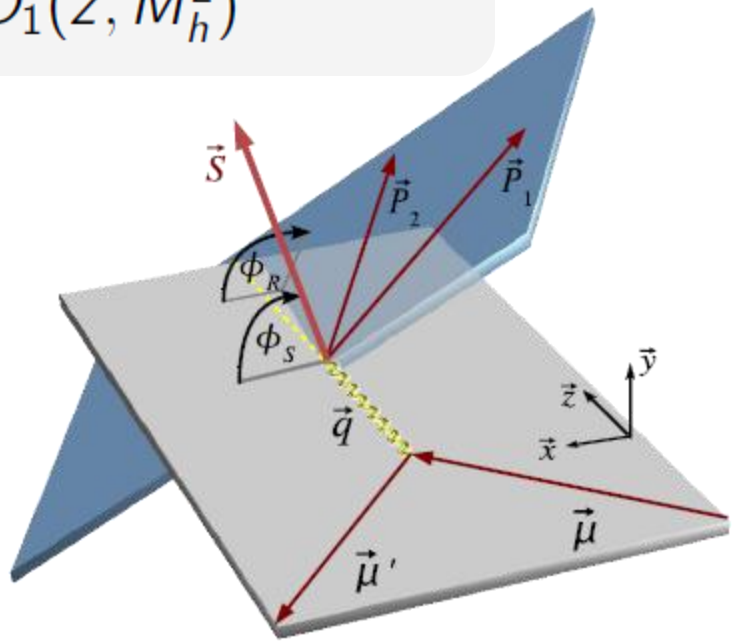
Alternative: couple $\Delta_T q$ to chiral odd 2-hadron interference FF $H_1^{\sphericalangle}$

$$A_{RS} \propto \frac{\sum_q e_q^2 \Delta_T q(x) H_1^{\sphericalangle}(z, M_h^2)}{\sum_q e_q^2 q(x) D_1(z, M_h^2)}$$

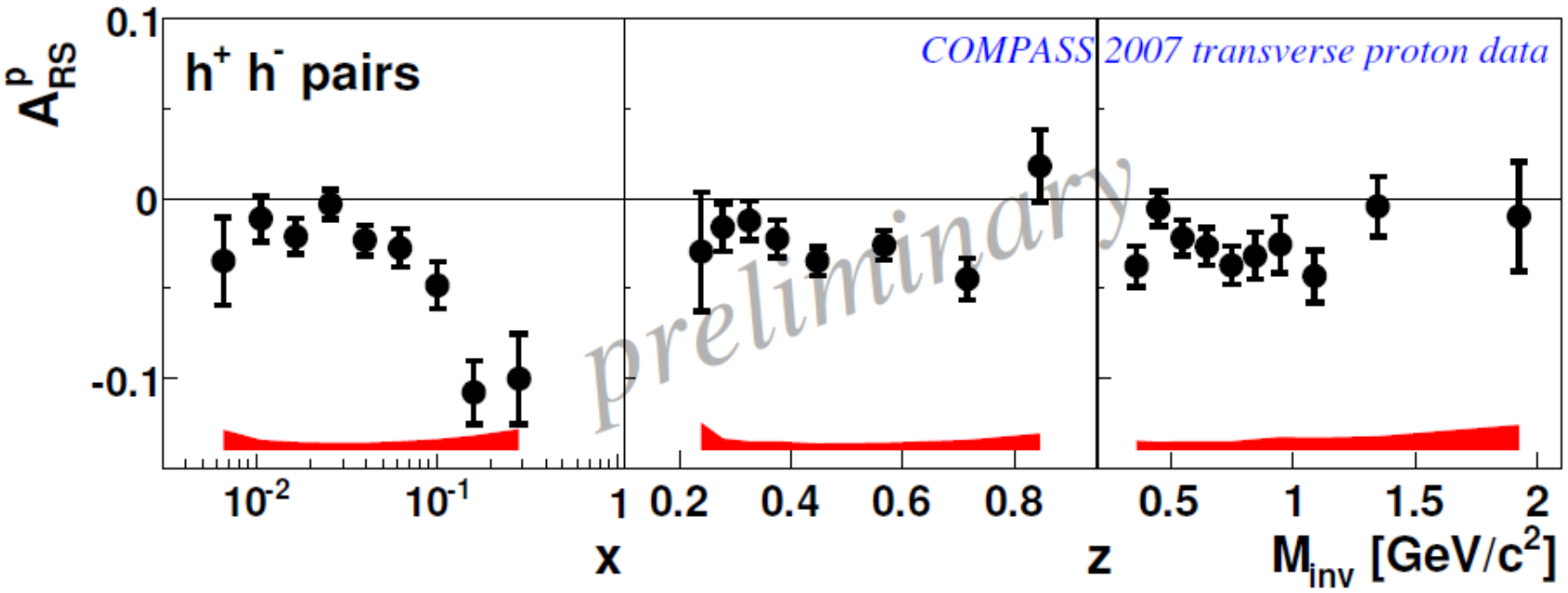
cross-section asymmetry:

$$\frac{\Delta\sigma}{\sigma} \propto A_{RS} \sin\phi_{RS} \sin\theta$$

$$\phi_{RS} = \phi_R + \phi_S - \pi; \quad \sin\theta \simeq 1$$



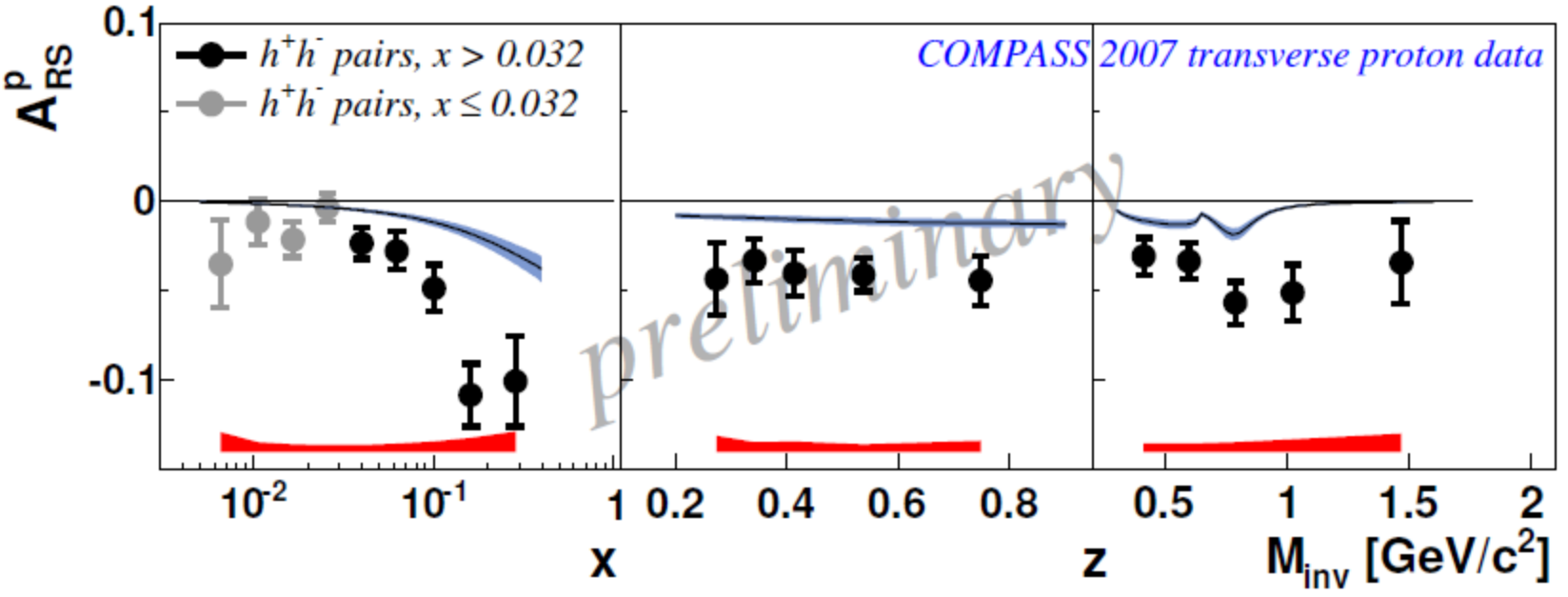
two-hadron asymmetry



- large asymmetries
- interference FF and transversity sizable

Comparison to a recent Fit

- Recent fit (COMPASS *p* not yet in)



Very recent prediction (Bacchetta, Radici Phys.Rev.D79:034029,2009)

Sivers function $\Delta_0^T q$ or $f_{1T}^{\perp}$

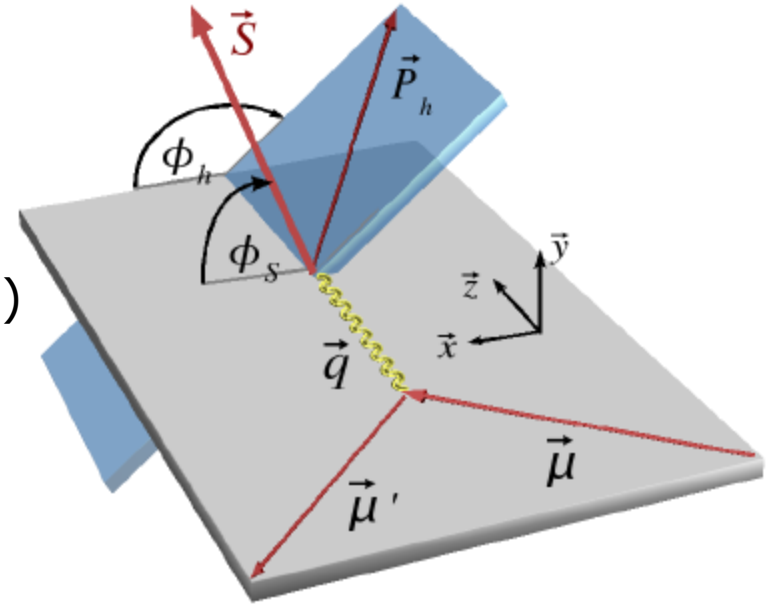
Sivers Asymmetry:

$$A_{Siv} = \frac{\sum_q e_q^2 \Delta_0^T q(x, p_T^h/z) D_q^h(z)}{\sum_q e_q^2 q(x, p_T^h/z) D_q^h(z)}$$

$$\frac{\Delta\sigma}{\sigma} \propto A_{Siv} \sin\Phi_S$$

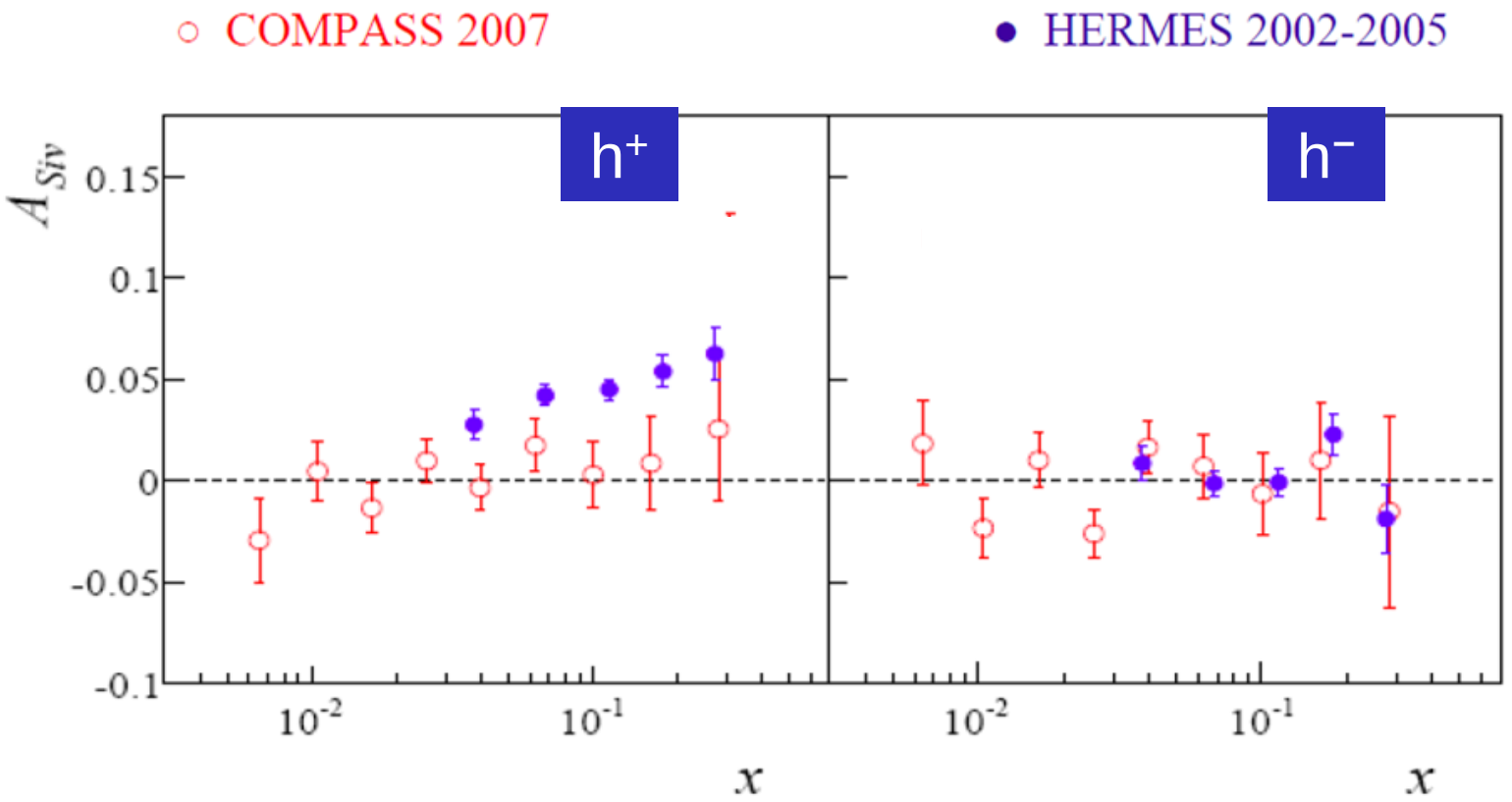
$$\Phi_S = \phi_h - \phi_S$$

- proposed (1990, Sivers)
- though to vanish (1993, Collins)
- resurrected (2002, Brodsky, Hwang, Schmitt)
- different sign in DY and SIDIS

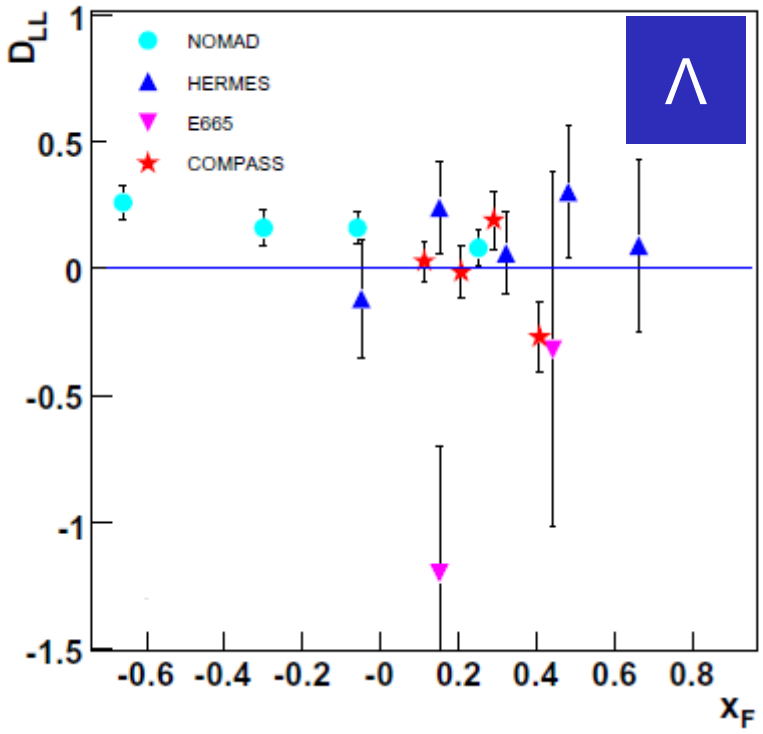


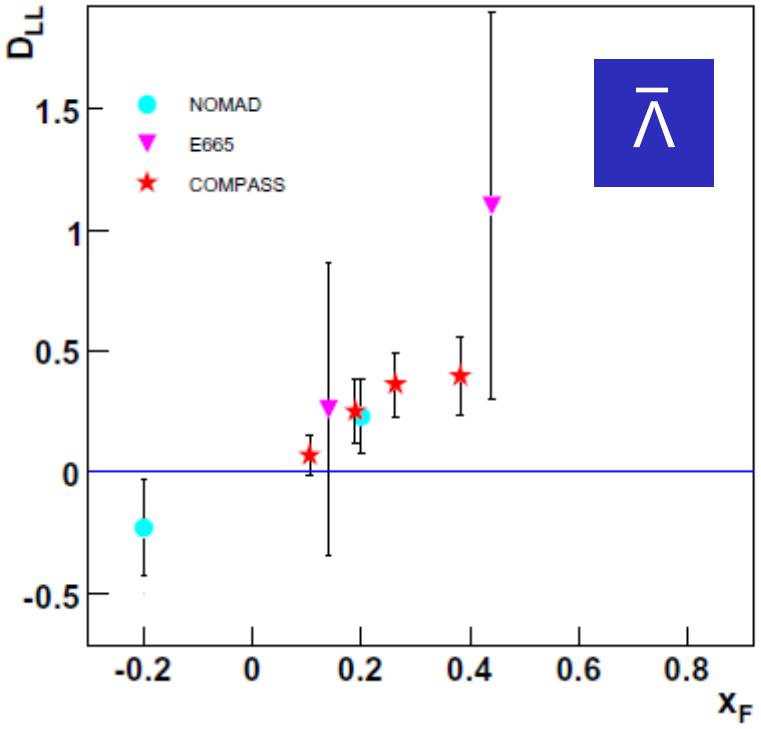
Proton Sivers Asymmetry

- compatible with zero for the deuteron
- large effect seen by HERMES, not confirmed by COMPASS
- clarification needed



Longitudinal spin transfer to Λ & $\bar{\Lambda}$





- non-zero D_{LL} related to polarisation of strange (anti) quarks (?)

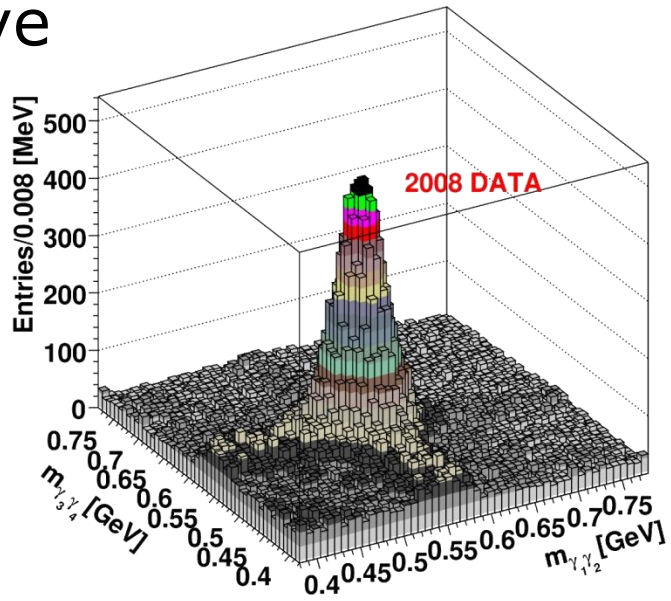
Physics with hadron beams

2004: Pilot run with 190 GeV/c π^- beam and heavy targets (Pb), few days only

2008: full year with LH_2 target (40 cm) with recoil detector, mainly π^- beam (4% *K*), some data with *p*/ π^+ beam (75/25%)

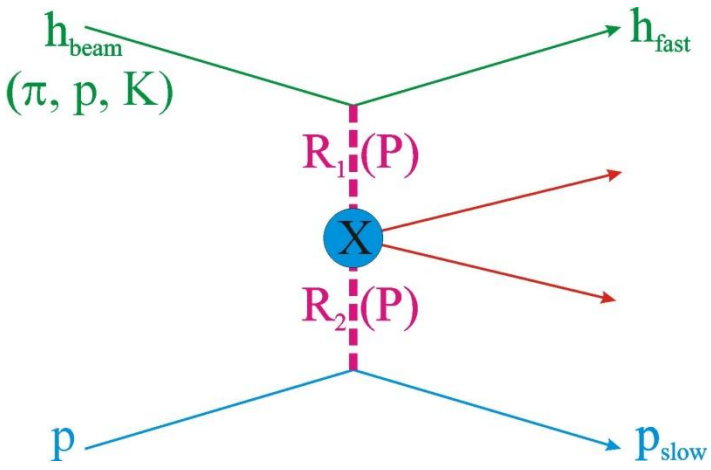
2009: LH2 target, Pb, Ni positive and negative beams

more: Ismail UMAN:
Thu, 24.09. Parallel 5C
Room:B326



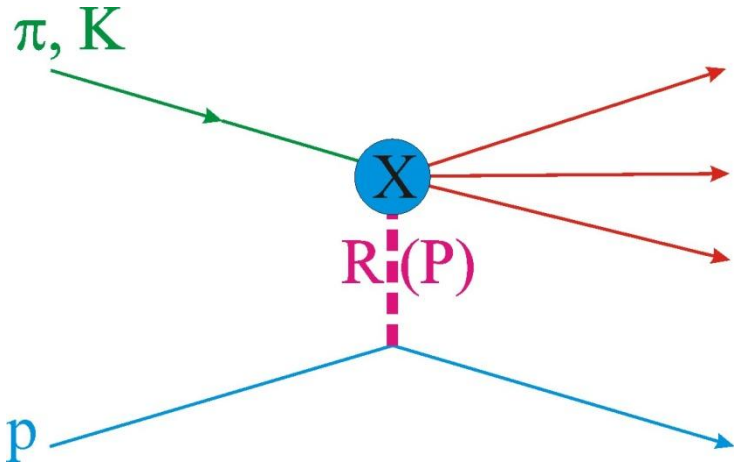
Hadron Spectroscopy @ COMPASS

Central production



- Rapidity gap between p_{slow}, h_{fast}, X
- Beam particle looses little of its energy
- Particles at large angles from X decays
- Possible source of glueballs (DPE)

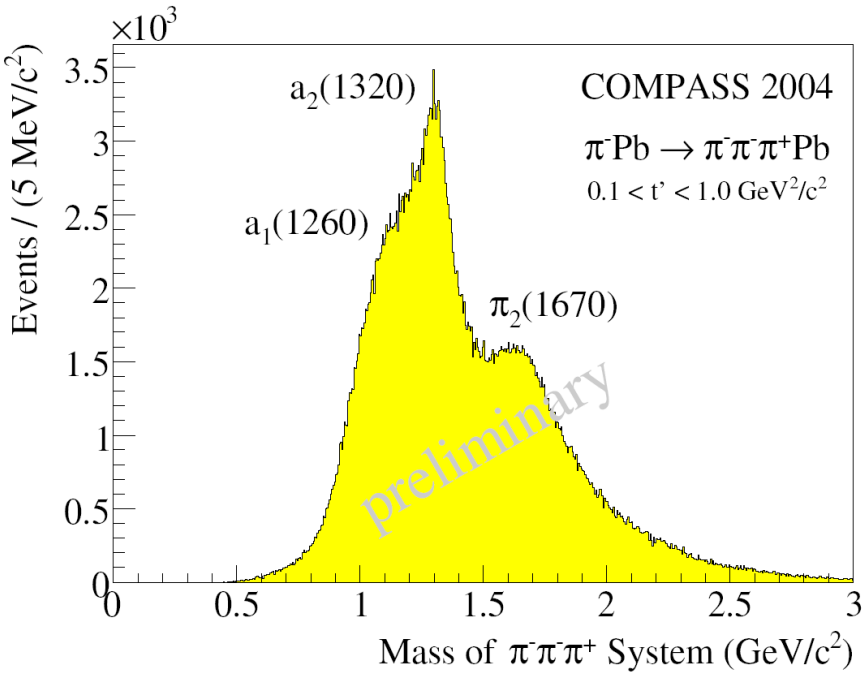
Diffractive dissociation

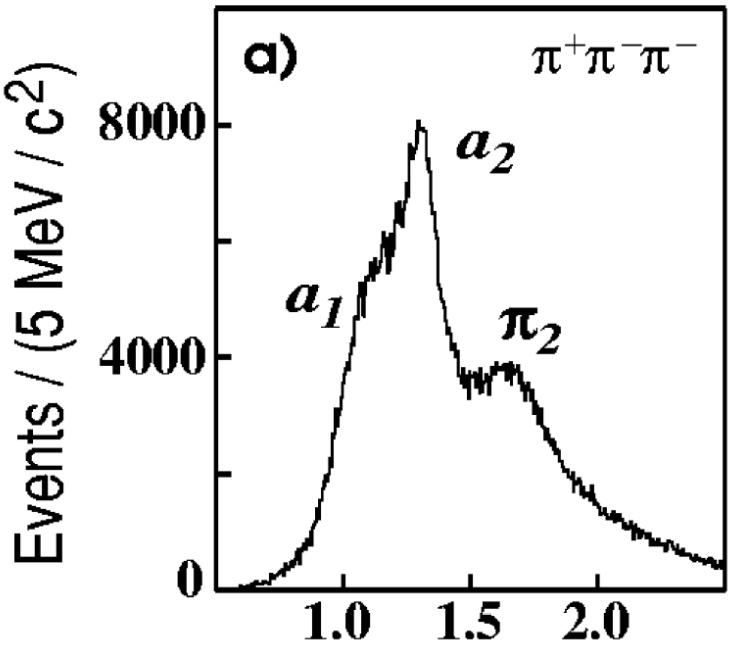


- Forward kinematics
- Particles at small angles
- Study of J^{PC}-exotic mesons

Example: 3π final state (2004 data)

$$\pi^- + \mathrm{Pb} \rightarrow \pi^-\pi^-\pi^+ + \mathrm{Pb}$$





COMPASS: p_π=190 GeV/c

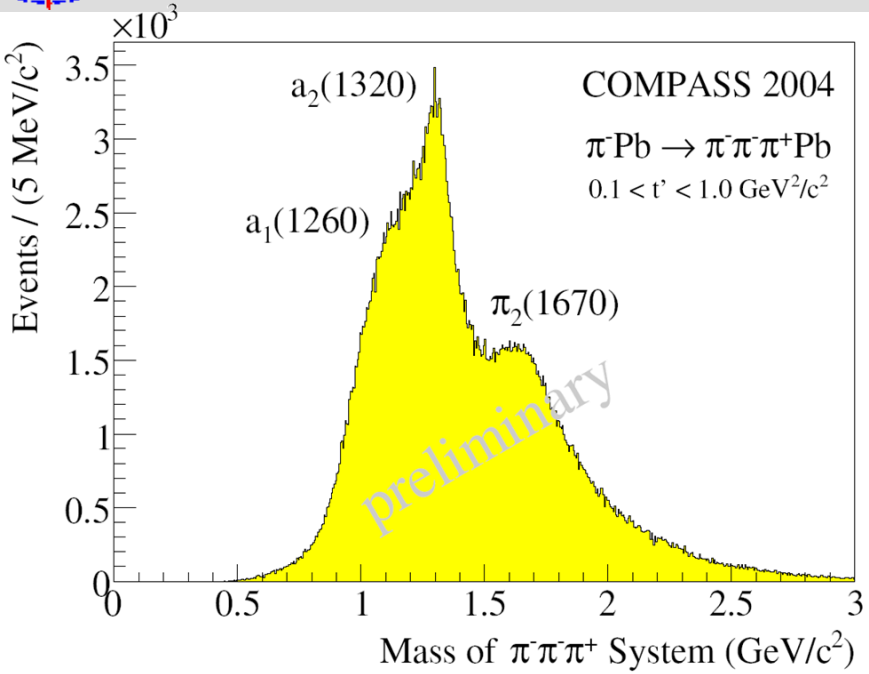
- 4M events in 3 days (full t range)
- 450k events in 0.1<t'<1.0 GeV²/c²

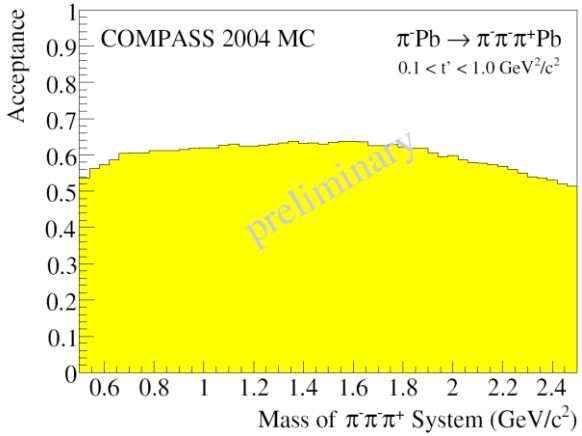
BNL852: p_π=18 GeV/c

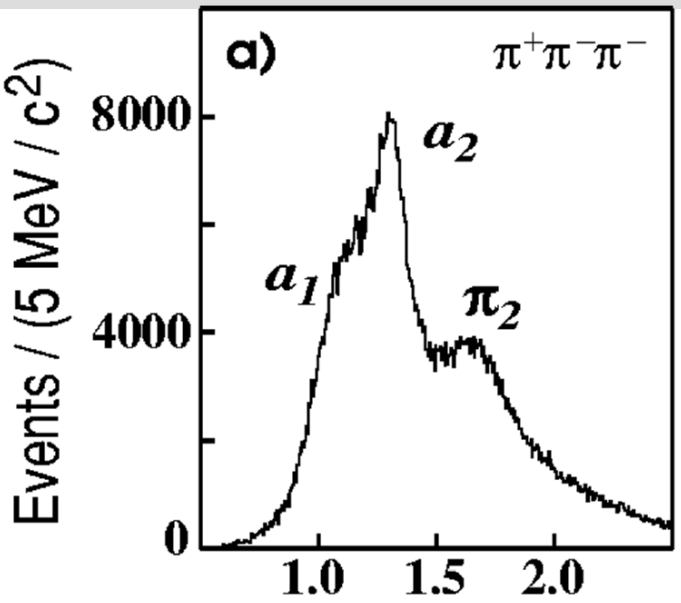
- 250k events ⇨ $\pi_1(1600)$

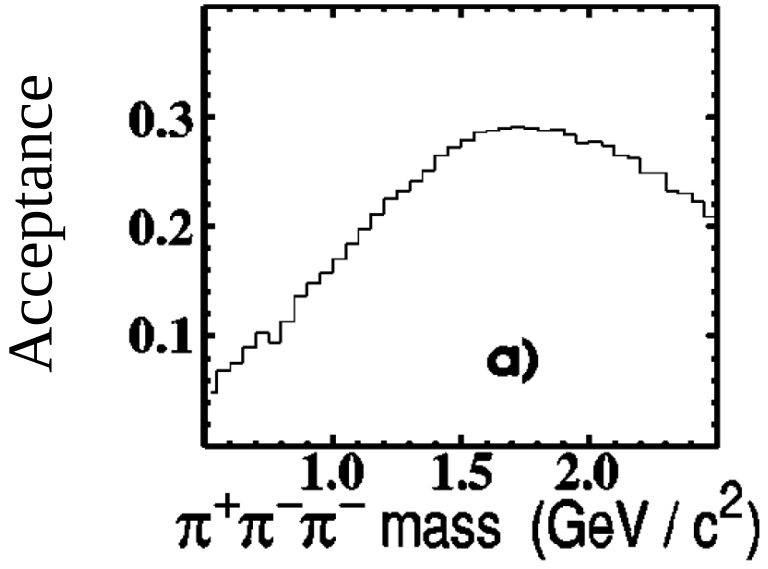
this and following slides: from B. Ketzer

Invariant Mass of 3π System

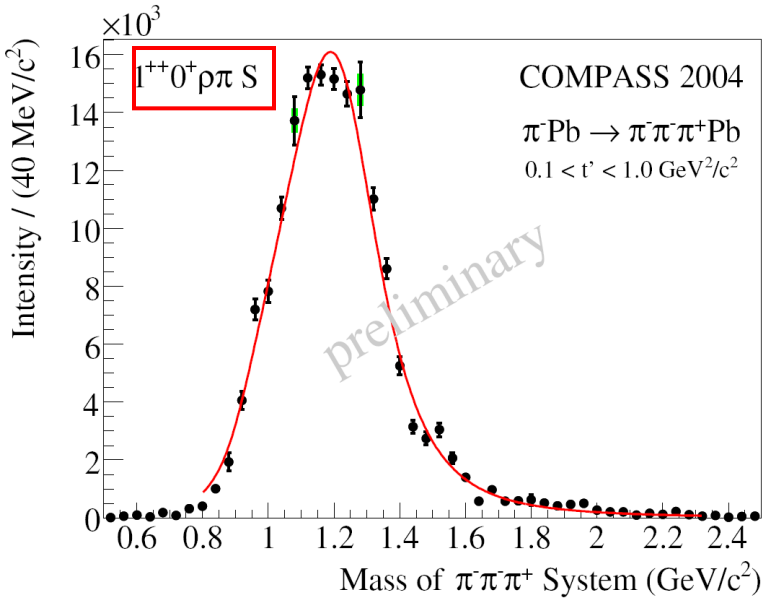


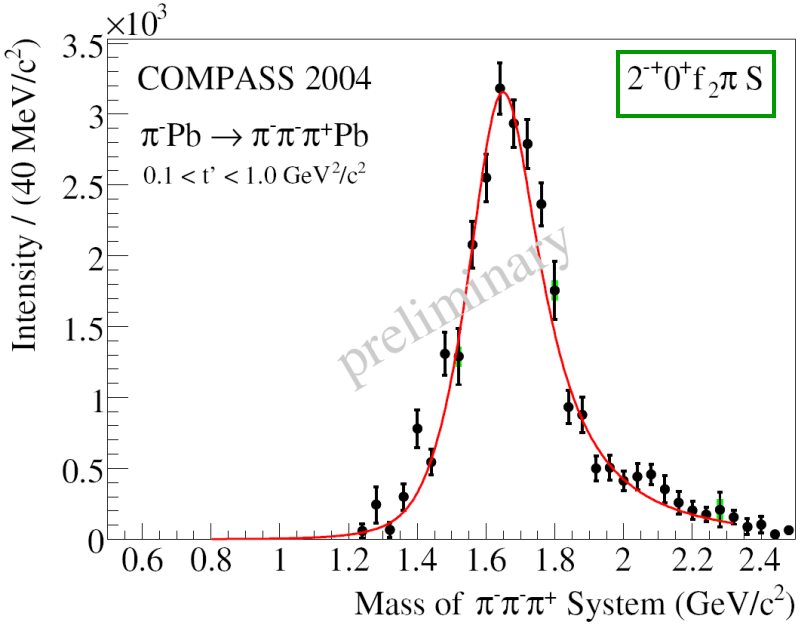


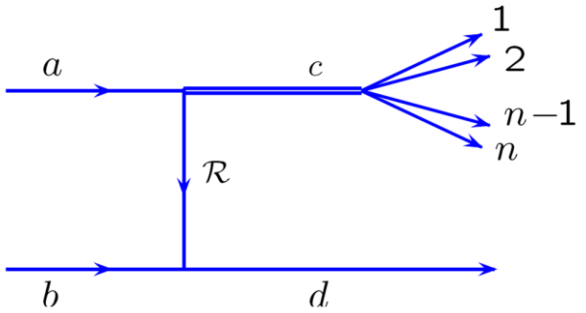




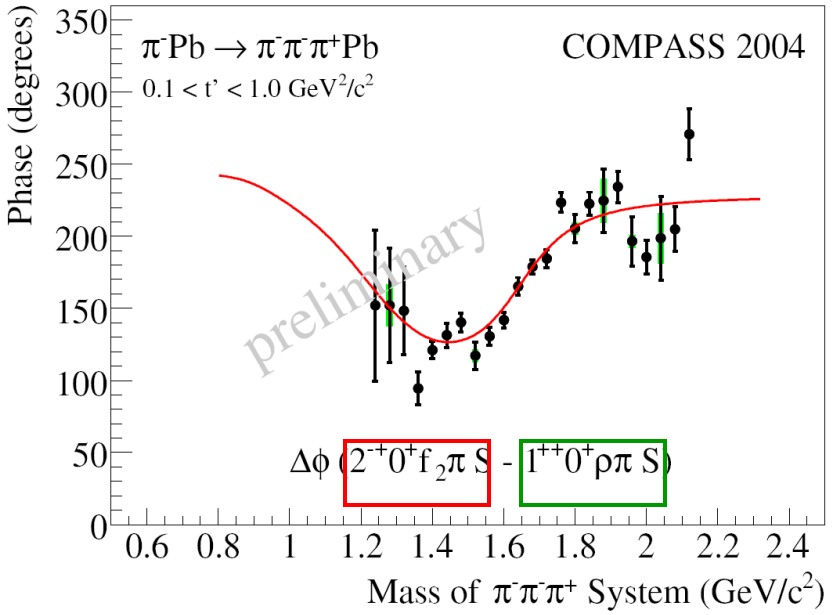
$a_1(1260)$ and $\pi_2(1670)$ from PWA





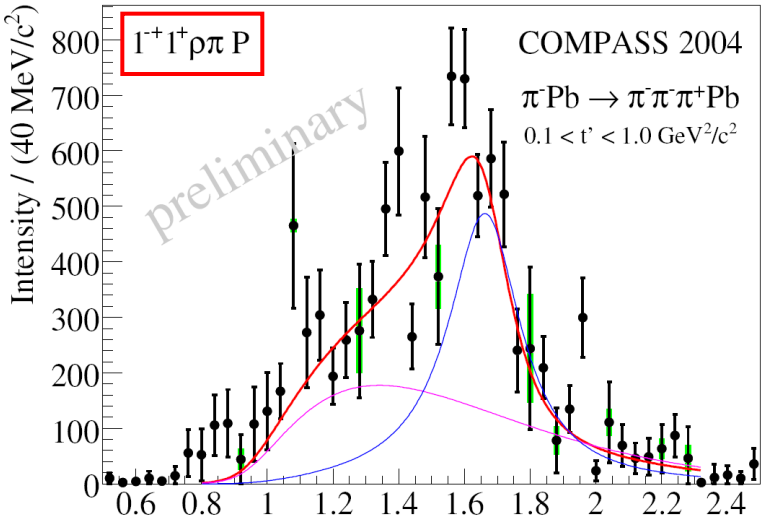


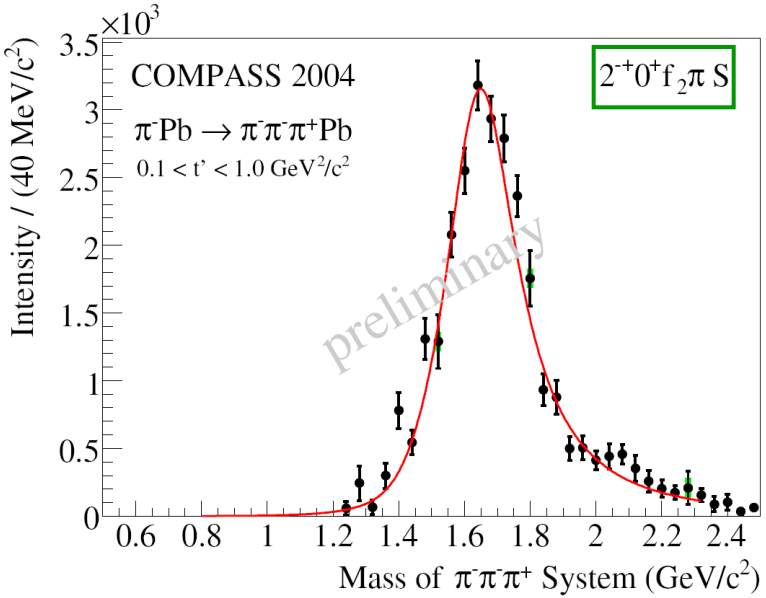
42 waves considered in PWA
6 dominant waves in mass fit

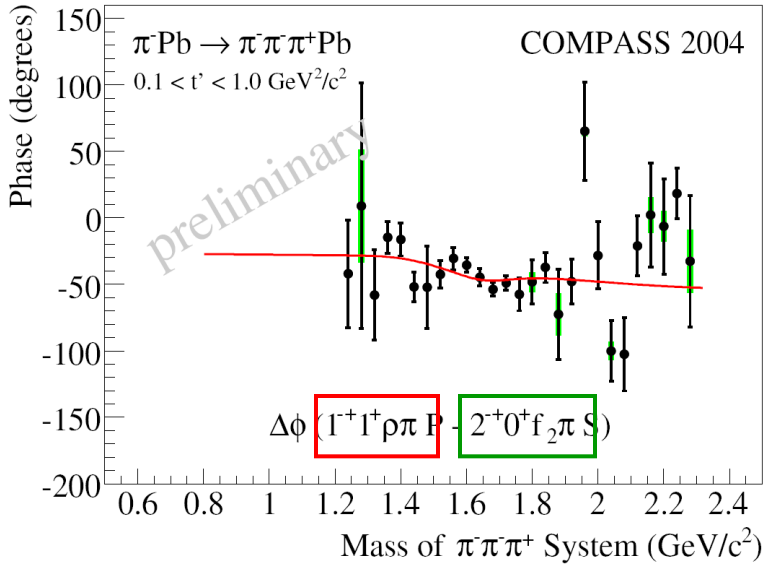


B. Ketzer, Int. J. Mod. Phys. A 24, 245 (2009)

$\pi_1(1600)$ and $\pi_2(1670)$



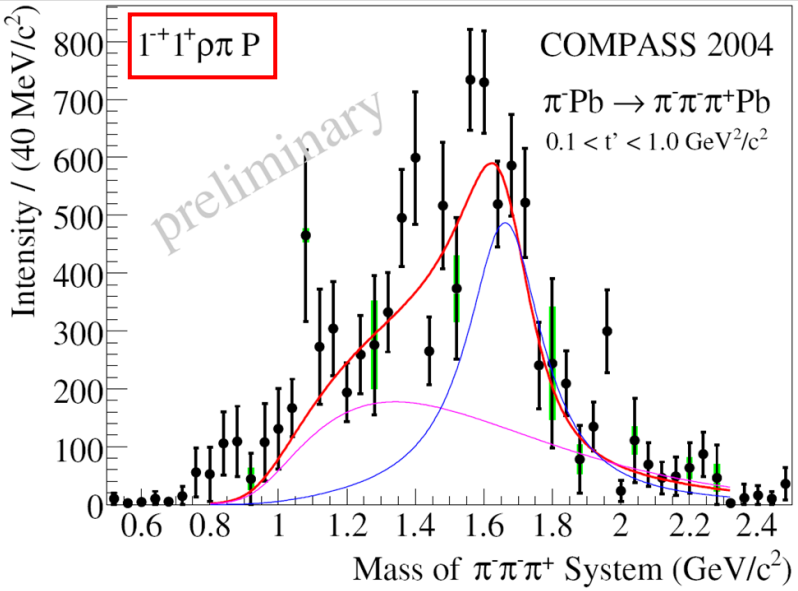


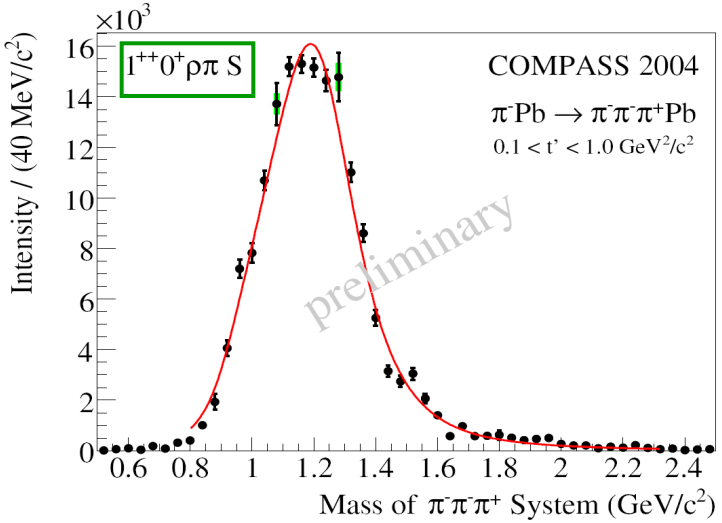


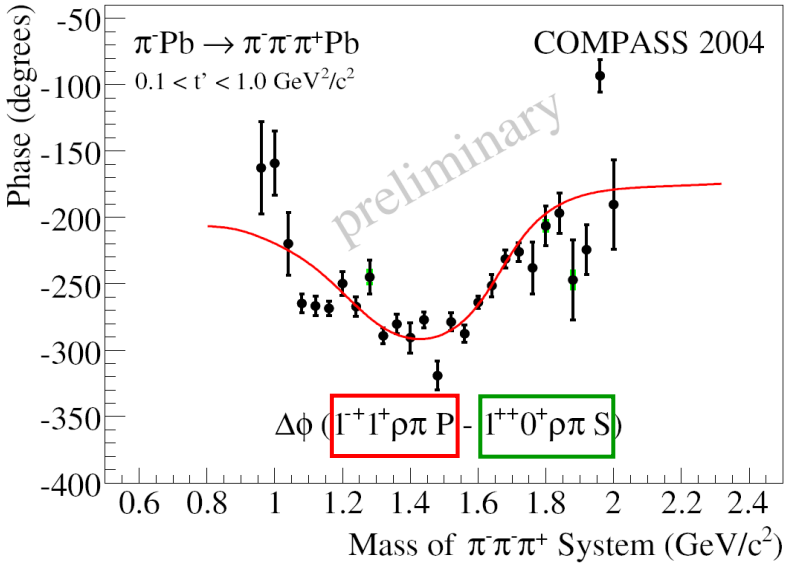
$J^{PC}=1^{-+}$ exotic wave in $\pi^-\pi^-\pi^+$

slow phase motion wrt $\pi_2(1670)$

$\pi_1(1600)$ and $a_1(1260)$



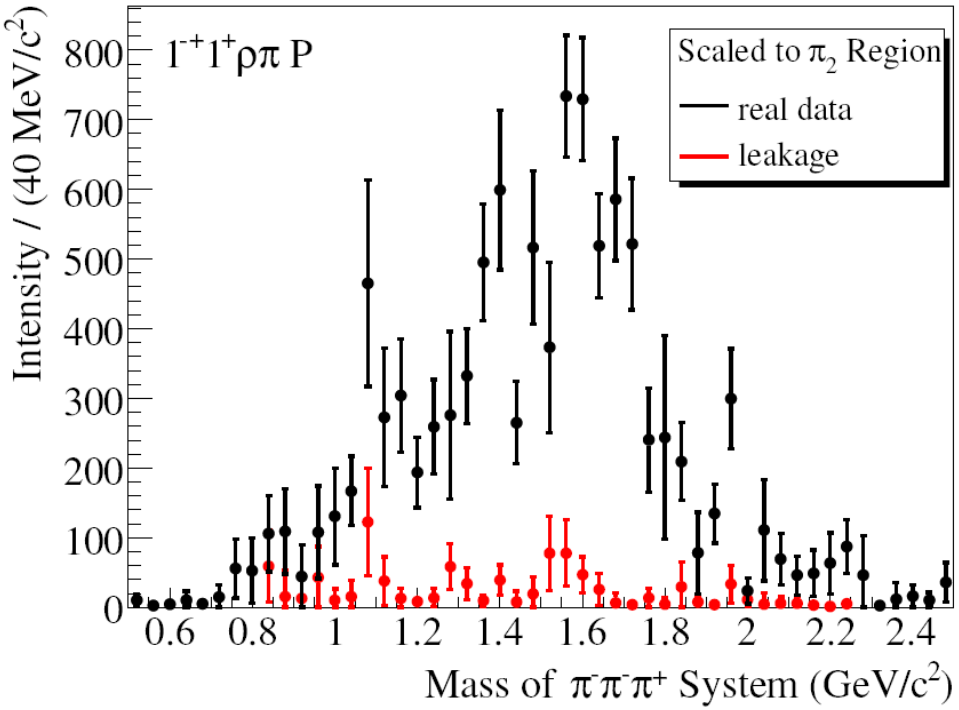




strong phase motion wrt $a_1(1260)$

Leakage Study

- 1150000 events generated from 15 dominant waves
  - including $J^{PC}=2^{-+}$ M=0,1
  - excluding $J^{PC}=1^{-+}$ exotic wave
- full reconstruction + PWA



⇨ less than 5% leakage into 1^{-+} wave

Outlook

- huge amount of spectroscopy data collected in 2008/2009
- approved 2 year measurements with muon beam and pol. proton target
  - transversity, Sivers, Boer-Mulders
  - longitudinal: g_1, g_1^{NS}, flavour separation, Δs
- plans for measurements of the pion and (maybe) kaon electrical and magnetic polarisabilities and further spectroscopy studies after analysis 08/09 data
- proposal for GPD and Drell-Yan measurements in preparation


COMPASS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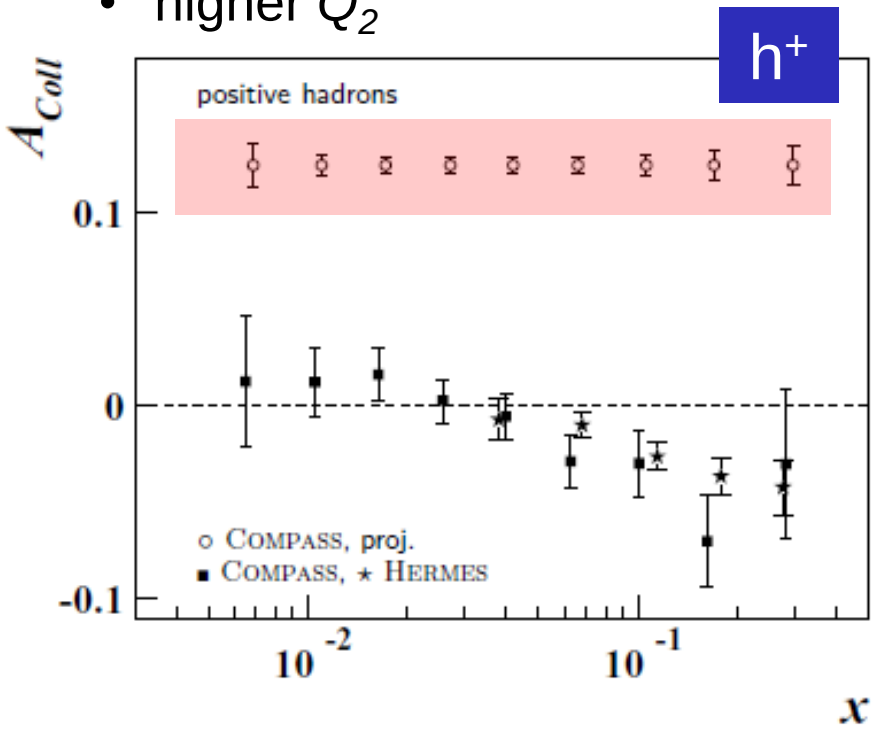
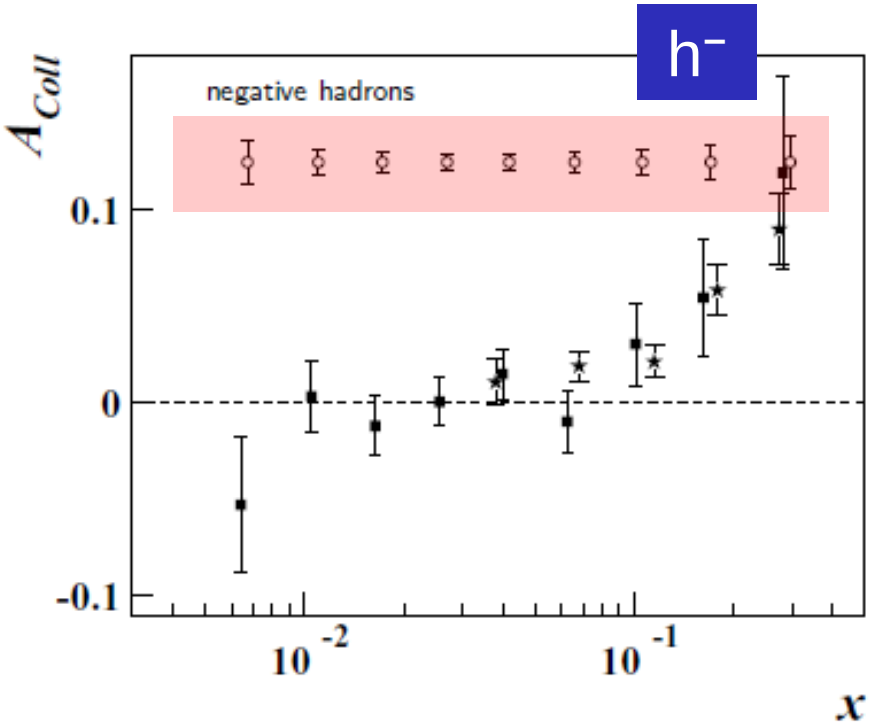
Transverse spin structure

Collins asymmetry:

- match HERMES precision at large *x*
- improve precision at small *x*
- higher Q_2

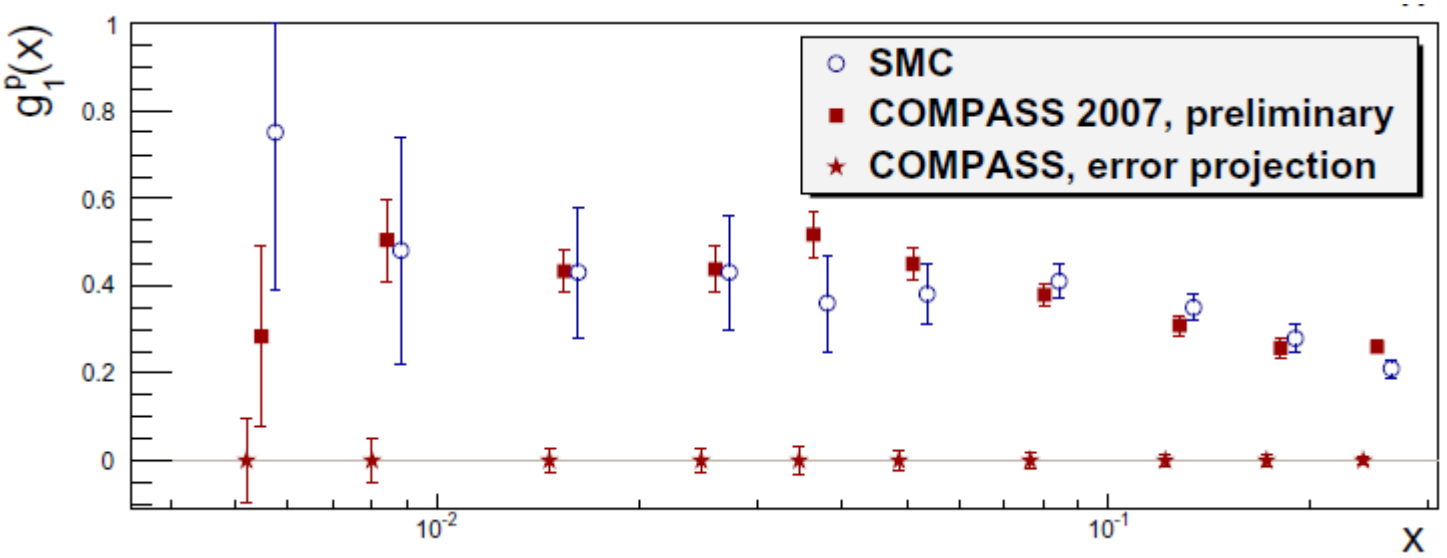




Longitudinal Spin Structure

proton $g_1(x)$

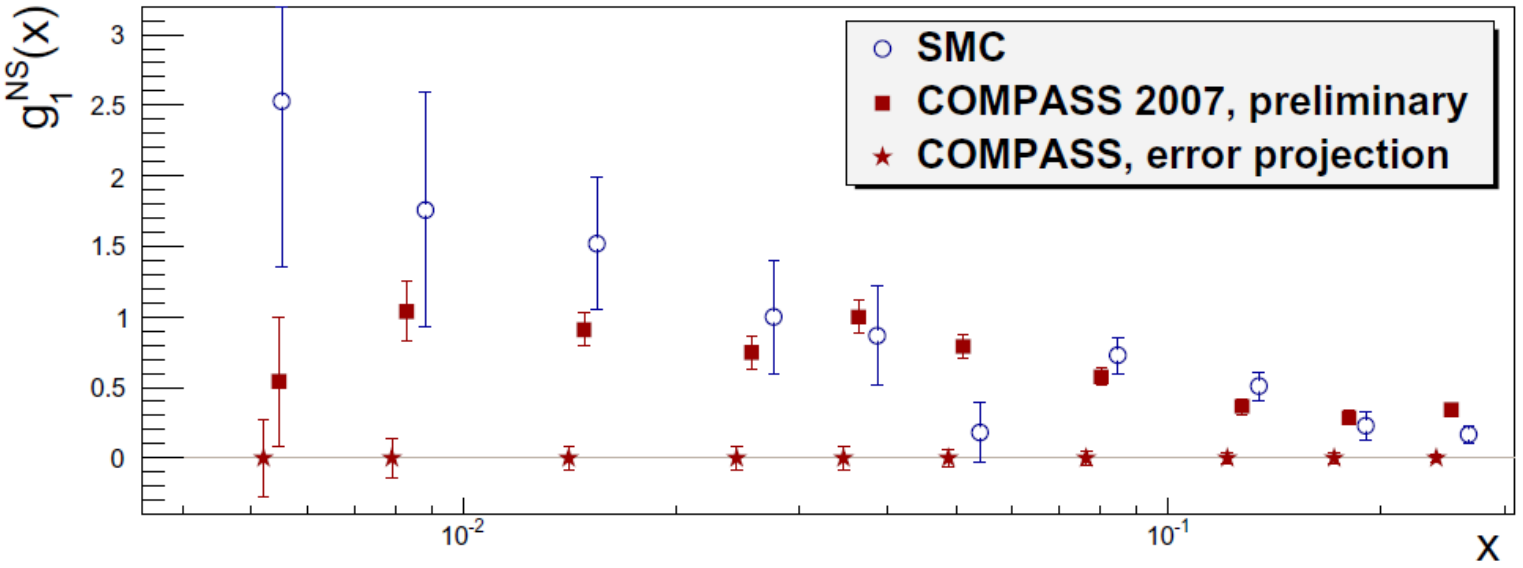
- small x behaviour very interesting
- only COMPASS can provide further data until the advent of a pol. ep collider



Non-singlet structure function

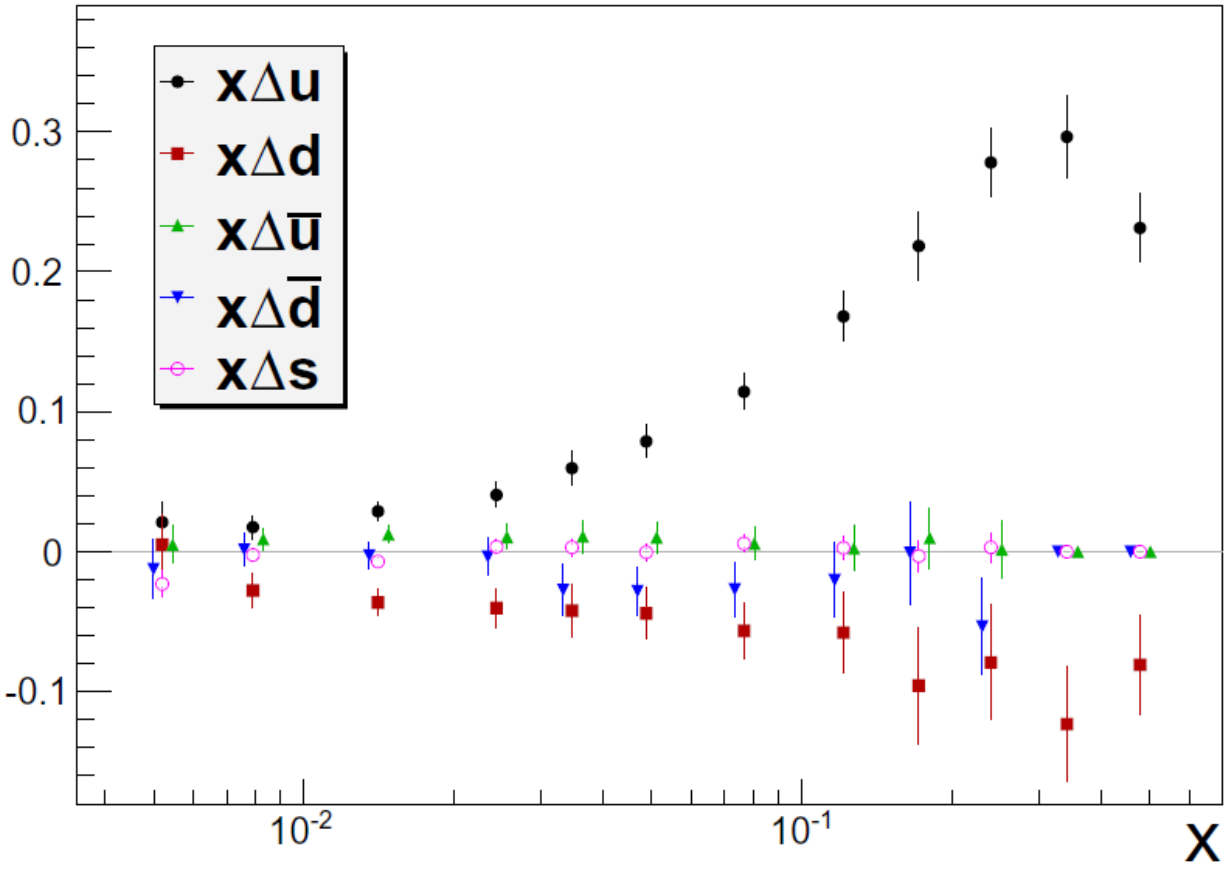
non-singlet structure function: Bjorken sum rule

$$g_1^{NS}(x) = g_1^p(x) - g_1^n(x) \qquad \Gamma_1^{NS} = \Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_V}\right|$$

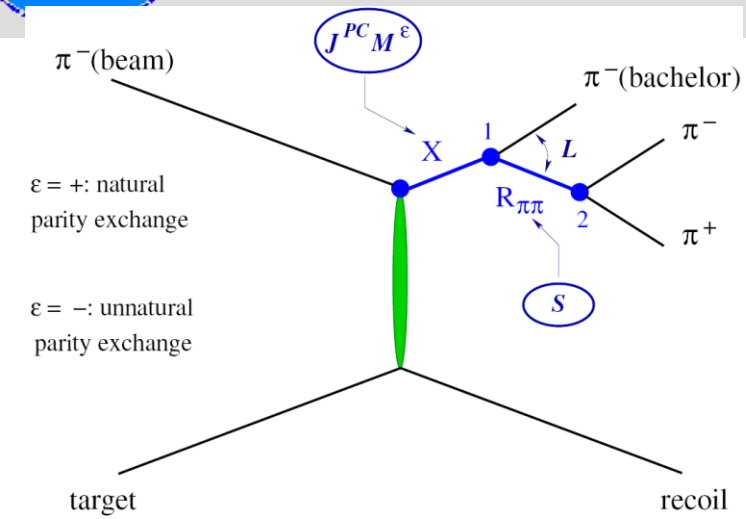


Flavour separated PDFs

projection for flavour separation from semi-inclusive asymmetries



PWA Technique



- t-channel Reggeon exchange
- Reflectivity basis in G-J frame
- At high s: $\varepsilon = \eta$ of Regge trajectory
- Isobar model

1. **Mass-independent PWA** of angular distributions in 40 MeV mass bins

$$\sigma_{\text{indep}}(\tau) = \sum_{\varepsilon=\pm1}\sum_{r=1}^{N_r}\left|\sum_i T_{ir}^{\varepsilon}\psi_i^{\varepsilon}(\tau)\Big/\sqrt{\int\left|\psi_i^{\varepsilon}(\tau')\right|^2 d\tau'}\right|^2$$

- 42 partial waves ***i*=$J^{PC}M^{\varepsilon}$[...]*L***

[...]=isobar $(\pi\pi)_S$, $f_0(980)$, $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$

Waves used in PWA

$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [GeV]
$0^{-+}0^{+}$	S	$f_0\pi$	1.40
$0^{-+}0^{+}$	S	$(\pi\pi)_S\pi$	-
$0^{-+}0^{+}$	P	$\rho\pi$	-
$1^{-+}1^{+}$	P	$\rho\pi$	-
$1^{++}0^{+}$	S	$\rho\pi$	-
$1^{++}0^{+}$	P	$f_2\pi$	1.20
$1^{++}0^{+}$	P	$(\pi\pi)_S\pi$	0.84
$1^{++}0^{+}$	D	$\rho\pi$	1.30
$1^{++}1^{+}$	S	$\rho\pi$	-
$1^{++}1^{+}$	P	$f_2\pi$	1.40
$1^{++}1^{+}$	P	$(\pi\pi)_S\pi$	1.40
$1^{++}1^{+}$	D	$\rho\pi$	1.40
$2^{-+}0^{+}$	S	$f_2\pi$	1.20
$2^{-+}0^{+}$	P	$\rho\pi$	0.80
$2^{-+}0^{+}$	D	$f_2\pi$	1.50
$2^{-+}0^{+}$	D	$(\pi\pi)_S\pi$	0.80
$2^{-+}0^{+}$	F	$\rho\pi$	1.20
$2^{-+}1^{+}$	S	$f_2\pi$	1.20
$2^{-+}1^{+}$	P	$\rho\pi$	0.80
$2^{-+}1^{+}$	D	$f_2\pi$	1.50
$2^{-+}1^{+}$	D	$(\pi\pi)_S\pi$	1.20
$2^{-+}1^{+}$	F	$\rho\pi$	1.20

$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [GeV]
$2^{++}1^{+}$	P	$f_2\pi$	1.50
$2^{++}1^{+}$	D	$\rho\pi$	-
$3^{++}0^{+}$	S	$\rho_3\pi$	1.50
$3^{++}0^{+}$	P	$f_2\pi$	1.20
$3^{++}0^{+}$	D	$\rho\pi$	1.50
$3^{++}1^{+}$	S	$\rho_3\pi$	1.50
$3^{++}1^{+}$	P	$f_2\pi$	1.20
$3^{++}1^{+}$	D	$\rho\pi$	1.50
$4^{-+}0^{+}$	F	$\rho\pi$	1.20
$4^{-+}1^{+}$	F	$\rho\pi$	1.20
$4^{++}1^{+}$	F	$f_2\pi$	1.60
$4^{++}1^{+}$	G	$\rho\pi$	1.64
$1^{-+}0^{-}$	P	$\rho\pi$	-
$1^{-+}1^{-}$	P	$\rho\pi$	-
$1^{++}1^{-}$	S	$\rho\pi$	-
$2^{-+}1^{-}$	S	$f_2\pi$	1.20
$2^{++}0^{-}$	P	$f_2\pi$	1.30
$2^{++}0^{-}$	D	$\rho\pi$	-
$2^{++}1^{-}$	P	$f_2\pi$	1.30
FLAT			

Summary of Waves

State	(GeV)	COMPASS ± stat ± syst	PDG
$a_1(1260)$	M	$1.256 \pm 0.006 + 0.007 - 0.017$	1.230 ± 0.040
	Γ	$0.366 \pm 0.009 + 0.028 - 0.025$	0.250 to 0.600
$a_2(1320)$	M	$1.321 \pm 0.001 + 0.000 - 0.007$	1.3183 ± 0.0006
	Γ	$0.110 \pm 0.002 + 0.002 - 0.015$	0.107 ± 0.005
$\pi_1(1600)$	M	$1.660 \pm 0.010 + 0.000 - 0.064$	$1.653^{+0.018}_{-0.015}$
	Γ	$0.269 \pm 0.021 + 0.042 - 0.064$	$0.225^{+0.045}_{-0.028}$
$\pi_2(1670)$	M	$1.659 \pm 0.003 + 0.024 - 0.008$	1.6724 ± 0.0032
	Γ	$0.271 \pm 0.009 + 0.022 - 0.024$	0.259 ± 0.009
$\pi(1800)$	M	$1.785 \pm 0.009 + 0.012 - 0.006$	1.812 ± 0.014
	Γ	$0.208 \pm 0.022 + 0.021 - 0.037$	0.207 ± 0.013
$a_4(2040)$	M	$1.884 \pm 0.013 + 0.050 - 0.002$	2.001 ± 0.010
	Γ	$0.295 \pm 0.024 + 0.046 - 0.019$	0.313 ± 0.031

Publication being prepared, to be submitted

Summary of Waves