Spin physics at COMPASS: present and future

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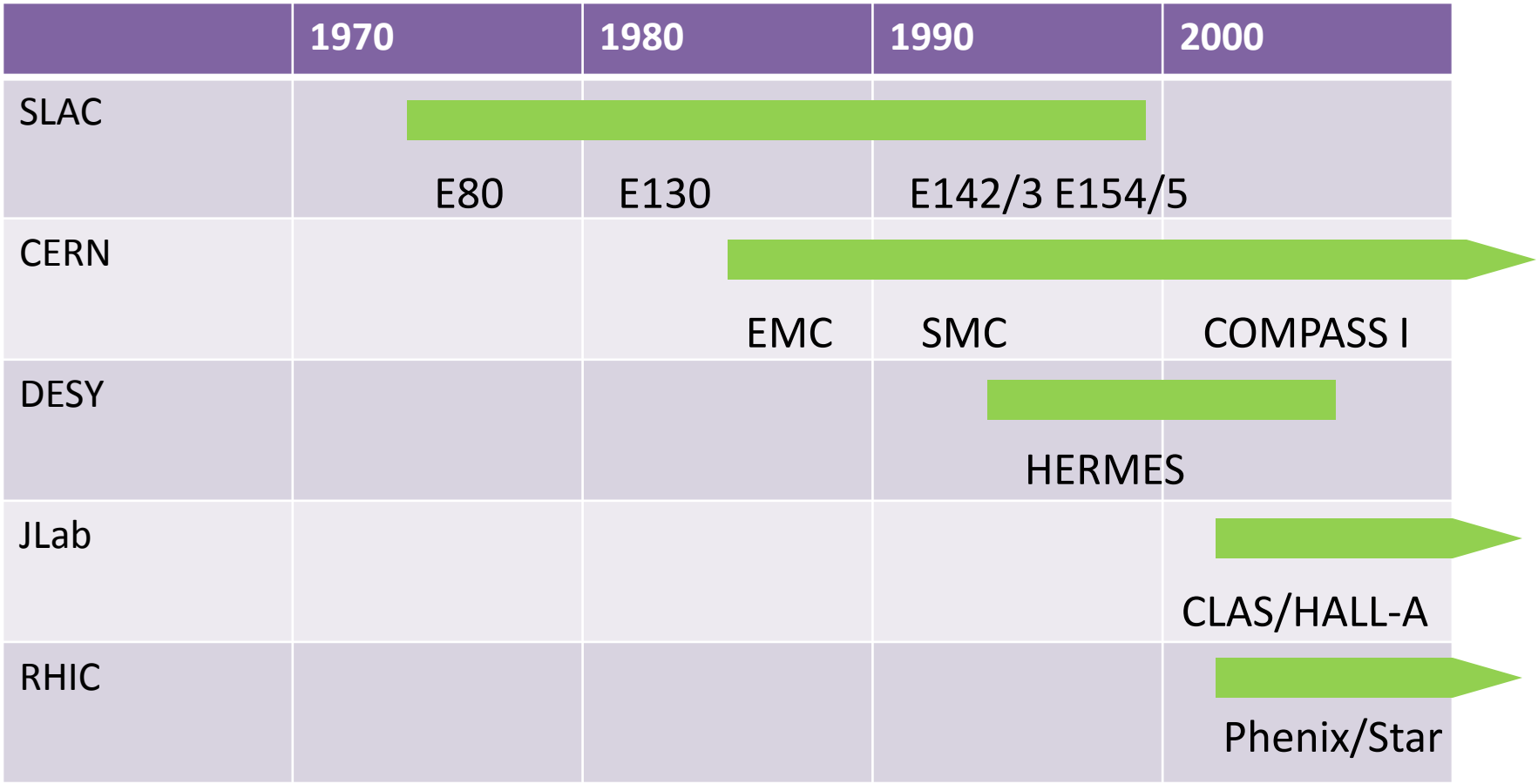
CERN/PH
On behalf of the COMPASS Collaboration

Enrico Fermi School (Course CLXXX), Varenna, 28 June - 11 July, 2011

Plan

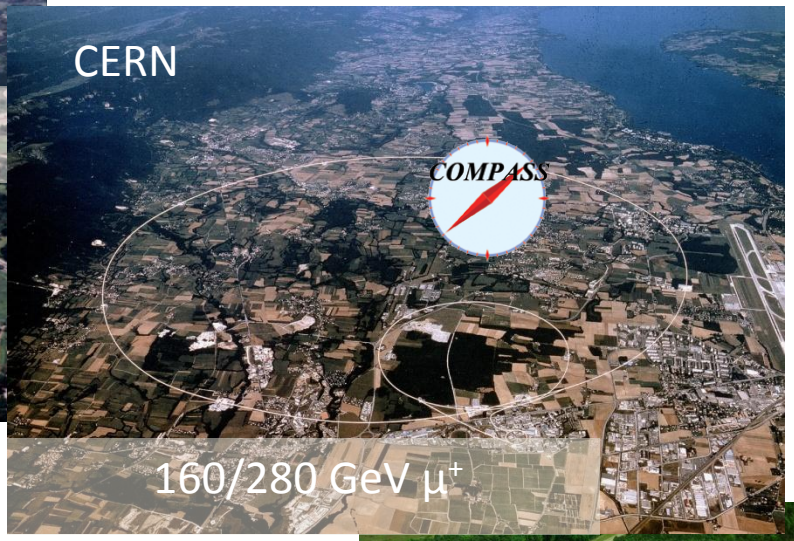
- COMPASS I
  - Goals
  - Experiment
  - Results
    - Helicity distributions
    - Gluon polarization
    - Transverse spin
    - TMDs
- COMPASS II
  - Drell-Yan
  - DVCS/GPDs
  - Outlook

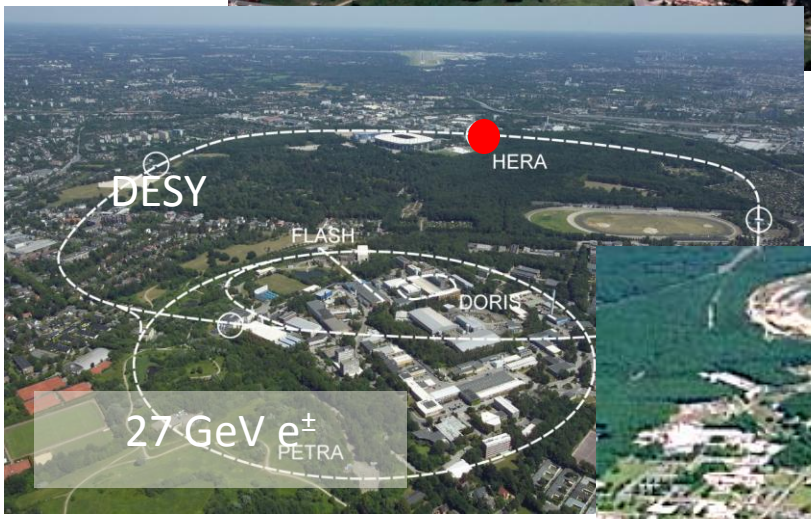
Global effort: Pol. DIS/pp

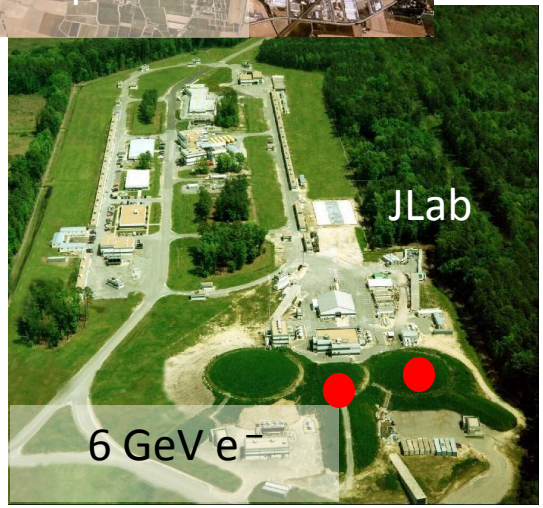


- A worldwide effort since decades

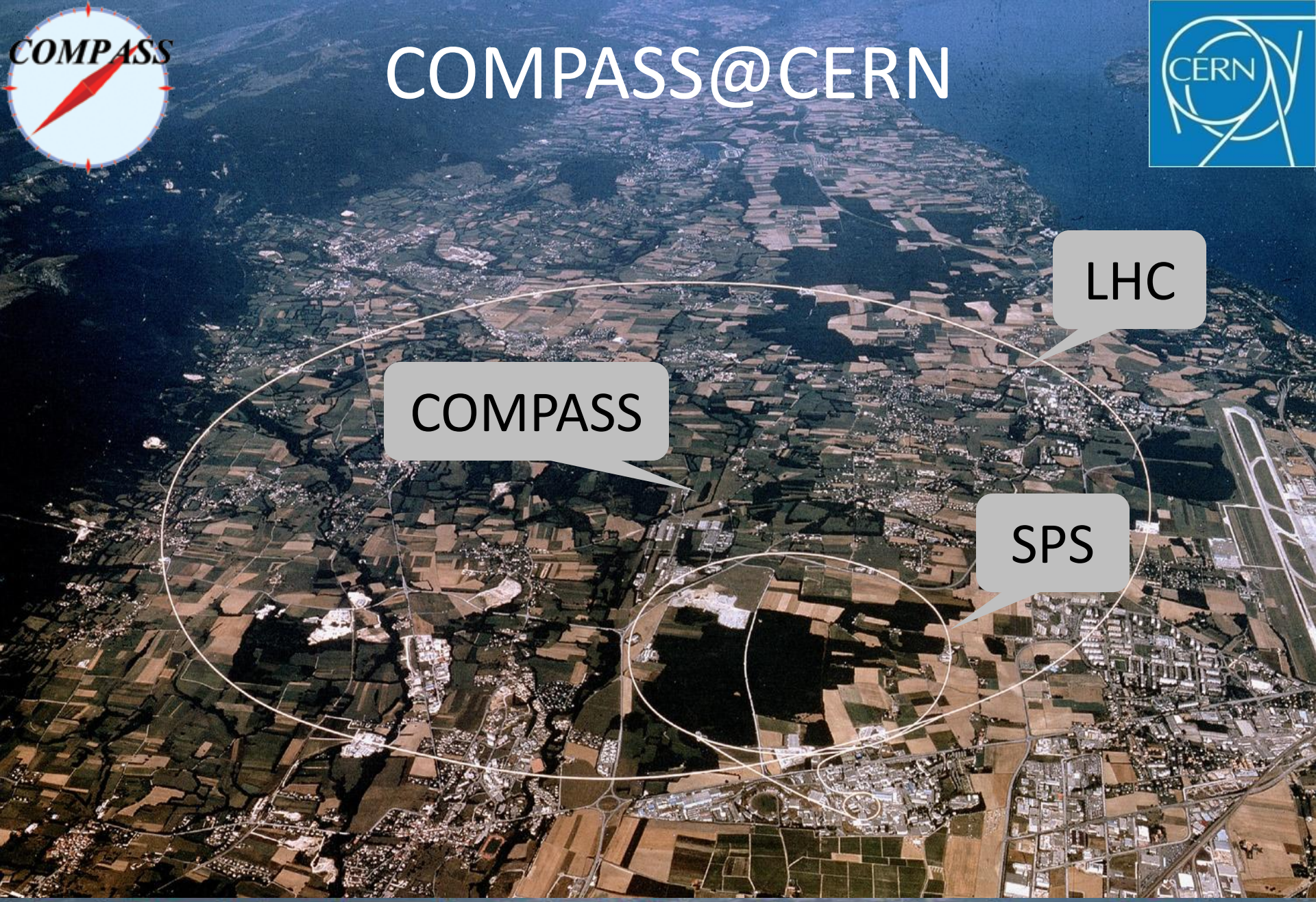
Laboratories







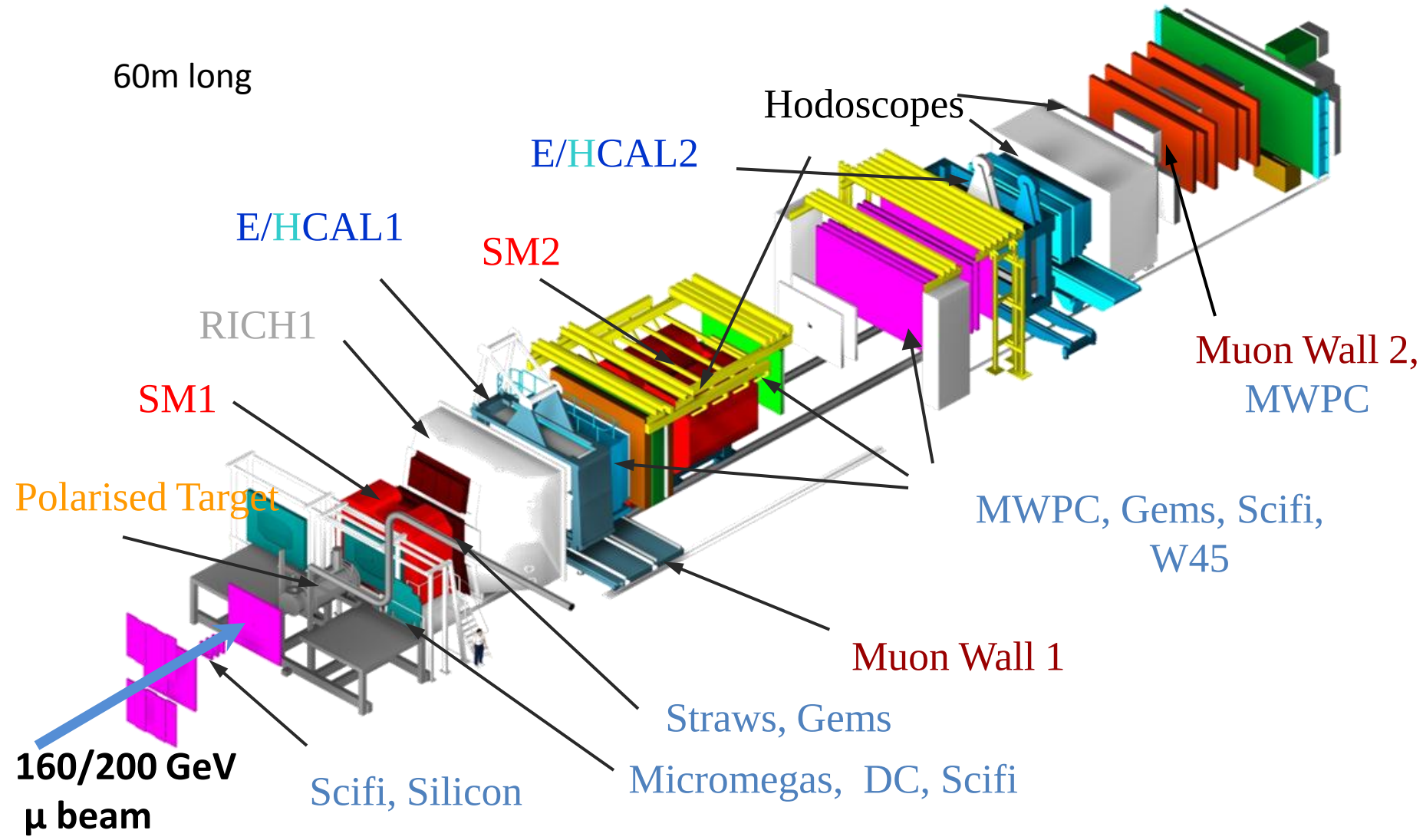
COMPASS@CERN



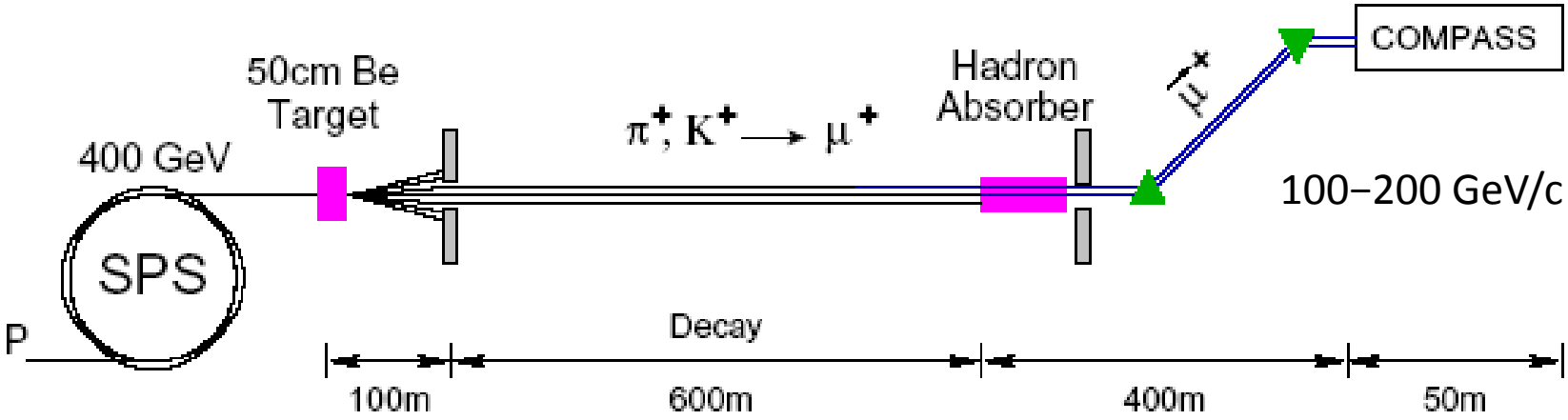
COMPASS I: Goals

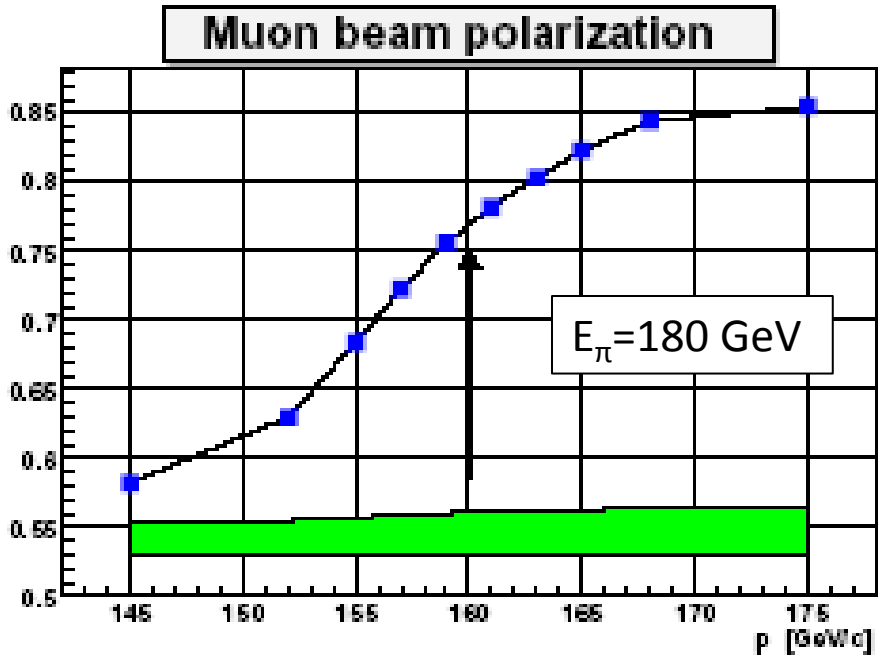
- Founded 1996, approved 1998, first data 2002
- Goals of the semi-inclusive measurements
  - Helicity distributions
  - Gluon polarization
  - Transversity PDF
  - Meson and baryon spectroscopy , π polarizability (not discussed here)

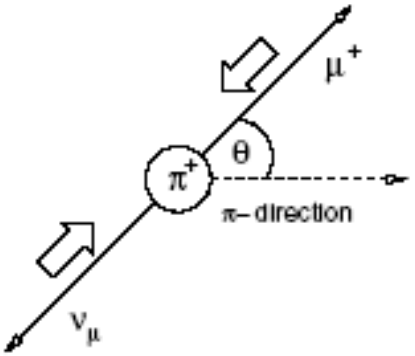
Experiment: Spectrometer



CERN muon beam







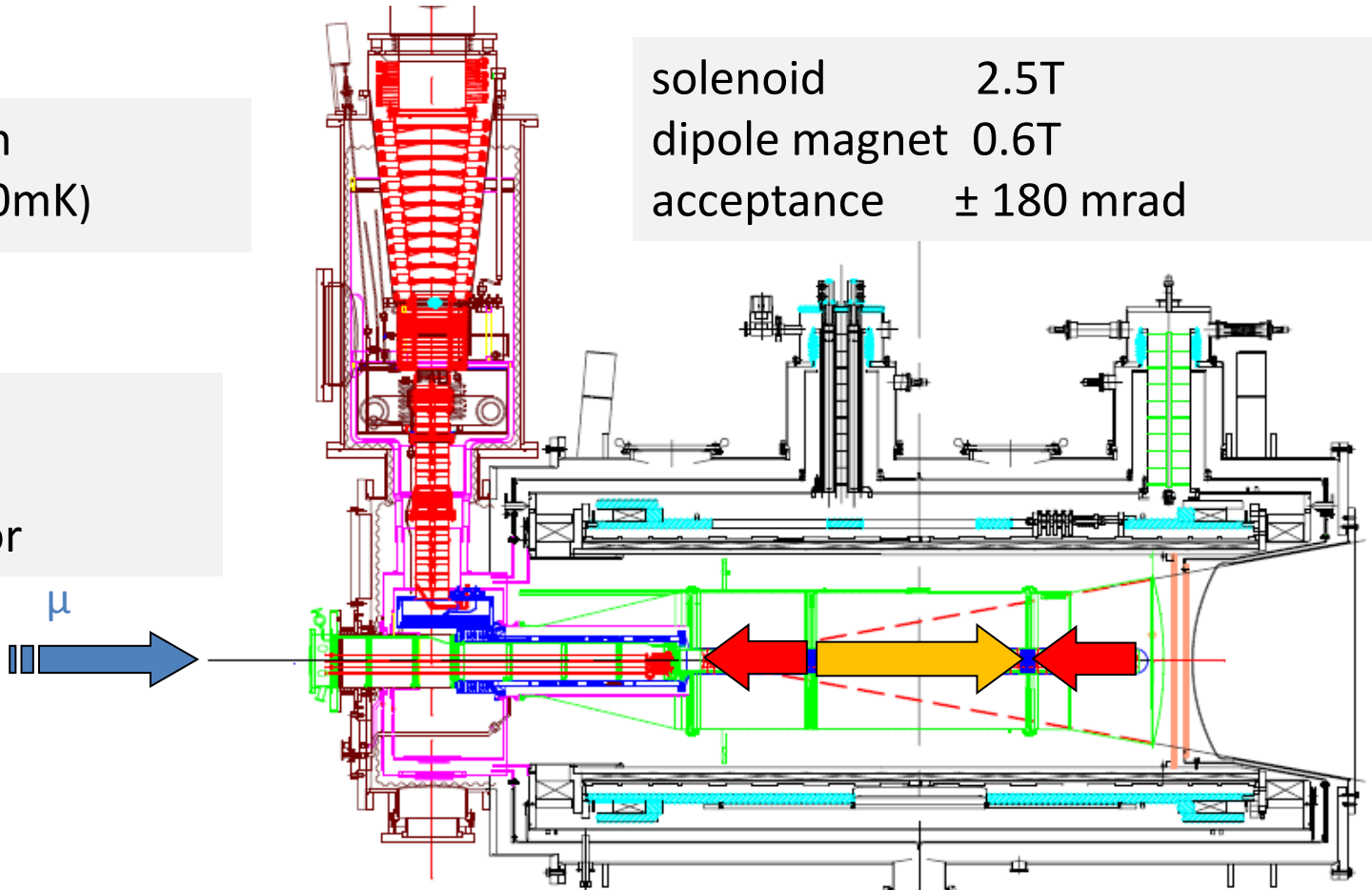
Energy	160 GeV
Intensity	$2 \cdot 10^8 \mu$/Spill
Polarisation	$\approx 76\,\%$

Polarized target system

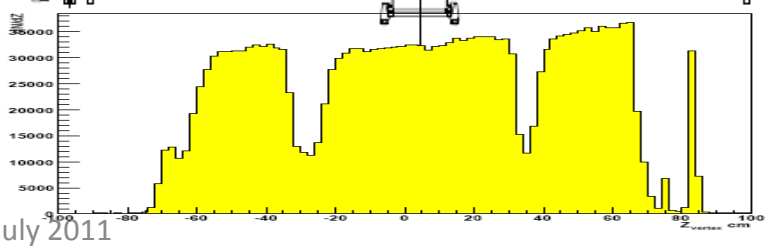
^{3}He – ^{4}He dilution refrigerator (T~50mK)

^{6}LiD/NH_3 (d/p)
50/90% pol.
40/16% dil. factor

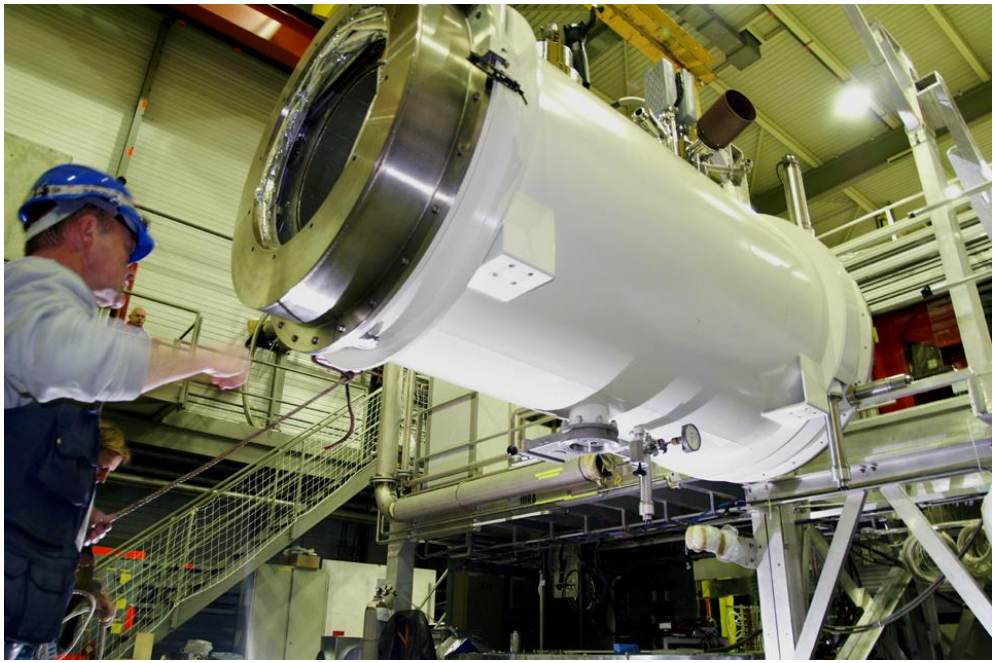
solenoid 2.5T
dipole magnet 0.6T
acceptance ± 180 mrad

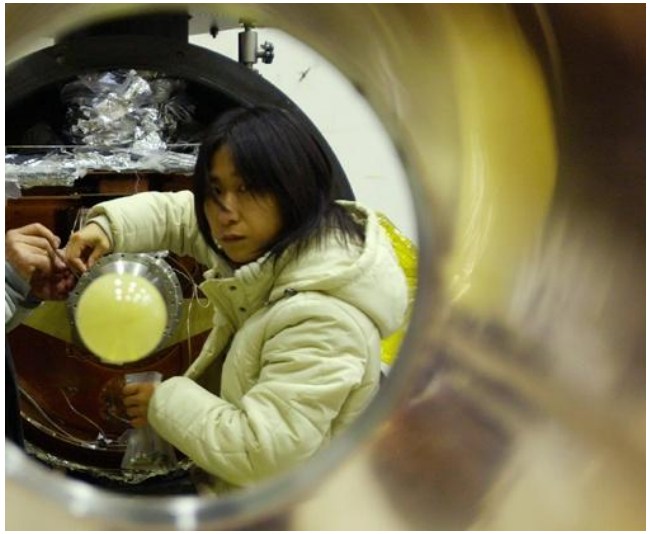


Recontructed interaction vertices



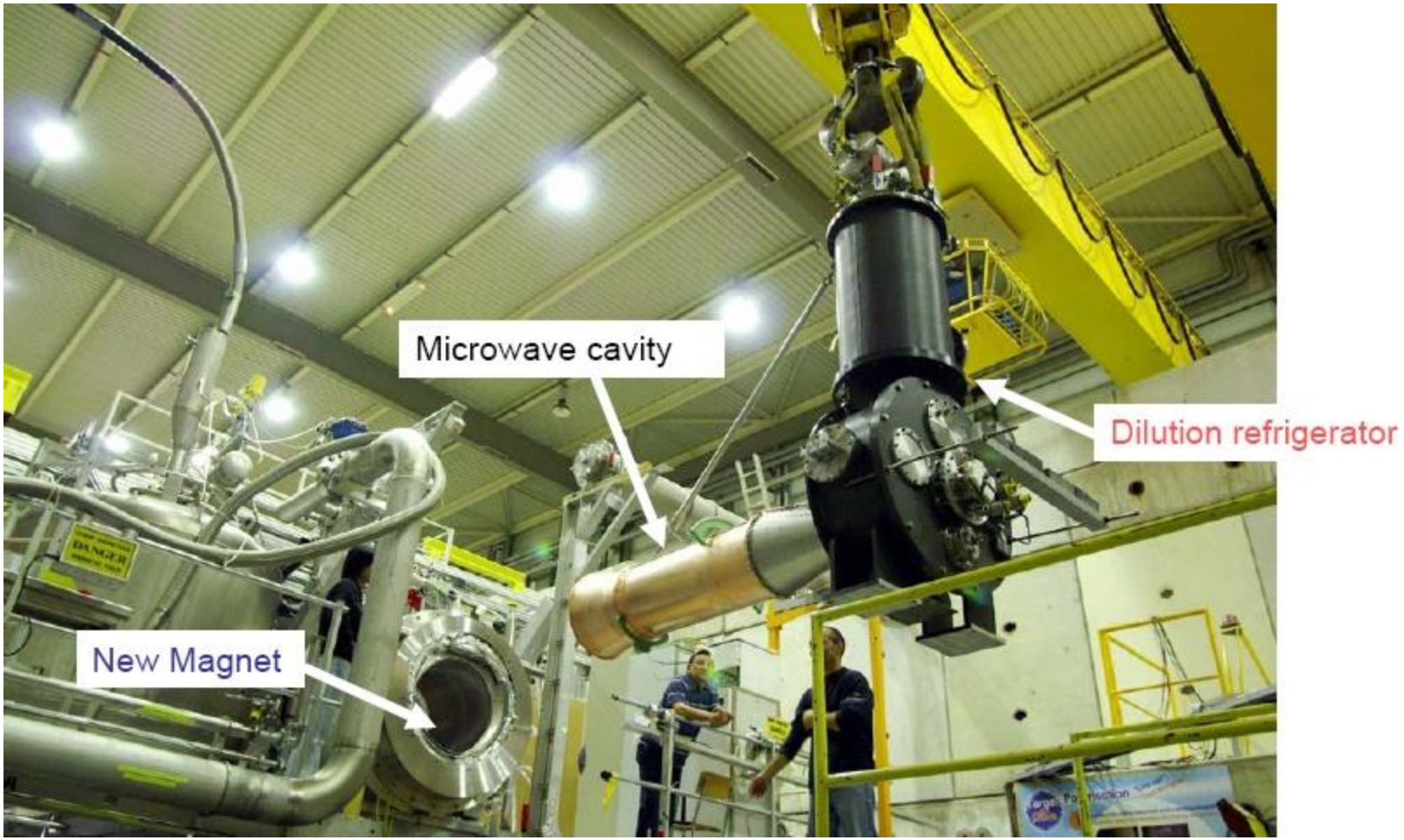
Polarized target



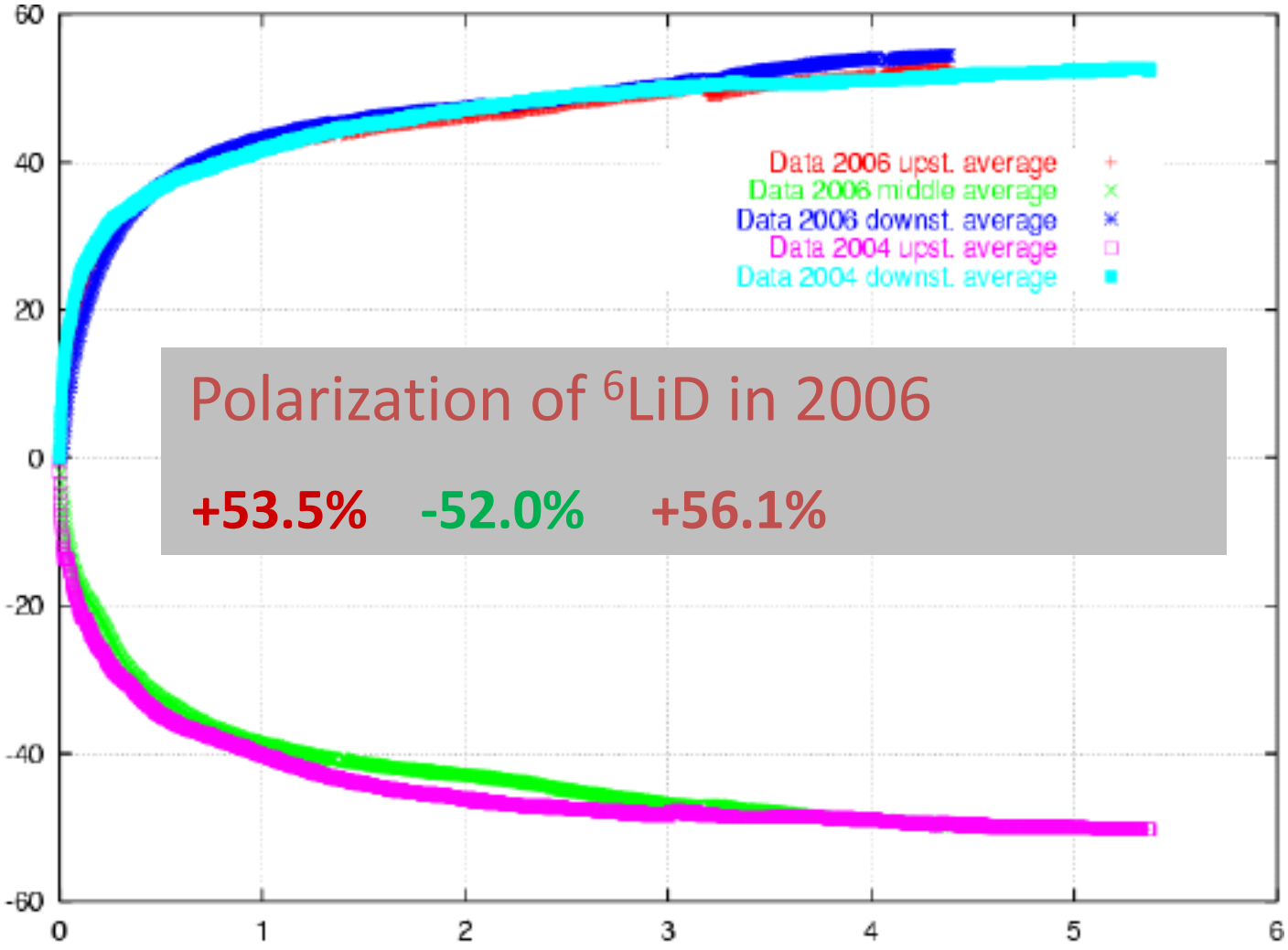


The coldest place @ CERN:
60mK, 1/30 of LHC magnets temperature

Polarized target installation



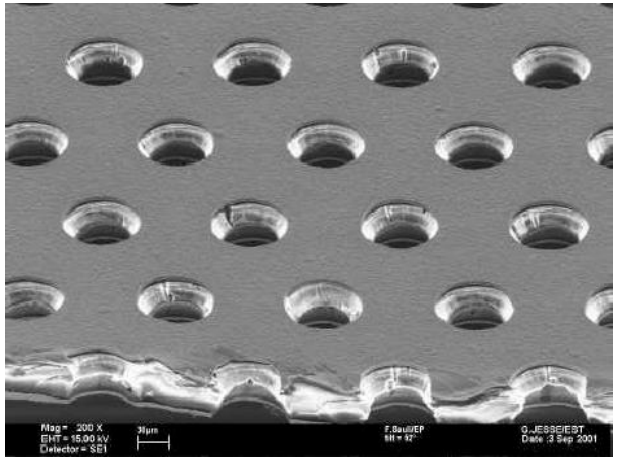
Polarized target performance

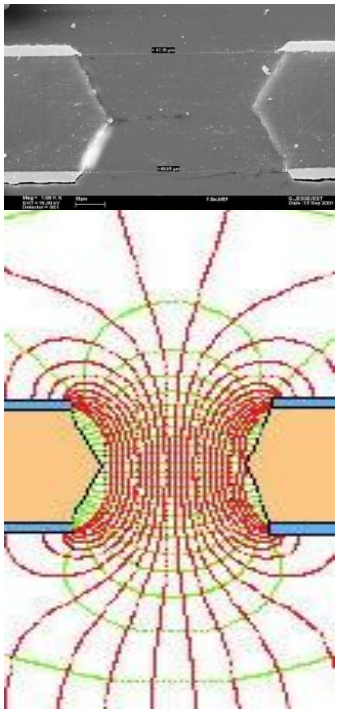


Tracking example: GEMs

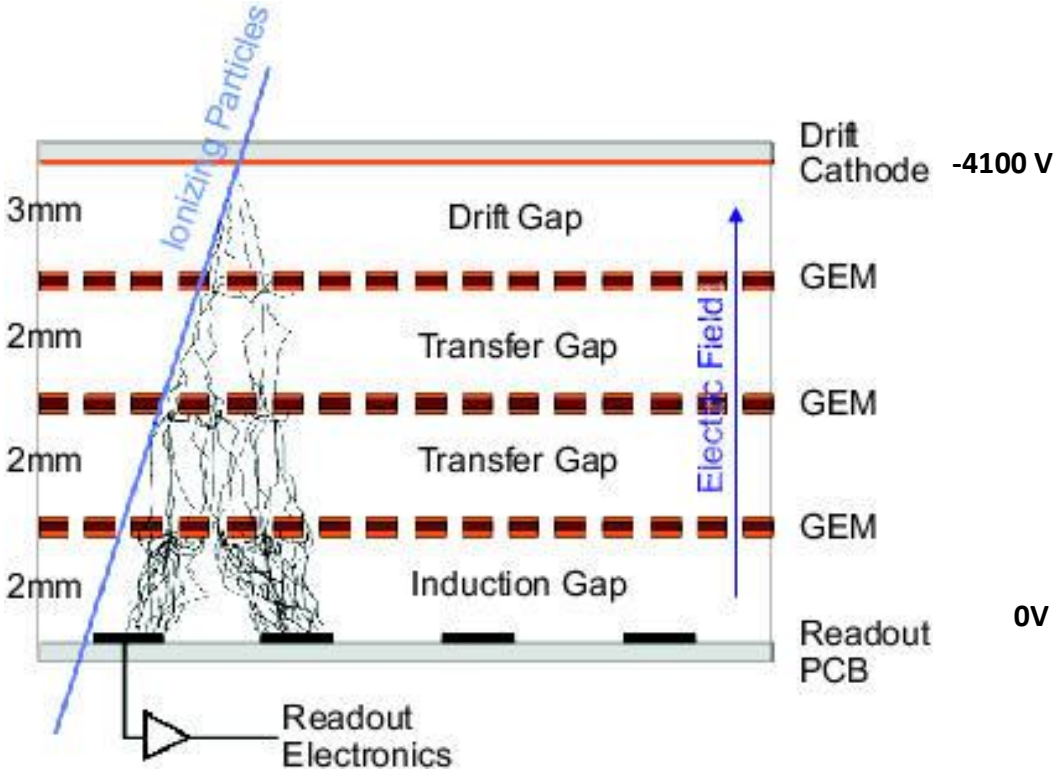
Gaseous Electron Multiplier

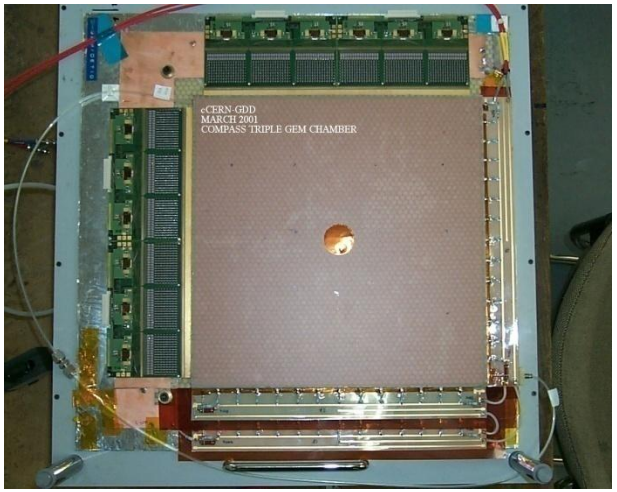
Gem foil





GEMs

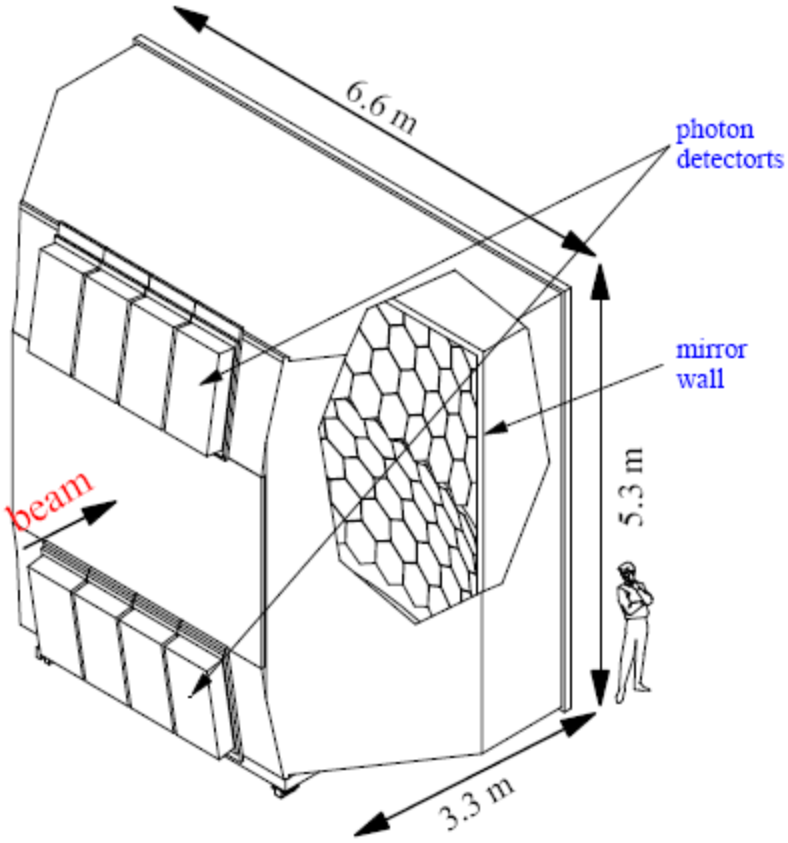




- 20 triple Gems detectors
- in 10 stations
- 40 coordinates
- size 30×30 cm^2
- 12 ns time resolution
- 50 µm space resolution
- efficiency ≈97 %
- Ar/CO_2 70/30 %

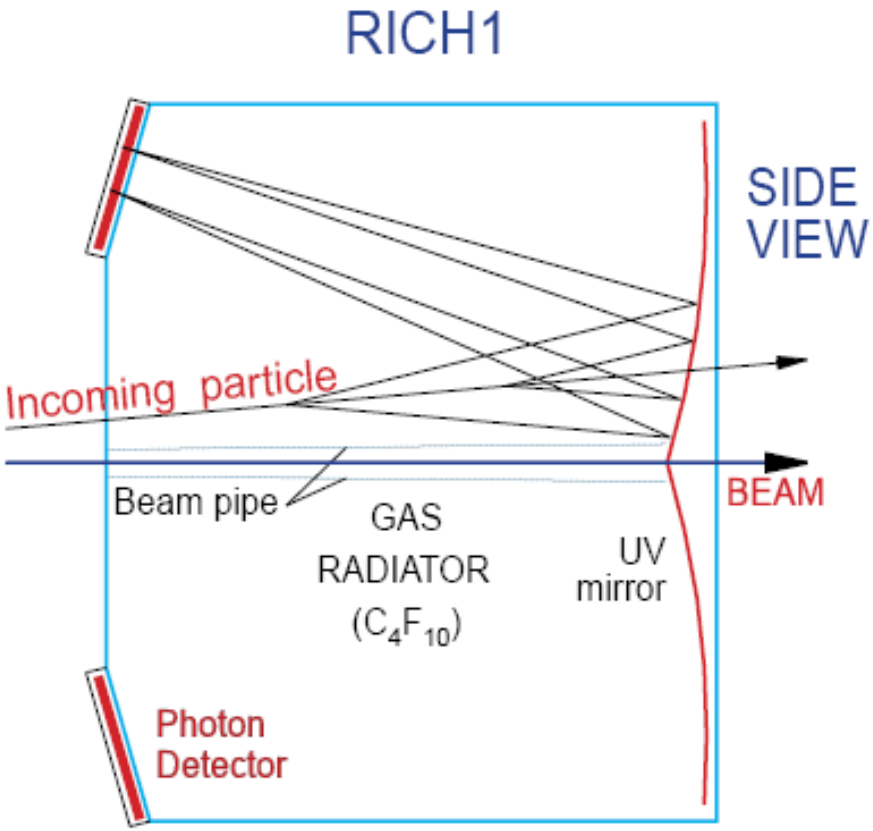
Particle identification: RICH

- 80 m^3 (3 m C_4F_{10} radiator)
- 116 UV mirrors
- 5.3 m^2 UV detectors
  - MWPC CsI photo-sensitive cathodes
  - 8×8 mm^2 pads
- 84k analog r/o channels
- 2006: inner quarter with maPMTs

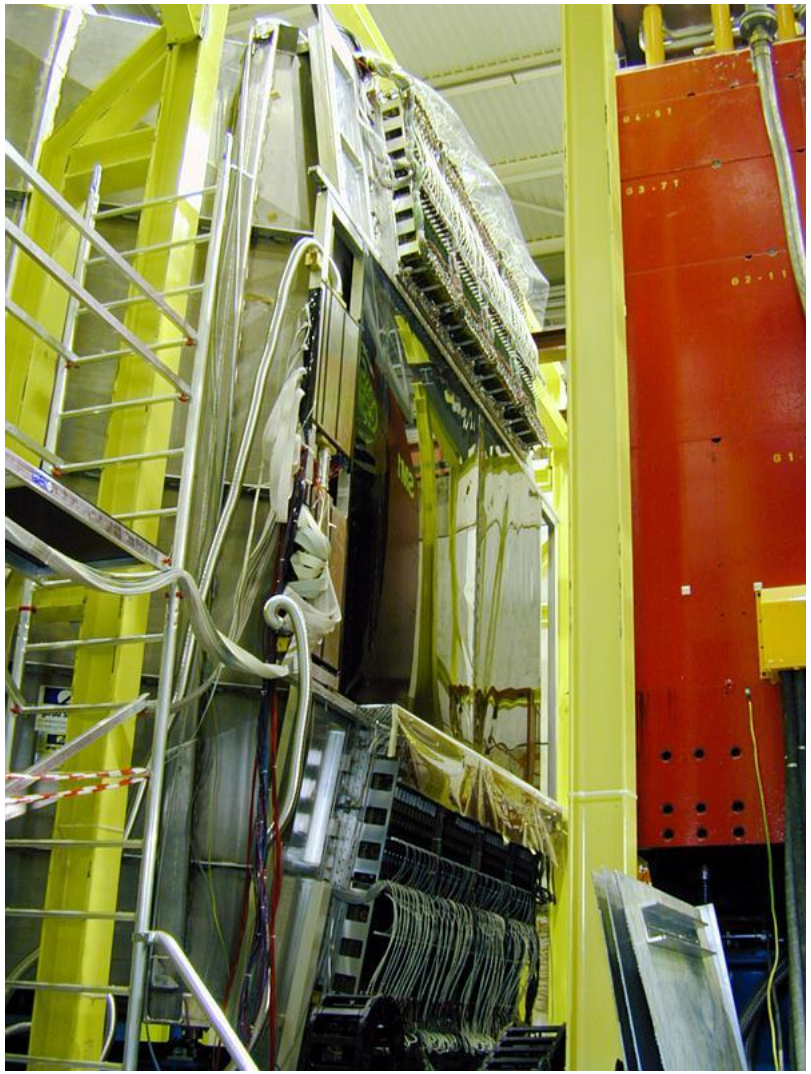


RICH

- π/K separation up to 60 GeV/*c*
- Large angular acceptance



RICH



Results: Data taking

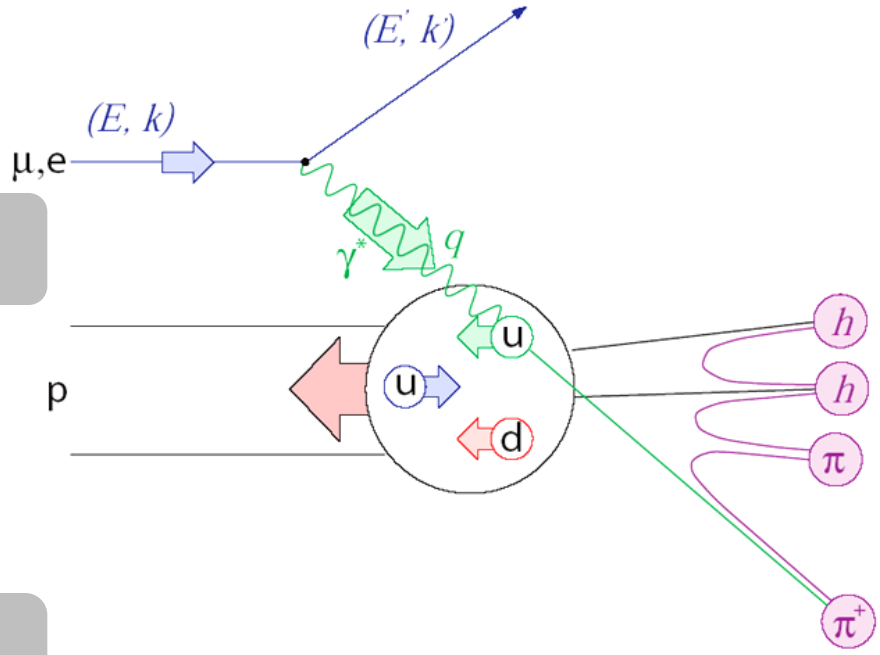
Data taking:

- 2002–2004: polarized **deuteron** target (^{6}LiD), longitudinal & transverse polarization
- 2005: CERN shutdown
- 2006: polarized **deuteron** target (^{6}LiD), long.
- 2007: polarized **proton** target (NH_3), longitudinal & transverse polarization
- 2008-2009: spectroscopy
- 2010: polarized **proton** target (NH_3) , transv.
- 2011: polarized **proton** target (NH_3) , long.

Results: helicity structure

X-sect. asymmetries

$$\frac{A_{exp}}{f\, P_\mu\, P_T\, D} \simeq A_1$$



- Inclusive scattering

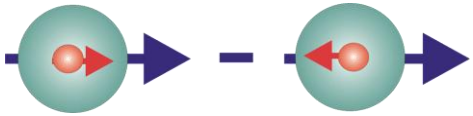
$$A_1 = \frac{\sum_q e_q^2 g_1^q(x,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2)}$$

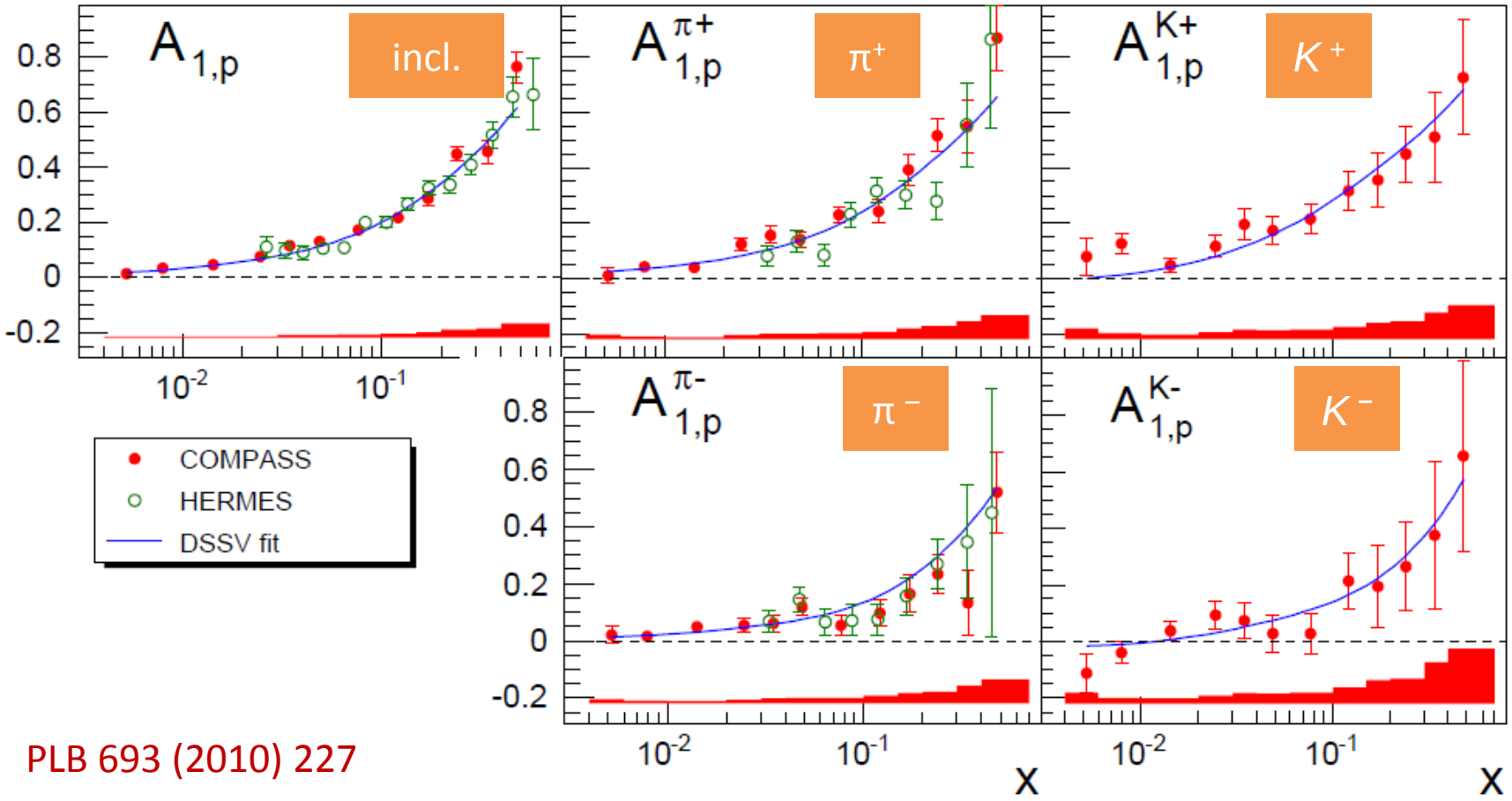
- Semi-inclusive scattering

$$A_1^h = \frac{\sum_q e_q^2 g_1^q(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2) D_{1q}^h(z,Q^2)} \qquad z = E_h/\nu$$

Proton A_1 asymmetries

incl. & semi-incl. asymmetries
for identified π's and *K's*





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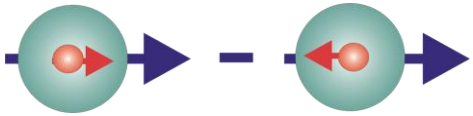
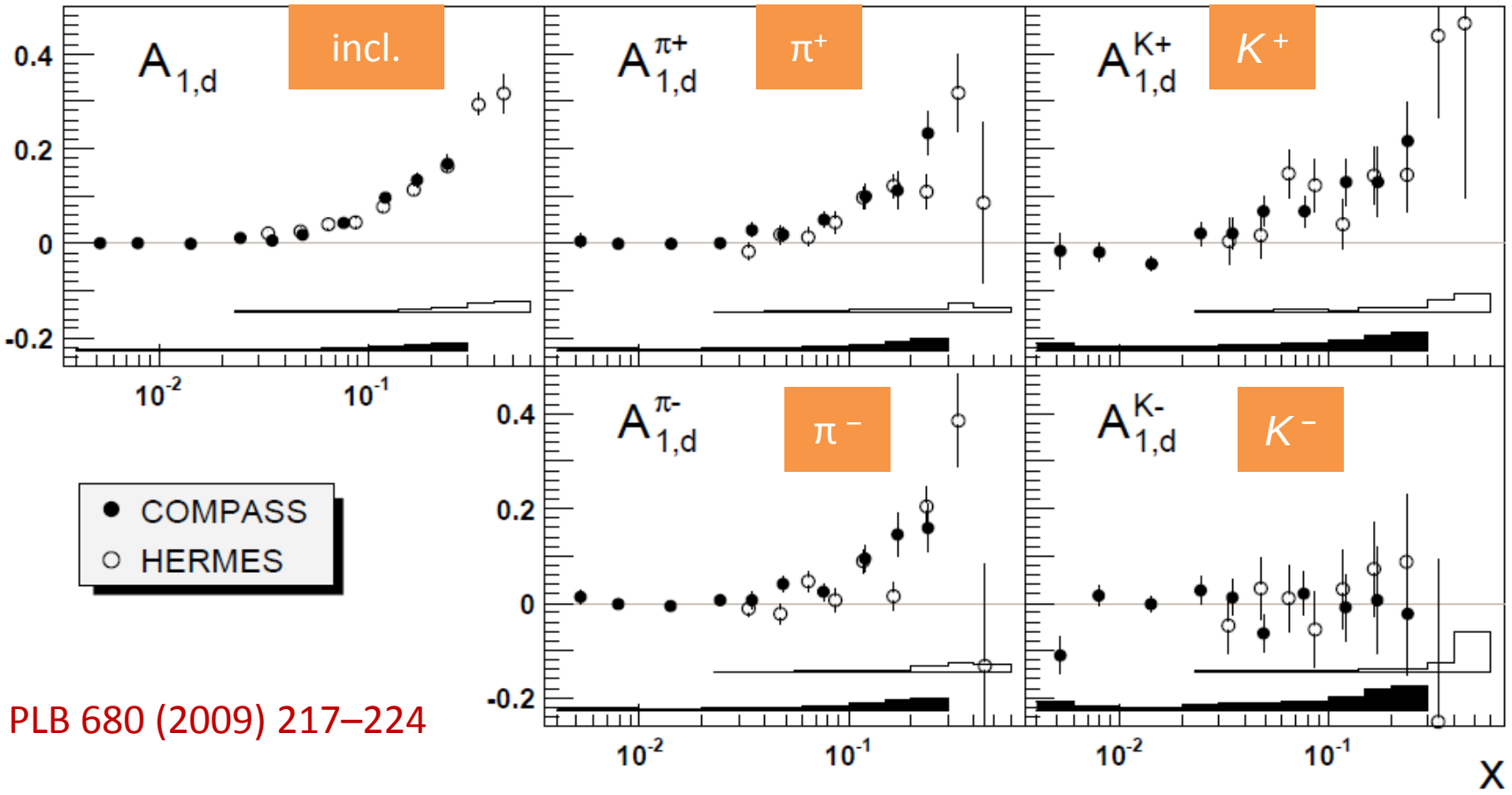
Deuteron A_1 asymmetries

Inclusive & semi-inclusive asymmetries for identified π's and *K's*





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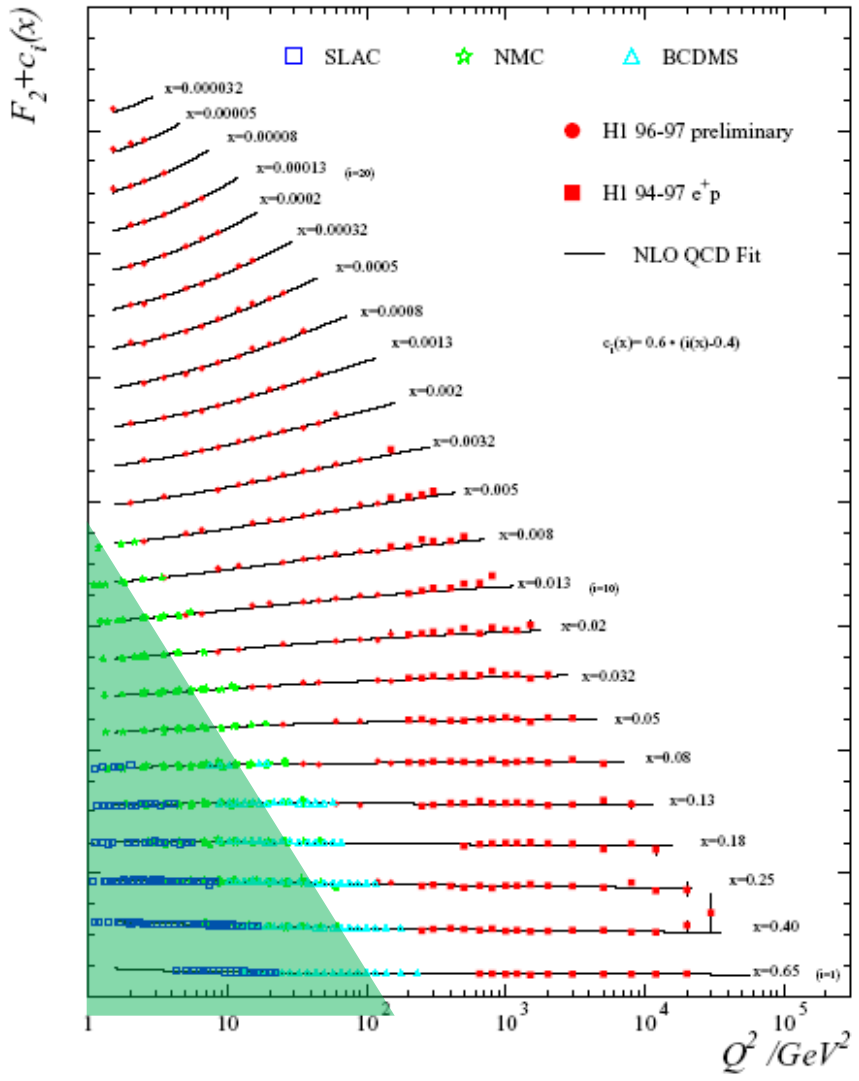
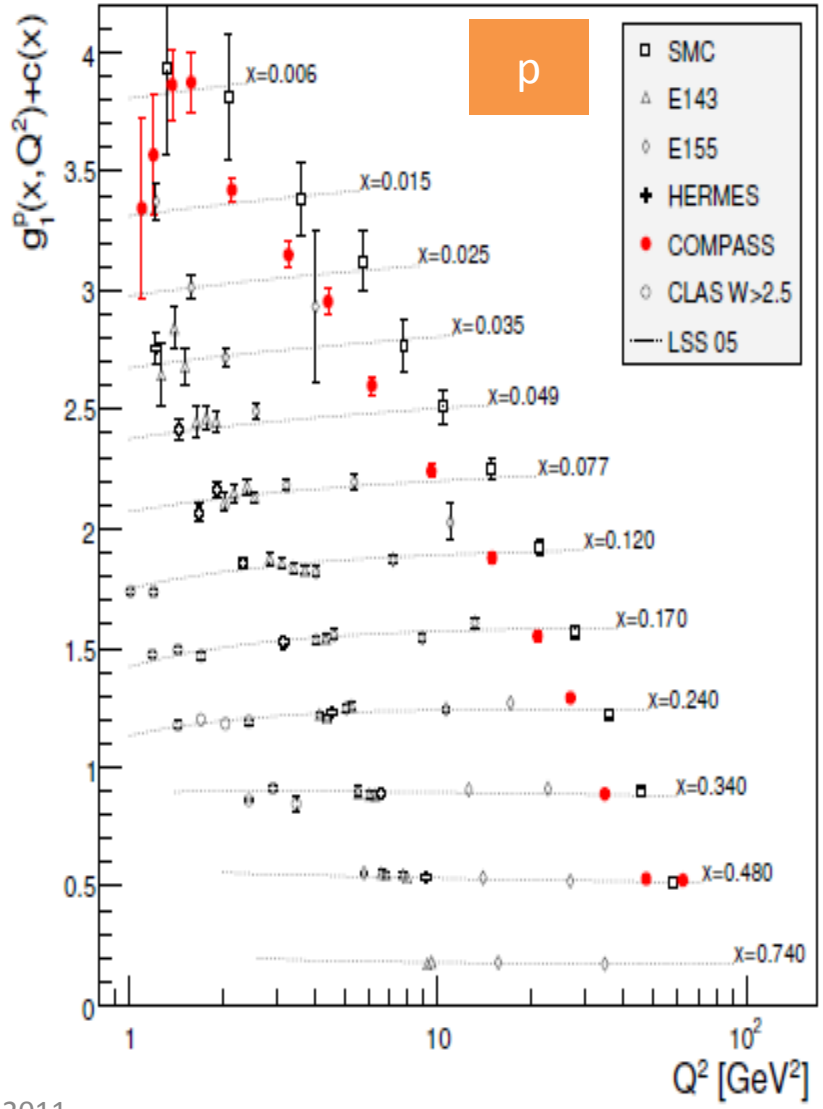
$F_2(x,Q^2)$ + $g_1(x,Q^2)$


$F_2+c_i(x)$
SLAC
NMC
BCDMS
H1 96-97 preliminary
H1 94-97 e+p
NLO QCD Fit
$c_i(x) = 0.6 \cdot (i(x)-0.4)$
Q^2 /GeV^2

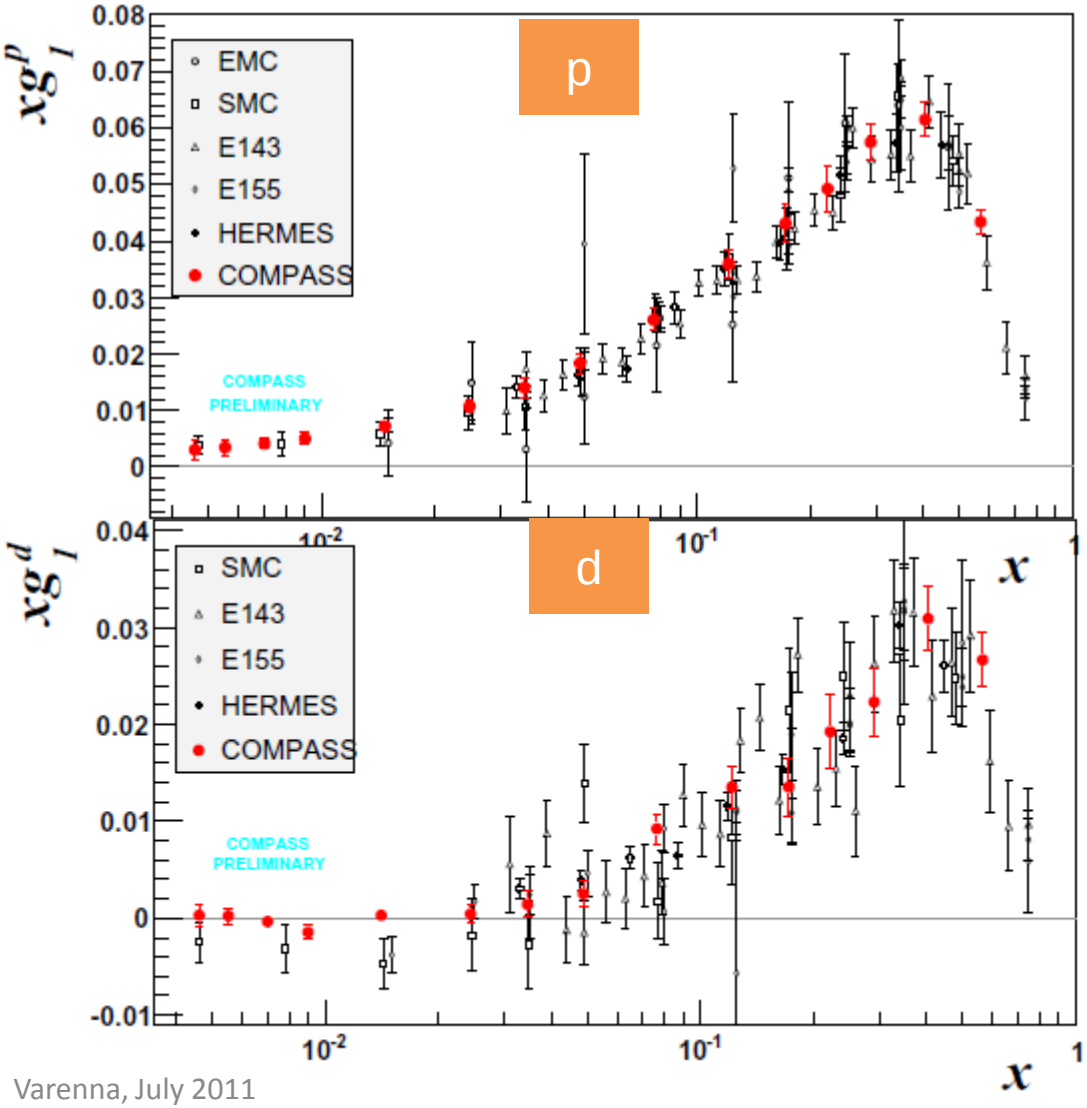

p
SMC
E143
E155
HERMES
COMPASS
CLAS W>2.5
LSS 05
$g_1^p(x,Q^2)+c(x)$
Q^2 [GeV^2]

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

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

- deuteron data:
- $\Delta\Sigma = 0.33 \quad 0.03 \quad 0.05$
- $\Delta s + \Delta s = -0.08 \quad 0.01 \quad 0.02$

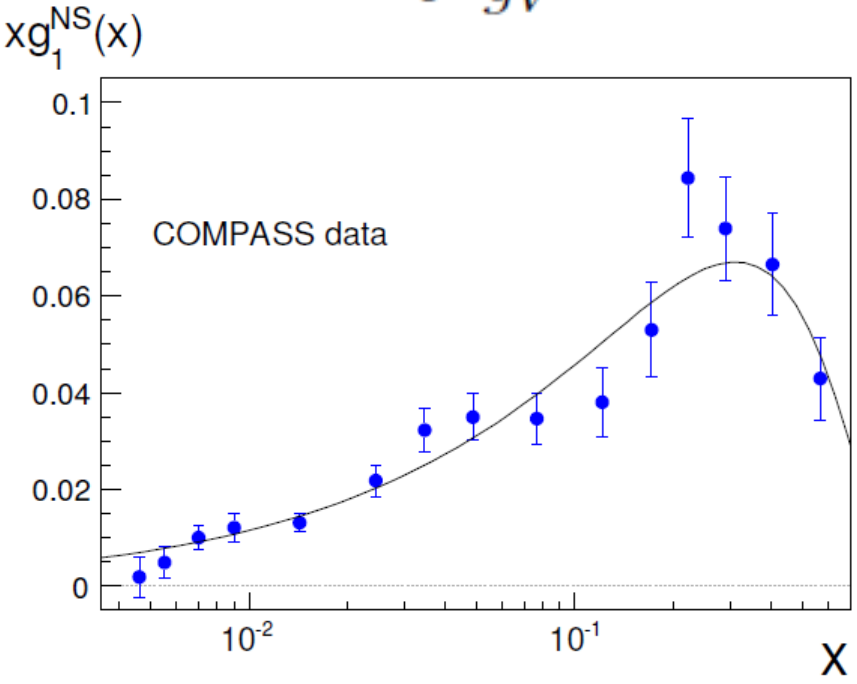
- ($\Delta\Sigma = a_0$, evol. to $Q^2=\infty$)

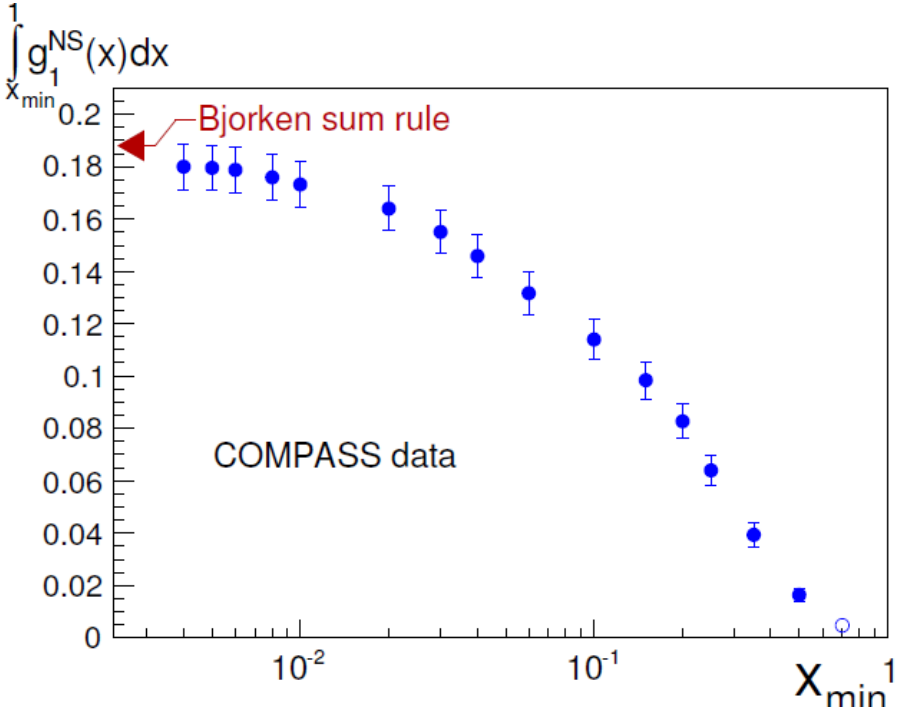


Bjorken sum rule

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

$$g_1^{NS}(x,Q^2) = g_1^p(x,Q^2) - g_1^n(x,Q^2)$$





$$|g_A/g_V| = 1.28 \pm 0.07(\text{stat.}) \pm 0.10(\text{syst.})$$

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$$|g_A/g_V| = 1.269$$ from neutron β decay

Flavour distributions: $\Delta\bar{s} = \Delta s$?

LO analysis of 5p+5d asymmetries, DSS FF

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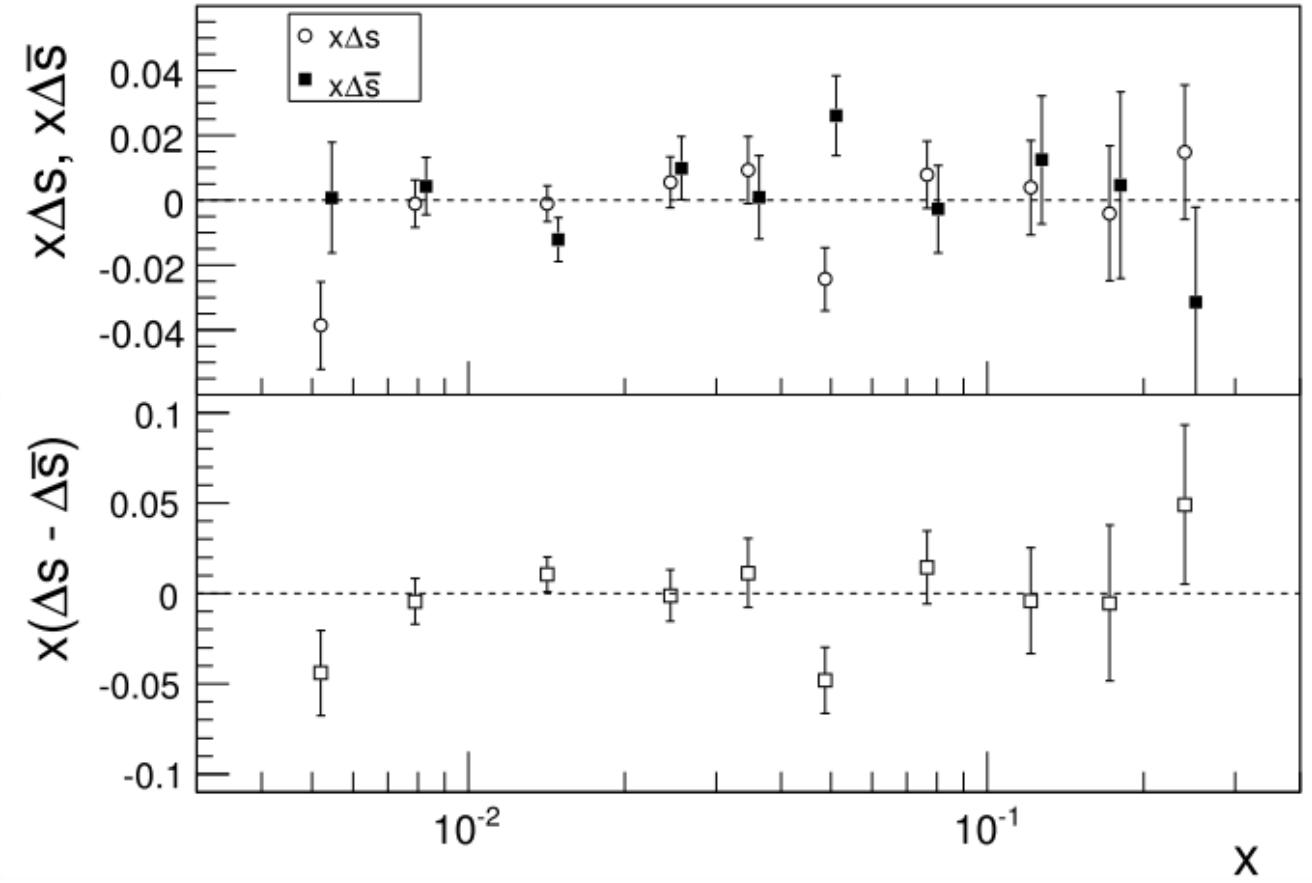
6 flavours: u, d, s, $\bar{u}$, $\bar{d}$, $\bar{s}$

No significant difference! Go on assuming $\Delta s = \Delta\bar{s}$



Flavour distributions

LO analysis of 5p+5d asymmetries, DSS FF
Line: NLO DSSV not including these data

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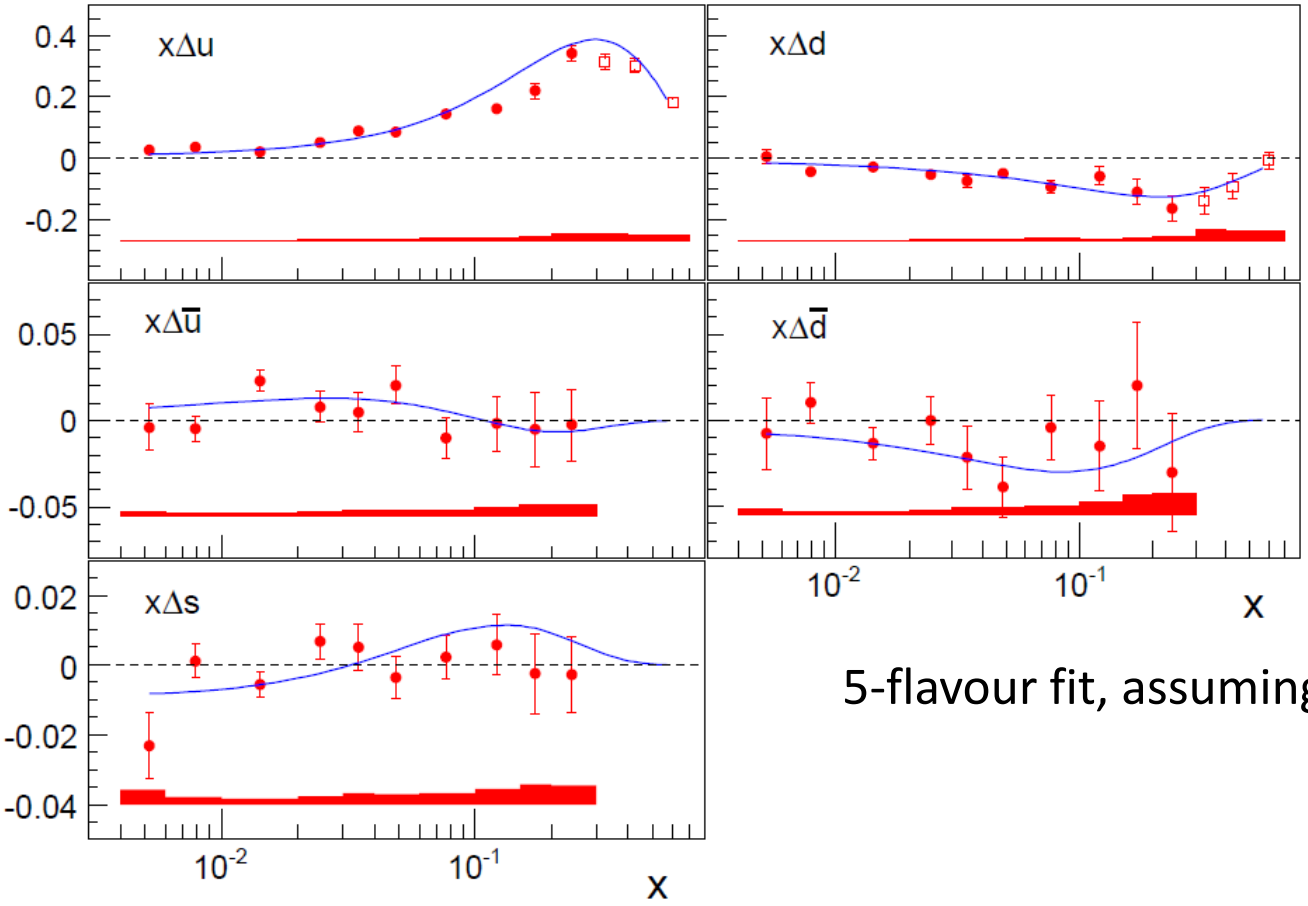
PRD80 (2009) 034030



5-flavour fit, assuming $\Delta s = \Delta\bar{s}$

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

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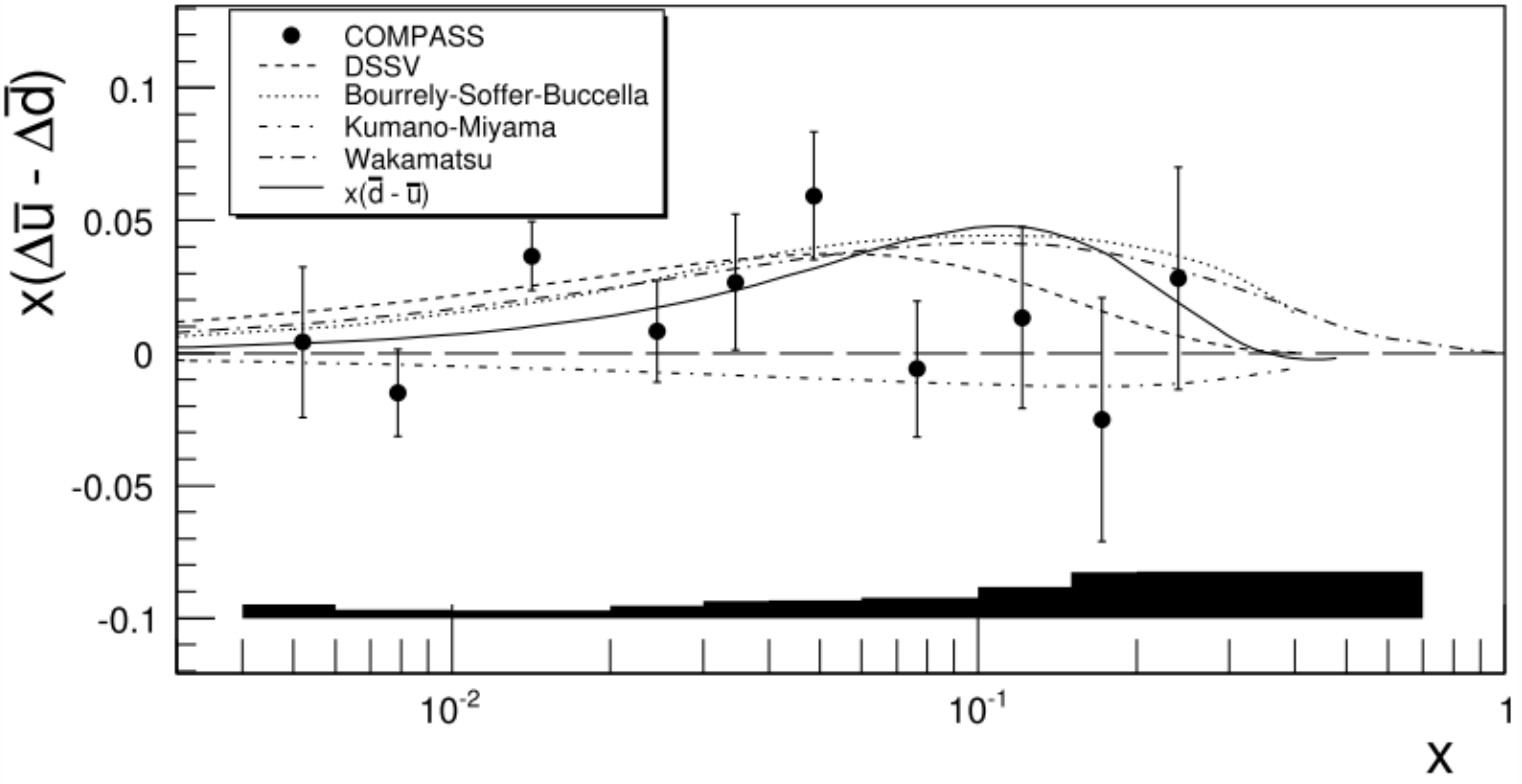
- Rather small effect, $\Delta\overline{u} > \Delta\overline{d}$



Truncated first moments

$$\int_{0.004}^{x_{max}} \Delta q(x)\, dx$$

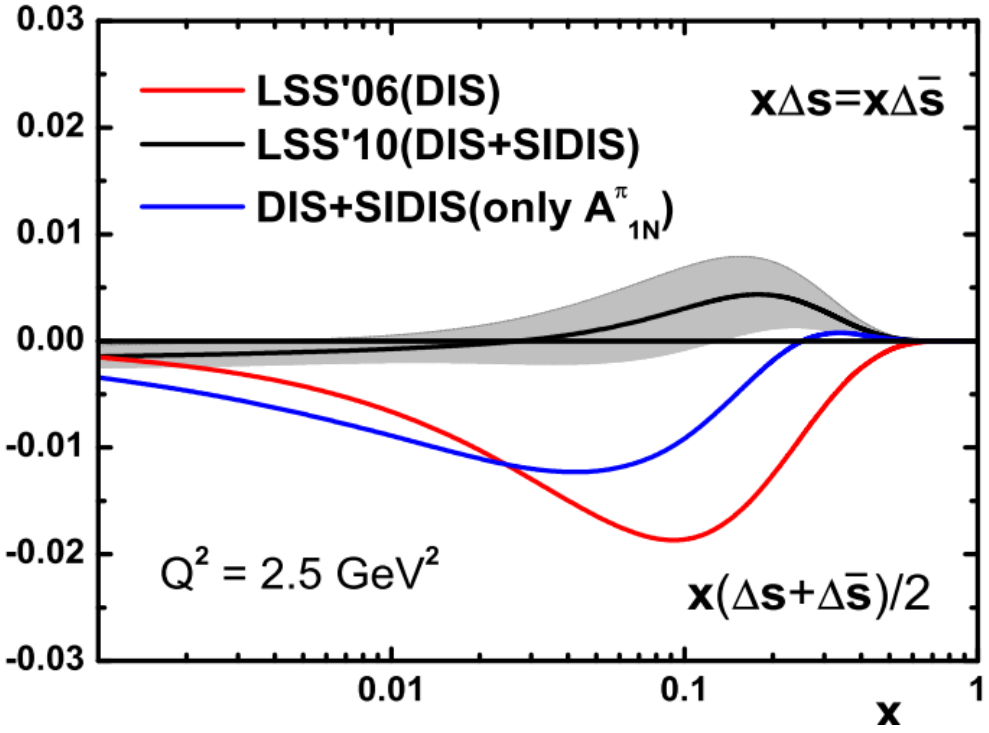
Δs small, compatible with zero

x range	$0.004 < x < 0.3$	$0.004 < x < 0.7$
Δu	$0.47 \pm 0.02 \pm 0.03$	$0.69 \pm 0.02 \pm 0.03$
Δd	$-0.27 \pm 0.03 \pm 0.02$	$-0.33 \pm 0.04 \pm 0.03$
$\Delta \bar{u}$	$0.02 \pm 0.02 \pm 0.01$	—
$\Delta \bar{d}$	$-0.05 \pm 0.03 \pm 0.02$	—
$\Delta s(\Delta \bar{s})$	$-0.01 \pm 0.01 \pm 0.01$	—
Δu_v	$0.46 \pm 0.03 \pm 0.03$	$0.67 \pm 0.03 \pm 0.03$
Δd_v	$-0.23 \pm 0.05 \pm 0.02$	$-0.28 \pm 0.06 \pm 0.03$
$\Delta \bar{u} - \Delta \bar{d}$	$0.06 \pm 0.04 \pm 0.02$	—
$\Delta \bar{u} + \Delta \bar{d}$	$-0.03 \pm 0.03 \pm 0.01$	—
$\Delta \Sigma$	$0.15 \pm 0.02 \pm 0.02$	$0.31 \pm 0.03 \pm 0.03$

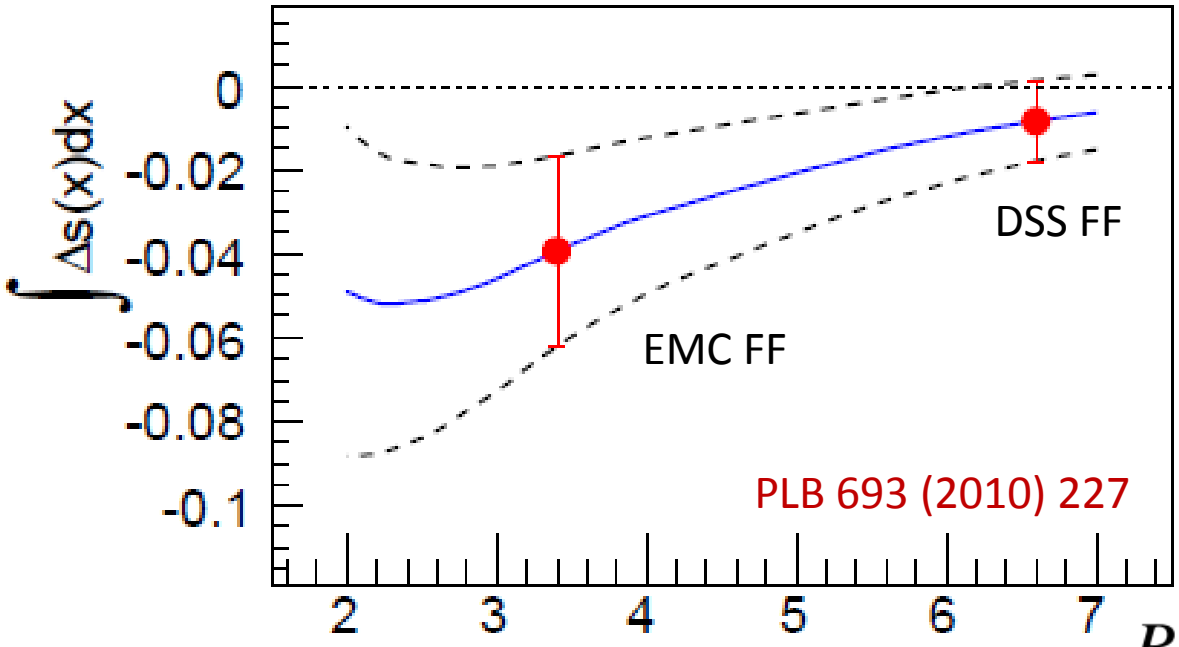
Inclusive data favour Δs < 0

J. Phys.: Conf. Ser. **295** 012054

- Inclusive data only
  Δs ≈ −0.08 0.01
- Semi-inclusive point to
  Δs ≈ 0
- Shape of Δs(*x*) at small *x* unknown
- Δs determination crucially depends on the **fragm. functions** used:
  DSS, DNS, HKNS, EMC, …



Strange quark FFs



DSS: PRD75 (2007)

EMC: NPB321 (1989)

$$R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)\mathrm{d}z}{\int D_{u}^{K^+}(z)\mathrm{d}z}$$

Measurements of *K* and π multiplicities are mandatory!

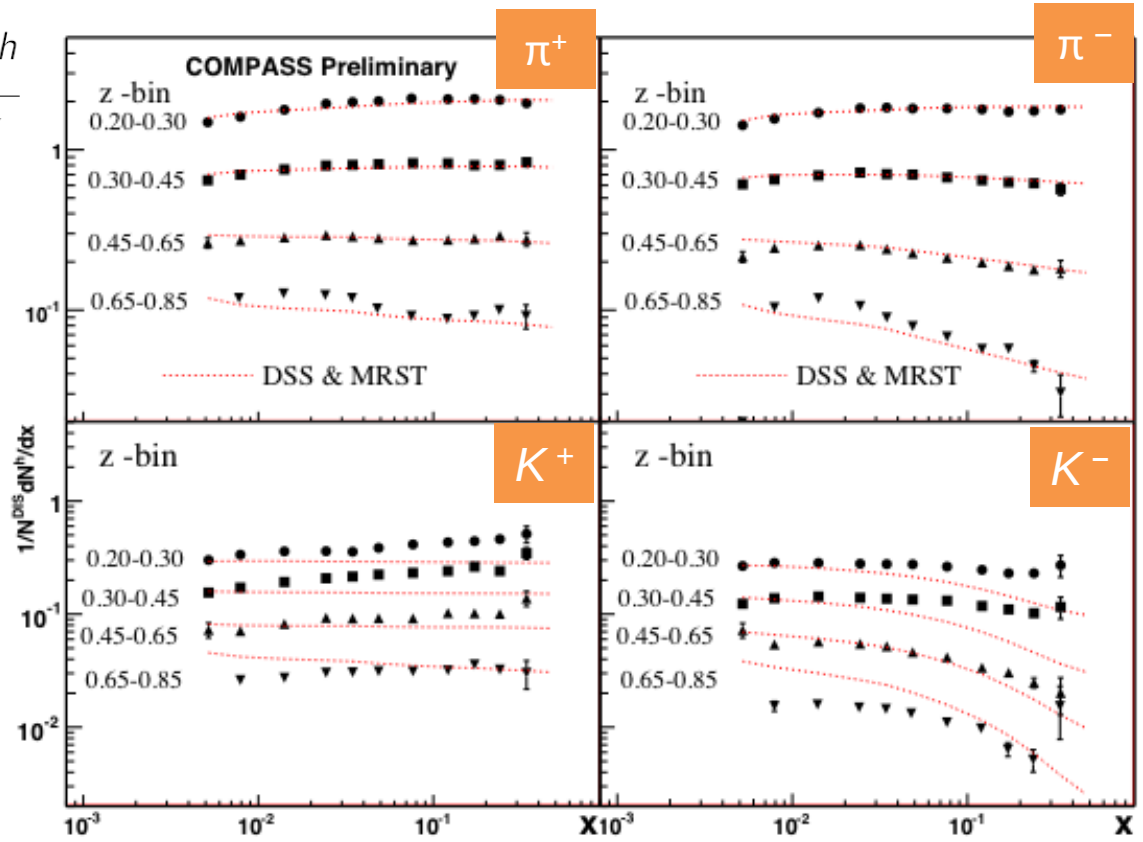
Multiplicities for *K*'s and π's

LO: $$\frac{1}{N^{\mathrm{DIS}}(x,Q^2)}\frac{\mathrm{d}N^h}{\mathrm{d}x\,\mathrm{d}z\,\mathrm{d}Q^2} = \frac{\sum_q e_q^2 f^q(x,Q^2)\, D^h_{1,q}(z,Q^2)}{\sum_q e_q^2 f^q(x,Q^2)}$$

Unpolarised data $\frac{1}{N^{\mathrm{DIS}}}\frac{\mathrm{d}N^h}{\mathrm{d}x}$

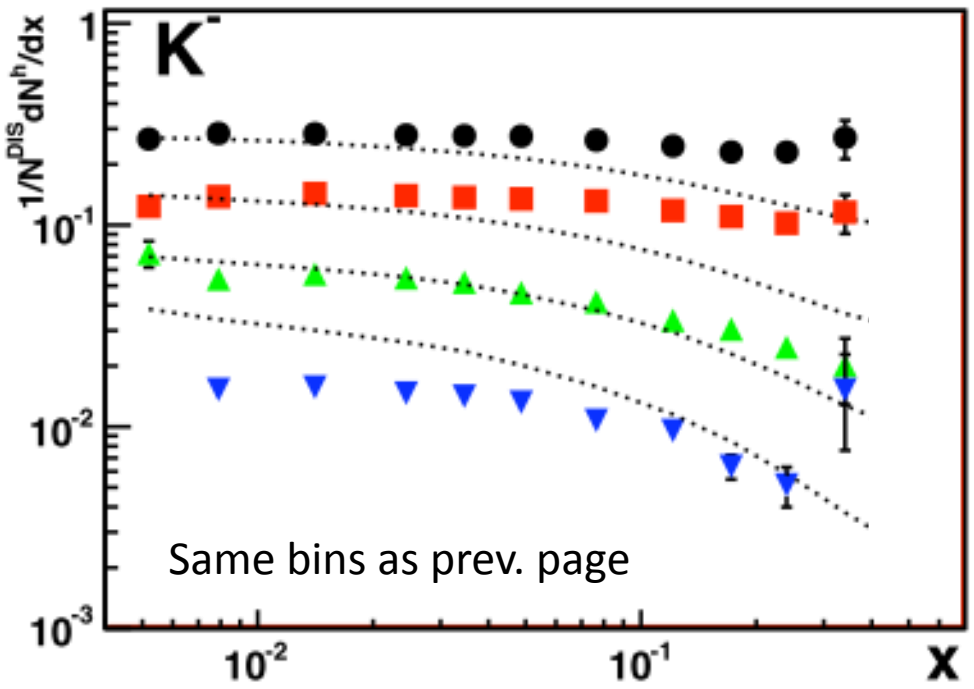
For the *z* bins:
0.20 – 0.30
0.30 – 0.45
0.45 – 0.65
0.65 – 0.85

Lines: MRST04 PDF
+ DSS FF (LO)



K multiplicities, closer look

- π multiplicities ± in agreement with LO calc.
- Big deviations for *K*'s → **consequences for FF!**
- Data to be in-cluded in global analyses
- Only 4 weeks of data, more to come



Gluon polarization

EMC result 1987/88: quark spins contribute little to nucleon spin!
$\Delta\Sigma$ compatible with zero

$$\Delta\Sigma = \sum_q \int g_1^q(x)\mathrm{d}x = \sum_q \int \Delta q(x)\mathrm{d}x$$

A crisis in the parton model: where, oh where is the proton's spin?

E. Leader[1] and M. Anselmino[2]
Birkbeck College, University of London, London, UK
Dipartimento di Fisica Teorica, Università di Torino, I-10125 Torino, Italy

Received 18 March 1988

Quark spin hidden by large gluon polarization via axial anomaly?

E2-88-287

A.V.Efremov, O.V.Teryaev*

SPIN STRUCTURE OF THE NUCLEON AND TRIANGLE ANOMALY

THE ANOMALOUS GLUON CONTRIBUTION TO POLARIZED LEPTOPRODUCTION

G. ALTARELLI and G.G. ROSS [1]
CERN, CH-1211 Geneva 23, Switzerland

Received 29 June 1988

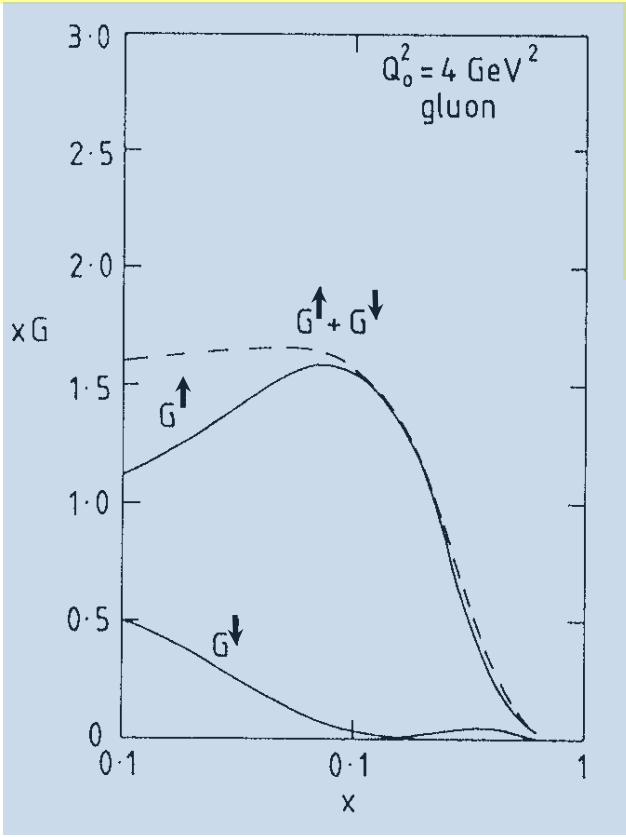
Lepton-Photon Conf. 1989

To summarise, let us return to the fit of Fig. 7 and 8. At $Q^2=10GeV^2$ this corresponds to $\Delta g=6.3$ and so the proton helicity is given by

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta g + L_z$$

$$= 0.35 + 6.3 - 6.15$$

G. Ross 1989



possible scenario:

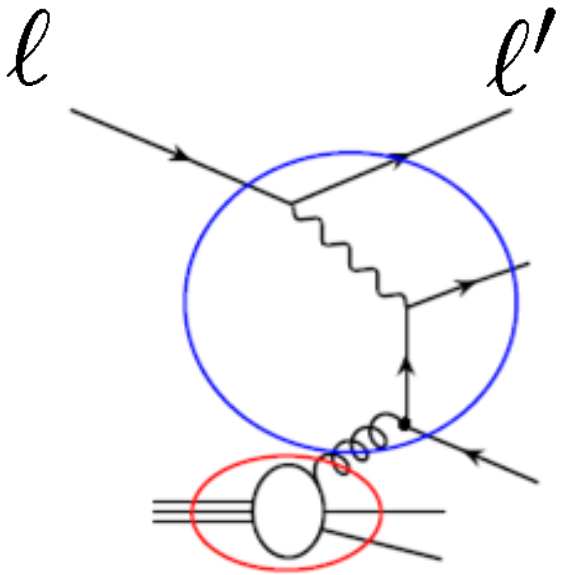
$\Delta G \approx 6$ ($Q^2=10\ GeV^2$)

$\Delta g/g(x) = 1$ for $x_g > 0.1$

Let's measure!

Photon–gluon fusion (PGF)

Gluon polarization is measurable in PGF



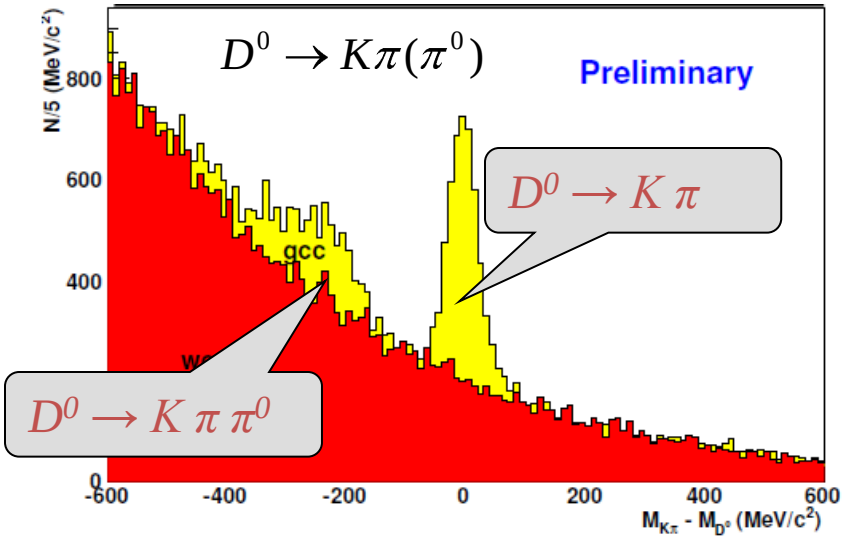
$$A_{\parallel} = R_{pgf} \langle \hat{a}_{pgf} \rangle \frac{\Delta G}{G}$$

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

Hadron production

- Analysis of hadron-pair asymmetries:
  - open charm: single *D* meson — AROMA

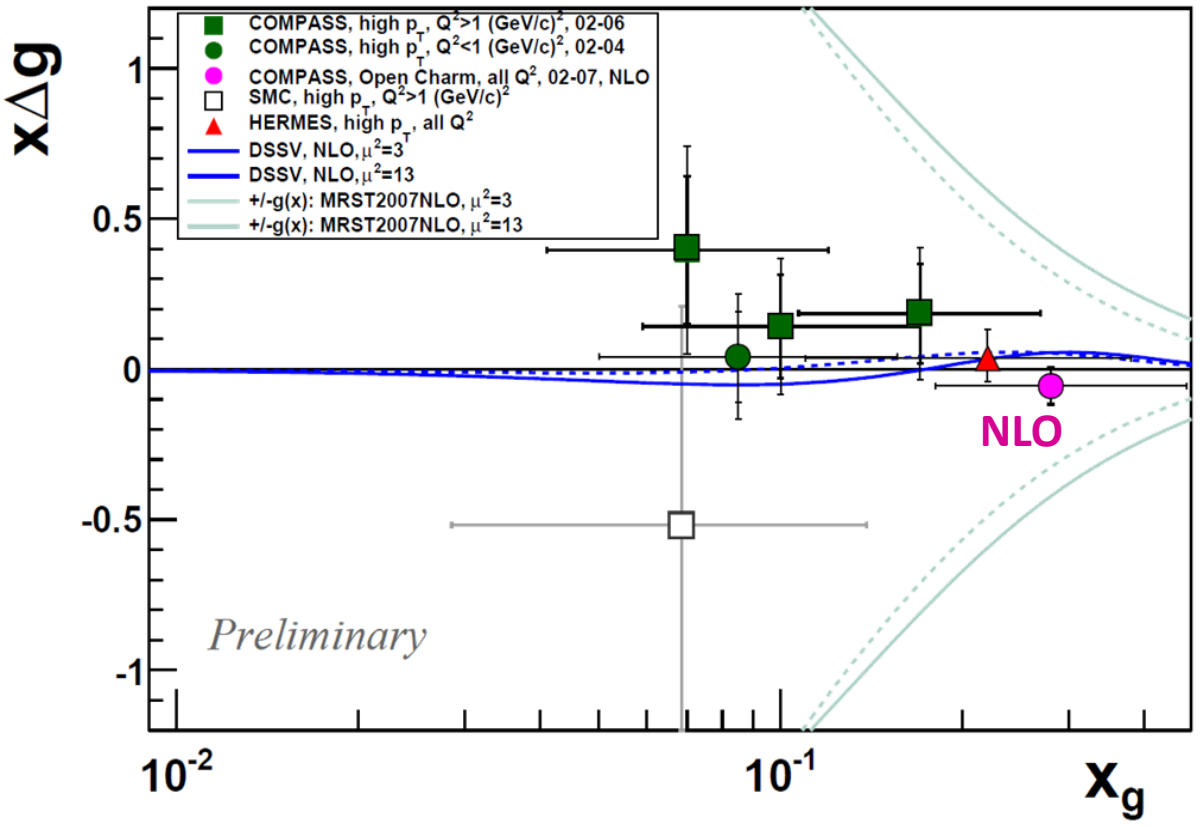
    cleanest process wrt physics background



  - high-p_T hadron pairs with $Q^2 > 1$ GeV^2 — LEPTO
  - high-p_T hadron pairs with $Q^2 < 1$ GeV^2 — PYTHIA
  - Single hadron production $Q^2 < 0.1$ GeV^2 — NLO, Vogelsang et al.

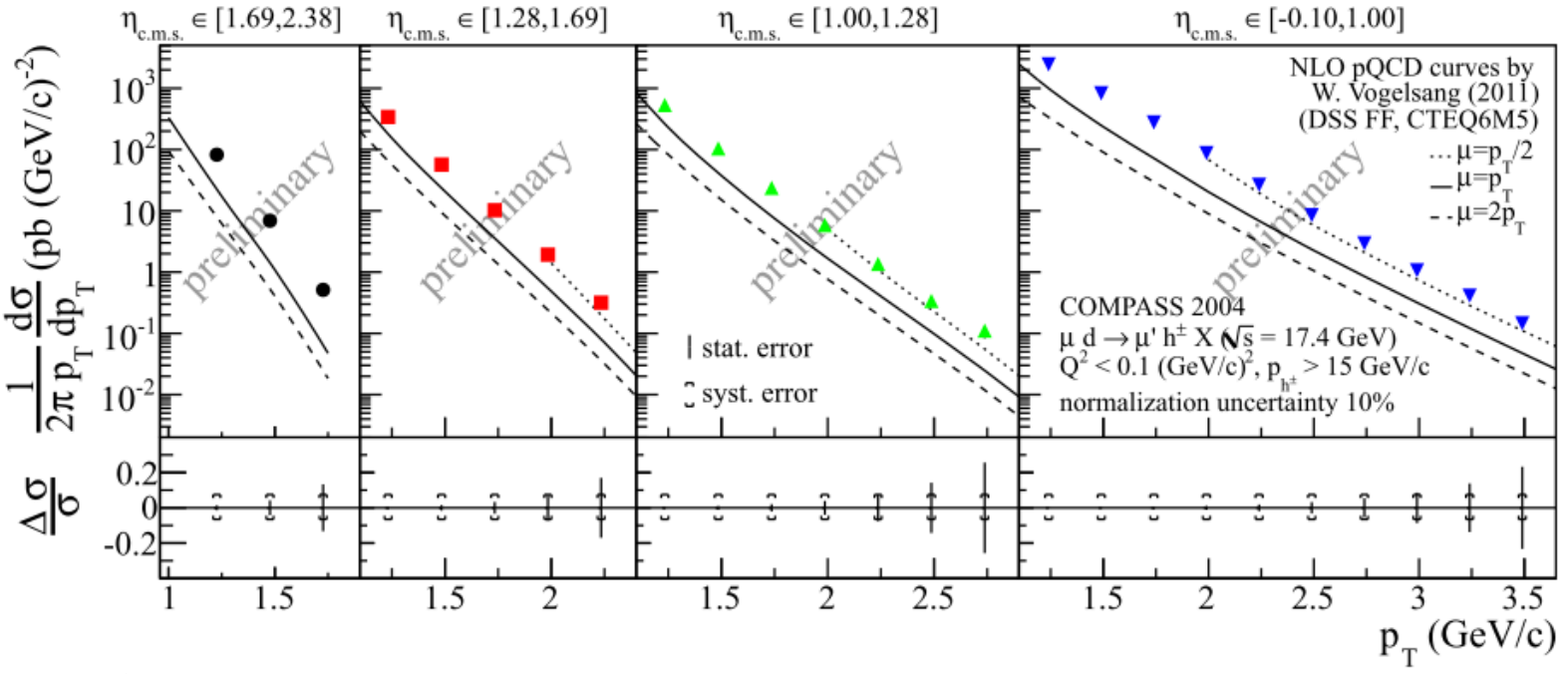
Results for Δg

- All results compatible with zero!
- Confirmed by RHIC results in *pp*



Single hadron production

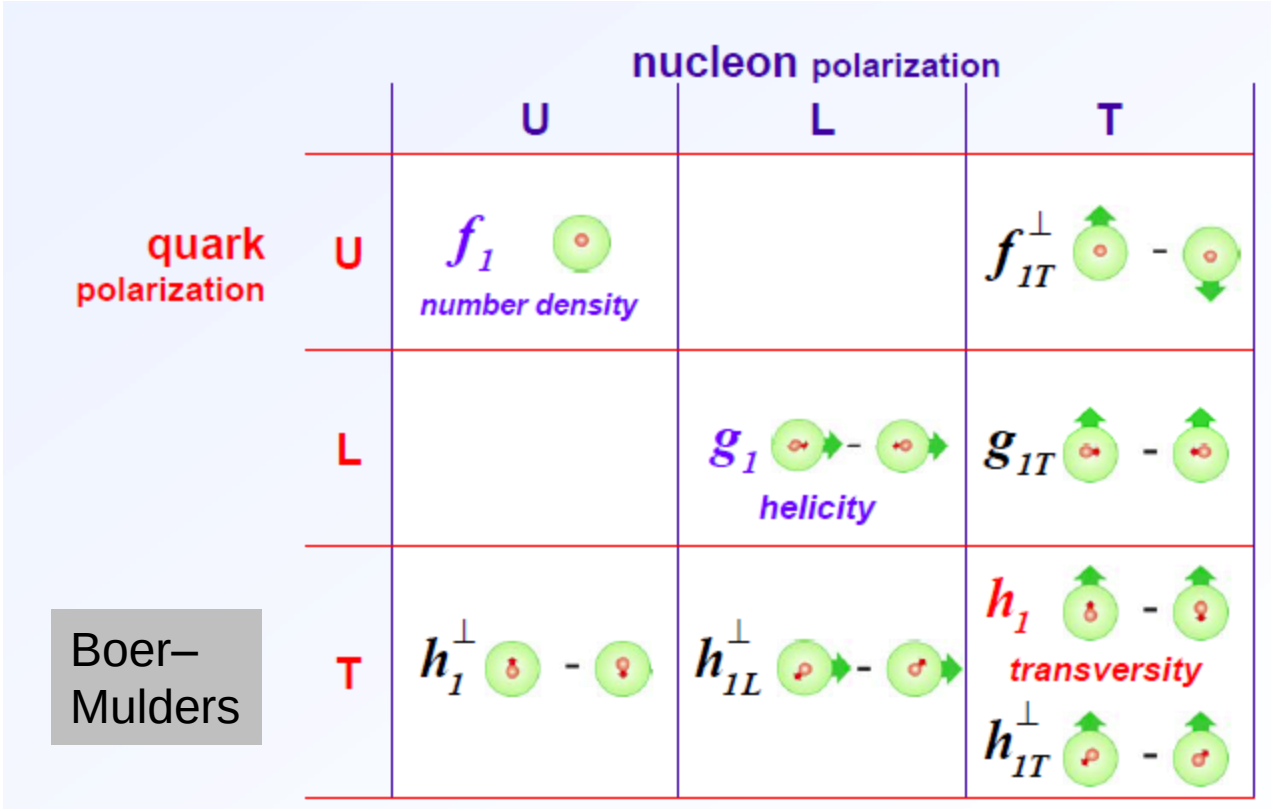
- Calculations exist in NLO for small Q^2 large p_T Vogelsang et al.
- Theory applicable at COMPASS? YES! Preferred scale $\mu=p_T/2$
- Next steps: asymmetries, inclusion into global analyses of Δg
- Much more data on tape



Results: transverse spin structure

TMD parton distributions

- 8 intrinsic-transverse-momentum dependent PDFs at LO
- Azimuthal asymmetries with different angular modulations in the hadron and spin azimuthal angles, Φ_h and Φ_s



Transversity PDF h_1

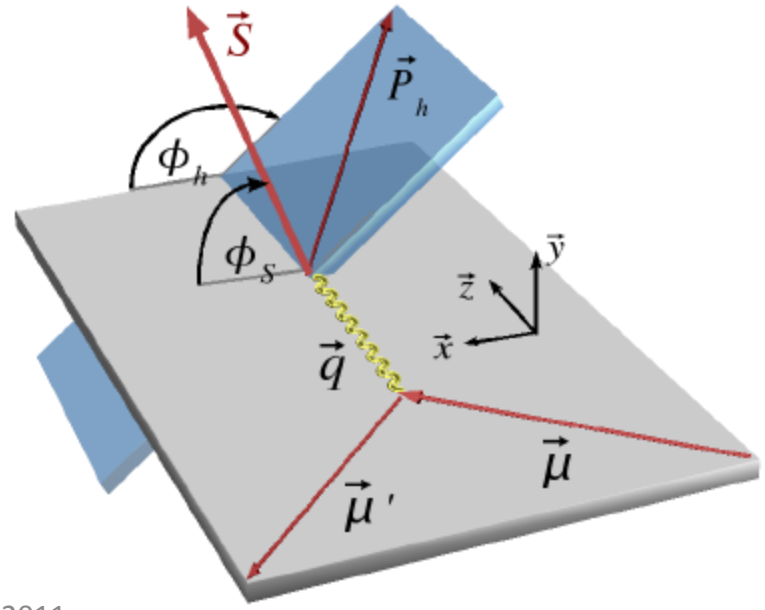
- Couple h_1 PDF to chiral-odd Collins FF $H_1^\perp$

$$A_{Coll}^h \propto \frac{\sum_q e_q^2 h_1^q(x) H_1^{\perp h/q}(z, P_{hT})}{\sum_q e_q^2 f_1^q(x) D^{h/q}(z)}$$

Azimuthal cross-section asymmetry:

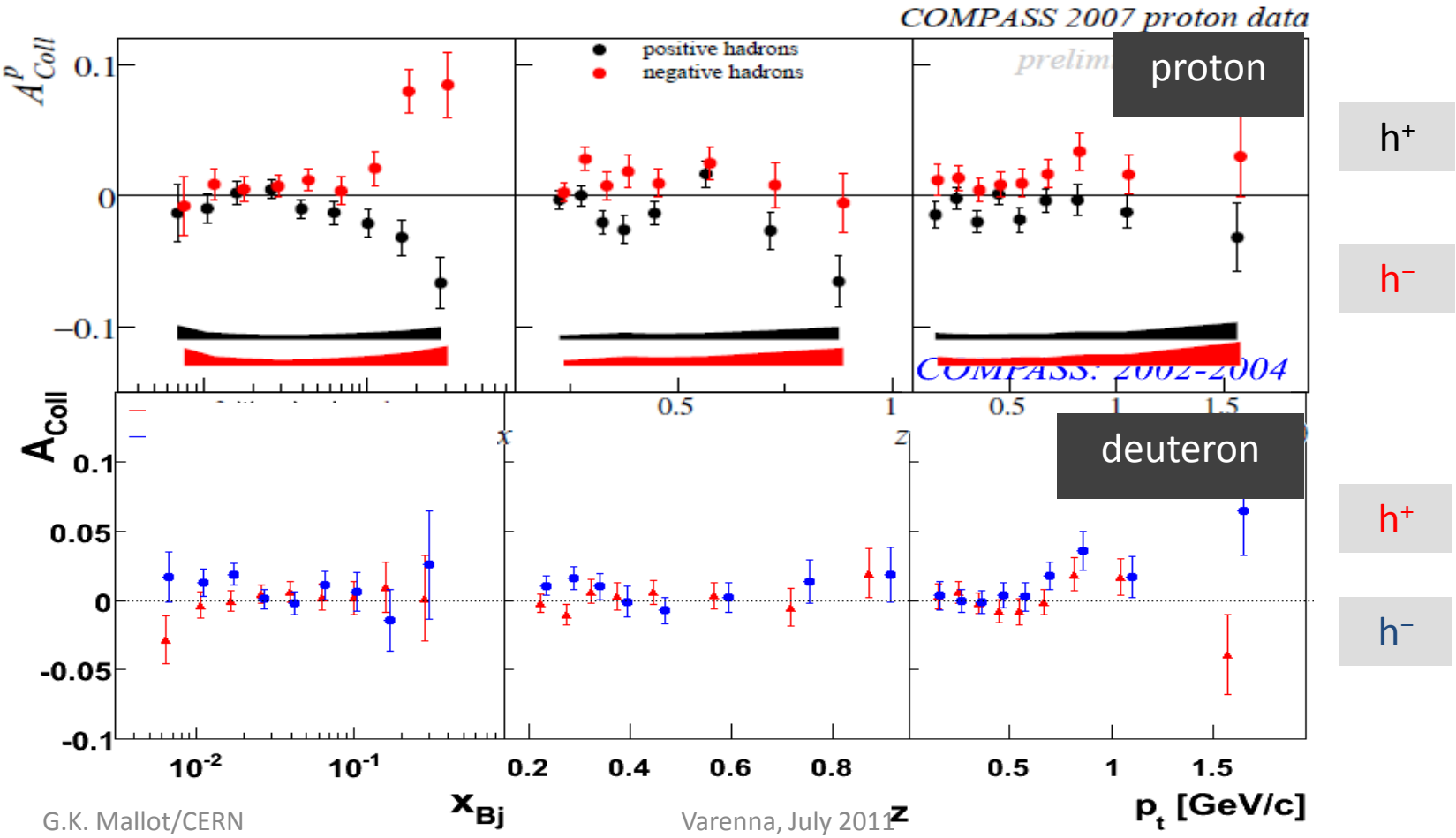
$$\frac{\Delta\sigma}{\sigma} \propto A_{Coll} \sin\Phi_C$$

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

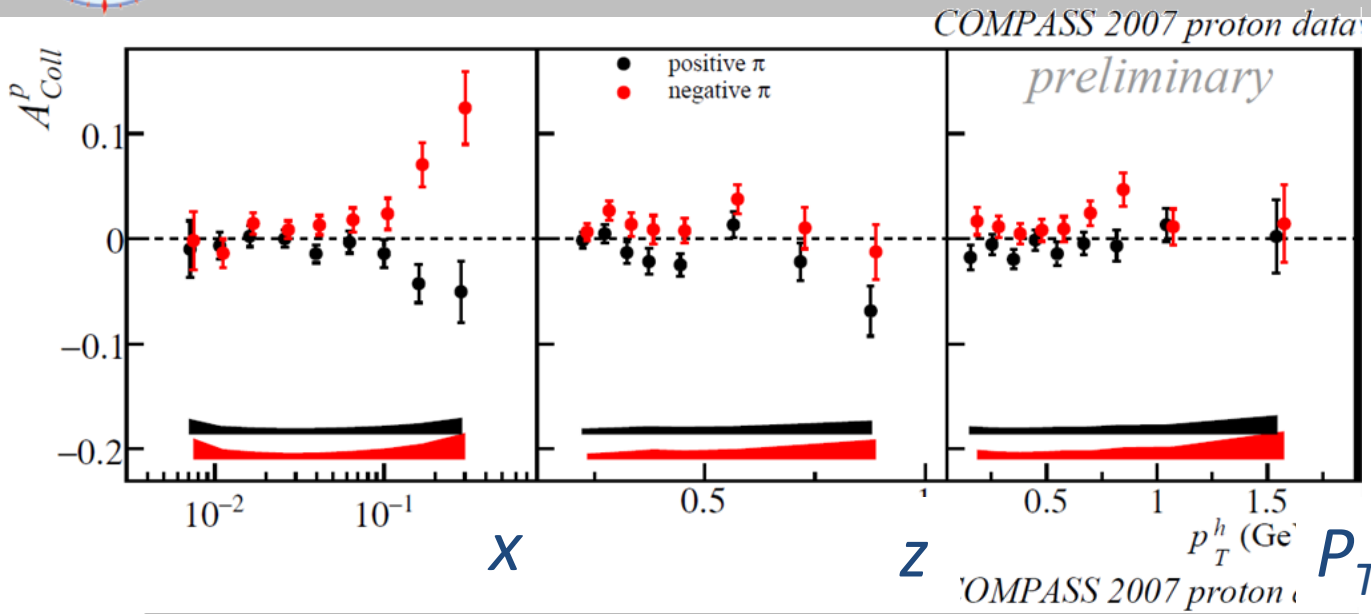


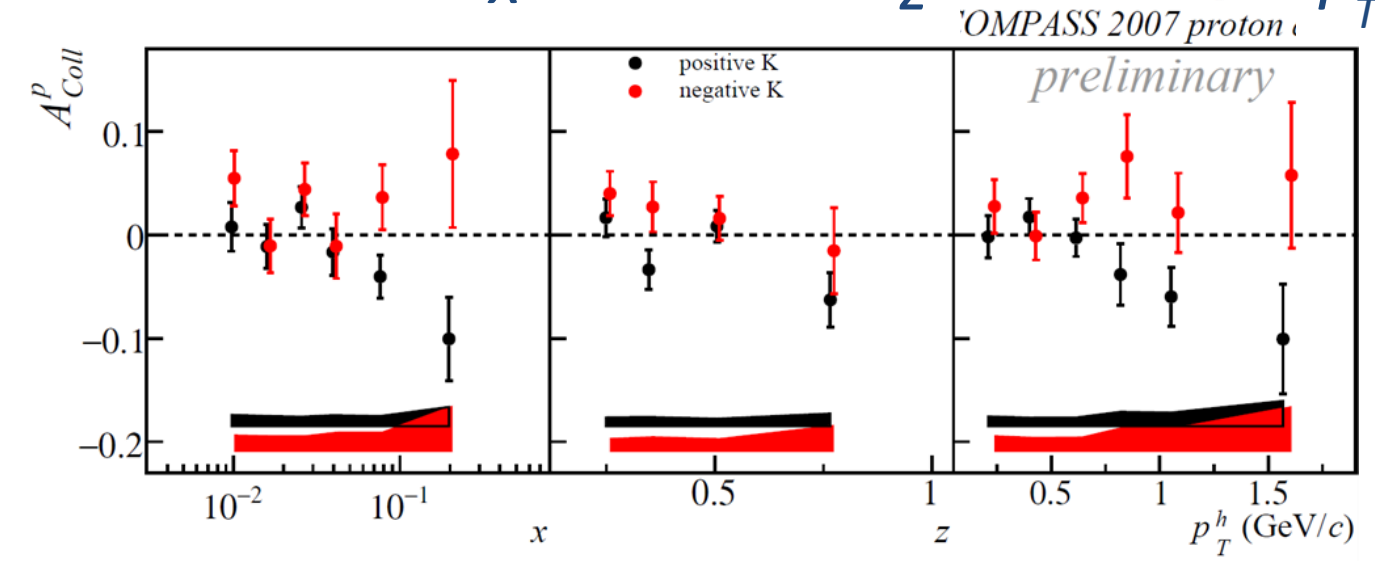
Collins Asymmetries

- large asymmetry for proton ~10%
- zero deuteron result important ⇒ opposite sign of u and d



Collins proton: identified hadrons





π

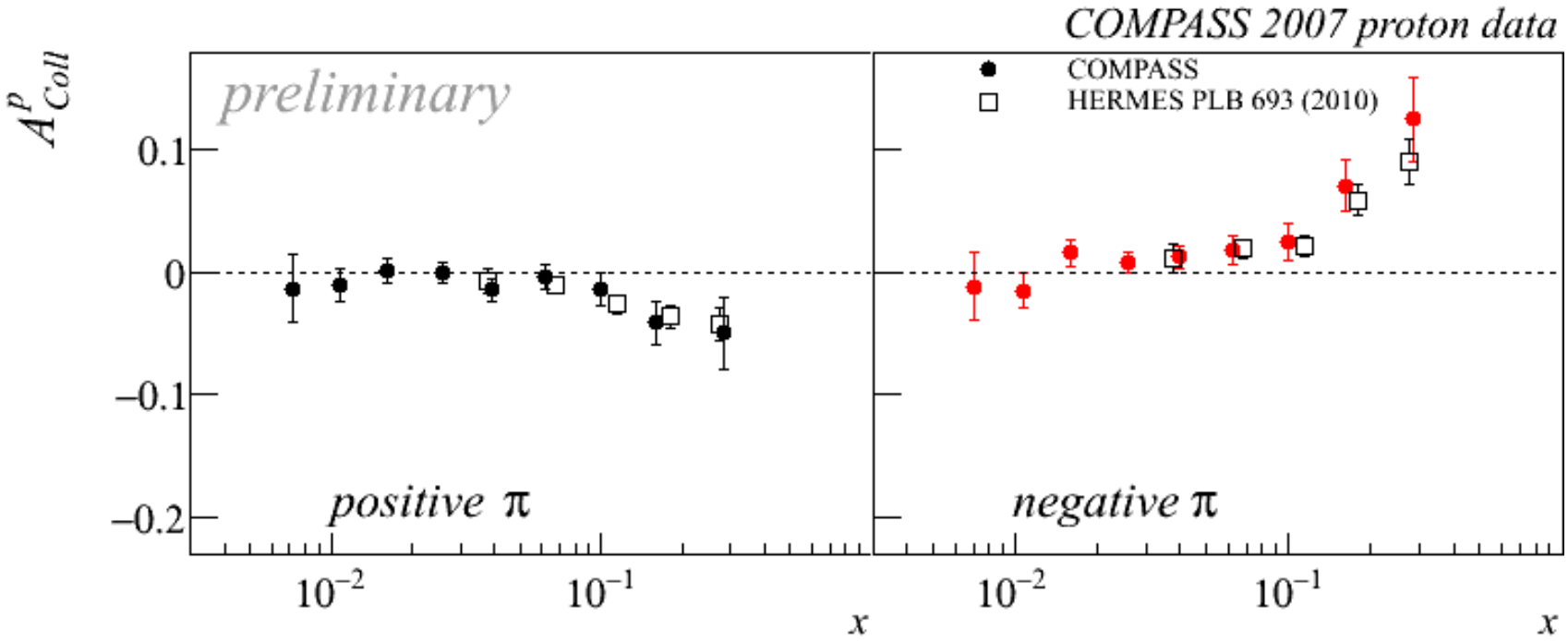
positive

negative

K

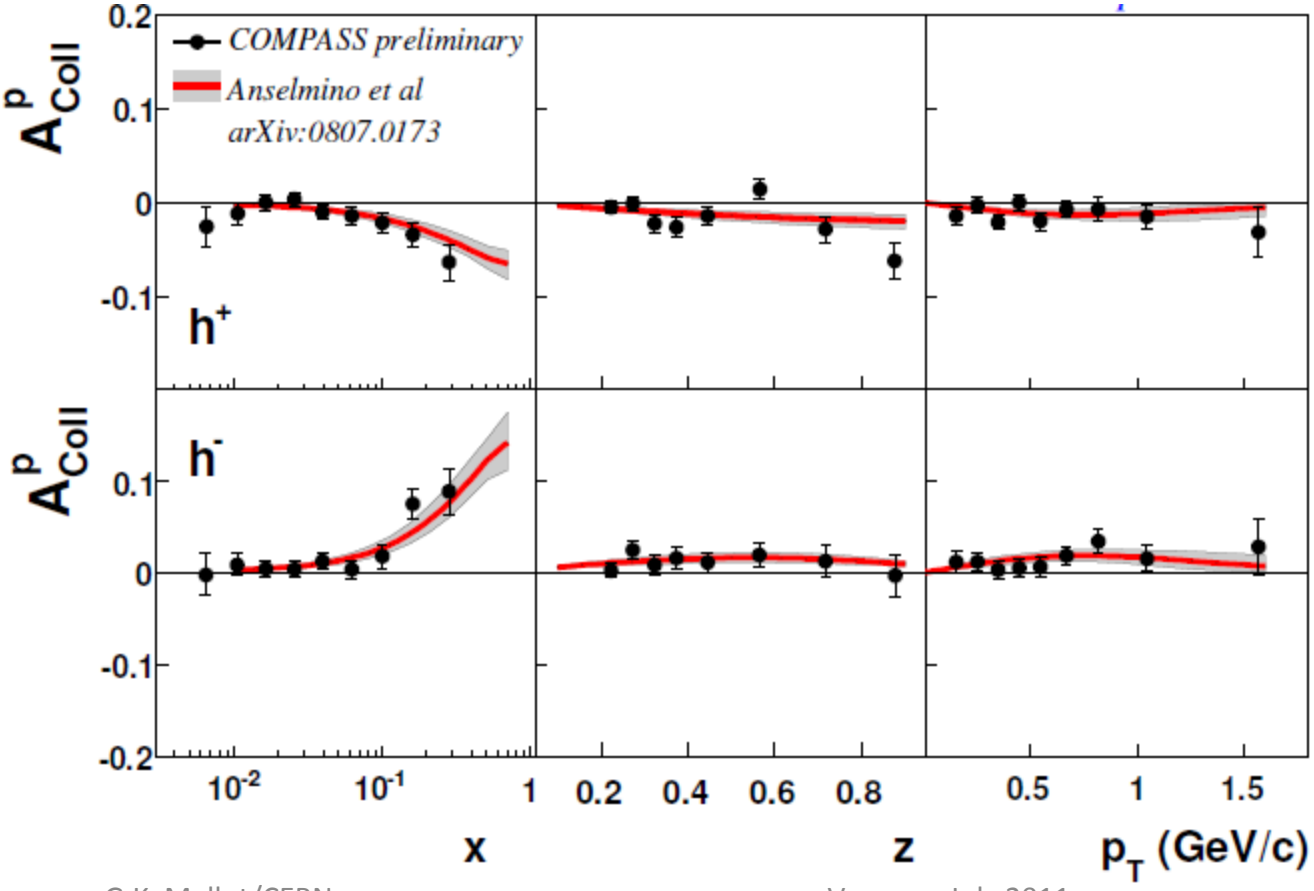
Collins: Comparison to Hermes

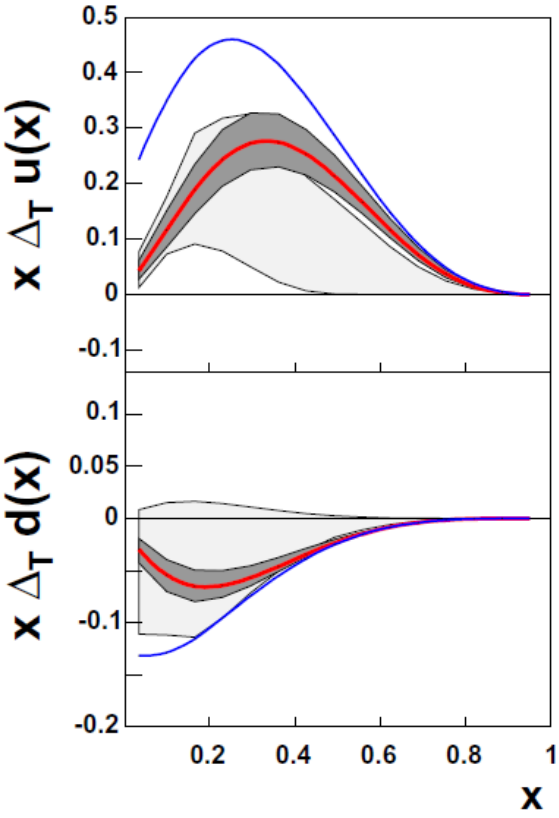
- Good agreement



Global Fit

- Fit to COMPASS *d*, HERMES, BELLE (Collins FF, e^+e^-)
- in good agreement with new proton data





Transversity PDF h_1 via 2-hadron

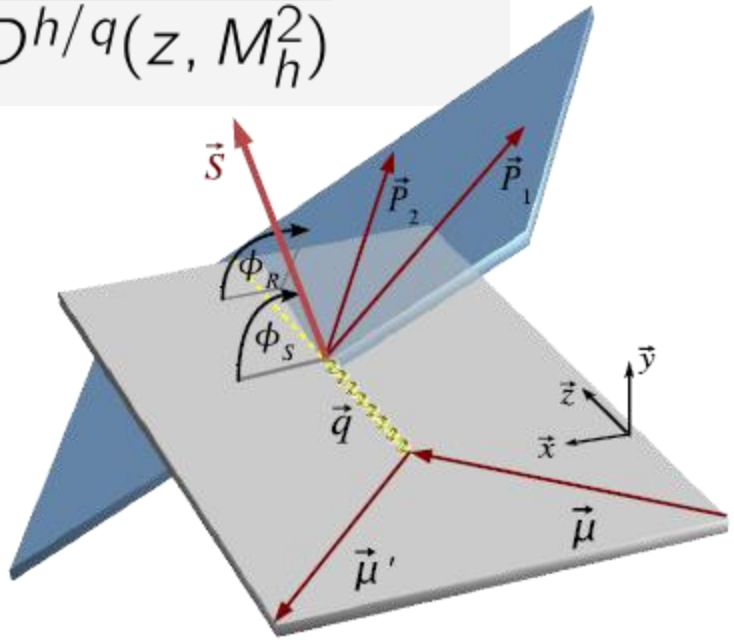
- Alternative: couple h_1 to chiral-odd 2-hadron interference FF $H_1^{\sphericalangle}$

$$A_{RS} \propto \frac{\sum_q e_q^2 h_1^q(x) H_1^{\sphericalangle}(z, M_h^2)}{\sum_q e_q^2 f_1^q(x) D^{h/q}(z, M_h^2)}$$

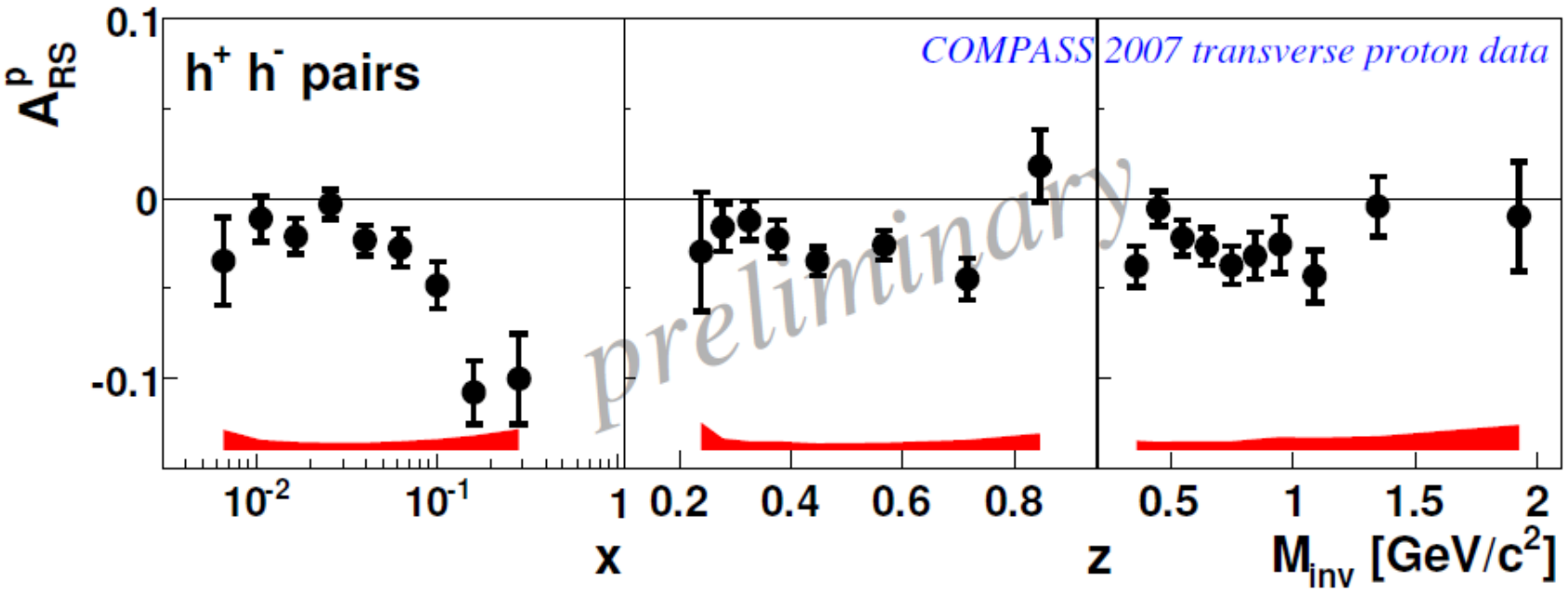
cross-section asymmetry:

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

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



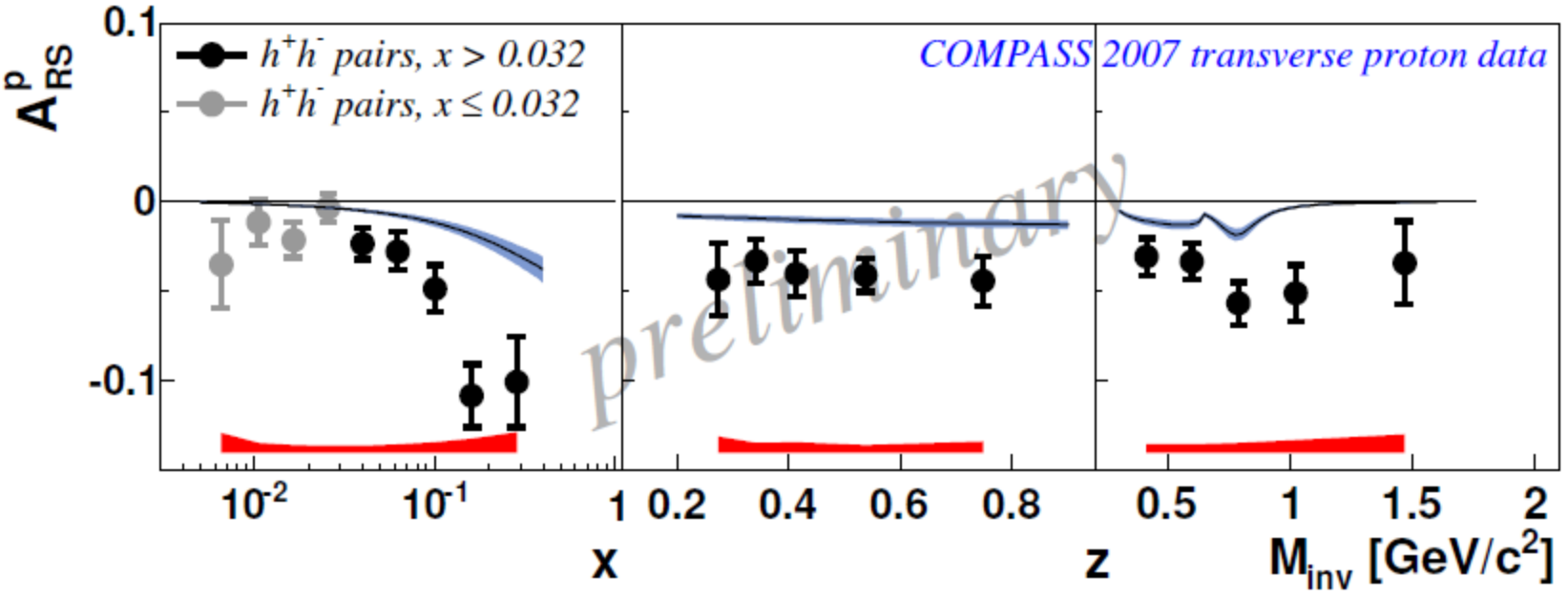
two-hadron asymmetry



- large asymmetries
- interference FF and transversity sizable

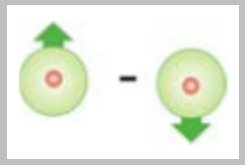
Comparison to a recent Fit

- Recent fit (dominated by HERMES, COMPASS *p* not yet in)



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

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

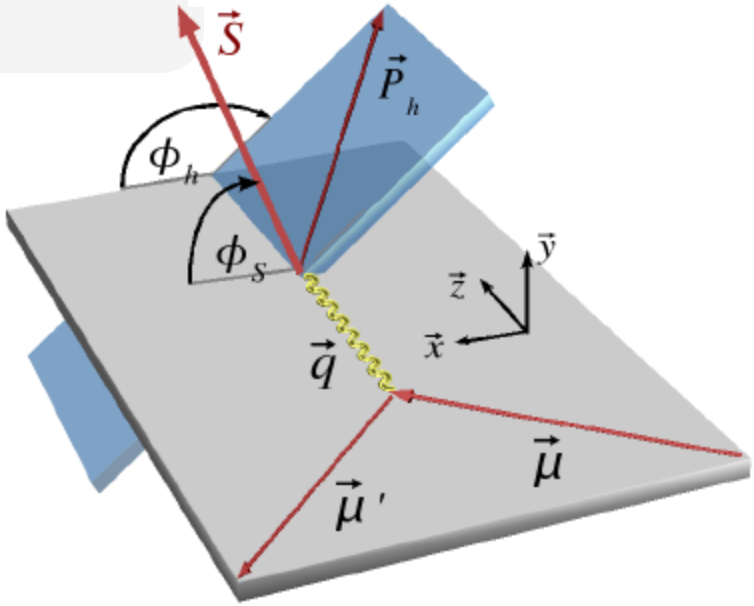


- Sivers Asymmetry:

$$A_{\mathrm{Siv}}^{h} \propto \frac{\sum_q e_q^2 f_{1\mathrm{T}}^{\perp q}(x, k_T) D^{h/q}(z, P_{hT})}{\sum_q e_q^2 f_1^q(x) D^{h/q}(z)}$$

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

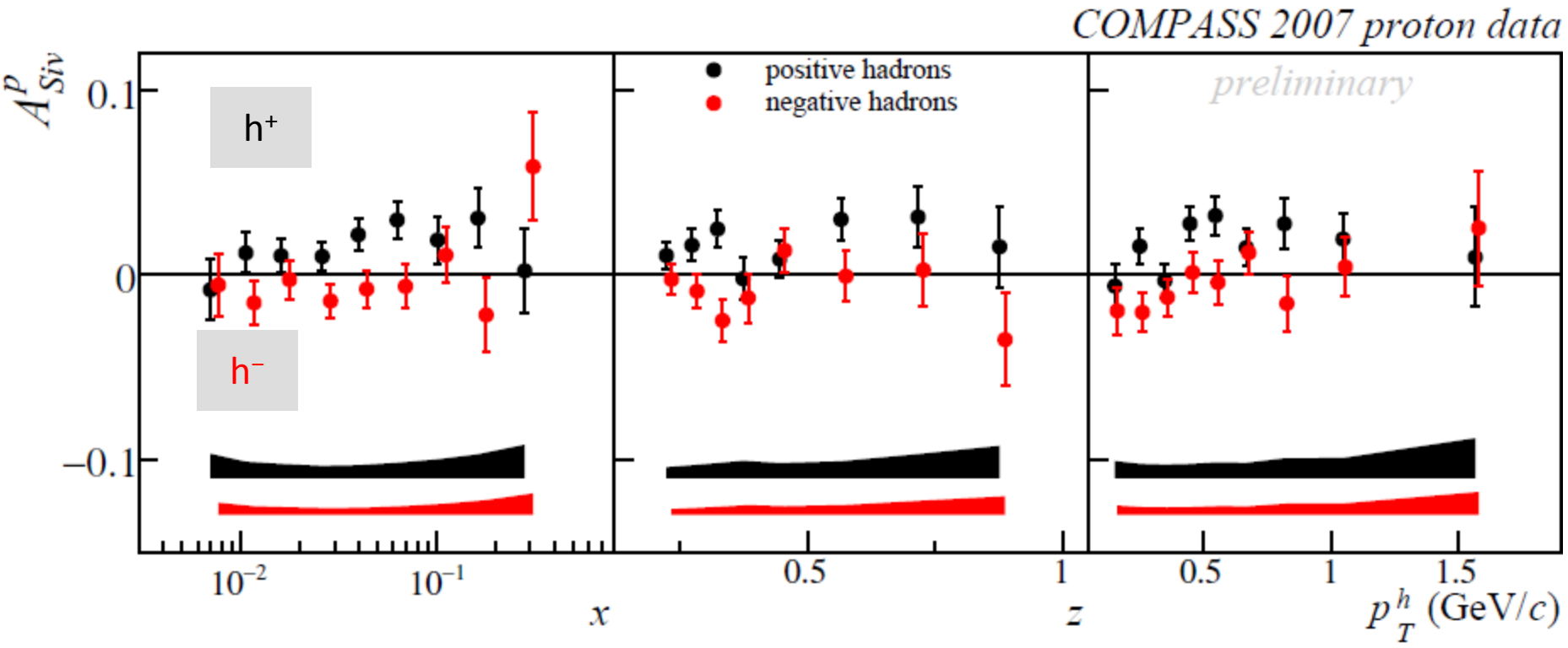
$$\Phi_S = \phi_h - \phi_S$$

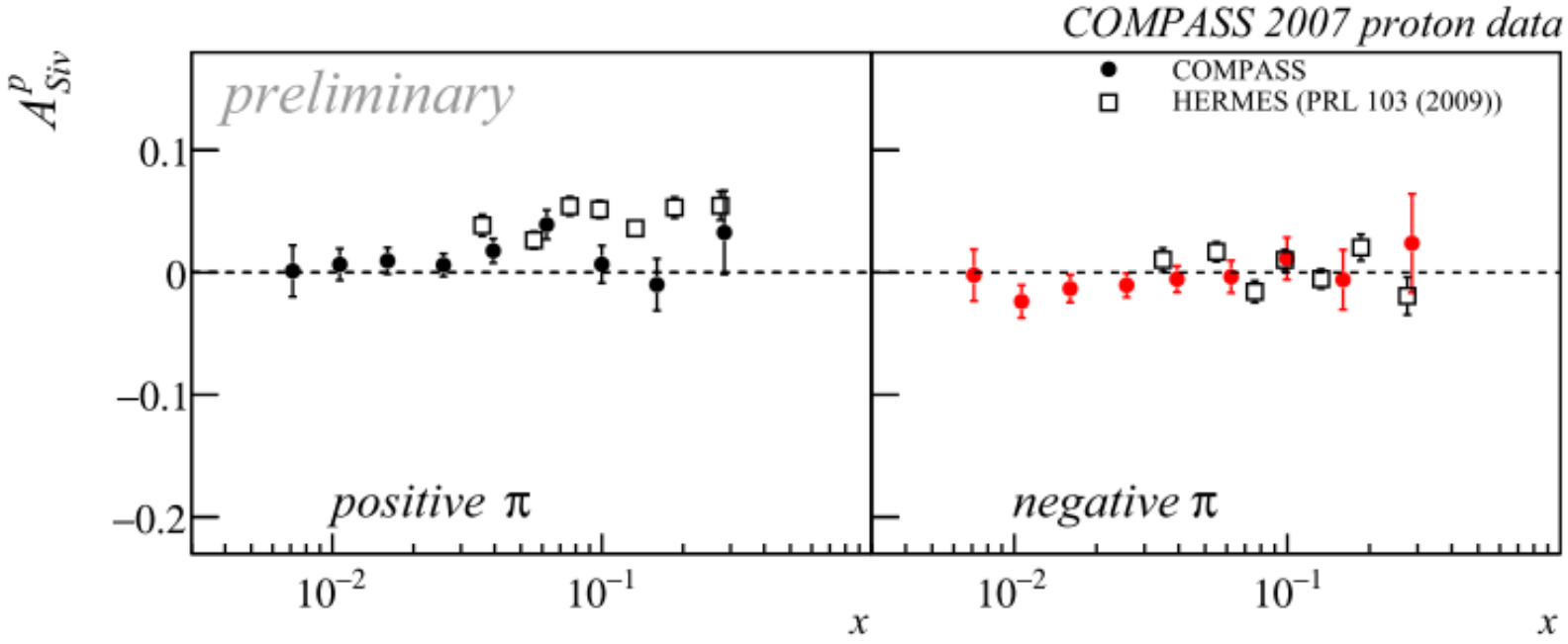


- proposed (1990, Sivers)
- thought to vanish (1993, Collins)
- resurrected (2002, Brodsky, Hwang, Schmitt)
- different sign in DY and SIDIS

Proton Sivers Asymmetry

- compatible with zero for the deuteron
- non-zero asymmetry for pos. hadrons

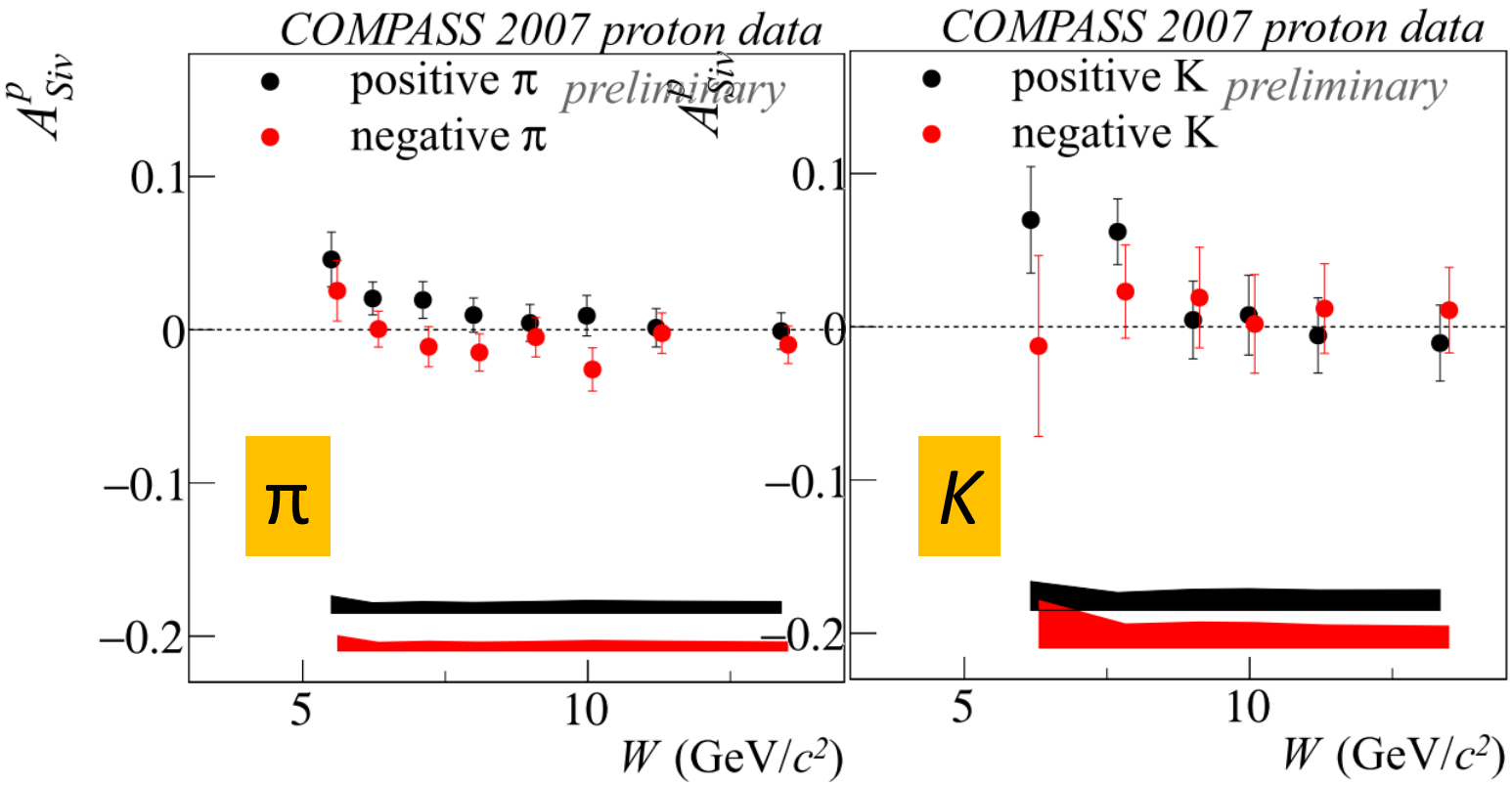




- Hermes data show somewhat larger asymmetry for positive π's

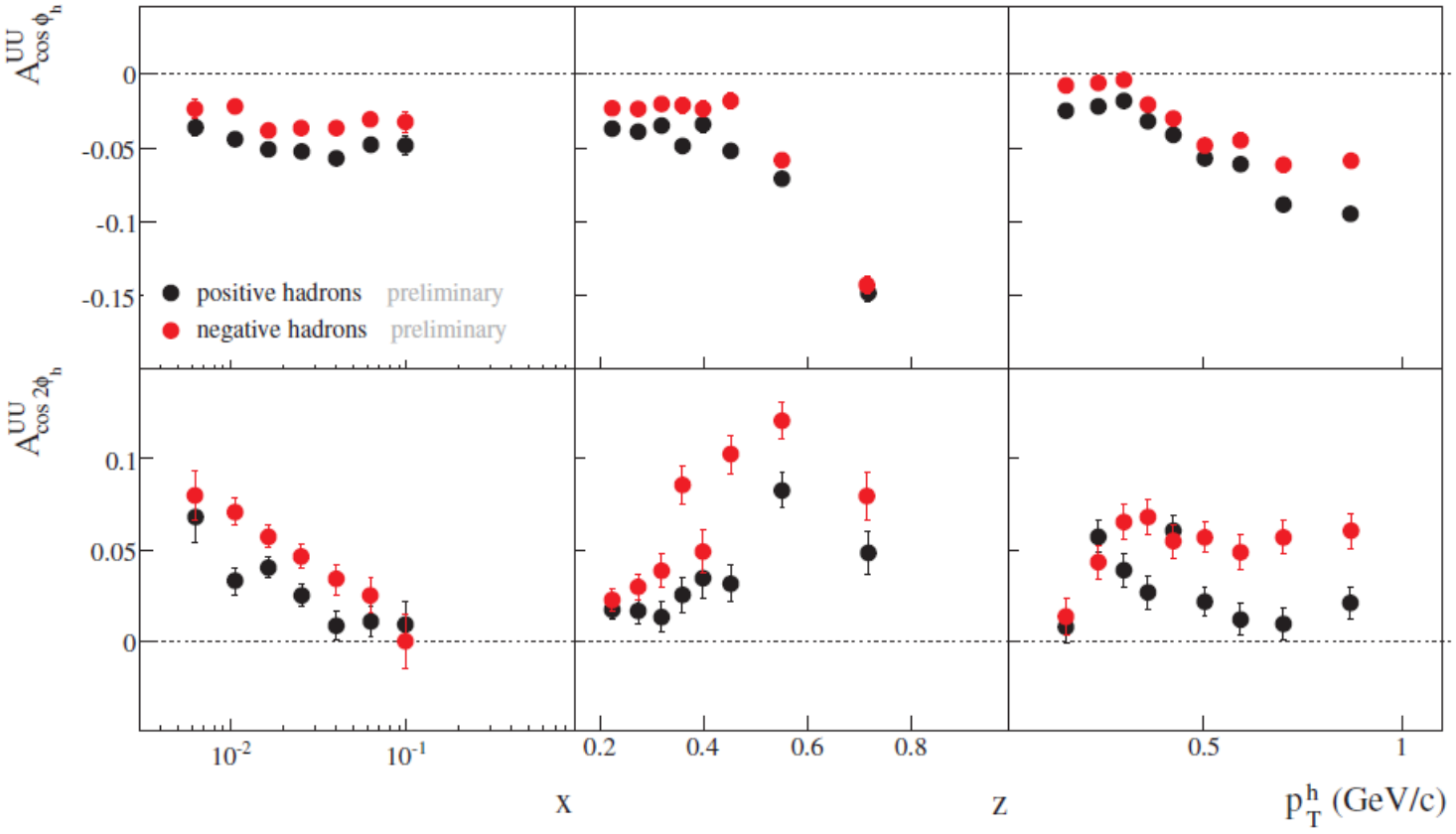
Sivers as function of *W*

- Tendency for asymmetries to increase towards small *W*, however some correlation with other kinematic variables



Spin-averaged asymmetries

- Unpolarized target ^{6}LiD (deuteron)
- Kinematic factor devided out
- sin ϕ modulation is small



cos ϕ

"Cahn"

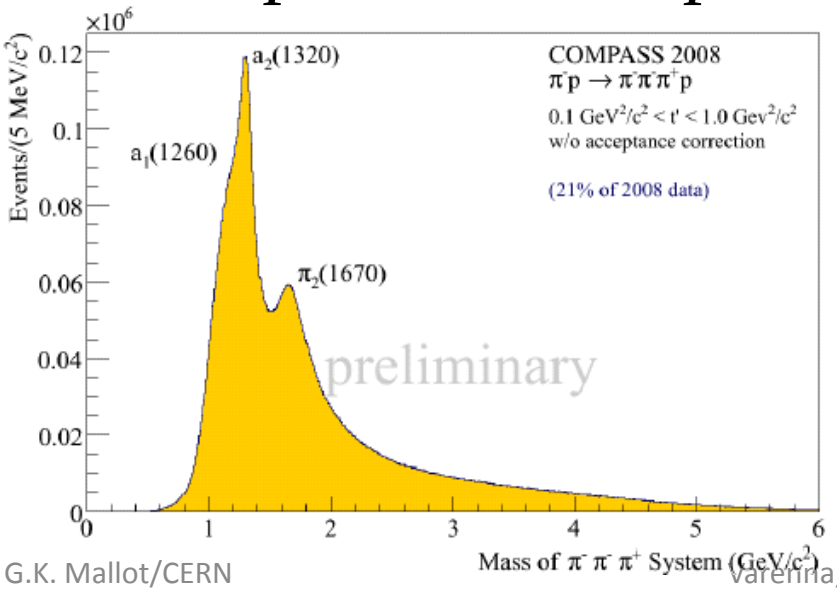
cos 2ϕ

" Boer-Mulders"

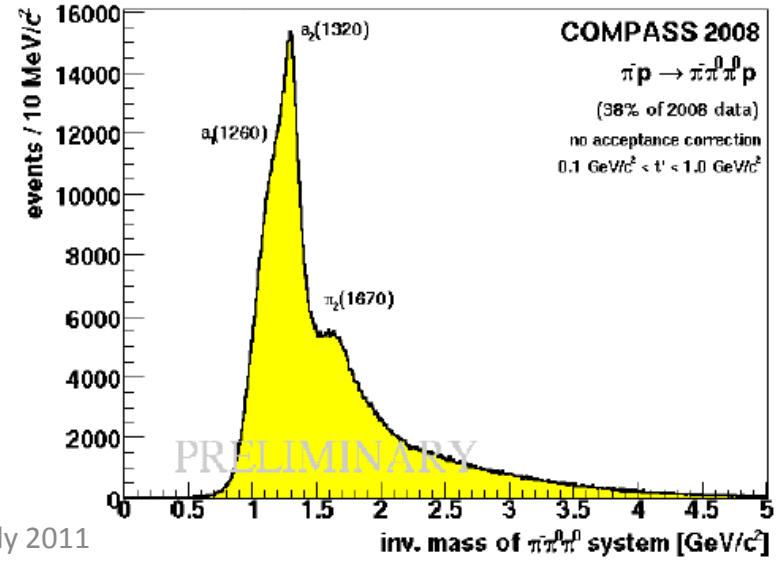
COMPASS is more!

- Rich physics programme with hadron beams (2008,2009,2012)
- Proton, pion and kaon beams
- Pion/kaon polarizability
- Meson and baryon spectroscopy, PWA

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



$$\pi^- p \to \pi^- \pi^0 \pi^0 p$$



What's next?

- Focus on transverse structure of the nucleon

- Transverse size and orbital angular momentum (**GPD**s)
- Restricted universality of T-odd TMDs (Sivers, Boer-Mulders), sign change from SIDIS to **DY**, additional TMDs (pretzelocity, worm-gear)

- COMPASS-II Proposal wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf
- Other new facilitites/experiments
  - JLAB, RHIC, JLAB 11 GeV, JPARC,
  - ENC, eRHIC/ELIC, NICA/SPD

COMPASS-II

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–SPSC–2010–014
SPSC-P-340
May 17, 2010

- Generalized Parton Distributions (GPD)
- Drell-Yan
- Pion (and kaon) Polarizabilities

COMPASS-II Proposal

Approved December 2010

The COMPASS Collaboration

GPD's

- Novel concept, universal, H, $\tilde{H}$, E, $\tilde{E}$
- H (E) nucleon helicity (non)conservation
- Nucleon form factors and PDFs as limiting cases
- Correlating transverse spatial and longitudinal momentum degrees of freedom ('tomography')

Total orbital momentum:

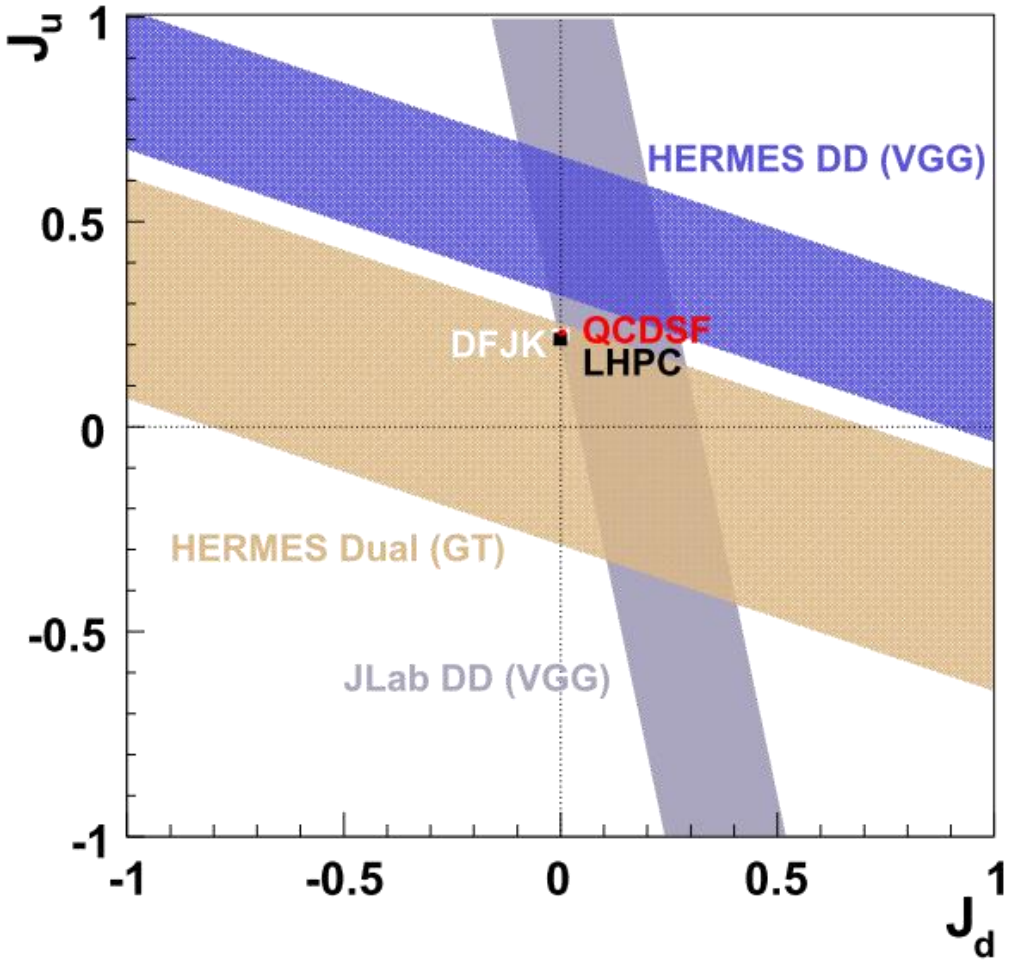
$$J^f(Q^2) = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} \mathrm{d}x\, x \left[H^f(x,\xi,t,Q^2) + E^f(x,\xi,t,Q^2)\right]$$

X.-D. Ji, PRL 78 (1997) 610

x is not x-Bjorken

Orbital angular momentum

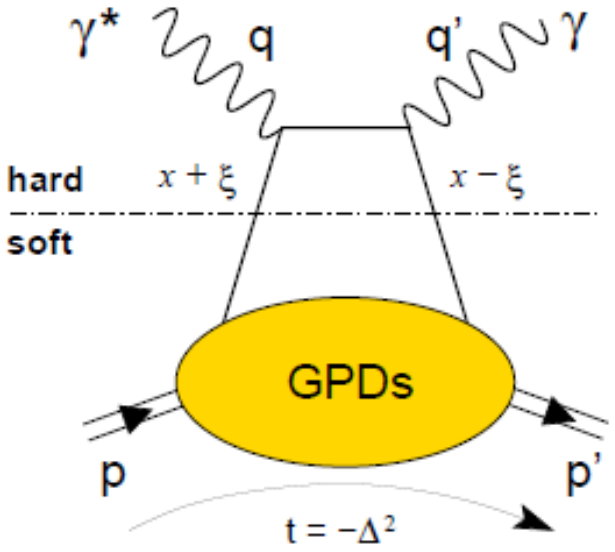
A model-dependent case-study

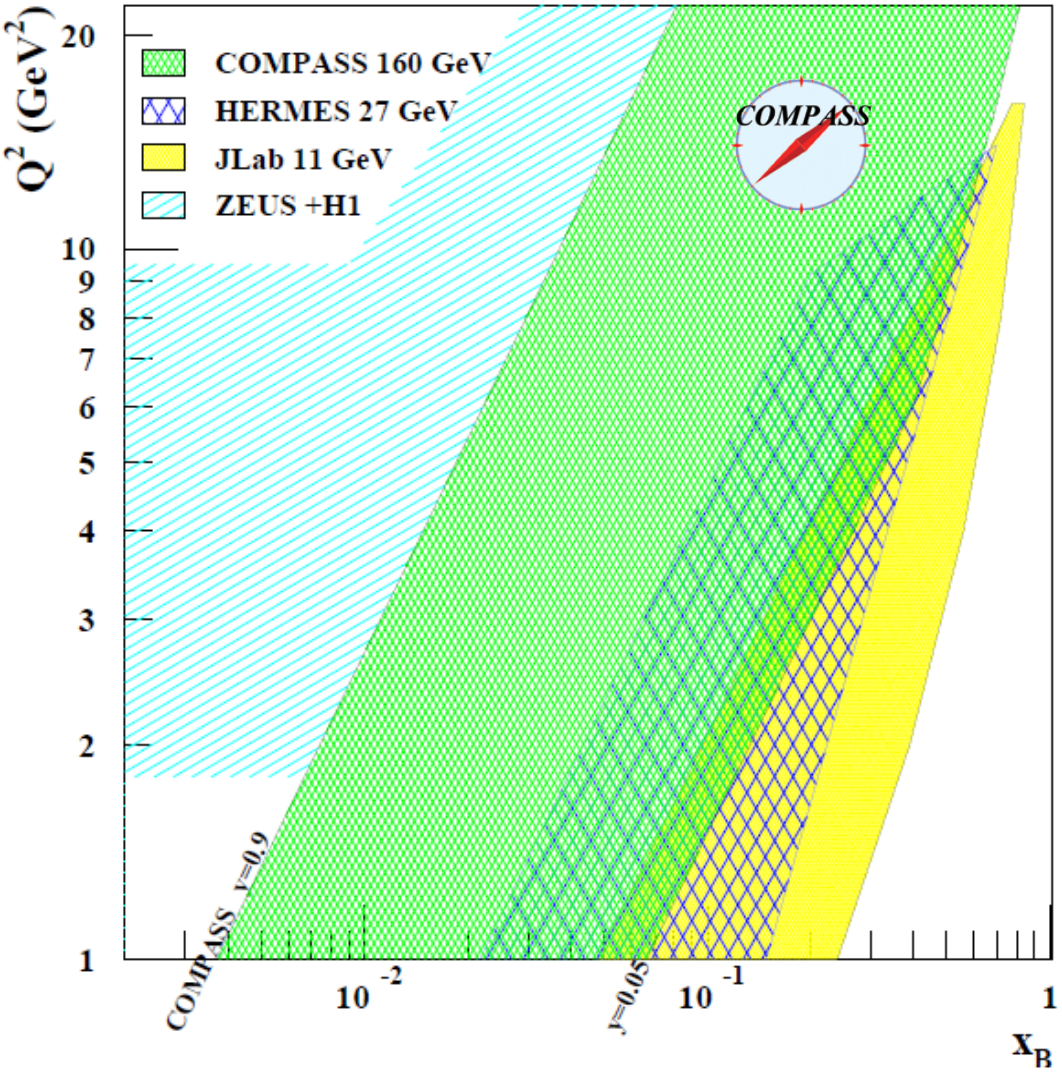


JHEP06 (2008) 066

DVCS

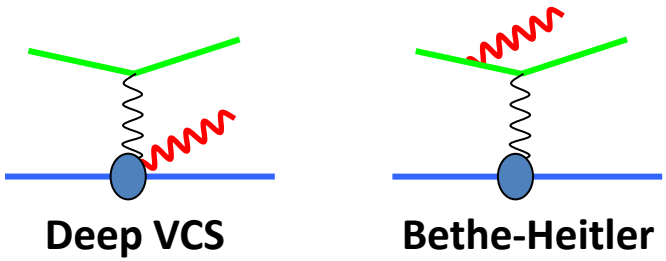
- DVCS is the cleanest process to determine GPDs
- need a world-wide effort
- Global analysis over large kinematic range mandatory
- COMPASS-II: from HERA to JLAB 12 GeV kinematics





DVCS

- DVCS can be separated from BH and the GPD *H* can constrained the cross section using different charge & spin (e_μ & P_μ) combinations of the μ beam
- Note: $\mu^\pm$ have opposite polarization at COMPASS



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

Charge & Spin difference and sum:

$$\mathcal{D} = d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}} = 2(d\sigma_0^{DVCS} + Re\, I)$$

$$\mathcal{S} = d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}} = 2(d\sigma^{BH} + d\sigma_0^{DVCS} + Im\, I)$$

Related to:

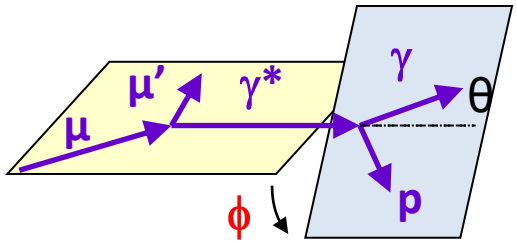
$H(x=\xi,\xi,t)$

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

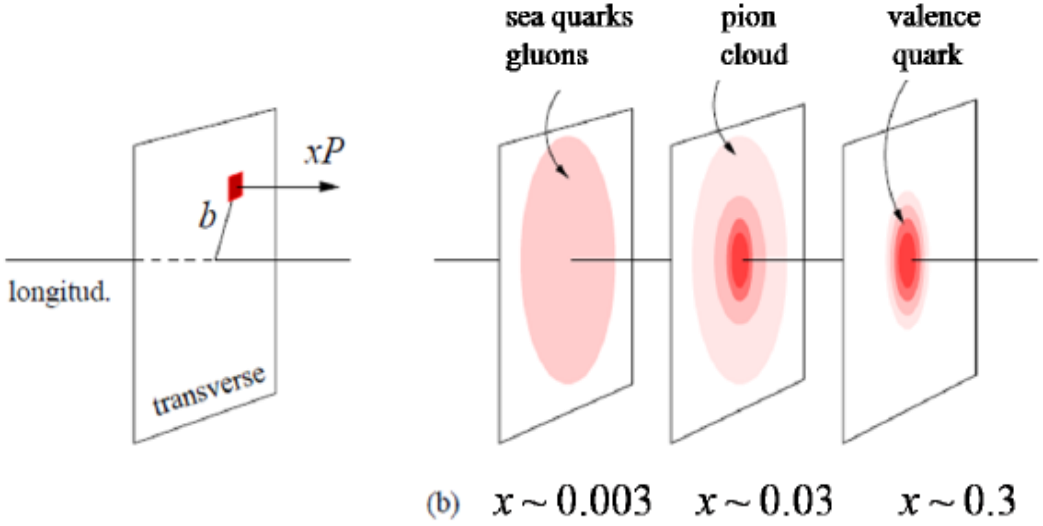
`Tomography'

- Subtract BH from $\mathcal{S}$, intergrate over $\phi \rightarrow$ unpol. DVCS x-sect
- $\xi=0 \rightarrow t = -\Delta_T^2$, no long. transfer

$$q^f(x, \boldsymbol{b}_\perp) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} H^f(x, 0, -\boldsymbol{\Delta}_\perp^2)$$



- Transverse size as function of longitudinal momentum fraction



Independent of a GPD parametrisation!

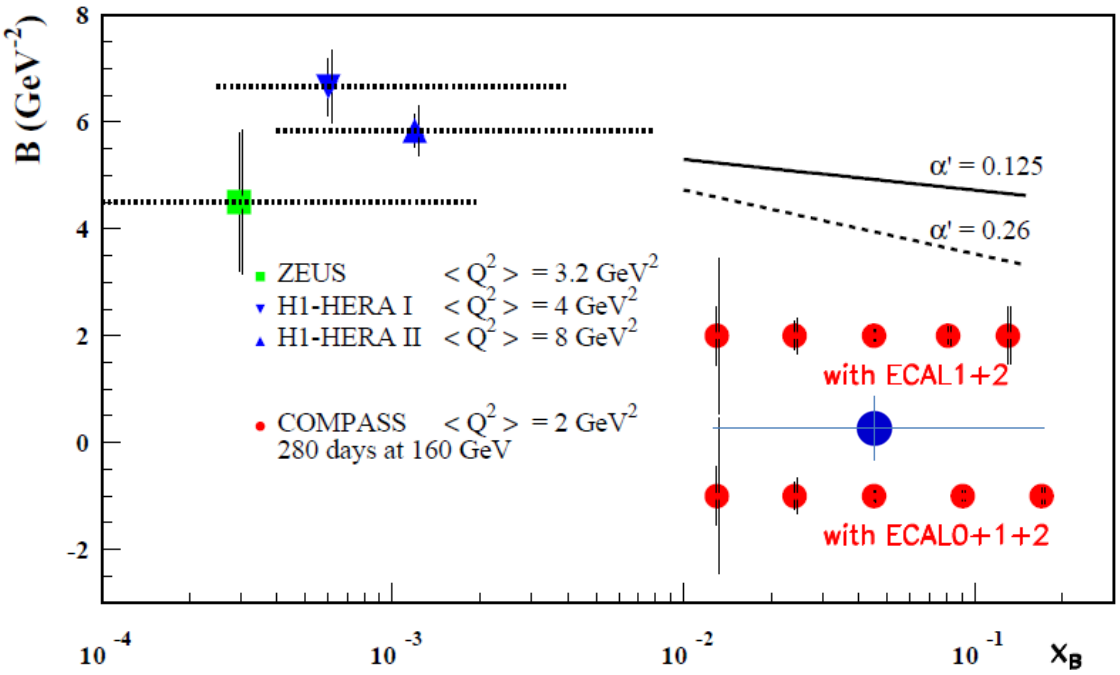
COMPASS-II projection

- COMPASS-II projection, 2 years of data taking
- Pilot run 2012
- x_B region unique to COMPASS

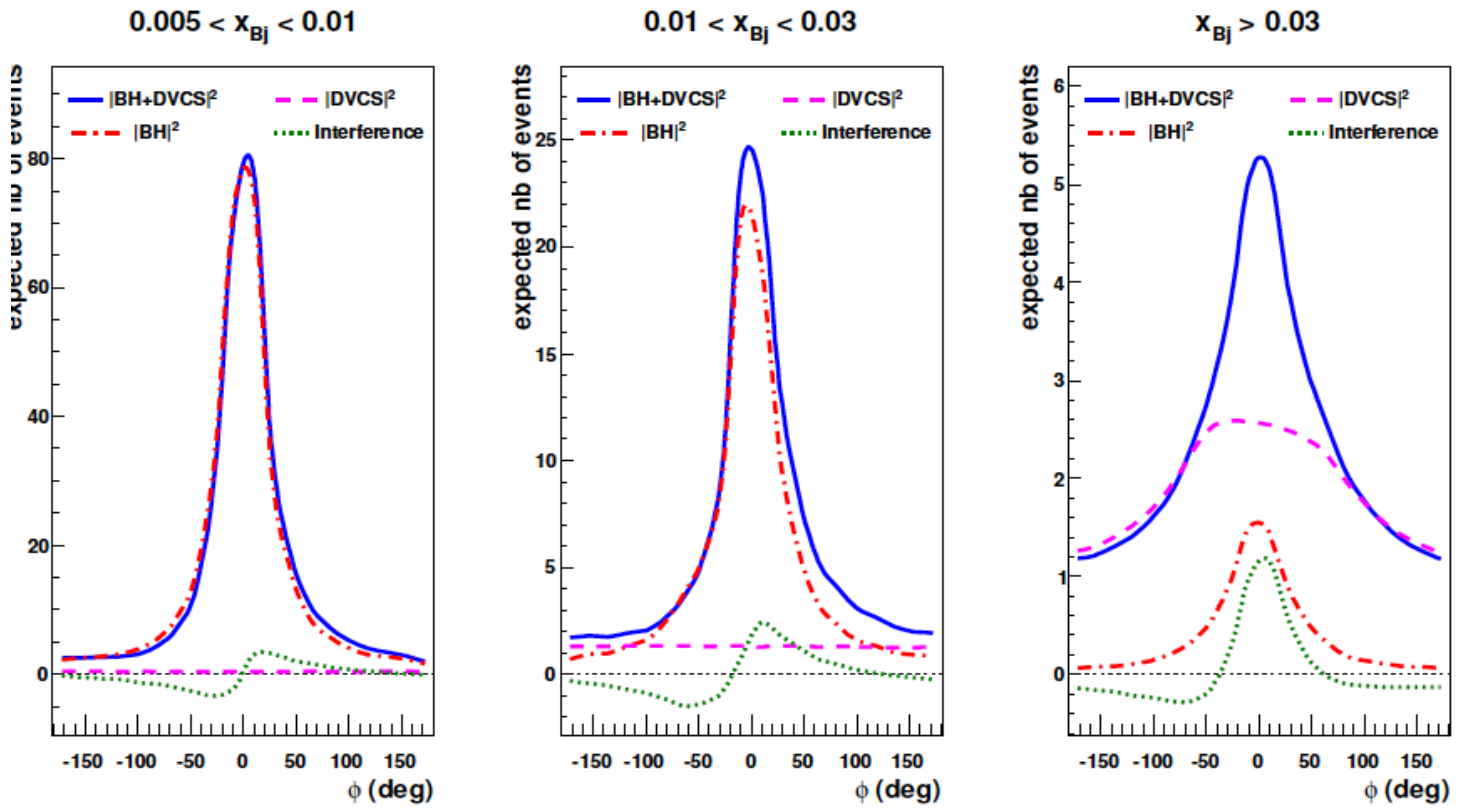
$$\frac{d\sigma_0^{DVCS}}{dt} \propto \exp(-B(x_B)|t|)$$

$$\langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$$

$$B(x_B) = B_0 + 2\alpha' \log\frac{x_0}{x_B}$$



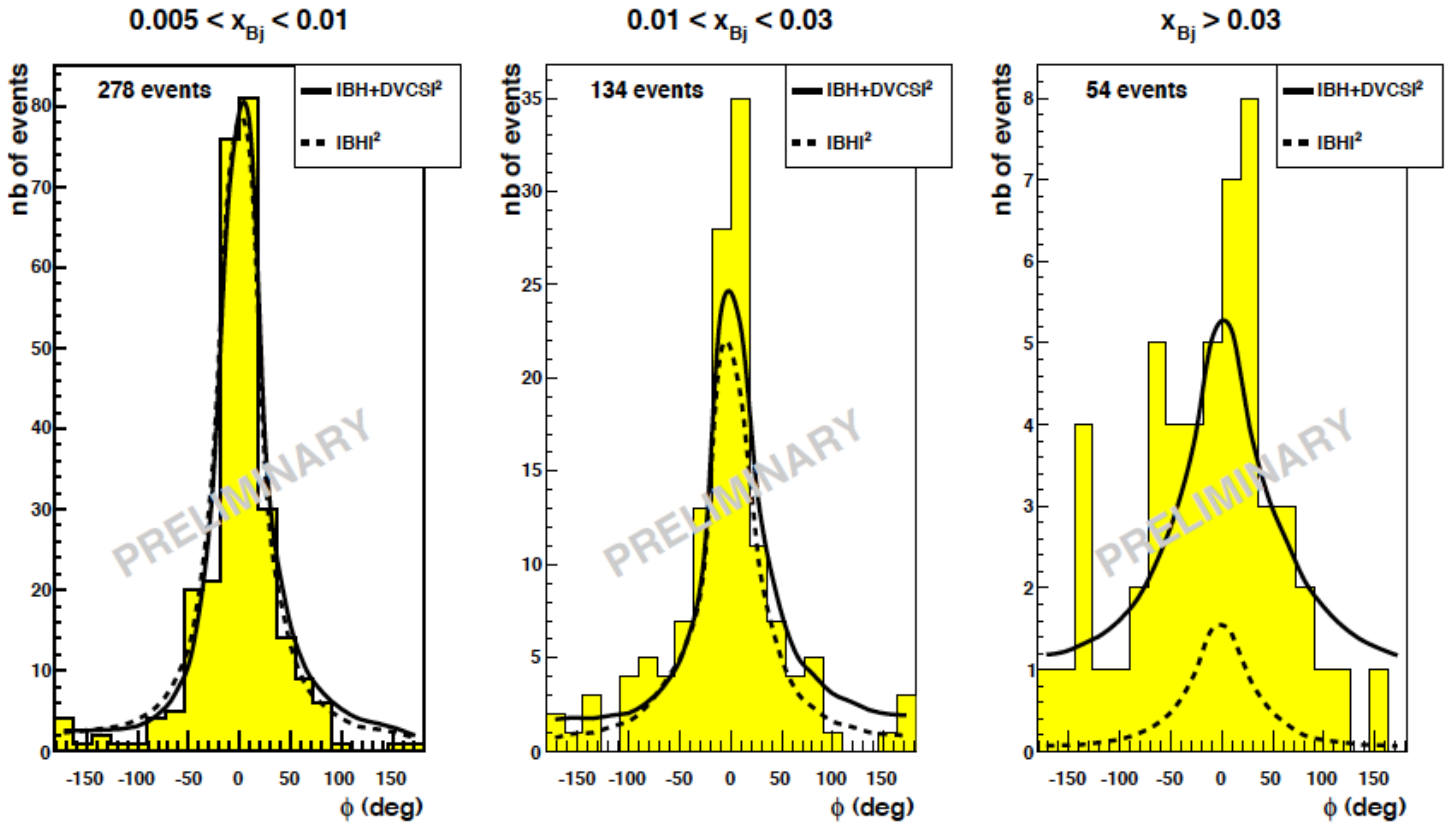
BH vs DVCS simulation



- Rapid variation of relative contributions with x_B
- Normalisation of BH contributon at small x_B

BH vs DVCS data

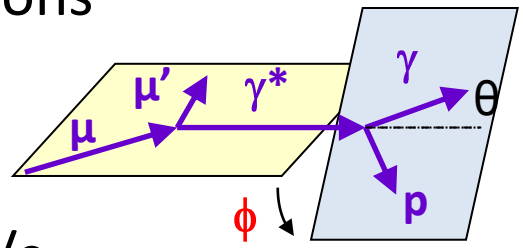
- Test runs in 2008/2009 – 40 cm long H_2 target
- Clear DVCS signal, BH can be subtracted



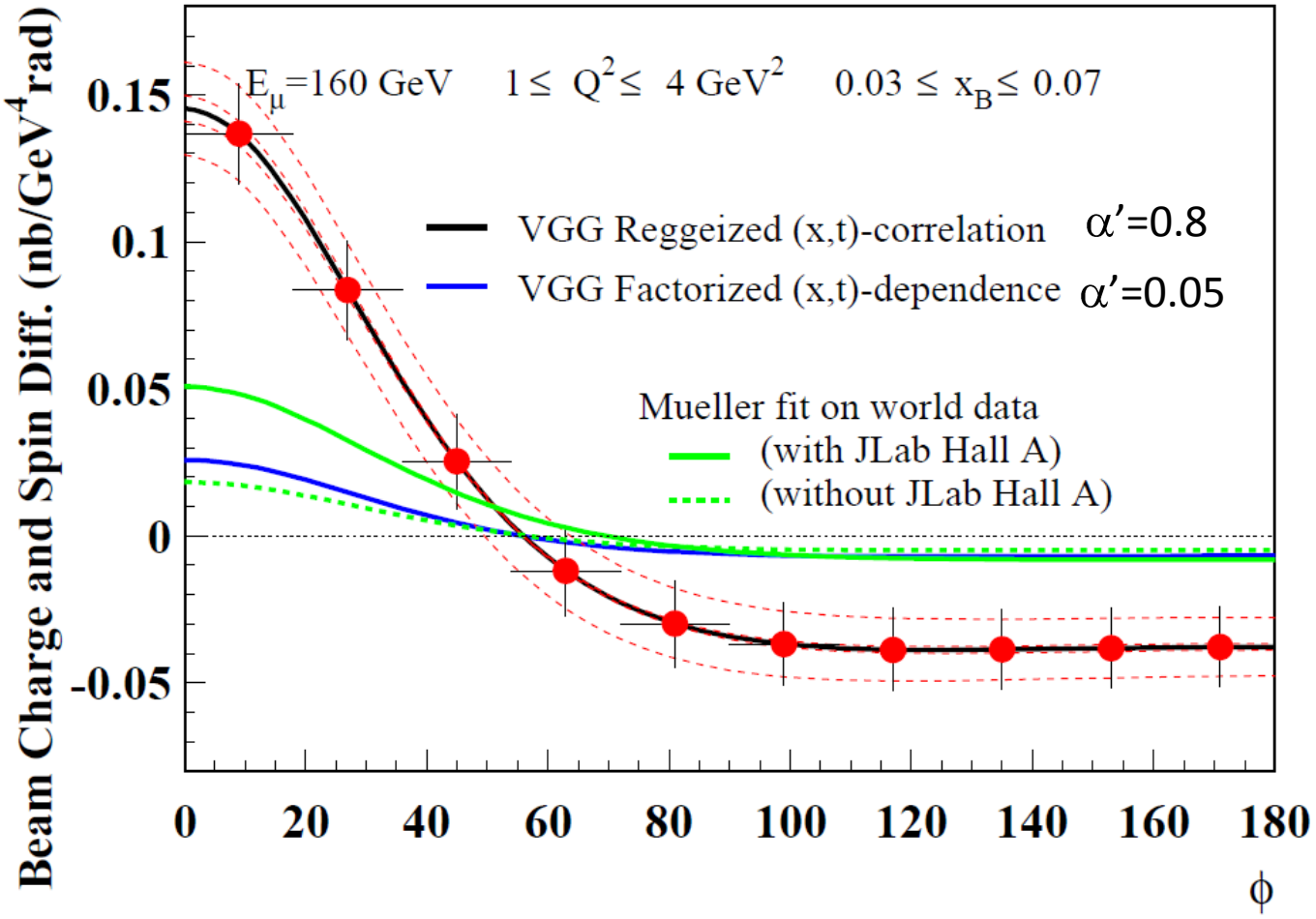
COMPASS II proj. data set

- Charge & spin asymmetry
- Sensitive to GPD *H* models
- Cancelation of several experimental uncertainties
- Easier to measure than absolute cross-sections
- Asymmetries, sums and differences in $6x_B \times 4\ Q^2$ bins as function of ϕ
- Simulation for 2 years data taking, 160 GeV/c and a 2.5 m long liquid H_2 target
- Not shown: Deeply virtual vector meson production

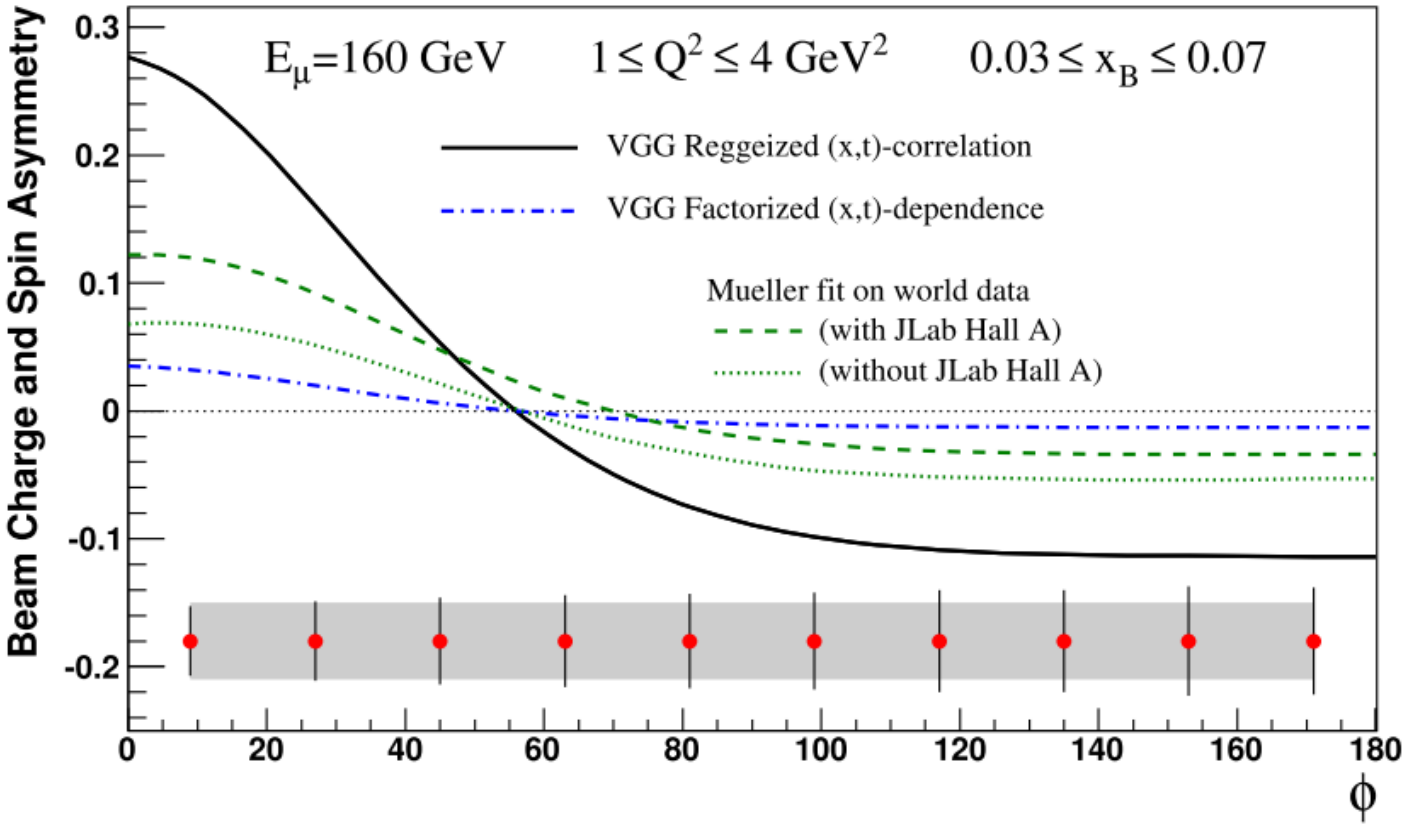
$$\mathcal{A} = \frac{d\sigma^{\overleftarrow{\rightarrow}} - d\sigma^{\overleftarrow{\leftarrow}}}{d\sigma^{\overleftarrow{\rightarrow}} + d\sigma^{\overleftarrow{\leftarrow}}} = \frac{\mathcal{D}}{\mathcal{S}}$$



Proj. charge & spin difference

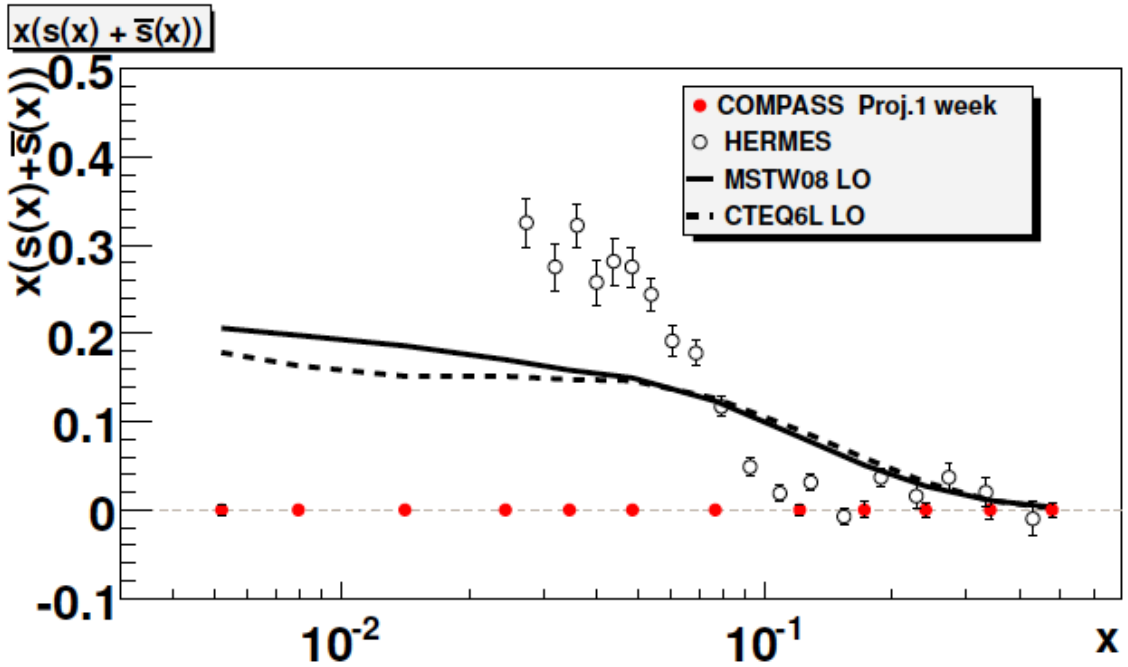


Proj. charge & spin asymmetry



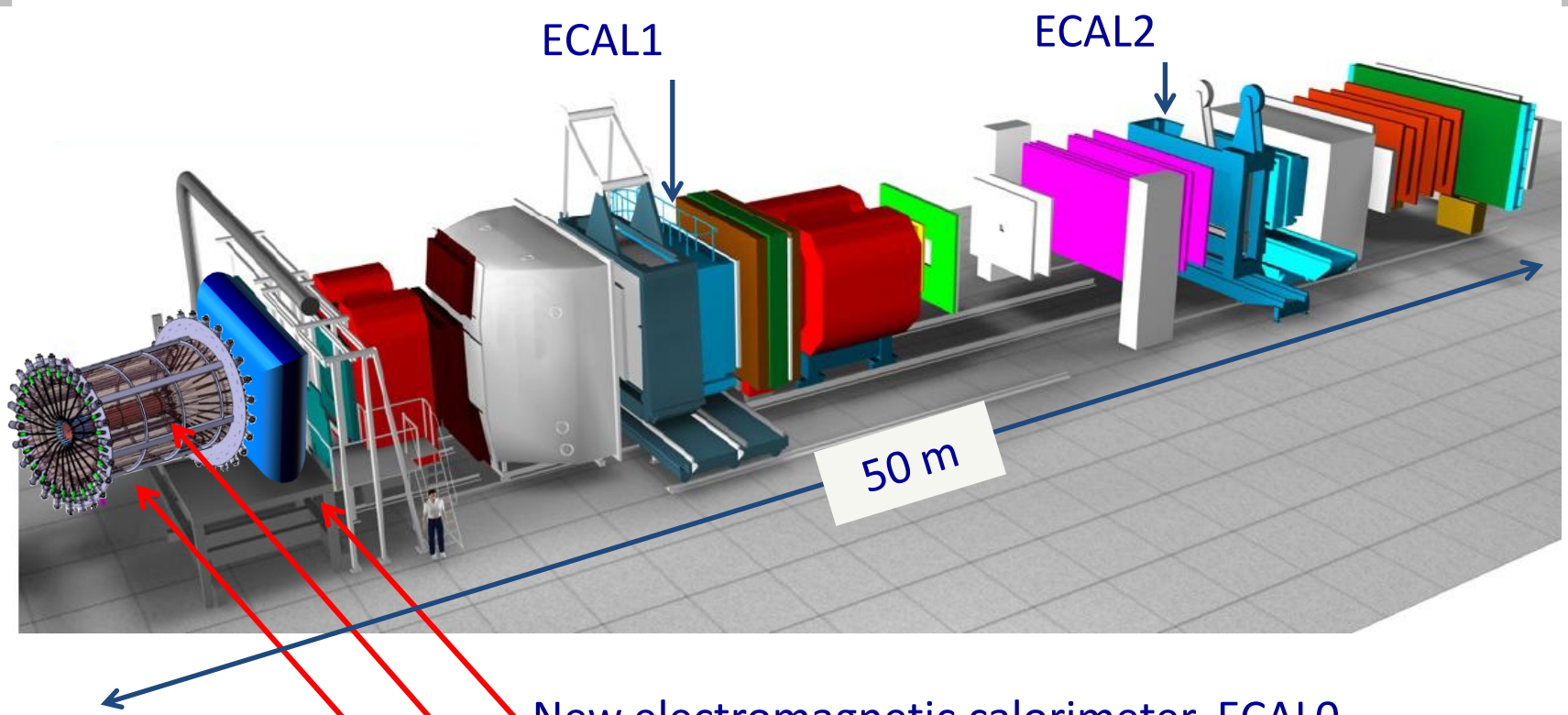
Semi-inclusive DIS

- COMPASS I had ^{6}LiD and NH_3 (i.e. deuterons for unpol.)
- COMPASS II pure hydrogen target in parallel with DVCS
  - $A^{\cos\phi}$, $A^{\cos 2\phi}$, $A^{\sin\phi}$ for proton
  - Hadron multiplicities for FF, strange quark PDF



Proj. for 1 week

DVCS – main new equipment

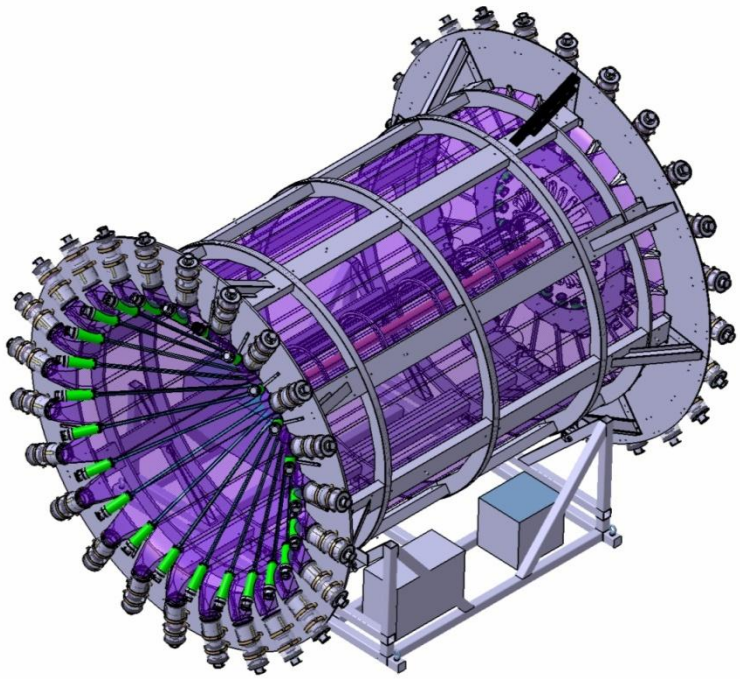


New electromagnetic calorimeter, ECAL0

Liquid hydrogen target, 2.5 m long

Proton Time-Of-Flight detector, 4.0 m long

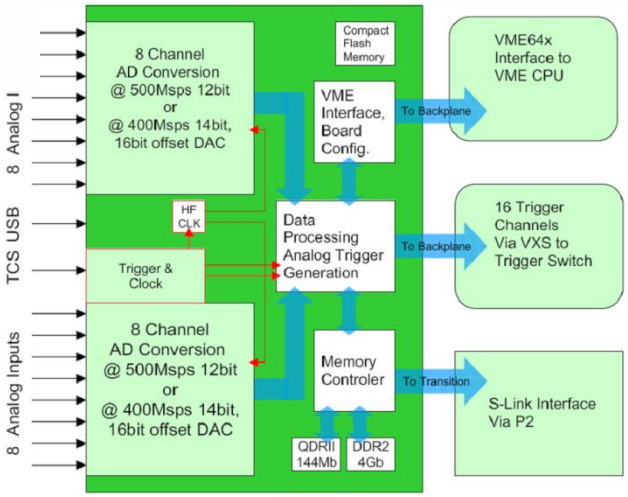
Experimental setup: Camera

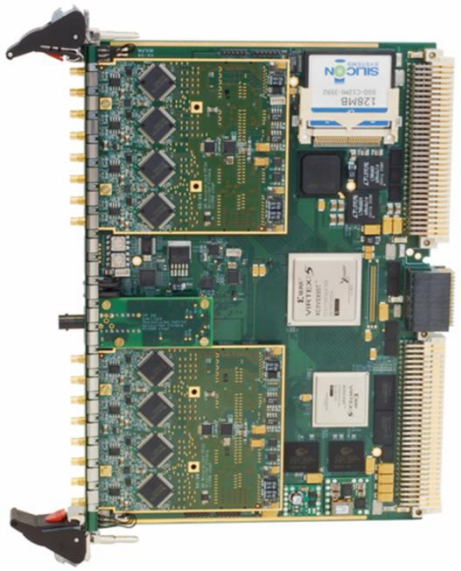


- 2 barrels 4m long long scintillators
- ~ 300ps timing resolution
- 2.5 m long LH2 target

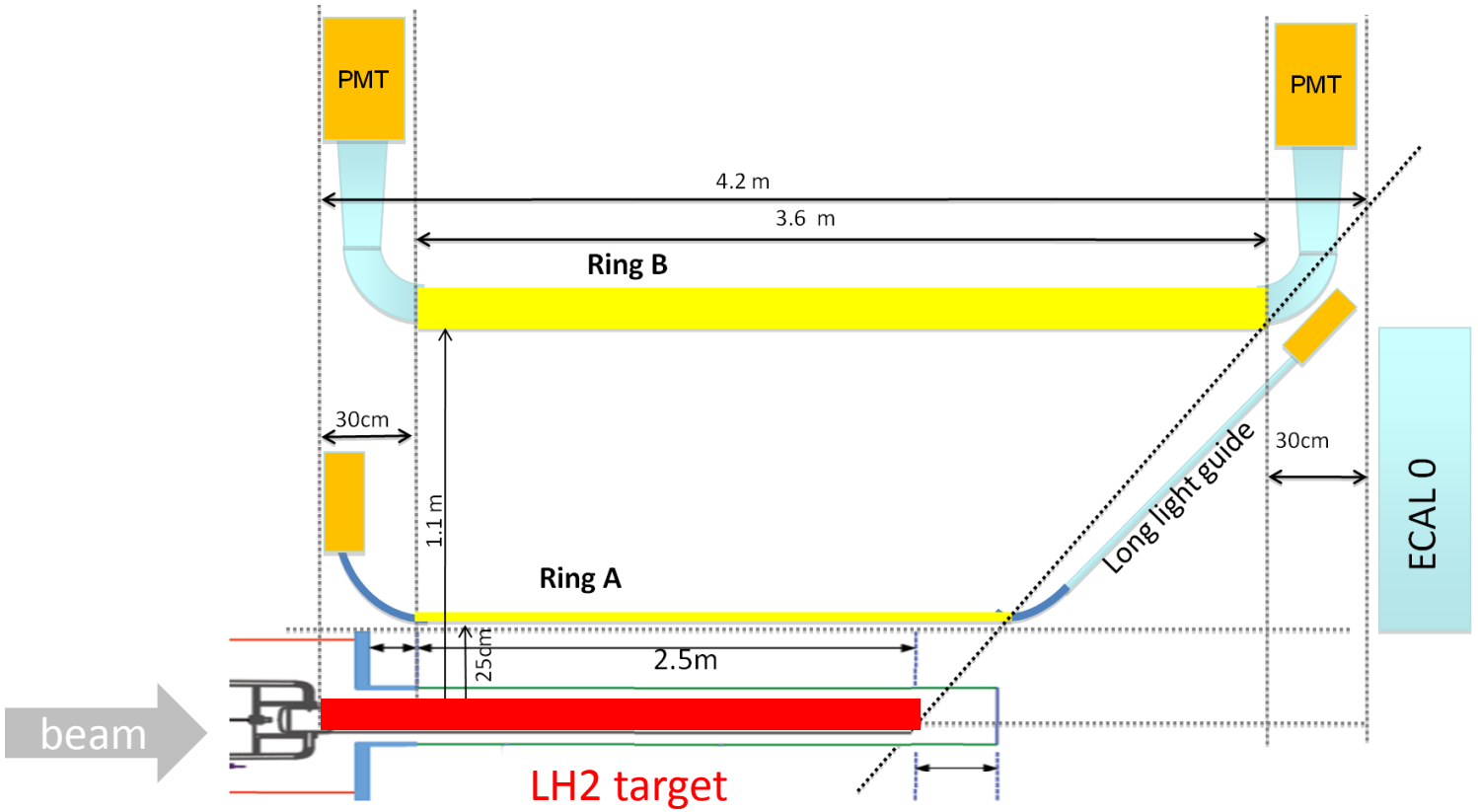
Gandalf Readout Project:

1 GHz digitalisation of the PMT signal to cope for high rate





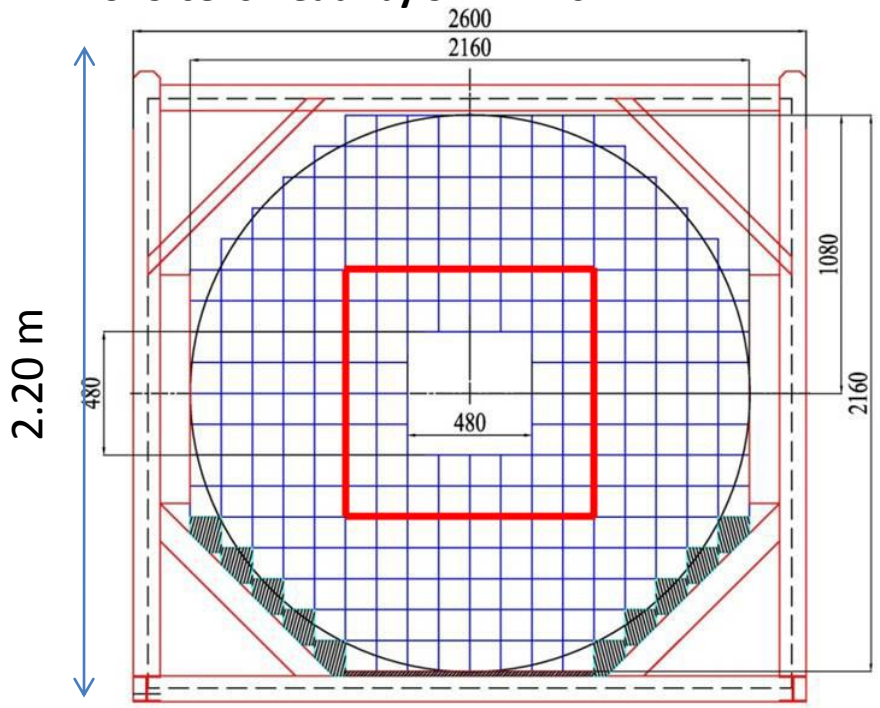
Geometry target region



ECAL0

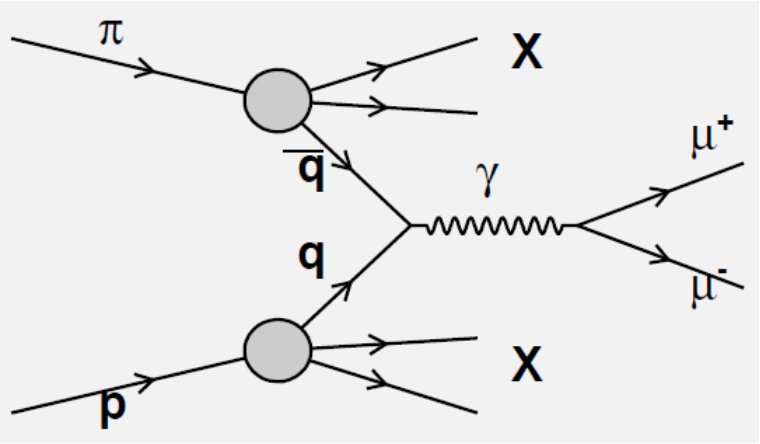
- new **ECAL0** large angle calorimeter
- Multipixel Avalanche Photodiode readout

ECAL0 248 modules (12 × 12 cm²)
of 9 cells read by 9 MAPDs



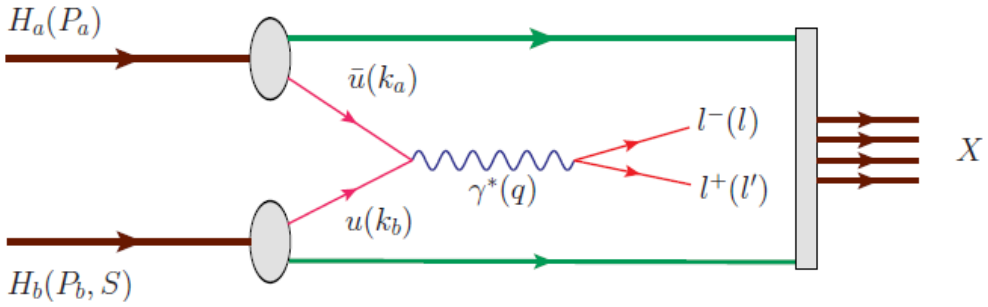
Drell–Yan Process

- No fragmentation function involved
- Convolution of two PDFs
- Best: pol. antiproton–proton (long-term)
- Simpler: negative pion on pol. proton (short-term)
- Pion valence anti-u annihilates with proton u

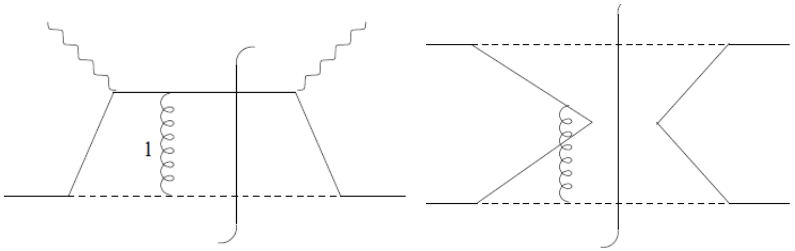


$$\sigma^{DY} \propto f_{\overline{u}|\pi^-} \otimes f'_{u|p}$$

Restricted universality in SIDIS and DY



T-odd TMD



`gauge link changes sign for T-odd TMD', restricted universality of T-odd TMDs

SIDIS: FSI

DY:ISI

J.C. Collins, PLB536 (2002) 43

$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{DIS} \quad \text{and} \quad h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{DIS}$$

Sivers

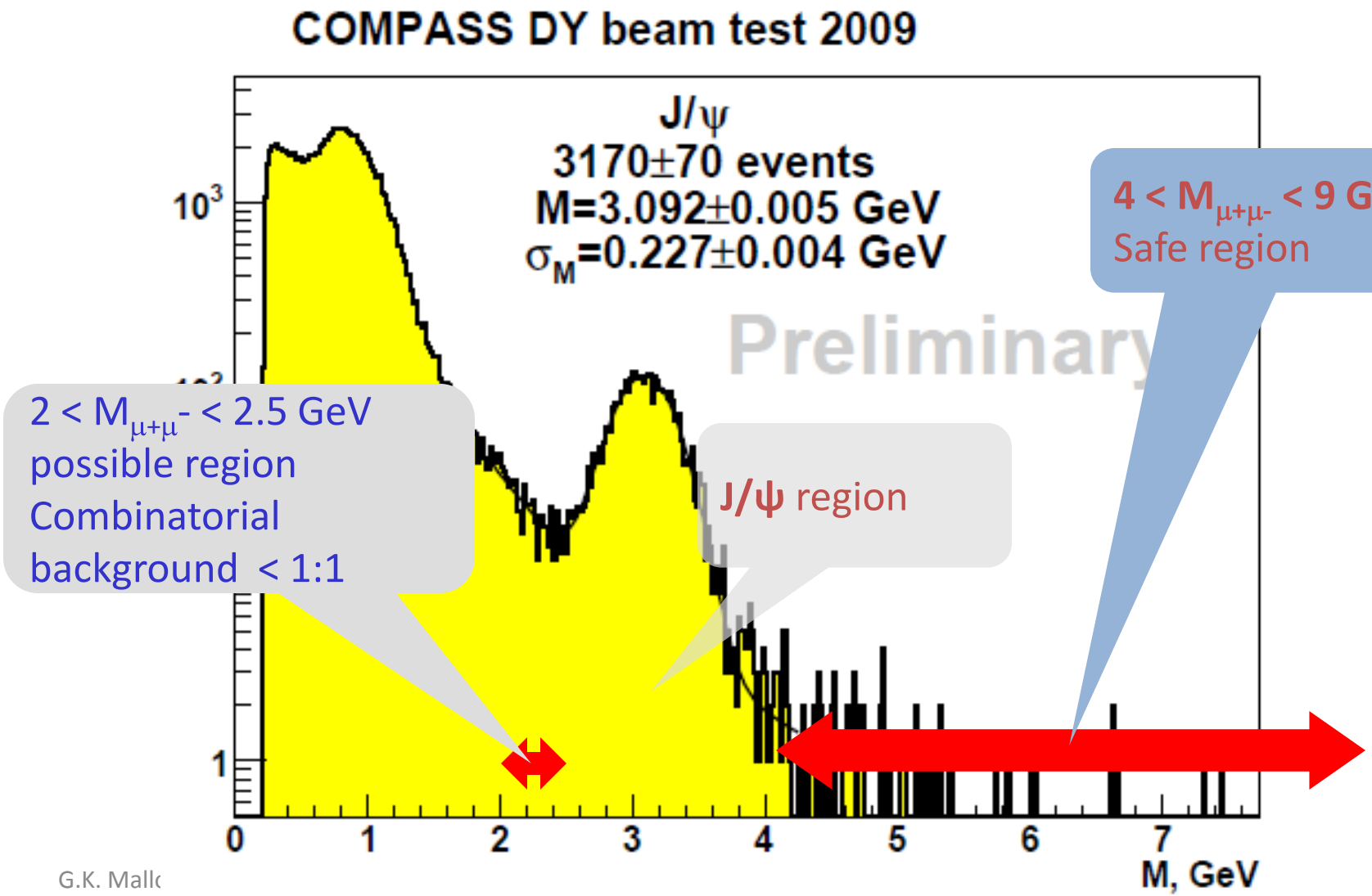
Boer-Mulders

Future DY experiments

Facility		Type	s (GeV^2)	Time-line
RHIC (STAR, PHENIX)	[147]	collider, $p^{\Uparrow}p^{\Uparrow}$	200^2, 500^2	> 2014
RHIC(internal target)	[148]	fixed target, $p^{\Uparrow}p^{\Uparrow}$	500	> 2015
E906 (Fermilab)	[149]	fixed target, pp,	226	> 2010
J-PARC	[150]	fixed target, $pp^{\Uparrow}$	$60 \div 100$	> 2015
GSI(PAX)	[151]	collider, $\overline{p}^{\Uparrow}p^{\Uparrow}$	200	> 2017
GSI (Panda)	[152]	fixed target, $\overline{p}p$	30	> 2016
NICA	[153]	collider, $p^{\Uparrow}p^{\Uparrow}$, $d^{\Uparrow}d^{\Uparrow}$	676	> 2014
COMPASS	(this Paper)	fixed target, $\pi^- p^{\Uparrow}$	$300 \div 400$	2014

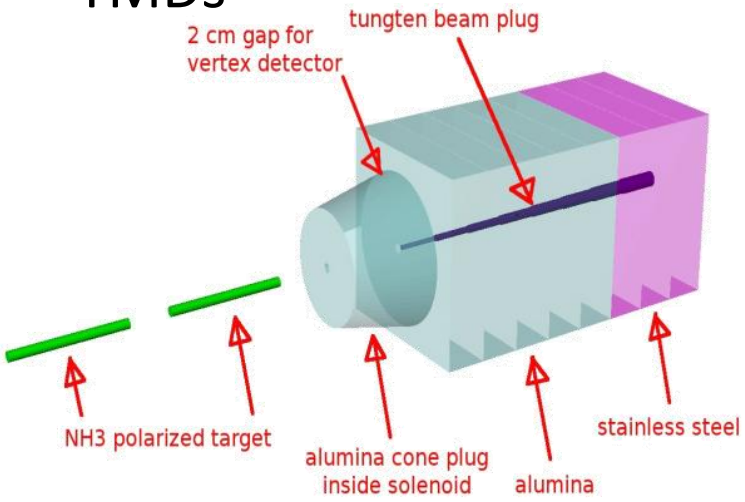
RHIC AnDY	collider	pp pol.	500^2	> 2013

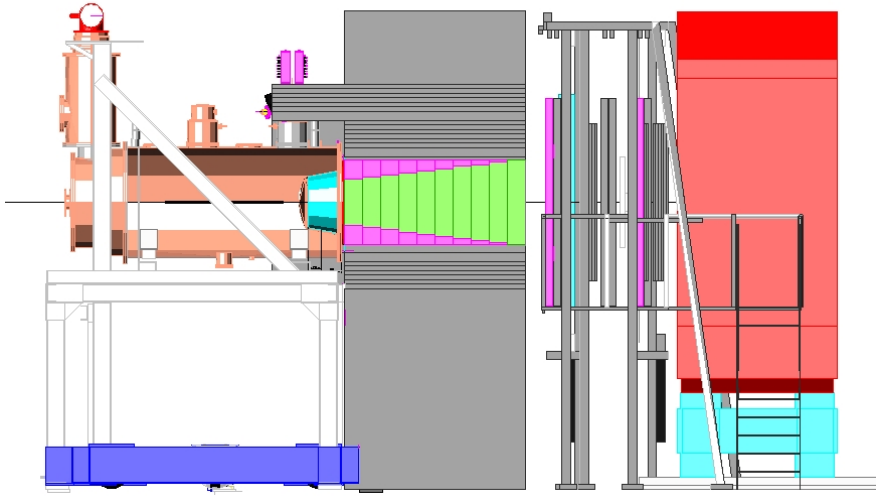
Drell–Yan muon pair mass regions



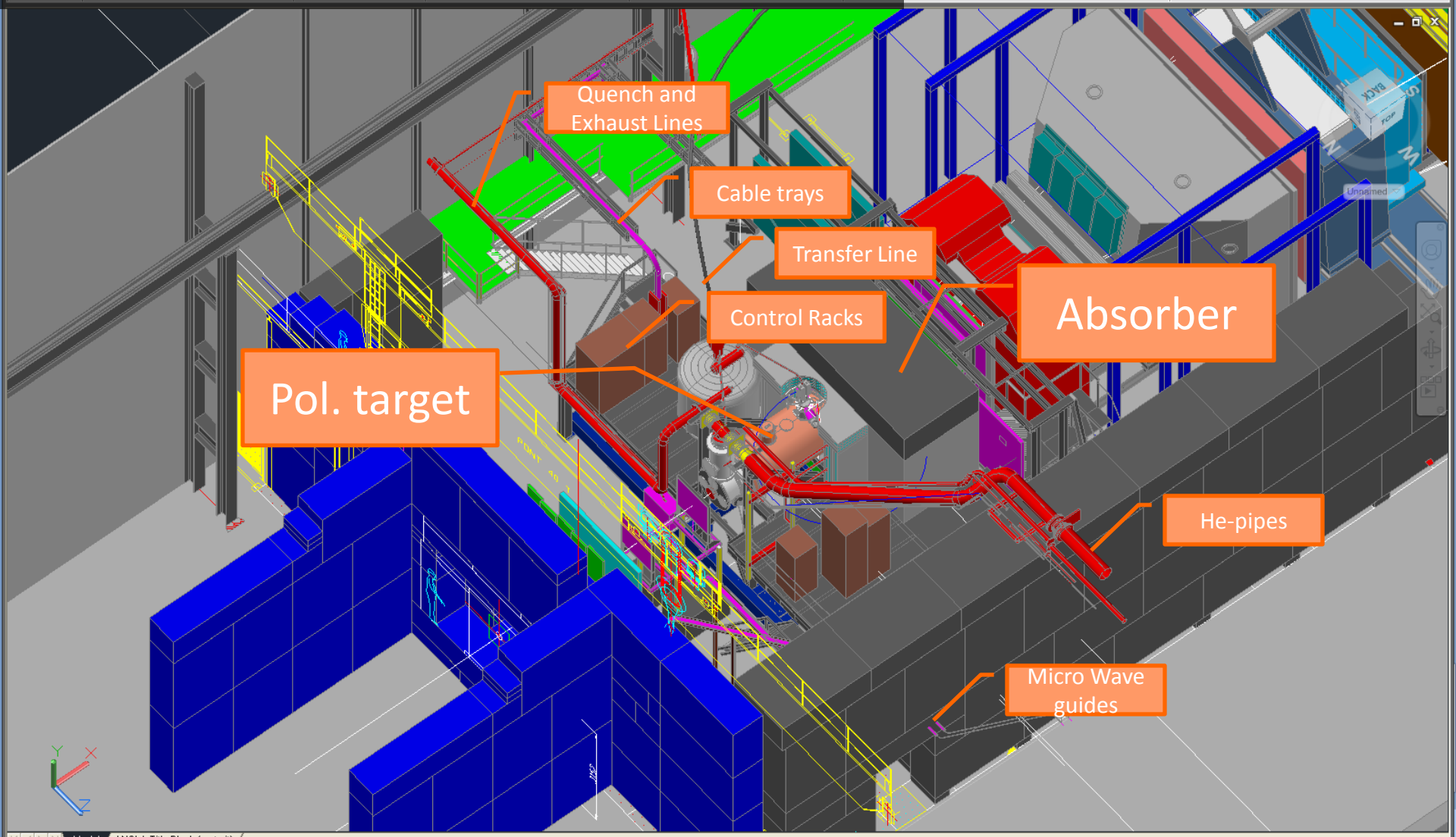
COMPASS-II Polarised Drell-Yan

- COMPASS-II: 190 GeV/c π^- beam on transversely pol. proton target
- π^- valence u-antiquark picks nucleon's u quark in valence region (u-quark dominance)
- Access to transversity , the T-odd Sivers and Boer-Mulders TMDs



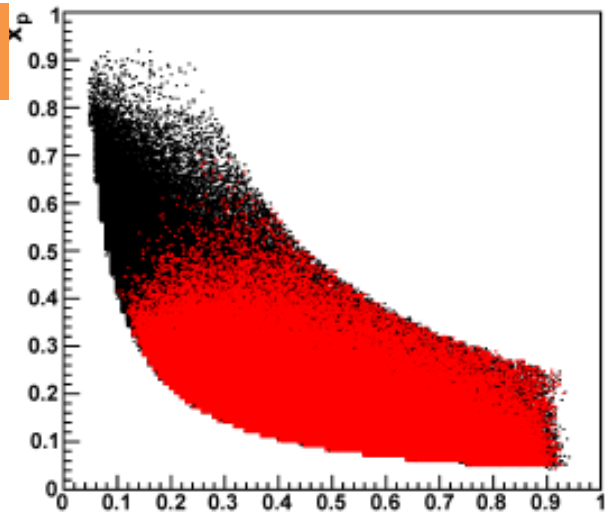


Major rearrangement of target region

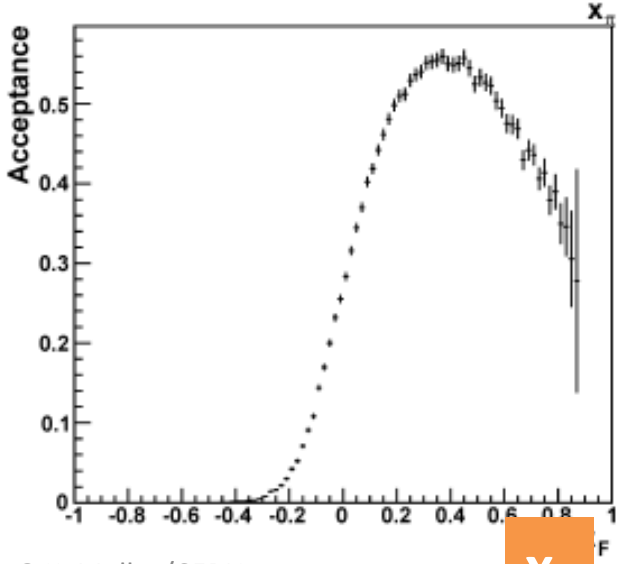


COMPASS polarized DY

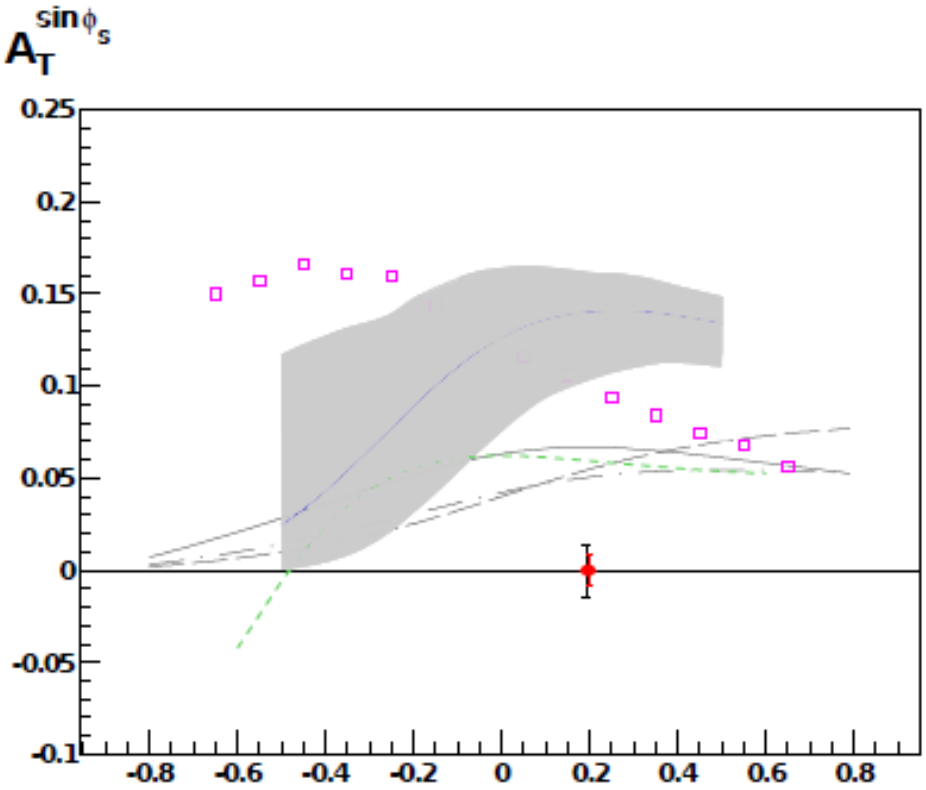
x_p



x_π



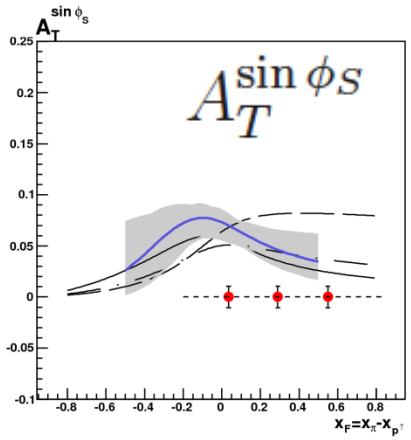
x_F

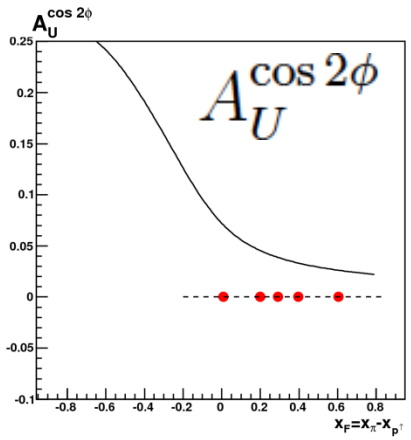


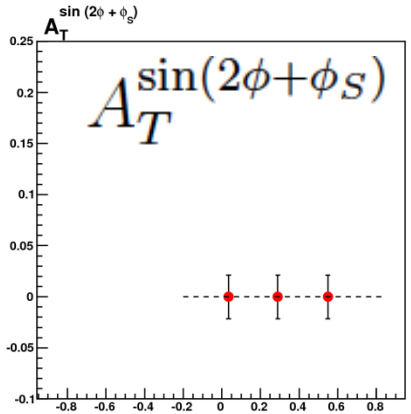
$x_F = x_\pi - x_p$

More projections

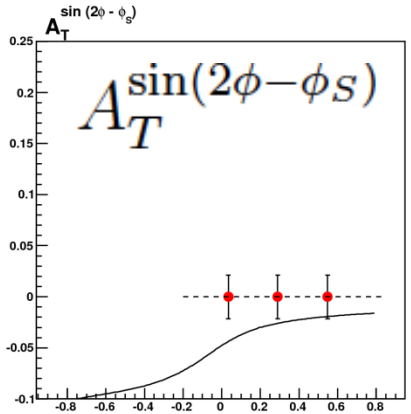
$2.0 \leq M_{\mu\mu} \leq 2.5\ \mathrm{GeV}/c^2$





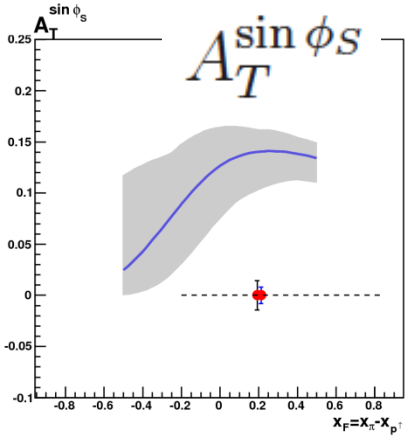


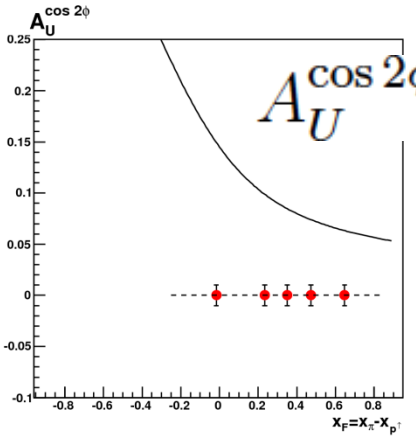
$x_F=x_\pi-x_{p\Uparrow}$

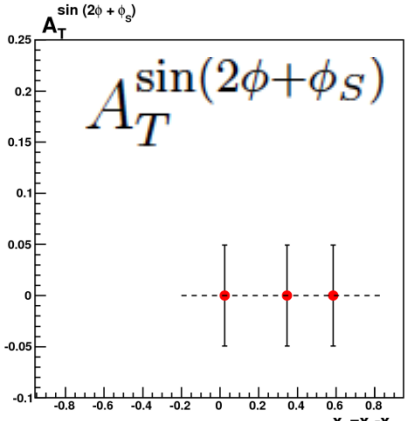


$x_F=x_\pi-x_{p\Uparrow}$

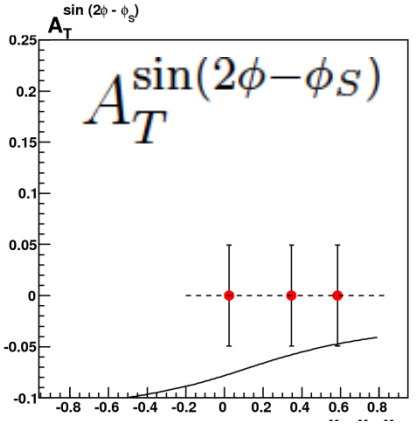
$4. \leq M_{\mu\mu} \leq 9.\ \mathrm{GeV}/c^2$







$x_F=x_\pi-x_{p\Uparrow}$



$x_F=x_\pi-x_{p\Uparrow}$

COMPASS-II schedule

2012 Primakoff scattering:	Polarizabilities of π and K
DVCS pilot run:	t-slope, transverse size
2013 Accelerator shutdown	
2014 Drell-Yan :	Universality of TMDs
2015–2016 DVCS and DVMP:	Study GPDs, "nucleon tomography"
Unpolarized SIDIS:	FF, strangeness PDF, TMDs

Caveat: CERN Accelerator schedule not fixed beyond Nov 2012

Summary

- Wealth of data from COMPASS, more to come, e.g
  - COMPASS: 2010 p transverse, 2011 p longitudinal
  - Single hadron production asymmetries (ΔG)
  - Hadron spectroscopy
- Focus shifting to 3D structure of the nucleon
- COMPASS II will make major contributions
- Exciting times ahead (also off-LHC)

(Nucleon) Spin is fun