



Outline

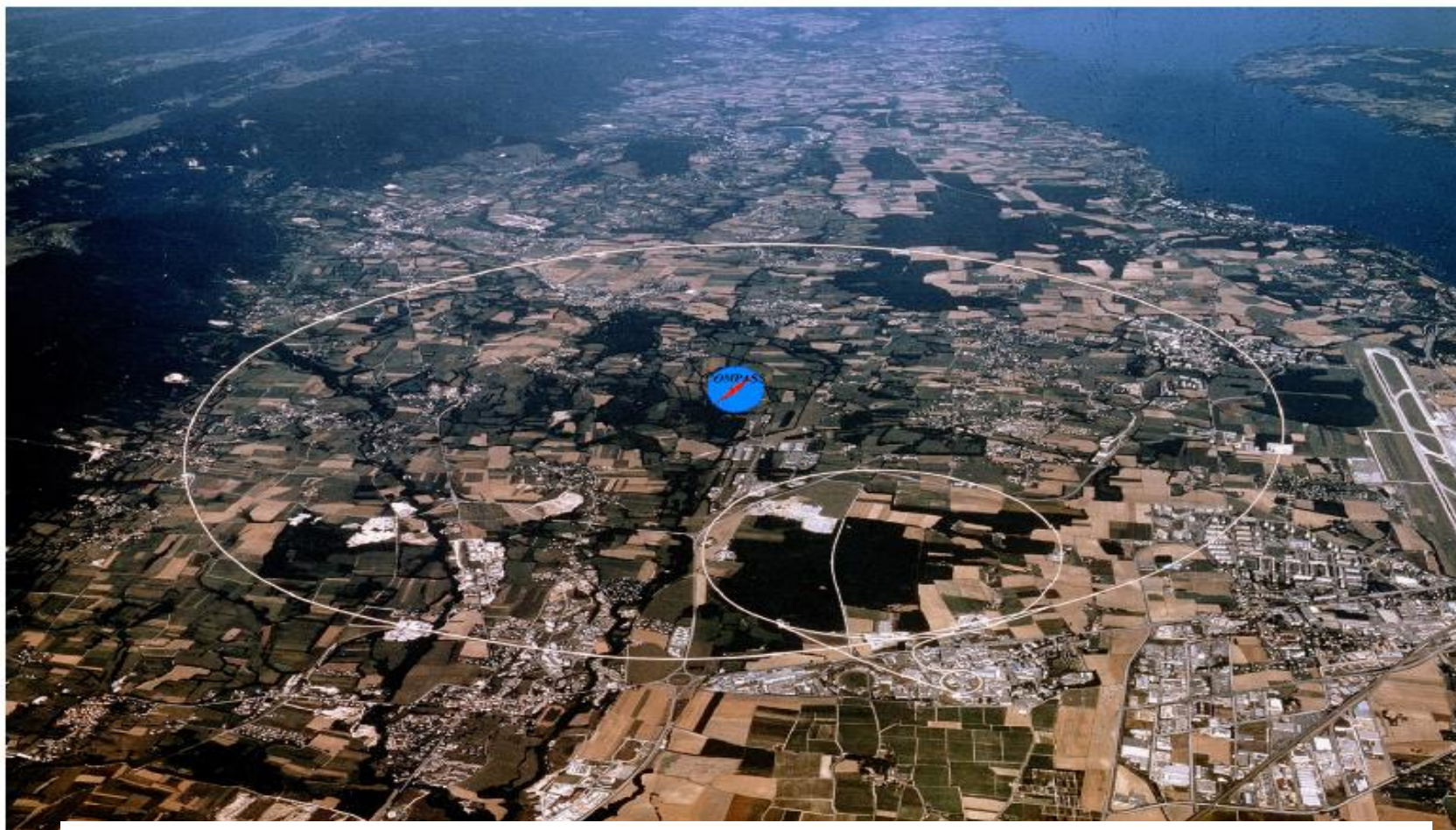


1. **COMPASS facility at CERN**
2. **Hadron spectroscopy**
 - Light quark spectroscopy
 - Heavy state X(3872)
3. **Nucleon structure with muon beam**
 - Transversity
 - Sivers
 - Multiplicities
4. **GPDs access via DVCS and DVMP**
5. **Polarised Dell-Yan experiment**
6. **COMPASS beyond 2020**
 - COMPASS short term future
 - COMPASS-like experiment long term future
7. **Summary**

See as well talks by Franco, Stephane, Alexey, Catarina, Bakur, Boris, Johannes, Vincent,

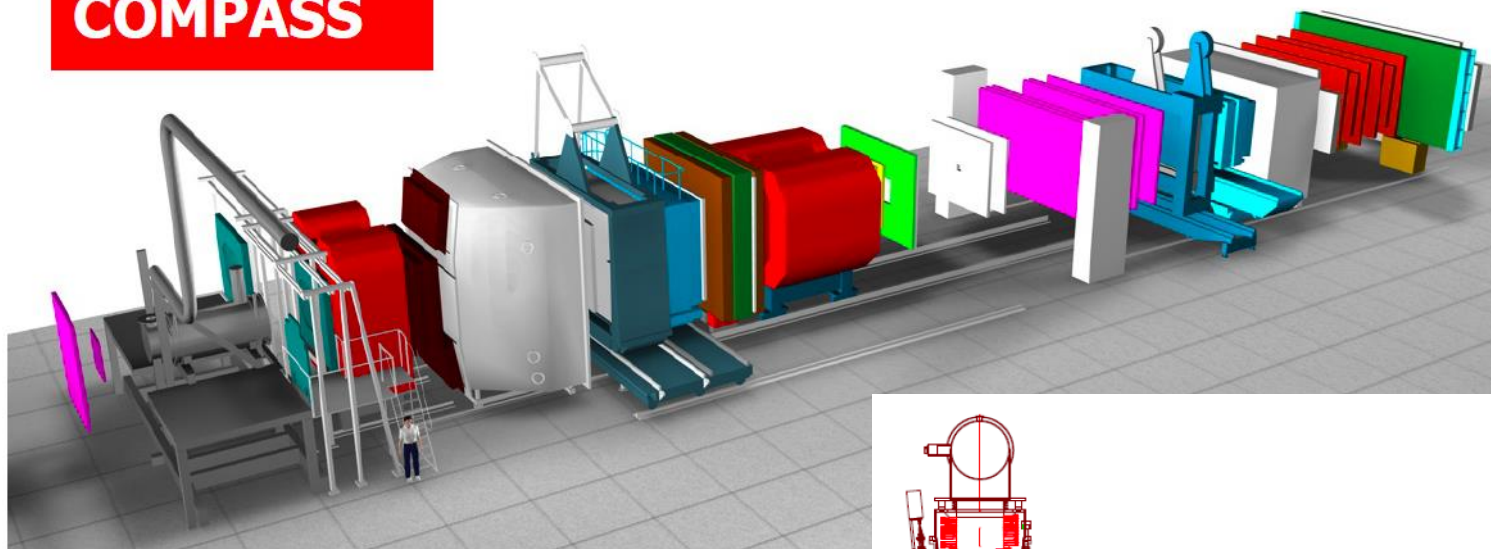
COMPASS QCD facility at CERN (SPS)

COmmon MUon PProton Apparatus for Structure and Spectroscopy



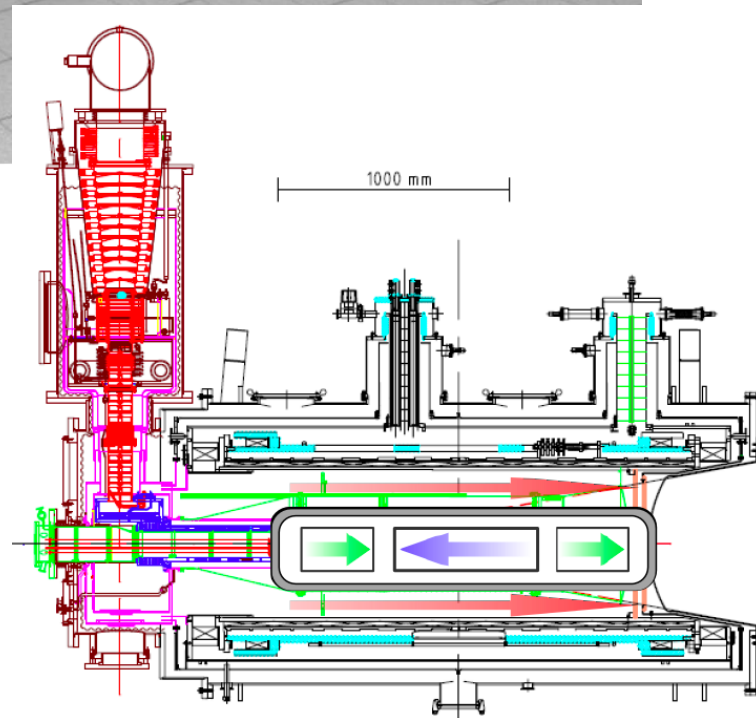
~240 physicists, 12 countries + CERN, 24 institutions

COMPASS



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)

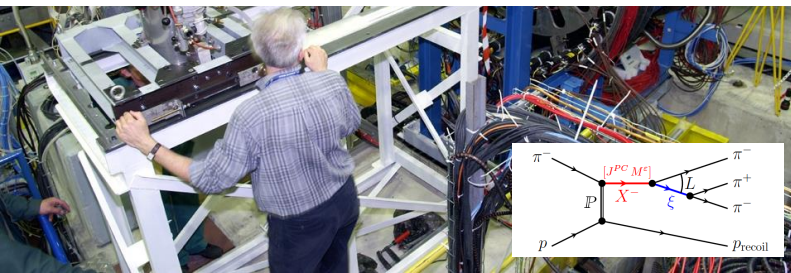




COMPASS QCD facility at SPS M2 beam line (CERN) (secondary hadron and lepton beams)

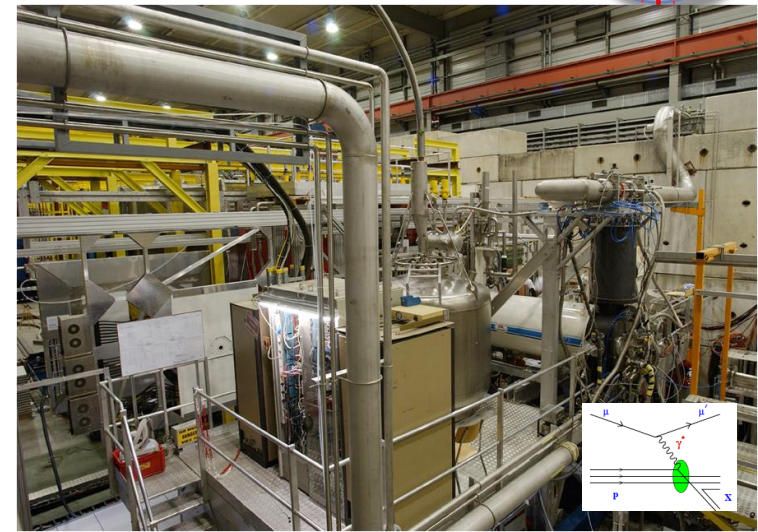


Exotic state, chiral dynamics



Hadron Spectroscopy & Polarizability

**COMPASS-I
1997-2011**



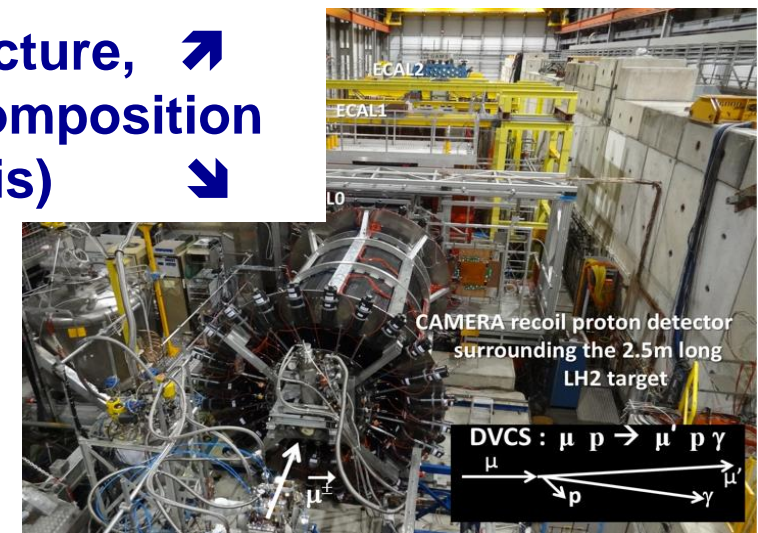
Polarised SIDIS



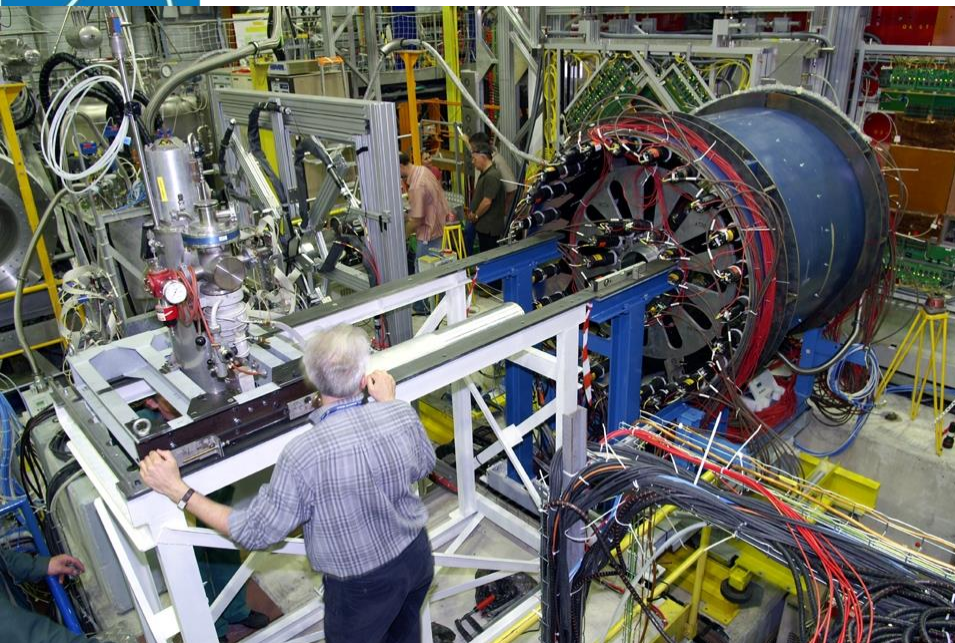
Polarised Drell-Yan

**3D hadron structure, ↗
Proton spin decomposition
↘ (spin crisis) ↘**

**COMPASS-II
2012-..**



DVCS (GPDs) + unp. SIDIS

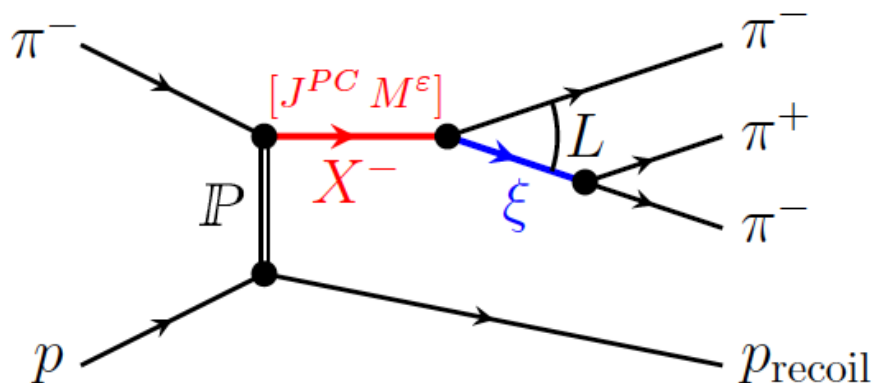


2008-2009 data taking, 190 GeV/c
hadron beam on a hydrogen target.

3π data sample $\sim 50 \times 10^6$ 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).

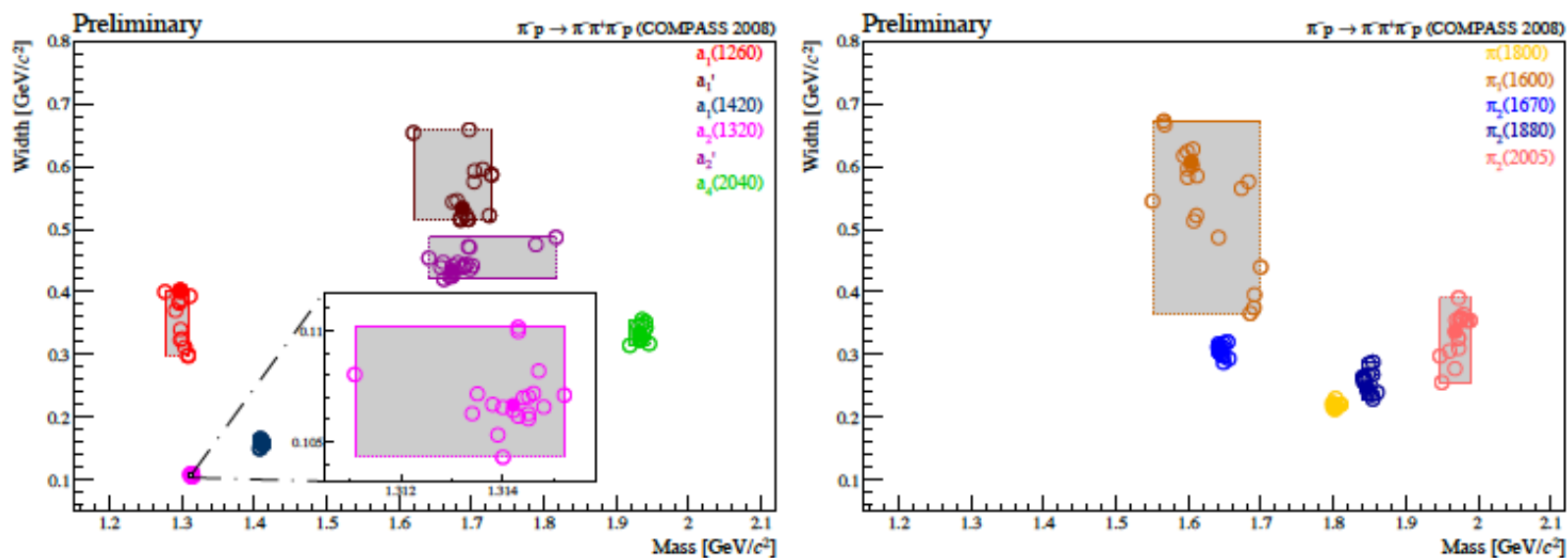
A lot of work to be invested to develop new
methods in order to cope with huge data
sample.



Analysis steps:

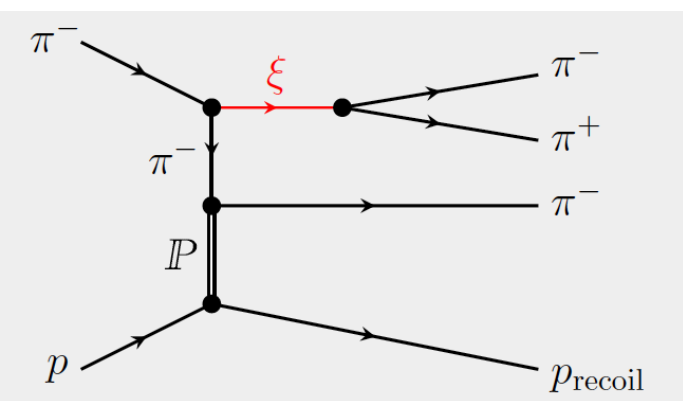
1. p-w decomposition: 88x88 spin-density matrix for each t' (f.m. transfer squared) and $m_{3\pi}$ bin (mass-independent fit)
2. For selected wave set (14 waves, 60% of total intensity) fit of the spin-density matrix by a resonance models (B.-W. + coherent non-resonant term)

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.

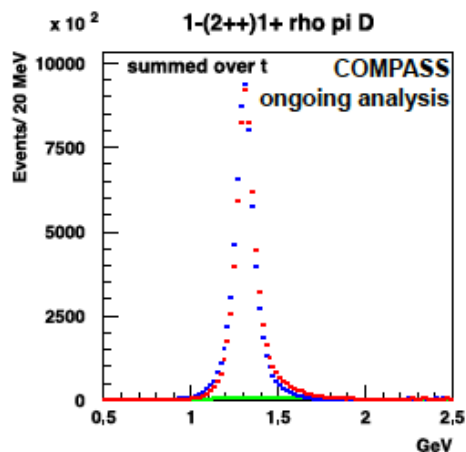
Plotted – closed circles – best fit parameters, rectangles – systematic uncertainties for 11 resonant components used in the resonance-model fit to the spin-density matrix of selected 14 waves



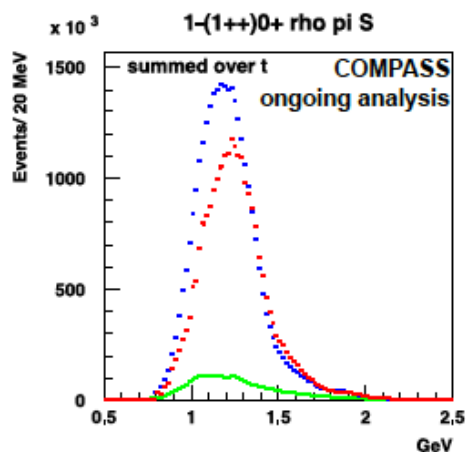
Non-resonant contribution – main contributor to systematic. Believed it is caused by pion fluctuation into $\pi^+\pi^-$ isobar ($\rho(770)$) and virtual π – Deck amplitude. It projects in many waves.

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

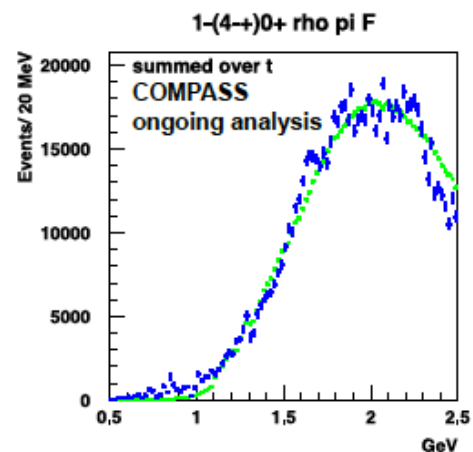
- low non-resonant contribution - stays unchanged (a)
- considerable fraction of non-resonant contribution – absorbed into Deck amplitude (b)
- high spin waves – Deck contribution absorbs all intensity (c)



(a)



(b)

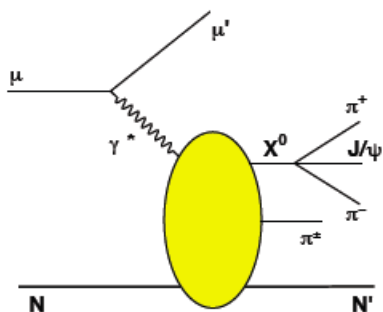


(c)

Exotic X(3872) lepto-production update

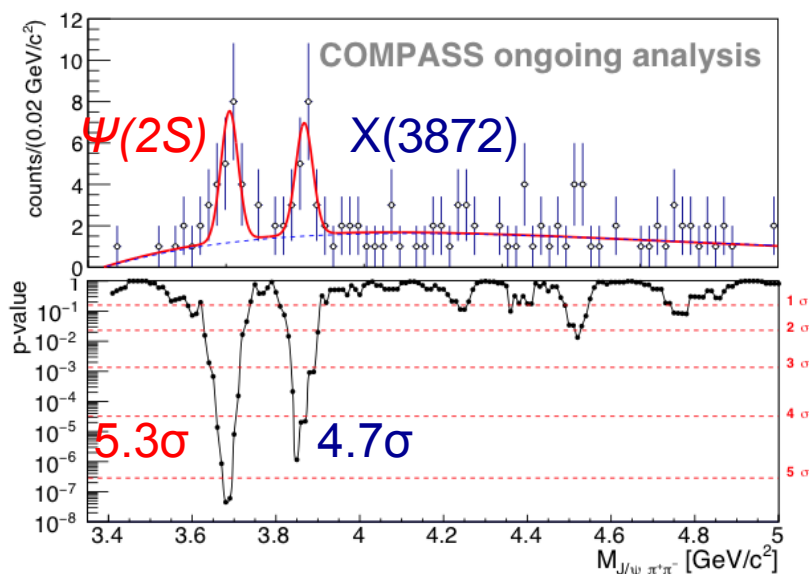
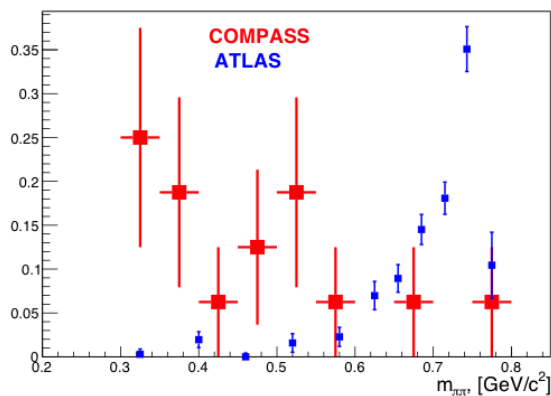
X(3872) is the first charmonium-like exotic hadron discovered by the Belle collaboration in 2003 and studied than in other experiments. Various interpretations exists: tetra-quark, DD^* -molecule, hybrid $c\bar{c}g$ state, glue-ball or else.

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



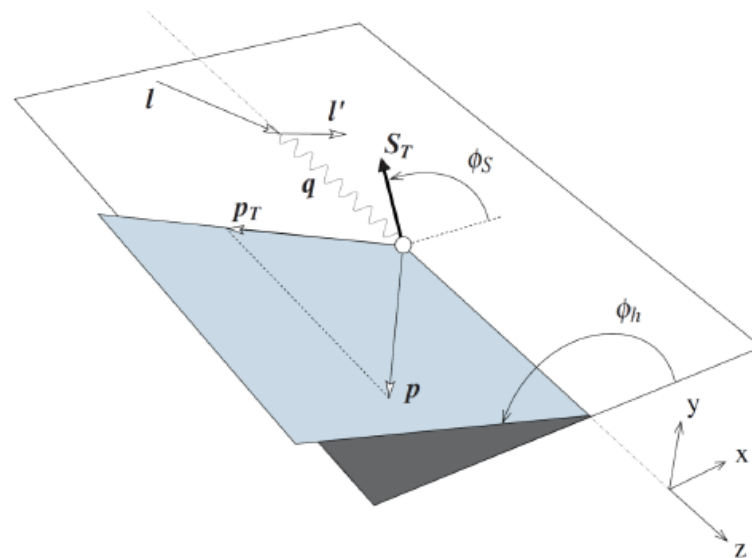
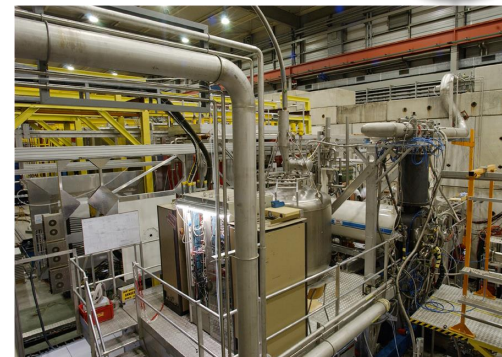
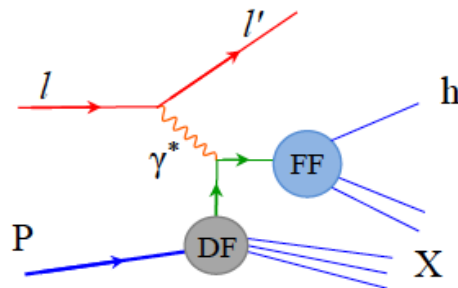
COMPASS muon beam data 2003→2010
Study $J/\psi\pi^+\pi^-\pi^\pm$ subsystem of exclusive final state $J/\psi\pi^+\pi^-\pi^\pm$

COMPASS di-pion mass spectrum is different compared to the Atlas observation.



$$\sigma_{\gamma N \rightarrow X(3872) \pi^\pm N'} \times \mathcal{B}_{X(3872) \rightarrow J/\psi \pi \pi} = 71 \pm 28(\text{stat.}) \pm 39(\text{syst.}) \text{ pb}$$

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) (F_{UU,T} + \varepsilon F_{UU,L}) \right] \times \left\{ \begin{array}{l} \left[1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \right. \\ \left. + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \right] \\ + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h - \phi_S)} \sin(2\phi_h - \phi_S) \end{array} \right] \\ + S_T \lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h - \phi_S)} \cos(2\phi_h - \phi_S) \end{array} \right] \end{array} \right\}$$



$$A_{U(L),T}^{w(\phi_h, \phi_S)} = \frac{F_{U(L),T}^{w(\phi_h, \phi_S)}}{F_{UU,T} + \varepsilon F_{UU,L}}; \quad \varepsilon = \frac{1 - y - \frac{1}{4} \gamma^2 y^2}{1 - y + \frac{1}{2} y^2 + \frac{1}{4} \gamma^2 y^2}, \quad \gamma = \frac{2Mx}{Q}$$

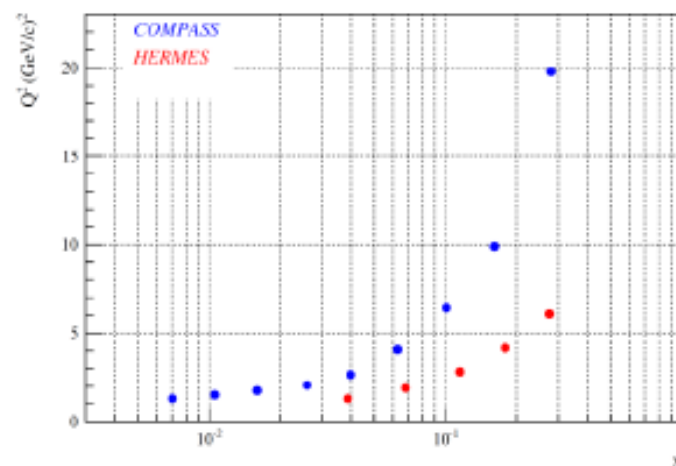
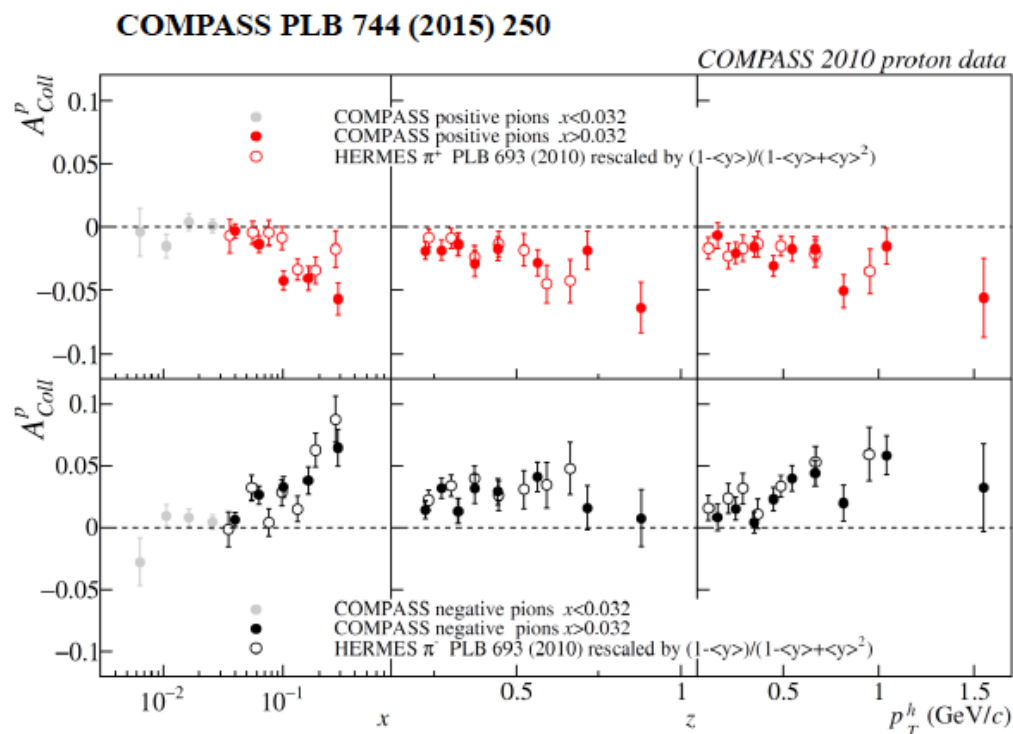
Collins asymmetry (transversity) zero knowledge ~10 years ago

First seen non zero asymmetry by HERMES on p in 2004

COMPASS:

- Measured on p/D in SIDIS and in di-hadron SIDIS
- Compatible results COMPASS/HERMES
- No (or very slow) QCD evolution? Very intriguing result!

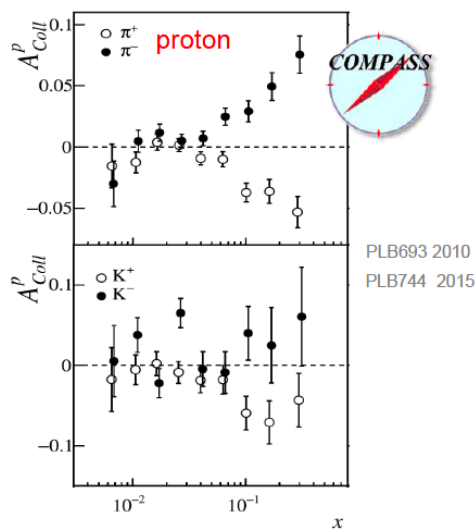
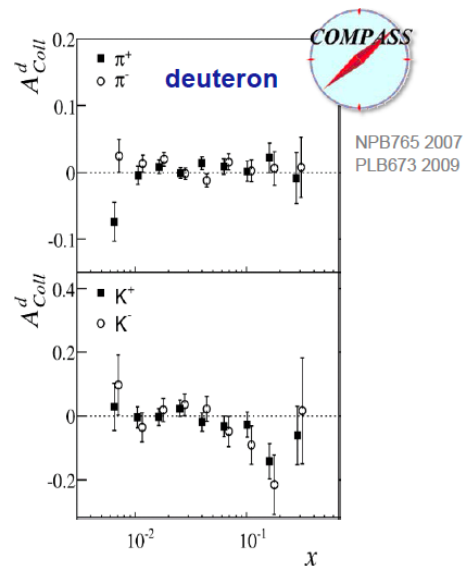
$$A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$



Collins asymmetry (transversity)

Deuteron data – flavour separation possible

COMPASS:

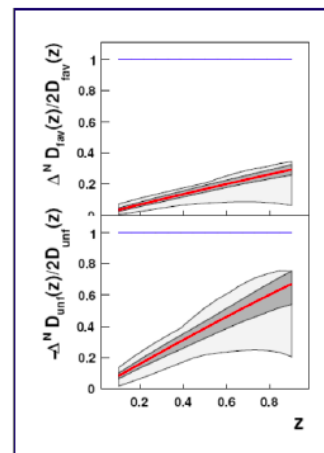
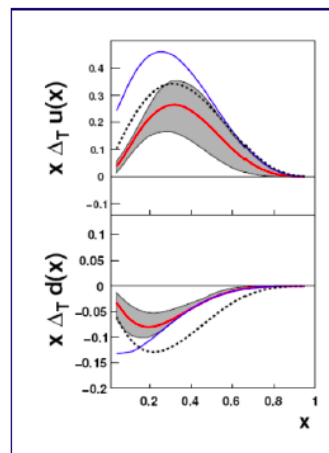


Flavour dependent

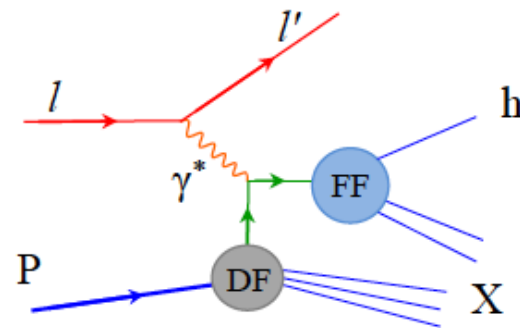
M. Anselmino et al., Nucl. Phys. Proc. Suppl. 2009

fit to HERMES p, COMPASS d, Belle e+e- data

Reasonably well
constrained using Belle &
Hermes & COMPASS
data



$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) (F_{UU,T} + \varepsilon F_{UU,L}) \right] \times \left\{ \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ & + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \\ & + S_T \left[\begin{aligned} & A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ & + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ & + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \\ & + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ & + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h - \phi_S)} \sin(2\phi_h - \phi_S) \end{aligned} \right] \\ & + S_T \lambda \left[\begin{aligned} & \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h - \phi_S)} \cos(2\phi_h - \phi_S) \end{aligned} \right] \end{aligned} \right\}$$



Quark \ Nucleon	U	L	T
U	$f_1^q(x, k_T^2)$ number density		$h_1^q(x, k_T^2)$ Boer-Mulders
L		$g_1^q(x, k_T^2)$ helicity	$h_{1L}^q(x, k_T^2)$ worm-gear L
T	$f_{1T}^q(x, k_T^2)$ Sivers	$g_{1T}^q(x, k_T^2)$ Kotzinian-Mulders worm-gear T	$h_1^q(x, k_T^2)$ transversity $h_{1T}^q(x, k_T^2)$ pretzelosity

+ two FFs: $D_{1a}^h(z, P_\perp^2)$ and $H_{1a}^{\perp h}(z, P_\perp^2)$



Sivers asymmetry: first round (earlier 2000):

Sivers 2004 – first Hermes data at proton – non zero asymmetry, COMPASS at deuteron - zero



COMPASS Results of 2005

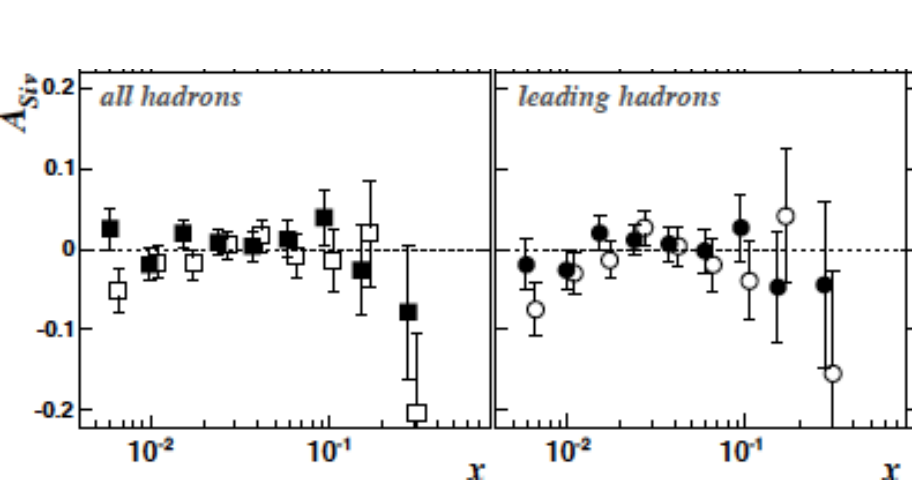
Hep-ex/0503002

Solid state ^6LD polarised target

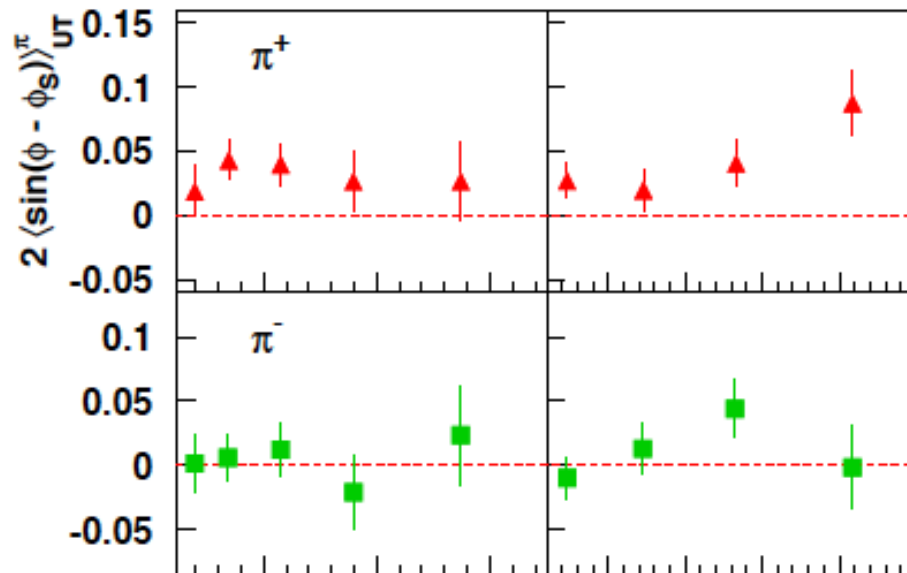
Hermes Results of 2004

hep-ph/0408013

Gaseous H_2 polarized target



Full points – positive hadrons,
Open points – negative hadrons

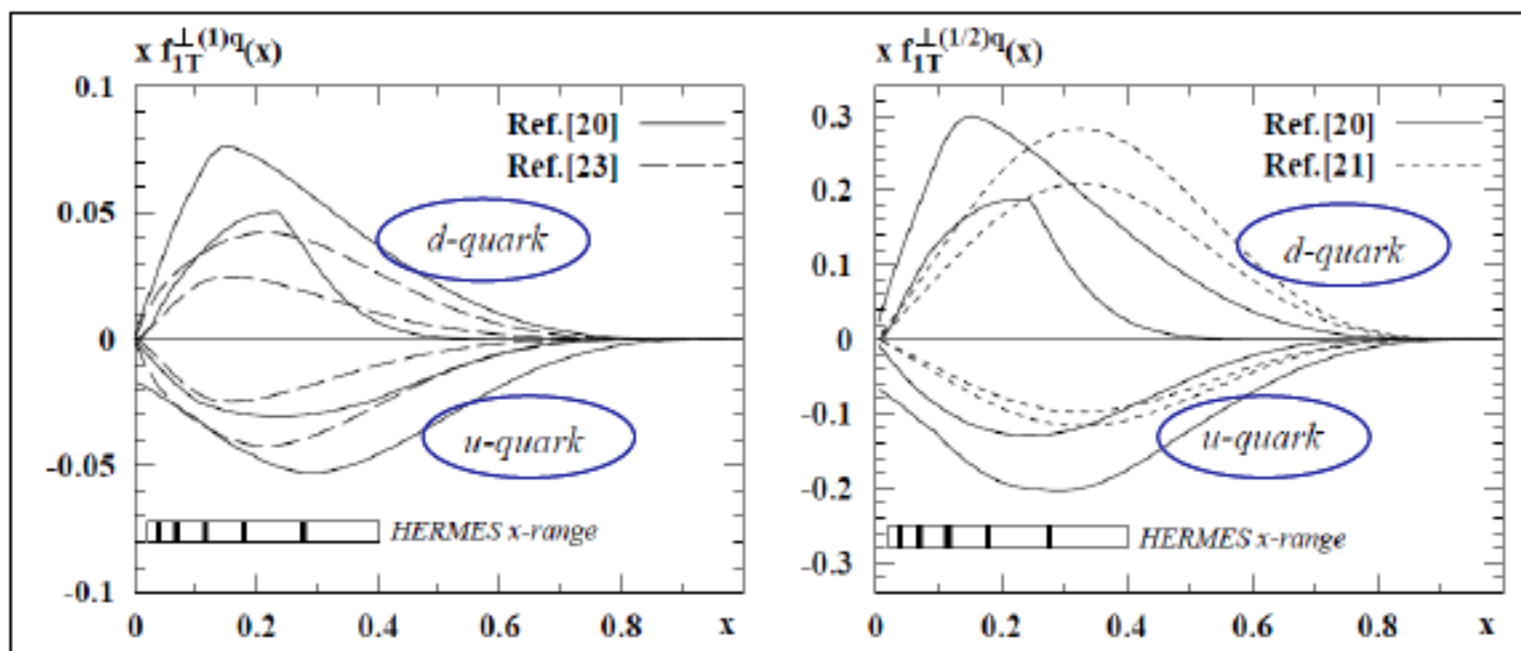


DOUBTS.....

$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

Joint data analysis from Hermes and COMPASS – no contradictions

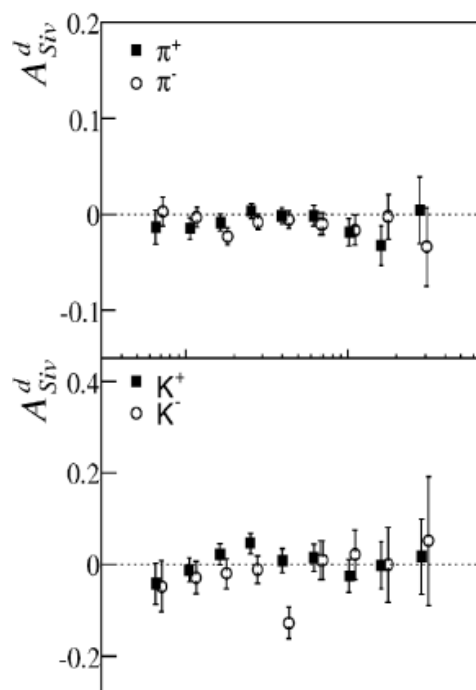
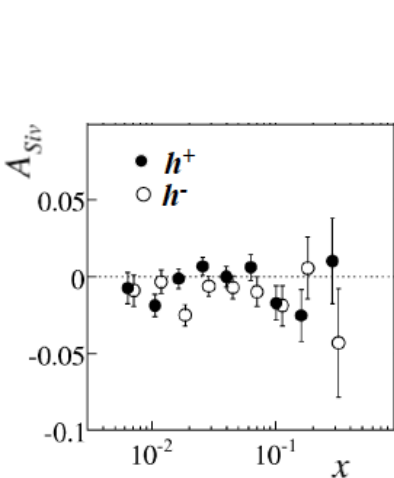
As it was shown by Mauro Anselmino and Colleagues (second half of 2005) when first extraction of Sivers function has been performed from Hermes and COMPASS data (Transversity'2005, hep-ph/051101) that the contributions from u- and d-quarks are opposite



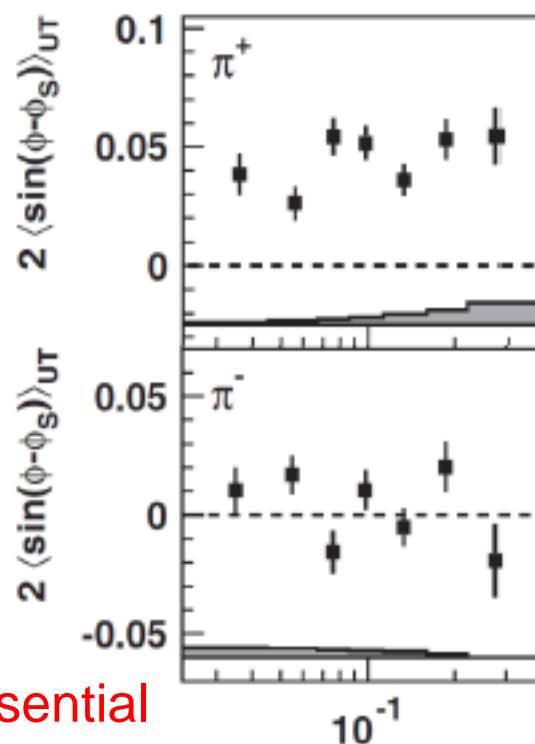
Sivers 2009 – final results Hermes&COMPASS data perfectly fits together

COMPASS Final results on deuteron
(data 2002-2004) PLB 673 (2009)

Hermes Final results on proton
PRL 103 (2009)

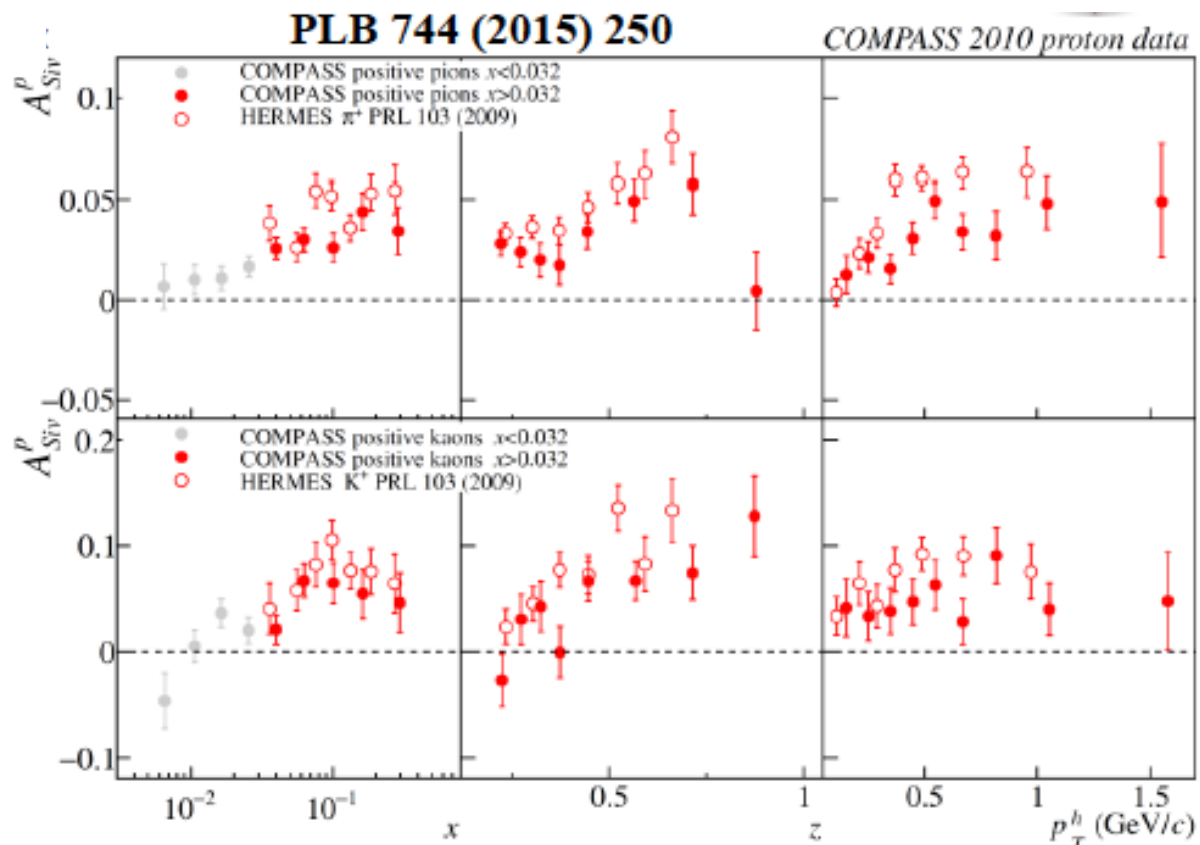
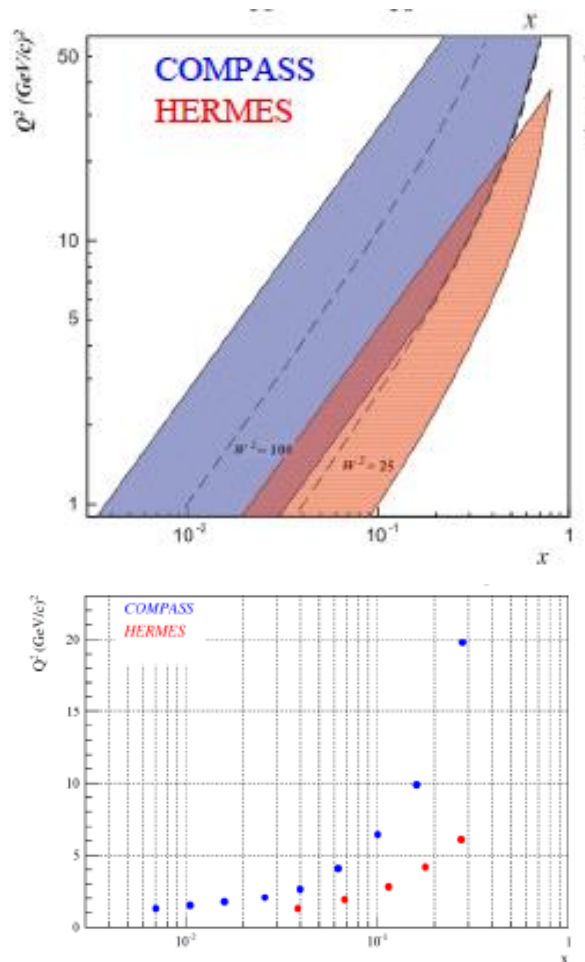


Flavour separation is essential



COMPASS \leftrightarrow Hermes proton data COMPASS Sivers is smaller – QCD evolution eff.?

Even if exist evolution has to be rather slow



NEW!! Access to TMD-FFs via hadron multiplicities

TMD multiplicity – ratio of hadron yields and the number of DIS events in multi-dimensional space is the most relevant experimental observable to investigate spin-averaged TMD-PDFs and TMD-FFs
⁶LiD (deuteron) isoscalar target

$$\frac{dN^h}{dN^{\text{DIS}}} \propto \sum_q e_q^2 q D_q^h$$

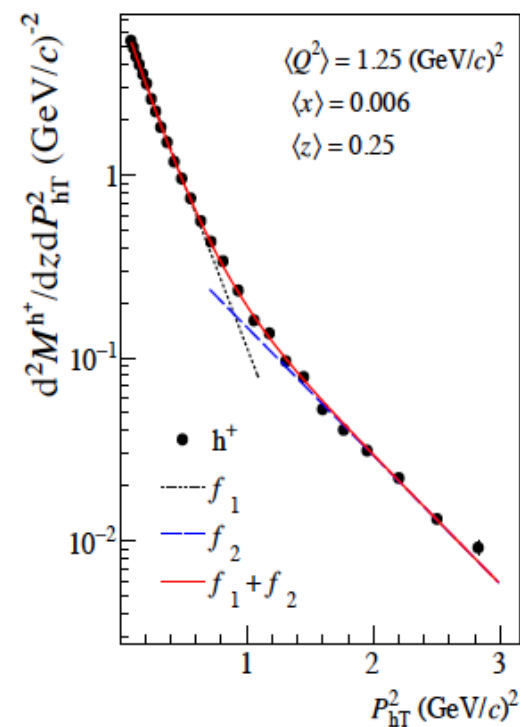
the cross-section **dependence on p_{Th}** comes from:

- intrinsic k_T of the quarks
- p_\perp generated in the quark fragmentation

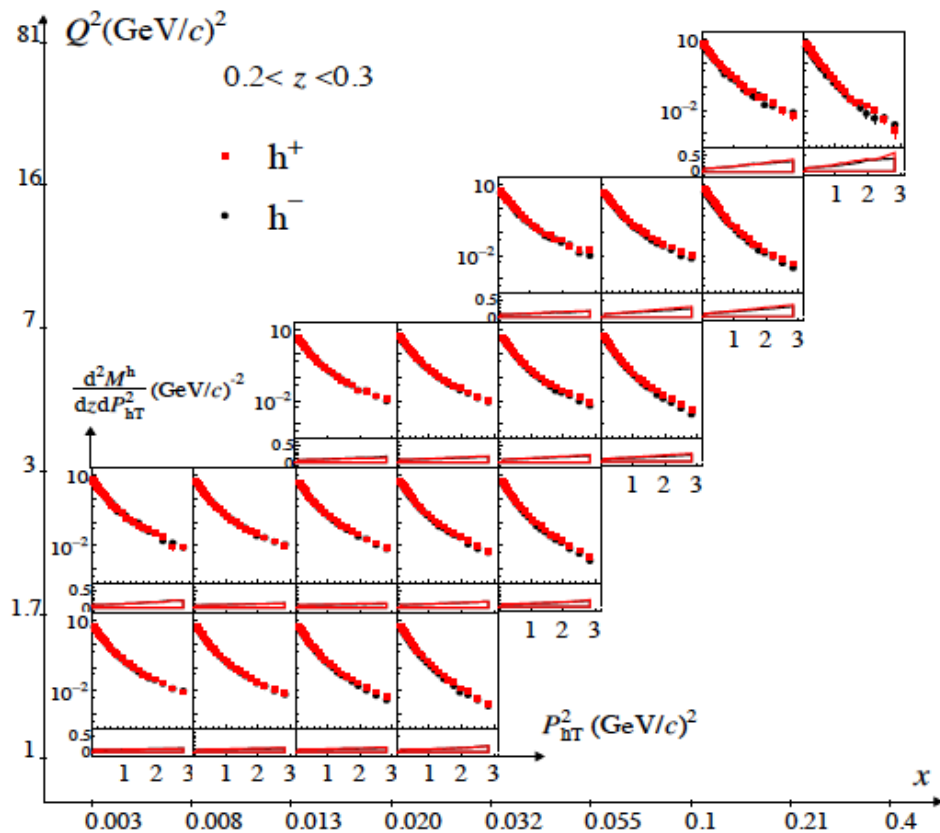
$$\langle p_{Th}^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_T^2 \rangle$$

The small P_{hT}^2 region ($< 1 \text{ (GeV/c)}^2$) - hadron transverse momenta are expected to arise from non-perturbative effects

Larger P_{hT}^2 - contributions from higher-order perturbative QCD are expected to dominate.



NEW!! TMD hadron multiplicities in SIDIS (multidimensional)



arXiv:1709.07374v1

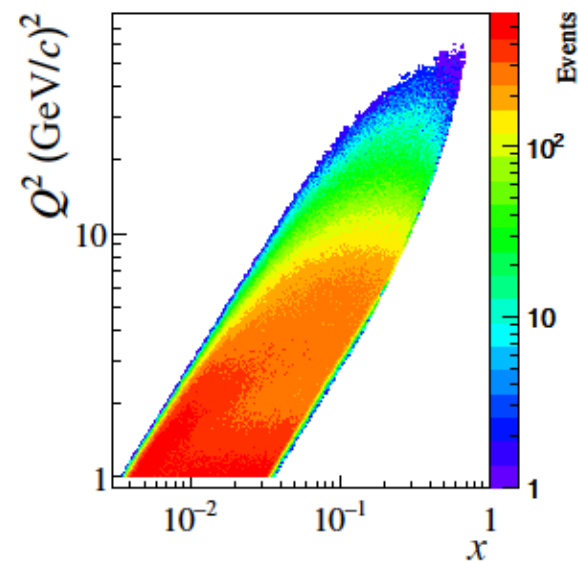
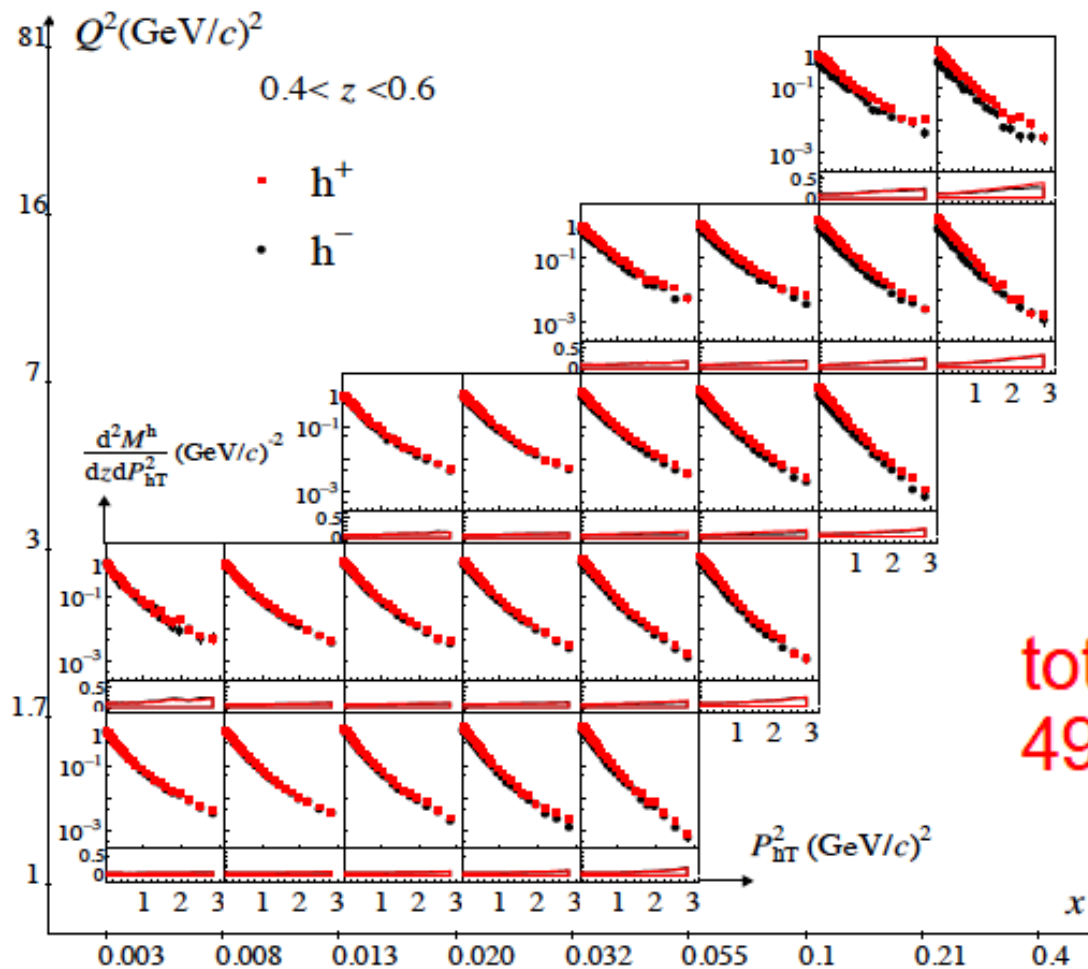


Fig. 5: Multiplicities of positively (full squares) and negatively (full circles) charged hadrons as a function of P_{hT}^2 in (x, Q^2) bins for $0.2 < z < 0.3$. Error bars on the points correspond to the statistical uncertainties. The systematic uncertainties (σ_{sys}/M^h) are shown as bands at the bottom.

NEW!! TMD hadron multiplicities in SIDIS (multidimensional)

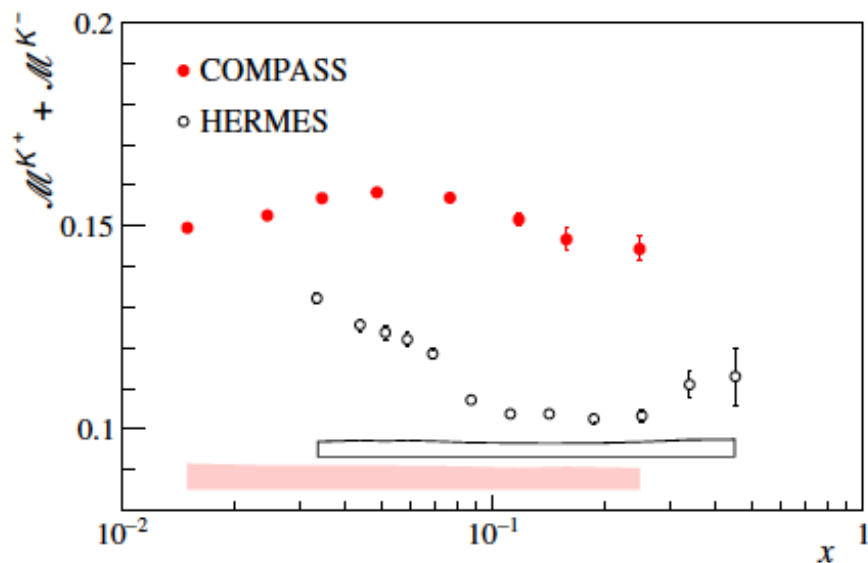


total:
4918 data points

Fig. 7: Same as Fig. 5 for $0.4 < z < 0.6$.

Charged kaon multiplicities (2006 160 GeV ^6LiD) – published in [PLB 767 \(2017\) 133](#)

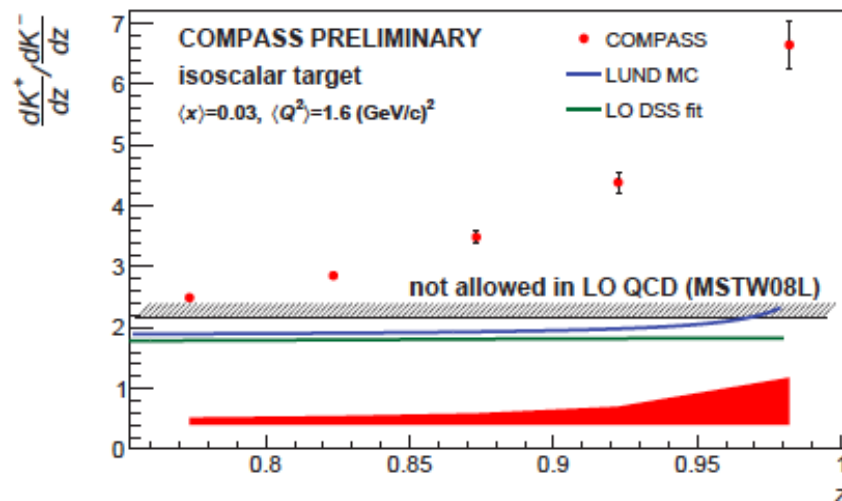
The 3-dimensional data set (x , y and z) → an important input for future NLO pQCD analyses of world data in terms of FFs.

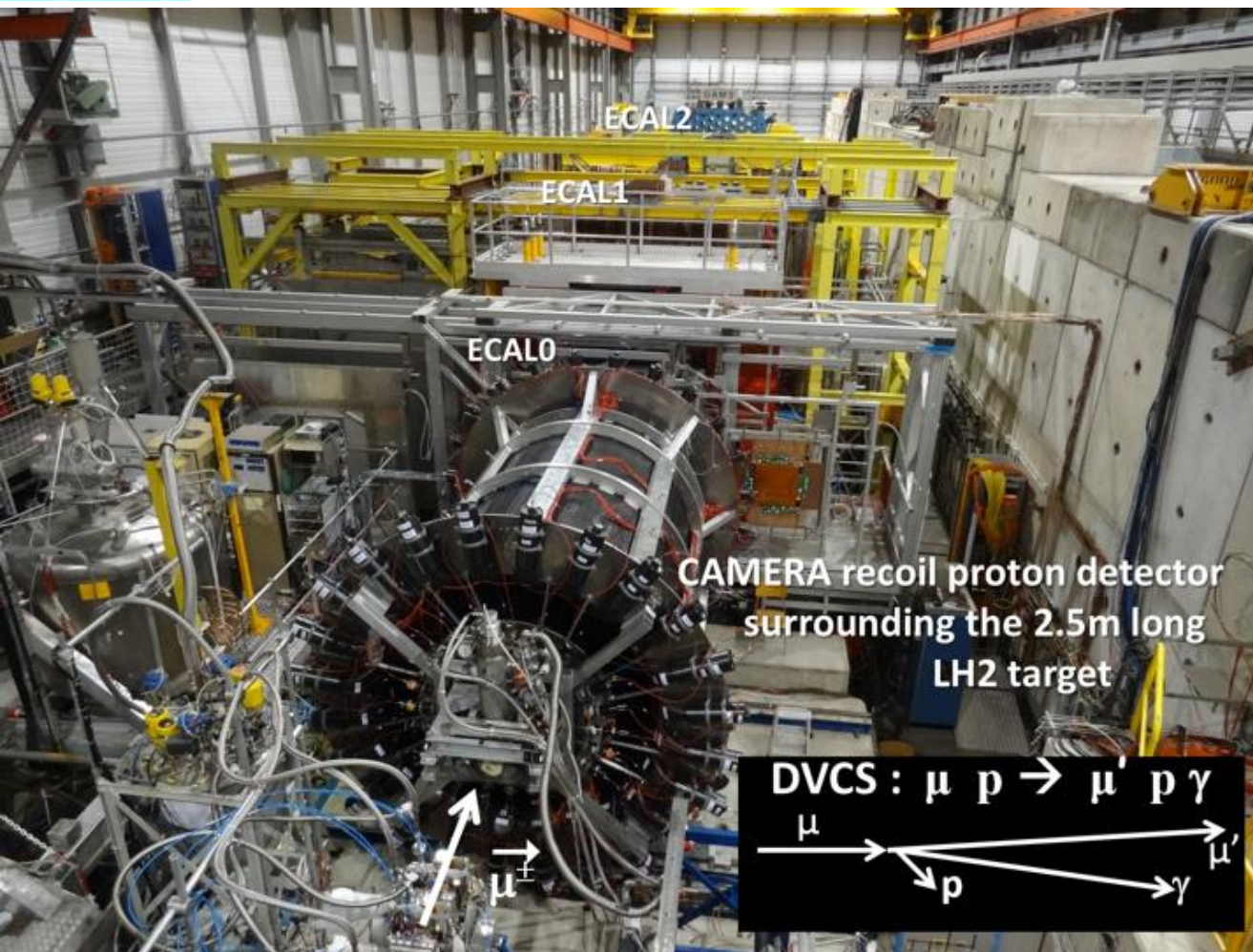


Important message – HERMES and COMPASS data are in tension.

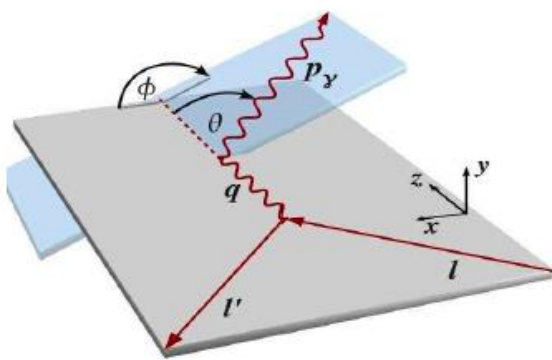
Can not be explained only by different Q^2 range, the discussion is going on.

Recently new results were produced on the kaon multiplicity ratio K^+/K^- , at high z , $0.75 < z < 1$. Surprisingly our data go far beyond the LO upper boundary value of $(u+d)/(\bar{u}+\bar{d})$ calculated at $x=0.03$ using MSTW08L as well as beyond the actual predictions of the K^+/K^- multiplicity ratio using Lund model or LO DSS fit.



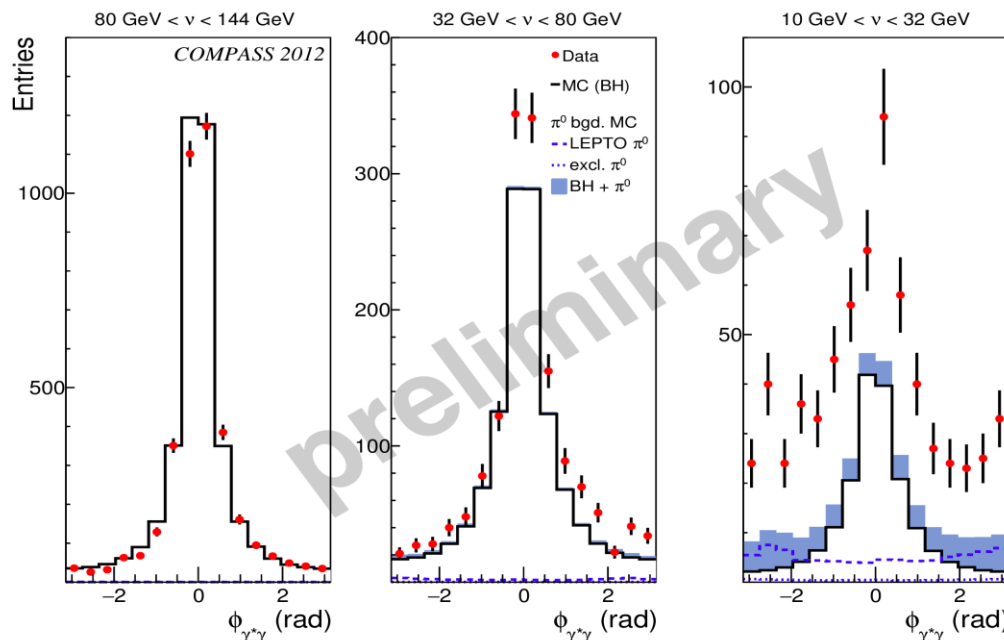


2012, 20 days long
data taking, 160 GeV
pion beam for
calibration, μ^+ and μ^-
for physics, 2.5 meters
long LH_2 target

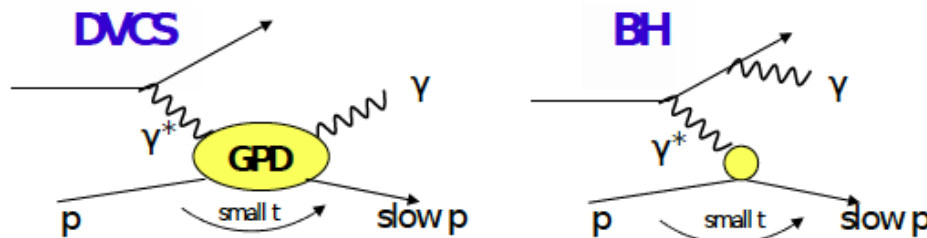


t-dependence of DVCS x-section

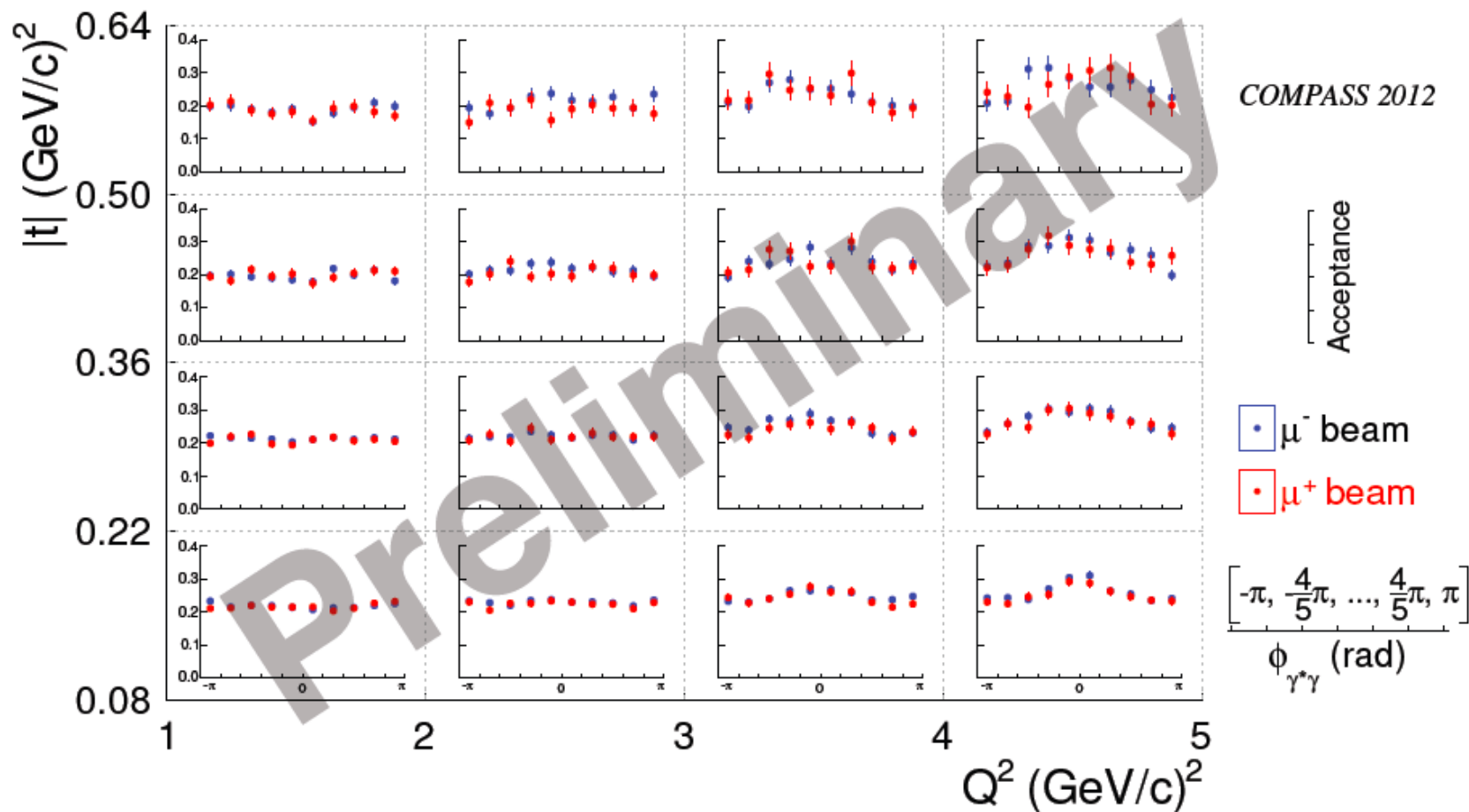
- Exclusive γ event selection
- π^0 bgd. estimation
- Kinematic fit
- Acceptance corrections
- Cross-section ($\gamma^* p \rightarrow \gamma p$)



Two competing processes (Bethe-Heitler and DVCS)
Contribute differently in the different $x(\nu)$ -ranges



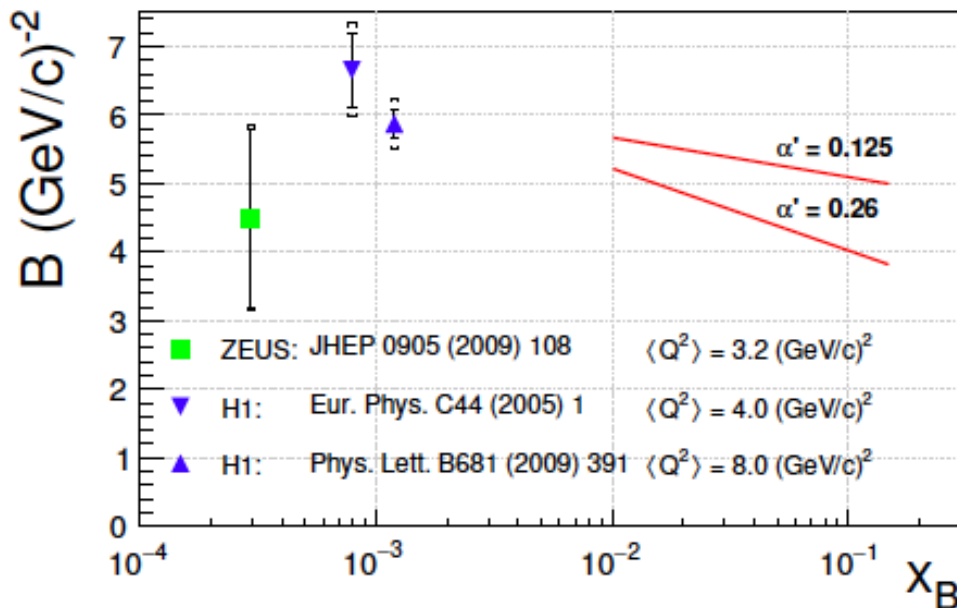
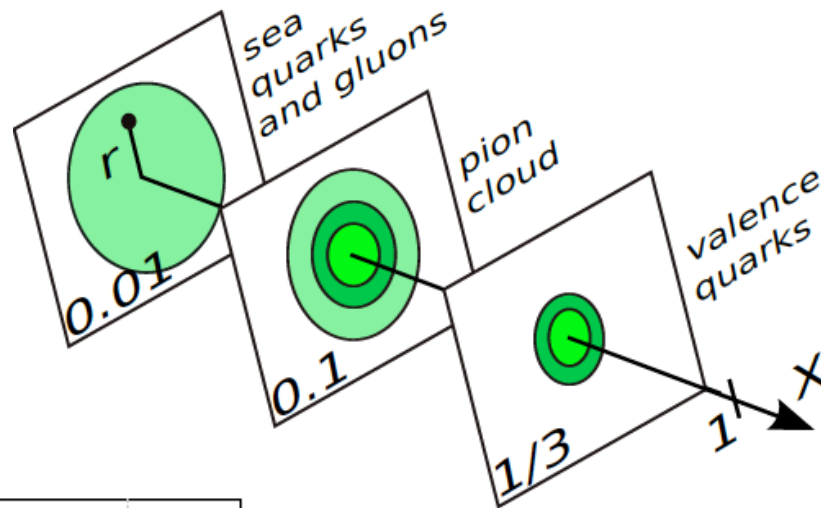
COMPASS acceptance for DVCS: rather smooth and symmetric in $\phi_{\gamma^*\gamma}$



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

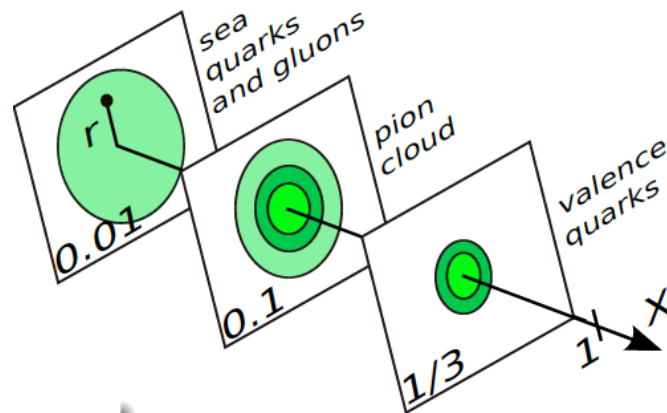
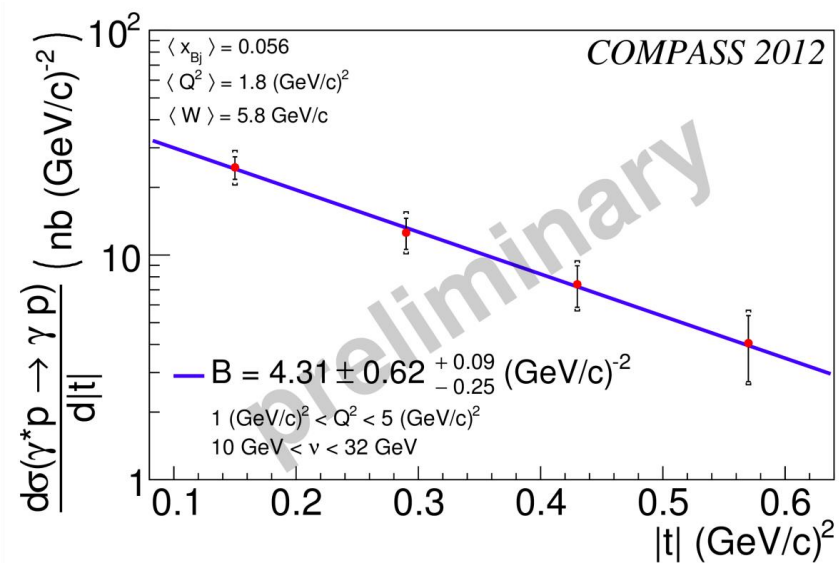
$$\frac{d\sigma}{d|t|} \propto e^{-B|t|}; \quad \langle r_{\perp}^2 \rangle \sim 2B(x_{Bj})$$

at small x_{Bj}

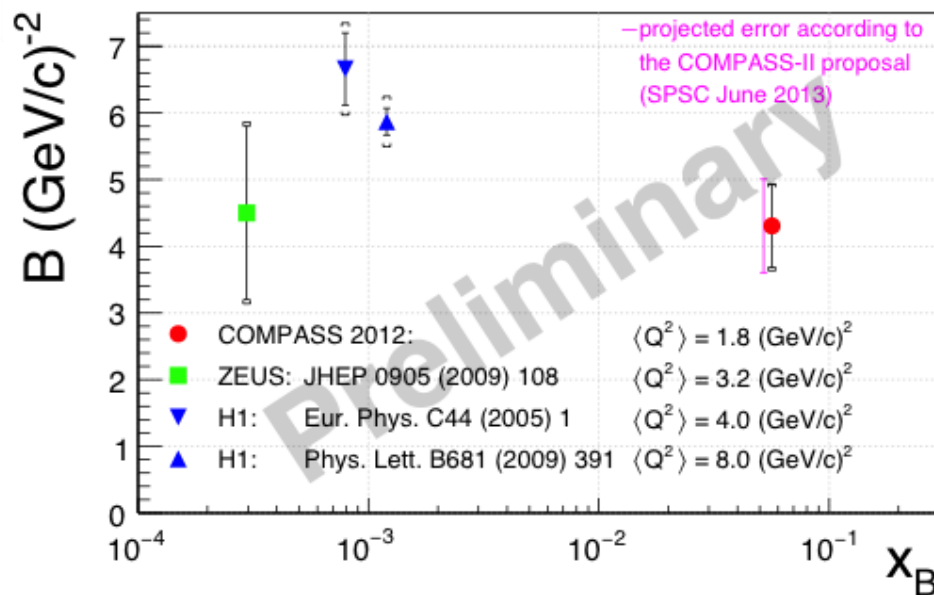


$$B(x_B) = B_0 + 2\alpha' \log\left(\frac{x_0}{x_B}\right)$$

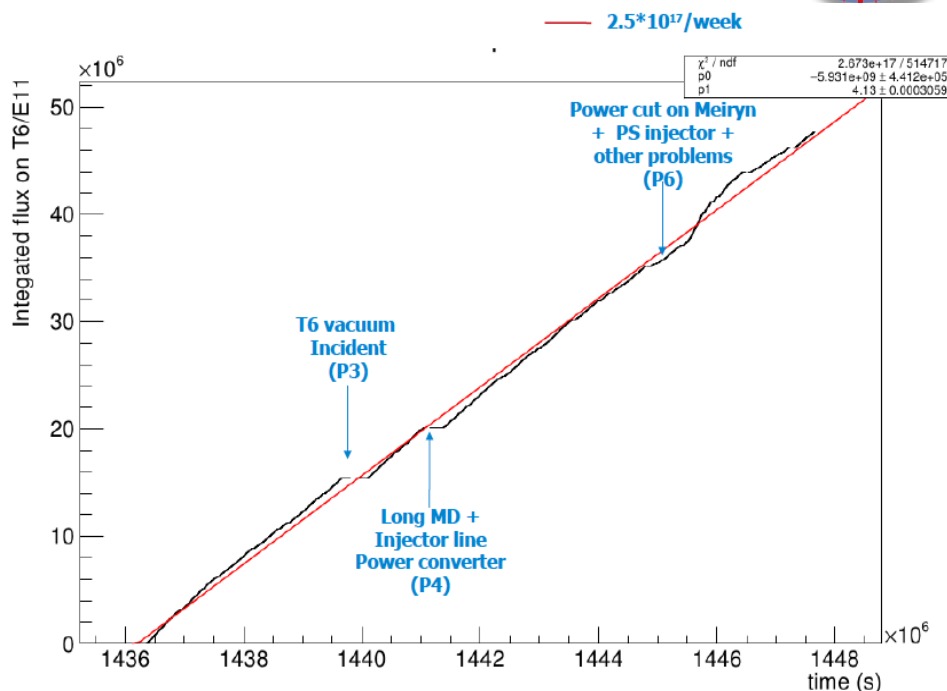
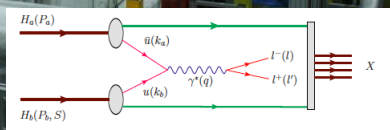
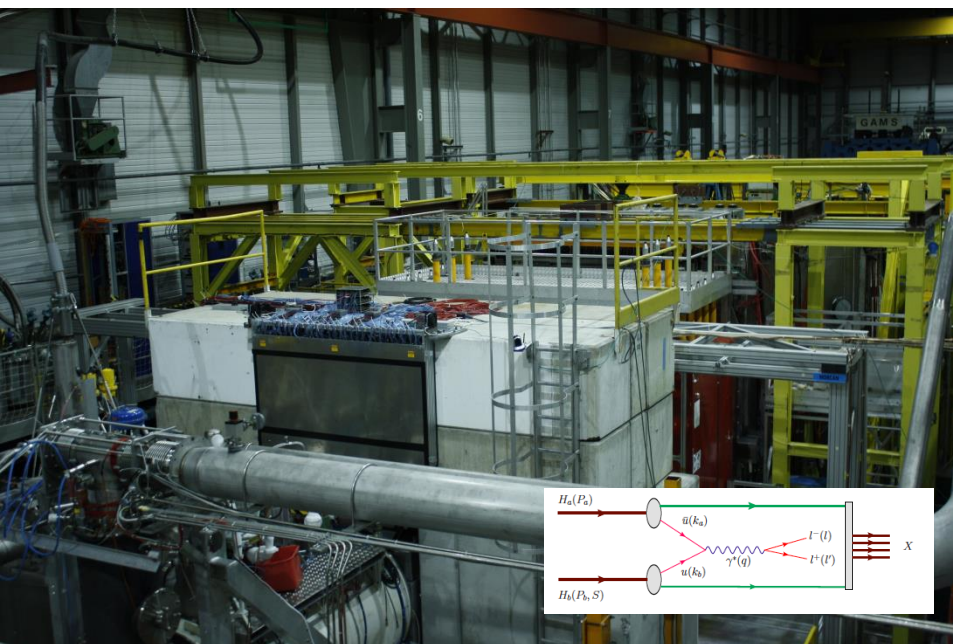
DVCS 2012 V: t -slope



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



First ever polarised Drell-Yan data set successfully collected



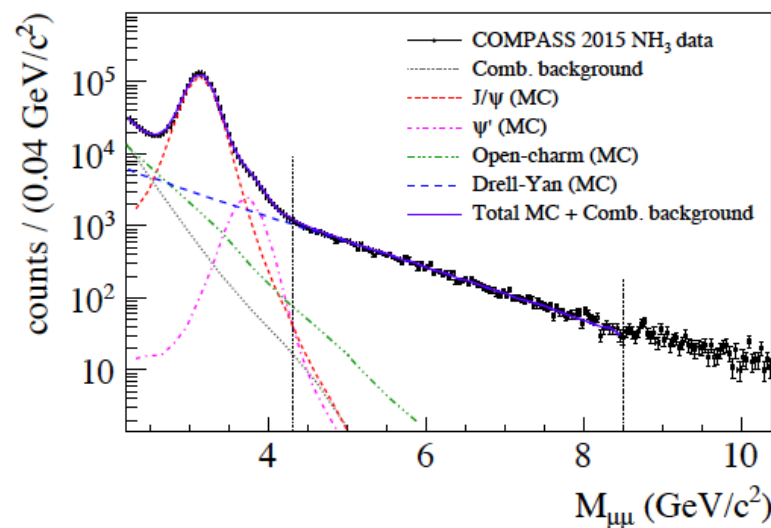
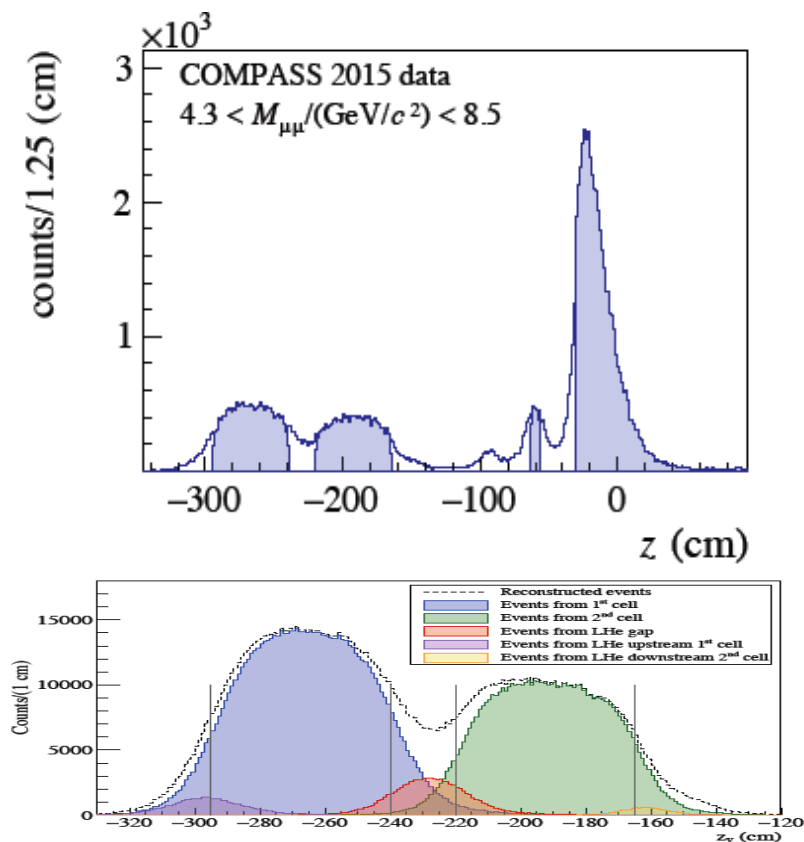
The final statistics penalised by late start (08/07/2015) because of the PT magnet and spectrometer commissioning.

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

Good machine performance: on average 84%

Good spectrometer availability: ~80%

First ever polarised Drell-Yan paper ([CERN-EP/2017-003](https://arxiv.org/abs/1701.02453), [hep-ex/1701.02453](https://arxiv.org/abs/1701.02453)) has been submitted to PRL – very positive comments by referees, being published soon.

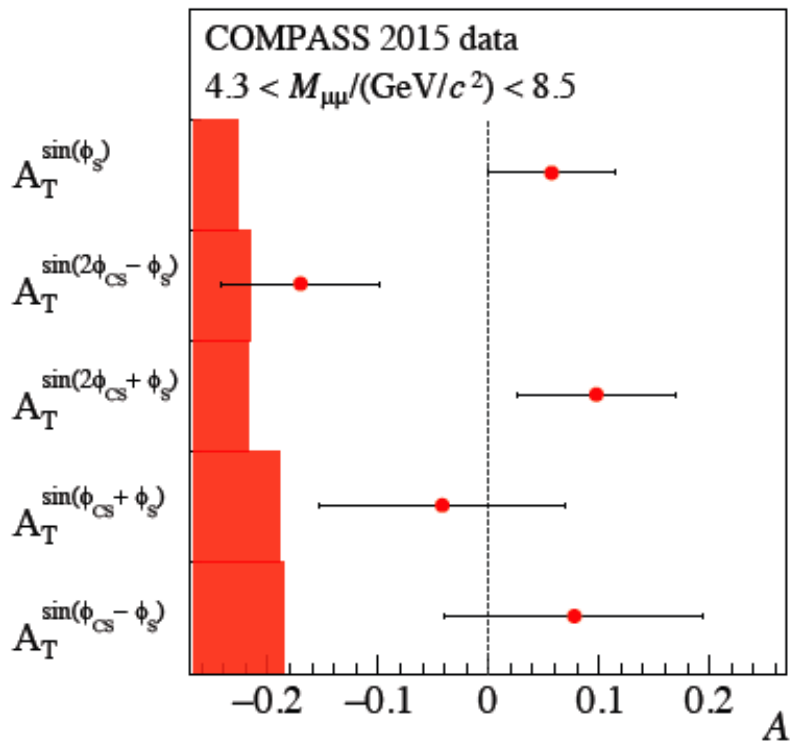


Total number of J/ψ (NH_3) is **$\sim 1.500.00$**

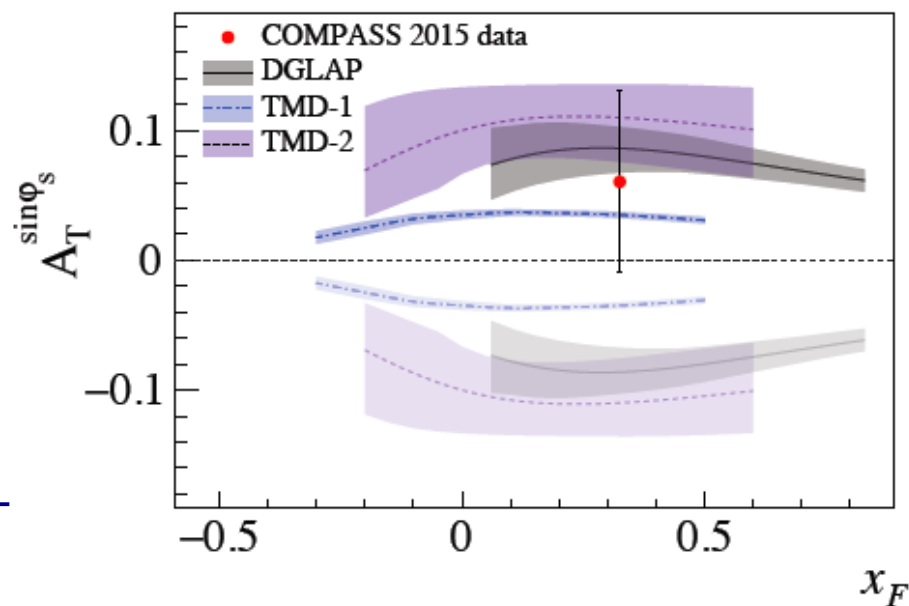
Total number of HM DY ($4.3 \text{ GeV}/c^2 < M_{\mu\mu} < 8.5 \text{ GeV}/c^2$) (NH_3) is **~ 35.000**

COMPASS Drell-Yan Run 2015 results V

Results on TSA & Sivers sign change



Mean TSAs. Systematic uncertainties are shown as error bands next to the vertical axis.



The measured mean Sivers asymmetry and the theoretical predictions for different Q^2 evolution schemes from Anselmino (DGLAP), Echevarria (TMD1) and Sun (TMD2). The dark-shaded (light-shaded) predictions are evaluated with (without) the sign-change hypothesis.

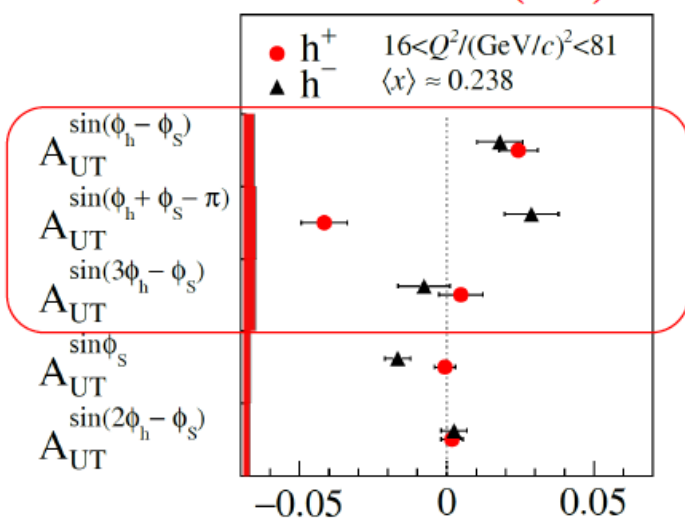
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

$$\left. + S_T \left[\begin{aligned} & A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ & + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ & + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \\ & + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ & + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h - \phi_S)} \sin(2\phi_h - \phi_S) \end{aligned} \right] \right\}$$

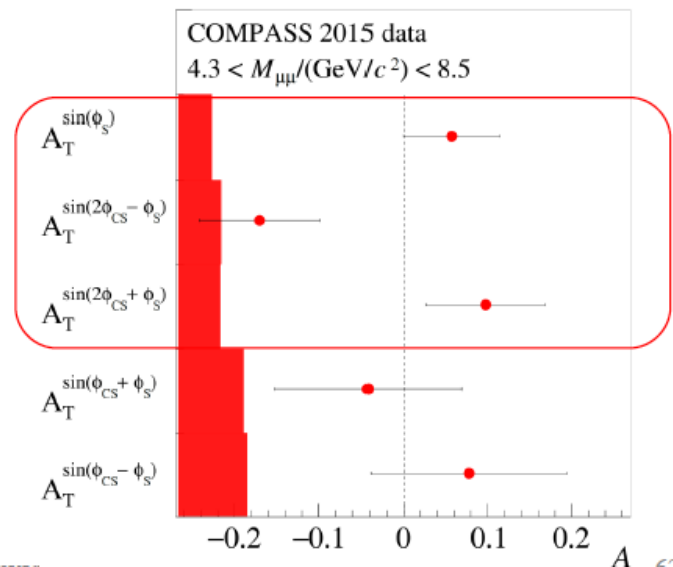
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS}) \left\{ 1 + \dots \right.$$

$$\left. + S_T \left[\begin{aligned} & A_T^{\sin\varphi_S} \sin\varphi_S \\ & + D_{[\sin^2\theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right. \right. \\ & \quad \left. \left. + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \right) \right. \\ & + D_{[\sin 2\theta_{CS}]} \left(A_T^{\sin(\varphi_{CS} - \varphi_S)} \sin(\varphi_{CS} - \varphi_S) \right. \\ & \quad \left. + A_T^{\sin(\varphi_{CS} + \varphi_S)} \sin(\varphi_{CS} + \varphi_S) \right) \end{aligned} \right] \right\}$$

COMPASS PLB 770 (2017) 138



COMPASS [arXiv:1704.00488 \[hep-ex\]](https://arxiv.org/abs/1704.00488)





Further improvements for 2018 Drell-Yan Run CEDARs system



One of the main goals of the polarised Drell-Yan program at COMPASS is **unambiguous verification of the Sivers asymmetry sign change.**

First year of DY data taking (2015) was very successful, the validity of the experimental approach was proven and significant statistics were collected. The statistical uncertainty of Sivers asymmetry was found to be equal to 0.057.

In order to unambiguously verify the Sivers sign change our goal is to reduce the statistical error for total DY data sample (2015+2018) by factor ~ 2 down to **~ 0.03** .

The number of improvements are planned for 2018 data taking compared to 2015:

- Shorter commissioning time and longer data taking period (factor ~ 1.3 gain);
- New beam telescope as we were suffering in 2015 from insufficient redundancy (at least 3 more SciFi planes) (gain in incoming track reconstruction efficiency of at least 10%);
- Better spectrometer protection against high radiation in the area (factor 1.1)
- Improvements on trigger system (purity and efficiency), reduced DAQ and Veto system dead time (hard to quantify right now, factor of ~ 1.2)
- Further optimisation of the Polarised target polarization procedure, higher average PT polarisation (potentially factor $\sim 1.1-1.2$)
- Neural network techniques will be applied to subtract resonant background (factor ~ 1.4)

IMPORTANT: In order to carry out the DY program with kaons and antiprotons the CEDARs system will be upgraded: new photomultipliers, read/out, thermal insulation.



Beyond 2020 dedicated Workshop

This week – regular annual COMPASS Workshop (IWHSS'16 Kloster Seeon)



COMPASS beyond 2020 Workshop

2-

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

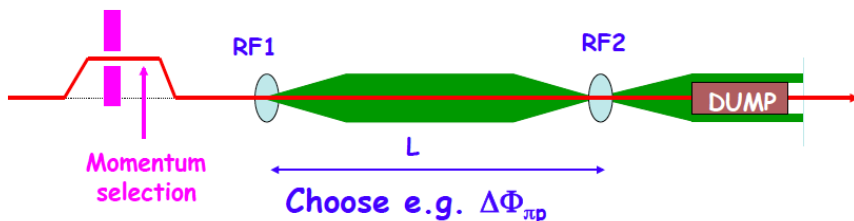
222-R-001 (CERN)

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

- 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-PARC (Japan), EIC – China;
- 7 COMPASS talks (chronol.) – SIDIS, GPDs, Chiral Dynamics, astrophysics (dark matter), Drell-Yan, hadron spectroscopy;
- 2 “round-table”-like discussions on possible future with hadron and muon beams;
- **Outcome of the Workshop:**
 - RF Separated antiproton/kaon beam would provide a unique opportunity for future fixed target COMPASS-like program at CERN
 - Existing muon and hadron beam allows to extend current COMPASS program by doing unique or first class measurements of exclusive processes, SIDIS and Drell-Yan

RF separated antiproton/kaon beam – essential for the future of the COMPASS-like experiment at SPS



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

“Normal” h^- beam composition:
 $\sim 97\%$ (π) $\sim 2.5\%$ (K) $\sim 0.5\%$ (pbar)

Assumptions:

- 8×10^7 antiprotons for 10^{13} ppp (10 seconds) (optimistic estimate by Lau Gatignon);
- we assume here 4×10^{13} protons.

Antiprotons RF separated beam: 3.2×10^7 /s - Gain is a factor of **50 compared to the standard h^- beam for Drell-Yan experiment** ($\sim 1\%$ of h^- beam 6×10^7 /s dominated by π^-)

Using the same assumption for RF separated kaon beam, possible kaon beam intensity is 8×10^6 /s - Gain is a factor of **80 compared to the standard “spectroscopy” h^- beam**

High intensity RF separated beam will provide unique opportunities for Hadron Spectroscopy and Drell-Yan physics



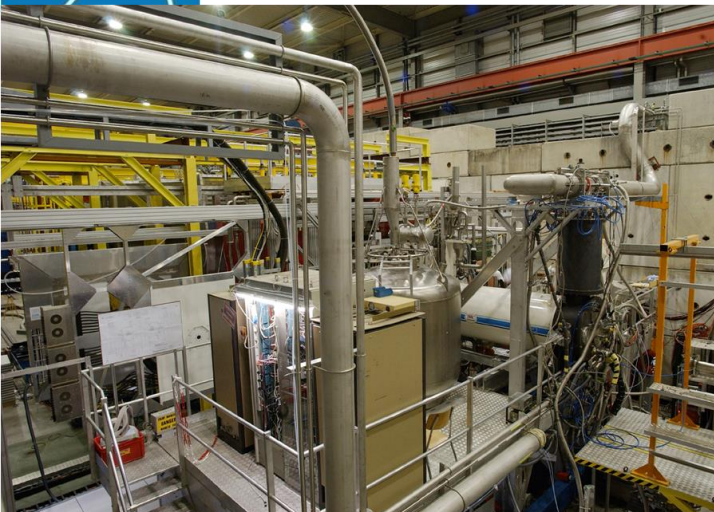
Short term COMPASS future



Short term future COMPASS Proposal (extension of the COMPASS-II experiment) was submitted to the SPSC ~1 month ago. The goal is to ensure COMPASS running after Long Shutdown II (2019-2020) for at least one year to keep collaboration going on and to provide an access to fresh funds.

Decision by the SPSC (recommendation) is expected in January 2018

Short term COMPASS future I : SIDIS – transversely polarised Deuteron Target (${}^6\text{LiD}$)



- TMD PDFs and Transversity $h_1(x)$ are flavour dependent.
- Flavour separation \rightarrow data on both proton (NH_3) and deuteron (${}^6\text{LiD}$) transversely polarised targets.
- Proton data set is factor of 4 compare to deuteron (see error bars for transversity $h_1(x)$ in the plot below)
- It is logical to increase the deuteron data set (so far the only data sets available are COMPASS (${}^6\text{LiD}$) and CLAS (${}^3\text{He}$) targets).

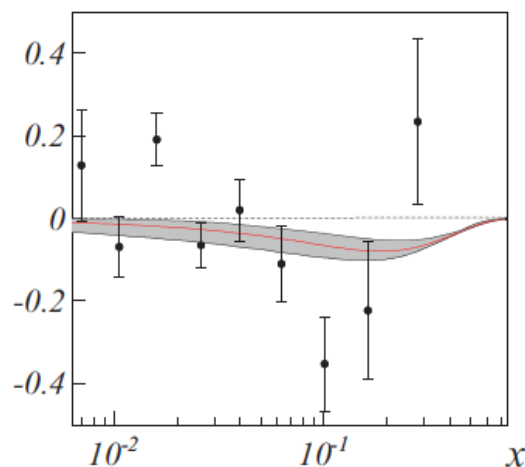
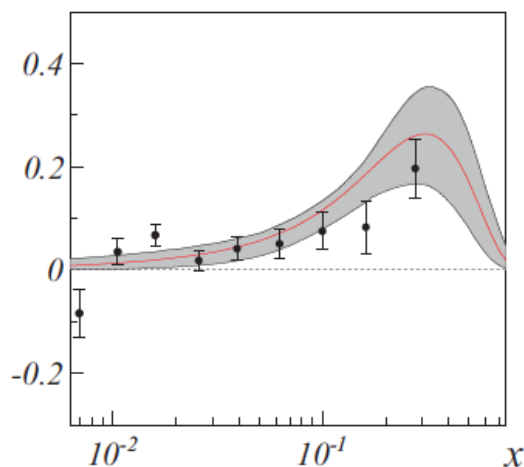


Fig. 6: $xh_1^u(x)$ (left) and $xh_1^d(x)$ (right) from the 'two hadron' asymmetries of 2010 proton and of 2002-2004 deuteron data (from[30]). The curves show the transversity PDFs obtained from a fit of Collins asymmetries [29]

Competitors:
- No competitors in
our kinematic range,
Jlab will start by 2020



Short term COMPASS future I :

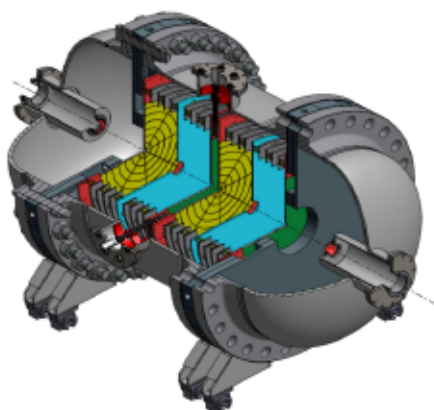
Proton radius measurement in elastic mu-p scattering



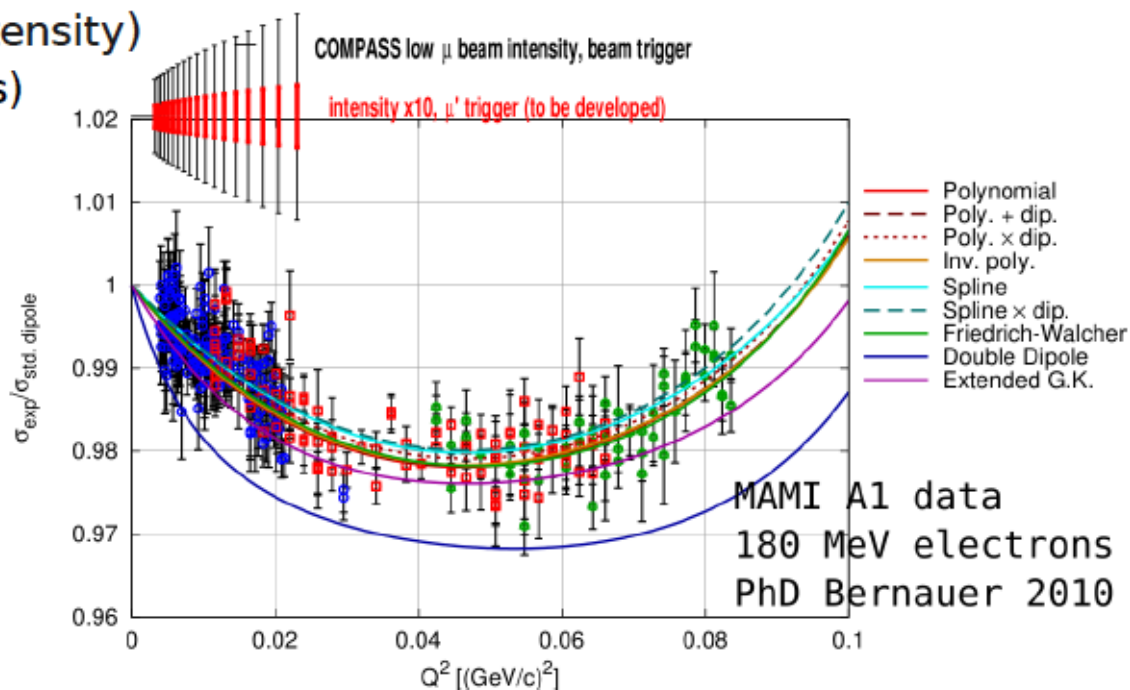
- 100 GeV SPS muon beam (M2)
- Hydrogen high-pressure active TPC target cell (PNPI development)
- Measure the cross-section (shape) over broad Q^2 range $10^{-4} \dots 10^{-1}$
- From $10^{-3} \dots 2 \cdot 10^{-2}$ fit the proton radius (slope of electric form factor)
 - Precision 0.03 fm with conservative beam trigger (0.5% beam intensity)
- Goal: 0.01 fm (from 180 days) trigger concept to be solved

unique because...

- muon beam requires a factor 10 smaller radiative corrections than e^- beams (vs. Mainz, Jlab)
- high-energy muon beam, very small scattering angles: practically no Coulomb correction (vs. MUSE)
- best systematics control



IKAR active target cell
A. Vorobyev, St. Petersburg



Oleg Denisov



Long term COMPASS future

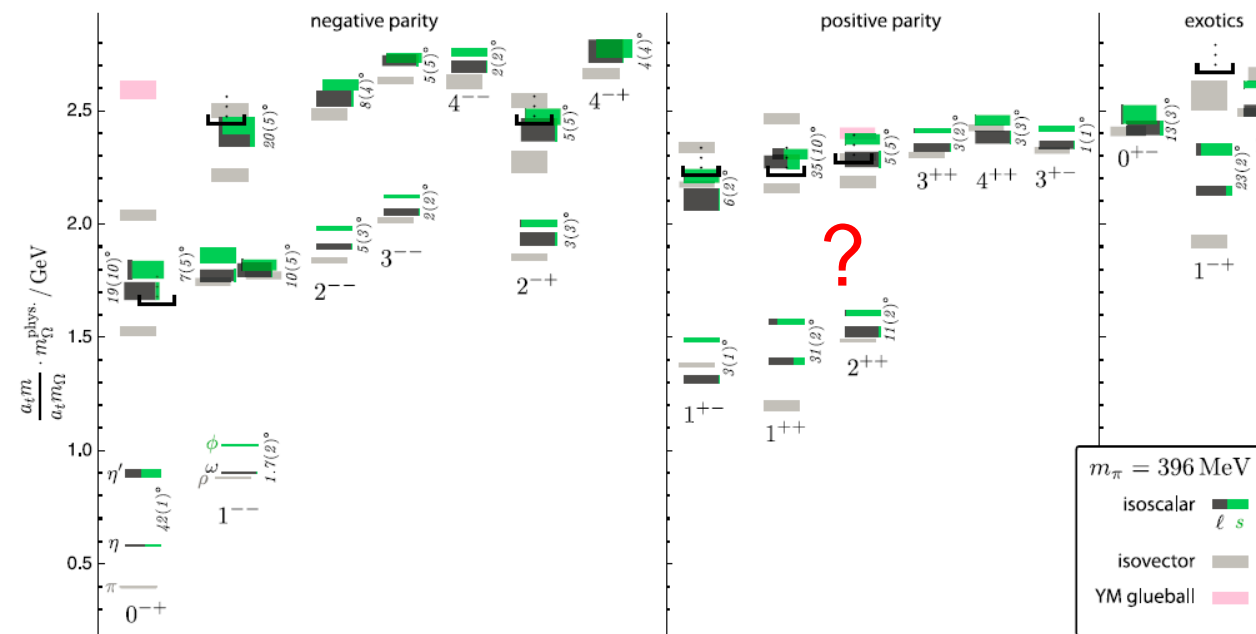


Long term future COMPASS-like experiment Lol (new physics) is under preparation now. The goal is to bring together strongly renewed COMPASS-based Collaboration (will have a different name) enthusiastic about opportunities of doing physics at CERN with conventional and newly designed RF separated kaon and antiproton beams. The total duration of the program might reach 7-8 years of running with hadron and muon beams.

Indications by European Strategy Group is expected at the beginning of 2020 (May?).

RF separated beam – Hadron spectroscopy (i)

Light Meson Sector & COMPASS contribution

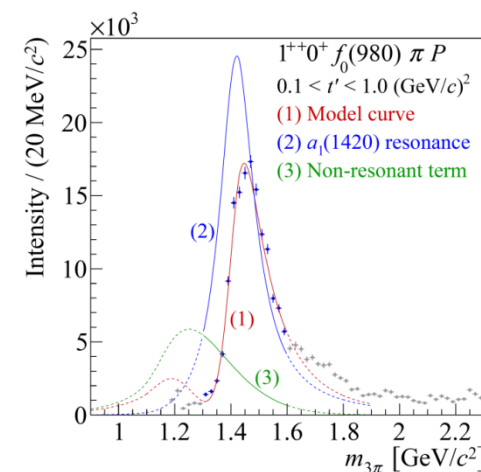


3π data sample $\sim 50 \times 10^6$
exclusive events – factor 10 to 100 to previous experiment

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

COMPASS: $a_1(1420)$

It is shown that we have elaborated adequate methods to cope with huge statistics and produced nice results



[C. Adolph et al., COMPASS, PRL 115, 082001 (2015)]



RF separated beam – Hadron spectroscopy (ii)

Light and Strange Meson Spectrum



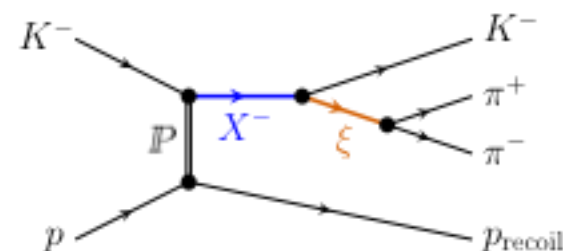
RF separated kaon beam $\sim 8 \times 10^6$ /s, beam momentum ~ 100 GeV

What can we contribute as COMPASS?

- State-of-the-art high-resolution spectrometer with full PID
- Advanced analysis techniques being developed in the light-quark sector

Method to be used: Kaon beam diffraction scattering on LH_2 and thin nuclear targets

- Goal: ~ 10 larger data sample than existing worldwide what would make possible to have similar to pion diffraction wave set: 88 waves in 11 t' bins;
- COMPASS could rewrite PDG tables for strange mesons
- Extend studies of chiral dynamics to strange sector



No real competitors

JParc - $\sim 10^5$ /s, low momenta kaons

JLab - $\sim 10^4$ /s, K^0 long beam, lower momenta

Unique opportunity



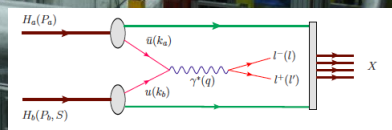
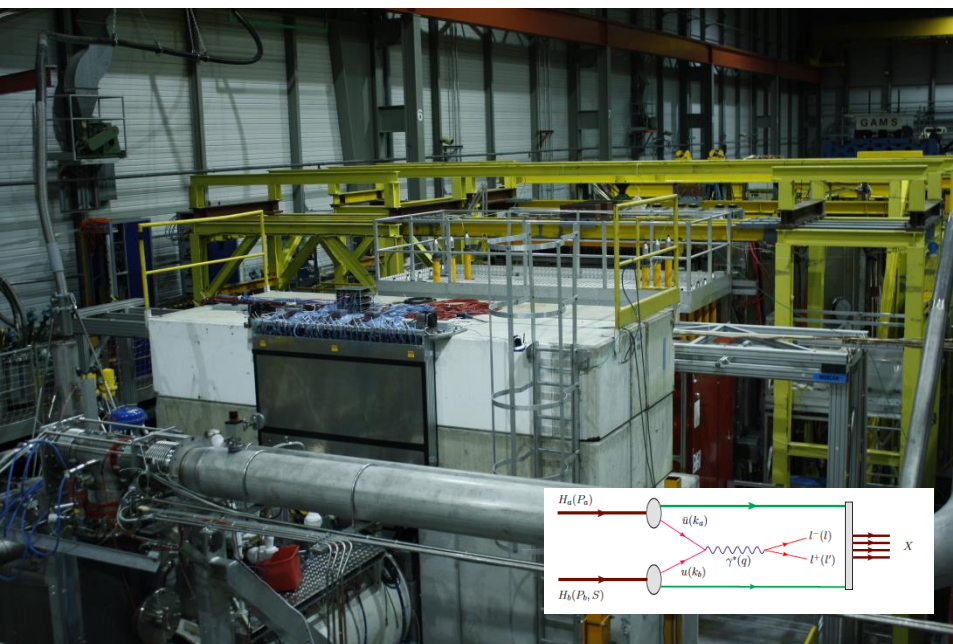
Running/planned Drell-Yan experiments, COMPASS (π^- beam on p^\uparrow) – unique experiment



Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($\text{cm}^{-2} \text{s}^{-1}$)		P_b or P_t (f)	rFOM [#]	Timeline
COMPASS (CERN)	$\pi^\pm + p^\uparrow$	190 GeV $\sqrt{s} = 19$	$x_t = 0.1 - 0.3$	2×10^{33}	0.14	$P_t = 80\%$ $f = 0.22$	1.0×10^{-3}	2014-2015, 2018
PANDA (GSI)	$p\bar{p} + p^\uparrow$	15 GeV $\sqrt{s} = 5.5$	$x_t = 0.2 - 0.4$	2×10^{32}	0.07	$P_t = 90\%$ $f = 0.22$	1.1×10^{-4}	>2025
AFTER	$p^\uparrow + p$	7 TeV $\sqrt{s} = 120$	$x_b = 0.1 - 0.9$	2×10^{32}	0.06	$P_b = 100\%?$	2.3×10^{-5}	>2020
NICA (JINR)	$p^\uparrow + p$	collider $\sqrt{s} = 26$	$x_b = 0.1 - 0.8$	1×10^{32}	0.04	$P_b = 70\%$	6.8×10^{-5}	>2023
PHENIX/STAR (RHIC)	$p^\uparrow + p^\uparrow$	collider $\sqrt{s} = 510$	$x_b = 0.05 - 0.1$	2×10^{32}	0.08	$P_b = 60\%$	1.0×10^{-3}	>2018
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 - 0.5$ $x_b = 0.05 - 0.6$	8×10^{31} 6×10^{32}	0.08	$P_b = 60\%$ $P_b = 50\%$	4.0×10^{-4} 2.1×10^{-3}	>2021
SeaQuest (FNAL: E-906)	$p + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 - 0.9$ $x_t = 0.1 - 0.45$	3.4×10^{35}	---	---	---	2012 - 2017
Pol tgt DY[‡] (FNAL: E-1039)	$p + p^\uparrow$	120 GeV $\sqrt{s} = 15$	$x_t = 0.1 - 0.45$	4.4×10^{35}	0 – 0.2*	$P_t = 85\%$ $f = 0.176$	0.15	2018-2019
Pol beam DY[§] (FNAL: E-1027)	$p^\uparrow + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 - 0.9$	2×10^{35}	0.04	$P_b = 60\%$	1	2020

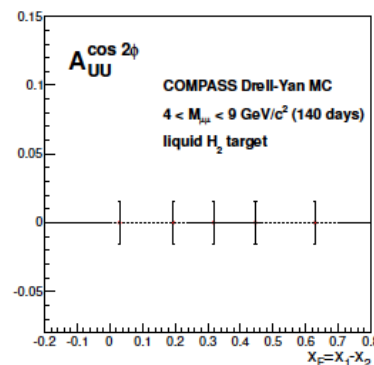
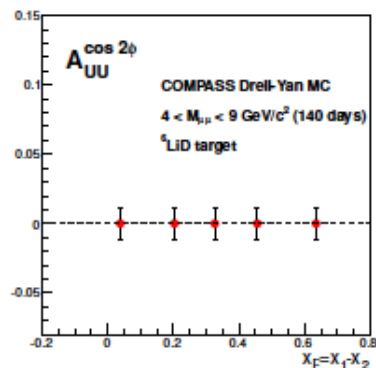
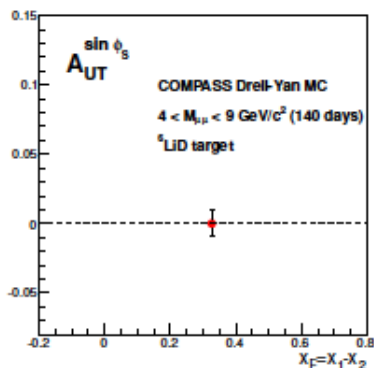
[‡] 8 cm NH_3 target / [§] $L = 1 \times 10^{36} \text{ cm}^{-2} \text{s}^{-1}$ (LH_2 tgt limited) / $L = 2 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$ (10% of MI beam limited)

*not constrained by SIDIS data / [#] rFOM = relative lumi * P^2 * f^2 wrt E-1027 ($f=1$ for pol p beams, $f=0.22$ for π^- beam on NH_3)



The same arguments as for SIDIS TMDs flavour separated extraction valid as well for our Drell-Yan data, both TMDs and “normal” pion PDFs.

- World largest Drell-Yan data set on NH_3 (first ever polarised data)
- In order to perform f.s. – must to have data on ${}^6\text{LiD}$, will be first ever data sample (projections are shown)
- Pion PDFs flavour separation
- Shorter exposition on unpolarised LH_2 target is required to test fundamental Lam-Tung relation and to extract Boer-Mulders TMD using “clean” (no nuclear effects) LH target – complementary to SIDIS.



Unique, no competitors



RF separated beam – Drell-Yan (i)



RF separated antiproton/kaon beam, the maximal possible beam intensity (very rough estimate) of $\sim 3\text{--}4 \times 10^7$ /s can be reached (antiprotons) and $\sim 8 \times 10^6$ /s (kaons)

Assuming flux of 1×10^7 /s for kaon/antiproton,
background free high mass range $4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$ and
140 days of data taking with the efficiency of 2015 Drell-Yan Run.

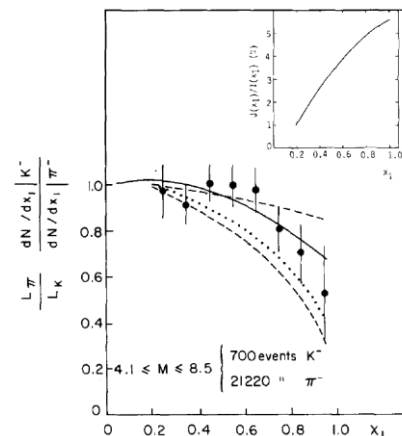
	NH ₃	Al (7cm)	W	NA3	NA10	E537	E615
K^- beam	14,000	2,800	29,600	700			
\bar{p} beam	15,750	2,750	22,500			387	

The overall gain for RF separated beam compare to previous experiments is factor 50 to 100

RF separated beam – Drell-Yan (ii) kaon-induced DY

- Kaon-induced DY is the only source of information on **kaon structure which is unknown**
- Together with pion induced DY will represent the unique data set for unstable particle structure study
- Unpolarised case, possibility to use different nuclear targets targets (like LH₂, Al, W, Cu):
 1. Kaon structure function (PDFs)
 2. Nucleon strange quark structure
 3. Fundamental Lam-Tung relation for kaon
 4. Boer-Mulders TMDs (quark-spin – quark-k_T correl.) for kaons
 5. EMC effects & flavour dependent EMC effects (kaons)
 6. Kaon Distribution Amplitude, J/ψ production mechanism

$$\frac{d\sigma^{K^-} / dx_1}{d\sigma^{\pi^-} / dx_1} = \frac{\bar{u}_K}{\bar{u}_\pi}(x_1)$$



Collaboration, PLB 93, 354 (1980)

**No competitors,
unique data**

NA10 π-W

194 GeV/c

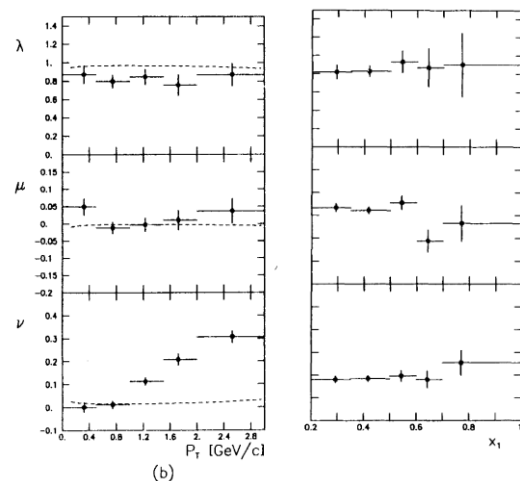
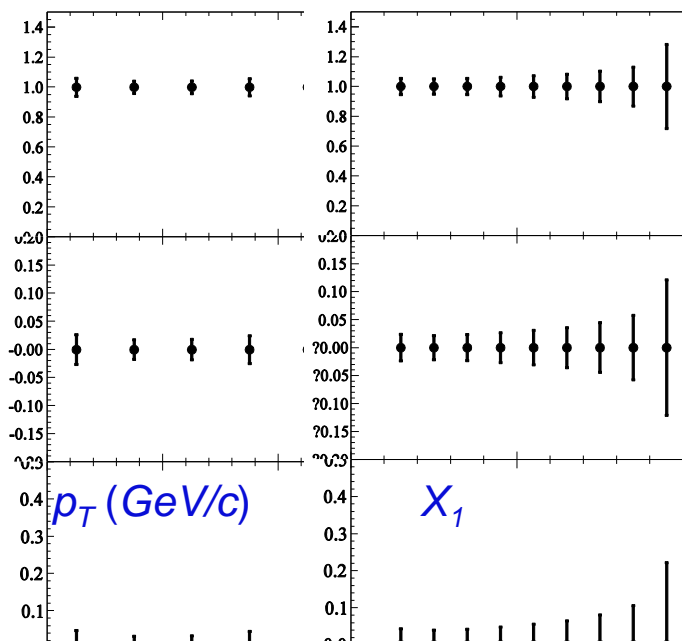


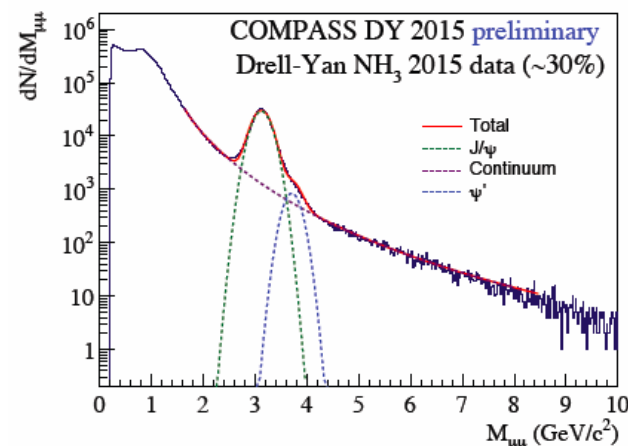
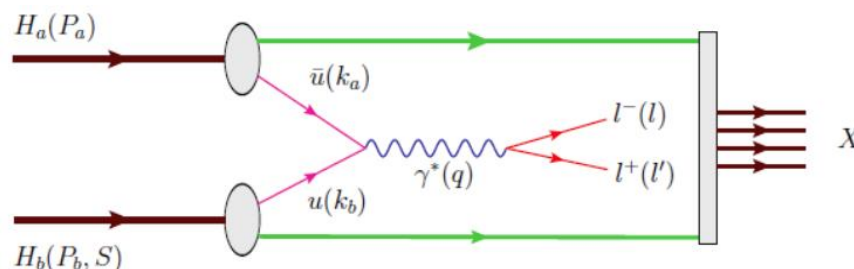
Fig. 3

COMPASS K-W

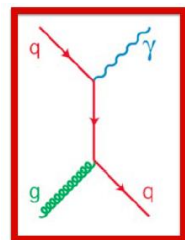


RF separated beam - Drell-Yan (iii) antiproton-induced Drell-Yan

- Antiproton-induced polarised DY makes **TMD's extraction model independent**
- Allows to profit from good knowledge of proton PDFs (from SIDIS) and as alternative probe permits to test TMDs universality
- New data on all TMDs induced asymmetries in both High Mass and J/ψ regions:
 1. **Model independent Boer-Mulders** (quark-spin – quark- k_T correl.) **extraction (CPT equiv.)**
 2. **Model independent Transversity extraction**
 3. **Lam-Tung relation for antiprotons (QCD effects)**
 4. **Sivers asymmetry** (nucleon-spin – quark- k_T correlations) **with no uncertainty from pion PDFs**
 5. **Sivers function for gluons (J/ψ regions)**
 6. **Flavour separated TMDs extraction**
 7. **EMC effects & flavour dependent EMC effects**

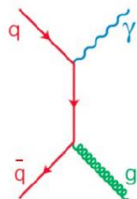


**No competitors,
unique data**

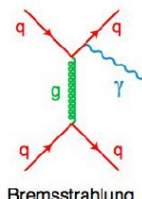


dominating diagram

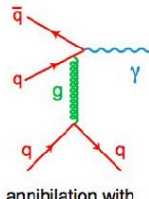
LO



Higher order
(fragmentation photons)



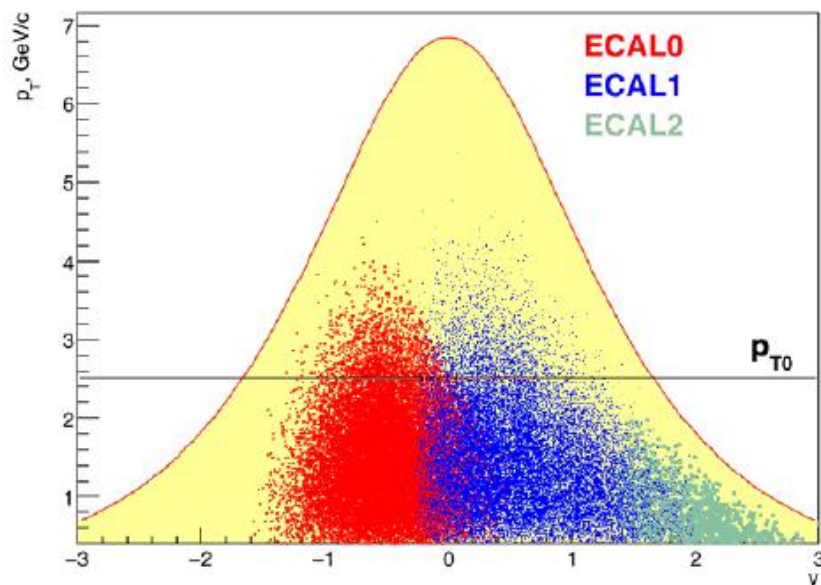
Bremsstrahlung



annihilation with scattering

$$d\sigma_{AB} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b f_a^A(x_a, \mu^2) f_b^B(x_b, \mu^2) d\sigma_{ab \rightarrow \gamma X}(x_a, x_b, \mu^2).$$

access to gluon distributions in hadrons

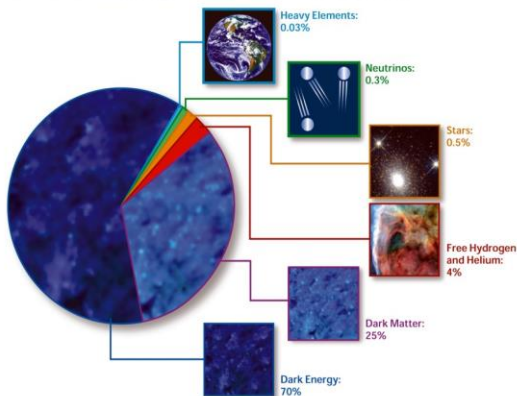


Gluon structure of the kaon is completely unknown while gluon contribution to its mass is especially important for understanding of the nature of the kaon. Some models conclude about much smaller gluon contribution in the kaon rather than in the pion while opposite arguments based on the experimental results have been also expressed. Prompt photon production in the hard process of the gluon Compton scattering in kaon- nucleon interaction provides access to the gluon PDFs of the kaon.

The data taking with the kaon beam has to be preceded by data taking with a pion beam at similar conditions for detailed study of systematic effects.

Unique, no competitors

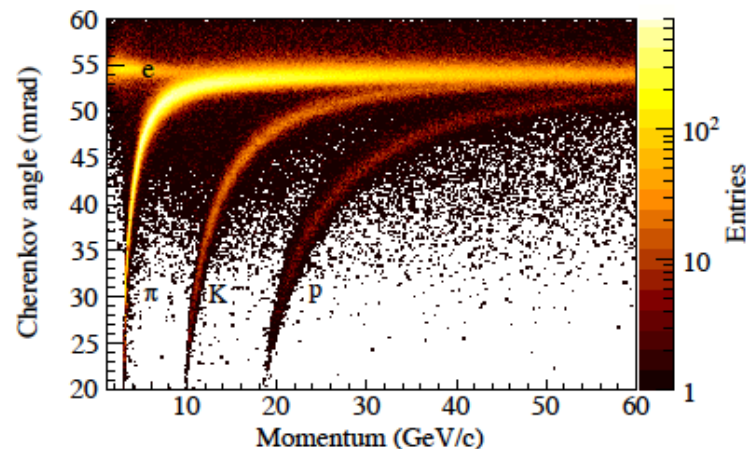
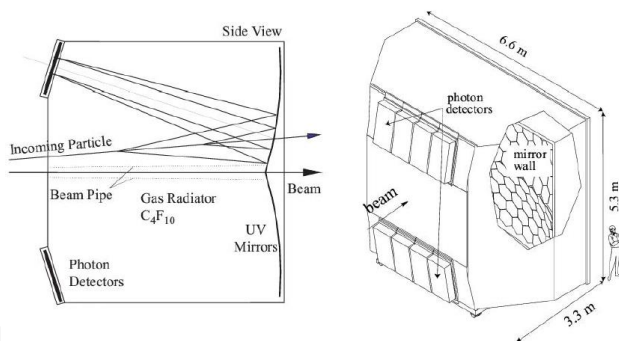
COMPOSITION OF THE COSMOS



- New AMS(2) data – the antiparticle flux is well known now (few % pres.);
- Two type of processes contribute – SM interactions (proton on the ISM with the production for example antiprotons in the f.s.) and contribution from dark particle – antiparticle annihilation;
- In order to detect a possible excess in the antiparticles flux a good knowledge of inclusive cross sections of p-He interaction with antiparticles in the f.s. is a must, currently the typical precision is of 30-50%.

Thus the primary goal is to measure inclusive antiproton (positron, gamma) production cross section in a wide kinematical range with the precision <10%. **Compared to NA49 COMPASS have factor ~1000 as luminosity.** COMPASS:

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



Summary



- **COMPASS: from glorious past to bright future**
- “Beyond 2020” workshop at CERN (March 20-22 2016) → success, strong interest in the hadron physics community, anticipate PBC activity initiated by CERN
- RF separated antiproton/kaon beam will provide unique opportunity for hadron spectroscopy and Drell-Yan physics
- Existing muon and hadron beams offer unique possibilities to extend current COMPASS program by adding new measurement
- Short term future proposal (SIDIS + Proton Radius) has been already submitted to SPSC, Long term future Lol is in preparation, will be made public at the beginning of 2018





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
GEANT3 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

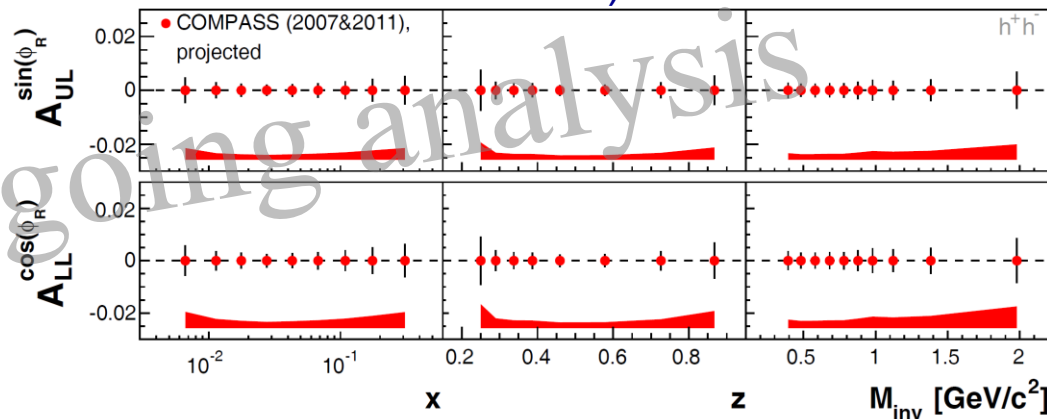
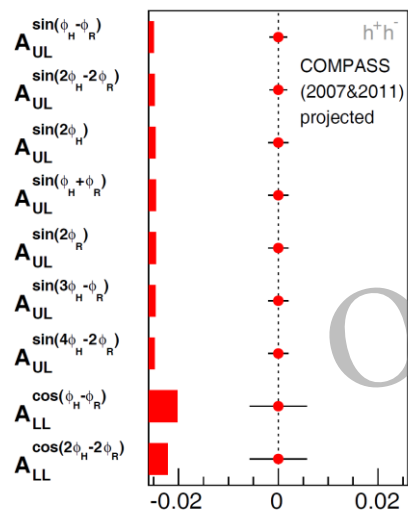
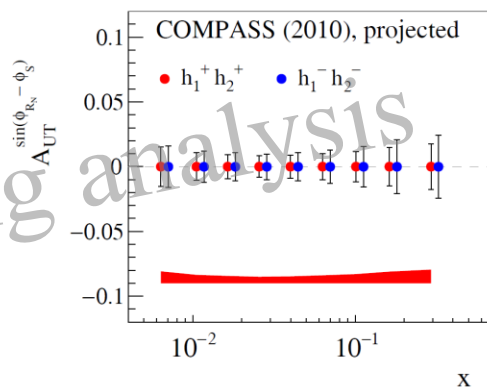
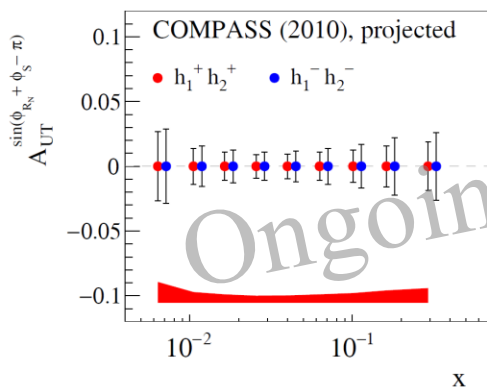
SIDIS transverse & longitudinal II

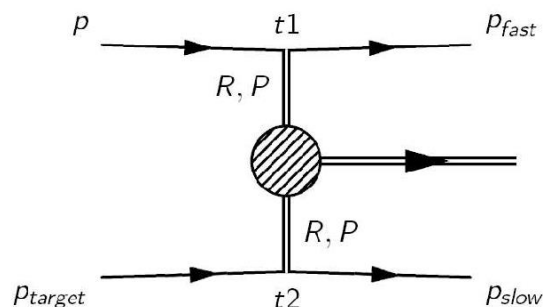
di-hadron TSA and LSA (SKIP?)

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)

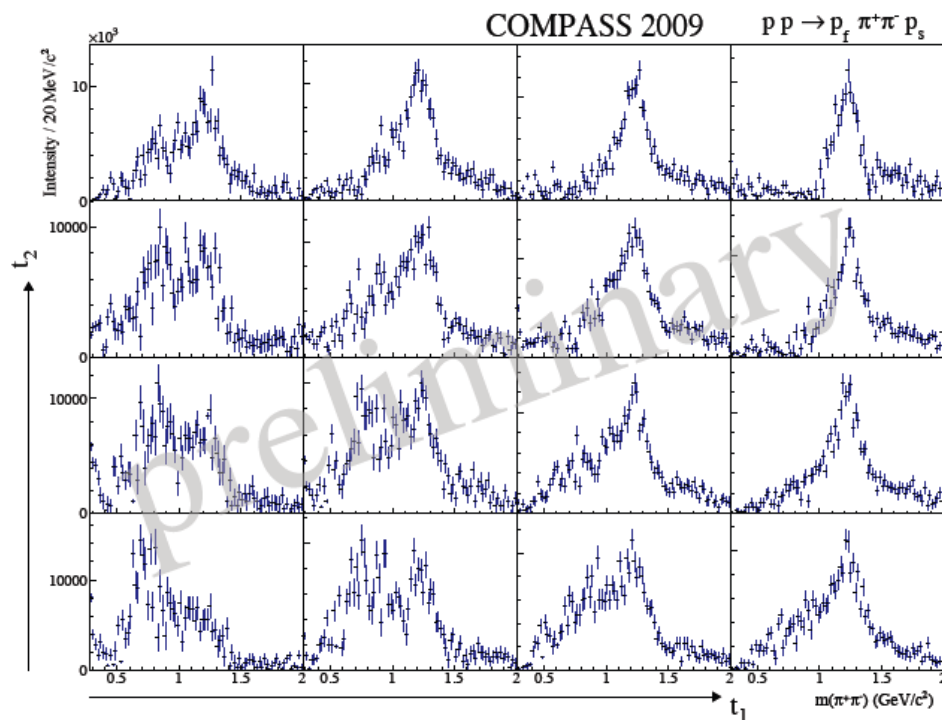


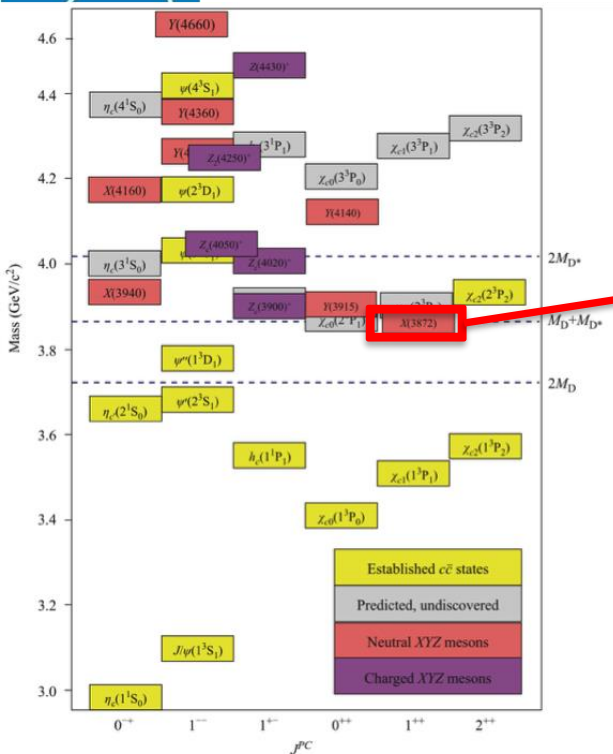


Central production, 2008 and 2009 data.

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.

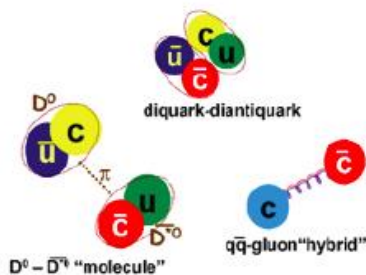




X(3872) is the first charmonium-like exotic hadron discovered by the Belle collaboration in 2003 and studied than in other experiments. Various interpretations exists: pure $c\bar{c}$ state, tetraquark, DD^* - molecule, hybrid ccg state, glueball or else.

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

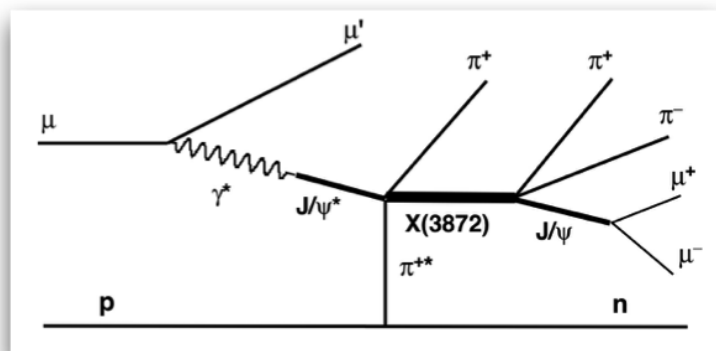
State	M /MeV	Γ /MeV	J^{PC}	Process (decay mode)	Experiment
X(3872)	3871.68 ± 0.17	< 1.2	1^{++}	$B \rightarrow K + (J/\psi \pi^+ \pi^-)$ $p\bar{p} \rightarrow (J/\psi \pi^+ \pi^-) + \dots$ $B \rightarrow K + (J/\psi \pi^+ \pi^- \pi^0)$ $B \rightarrow K + (D^0 \bar{D}^0 \pi^0)$ $B \rightarrow K + (J/\psi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



Never observed so far in lepto-production process

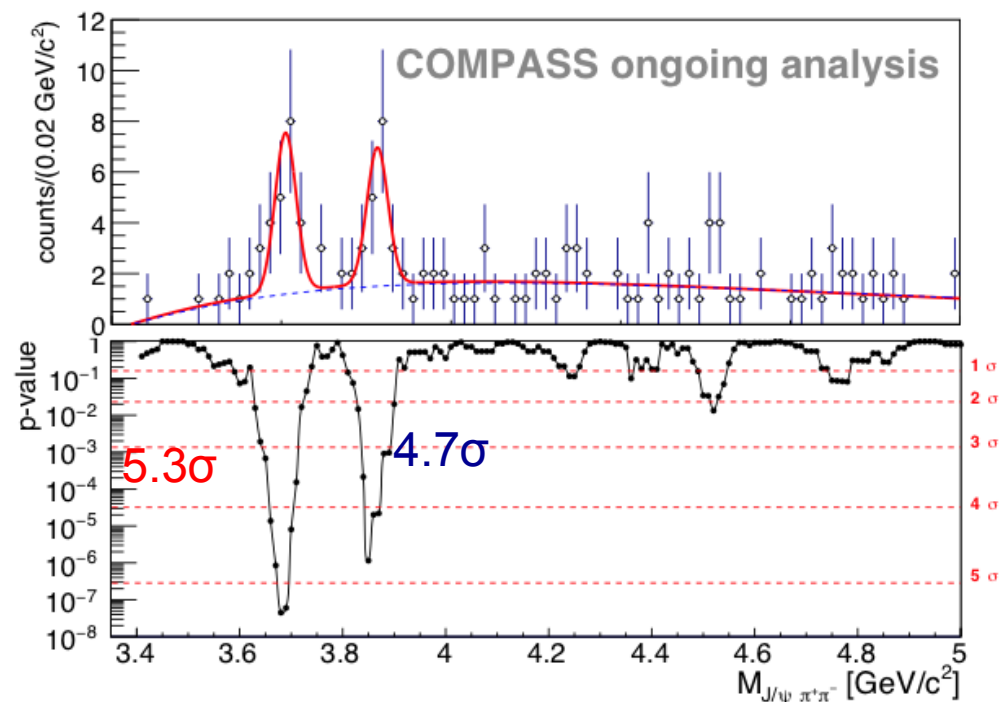
COMPASS muon beam data 2003→2010

Study $J/\psi\pi^+\pi^-$ subsystem of exclusive final state $J/\psi\pi^+\pi^-\pi^\pm$



$$N_{\psi(2S)} = 16.1 \pm 5.2$$

$$N_{X(3872)} = 13.9 \pm 4.9$$

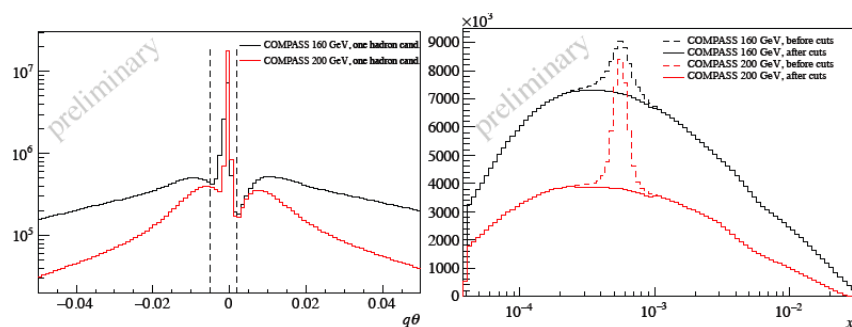


$$M_{\psi(2S)} = 3680 \pm 8 \text{ MeV (nominal 3686.1)}$$

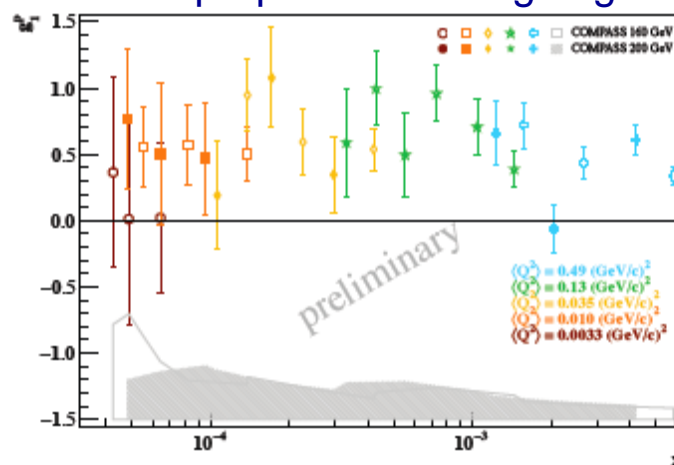
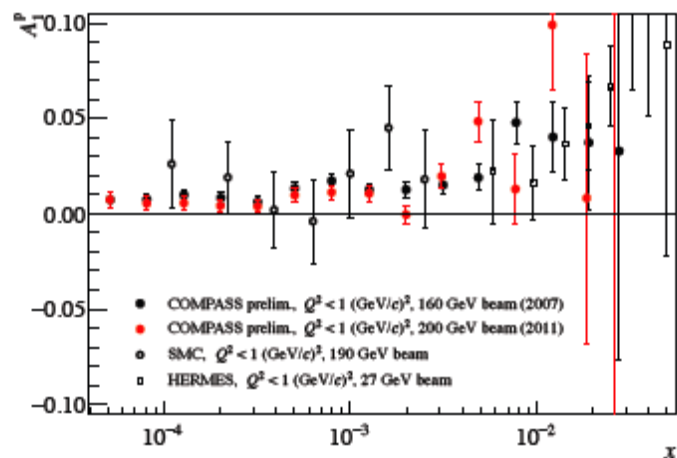
$$M_{X(3872)} = 3860 \pm 8 \text{ MeV (nominal 3871.7)}$$

Proton 2007 and 2011 $Q^2 < 1$

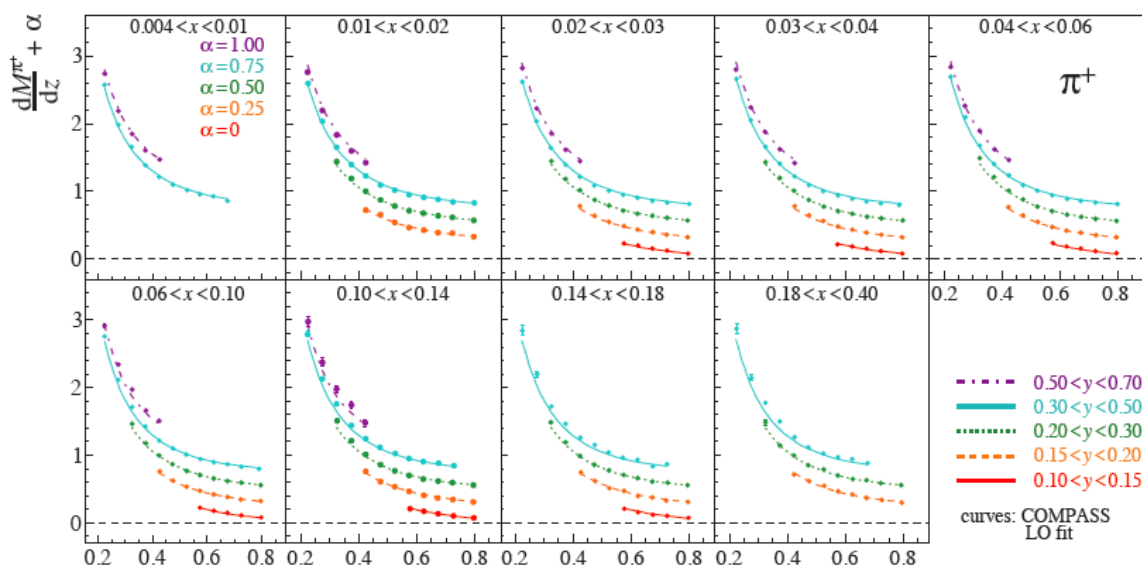
The main challenge in the low- Q^2 analysis is the suppression of events due to muon scattering off target electrons. These events are removed by a cut on the product of the angle between the virtual photon and the electron candidate and the particle charge $q\theta$.



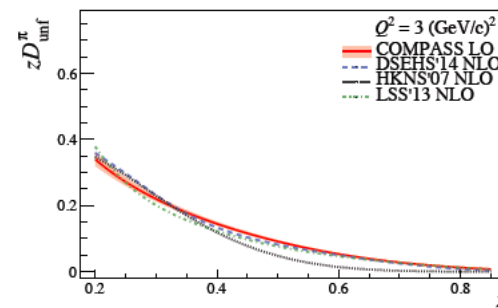
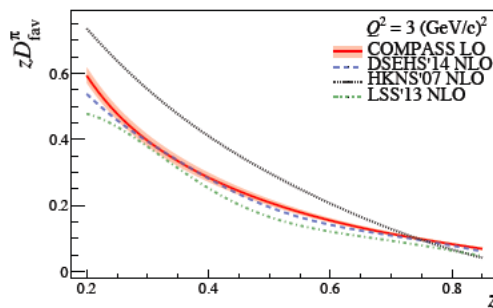
The results for A_1^p for both data sets are compared to previous measurements. The increase in precision is evident. The COMPASS data show a small, nearly constant asymmetry of about 1% at small x . The resulting values for g_1^p are shown in together with the systematic error band. For comparison with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



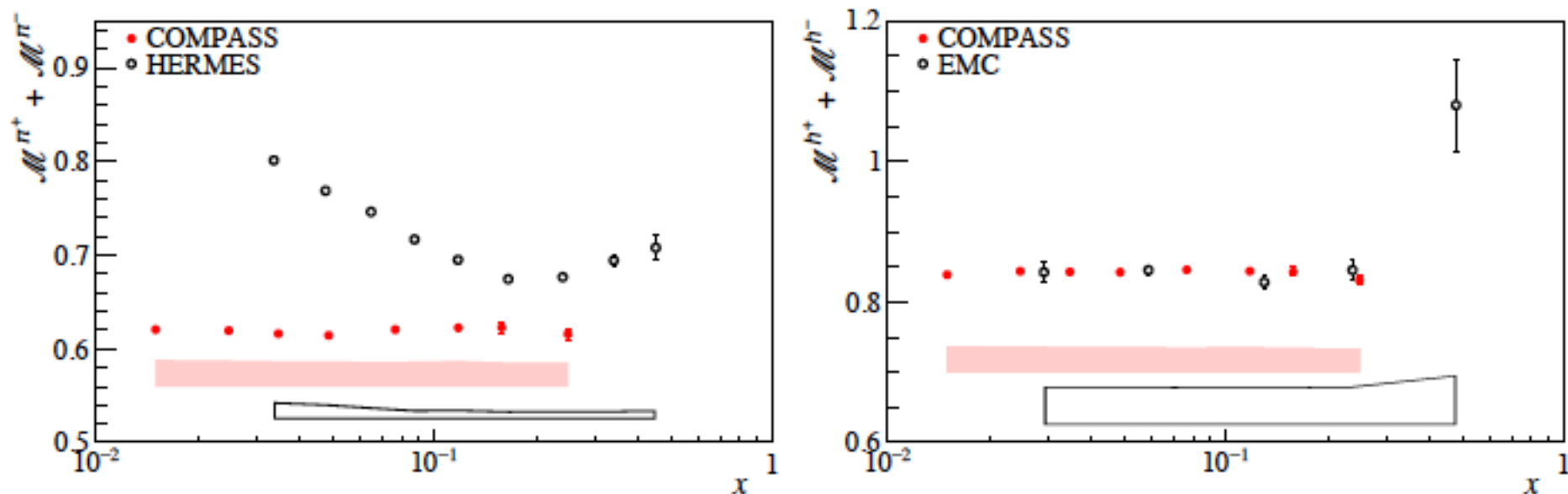
Charged pion and unidentified hadron multiplicities (2006 160 GeV muon beam and an iso-scalar target (${}^6\text{LiD}$)) – submitted to PLB. Positive reaction by referees, preparing answers to their questions. The 3-dimensional data set (x , y and z) \rightarrow an important input for future NLO pQCD 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.



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...

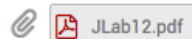


mgp-Polarized-Drel...



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

Speaker: Dr. Carlos Munoz Camacho (Jefferson Lab)



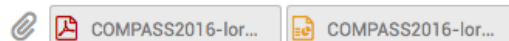
15:00 **Opportunities with polarized beams at RHIC/EIC 30'**

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



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

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



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

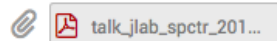
16:30 - 18:30 **Afternoon session II**

Convener: Bernhard Ketzer (Universitaet Bonn (DE))



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

Speaker: Dr. Eugene Chudakov (Jefferson Lab)



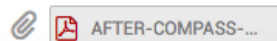
17:00 **Competition and complementarity in spectroscopy from e+e- machines 30'**

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



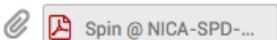
17:30 **Studying the nucleon structure, quarkonium production and spin effects with AFTER@LHC 30'**

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



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

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



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



Tuesday, 22 March 2016

09:00 - 10:30

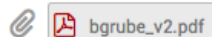
Morning session I

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



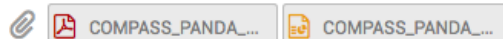
09:00 **Possible future hadron spectroscopy measurements at COMPASS 30'**

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



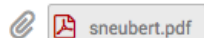
09:30 **Initial Measurements of Hadron Spectroscopy and Nucleon Structure with Antiprotons by PANDA 30'**

Speaker: James Ritman (CERN)



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

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



10:30 - 11:00

Coffee break (Building 222)

11:00 - 13:00

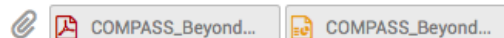
Morning session II

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



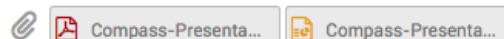
11:00 **Study hadron partonic structure at J-PARC and EIC/China 30'**

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



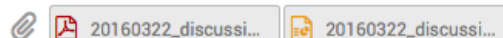
11:30 **Future beam options for fixed-target experiments at CERN 30'**

Speaker: Lau Gatignon (CERN)



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

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



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'

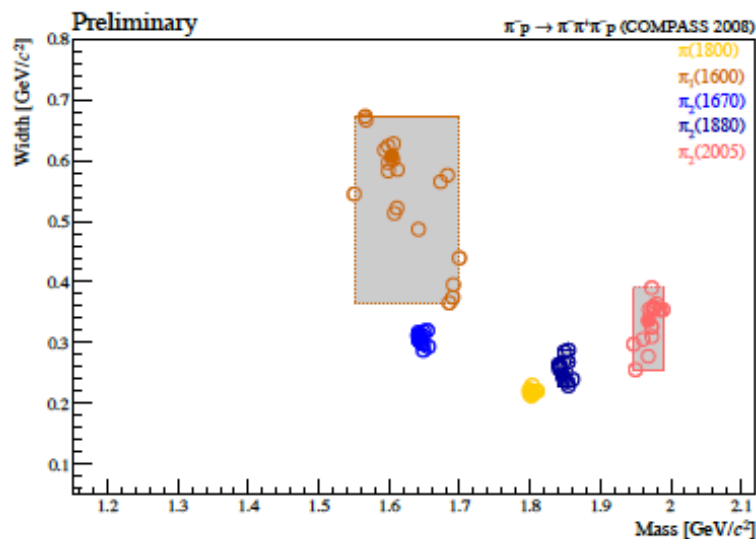
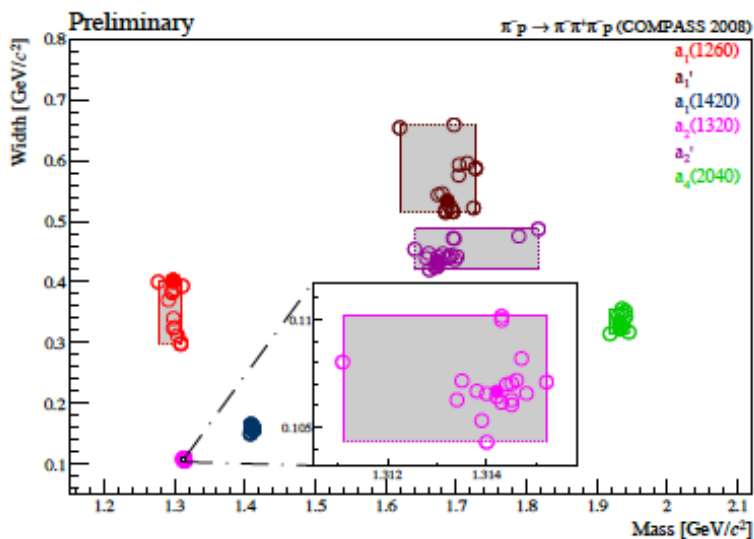
Speaker: Oleg Denisov (INFN, sezione di Torino)

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:

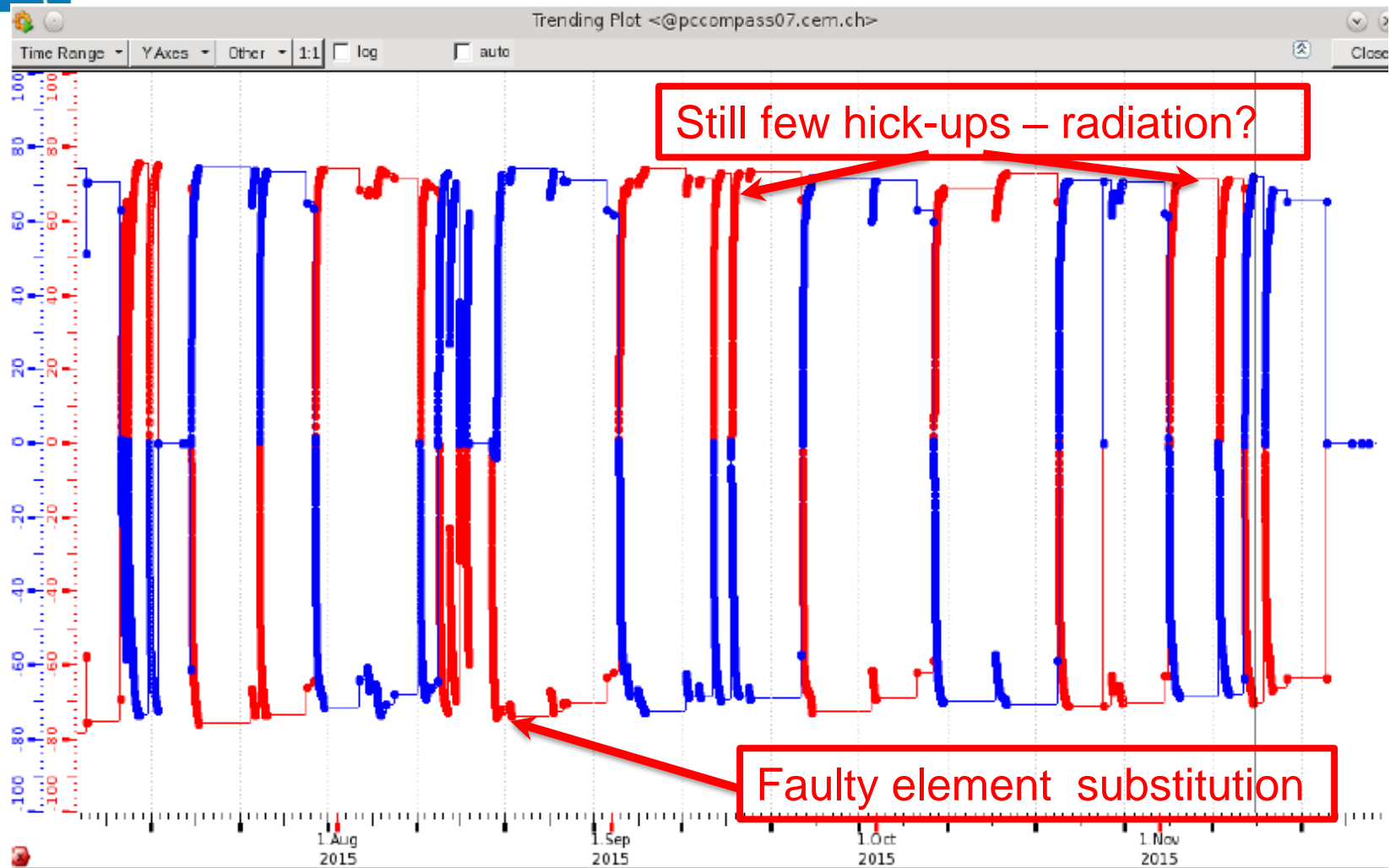
- 14 waves versus 6
- simultaneous fit in all 11 t' bins resulting in better separation of the resonant and non-resonant contribution as they have different t' dependences

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

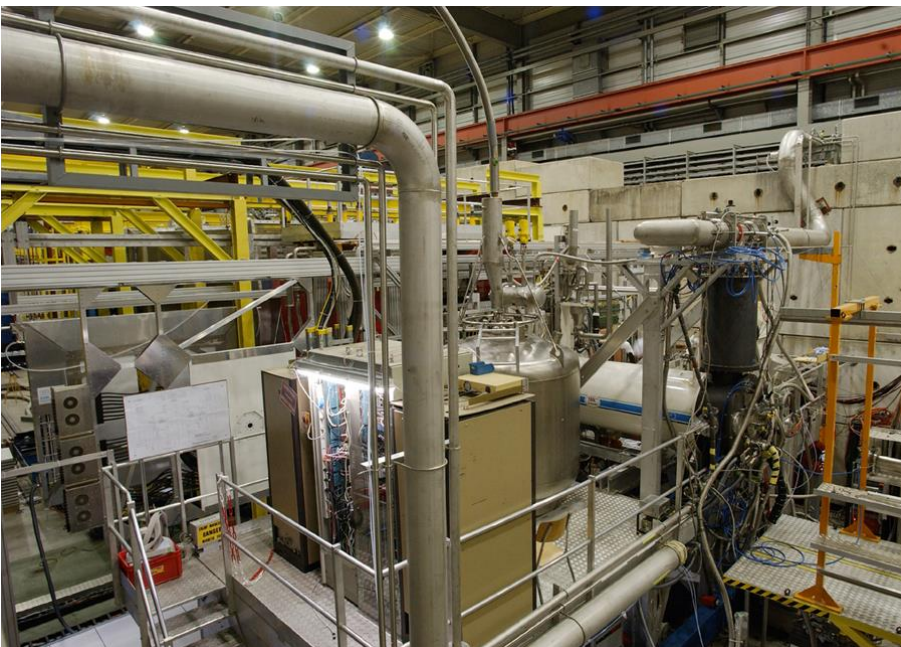


COMPASS Drell-Yan Run 2015 III

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



Deuteron data:

Published:

2002 and 2004 $Q^2 > 1$

This report – Deuteron 2006 $Q^2 > 1$

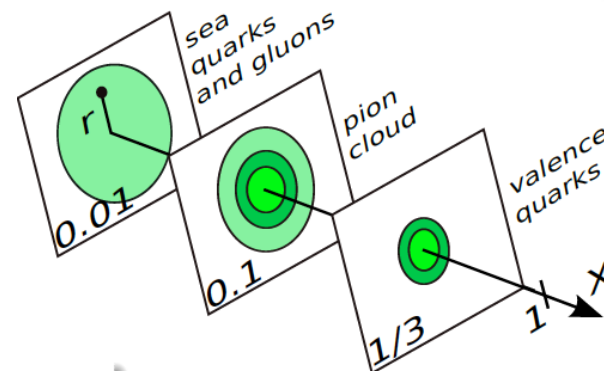
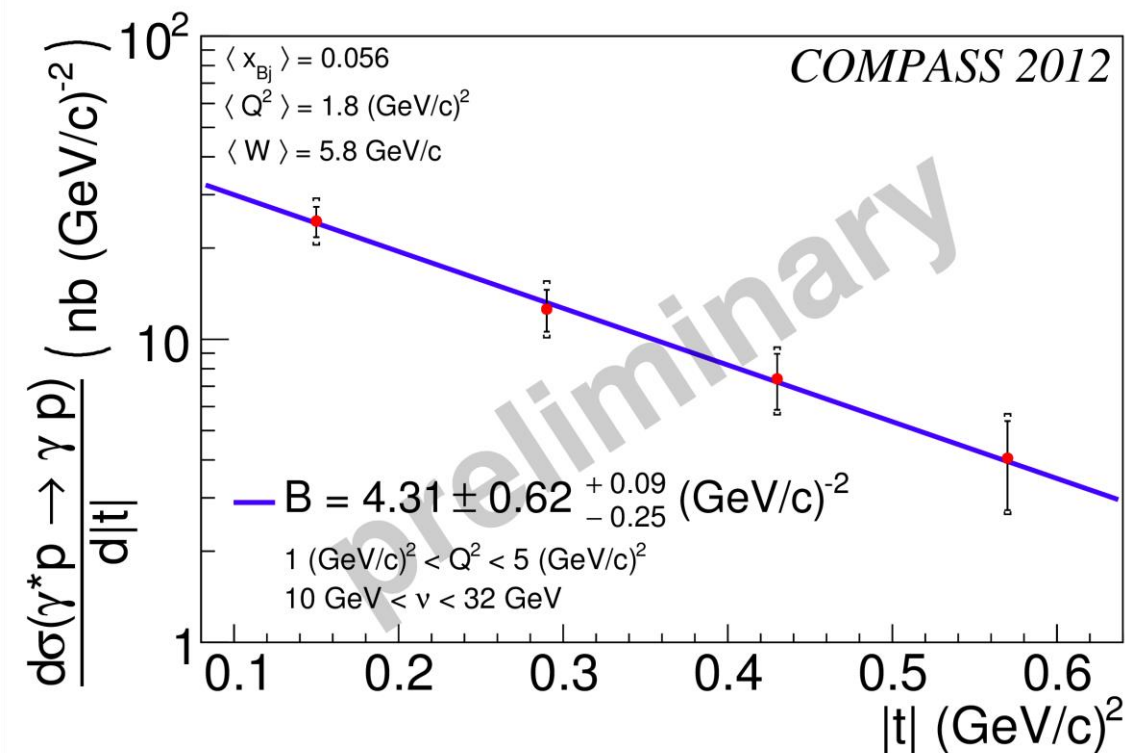
Proton data:

Published:

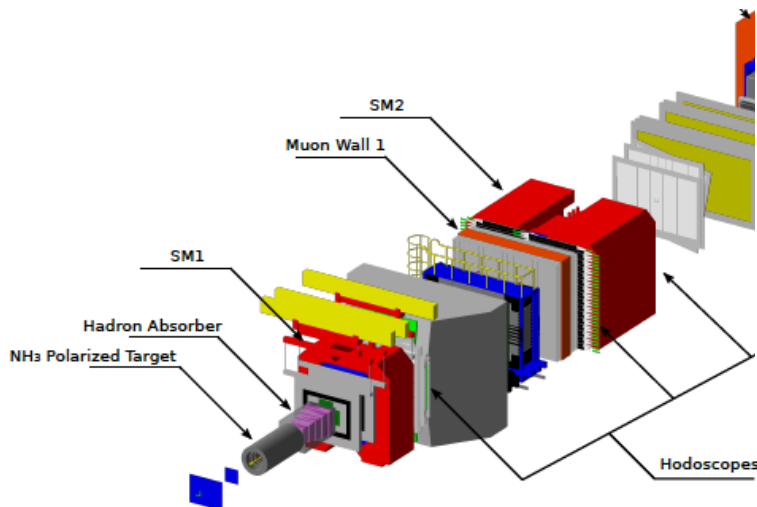
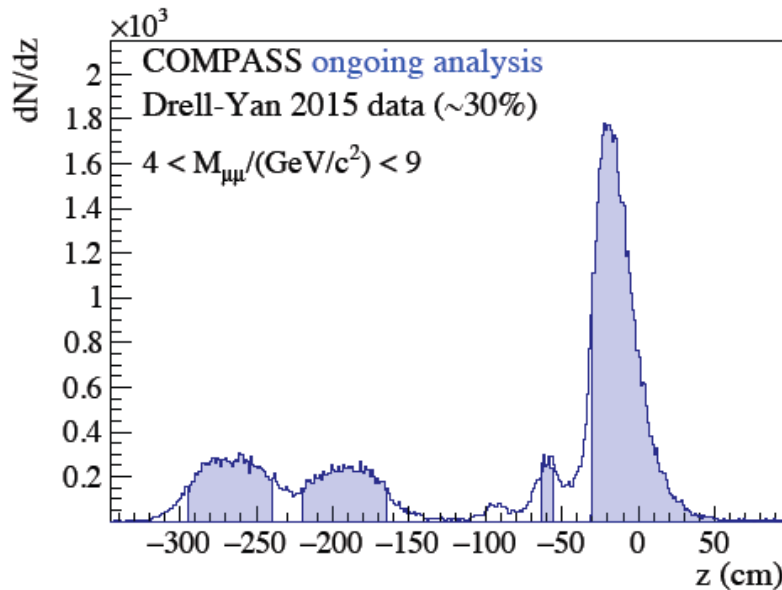
2007, 2011 $Q^2 > 1$

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

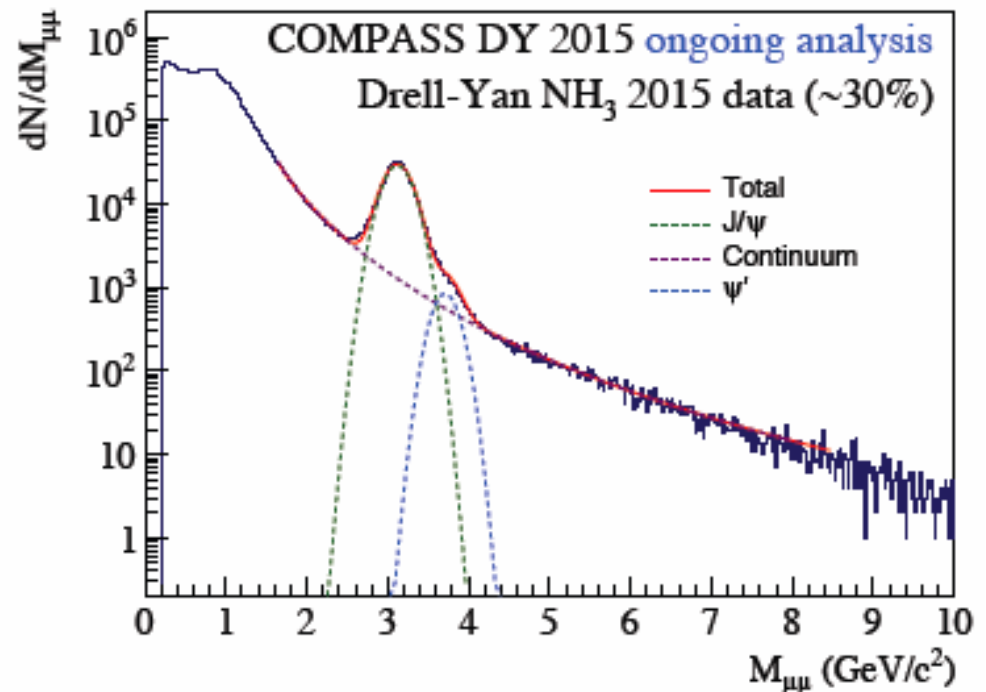
DVCS 2012 results V: t -slope



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



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 ($M_{\mu\mu} > 4 \text{ GeV}/c^2$) is **18198**

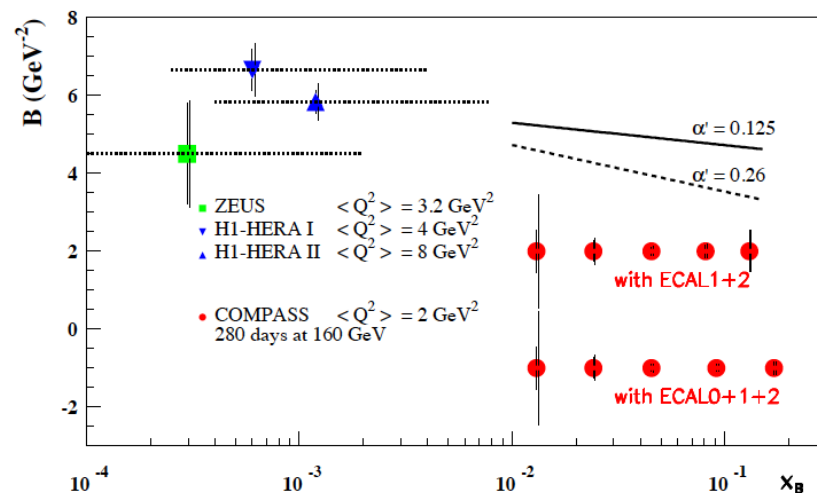
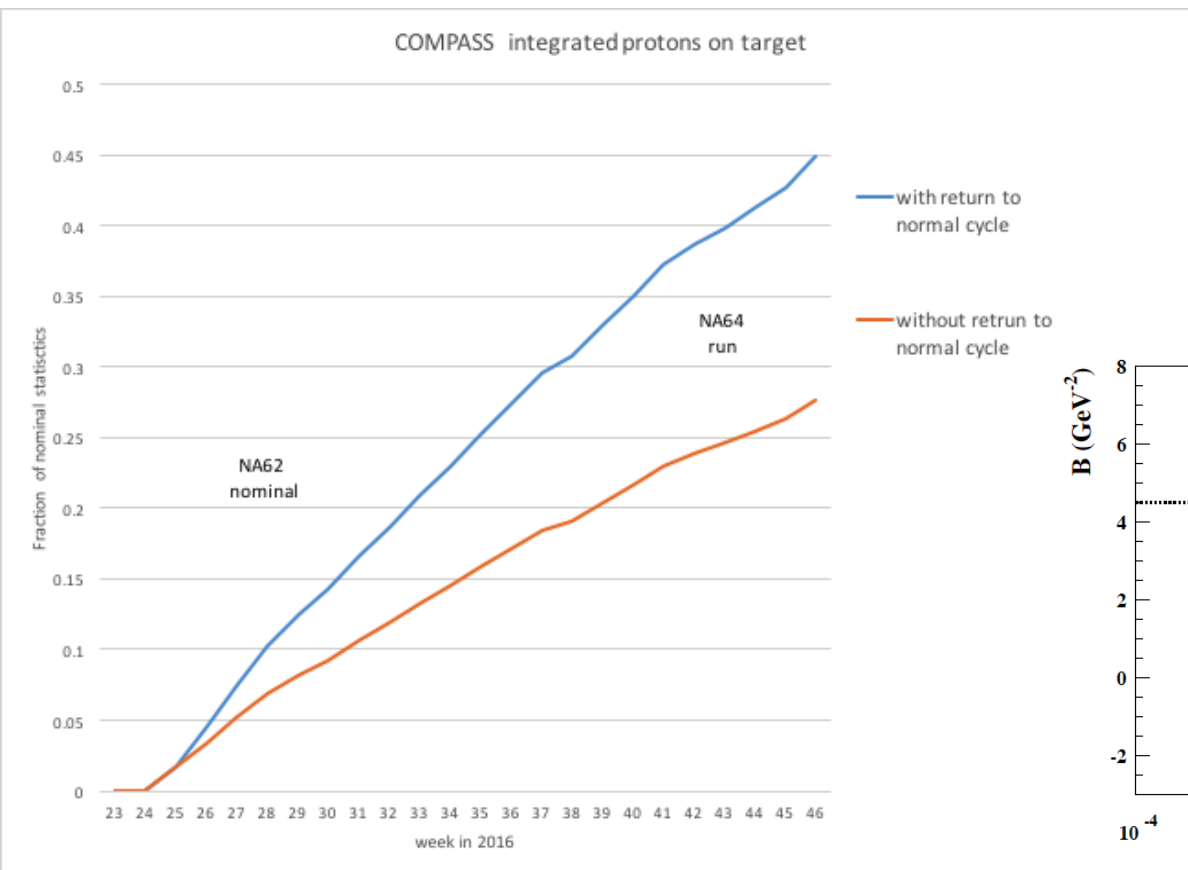
DVCS run 2016 – projections and impact

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

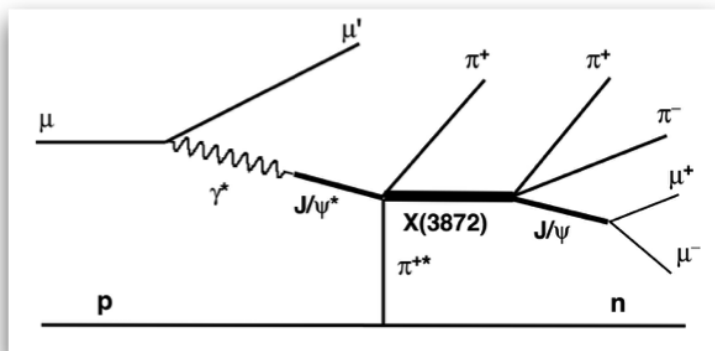
Channel	status	details
Leptoproduction of $\psi(2S)$ and $X(3872)$	new	pbw
Pion polarisability from 2012 data	update	study of systematic effects using muon control data
Determination of the chiral dynamics in $\pi^+\gamma \rightarrow \pi^-\pi^0\pi^0$	update	ongoing
Measurement of chiral anomaly in $\pi^+\gamma \rightarrow \pi^-\pi^0$	new	started
New axial-vector meson $a_1(1420)$ in $\pi^-p \rightarrow \pi^-\pi^-\pi^+p_{\text{recoil}}$	final	PRL 115 (2015) 082001
Resonance Production and $\pi\pi$ S-wave in $\pi^-p \rightarrow \pi^-\pi^-\pi^+p_{\text{recoil}}$	final	submitted to PRD 88-wave PWA in 11 t' bins
Extraction of 3π resonances in $\pi^-p \rightarrow \pi^-\pi^-\pi^+p_{\text{recoil}}$	update	simultaneous fit of 14 waves in 11 t' bins pbw
Study of non-resonant contributions in $\pi^-p \rightarrow \pi^-\pi^-\pi^+p_{\text{recoil}}$	new	inclusion of Deck amplitude into PWA
Study of $\pi^+\pi^-$ subsystem in $\pi^-p \rightarrow \pi^-\pi^-\pi^+p_{\text{recoil}}$	update	extension of method to more waves
Central production of $\pi^+\pi^-$ in $pp \rightarrow p_{\text{fast}}\pi^-\pi^+p_{\text{recoil}}$	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 longitudinally pol. SIDIS from 2011 proton data	starting	ongoing
2007&2011 proton g_1 at $Q^2 < 1 \text{ GeV}^2/c$	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 $Q^2 < 1 (\text{GeV}/c)^2$	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 asymmetries for longitudinally polarised target	final	pbw
Exclusive Omega production	final	submission



In order to estimate the width of X(3872) we use $\psi(2S)$ 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 $\psi(2S)$

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

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

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

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

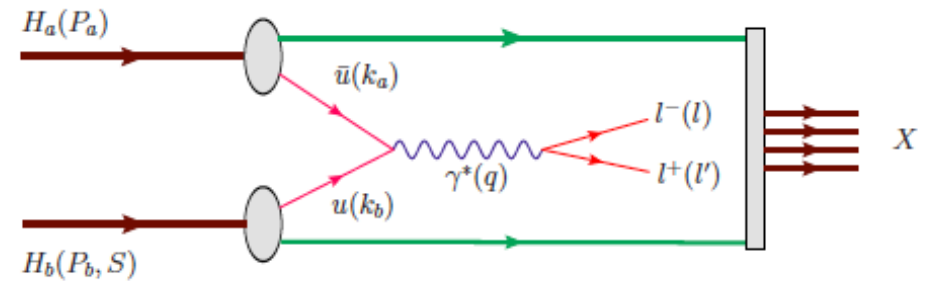
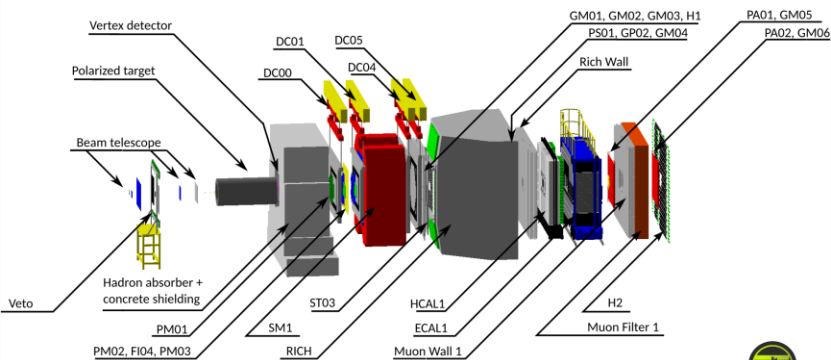
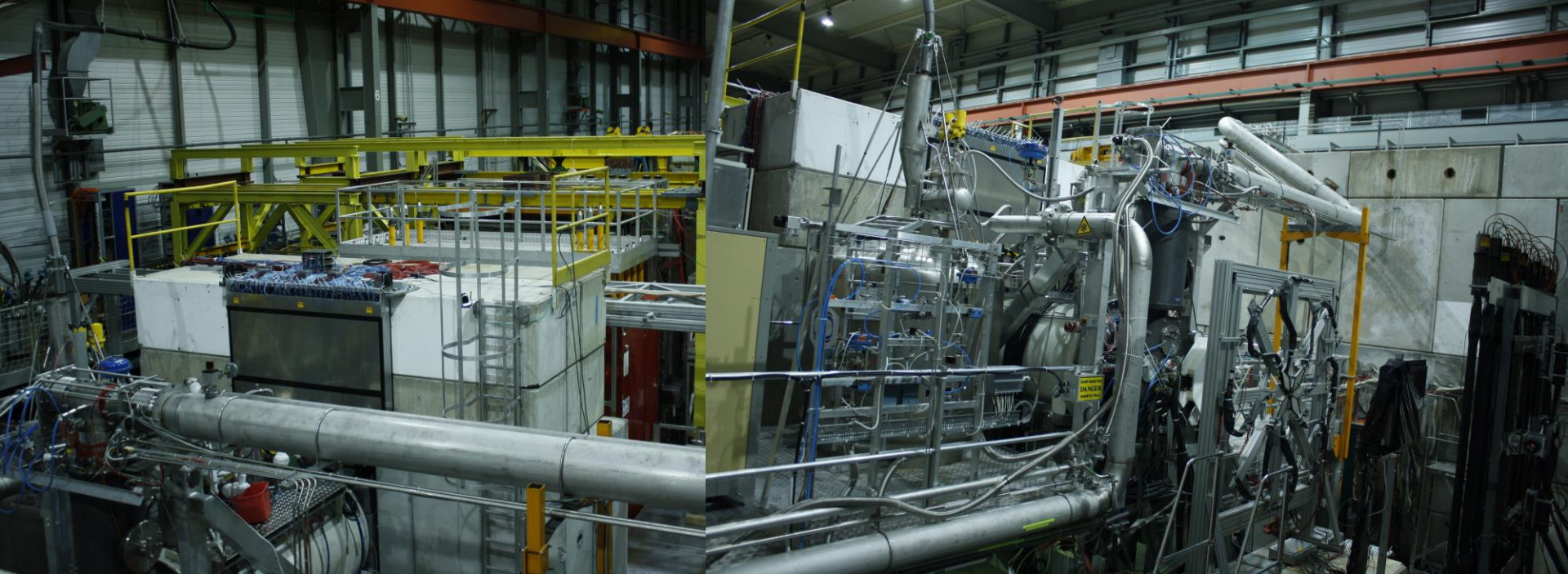
as $\Gamma_{X(3872)} < 1.2 \text{ MeV}$ CL=90%, and

$$\Gamma_{X(3872)} = R \times \frac{\Gamma_{\psi(2S) \rightarrow J/\psi \pi \pi} \times B_{\psi(2S) \rightarrow J/\psi \pi \pi}}{B_{X(3872) \rightarrow J/\psi \pi \pi}^2} > 80 \text{ keV}/c^2.$$

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

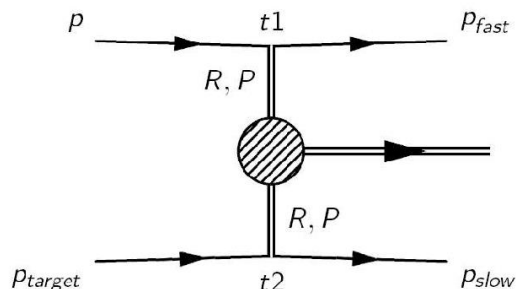


Central production I

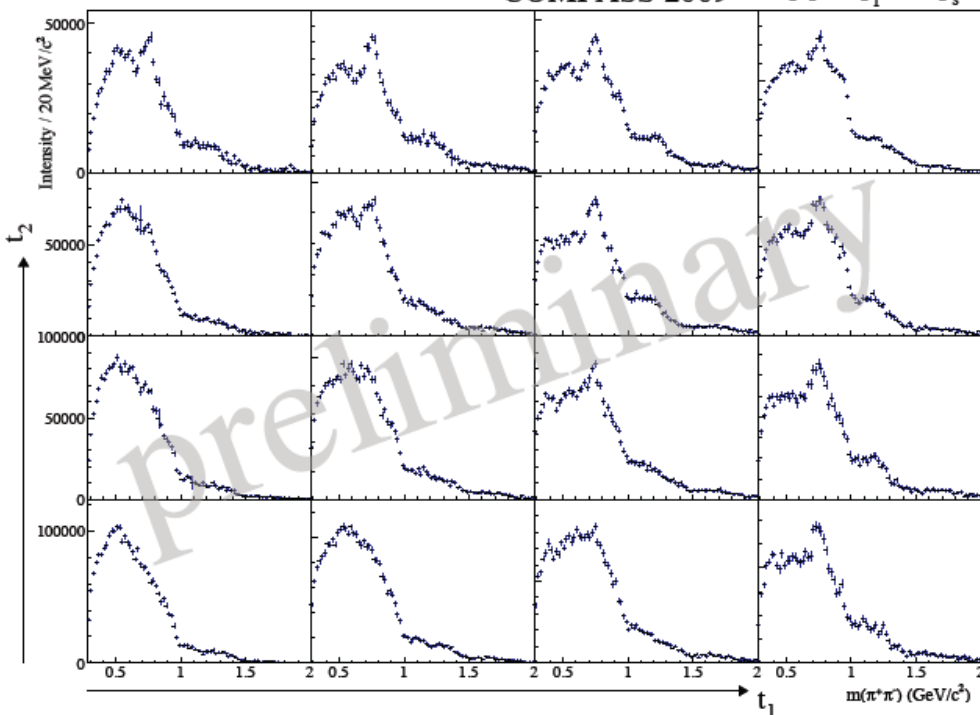
Central production, proton beam in 2008 and 2009.

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 $M \leq 1$) contribute significantly.



COMPASS 2009 $p p \rightarrow p_f \pi^+ \pi^- p_s$



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

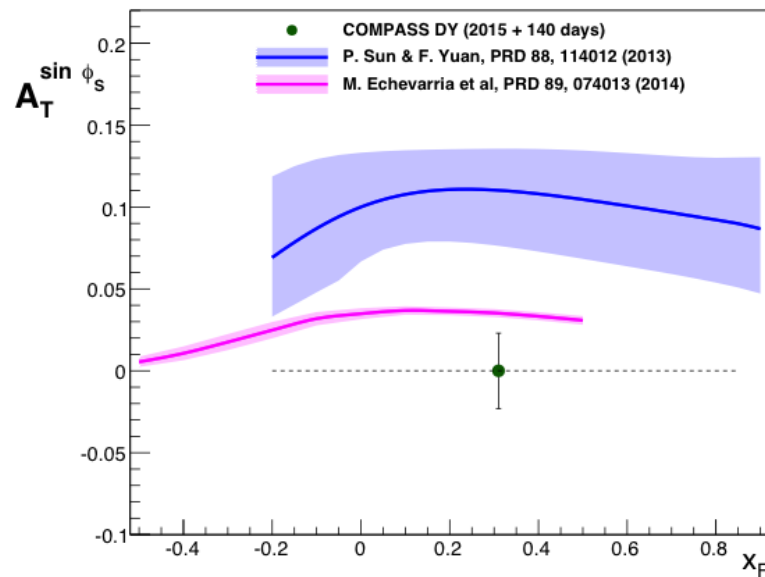
Low t_1 and t_2 - $\rho(770)$ signal has practically vanished. These bins are dominated by a double-Pomeron exchange mechanism where ρ production is forbidden (C-parity conservation)

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

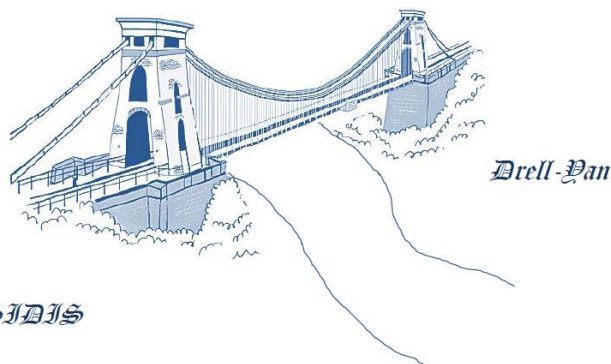
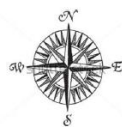
Goal: to increase a total polarised data sample by at least **factor 2** in order to achieve the statistical error on **Sivers asymmetry (2015+2018) of $\sim 2\%$** (small asymmetry in case of fast TMDs evolution) and to collect world largest kaon and anti-proton induced DY data sample.

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	—

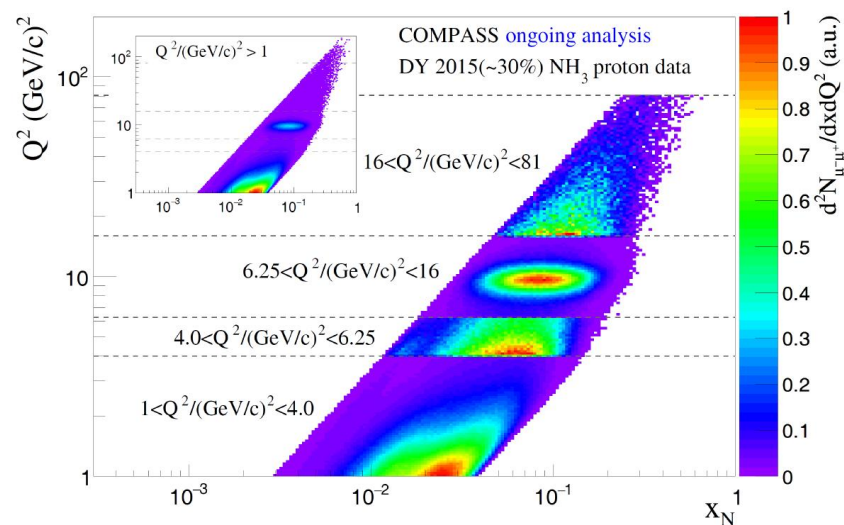
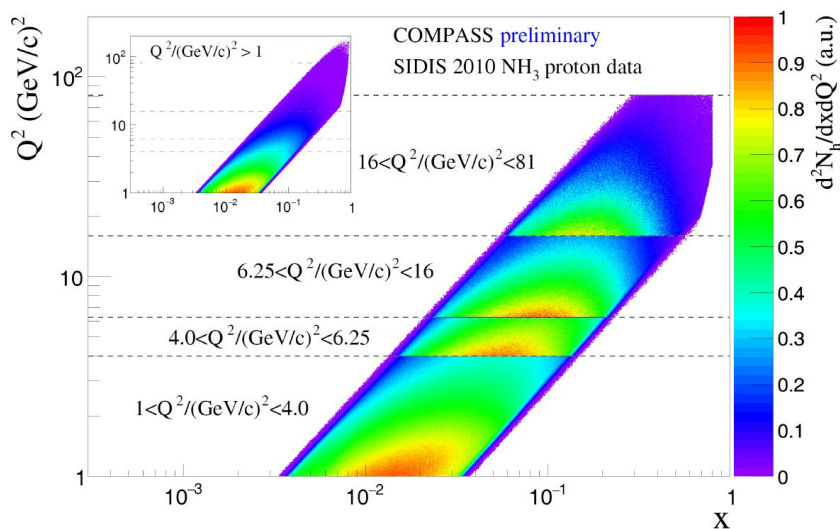


SIDIS

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

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

For final publication the newly produced 2010 data will be used



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

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

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

Important: large statistics, good acceptance.

Allows to extract first momentum of Sivers

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

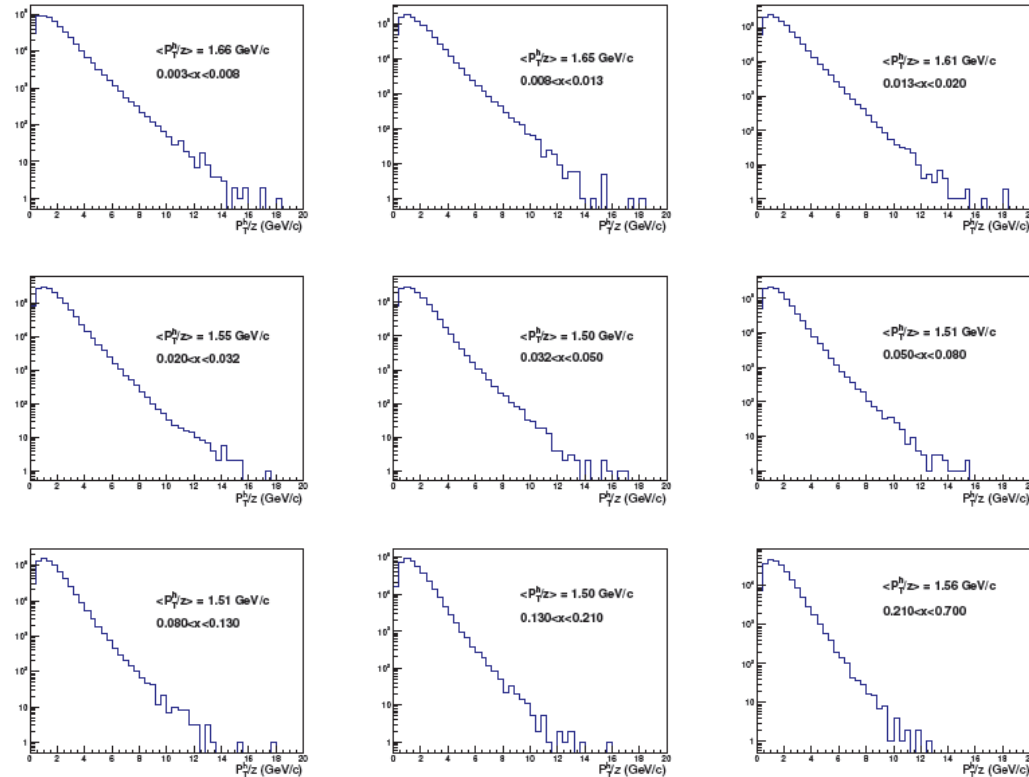










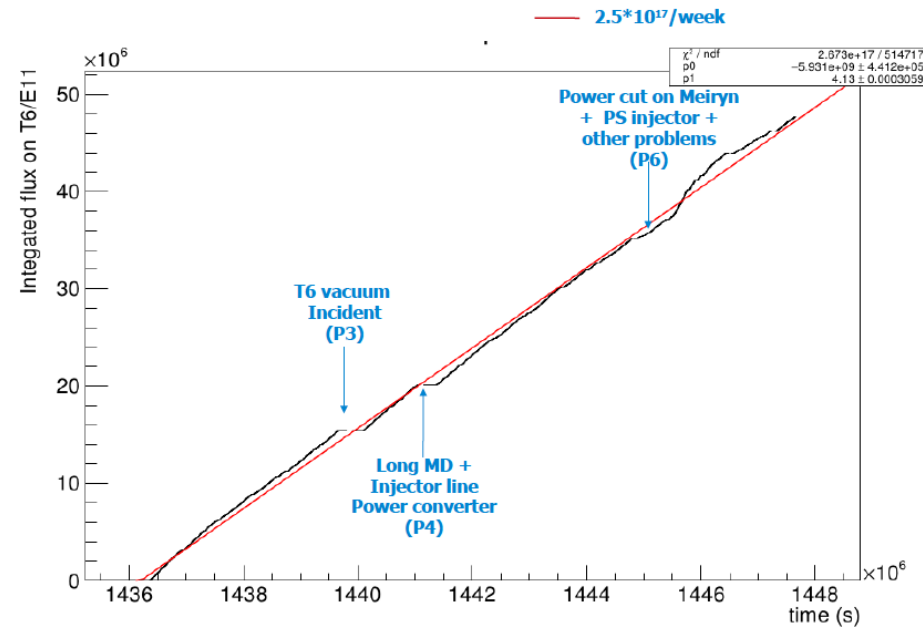
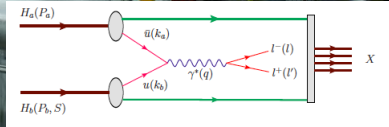
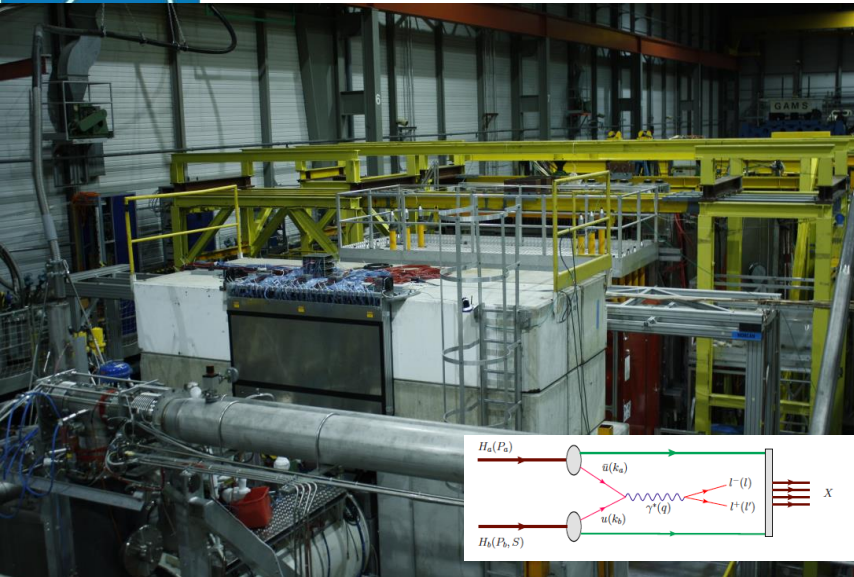
Fig. 18: Typical p_T^h/z distributions in the nine standard COMPASS x bins.

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

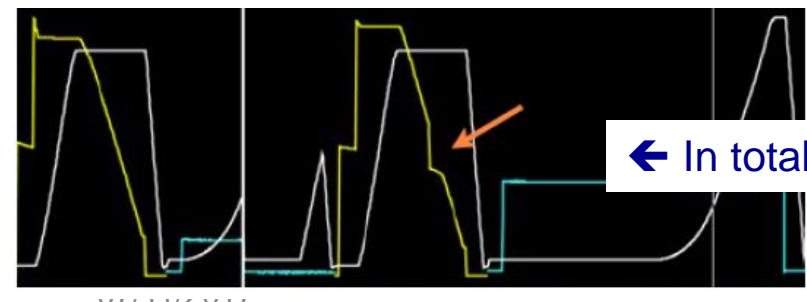
subm. 2015				
21.01.15	<i>Observation of a new narrow axial-vector meson $a_1(1420)$</i>	 tar	PRL 115 (2015) 082001 DOI	CERN-PH-EP/2015-015 hep-ex/1501.05732
26.03.15	<i>The spin structure function g_1^p of the proton and a test of the Bjorken sum rule</i>	 tar	PLB 753 (2016) 18 DOI	CERN-PH-EP/2015-085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

More papers are in pipeline:

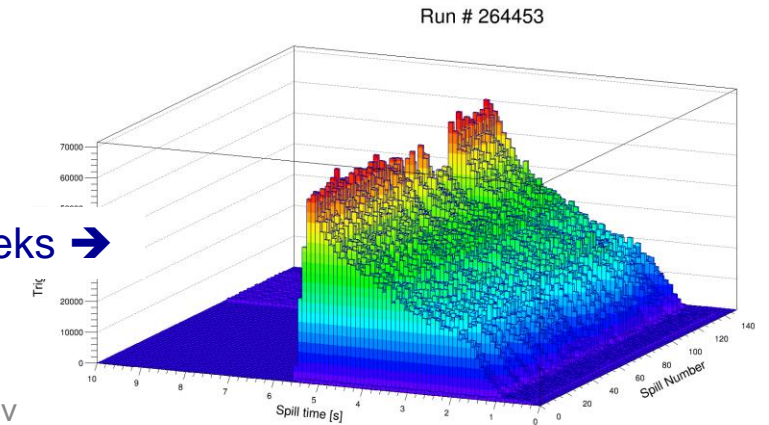
1. Multiplicities of charged kaons (almost finished)
2. Multiplicities of the neutral kaons (draft1 in progress)
3. $\pi_1(1600)$ – drafted
4. Extraction of A_1^p and g_1^p for $Q^2 < 1$ (GeV/c)² in two-dimensional bins from the 2007 and 2011 longitudinal data (draft1 in progress)
5. A_1^d 2002-2006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



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%



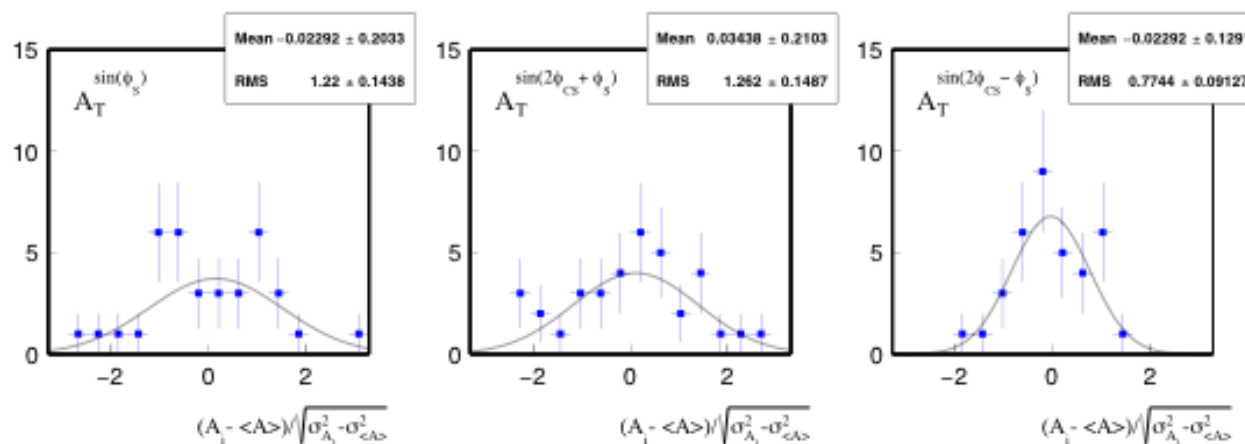
← In total several weeks →



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

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%)
Compatibility of periods (**preliminary**)



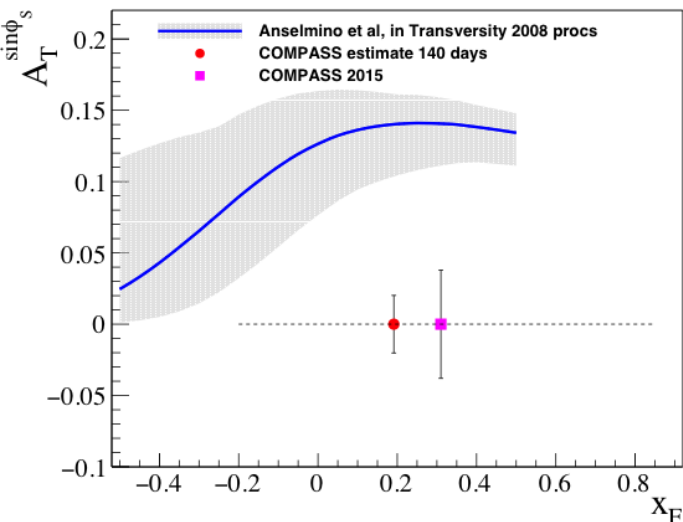
$$\delta A_T^{\sin \phi_S}(x_a, x_b) = \frac{1}{f |S_T|} \frac{\sqrt{2}}{\sqrt{N(x_a, x_b)}}.$$

Total number of DY events ($M_{\mu\mu} > 4 \text{ GeV}/c^2$) 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



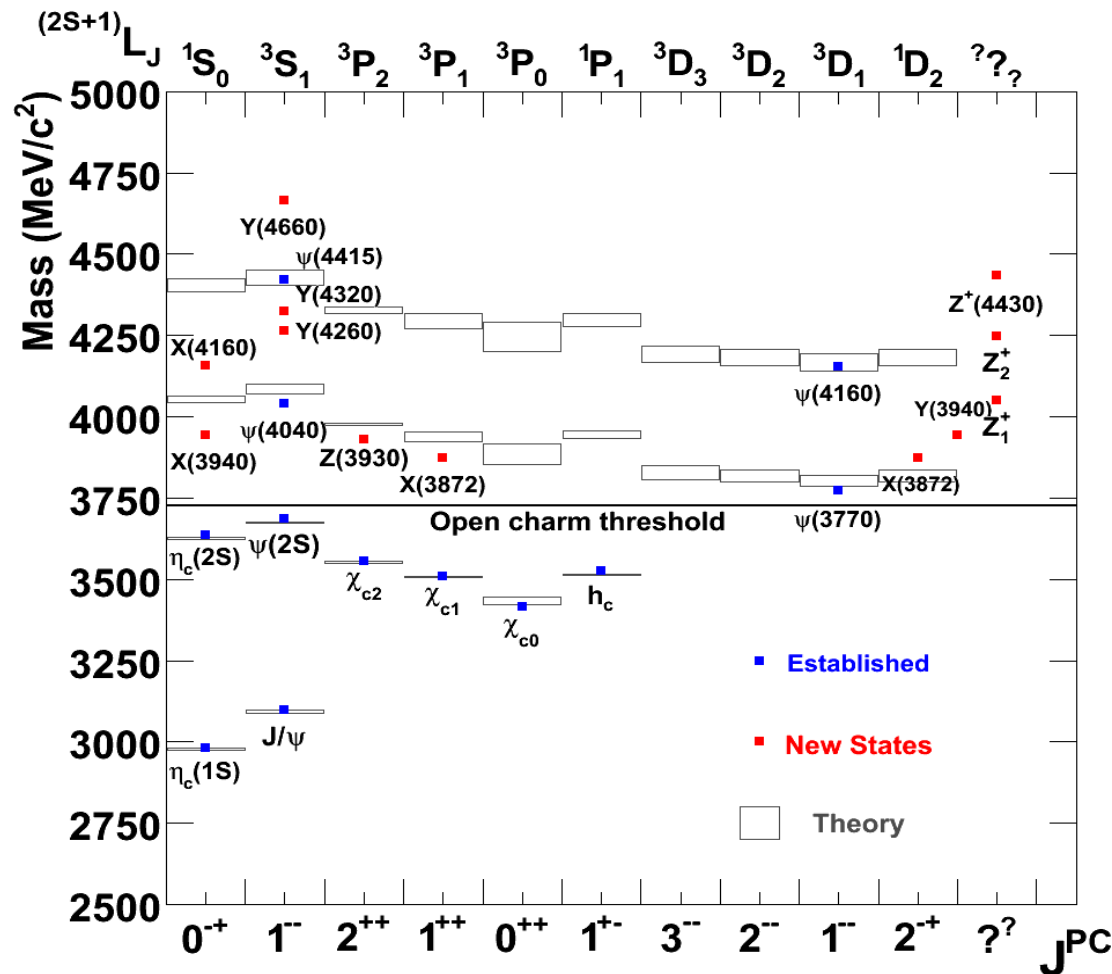
Using only 2015 data the Sivers sign change can be only established if the asymmetry is large (>0.1), which is unlikely if TMD evolution is fast (recent theory developments).

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:

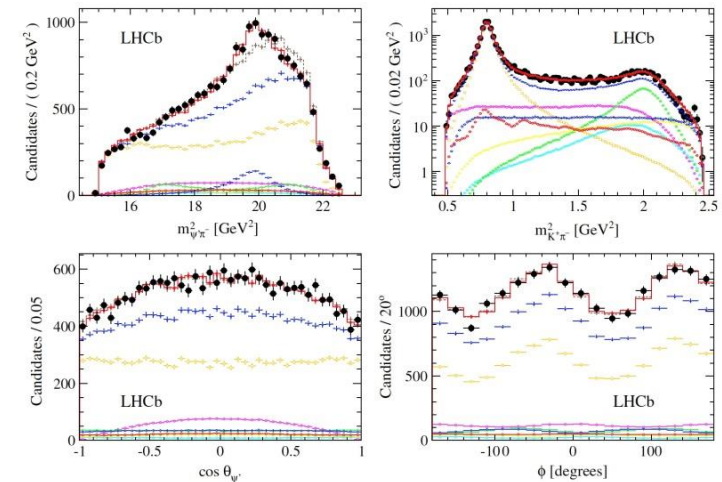
- Running time ~ 100 days vs 140 (Proposal)
- PT polarisation (80% vs 90%),
- Quality/kinematic cuts (conservative): 30%

Overall spectrometer performance and beam parameters – as expected



- Many new (narrow) states discovered in recent years
- Assignment not clear
- Some definitively not charmonium-like

LHCb: $Z(4430)^-: 13.9 \sigma$



[LHCb, PRL 112, 222002 (2014)]

[V. Santoro, Hadron 2015]