COMPASS – a versatile facility at CERN

25 years since approval and 20 years since first data-taking
100 years after the Stern-Gerlach exp. and 35 years after EMC ‘spin crisis’

Barbara Badelek
University of Warsaw

QNP2022, Florida State University, 5-9 September, 2022
Happy 25th Birthday COMPASS

Congratulations; what a great ride you’ve had!

Arguably the most comprehensive experimental detector system & collaboration to study hadron structure using complementary tools: Muon (L,T) DIS, Hadron Scattering, DVCS and Drell-Yan

From 1995 (letter of intent) until to today:
~130 Diploma/Masters/Bachelor’s Theses
~130 Ph.D. Theses
~10 Habilitation Theses
~75 Peer Reviewed Publications

A high bar for future experimental ventures

Slide courtesy A. Deshpande, IWHSS2022
COMPASS Proposal
Slide courtesy G. Mallot, IWHSS2022

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/SPSLC 96-14
SPSC/P 297
March 1, 1996

PROPOSAL

Common Muon and Proton Apparatus for Structure and Spectroscopy

The COMPASS Collaboration

Abstract

We propose to study hadron structure and hadron spectroscopy with high-rate hadron and muon beams and a new spectrometer to be built at the CERN SPS. The experiment can start up in 1999 and a program of physics measurements for an initial period of 5 more years is planned.
The M2 beam line supplies muons ($\mu^\pm$) and hadrons ($\pi^\pm$, $K^\pm$, $p$, $\bar{p}$) to the North Area.
COmmon Muon and Proton Apparatus for Structure and Spectroscopy

~ 200 physicists, ~ 25 institutes from 13 countries

A fixed-target experiment at the SPS at CERN

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Versatile COMPASS in EHN2

Slide courtesy G. Mallot, PBC 2017

COMPASS-I
1997-2011

Hadron Spectroscopy & Polarisability

Polarised SIDIS

COMPASS-II
2012-2018

Polarised Drell-Yan

DVCS (GPDs) + unp. SIDIS

Barbara Badelek (Warsaw)
Versatile COMPASS facility at the M2 beam line at CERN

Two stages
Calorimetry
Particle identification (Muon Walls, RICH)
Large, solid state polarised targets: $^6\text{LiD, NH}_3$
Liquid H$_2$ and nuclear targets
Beams: 160 (200) GeV $\mu^\pm$ (80% polarised)
  190 GeV hadrons
  $2(1) \times 10^8$/spill

Examples of COMPASS facility performance:
target in the muon setup

* Polarisation reversal by $\vec{B}$ rotation

Interaction point position in the NH$_3$ target,
$Q^2 < 1 \text{ (GeV/c)}^2$

* Material: solid $^6\text{LiD} \text{ (NH}_3\text{)}$
* Polarisation: $\sim 50\% \text{ (} \sim 90\% \text{), by the Dynamical Nuclear Polarisation}$
* Dilution: $f \sim 0.4 \text{ (} \sim 0.15 \text{)}$
* Polar acceptance: $\sim 70 \text{ mrad} \text{ (} \sim 180 \text{ mrad after 2005)}$
* Polarisation reversal by $\vec{B}$ rotation

Courtesy A.S. Nunes, PhD, University of Lisbon, 2017
Examples of COMPASS facility performance:
RICH and RPD in the hadron beam setup; kinem.acceptance

RICH particle identification, $C_4F_{10}$ radiator

Proton Recoil Detector (outer ring)

Lowest $x$ in COMPASS (and SMC)
Nucleon in 1-D, 3-D and 5-D
Nucleon partonic structure (courtesy of Yu-Hsiang Lien, COMPASS)
Nucleon in 1-D

⇒ Longitudinal spin structure
Partonic structure of the nucleon; distribution functions

Three twist-two quark distributions in QCD (momentum, helicity & transversity) after integrating over the quark intrinsic $k_t$

\[ q(x) = \begin{array}{c}
\end{array} \]

Quark momentum DF; well known (unpolarised DIS $\rightarrow F_{1,2}(x, Q^2)$).

\[ \Delta q(x) = \begin{array}{c}
\end{array} \]

Difference in DF of quarks with spin parallel or antiparallel to the nucleon’s spin in a longitudinally polarised nucleon; less well known (polarised DIS $\rightarrow g_1(x, Q^2)$).

\[ \Delta_T q(x) = \begin{array}{c}
\end{array} \]

Difference in DF of quarks with spin parallel or antiparallel to the nucleon’s spin in a transversely polarised nucleon; poorly known (polarised DIS $\rightarrow h_1(x, Q^2)$).

Nonrelativistically: $\Delta_T q(x, Q^2) \equiv \Delta q(x, Q^2)$. OBS! $\Delta_T q(x, Q^2)$ are C-odd and chiral-odd; may only be measured with another chiral-odd partner, e.g. fragmentation function.
$g_1^P$ and $g_1^d$, $Q^2 > 1 \, (\text{GeV}/c)^2$, COMPASS full statistics

COMPASS NLO QCD fit to the world data at $W^2 > 10 \, (\text{GeV}/c^2)^2$

dashed line: extrapolation to $W^2 < 10 \, (\text{GeV}/c^2)^2$

**Proton**

**Deuteron**

COMPASS measurements at high $Q^2$ important for the QCD analysis! but little sensitive to $\Delta g$


Barbara Badelek (Warsaw)
NLO QCD fit to $p$, $d$, $^3$He world data

- $g_1^p$ clearly positive at low $x$ and raising with decreasing $x$
- $g_1^d$ consistent with zero at low $x$?

- $-1.5 < \Delta G < 0.5$, poorly constraint
  $\Rightarrow$ “direct methods”
- $\sigma_{stat.}$ (dark bands) $\ll \sigma_{syst.}$ (light b.)

COMPASS PL B 753 (2016) 18
Direct measurements of $\Delta g(x)$

Direct measurements – via the cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into $c\bar{c}$ (LO, NLO) or $q\bar{q}$ (high $p_T$ hadron pair (LO)): $A_{\gamma N}^{\text{PGF}} \approx \langle a_{\text{LL}}^{\text{PGF}} \rangle \frac{\Delta g}{g}$

COMPASS from SIDIS on d for any $(p_T)_h$ and at LO:

$\Delta g/g = 0.113 \pm 0.038\,\text{(stat.)} \pm 0.036\,\text{(syst.)}$ at $\langle Q^2 \rangle \approx 3\,\text{(GeV/c)}^2$, $\langle x_g \rangle \approx 0.10$

Clearly positive gluon polarisation but not large!

COMPASS, EPJC 77(2017) 209
Semi-inclusive asymmetries and parton distributions

- COMPASS: measured on both proton and deuteron targets for identified $\pi^+$, $\pi^-$ and (for the first time) $K^+$, $K^-$


- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV (without these results) describes the data well.
First moments of $g_1$ and singlet axial charge $a_0$

- First moments $\Gamma_1^P, \Gamma_1^d, \Gamma_1^N$
  - where $\Gamma_1^i = \int_0^1 g_1^i(x, Q^2) dx$

- In particular:
  - $\Gamma_1^N(Q^2) = \frac{1}{36} \left[ 4a_0 C_S(Q^2) + a_8 C_{NS}(Q^2) \right]$
  - $= \int_0^1 \frac{g_1^d(x, Q^2)}{1 - 1.5 \omega_D} dx$

- In the $\overline{MS}$: $a_0 = \Delta \Sigma = (\Delta u + \Delta \bar{u}) + (\Delta d + \Delta \bar{d}) + (\Delta s + \Delta \bar{s})$

- $\Gamma_1^N$ approaches asymptotic value already at $Q^2 = 3 \text{ (GeV/c)}^2$

- From COMPASS data alone:
  - $\Gamma_1^N(Q^2 = 3 \text{ (GeV/c)}^2) = 0.046 \pm 0.002_{\text{stat.}} \pm 0.004_{\text{syst.}} \pm 0.005_{\text{evol.}}$

- From COMPASS data alone (and $a_8$ from PRD 82 (2010) 114018):
  - $a_0(Q^2 = 3 \text{ (GeV/c)}^2) = 0.32 \pm 0.02_{\text{stat.}} \pm 0.04_{\text{syst.}} \pm 0.05_{\text{evol.}}$
  - (consistent with value from the COMPASS NLO QCD fit of world data).
Non-singlet structure function, \( g_{1NS}(x, Q^2) \)

- **Non-singlet structure function:**
  \[
  g_{1NS} = \frac{g_p}{g_n} = \frac{g_p(x, Q^2) - g_n(x, Q^2)}{2}
  = 2 \left[ g_{1P}(x, Q^2) - g_{1N}(x, Q^2) \right]
  \]

- Its moment connected to the Bjorken sum rule:
  \[
  \Gamma_{1NS}^{NS} (Q^2) = \int_0^1 g_{1NS}^N(x, Q^2) dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C_{1NS}^{NS} (Q^2)
  \]

- \( g_{1NS} \) calculated, NLO QCD fitted (only \( \Delta q_3 \)),
evolved to \( Q^2 = 3 \text{ (GeV/c)}^2 \)
and fit-extrapolated \( x \to 0, 1 \):
  \[
  \Gamma_{1NS}^{NS} = 0.192 \pm 0.007_{\text{stat.}} \pm 0.015_{\text{syst.}}
  \]
  \[
  \left| \frac{g_A}{g_V} \right| = 1.29 \pm 0.05_{\text{stat.}} \pm 0.10_{\text{syst.}}
  \]

- Neutron \( \beta \) decay gives: \( \left| \frac{g_A}{g_V} \right| = 1.2701 \pm 0.002 \)

- This validates the Bjorken sum rule with an accuracy of 9%.
$g_1^N$ in the nonperturbative ($Q^2 < 1 \text{ (GeV/c)}^2$ region)

Spin effects in $g_1^d$ at low $x$ and $Q^2$ absent ? Very clear spin effects in $g_1^D$ at low $x$ and $Q^2$
Nucleon in 3-D

⇒ Transverse Momentum Distributions (TMD)
Partonic structure of the nucleon; distribution functions

- In LT and considering $k_T$, 8 PDF describe the nucleon
  $\Rightarrow$ Transverse Momentum Dependent PDF

- QCD-TMD approach valid $k_T \ll \sqrt{Q^2}$

- After integrating over $k_T$
  only 3 survive: $f_1, g_1, h_1$

- TMD accessed in SIDIS and DY
  by measuring azimuthal asymmetries
  with different angular modulations

- SIDIS: e.g. $A_{Sivers} \propto \text{PDF} \otimes \text{FF}$

- DY: e.g. $A_{Sivers} \propto \text{PDF}^{\text{beam}} \otimes \text{PDF}^{\text{target}}$

- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

\[
h_{1T}^T(\text{SIDIS}) = -h_{1T}^T(\text{DY})
\]
(follows from QCD gauge invariance)

- OBS! transversity PDF is chiral-odd; may only be measured with another chiral-odd
  partner, e.g. fragmentation function.

- TMD parton distributions need TMD Fragmentation Functions!

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<th>QUARK</th>
<th>NUCLEON</th>
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<td>number density</td>
<td>$g_{1L}$</td>
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<tr>
<td>helicity</td>
<td>$h_{1T}^T$</td>
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Barbara Badelek (Warsaw)  COMPASS – a versatile facility at CERN
The 18 SIDIS Structure Functions

Unpolarized structure function

\[ f_1 \otimes D_1 \]

\[
\frac{d\sigma}{dx \, dy \, d\phi_S \, dz \, d\phi_h \, dP_T^2} = \frac{\alpha^2}{x \, y \, Q^2} \frac{y^2}{2(1-\varepsilon)} \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} \right. \\
+ \lambda_c \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} + S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \\
+ S_L \lambda_c \left[ \sqrt{1-\varepsilon^2} F_{LL} \right] \\
+ S_T \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} \right) + \varepsilon \sin(3\phi_h - 2\phi_S) F_{UT}^{\sin(3\phi_h - 2\phi_S)} \right. \\
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right] + S_T \lambda_c \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} \right. \\
+ \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \]

Sivers structure function

\[ f_{1T}^{\perp} \otimes D_1 \]

Collins structure function

\[ h_1 \otimes H_{1T}^{\perp} \]

Slide courtesy A. Bacchetta, IWHSS2022 (with changes)
Results for Collins asymmetry for protons \( \Rightarrow \Delta_T q \)

- Collins asymmetries for proton measured for +/- unidentified and identified hadrons...
- ...are large at \( x \gtrsim 0.03 \) and consistent with HERMES (in spite of different \( Q^2 \)!) 
- but negligible for the deuteron 
- COMPASS data on \( p,d \) + HERMES data on \( p \) + BELLE on \( e^+e^- \): \( \Rightarrow \Delta_T u, \Delta_T d \)

Results for the Sivers asymmetry for protons

Sivers asymmetries for proton measured for $+/-$ identified hadrons are large for $\pi^+$, $K^+$...

...and even larger at smaller $Q^2$ (HERMES)

COMPASS deuteron data show very small asymmetry

M. Anselmino et al., JHEP 1704(2017)046

Goal: measurement of $h_1^d$, $h_1^p$ and TMD PDFs for separate flavours

- Optimal separation $\implies$ comparable statistics on $d$ ($^6\text{LiD}$) and $p$ ($\text{NH}_3$) targets
- COMPASS $d$ data sets have 4 times less statistics than $p$
- Expected: deuteron statistics $\approx$ proton statistics on $d^\uparrow$.

Collins asym. presently

Collins asym. accuracy expected

(red - positive hadrons, black - negative hadrons)
First ever polarised Drell-Yan reaction measurements

- $\pi^- + p^\uparrow \rightarrow \mu^+ \mu^- + X$
- $\pi^-$ beam of 190 GeV/$c$, $\langle I \rangle \approx 7 \times 10^7 s^{-1}$, from CERN SPS
- Transversely polarized NH$_3$ target (2×55 cm) + Al target (7 cm) + W beam plug (120 cm)
SIDIS and Drell-Yan compatibility

\[ A_{\text{SIDIS}} \propto PDF_p \otimes FF \]
\[ A_{\text{DY}} \propto PDF_\pi \otimes PDF_p \]

Boer-Mulders
Sivers
Pretzelosity
Transversity

(courtesy of R. Longo, COMPASS)

Collins-Soper ref. frame (CS)
Target rest frame (S)
SIDIS and Drell-Yan acceptances in COMPASS

- COMPASS goals: test of the TMD PDFs universality; test of the Lam-Tung relation.
- In COMPASS, comparable \((x, Q^2)\) acceptance in SIDIS and DY. Unique!
- In both cases, cross-sections depend on (polar and azimuthal) asymmetries described by contributions of twist-2 (or higher) TMD PDFs.
- SIDIS and DY reactions for transversally polarised proton analysed and the asymmetries measured in bins of \(x_N, x_\pi, x_F, q_t\).
- Measured asymmetries agree with models
COMPASS Drell-Yan results

- Events of $4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$ are DY events with background: $\sim 4\%$

- DY events in the valence regions of $\pi$ and $N$
  \[ \langle x_\pi \rangle = 0.50, \quad \langle x_N \rangle = 0.17 \]
COMPASS TSA results

\[ A_{SIDIS} \propto PDF_p \otimes FF \]
\[ A_{DY} \propto PDF_\pi \otimes PDF_p \]

\[ A_{UU}^{cos(2\phi_h)} \propto h_{1,q}^{1/2} \otimes H_{1,q}^{1/2} \]
\[ A_{UT}^{sin(\phi_h-\phi_S)} \propto f_{1T,q}^{1/2} \otimes D_{1,q}^{1/2} \]
\[ A_{UT}^{sin(3\phi_h-\phi_S)} \propto h_{1,q}^{1/2} \otimes H_{1,q}^{1/2} \]
\[ A_{UT}^{sin(\phi_h+\phi_S)} \propto h_{1,q}^{1/2} \otimes H_{1,q}^{1/2} \]

\[ A_U^{cos(2\phi_{CS})} \propto h_{1,q}^{1/2} \otimes h_{1,q}^{1/2} \]
\[ A_T^{sin(\phi_{S})} \propto f_{1T,q}^{1/2} \otimes f_{1T,q}^{1/2} \]
\[ A_T^{sin(2\phi_{CS}+\phi_S)} \propto h_{1,q}^{1/2} \otimes h_{1,q}^{1/2} \]
\[ A_T^{sin(2\phi_{CS}-\phi_S)} \propto h_{1,q}^{1/2} \otimes h_{1,q}^{1/2} \]

- Boer-Mulders
- Sivers
- Pretzelosity
- Transversity

(courtesy of R. Longo, COMPASS)

COMPASS SIDIS Data,
PLB 770 (2017) 138

NEW RESULTS!

COMPASS Drell-Yan, NH3, 2015+2018 data preliminary
4.3 < M_{\mu\mu}(GeV/c^2) < 8.5

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COMPASS DY results: universality of the Sivers TMD

COMPASS DY result for Sivers asymmetry, $A_T^{\sin(\phi_S)}$
consistently with (predicted) sign change of the Sivers TMD, $f_{1T}^\perp$
Nucleon in 1+2D

⇒ Generalised Parton Distributions (GPD)
Access GPD through the DVCS/DVMP mechanism

- 4 GDPs \((H, E, \tilde{H}, \tilde{E})\) for each flavour and for gluons plus 4 chiral odd ones \((H_T, E_T, \tilde{H}_T, \tilde{E}_T)\)
- DVMP: factorisation proven for \(\sigma_L\) only
- All depend on 4 variables: \(x, \xi, t, Q^2\); DIS @ \(\xi = t = 0\); Later \(Q^2\) dependence omitted. **Careful! Here** \(x \neq x_B\)!
- \(H, \tilde{H}\) conserve nucleon helicity
- \(E, \tilde{E}\) flip nucleon helicity
- \(H, E\) refer to unpolarised distributions
- \(\tilde{H}, \tilde{E}\) refer to polarised distributions
- \(H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x)\)

\(H, E\) accessed in vector meson production *via* \(A_{UT}\) asymmetries
\(\tilde{H}, \tilde{E}\) accessed in pseudoscalar meson production *via* \(A_{UT}\) asymmetries
All 4 accessed in DVCS (\(\gamma\) production) in \(A_C, A_{LU}, A_{UT}, A_{UL}\)
Integrals of \(H, E, \tilde{H}, \tilde{E}\) over \(x\) give Dirac–, Pauli–, axial vector– and pseudoscalar vector form factors respectively.

**Important:**

\[
J^q_z = \frac{1}{2} \int dx \ x \left[ H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0) \right] = \frac{1}{2} \Delta \Sigma + L^q_z \quad (X. \ Ji)
\]
DVCS/DVMP: $\mu p \rightarrow \mu p\gamma(M)$; observables

$Q^2$ large, $t$ small

$N \xrightarrow{y_L} \Phi \xrightarrow{x+\xi} M \xleftarrow{x-\xi} N'$

**DVCS**

**known BH**

$\mu \xrightarrow{GPD} \gamma \xrightarrow{\text{small } t} \text{slow } p$

$$d\sigma^{\mu p_\rightarrow \mu p\gamma} = d\sigma^{BH} + (d\sigma^{\text{DVCS\ unpol}} + P_\mu d\sigma^{\text{DVCS\ pol}}) + e_\mu (\text{Re} I + P_\mu \text{Im} I)$$

**Observables for unpolarised target (Phase 1):**

- $S_{CS,u} \equiv \mu_+^{\leftarrow} + \mu_-^{\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{\text{DVCS\ unpol}} + e_\mu P_\mu \text{Im} I\right)$
- $D_{CS,u} \equiv \mu_+^{\leftarrow} - \mu_-^{\rightarrow} = 2\left(P_\mu d\sigma^{\text{DVCS\ pol}} + e_\mu \text{Re} I\right)$
- $A_{CS,u} \equiv \frac{\mu_+^{\leftarrow} - \mu_-^{\rightarrow}}{\mu_+^{\leftarrow} + \mu_-^{\rightarrow}} = \frac{D_{CS,u}}{S_{CS,u}}$

Each term $\phi$-modulated

If $\phi$-dependence integrated over $\Rightarrow$ twist-2 DVCS contribution;
if $\phi$-dependence analysed: $\Rightarrow$ Im $(F_1 H)$ and Re $(F_1 H)$; $H$ dominance @ COMPASS kin.

Analogously for transversely polarised target (Phase 2): $S_{CS,T}, D_{CS,T}, A_{CS,T} \Rightarrow E$
COMPASS DVCS signal at $E_\mu = 160$ GeV; $S_{CS,U}$

Pure BH
$\langle x \rangle \approx 0.0085$
$Q^2 \approx 1.8$ GeV$^2$

Interference BH/DVCS
$\langle x \rangle \approx 0.020$
$Q^2 \approx 2.0$ GeV$^2$

DVCS (above the BH)
$\langle x \rangle \approx 0.063$
$Q^2 \approx 2.1$ GeV$^2$

2012+2016 (part of) data

Approximately $5 \times$ higher statistics from 2016 still being analysed
COMPASS DVCS signal, ...cont’d

- Nucleon transverse imaging ("tomography"):

\[ S_{CS,U} \Rightarrow \frac{d\sigma_{DVCS}}{dt} \propto e^{-B(x_B)|t|} \]
where at low \( x_B \):
\[ B(x_B) \approx \frac{1}{2} \langle r_{\perp}^2(x_B) \rangle \]

Analysis of the 2016 data \( \text{(ongoing!)} \) is more refined; binning is in 3 or 4 variables \( (Q^2, t, \nu, \phi) \)

To determine the full \( x_{Bj} \) dependence of the transverse extension of partons, a global analysis of DVCS data of HERA, JLab, CERN needed.
QCD at low energies

⇒ hadron spectroscopy at COMPASS
Example: production of light mesons at COMPASS by 190 GeV $\pi^-$ p(A)

- Diffraction golden channel (“workhorse” reaction)
- About $150 \times 10^6$ events collected (more than $10 \times$ the statistics of other experiments)
- Most detailed and comprehensible analysis of $\pi^- \pi^- \pi^+$ final state so far; $\Rightarrow$ several mesons appearing in $2\pi$ and $3\pi$ spectra measured
- AMBER (and RF separated beam): high precision spectroscopy of strange mesons $\Rightarrow$ rewrite the PDG tables for strange mesons, in a single and self-consistent meas.
Example: resonance-like $a_1(1420)$ in $\pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p$

- An incredibly tiny signal extracted
- The signal consistent with prediction of $a_1(1260)$ decay via triangle singularity (Landau & Cutkosky, 1959)
  (other ways of distinguishing between a triangle singularity and resonance are under study)
COMPASS pion polarisability via Primakoff process

Electric ($\alpha$) and magnetic ($\beta$) polarisabilities (measured in fm$^3$): 

For an extended object they are related to inner forces determining the substructure → QCD at low energy (e.g. chiral perturbation theory, $\chi$PT)

Polarisabilities measured through modifications of bremsstrahlung (or Primakoff) reaction.

assuming $\alpha_\pi + \beta_\pi = 0$:
$\alpha_\pi = (2.0 \pm 0.6 \pm 0.7) \times 10^{-4}$ fm$^3$

$\chi$PT prediction:
$\alpha_\pi = (2.9 \pm 0.5) \times 10^{-4}$ fm$^3$

Another definite test of $\chi$PT, $F_{3\pi}$, accessible in a Primakoff $\pi^- \gamma \rightarrow \pi^- \pi^0$, measured recently by COMPASS together with $\Gamma_{\rho \rightarrow \pi \gamma}$: $(10.3 \pm 0.1 \pm 0.6)$ GeV$^{-3}$, in agreement with $\chi$PT $(9.78 \pm 0.05)$ GeV$^{-3}$

MORE DATA TO COME!
COMPASS time axis (A. Bacchetta, IWHSS2022)

Old Chinese compass

Hand-held compass

GPS compass

Exploration  Consolidation  Precision
COMPASS pioneered the study of the 3D structure of the nucleon and is the main actor in the consolidation phase.

Slide courtesy A. Bacchetta, IWHSS2022