

# **CONCLUDING REMARKS**

**for the**

## **XIII International Workshop on Hadron Structure and Hadron Spectroscopy**



**Suzdal, Russia, 18-20 May 2015**

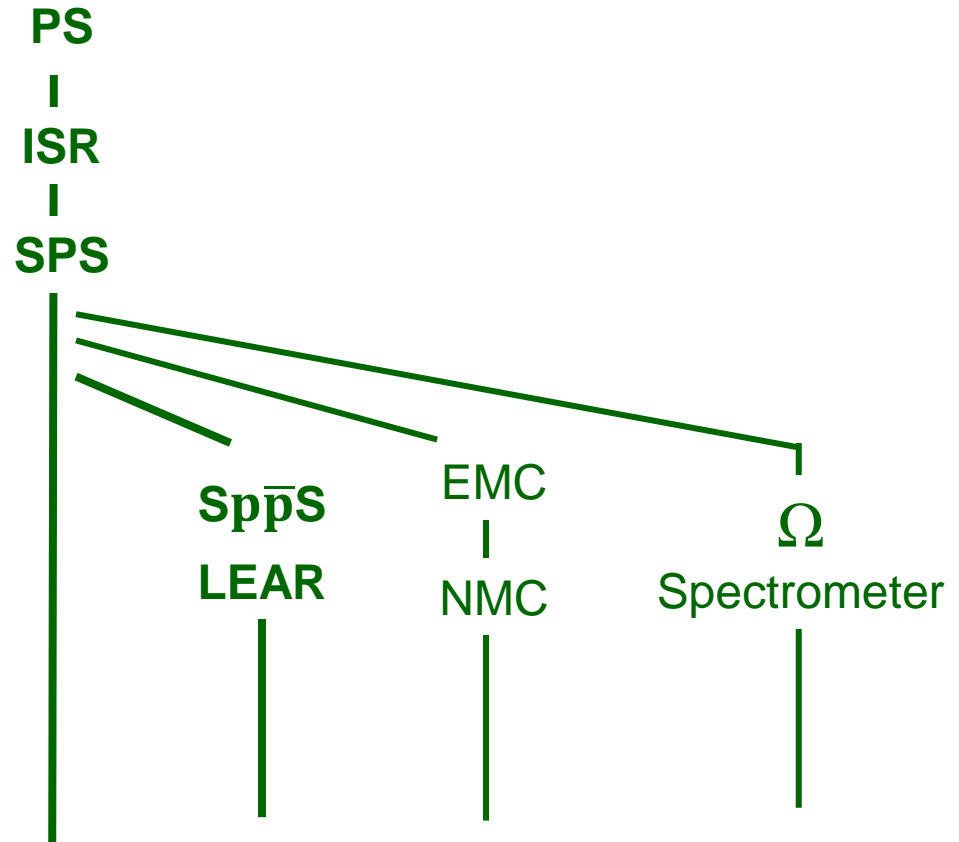
**Franco Bradamante**

**Trieste University & INFN**

# WHO WE'VE BEEN AND WHERE WE'RE GOING

CERN

*unlimited growth* '62



# WHO WE'VE BEEN AND WHERE WE'RE GOING

## CERN

*unlimited growth '62*

PS  
|  
ISR  
|  
SPS

Spp̄S  
|  
LEAR

EMC  
|  
NMC  
|  
SMC

Ω  
|  
Spectrometer

*Abragam Committee '86-'88*

LEP

# WHO WE'VE BEEN AND WHERE WE'RE GOING

## CERN

*unlimited growth '62*

PS

|  
ISR

|  
SPS

|

Spp̄S

LEAR

|

EMC

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NMC

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SMC

|

Ω

Spectrometer

|

*Abragam Committee '86-'88*

LEP

*Summer '95: closure of West Area*

*closure of LEAR*

*Summer '96: ~ 10% budget cut*

**Febr. '96: COMPASS Proposal**



# WHO WE'VE BEEN AND WHERE WE'RE GOING

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LEP

*Summer '96: ~ 10% budget cut*

Febr. '96: COMPASS Proposal

Sept. '96: recommendation from SPSC

# WHO WE'VE BEEN AND WHERE WE'RE GOING



Sept. 10, 1996: recommendation from SPSC

Sept. 11, 1996

S. Masciocchi

J.P. Stroot

Yu. Prokoshkin

# WHO WE'VE BEEN AND WHERE WE'RE GOING



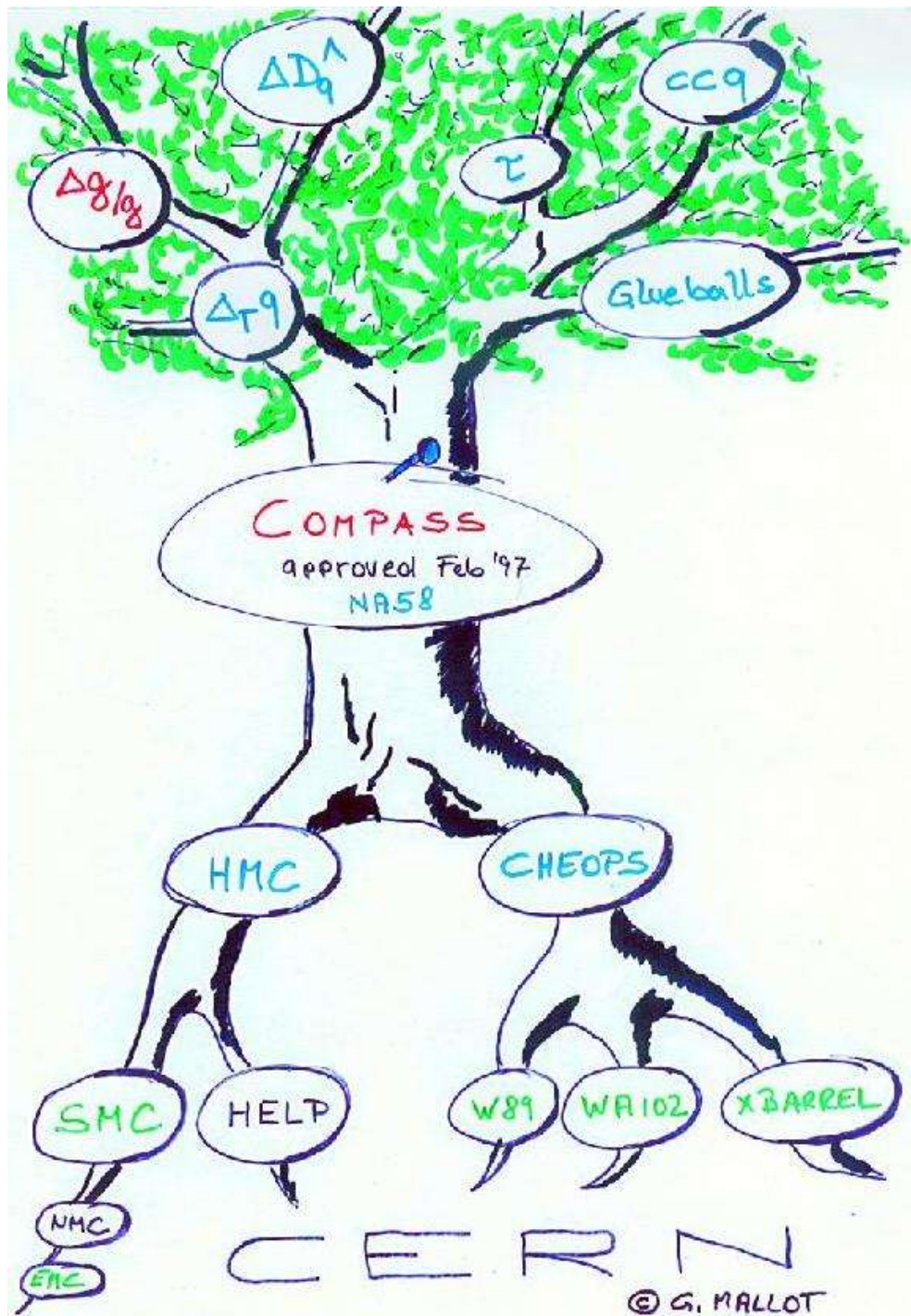
LEP

*Summer '96: ~ 10% budget cut*

Febr. '96: COMPASS Proposal

Sept. '96: recommendation from SPSC

Febr. '97: conditional approval by RB



© G. MALLOT



# WHO WE'VE BEEN AND WHERE WE'RE GOING



LEP

Summer '96: ~ 10% budget cut

Summer 2000: LEP shut down

Febr. '96: COMPASS Proposal

Sept. '96: recommendation from SPSC

Febr. '97: conditional approval by RB

March 1, 1997

Summer 2002:  
first data taking

# WHO WE'VE BEEN AND WHERE WE'RE GOING



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March 1, 1997

Summer 2002:  
first data taking

LHC

2012

2015

COMPASS-II

# International Workshops on Structure and Spectroscopy

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1999	Oct. 11-13	TUM Munich
2000	Oct. 9-12	Dubna
2002	Feb 18-20	Trieste
2003	Oct 1-3	Lisbon
2004	Mar 1-5	Paris
2005	Aug. 1-3	Prague
2006	Feb 15-17	Warsaw
2007	Mar 19-21	Freiburg
2008	Mar 31 Apr 2	Torino
2009	Apr 2-3	Mainz
2010	Mar 14-22	Venice (Venice International University /LMU Munich)
2011	Apr 7-8	Paris
2012	Apr. 16-18	Lisbon
2013	July 25-26	Erlangen
2015	May 21-22	Suzdal (Dubna)
2016	Sept.5-7	<i>Kloster Seeon (TUM Munich)</i>

# International Workshops on Structure and Spectroscopy

IN BETWEEN, several topical workshops at CERN

Future Physics at COMPASS

Sept. 26-27 2002

and outside

**Future Physics @ COMPASS**  
CERN, September 26-27 2002

**Scientific Advisory Committee**

- G. Altarelli (CERN)
- F. Bradamante (Trieste)
- C. Detraz (CERN)
- M. Faessler (München)
- J. Fellesse (CERN)
- S. Forte (Roma)
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**Local Organizing Committee**

- F. Bradamante (Trieste)
- C. Detraz (CERN)
- F. Kunhe (Saclay)
- M. Lamanna (CERN)
- G. Mallot (CERN)
- S. Paul (München)

**Workshop Topics:**

- Nucleon Spin Structure
- Transversity
- DVCS
- $\chi$ PT Tests
- Exotics and Glueballs
- Double-Charmed Baryons

<http://compass-cw2002.web.cern.ch/compass-cw2002/>

# International Workshops on Structure and Spectroscopy

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From the web page of one of the first Workshops

## Purpose of the workshop

A new experimental facility for hadron physics (COMPASS) is entering into operation at CERN in the summer of 2001.

The main objective of this workshop is to bring together theorists and experimentalists to discuss physics topics potentially accessible to this and similar facilities, with particular emphasis on

**spin structure of the nucleons, e.g.**

- the gluon polarization of a longitudinally polarized nucleon
- the spin structure functions of the nucleon, and their flavour decomposition

**and on hadron spectroscopy and hadron structure, e.g.**

- tests of chiral perturbation theory with Primakoff reactions
- light quark spectroscopy above 1.5 GeV
- spectroscopy of charmed and doubly charmed baryons

**It took us 10 years, 2002 - 2012,  
but this programme has been fulfilled**

**spin structure of the nucleons, e.g.**

- the gluon polarization of a longitudinally polarized nucleon ✓
- the spin structure functions of the nucleon, and their flavour decomposition both in the helicity sector and in the transverse spin case ✓  
MOST IMPORTANT: Sivers effect NEW!

**and on hadron spectroscopy and hadron structure, e.g.**

- tests of chiral perturbation theory with Primakoff reactions ✓  
CERN Press Release 2015
- light quark spectroscopy above 1.5 GeV ✓
- spectroscopy of charmed and doubly charmed baryons ✓

# most important workshop for COMPASS after the Aymar era



## New Opportunities in the Physics Landscape at CERN 10-13 May 2009

recommendations of Andreas Schäfer:

- **GPD** physics needs all the experimental input it can get.
- Naive T-odd asymmetries are sensitive to non-trivial gauge-link physics. They have to be investigated in **SIDIS** and **Drell-Yan** experiments.

Such studies could trigger fundamental theoretical developments going beyond collinear factorization.

**NEW ADDENDUM** submitted in June 2009  
runs 2010 – 2011    T and L polarized **SIDIS**

**NEW PROPOSAL submitted in May 2010  
and approved by CERN RB in December (!)**

**DRELL-YAN      1 year      !! already started !!**

**GPD and SIDIS   2 years      2016 - 2017**

**and even ideas for beyond**

reports in July 2012 for the European Strategy Preparatory Group

**ALL this in close contact with the  
international community**



**WHAT WE HAVE DONE**

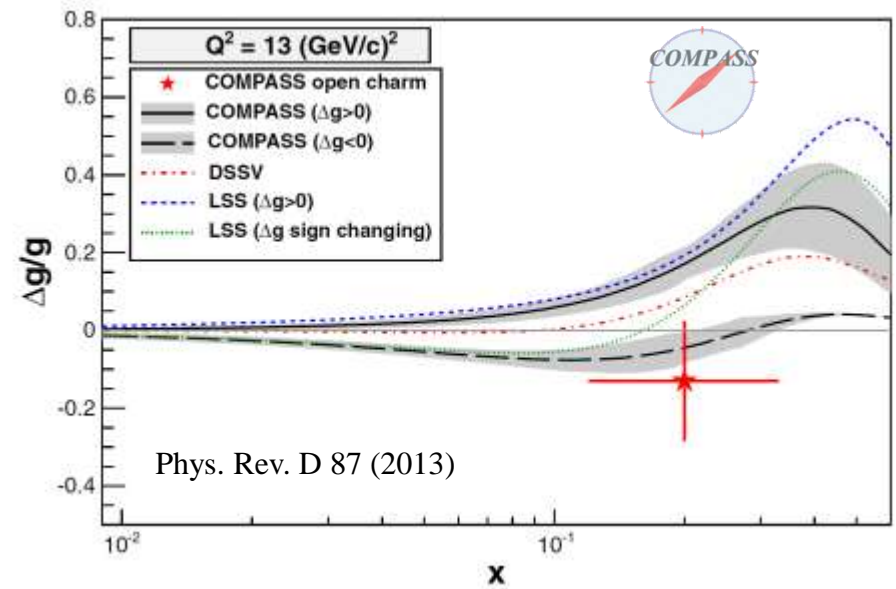
**and**

**WHAT REMAINS TO BE DONE**

# $\Delta G$

## $\Delta G$ by open charm

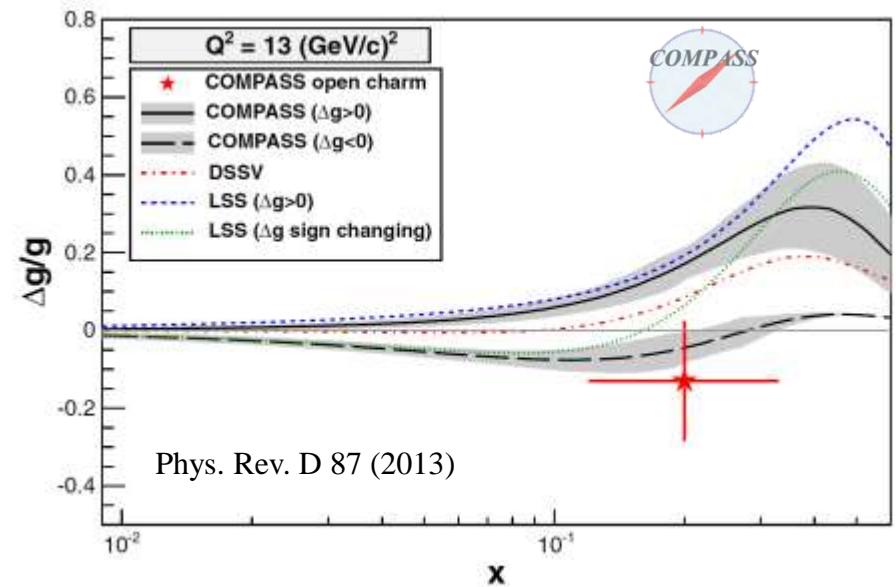
analysing power too small  
statistically limited



# $\Delta G$

## $\Delta G$ by open charm

analysing power too small  
statistically limited



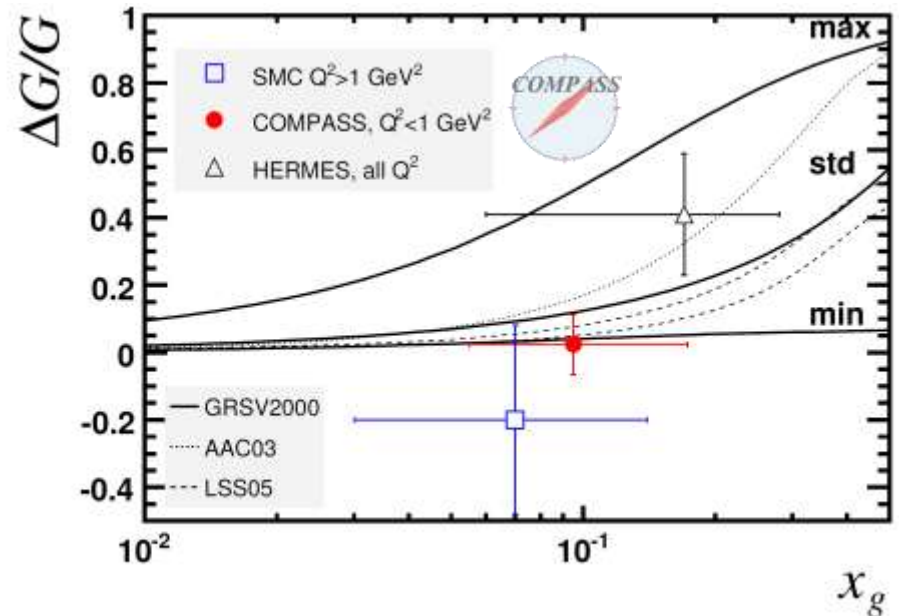
**BUT** we have invented the  
**high- $p_T$  hadron pair method**

A. Bravar, D. von Harrach, A. Kotzinian,  
Phys.Lett. B421 (1998)

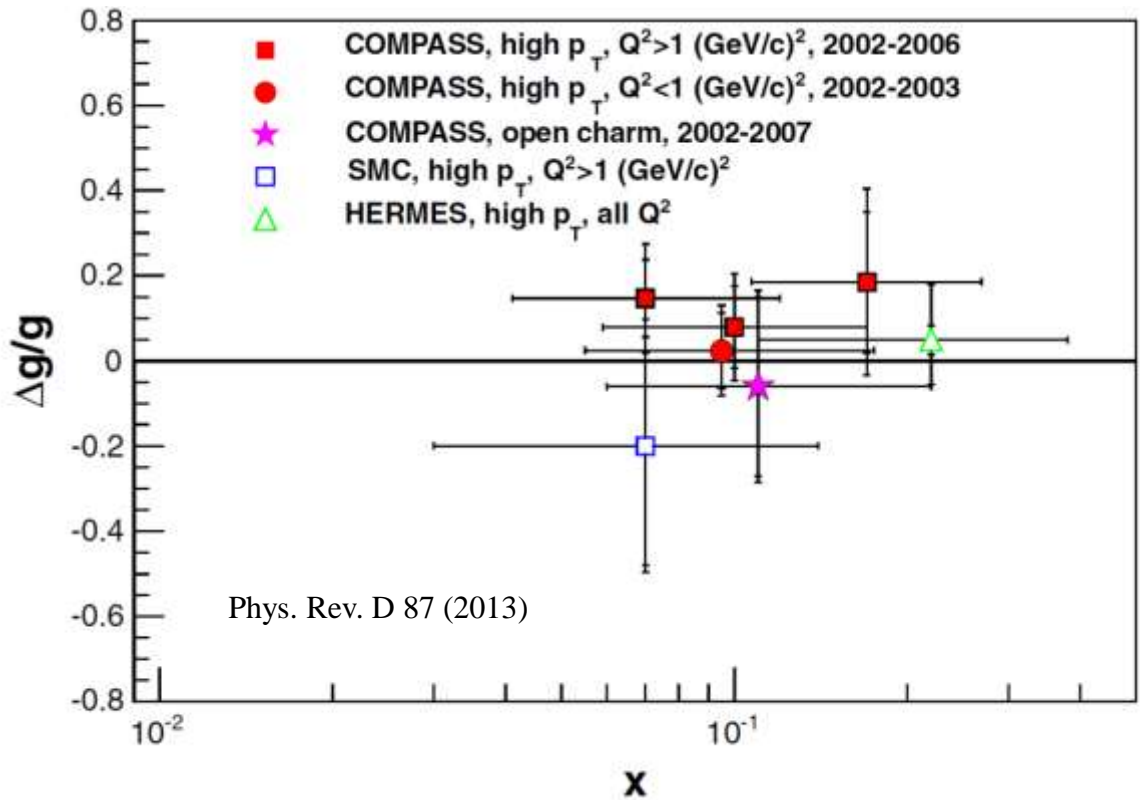
first exploited by HERMES

**COMPASS first to rule out  
large values of  $\Delta G$**

Phys. Lett. B 633 (2006)



## results at LO



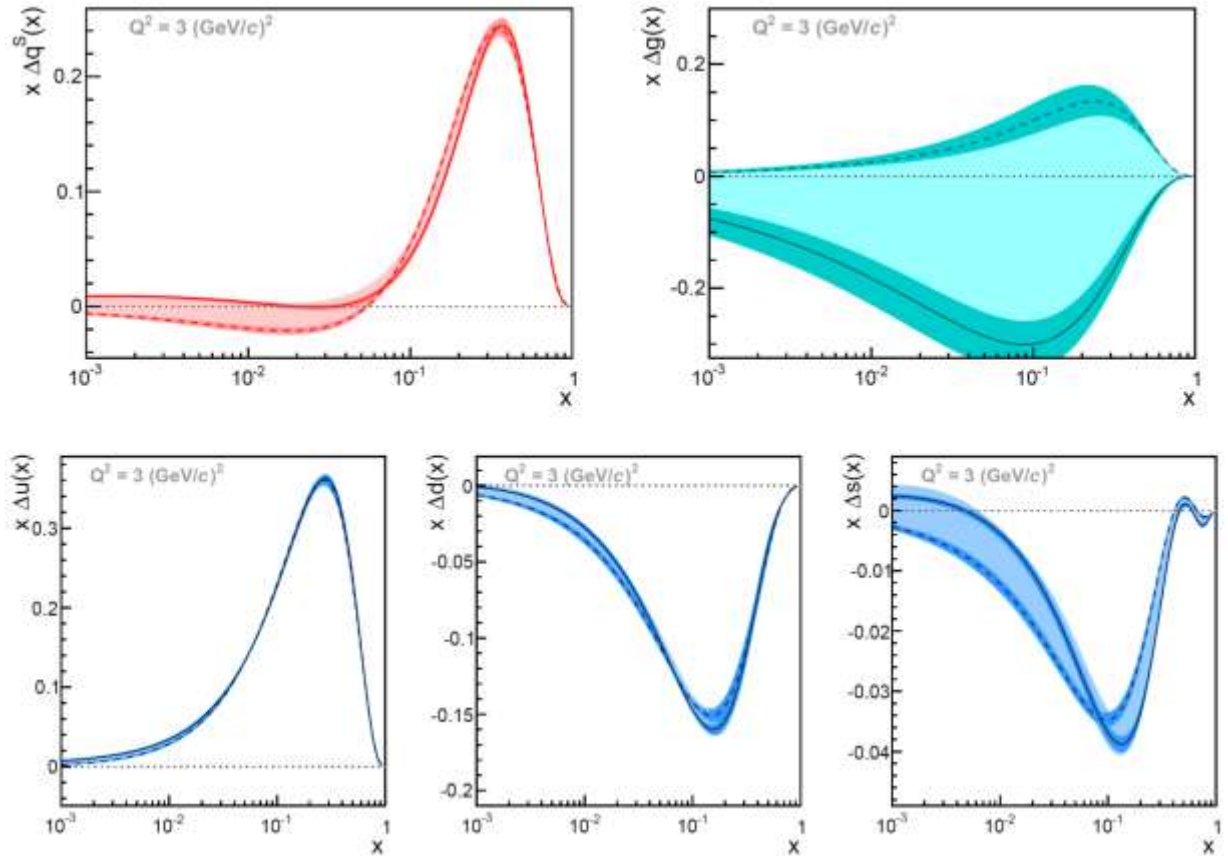
NB: COMPASS work on  $\Delta G$  ignored in

“The RHIC SPIN Program: Achievements and Future Opportunities “

arXiv:1501.01220 [nucl-ex]

# Helicity PDF and $\Delta\Sigma$

most recent  
QCD fits  
hep-ex/1503.08935  
subm. PLB



$a_0$  well constrained but  $\Delta\Sigma$  still affected by the  
poor knowledge of  $\Delta G$

# Extraction of $\Delta_s$

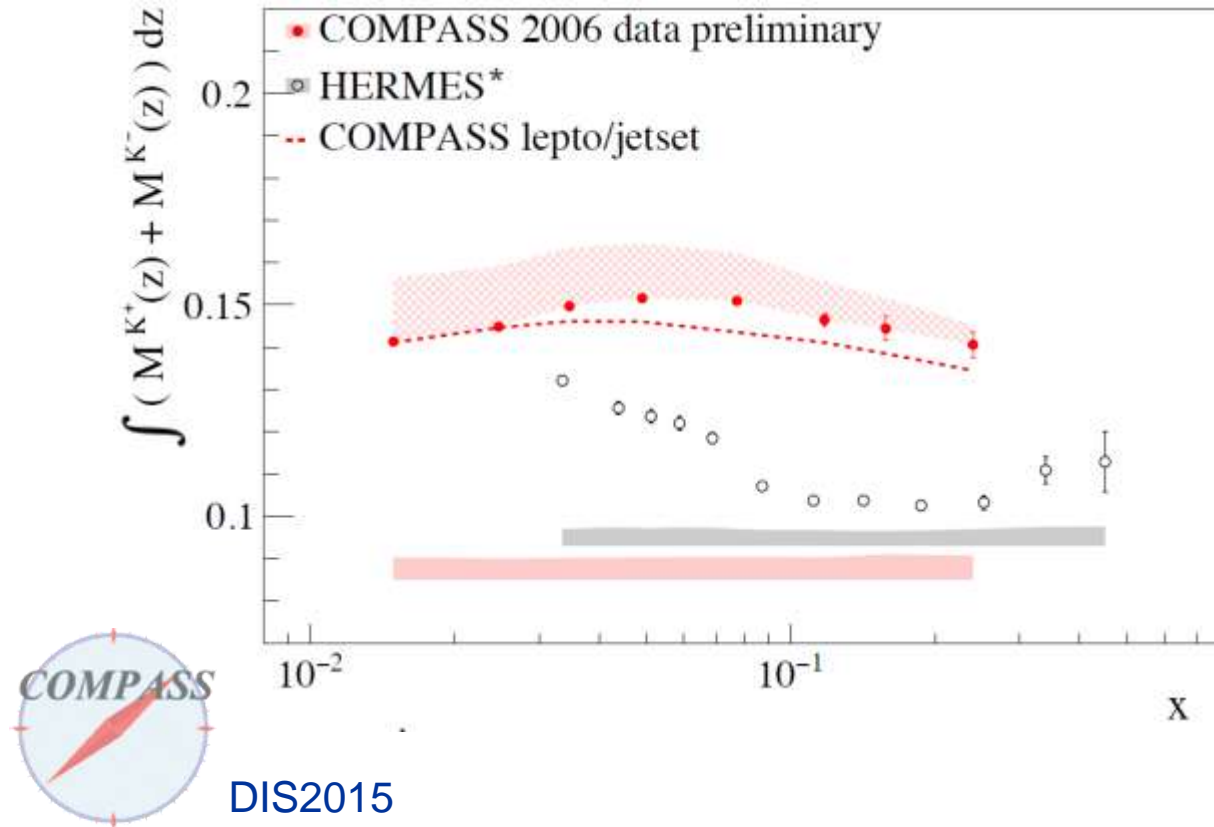
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**inconsistency between extraction from  
inclusive and semi-inclusive DIS data**

**uncertainty in the fragmentation functions  
→ hadron multiplicities**

# K Multiplicities in DIS

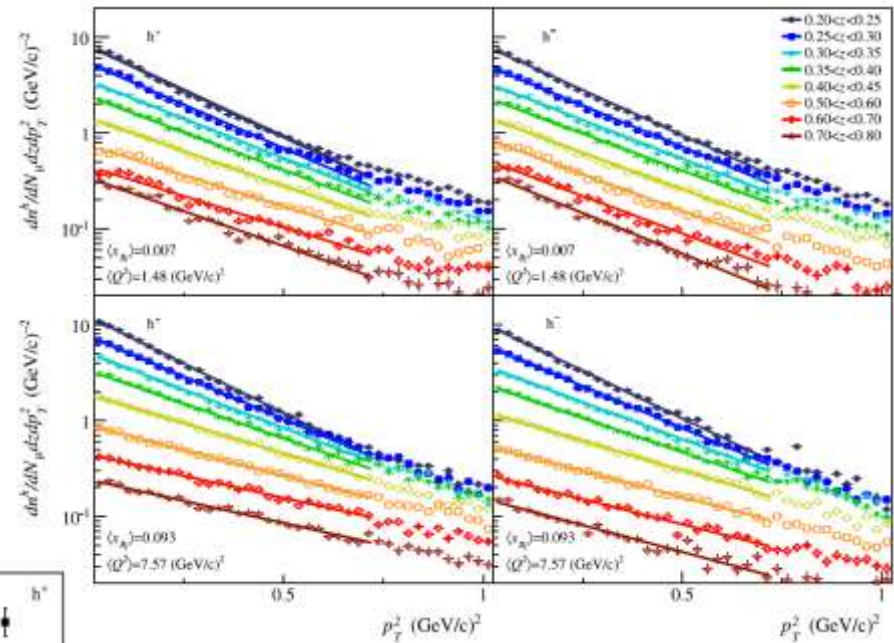
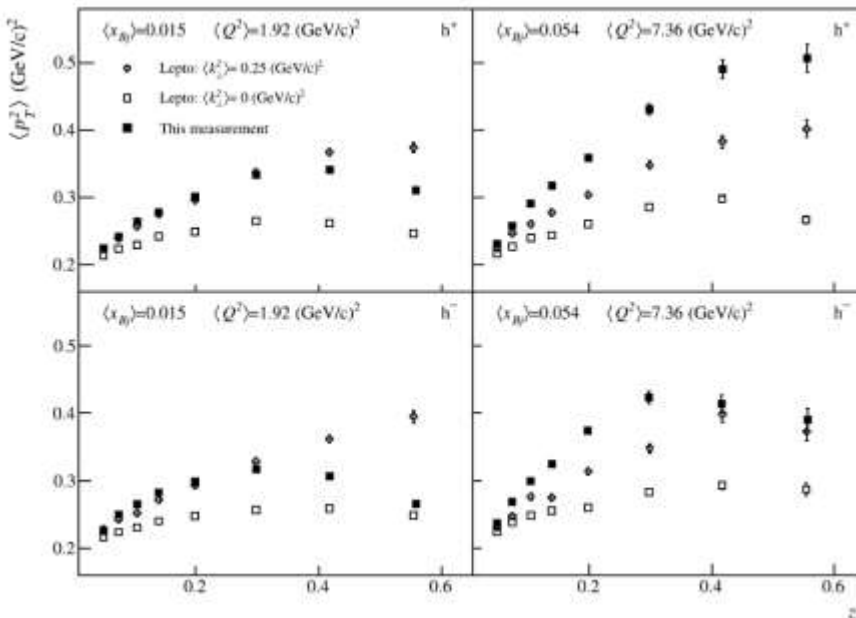
disagreement with HERMES still to be understood



# hadron transverse momentum distributions

huge map of  $x$ ,  $Q^2$ ,  $z$ ,  $W$   
dependence from 2004 data

Eur. Phys. J. C 73 (2013)



not easy to separate the intrinsic  
transverse momentum  $k_{\perp}$  of the  
parton from the hadron transverse  
momentum  $p_T$  with respect to the  
quark direction

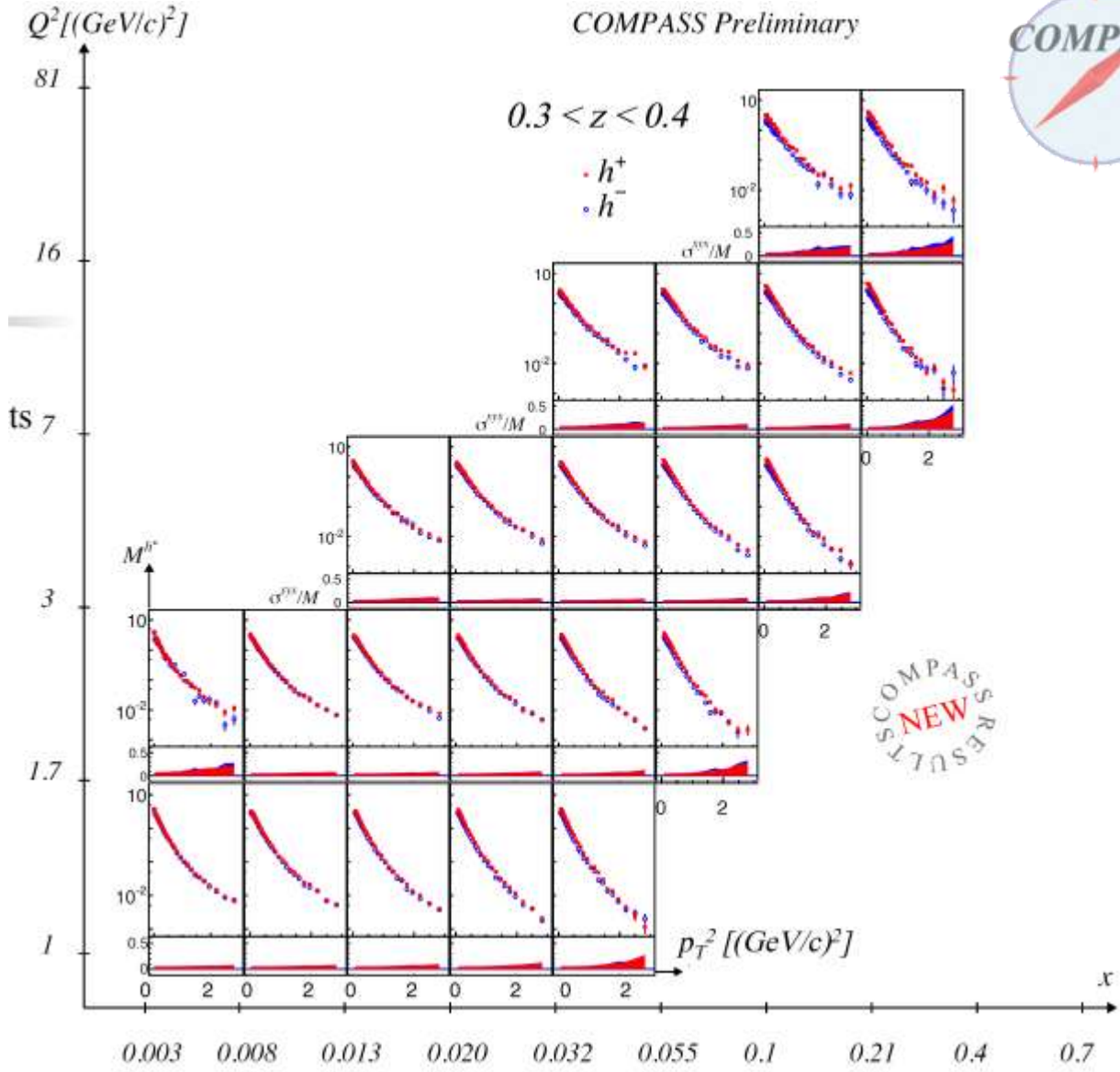
input from  $e^+e^-$  ?

Franco Bradamante



# hadron transverse momentum distributions

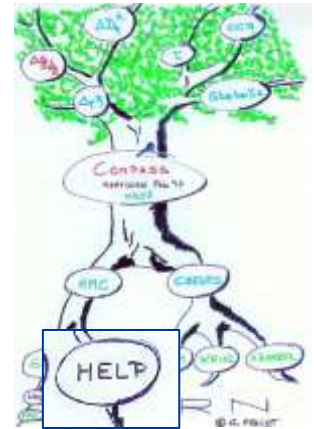
2006 data  
SPIN2014



# Transverse spin effects – Transversity PDF

**HELP experiment (L. Dick, R. Hess) rejected by CERN:  
regarded as black magic even by our Collaboration**

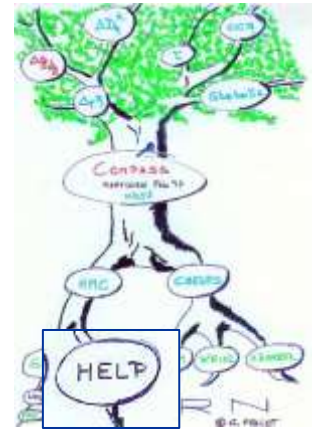
**accepted as a compromise  
20% of the running time with muon beam**



# Transverse spin effects – Transversity PDF

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**accepted as a compromise  
20% of the running time with muon beam**



**In my opinion the best results coming from COMPASS  
(and HERMES) in so far, and I am not the only one**

**549 citations HERMES p 2005  
330 citations COMPASS d 2005**

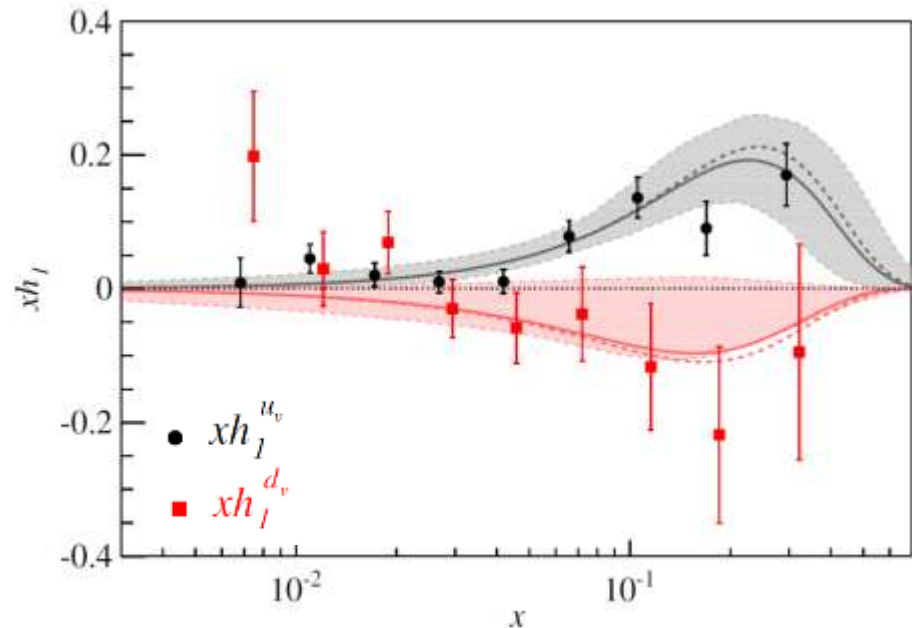
**MOST CITED**

# Transverse spin effects – Transversity PDF

Transversity is different from zero

it has been extracted from COMPASS, HERMES and  $e^+e^-$  data  
with “global” fits  
and  
point by point

see talk by  
Anna Martin



huge activity on these data

- $Q^2$  evolution of Collins FF
- tensor charge

more data  
on deuteron  
needed

# Transverse spin effects – Sivers PDF

---

the Sivers function story  
a long debate

important extension of the  
parton model → TMD

- 1992 introduced by D. Sivers
  - 1993 J. Collins demonstrates that it must vanish
  - 2002 S. Brodsky et al.: it can be  $\neq 0$  because of FSI
  - 2002 J. Collins: process dependent, change of sign SIDIS  $\leftrightarrow$  DY
- ....

**not in our Proposal (1996)**

luckily it can be measured in parallel with transversity

# Transverse spin effects – Sivers PDF

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happy end

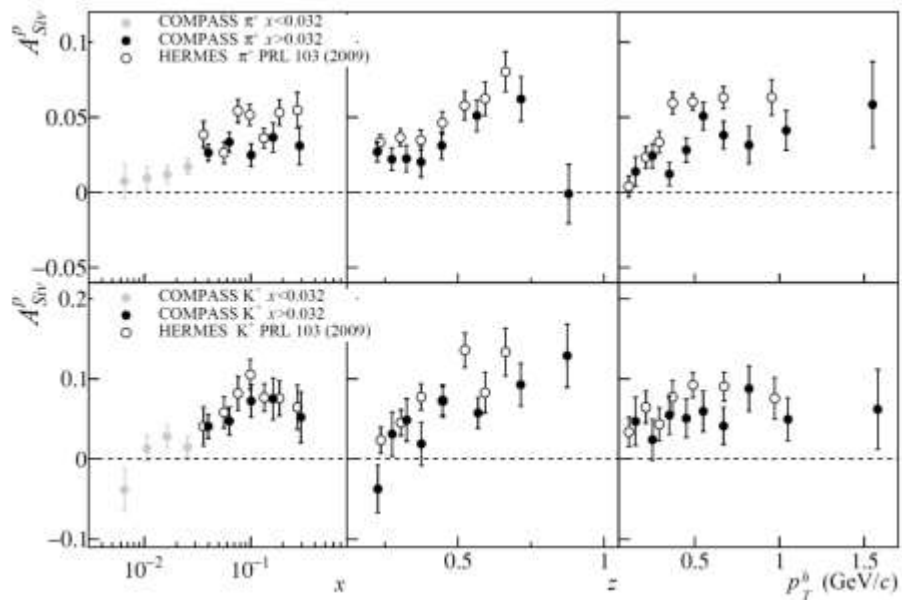
measured by HERMES and COMPASS to be different by zero

# Transverse spin effects – Sivers PDF

happy end

measured by HERMES and COMPASS to be different by zero

*plus interesting QCD evolution*



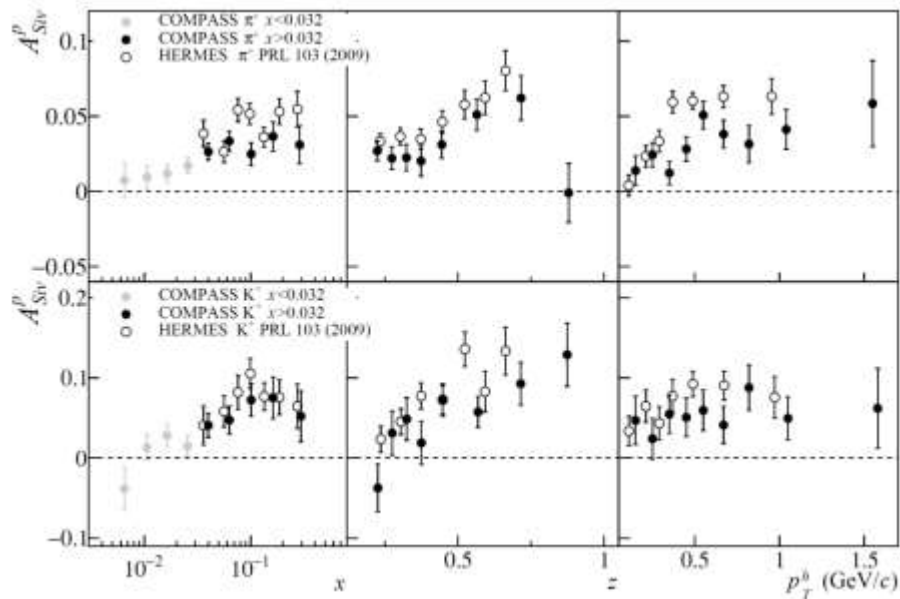
*very many papers !!*

# Transverse spin effects – Sivers PDF

happy end

measured by HERMES and COMPASS to be different by zero

*plus interesting QCD evolution*



*very many papers !!*

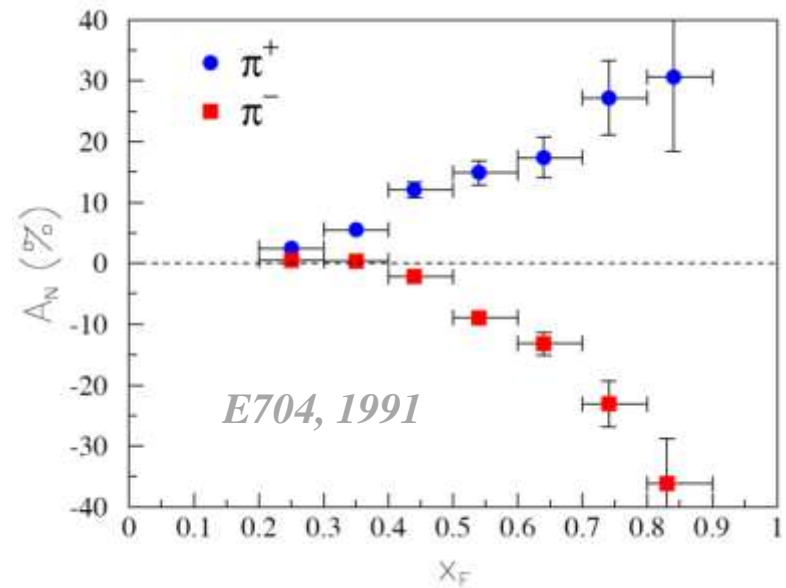
*plus important test ongoing to check the expected change of sign when going from SIDIS to Drell-Yan*



# Transverse spin effects – Sivers PDF

still to be done:

- link between Sivers function and OAM
- explain  $A_N$  in  $pp^\uparrow \rightarrow \pi X$



# study of the 3D structure of the nucleon

---

will go on at COMPASS

**DVCS / DVMP measurements**                      **2016-2017**

with  $\mu^+$  and  $\mu^-$  and a 2.5 m long LH target

*proposed to COMPASS by Nicole d'Hose already in 2002*

**and in parallel SIDIS**

**DRELL-YAN measurements**                      **2015 ...**

with  $\pi^-$  and  $p^\uparrow$  (NH<sub>3</sub>) target

*proposed by COMPASS at Villars 2004*

**and hopefully more later on ....**

# LASTLY, the OTHER side of the moon

# $\pi$ polarizability

---

had to be an “easy” measurement, to be done with an incomplete spectrometer

“the first” to be done

the lack of EM colorimetry allowed only for a short pilot run in 2004

but **the result of the 2009 run made us famous !**

PRL 114 (2015)



## COMPASS

Precise new result aligns with QCD benchmark  
p5

VIE

Luci  
the  
of li  
p5

## News

QCD PHYSICS

# COMPASS measures the pion polarizability

The COMPASS experiment at CERN has made the first precise measurement of the polarisability of the pion – the lightest composite particle built from quarks. The result confirms the expectation from the low-energy expansion of QCD – the quantum field theory of the strong interaction between quarks – but is at variance with the previously published values, which overestimated the pion polarisability by more than a factor of two.

Every composite system made from charged particles can be polarized by an external electromagnetic field, which acts to separate positive and negative charges. The size of this charge separation – the induced dipole moment – is related to the internal field by the polarizability. As a measure of the response of a complex system to an external force, polarizability is directly related to the system's stiffness against deformation, and hence the binding force between the constituents.

The pion, made up of a quark and an antiquark, is the lightest object bound by the strong force and has a size of about  $0.8 \times 10^{-15}$  m (0.6 fm). So to observe a measurable effect, the particle must be subjected to electric fields in the order of 100 kV across its diameter – that is, about  $10^{12}$  V/m. To achieve this, the COMPASS experiment made use of the electric field around nuclei. To high-energy pions, this



Such pion-photon Compton scattering, also known as the Primakoff mechanism, was explored in the early 1980s in an experiment at Serpukhov, but the small data sample led to only an imprecise value for the polarizability of  $6.8 \pm 1.4 (\text{stat.}) \pm 2.0 (\text{sys.}) \times 10^{-4} \text{fm}^3$ , when the systematic uncertainty was underestimated, presumably.

COMPASS has now achieved a modern Primakoff experiment, using a 190 GeV pion beam from the Super Proton Synchrotron at CERN directed at a rickety target. Importantly, COMPASS was also able to use muons, which are point-like and hence non-deformable, to calibrate the experiment. The Compton  $\pi^+ \rightarrow \pi^+$  scattering is corrected from the emission  $\pi^+ N \rightarrow \pi^+ N$  by selecting events from the Coulomb peak at small momentum

The COMPASS experiment at the North Area of the Proton Synchrotron at CERN studies hadrons like pions both with gluons and with more heavy – or powerful – quarks. (Image credit: CERN-EX-1105182-01)

transfer. From the analysis of a sample of 63000 events, the collaboration obtained a value of the pion electric polarizability of  $2.0 \pm 0.4 (\text{stat.}) \pm 0.7 (\text{sys.}) \times 10^{-4} \text{fm}^3$ , that is, almost 2 × 10<sup>-4</sup> of the pion's volume. This value is in good agreement with theoretical calculations in low-energy QCD, though differing along standing discrepancy between those calculations and previous experimental efforts to determine the polarizability.

Although this measurement is the first to allow a self-calibration, the accuracy is still below the quoted uncertainty of the calculations. With more data already recorded, the COMPASS collaboration expects to improve this result by a significant factor in the near future, and thereby probe further a benchmark calculation of non-perturbative QCD.

### Further reading

COMPASS Collaboration 2015 arXiv:1405.6377 [ hep-ex ], to be published in Phys. Rev. Lett.

### Sommaire en français

COMPASS mesure la polarisabilité du pion  
L'année internationale de la lumière  
Remise des prix pour l'exploration de la  
nouvelle physique de l'interaction forte





# Press echo in spring 2015



**ScienceDaily**  
Your source for the latest research news

**Featured Research**  
CERN experiment brings precision to a cornerstone of particle physics

Date: February 11, 2015

Source: CERN

**Summary:** The COMPASS experiment at CERN reports a key measurement on the strong interaction. The strong interaction binds quarks into protons and neutrons, and protons and neutrons into the nuclei of all the atoms from which matter is built. Inside every nucleon, particles called quarks make up a quark and an antiquark, and the interaction between them is the strong interaction. This interaction is the glue that holds the nucleus together. The possibility has existed since the 1930s, whether the strong interaction is the same for all particles with the same quantum numbers. This possibility has been tested with the COMPASS experiment. The result is in close agreement with theory.

# Focus.it

SCIENZA AMBIENTE TECNOLOGIA CULTURA COMPORTAMENTO FOTO

## L'interazione forte dei quark ha meno segreti

L'esperimento COMPASS al CERN fornisce una misura chiave dell'interazione forte.



Lo spettrometro dell'esperimento COMPASS. È lungo 60 metri e lo suo interno vengono sparati raggi di particelle subatomiche ad alta intensità.

**Neue Zürcher Zeitung**  
PHYSIK UND CHEMIE  
Pionen-Experiment am CERN  
**Da schwabbelt nichts**  
11.2.2015, 17:08 Uhr

rtz. Wieder hat ein Experiment die theoretischen Vorhersagen des Standardmodells der Teilchenphysik bestätigt. Diesmal massen die Forscher die Verformbarkeit sogenannter Pionen. Diese gibt Aufschluss darüber, wie stark die Bindungskraft zwischen den Elementarteilchen im Inneren von Atomkernen ist.

**AVENIR Fondamental**  
À LA UNE

**Le pion se déforme moins que prévu**

C'est la confirmation d'une donnée de physique fondamentale que fournit l'expérience COMPASS menée au CERN sur une mesure clé à l'interaction forte, la force qui lie quarks, neutrons et protons.



**ScienceSeeker**  
Science news from science newsmakers  
**CERN Physicists Measure Polarizability of Pion**

COMPASS collaboration have made the most precise measurement ever of the polarizability of the pion - the fundamental building block of matter. The pion is made up of quarks and leptons. Quarks are bound together in groups of three to make up the building blocks of matter.

Une expérience du CERN affine une mesure essentielle pour décrire l'interaction forte

L'expérience COMPASS du CERN, impliquant le CEA et des partenaires internationaux, rapporte une mesure clé de la physique fondamentale. Cette mesure concerne la déformabilité des pions, les briques de base de la matière. Les résultats, obtenus sur une mesure clé de la physique fondamentale, ont été publiés dans la revue Physics Review Letters, une revue de référence dans le domaine de la physique des particules.







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**Featured Research**

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Date: February 11, 2015

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**Summary:** The COMPASS experiment at CERN reports a key measurement on the strong interaction. The strong interaction binds quarks into protons and neutrons, and protons and neutrons into the nuclei of all the atoms from which matter is built. Inside every nucleon, particles called quarks make up a quark and an antiquark, and all the interactions among the quarks are described by a precise prediction on the strong interaction theory known as quantum chromodynamics. The possibility has existed since the 1930s, when the first measurements of the strong interaction were made, that the

## Neue Zürcher Zeitung

### Pionen-Experiment am CERN Da schwabb



**AVENIR Fondamental**  
À LA UNE

## Le pion se déforme moins que prévu

La confirmation d'une donnée de physique fondamentale que l'expérience COMPASS mesure au CERN sur une mesure relative, la force qui lie les quarks, neutrons et protons.

## Wydział Fizyki Uniwersytetu Warszawskiego

### Polaryzowalność pionów: pierwszy precyzyjny pomiar w CERN z udziałem fizyków warszawskich



Międzynarodowa współpraca COMPASS (Common Muon and Proton Apparatus for Structure and Spectroscopy, <http://www.compass.cern.ch/>), w skład której wchodzi około 250 fizyków z 33 laboratoriów na całym świecie, ogłosiła niedawno wyniki swoich badań nad polaryzowalnością pionów jakie od kilku lat prowadzi w Europejskim Laboratorium Fizyki Cząstek, CERN, w Genewie. Wyniki, opublikowane w najbardziej prestiżowym czasopiśmie naukowym The Physical Review Letters, wywołały wielką zainteresowanie światowej społeczności fizyków a władze CERN ogłosiły specjalny komunikat prób, na które się bowiem dotąd wykonał dokładny pomiar polaryzowalności pionów, którego nie

**НАУКА И ЖИЗНЬ**

19 февраля 2015

## Как COMPASS поляризовал пион

Пион оказался очень «жесткой» элементарной частицей – такой вывод сделали физики ЦЕРН на основе последних результатов в протонах и нейтронах, а протоны и нейтроны – в ядрах всех химических элементов, из которых построена материя. Частицы, состоящие из кварков и антикварков, называемые пионами, являются переносчиками сильного взаимодействия между кварками. Взаимодействие дает точное предсказание для физической величины.

Scientists from pion – the fundamental blocks [...]



Lo spettrometro dell'esperimento COMPASS. È lungo 60 metri e lo suo interno vengono sparati raggi di particelle subatomiche ad alta intensità.

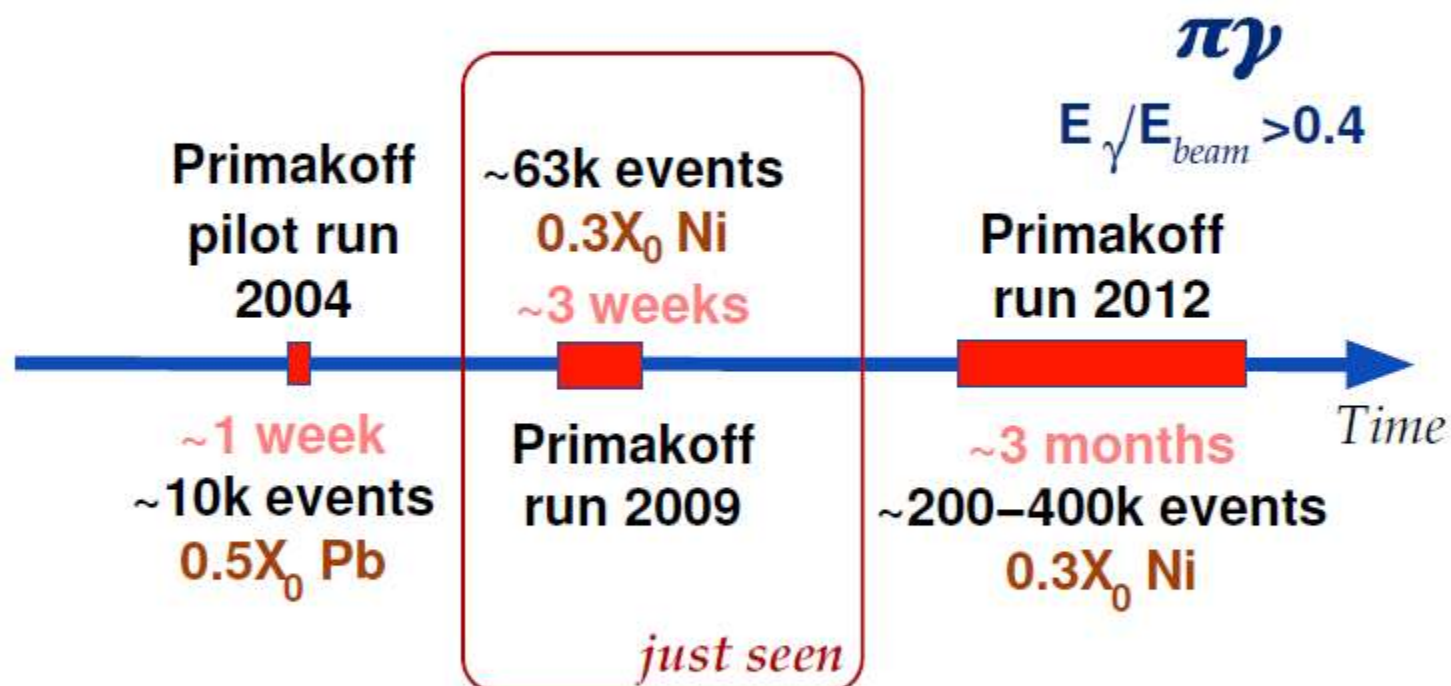
**irfu**

Une expérience du CERN affine une mesure essentielle pour décrire l'interaction forte

L'expérience COMPASS du CERN, impliquant le CEA et des partenaires internationaux, rapporte une nouvelle mesure de la polarisation du pion. Cette mesure est essentielle pour comprendre les propriétés du pion et de la force qui lie les quarks, neutrons et protons. Les résultats, présentés dans le plus grand des journaux de physique, le Physical Review Letters, ont été publiés avec le soutien des performances exceptionnelles de l'expérience.



# Pion polarisability measurements at COMPASS



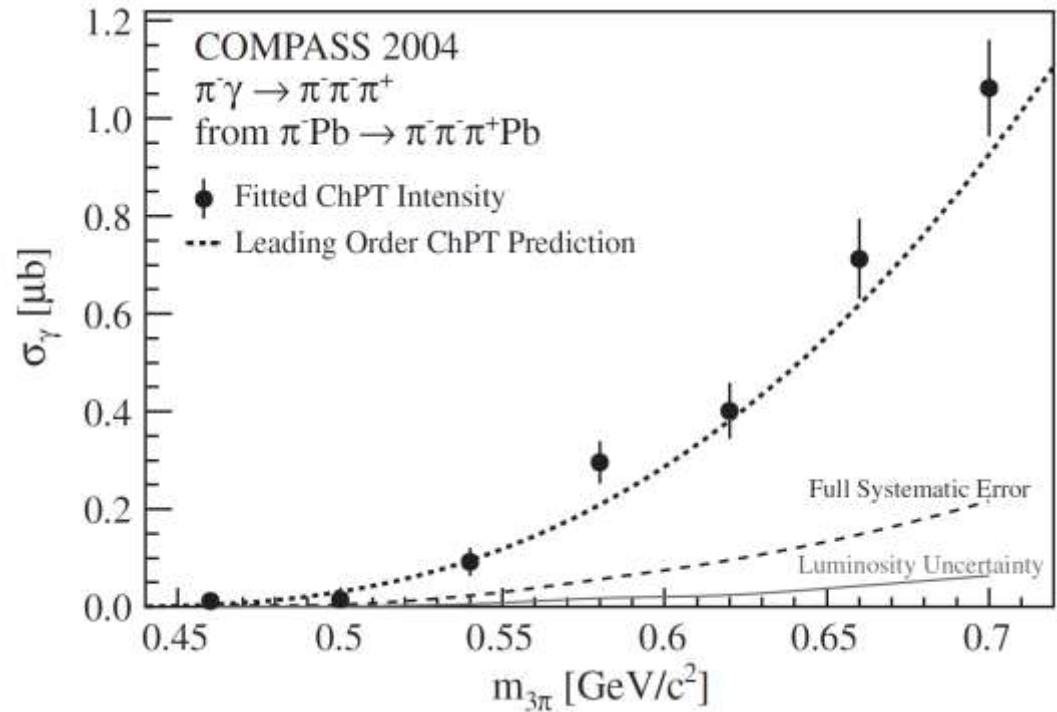


# More tests of chiral dynamics

Tests of chiral dynamics  
also in the channel

$$\pi^- \gamma \rightarrow \pi^- \pi^- \pi^-$$

PRL 108 (2012)

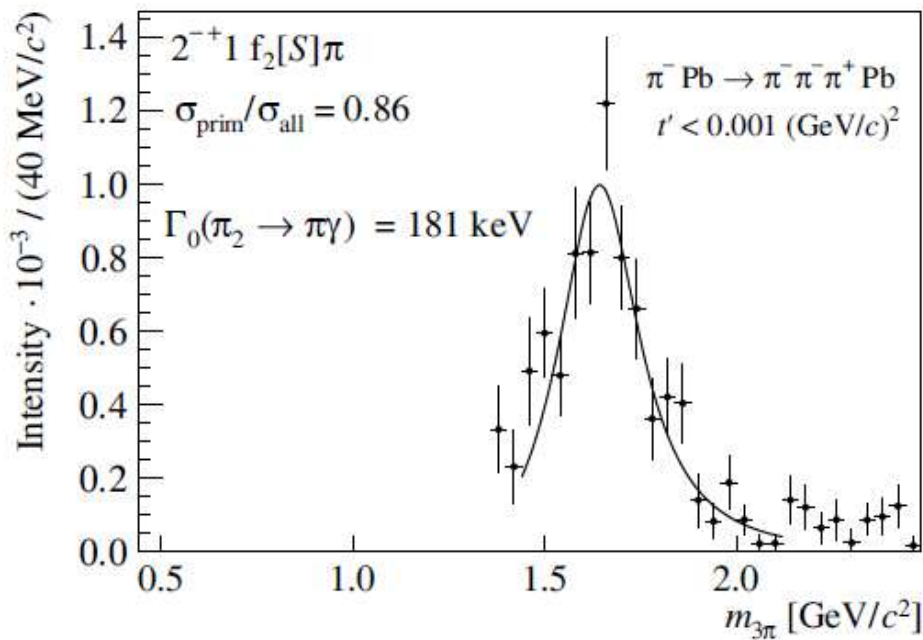


# More tests of chiral dynamics

## Radiative widths of $a_2(1320)$ and $\pi_2(1320)$

EPJA 50 (2014) 79

### EPJ A Highlights



# Light Meson Spectroscopy

---

Huge amount of data accumulated in 2008-2009

**Open problem:**  $J^{PC} = 1^{-+}$  exotic  $\pi_1(1600)$

PRL 104 (2010)


impressive phase-shift analysis  
investigation still ongoing



$\pi_1(1600)$



$\pi_1(1600)$



$\pi_1(1600)$

# Light Meson Spectroscopy

Huge amount of data accumulated in 2008-2009

**Open problem:**  $J^{PC} = 1^{-+}$  exotic  $\pi_1(1600)$

PRL 104 (2010)

impressive phase-shift analysis  
investigation still ongoing

**Mostly rewarding:**  $a_1(1420)$

sub PRL

a narrow state  $J^{PC} = 1^{++}$

observed in the exotic  $f^0(980) \pi$  channel

but at which price !!

phase-shift analysis of  $\pi^- p \rightarrow \pi^- \pi^- \pi^- p$  : **50 M events !**

**88 waves !**



# Concluding Remark

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**the work is not over**

**20 years have not been enough**

**as the CERN Director of Research says**

**“ it has not been easy to have COMPASS approved,  
it will not be easy to shut it down over the third  
millennium ”**