COMPASS

experiment NA58

The COMPASS experiment at CERN

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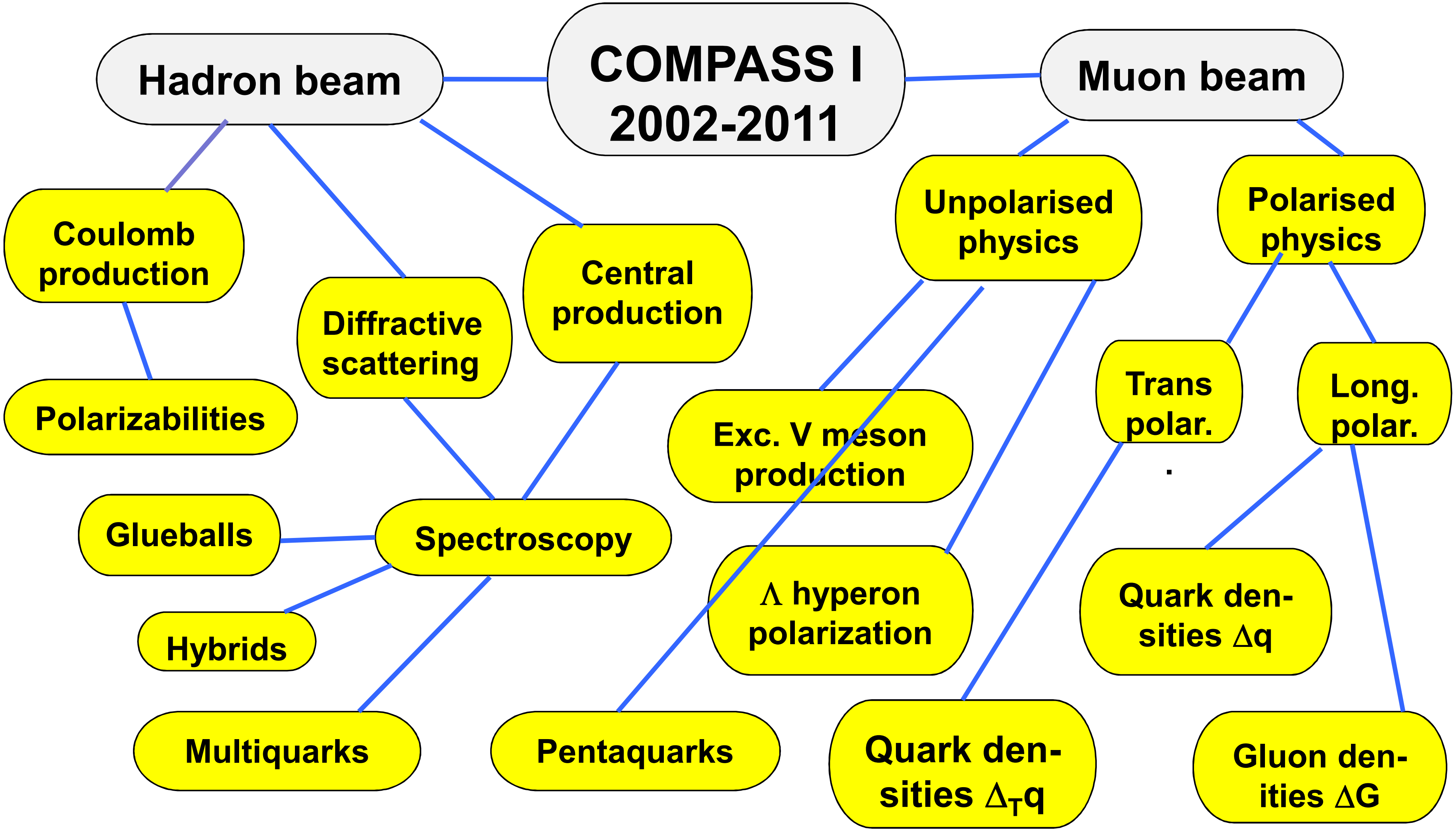
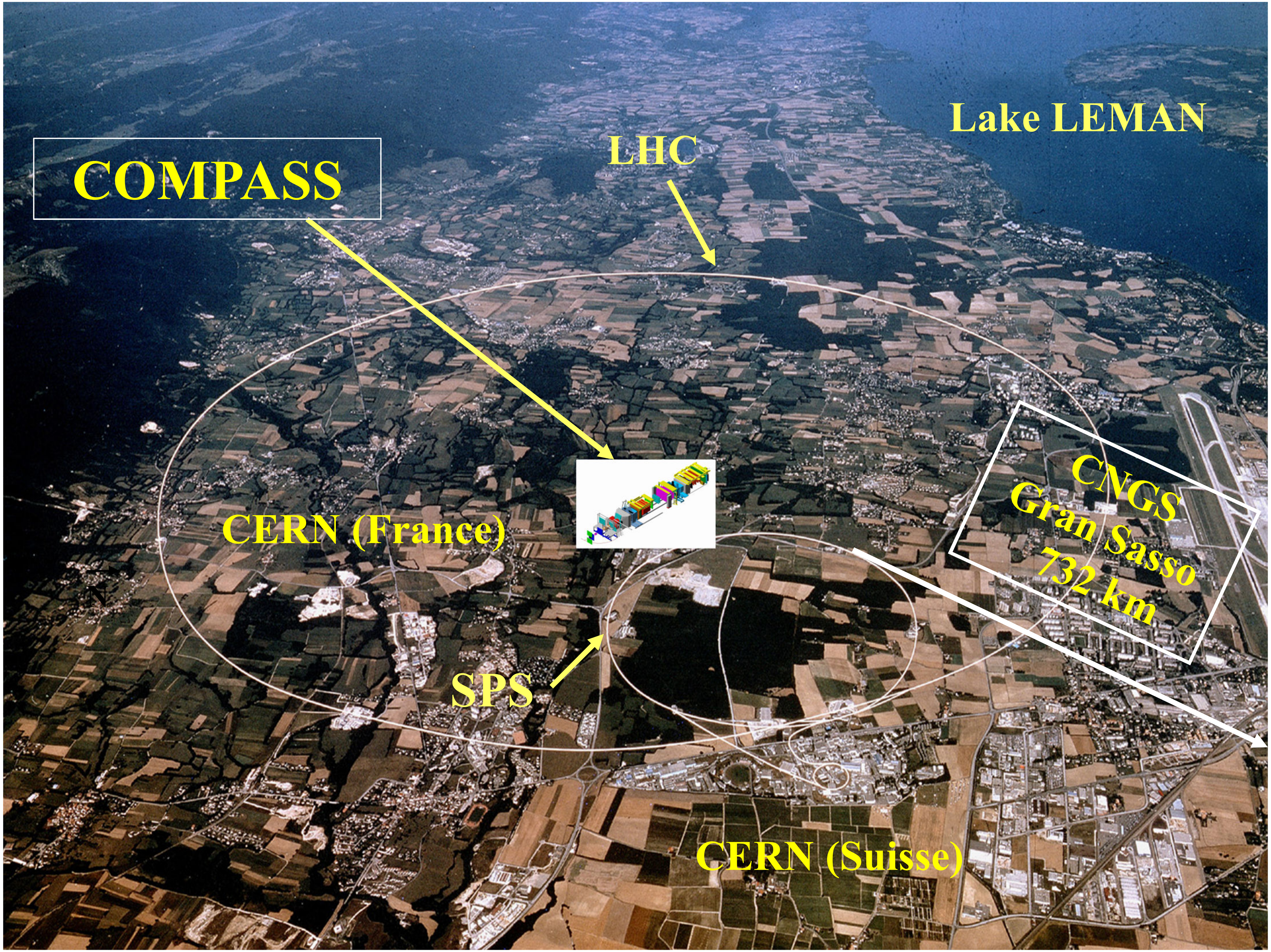
On behalf of the COMPASS Collaboration

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

~230 physicists
11 counties 20 Institutes



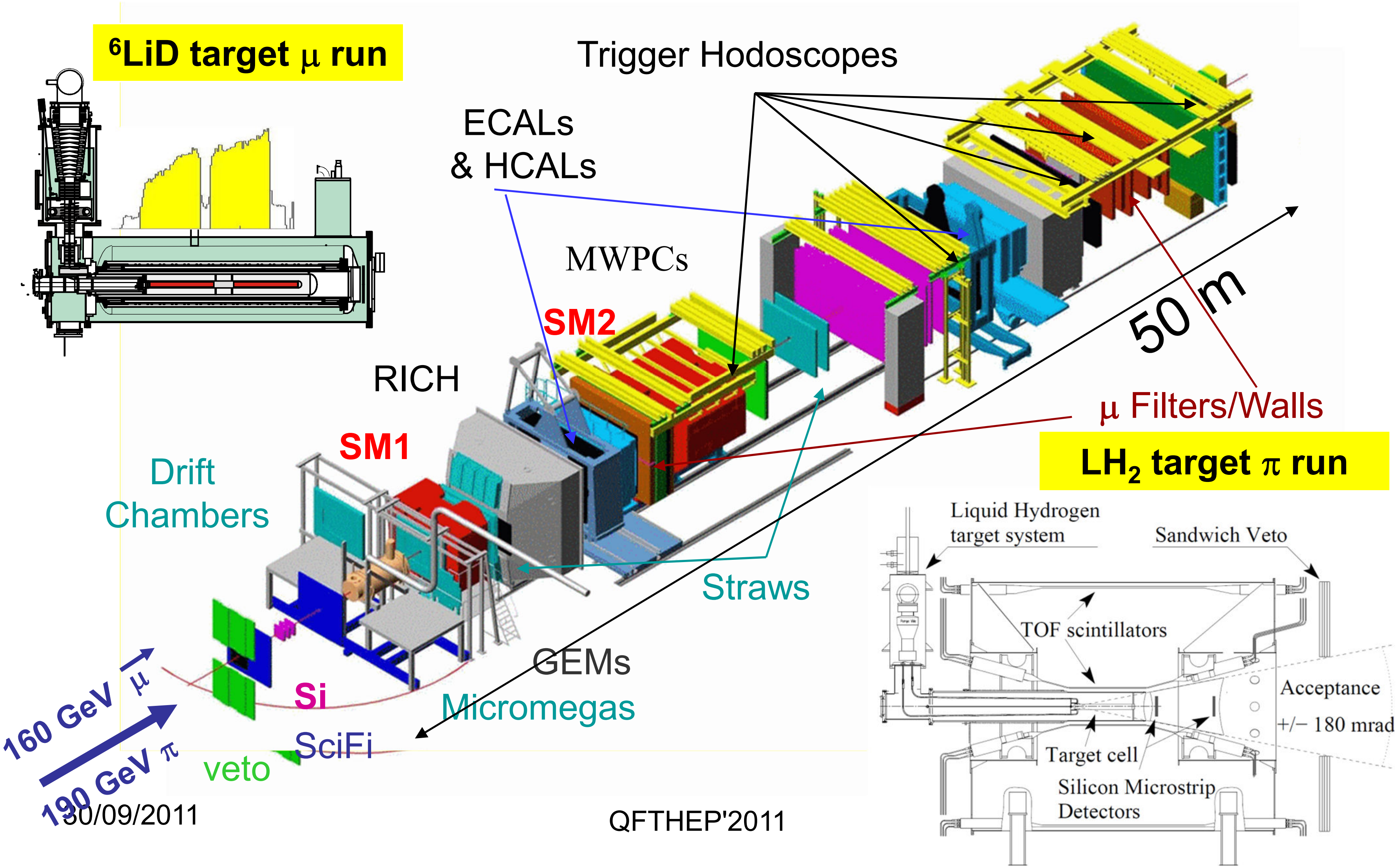


Lake LEMAN
LHC
COMPASS
CERN (France)
CNGS
Gran Sasso
732 km
SPS
CERN (Suisse)

TWO STAGE SPECTROMETER

COMPASS in μ run

NIM A 577(2007) 455



Outline

Data taken

2002-2004:160 GeV μ on ^{6}LiD **L,T**
2006 :160 GeV μ on ^{6}LiD **L**
2007 :160 GeV μ on NH_3 **T**

2010 :160 GeV μ on NH_3 **T**
2011 :200 GeV μ on NH_3 **L**

Part I: nucleon spin structure

1. **Longitudinal polarisation:** quark and gluon helicities
2. **Transverse polarisation:** Collins, Sivers asymmetries

2004 190 GeV π^-, μ on Pb (2 weeks)

2008 190 GeV π^- on LH_2
2009 190 GeV p,π^+ on LH_2, Pb, Ni, W

Part II: hadron reactions

1. **Diffractive** dissociation

2-3. Central and Coulomb productions

2112, SPS/LHC shutdown, 2014, 2015, 2016

Part III: COMPASS-II proposal

1-3. Primakoff / DVCS / Drell-Yan

Part I: nucleon spin structure

	1970	1980	1990	2000
SLAC	E80	E130	E142/3 E154/5	
CERN		EMC	SMC	COMPASS I
DESY			HERMES	
JLab				CLAS/HALL-A
RHIC				Phenix/Star

- A worldwide effort since decades

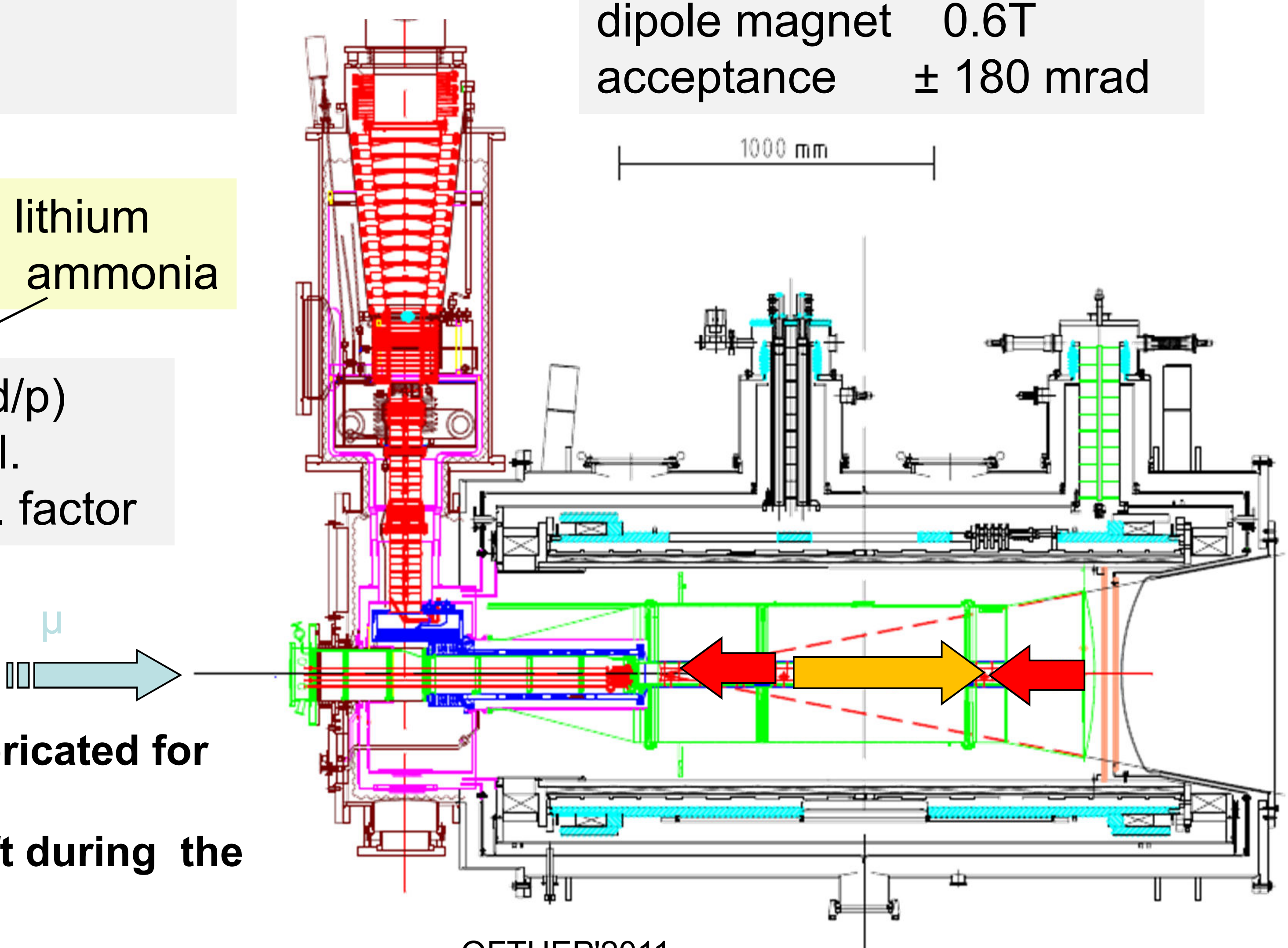
Key apparatus: polarised target

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

solenoid 2.5T
dipole magnet 0.6T
acceptance ± 180 mrad

Deuterated lithium
ammonia

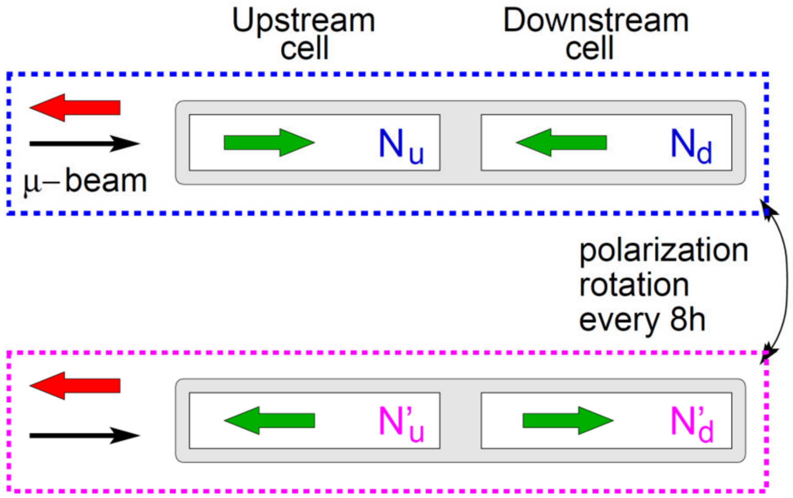
^{6}LiD/NH$_3$ (d/p)
50/90% pol.
40/16% dil. factor



biggest /fabricated for SMC coll.
Special shift during the data taking

Measurement of asymmetry

$$A_{\|} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$$



- **flux normalization:**

$$A_{\mathrm{exp}} = \frac{N_u - N_d}{N_u + N_d}$$

- **acceptance difference:**
  Polarisation rotation

- **take average asymmetry:**

$$\Rightarrow A_{\mathrm{exp}} = \frac{A + A'}{2} = \frac{1}{2}\left(\frac{N_u - N_d}{N_u + N_d} + \frac{N'_d - N'_u}{N'_u + N'_d}\right)$$

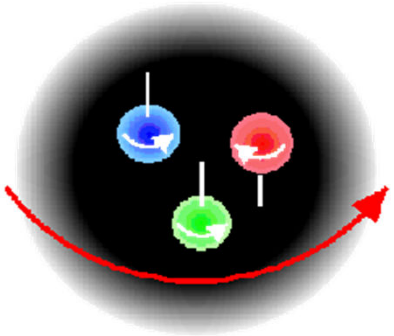
$\Rightarrow$ minimization of bias

- **experimental asymmetry**

$$A_{\mathrm{exp}} = p_\mu \; p_{\mathrm{T}} \; f \; A_{\|}$$

p_μ, p_{T} beam and target polarisation
f dilution factor

Nucleon spin puzzle since 1988



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

quarks — "past"

gluons — "present"

orb. mom. — "future"

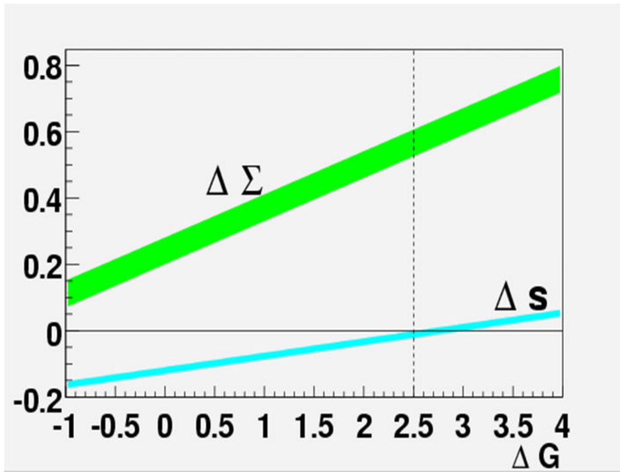
experiments

Measurement of ΔG is important for two reasons:

- as an element of nucleon spin puzzle

- possible role of axial anomaly in the a_0 interpretation ($a_0 \neq \Delta\Sigma$)

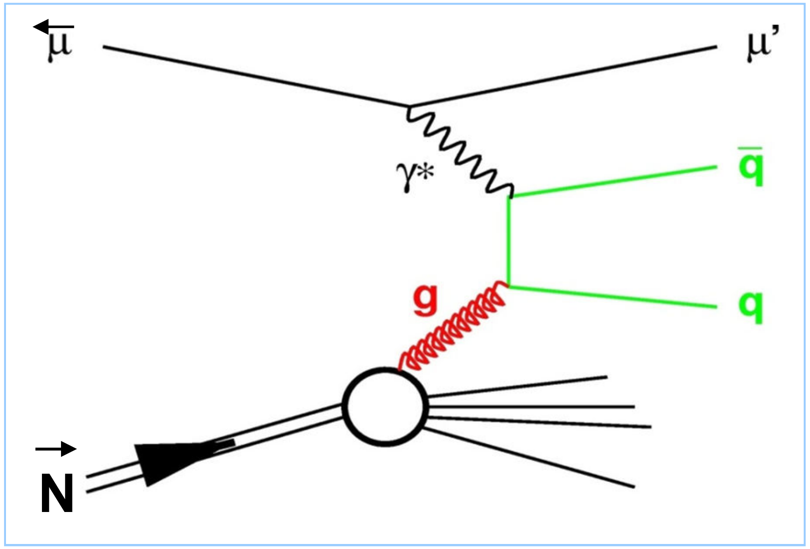
a_0 ($= \Delta\Sigma$) is measured to be ~0.30-0.35 instead of expected 0.6



$$a_0 = \Delta\Sigma - \frac{3\alpha_s}{2\pi}\Delta G$$

$\Delta G/G$ from μ N scattering

Photon Gluon Fusion (PGF)



$A_{]]} = R_{PGF} \langle a_{LL} \rangle \langle \Delta G/G \rangle + A_{bkg}$

Spin asymmetry of cross sections for longitudinal polarizations of beam and target, parallel and antiparallel

Open Charm

$$\gamma^{*} g \rightarrow c\bar{c} \rightarrow D^{0} X$$

→ clean channel

→ but experimentally difficult

$\sigma \approx 100$ nb… limited statistics

High-pT Hadron Pairs

$$\gamma^{*} g \rightarrow q\bar{q} \rightarrow h\bar{h}$$

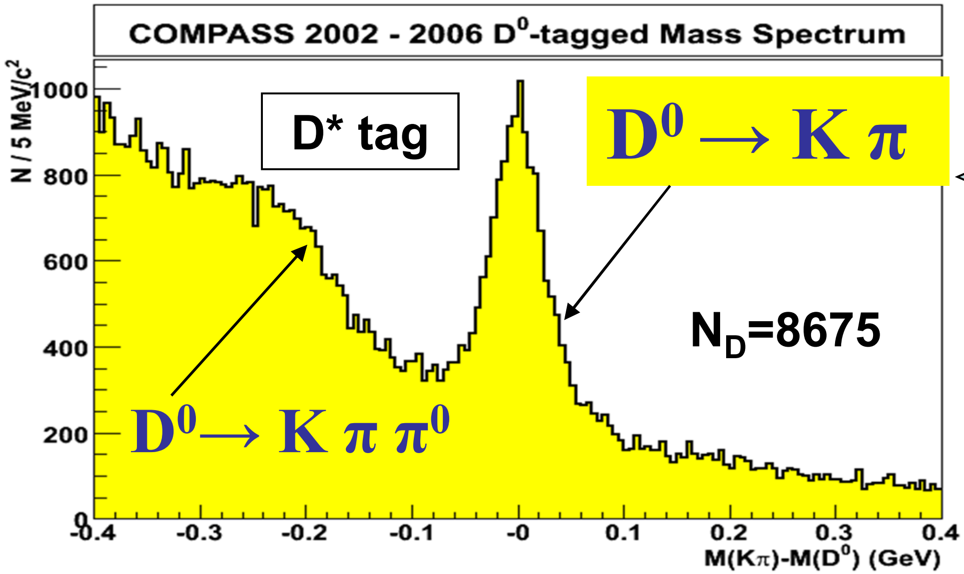
→ easy to get a statistics

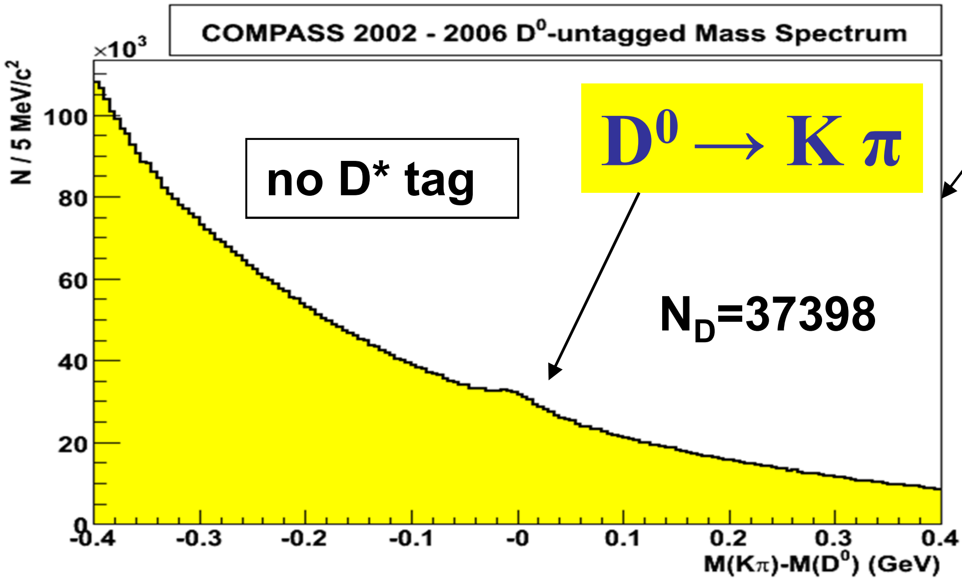
→ but physical background

2 cases $Q^2 < 1$ GeV^2 (90% stat)

& $Q^2 > 1$ GeV^2 (10% stat)

Open charm





$$D^{*+} \rightarrow D^0 \pi^+_{soft}$$

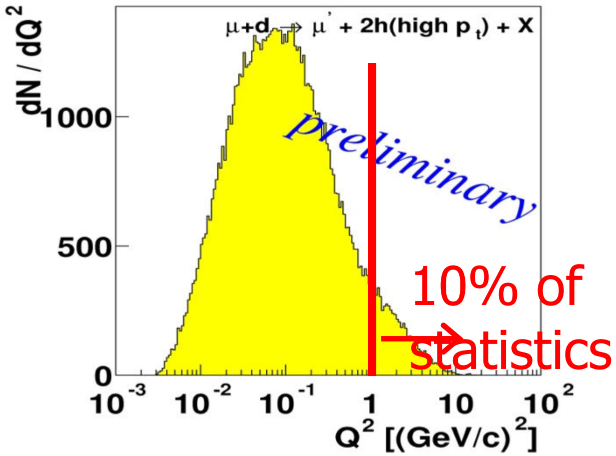
BR $\approx$ 68%

$$D^0 \rightarrow K^- \pi^+$$

BR $\approx$ 4%

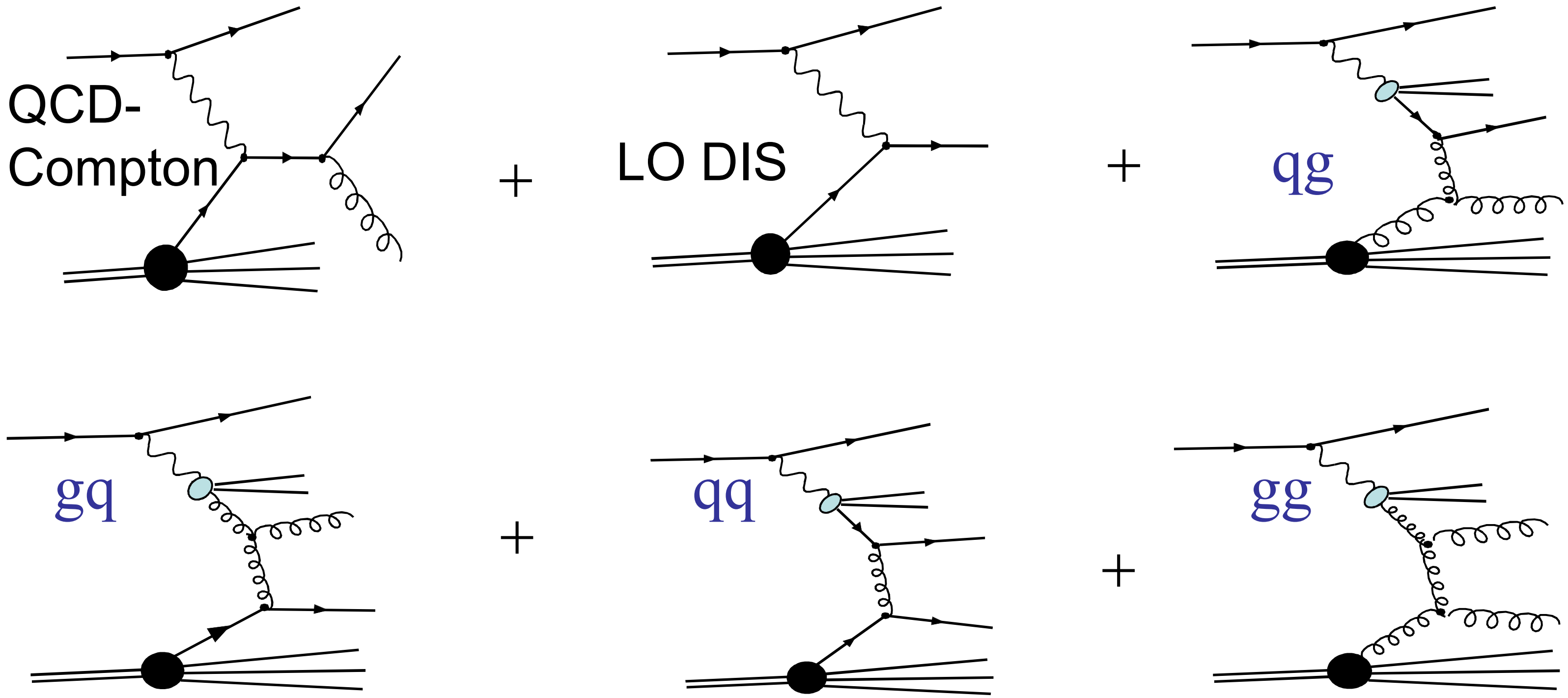
only

- golden channel, weak MC dependence
- small statistics, no vertex detector → no primary/secondary vertex separation

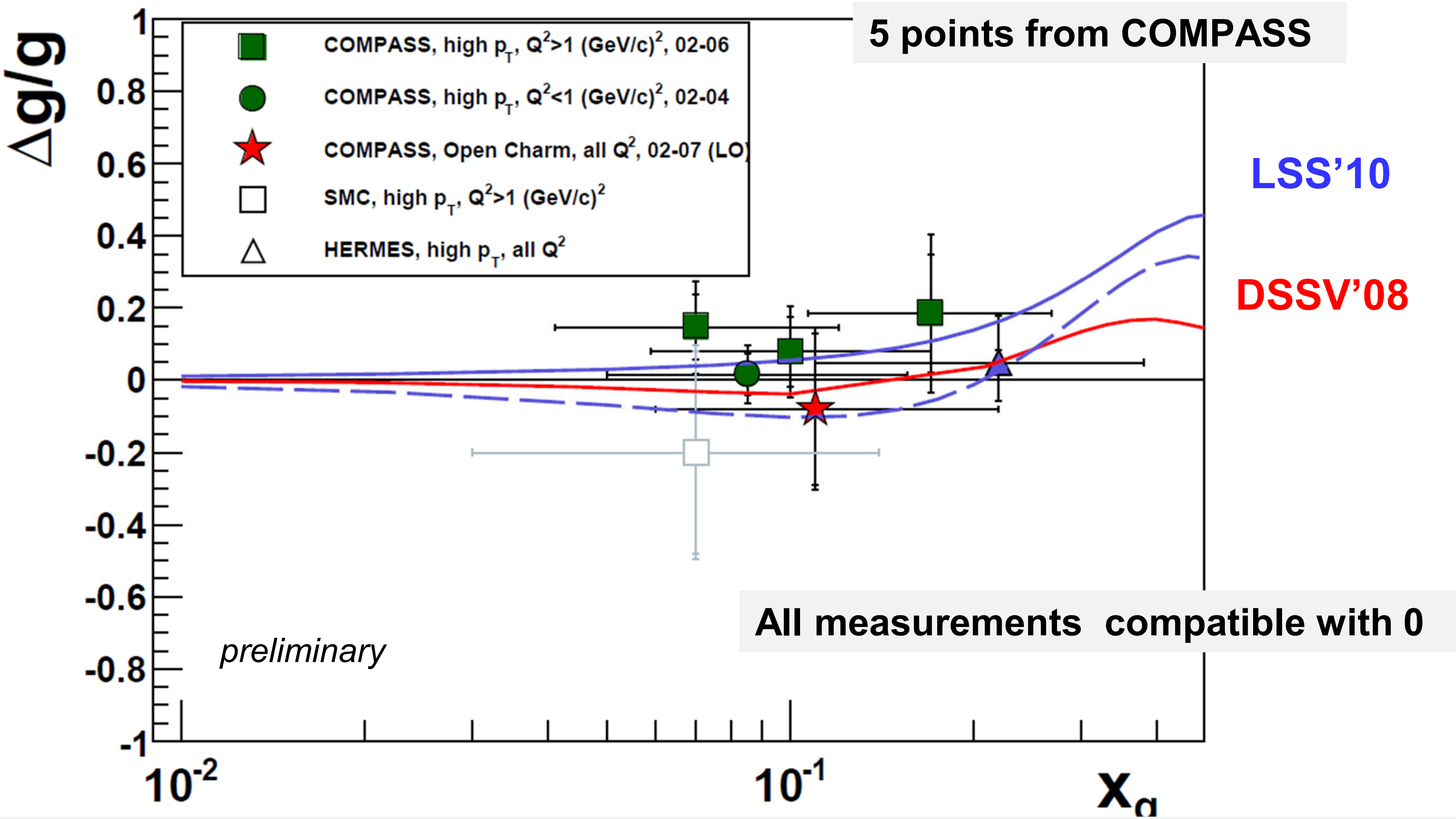


high p_T hadron pairs

- considerably higher statistics … but physical background, resolved photons processes (last 4) are important only for low Q^2



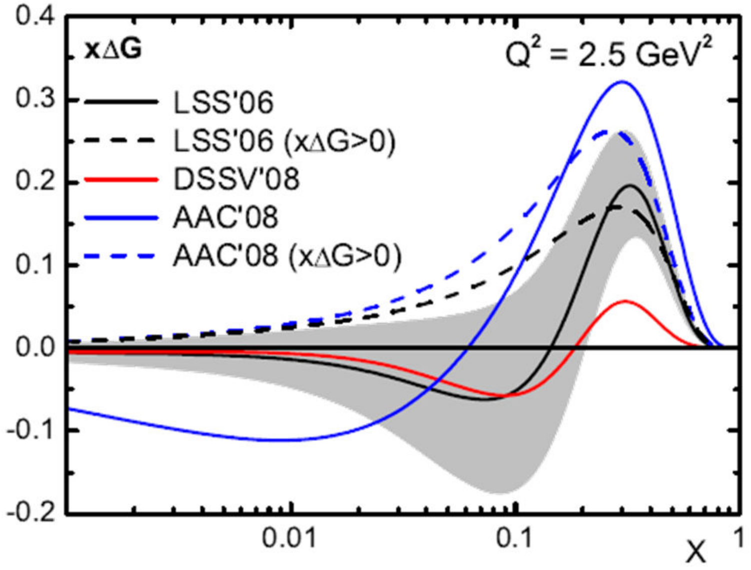
World direct measurements on ΔG/G in LO



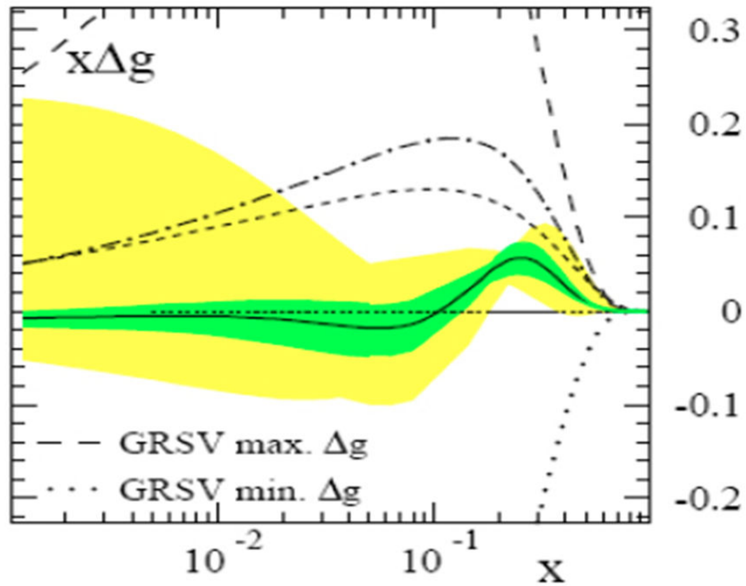
QCD fits → $|\Delta G| \approx 0.2-0.3$ as direct measurements point to a small value of ΔG ….. axial anomaly contribution is small → $a_0 \approx \Delta\Sigma$

Accessing ΔG: QCD fits to world data (DIS, SIDIS)

From Leader, Spin-2008



From DSSV, PRL 101, 2008



LSS-06 : Phys. Rev. D73, 2006 AAC'06 : Phys. Rev. D74, 2006 DSSV-08: Phys. Rev. Lett. 101, 2008

ΔG(x) may be: positive, negative, or sign-changing!

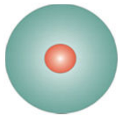
QCD analysis shows the first moment of **|ΔG|** ≈ 0.2-0.3;

ΔG~ 2.5 is needed to restore ΔΣ~0.6.

Semi-inclusive asymmetries and flavor separation

three distribution functions are necessary to describe the spin structure of the nucleon at LO in the collinear case

$q(x)$

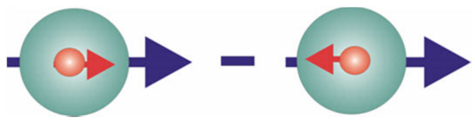


quark distribution

in unpolarized DIS

$l\,N \to l'\,X$

$\Delta q(x)$

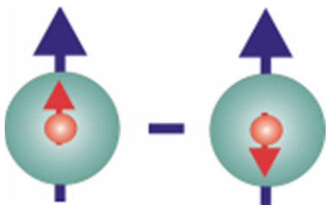


helicity distribution

in polarized DIS

$\vec{l}\,\vec{N} \to l'\,X$

$\Delta_T q(x) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$

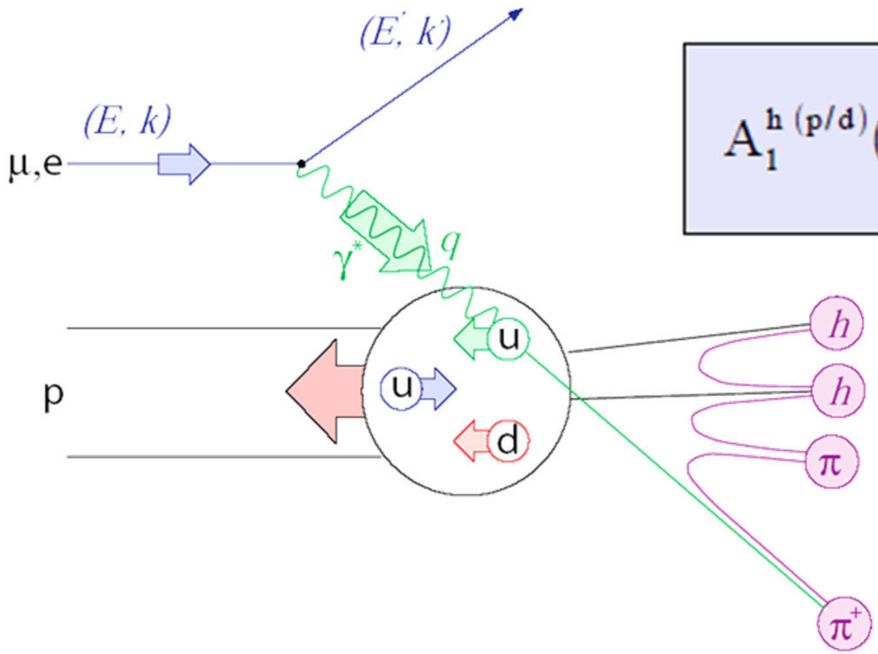


transversity distribution

in polarized SIDIS

$l\,N^{\uparrow} \to l'\,h\,X$	**Collins FF**
$l\,N^{\uparrow} \to l'\,h\,h\,X$	**Interference FF**
$l\,N^{\uparrow} \to l'\,\Lambda\,X$	**FF of $q^{\uparrow} \to \Lambda^{\uparrow}$**

Extraction of the quark helicity distributions from SIDIS

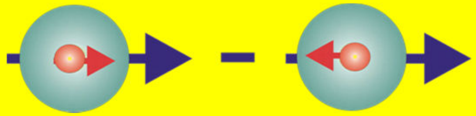


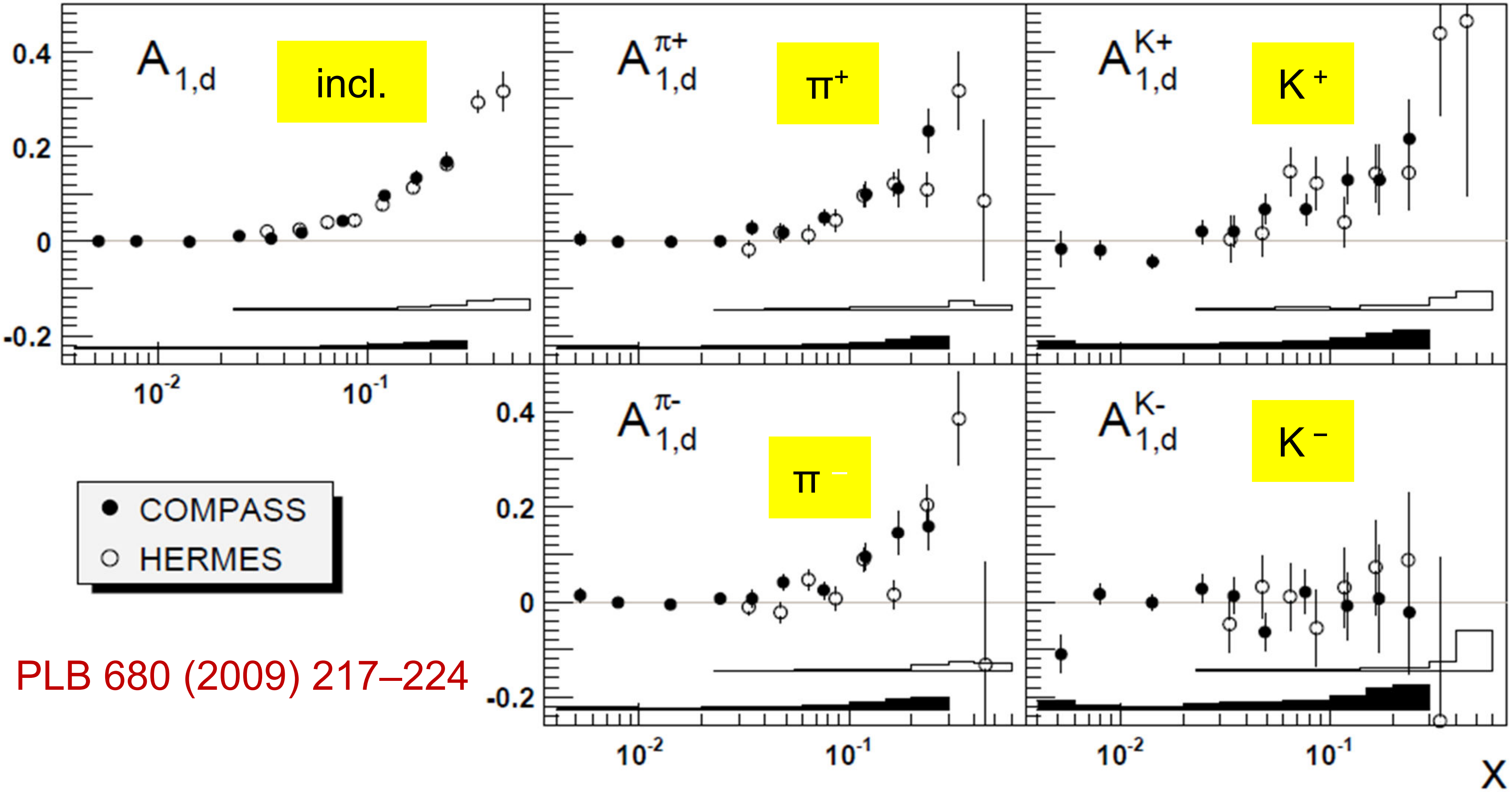
$$A_1^{h\,(p/d)}(x,z,Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}$$

the outgoing hadron tags
the quark flavor

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

Deuteron A_1 asymmetries





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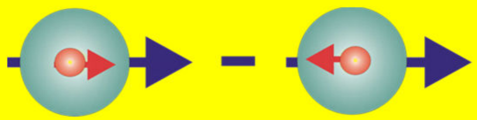
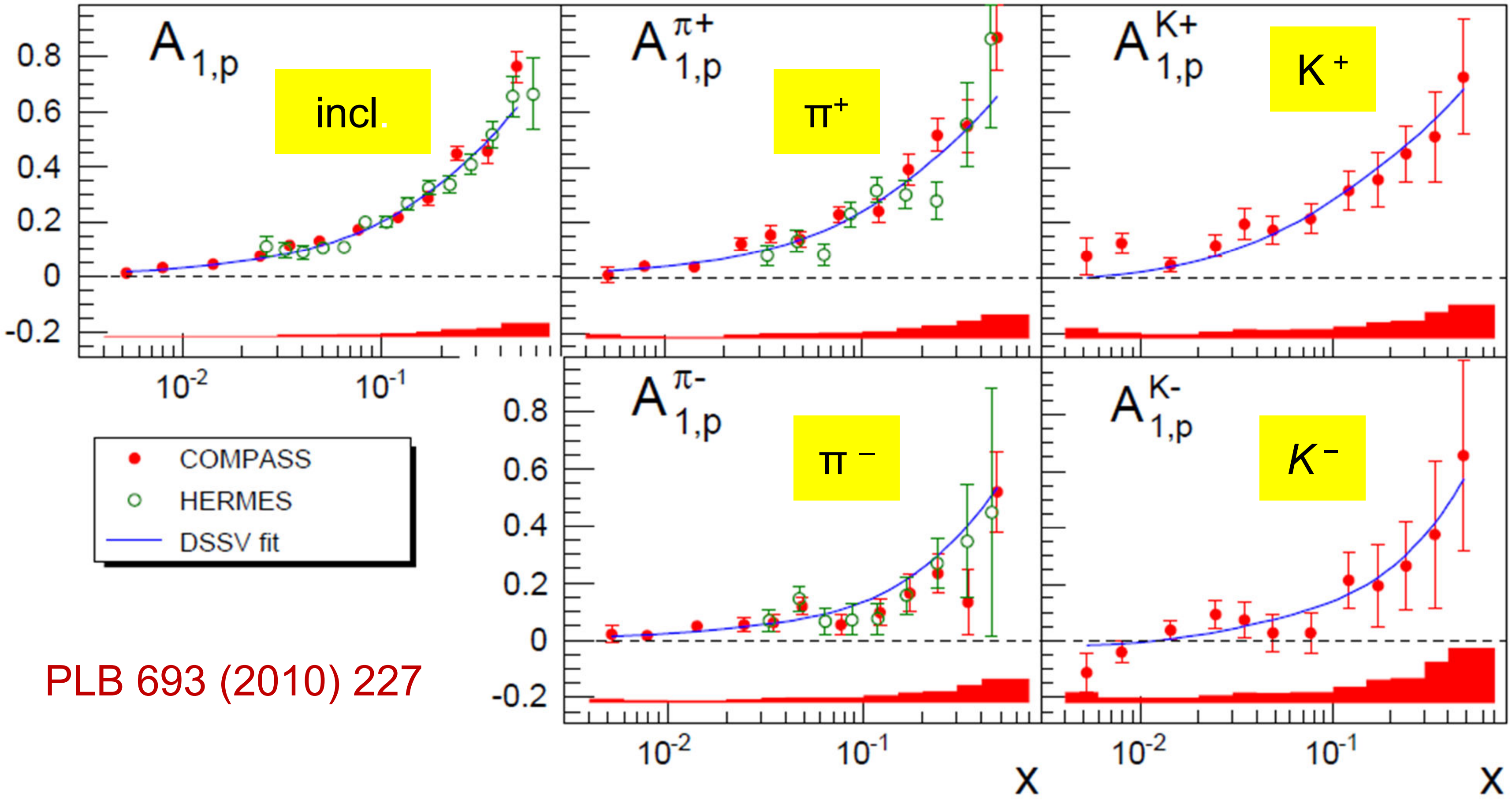
Both pions and kaons are identified

Determine 3 flavor non separated PDFs $\Delta u + \Delta d$, $\Delta\bar{u} + \Delta\bar{d}$ and $\Delta s = \Delta\bar{s}$

Proton A_1 asymmetries





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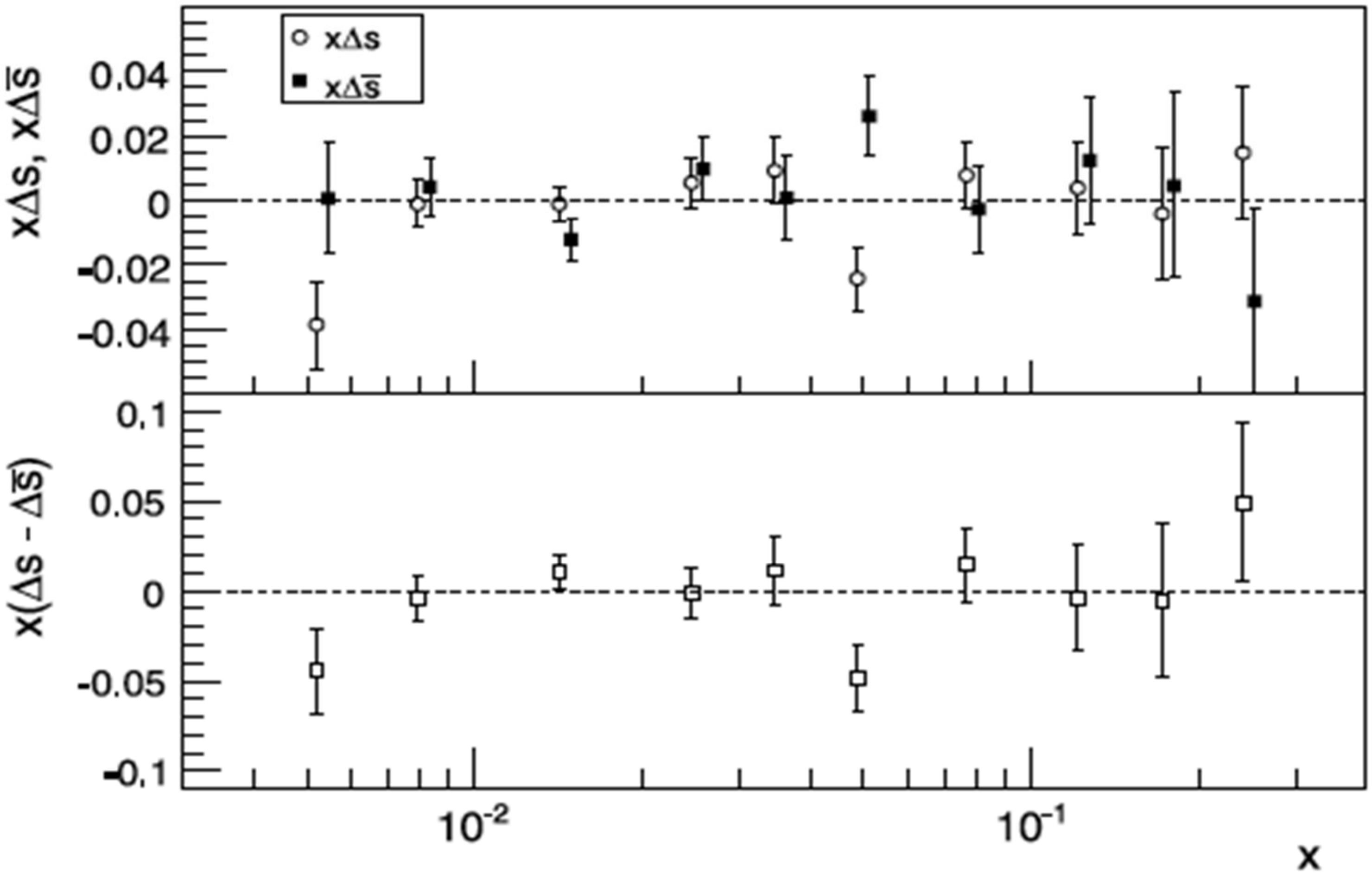
Leading Order (LO) fit of the 10 asymmetries (5d+5p)

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

Check the assumption $\Delta s = \Delta\bar{s}$ (a 6 flavors fit)

COMPASS Collaboration / Physics Letters B 693 (2010) 227–235

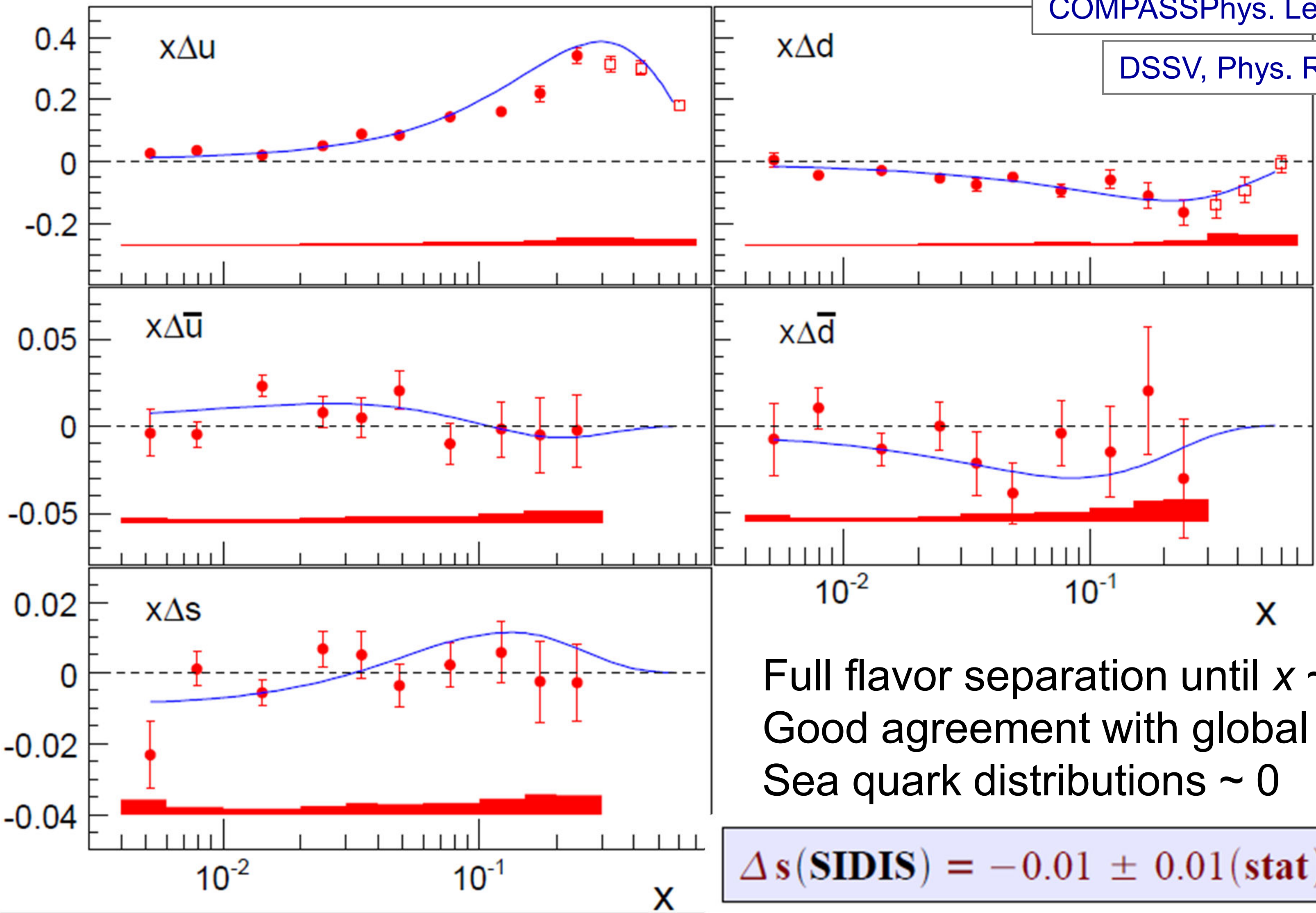


No significant difference! Go further assuming $\Delta s = \Delta s$

Quark helicities from SIDIS

COMPASSPhys. Lett. B693, 2010.

DSSV, Phys. Rev. D80, 2009



Q^2 = 3 $(GeV/c)^2$ and x < 0.3

Full flavor separation until *x* ~ 0.004
Good agreement with global fits
Sea quark distributions ~ 0

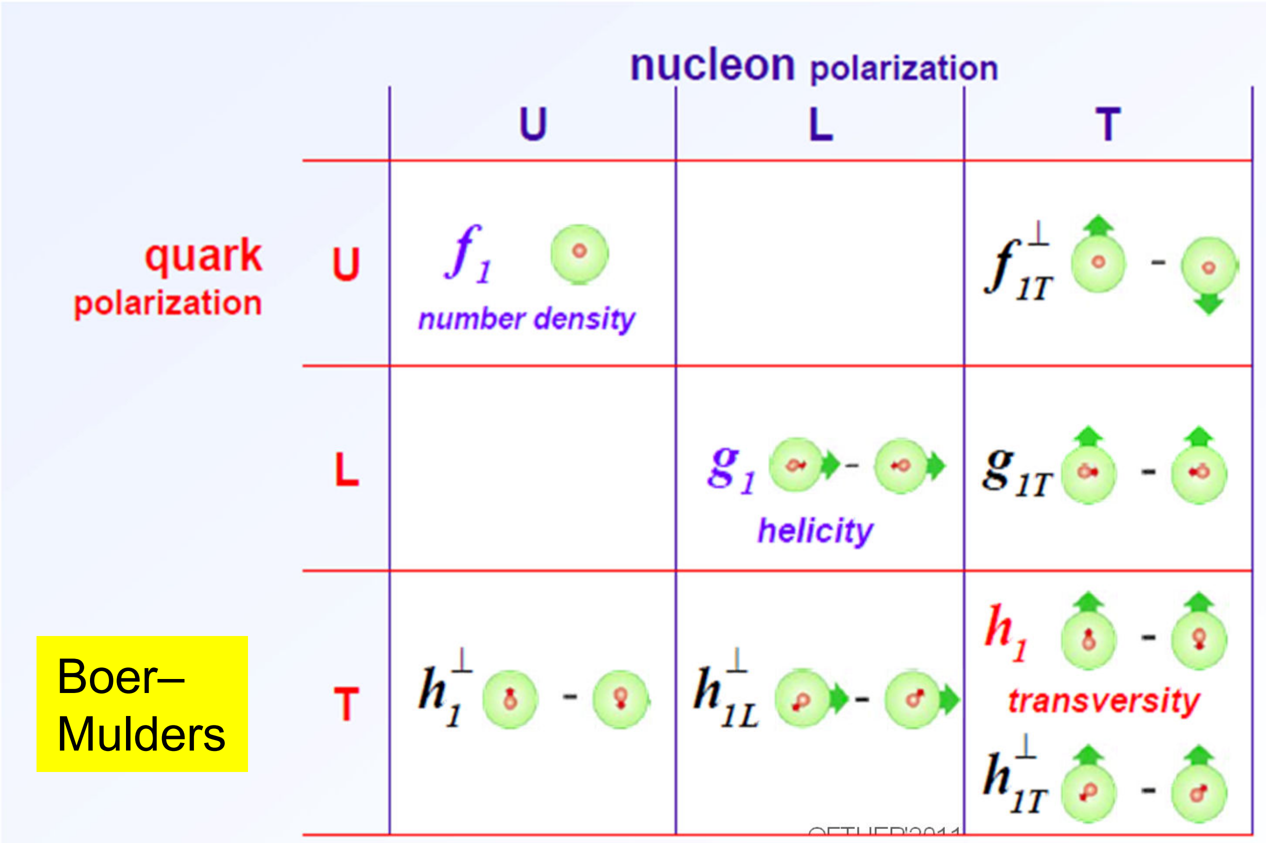
$$\Delta s(\mathbf{SIDIS}) = -0.01 \pm 0.01(\mathbf{stat}) \pm 0.01(\mathbf{syst})$$

$$0.003 < \mathbf{x} < 0.3$$

TMD parton distributions

taking into account the **quark intrinsic transverse momentum k_T** ,
at LO 8 PDFs are needed for a full description of the nucleon structure

Azimuthal asymmetries with different angular modulations in the hadron and spin azimuthal angles, Φ_h and Φ_s



Sivers $\Delta_0^T q$

Boer–Mulders

Transversity $\Delta_T q$

Pretzelosity

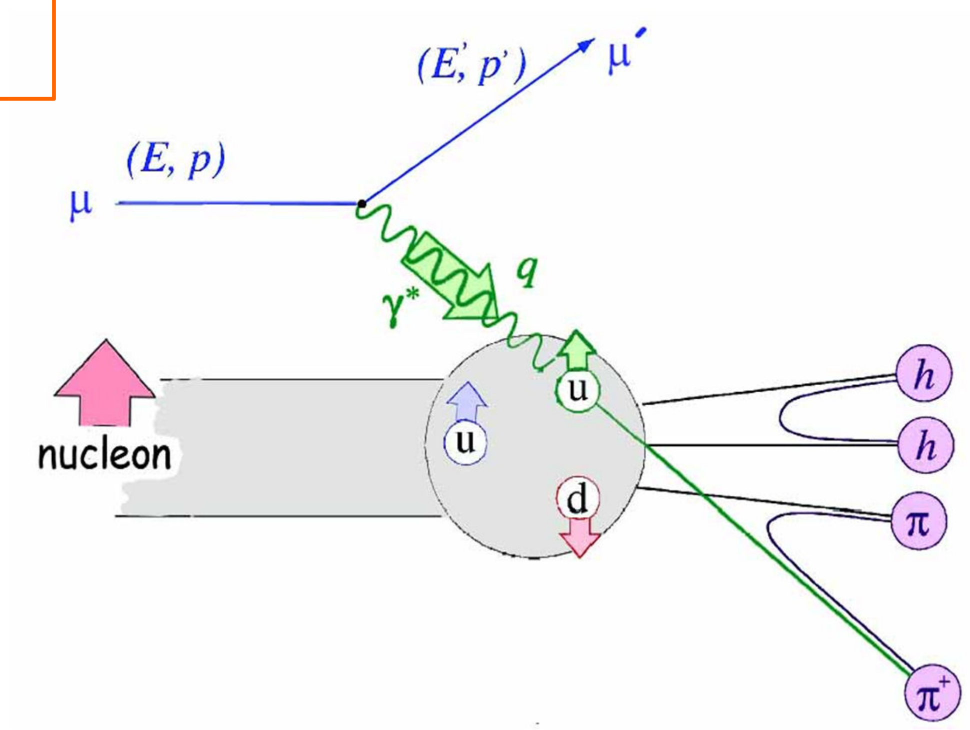
Collins and Sivers asymmetries in SIDIS

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

Measure simultaneously several azimuthal asymmetries, out of which

Collins: Outgoing hadron direction & quark transverse spin

Sivers: Nucleon spin & quark transverse momentum k_T



Collins **Sivers**

$$d\sigma_{SIDID} \propto \left[1 + a_1 \cdot \sin\phi_C + a_2 \cdot \sin\phi_S + ...\right]$$

Collins asymmetry

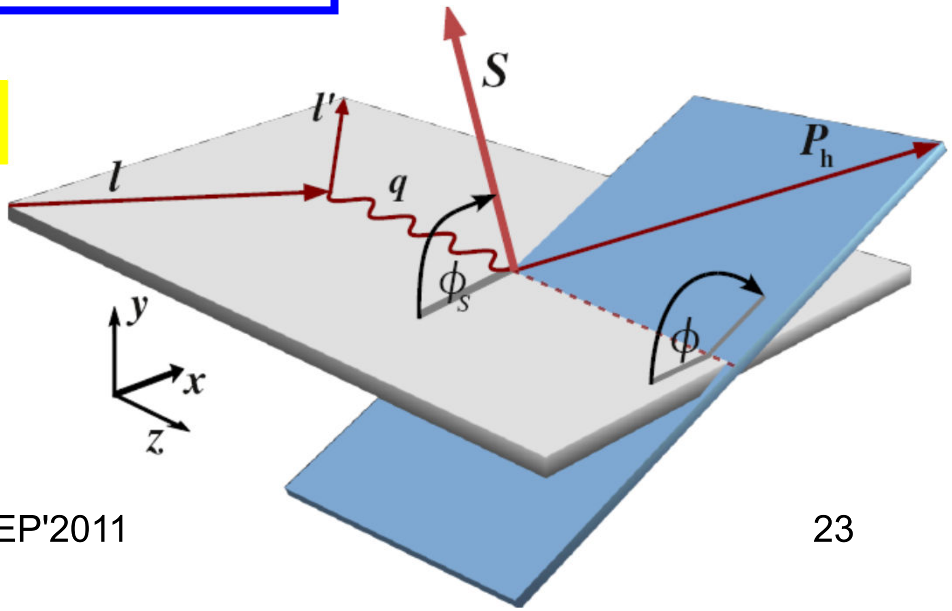
- Couple $\Delta_T q$ to chiral odd Collins FF $\Delta_T^0 D_q^h$

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

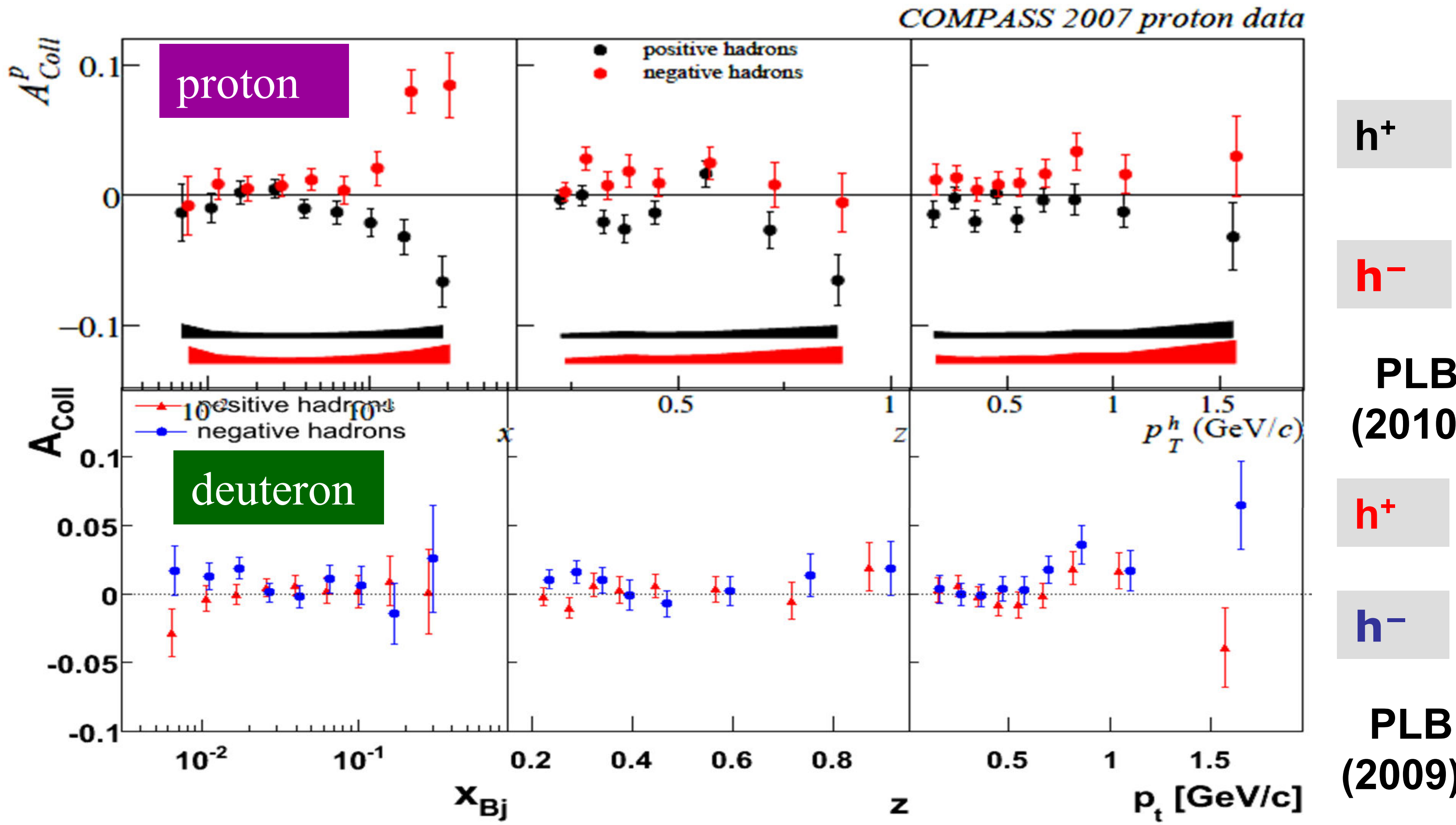
Azimuthal cross-section asymmetry:

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

$$\phi_{Coll} = \phi_h - \phi_s - \pi$$



COLLINS ASYMMETRIES for h⁺ h⁻



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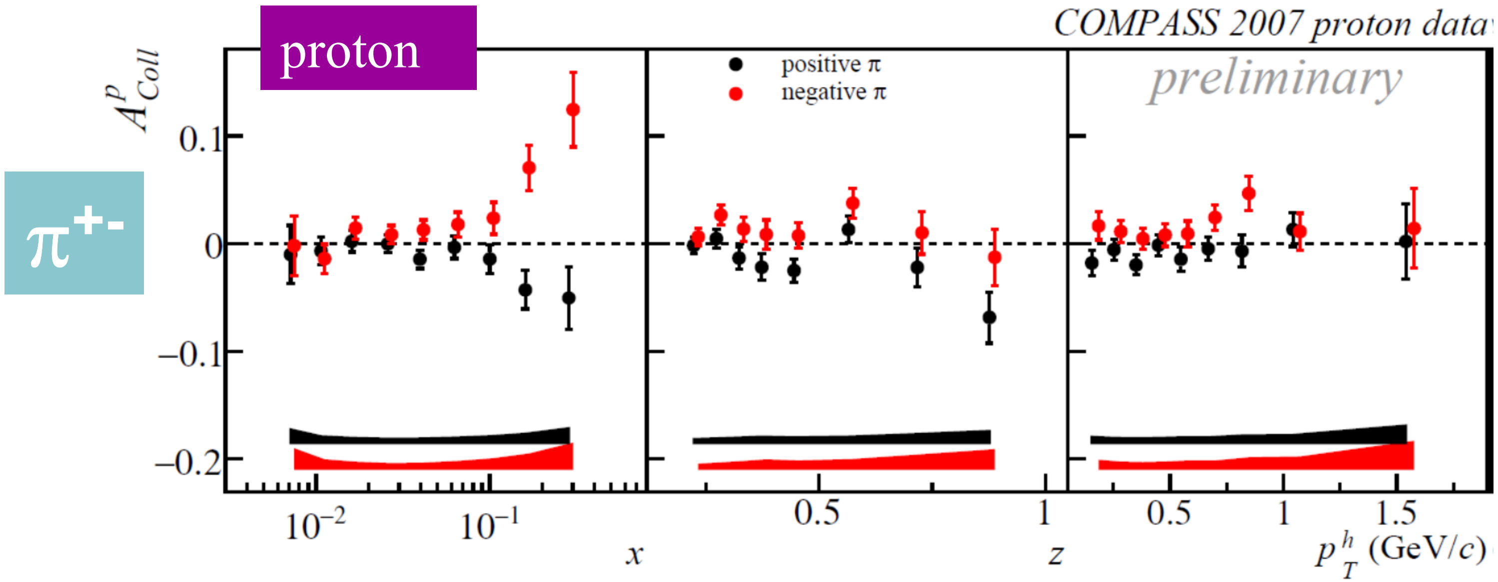
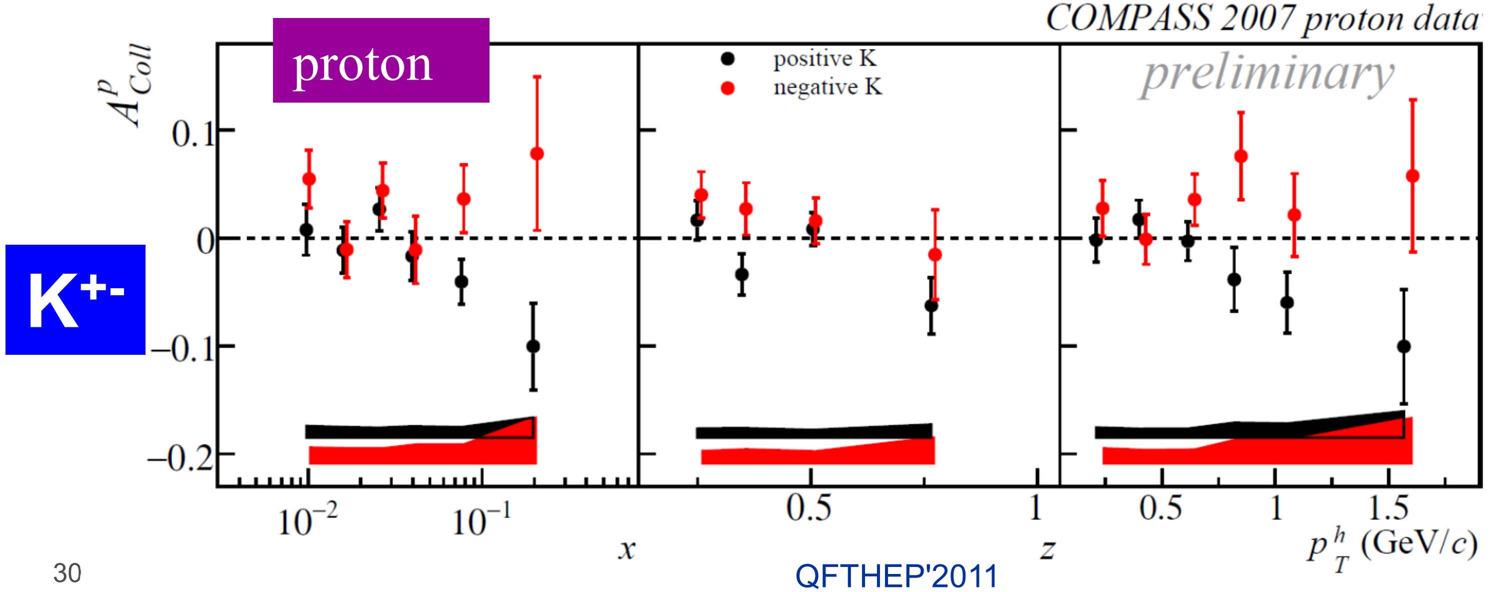
- large asymmetry for proton : about 10% , for both h^+ and h^-
- deuteron result → opposite sign of $\Delta_T u$ and $\Delta_T d$

COLLINS ASYMMETRIES for π & K



large asymmetry for π

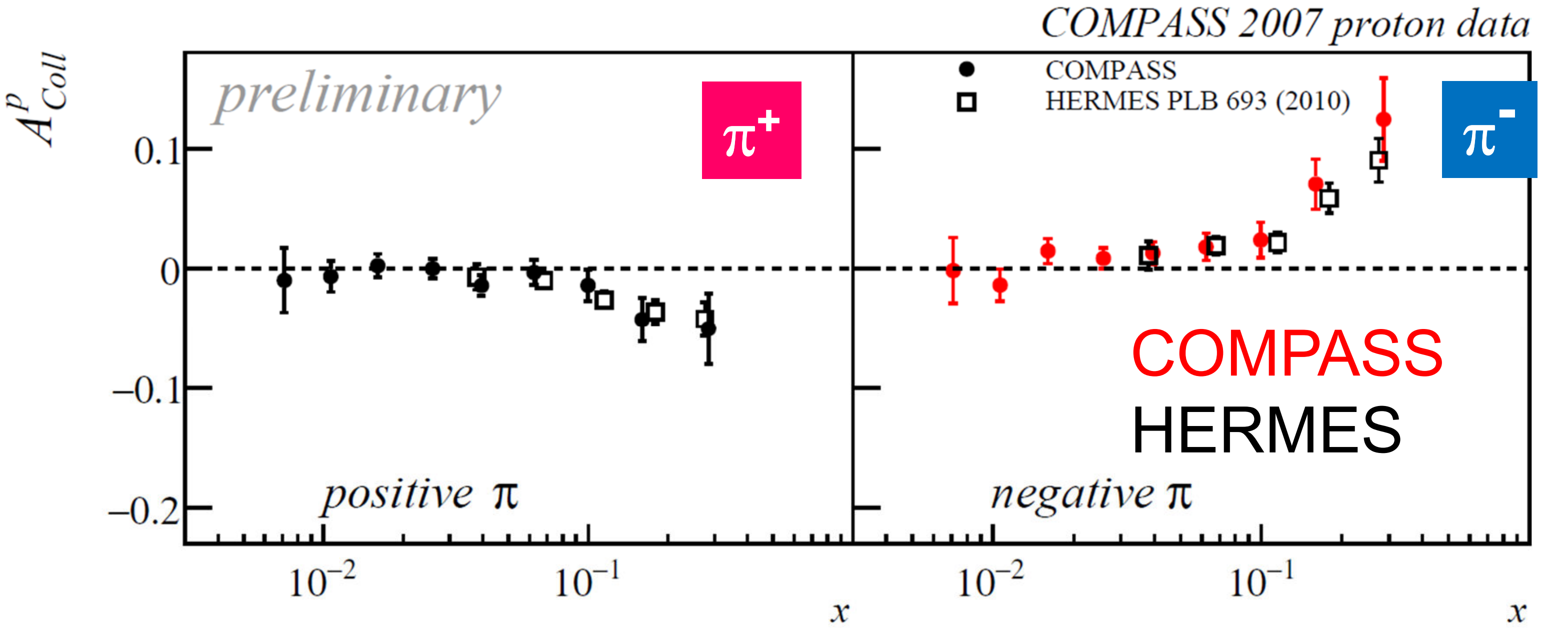


But, not clear for K

COMPASS-HERMES COMPARISON

in good agreement

proton



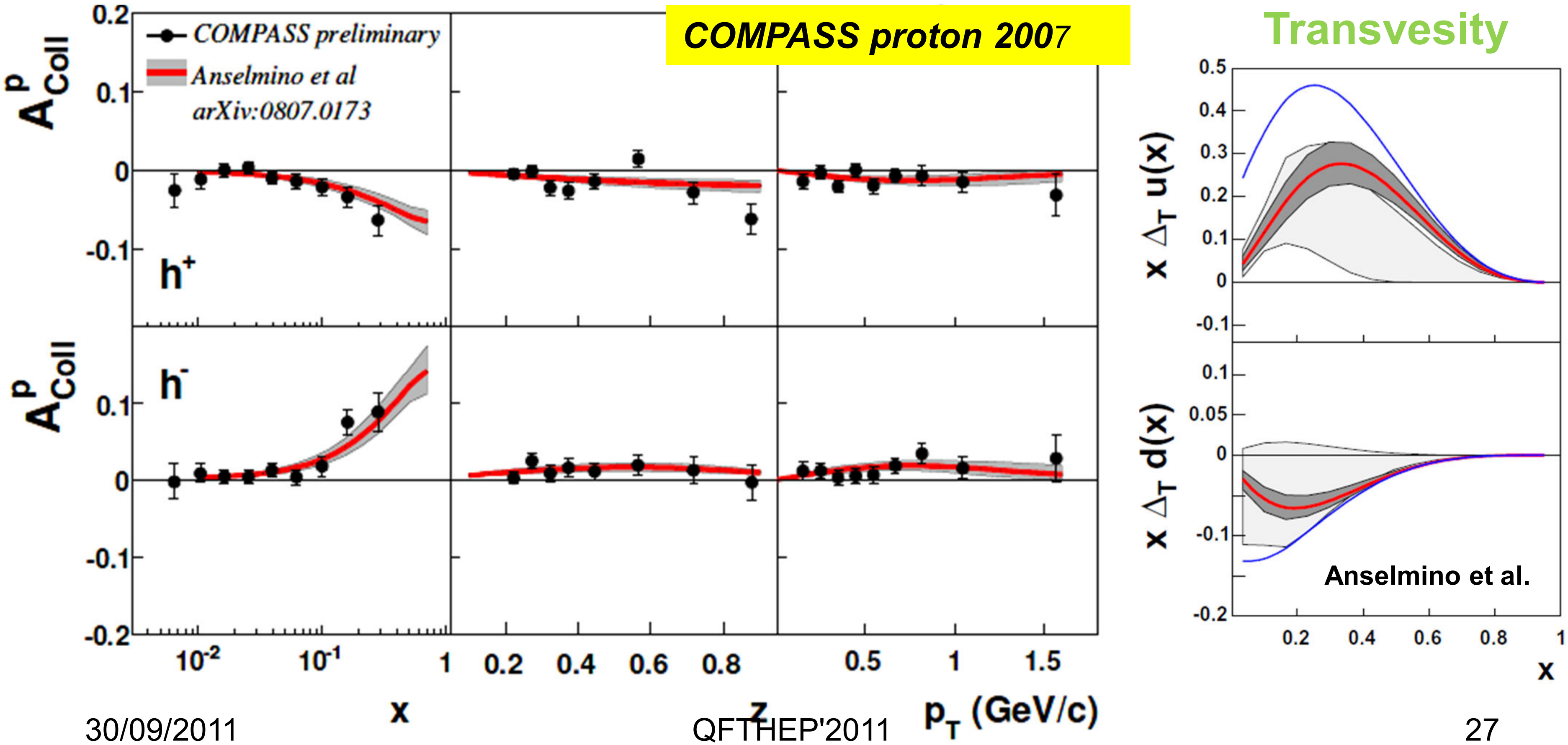
for charged pions

$$\Delta_T q \neq 0, \quad \Delta_T^0 D_q^\pi \neq 0$$

Solid evidence for: transversity PDF and Collins function to be different from zero

Transversity: global fit

- Fitting to A_{Coll}^d from COMPASS, A_{Coll}^p from HERMES and Collins F.F. from BELLE (e^+e^- scattering) → predictions
- good agreement with the new proton data of COMPASS
- $\Delta_T u$ and $\Delta_T d$ have opposite sign as expected from deuteron data



Sivers asymmetry

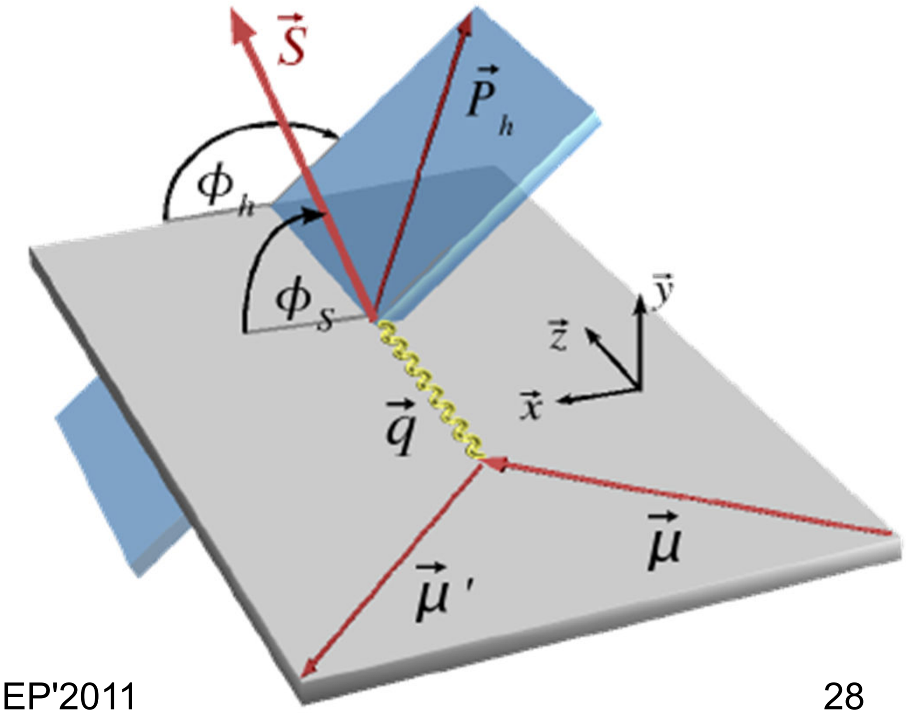
Sivers function $f_{1T}^{\perp}$

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

Azimuthal cross-section asymmetry

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

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



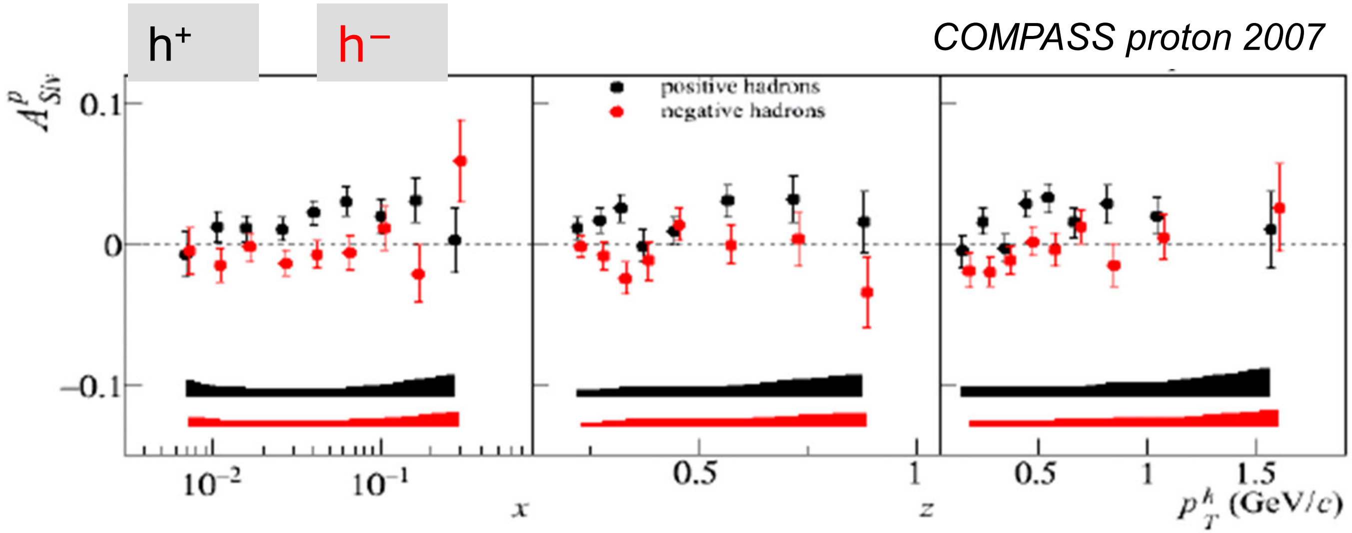
proposed (1990, Sivers)

thought to vanish (1993, Collins)

resurrected (2002, Brodsky, Hwang, Schmitt)

different sign in DY and SIDIS

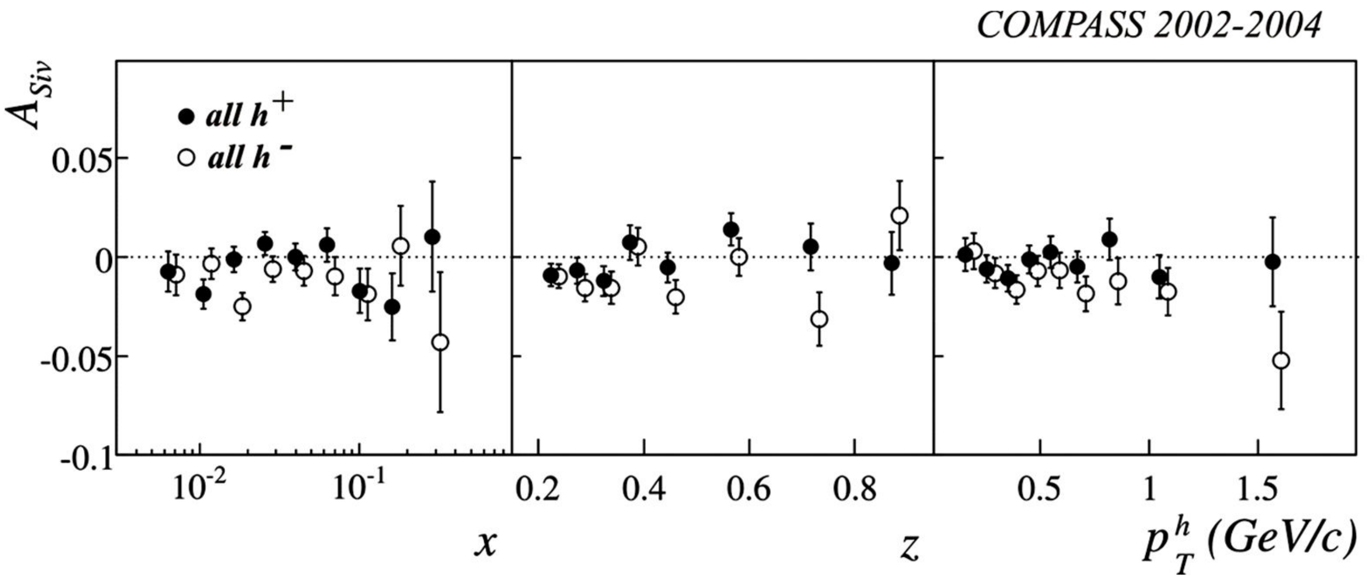
SIVERS ASYMMETRIES for h^+ h^-



Proton

slightly positive for h^+

PLB 692 (2010), 240

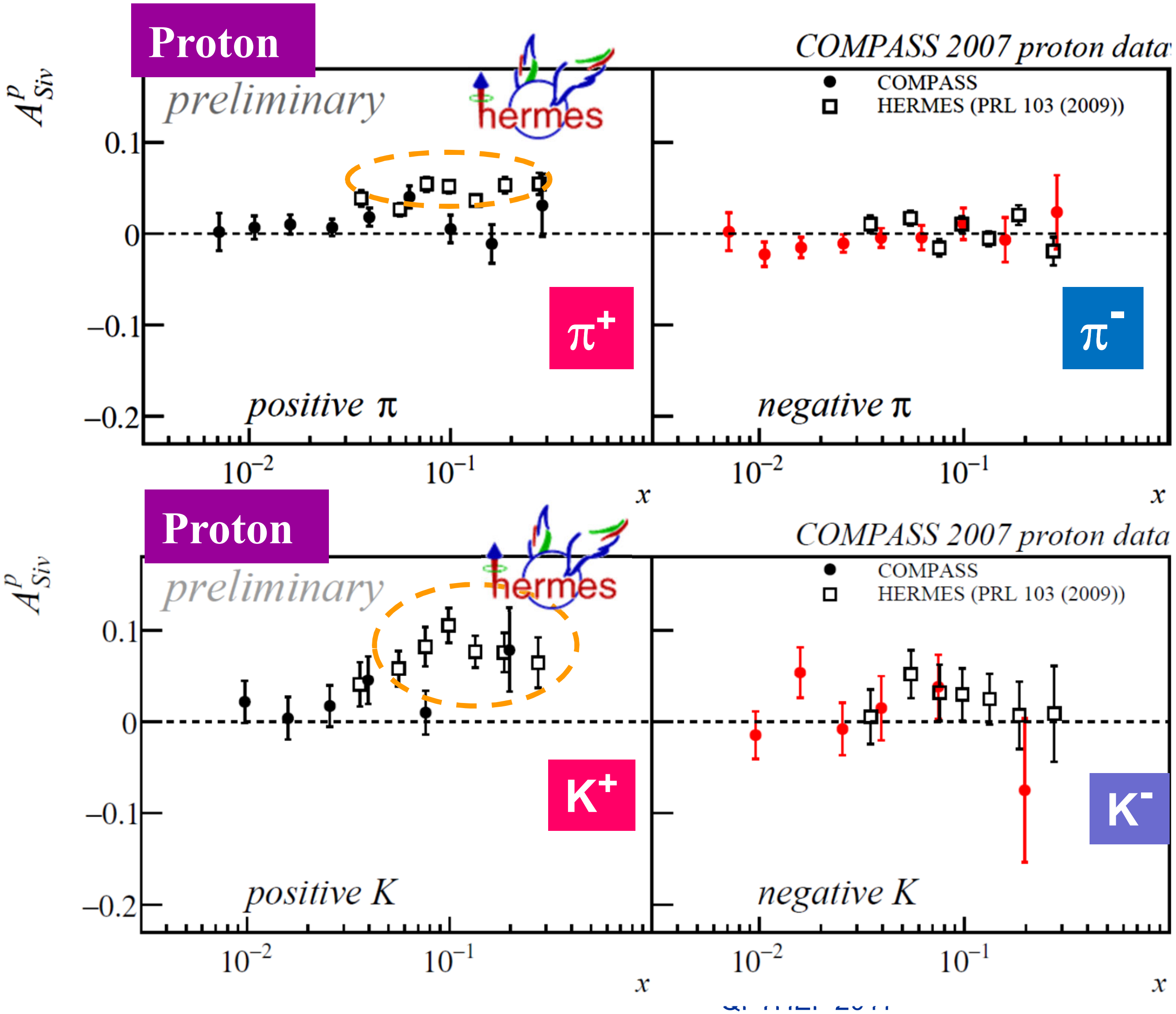


Deuteron

compatible with zero

PLB 673 (2009), 127

SIVERS ASYMMETRIES FOR π & K



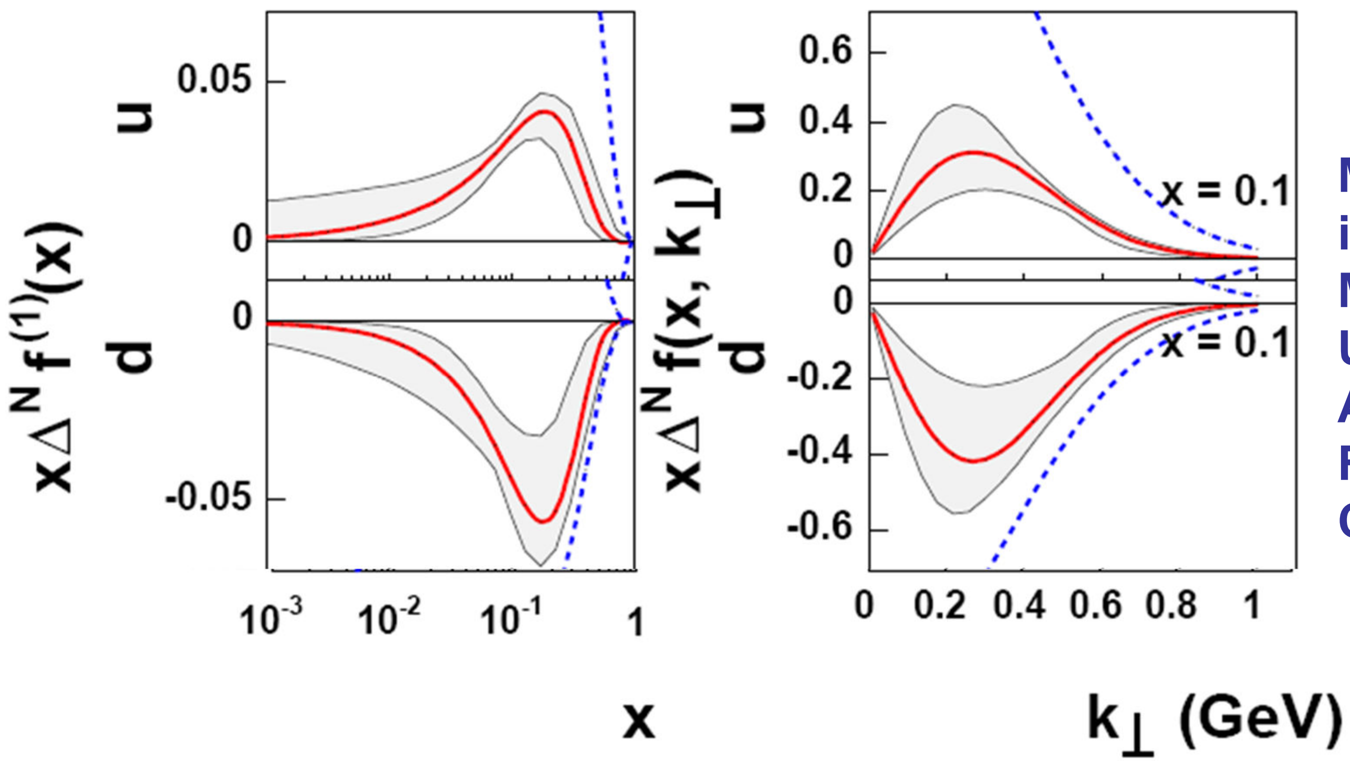
HERMES data show clear signals for π^+ & K^+

No definite conclusion with the COMPASS data due to limited statistics

More statistics with 2010 COMPASS data

SIVERS PDF GLOBAL FIT

Global fit using $A_d^{Siv}(\pi^{\pm})$ and $A_d^{Siv}(K^{\pm})$ from COMPASS and $A_p^{Siv}(\pi^{\pm})$ and $A_p^{Siv}(K^{\pm})$ from HERMES:



M. Boglione
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C. Turk

Conclusion (part I)

Direct measurements results indicate small **ΔG** around ***x* ≈ 0.1;**

QCD analysis of g_1 shows the first moment of **|ΔG|** ≈ 0.2-0.3;

ΔG>0 and ΔG<0 solutions describe data equally well

	ΔΣ		ΔG		<Lz>
1/2 =	**1/2 × 0.3**	**+**	**0.35**	**+**	**0.0**
1/2 =	**1/2 × 0.3**	**+**	**0.0**	**+**	**0.35**
1/2 =	**1/2 × 0.3**	**-**	**0.35**	**+**	**0.7**

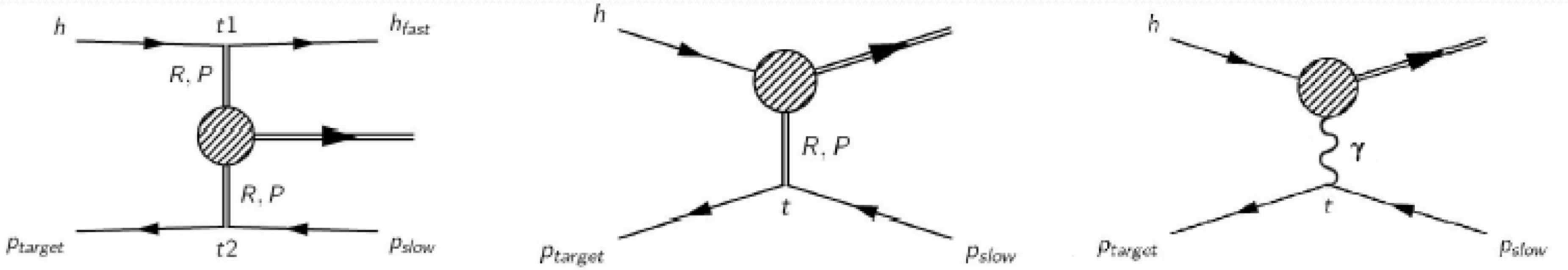
but direct measurements cannot
yet discriminate between them

Solid evidence for:
transversity PDF and Collins function to be different from zero

COMPASS is a major player in transverse spin physics
the study of transverse spin effects needs further precise measurements and the COMPASS facility is the only place where SIDIS can be measured at high energy
More COMPASS data: 2010 p transverse, 2011 p longitudinal polarisations

Part II: Hadron reactions

Central production: Diffractive dissociation: Coulomb production:



Gluon-rich environment
Rapidity gap

Spin-exotic mesons
Forward kinematics

Test of ChPT
Radiative widths

Meson states beyond the CQM ➔ $gg,\ ggg$ $q\bar{q}g$ $q\bar{q}q\bar{q}$

2004 190 GeV π^-, μ on Pb (short run)
2008 190 GeV π^- on LH_2
2009 190 GeV p,π^+,π^- on LH_2, Pb, Ni, W

Beam intensity: $5{\cdot}10^6$ had/s
Negative: 97% π, 2.5% K,
Positive: 75% p, 25% π

Diffractive pion dissociation

Diffractive scattering
- study of J^{PC} **exotic** mesons
- **t-channel** Reggeon exchange
- **forward** kinematics,
- target **stays intact**

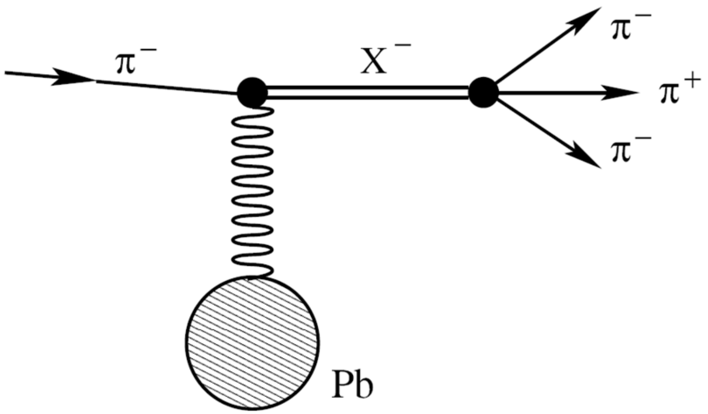
Hybrid candidates (1.3 - 2.2 GeV/c²):
lightest hybrid predicted: exotic **J^{PC} =1**$^{-+}$
- $\pi_1(1400)$: E852, VES, Crystal Barrel –> $\eta\pi$
- $\pi_1(1600)$: E852, VES –> $\rho\pi$, $\eta'\pi$, $f_1\pi$, $b_1\pi$
- $\pi_1(2000)$: E852 –> $f_1(1285)\,\pi$, $b_1(1235)\,\pi$

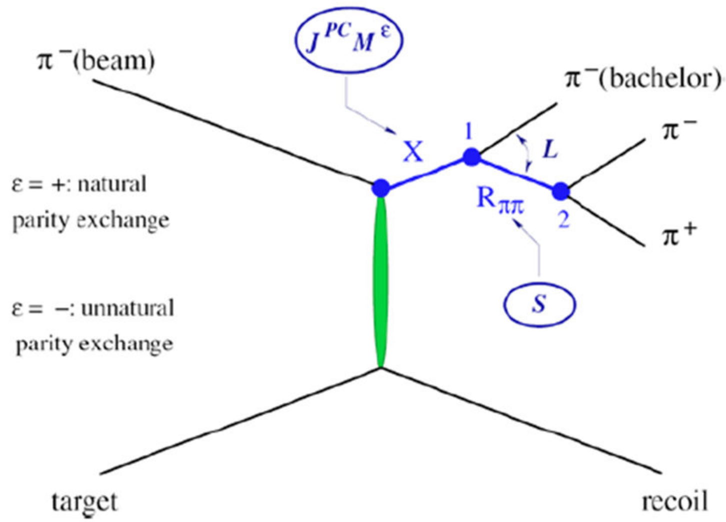
π^- **Pb** –-> $\pi^-\pi^+\pi^-$ **Pb**

PWA analysis: Isobar model

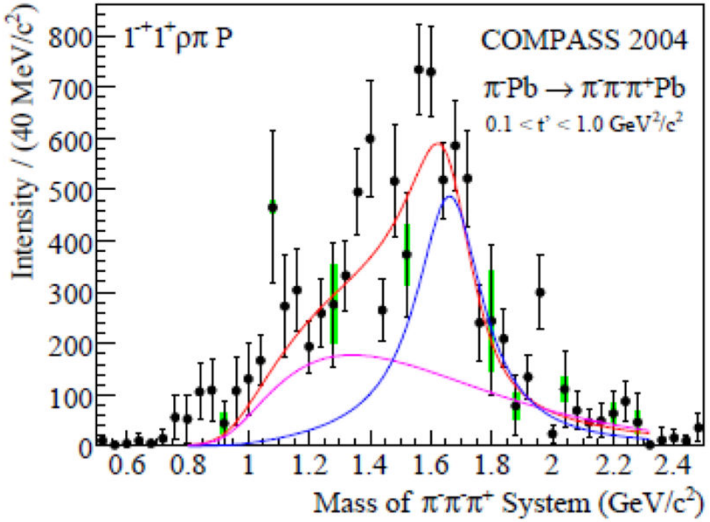
4 days data taking in 2004

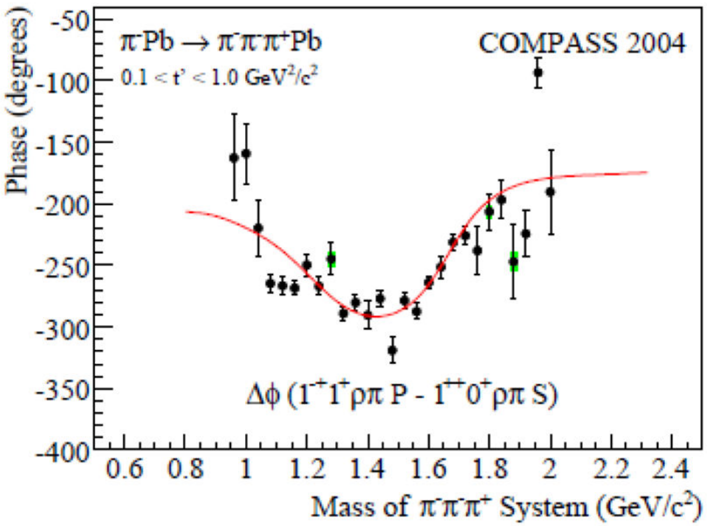
190 GeV π^- beam





Diffractive pion dissociation (2004 data, Pb target)





COMPASS, Phys. Rev. Lett. 104 (2010) 241803

PWA analysis of 420000 events
mom transfer $0.1 < t' < 1$ (GeV/c)^2
quasi-free nucleons in Pb
$a_1(1260)$, $a_2(1320)$ and $\pi_2(1670)$ are clearly visible

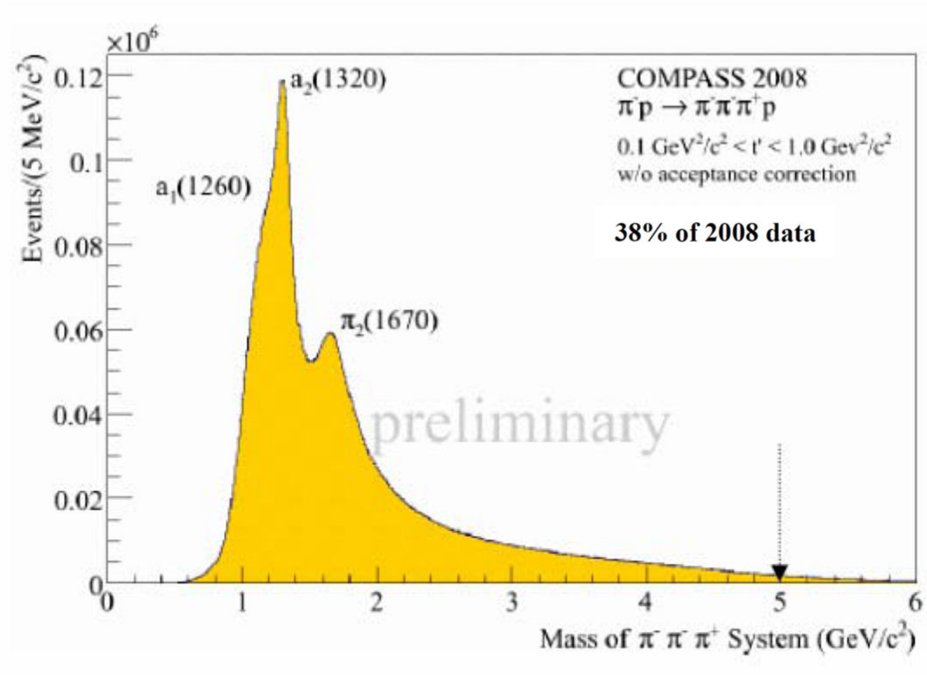
Significant spin exotic $J^{PC} = 1^{-+}$ wave

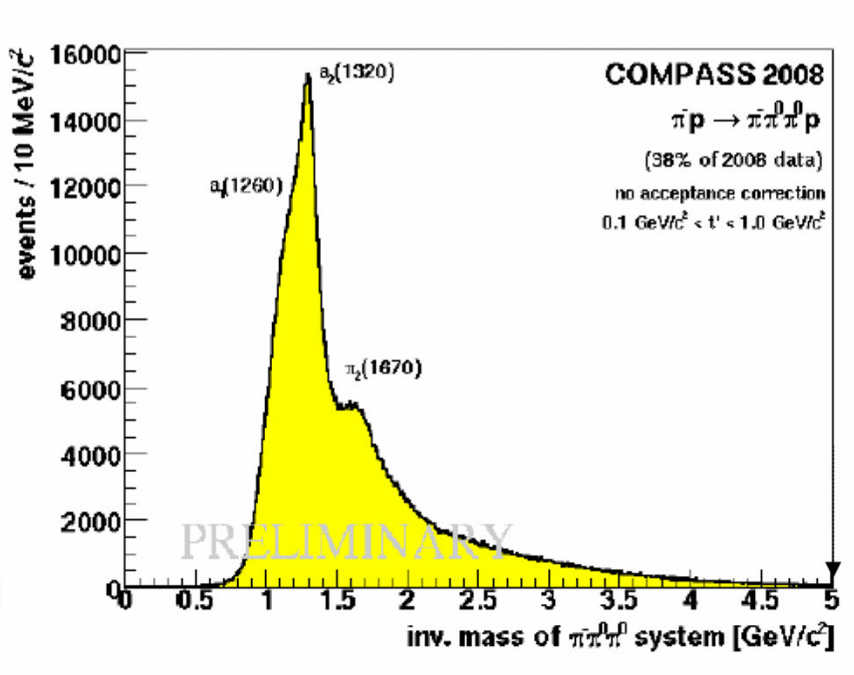
- $M = 1660 \pm 10^{+0}_{-64}$ MeV/c²
  $\Gamma = 269 \pm 21^{+42}_{-64}$ MeV/c²
- consistent with $\pi_1(1600)$
- Neglible leakage from other waves

Diffractive pion dissociation (2008 data, Proton target)

charged mode: $\pi^- p \to \pi^-\pi^+\pi^- p$ **neutral mode:** $\pi^- p \to \pi^-\pi^0\pi^0 p$

Well-known resonances are clearly seen

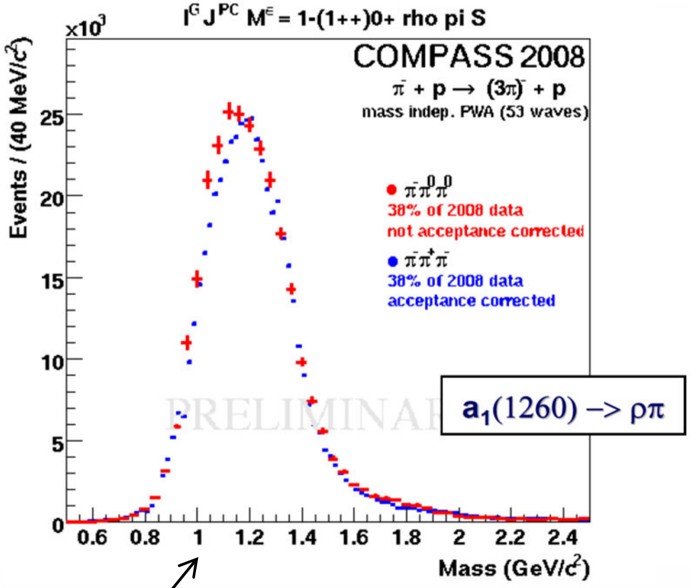


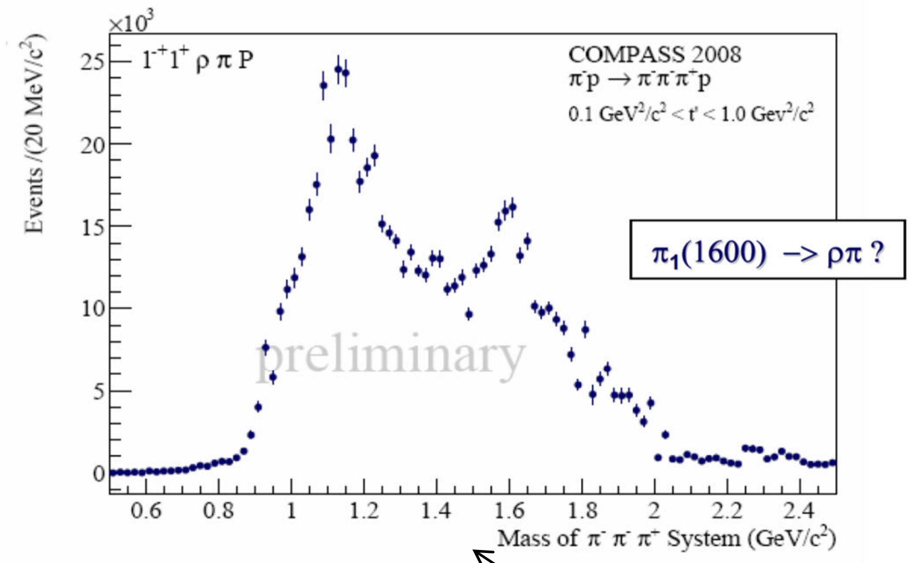


PWA: analysis ~ 24M events

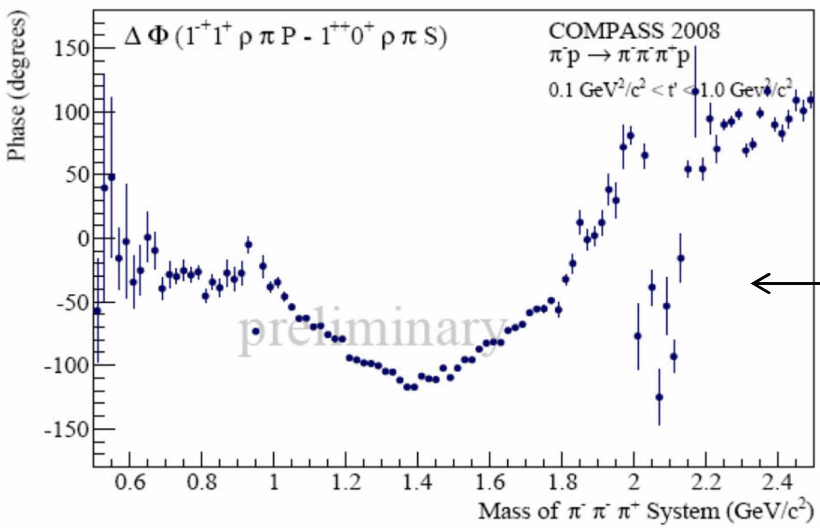
PWA:analysis ~ 1M events

First glimpse on the exotic wave $J^{PC} = 1^{-+}$





Good agreement between charged and neutral modes



Intensity:
signal at ~1.6GeV, leakage from $a_1(1260)$

Phase:
clean phase motion

Final states with strangeness: π & K beams

Glueball candidates decaying into KK

$f_0(1380)$,$f_0(1500)$: qq mixing with gg ?

Hybrid candidates decaying into KKπ

$\pi(1800)$: usual 3^1S_0 or Hybrid?

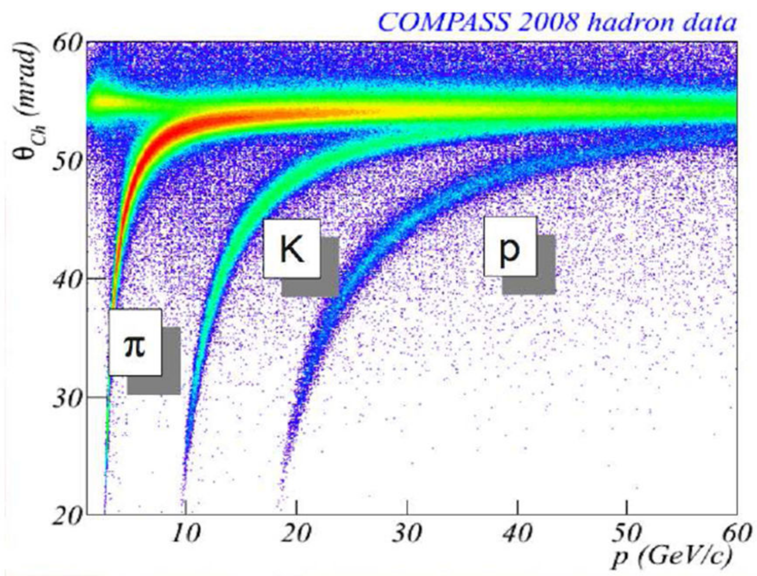
K from beam identified by CEDAR

K^+K^- identified by RICH:

10 GeV/c< P_K < 30 GeV/c

$$\pi^- p \rightarrow K^+ K^- \pi^- p,$$
$$\pi^- p \rightarrow K_s^0 K_s^0 \pi^- p,$$
$$\pi^- p \rightarrow K_s^0 K_L^0 \pi^- p,$$
$$K^- p \rightarrow K^- \pi^- \pi^+ p,$$

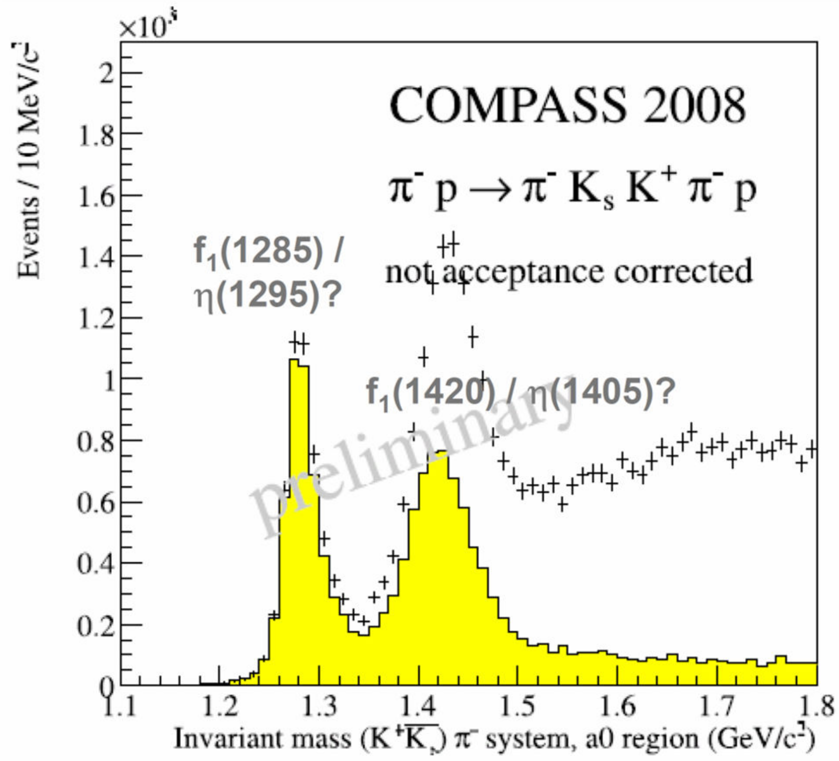
....



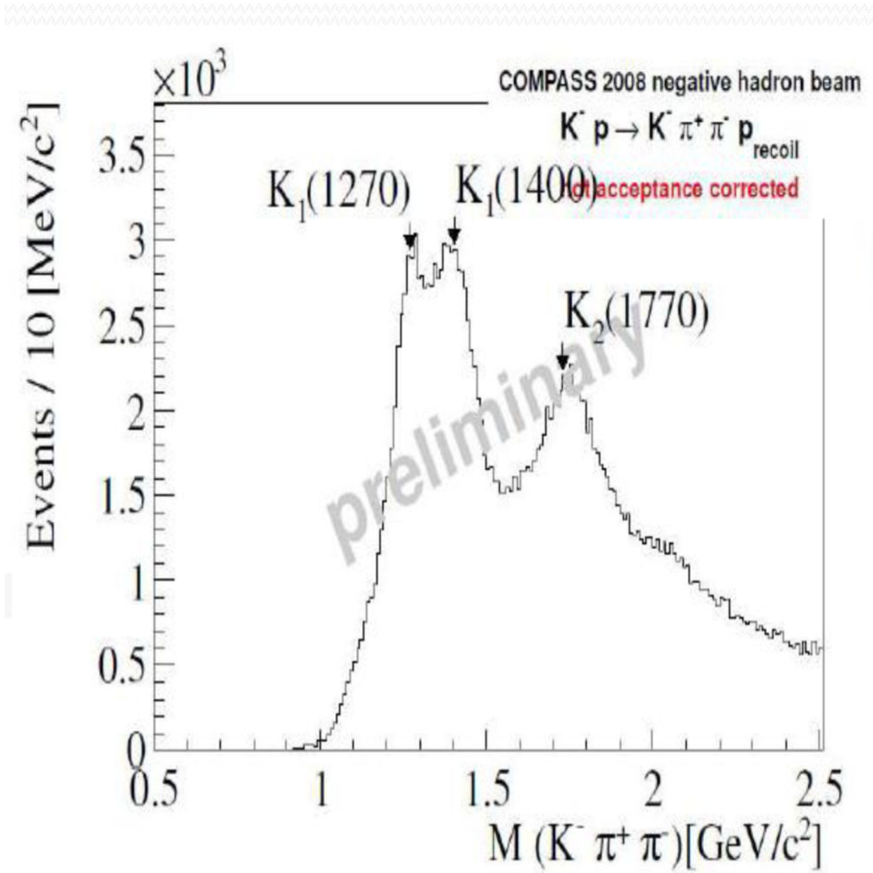
Final states with strangeness: π/K beams

$\pi^- p \rightarrow K\bar{K}\,\pi\,\pi^-\,p$

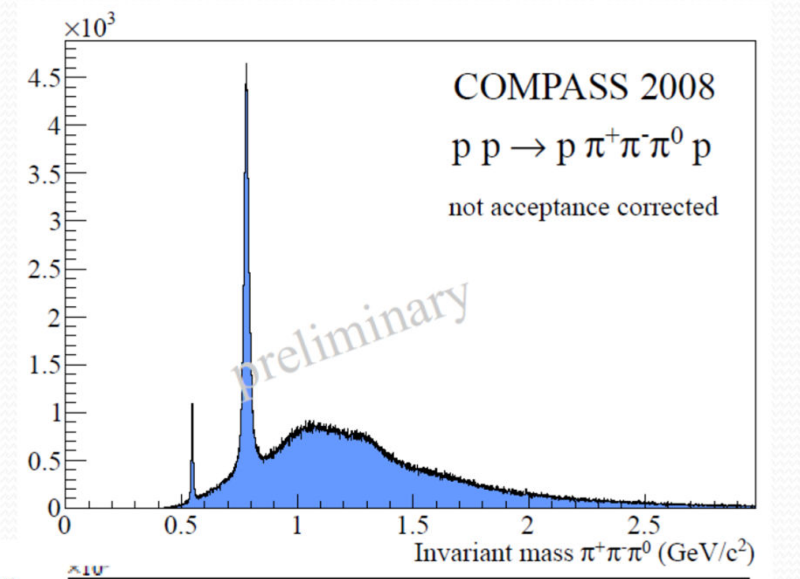
COMPASS 2008 data contain 10 times higher statistics than BNL.



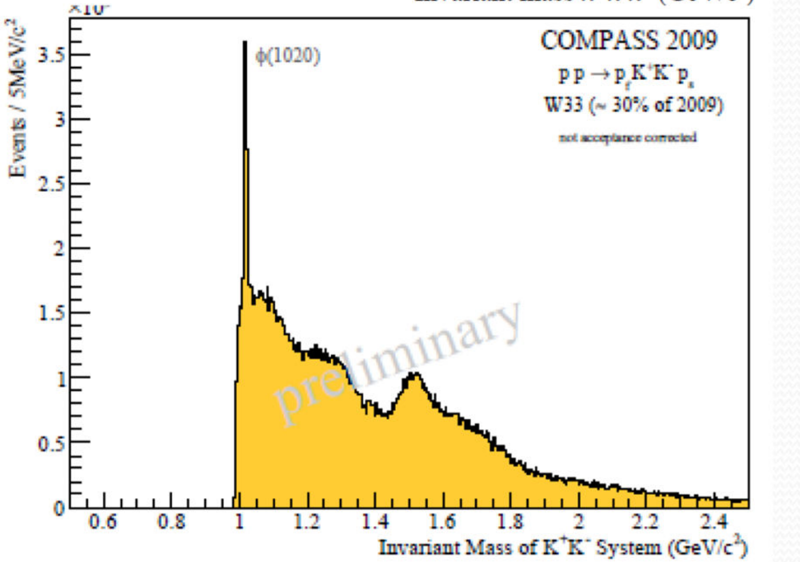
$K^- p \rightarrow K^- \pi^+ \pi^- p$

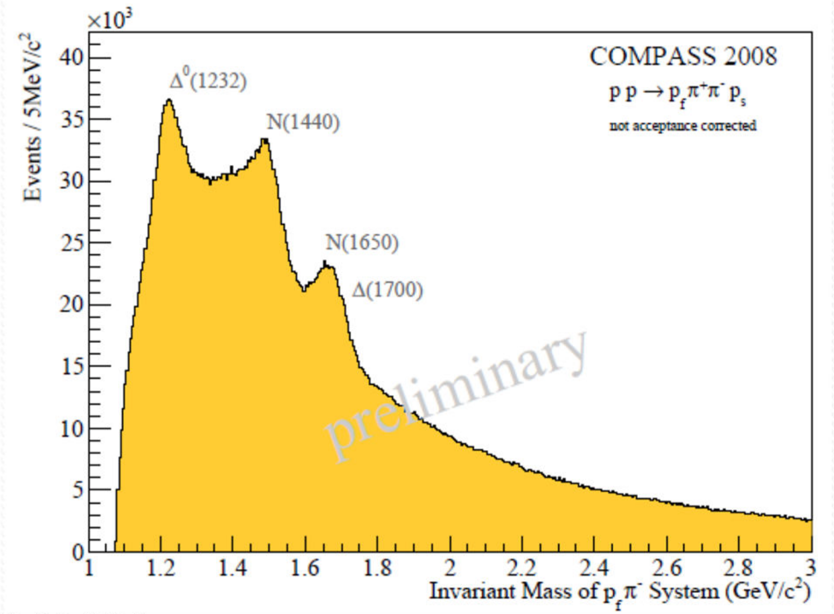


Physics with proton beam

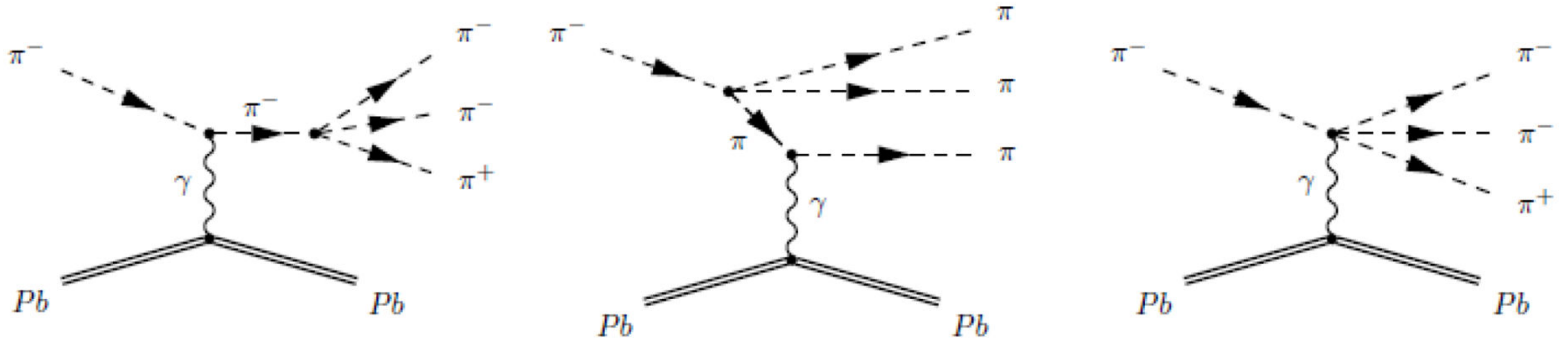


- Search for glueballs in central *pp* collisions
- Baryon spectroscopy
- Precise OZI tests





First Measurement of Chiral Dynamics in $\gamma\pi^- \to \pi^-\pi^-\pi^+$

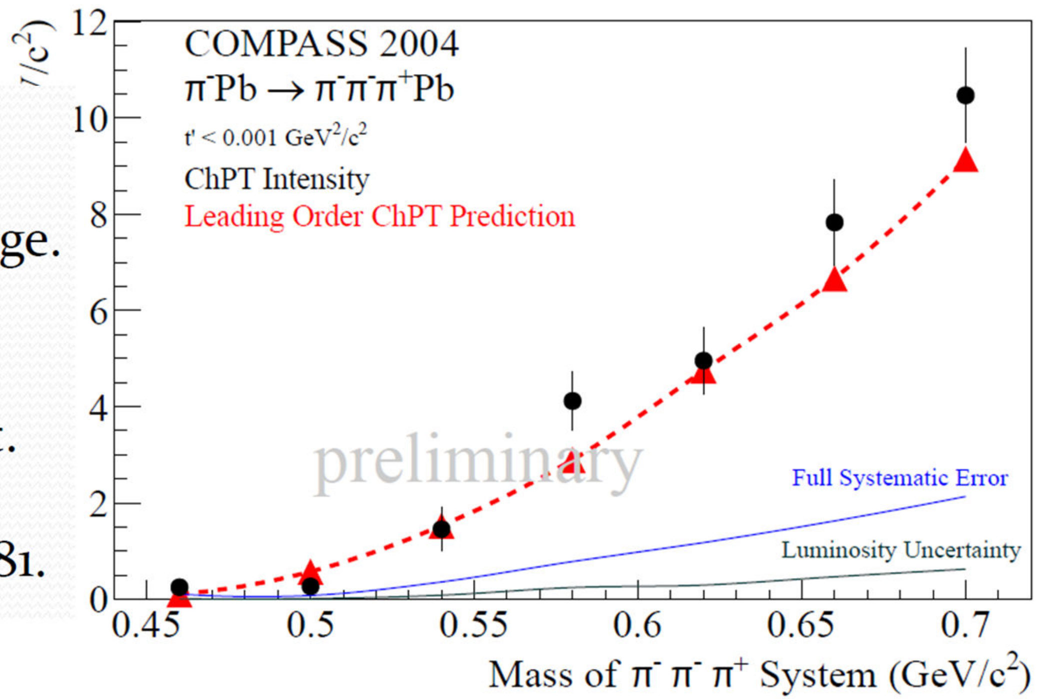


Low momentum transfer:

Contribution from photon exchange.

Low masses:

Only pions produced → ChPT test.
Results compared to LO ChPT predictions from EPJA 36 (2008) 181.



Publication comes soon

Conclusion (part II)

Evidence for QCD allowed states like multiquarks, glueballs and hybrids still not beyond doubt

COMPASS has excellent potential to contribute; it has access to 3 production mechanisms:

- Diffractive dissociation, Central and Coulomb productions
- Already observed the spin exotic wave $\pi_1(1600)$ in data from 2004 pilot run.
- Measures charged and neutral channels: Independent consistency check.
- Measures kaonic final states.
- A large amount of data were collected with hadron beam in 2008/2009 (10 – 100 times world statistics).

Part III: COMPASS II

COMPASS-II was approved by the CERN Research Board: Dec. 1, 2010.

COMPASS II

2012, SPS/LHC shutdown, 2014, 2015, 2016

DVSC & DVMP
Study GPDs, "nucleon tomography"

Unpolarized SIDIS
Fragmentation Functions, s-PDFs, TMDs

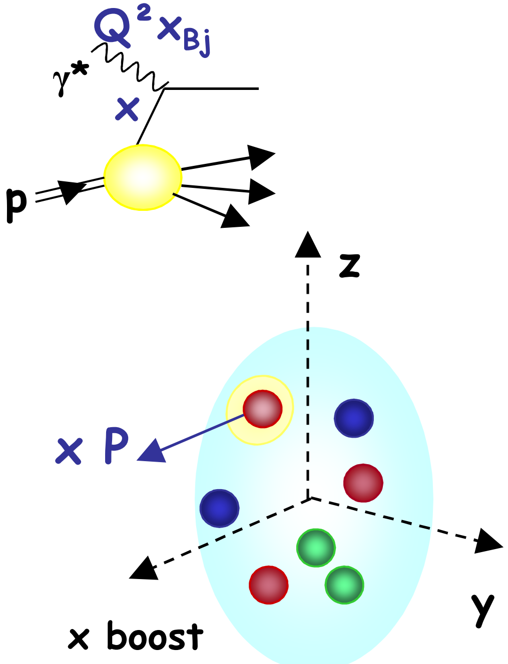
Drell-Yan
Universality of TMDs

Primakoff
Polarizabilities of π and K

From Inclusive and Semi-Inclusive experiments to Exclusive experiments

Deep Inelastic Scattering

ep→ eX

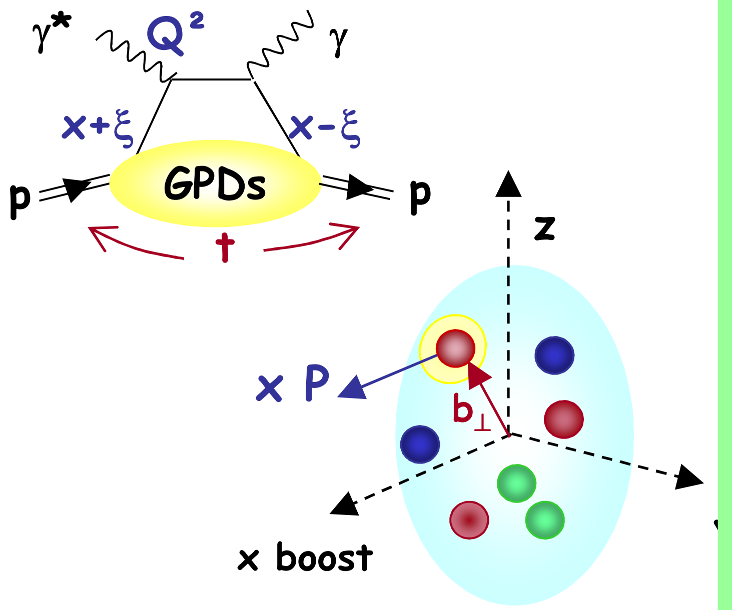


Parton Density q (x)

P_x

Hard Exclusive Scattering
Deeply Virtual Compton Scattering

ep→ epγ



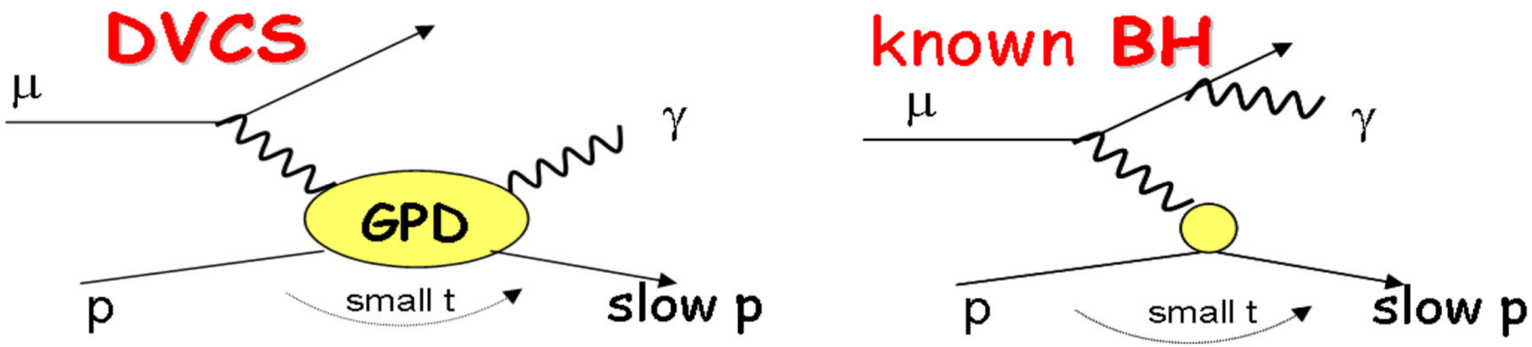
Generalized
Parton Distribution H(x,ξ,t)

$(P_x,\ b_\perp)$

Exclusive single-photon production

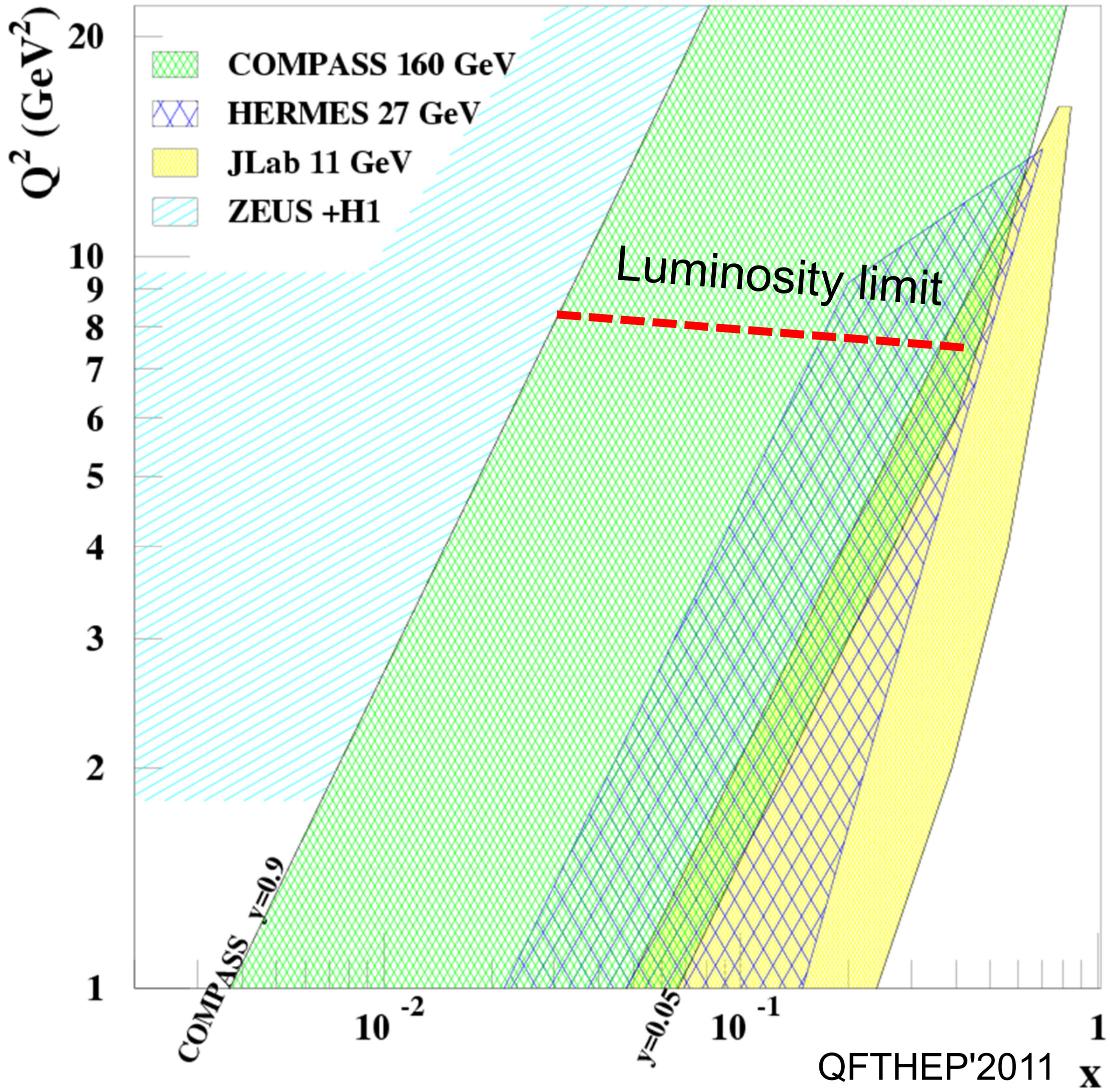
COMPASS experiment has excellent opportunity for studying Generalized Parton Distributions (GPDs), through Deeply Virtual Compton Scattering (DVCS) using highly-polarized $\mu^{\pm}$ beam line of the CERN SPS. DVCS is considered to be the theoretically cleanest of the experimentaly accessible processes to measure GPDs. The physical background - Bethe-Heitler (BH) process - is well studied.

$$d\sigma(\mu N \to \mu N\gamma) \propto |\mathscr{A}_{BH}|^2 + |\mathscr{A}_{DVCS}|^2 + \underbrace{\mathscr{A}_{BH}\mathscr{A}^*_{DVCS} + \mathscr{A}^*_{BH}\mathscr{A}_{DVCS}}_{I}.$$



$$\frac{d^4\sigma(\mu p \to \mu p\gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + [d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVSC}_{pol}] + e_\mu [\mathrm{Re}\, I + P_\mu \mathrm{Im}\, I]$$

Kinematic domain accessible at COMPASS



CERN High energy muon - beam 100 - 190 GeV

μ+ and μ- available

80% Polarisation

with opposite polarization

with a 2.5m long LH_2 target

$L = 10^{32}$ cm^{-2} s^{-1}

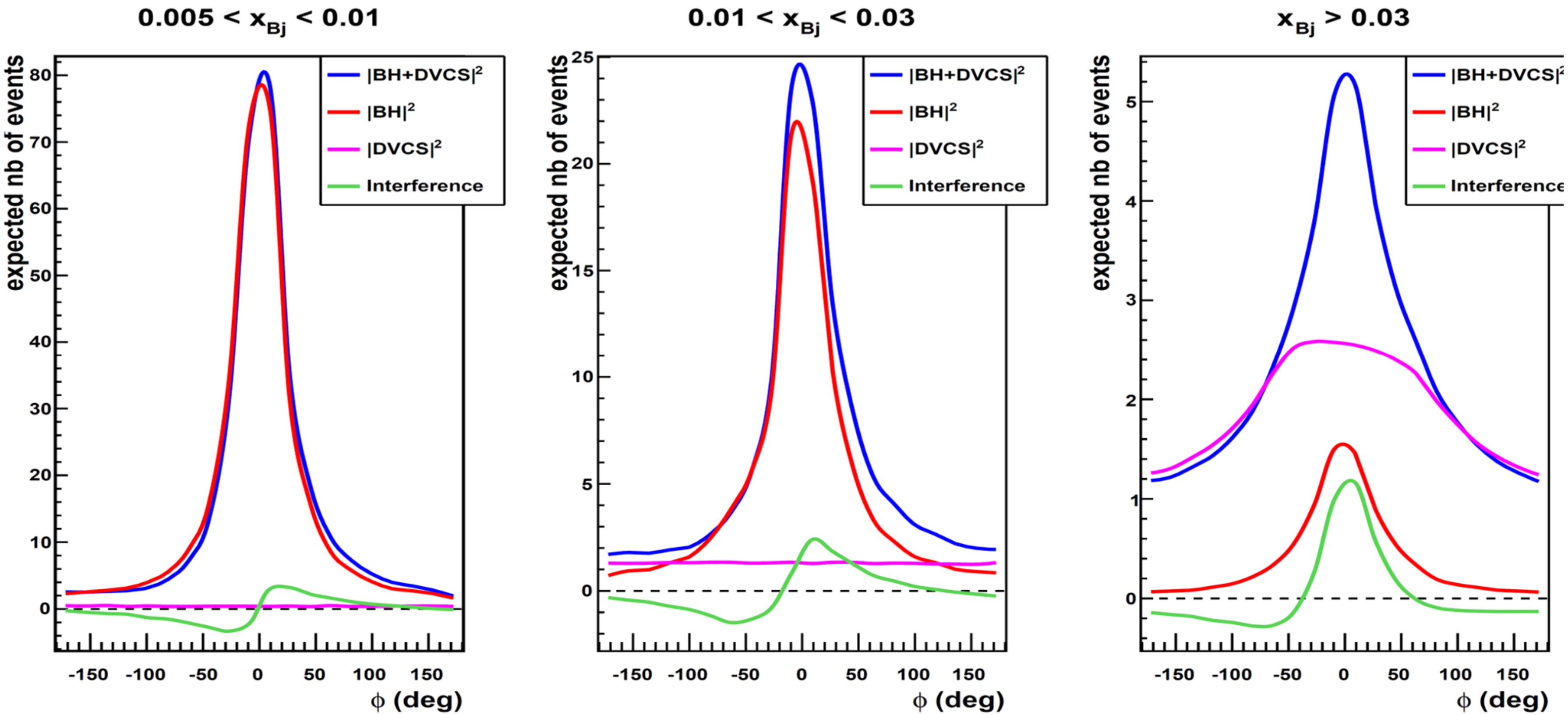
$Q^2 \rightarrow$ 8 GeV^2

$\rightarrow$ 16 GeV^2 if luminosity increased by factor 4

$\sim 10^{-2} < x < \sim 10^{-1}$

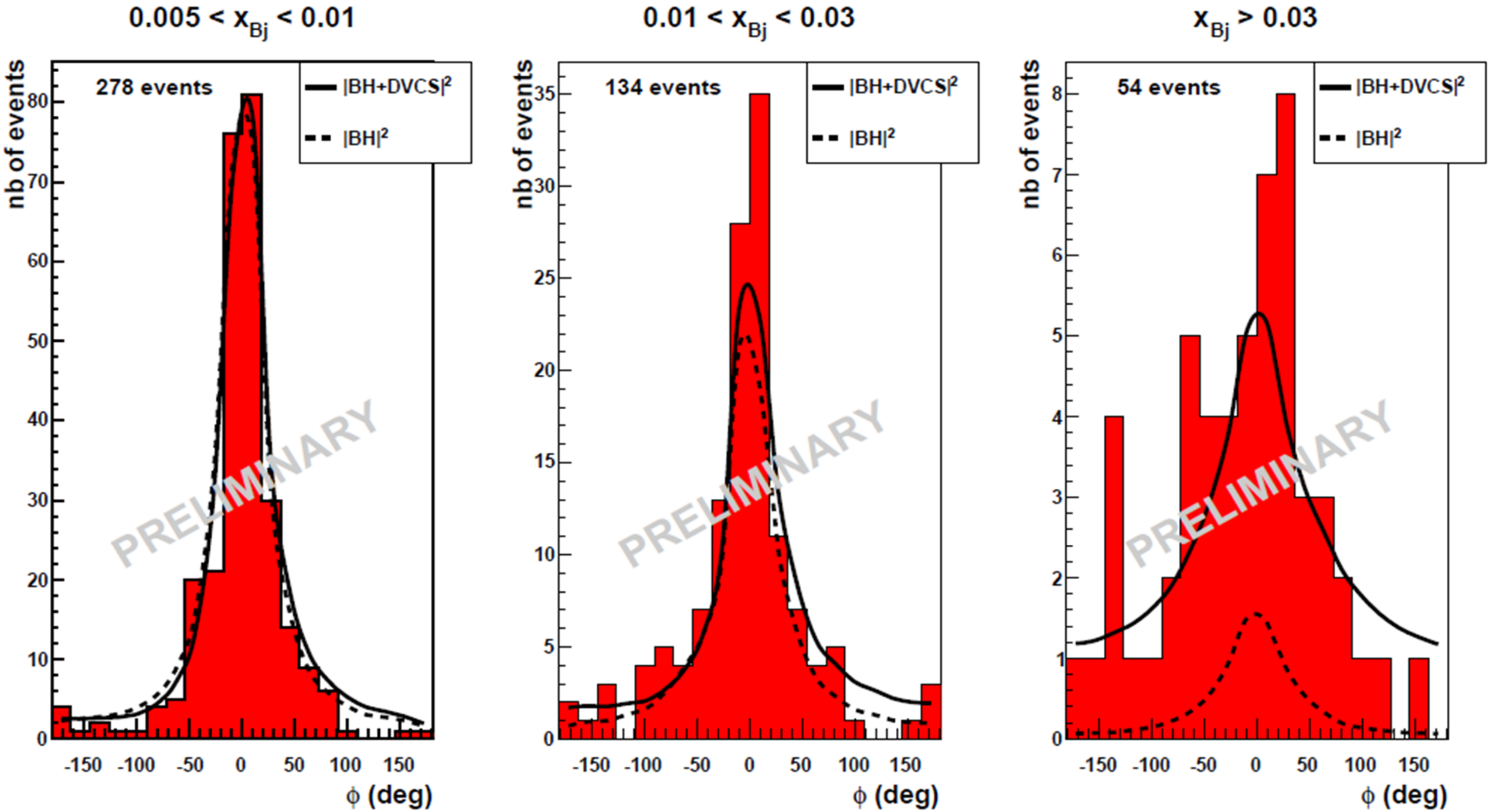
$x \rightarrow$ 0.20 with extension of present calorimetry

Comparison of BH and DVCS at 160 GeV



BH dominates	BH and DVCS at the same level	DVCS dominates
excellent reference yield	*access to DVCS amplitude through the interference*	*study of* $d\sigma^{DVCS}/d\|t\|$

2009 beam test : DVCS signal



Excess of events for x_{bj}>0.03 is a sign for DVCS

DVCS measurement with polarized μ^+ and μ^- beams

$$\mu^{+\downarrow}(P=-0.8),\ \mu^{-\uparrow}(P=0.8) \qquad \frac{\mathrm{d}^4\sigma(\mu p \to \mu p \gamma)}{\mathrm{d}x_{Bj}\mathrm{d}Q^2\mathrm{d}|t|\mathrm{d}\phi} = \mathrm{d}\sigma$$

At the first stage unpolarized LH_2 target will be used

- Beam charge & Spin Sum: $\mathcal{S}_{CS,U} \equiv \mathrm{d}\sigma^{+\downarrow} + \mathrm{d}\sigma^{-\uparrow}$
- Beam charge & Spin Difference: $\mathcal{D}_{CS,U} \equiv \mathrm{d}\sigma^{+\downarrow} - \mathrm{d}\sigma^{-\uparrow}$
- additionally deeply virtual meson production

$\mathcal{S}_{CS,U}$ gives a possibility of “nucleon tomography”:
to extract the t-slope of the DVCS cross section $\mathrm{d}\sigma/\mathrm{d}|t| \sim \exp(-B|t|)$

the analyses of the azimuthal angular dependence of $\mathcal{S}_{CS,U}$ & $\mathcal{D}_{CS,U}$ provides with only real or only the imaginary part of the DVCS amplitude

Also: beam charge & spin asymmetry: $\mathcal{A}_{CS,U} = \mathcal{D}_{CS,U}/\mathcal{S}_{CS,U}$

DVCS measurement with polarized μ^+ and μ^- beams

$\mu^{+\downarrow}(P=-0.8),\ \mu^{-\uparrow}(P=0.8)$ $\qquad \frac{d^4\sigma(\mu p \to \mu p \gamma)}{dx_{Bj}dQ^2d|t|d\phi} = d\sigma$

At the first stage unpolarized LH_2 target will be used

- Beam charge & Spin Sum: $\mathcal{S}_{CS,U} \equiv d\sigma^{+\downarrow} + d\sigma^{-\uparrow}$
- Beam charge & Spin Difference: $\mathcal{D}_{CS,U} \equiv d\sigma^{+\downarrow} - d\sigma^{-\uparrow}$
- additionally deeply virtual meson production

At the second stage transversely polarized NH_3 target will be used

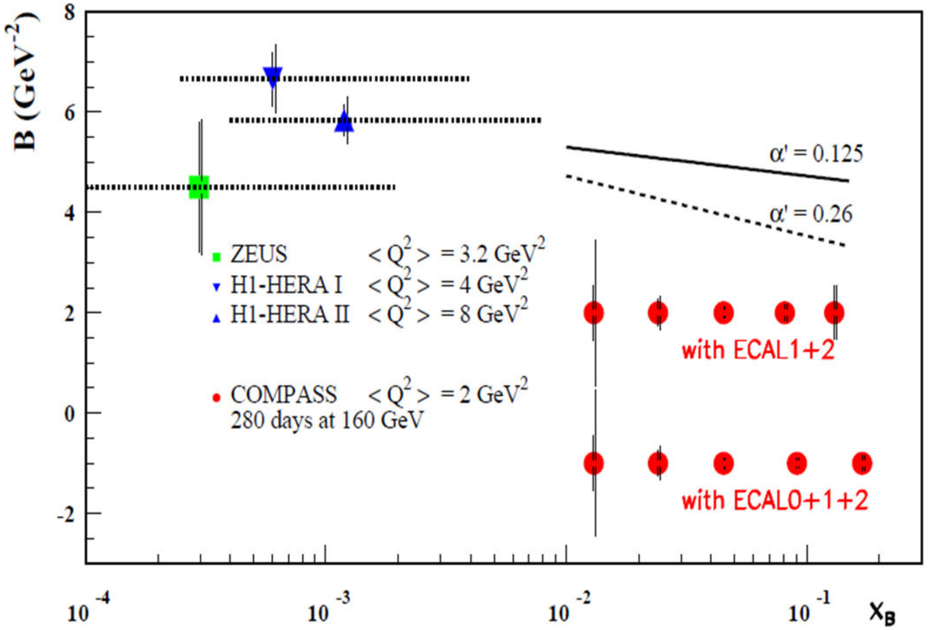
- $\mathcal{D}_{CS,T} \equiv \left(d\sigma^{+\downarrow}(\phi,\phi_S) - d\sigma^{+\downarrow}(\phi,\phi_S+\pi)\right) - \left(d\sigma^{-\uparrow}(\phi,\phi_S) - d\sigma^{+\uparrow}(\phi,\phi_S+\pi)\right)$
- $\mathcal{S}_{CS,T} \equiv \left(d\sigma^{+\downarrow}(\phi,\phi_S) - d\sigma^{+\downarrow}(\phi,\phi_S+\pi)\right) + \left(d\sigma^{-\uparrow}(\phi,\phi_S) - d\sigma^{+\uparrow}(\phi,\phi_S+\pi)\right)$
- yielding two asymmetries $\mathcal{A}^D_{CS,T} = \frac{\mathcal{D}_{CS,T}}{\Sigma_{unpol}}$ and $\mathcal{A}^S_{CS,T} = \frac{\mathcal{S}_{CS,T}}{\Sigma_{unpol}}$

Access to t-slope – transverse partonic structure of nucleon

From $S_{U,CS}$: transverse imaging

$d\sigma_{DVCS} / d|t| \sim \exp(-B|t|)$

$B \sim ½ \langle r^2 \rangle \quad B(x) = b_0 + 2\alpha' \ln(x_0/x)$

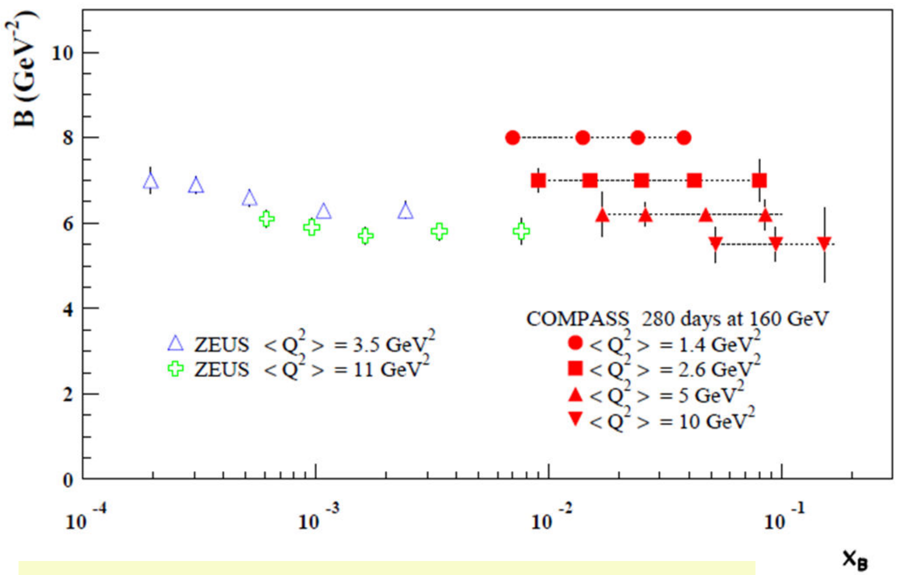


2.5 σ slope meas. for :
α' > 0.26 (ECAL 1+2)
α' > 0.125 (ECAL 0+1+2)

Exclusive production of rho mesons

$d\sigma_{\rho VMP} / d|t| \sim \exp(-B|t|)$

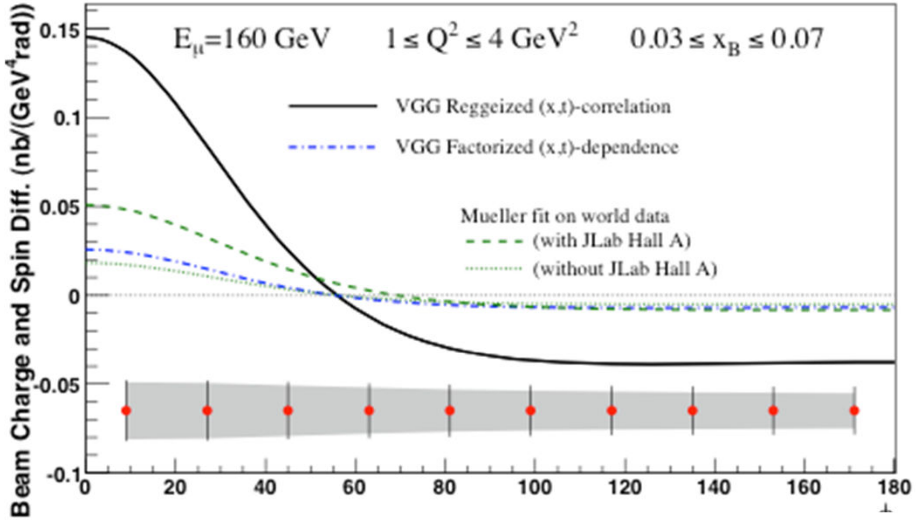
$Q^2=1$ GeV^2 $B \sim 8$ GeV^{-2}
$Q^2=10$ GeV^2 $B \sim 5.5$ GeV^{-2}

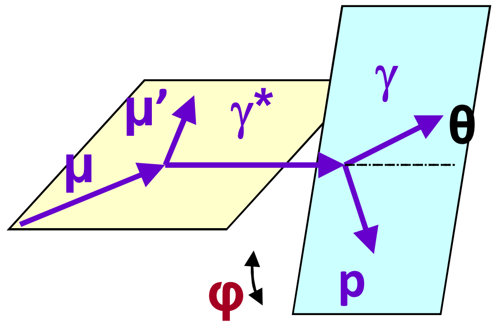


Projections for: E_μ=160 GeV 2 years of running
$L = 1222$ pb^{-1} $\varepsilon_{global} = 10$ %

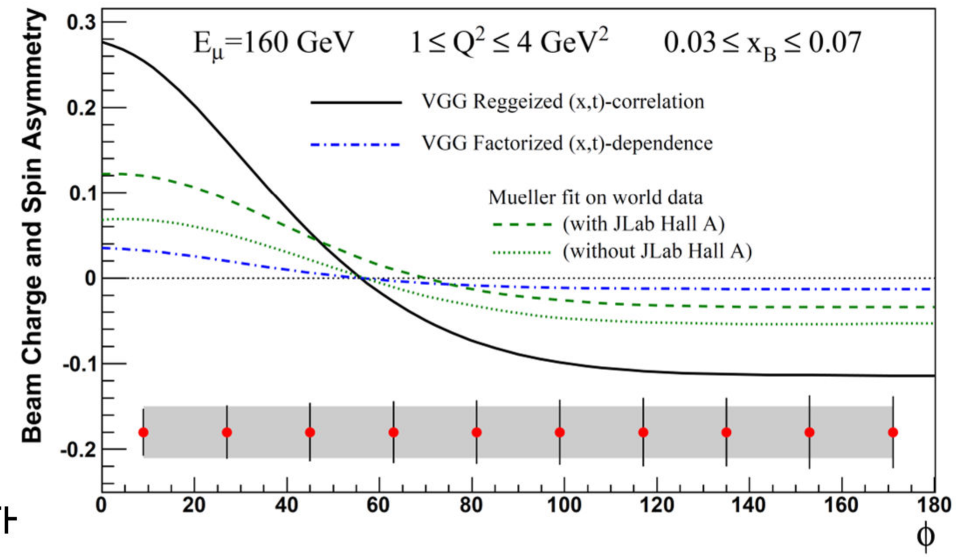
Azimuthal dependence analysis

$D_{U,CS}$: Beam Charge & Spin Difference





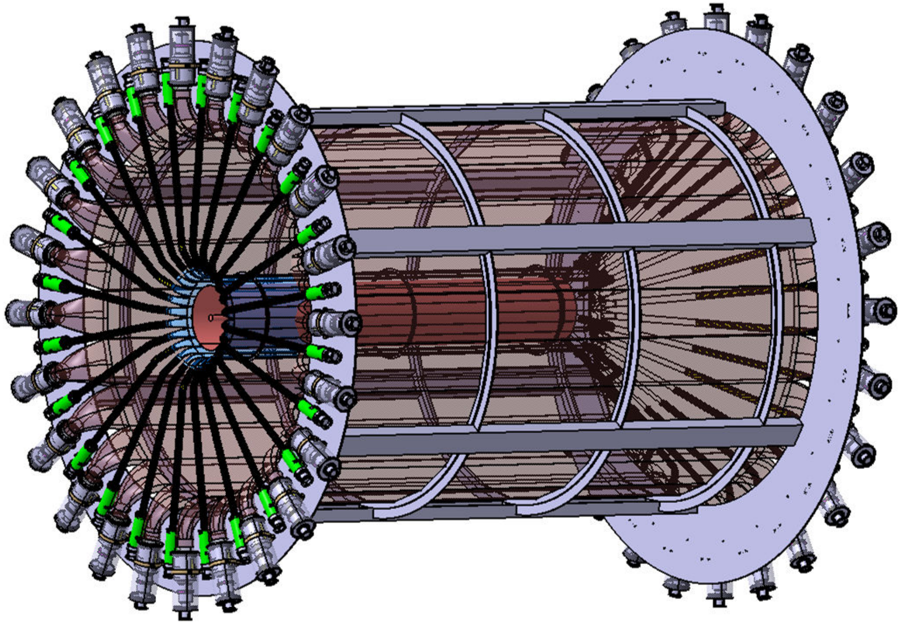
$A_{U,CS}$: Beam Charge & Spin Asymmetry



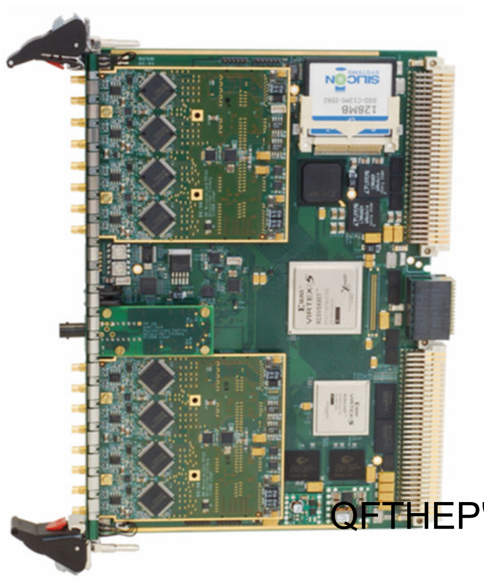
2 years of running will permit us to study a two dimensional dependence

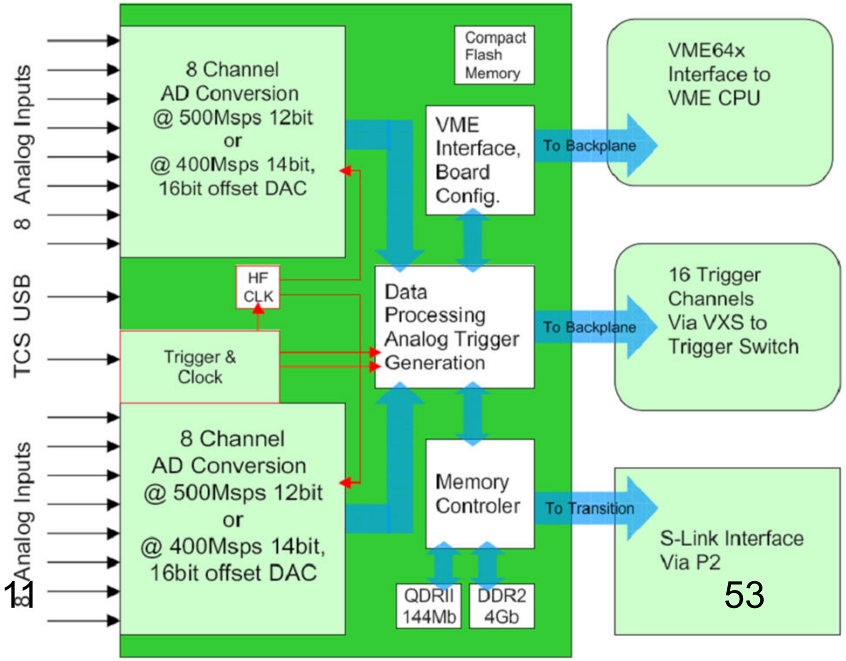
Q^2, x_{Bj} or t, x_{Bj}

Recoil proton detector for 2.5 m long LH_2 target (Saclay/Freiburg)



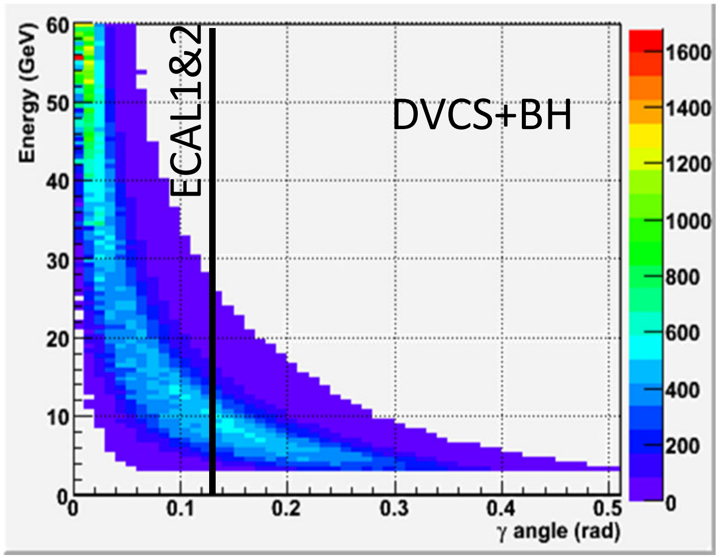
- 4 m long scintillator slabs
- ~ 300 ps timing resolution
- 30º prototype tested successfully





Gandalf Project:
1 GHz digitalisation of the PMT signal to cope with high rate

New large-angle electromagnetic calorimeter ECAL0 (Dubna)



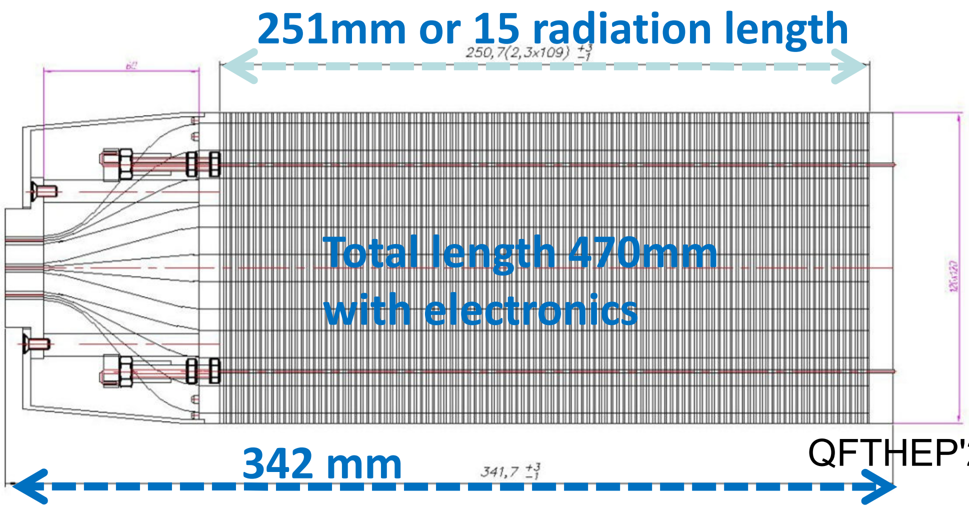
Requirements
- Photon energy range 0.2- 30 GeV
- Size: 360cm x 360cm ;
- Granularity 4x4 – 6x6 cm^2
- Energy resolution < 10.0%/√E (GeV)
- Thickness < 50 cm,
- Insensitive to the magnetic field.

Prototype under studies

Shaschlyk module with AMPD readout

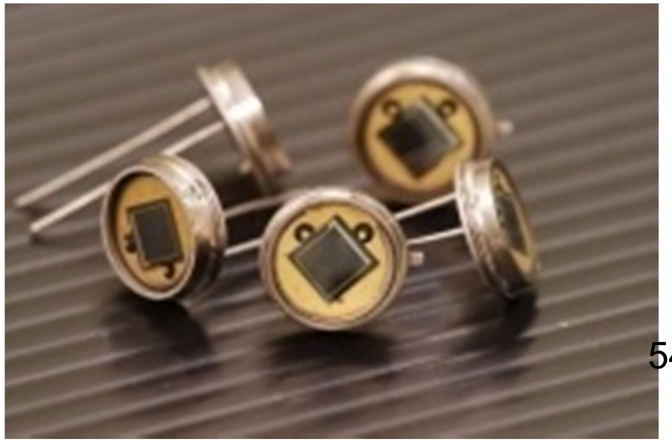
new shashlyk modules for tests in 2011

109 plates made of Sc 0.8 mm /Pb 1.5 mm



Avalanche Micropixel Photo Diodes

3 x 3 mm^2, density of pixels 40 000/mm^2



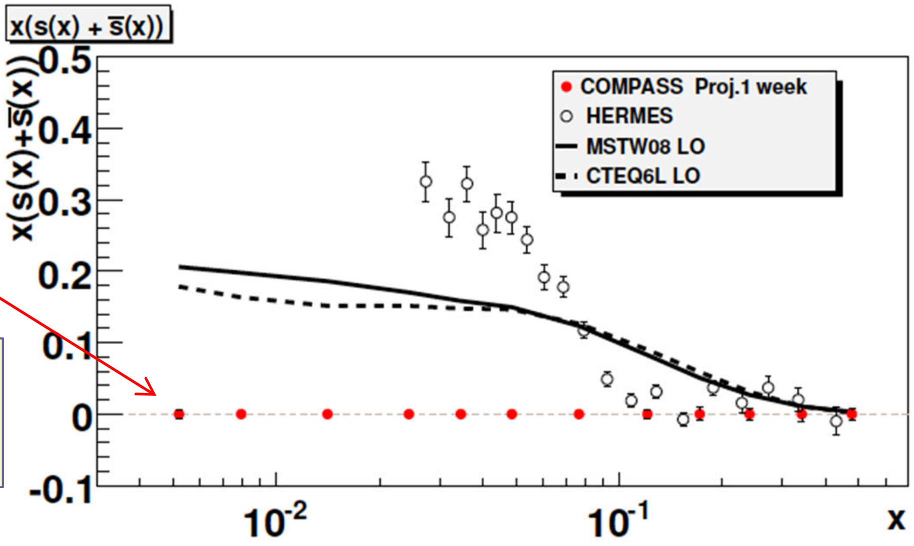
Semi-inclusive DIS (in parallel with DVCS)

- Features
  - Pure hydrogen target
  - High-performance particle identification for $\pi^+,\pi^-,\pi^0,K^+,K^-,K^0$ etc…

- Measurements of:

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

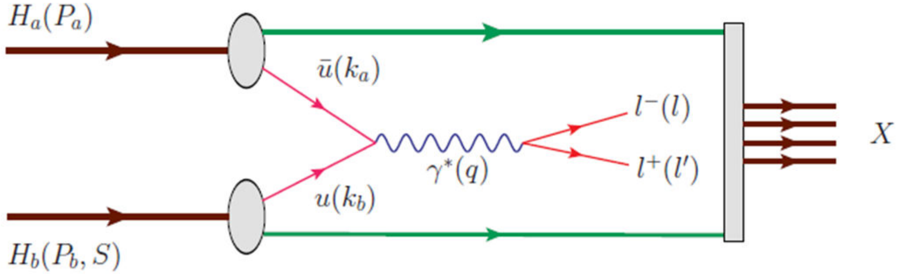
  - Multiplicities
    Input to global FF analysis
  - Strange quark PDF
    down to x=0.004

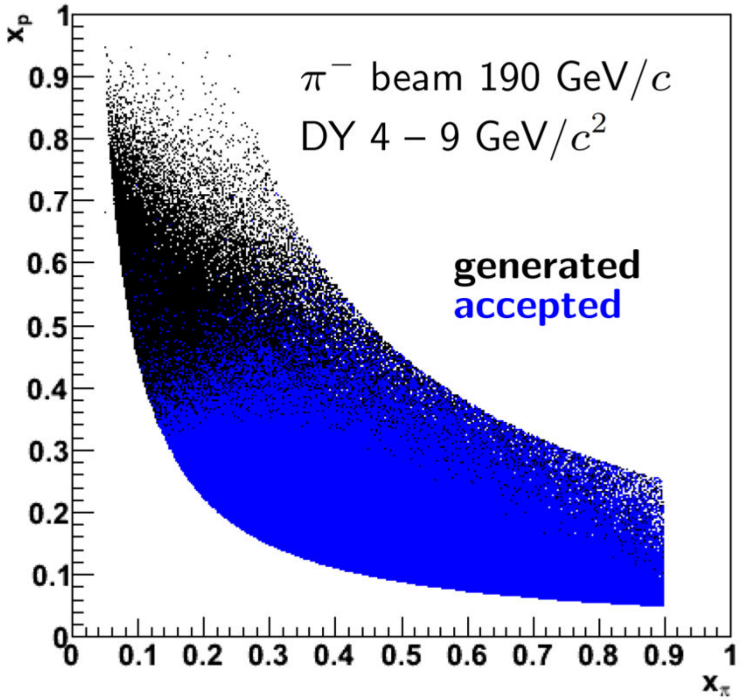


1 week of beam
2.5 m liquid H_2 target

$$\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X$$

Polarized Drell-Yan measurements





→pion valence anti-u annihilates with proton u

→access to 4 azimuthal modulations: Boer-Mulders, Sivers, pretzelosity and transversity PDFs

$$\sigma^{SIDIS} \propto TMD_p(x, k_T) \otimes D_f^h(z, Q^2)$$

$$\sigma^{DY} \propto TMD_\pi \otimes TMD_p$$

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

J.C. Collins, PLB536 (2002) 43

Sivers:

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

Boer-Mulders:

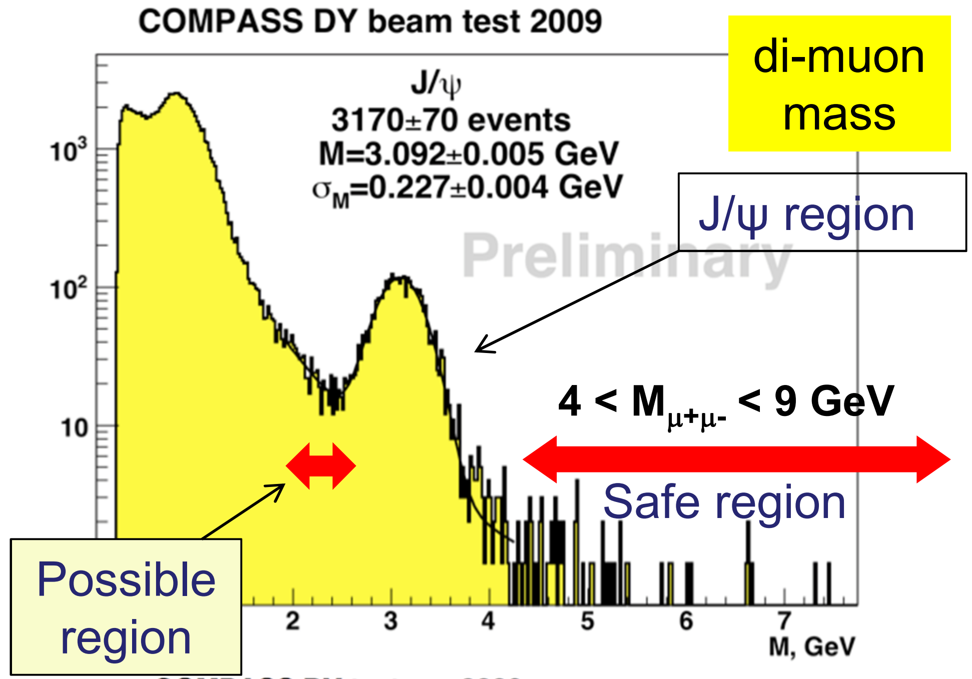
$$h_1^{\perp}(SIDIS) = -h_1^{\perp}(DY)$$

Feasibility of the measurement (DY test 2009)

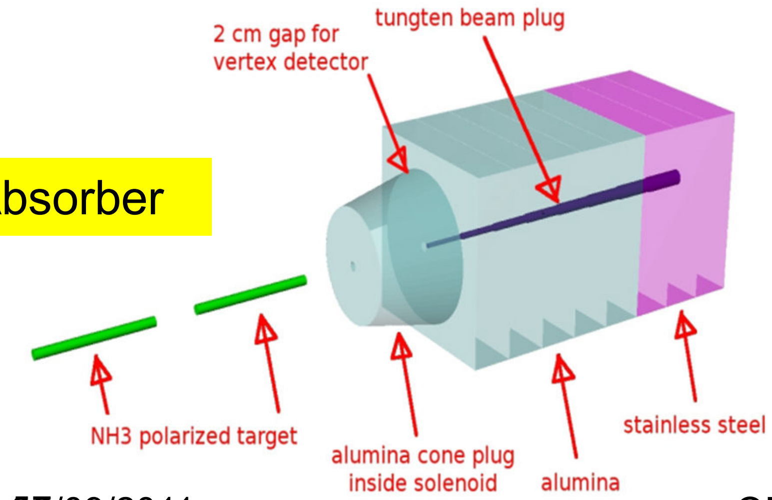
	Expected	Found
J/ψ	3600±600	3170±70
DY M>4 GeV	110±22	84±10

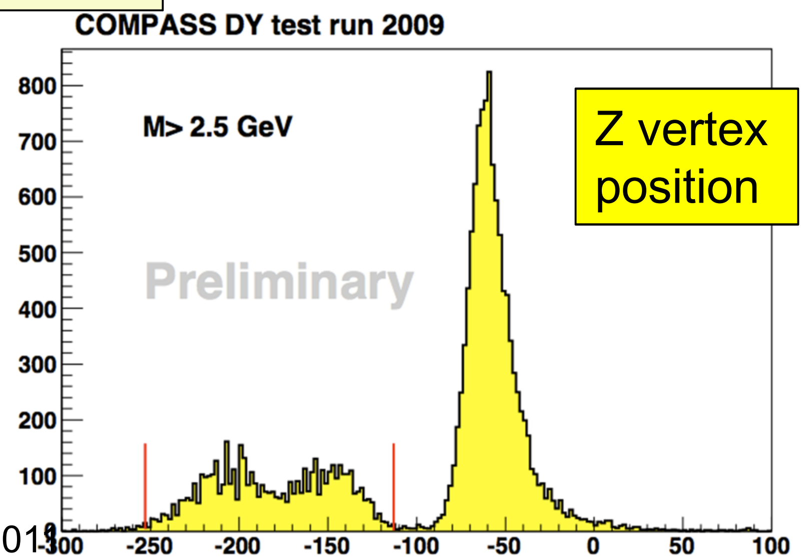
→Promising results of the test

For future : intensity up to 10^9 π/spill
→ new full size Absorber
→ new tracking planes after the target

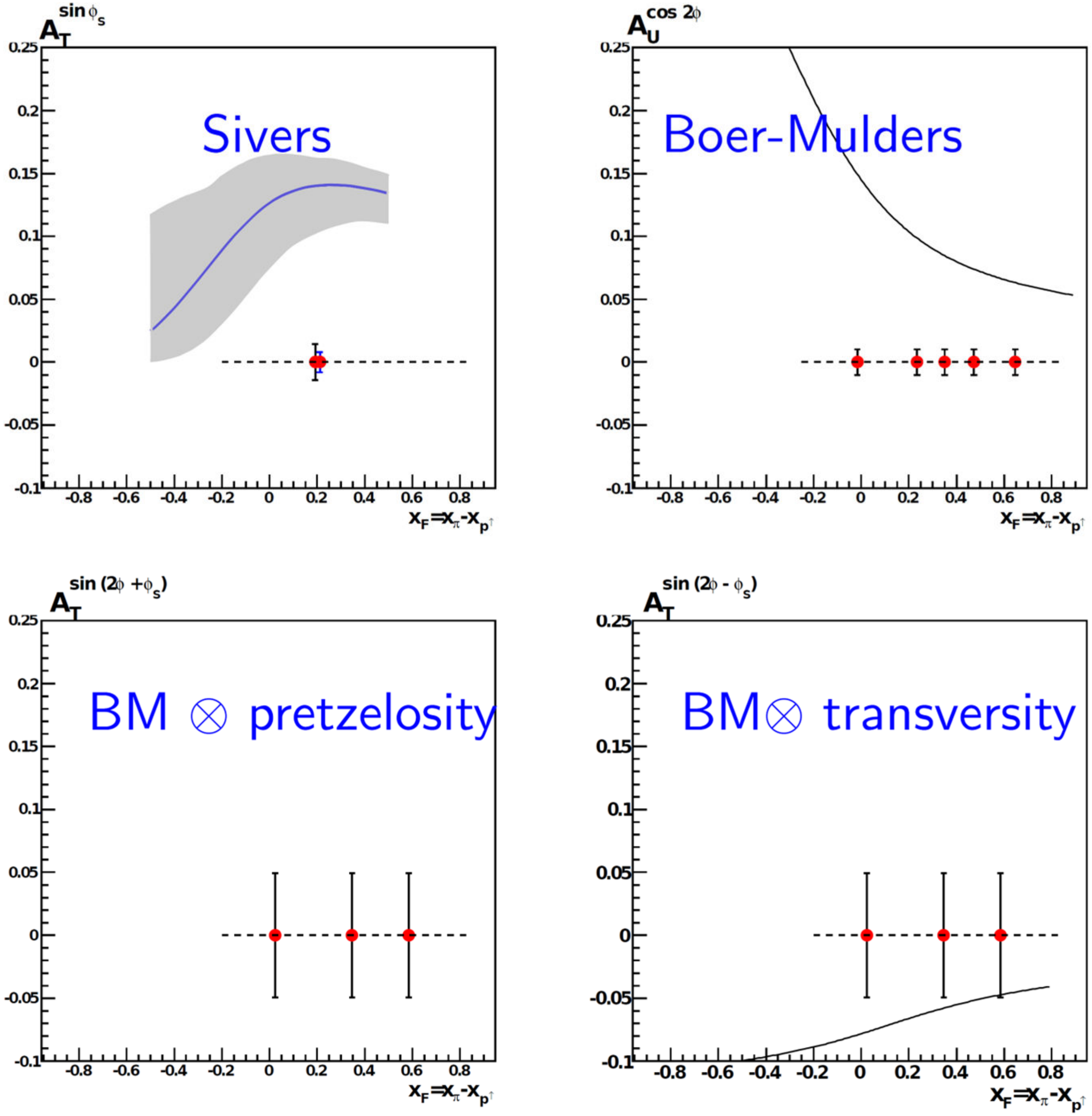


Absorber





Projections for azimuthal asymmetries



4 GeV<$M_{\mu\mu}$<9 GeV

projections with
2 years of data
$6 \cdot 10^8\, \pi$ spill $(9.6\ s)$
1.1 m pol. NH_3

key measurements:

→TMD universality,

→change of sign from SIDIS to DY,

→study of J/ψ production mechanism

Testing ChPT

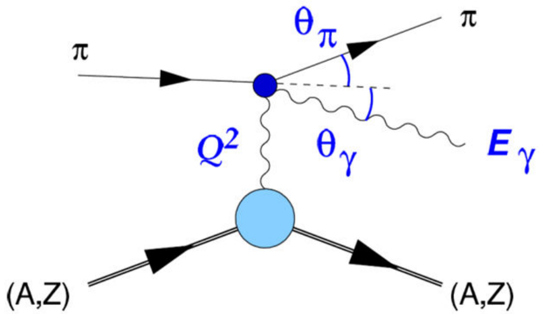
$$\pi^- Z \to \pi^- Z \gamma$$

2-loop chiral prediction

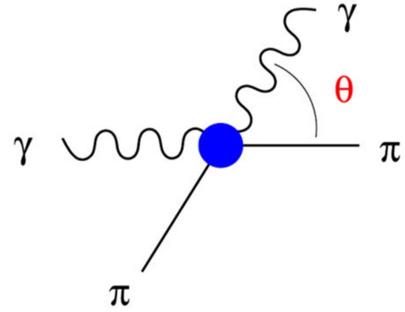
$$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) 10^{-4} \text{ fm}^3$$

$$\alpha_\pi - \beta_\pi \text{ from } 4 \text{ to } 14 \cdot 10^{-4} \text{ fm}^3$$

measurments

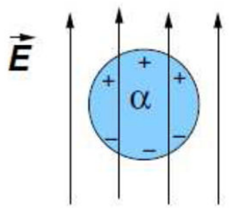


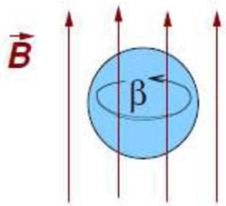
Primakoff



Inverse Compton

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \left[\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}}\right]_{point-like} + C\,\frac{s - m_\pi^2}{s^2}\,\mathcal{P}(\alpha_\pi, \beta_\pi)$$





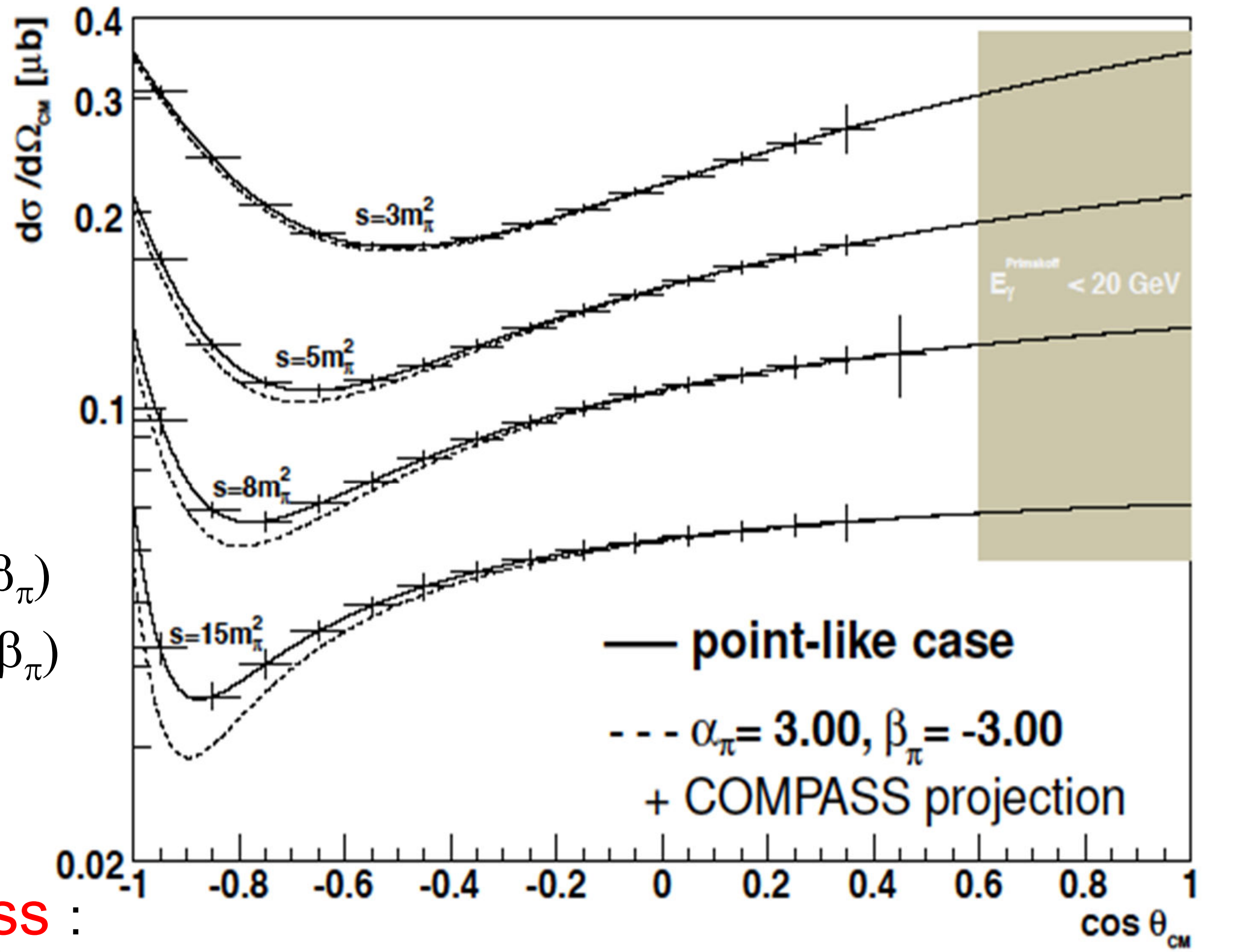
Polarizability:

$$\mathcal{P} = (1 - \cos\theta_{cm})^2\,(\alpha_\pi - \beta_\pi)$$
$$+ (1 + \cos\theta_{cm})^2\,(\alpha_\pi + \beta_\pi)\,\frac{s^2}{m_\pi^4}$$
$$+ (1 - \cos\theta_{cm})^3\,(\alpha_2 - \beta_2)\,\frac{(s - m_\pi^2)^2}{24s}$$

Pion polarisability measurements

COMPASS features

- Energy: 190 GeV
- High-I pion beam
- Muon beam = ref.
- For'd anlgles: $(\alpha_\pi+\beta_\pi)$
- Back'd angles $(\alpha_\pi-\beta_\pi)$

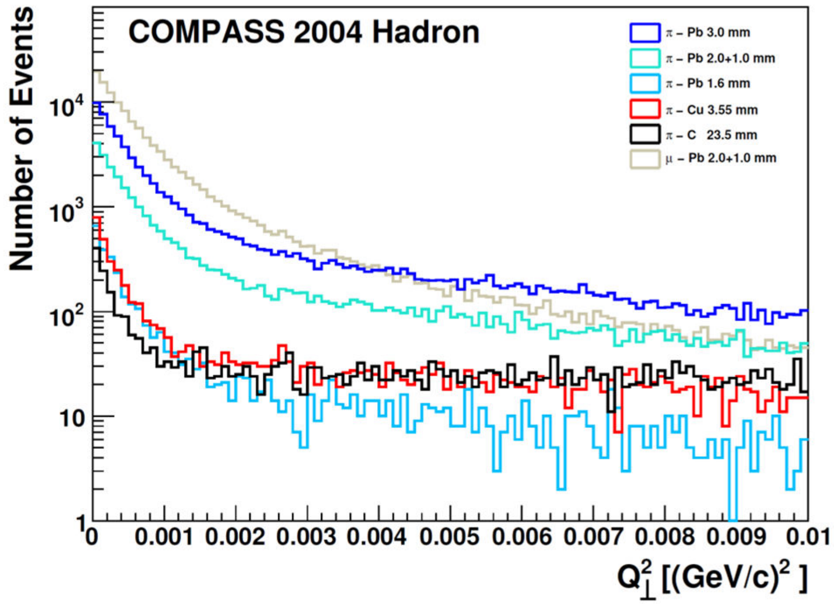


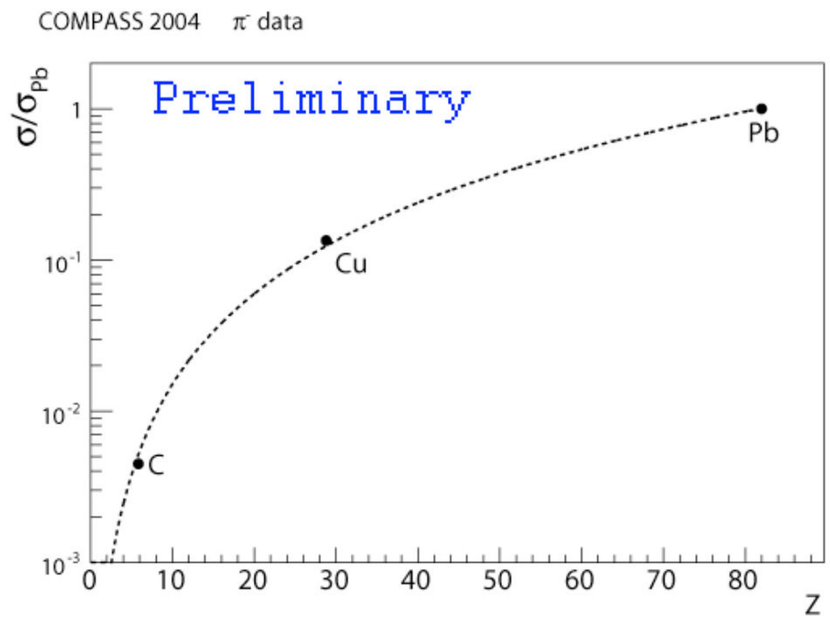
Unique at Compass :

- kaon component in hadron beam: kaon polarisability accessible
- availability of a muon beam (point like) for comparison/systematics
- switching between pion and muon beam within few hours possible

Projections for polarisabilities

Two Primakoff test runs were performed in 2004 & 2009





- expected precision of the new measurement:

in 120 d 90 d with π, 30 d of μ beam	$\alpha_\pi - \beta_\pi$ $(10^{-4}\ \mathrm{fm}^3)$	$\alpha_\pi + \beta_\pi$ $(10^{-4}\ \mathrm{fm}^3)$	$\alpha_2 - \beta_2$ $(10^{-4}\ \mathrm{fm}^5)$
2-loop ChPT prediction	5.70 ± 1.0	$.016 \pm 0.10$	16
COMPASS sensitivity	± 0.66	± 0.25	± 1.94

Conclusion (part III)

COMPAS has a great potential in new fields and work is started to get the spectrometer upgraded for the new programs:

- DVCS and DVMP for the study of GPDs in a kinematic region not yet covered by experiments
- in parallel with GPD measurement rich program in unpolarised DIS and SIDIS
- first polarised Drell-Yan experiment to study TMDs
- measurement of pion (kaon) polarisabilities
- data taking in 2012, 2014-2016