Recent results and future plans of the COMPASS Collaboration

106° CONGRESSO NAZIONALE

SOCIETÀ ITALIANA DI FISICA

14-18 settembre 2020

The COMPASS Experiment at CERN SPS

Spectroscopy and π polarizabilities

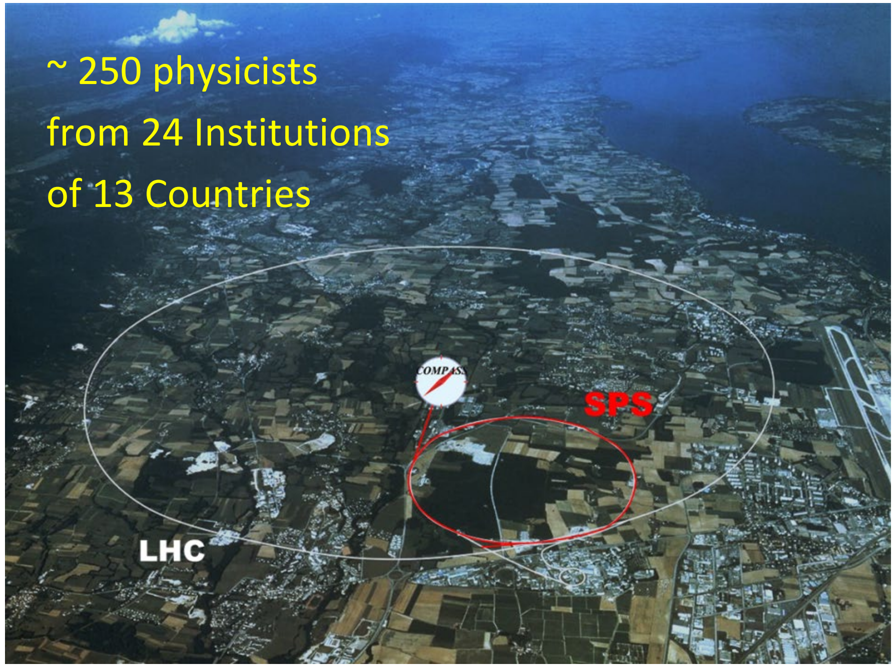
The hadron structure

2021-22: Tensor charge and proton radius

M2 beam line: LoI for a QCD Facility at CERN

Stefano Levorato
on behalf of the COMPASS collaboration

The COMPASS Collaboration



~ 250 physicists
from 24 Institutions
of 13 Countries

Дубна (LPP and LNP),
Москва (INR, LPI, State University), Протвино

Warsawa (NCBJ),
Warsawa (TU)
Warsawa (U)

Praha (CU/CTU)
Liberec (TU)
Brno (ISI-ASCR)

Calcutta (Matriviani)

Taipei (AS)

CERN

Yamagata

Lisboa/Aveiro

Tel Aviv

Bochum,
Bonn (ISKP & PI), Erlangen, Freiburg,
Mainz, München TU

USA (UIUC)

Saclay

Torino (University, INFN),
Trieste (University, INFN)

Experiments with muon beam:

COMPASS - I (2002 – 2011)

Spin structure, Gluon polarization
Flavor decomposition
Transversity
Transverse Momentum-dependent PDF

COMPASS - II (2012 – 2021) …

DVCS and HEMP
Unpolarized SIDIS and TMDs

Experiments with hadron beams:

Pion polarizability
Diffractive and Central production
Light meson spectroscopy
Baryon spectroscopy

Pion and Kaon polarizabilities
Drell-Yan studies

Proposed physics programme:

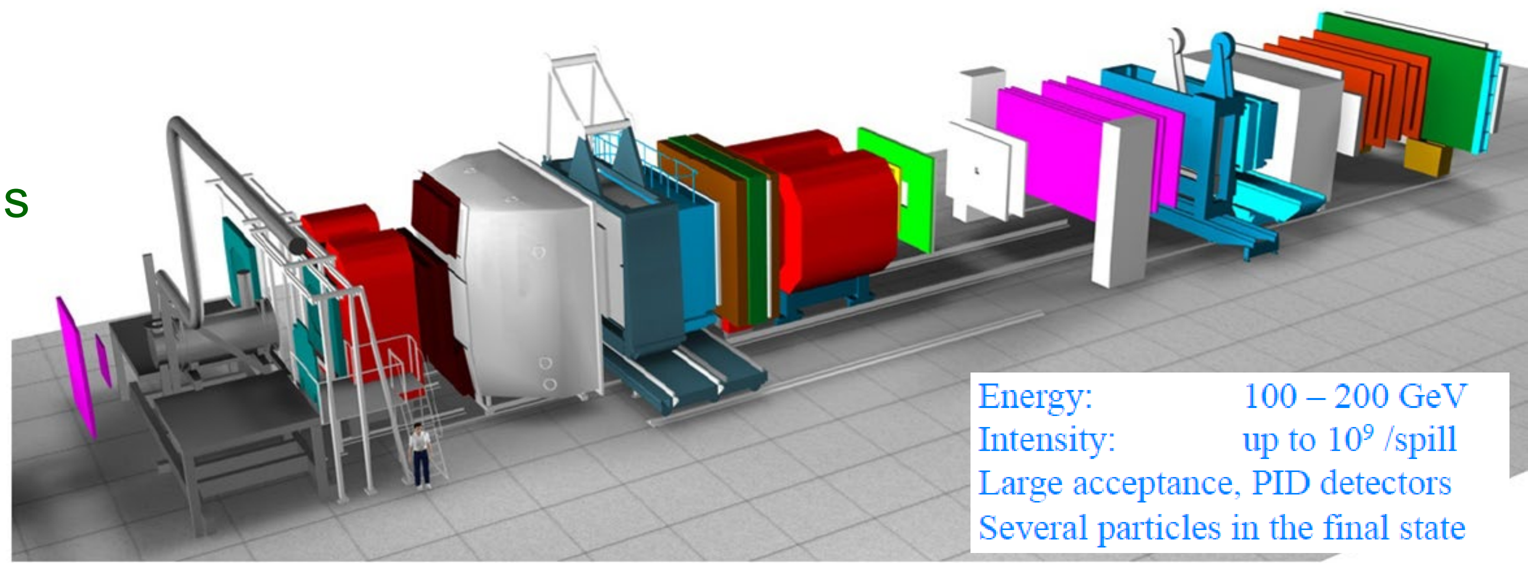
hadron spectroscopy (p, π, K)

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

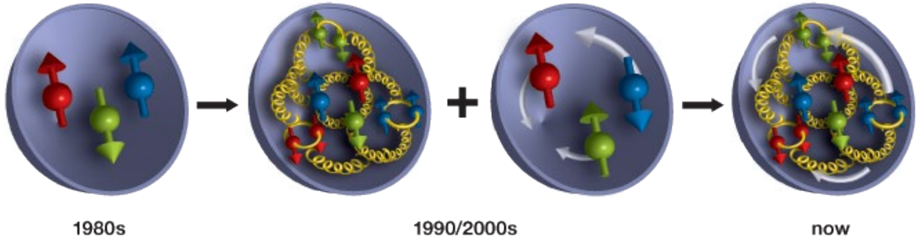
nucleon structure (μ)

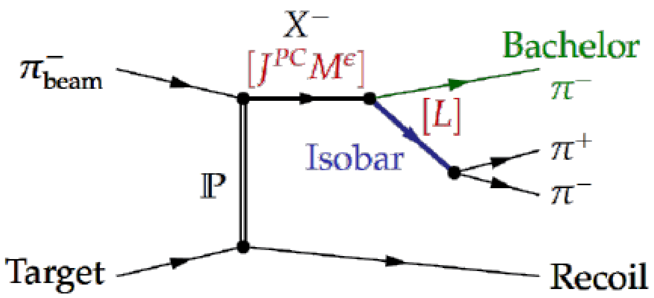
- longitudinal spin structure - SIDIS
- transverse spin structure - SIDIS

- Drell-Yan (π)
- DVCS (SIDIS) (μ)

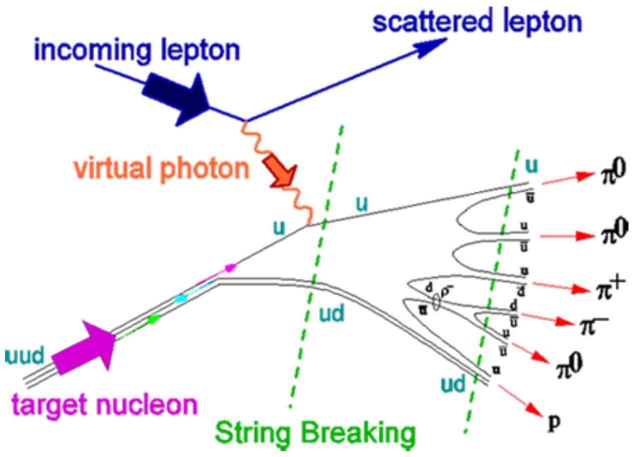


Energy: 100 – 200 GeV
Intensity: up to 10^9 /spill
Large acceptance, PID detectors
Several particles in the final state





X decay is chain of successive two-body decays



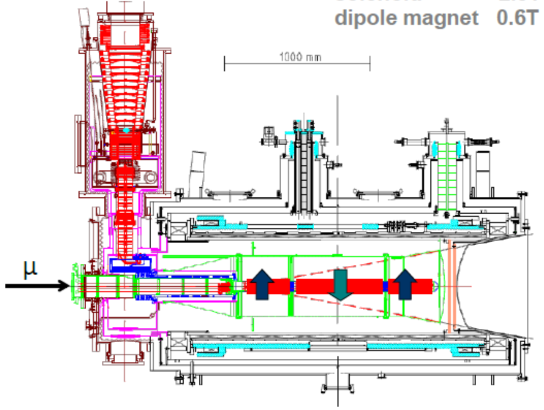
Polarized target and Particle Identification

the polarized target system (>2005)

COMPASS

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

solenoid 2.5T
dipole magnet 0.6T

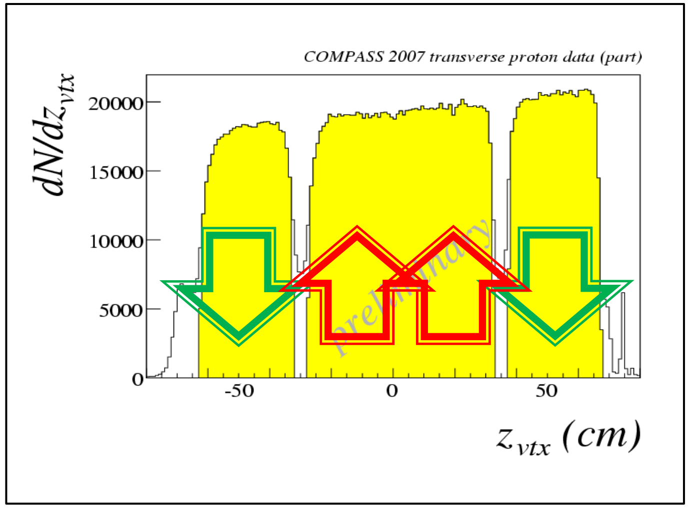


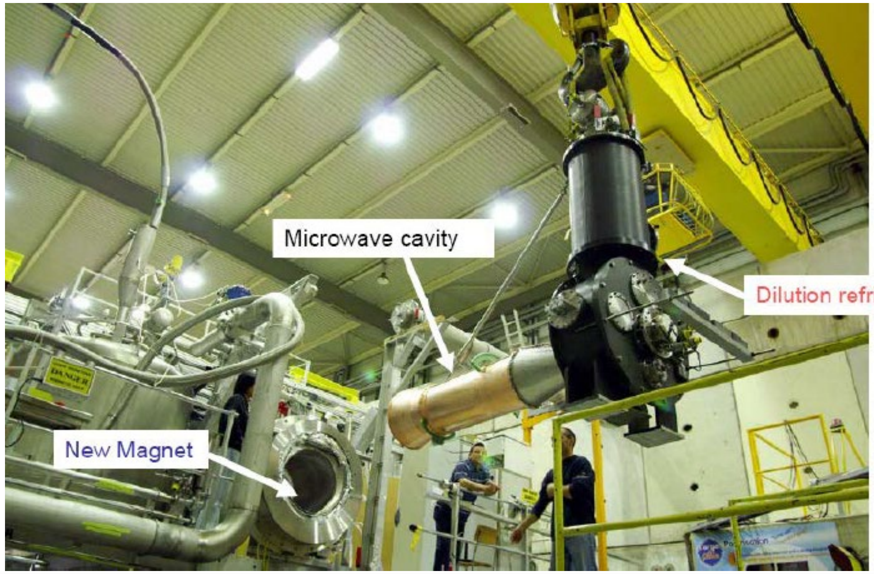
acceptance > ± 180 mrad

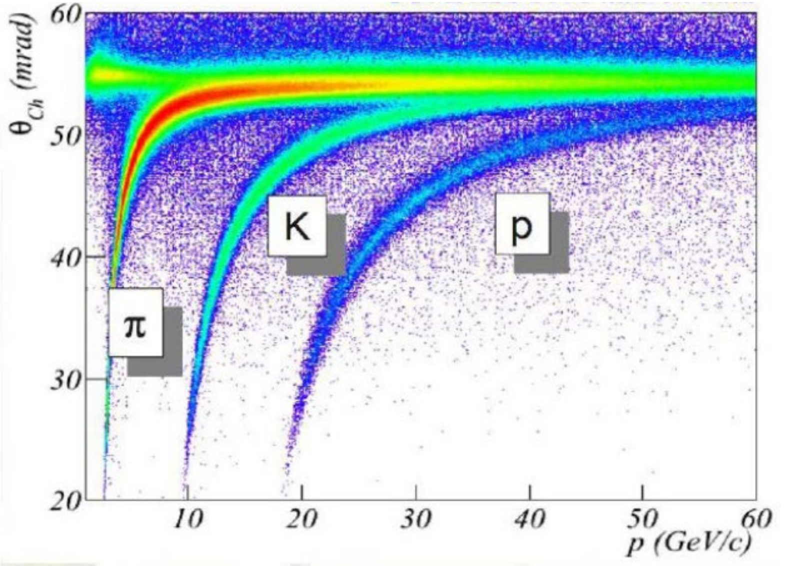
3 target cells
30, 60, and 30 cm long

opposite polarisation

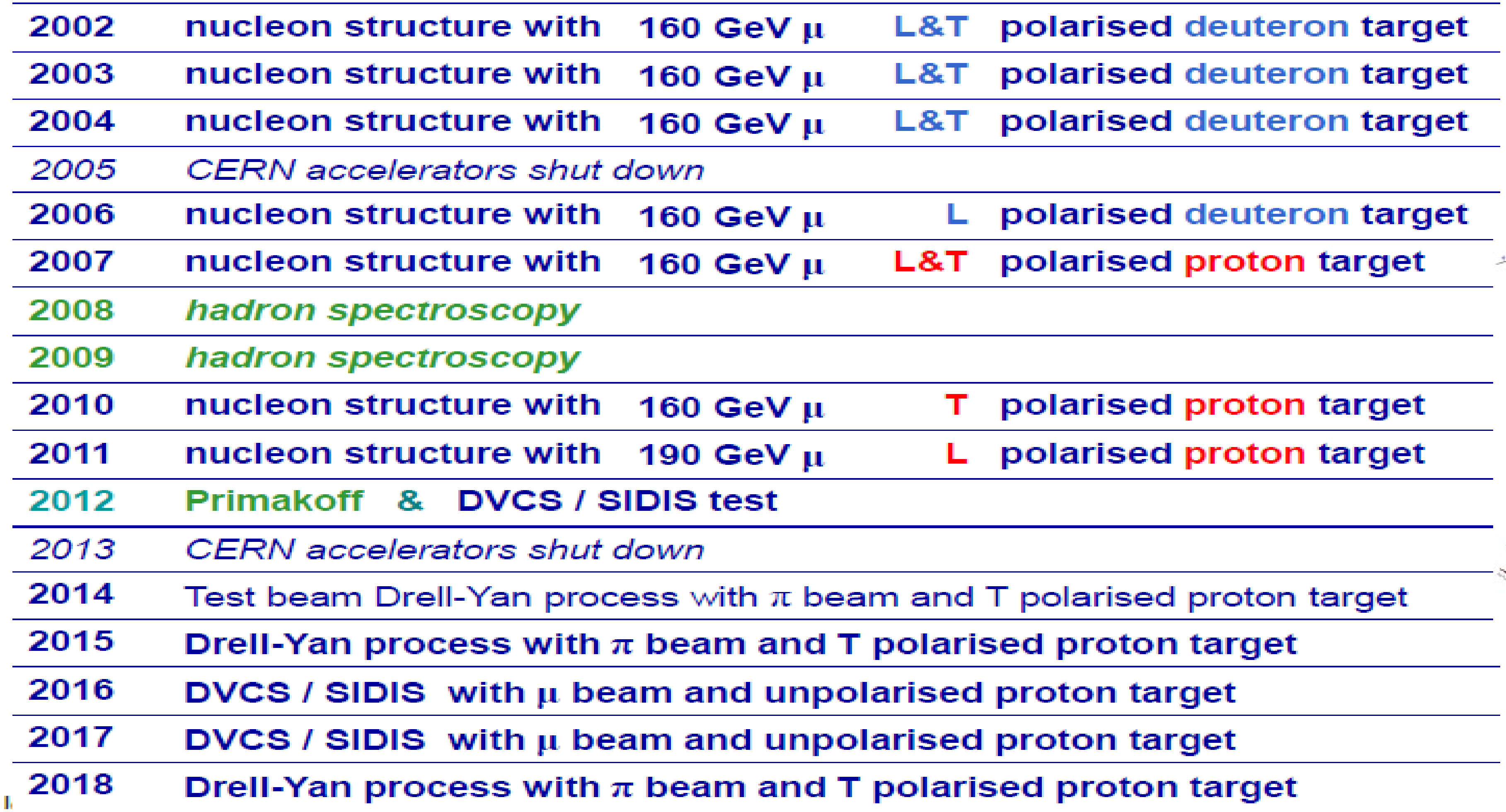
	d (^{6}LiD)	p (NH$_3$)
polarization	50%	90%
dilution factor	40%	16%



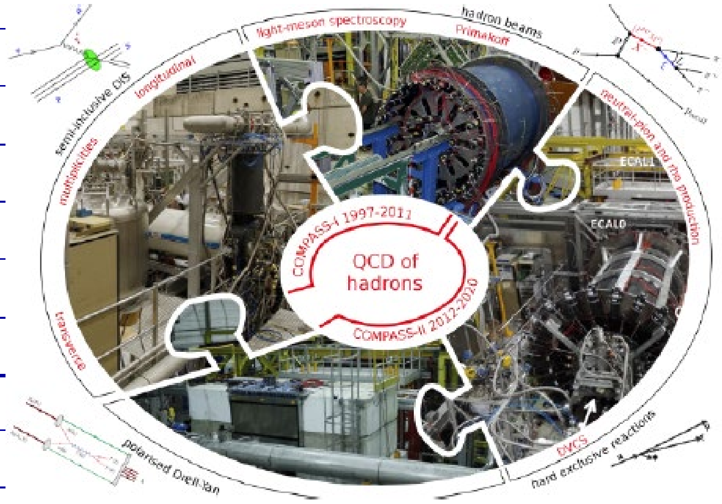




Wide physics programme



2002	nucleon structure with	160 GeV μ	L&T	polarised deuteron target
2003	nucleon structure with	160 GeV μ	L&T	polarised deuteron target
2004	nucleon structure with	160 GeV μ	L&T	polarised deuteron target
2005	*CERN accelerators shut down*			
2006	nucleon structure with	160 GeV μ	L	polarised deuteron target
2007	nucleon structure with	160 GeV μ	L&T	polarised proton target
2008	*hadron spectroscopy*			
2009	*hadron spectroscopy*			
2010	nucleon structure with	160 GeV μ	T	polarised proton target
2011	nucleon structure with	190 GeV μ	L	polarised proton target
2012	Primakoff & DVCS / SIDIS test			
2013	*CERN accelerators shut down*			
2014	Test beam Drell-Yan process with π beam and T polarised proton target			
2015	Drell-Yan process with π beam and T polarised proton target			
2016	DVCS / SIDIS with μ beam and unpolarised proton target			
2017	DVCS / SIDIS with μ beam and unpolarised proton target			
2018	Drell-Yan process with π beam and T polarised proton target			

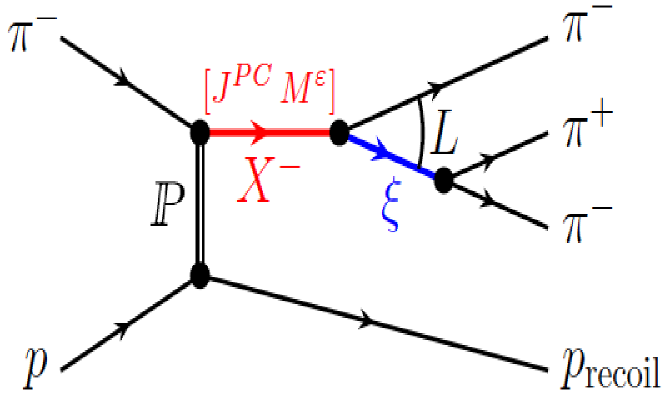


2021 nucleon structure with 160 GeV μ T polarized deuteron target

Hadron structure and hadron excitation spectrum

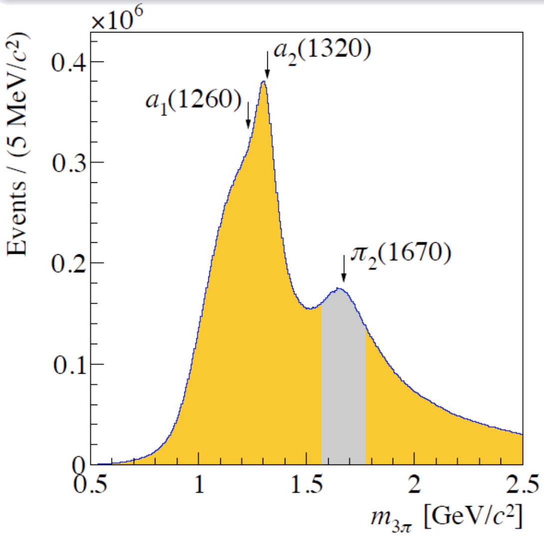
2008-2009 data taking, 190 GeV/c hadron beam on a hydrogen target.

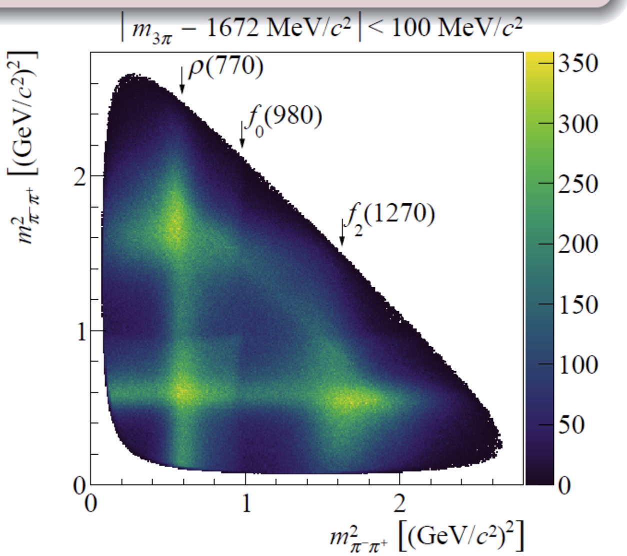
COMPASS has performed the most comprehensive analysis of isovector resonances decaying into ηπ, η'π, or π− π− π+ final states.



Isobar Model: X decay is a chain of successive two body decays

- 46×10^6 $\pi^-\pi^-\pi^+$ events ⇒ approx. 10× previous experiments





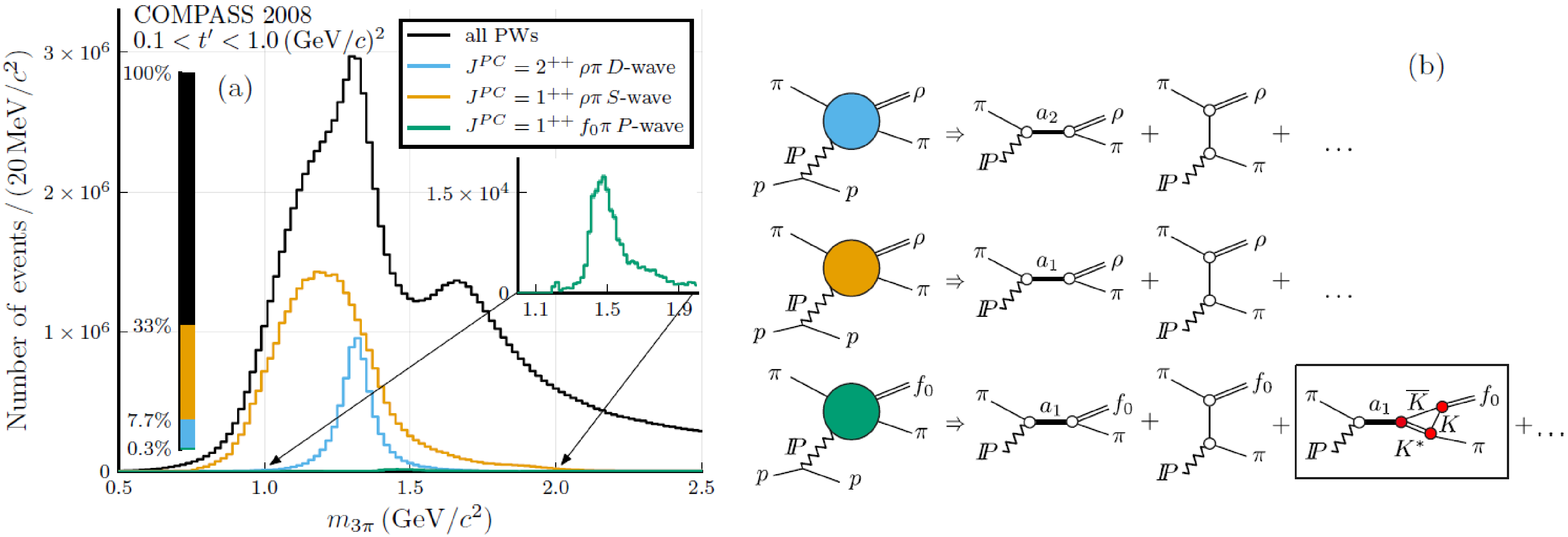
"Light-meson spectroscopy with COMPASS", Progress in Particle and Nuclear Physics 11 (July 2020) 103755

- Partial Wave analysis (PWA) in mass bins up to 88 waves
- Fit of spin density matrix for major waves with Breit-Wigner

Collaboration with Joint Physics Analysis Center (JPAC)

Diffractive dissociation PWA of the reaction $\pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p$

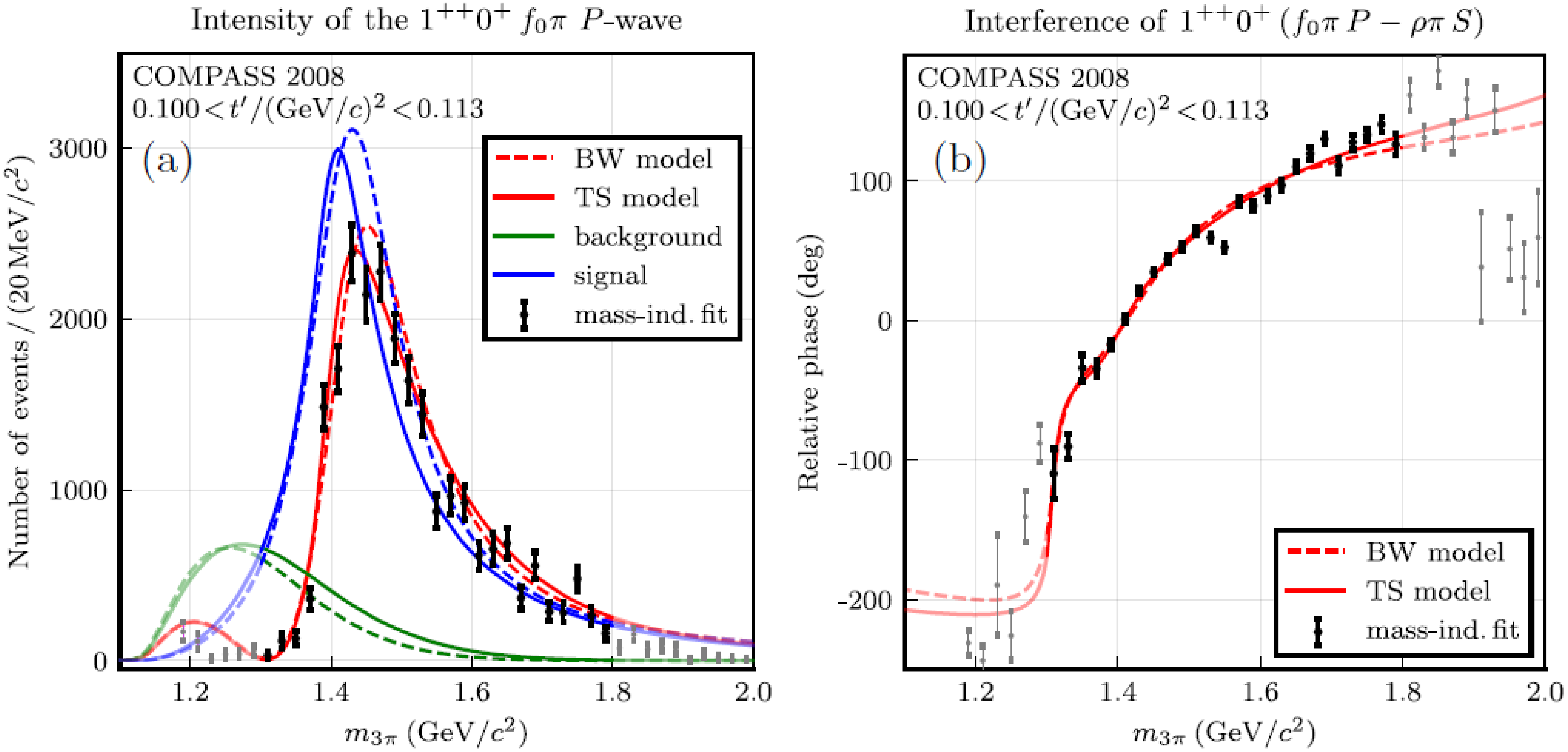
Resonance-like signal, $a_1(1420)$, found in the $f_0(980)\,\pi$ P 1++ partial wave, PRL 115, 082001 (2015) not fitting into the $q\bar{q}$ scheme of ordinary mesons Interpretations: tetraquark, molecule-like, etc.



Kinematic effect (triangle singularity) in the decay of $a_1(1260)$ into $K^*(892)\,\overline{K}$ + c.c., and rescattering of the $\overline{K}$ with the K from the K^* decay into the observed $f_0(980)$

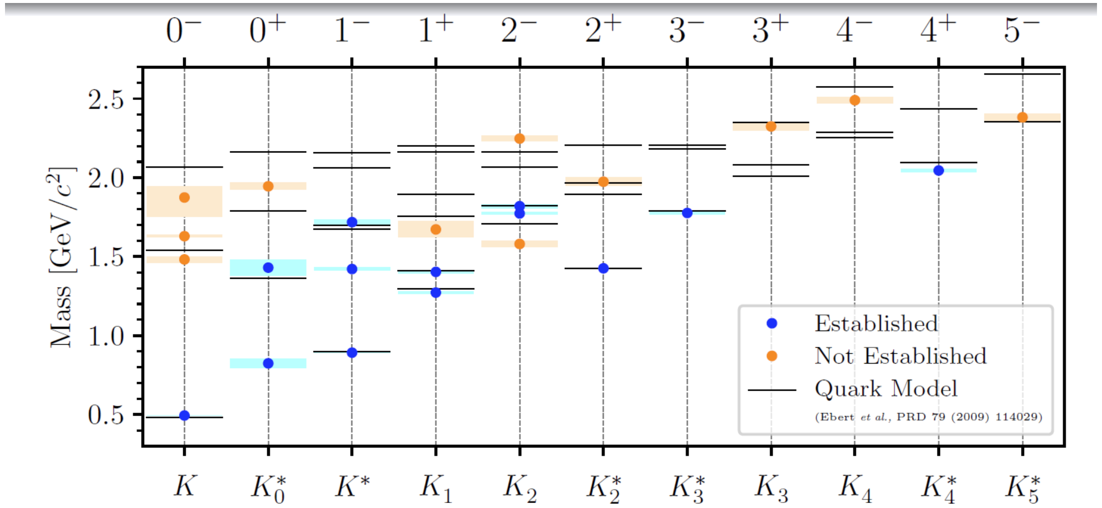
The Triangle Singularity (TS) model is fitted to our partial-wave data.

Less parameters than the resonance hypothesis (BW). TS fit has slightly better quality → no need for an additional resonance.

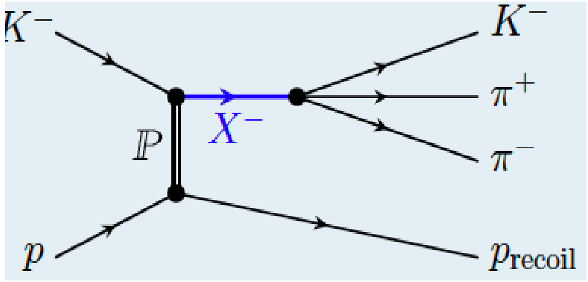


Kaon Spectroscopy

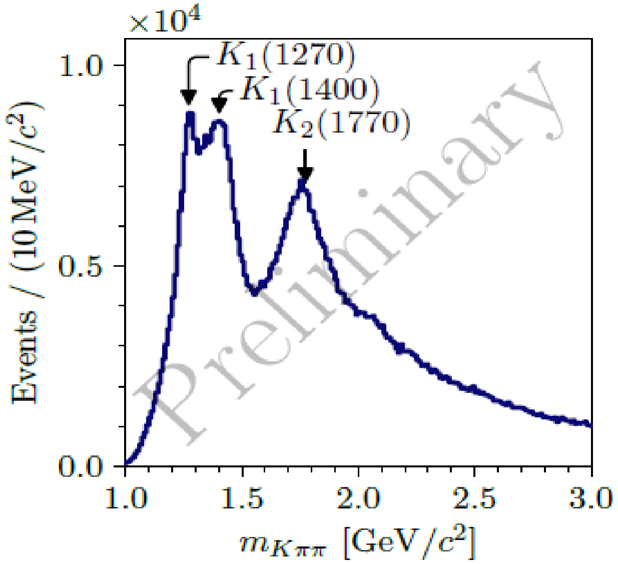
The PDG lists 25 kaon states, 12 of which need confirmation.

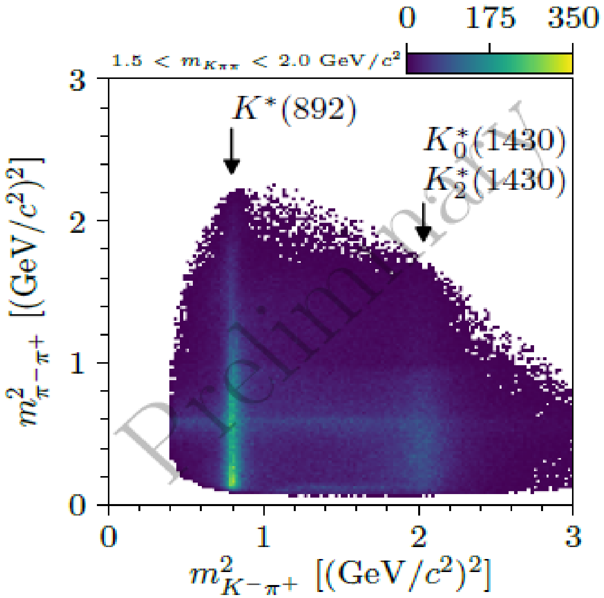


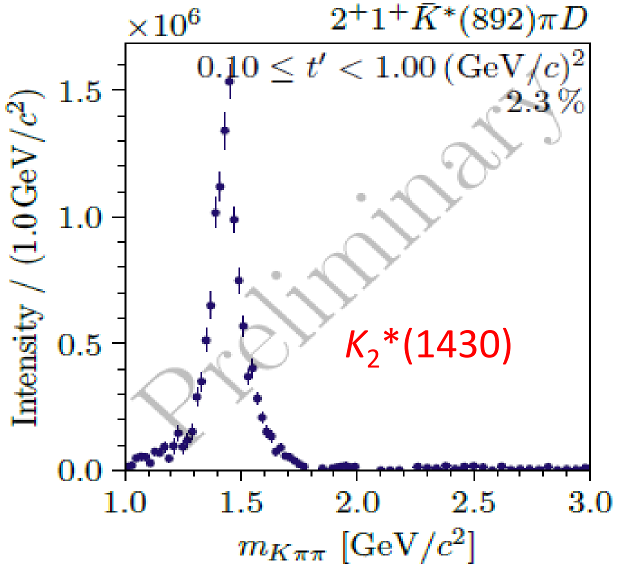
2.4% K^- in the 190 GeV/*c* negative hadron beam. (CEDAR)



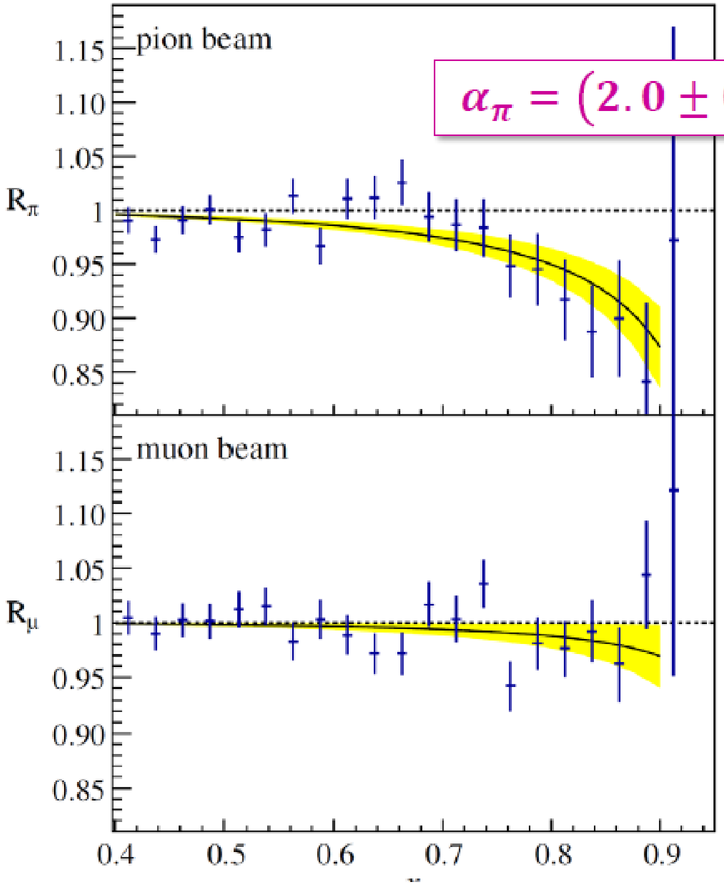
We have 720 000 exclusive $K^- \pi^- \pi^+$ events in the range $1{:}0 < m_{K\pi\pi} < 3{:}0$ GeV/c^2 and $0{:}1 < t' < 1{:}0$ (GeV/c)^2.







Pion polarizabilities π −γ → π −γ

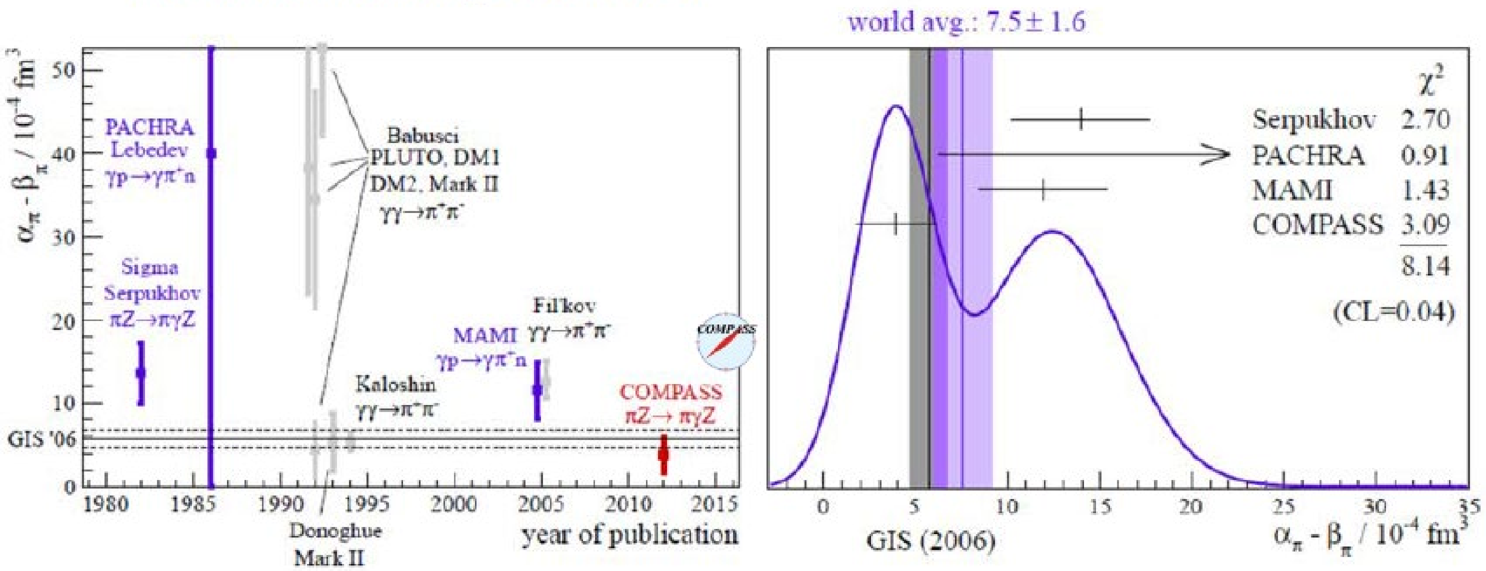


PRL 114 (2015) 062002

$$\alpha_\pi = \left(2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}\right) \cdot 10^{-4}\mathrm{fm}^3$$

assuming $\alpha_\pi = -\beta_\pi$

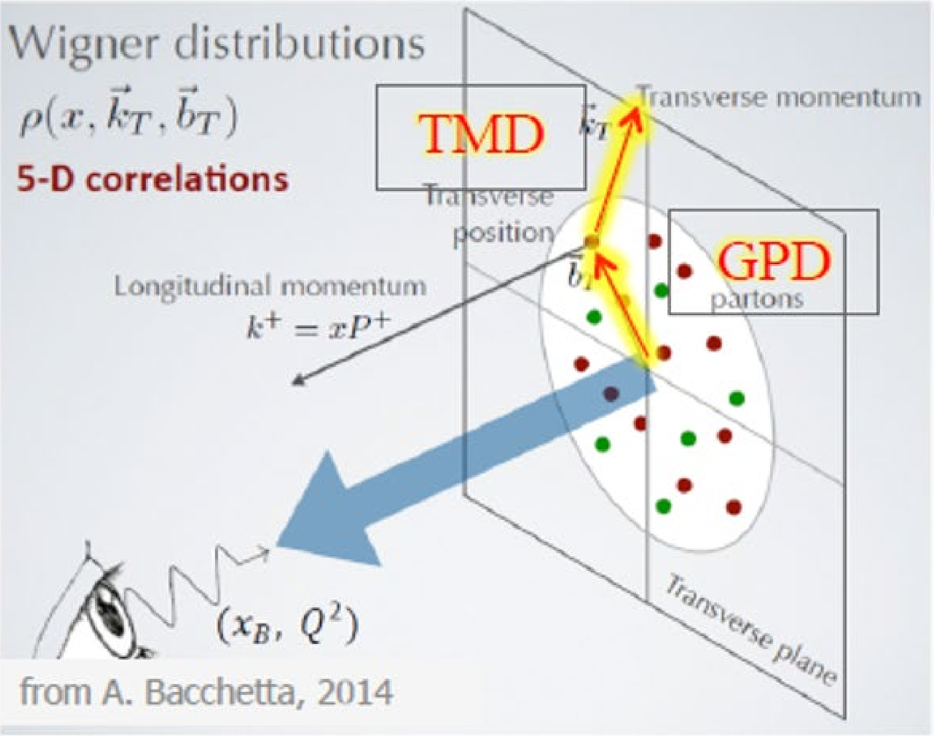
world data including COMPASS



the COMPASS result is in significant tension with the earlier measurements

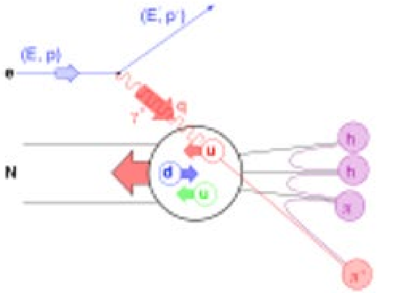
the expectation from ChPT is confirmed within the uncertainties

Structure of the nucleon

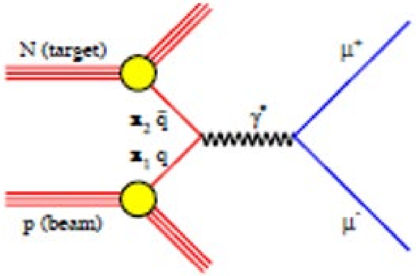


from A. Bacchetta, 2014

Semi-Inclusive DIS

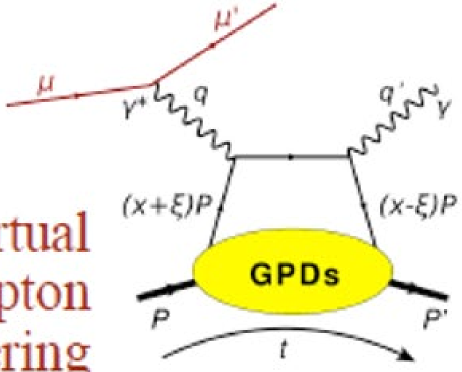


Drell-Yan process



Transversity Momentum Distributions: TMD (x,k_T):
probe the transverse parton momentum dependence

Deeply Virtual
Compton
Scattering

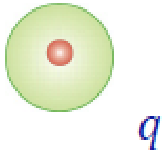


Generalized Parton Distributions : GPD (x,b_T):
probe the transverse parton distance dependence

COMPASS explores the multi dimensional structure of the nucleon both in momentum and in configuration space, via SIDIS, D-Y and DVCS/DVMP

Structure of the nucleon: collinear description

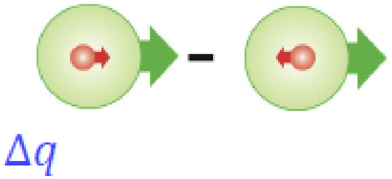
collinear description leading twist



q

number density

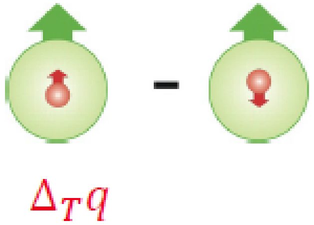
very well known



Δq

helicity distribution

well known



$\Delta_T q$

transversity distribution

- correlation between the transverse polarisation of the nucleon and the transverse polarisation of the quark
- a chirally-odd distribution, not observable in DIS
- related to **tensor charge**
- first experimental evidence in 2005

nucleon polarisation

quark polarisation

	U	L	T
U	f_1		
L		g_1	
T			h_1

Structure of the nucleon including transverse momentum dependence

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

correlations between parton transverse
momentum, parton spin and nucleon spin

SIDIS gives access to all of them

nucleon polarisation

quark polarisation

	U	L	T
U	f_1		$f_{1T}^{\perp}$
L		g_1	g_{1T}
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 $h_{1T}^{\perp}$

h_1

$f_{1T}^{\perp}$ **Sivers PDF**

correlation between the transverse polarization of the nucleon and the transverse momentum of the partons

Semi-Inclusive Deep Inelastic Scattering cross section

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

Semi-Inclusive Deep Inelastic Scattering cross section

14 independent azimuthal modulations

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP^2_{h\perp}} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F$$

$h_1^\perp H_1^\perp$

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

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

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

$f_{1T}^\perp D_1$

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

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

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

$h_1 H_1^\perp$

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

$g_{1T} D_1$

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

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

leading twist amplitudes
→ convolutions of the
transversity and
TMD PDFs and FFs

SIDIS

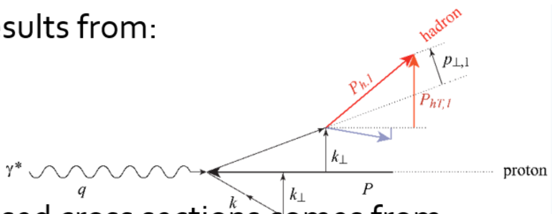
- allows to disentangle the effects related to the different TMD PDFs and to access all of them
- by identifying the final state hadrons and using different targets allows for flavour separation

→ *very powerful tool*

ALL modulations measured by COMPASS

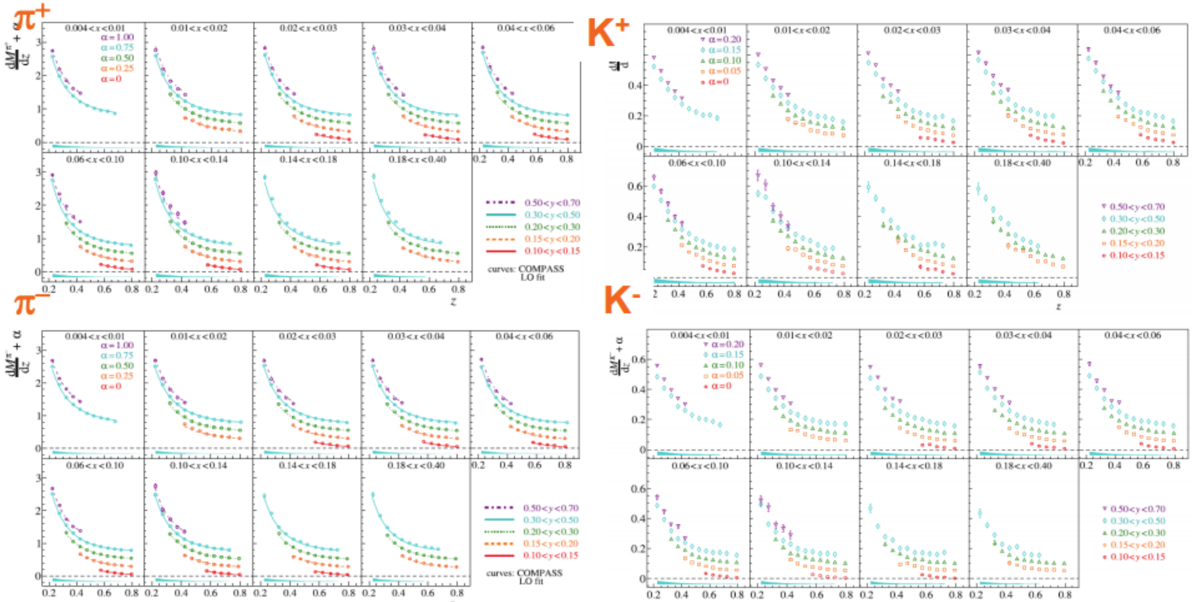
Unpolarized SIDIS

- The cross-section dependence from P_{hT} results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation



- The azimuthal modulations in the unpolarised cross sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

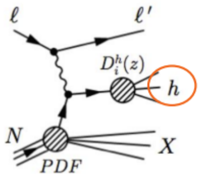
COMPASS π and K multiplicities vs z in (x,y) bins



- Isoscalar target (^{6}LiD)
- More than 1200 points in total, various Q^2 staggered vertically for clarity
- Strong z dependence
- $M(\pi^+) \sim M(\pi^-)$ and $M(K^+) > M(K^-)$

PLB 764 (2017) 001
PLB 767 (2017) 133

→ Measure hadron multiplicities in **SIDIS:** **$\mu^+d \to \mu^+h^\pm X$** h= π, K, p



$z = E_h/(E_\mu - E_\mu')$

PDFs FFs

$$\frac{dM^h(x,Q^2,z)}{dz} \underset{\text{at LO}}{=} \frac{\sum_q e_q^2 f_q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 f_q(x,Q^2)}$$

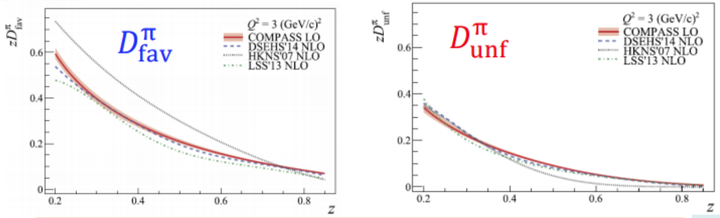
PDFs depend on x, while FFs depend on z

→ With kaons, access typically : $s(x,Q^2).D_S^K(z,Q^2)$

π and K multiplicities constitute an input to global NLO QCD analyses to extract quark FFs

From multiplicities to quark Fragmentation Functions

Pions Results from COMPASS LO fits assuming 2 independent FFs: D^π_{fav} D^π_{unf}



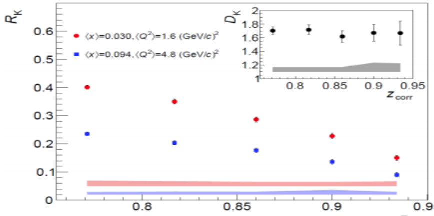
- As expected, $D^\pi_{\text{fav}} > D^\pi_{\text{unf}}$
- COMPASS LO fit results ~agree with DSEHS and LSS NLO.

PLB 764 (2017) 001

M(K⁻)/ M(K⁺) at high *z* – Results vs *z*

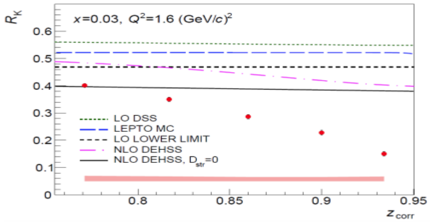
Isoscalar target

Ratio measured vs *z* in two *x* bins



PLB 786 (2018) 390

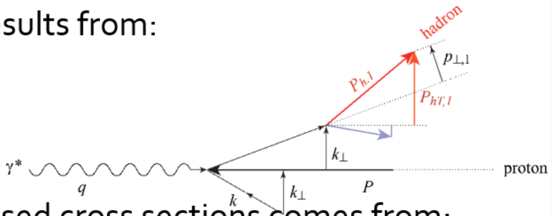
Compare to theory, bin *x*=0.03



M(K⁻) / M(K⁺) ratio well below expectations at high *z*

Unpolarized SIDIS, azimuthal modulations

- The cross-section dependence from P_{hT} results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation



- The azimuthal modulations in the unpolarised cross sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

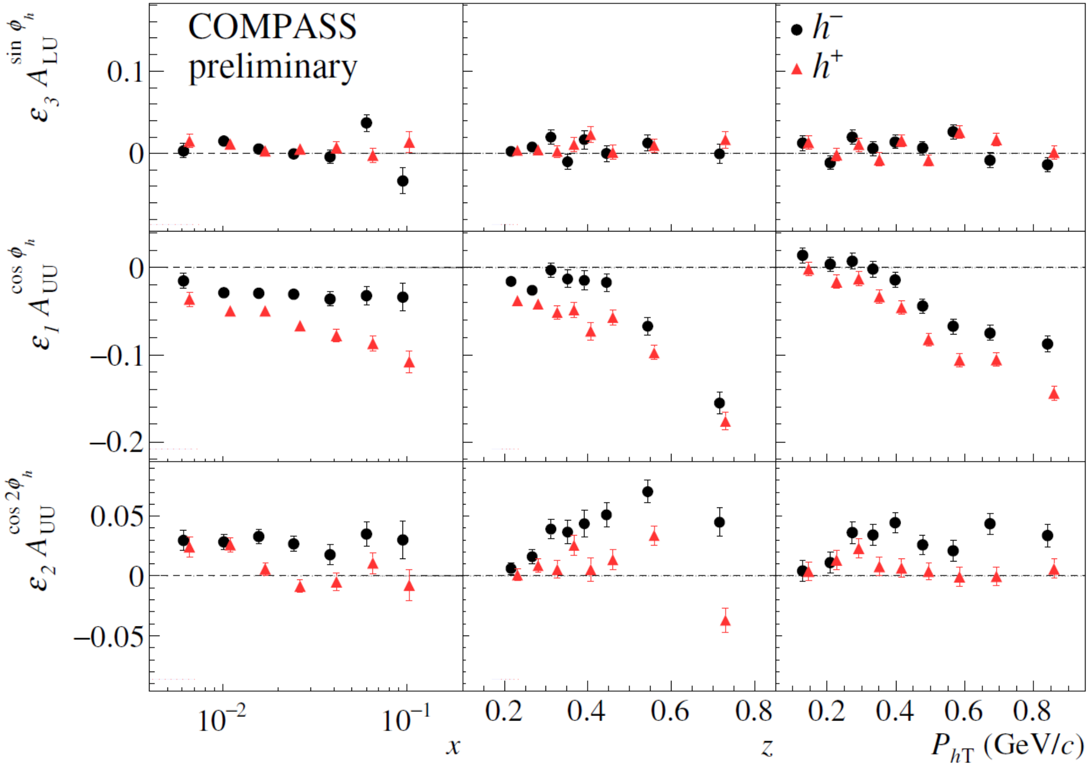
When looking at the content of the structure functions/modulations in terms of TMD PDFs for the cos ϕ_h and cos $2\phi_h$ we can write:

$$F_{UU}^{\cos\phi_h} = -\frac{2M}{Q} C\left[\frac{\hat{h}\cdot\vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp}{M}\frac{\vec{P}_{hT} - z(\hat{h}\cdot\vec{k}_\perp)}{zM_h M} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

$$F_{UU}^{\cos 2\phi_h} = C\left[\frac{(\hat{h}\cdot\vec{k}_\perp)(\hat{h}\cdot\vec{p}_\perp) - \vec{p}_\perp\cdot\vec{k}_\perp}{MM_h} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

In the cos $2\phi_h$ Cahn effects enters only at twist4

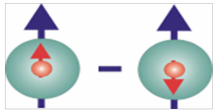
$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C\left[\left\{2\left(\hat{h}\cdot\vec{k}_\perp\right)^2 - k_\perp^2\right\} f_1 D_1\right]$$



Strong kinematic dependences

Polarized SIDIS, Transversity

$$h_1^q(x) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$$



$q = u_v, d_v, q_{sea}$
quark with **spin** parallel to the nucleon spin in a transversely polarised nucleon

- probes the relativistic nature of quark dynamics
- no contribution from the gluons → simple Q^2 evolution
- Positivity: Soffer bound……………. $2|h_1^q| \le f_1^q + g_1^q$ *Soffer, PRL 74 (1995)*
- first moments: tensor charge………. $\delta q(Q^2) = \int_0^1 dx[h_1^q(x) - h_1^{\bar{q}}(x)]$
- is chiral-odd: decouples from inclusive DIS *Bakker, Leader, Trueman, PRD 70 (04)*

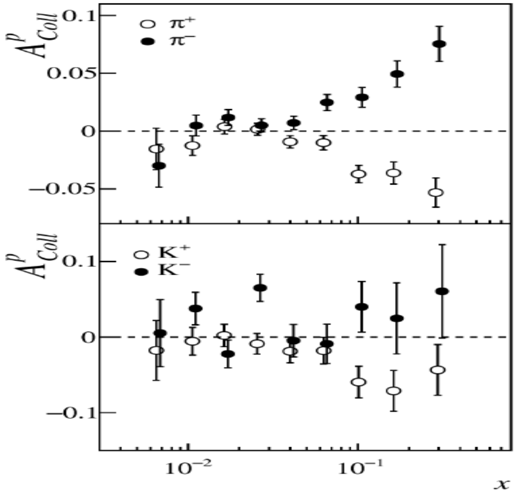
observable effects are given only by the product of h_1^q (x) and an other chiral-odd function

can be measured in SIDIS on a transversely polarised target via "quark polarimetry"

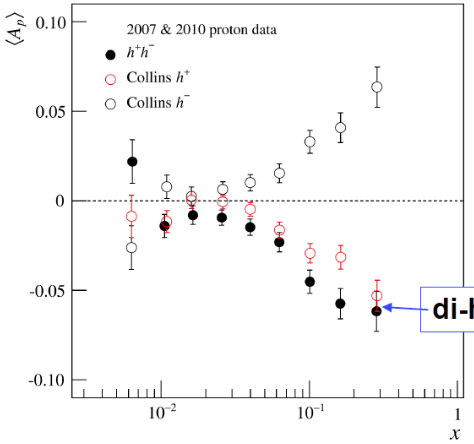
$\ell N^{\uparrow} \rightarrow \ell' h X$	**"Collins" asymmetry** **"Collins" Fragmentation Function**
$\ell N^{\uparrow} \rightarrow \ell' h h X$	**"two-hadron" asymmetry** **"Interference" Fragmentation Function**
$\ell N^{\uparrow} \rightarrow \ell' \Lambda X$	**Λ polarisation** **Fragmentation Function of q↑→Λ**

measured for the first time

Collins asymmetry
all proton data



PLB 744 (2015) 250
PLB 717 (2012) 376

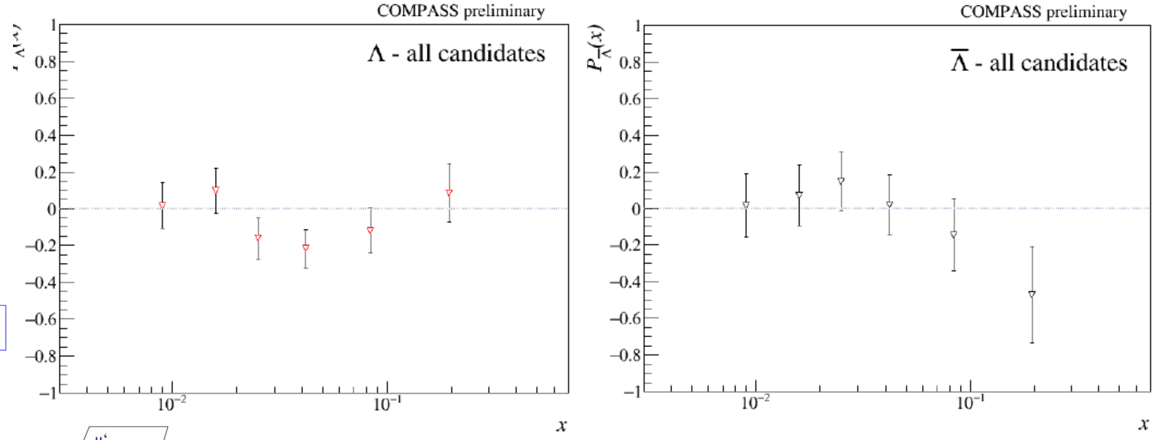


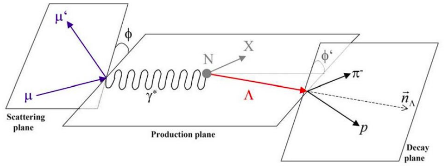
di-hadron asymmetry

PLB 736 (2014) 124

study of the interplay between Collins and di-hadron asymmetries – not independent

PLB 753 (2016) 406



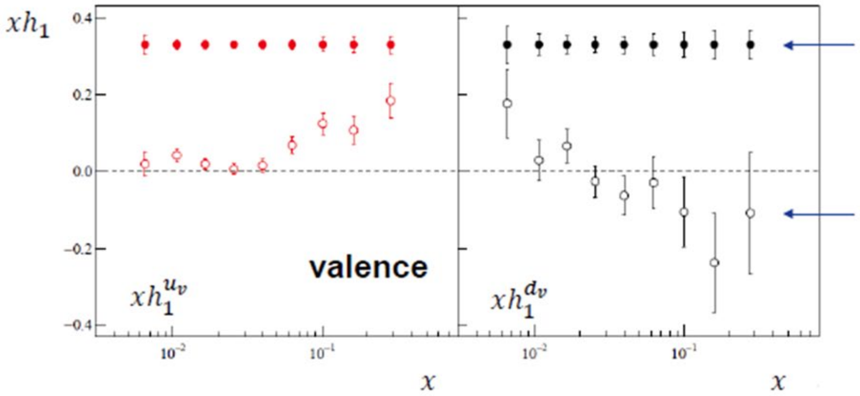


$$\frac{dN}{d\cos\theta^*} \propto A(1 + \alpha P_{\Lambda(\bar{\Lambda})}\cos\theta^*)$$

Run 2021: SIDIS on transv. pol. deuterons

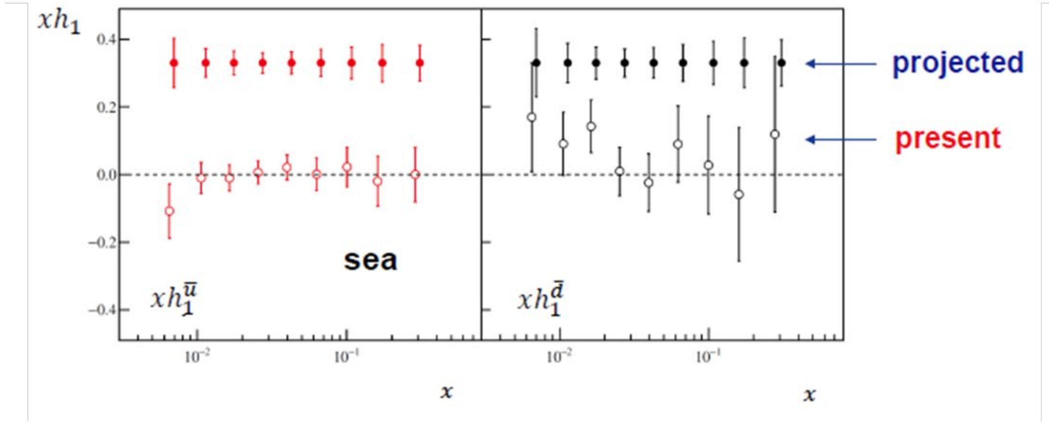
One year of run with 160 GeV muons to measure SIDIS off transversely polarised d the missing measurement to complete the COMPASS exploratory programme collecting the same statistics as in 2010,

The deuteron asymmetries will have a statistical uncertainty $\boldsymbol{\sigma_d \cong 0.6\, \sigma_p^{2010}}$



projected
gain 1.2 to 2.0 for u
1.8 to 4.0 for d

present
PRD 91(2015) 014034
from COMPASS p, d
and e+e- data

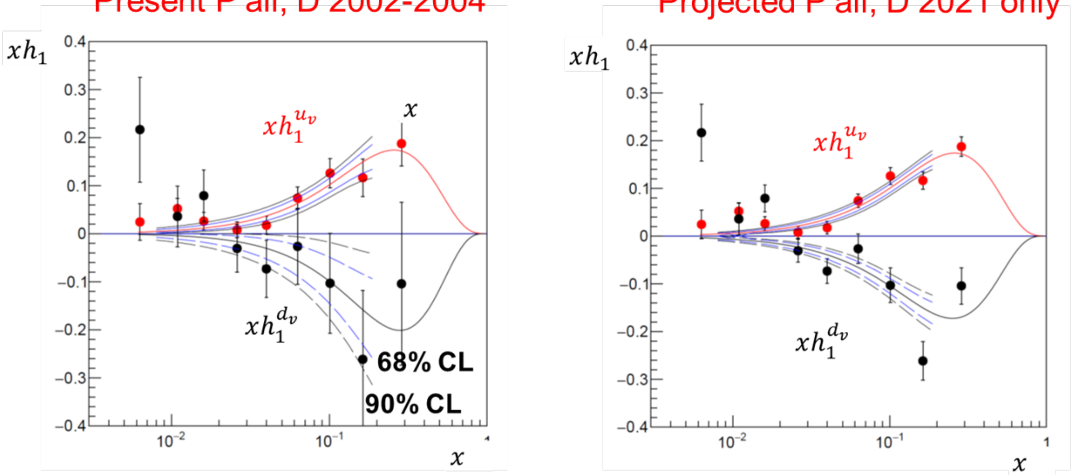


projected

present

Present P all, D 2002-2004

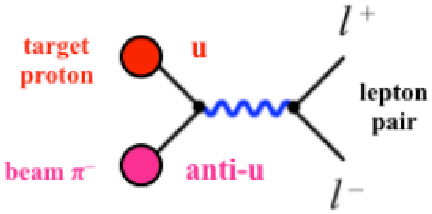
Projected P all, D 2021 only



	$\delta_u = \int_{\Omega_x} dx h_1^{u_v}(x)$	$\delta_d = \int_{\Omega_x} dx h_1^{d}(x)$	$g_T = \delta_u - \delta_d$
present	$0.201 \pm \mathbf{0.032}$	$-0.189 \pm \mathbf{0.108}$	$0.390 \pm \mathbf{0.087}$
projected	$0.201 \pm \mathbf{0.019}$	$-0.189 \pm \mathbf{0.040}$	$0.390 \pm \mathbf{0.044}$

Ω_x:0.008÷0.210

Drell-Yan

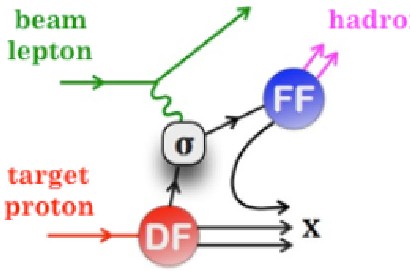


Sivers (proton) ⊗ unpolarized distribution function (pion)

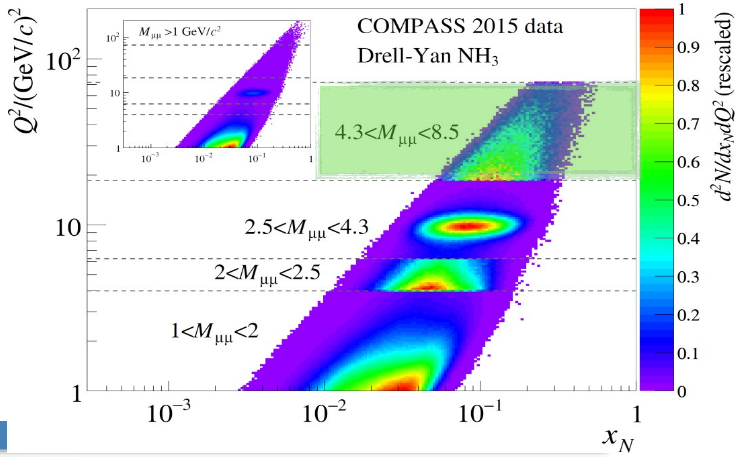
The **Sivers** TMD is expected to have the **same magnitude**, but **opposite sign** in SIDIS vs. DY. The same applies to the **Boer-Mulders** function.

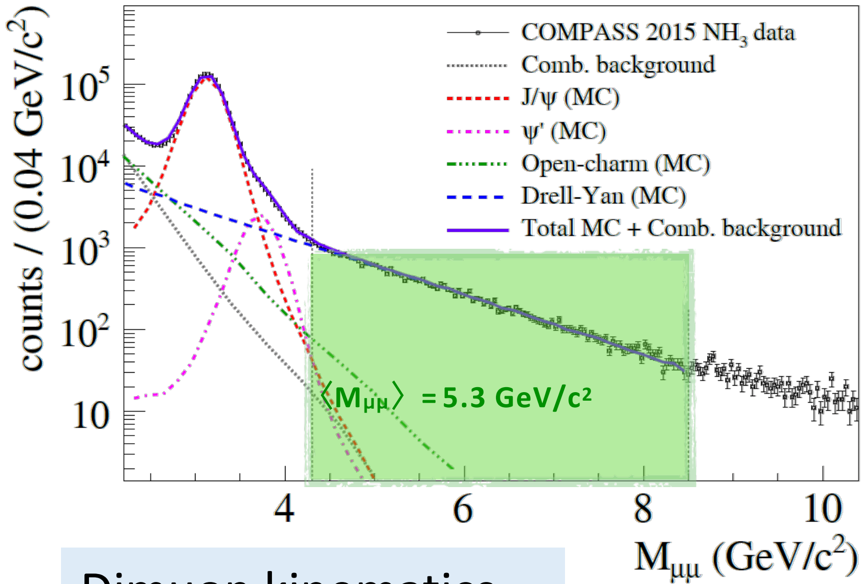
Crucial test of TMD framework.

Semi-Inclusive Deep-Inelastic Scattering



Sivers (proton) ⊗ unpolarized fragmentation function

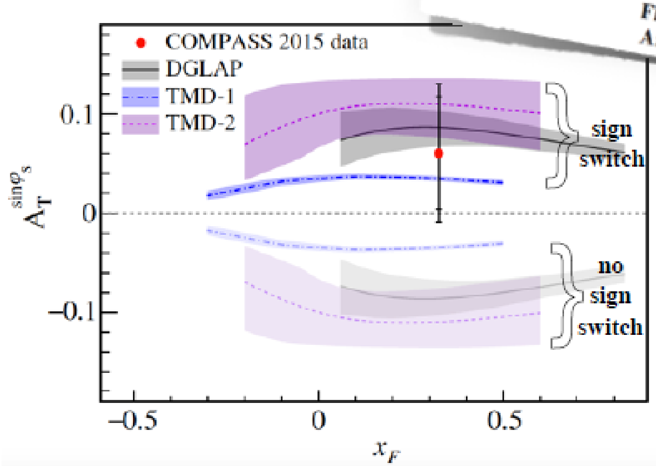


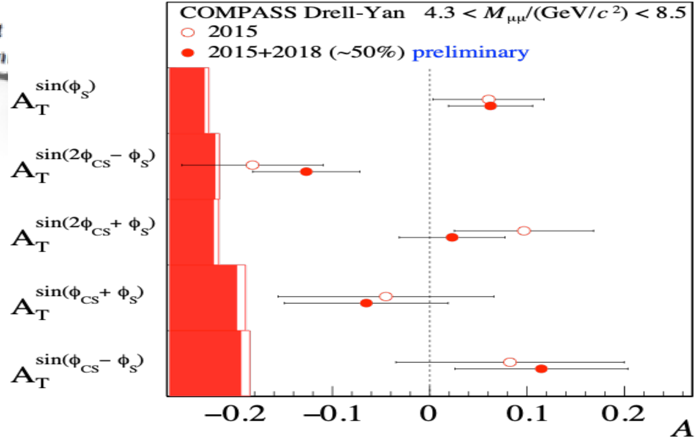


Dimuon kinematics

PRL 119, 112002 (2017) PHYSICAL REVIEW

First Azim

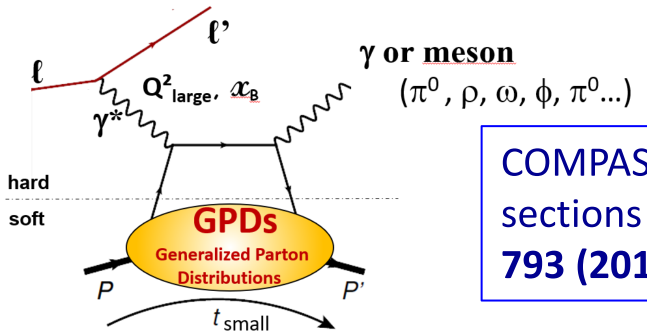




"DGLAP" M. Anselmino, M. Boglione, U. D'Alesio, F. Murgia, and A. Prokudin, J. High Energy Phys. 04 (2017) 046.
"TMD 1" M. G. Echevarria, A. Idilbi, Z.-B. Kang, and I. Vitev, Phys. Rev. D 89, 074013 (2014).
"TMD 2" P. Sun and F. Yuan, Phys. Rev. D 88, 114012 (2013).

Exclusive π^0 production on unpolarised proton (DVMP)

COMPASS 2012 data

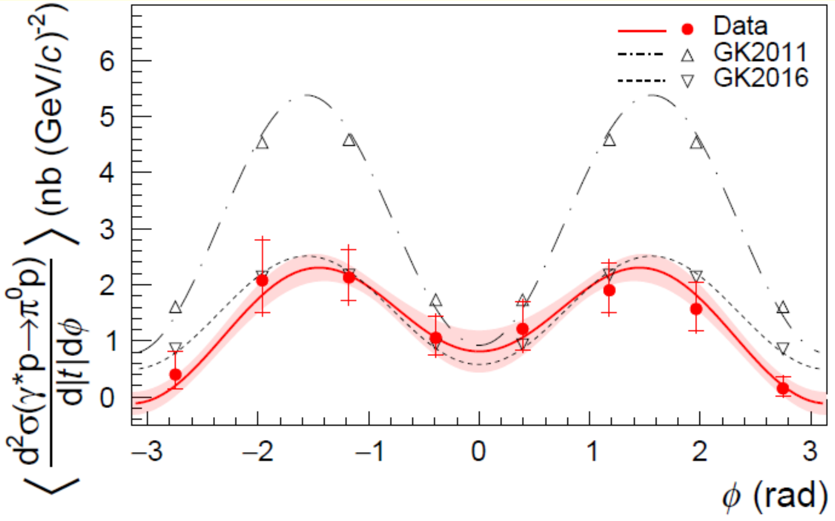


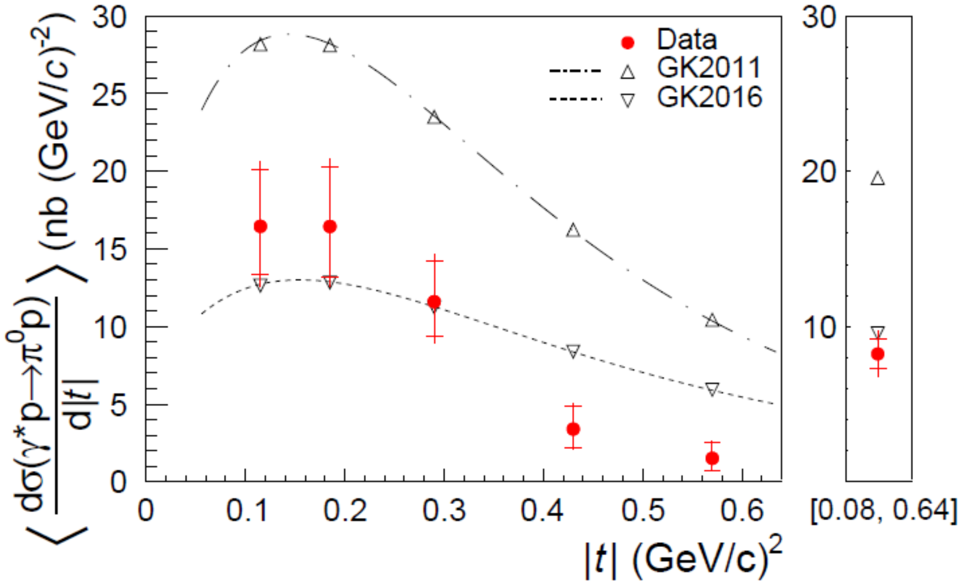
COMPASS DVCS cross sections published: **PLB 793 (2019) 188**;

$\mu\, p \rightarrow \mu\, \pi^0\, p$

$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\boxed{\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right)} + \epsilon\cos 2\phi_\pi \boxed{\frac{d\sigma_{TT}}{dt}} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \boxed{\frac{d\sigma_{LT}}{dt}}\right]$$

PLB 805 (2020) 135454, hep-ex/1903.12030



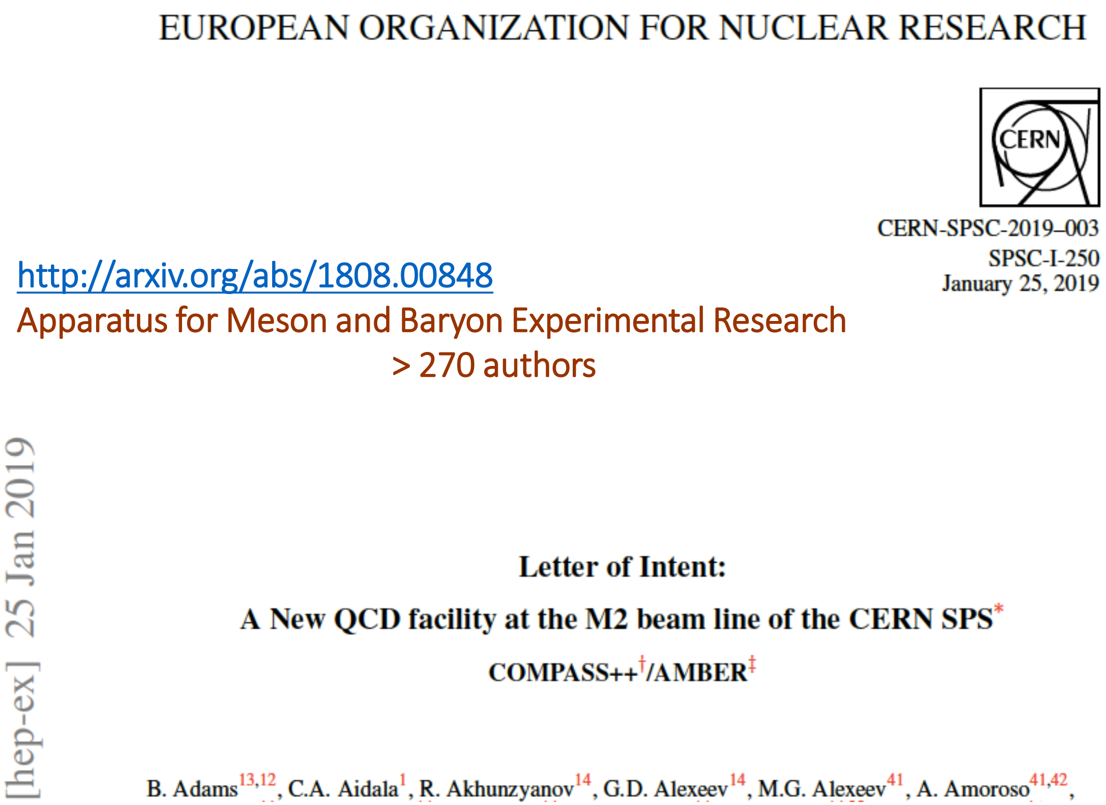


σ_L depends on H, E: leading twist contribution → should be dominant.

surprisingly σ_T , σ_{TT} , σ_{LT} involving also H_T and E_T are found to be large

Goloskokov-Kroll

COMPASS++/AMBER: a New QCD Facility at CERN SPS



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2019–003
SPSC-I-250
January 25, 2019

[hep-ex] 25 Jan 2019

Letter of Intent:

A New QCD facility at the M2 beam line of the CERN SPS*

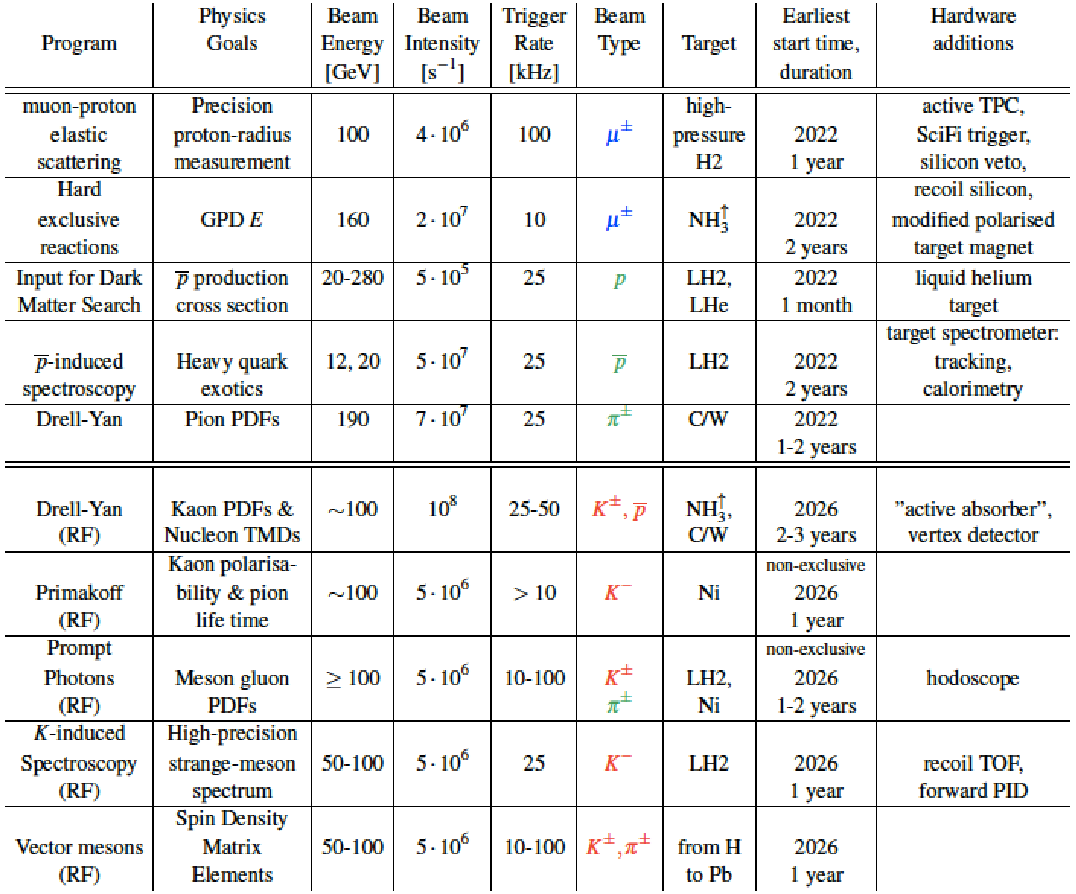
COMPASS++†/AMBER‡

B. Adams[13,12], C.A. Aidala[1], R. Akhunzyanov[14], G.D. Alexeev[14], M.G. Alexeev[41], A. Amoroso[41,42],

http://arxiv.org/abs/1808.00848

Apparatus for Meson and Baryon Experimental Research

> 270 authors



Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	~100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	~100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

Table 2: Requirements for future programmes at the M2 beam line after 2021. Muon beams are in blue, conventional hadron beams in green, and RF-separated hadron beams in red.

Emergency of Hadronic Mass, mass budget in the proton

How does the all visible matter in the universe come about and what defines its mass scale?

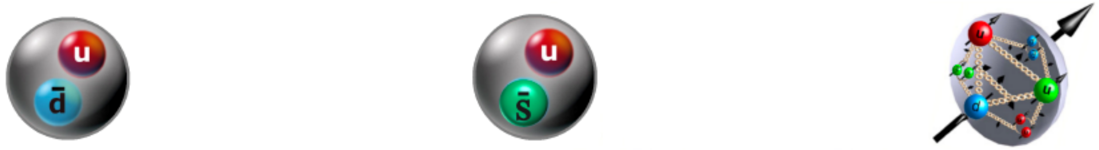
The Higgs-boson does NOT help to answer this question.

✓ The Higgs-boson mechanism produces only a small fraction of all visible mass

✓ The Higgs-generated mass scales explain neither the “huge” proton mass nor the ‘nearly-masslessness’ of the pion

One of the possible proton mass decomposition (calculation on lattice)
Yi-Bo Yong et al., Phys.Rev.Lett. 121 (2018) no.21, 212001

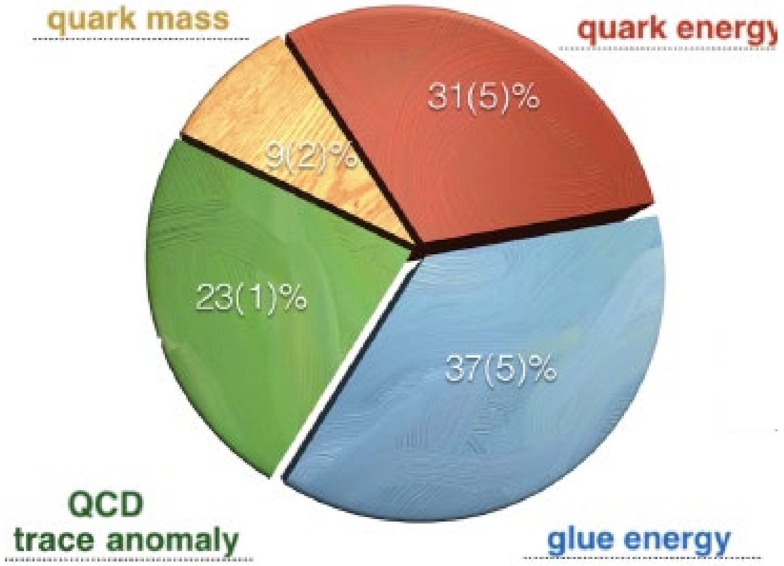
$$M = \overbrace{\underset{\text{Quark Energy}}{E_q} + \underset{\text{Gluon Energy}}{E_g}}^{\text{Relativistic motion}} + \overbrace{\underset{\text{Quark Mass}}{\chi_{m_q}} + \underset{\text{Trace Anomaly}}{T_g}}^{\text{Quantum fluctuation}}$$



Pion	Kaon	Proton
$M_\pi \sim 140\text{MeV}$	$M_K \sim 490\text{MeV}$	$M_p \sim 940\text{MeV}$
Spin 0	Spin 0	Spin 1/2
2 light valence quarks	1 light and 1 “heavy” valence quarks	3 light valence quarks

Higgs generated masses of the valence quarks:

$M_{(u+d)}$ ~ 7 MeV $M_{(u+s)}$ ~ 100 MeV $M_{(u+u+d)}$ ~ 10 MeV



Outline

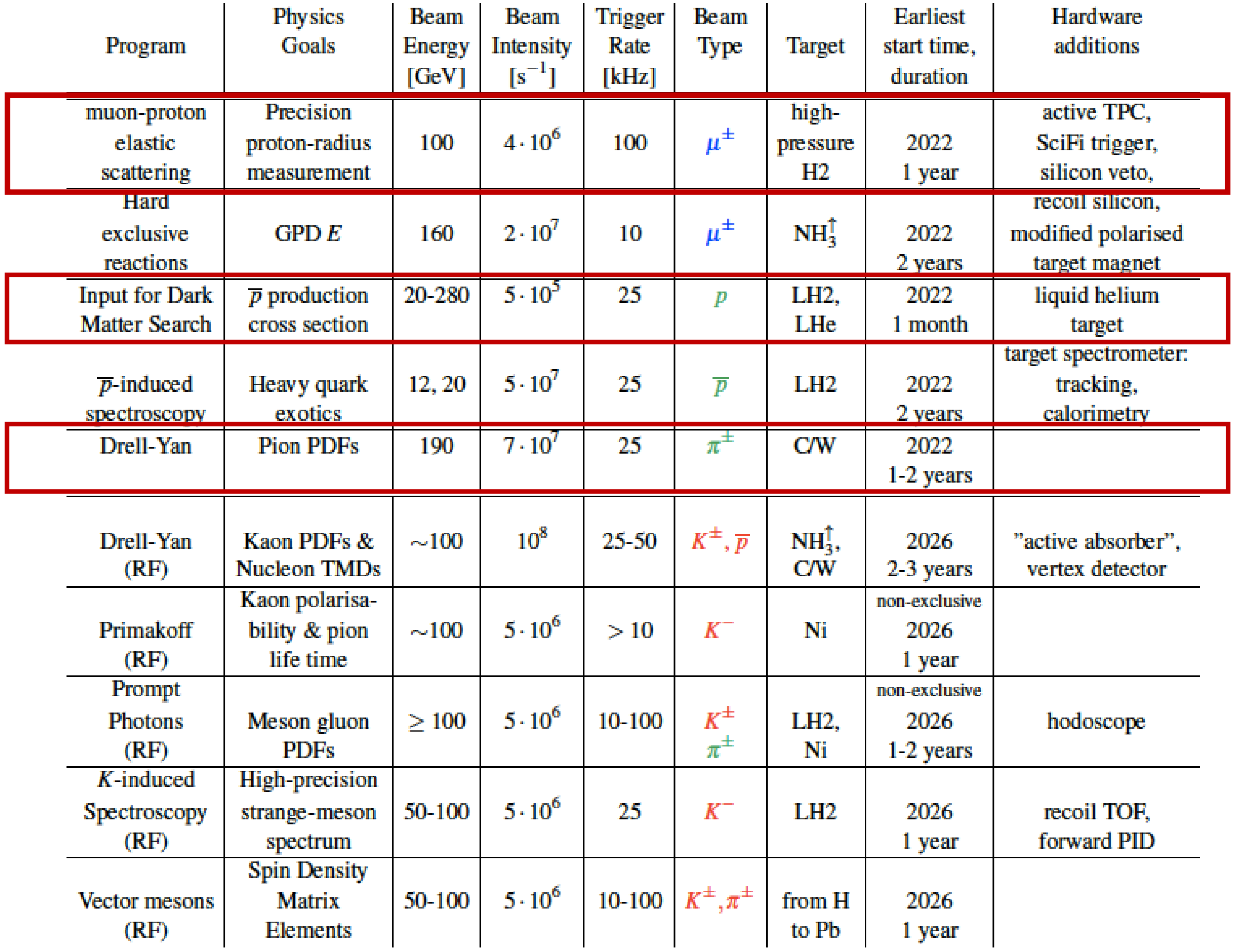


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Table 2: Requirements for future programmes at the M2 beam line after 2021. Muon beams are in blue, conventional hadron beams in green, and RF-separated hadron beams in red.

PHASE-1

Conventional hadron and muon beams

2022 ➔ 2025 and beyond

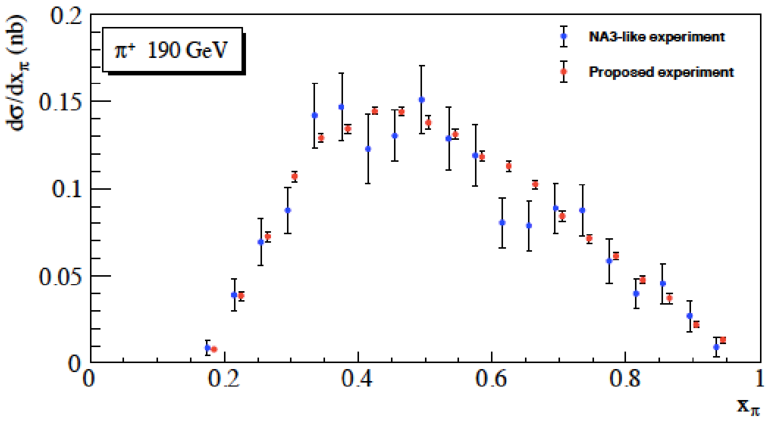
PHASE-2

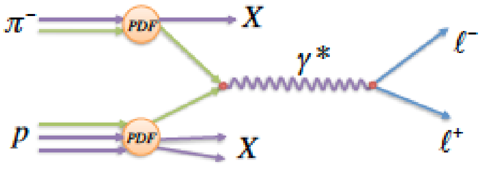
Conventional and RF-separated Hadron/Hadron and muon beam

2026 and beyond

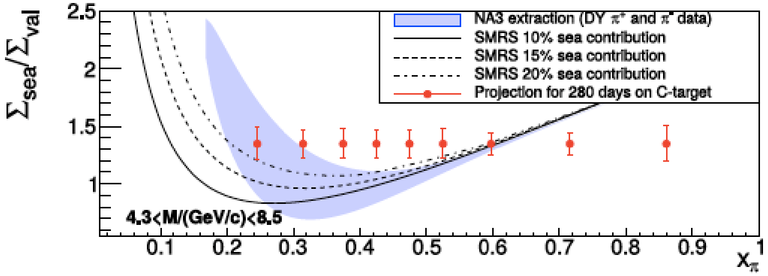
Outline

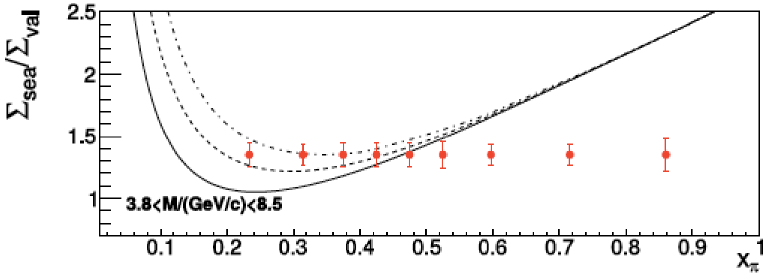
Pion structure in pion induce DY
Expected accuracy as compared to NA3





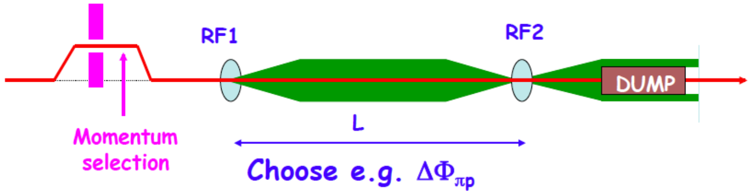
- 90's: NA3, NA10, E615
- 10's: COMPASS-II
- 20's: COMPASS++



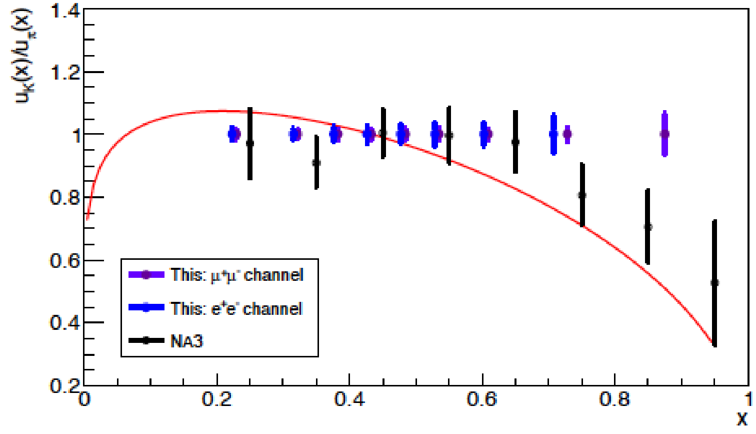


- $\Sigma_V = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: only valence-valence
- $\Sigma_S = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$: no valence-valence
- Collect at least a **factor 10 more statistics** than presently available
- Minimize nuclear effects on target side
  - Projection for 2 × 140 days of Drell-Yan data taking
  - π^+ to π^- 10:1 time sharing
  - 190 GeV beams on Carbon target ($1.9\lambda_{int}^{\pi}$)
  - Improvement of shielding to double the intensity is under investigation

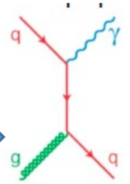
Kaon structure in Kaon induce DY
Needs **RF separated** beam



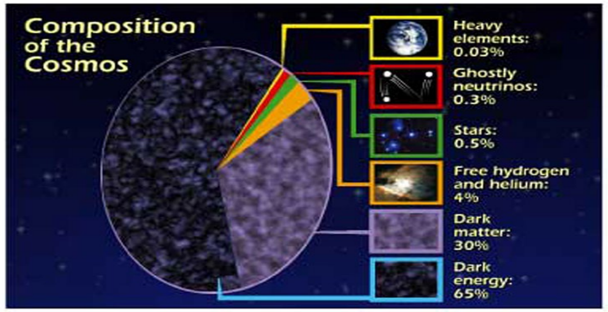
$\Delta\Phi = 2\pi\ (L\ f\ /\ c)\ (\beta_1^{-1} - \beta_2^{-1})$ with $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$



To extract pion and kaon pdf, in particular gluon pdf



Antiproton production cross section



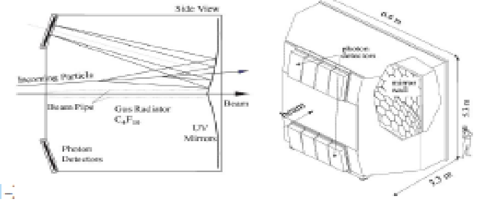
From the AMS data the antiparticle flux is well known, two type of processes contribute

- SM interaction , protons on the interstellar medium with the production of antiproton
- Antiparticle annihilation

In order to detect a possible excess in the antiparticles flux a good knowledge of the inclusive cross section of p-He interactions

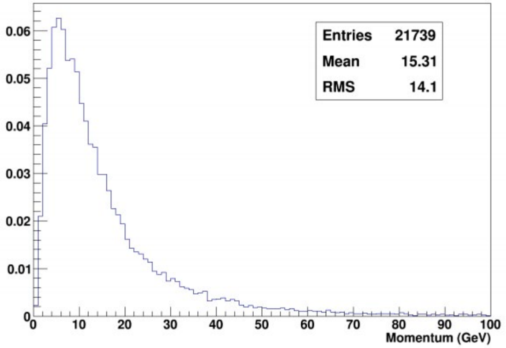
The goal is to measure the inclusive antiproton cross section production in a wide kinematical range with a precision < 10%. C++/AMBER luminosity is a 1000 times The NA49 one

- Proton beam energy range 50-250 GeV
- Secondary particles identification:
  - Antiprotons (RICH)
  - Positrons and Gamma (ECals)

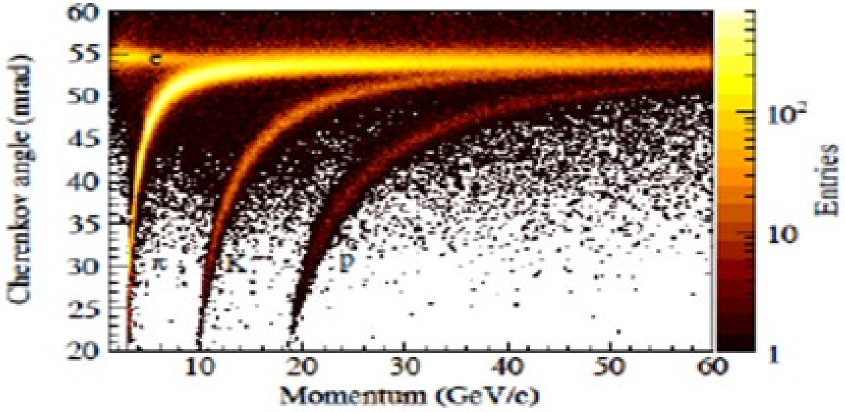


7-11-

Figure 34. COMPASS RICH-1: principle and artistic view.



Momentum spectrum of anti-p produced in p+ p interactions at 190 GeV/c



New low momenta is envisaged for the measurement

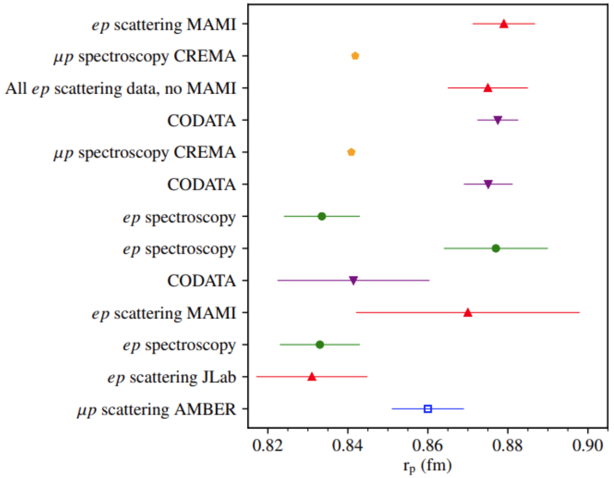
The Proton-Radius Puzzle

Data from spectroscopy and e-p scattering
Several experiments with different approaches measured the proton radius with contradicting results.

- Hydrogen spectroscopy:
  → muonic or ordinary hydrogen
  → highest precision using laser spectroscopy
  → favoured value of (0.841±0.001) fm

- Electron-hydrogen scattering:
  → measurement using momentum transfer
  → recent data: MAMI A1 (2010) or JLab (2011)
  → favoured value of (0.879±0.008) fm
  → new in 2019: PRad value of (0.831±0.014) fm

- Two significantly different values obtained
  → the proton-radius puzzle



Cross section, form factor, and the proton charge-radius
Measurement of electric form factor allows to calculate proton charge-radius.

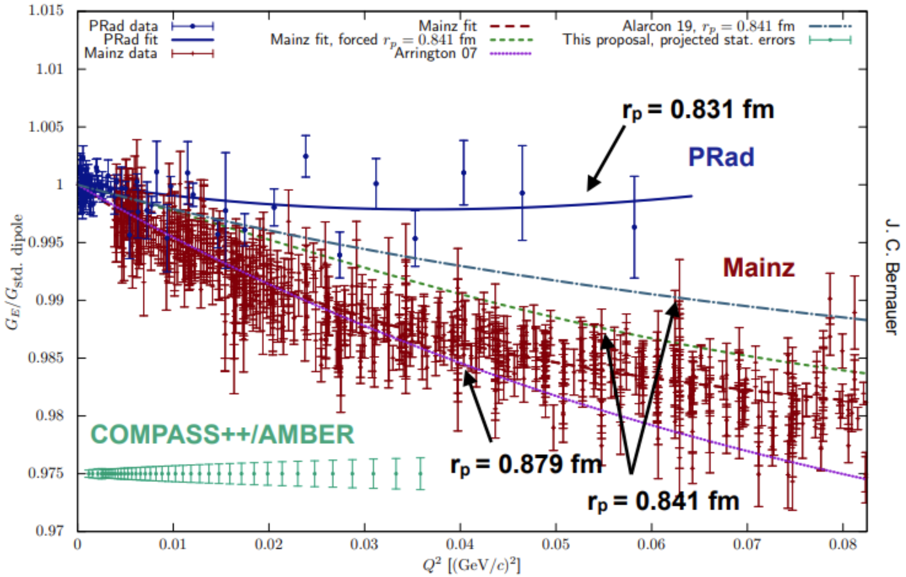
- Electric form-factor G_E defines the proton charge-radius at momentum transfer $Q^2 = 0$:

$$< r_p^2 > = -6\hbar^2 \cdot \left.\frac{dG_E(Q^2)}{dQ^2}\right|_{Q^2\to 0}$$

- Access to form factors G_E^2 and G_M^2 in Rosenbluth separation of cross section:

$$\frac{d\sigma^{\mu p\to\mu p}}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} R\left(\epsilon G_E^2 + \tau G_M^2\right)$$

$$R = \frac{\vec{p_\mu}^2 - \tau\left(s - 2m_p^2(1+\tau)\right)}{\vec{p_\mu}^2(1+\tau)} \quad \epsilon = \frac{E_\mu^2 - \tau\left(s - m_\mu^2\right)}{\vec{p_\mu}^2 - \tau\left(s - 2m_p^2(1+\tau)\right)} \quad \tau = \frac{Q^2}{(4m_P^2)}$$

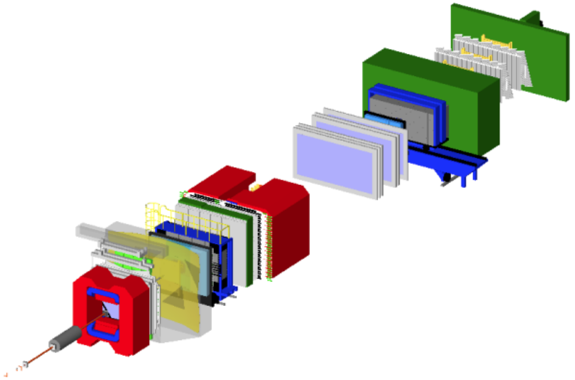


- Suppress magnetic form factor G_M^2
  → Requires $\tau \to 0$
  → Measurement at low-Q^2 values of $\mathcal{O}(<10^{-2})$
- Measurement at high-energy $\mathcal{O}$(10 - 100 GeV)
  → Results in $\varepsilon \to 1$
  → Cross-section directly proportional to G_E^2

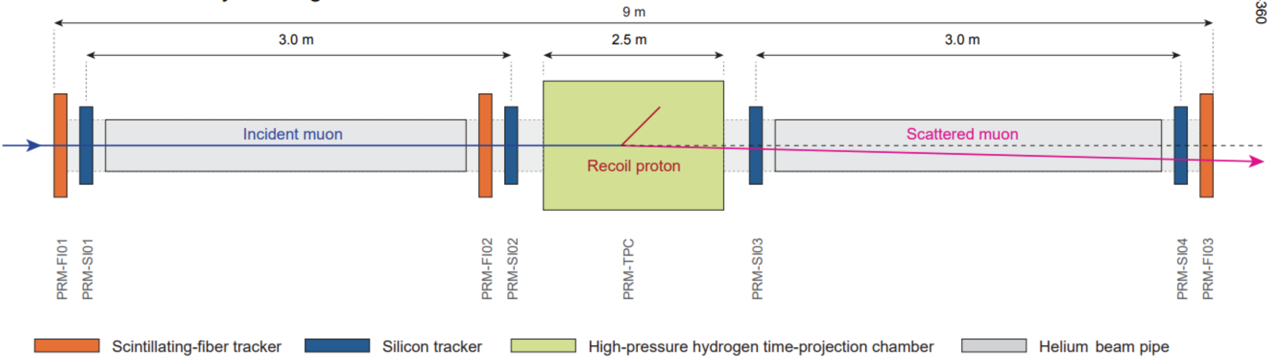
The Proton-Radius Puzzle: new hardware requirements

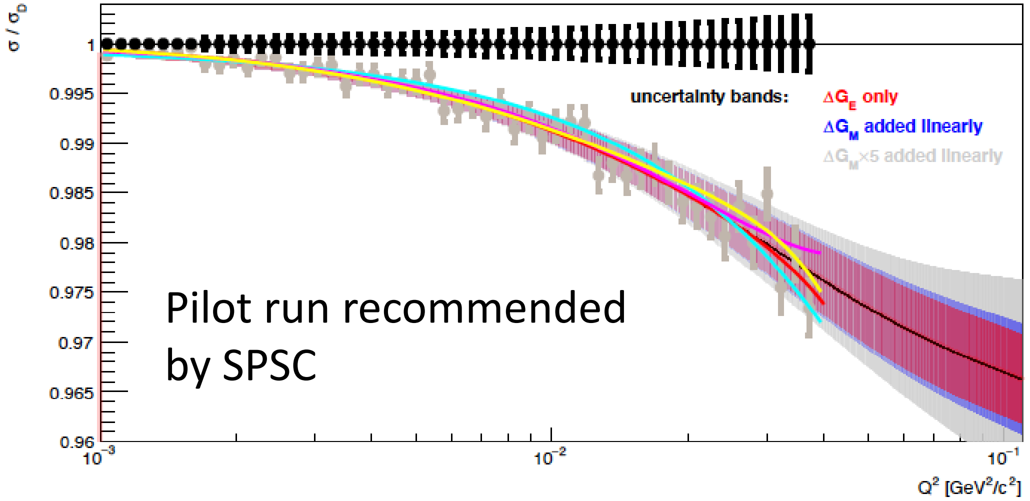
Measurement of low-Q^2 elastic-scattering
Detection of low-energetic recoil-protons and scattered muons with small scattering-angle.

- Silicon trackers along large leaver-arm to measure small scattering-angles
- Fiber tracker timing and trigger (fallback)
- TPC as an active target with the ability to measure the low-energetic recoil-proton
- New continuously-running DAQ



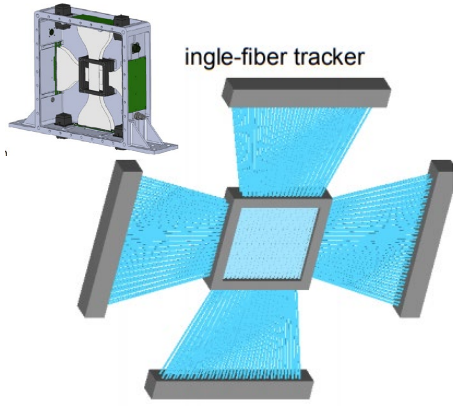
CERN-SPSC-2019-022; SPSC-P-360



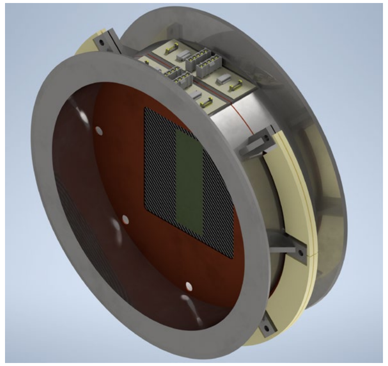


Pilot run recommended by SPSC

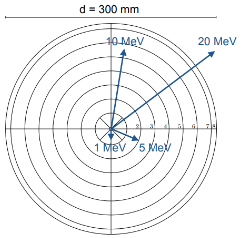
- COMPASS spectrometer → Momentum measurement of scattered muon → Radiative background using electromagnetic calorimeter → Muon identification with muon filter and hodoscope

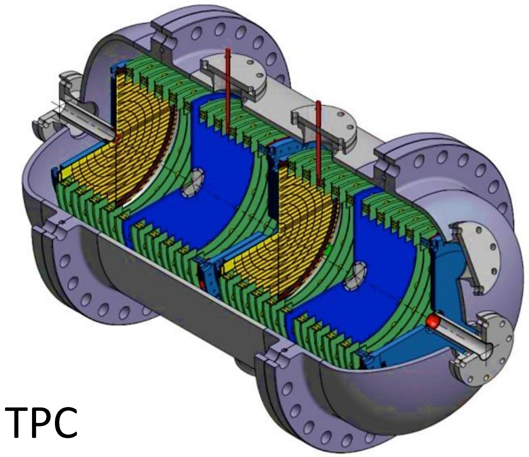


200μm fiber redout

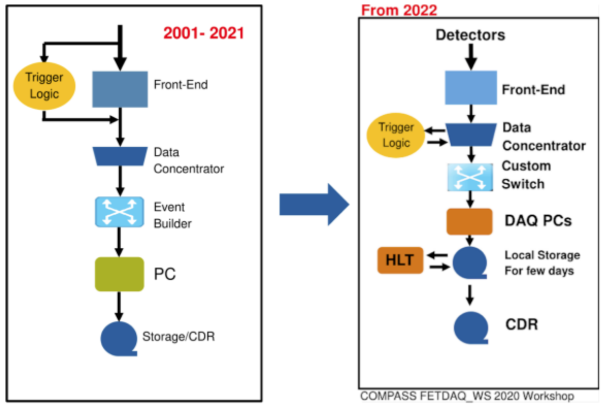


Silicon Pixel-Detector Based on ALPIDE





20 bar H_2 TPC



New TL DAQ

Outline

COMPASS has provided in the last 20 years a broad spectrum of results, still some questions like the emergency of the hadronic mass as well as the spin puzzle remain opened and of extreme interest.

In the tradition of the COMPASS spirit a wide spectrum of new measurements have been proposed by the COMPASS++/AMBER collaboration with conventional and RF separated beams

In 2021, 22 , 23 the COMPASS experiment will perform precise measurement on Transversity and the new collaboration will shed light on the proton radius puzzle.

Grazie