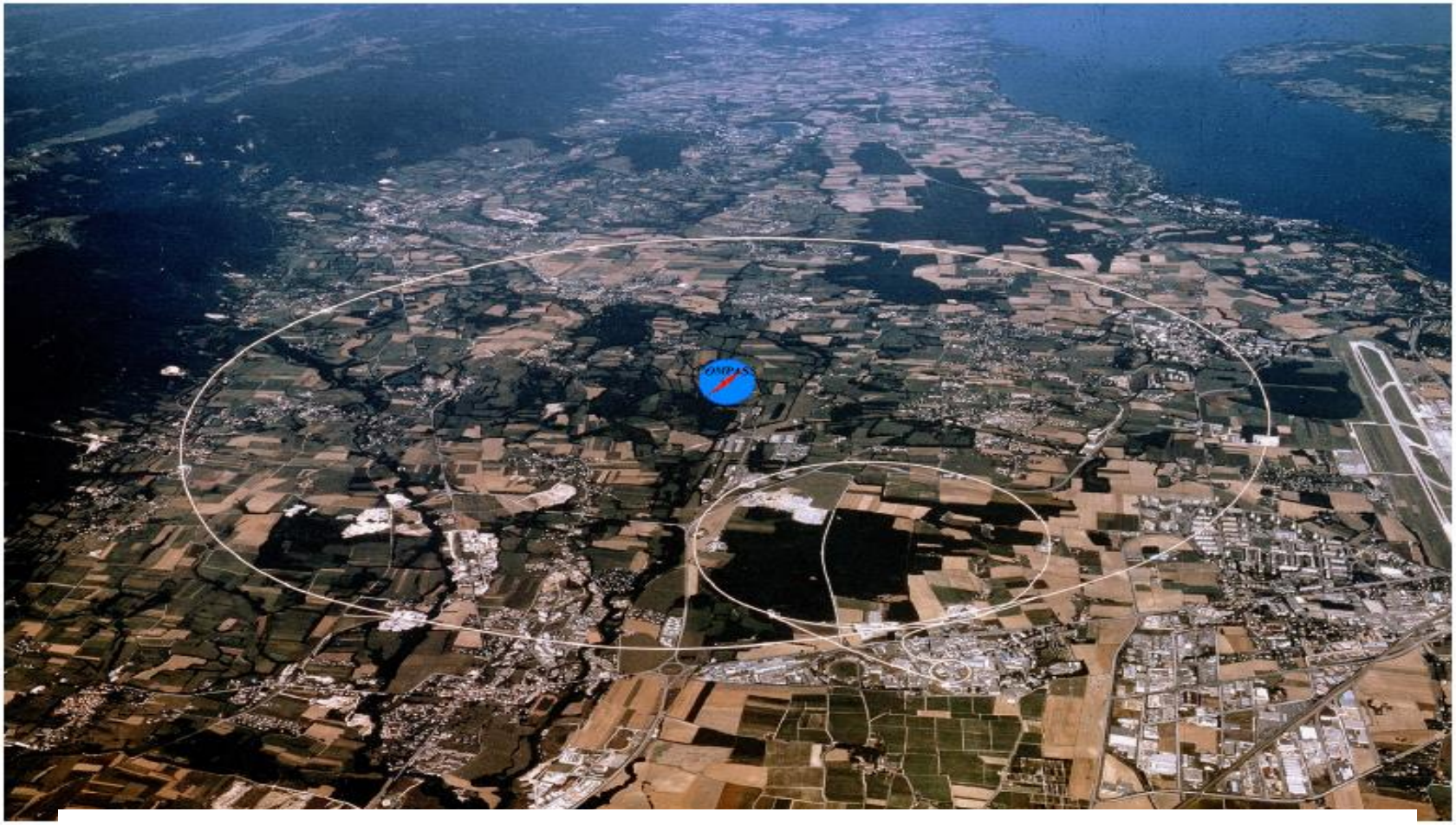
Outline

1. **Hadron structure and excited states**
   - Light quark spectroscopy - update
   - Pion polarizability and ChPT applicability test
2. **Nucleon structure with muon beam**
   - Multiplicities
   - Azimuthal asymmetries transverse/longitudinal
3. **DVCS and DVMP**
   - DVCS – 2016+2017
4. **Dell-Yan**
   - 2015+2018 data set
5. **Proton radius Beam test**
6. **2021 deuteron run**
7. **Summary**

Only selected topics were addressed in the talk, see COMPASS annual report for detailed info.

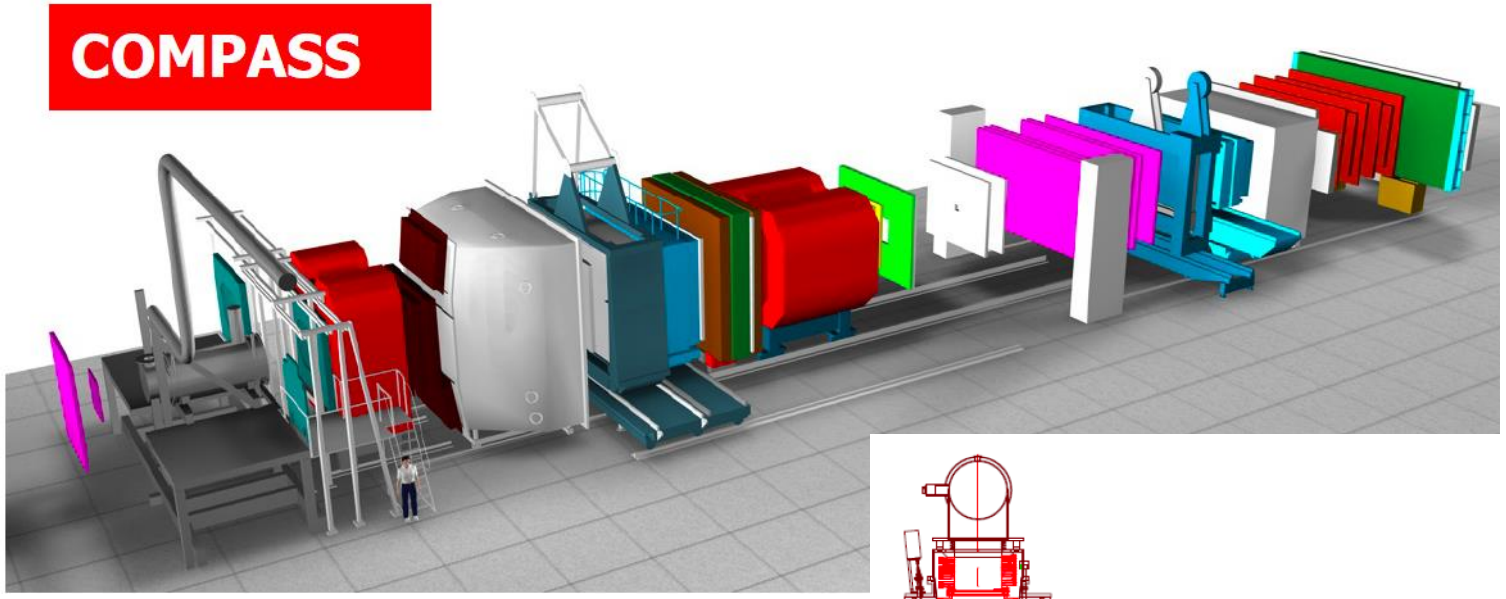
COMPASS QCD facility at CERN (SPS)

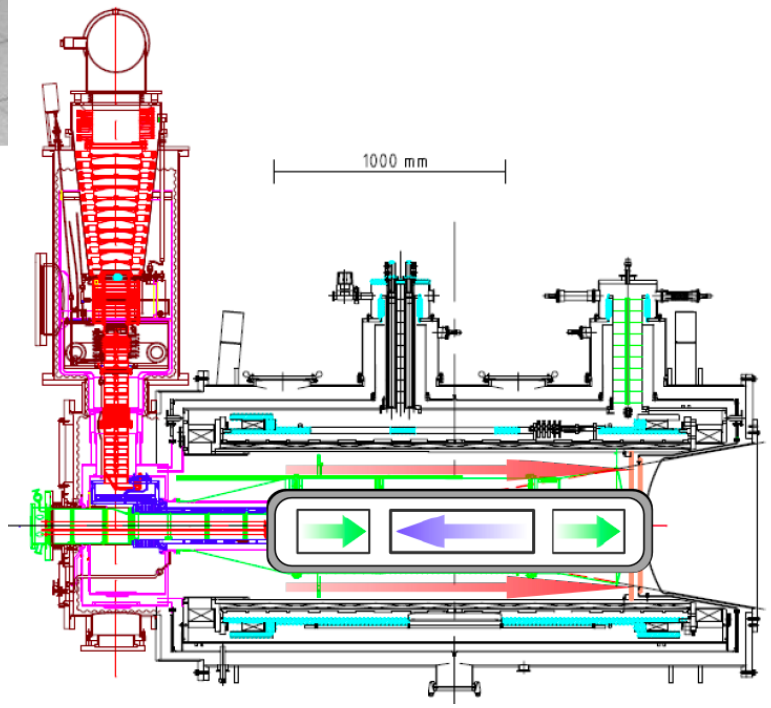
COmmon Muon Proton Apparatus for Structure and Spectroscopy



~210 physicists, 12 countries + CERN, 24 institutions

COMPASS Spectrometer at SPS M2 beam line (CERN)



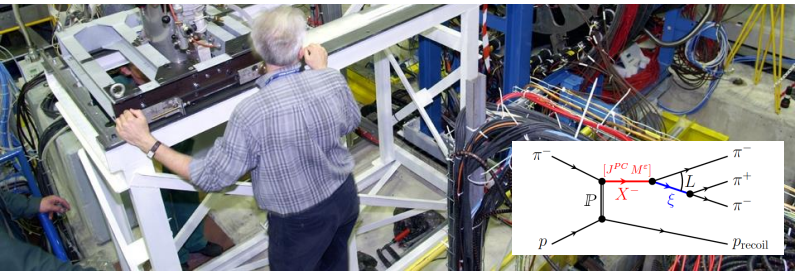


Universal and flexible apparatus.
Most important features of the two-stage COMPASS Spectrometer:

1. Muon, electron or hadron beams with the momentum range 20-250 GeV and intensities up to 10^8 particles per second
2. Solid state polarised targets (NH_3 or ^6LiD) as well as liquid hydrogen target and nuclear targets
3. Powerful tracking (350 planes) and PiD systems (Muon Walls, Calorimeters, RICH)

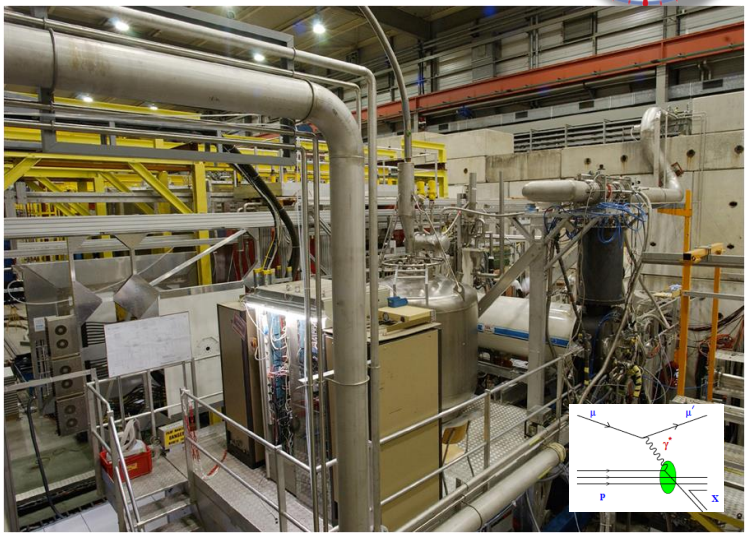
COMPASS QCD facility at SPS M2 beam line (CERN)
(secondary hadron and lepton beams)

Exotic states, chiral dynamics



Hadron Spectroscopy & Polarisability

COMPASS-I
1997-2011

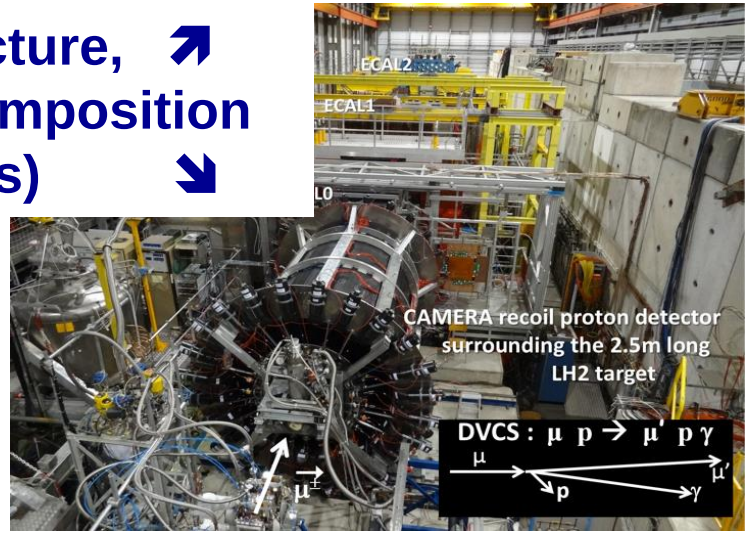


Polarised SIDIS

3D hadron structure,
Proton spin decomposition
(spin crisis)

Polarised Drell-Yan

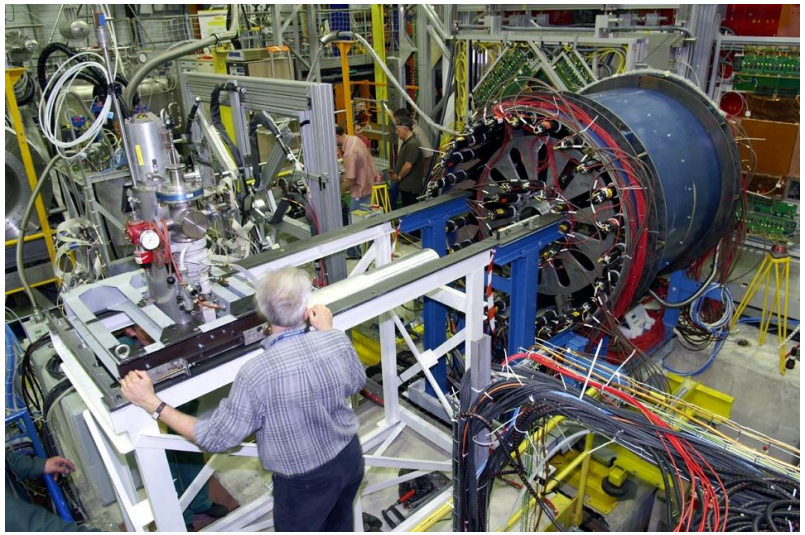
COMPASS-II
2012-2020

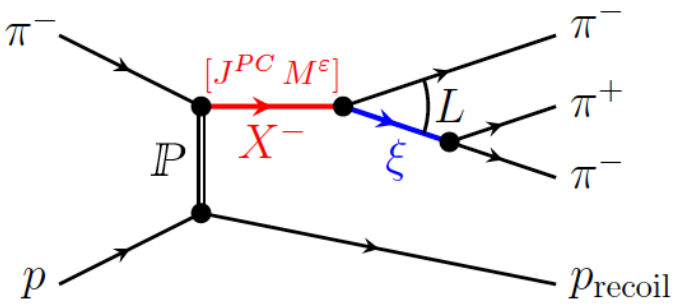


DVCS (GPDs) + unp. SIDIS

Diffractive dissociation I

main results





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

3π data sample ~50×10^6 exclusive events – factor 10 to 100 to previous experiment

Potential illustration – discovery of a new resonance-like $a_1(1420)$ state in $1^{++}0^+$ $f_0(980)\pi$ P wave (PRL).

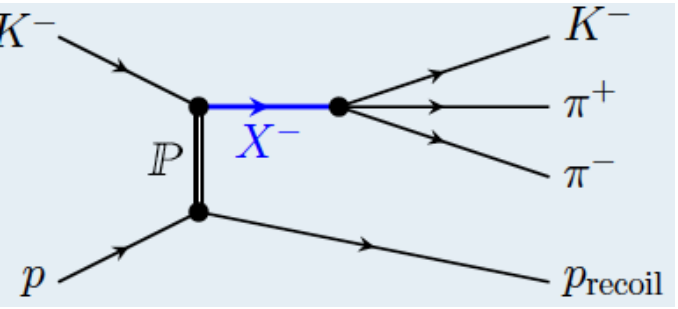
A lot of work has been invested to develop new methods in order to cope with huge data sample.
A lot of work has been invested to develop new methods in order to cope with huge data sample.

An extensive papers that describes the PWA method and the results from this analysis has recently been published (PRD 95 (2017) 032004, PRD 98 (2018) 092003). Major step forward in the field: 100 bins in $m_{3\pi}$ (0.5 to 2.5 GeV/c^2) and 11 in t' (0.1 to 1.0 (GeV/c)^2), 88 waves up to spin 6.

Analysis steps:
1. p-w decomposition: 88x88 spin-density matrix for each t' (f.-m. transfer squared) and $m_{3\pi}$ bin (mass-independent fit)
2. For selected wave set (14 waves, 60% of total intensity) fit of the spin-density matrix by a resonance models (B.-W. + coherent non-resonant term)

Diffractive dissociation II

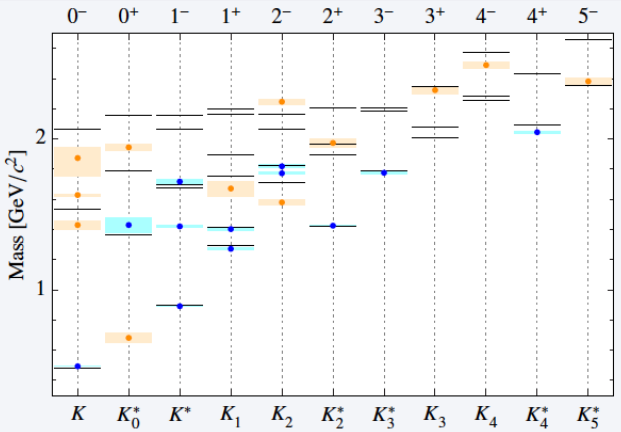
new results: strange sector



In 2008 and 2009 runs, we obtain about 728 000 exclusive $K^- \pi^- \pi^+$ events (x4 compare to WA03). The analysis is more complicated compare to 3π final state as non only $\pi^- \pi^+$ but also $K^-\pi^+$ isobars. Currently we use 6 isobars to analyse $\pi\pi$ final states and another 6 to $K\pi$. We use 4 t' bins and 20 to 40 MeV/c^2 mass bins in the range 0-3 GeV/c^2. Clear signal from dominant states was observed

PDG 2016: 25 kaon states below 3.1 GeV/c^2

- Only 12 kaon states in summary table, 13 need confirmation
- Many predicted quark-model states still missing
- Some hints for supernumerous states

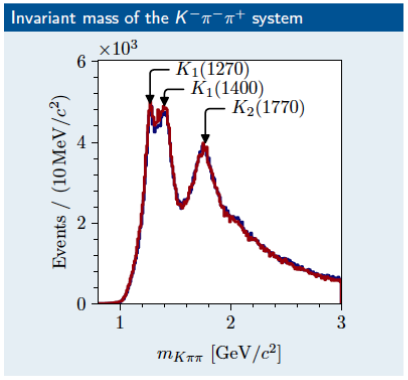


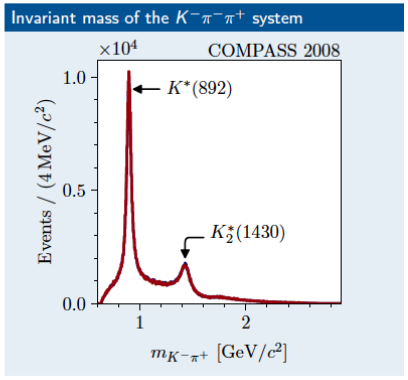
[Courtesy S. Wallner, TUM]

Boris Grube, TU München | Hadron Spectroscopy with Kaon Beam

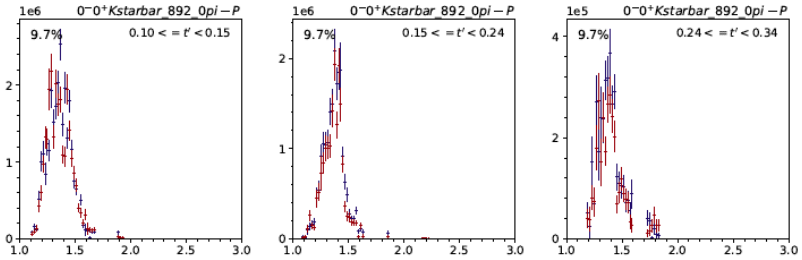
2009 Data

Comparison of 2008 (blue) vs 2009 (red) Data





S. Wallner | Event Selection of the $K^-\pi^-\pi^+$ Final State in 2008 and 2009 Data | 25 / 31



Diffractive dissociation III

new results on odd-spin waves + work in proigress

Joint effort with JPAC

In collaboration with Joint Physics Analysis Center (JPAC) eta$^{(')}$ pi$^-$ final state analysis as odd-spin waves have spin-exotic quantum number. More refined with respect to the simple Breit-Wigner approach analysis of the P- and D-waves in eta pi$^-$ and eta$^{'}$ pi$^-$ final states shows that only one resonance pole consistent with spin exotic $\pi_1(1600)$ is necessary to describe both waves (no need for two close in mass spin-exotic states $\pi_1(1600)$ and $\pi_1(1400)$.

WORK in Progress: Because of the huge data set a special effort has to be taken to reduce systematic uncertainties and to refine analysis model/method.

1. Choice of parametrization for the $\pi^+ \pi^-$ isobar amplitude

2. Another source of systematic uncertainties is a truncation of the partial-wave expansion. We have developed a method which permit automatically define the wave set depending on mass of 3π system.

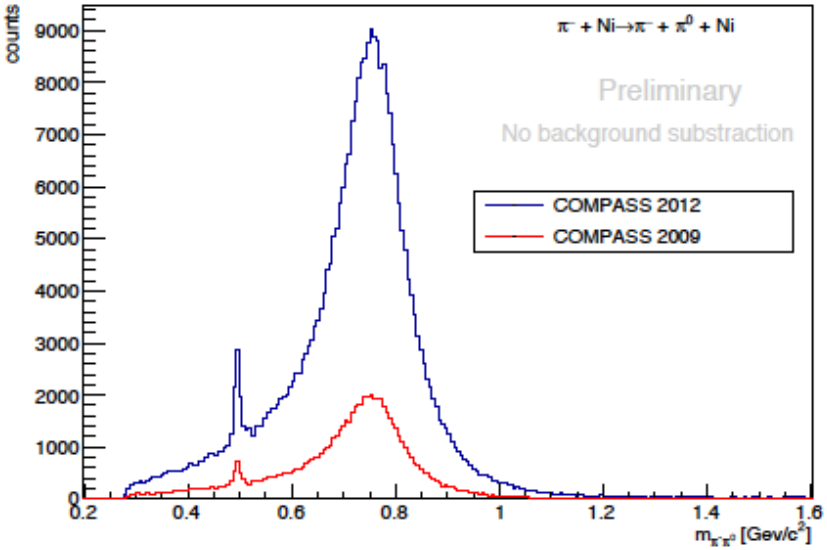
Measurement of chiral dynamics in the reaction $\pi^- \gamma^* \rightarrow \pi^- \pi^0$

Data taking periods in 2009 and 2012, we concentrate on $\pi^- \gamma^* \rightarrow \pi^- \pi^0$ (other final states like $\pi^- \gamma^* \rightarrow \pi^- \gamma$, $\pi^- \gamma^* \rightarrow \pi^- \pi^- \pi^+$, $\pi^- \gamma^* \rightarrow \pi^- \pi^0 \pi^0$ are available) in order to study chiral anomaly $F_{3\pi}$.

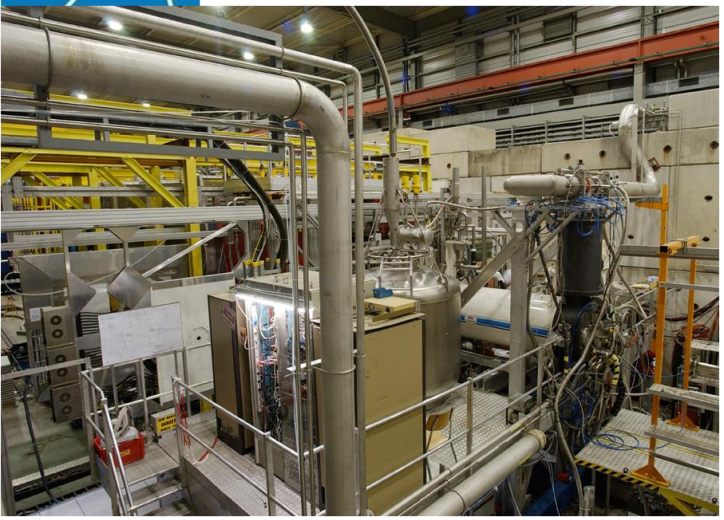
$\pi^- \pi^0$ final state is dominated by rho(770) resonance. Previous experiments that measured $F_{3\pi}$ to 10% level were restricted to the threshold mass region because of the low mass tail of the rho, with limited control over systematic.

New in our analysis:

- Analysis of the $\pi^- \pi^0$ mass spectrum in Hoferichter approach (extension of the ChPT amplitude up to ~ 1 GeV/c^2 by including rho(770) via dispersion relation) in a much wider mass range ➔ precise $F_{3\pi}$ measurement + rho radiative coupling extraction;
- New method to control the integrated luminosity via K^- decay channel in $\pi^- \pi^0$ and $\pi^- \pi^0 \pi^0$. Both channels Gives now compatible results (after detailed study of the Acceptance corrections in MC)

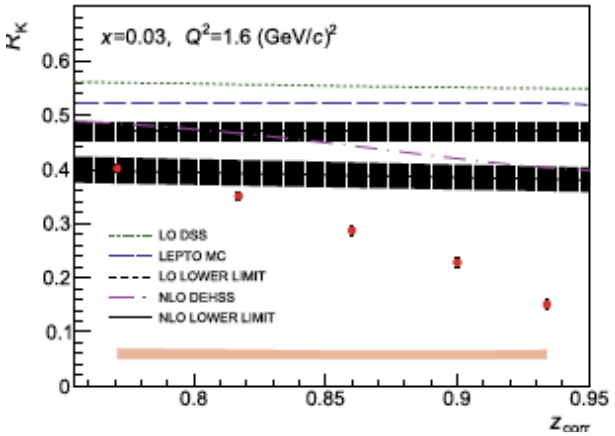


SIDIS Multiplicities

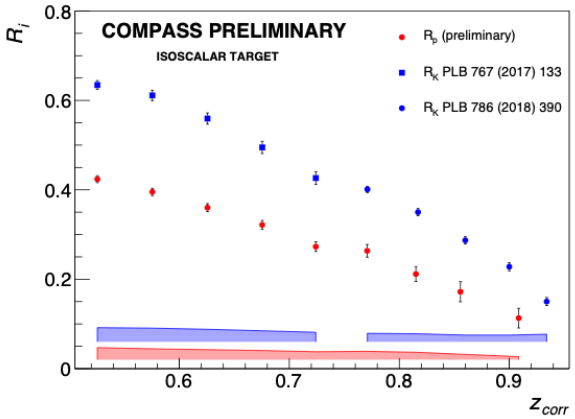


In the last report we summarised our studies of K^-/K^+ multiplicity ratio R_K in the region of high z, (z > 0:75) (PLB 786 (2018) 390). The obtained results were below the lower limit obtained from LO and NLO pQCD calculations. The discrepancy between measured RK and lower limit expected from pQCD was increasing with z and reached a factor 2.5 for the highest measured z value, about 0.93.

Kaon multiplicities ratio shows also strong dependence on the $M_{missing}$ of the process, so remaing phase space has to be taking into account.

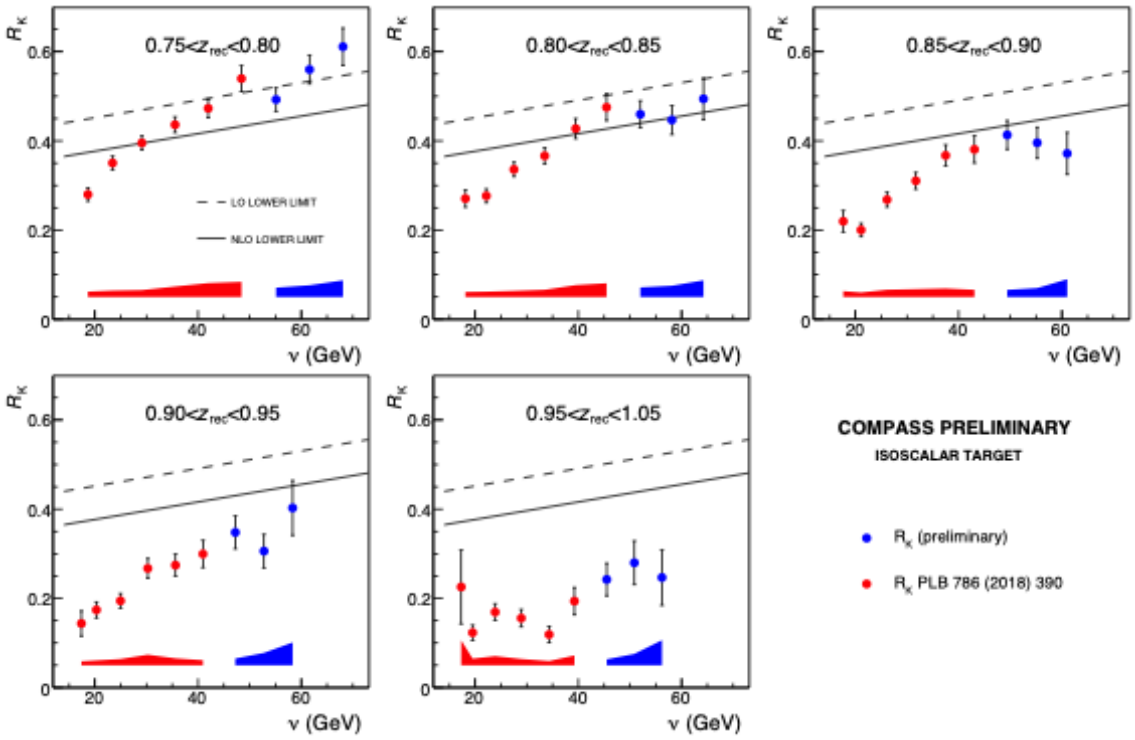


Using our 2006 data set we have continued our multiplicities study for protons and antiprotonsvby extracting the pbar/p multiplicity ratio R_p for z > 0.5. We have found that in the whole measured phase space the ratio is below the lower limit allowed by LO pQCD of about 0.5. Note that the discrepancy to the LO QCD prediction is much larger in the proton case than for kaons.



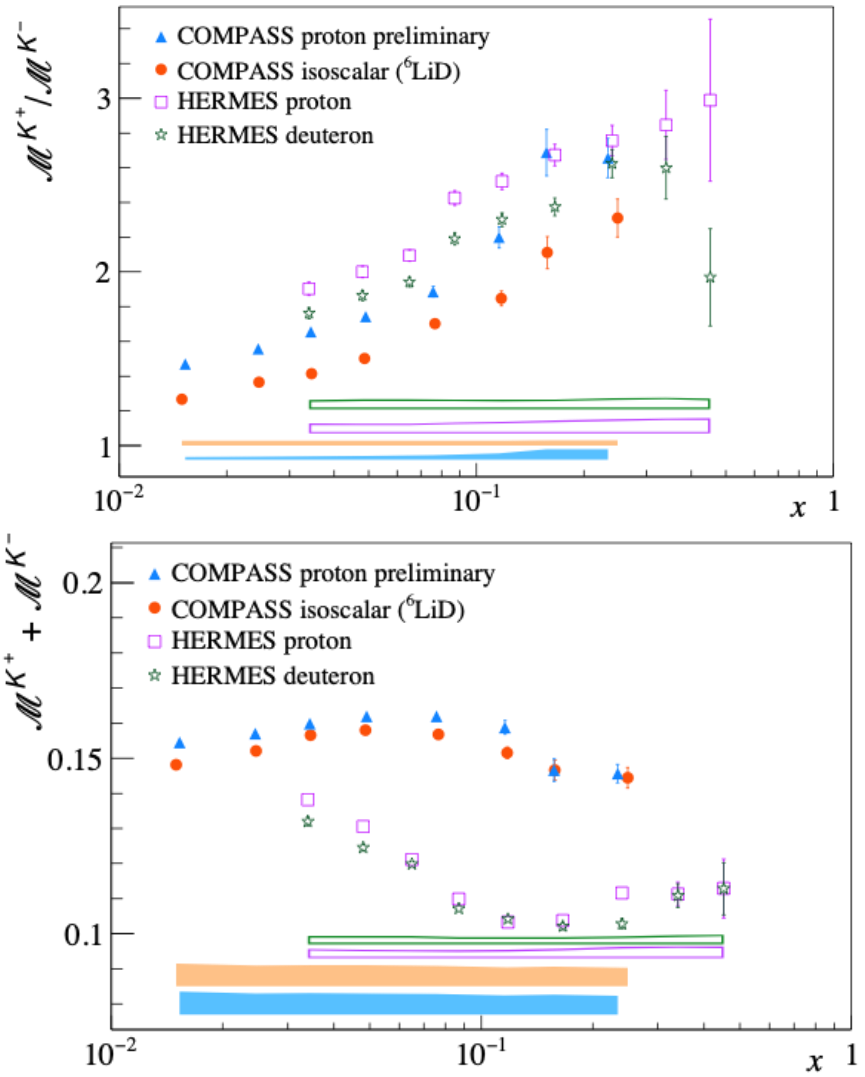
SIDIS (kaon/proton) multiplicities

Over the past year the range of ν has been extended by increasing hadron momentum range (better K separation at high momenta (NN technique). Additional points were added for each Z bin studied before. Sort of saturation effect could be noticed.



SIDIS (kaon/proton) multiplicities

We have started 2016 data analysis (LH^2 target) in order to extract kaon multiplicities on proton target. As a first step we have extracted R_k in the same bins as for the iso-scalar target data (integrating over z and averaging over y).
It is expected that proton R_k is 10-20% higher compared to isoscalar.

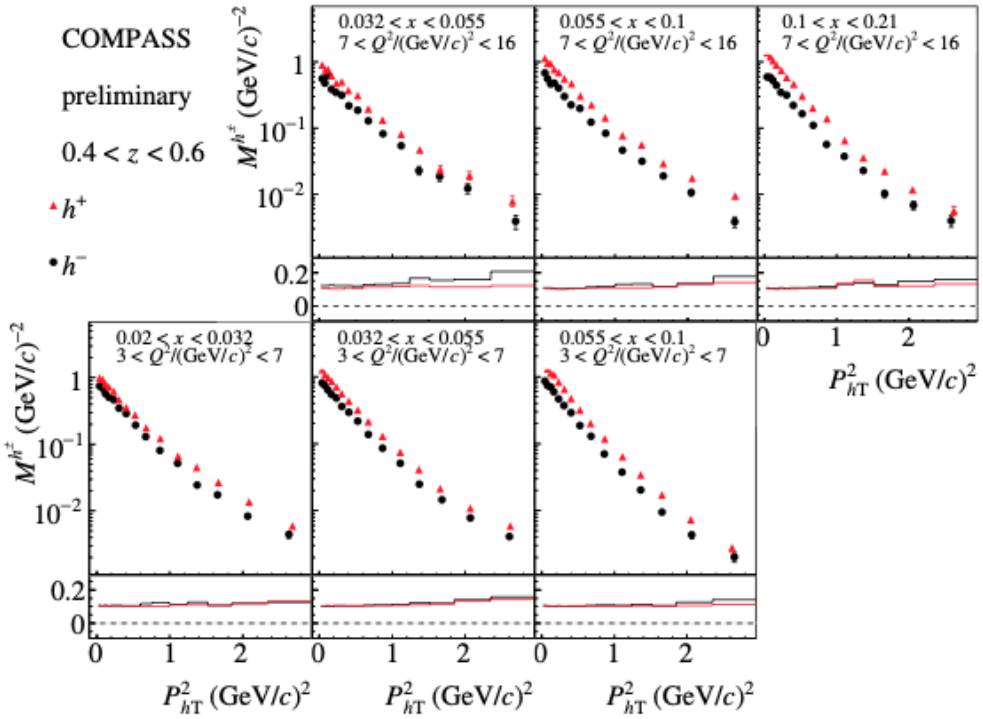


Important message – HERMES and COMPASS data are still in tension.
Can not be explained only by different Q^2 range, the discussion is going on.

SIDIS (kaon/proton) P_T dependent multiplicities

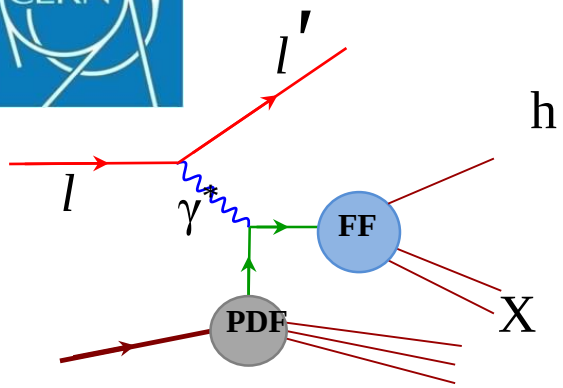
Another multiplicity related activity: extraction form our 2016 proton data P_T dependent multiplicities. As a first step we use the same kinematical (x, Q^2, z) bins as for the deuteron data.

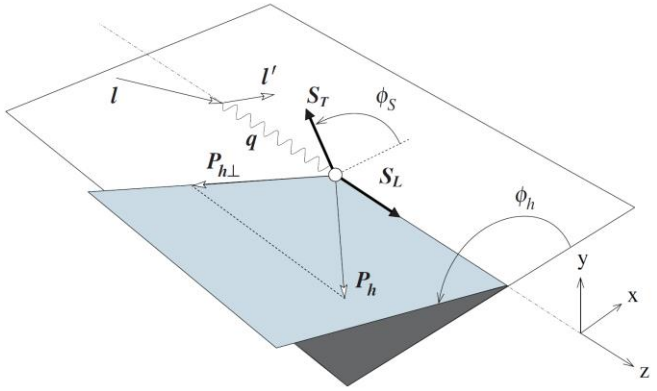
Released data corresponds to the range where the acceptance corrections to P_T distributions < 30%. Shown results corresponds to <1/10 of all available statistics.



SIDIS transverse & longitudinal

We continue to scrutinize polarised SIDIS data by studying various target spin-dependent azimuthal asymmetries.
General expression for SIDIS cross-section in terms of asymmetries





$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}(p_T^h)^2\,\mathrm{d}\phi_h\,\mathrm{d}\psi} = 2\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right](F_{UU,T}+\varepsilon F_{UU,L})$$
$$\times\Big\{1+\sqrt{2\varepsilon\,(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos(2\phi_h)}\cos(2\phi_h)+\lambda\sqrt{2\varepsilon\,(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$
$$+S_L\Big[\sqrt{2\varepsilon\,(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin(2\phi_h)}\sin(2\phi_h)\Big]$$
$$+S_L\lambda\Big[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon\,(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\Big]$$
$$+S_T\Big[A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)+\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)+\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)$$
$$+\sqrt{2\varepsilon\,(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S+\sqrt{2\varepsilon\,(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big]$$
$$+S_T\lambda\Big[\sqrt{\left(1-\varepsilon^2\right)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)$$
$$+\sqrt{2\varepsilon\,(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S+\sqrt{2\varepsilon\,(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\},$$

LO LSA/TSA	twist-2: PDF ⊗ FF
$A_{UL}^{\sin(2\phi_h)}$	$h_{1L}^{\perp q}\otimes H_{1q}^{\perp h}$
A_{LL}	$g_{1L}^{q}\otimes D_{1q}^{h}$
$A_{UT}^{\sin(\phi_h-\phi_S)}$	$f_{1T}^{\perp q}\otimes D_{1q}^{h}$
$A_{UT}^{\sin(\phi_h+\phi_S-\pi)}$	$h_{1}^{q}\otimes H_{1q}^{\perp h}$
$A_{UT}^{\sin(3\phi_h-\phi_S)}$	$h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}$
$A_{LT}^{\cos(\phi_h-\phi_S)}$	$g_{1T}^{q}\otimes D_{1q}^{h}$

subleading LSA/TSA	higher-twist PDF ⊗ FF	WWA twist-2: PDF ⊗ FF
$A_{UL}^{\sin(\phi_h)}$	$xh_L^q\otimes H_{1q}^{\perp h}$, $xf_L^{\perp q}\otimes D_{1q}^h$	$h_{1L}^{\perp q}\otimes H_{1q}^{\perp h}$
$A_{LL}^{\cos(\phi_h)}$	$xe_L^q\otimes H_{1q}^{\perp h}$, $xg_L^{\perp q}\otimes D_{1q}^h$	$g_{1L}^q\otimes D_{1q}^h$
$A_{UT}^{\sin(\phi_S)}$	$xf_T^q\otimes D_{1q}^h$, $xh_T^q\otimes H_{1q}^{\perp h}$, $xh_T^{\perp q}\otimes H_{1q}^{\perp h}$	$f_{1T}^{\perp q}\otimes D_{1q}^h$, $h_1^q\otimes H_{1q}^{\perp h}$
$A_{UT}^{\sin(2\phi_h-\phi_S)}$	$xf_T^{\perp q}\otimes D_{1q}^h$, $xh_T^q\otimes H_{1q}^{\perp h}$, $xh_T^{\perp q}\otimes H_{1q}^{\perp h}$	$f_{1T}^{\perp q}\otimes D_{1q}^h$, $h_1^q\otimes H_{1q}^{\perp h}$
$A_{LT}^{\cos(\phi_S)}$	$xg_T^q\otimes D_{1q}^h$, $xe_T^q\otimes H_{1q}^{\perp h}$, $xe_T^{\perp q}\otimes H_{1q}^{\perp h}$	$g_{1T}^q\otimes D_{1q}^h$
$A_{LT}^{\cos(2\phi_h-\phi_S)}$	$xg_T^{\perp q}\otimes D_{1q}^h$, $xe_T^q\otimes H_{1q}^{\perp h}$, $xe_T^{\perp q}\otimes H_{1q}^{\perp h}$	$g_{1T}^q\otimes D_{1q}^h$

SIDIS transverse

New approach - weighted asymmetries

Asymmetries obtained by weighting the spin-dependent part of the cross-section with powers of p^h_T.

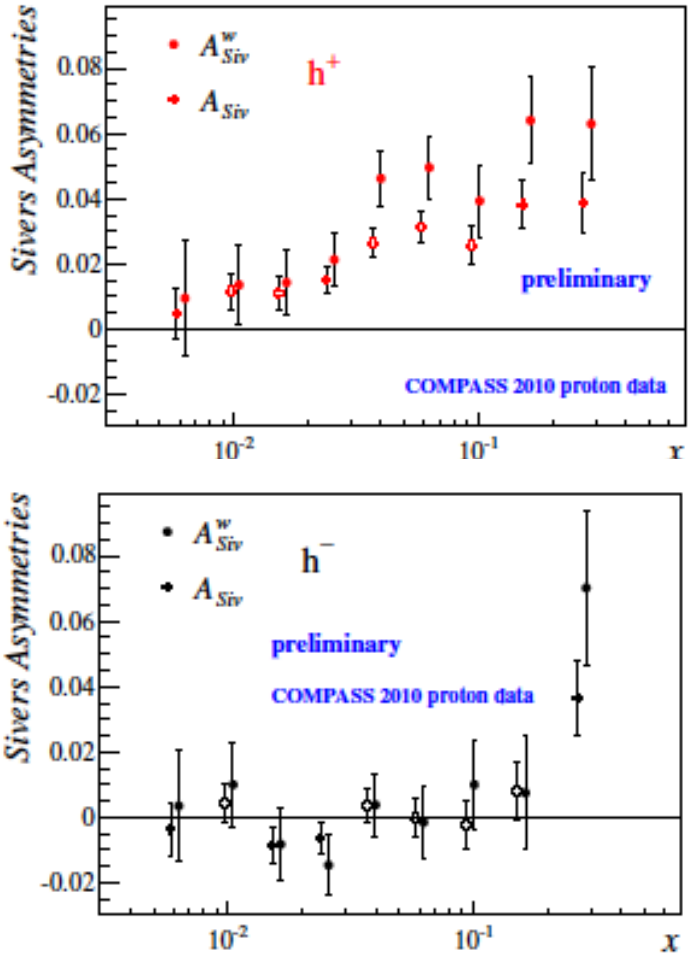
Main advantage - convolution integrals becomes products ➔ no parametrization of the unknown transverse momentum dependence of PDFs and FFs is needed..

$$A_{Siv}^{(p_T^h/zM)}(x,z) = 2\frac{\sum_q e_q^2 f_{1T}^{\perp(1)\,q}(x)\cdot D_1^q(z)}{\sum_q e_q^2 f_1^q(x)\cdot D_1^q(z)},$$

Important: large statistics, good acceptance.

Allows to extract first moment of Sivers

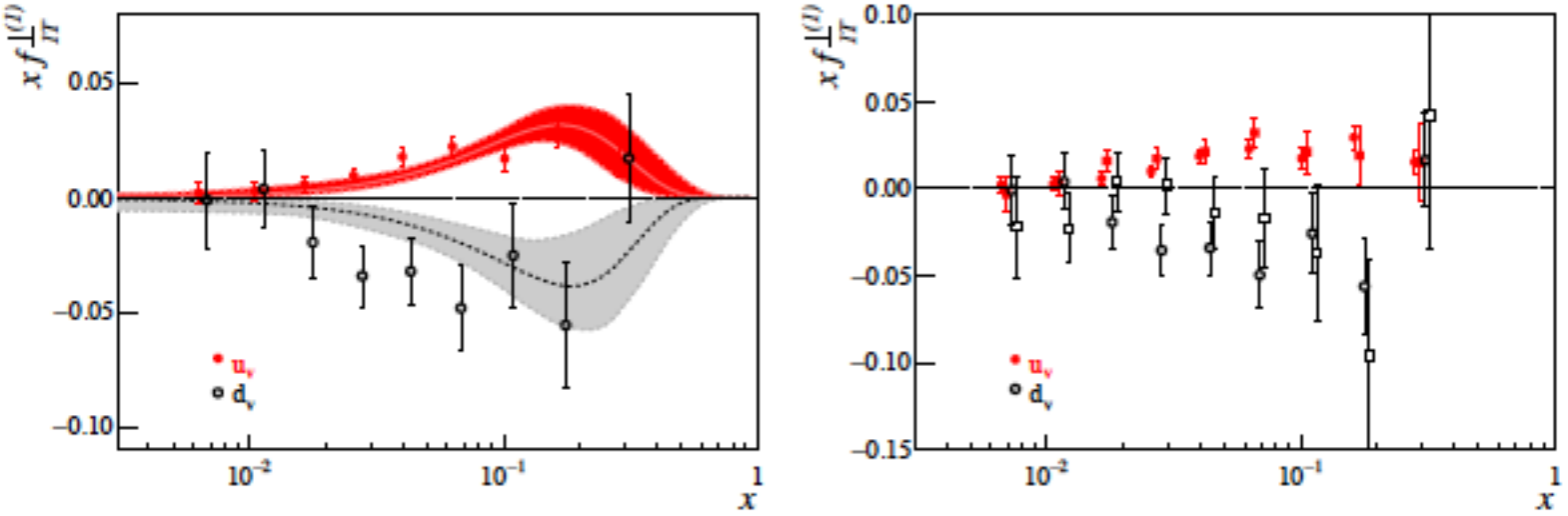
$$f_{1T}^{\perp(1)}(x,Q^2) = \int d^2k_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x,k_T,Q^2).$$



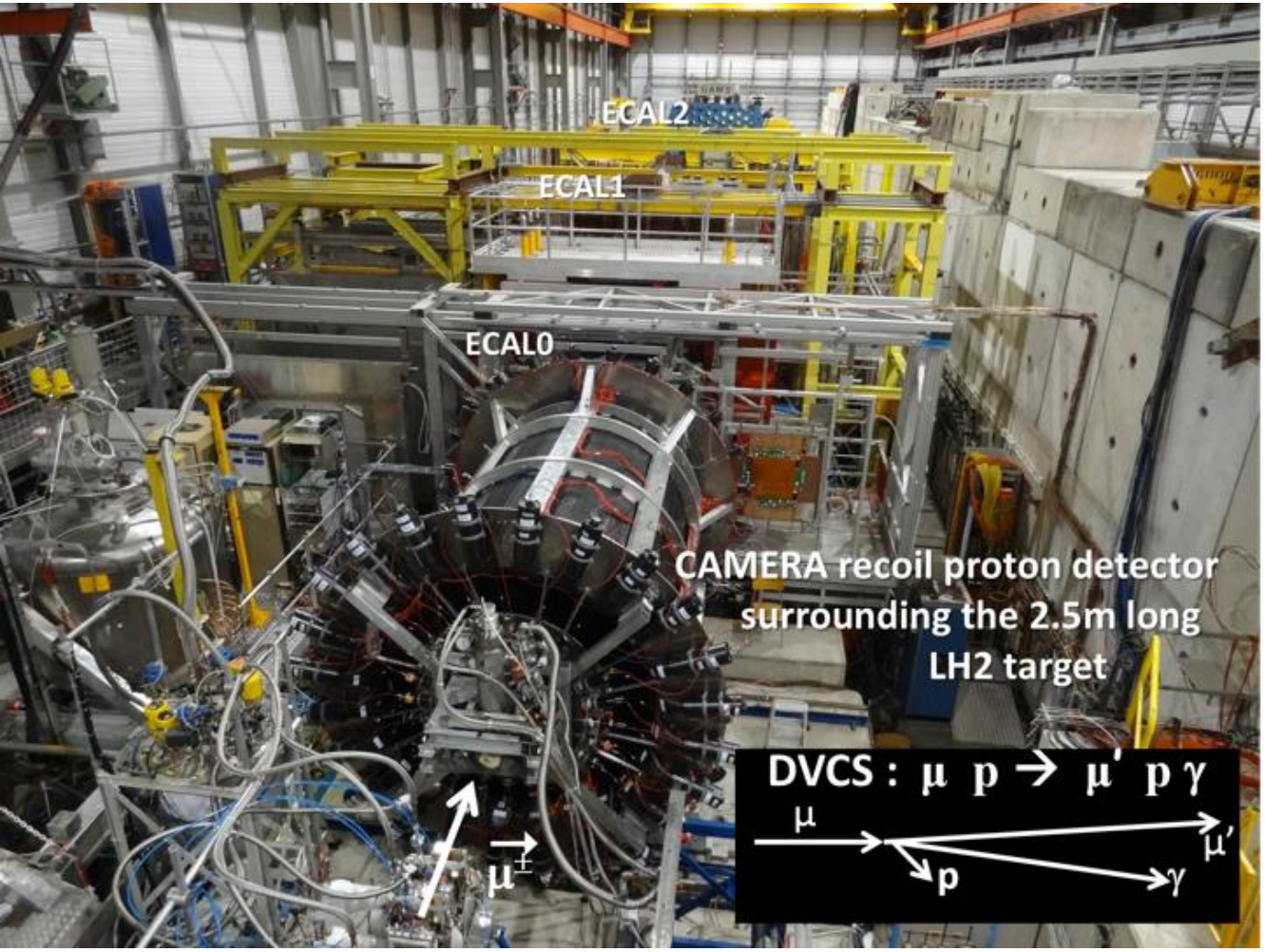
This is a first data on p^h_T weighted Sivers asymmetry

SIDIS transverse
New approach - weighted asymmetries

The measurement of the Sivers asymmetries weighted with the hadron transverse momentum in the N system PT , was already described in the previous report. Also, the first moments of the Sivers functions for the u_v and d_v quarks could be extracted in each x bin from the P_T/zM-weighted Sivers asymmetries with no assumptions on the transverse momentum dependence of PDFs ans FFs. Because of the lack of deuteron data the Sivers function for the sea quarks had to be assumed vanish. The first moments of the Sivers functions are shown in fig. 23, together with previous extractions from d and p data. As can be seen the agreement is good. This is an important fact, since the Sivers function is a recently introduced PDF, and its knowledge is still scarce: the agreement among extractions which use different methods strengthen the robustness of the result.

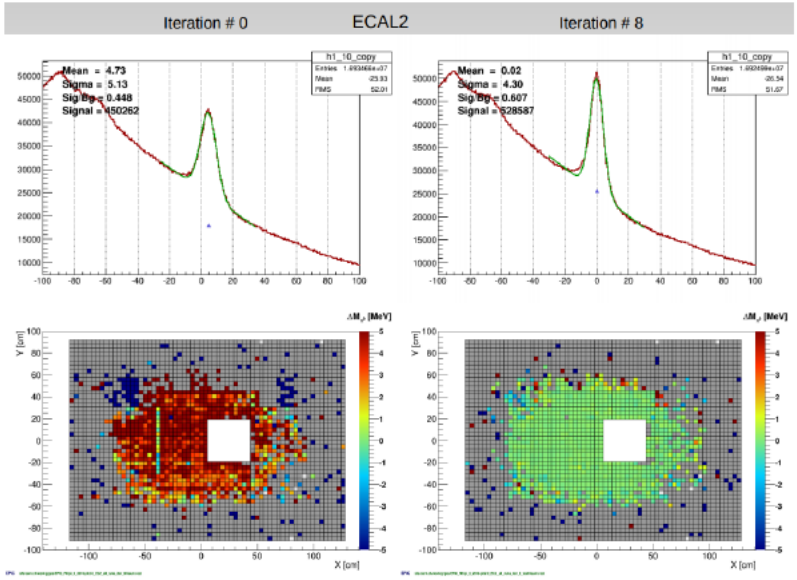


GPD 2016-17
(first DVCS results were reported last year)



2016-17, 160 GeV pion beam for calibration, μ^+ and μ^- for physics, 2.5 meters long LH_2 target

DVCS 2016/17 calibrations etc



In 2016 and 2017 we were taking data with Approximately the same mu+ and mu- beam Intensities in order to avoid normalization Problems faced during 2012 DVCS pilot run.

Significant time were spent to calibrate Ecals And Proton Recoil Detector.
Data looks fine now.

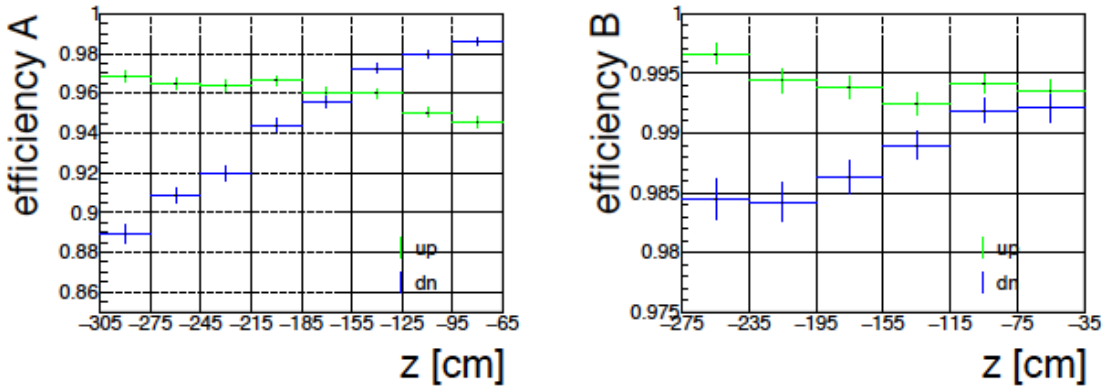
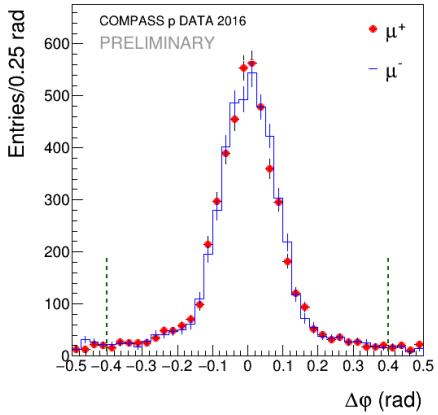


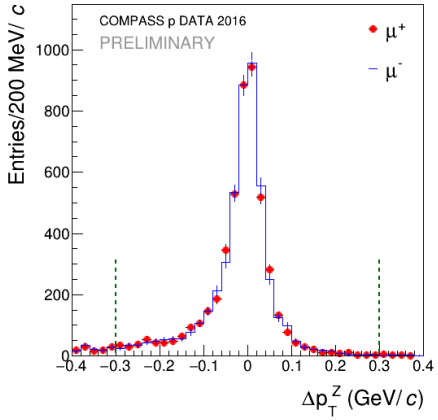
Fig. 13: Average efficiencies of all up- and downstream PMTs vs. the z position in the scintillators in the kinematic range $0.08\,(\mathrm{GeV/c})^2 \leq t \leq 0.64\,(\mathrm{GeV/c})^2$.

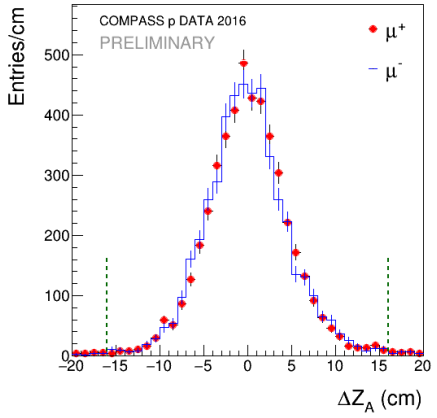
DVCS 2016/17

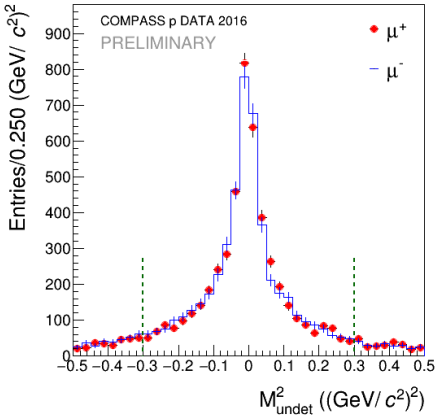
mu+/mu- normalisation

Mu+/mu- normalisation issue is not there any more in exclusive reaction $\mu p \rightarrow \mu' p' \gamma$





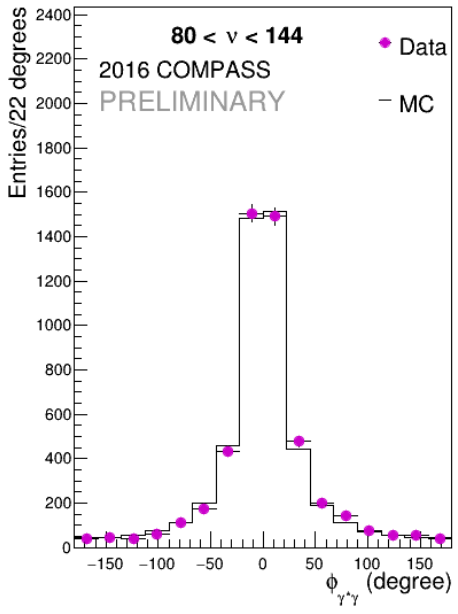


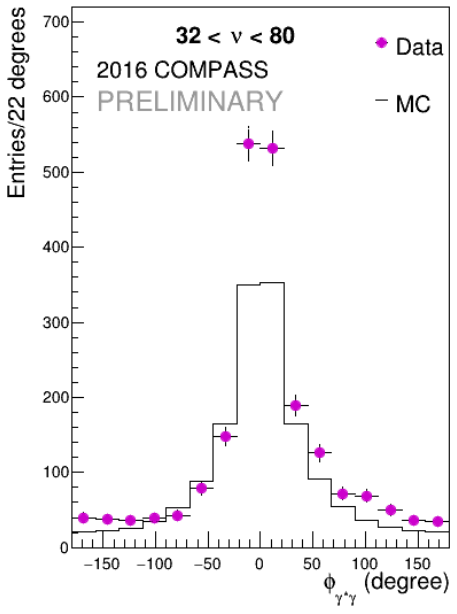


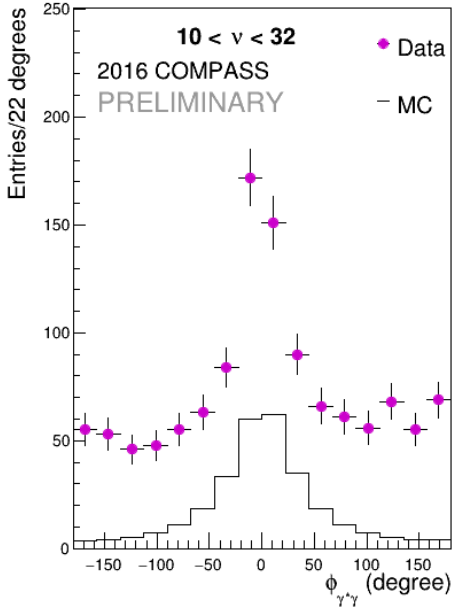
All distribution obtained with mu- beam was normalised to the same luminosity (or the same number of muons) for which distributions for mu+ beam weer obtained. At variance to 2012 DVCS pilot run (~10-15% difference) pilot run we see very good agreement.

DVCS 2016/17 progress

At the very preliminary stage of this analysis we can present the exclusive single photon events obtained as a function of for the sum of the mu+ and mu- beam contributions in 3 ranges (as for the 2012 results). The data are compared to the BH MC prediction normalized to the bin at large (80 < ν < 144 GeV).

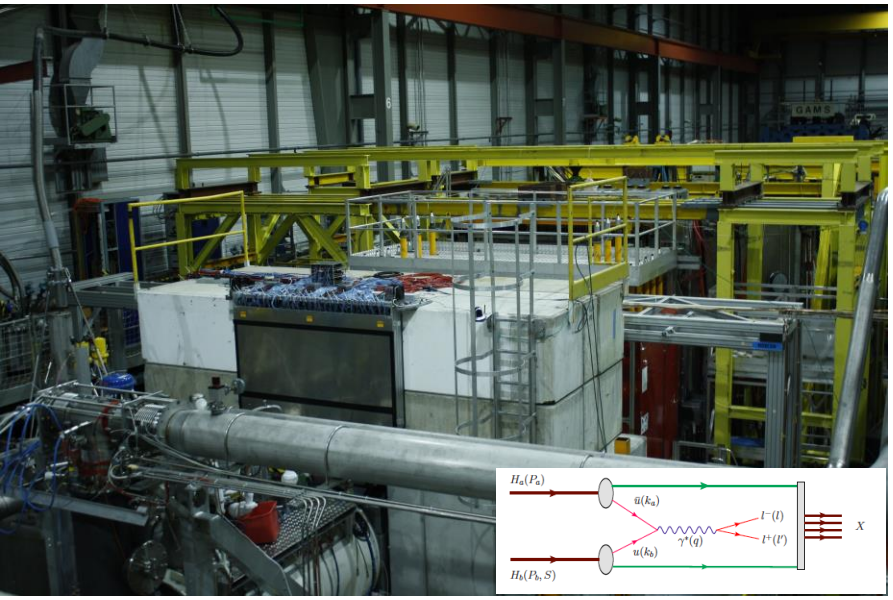






COMPASS Drell-Yan Run 2015/18 results

First ever polarised Drell-Yan data



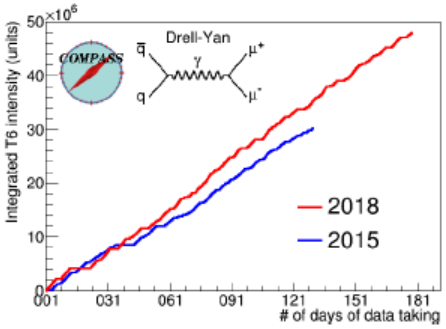
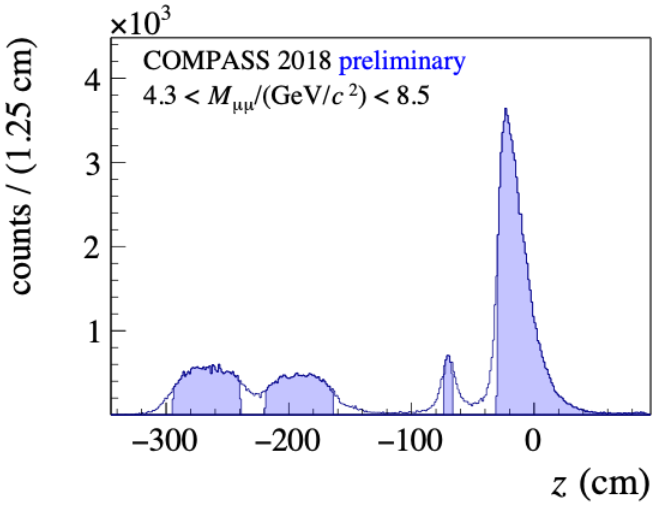


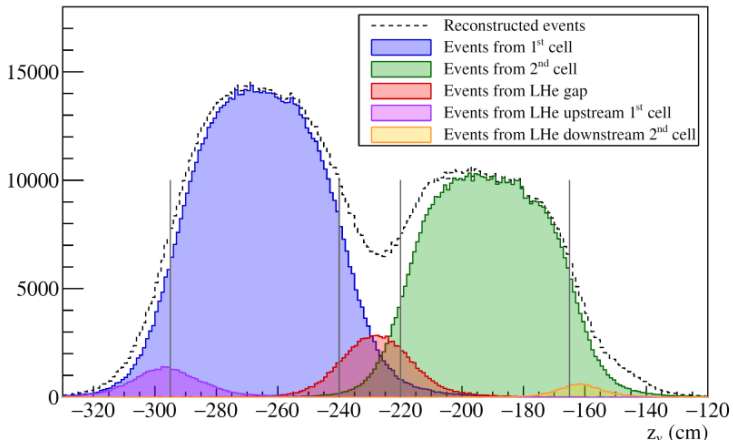
Table 2: Average polarisation in transverse mode for the four spin state configuration during 2018 and 2015 Drell-Yan runs.

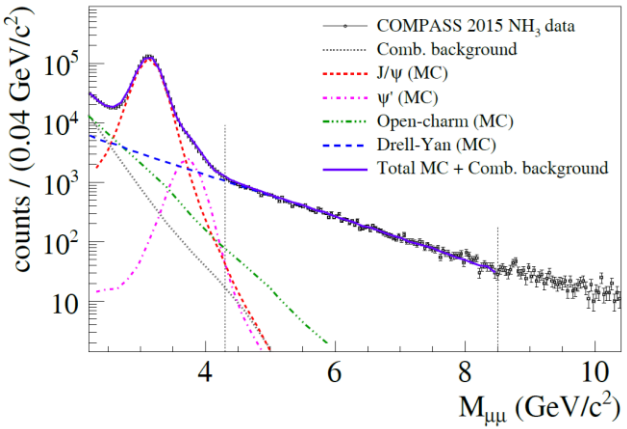
Year	upstream cell		downstream cell	
	↑	↓	↑	↓
2018	75.5%	-69.8%	72.4%	-68.4%
2015	74.2%	-71.4%	69.2%	-67.0%

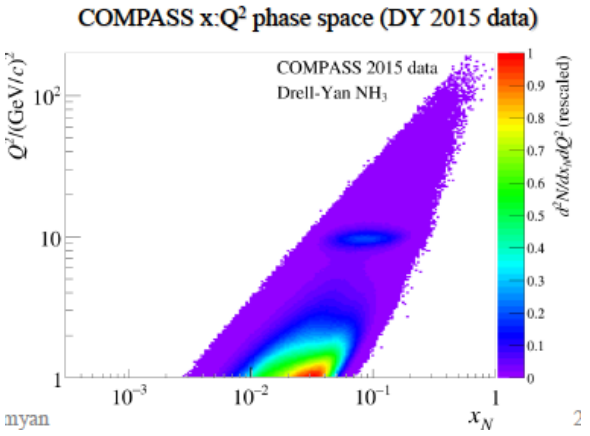
2015:
Good machine performance: on average 84%
Good spectrometer availability: ~80%
2018:
Poor machine performance: ~ 74%
Lower compared to 2015 spectrometer efficiency: ~74 %

DY@COMPASS 2015 and 2018 Run

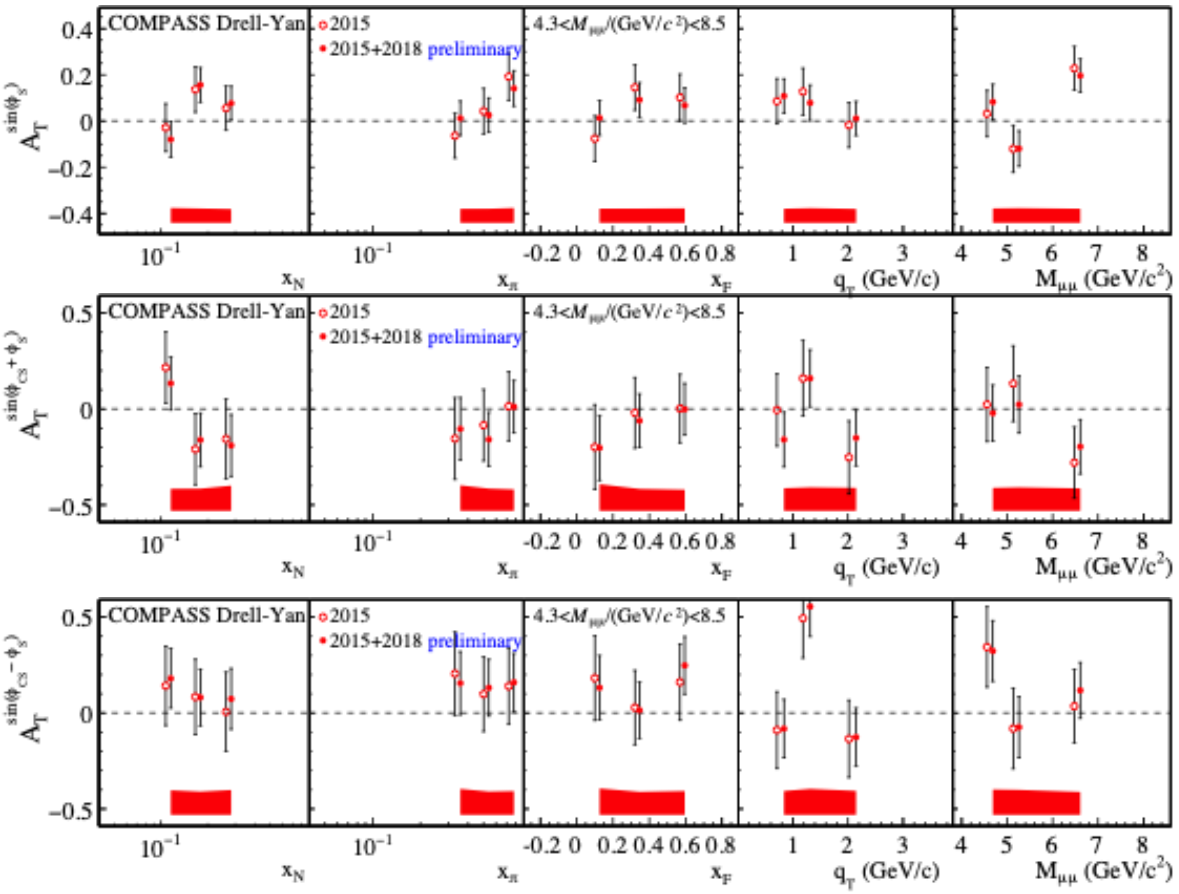


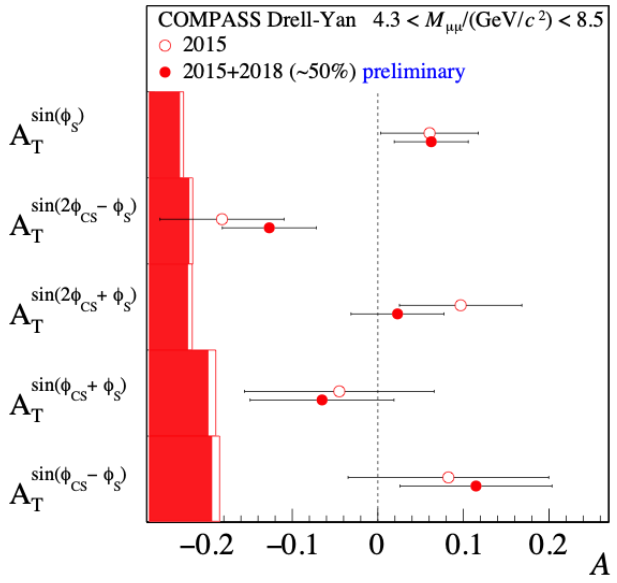






COMPASS Drell-Yan Run 2015/2018 results



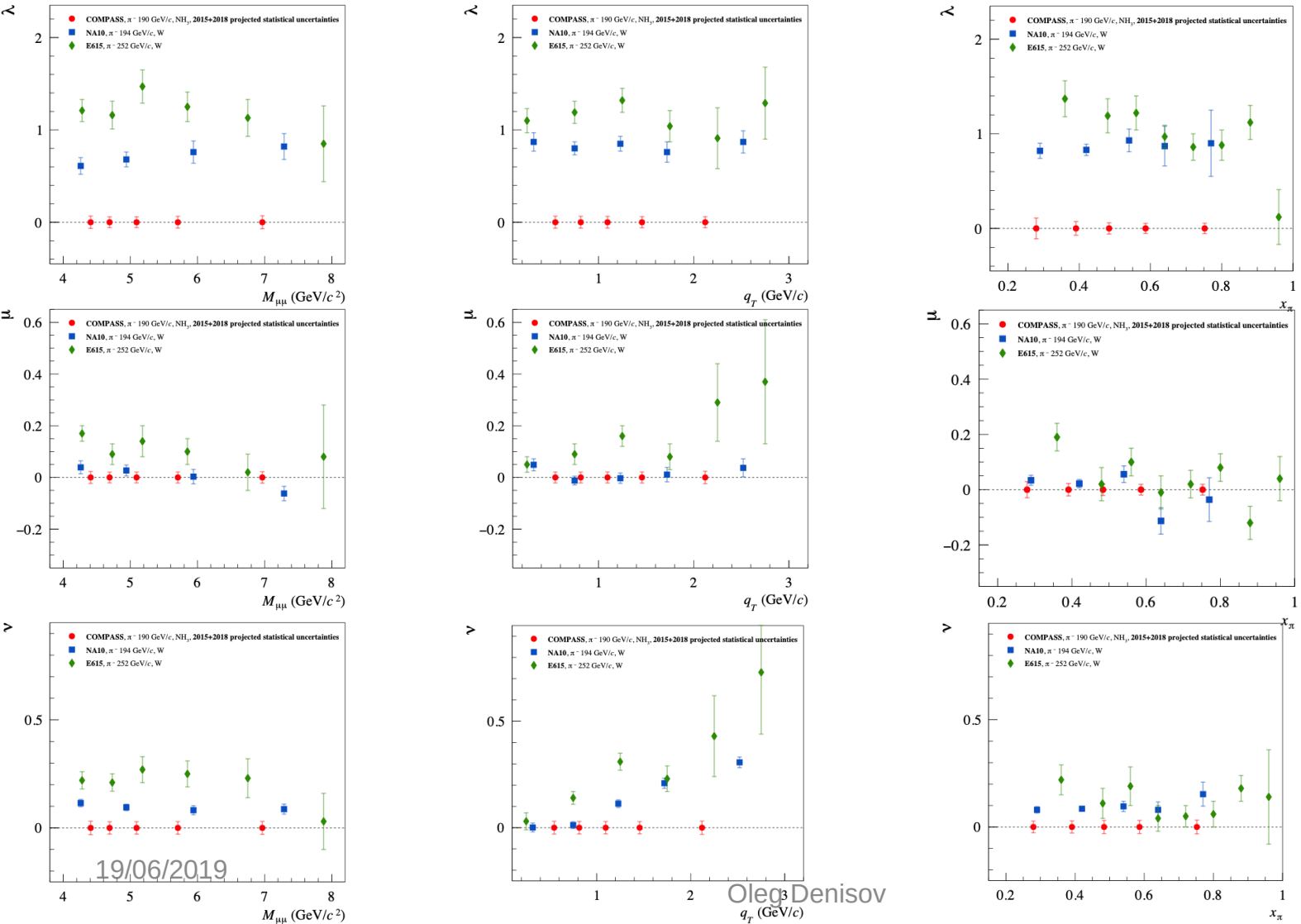


COMPASS-II preliminary
2015 + 50% 2018 results

COMPASS Drell-Yan Run 2015 results

Unpolarised data I

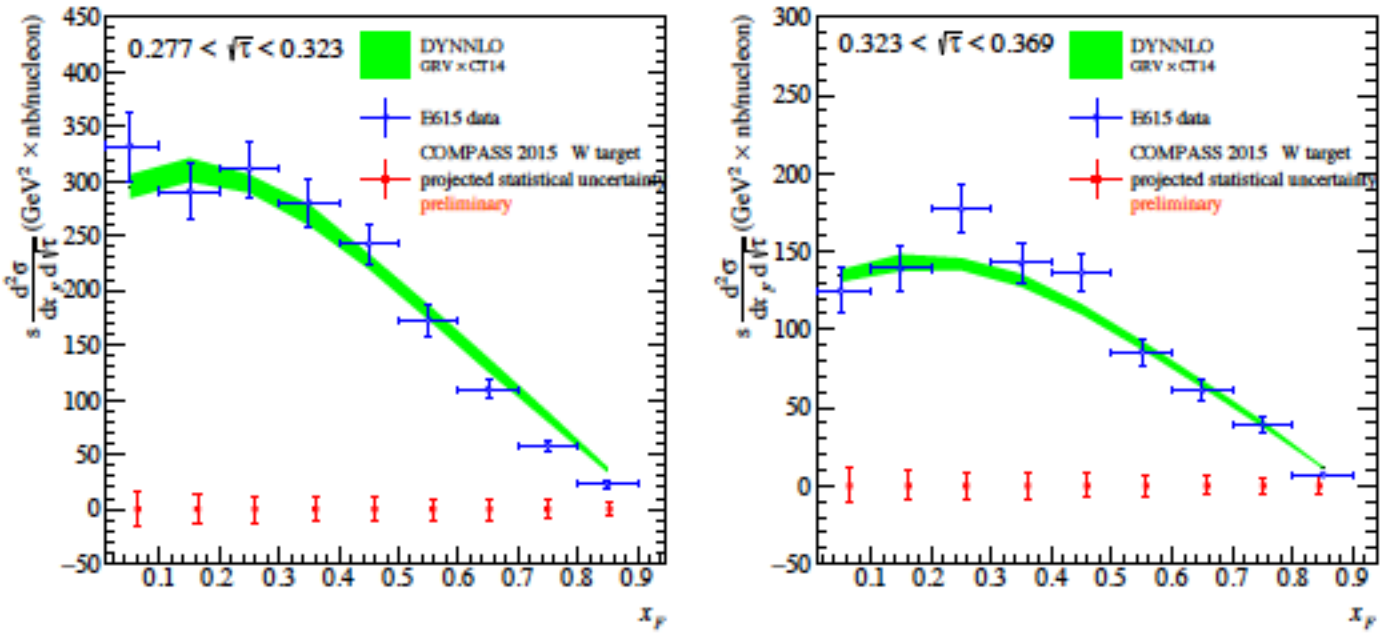
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\sin^2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$



COMPASS Drell-Yan Run 2015 results

Unpolarised data II

COMPASS-II DY absolute cross-sections, work in progress, below projections for 2015 (W)) compared to E615



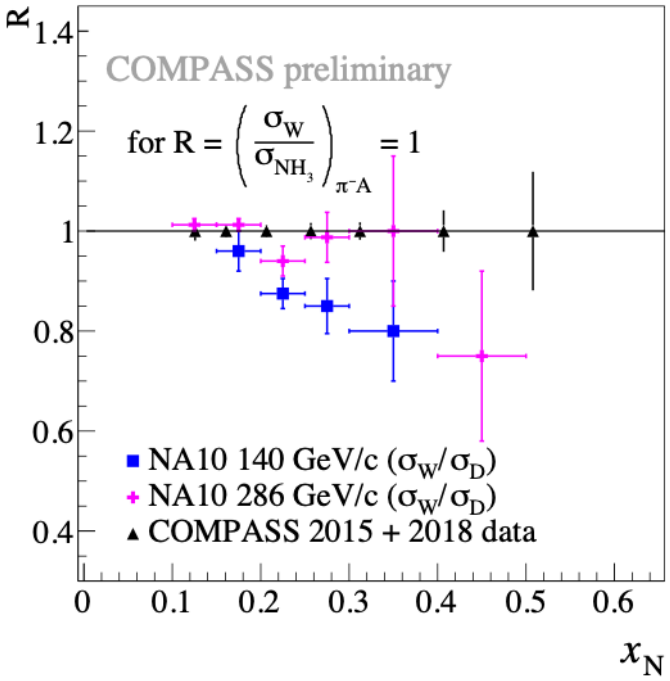
COMPASS Drell-Yan Run 2015 results

Unpolarised data III

COMPASS-II DY – nuclear effects (EMC)

The ratio $R_{\pi^- A}$ of the Drell-Yan cross-sections per nucleon for the NH_3 and W targets of COMPASS corrected for the difference in number of protons and neutrons, can be expressed as

$$R_{\pi^- A} = \frac{\sigma_W}{\sigma_{NH_3}} = \frac{\mathcal{L}_{NH_3}}{\mathcal{L}_W} k_{pn} \frac{N^W_{\mu\mu}\, Acc^{NH_3}}{N_{\mu\mu}\, Acc^W} = C \frac{N^W_{\mu\mu}}{N^{NH_3}_{\mu\mu}} \quad (8)$$



Proton Radius beam test in 2018

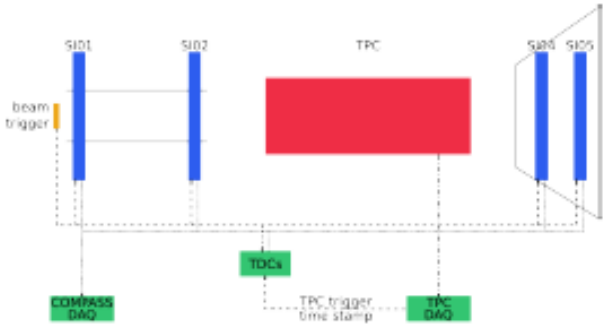
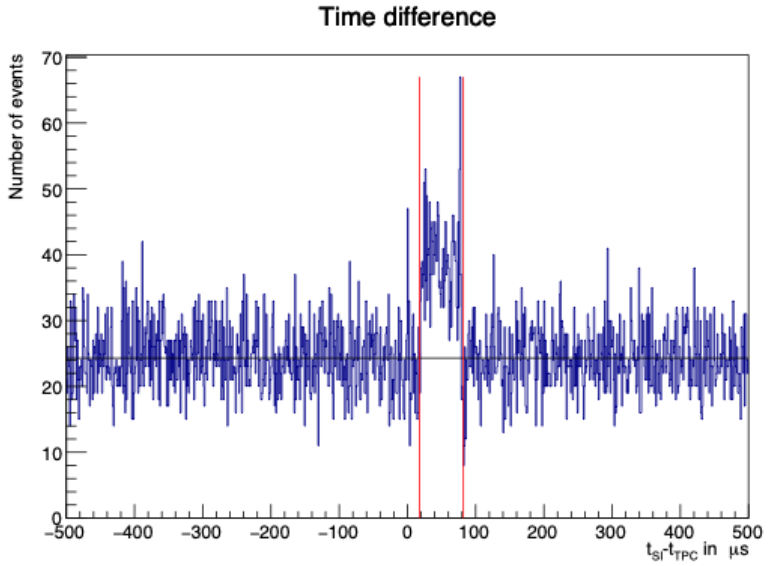
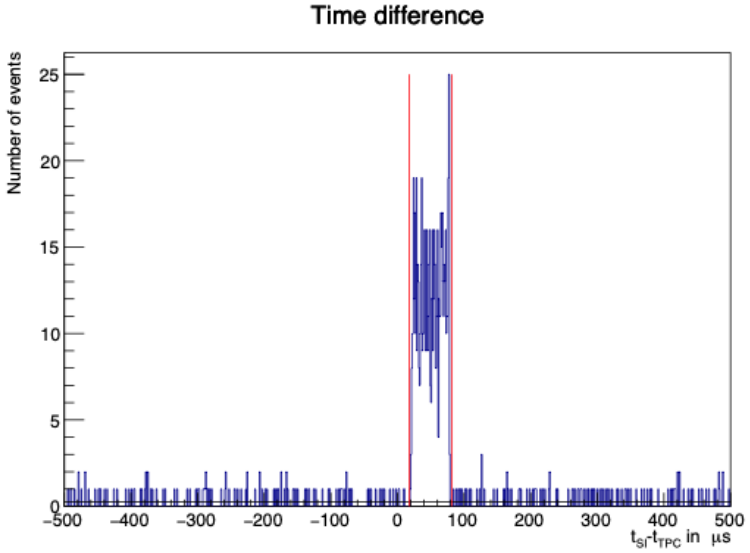


Fig. 50





Theta>=0.2 mrad and radial cuts

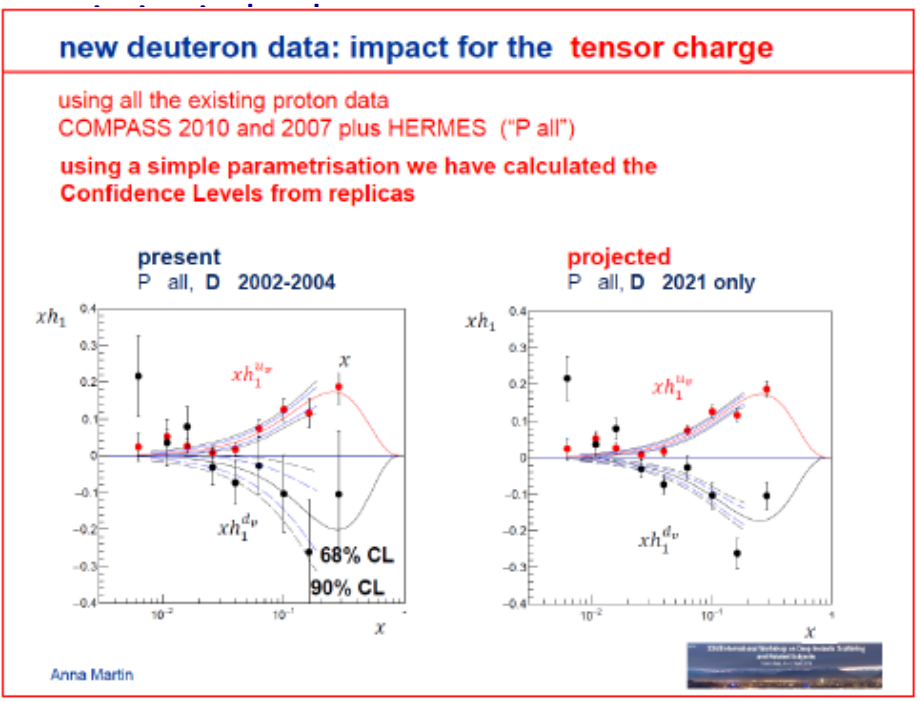
additional cuts on the z-coordinate and that the central pads of the TPC anode are hit

Masters thesis, Martin Hoffmann, Helmholtz-Institut fur Strahlen- und Kernphysik, Universitat Bonn

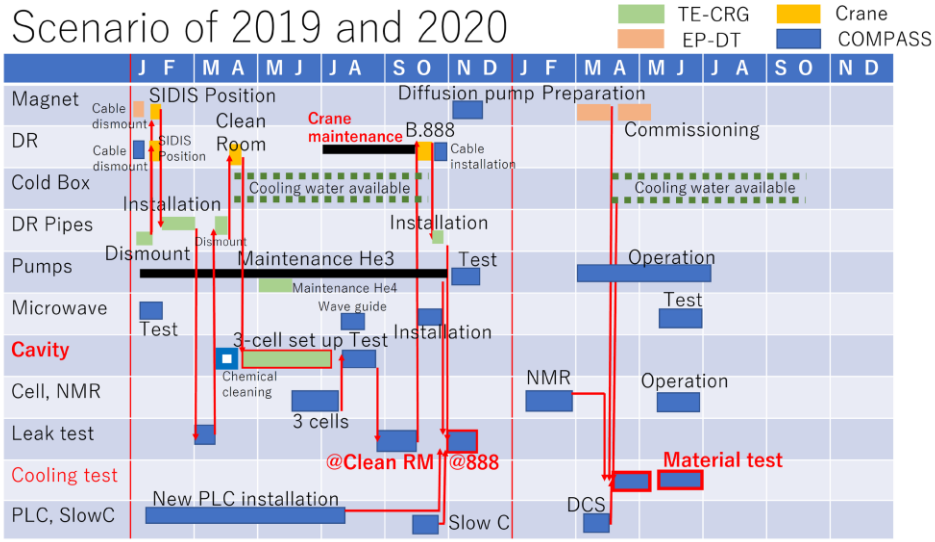
COMPASS deuteron run in 2021

One year of data taking with muon beam and transversely polirased deuteron target was Approved by CERN RB in June 2018 (150 days of running).

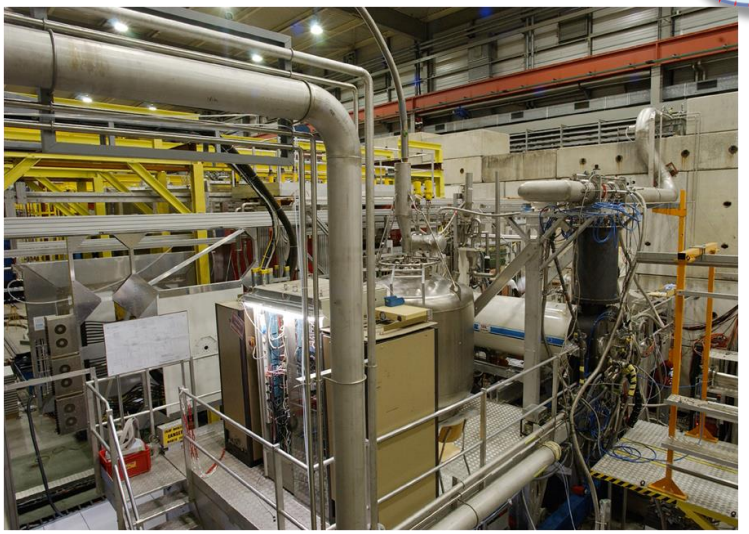
Motivation: COMPASS has very unbalance data set on TP targets: deuteron data set
Is almost order of magnitude smaller compared to proton. In order to extract flavour separated
TMDs, Transversity and to constrain tensor charge one has to have approximately equal



Hardware-wise the most "heavy" activity to be carried out is a COMPASS PT preparation.



Change over for 2021 SIDIS Deuteron Run run



Jan 2019: Target platform movement
Feb-April 2019: Target pipes/cables installation
HM04/HM05 position adjustment
PA03/PA05 refurbishment
May 2019: DR removal, 3 cell modification
June 2019: cavity test, DR reinstallation,
DC5 transport to clean area,
SciFi 4 reinstallation
Aug-Sept. 2019: crane renovation
Sep. 2019: repair loose wire DC5 Y2
Oct. 2019: start RICH Wall refurbishment
Dec. 2019: DC4 to clean area for repair

Summary

- Analysis are going on for all research lines: Spectroscopy, SIDIS, Drell-Yan and GPDs

- Preparations for 2021 are well on track

Thank you!

SPARES