# The COMPASS Experiment
# and
# the SPIN structure of the NUCLEON

**Franco Bradamante**
**Trieste University and INFN**

**Prague Scientific Symposium 26/10/2012**

COMPASS

*COmmon*
*Muon and*
*Proton*
*Apparatus for*
*Structure and*
*Spectroscopy*

**fixed target experiment at the CERN SPS**

***COmmon***
***Muon and***
***Proton***
***Apparatus for***
***Structure and***
***Spectroscopy***

**fixed target experiment at the CERN SPS**

## physics programme:

**hadron spectroscopy** (p, π, K)

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

**nucleon structure** (μ)

- longitudinal spin structure
- transverse momentum and transverse spin structure

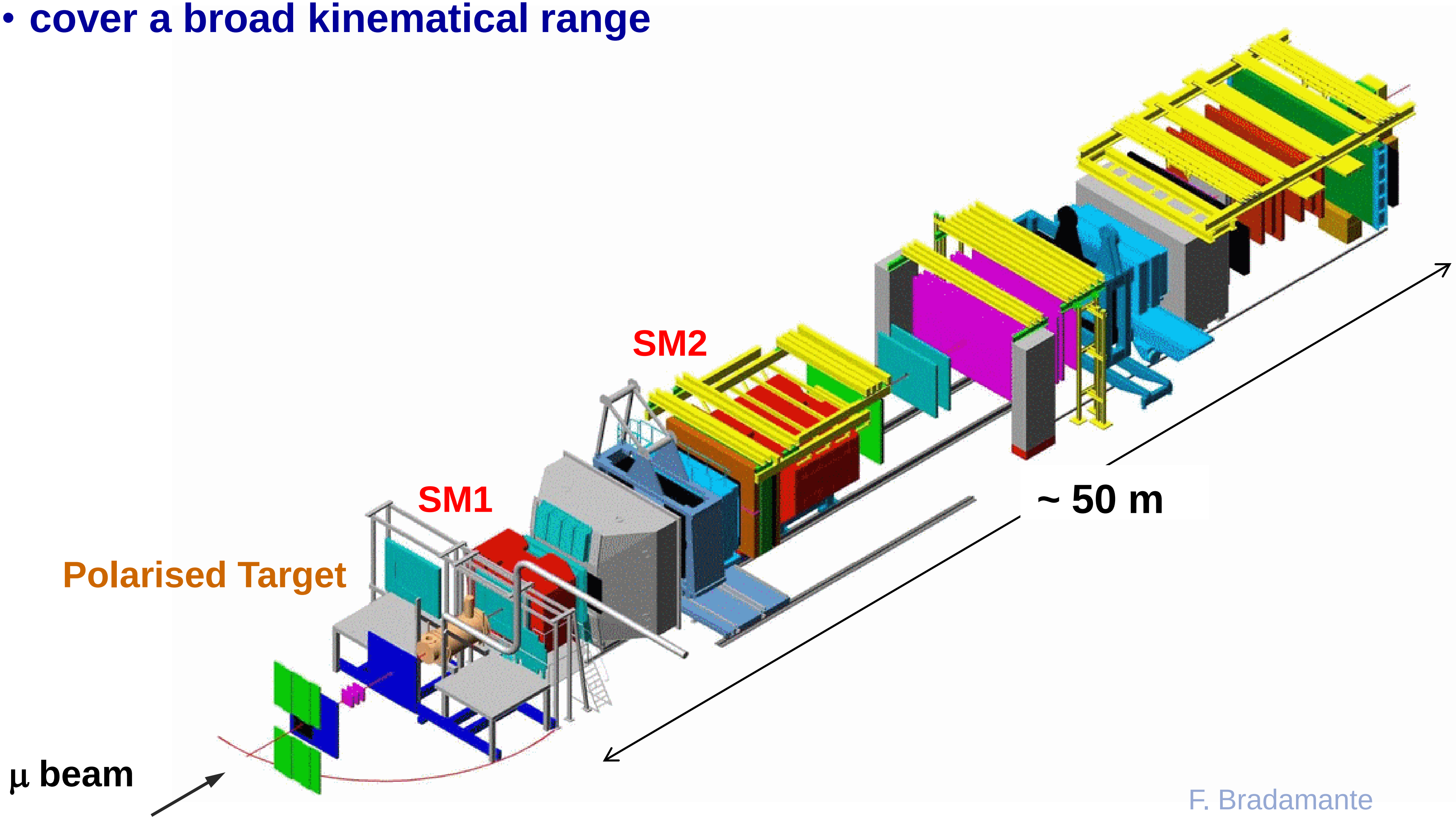
# The Spectrometer

designed to

- use high energy beams
- have large angular acceptance
- cover a broad kinematical range

two stages spectrometer

- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)



F. Bradamante

# The Spectrometer

**designed to**

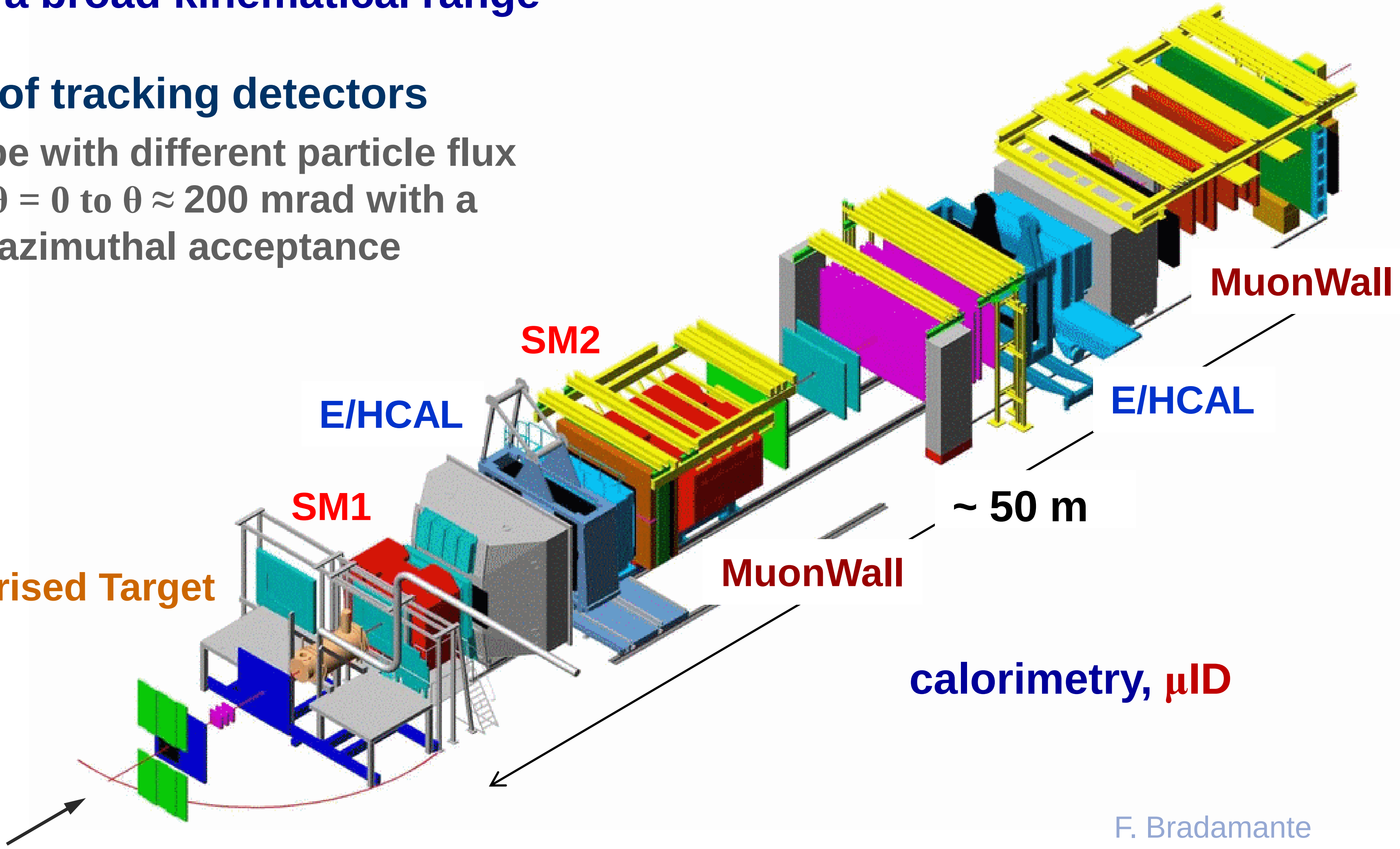
- **use high energy beams**
- **have large angular acceptance**
- **cover a broad kinematical range**

**two stages spectrometer**

- **Large Angle Spectrometer (SM1)**
- **Small Angle Spectrometer (SM2)**

**variety of tracking detectors**

**to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad with a good azimuthal acceptance**



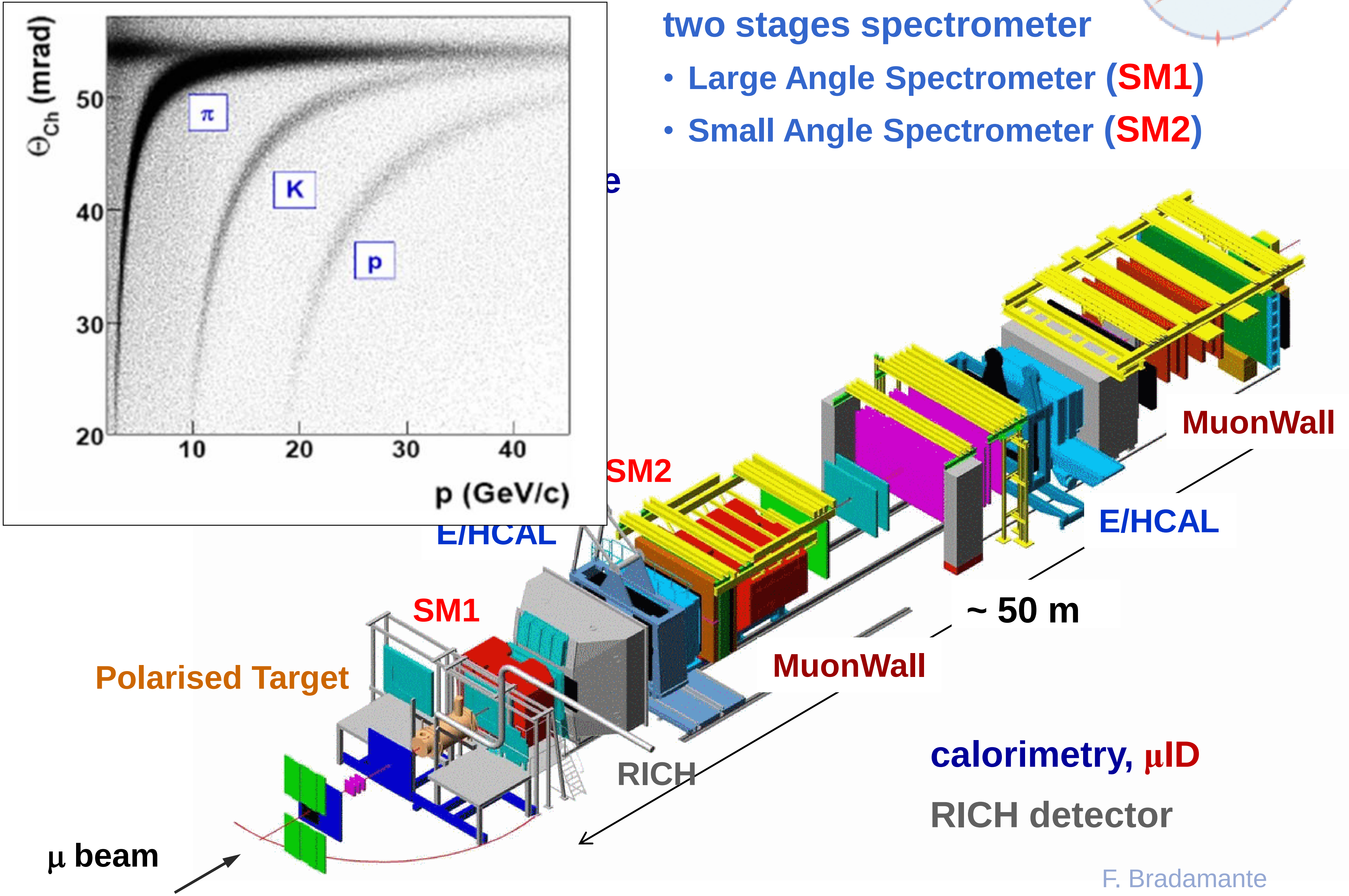
**calorimetry, μID**

F. Bradamante

# The Spectrometer

two stages spectrometer

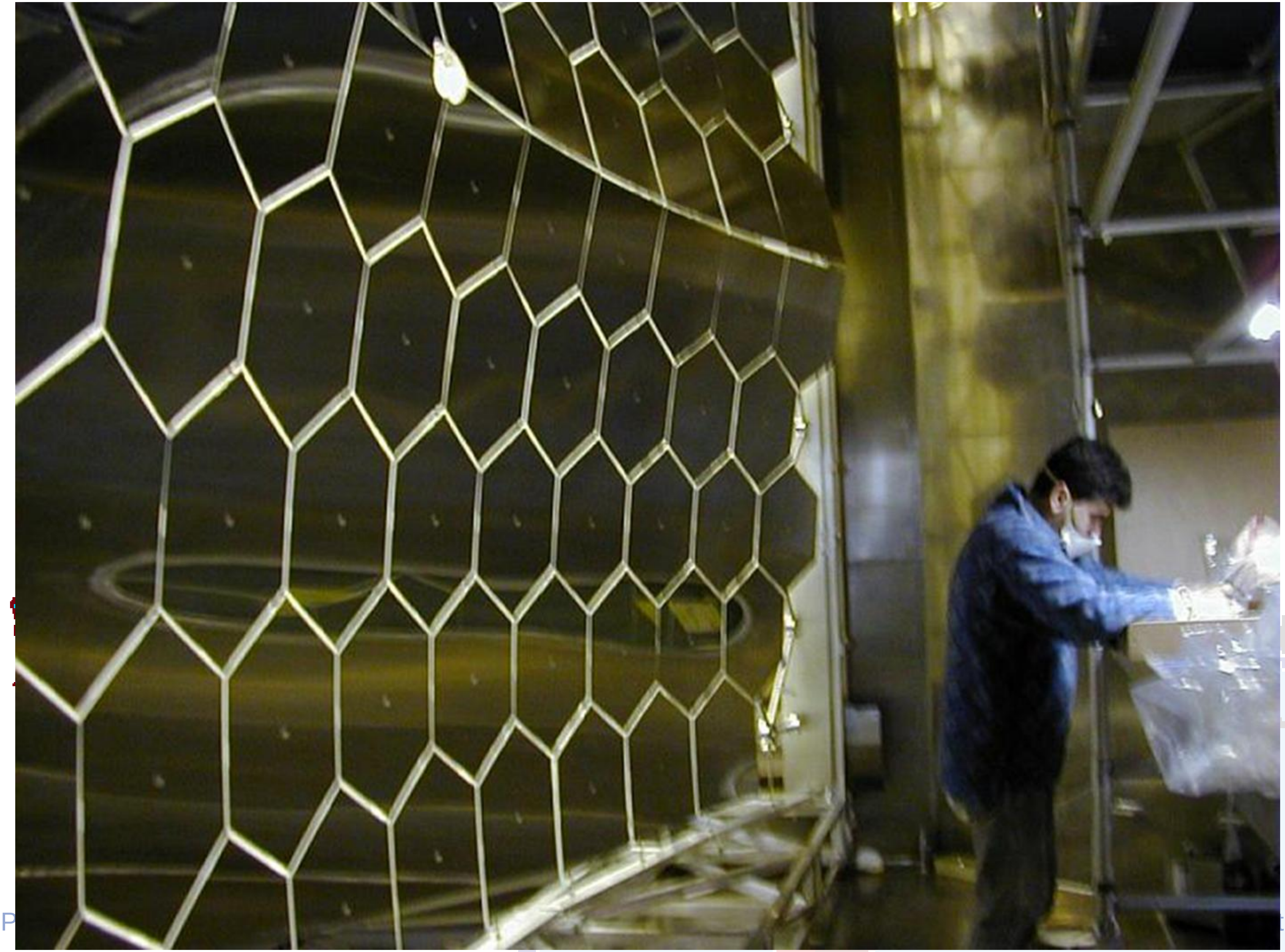
- Large Angle Spectrometer (**SM1**)
- Small Angle Spectrometer (**SM2**)



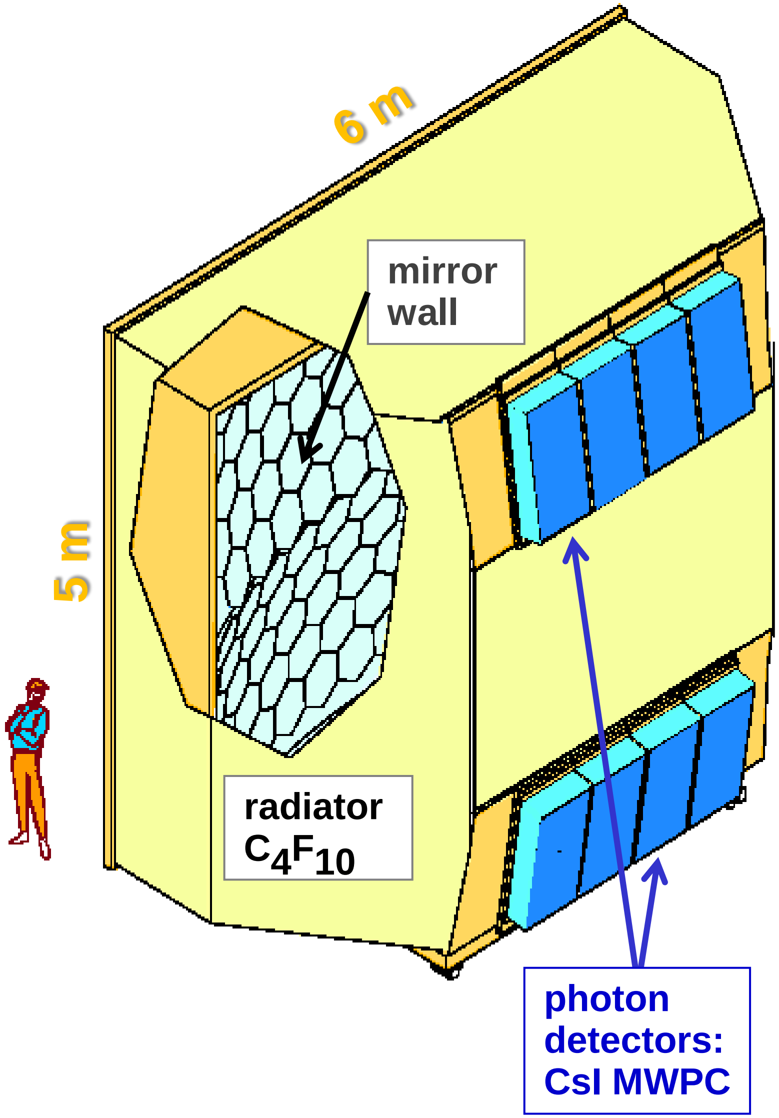
**calorimetry, μID**

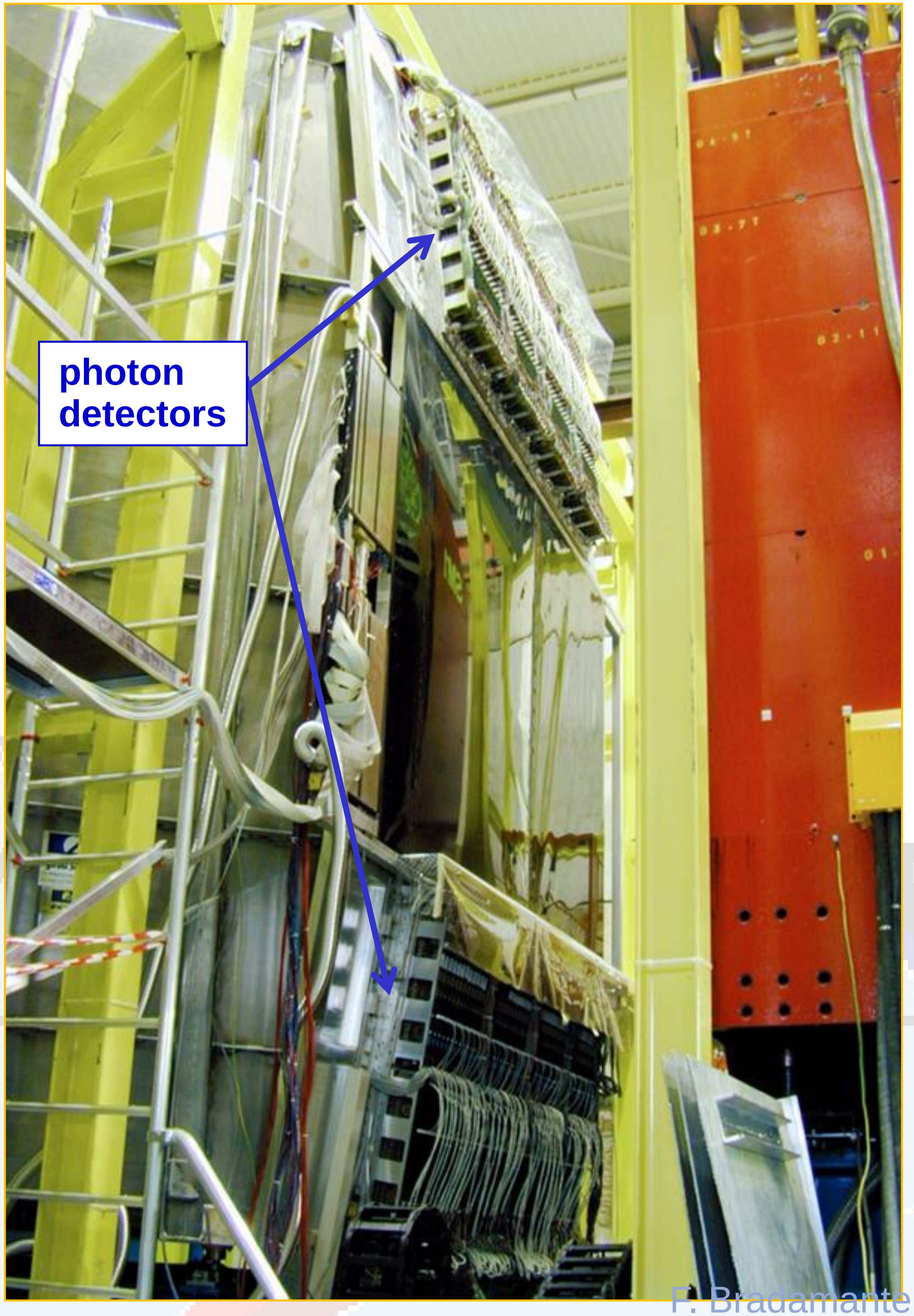
**RICH detector**

# The RICH 1 (<2005)

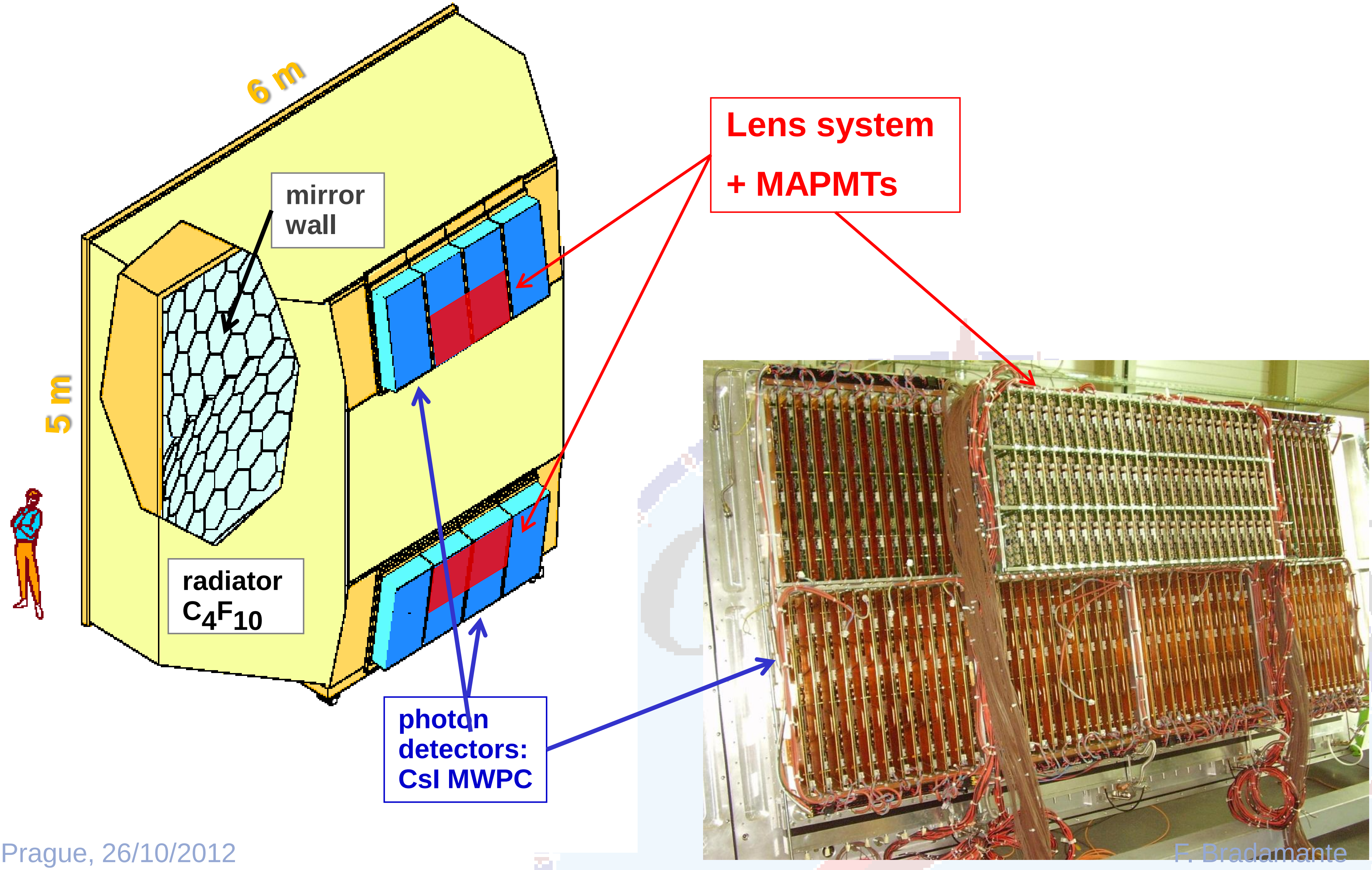


# The RICH 1 (<2005)





# The RICH 1 **Upgrade** (2005)



mirror wall

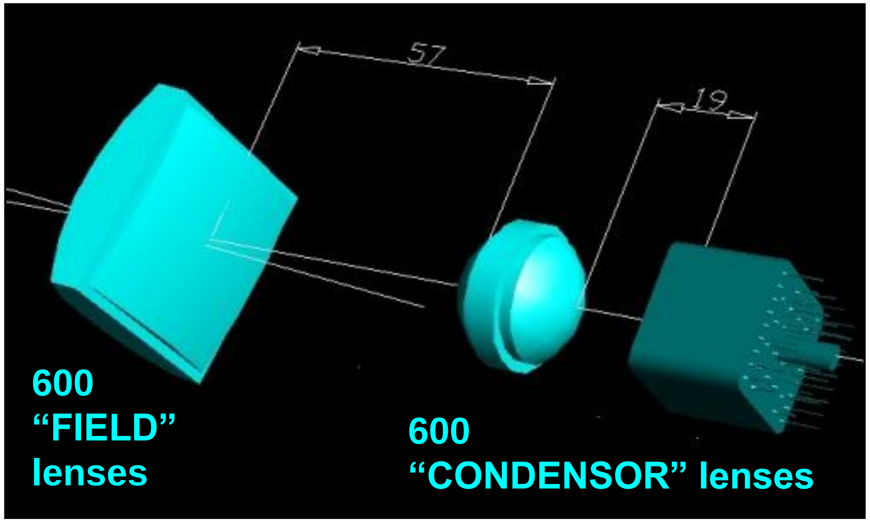
radiator $C_4F_{10}$

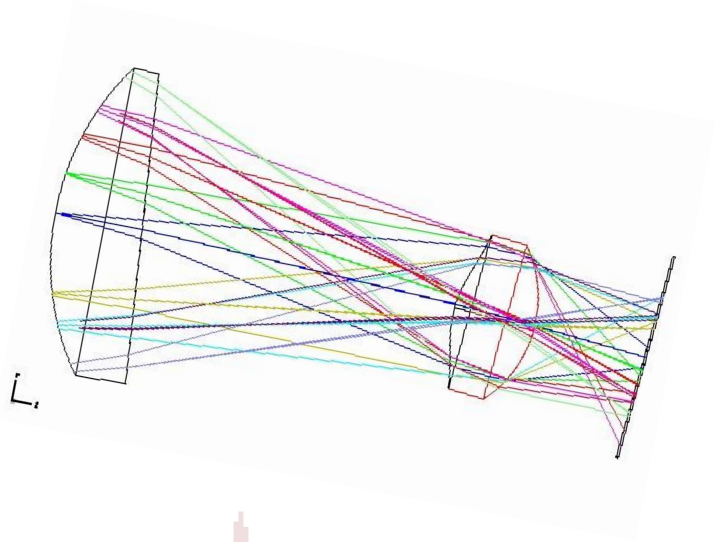
**Lens system**

**+ MAPMTs**

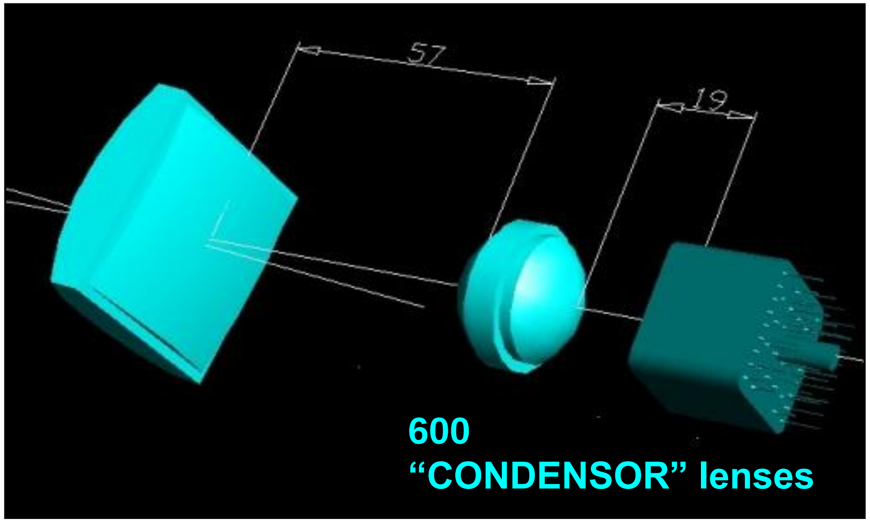
**photon detectors: CsI MWPC**

# The RICH 1 Upgrade (2005)

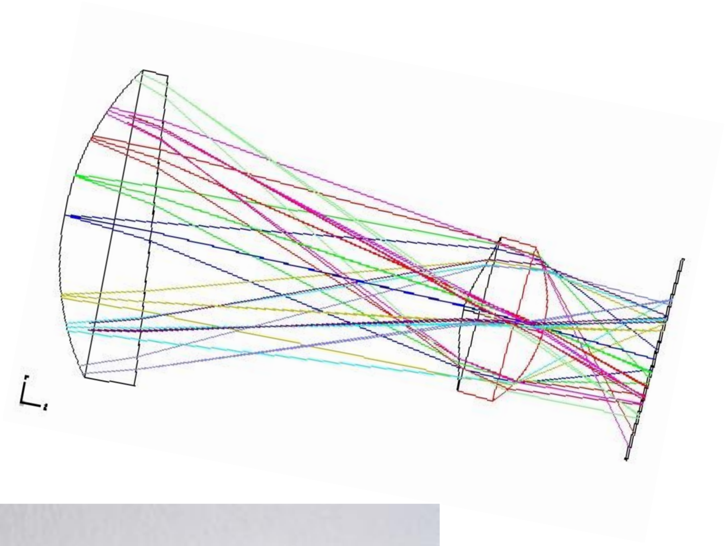




# The RICH 1 Upgrade (2005)

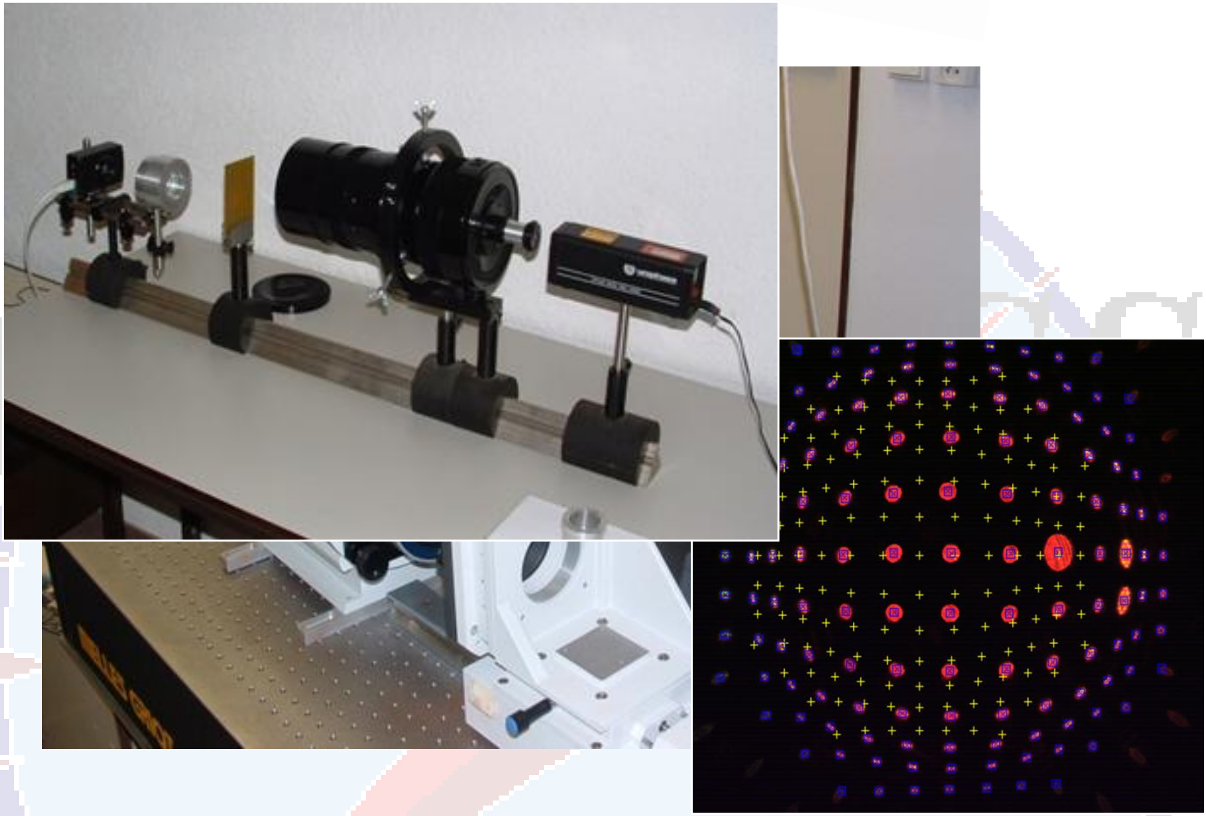


600
“CONDENSOR” lenses



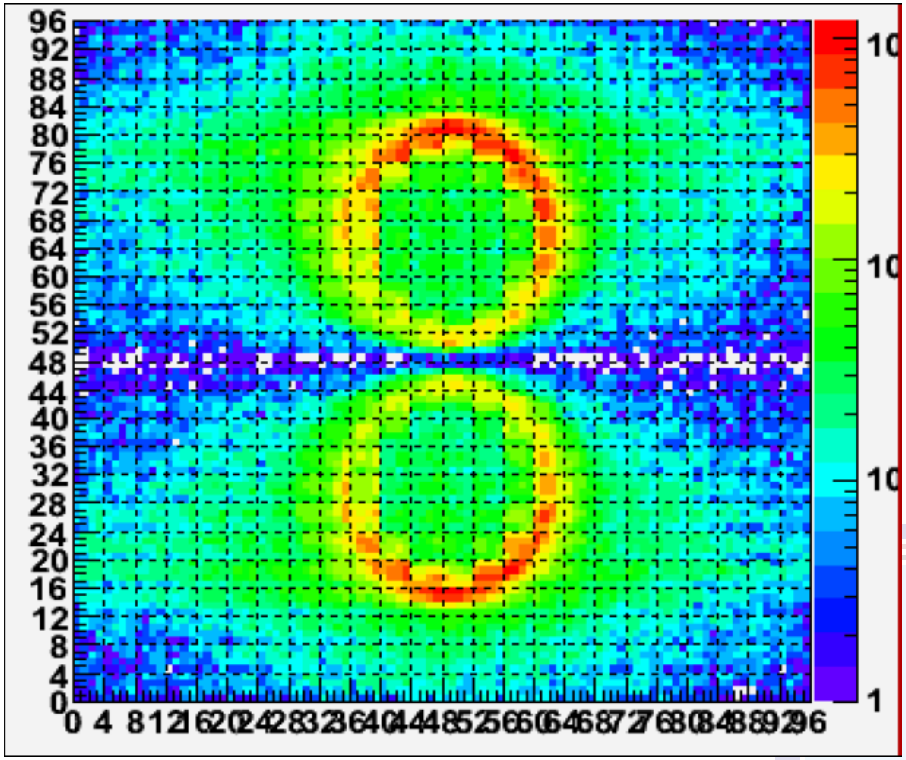
optical parameters,
interferometric measurements
Optical Development
Workshop of CAS
(Turnov, CZ)

optical parameters,
Hartmann test,
University of
Liberec (CZ)

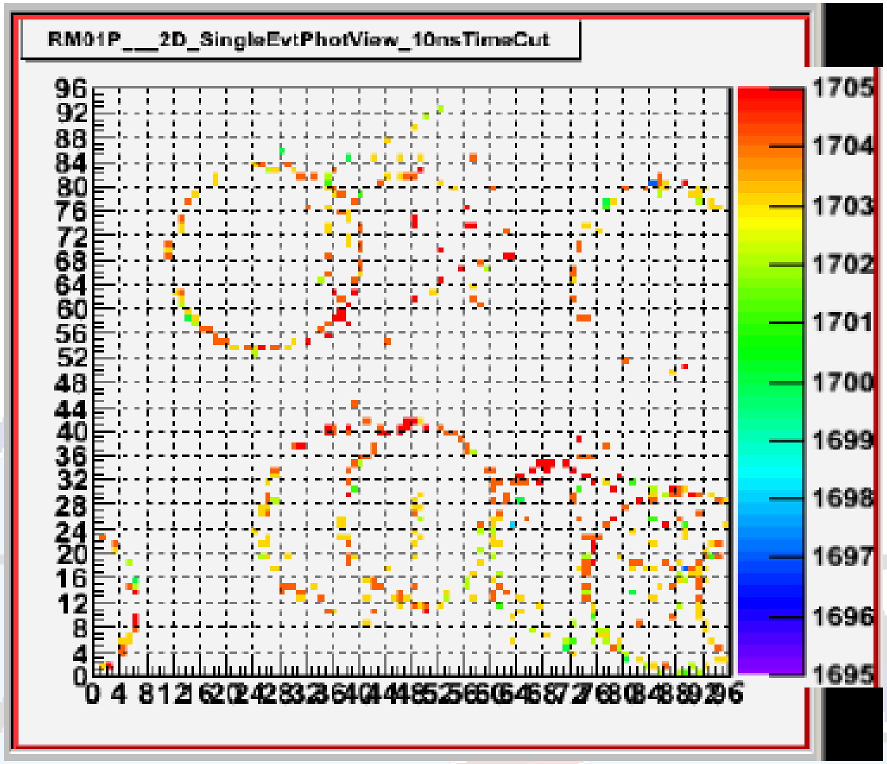


# The RICH 1 (>2005)

**sum over several events**



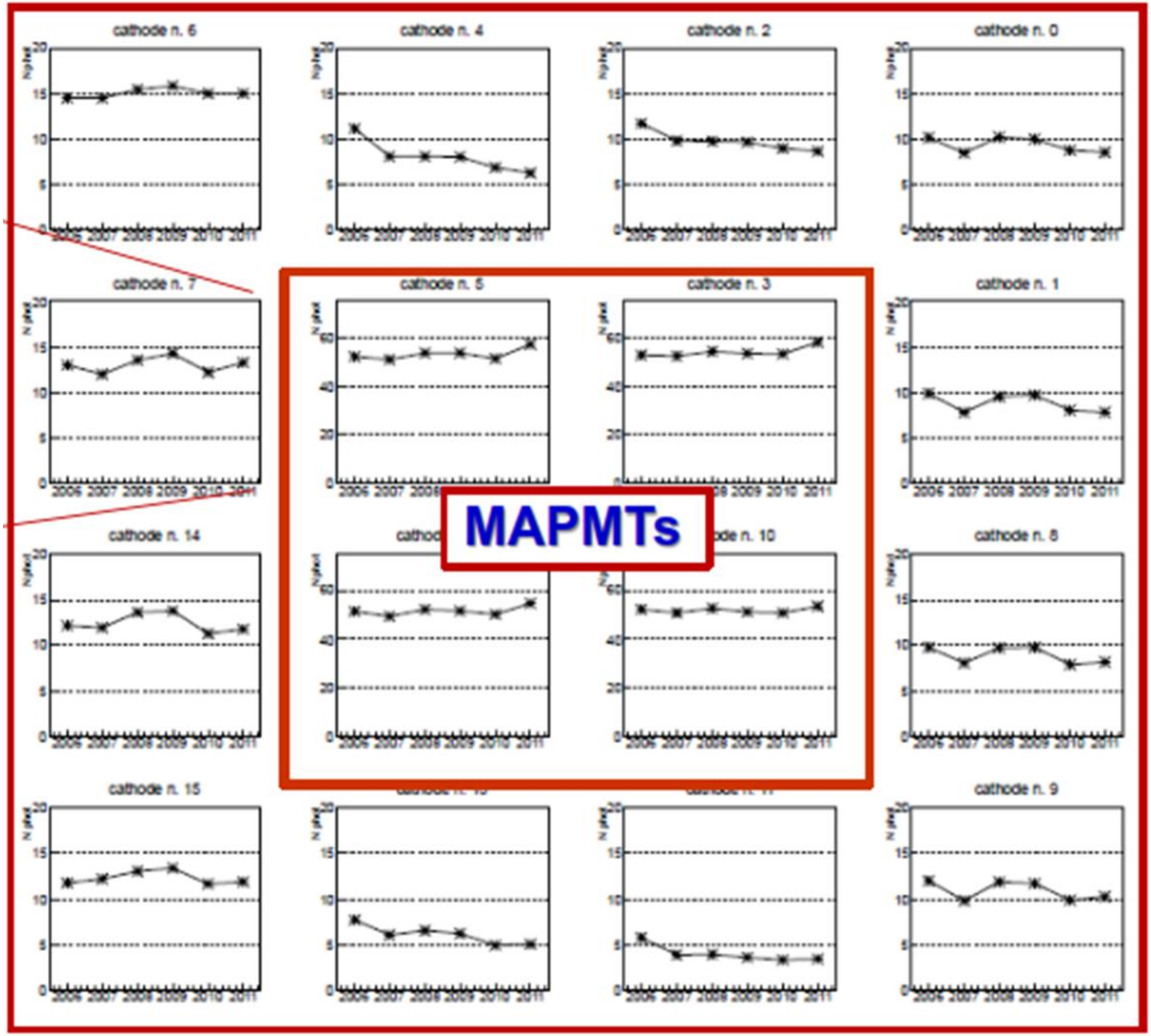
**a single event**



# The RICH 1 (2006-2011)

**mean number of photons / ring in the different photon detector sectors**

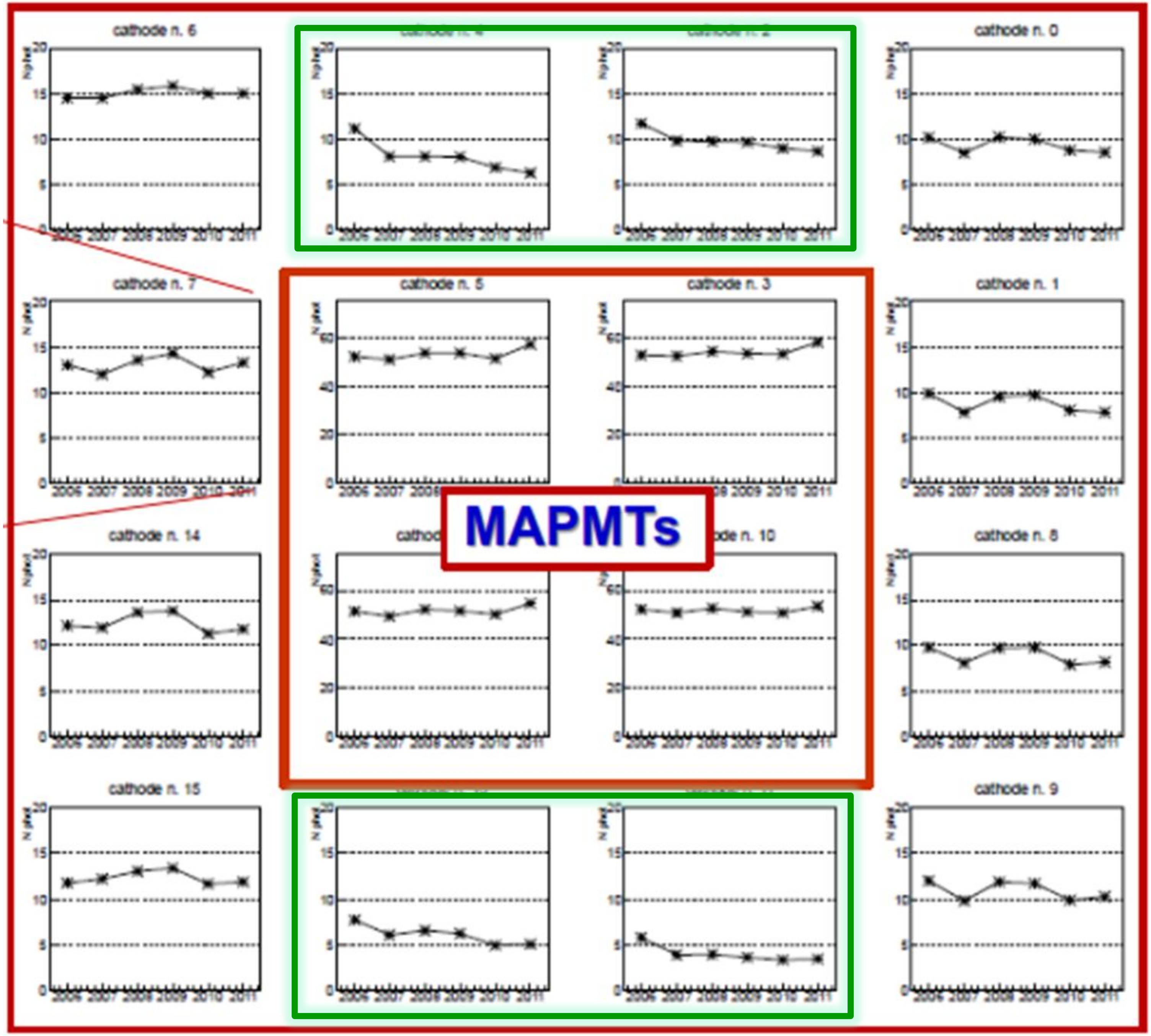
**~ 10 on MWPC**
**~ 60 on MAPMTs**



# The RICH 1 (2006-2011)

**mean number of photons / ring in the different photon detector sectors**

**~ 10 on MWPC**
**~ 60 on MAPMTs**

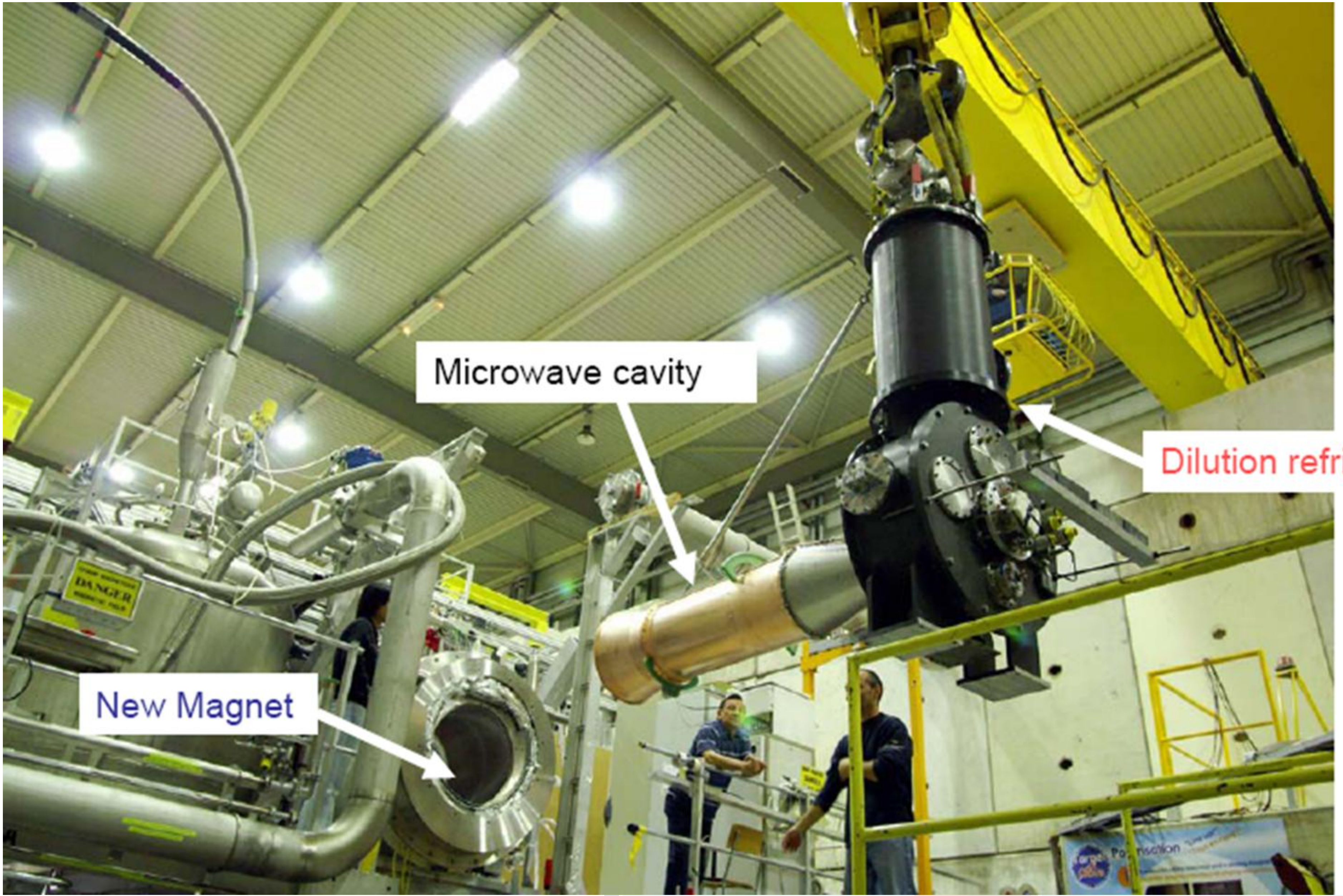


**upgrade for DVMP/SIDIS 2015-…**

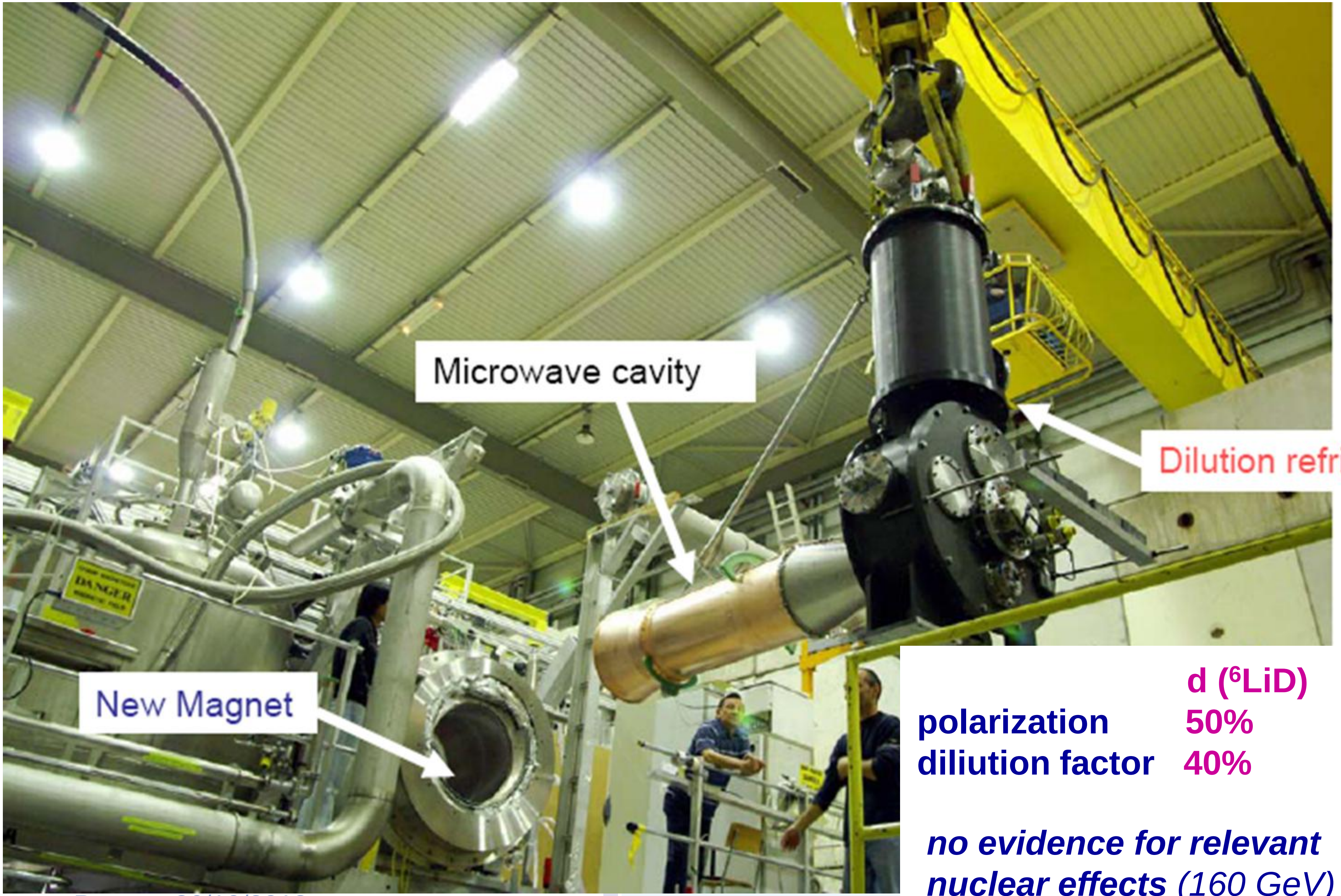
**Trieste**
**Turin**
**Freiburg**
**Prague**

# The Polarized Target System (>2005)

# The Polarized Target System (>2005)



# The Polarized Target System (>2005)



| | d ($^6$LiD) | p ($NH_3$) |
|---|---|---|
| **polarization** | 50% | 90% |
| **diliution factor** | 40% | 16% |

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

# Data Taking

# Data Taking

| | | | | |
|---|---|---|---|---|
| **2002** | **nucleon structure with** | **160 GeV $\mu$** | **L&T** | **polarised deuteron target** |
| **2003** | **nucleon structure with** | **160 GeV $\mu$** | **L&T** | **polarised deuteron target** |
| **2004** | **nucleon structure with** | **160 GeV $\mu$** | **L&T** | **polarised deuteron target** |
| *2005* | *CERN accelerators shut down* | | | |
| **2006** | **nucleon structure with** | **160 GeV $\mu$** | **L** | **polarised deuteron target** |
| **2007** | **nucleon structure with** | **160 GeV $\mu$** | **L&T** | **polarised proton target** |
| **2008** | **hadron spectroscopy** | | | |
| **2009** | **hadron spectroscopy** | | | |
| **2010** | **nucleon structure with** | **160 GeV $\mu$** | **T** | **polarised proton target** |
| **2011** | **nucleon structure with** | **190 GeV $\mu$** | **L** | **polarised proton target** |
| **2012** | **Primakoff & DVCS / SIDIS test** | | | |

# COMPASS   Physics case

## … from a talk at SPIN 2000

acknowledgement that it is still worthwhile to invest in trying to answer some questions which have been with us since 30 years

- **how is a nucleon made up ?**

**! spin structure !**

- **are there non qqq or $q\bar{q}$ hadrons ?**

**! exotics !**

***fundamental problems of QCD***

- **role of the axial anomaly to the spin of the proton**
- **glueballs ⟺ non abelian nature of QCD**

# the COMPASS experiment and the HADRON PROGRAM

# Hadron Spectroscopy

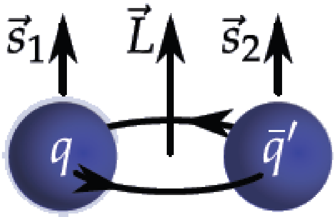
**mesons**

quantum numbers in CQM

$$S = 0, 1; \quad \vec{J} = \vec{L} + \vec{S}; \quad P = (-1)^{L+1}; \quad C = (-1)^{L+S}$$

forbidden (exotic QN's)

$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$$



# Hadron Spectroscopy

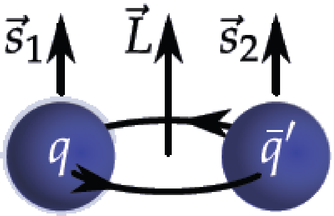
**mesons**

quantum numbers in CQM

$$S = 0, 1; \;\; \vec{J} = \vec{L} + \vec{S}; \;\; P = (-1)^{L+1}; \;\; C = (-1)^{L+S}$$

forbidden (exotic QN's)

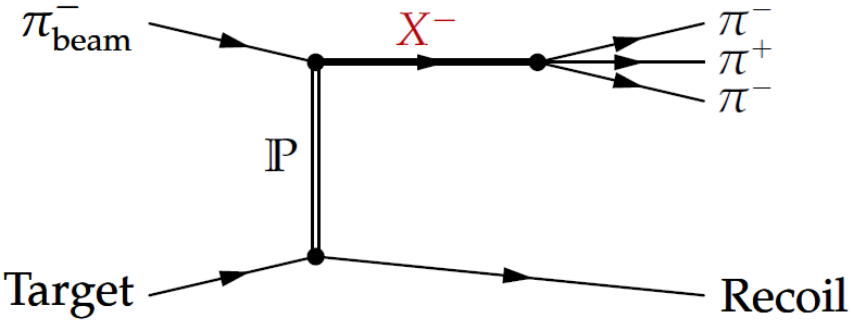
$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$$



**more states in QCD:**

**hybrids** $|q\bar{q}g\rangle$**,** **glueballs** $|gg\rangle$**,** **multiquark states** $|qq\bar{q}\bar{q}\rangle$

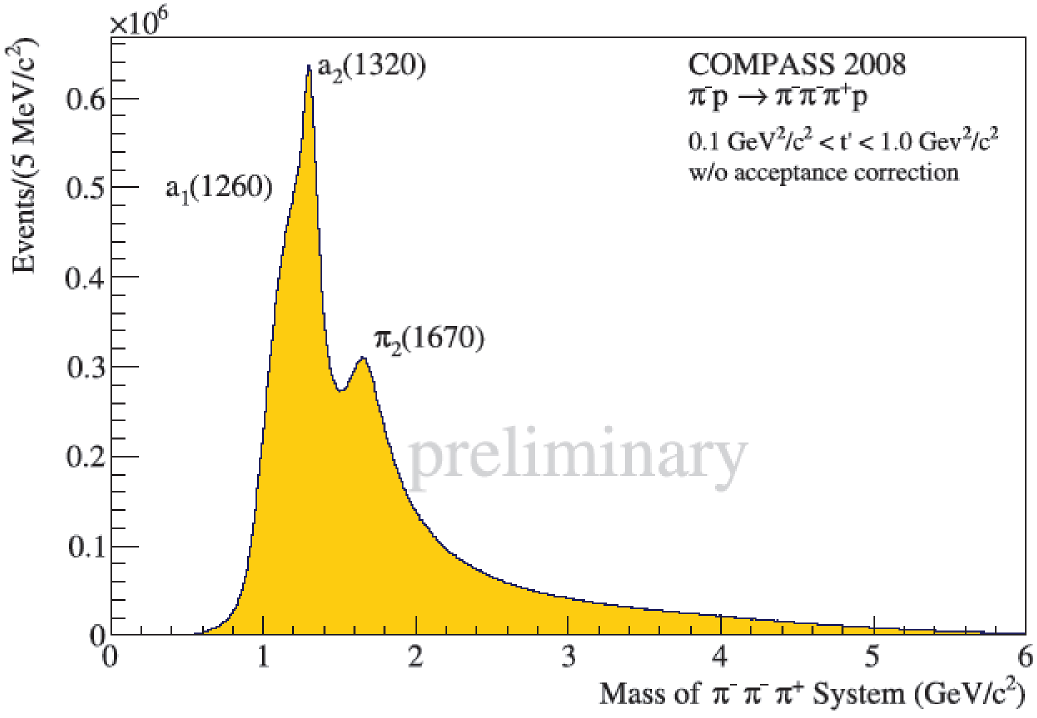
diffractive dissociation:

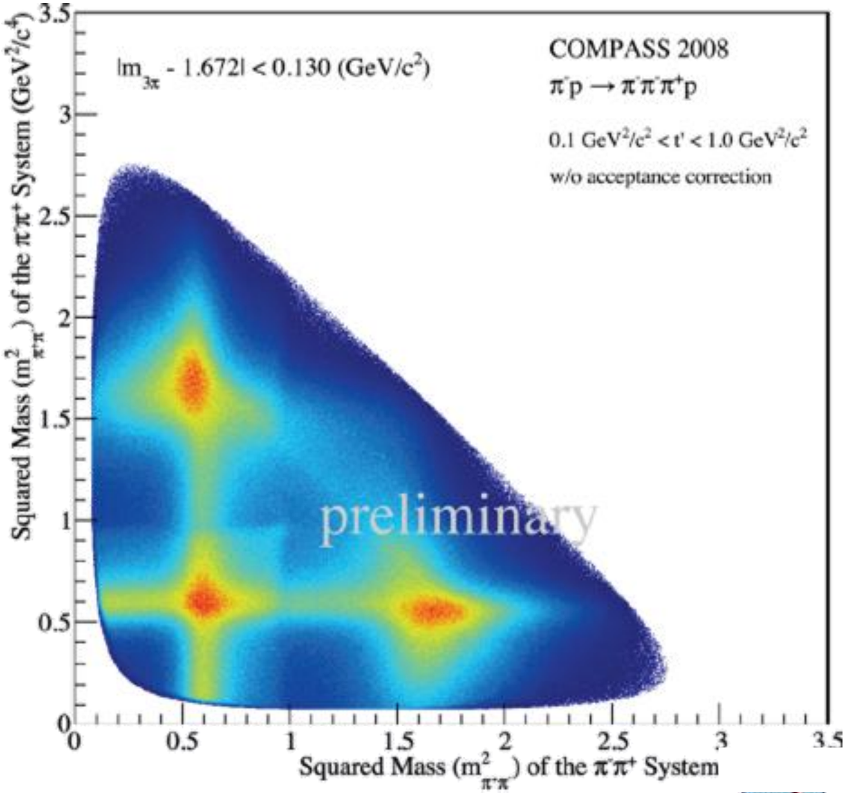


# Hadron Spectroscopy

**example:** $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$

**sample with 100M events**



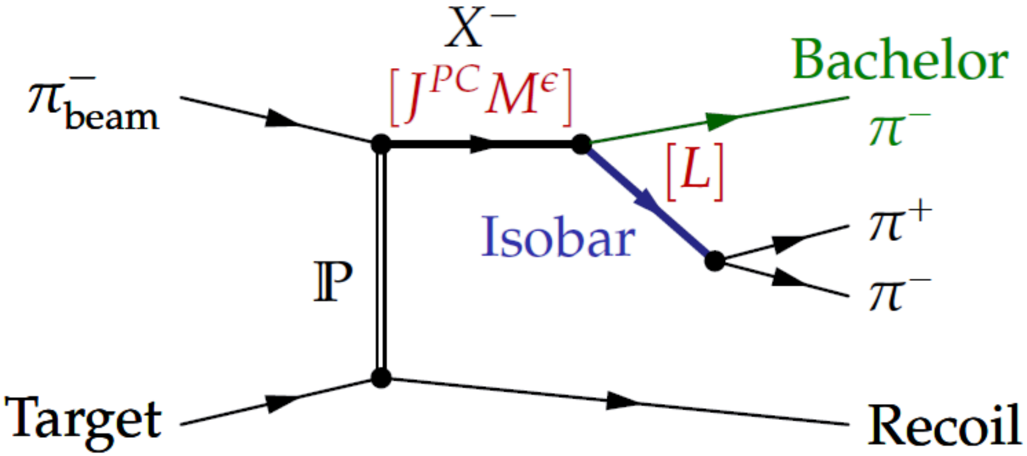


# Hadron Spectroscopy

example: $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

- **Isobar model:**

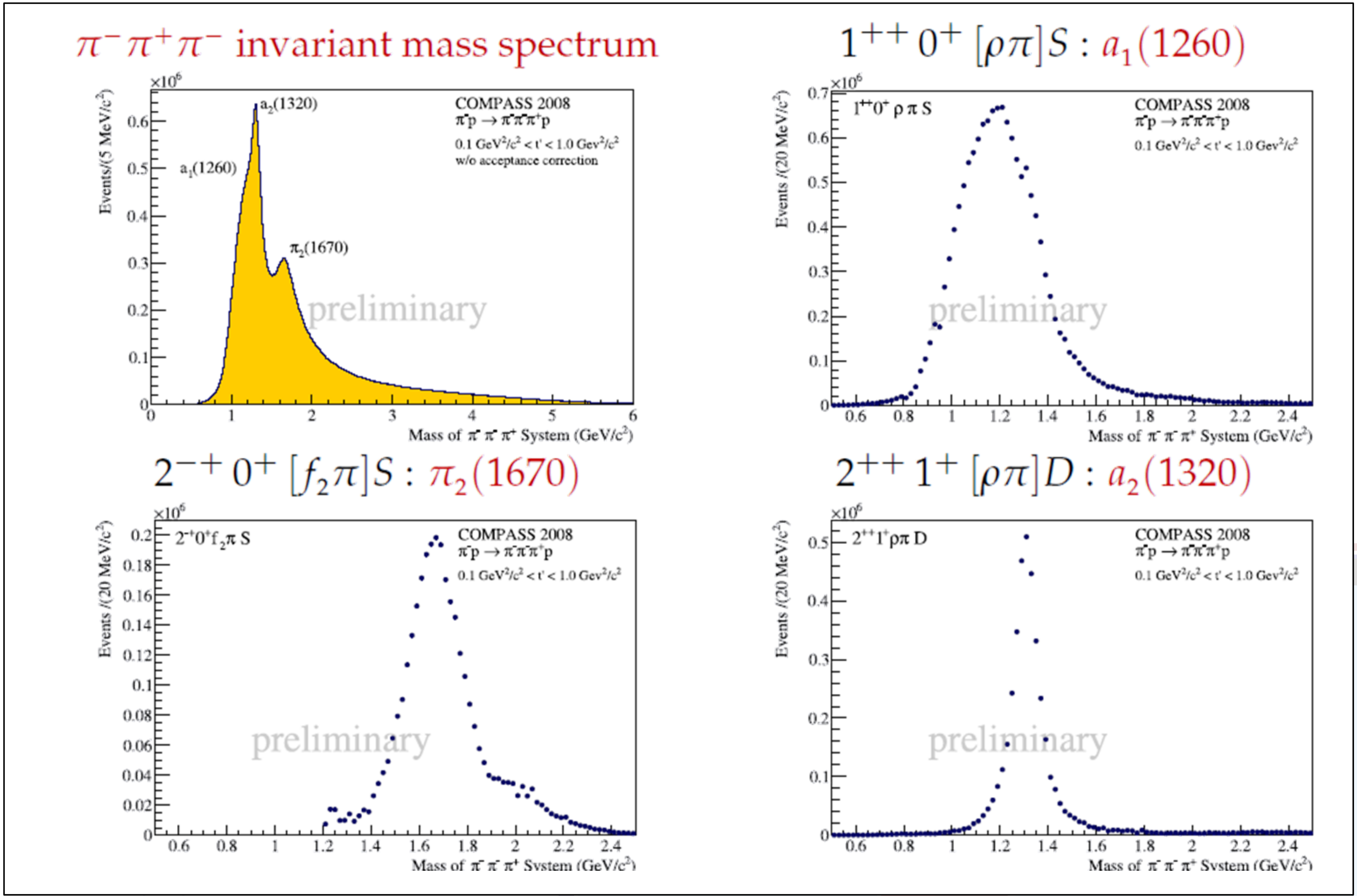
  ***X* decay is chain of successive two-body decays**



- **Analysis:**
  - **Partial Wave Analysis (PWA) in mass bins with up to 53 waves**
  - **fit of spin-density matrix for major waves with Breit-Wigner**

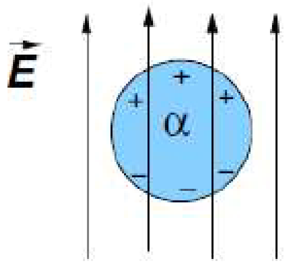
# Hadron Spectroscopy

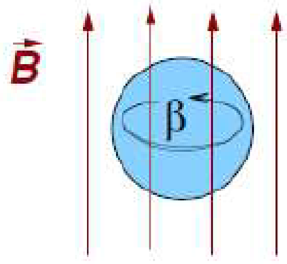
**example:** $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ **major waves**

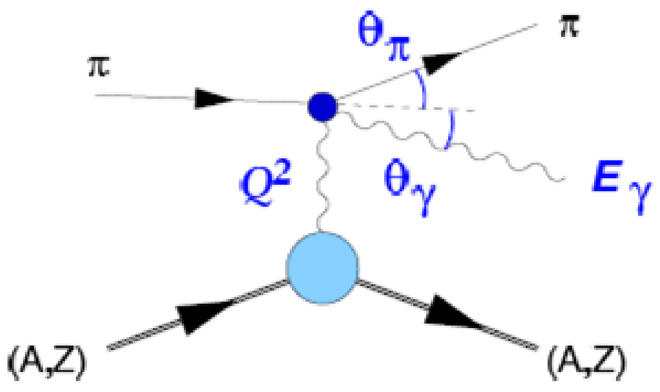


# COMPASS hadron programme: Tests of $\chi$PT

# COMPASS hadron programme: Tests of χPT







**pion (and kaon) polarisability via Primakoff scattering**

**present exp. situation confused**

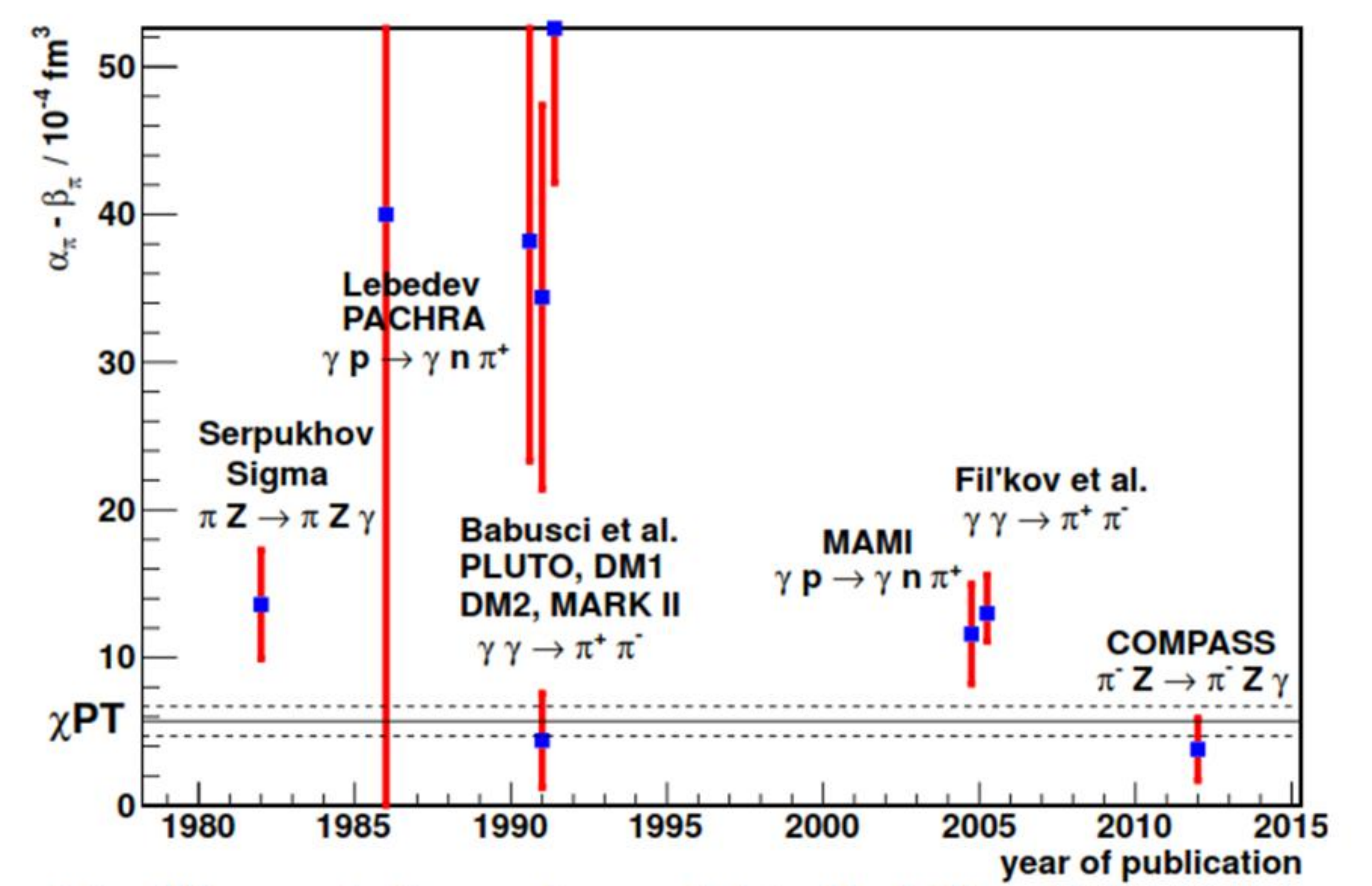
| | $\alpha_\pi - \beta_\pi$ $(10^{-4}\ \mathrm{fm}^3)$ | $\alpha_\pi + \beta_\pi$ $(10^{-4}\ \mathrm{fm}^3)$ | $\alpha_2 - \beta_2$ $(10^{-4}\ \mathrm{fm}^3)$ |
|---|---|---|---|
| 2-loop ChPT prediction | 5.7 ± 1.0 | 0.16 ± 0.10 | 16 |
| COMPASS sensitivity | ± 0.66 | ± 0.025 | ± 1.94 |

# COMPASS hadron programme: Tests of χPT

## pion polarisability via Primakoff scattering

## preliminary result, 2009 data

$$\alpha_\pi = 1.9 \pm 0.7_{stat} \pm 0.8_{syst} \cdot 10^{-4}\, fm^3$$



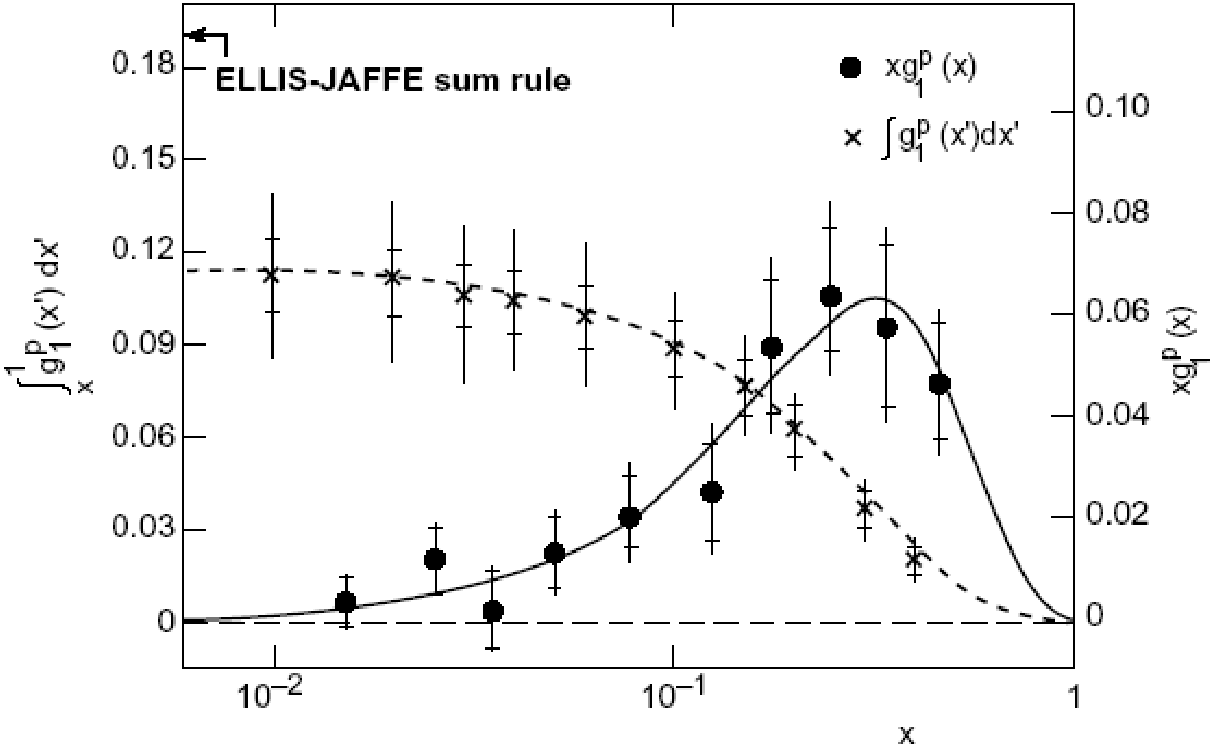
0.8 σ difference to Gasser, Ivanov, Sainio, Nucl. Phys. B 745 (2006)

# the COMPASS experiment and the SPIN Structure of the NUCLEON

# The Quark Contribution to the Nucleon Spin

**EMC**

**1988**



$$\Gamma_1^p = 0.123 \pm 0.013 \pm 0.019$$

$$\Delta\Sigma = 0.12 \pm 0.17$$

→ **SPIN CRISIS**

# The Quark Contribution to the Nucleon Spin

**QUARK MODEL**

$$|\mathrm{p}\rangle = |\mathrm{uud}\rangle \qquad |\mathrm{n}\rangle = |\mathrm{udd}\rangle$$

**SU(6)**

**magnetic moments:**

$$\mu_p = \frac{4}{3}\mu_u - \frac{1}{3}\mu_d \qquad \mu_n = \frac{4}{3}\mu_d - \frac{1}{3}\mu_u$$

**assuming u and d Dirac particles with** $m \cong \frac{1}{3}M_N$

$$\mu_u = \frac{q\hbar}{2m_u c} = 2\mu_N \qquad \mu_d = -\mu_N$$

$$\frac{\mu_p}{\mu_n} = -\frac{3}{2}$$

$$\mu_p = 3\mu_N \qquad \mu_n = -2\mu_N$$

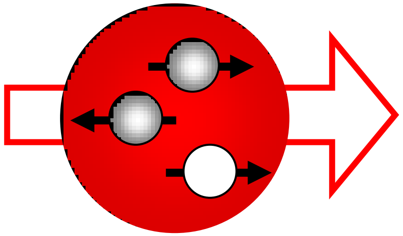
# The Quark Contribution to the Nucleon Spin

**in this model the spin of the nucleon is given by the spin of the quarks**

**probability of finding a quark in a given state of polarization**

$$\overset{\rightrightarrows}{u} = \frac{5}{3} \qquad \overset{\leftrightarrows}{u} = \frac{1}{3} \qquad \Delta u = \overset{\rightrightarrows}{u} - \overset{\leftrightarrows}{u} = \frac{4}{3}$$

$$\overset{\rightrightarrows}{d} = \frac{1}{3} \qquad \overset{\leftrightarrows}{d} = \frac{2}{3} \qquad \Delta d = \overset{\rightrightarrows}{d} - \overset{\leftrightarrows}{d} = -\frac{1}{3}$$



$$\boxed{\Delta\Sigma = \Delta u + \Delta d = 1}$$

# The Quark Contribution to the Nucleon Spin

## CRITICAL REVIEW OF THE CONCEPTS

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

## NECESSITY

- **to remeasure the proton**
- **to measure the neutron**
- **to measure $\Delta$G**

# The Quark Contribution to the Nucleon Spin

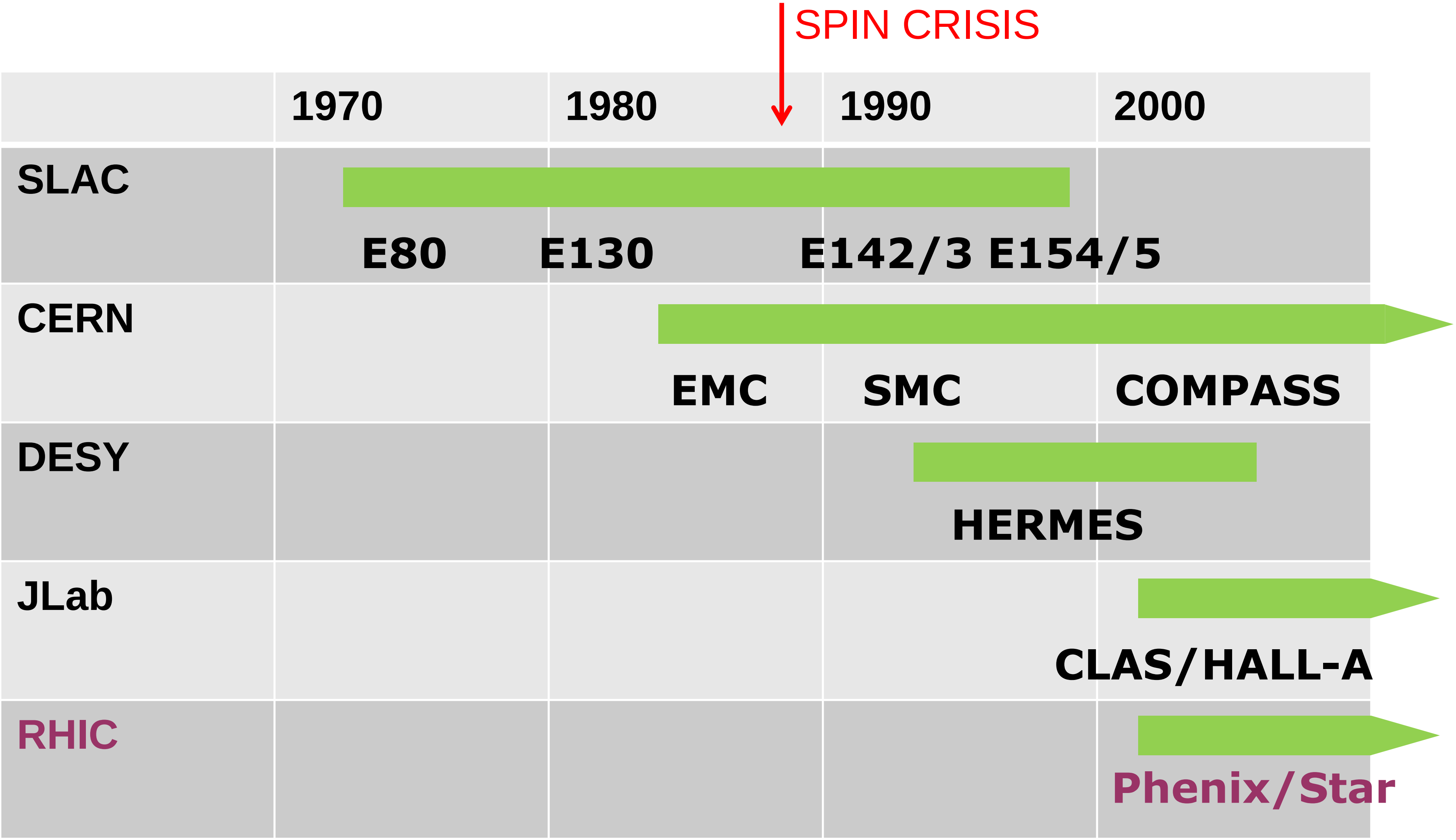
## experiments

**a worldwide effort since decades**

# The Quark Contribution to the Nucleon Spin

## experiments

a worldwide effort since decades



# The Quark Contribution to the Nucleon Spin

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$ **Helicity PDFs**

$$\Delta q = \int_0^1 \left[\Delta q(x) + \Delta\bar{q}(x)\right] dx \;\; = \int_0^1 \left[q^+(x) - q^-(x) + \bar{q}^+(x) - \bar{q}^-(x)\right] dx$$

**$\Delta q$'s** **can be extracted from the DIS cross-section asymmetry for parallel and antiparallel lepton and nucleon spins**

**Inclusive DIS, beam and target longitudinally polarized**

$$\frac{d\Delta\sigma}{dx\,dy} = \lambda \cdot \frac{e^4}{4\pi^2 Q^2} \cdot \left[\left(1 - \frac{y}{2} - \frac{y^2}{4} \cdot \gamma^2\right) \cdot g_1 - \frac{y}{2} \cdot \gamma^2 \cdot g_2\right]$$

$$d\sigma = d\bar{\sigma} \underset{\uparrow}{\pm} d\Delta\sigma$$

beam/target helicity

**$g_1$ measured at SLAC, EMC, SMC, HERMES, COMPASS**

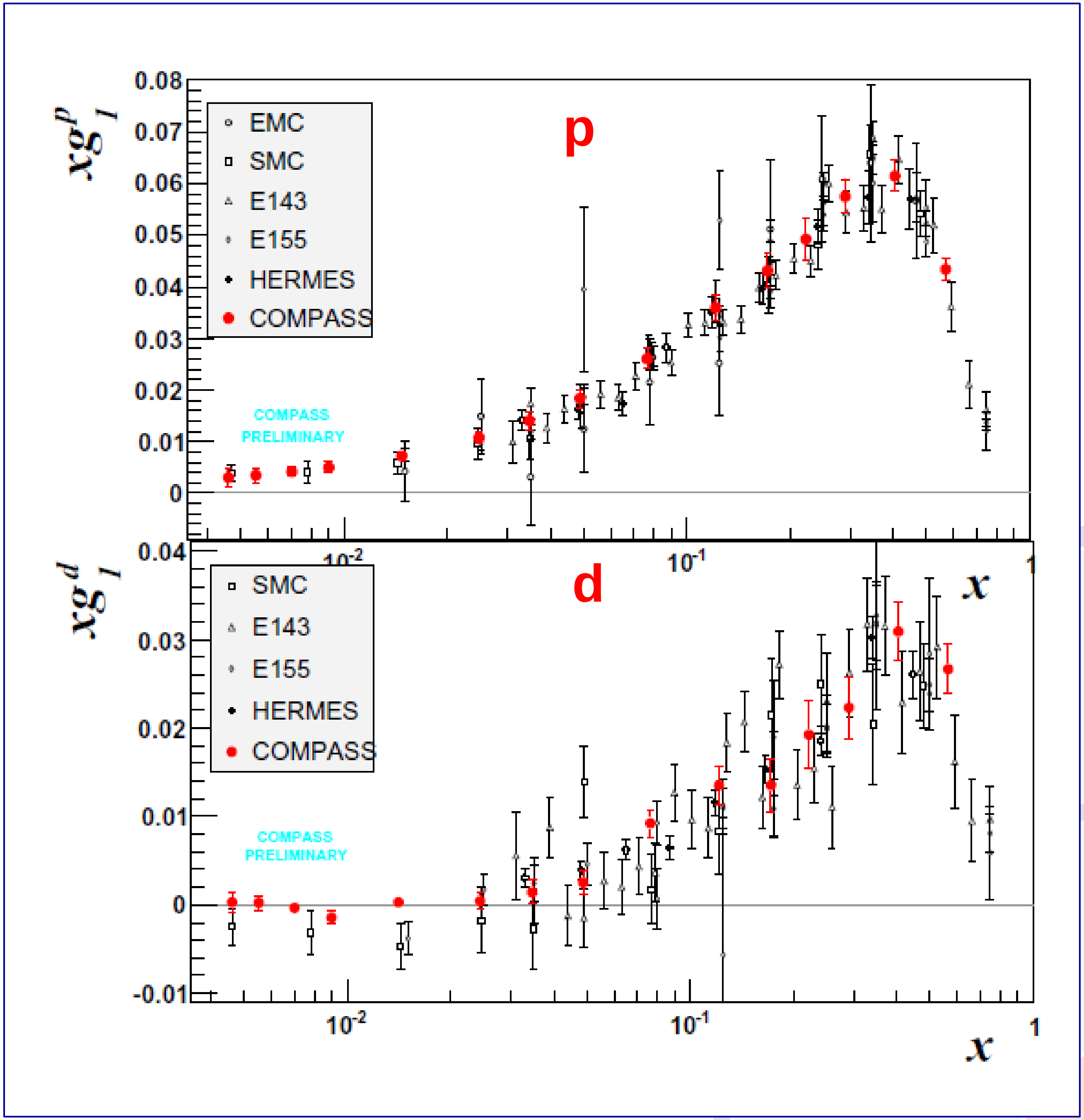
$g_2$ suppressed by a factor $\gamma^2 \approx 0.01$ at 100 GeV (SMC, SLAC)

**in the parton model**

$$g_1(x) = \frac{1}{2} \sum_q e_q^2 \cdot \left[\Delta q(x) + \Delta\bar{q}(x)\right]$$

# The Structure Function $g_1(x,Q^2)$

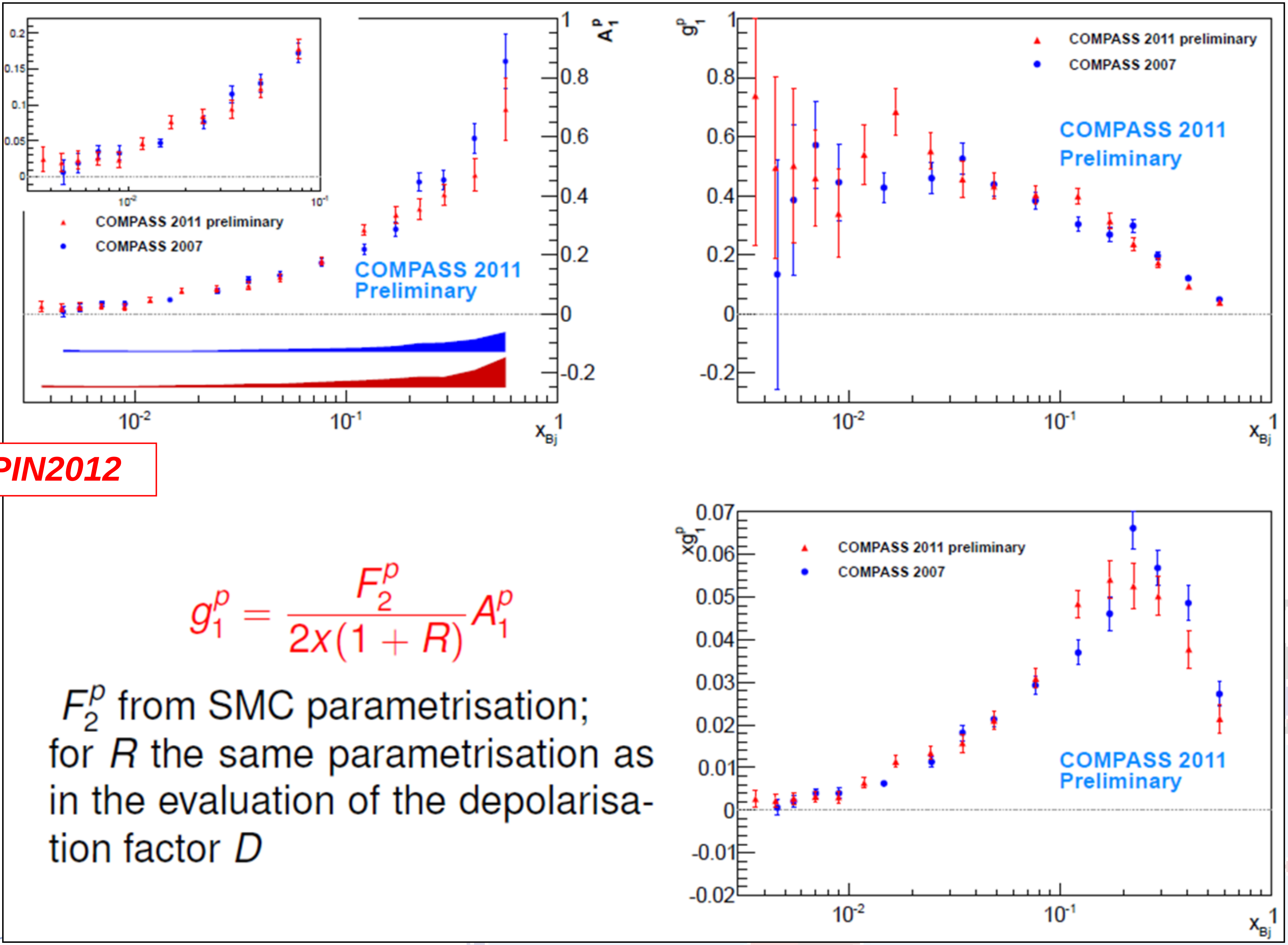
# The Structure Function $g_1(x,Q^2)$



- **very precise data**
- **only COMPASS for $x < 0.01$ ($Q^2 > 1$)**
- **deuteron data:**
  **$\Delta\Sigma = 0.33 \pm 0.03 \pm 0.05$**
  **$\Delta s + \Delta\bar{s} = -0.08 \pm 0.01 \pm 0.02$**

F. Bradamante

# The Structure Function $g_1(x,Q^2)$



**SPIN2012**

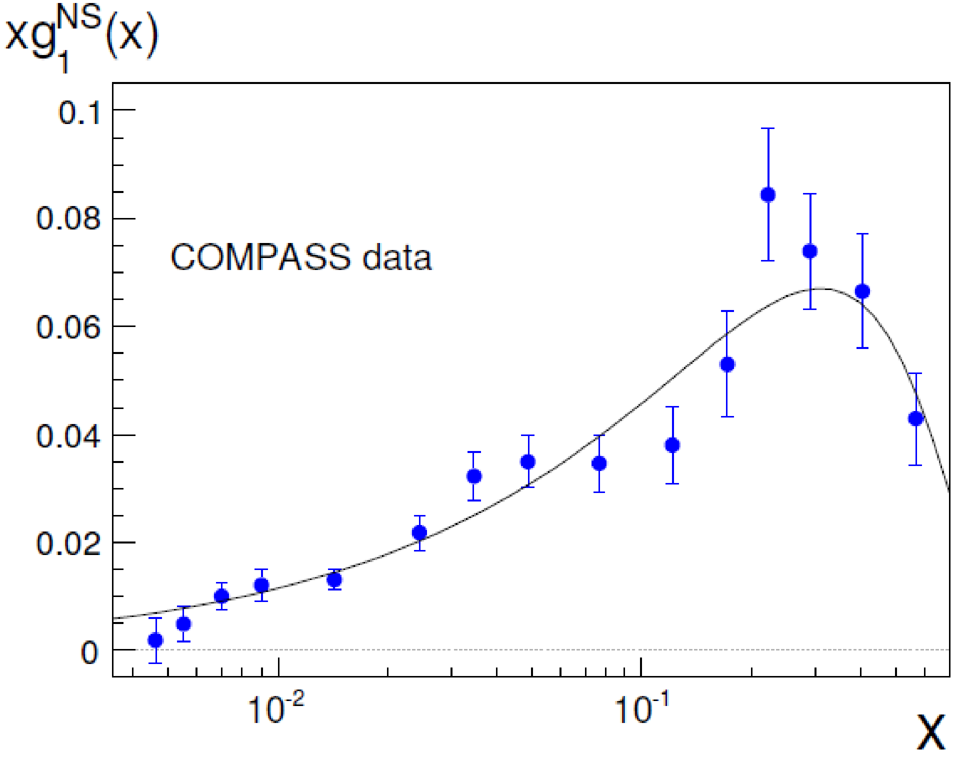
$$g_1^p = \frac{F_2^p}{2x(1+R)} A_1^p$$

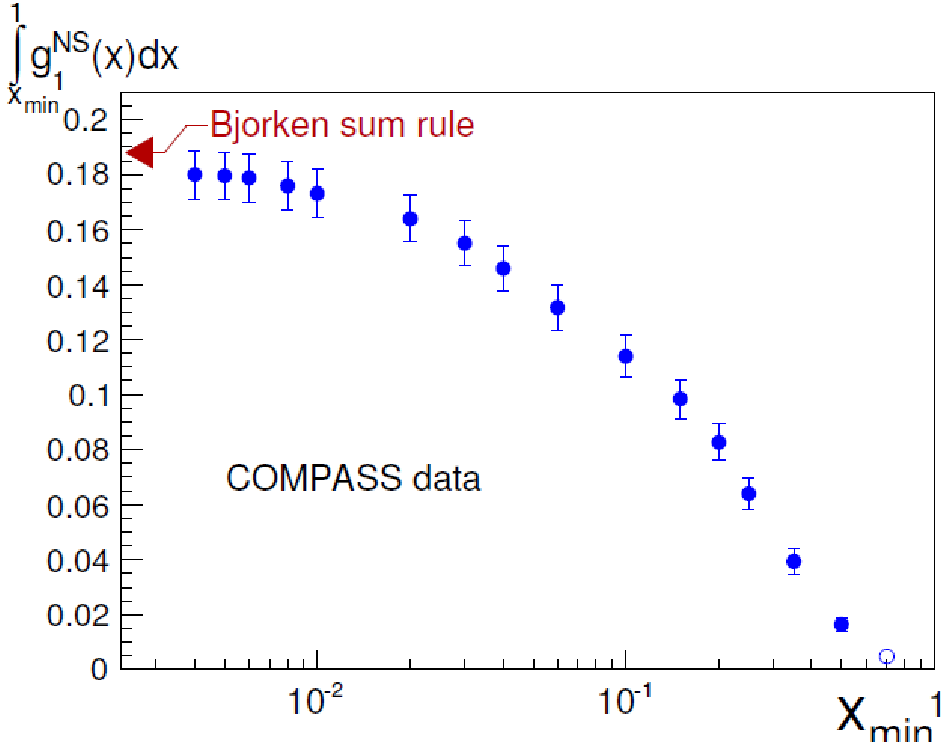
$F_2^p$ from SMC parametrisation; for $R$ the same parametrisation as in the evaluation of the depolarisation factor $D$

# The Structure Function $g_1(x,Q^2)$

## Bjorken sum rule

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





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

**PLB 690 (2010) 466**

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

# The Gluon Contribution to the Nucleon Spin

## Measurements of $\Delta G/G$

### direct

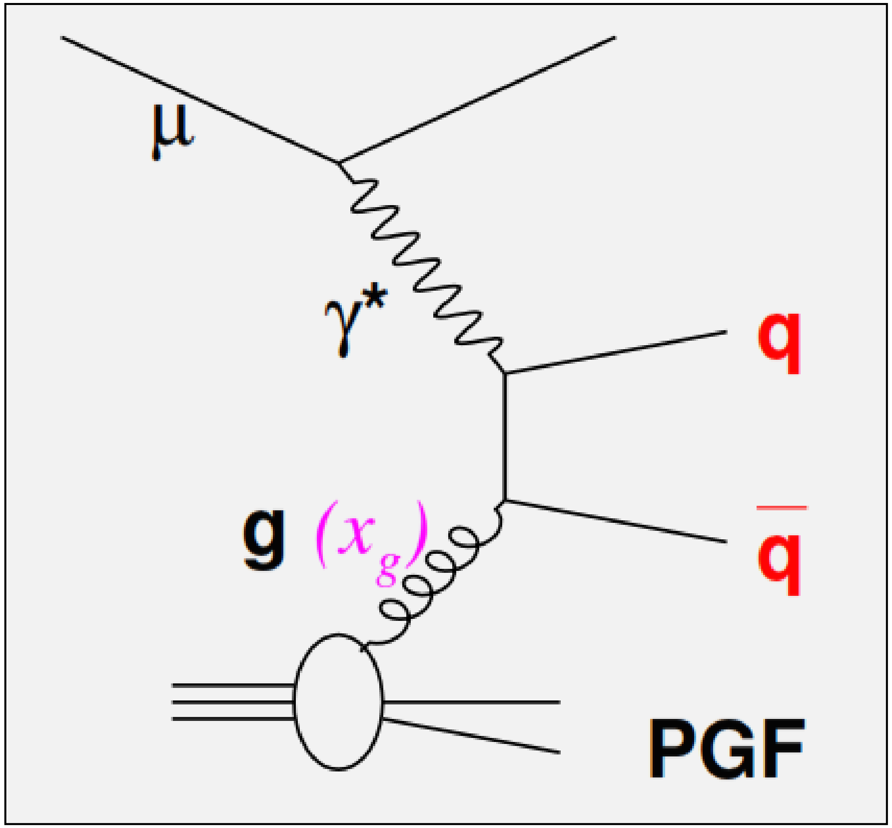
- **cross-section asymmetry for charm production**
- **cross-section asymmetry for high $p_T$ hadron pairs**

### indirect

- **scale violation of $g_1$(x,Q2) (QCD fit)**
  *SMC, SLAC Experiments, HERMES, COMPASS*

# Direct Measurements of ΔG/G

## Photon Gluon Fusion

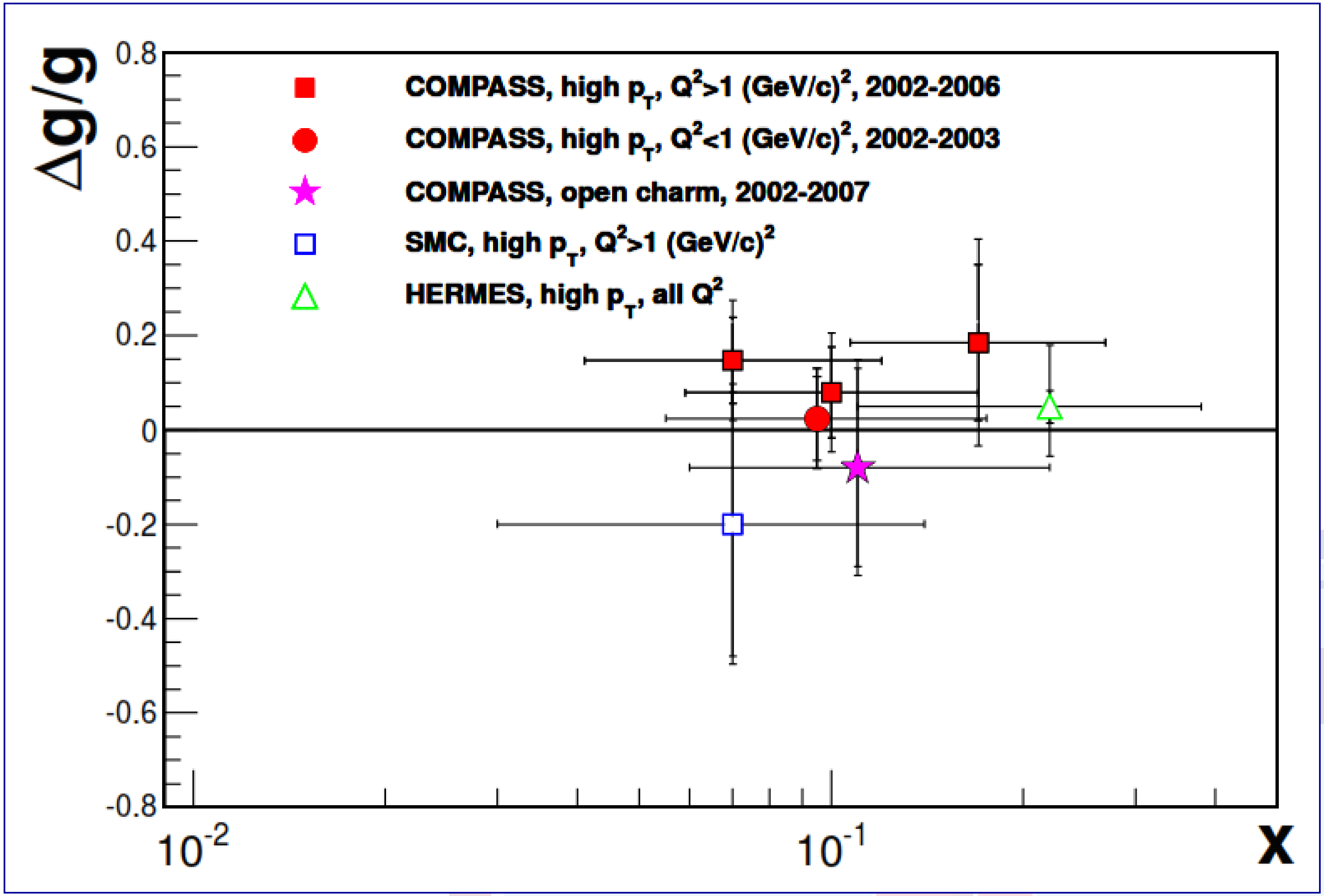


**q = c** **cross section difference in charmed meson production**
→ theory well understood
→ experiment challenging
**COMPASS**

**q = u,d,s** **cross section difference in 2+1 jet production: events with hadrons with high-$p_t$**
→ experiment easy
→ theory more difficult
**COMPASS & HERMES**

# The Gluon Contribution to the Nucleon Spin

## all LO results



# THE SPIN PUZZLE

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

$\Delta\Sigma$ ~ 1/3

$\Delta$ G small

- necessity to address $L_q$ and $L_g$ → Ji sum rule

  GPD

- GROWING INTEREST IN
  TRANSVERSE SPIN PHENOMENA

# The Structure of the Nucleon

**three distribution functions are necessary to describe the quark structure of the nucleon at LO in the collinear case** (Jaffe and Ji, 1991)

| | | **nucleon** polarisation | | |
|---|---|---|---|---|
| | | U | L | T |
| **quark** polarisation | U | $f_1$ <br>***number density*** **q** | | |
| | L | | $g_1$ <br>***helicity*** **Δq** | |
| | T | | | |

# The Structure of the Nucleon

**three distribution functions are necessary to describe the quark structure of the nucleon at LO in the collinear case** (Jaffe and Ji, 1991)

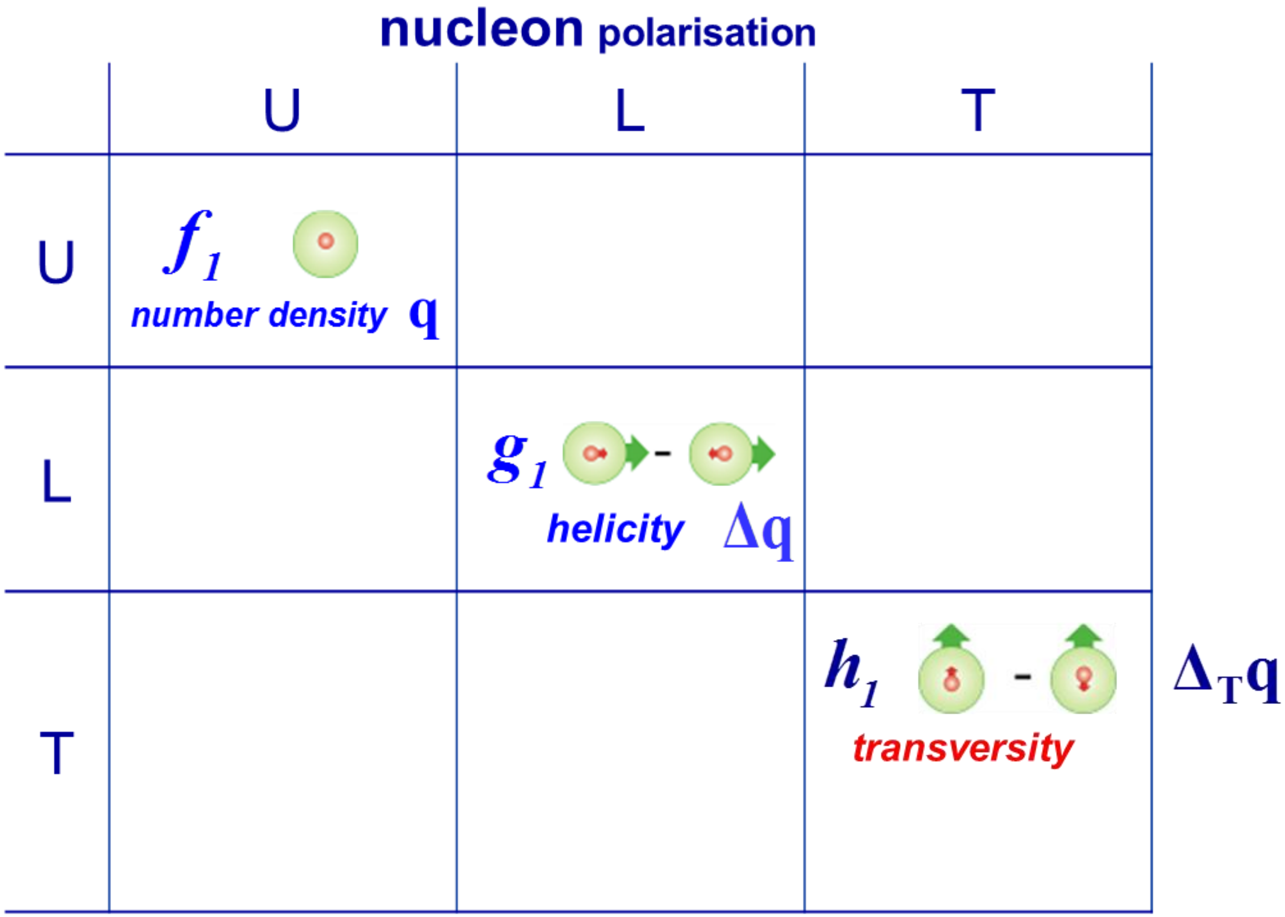
**transversity PDF**

correlation between the transverse polarisation of the nucleon and the transverse polarisation of the quark

**chiral odd**

**can not be measured in inclusive DIS,**

**still poorly known**



**nucleon** polarisation

**quark** polarisation

| | U | L | T |
|---|---|---|---|
| U | $f_1$<br>*number density* $q$ | | |
| L | | $g_1$ -<br>*helicity* $\Delta q$ | |
| T | | | $h_1$ - $\Delta_T q$<br>*transversity* |

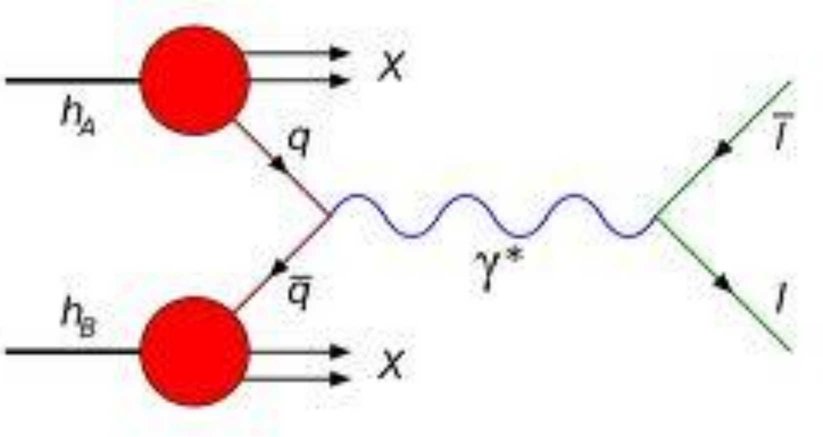
# Probing Transversity

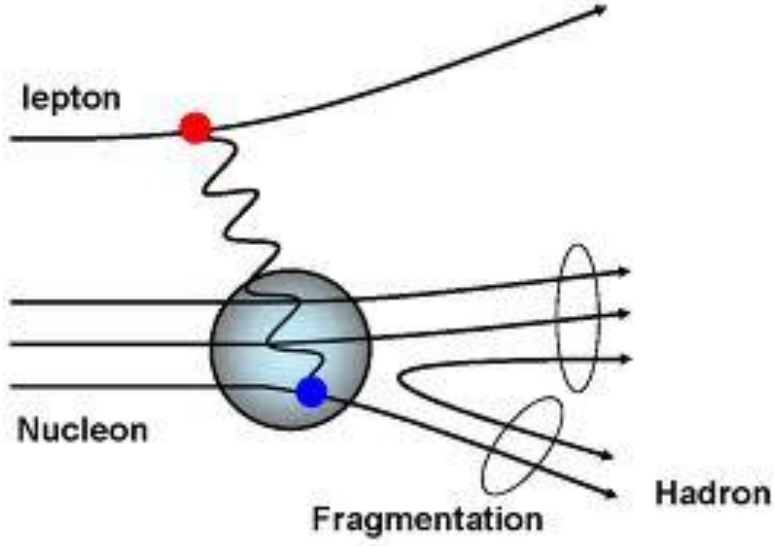
**transversely polarized DY**

(as proposed by Ralston & Soper)

**$A_{TT}$ in pp DY very small**

**dream option: measure ppbar DY**





**Semi-Inclusive Deep Inelastic Scattering**

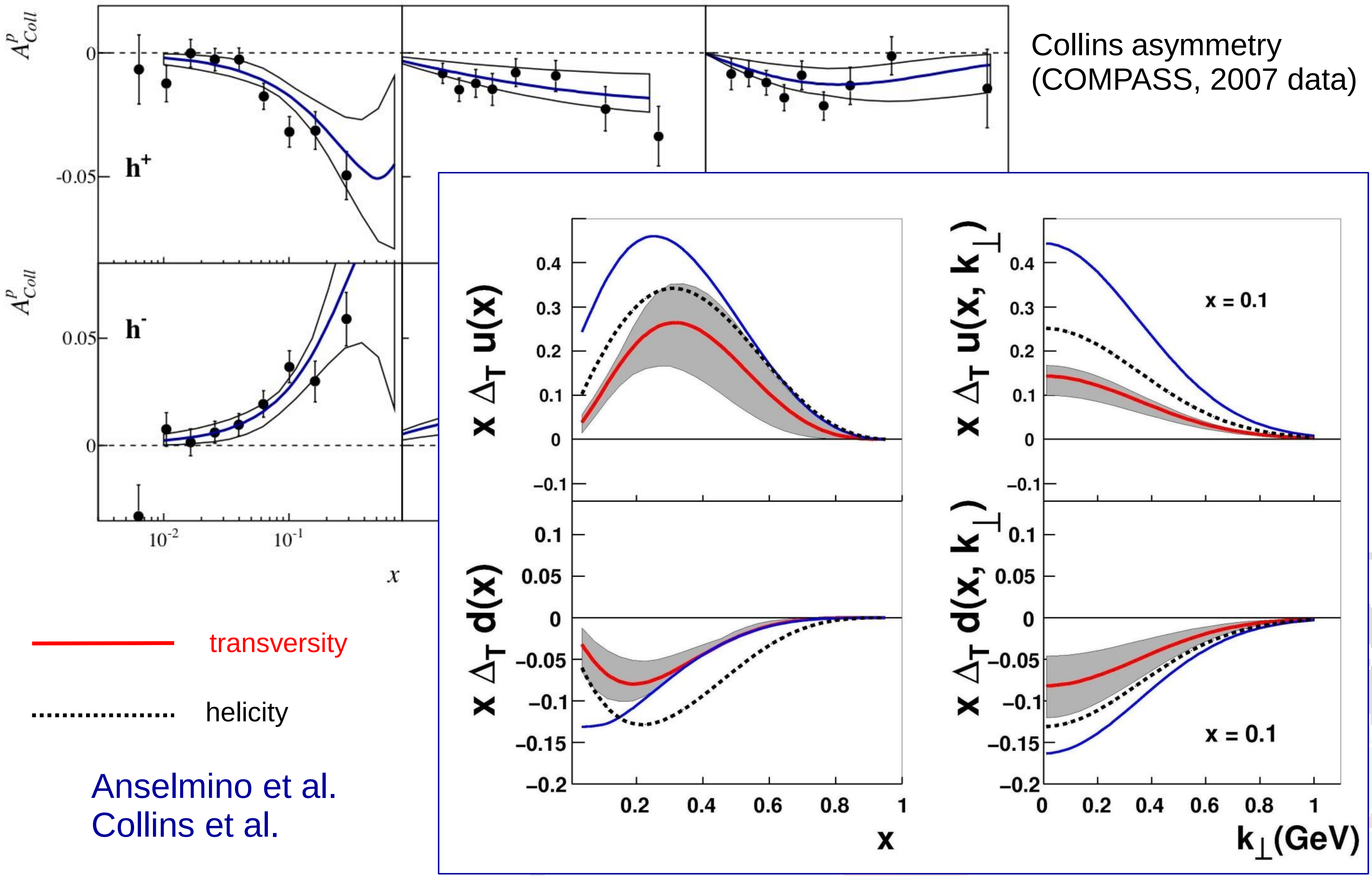
**Collins asymmetry: sin ($\phi_h + \phi_S$)**

correlation between spin of quark and transverse momentum of hadrons

convolution of Transversity and Collins FF

**measurable as an azimuthal modulation of the hadrons**

# Transversity distribution extracted from SIDIS



Collins asymmetry
(COMPASS, 2007 data)

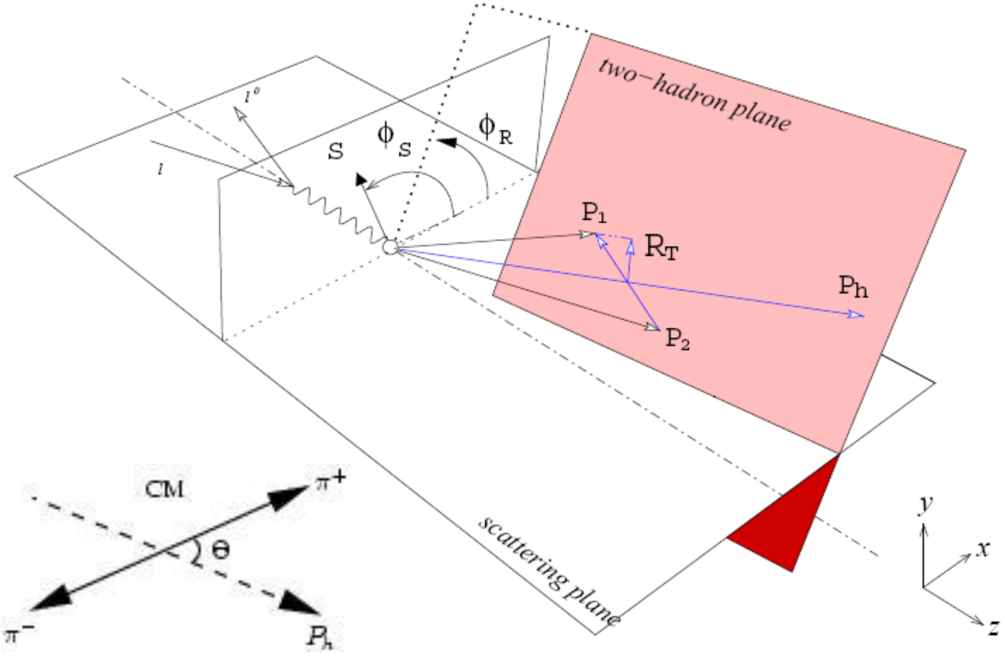
transversity

helicity

Anselmino et al.
Collins et al.

# Alternative way to access Transversity in SIDIS

## two-hadron asymmetry



**azimuthal asymmetry in**

$$\phi_{RS} = \phi_{R\perp} + \phi_s$$

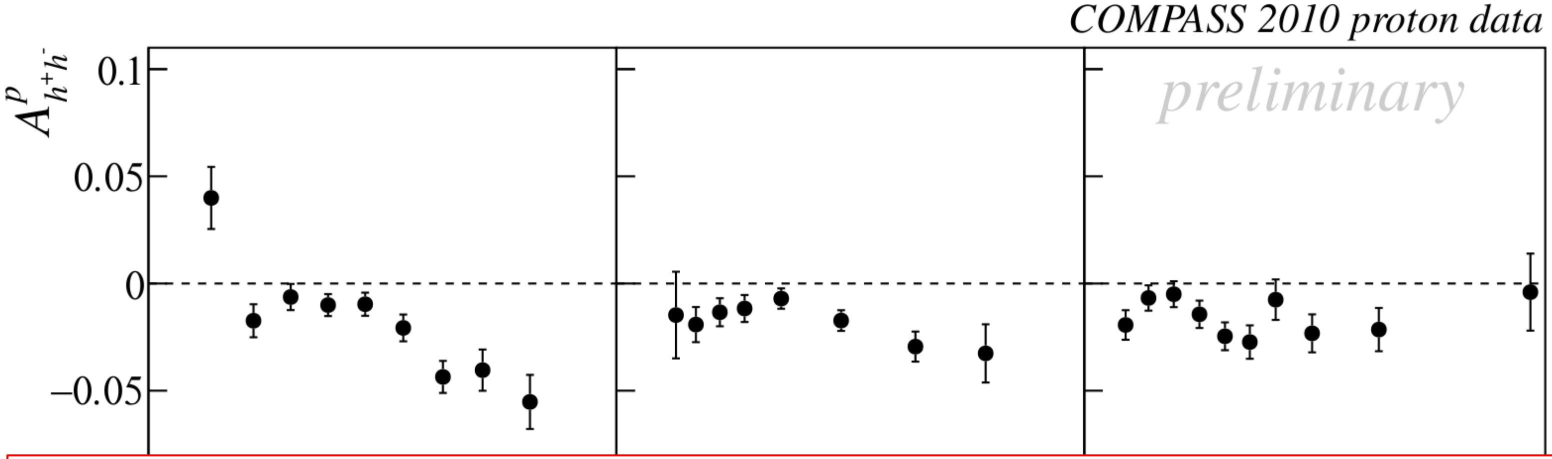
$\phi_{R\perp}$ is the azimuthal angle of the plane defined by the two hadrons

**product of Transversity and Interference FF**

A. Bacchetta, M. Radici, hep-ph/0407345
X. Artru, hep-ph/0207309

# Alternative way to access Transversity in SIDIS

## two-hadron asymmetry

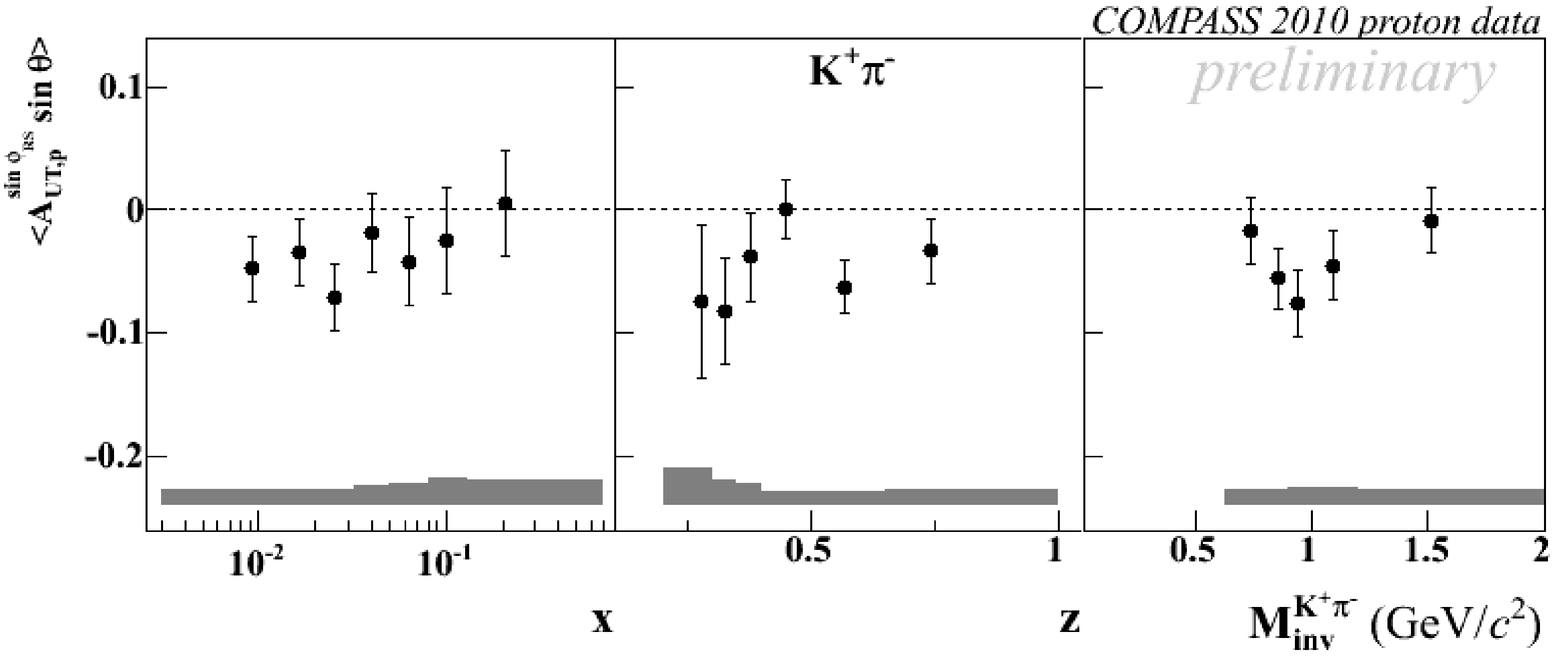


**h+h- asymmetry**

Transevrsity2011,
2010 data

**K+π- asymmetry**

SPIN2012,
2010 data

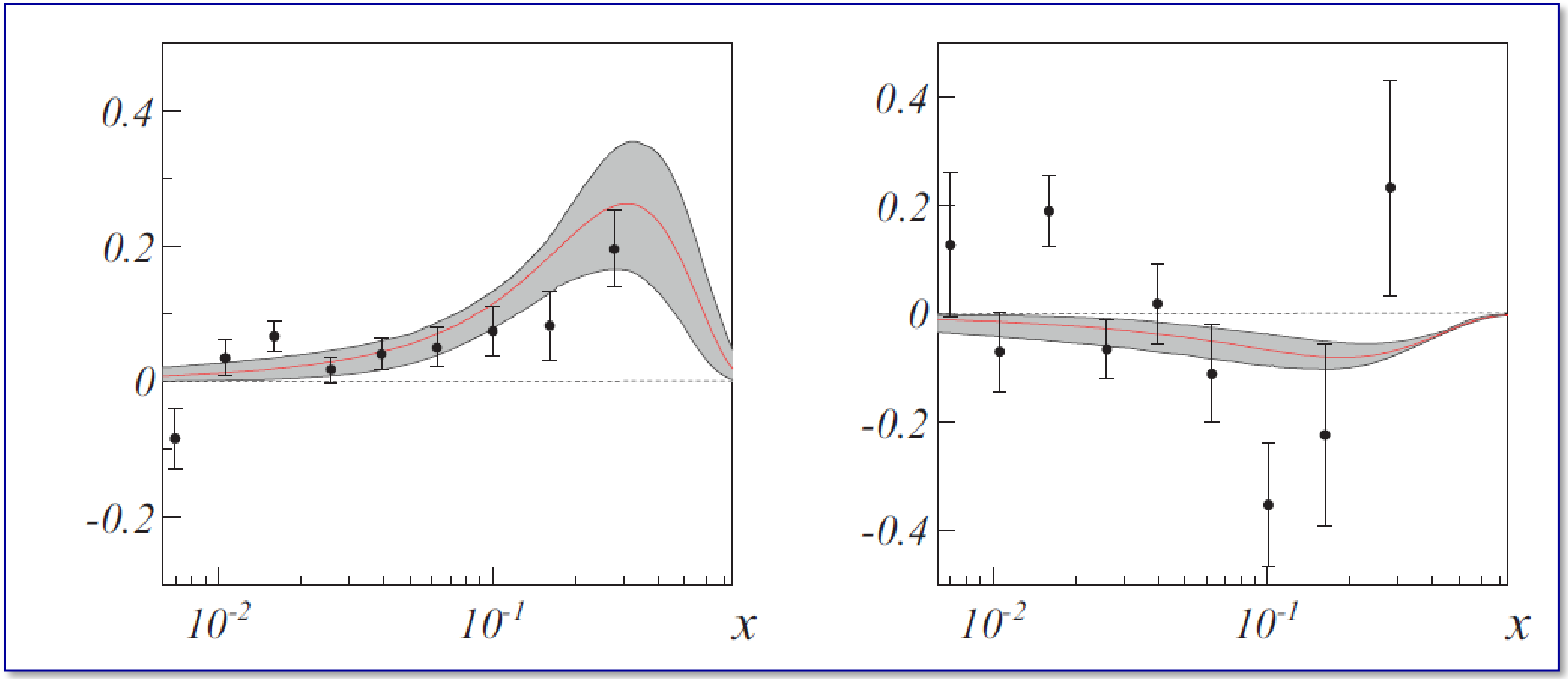


# Transversity distribution extracted from two-hadron asymmetries in SIDIS

following the work of A Bacchetta, A. Courtoy, M Radici
Phys.Rev.Lett.107:012001,2011

**first direct extraction of u and d transversity using deuteron 2002-2004 and proton 2010 COMPASS results**

C.Elia Ph.D Thesys, Trieste 2012



**curves: global fits of COMPASS d, HERMES p, BELLE e+e- data**
(M. Anselmino et al. PRD 75 (2007) 054032)

**… BUT …**

# … going beyond collinear pQCD…

- **There are some phenomena involving transverse momenta (and transverse spin) which are not accounted for by a collinear pQCD description**

- **When the observed transverse momentum $P_T$ is much smaller than the hard scale Q (two-scale process), one has to introduce the transverse-momentum dependent (or "unintegrated") distributions (TMDs)**

- **The TMD physics was prompted by the study of transverse spin phenomena but has also led to an improved QCD knowledge of ordinary, unpolarized, TMDs**

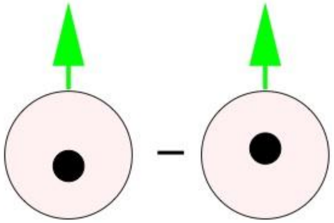
# … going beyond collinear pQCD…

**transverse spin couples to transverse momentum giving rise to a number of possible correlations**

**Sivers function:**

**unpolarized quarks in a transversely polarized nucleon**

$f_{1T}^{\perp} =$



$-$

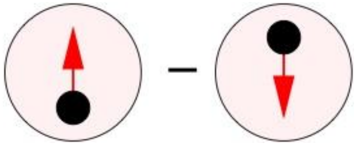
$$f_{q/p^\uparrow}(x,\boldsymbol{p}_T) = f_1^q(x,p_T^2) - f_{1T}^{\perp q}(x,p_T^2)\frac{(\hat{\boldsymbol{P}}\times\boldsymbol{p}_T)\cdot\boldsymbol{S}}{M}$$

→ azimuthal single-spin **sin ($\phi_h$ – $\phi_S$)** asymmetry

**Boer-Mulders function:**

**transversely polarized quarks in an unpolarized nucleon**

$h_1^{\perp} =$



$-$

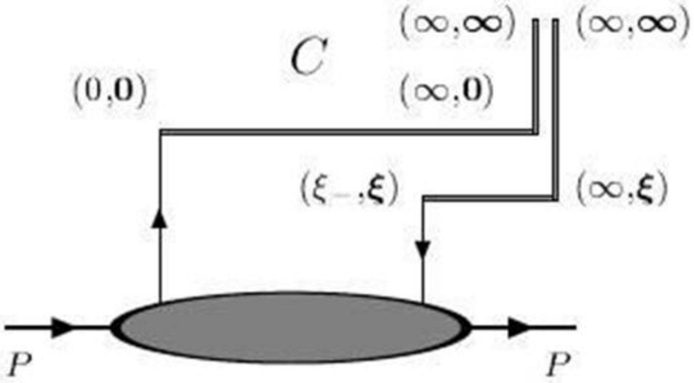
$$f_{q^\uparrow/p}(x,\boldsymbol{p}_T) = \frac{1}{2}\left[f_1^q(x,p_T^2) - h_1^{\perp q}(x,p_T^2)\frac{(\hat{\boldsymbol{P}}\times\boldsymbol{p}_T)\cdot\boldsymbol{S}_q}{M}\right]$$

→ azimuthal **cos $\phi_h$** and **cos 2$\phi_h$** asymmetries

# … going beyond collinear pQCD…

## the gauge structure of TMDs

$$(x, \boldsymbol{k}_T) = \int \frac{\mathrm{d}\xi^-}{2\pi} \int \frac{\mathrm{d}^2\boldsymbol{\xi}_T}{(2\pi)^2} \mathrm{e}^{\mathrm{i}xP^+\xi^-}\, \mathrm{e}^{-\mathrm{i}\boldsymbol{k}_T\cdot\boldsymbol{\xi}_T}\, \langle P,S|\bar{\psi}(0)\,\mathcal{W}[0,\xi]\,\psi(\xi)|P,S\rangle|_{\xi^+=0}$$



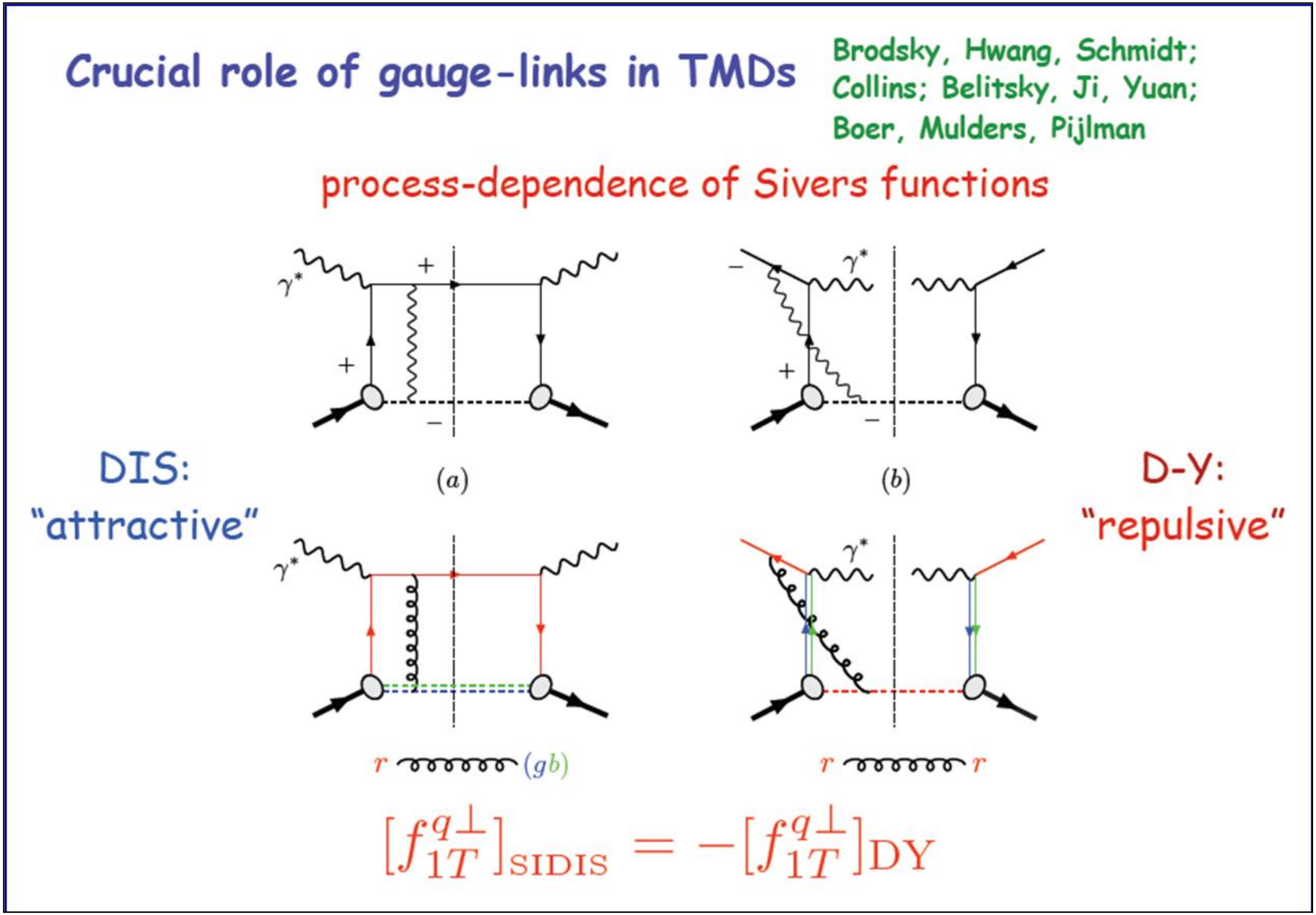
$$\text{SIDIS}: \mathcal{W}[0,\xi] = \mathcal{W}^-[0,\infty]\,\mathcal{W}^T[0_T,\infty_T]\,\mathcal{W}^T[\infty_T,\xi_T]\,\mathcal{W}^-[\infty,\xi]$$

**the existence of Sivers and Boer-Mulders functions is a consequence of the gauge link structure, which also implies**

**TMD (SIDIS) = - TMD (DY)**

this is a fundamental test of gauge invariance

# … going beyond collinear pQCD…



Crucial role of gauge-links in TMDs

Brodsky, Hwang, Schmidt;
Collins; Belitsky, Ji, Yuan;
Boer, Mulders, Pijlman

process-dependence of Sivers functions

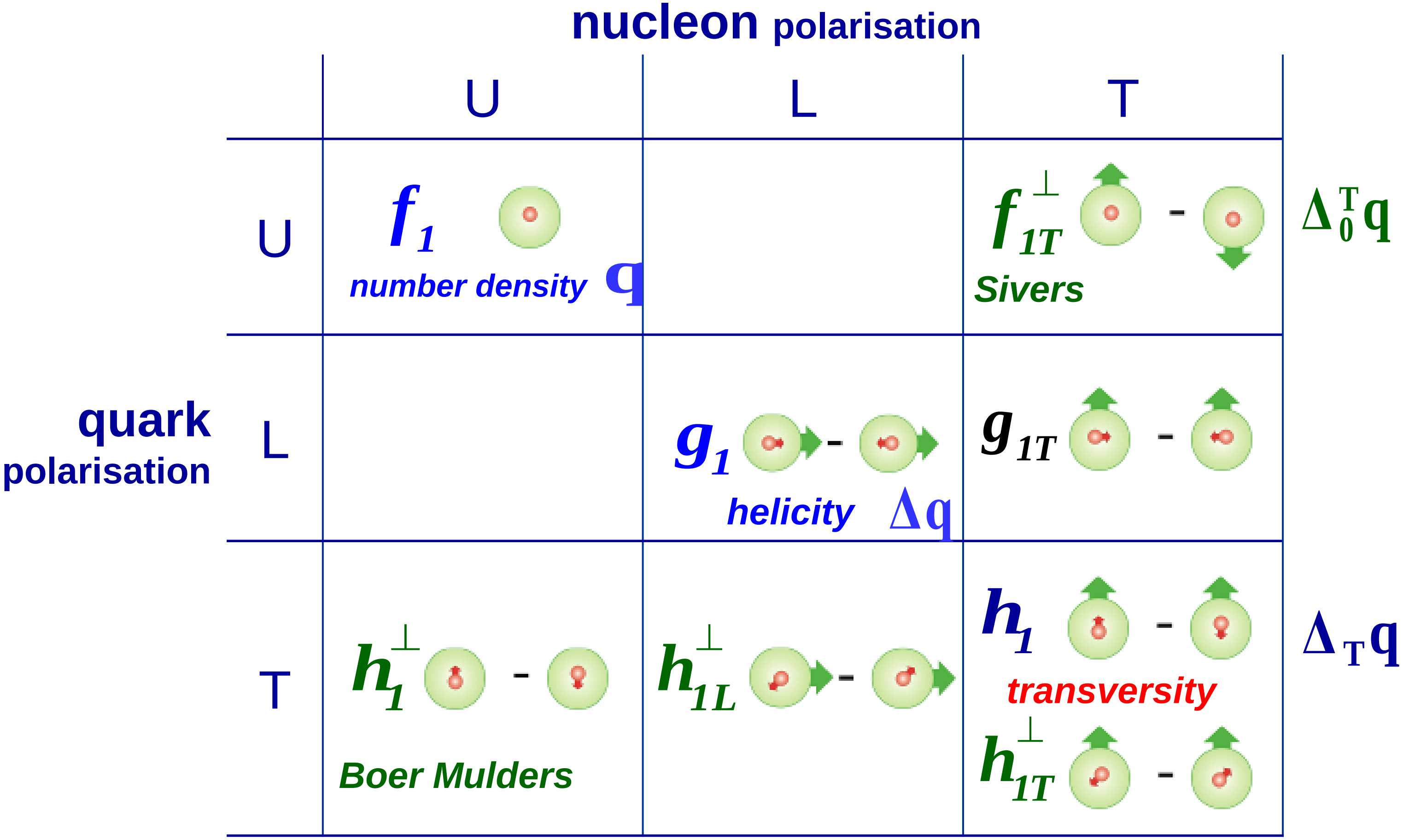
DIS:
“attractive”

D-Y:
“repulsive”

$$[f_{1T}^{q\perp}]_{\mathrm{SIDIS}} = -[f_{1T}^{q\perp}]_{\mathrm{DY}}$$

# The Structure of the Nucleon

**taking into account the quark intrinsic transverse momentum $k_T$ ,
at leading order other 6 TMD PDFs are needed for a full description
of the nucleon quark structure**



**nucleon** polarisation

| | | U | L | T | |
|---|---|---|---|---|---|
| | U | $f_1$ ○ *number density* $q$ | | $f_{1T}^{\perp}$ ○ - ○ *Sivers* | $\Delta_0^T q$ |
| **quark** polarisation | L | | $g_1$ ○ - ○ *helicity* $\Delta q$ | $g_{1T}$ ○ - ○ | |
| | T | $h_1^{\perp}$ ○ - ○ *Boer Mulders* | $h_{1L}^{\perp}$ ○ - ○ | $h_1$ ○ - ○ *transversity*<br>$h_{1T}^{\perp}$ ○ - ○ | $\Delta_T q$ |

# The Structure of the Nucleon

**taking into account the quark intrinsic transverse momentum $k_T$ ,
at leading order other 6 TMD PDFs are needed for a full description
of the nucleon quark structure**

**Sivers function**

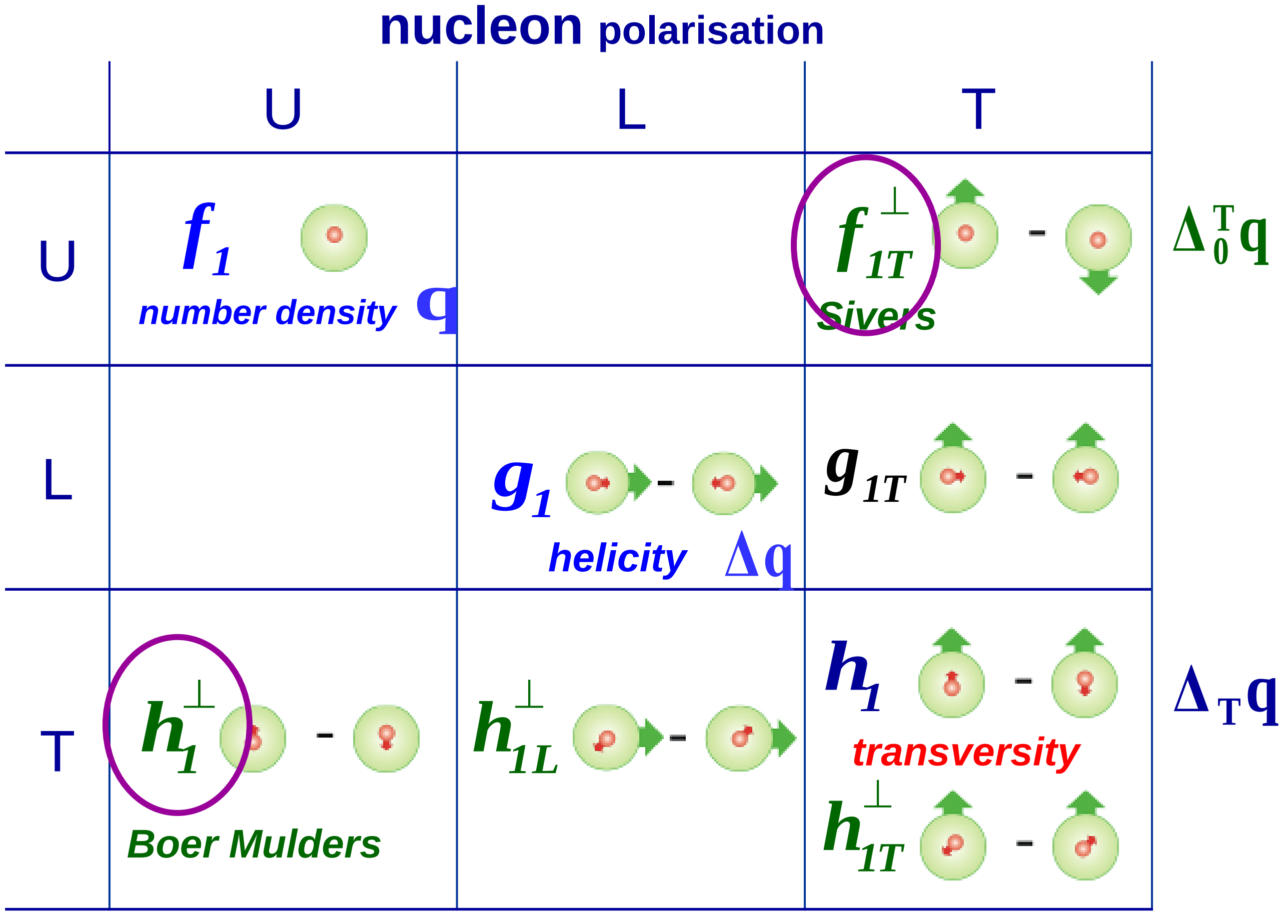
correlation between the transverse spin of the nucleon and the transverse momentum of the quark

*sensitive to orbital angular momentum*

**Boer-Mulders function**

correlation between the transverse spin and the transverse momentum of the quark in unpol nucleons

*T-odd*



**nucleon** **polarisation**

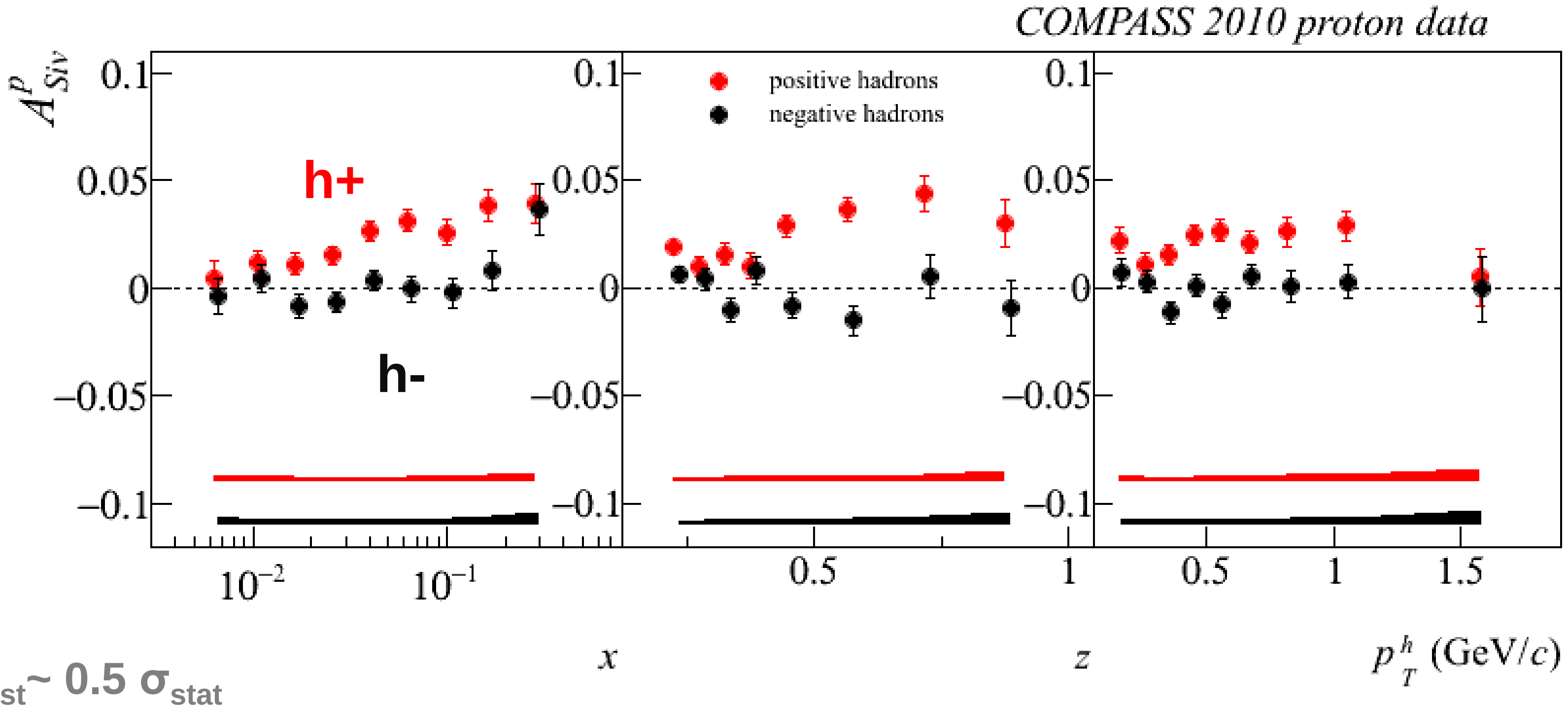
**quark** **polarisation**

| | U | L | T | |
|---|---|---|---|---|
| U | $f_1$ *number density* $q$ | | $f_{1T}^{\perp}$ *Sivers* | $\Delta_0^T q$ |
| L | | $g_1$ *helicity* $\Delta q$ | $g_{1T}$ | |
| T | $h_1^{\perp}$ *Boer Mulders* | $h_{1L}^{\perp}$ | $h_1$ *transversity*<br>$h_{1T}^{\perp}$ | $\Delta_T q$ |

**SIDIS gives access to all of them**

# Sivers asymmetry on proton

**charged hadrons, 2010 data** PLB 717 (2012) 383

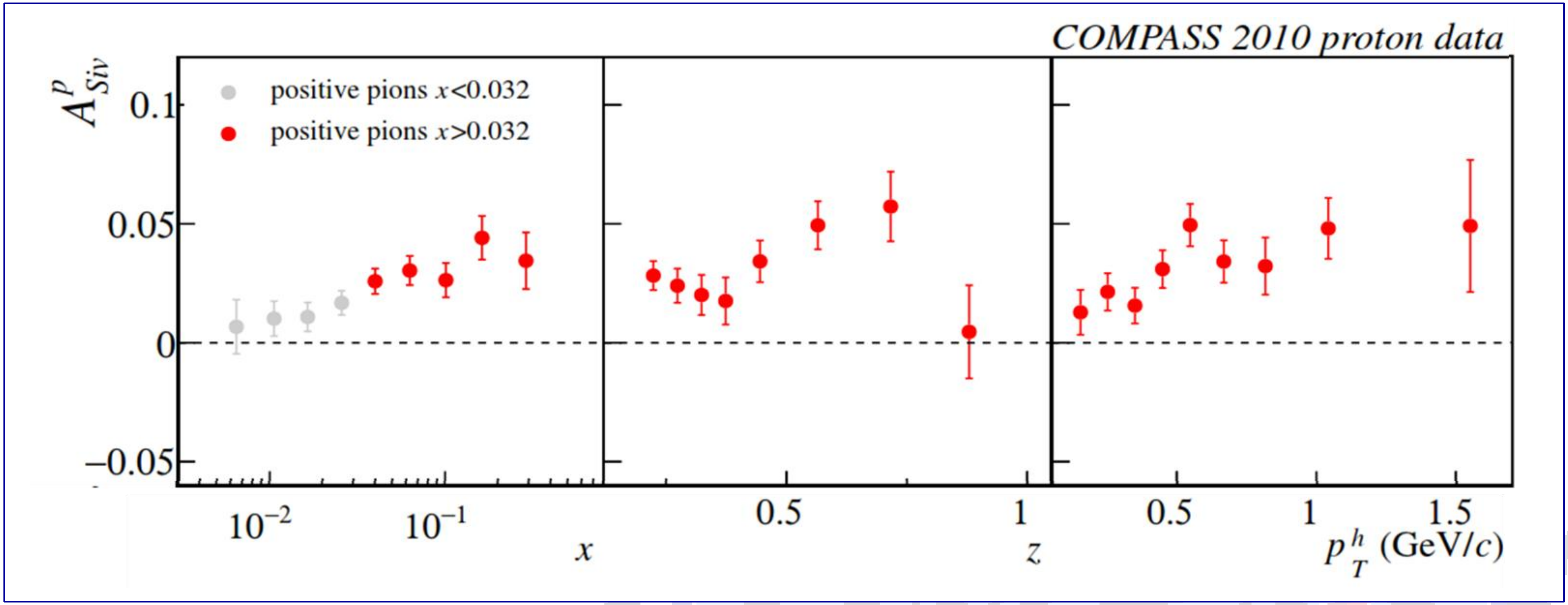


$\sigma_{syst}$~ 0.5 $\sigma_{stat}$

**clear positive signal for h$^+$, which extends to small x**
**EVIDENCE FOR ORBITAL ANGULAR MOMENTUM OF QUARKS**

# Sivers asymmetry on proton

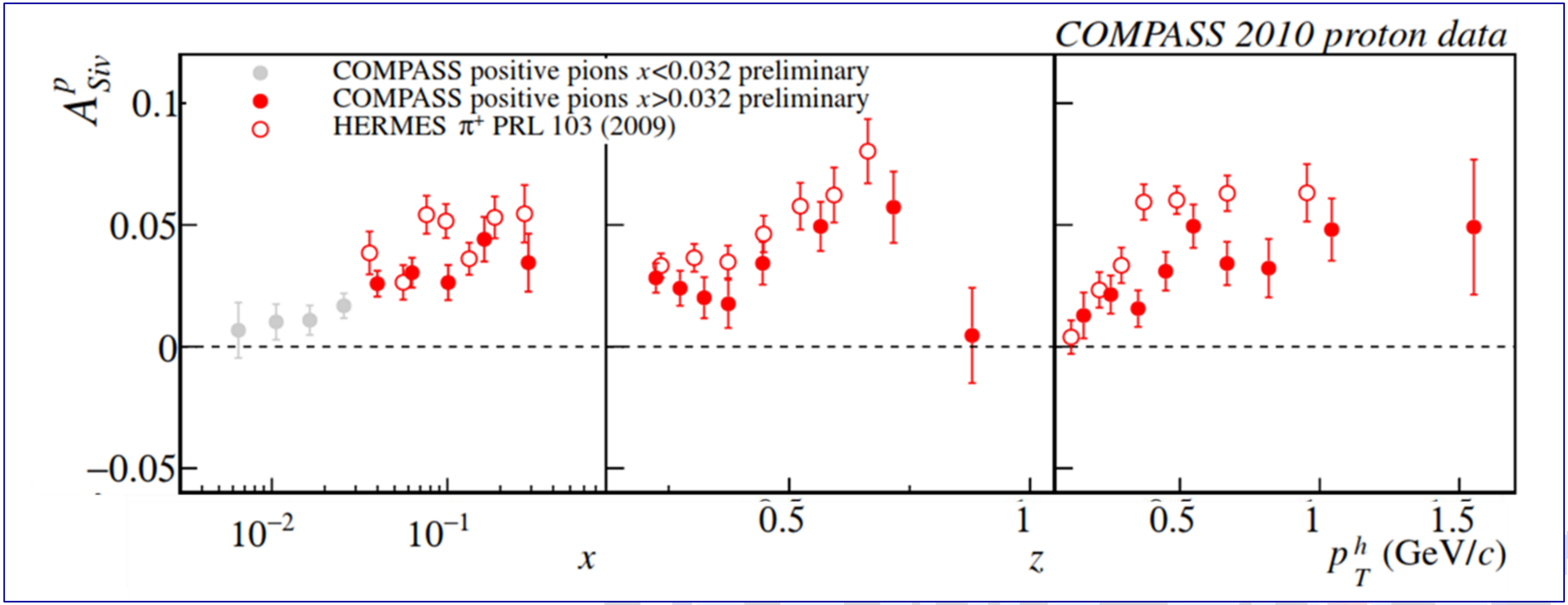
**charged pions, 2010 data** SPIN2012



**comparison with HERMES**

# Sivers asymmetry on proton

**charged pions, 2010 data** SPIN2012



**comparison with HERMES**

**… TMD Q2 evolution: the very new developments !**

# CONCLUSIONS

- the quarks contribute 1/3 of the nucleon spin
- the relative size of DG and L not clearly assessed
- COMPASS II will address L via DVCS

- TRANSVERSE SPIN AND MOMENTUM PHENOMENA:

  NEW Properties of matter have been unveiled

  Transversity and Collins effect,  Sivers effect

  *OTHER correlations are still possible (Boer-Mulders)*

- COMPASS II should be able to
  - test the predicted sign change of the Sivers function from SIDIS to D-Y
  - perform precise measurements of unpolarised SIDIS azimuthal asymmetries on p

- COMPASS has a great discovery potential for glueballs and hybrids

THANK YOU !

# future measurements

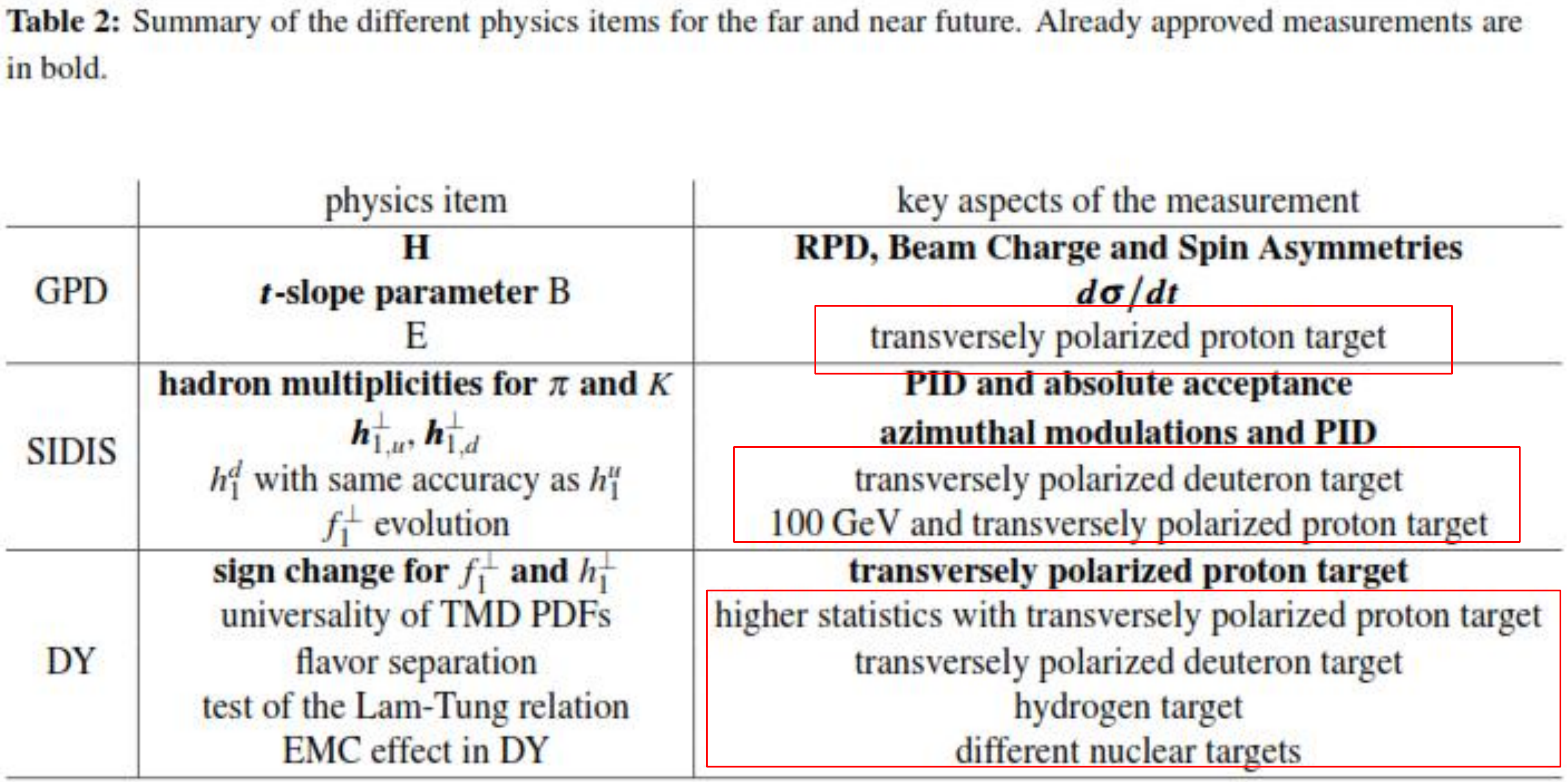
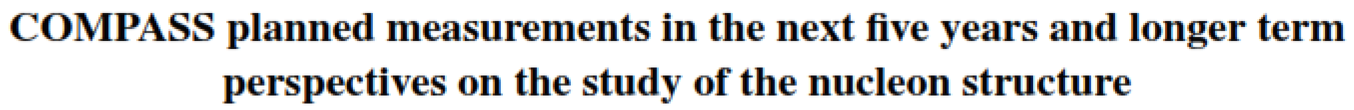


**Table 2:** Summary of the different physics items for the far and near future. Already approved measurements are in bold.

| | physics item | key aspects of the measurement |
|---|---|---|
| GPD | **H** | **RPD, Beam Charge and Spin Asymmetries** |
| | **$\boldsymbol{t}$-slope parameter** B | $\boldsymbol{d\sigma/dt}$ |
| | E | transversely polarized proton target |
| SIDIS | **hadron multiplicities for $\pi$ and $K$** | **PID and absolute acceptance** |
| | $\boldsymbol{h_{1,u}^{\perp}, h_{1,d}^{\perp}}$ | **azimuthal modulations and PID** |
| | $h_1^d$ with same accuracy as $h_1^u$ | transversely polarized deuteron target |
| | $f_1^{\perp}$ evolution | 100 GeV and transversely polarized proton target |
| DY | **sign change for $f_1^{\perp}$ and $h_1^{\perp}$** | **transversely polarized proton target** |
| | universality of TMD PDFs | higher statistics with transversely polarized proton target |
| | flavor separation | transversely polarized deuteron target |
| | test of the Lam-Tung relation | hydrogen target |
| | EMC effect in DY | different nuclear targets |

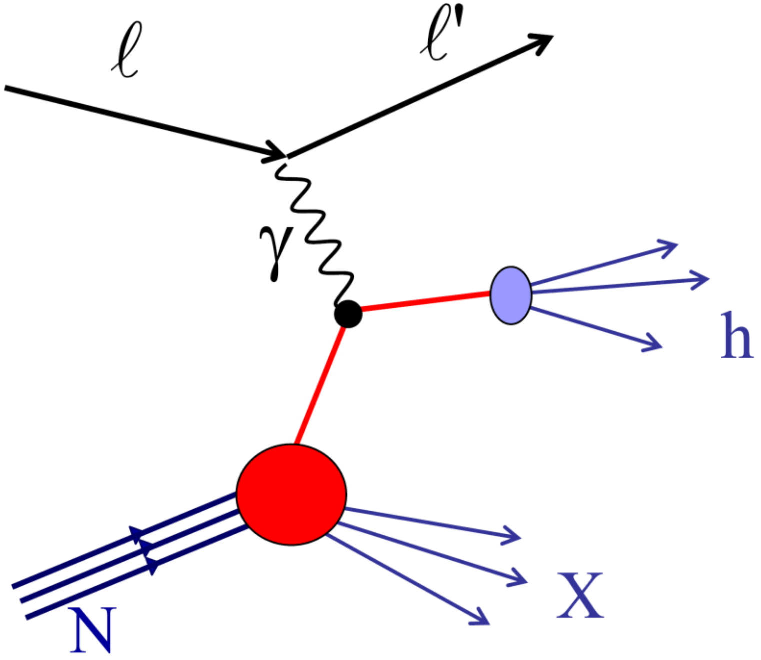
**P. Newman in Cracow**



**COMPASS planned measurements in the next five years and longer term perspectives on the study of the nucleon structure**

# Semi-Inclusive Deep Inelastic Scattering

**hard interaction of a lepton with a nucleon via virtual photon exchange**

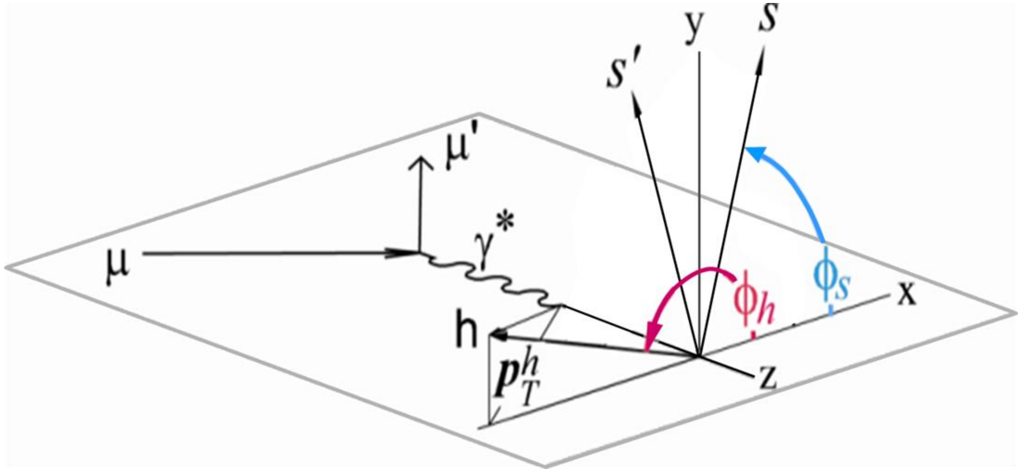


$$x = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot q}{P\cdot \ell} =_{LAB} \frac{E-E'}{E}$$

$$Q^2 = -q^2 \qquad W^2 = (P+q)^2$$

$$z = \frac{P\cdot P_h}{P\cdot q} =_{LAB} \frac{E_h}{E-E'}$$

$$\boxed{\sigma^{\ell N\to \ell hX} \propto \sum_q q(x) \otimes \sigma^{\ell q\to \ell q} \otimes D_q^h(z)}$$



# Semi-Inclusive Deep Inelastic Scattering

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

unpol target

→ pol target

$$+\,S_{\parallel}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]+S_{\parallel}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

↑ pol target

$$+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

**18 structure functions**

# Semi-Inclusive Deep Inelastic Scattering

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\cos\phi_h}\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\,\overset{h_1^\perp H_1^\perp}{\boxed{\cos(2\phi_h)}}\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\sin\phi_h}\,F_{LU}^{\sin\phi_h}$$

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\,\overset{h_{1L}^\perp H_1^\perp}{\boxed{\sin(2\phi_h)}}\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_h}\,F_{LL}^{\cos\phi_h}\right]$$

$$+\,|\boldsymbol{S}_\perp|\Big[\boxed{\sin(\phi_h-\phi_S)}\,\overset{f_{1T}^\perp D_1}{\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)$$

$$+\,\varepsilon\,\underset{h_1 H_1^\perp}{\boxed{\sin(\phi_h+\phi_S)}\,F_{UT}^{\sin(\phi_h+\phi_S)}}+\varepsilon\,\overset{h_{1T}^\perp H_1^\perp}{\boxed{\sin(3\phi_h-\phi_S)}\,F_{UT}^{\sin(3\phi_h-\phi_S)}}$$

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_S}\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin(2\phi_h-\phi_S)}\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\overset{g_{1T}D_1}{\boxed{\cos(\phi_h-\phi_S)}\,F_{LT}^{\cos(\phi_h-\phi_S)}}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos(2\phi_h-\phi_S)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

**14 independent azimuthal modulations**

# Semi-Inclusive Deep Inelastic Scattering

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\cos\phi_h}\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\,\overset{h_1^\perp H_1^\perp}{\boxed{\cos(2\phi_h)}}\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\sin\phi_h}\,F_{LU}^{\sin\phi_h} \\
&\quad+S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\,\overset{h_{1L}^\perp H_1^\perp}{\boxed{\sin(2\phi_h)}}\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\right. \\
&\quad+|\boldsymbol{S}_\perp|\left[\overset{f_{1T}^\perp D_1}{\boxed{\sin(\phi_h-\phi_S)}}\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\right. \\
&\qquad+\varepsilon\,\underset{h_1 H_1^\perp}{\boxed{\sin(\phi_h+\phi_S)}}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\overset{h_{1T}^\perp H_1^\perp}{\boxed{\sin(3\phi_h-\phi_S)}}\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad\left.+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_S}\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin(2\phi_h-\phi_S)}\,F_{UT}^{\sin(2\phi_h-\phi_S)}\right] \\
&\quad+|\boldsymbol{S}_\perp|\lambda_e\left[\sqrt{1-\varepsilon^2}\,\overset{g_{1T} D_1}{\boxed{\cos(\phi_h-\phi_S)}}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi_S}\right. \\
&\qquad\left.+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos(2\phi_h-\phi_S)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\Big\},
\end{aligned}
$$

**14 independent azimuthal modulations**

**amplitudes of the modulations**
**→ TMD PDFs**

# Semi-Inclusive Deep Inelastic Scattering

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\cos\phi_h}\,F_{UU}^{\cos\phi_h}$$

$h_1^\perp H_1^\perp$

$$+\,\varepsilon\,\boxed{\cos(2\phi_h)}\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\sin\phi_h}\,F_{LU}^{\sin\phi_h}$$

$h_{1L}^\perp H_1^\perp$

$$+\,S_\parallel\,\Bigg[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\,\boxed{\sin(2\phi_h)}\,F_{UL}^{\sin 2\phi_h}\Bigg]+S_\parallel\lambda_e\,\Bigg[\sqrt{1-\varepsilon^2}$$

$f_{1T}^\perp D_1$

$$+\,|\boldsymbol{S}_\perp|\,\Bigg[\boxed{\sin(\phi_h-\phi_S)}\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon$$

$$+\,\varepsilon\,\boxed{\sin(\phi_h+\phi_S)}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon$$

$h_1\,H_1^\perp$

$$+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\boxed{\sin\phi_S}\,F_{UT}^{\sin\phi_S}+\sqrt{}$$

$g_{1T} D_1$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\,\Bigg[\sqrt{1-\varepsilon^2}\,\boxed{\cos(\phi_h-\phi_S)}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi}$$

$$+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos(2\phi_h-\phi_S)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},$$

**14 independent azimuthal modulations**

**amplitudes of the modulations**
**→ TMD PDFs**

**SIDIS**

- **allows to disentangle the effects related to the different TMD PDFs and to access all of them**
- **by identifying the final state hadrons and using different targets allows for flavour separation**

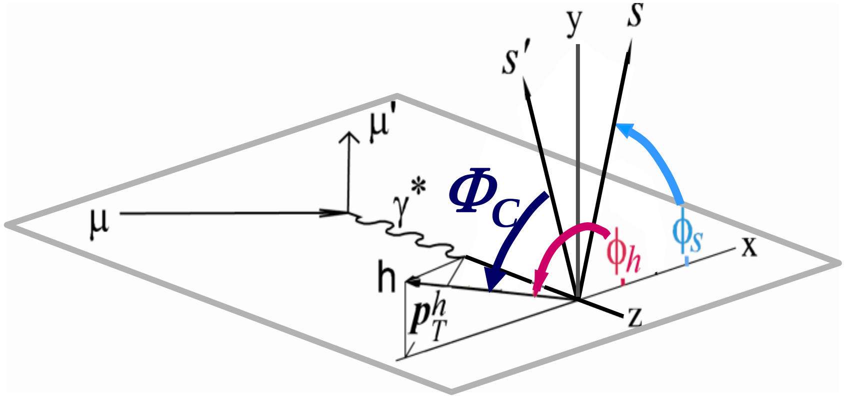
**→ *very powerful tool***

**all the amplitudes** (AA) **have been measured in COMPASS**

# Collins asymmetry

**amplitude of the $\sin\Phi_C$ modulation in the azimuthal distribution of the final state hadrons**

$$N_h^{\pm}(\Phi_C) = N_h^0\left[1 \pm P_T \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_C\right]$$



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

transversity

**"Collins FF"**

BELLE,
BaBar

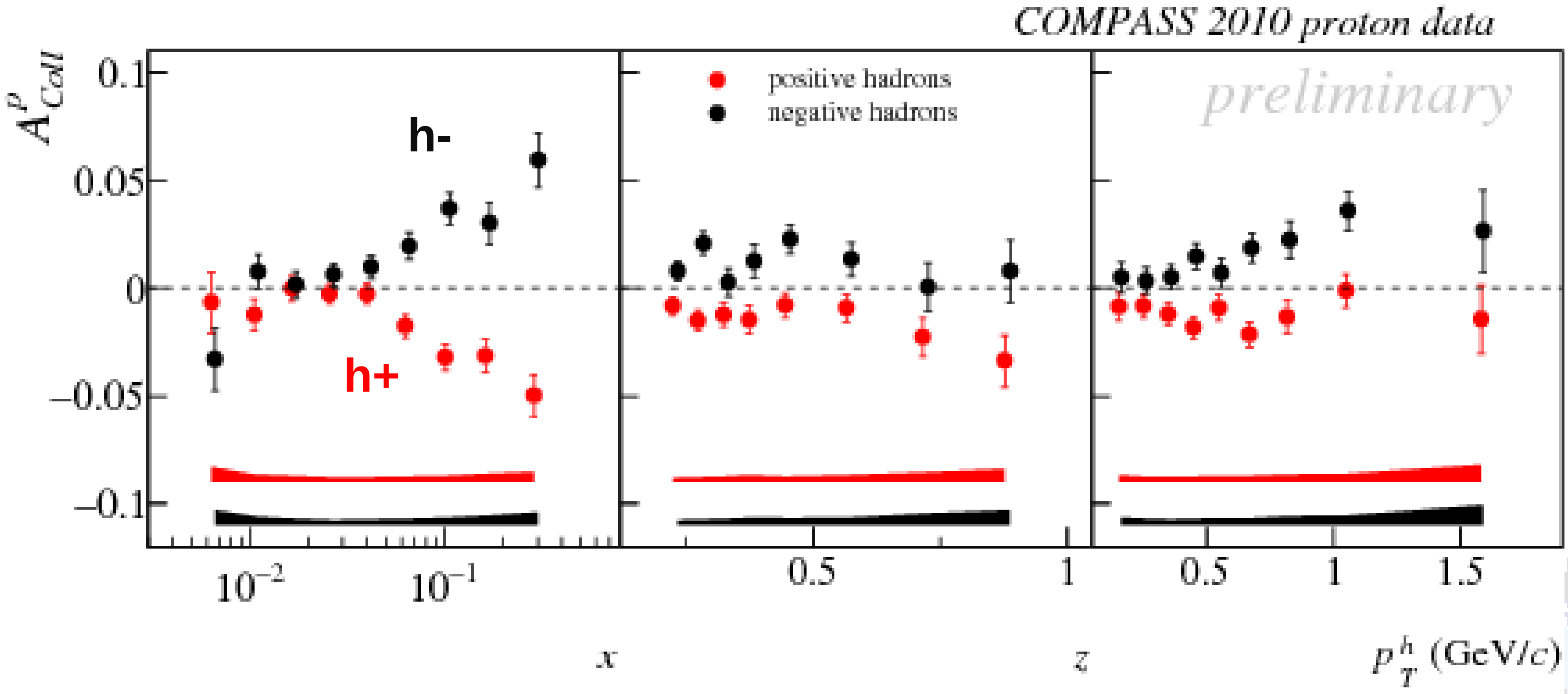
$$A_{Coll} \approx \frac{\sum_q e_q^2 \, h_{1q} \otimes H_{1q}^{\perp h}}{\sum_q e_q^2 \, f_{1q} \otimes D_{1q}^h}$$

**today the most promising way to access transversity,** together with 2h asymmetry

# Collins asymmetry on proton

**charged hadrons**

**2010 data**

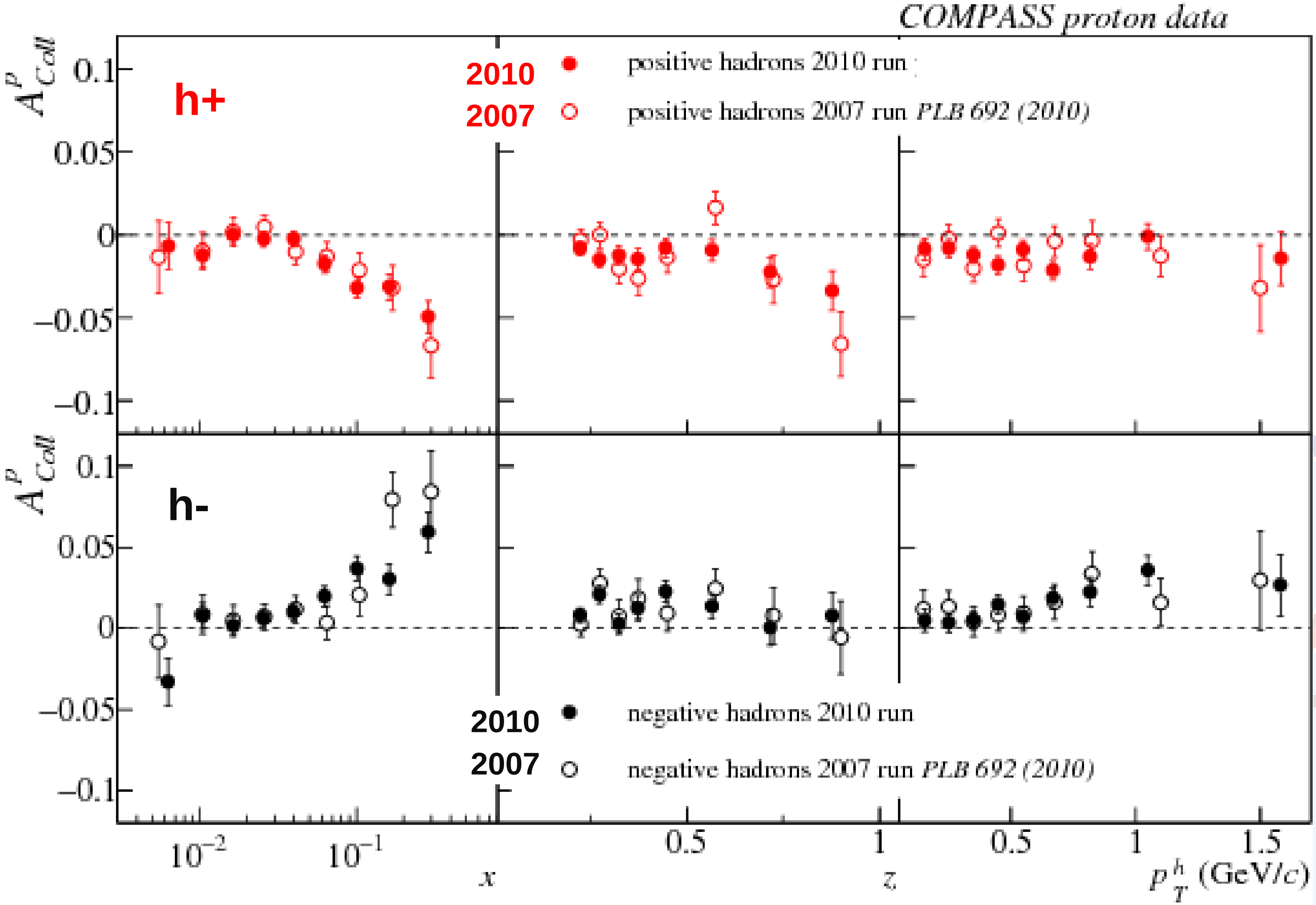


$\sigma_{syst} \sim 0.5\ \sigma_{stat}$

# Collins asymmetry on proton

**charged hadrons**

**2010 vs 2007 data**

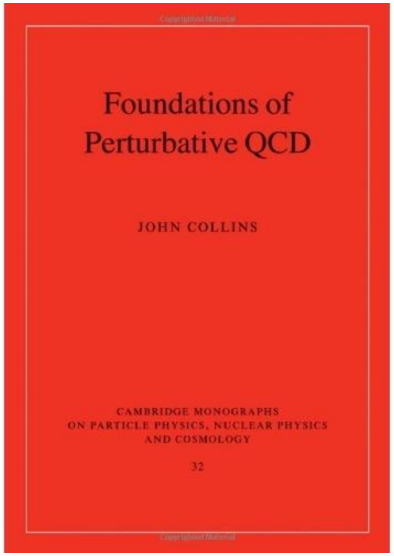


**nice confirmation, with better statistics**

# TMD factorization

Observables = Universal TMDs × pQCD Coefficients

$$
\begin{aligned}
W^{\mu\nu} =& \\
&\sum_f |\mathcal{H}_f(Q;\mu)^2|^{\mu\nu} \int d^2\mathbf{k}_{1T}\, d^2\mathbf{k}_{2T}\, \delta^{(2)}(\mathbf{k}_{1T} + \mathbf{q}_T - \mathbf{k}_{2T}) \\
&\times F_{f/p}(x, \mathbf{k}_{1T}; \mu; \zeta_F)\, D_{h/f}(z, z\mathbf{k}_{2T}; \mu; \zeta_D) \\
&= \sum_f |\mathcal{H}_f(Q;\mu)^2|^{\mu\nu} \int \frac{d^2\mathbf{b}_T}{(2\pi)^2}\, e^{-i\mathbf{q}_T\cdot\mathbf{b}_T} \\
&\times \tilde{F}_{f/p}(x, \mathbf{b}_T; \mu; \zeta_F)\, \tilde{D}_{h/f}(z, \mathbf{b}_T; \mu; \zeta_D)
\end{aligned}
$$



Foundations of
Perturbative QCD

JOHN COLLINS

CAMBRIDGE MONOGRAPHS
ON PARTICLE PHYSICS, NUCLEAR PHYSICS
AND COSMOLOGY

32

Collins, Soper
Ji, Ma, Yuan

# The Quark Contribution to the Nucleon Spin

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

in polarised DIS one measures

$$g_1(x) = \frac{1}{2}\sum_q e_q{}^2 \cdot \Delta q(x) \qquad \Gamma_1 = \int_0^1 g_1(x)\,dx$$

using complementary information from
the WEAK DECAY CONSTANTS of the BARYONS

$$\Delta u - \Delta d = F + D = 1.257 \pm 0.003$$

$$\Delta u + \Delta d - 2\,\Delta s = 3F - D = \sqrt{3}\cdot[0.34 \pm 0.02]$$

one can get $\Delta u$, $\Delta d$, $\Delta s$ and then $\Delta\Sigma$