Outline

1. **Hadron structure and excited states**
   - Light quark spectroscopy
   - Heavy state X(3872)
2. **Nucleon structure with muon beam**
   - Longitudinal spin structure functions
   - Azimuthal asymmetries transverse/longitudinal
   - Multiplicities
3. **Results from the DVCS 2012 Pilot Run**
4. **Polarised Dell-Yan Run 2015**
5. **The 2016/17 GPD and SIDIS Run**
6. **DVCS statistics – 2016 projection**
7. **Request for a Drell-Yan Run in 2018**
8. **Beyond 2020 Workshop**
9. **Summary**

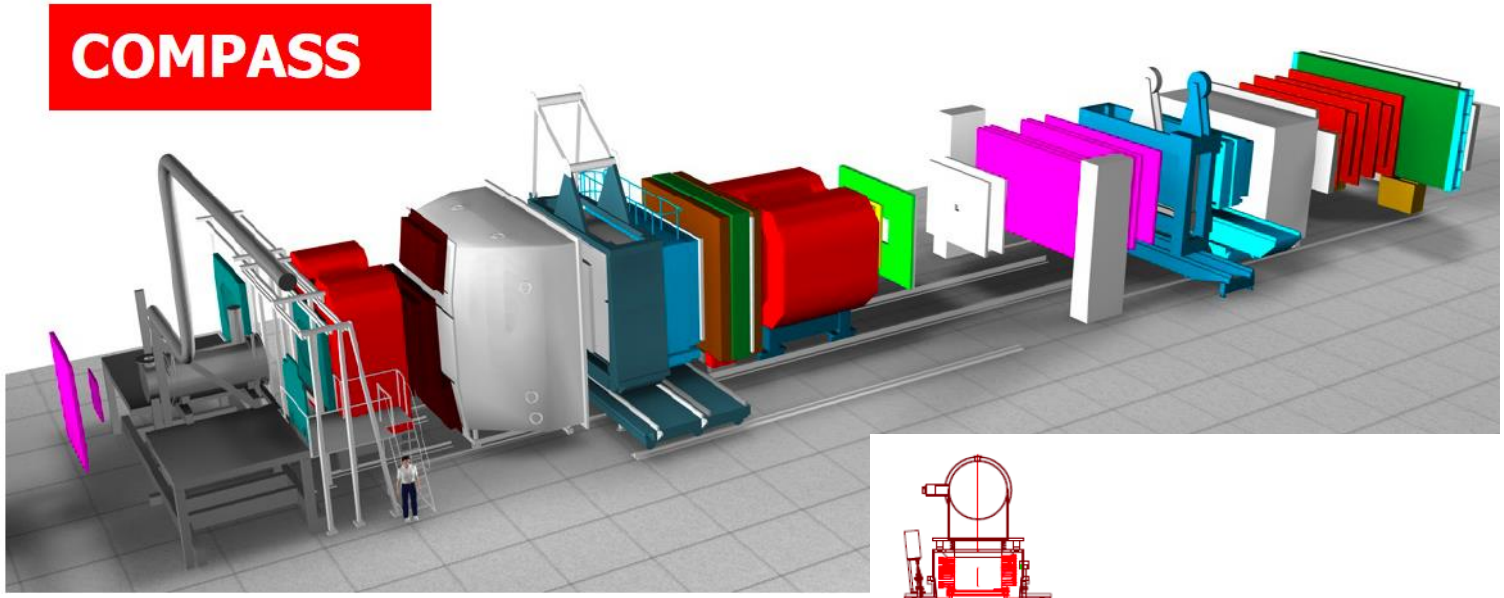
Time constraints - this talk is not covering central production, pion polarisability, weighted asymm., Sivers in DY range……(Annual report + spare slides)

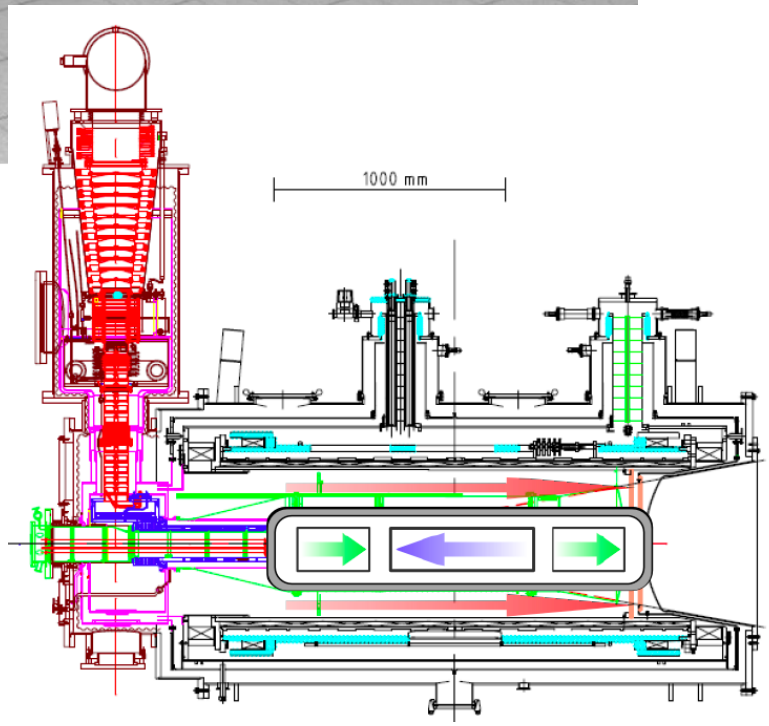
COMPASS QCD facility at CERN (SPS)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

~240 physicists, 12 countries + CERN, 24 institutions

COMPASS Spectrometer at SPS M2 beam line (CERN)



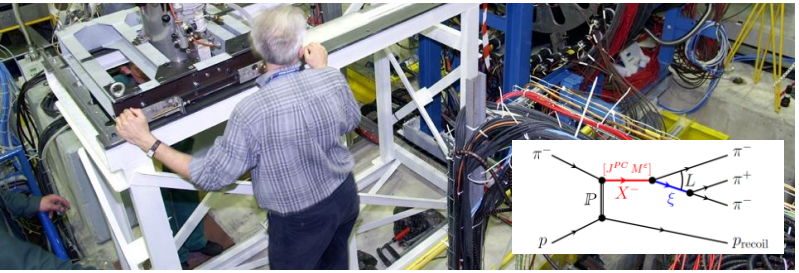


Universal and flexible apparatus.
Most important features of the two-stage COMPASS Spectrometer:

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)

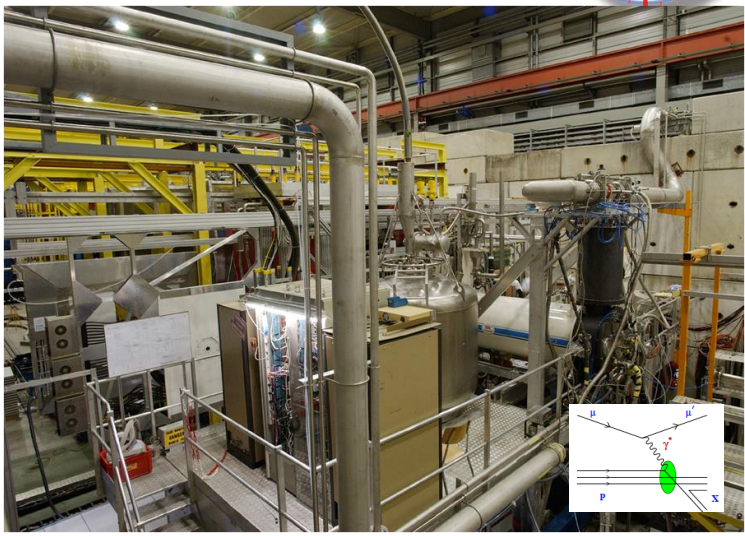
COMPASS QCD facility at SPS M2 beam line (CERN)
(secondary hadron and lepton beams)

Exotic state, chiral dynamics



Hadron Spectroscopy & Polarisability

COMPASS-I
1997-2011

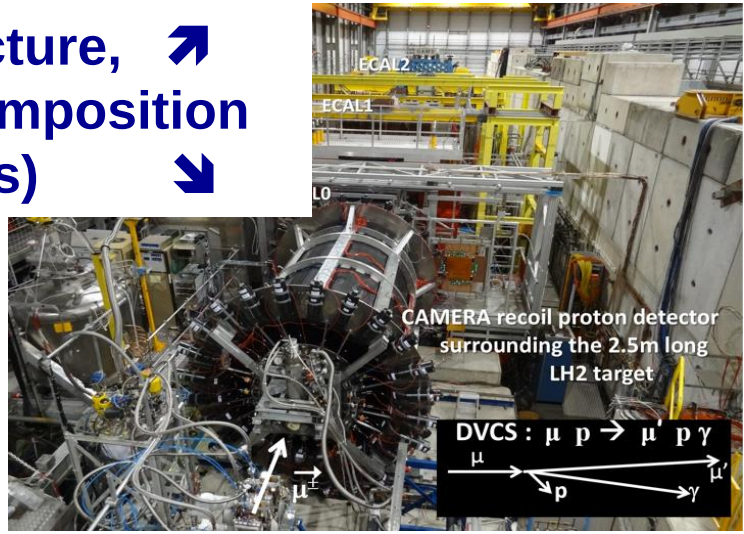


Polarised SIDIS

Polarised Drell-Yan

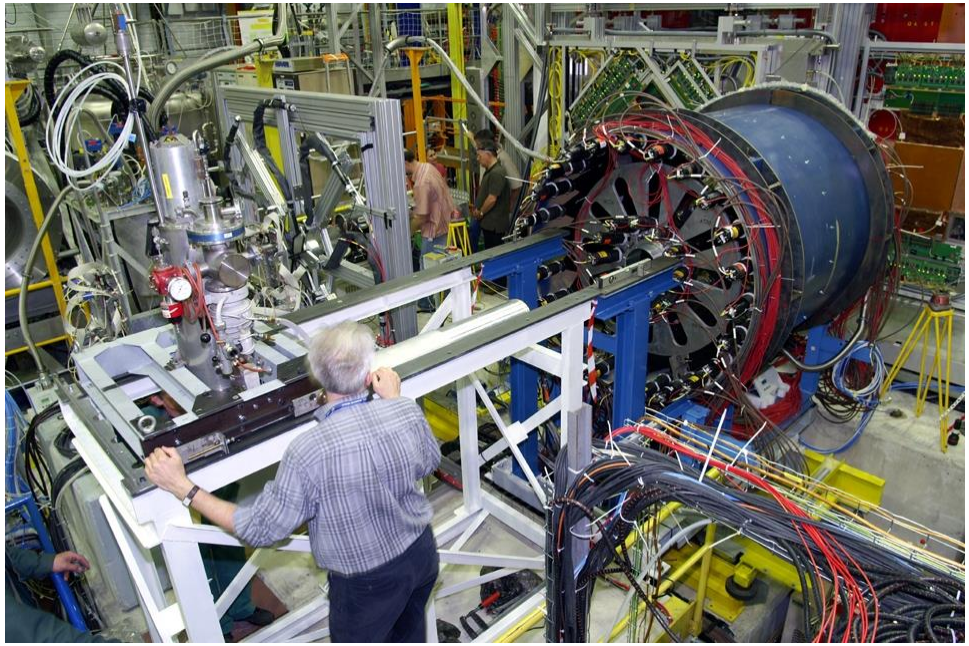
3D hadron structure,
Proton spin decomposition
(spin crisis)

COMPASS-II
2012-..



DVCS (GPDs) + unp. SIDIS

Diffractive dissociation I

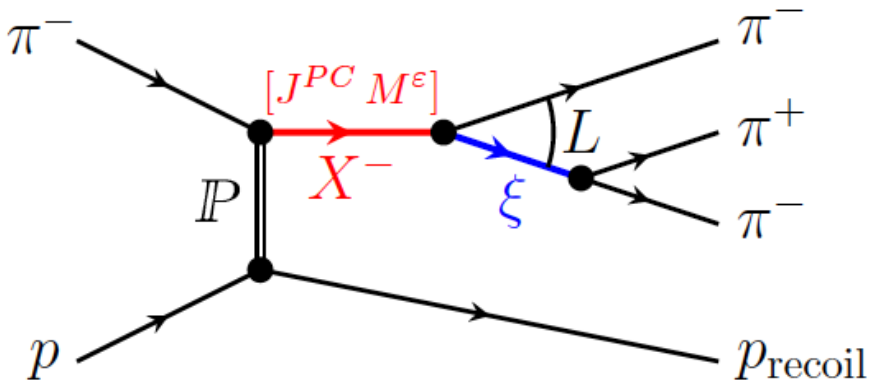


2008-2009 data taking, 190 GeV/c hadron beam on a hydrogen target.

3π data sample ~50x10^6 exclusive events – factor 10 to 100 to previous experiment

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

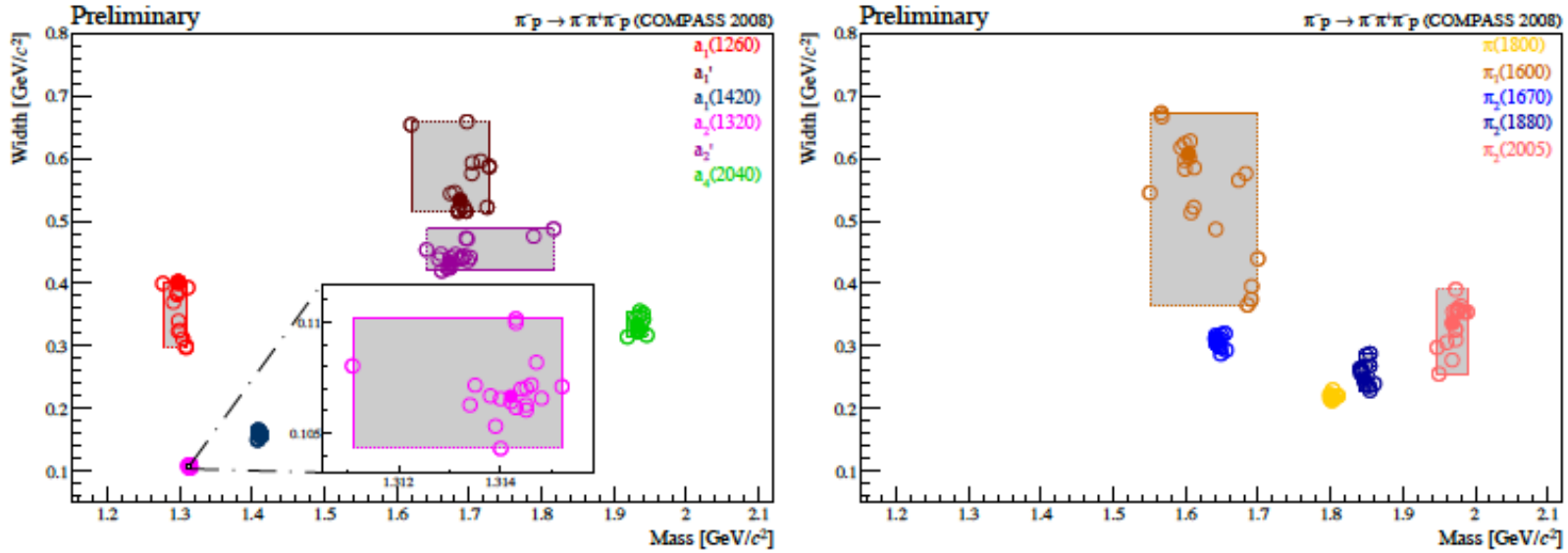
A lot of work to be invested to develop new methods in order to cope with huge data sample.



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)

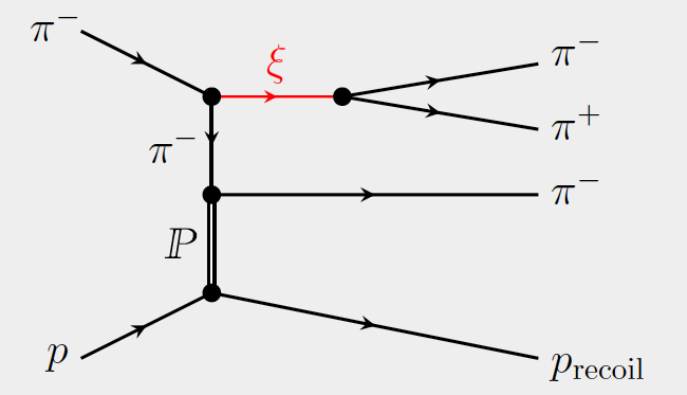
Diffractive dissociation II

Statistical uncertainties are negligible compared to systematic ones. Extensive studies were performed to estimate the systematic uncertainties by varying the fit model. For all 14 selected p.w. most of resulting resonance parameters are in agreement with PDG averages, so we are confident in our method.



Left – *a*-like mesons, right – *π*-like mesons.
Plotted – closed circles – best fit parameters, rectangles – systematic uncertainties for 11 resonant components used in the resonance-model fit to the spin-density matrix of selected 14 waves

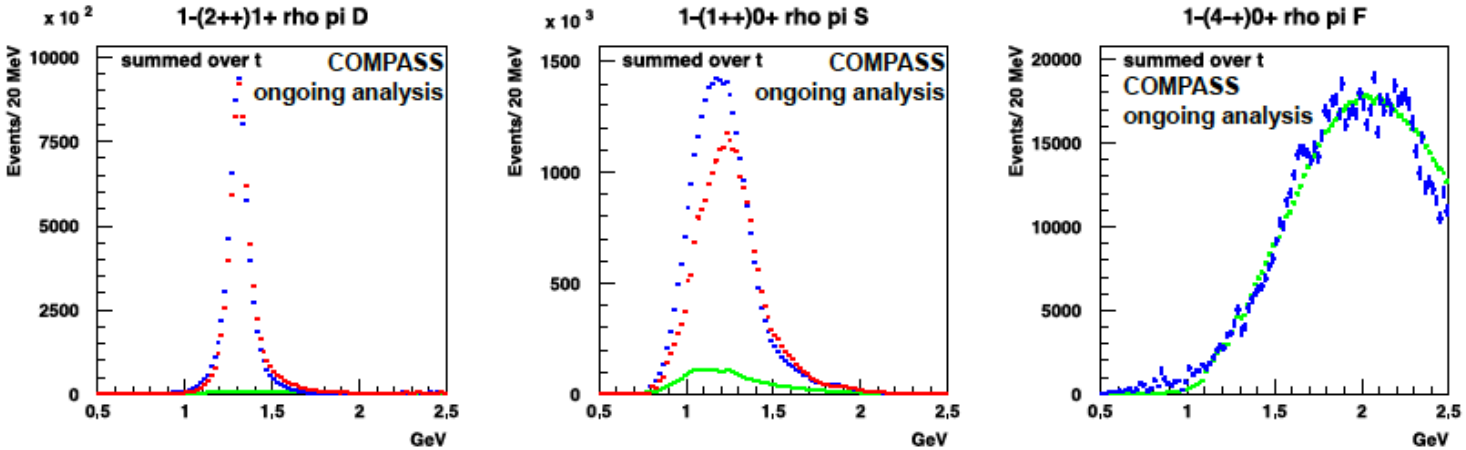
Diffractive dissociation III



Non-resonant contribution – main contributor to systematic. Believed it is caused by pion fluctuation into $\pi^+\pi^-$ isobar (ρ(770)) and virtual π – Deck amplitude. It projects in many waves.

Deck amplitude was introduces in the mass-independent fit (very promising): blue – no Deck, Red + Green – (resonant + Deck)

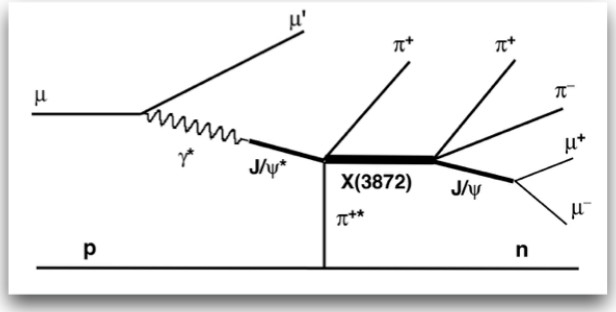
- low non-resonant contribution - stays unchanged (a)
- considerable fraction of non-resonant contribution – absorbed into Deck amplitude (b)
- high spin waves – Deck contribution absorbs all intensity (c)



(a) (b) (c)

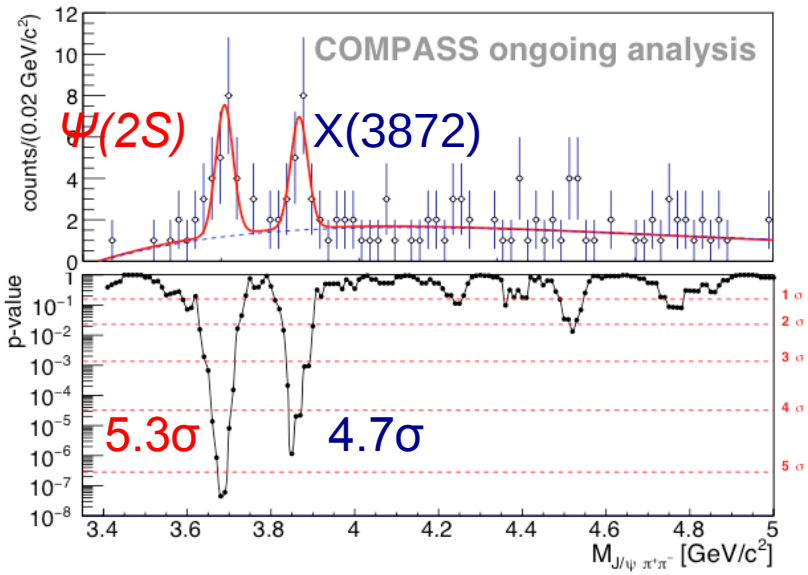
Exotic X(3872) lepto-production

X(3872) is the first charmonium-like exotic hadron discovered by the Belle collaboration in 2003 and studied than in other experiments. Various interpretations exists: tetraquark, *DD**-molecule, hybrid *ccg* state, glueball or else.
Additional information on its width would help to shed light on its nature.



COMPASS muon beam data 2003➔2010
Study $J/\psi\pi^+\pi^-$ subsystem of exclusive final state $J/\psi\pi^+\pi^-\pi^\pm$

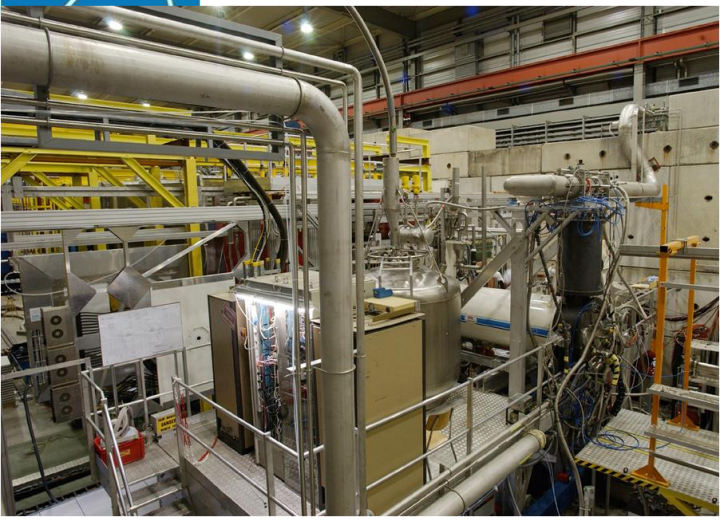
In order to estimate the width of X(3872):
-we use *ψ(2S)* as a reference signal,
-we assume that production mechanism is the same (CEX) and
-we neglect the phase space and acceptance difference
-we profit of the known parameters of *ψ(2S)*



$\Gamma_{X(3872)\to J/\psi\pi\pi} < 210$ keV at 90% conf. level, and $\Gamma_{X(3872)} > 80$ keV,
This is first ever X(3872) observation in lepto-production

(SI)DIS longitudinal I

Deuteron 2006 $Q^2>1$

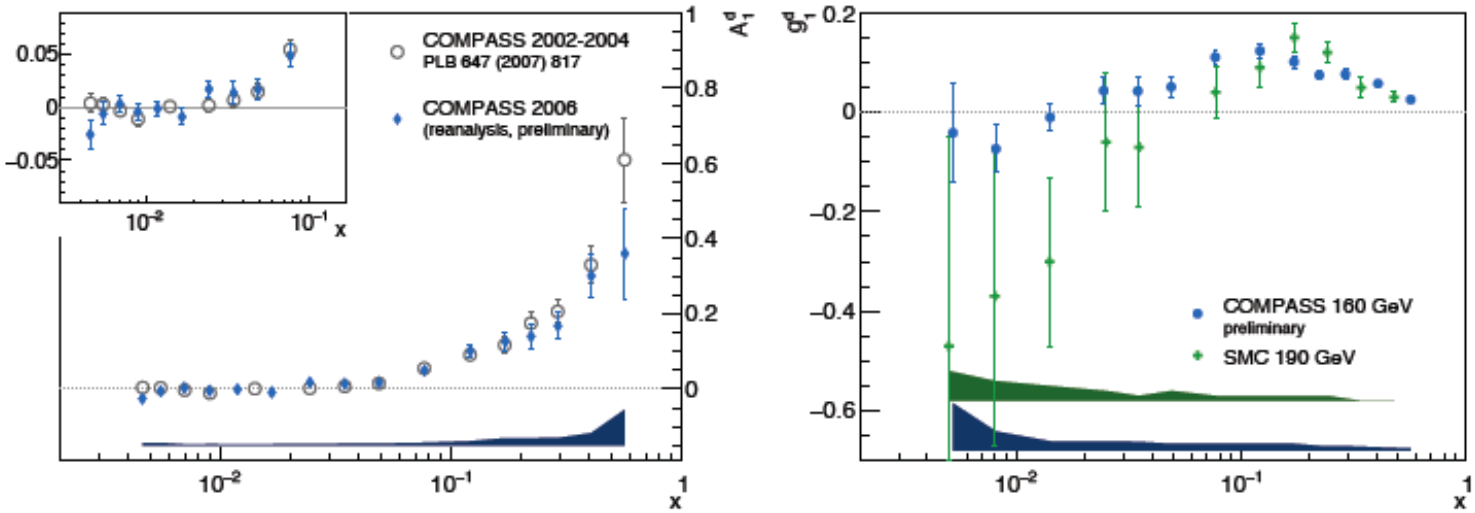


The 2006 data ~ 2002–2004.

Now we have final COMPASS deuteron data set (2002-2004, 2006) for double spin asymmetry A_1^d and longitudinal spin structure function g_1^d (global NLO fit).

The x-dependence of g_1^d do not support large negative values of the structure function at low x seen by SMC.

Publication is well advanced (final g_1^d results)



(SI)DIS longitudinal II

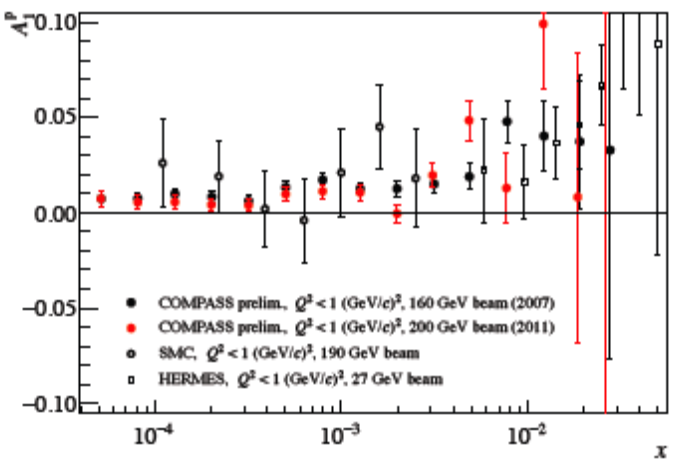
Proton 2007 and 2011 $Q^2 < 1$

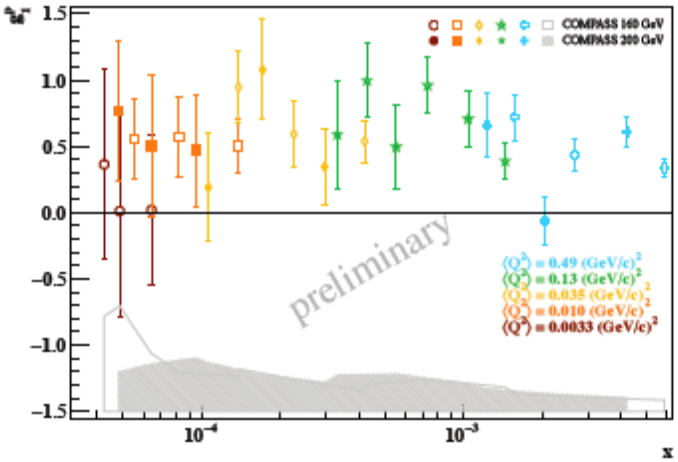
Large gain in the precision (see A_1^p for both data).

Small, nearly constant asymmetry of about 1% at small x.

The resulting values for g_1^p will be published in various binnings, e.g. x, Q^2 and ν, x for comparison with theory predictions.

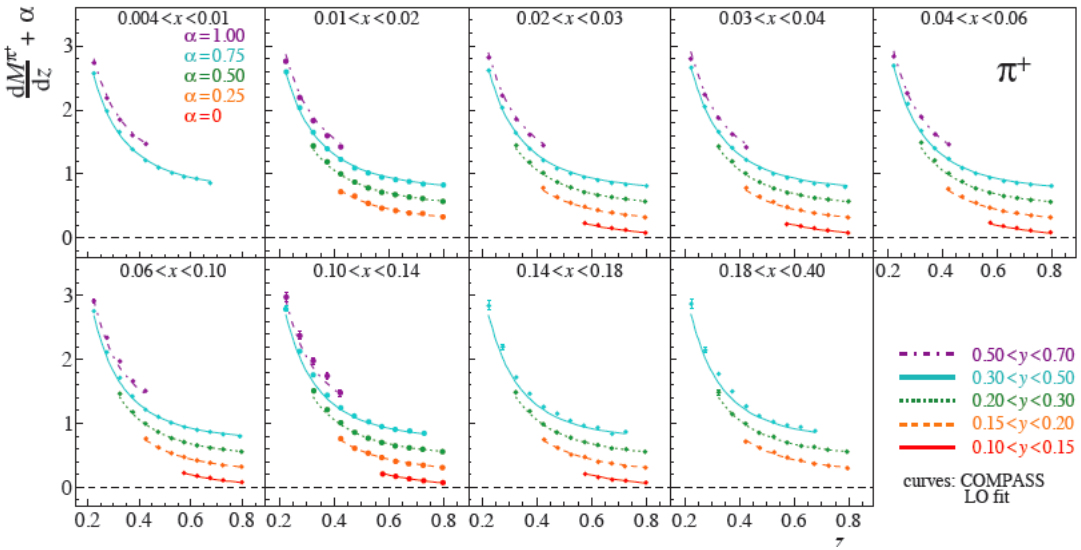
The paper preparation is ongoing.

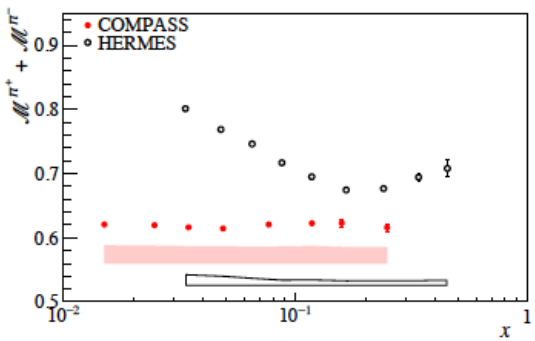


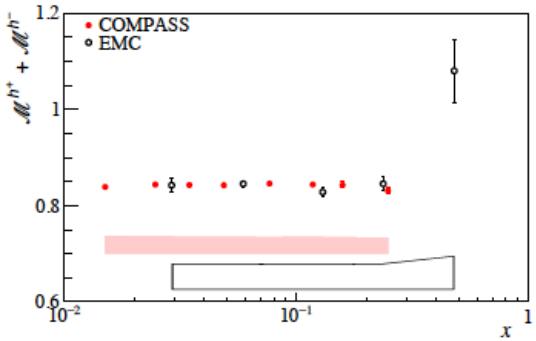


SIDIS multiplicities

Charged pion and unidentified hadron multiplicities (2006 160 GeV ^{6}LiD) – submitted to PLB. Very positive reaction by referees. The 3-dimensional data set (*x*, *y* and *z*) ➔ an important input for future NLO pQCD analyses of world data in terms of FFs.





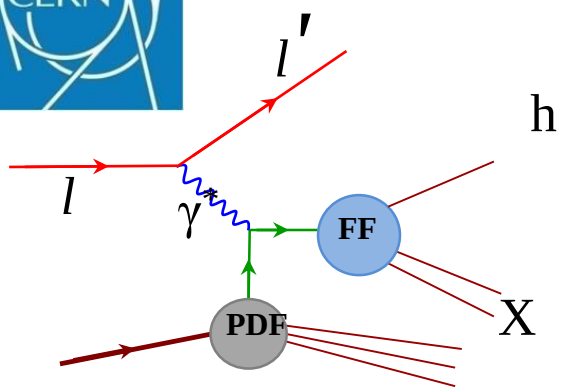


Comparing COMPASS data with HERMES and EMC:
EMC - excellent agreement
HERMES – there is a discrepancy, may be because of the different energy and different kinematics.

Charged kaon multiplicities: the same data set (6 weeks of 2006) – publication in preparation;

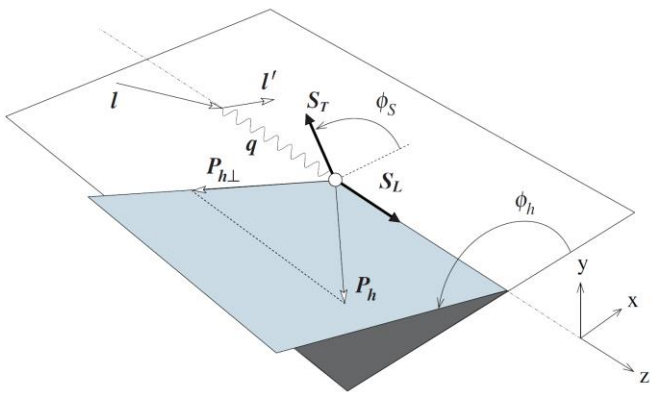
Neutral kaon multiplicities: (6 weeks of 2006 and 2012 pure LH_2 target) – first results are obtained, systematic studies are going on.

SIDIS transverse&longitudinal I



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

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

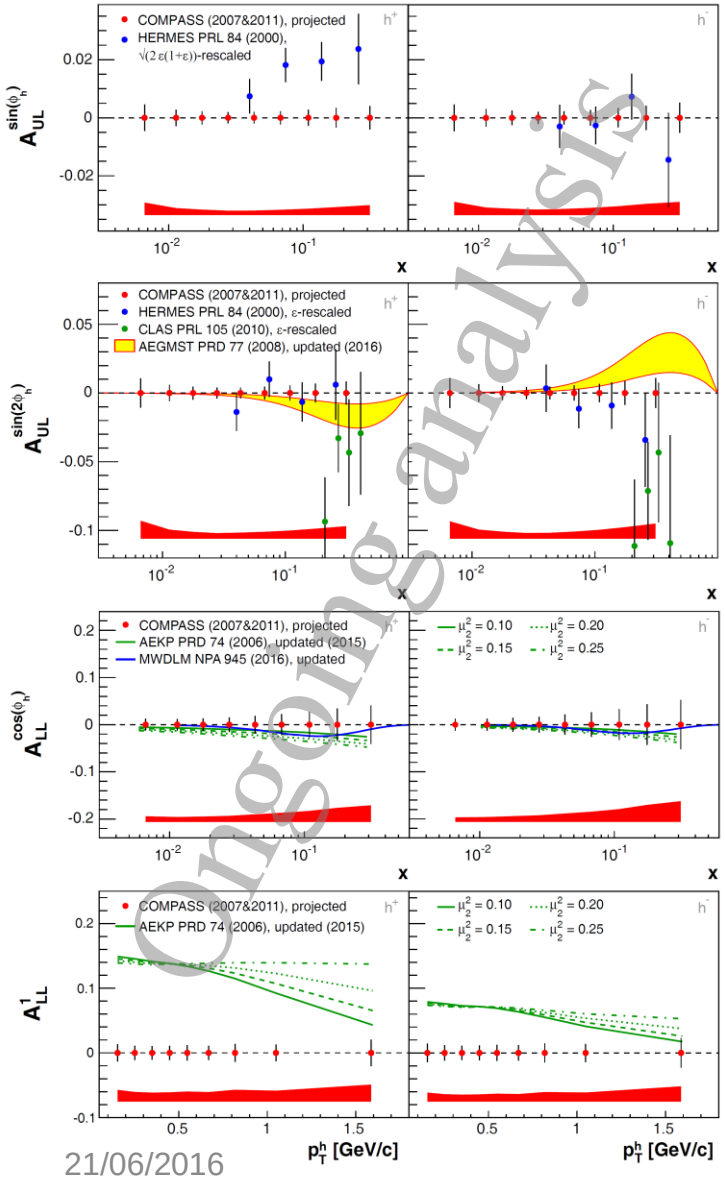


LO LSA/TSA	twist-2: PDF ⊗ FF
$A_{UL}^{\sin(2\phi_h)}$	$h_{1L}^{\perp q}\otimes H_{1q}^{\perp h}$
A_{LL}	$g_{1L}^{q}\otimes D_{1q}^{h}$
$A_{UT}^{\sin(\phi_h-\phi_S)}$	$f_{1T}^{\perp q}\otimes D_{1q}^{h}$
$A_{UT}^{\sin(\phi_h+\phi_S-\pi)}$	$h_{1}^{q}\otimes H_{1q}^{\perp h}$
$A_{UT}^{\sin(3\phi_h-\phi_S)}$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

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&longitudinal II

longitudinal target spin-dependent asymmetries (LSA)



So far we have published only deuteron LSAs (data 2002-2004)

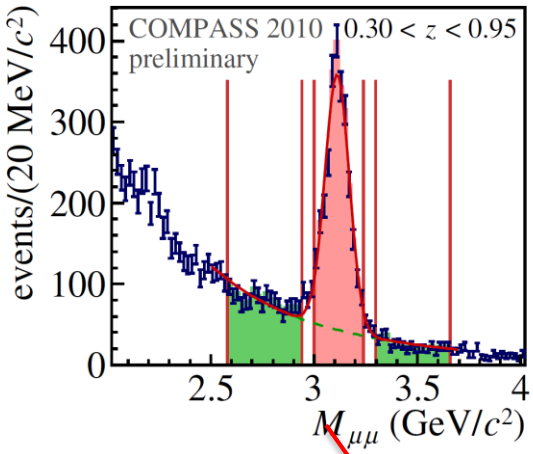
Here is a first look at the longitudinally polarised proton target (2007 and 2011 Runs).

Only statistical errors are shown, expected precision is much higher compared to the results obtained by HERMES and CLAS collaborations.

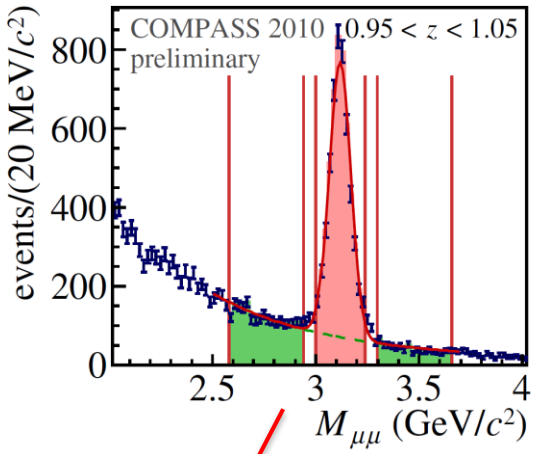
SIDIS transverse

NEW analysis topics: Gluon Sivers asymmetry using J/ψ

Inclusive

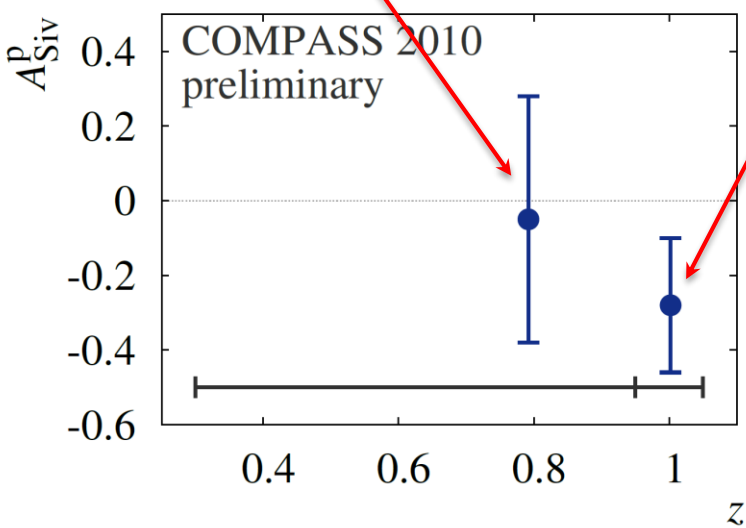


Exclusive

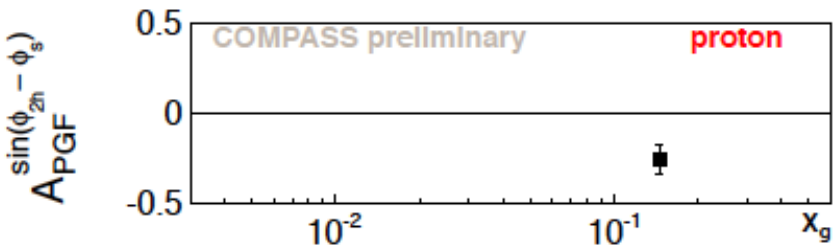


2010 transverse proton Run

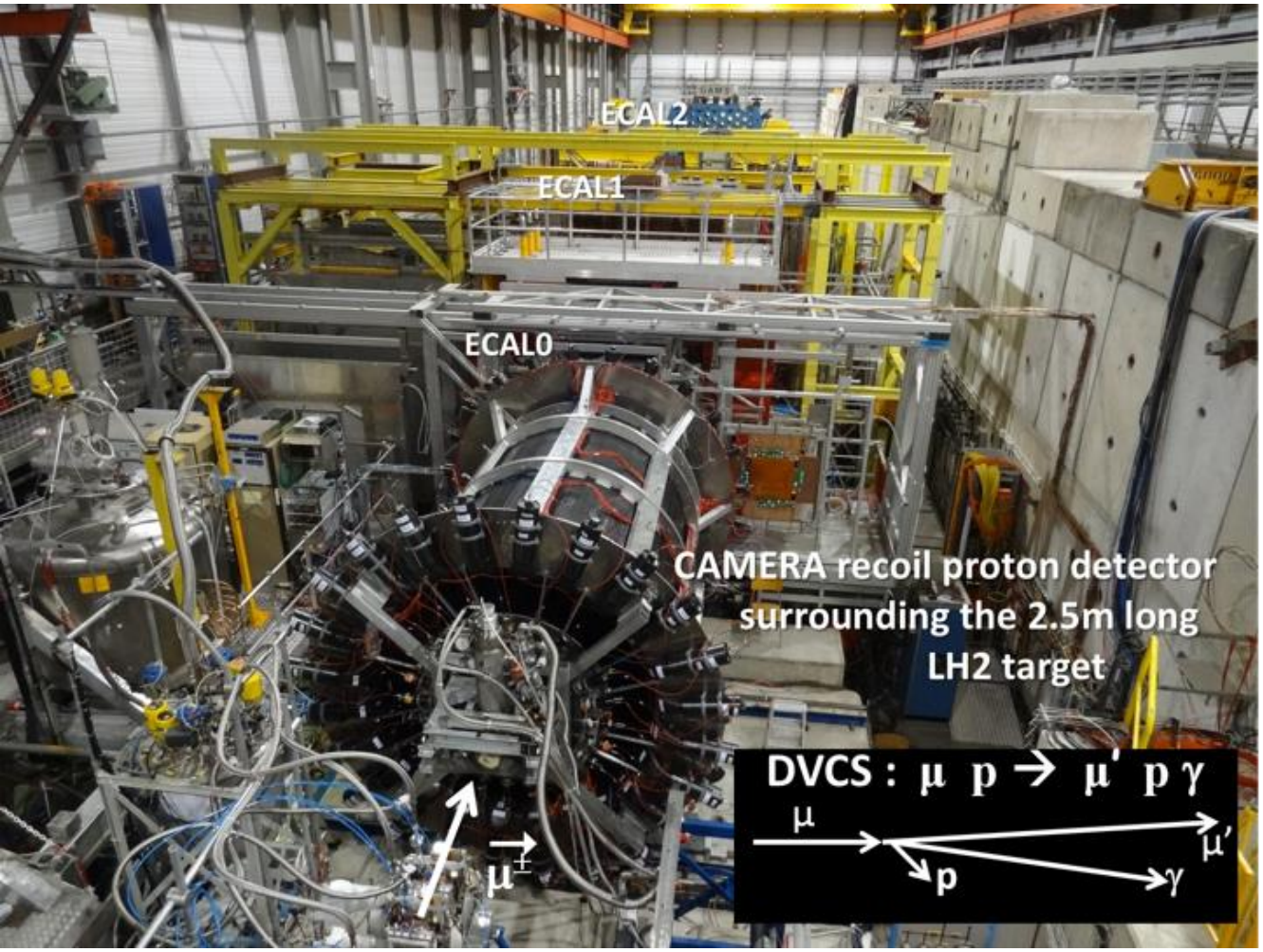
$$\mu\, p \longrightarrow \mu'\, J/\psi\, X$$



Previously published gluon Sivers asymmetry - opposite-sign di-hadron high-p_T sample were used, 2010 transverse proton Run.

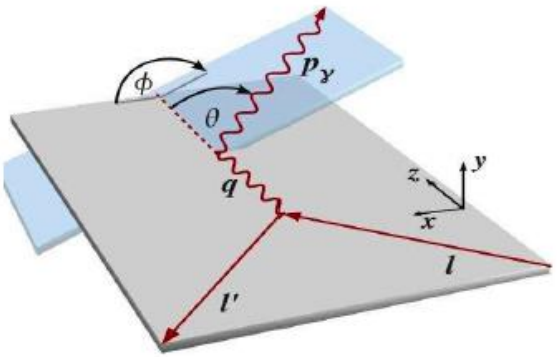


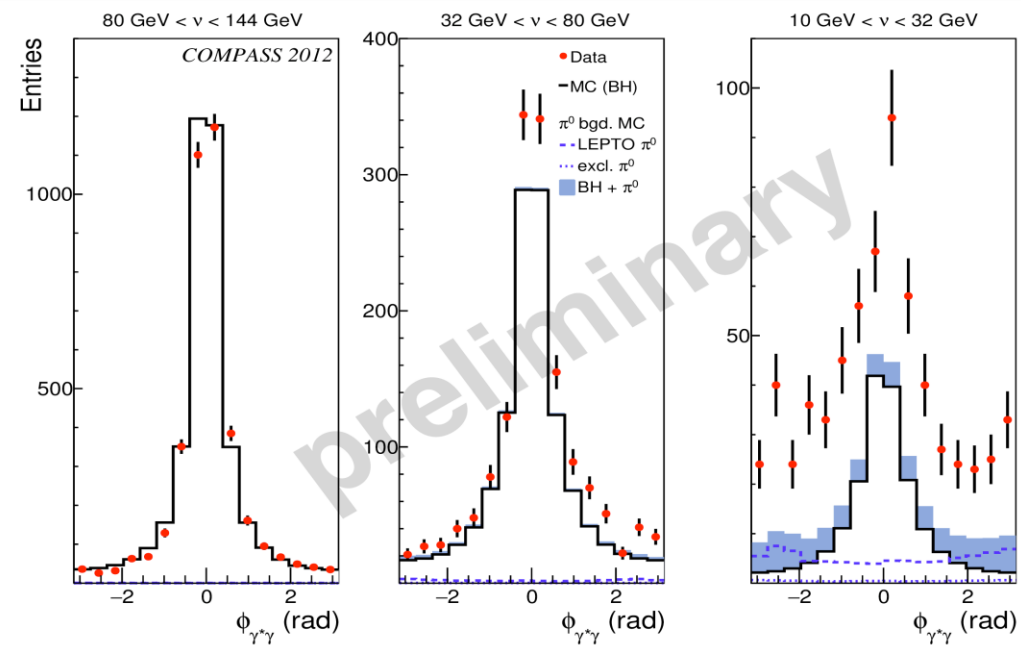
DVCS 2012 results I



2012, 20 days long data taking, 160 GeV pion beam for calibration, μ^+ and μ^- for physics, 2.5 meters long LH_2 target

DVCS 2012 results II



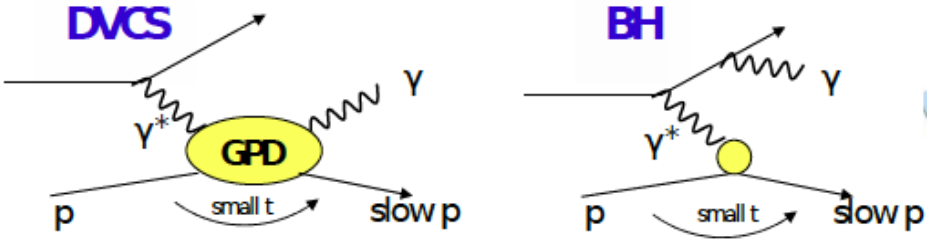


t-dependence of DVCS x-section

- Exclusive γ event selection
- π^0 bgd. estimation
- Kinematic fit
- Acceptance corrections
- Cross-section ($\gamma^* p \to \gamma p$)

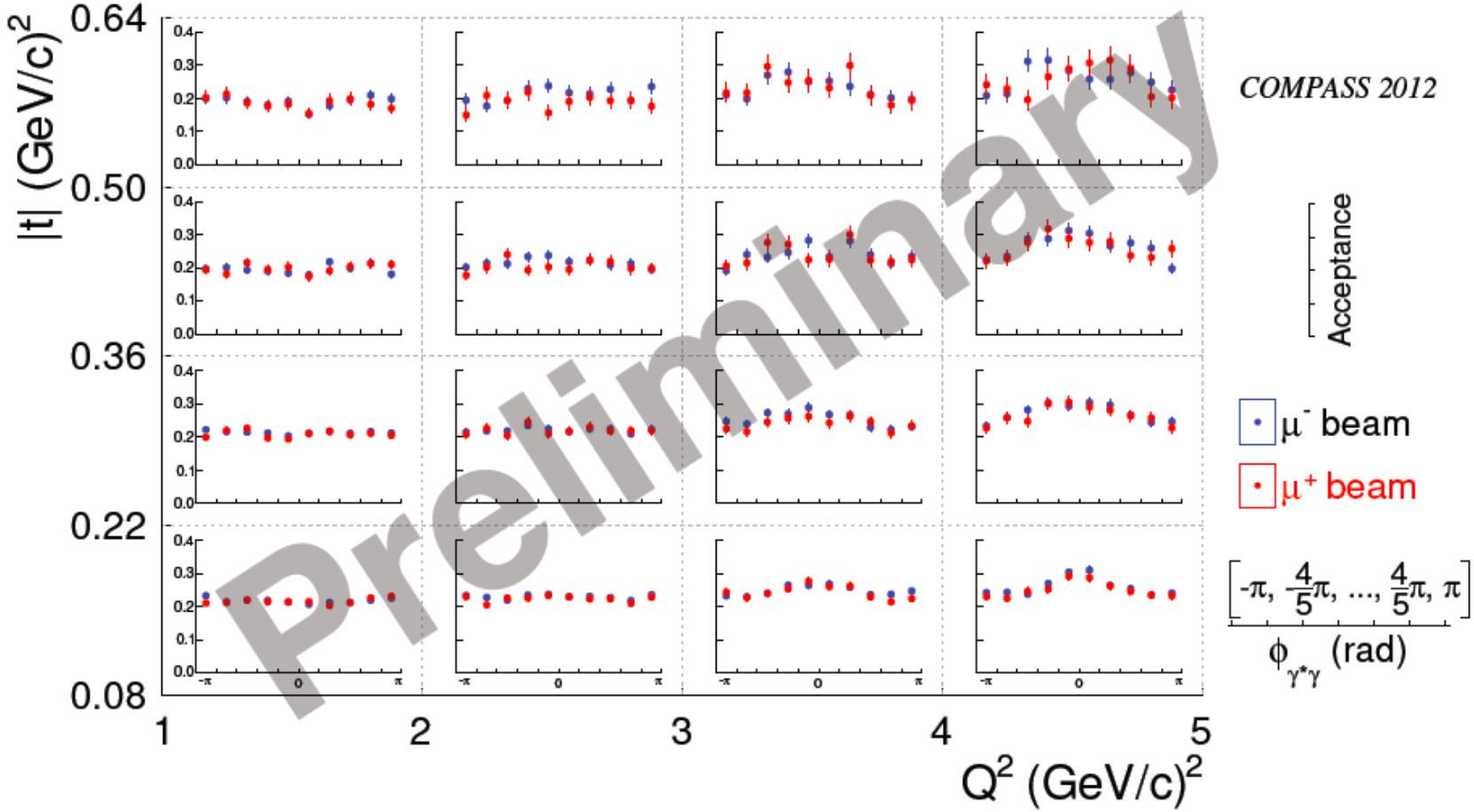
$\Downarrow$

Two competing processes (Bethe-Heitler and DVCS)
Contribute differently in the different *x(ν)*-ranges



DVCS 2012 results III

COMPASS acceptance for DVCS: rather smooth and symmetric in $\phi_{\gamma^*\gamma}$

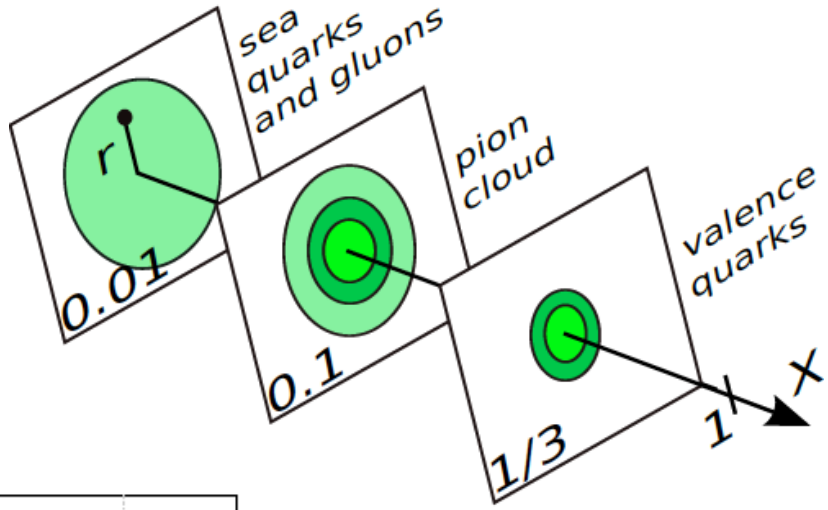


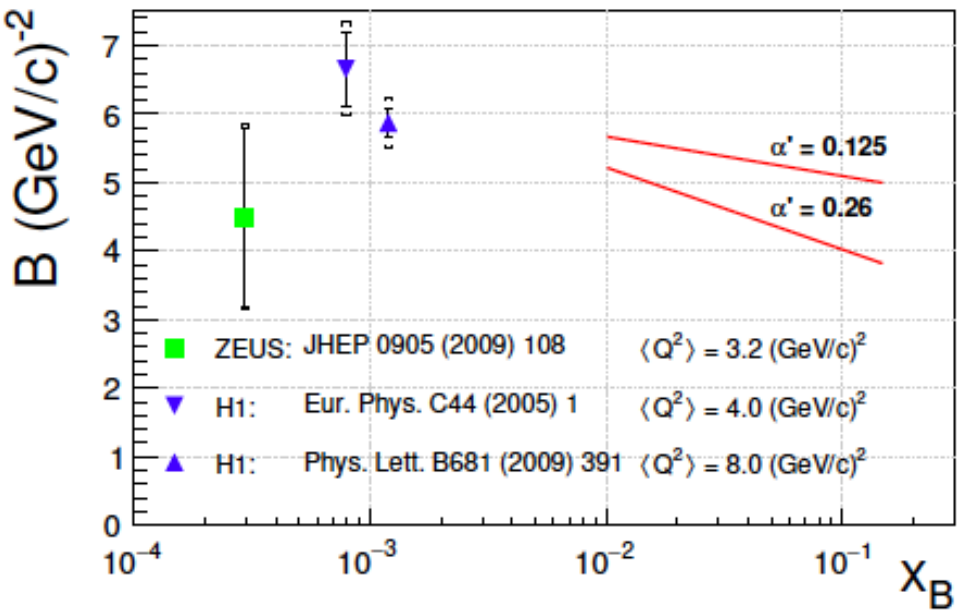
DVCS 2012 results IV: *t*-slope

- Using: $(d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$
- Integrate over ϕ
- Subtract Bethe-Heitler (BH)

$$\frac{d\sigma}{d|t|} \propto e^{-B|t|}; \; < r_\perp^2 > \sim 2B(x_{Bj})$$

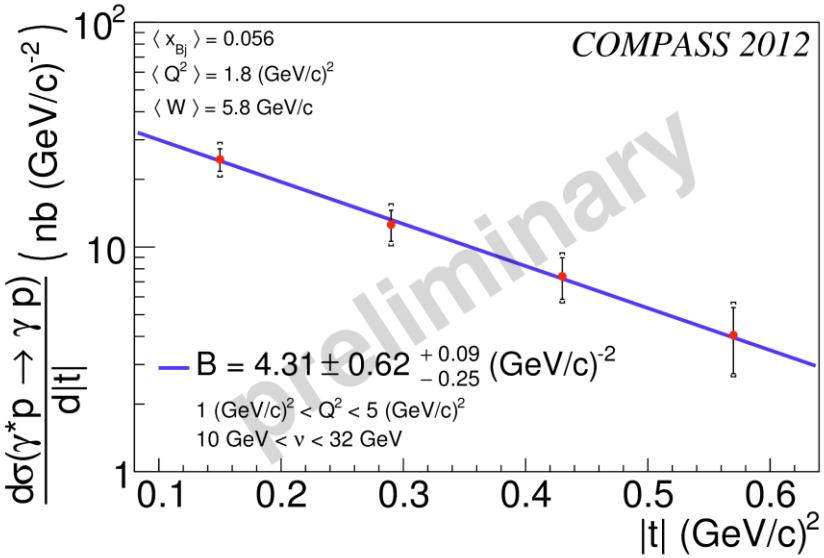
at small x_{Bj}

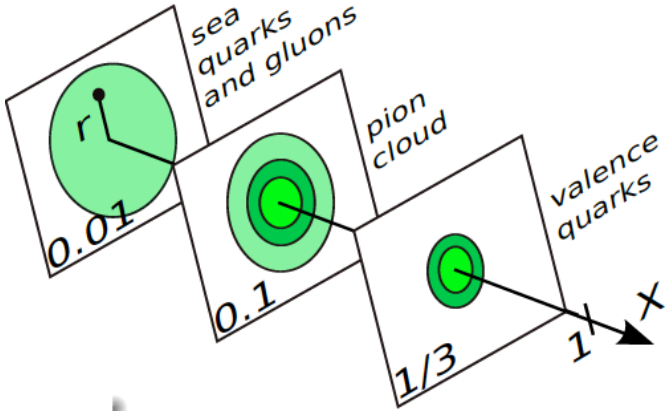




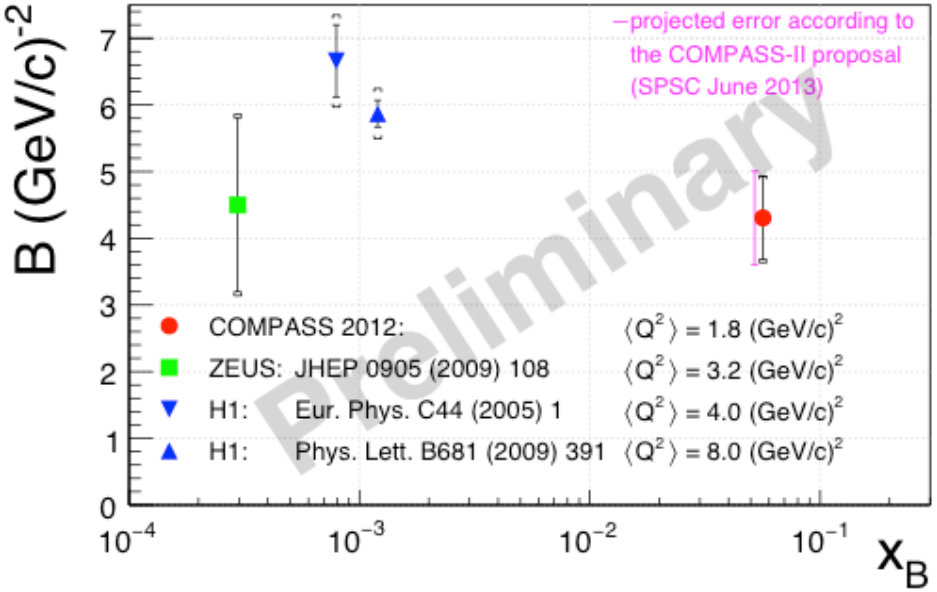
$$B(x_B) = B_0 + 2\,\alpha' \log(\tfrac{x_0}{x_B})$$

DVCS 2012 results V: *t*-slope



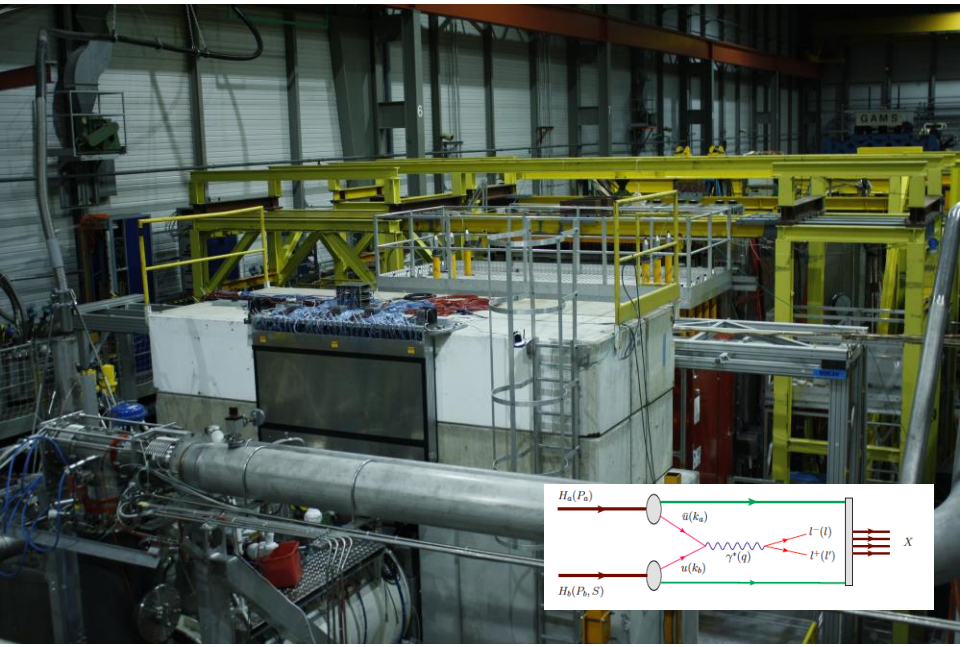


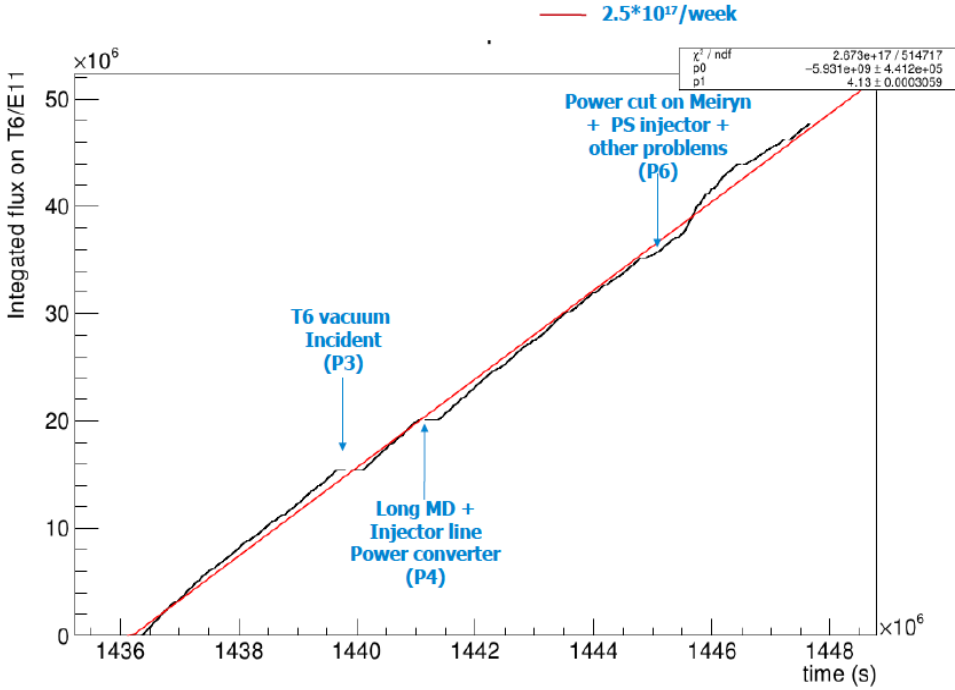
$$B = 4.31 \pm 0.62 \, ^{+0.09}_{-0.25} \, (\mathrm{GeV}/c)^{-2}$$



COMPASS Drell-Yan Run 2015 I

First ever polarised Drell-Yan data set successfully collected





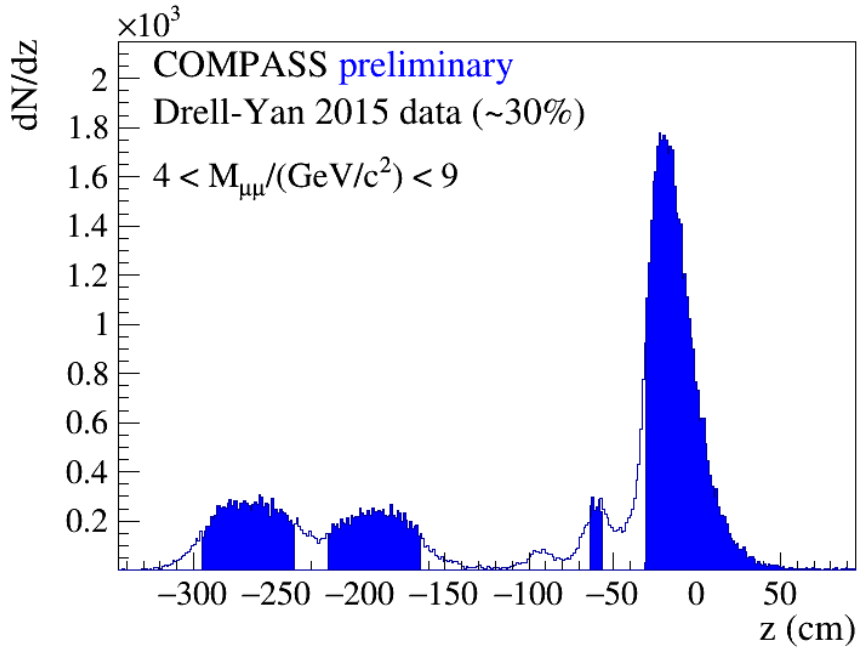
The final statistics penalised by late start (08/07/2015) because of the PT magnet and spectrometer commissioning.

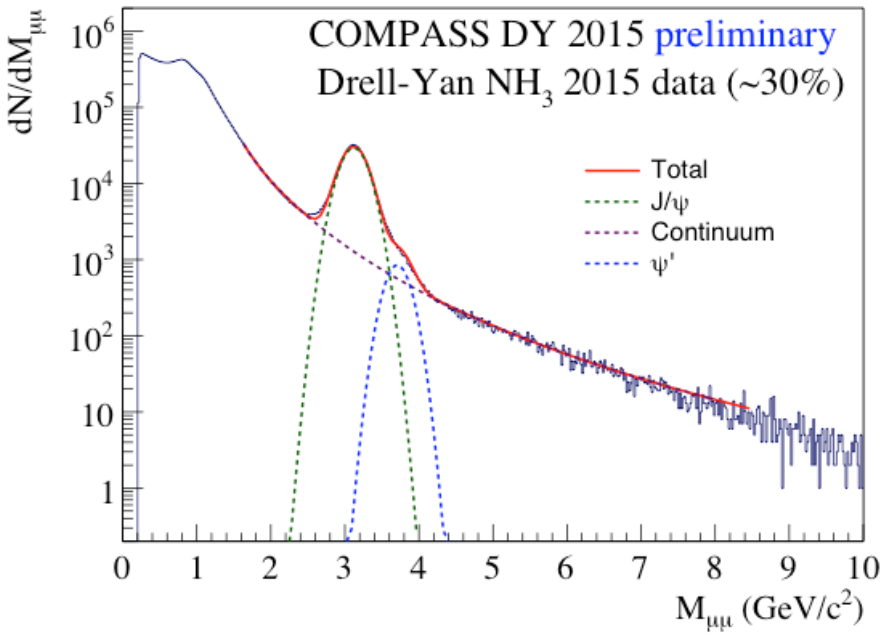
9 periods are collected (~2 weeks long each, polarisation is inverted after first week)

Good machine performance: on average 84%
Good spectrometer availability: ~80%

COMPASS Drell-Yan Run 2015 II
Data Analysis

Three periods (out of 9) produced and analysed,
Stability, quality and kinematic cuts as well as event selection **are conservative and not yet final.**

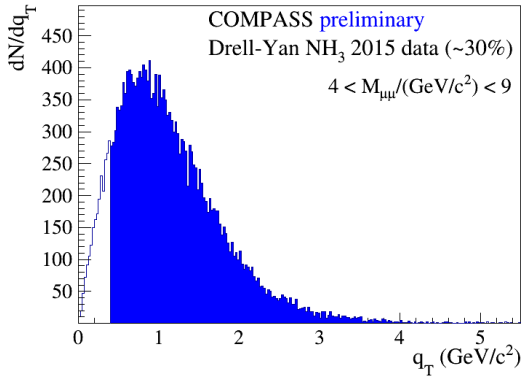


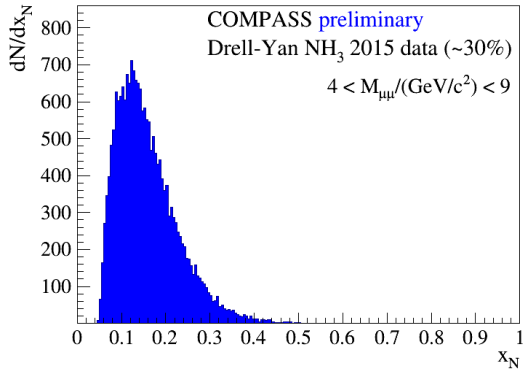


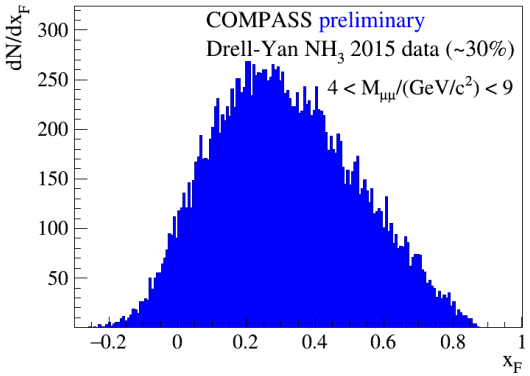
Total number of *J/ψ* is **644000 ± 885**
Total number of HM ($M_{\mu\mu}$ > 4 GeV/ c^2) is **18198**

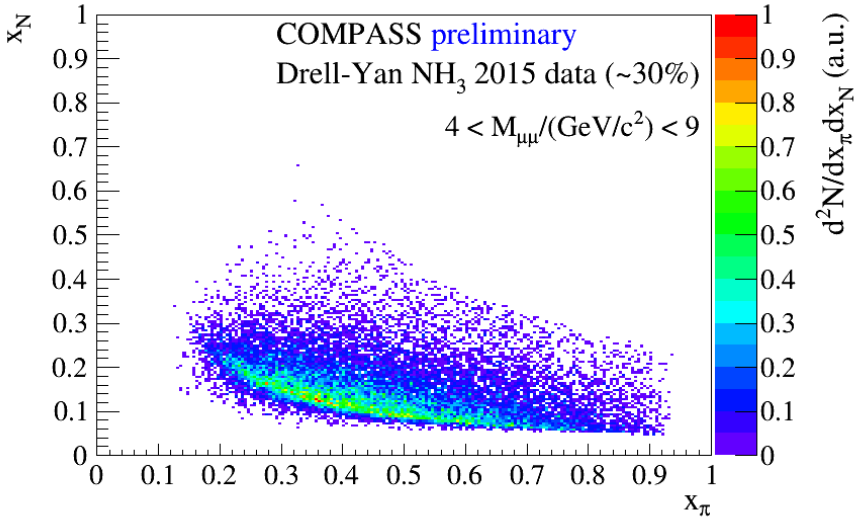
COMPASS Drell-Yan Run 2015 III
Data Analysis

Three periods (out of 9) produced and analysed



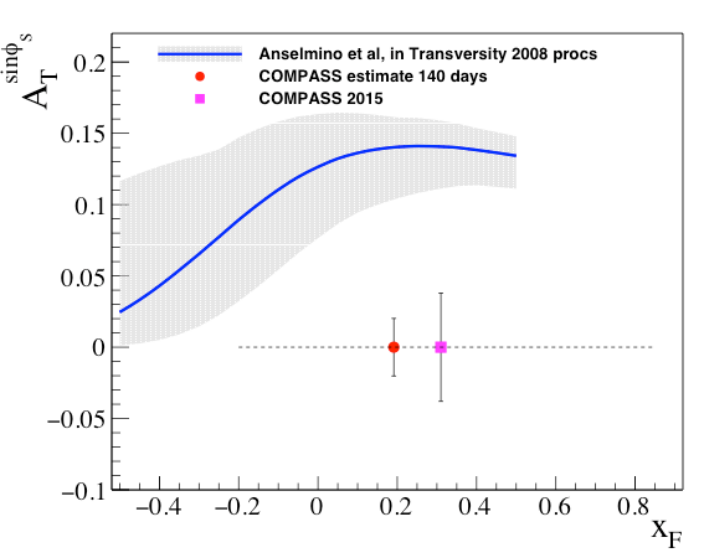






COMPASS Drell-Yan Run 2015 V
Data Analysis

$$\delta A_T^{\sin\phi_S}(x_a, x_b) = \frac{1}{f\,|S_T|}\frac{\sqrt{2}}{\sqrt{N(x_a, x_b)}}.$$



Total number of DY events ($M_{\mu\mu}$ > 4 GeV/ c^2) in the final 2015 data set after stability, quality and kinematic cuts:
- 55000 (80000 after basic cuts – reported to SPSC)
- Proposal expectations (2010): 115000

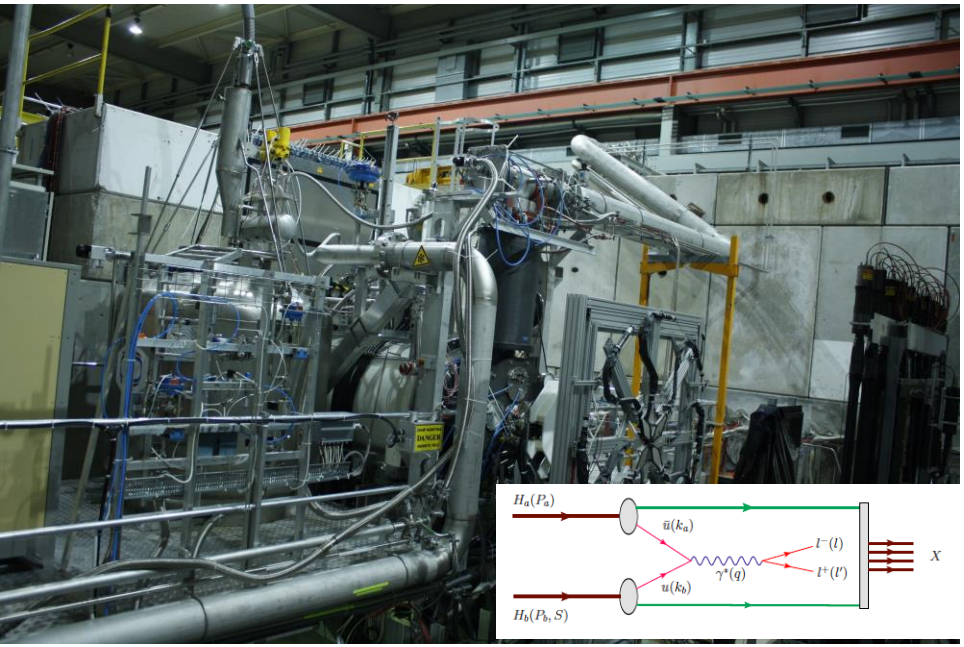
Projections on the statistical error 2015:
- real data analysis (extrap. from 3 periods): 0.038

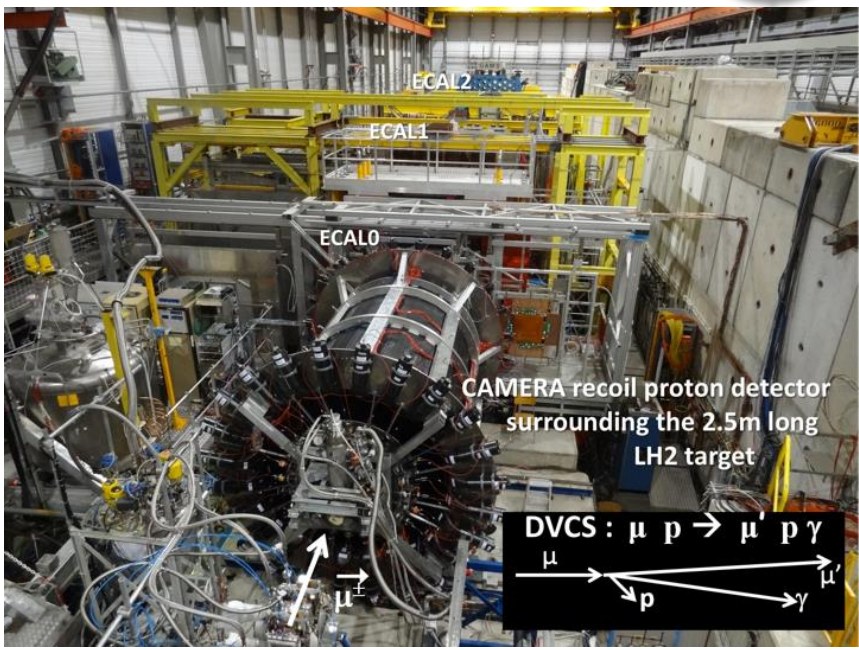
Using only 2015 data the Sivers sign change can be only established if the asymmetry is large (>0.1), which is unlikely if TMD evolution is fast (recent theory developments).

Statistical error quoted in the Proposal is: 0.023
The major difference come from the shorter physics data taking time, PT performance (polarisation) and quality/kinematic cuts:
- Running time ~100 days vs 140 (Proposal)
- PT polarisation (80% vs 90%),
-Quality/kinematic cuts (conservative): 30%

Overall spectrometer performance and beam parameters – as expected

The 2016/17 GPD and SIDIS Run I



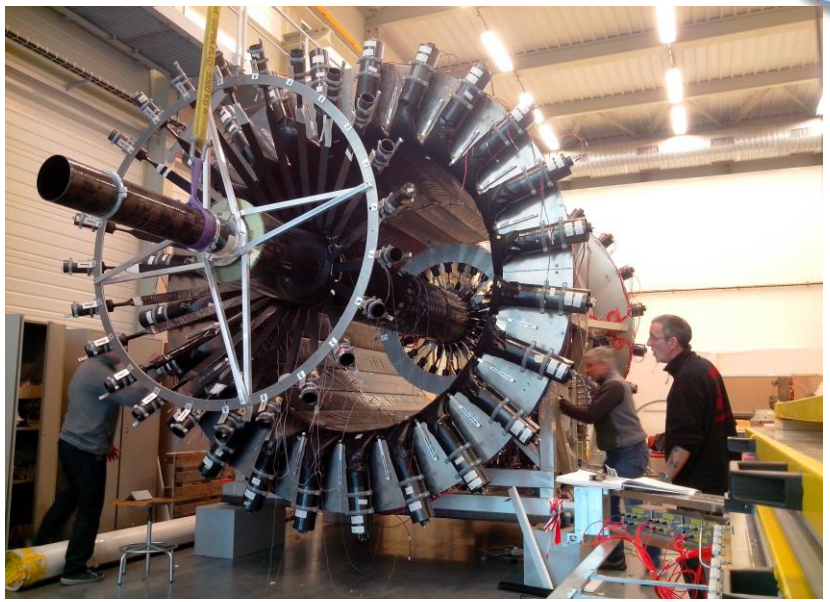


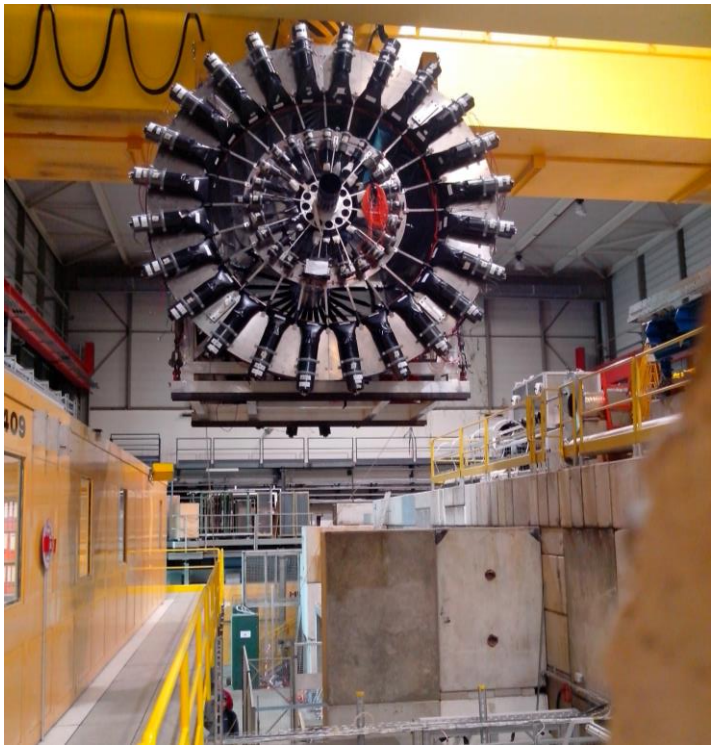
The transformation of the target area of the experiment started immediately after the end of the 2015 run on November 16, 2015. The beam detectors were dismounted and the target loading platform installed to remove the target material from the polarised target system. The hadron absorber downstream of the target was removed before the end of 2015 and DC5 and RICH photon detectors were taken out for repair and upgrade. In January, the entire target system was craned to garage position to make space for the installation of the CAMERA detector with its liquid hydrogen target and ECAL0.

In total about 100 COMPASS members and at least seven different CERN groups were involved

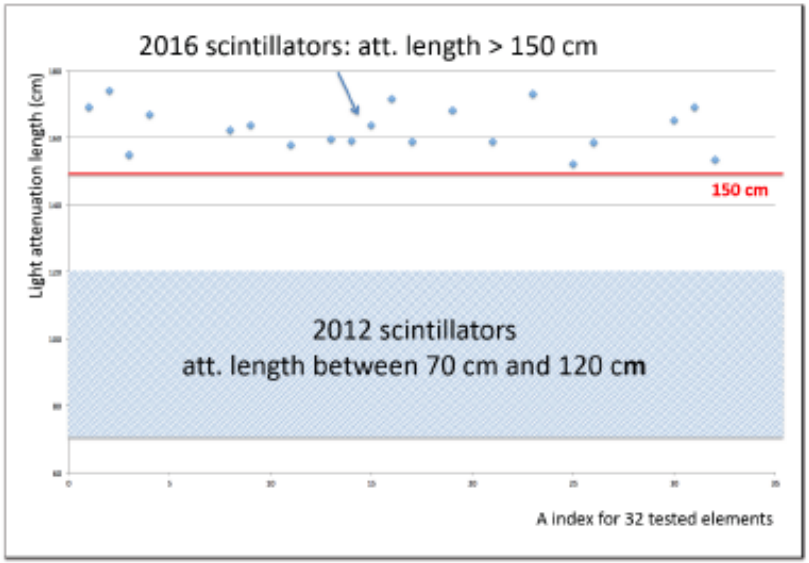
The 2016/17 GPD and SIDIS Run II CAMERA

insertion of ring A, 10/2/2016





installation in hall, 15/2/2016



The 2016/17 GPD and SIDIS Run III ECal0

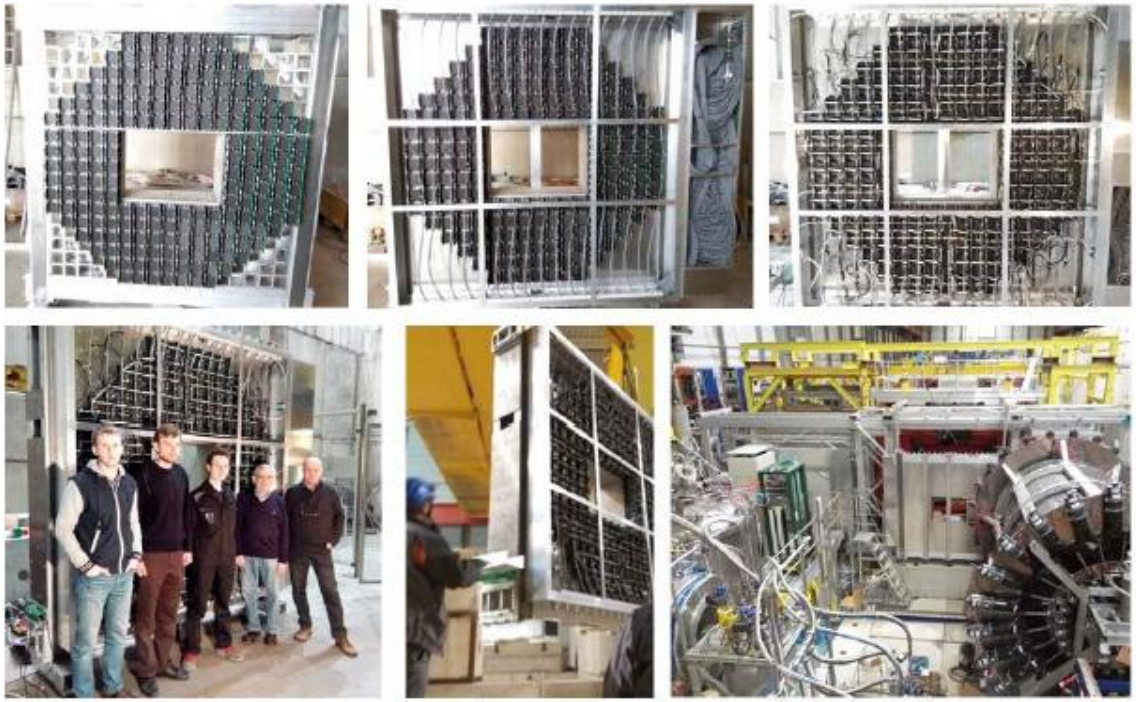
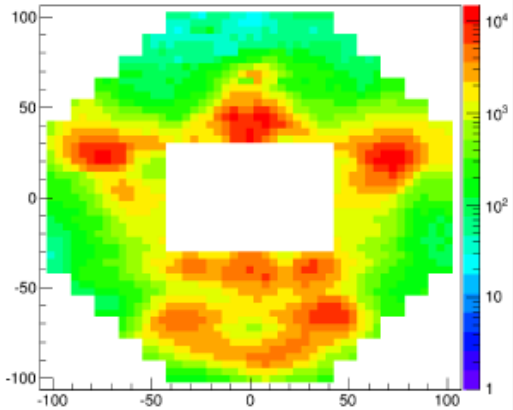


Fig. 49: ECAL0 assembly and final positioning in the spectrometer (March, 2016)

High granularity shashlyk-type calorimeter, 4x4 cm cell size, 109 alternating layers of lead (0.8 mm) and scintillating material (1.5 mm) read out by micro-pixel avalanche Photodiodes (MAPD) MPPC S12572-10P from Hamamatsu



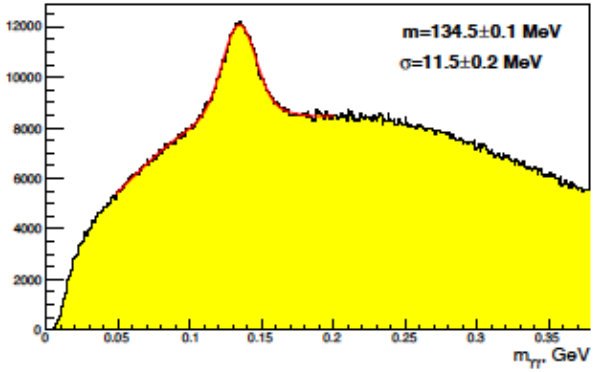
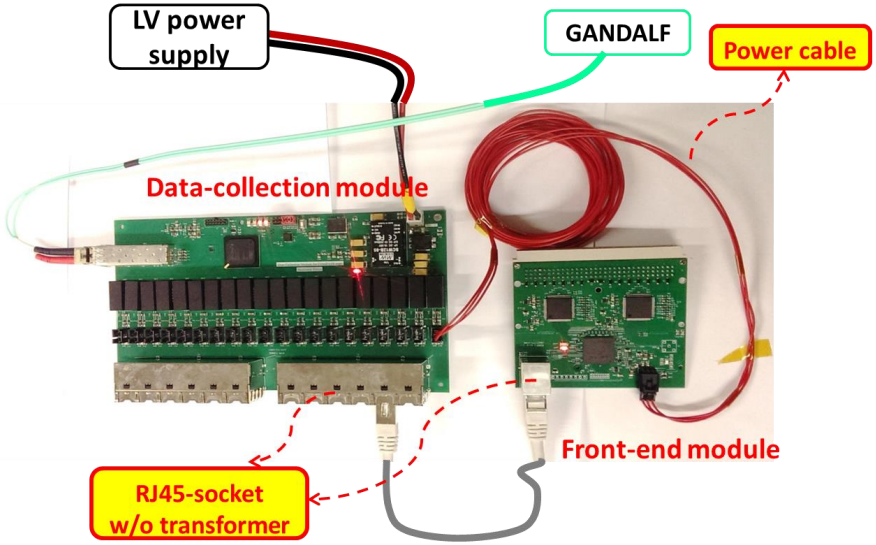
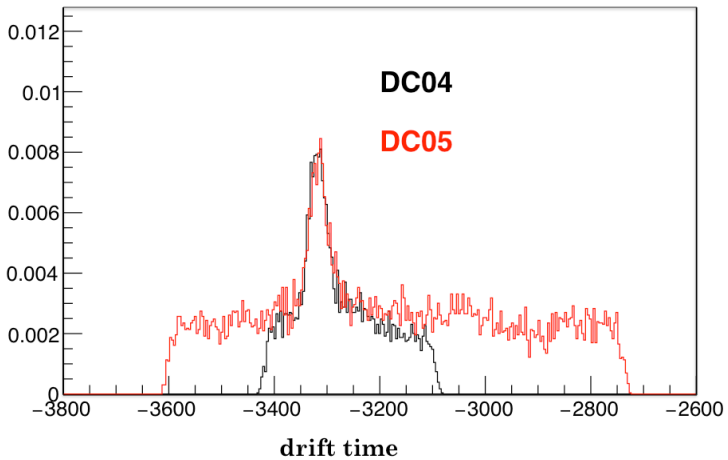


Fig. 53: Invariant mass spectrum for photon pairs reconstructed in ECAL0.

The 2016/17 GPD and SIDIS Run V
DC05 f/e upgrade + LH_2 target

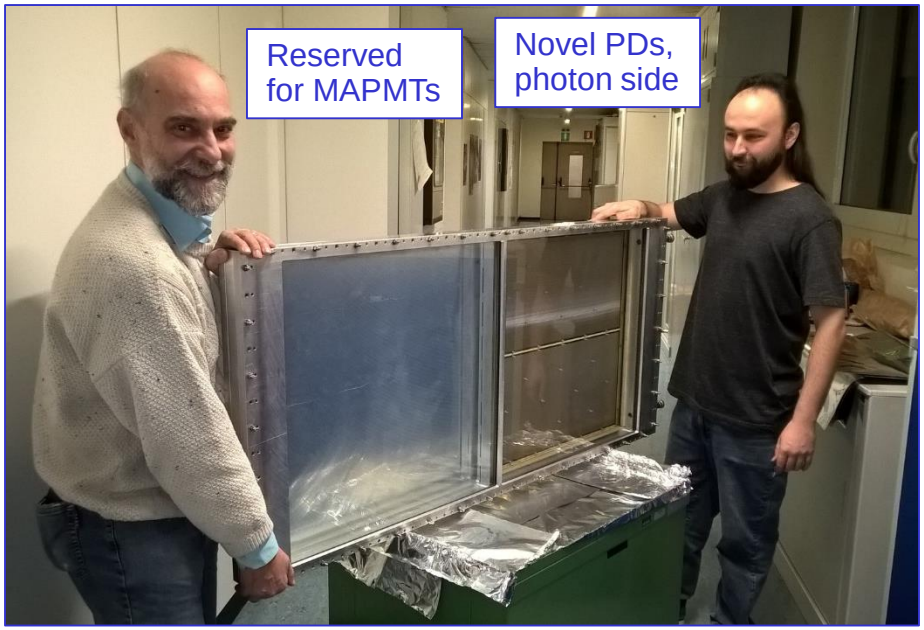




DC5 & DC5 f/e electronics performance is OK in 2016

The 2016/17 GPD and SIDIS Run IV RICH

Upgrade with novel photon detectors:
Micro-Megas + thick GEM hybrid
1/4 of detector replaced (was MWPC)
installed, nominal gas and HV
Commissioning is going on (f/e electronics)



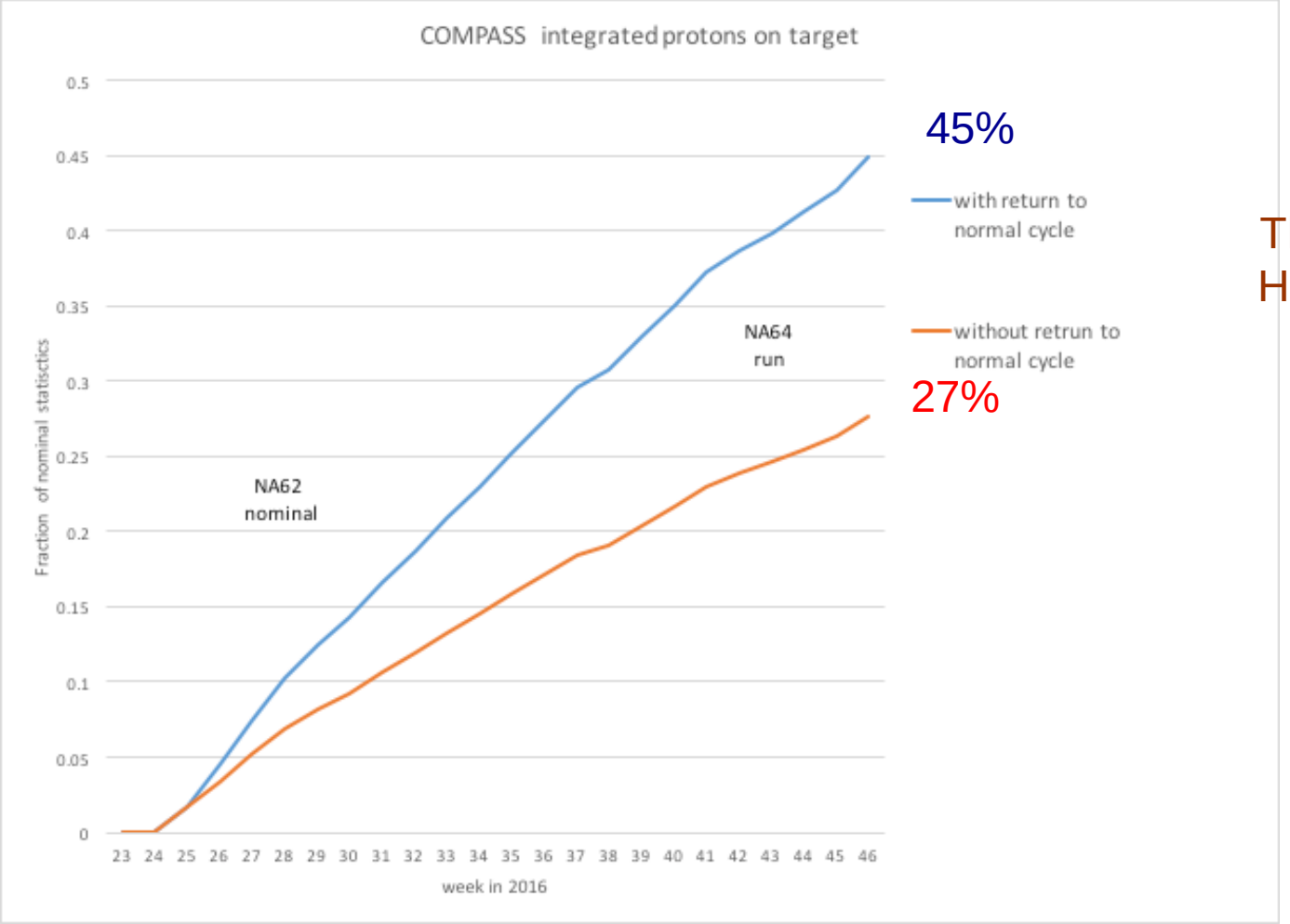
DVCS run 2016 – projections and impact

We are taking physics data since last week - beam availability is the main problem.

Optimistic scenario : ~45-50% compared to the Proposal

Pessimistic scenario: ~27%

Thus after 2 years (2016-2017): 63% - 75% (assumption 2017 – 100%)



Thanks a lot to Henric Wilkens

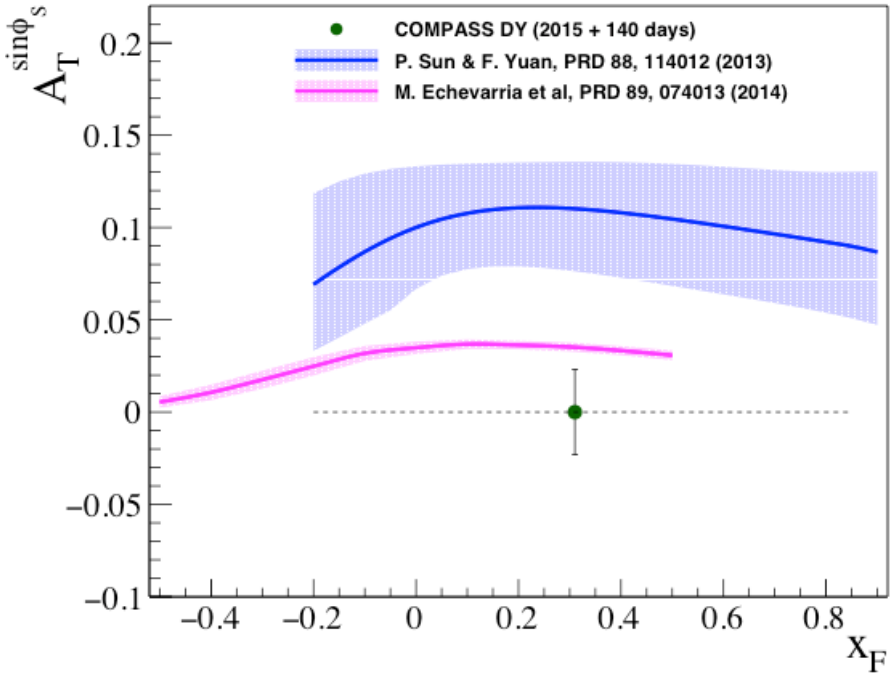
Request for a Drell-Yan Run in 2018 I

COMPASS-II proposal contains already the request for 2 years of Drell-Yan running (only one year DY approved originally taking into 3 years period between LS1 and LS2), we plan to complete COMPASS-II with DY run in 2018.

Goal: unambiguously verify Sivers asymmetry sign change

We aim to triple a total polarised data sample in order to achieve the statistical error on Sivers asymmetry (2015+2018) of ~ 0.02 (we have to be ready for small asymmetry in case of fast TMDs evolution) and to collect world largest kaon and anti-proton DY data sample.

Hardware upgrade:
CEDARS system for efficient kaon and anti-proton tagging



Request for a Drell-Yan Run in 2018 II

- Can not postpone the measurement as SeaQuest (FermiLab) and Star (RHIC) will start their polarised Drell—Yan programs in 2017
- A large investment in PT magnet refurbished in 2013-2014, new control and power supply system in 2014
- need to keep on stand-by and to partly rebuild the polarised target group, impossible without a clear perspective
- some groups interested in joining for a second year of DY, large number of students/groups involved/interested in DY analysis

TIMING constraints:
- need to extend MoU in Nov. 2016 FRC (validity end 2017)
- request on 2018 requires an approval before the FRC meeting

Beyond 2020 Workshop I

COMPASS beyond 2020 Workshop

21 Mar 2016, 08:05 → 22 Mar 2016, 17:10 Europe/Zurich

222-R-001 (CERN)

Description The goal of the workshop is to explore hadron physics opportunities for fixed-target COMPASS-like experiments at CERN beyond 2020 (CERN Long Shutdown 2 2019-2020). The programme comprises

- Reviews of the various physics domains: TMDs, GPDs, FFs, spectroscopy, exotics, tests of ChPT, astrophysics

- Reviews of physics results expected in the next 10 years from major labs around the world

- Some critical long-term issues of the COMPASS spectrometer

- Discussions

- Good attendance (>100 physicists), large interest
- 11 “outside” review talks – Jefferson Lab, RHIC, Fermilab, KEK (Japan) BEPC II (IHEP, Beijing), NICA (JINR, Dubna), CERN (After, LHCb), GSI (Panda), J-PARK (Japan), EIC - China
- 7 COMPASS talks (chronol.) – SIDIS, GPDs, Chiral Dynamics, astrophysics (dark matter), Drell-Yan, hadron spectroscopy
- Contributions to Physics Beyond Colliders Workshop:
  - Session 3 of the PBC (potential future of existing programs) – on invitation
  - 2 Abstracts for Session 4 (new experimental ideas) – RF separated kaon/anti-proton beam for DY and spectroscopy

Summary

- DVCS from 2012 confirms the expectation (stat. error projections)
- 2016 Run – we are taking data but suffering from the beam intensity/duty cycle
- 2015 – the performance of the apparatus confirmed, but suffered from late commissioning of the PT Magnet and spectrometer
- Light quarks hadron spectroscopy – we are progressing well on the development of the sophisticated analysis model and data analysis
- New at COMPASS – heavy quark spectroscopy with muon beam
- Good progress on the SIDIS data analysis: longitudinal, transverse/TMD and multiplicities (FF)
- 2018 – Drell-Yan run is needed to unambiguously establish Sivers asymmetry sign change
- 2020 Workshop – very successful, plans beyond 2020 were discussed and developed ➔ PBC at CERN

Thank you!

SPARES

Pion polarisability & chiral anomaly

After all necessary preparation (calibrations, alignment etc.)
the raw data of the 2012 (Primakoff Run) have been produce in 2015.
AT the same time the Monte Carlo environment has been migrated from GEAT3 based COMGEANT to the new GEANT4/C++ based framework TGEANT. TGEANT is heading now to become the new standard for the Whole Collaboration.
The data sample is factor 3 to 4 larger compared to the published 2009 data.
goal: separate determination of $\alpha + \beta$ in extended kin. range

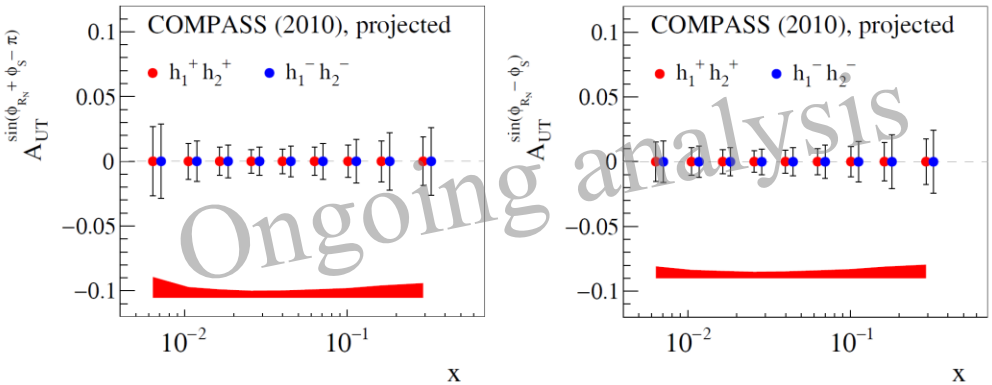
SIDIS transverse&longitudinal II

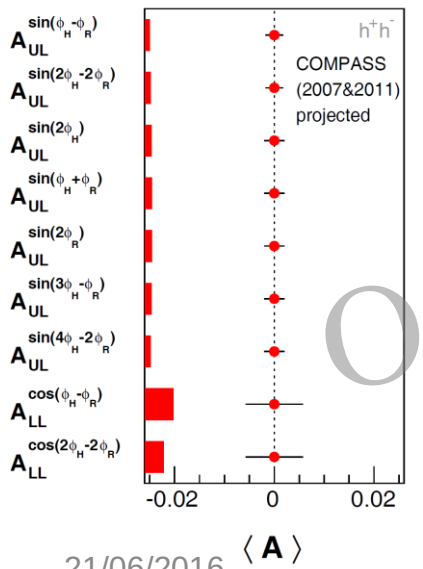
di-hadron TSA and LSA (SKIP?)

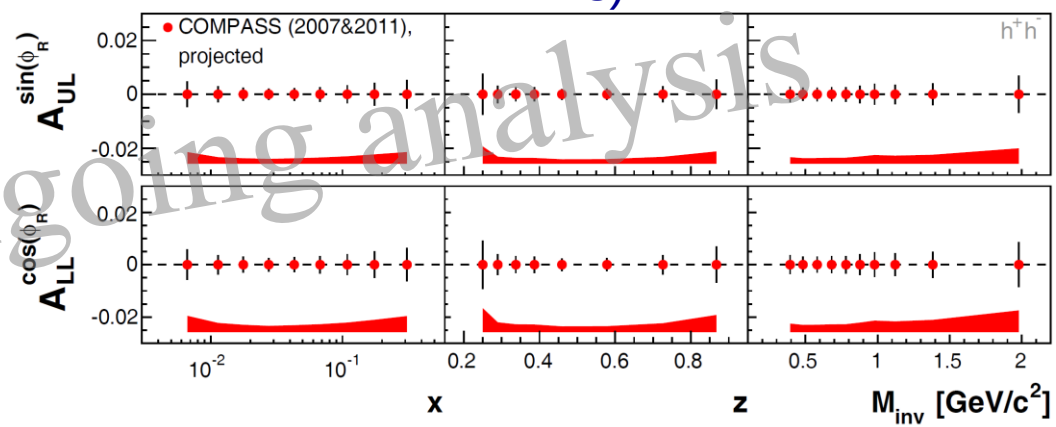
We have already published di-hadron TSA for opposite-sign hadrons, this is a continuation for same-sign. It is an alternative way to access TMD PDF wrt to single hadron asymmetries.

DTSA – transversely polarised proton 2010

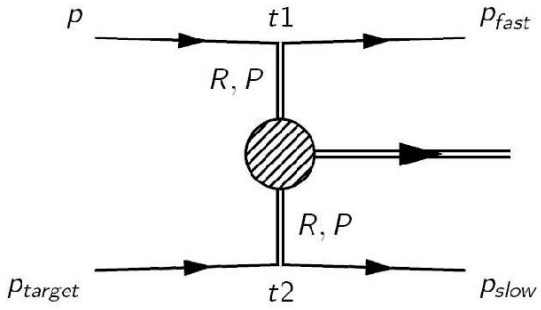
DLSA - longitudinally polarised proton target, 2007 and 2011 Runs – first ever look at the longitudinal asymmetries (access in particular to unknown twist-3 PDFs)



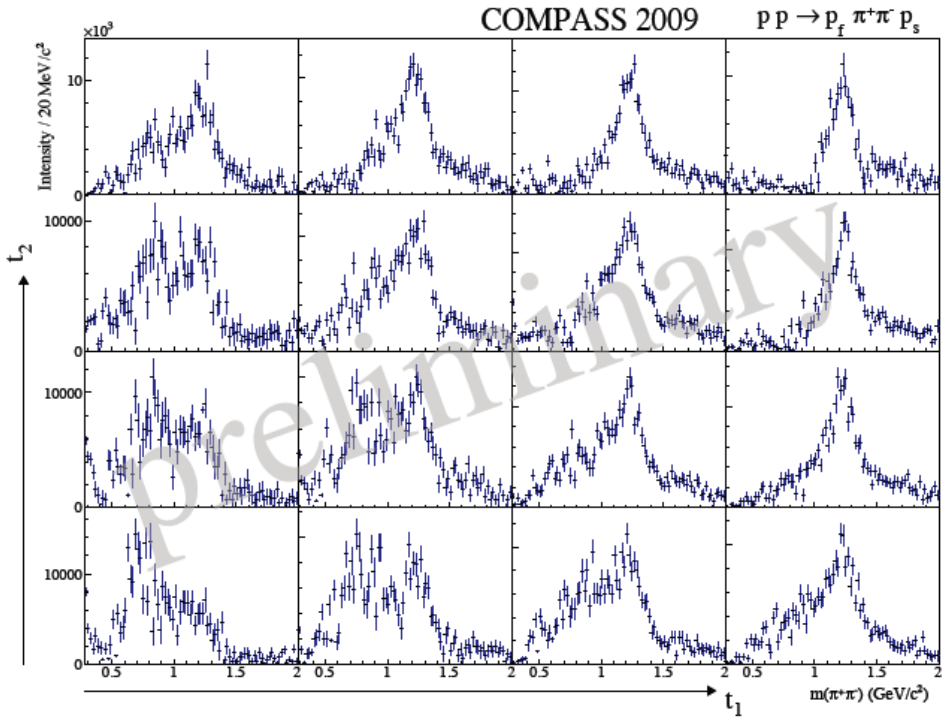




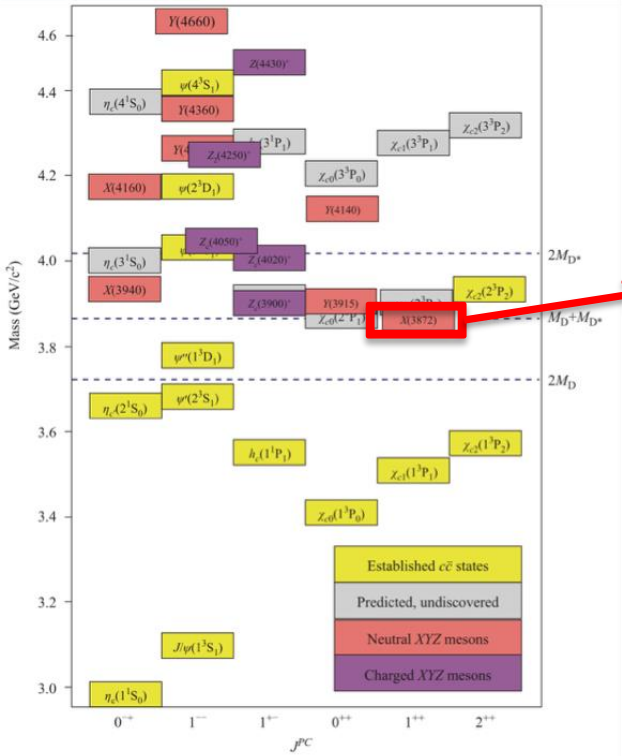
Central production II



Central production, 2008 and 2009 data.
t_1 t_2 bins, D-wave.
Interestingly, the $f_2(1270)$ signal in the D wave shows a very similar behaviour, which puts strong doubts on the common belief that the f_2 (1270) is produced copiously in double-Pomeron processes.



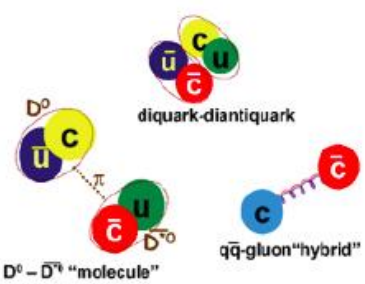
Exotic X(3872) lepto-production I



X(3872) is the first charmonium-like exotic hadron discovered by the Belle collaboration in 2003 and studied than in other experiments. Various interpretations exists: pure *ccbar* state, tetraquark, *DD**- molecule, hybrid *ccg* state, glueball or else.

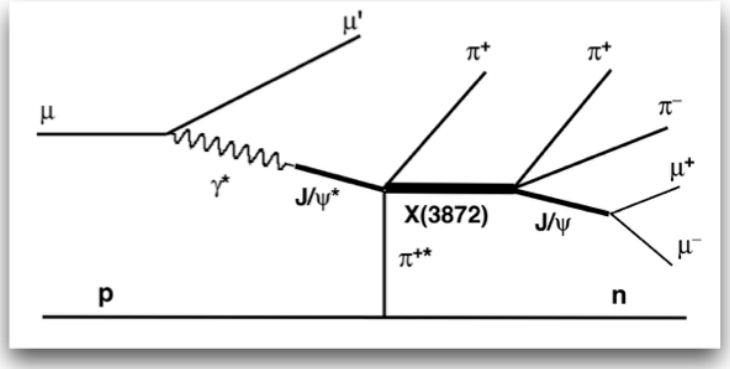
Additional information on its width would help to shed light on its nature.

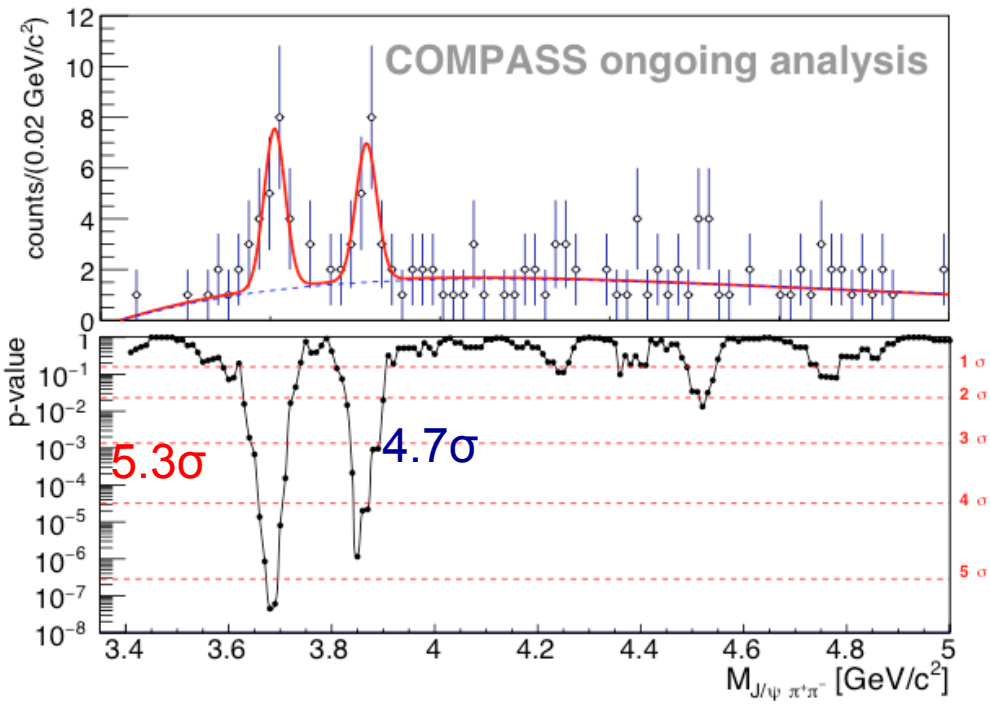
State	M /MeV	Γ /MeV	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.68±0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [95, 102], BaBar [98], LHCb [103]
				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + \ldots$	CDF [96, 104, 105, 160], D0 [97]
				$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [107], BaBar [72, 73]
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [108, 109], BaBar [110]
				$B \to K + (J/\psi\,\gamma)$	BaBar [137], Belle [138], LHCb [141]
				$B \to K + (\psi'\,\gamma)$	BaBar [137], Belle [138], LHCb [141]
				$pp \to (J/\psi\,\pi^+\pi^-) + \ldots$	LHCb [99], CMS [100] ATLAS
				$e^+e^- \to \gamma X(3872)$	BES-III



Exotic X(3872) lepto-production II

Never observed so far in lepto-production process
COMPASS muon beam data 2003➔2010
Study $J/\psi\pi^+\pi^-$ subsystem of exclusive final state $J/\psi\pi^+\pi^-\pi^\pm$





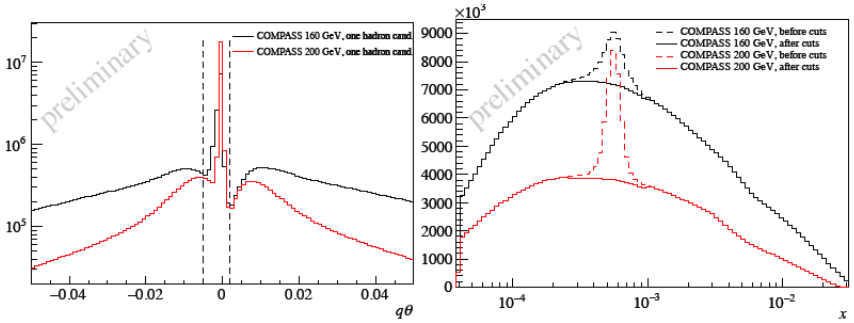
$N_{\psi(2S)} = 16.1 \pm 5.2$
$N_{X(3872)} = 13.9 \pm 4.9$

$M_{\psi(2S)} = 3680 \pm 8$ MeV (nominal 3686.1)
$M_{X(3872)} = 3860 \pm 8$ MeV (nominal 3871.7)

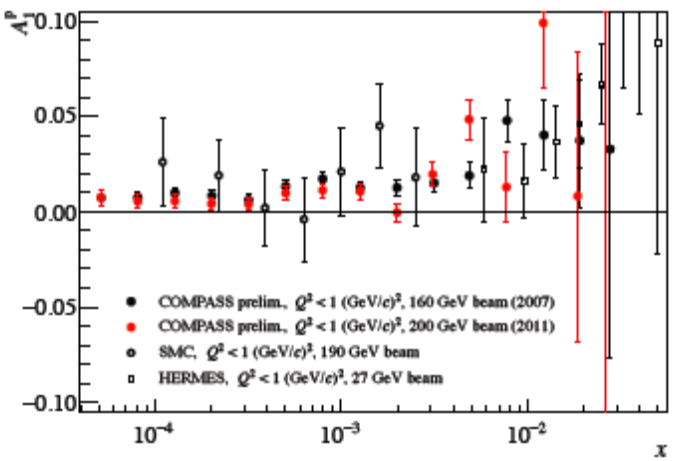
SIDIS longitudinal II

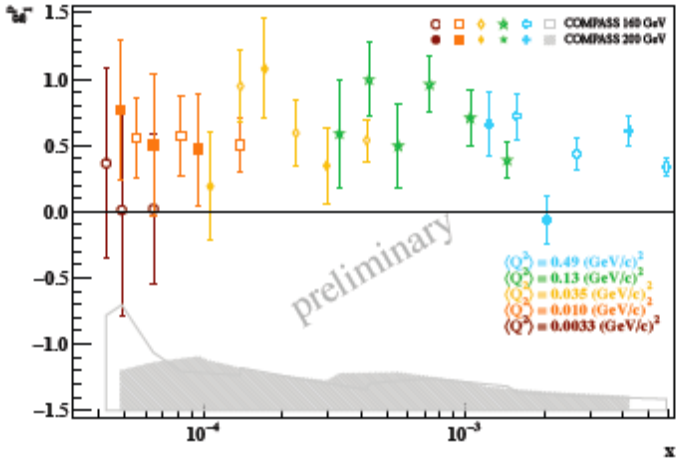
Proton 2007 and 2011 $Q^2 < 1$

The main challenge in the low-Q^2 analysis is the suppression of events due to muon scattering off target electrons. These events are removed by a cut on the product of the angle between the virtual photon and the electron candidate and the particle charge $q\vartheta$.



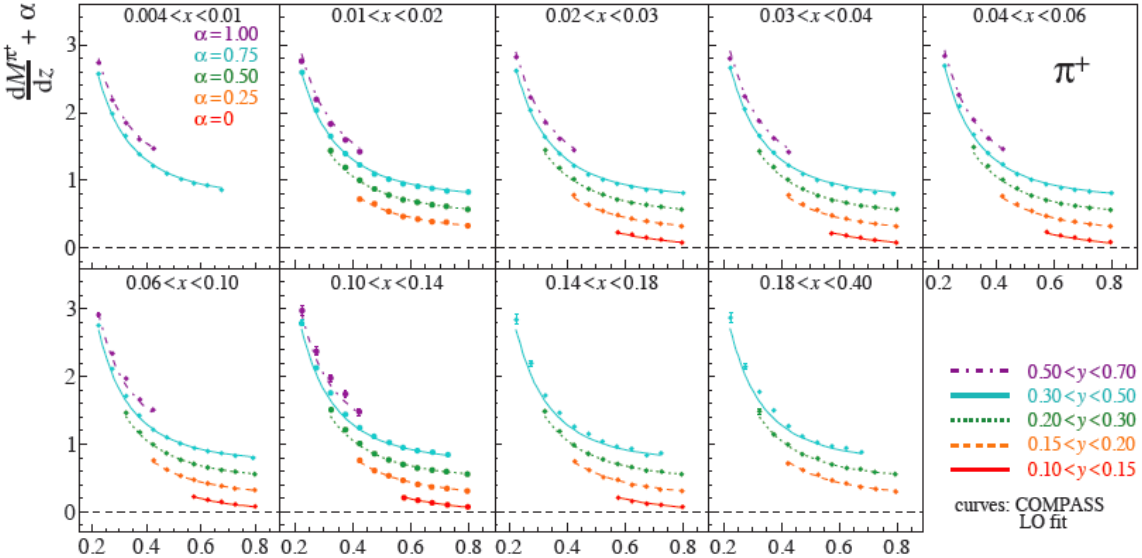
The results for A_1^p for both data sets are compared to previous measurements. The increase in precision is evident. The COMPASS data show a small, nearly constant asymmetry of about 1% at small x. The resulting values for g_1^p are shown in together with the systematic error band. For comparison with model predictions various binnings, e.g. x, Q^2 and ν, x.
The preparation is ongoing.



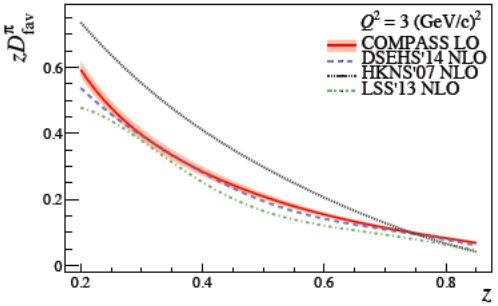


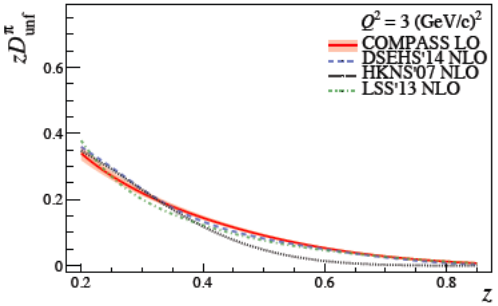
SIDIS multiplicities I

Charged pion and unidentified hadron multiplicities (2006 160 GeV muon beam and an iso-scalar target (^{6}LiD)) – submitted to PLB. Positive reaction by referees, preparing answers to their questions. The 3-dimensional data set (*x, y* and *z*) ➔ an important input for future NLO pQCD analyses of world data (FF into pions and hadrons determinations).



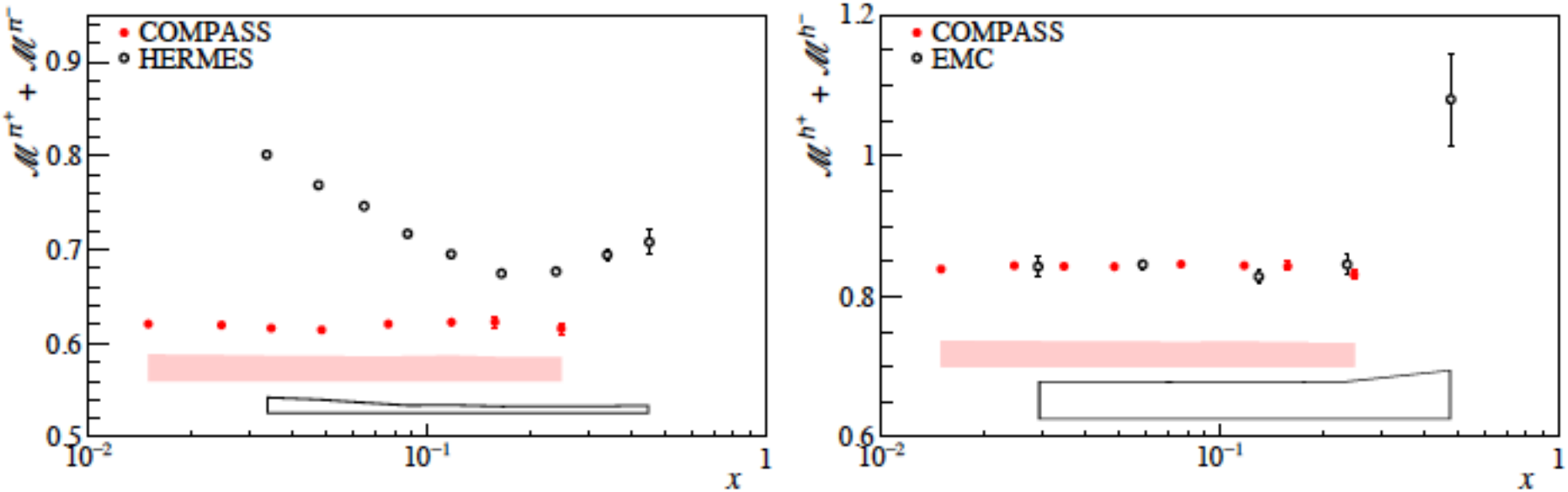
A combined leading-order (LO) pQCD fit to the π^+ and π^- multiplicities (COMPASS pion data only), was performed to extract the favoured and unfavoured FFs to pions - results are close to recent NLO analyses.





SIDIS multiplicities II

Comparing COMPASS data with HERMES and EMC: figure shows the sum of result for the sum π^+ and π^- multiplicities integrated over *z* from 0.2 to 0.85 and averaged over *y* between 0.1 and 0.7, as a function of *x*. The expected weak *x* dependence is indeed observed in the data.
In the same figure, the results of HERMES integrated over *z* from 0.2 to 0.8 are shown using the so-called x representation. Note however that the HERMES data were measured at a lower energy and correspond to different kinematics. The results from COMPASS and EMC, which correspond to comparable kinematics, are found in excellent agreement.



Charged kaon multiplicities: the same data set (6 weeks of 2006) – publication in preparation
Neutral kaon multiplicities: (6 weeks of 2006 and 2012 pure LH_2 target) – first results are obtained, systematic studies are going on.

Beyond 2020 Workshop I

COMPASS beyond 2020 Workshop

21 Mar 2016, 08:05 → 22 Mar 2016, 17:10 Europe/Zurich

222-R-001 (CERN)

Description The goal of the workshop is to explore hadron physics opportunities for fixed-target COMPASS-like experiments at CERN beyond 2020 (CERN Long Shutdown 2 2019-2020). The programme comprises

- Reviews of the various physics domains: TMDs, GPDs, FFs, spectroscopy, exotics, tests of ChPT, astrophysics
- Reviews of physics results expected in the next 10 years from major labs around the world
- Some critical long-term issues of the COMPASS spectrometer
- Discussions

Videoconference Rooms COMPASS_Beyond_2020_Workshop Join

Monday, 21 March 2016

09:00 → 10:30 Morning session I

Convener: Nicole D'Hose (CEA/IRFU,Centre d'etude de Saclay Gif-sur-Yvette (FR))

09:00 Opening welcome — 15m

Speaker: Gerhard Mallot (CERN)

2020.pdf 2020.pptx

09:15 A window of opportunity for SIDIS measurements at COMPASS beyond 2020 — 40m

Speaker: Andrea Bressan (Universita e INFN, Trieste (IT))

bressan_20160321.... bressan_20160321....

Beyond 2020 Workshop II

09:55 **Opportunities for constraining GPDs at COMPASS after 2020** *35'*
Speaker: Caroline Kathrin Riedl (Univ. Illinois at Urbana-Champaign (US))
GPD-COMPASS-Fu...

10:30 - 11:00 Coffee break (Building 222)

11:00 - 12:30 Morning session II
Convener: Fabienne Kunne (CEA/IRFU,Centre d'etude de Saclay Gif-sur-Yvette (FR))

11:00 **Opportunities for Experiments with Hadrons in the Regime of Chiral Dynamics** *30'*
Speaker: Jan Michael Friedrich (Technische Universitaet Muenchen (DE))
friedrich_20160320...

11:30 **Opportunity to contribute in the search of dark matter** *30'*
Speakers: Fiorenza Donato (INFN - National Institute for Nuclear Physics), Dr. Michela Chiosso (University of Torino and INFN)
CompassBeyond20... Michela_Beyond20...

12:00 **Progress and opportunities of unpolarised Drell-Yan program** *30'*
Speaker: Wen-Chen Chang (Academia Sinica (TW))
COMPASS_Beyond... COMPASS_Beyond...

12:30 - 14:00 Lunch break (CERN Restaurant 1)

14:00 - 16:00 Afternoon session I
Convener: Daniele Panzieri (Universita e INFN Torino (IT))

14:00 **Polarised Drell-Yan and GPDs** *30'*
Speaker: Matthias Grosse-Perdekamp (Univ. Illinois at Urbana-Champaign (US))
mgp-Polarized-Drel... mgp-Polarized-Drel...

14:30 **The 3D structure of hadrons at Jefferson Lab** *30'*

Speaker: Dr. Carlos Munoz Camacho (Jefferson Lab)

JLab12.pdf

15:00 **Opportunities with polarized beams at RHIC/EIC** *30'*

Speaker: Dr. Ernst Sichtermann (Lawrence Berkeley National Laboratory)

COMPASS_beyond_...

15:30 **Fermilab opportunities on polarized Drell-Yan** *30'*

Speaker: Prof. Wolfgang Lorenzon (Michigan Uni. (US))

COMPASS2016-lor... COMPASS2016-lor...

16:00 - 16:30 Coffee break (Building 222)

16:30 - 18:30 Afternoon session II

Convener: Bernhard Ketzer (Universitaet Bonn (DE))

16:30 **Future Spectroscopy Studies at Jefferson Lab** *30'*

Speaker: Dr. Eugene Chudakov (Jefferson Lab)

talk_jlab_spctr_201...

17:00 **Competition and complementarity in spectroscopy from e+e- machines** *30'*

Speaker: Dr. Soeren Lange (Giessen (DE))

COMPASS.pdf

17:30 **Studying the nucleon structure, quarkonium production and spin effects with AFTER@LHC** *30'*

Speaker: Jean-Philippe Lansberg (IPN Orsay, Paris Sud U. / IN2P3-CNRS)

AFTER-COMPASS-...

18:00 **Spin @ NICA** *30'*

Speaker: Igor Savin (Joint Inst. for Nuclear Research (RU))

Spin @ NICA-SPD-...

19:30 - 21:30 Workshop Buffet (Glassbox Restaurant 1)

Tuesday, 22 March 2016

09:00 - 10:30 **Morning session I**

Convener: Stephan Paul (Technische Universitaet Muenchen (DE))

09:00 **Possible future hadron spectroscopy measurements at COMPASS** *30'*

Speaker: Boris Grube (Technische Universitaet Muenchen (DE))

bgrube_v2.pdf

09:30 **Initial Measurements of Hadron Spectroscopy and Nucleon Structure with Antiprotons by PANDA** *30'*

Speaker: James Ritman (CERN)

COMPASS_PANDA_... COMPASS_PANDA_...

10:00 **Spectroscopy and Hadron Physics at LHCb** *30'*

Speaker: Sebastian Neubert (Ruprecht-Karls-Universitaet Heidelberg (DE))

sneubert.pdf

10:30 - 11:00 Coffee break (Building 222)

11:00 - 13:00 **Morning session II**

Convener: Eva-Maria Kabuss (Johannes-Gutenberg-Universitaet Mainz (DE))

11:00 **Study hadron partonic structure at J-PARC and EIC/China** *30'*

Speaker: Wen-Chen Chang (Academia Sinica (TW))

COMPASS_Beyond... COMPASS_Beyond...

11:30 **Future beam options for fixed-target experiments at CERN** *30'*

Speaker: Lau Gatignon (CERN)

Compass-Presenta... Compass-Presenta...

12:00 **Discussion (muon beam, SIDIS and GPDs)** *1h0'*

Speakers: Discussion prepared by Gerhard Mallot, Gerhard Mallot (CERN)

20160322_discussi... 20160322_discussi...

13:00 - 14:00 Lunch break (CERN Restaurant 1)

Beyond 2020 Workshop V

14:00 - 16:00 **Afternoon session I**

Convener: Jechiel Lichtenstadt (High Energy Physics Department)

14:00 **Discussion (hadron beams, Spectrosc., Polariz., Drell-Yan, Astro)** *1h0'*

Speakers: Discussion prepared by Oleg Denisov, Oleg Denisov (INFN, sezione di Torino)

Oleg_Beyon2020_h... Oleg_Beyon2020_h...

15:00 **Detector Status Overview and Upgrades** *30'*

Speaker: Johannes Bernhard (Johannes-Gutenberg-Universitaet Mainz (DE))

CompassBeyond20... CompassBeyond20...

15:30 **Spectrometer DAQ/FE after 2018** *30'*

Speaker: Igor Konorov (Technische Universitaet Muenchen (DE))

fe_daq_20160321.p...

16:00 - 16:10 **Closing remarks and end of the meeting** *10'*

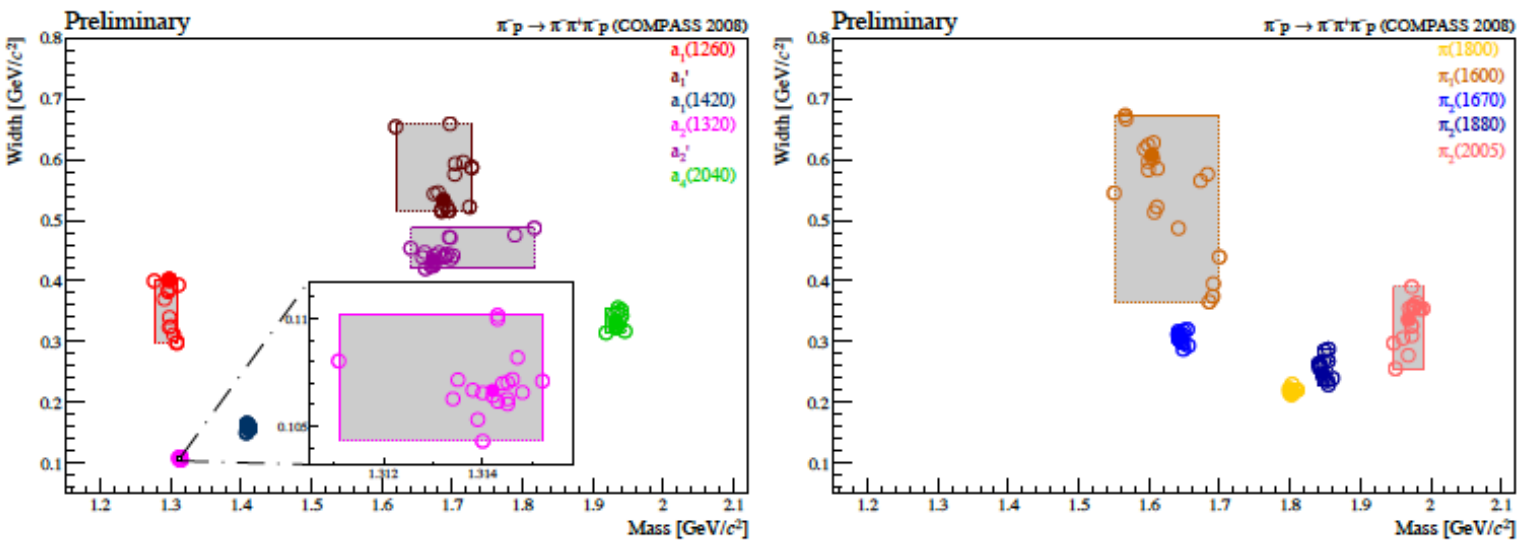
Speaker: Oleg Denisov (INFN, sezione di Torino)

Diffractive dissociation II

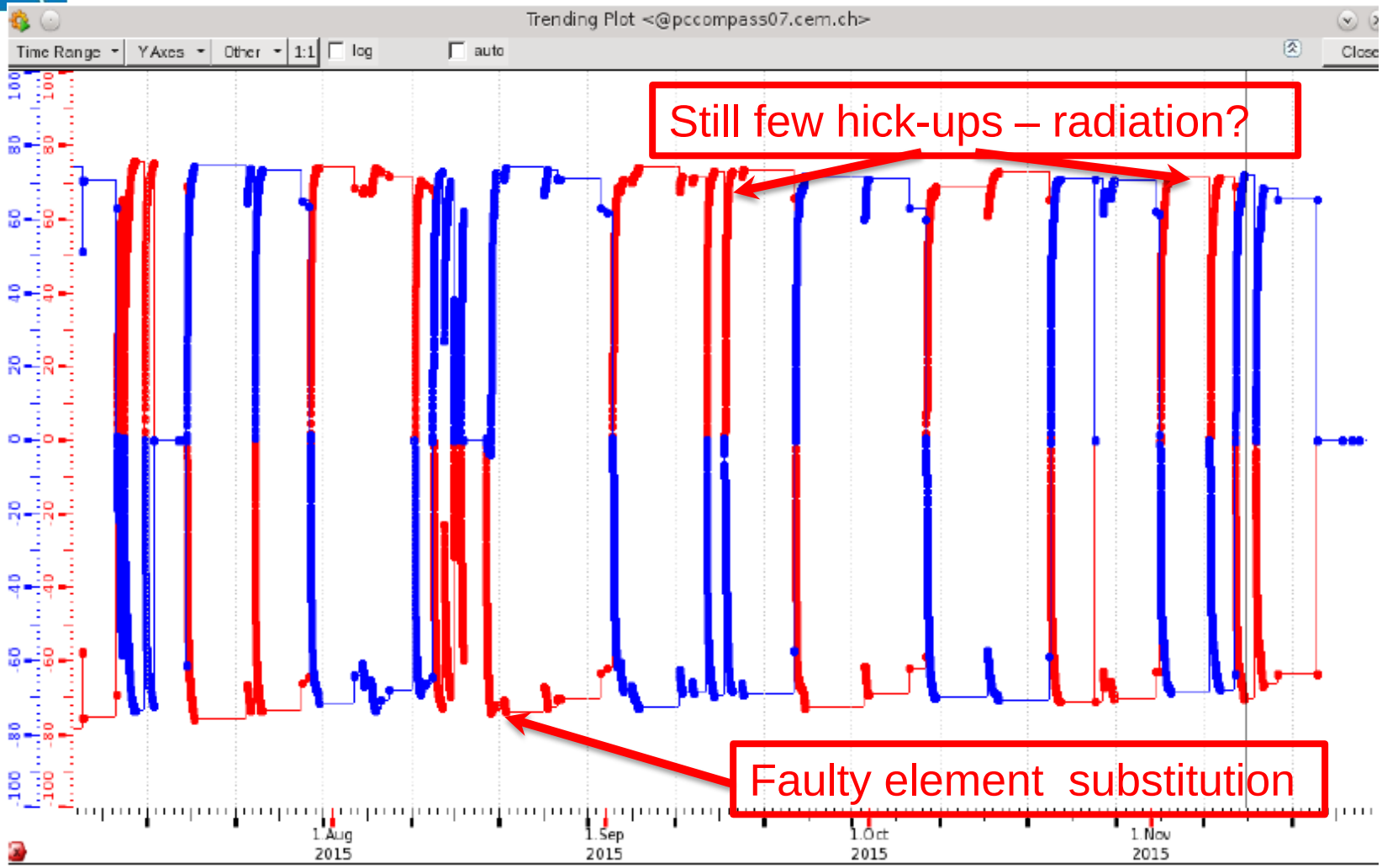
Partial Wave	Resonance(s)
$0^{-+}\,0^{+}\,f_0(980)\,\pi\,S$	$\pi(1800)$
$1^{++}\,0^{+}\,\rho(770)\,\pi\,S$	$a_1(1260)$, a_1'
$1^{++}\,0^{+}\,f_2(1270)\,\pi\,P$	$a_1(1260)$, a_1'
$2^{++}\,1^{+}\,\rho(770)\,\pi\,D$	$a_2(1320)$, a_2'
$2^{++}\,2^{+}\,\rho(770)\,\pi\,D$	$a_2(1320)$, a_2'
$2^{++}\,1^{+}\,f_2(1270)\,\pi\,P$	$a_2(1320)$, a_2'
$2^{-+}\,0^{+}\,\rho(770)\,\pi\,F$	$\pi_2(1670)$, $\pi_2(1880)$, $\pi_2'(2005)$
$2^{-+}\,0^{+}\,f_2(1270)\,\pi\,S$	$\pi_2(1670)$, $\pi_2(1880)$, $\pi_2'(2005)$
$2^{-+}\,1^{+}\,f_2(1270)\,\pi\,S$	$\pi_2(1670)$, $\pi_2(1880)$, $\pi_2'(2005)$
$2^{-+}\,0^{+}\,f_2(1270)\,\pi\,D$	$\pi_2(1670)$, $\pi_2(1880)$, $\pi_2'(2005)$
$4^{++}\,1^{+}\,\rho(770)\,\pi\,G$	$a_4(2040)$
$4^{++}\,1^{+}\,f_2(1270)\,\pi\,F$	$a_4(2040)$
$1^{++}\,0^{+}\,f_0(980)\,\pi\,P$	$a_1(1420)$
$1^{-+}\,1^{+}\,\rho(770)\,\pi\,P$	$\pi_1(1600)$

Compared to the previous analysis:
- 14 waves versus 6
- simultaneous fit in all 11 *t'* bins resulting in better separation of the resonant and non-resonant contribution as they have different *t'* dependences

Good results on stability test of our fit model: the resulting resonance parameters are in agreement with PDG averages.

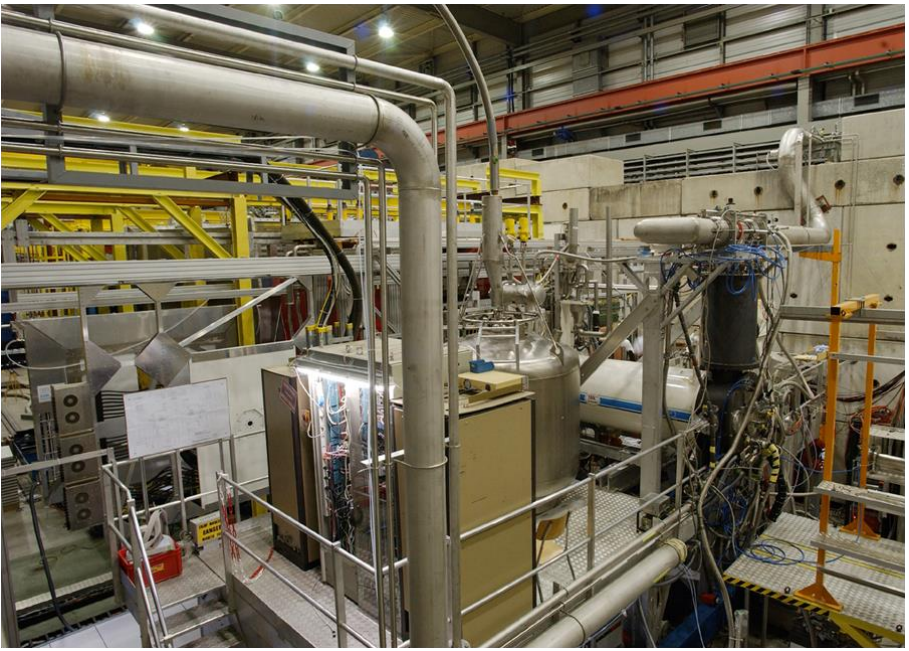


COMPASS Drell-Yan Run 2015 III
Polarised Target & PT Magnet



On-line polarization value is plotted here, after application of the **very preliminary** calibration
Procedure polarization was reaching ~80% what fits our expectations

SIDIS longitudinal



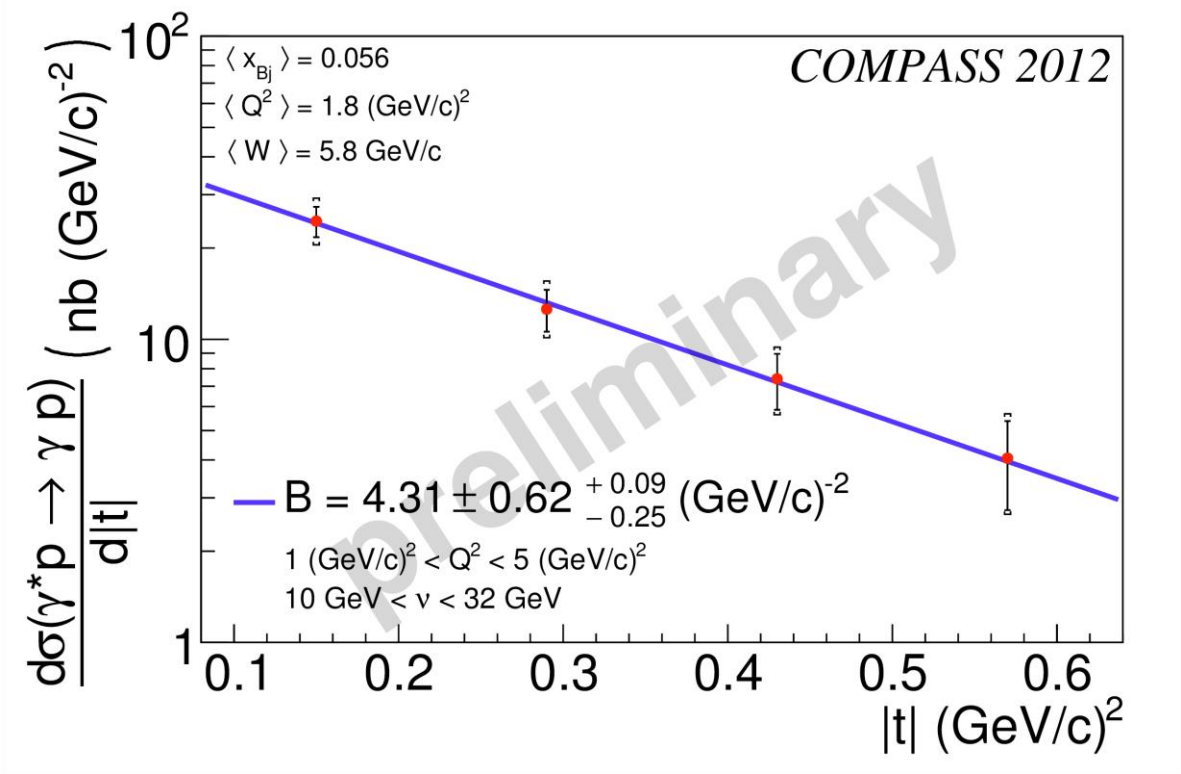
Deuteron data:
Published:
2002 and 2004 Q^2>1

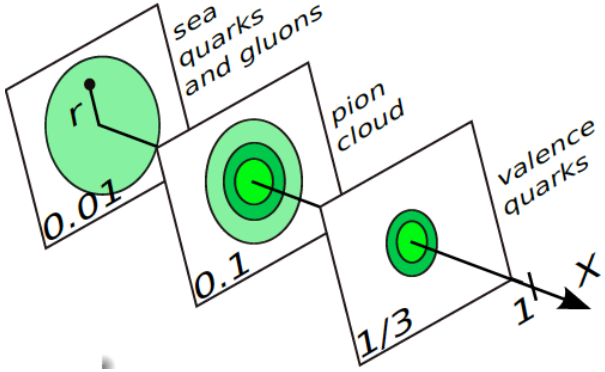
This report – Deuteron 2006 Q^2>1

Proton data:
Published:
2007, 2011 $Q^2 > 1$

This report: Proton 2007, 2011 $Q^2 < 1$

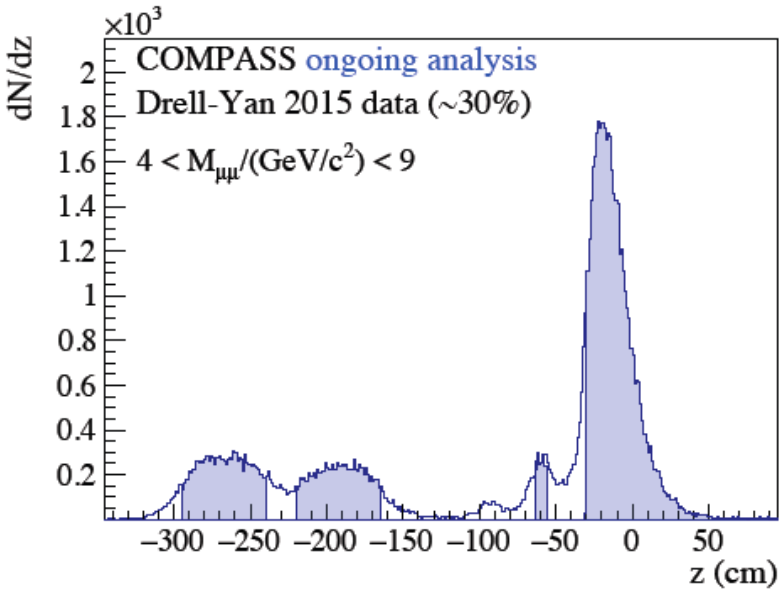
DVCS 2012 results V: *t*-slope



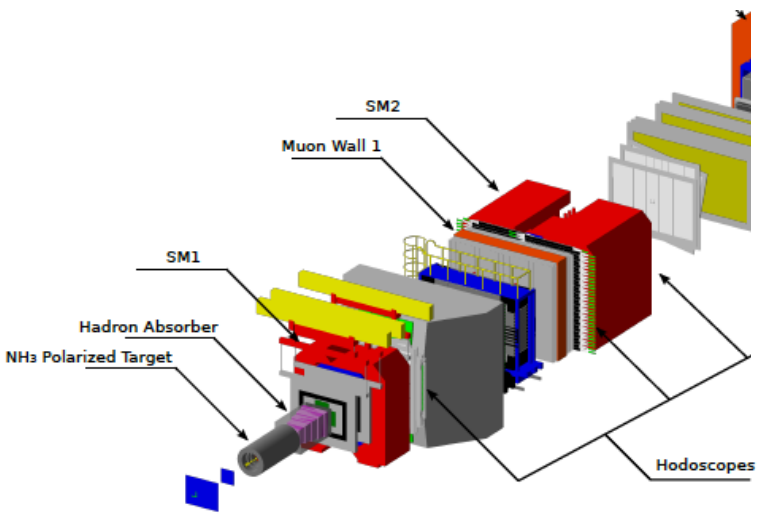


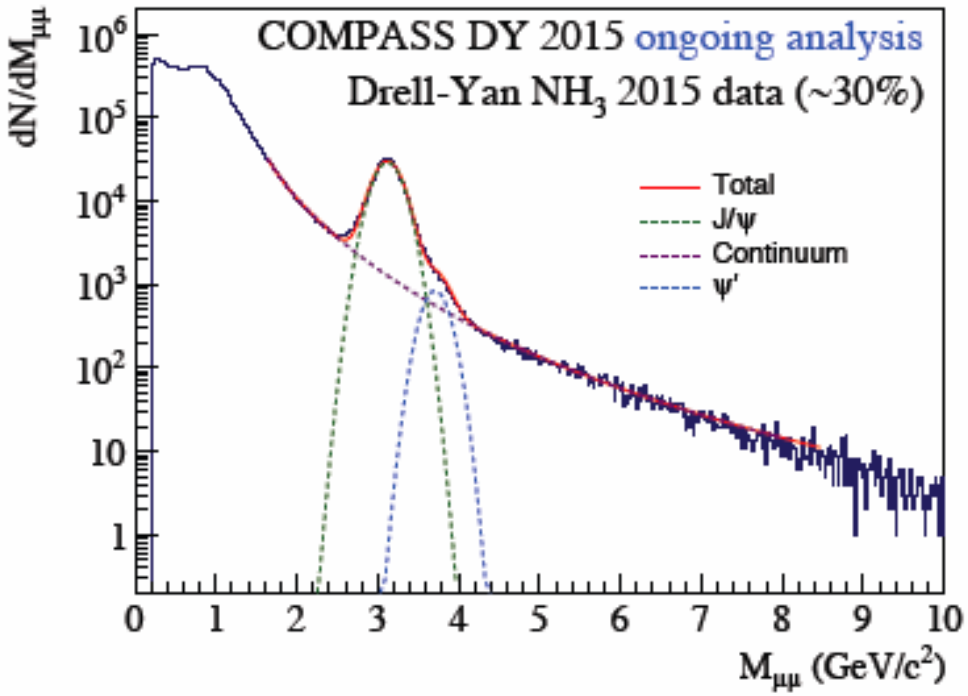
N.B. the probability for all point to stay at the same line is 7%

COMPASS Drell-Yan Run 2015 III
Data Analysis



Three periods (out of 9) produced and analysed, Stability, quality and kinematic cuts as well as event selection **are conservative and not yet final.**



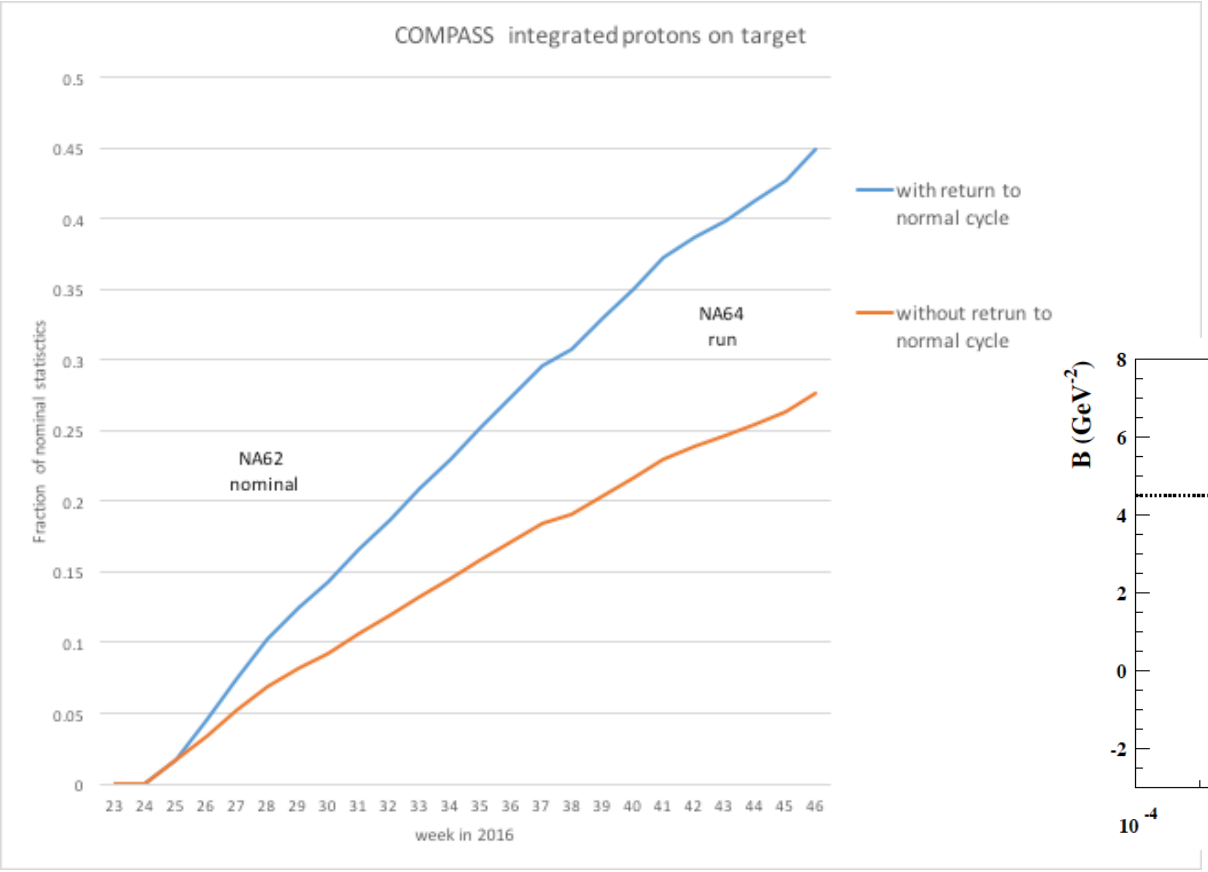


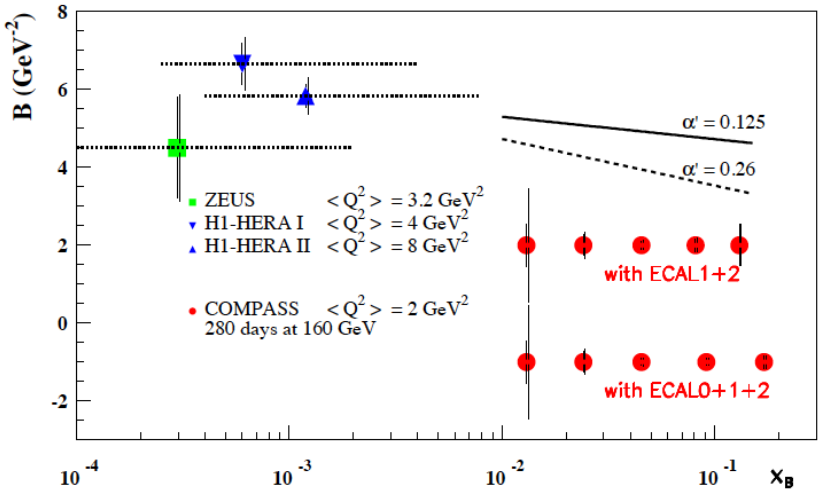
Total number of J/ψ is **644000 ± 885**

Total number of HM ($M_{\mu\mu}$ > 4 GeV/ c^2) is **18198**

DVCS run 2016 – projections and impact

Beam availability is the main problem.
Optimistic scenario : ~45-50% compared to the Proposal
Pessimistic scenario: ~25%
Thus after 2 years (2016-2017): 63% - 75% (assumption 2017 – 100%)





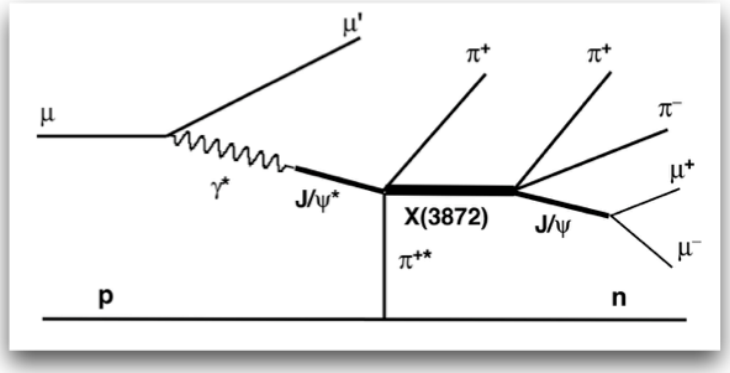
Light quarks hadron spectroscopy, exotic charmonium-like states

Channel	status	details
Leptopoduction of $\psi(2S)$ and $X(3872)$	new	pbw
Pion polarisability from 2012 data	update	study of systematic effects using muon control data
Determination of the chiral dynamics in $\pi^+\gamma \to \pi^-\pi^0\pi^0$	update	ongoing
Measurement of chiral anomaly in $\pi^+\gamma \to \pi^-\pi^0$	new	started
New axial-vector meson $a_1(1420)$ in $\pi^- p \to \pi^-\pi^-\pi^+ p_{\text{recoil}}$	final	PRL 115 (2015) 082001
Resonance Production and $\pi\pi$ S-wave in $\pi^- p \to \pi^-\pi^-\pi^+ p_{\text{recoil}}$	final	submitted to PRD 88-wave PWA in 11 t' bins
Extraction of 3π resonances in $\pi^- p \to \pi^-\pi^-\pi^+ p_{\text{recoil}}$	update	simultaneous fit of 14 waves in 11 t' bins pbw
Study of non-resonant contributions in $\pi^- p \to \pi^-\pi^-\pi^+ p_{\text{recoil}}$	new	inclusion of Deck amplitude into PWA
Study of $\pi^+\pi^-$ subsystem in $\pi^- p \to \pi^-\pi^-\pi^+ p_{\text{recoil}}$	update	extension of method to more waves
Central production of $\pi^+\pi^-$ in $pp \to p_{\text{fast}}\pi^-\pi^+ p_{\text{recoil}}$	update	analysis in (t_1, t_2) bins

Nucleon structure study using muon beam

Channel	status	details
Muon data		
NLO pQCD fit to the $g_1^{p,n,d}$ world data and the test of the Bjorken sum rule including the 2011 g_1^p data	final	PLB 753 (2016) 18
NLO pQCD fit to the $g_1^{p,n,d}$ world data and the test of the Bjorken sum rule including the 2006 g_1^d data	update	pbw
Pion and kaon asymmetries from longidinally pol. SIDIS from 2011 proton data	starting	ongoing
2007&2011 proton g_1 at $Q^2 < 1$ GeV$/c$	final	pbw
Determination of $\Delta g/g$ using the all-p_T events	final	publishing, hep-ex/1512.05053
Asymmetry of inclusive photoproduction of hadrons with high-p_T at $Q^2 < 1$ (GeV$/c$)^2	final	PLB 753 (2016) 573
π multiplicities (2006 data) and FFs to pions	final	publishing, hep-ex/1604.02695
Kaon multiplicities (2006 data) and FFs to kaons	update	pbw
Neutral kaon multiplicities (2006 data) and FFs to kaons	new	ongoing
p_T^h dependence of multiplicities (2006 data)	update	ongoing
Interplay between Collins and two hadron asymmetries	final	PLB 753 (2016) 406
The Sivers asymmetries in the Drell-Yan $x - Q^2$ region	final	pbw
Multidimensional analysis of all eight transverse asymmetries	final	pbw
Weighted azimuthal asymmetries (2010 proton)	new	ongoing
The Sivers asymmetries for gluons in the proton and deuteron	final	pbw
Azimuthal asymmtries for longitudinally polarised target	final	pbw
Exclusive Omega production	final	submission

Exotic X(3872) lepto-production II



In order to estimate the width of X(3872) we use *ψ(2S)* as a reference signal,
we assume that production mechanism is the same (CEX) and
we neglect the phase space and acceptance difference
We profit of the known parameters of *ψ(2S)*

$$\frac{N_{X(3872)}}{N_{\psi(2S)}} = \frac{\Gamma_{X(3872)\to J/\psi\pi\pi} BR_{X(3872)\to J/\psi\pi\pi}}{\Gamma_{\psi(2S)\to J/\psi\pi\pi} BR_{\psi(2S)\to J/\psi\pi\pi}} = \frac{\Gamma^2_{X(3872)\to J/\psi\pi\pi}\Gamma_{\psi(2S)}}{\Gamma^2_{\psi(2S)\to J/\psi\pi\pi}\Gamma_{X(3872)}} = 0.9 \pm 0.4$$

For *ψ(2S)*: $\Gamma_{\psi(2S)}$ = 298 keV, $\Gamma_{\psi(2S)\to J/\psi\pi\pi}$ = 103 keV,

thus $\Gamma_{X(3872)\to J/\psi\pi\pi} BR_{X(3872)\to J/\psi\pi\pi} = 32 \pm 14\ keV.$

$$\Gamma_{X(3872)\to J/\psi\pi\pi} = \Gamma_{\psi(2S)\to J/\psi\pi\pi}\sqrt{R \times \frac{\Gamma_{X(3872)}}{\Gamma_{\psi(2S)}}} < 210\,\mathrm{keV}/c^2 \text{ at 90\% confidence level.}$$

as $\Gamma_{X(3872)}$<1.2 MeV CL=90%, and

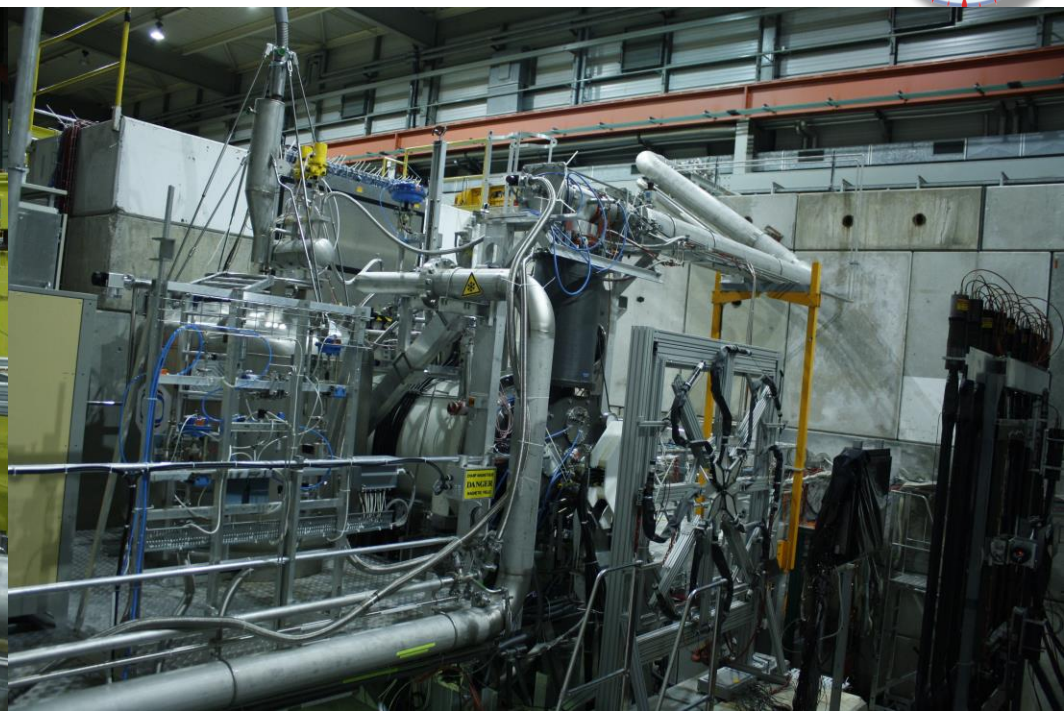
$$\Gamma_{X(3872)} = R \times \frac{\Gamma_{\psi(2S)\to J/\psi\pi\pi} \times B_{\psi(2S)\to J/\psi\pi\pi}}{B^2_{X(3872)\to J/\psi\pi\pi}} > 80\,\mathrm{keV}/c^2.$$

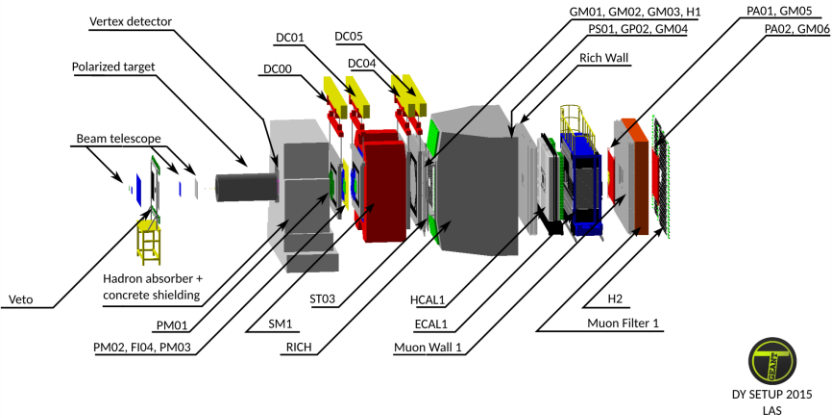
First ever observation in photo – production experiments,

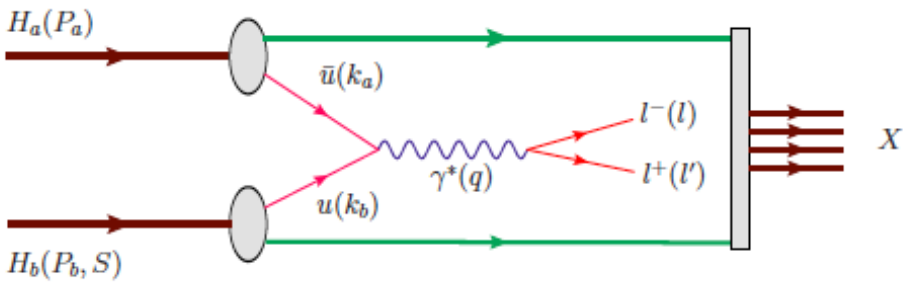
More to come from CLAS or GlueX

COMPASS Drell-Yan Run 2015 I

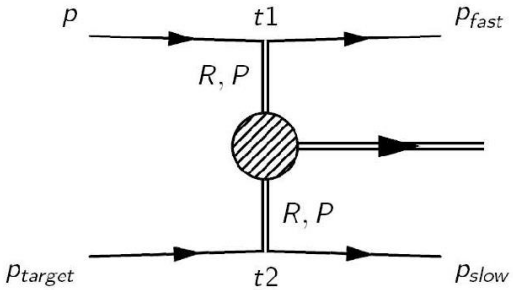
First ever polarised Drell-Yan data





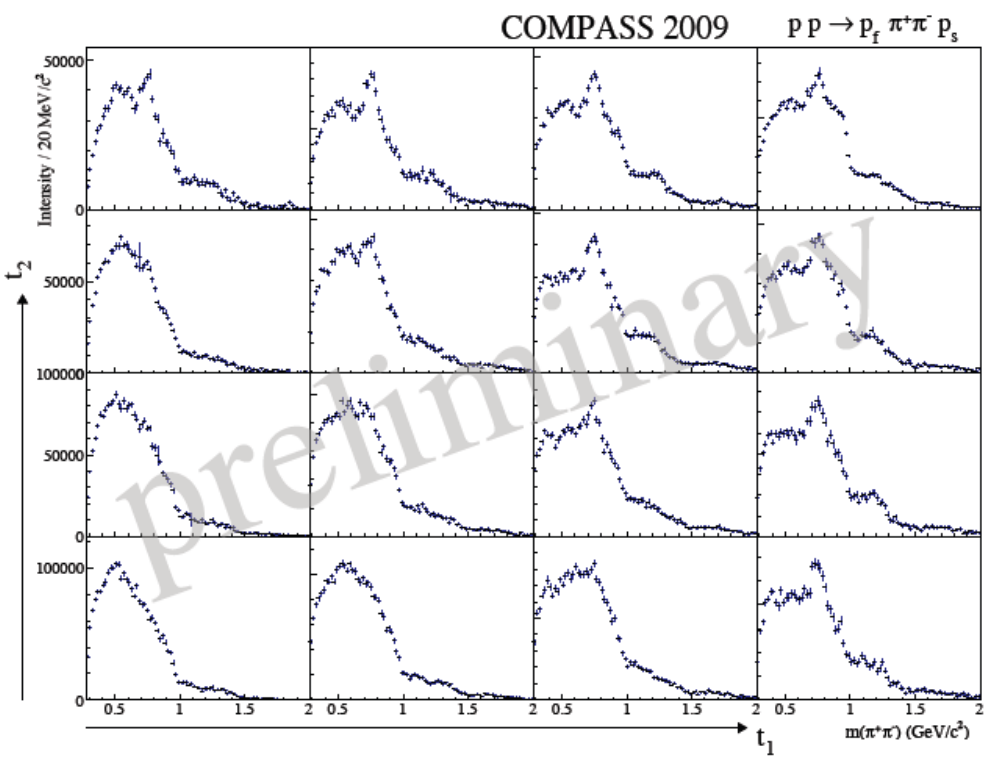


Central production I



Central production, proton beam in 2008 and 2009.

Analysis is in progress:
- two mesons in the final state ($\pi^+\pi^-$, $\pi^0\pi^0$ and $K^+ K^-$)
- at COMPASS kinematics P-R, R-R and diffraction processes
- *S*, *P* and *D* waves (spin projection M ≤ 1) contribute significantly.



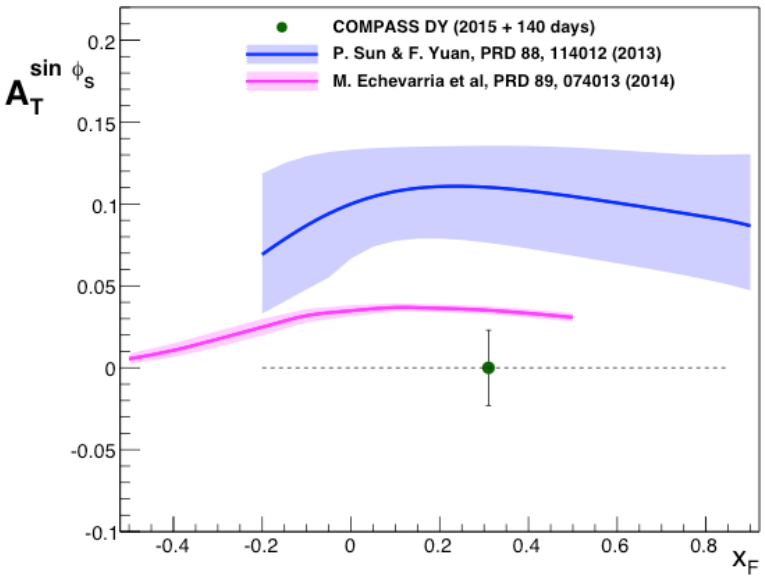
S wave exhibit some contamination by $\rho(770)$ meson – to clarify PWA was performed in t_1 t_2 bins.

Low t_1 and t_2 - ρ (770) signal has practically vanished. These bins are dominated by a double-Pomeron exchange mechanism where ρ production is forbidden (C-parity conservation)

More work is needed to develop a method that correctly takes into account the $\rho(770)$ contamination in the *S*-wave.

Request for a Drell-Yan Run in 2018 II

Goal: to increase a total polarised data sample by at least factor 2 in order to achieve the statistical error on Sivers asymmetry (2015+2018) of ~ 2% (small asymmetry in case of fast TMDs evolution) and to collect world largest kaon and anti-proton induced DY data sample.



List of upgrades/improvements:
- Faster commissioning, longer running time
- PT & PT Magnet performance
- SciFi beam telescope performance (additional plane(s))
- Tracking performance in LAS (DC5 with new f/e)
- DAQ and Veto dead time reduction
- Sensitive spectrometer elements protection against radiation
- Overall performance and spectrometer stability
- Efficient kaon and anti-proton tagging

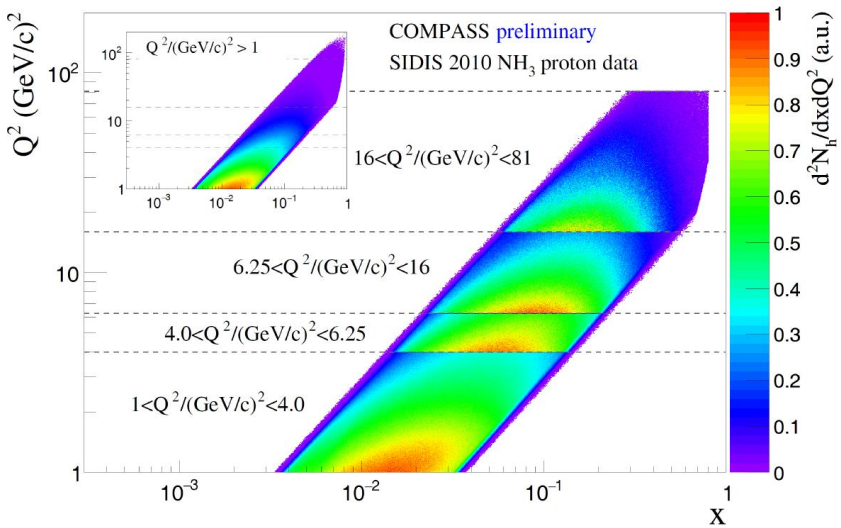
	COMPASS (projections)			NA3 [55]	NA10 [56]	E537 [57]	E615 [58]
target/beam	NH_3	Al	W	Pt	W	W	W
π^-	145000	11500	318000	32288	285800	1101	27977
K^-	1200	100	3000	700	–	–	–
$\bar{p}$	860	60	1500	–	–	387	–

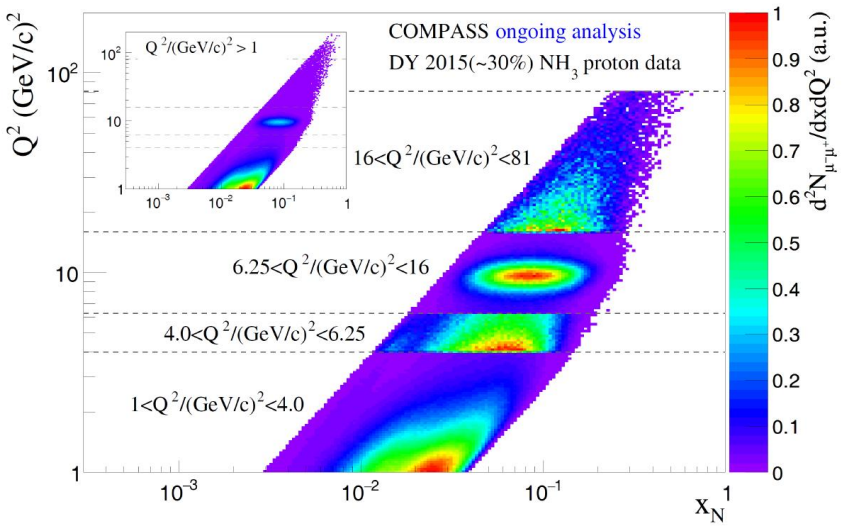
SIDIS transverse&longitudinal III

Most awaited result of COMPASS-II (Drell-Yan) – Sivers sign change from SIDIS to Drell-Yan. Important: the same kinematic range, to avoid large TMD evolution effects.

2010 proton SIDIS: Sivers asymmetry in HM (4 GeV/c^2 < Q < 9 GeV/c^2). Drell-Yan range. The first release (2014) has shown significant Sivers asymmetry.

For final publication the newly produced 2010 data will be used





SIDIS transverse V

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 parametrisation of the unknown transverse momentum dependence of PDFs and FFs is needed..

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

<u>Important</u>: large statistics, good acceptance.

Allows to extract first momentum of Sivers

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

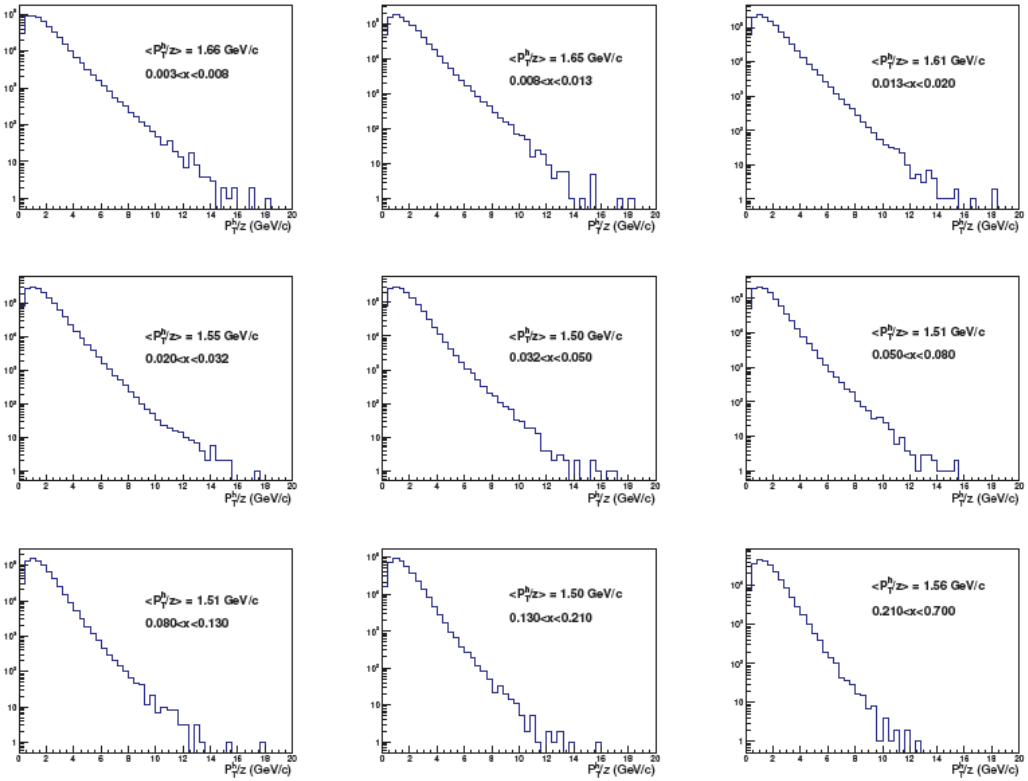


Fig. 18: Typical p_T^h/z distributions in the nine standard COMPASS x bins.

At large and moderate x p^h_T/z stays < Q, so we are in the range of TMDs formalism applicability

COMPASS Publications 2015/16

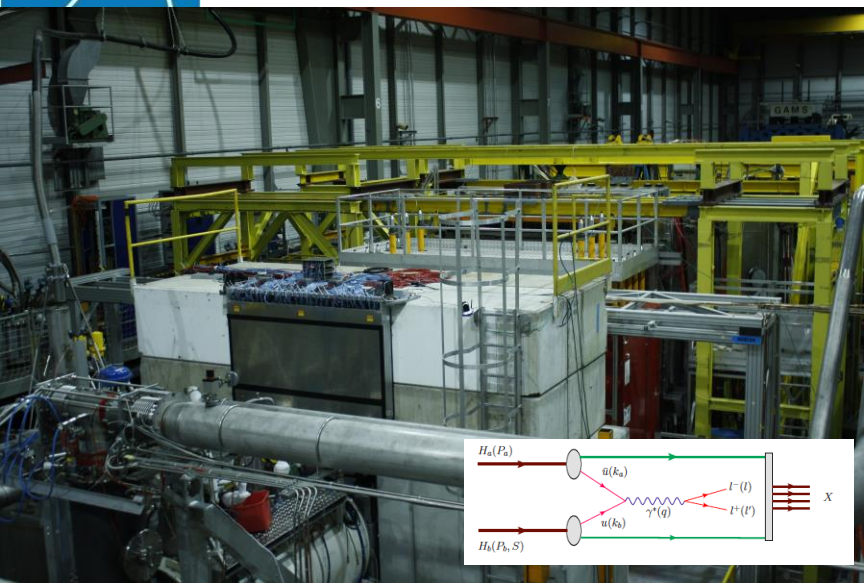
subm. 2015				
21.01.15	*Observation of a new narrow axial-vector meson $a_1(1420)$*	tar	PRL 115 (2015) 082001 DOI	CERN-PH-EP/2015-015 hep-ex/1501.05732
26.03.15	*The spin structure function g_1^p of the proton and a test of the Bjorken sum rule*		PLB 753 (2016) 18 DOI	CERN-PH-EP/2015-085 hep-ex/1503.08935
27.07.15	*Interplay among transversity induced asymmetries in hadron leptoproduction*	tar	PLB 753 (2016) 406 DOI	CERN-PH-EP/2015-199 hep-ex/1507.07593
28.08.15	*Resonance Production and $\pi\pi$ S-wave in $\pi^-+p\rightarrow\pi^-\pi^-\pi^++p_{recoil}$ at 190 GeV/c*	tar	sub PRD	CERN-PH-EP/2015-233 hep-ex/1509.00992
8.09.15	*Longitudinal double spin asymmetries in single hadron quasi-real photoproduction at high p_T*	tar	PLB 753 (2016) 573 DOI	CERN-PH-EP-2015-245 hep-ex/1509.03526
16.12.15	*Leading-order determination of the gluon polarisation using a novel method*	tar	sub PLB	CERN-PH-EP-2015-328 hep-ex/1512.05053
subm. 2016				
10.04.2016	*Multiplicities of charged pions and unidentified charged hadrons from deep-inelastic scattering of muons off an isoscalar target*	tar	sub PLB	CERN-EP/2016-095 hep-ex/1604.02695
11.06.2016	*Exclusive ω meson muoproduction on transversely polarised protons*	tar	to be sub NPB	hep-ex/1606.03725

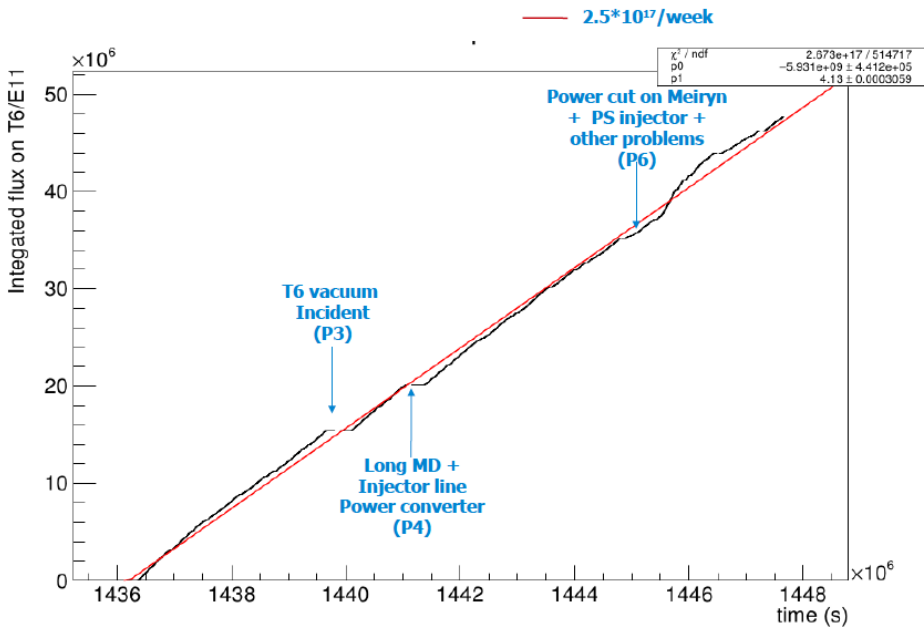
More papers are in pipeline:

1. Multiplicities of charged kaons (almost finished)
2. Multiplicities of the neutral kaons (draft1 in progress)
3. $\pi_1(1600)$ – drafted
4. Extraction of A_1^p and g_1^p for Q2 < 1 $(GeV/c)^2$ in two-dimensional bins from the 2007 and 2011 longitudinal data (draft1 in progress)
5. A_1^d 2002-2006 data, final paper (draft1 in progress)
6. Transverse spin and TMD PDFs in the Drell-Yan kinematic range (finished)
7. The Sivers asymmetry of the gluons on transversely polarized deuterons and protons (draft1 in progress)
8. …..

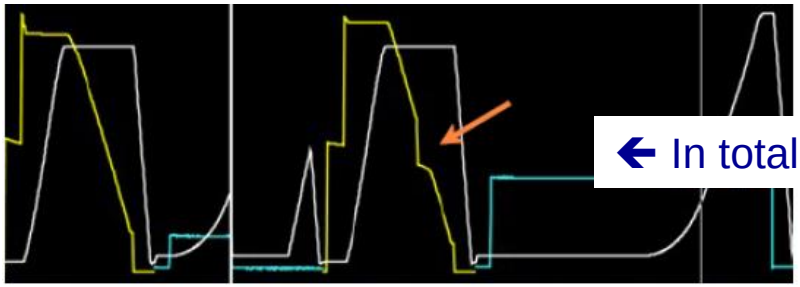
COMPASS Drell-Yan Run 2015 I

First ever polarised Drell-Yan data set successfully collected

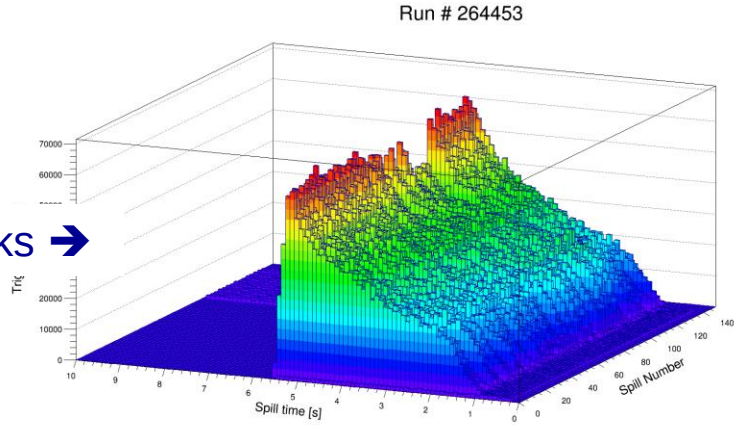




Late start (08/07/2015) because of the PT magnet (manpower availability) and spectrometer commissioning.
9 periods are collected (~2 weeks long each, polarisation is inverted after first week)
Good machine performance: on average 84% Good spectrometer availability: ~80%



← In total several weeks →



COMPASS Drell-Yan Run 2015 IV
Data Analysis

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \overset{LO}{=} \frac{\alpha^2}{Fq^2}\hat{\sigma}_U \Big\{ 1 + D_{[\sin^2\theta]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} + \tag{12}$$
$$+ S_T \Big[A_T^{\sin\phi_S} \sin\phi_S +$$
$$+ D_{[\sin^2\theta]} \Big(A_T^{\sin(2\phi_{CS}+\phi_S)} \sin(2\phi_{CS}+\phi_S) + A_T^{\sin(2\phi_{CS}-\phi_S)} \sin(2\phi_{CS}-\phi_S) \Big) \Big] \Big\},$$

The asymmetries are extracted separately for each period (3 x 4 bins in for each period).
The compatibility checks performed – no strong inconsistencies between different periods.

COMPASS Drell-Yan NH3 2015 data (~30%)
Copatibility of periods (preliminary)