Dilepton Productions with Meson and Antiproton Beams
2017.11.06-10, Trento, Italy

Overview of COMPASS - Past, Present, and Future

Oleg Denisov (CERN/INFN-Torino)

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**

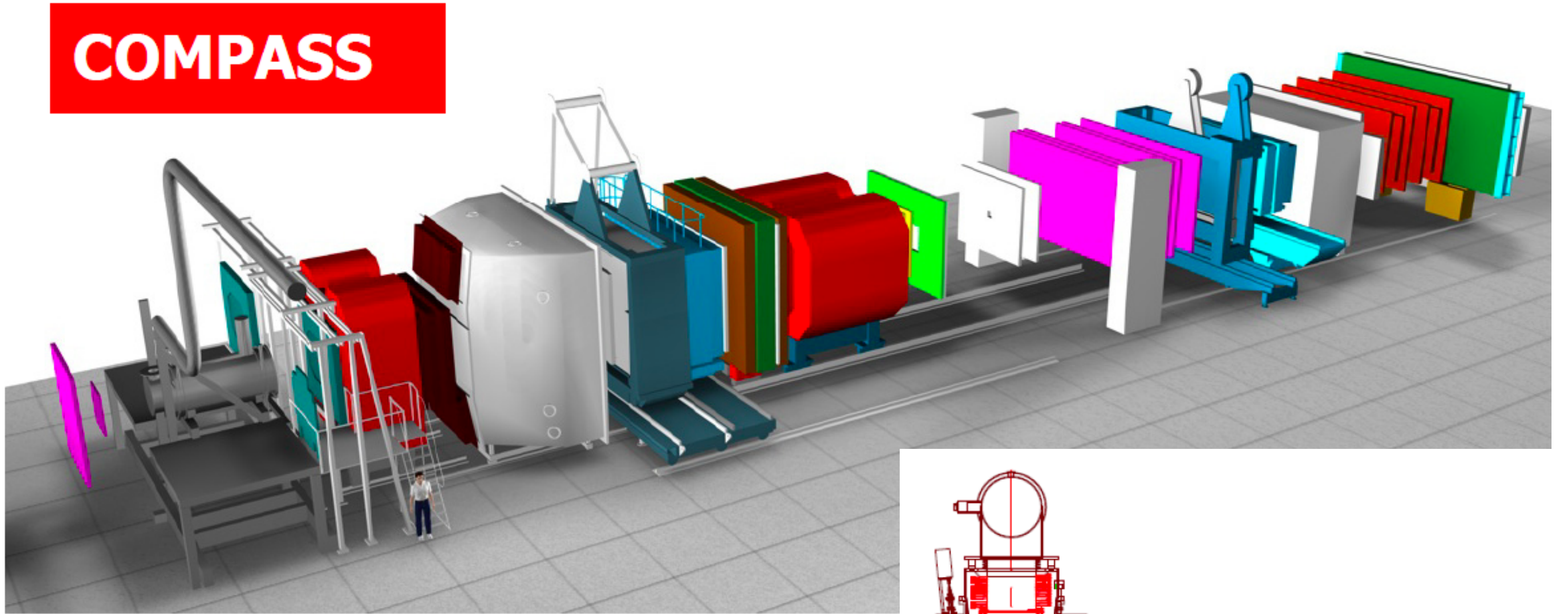
See as well talks by Franco, Stephane, Alexey, Catarina, Bakur, Boris, Johannes, Vincent, …..

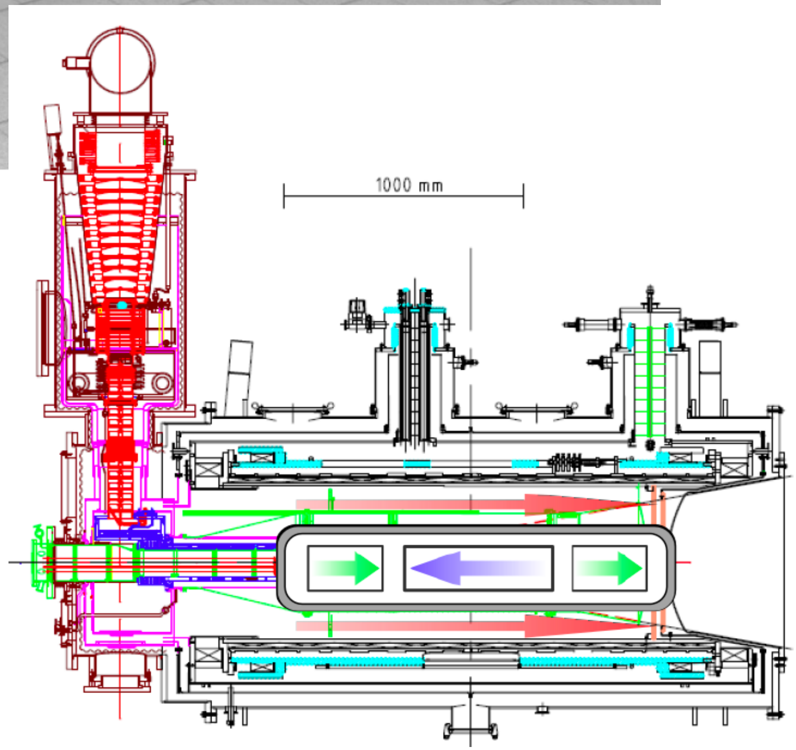
COMPASS QCD facility at CERN (SPS)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

~240 physicists, 12 countries + CERN, 24 institutions

COMPASS Spectrometer at SPS M2 beam line (CERN)



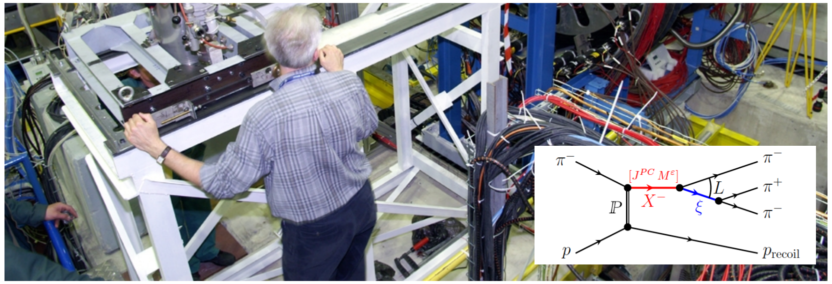


Universal and flexible apparatus.
Most important features of the two-stage COMPASS Spectrometer:

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)

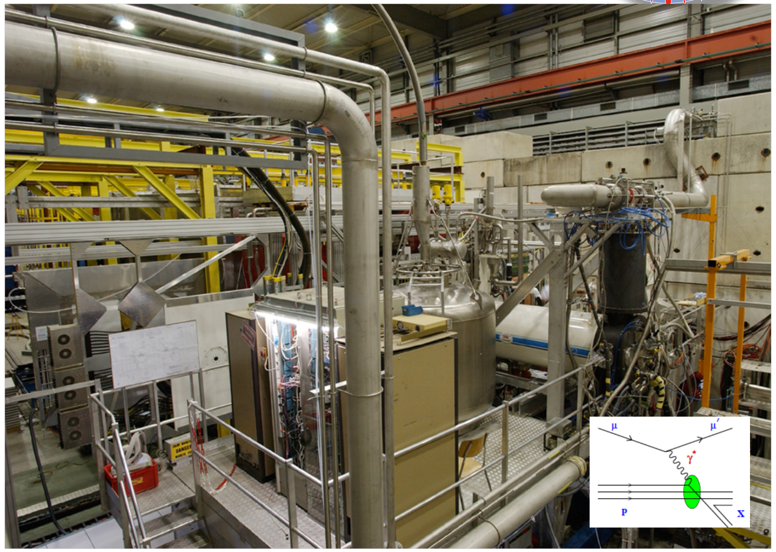
COMPASS QCD facility at SPS M2 beam line (CERN)
(secondary hadron and lepton beams)

Exotic state, chiral dynamics

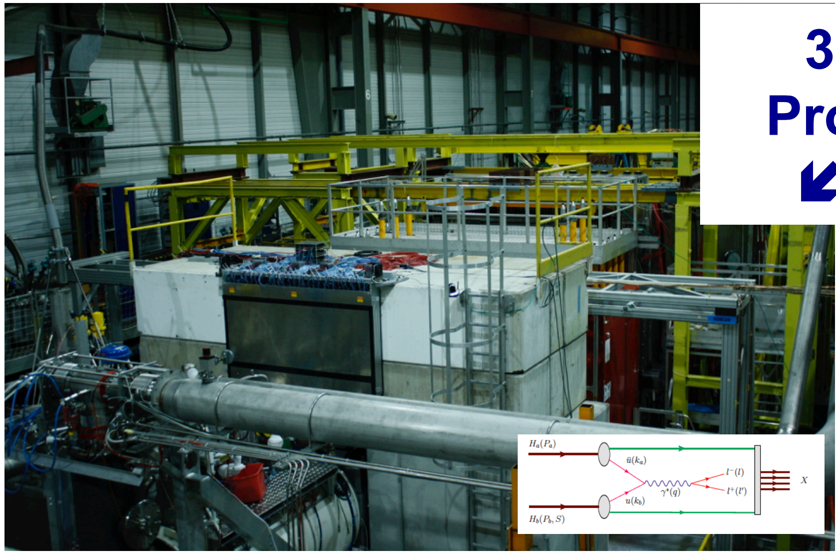


Hadron Spectroscopy & Polarizability

COMPASS-I
1997-2011



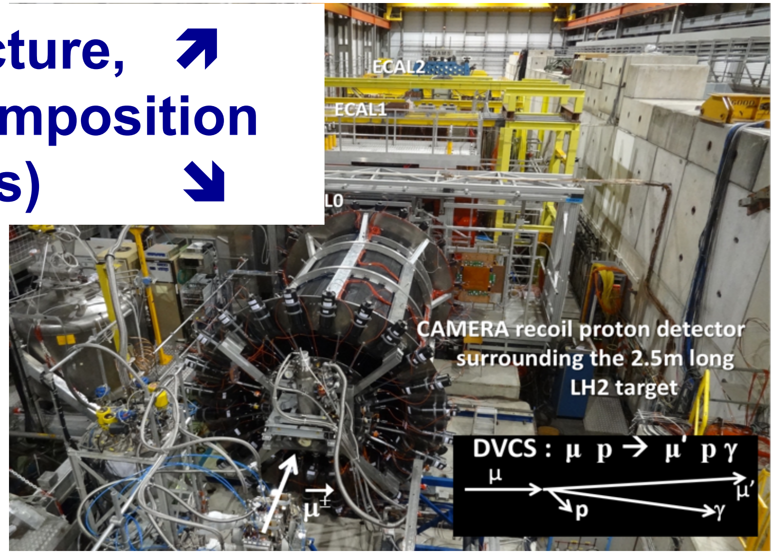
Polarised SIDIS



Polarised Drell-Yan

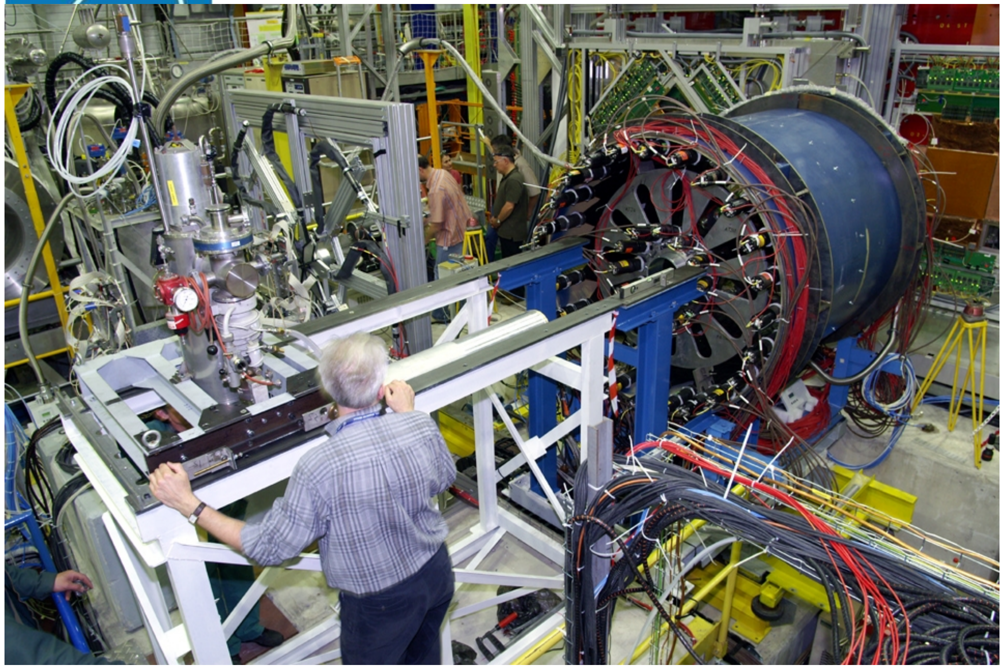
3D hadron structure, ↗
Proton spin decomposition
↙ (spin crisis) ↘

COMPASS-II
2012-..



DVCS (GPDs) + unp. SIDIS

Diffractive dissociation I

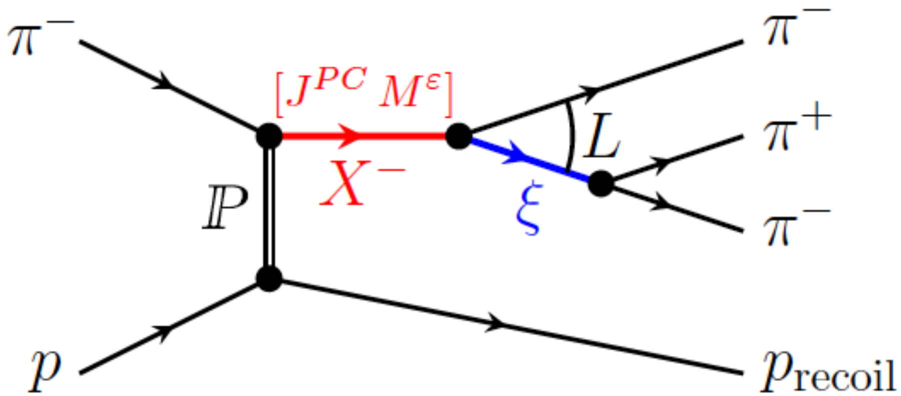


2008-2009 data taking, 190 GeV/c hadron beam on a hydrogen target.

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).

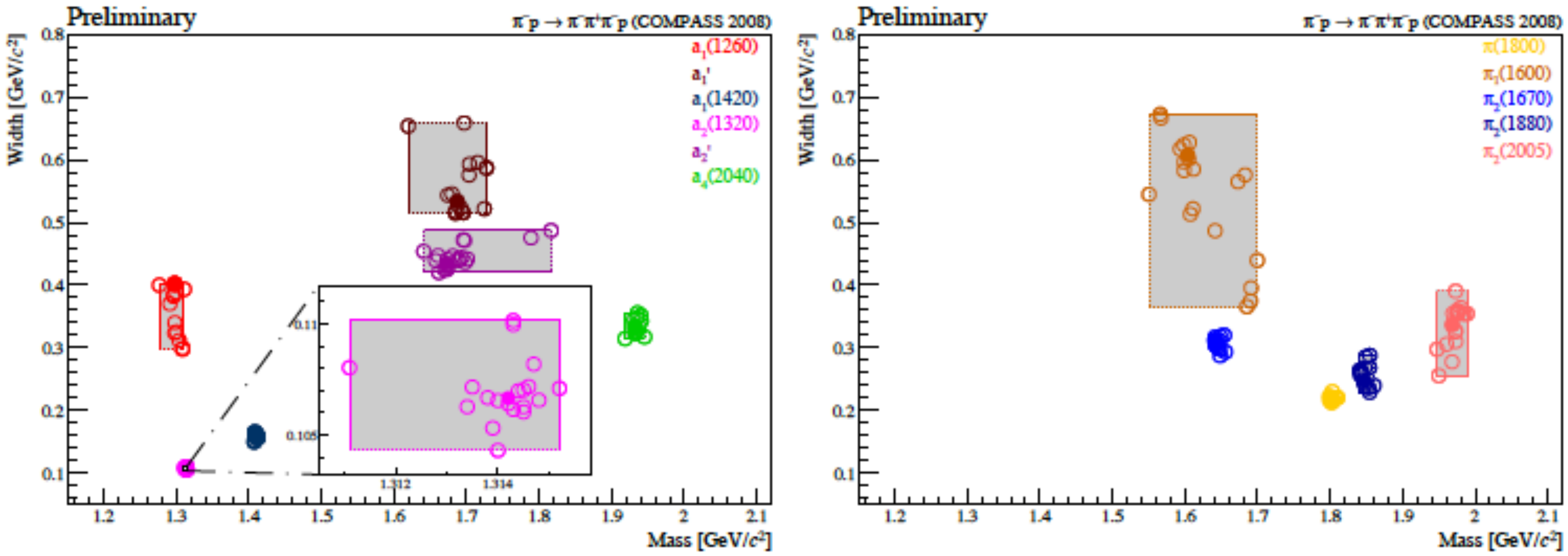
A lot of work to be invested to develop new methods in order to cope with huge data sample.



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)

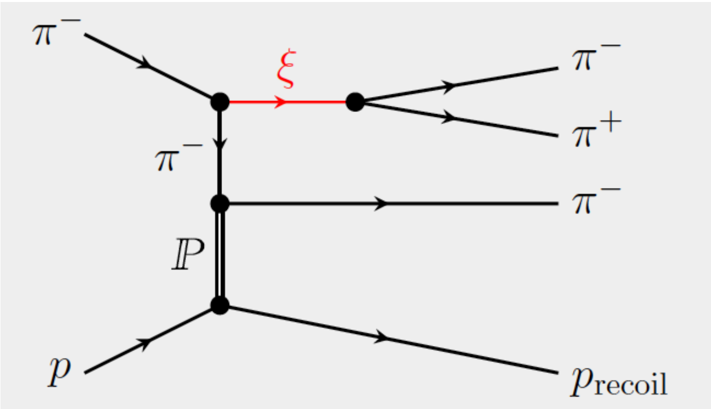
Diffractive dissociation II

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

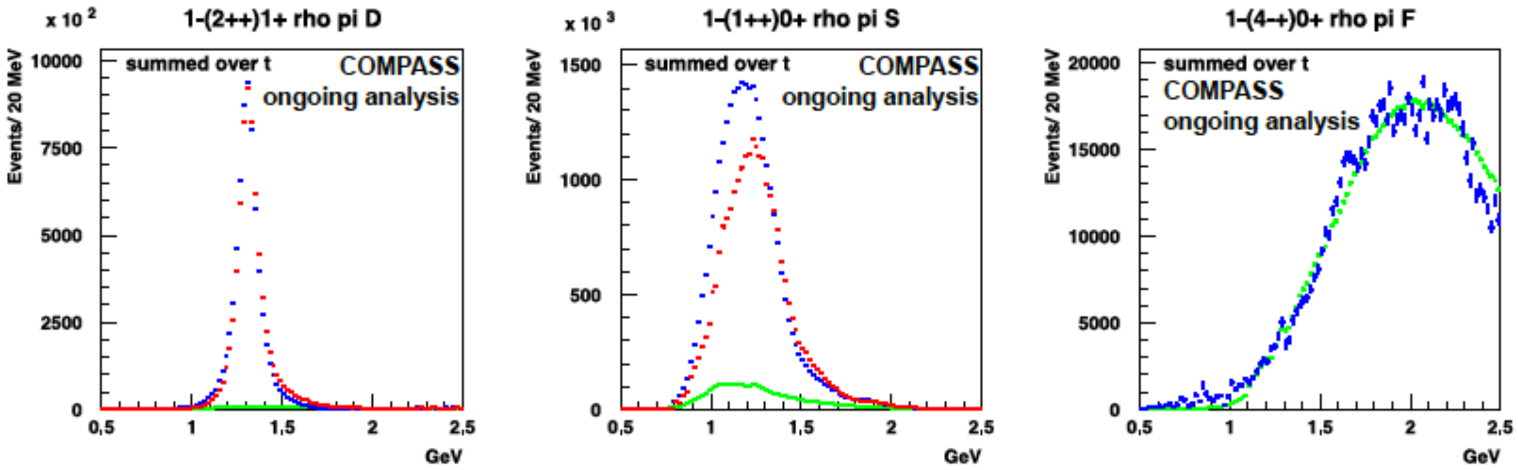
Diffractive dissociation III



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)

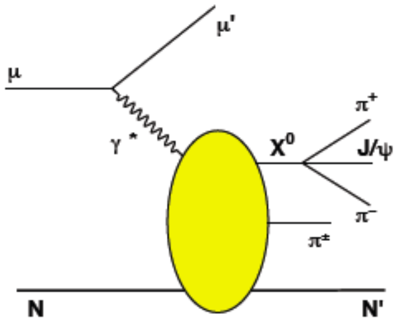
- low non-resonant contribution - stays unchanged (a)
- considerable fraction of non-resonant contribution – absorbed into Deck amplitude (b)
- high spin waves – Deck contribution absorbs all intensity (c)



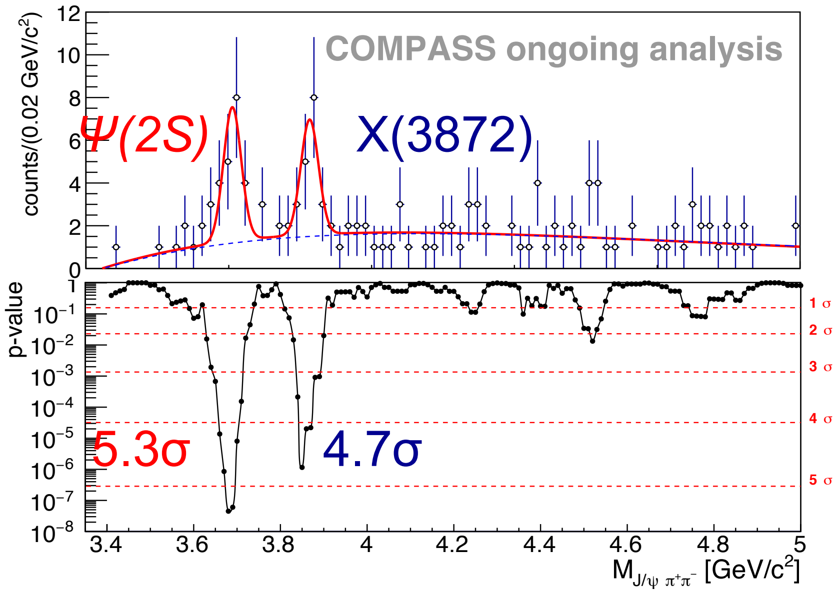
(a) (b) (c)

Exotic X(3872) lepto-production update

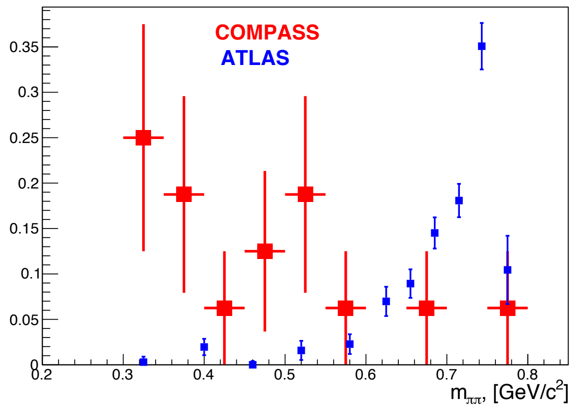
X(3872) is the first charmonium-like exotic hadron discovered by the Belle collaboration in 2003 and studied than in other experiments. Various interpretations exists: tetra-quark, *DD**-molecule, hybrid *ccg* state, glue-ball or else.
Additional information on its width would help to shed light on its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



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



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



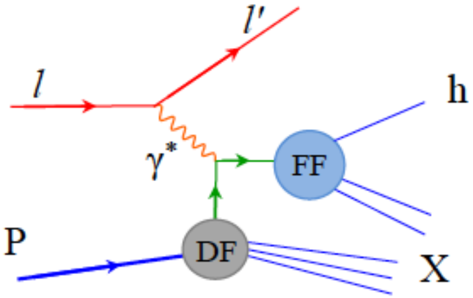
$$\sigma_{\gamma N \to X(3872)\pi^\pm N'} \times \mathcal{B}_{X(3872)\to J/\psi\pi\pi} = 71 \pm 28(\text{stat.}) \pm 39(\text{syst.})\ \text{pb}$$

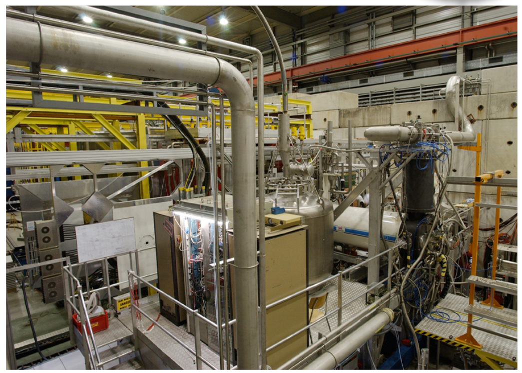
SIDIS →

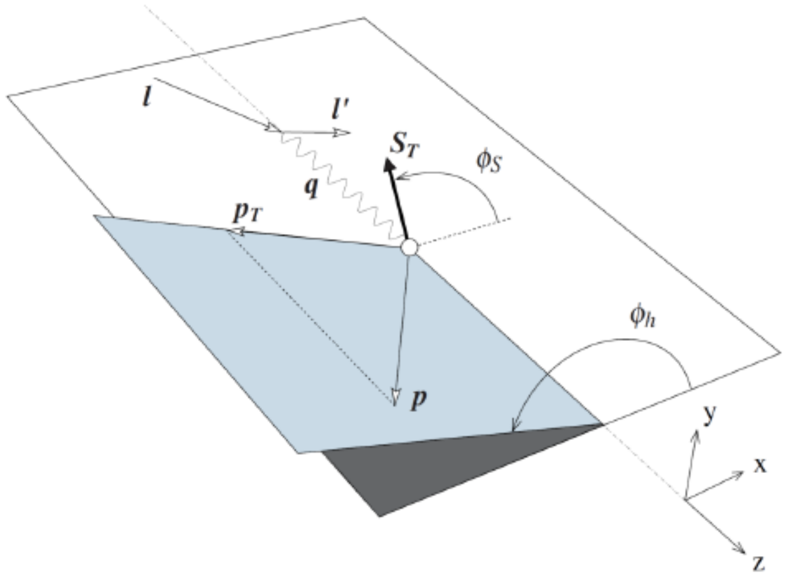
18 structure functions
14 azimuthal modulations

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right](F_{UU,T}+\varepsilon F_{UU,L})$$

$$\times\left\{\begin{array}{l}
1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\
+\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\
+S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] \\
+S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right] \\
+S_T\left[\begin{array}{l}
A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\
+\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\
+\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\
+\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\
+\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)
\end{array}\right] \\
+S_T\lambda\left[\begin{array}{l}
\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\
+\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\
+\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)
\end{array}\right]
\end{array}\right\}$$







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

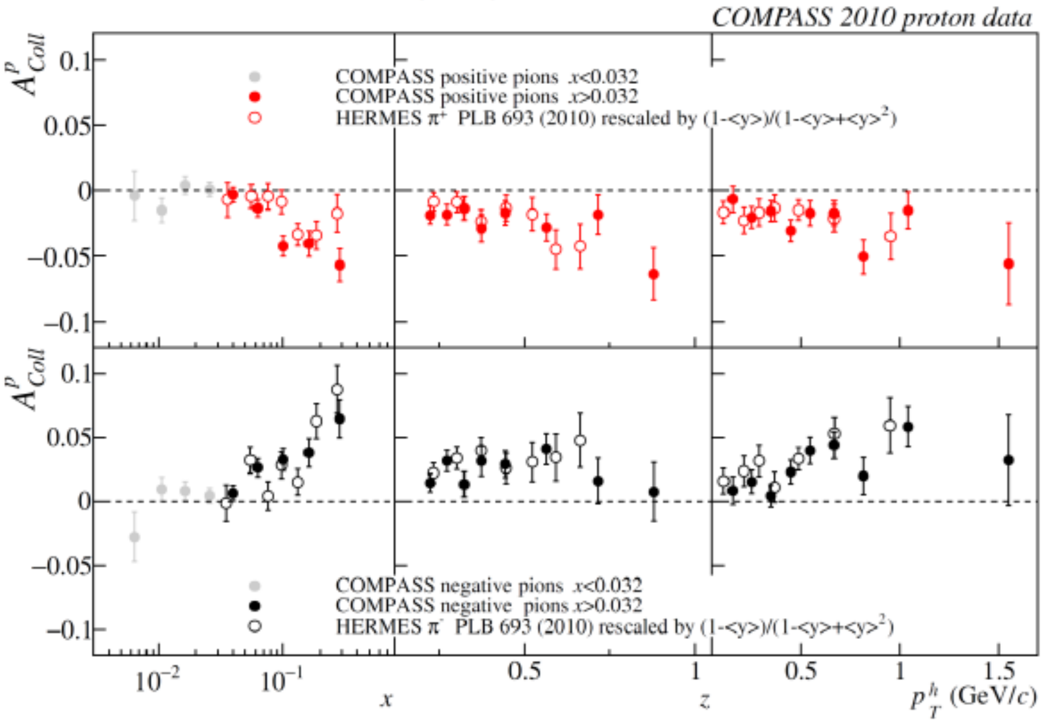
Collins asymmetry (transvesrsity)
zero knowledge ~10 years ago

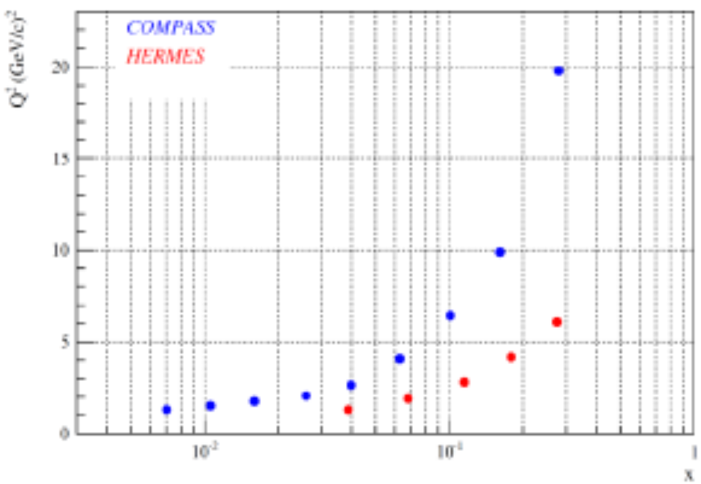
First seen non zero asymmetry by HERMES on p in 2004

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!

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

COMPASS PLB 744 (2015) 250

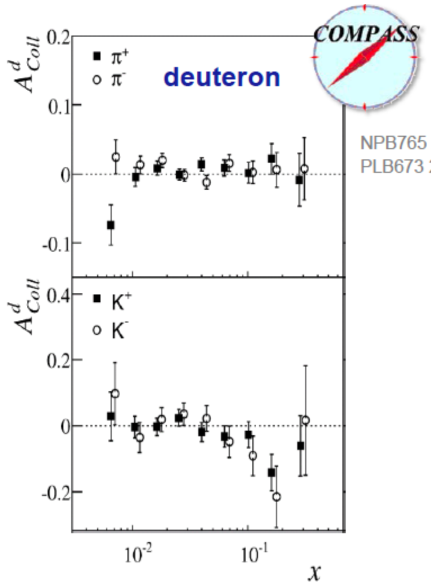




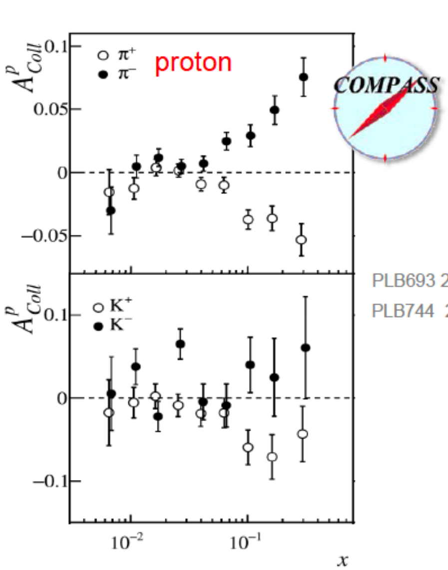
Collins asymmetry (transvesrsity)

Deuteron data – flavour separation possible

COMPASS:



NPB765 2007
PLB673 2009

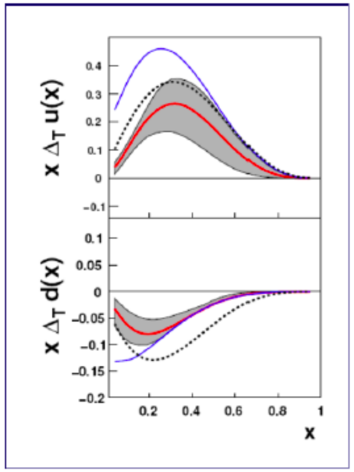


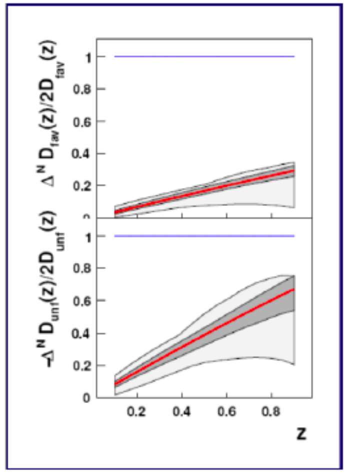
PLB693 2010
PLB744 2015

Flavour dependent

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

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



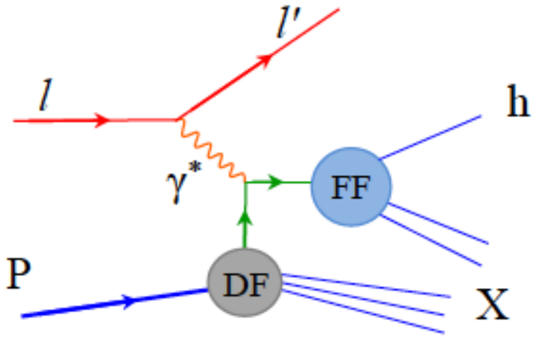


Reasonably well constrained using Belle & Hermes & COMPASS data

SIDIS → **18 structure functions**
14 azimuthal modulations

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times \left\{ \begin{array}{l} 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ +\ \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\ +\ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] \\ +\ S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right] \\ +\ S_T\left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S) \end{array}\right] \\ +\ S_T\lambda\left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ +\ \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ +\ \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) \end{array}\right] \end{array} \right\}$$



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

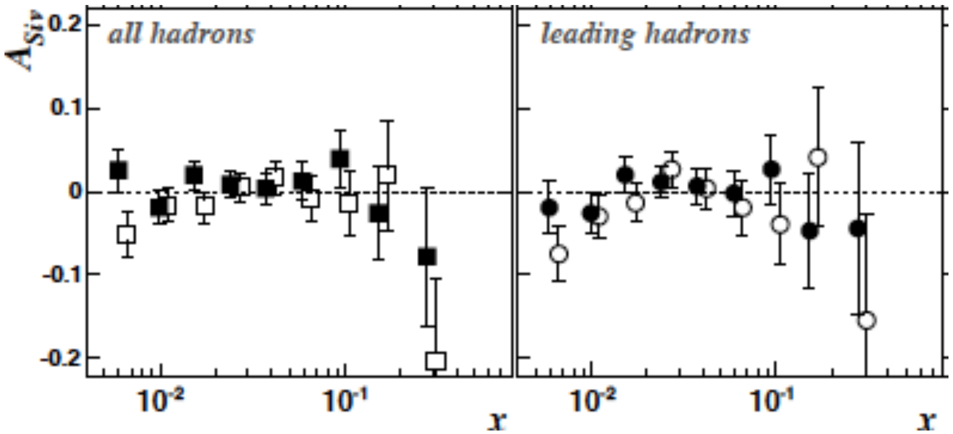
+ two FFs: $D_{1q}^h(z,P_\perp^2)$ and $H_{1q}^{\perp h}(z,P_\perp^2)$

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 ^{6}LD polarised target



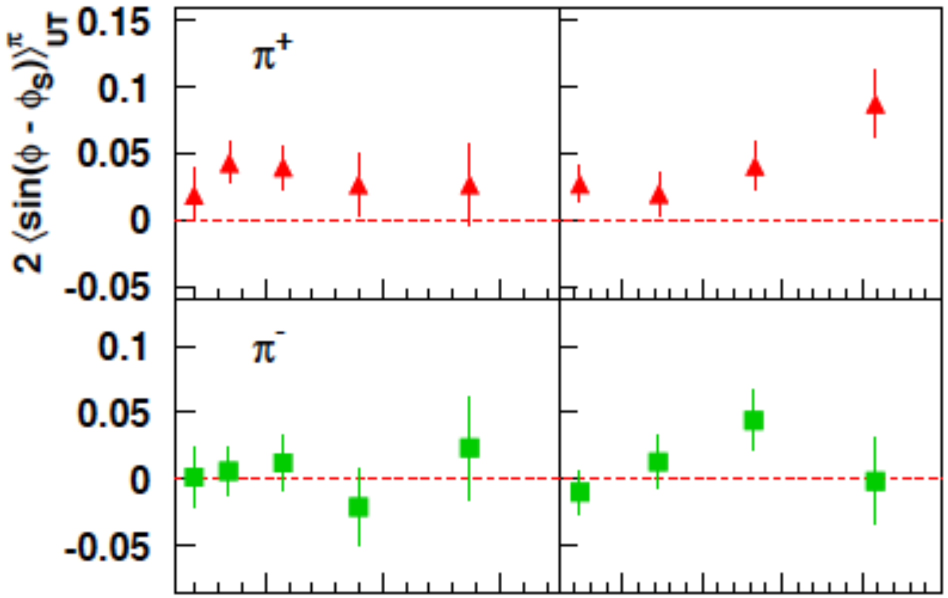
Full points – positive hadrons,
Open points – negative hadrons

DOUBTS…..

Hermes Results of 2004

hep-ph/0408013

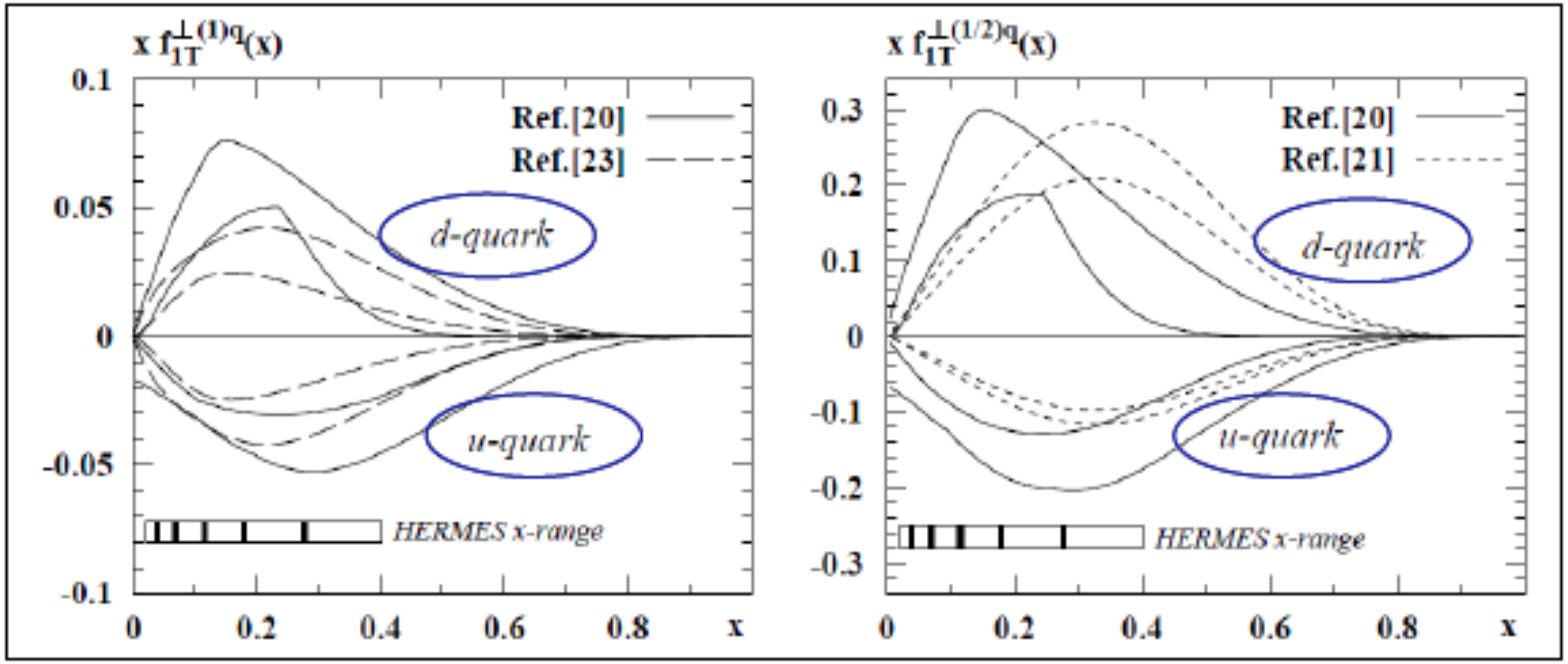
Gaseous H_2 polarized target



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

Joint data analysis form Hermes and COMPASS – no contradictions

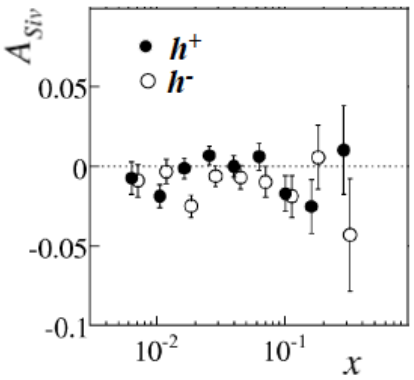
As it was shown by Mauro Anselmino and Colleagues (second half of 2005) when first extraction of Sivers function has been performed from Hermes and COMPASS data (Transversity'2005, hep-ph/051101)) that the contributions from u- and d-quarks are opposite

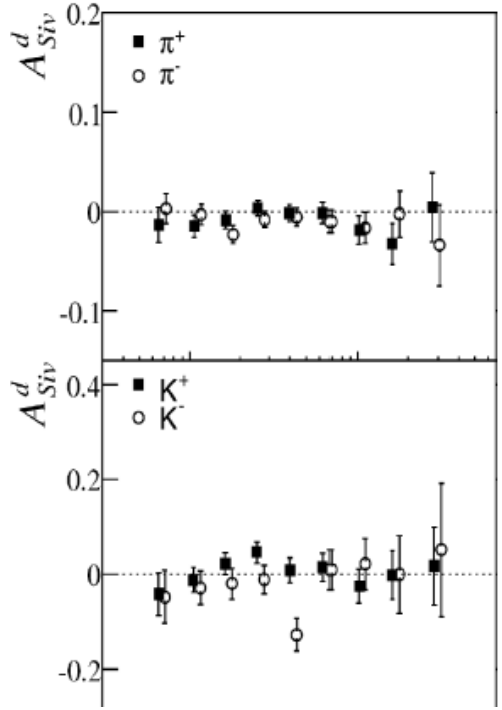


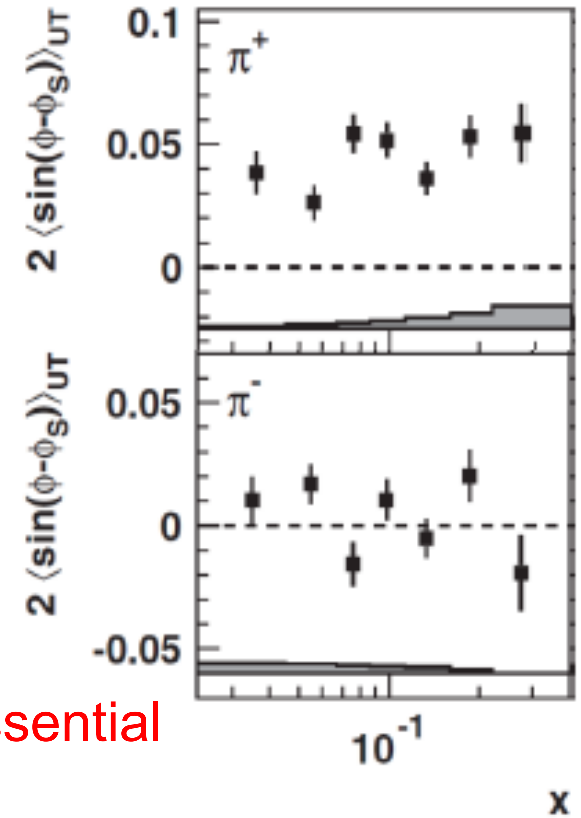
Sivers 2009 – final results Hermes&COMPASS data perfectly fits together

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

Hermes Final results on proton PRL 103 (2009)



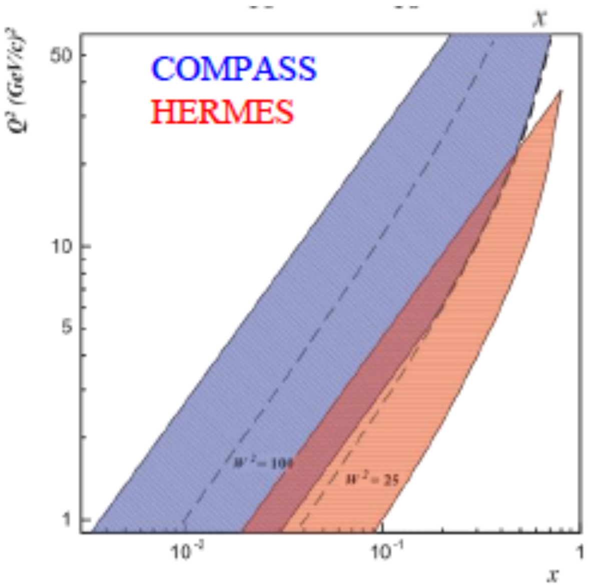


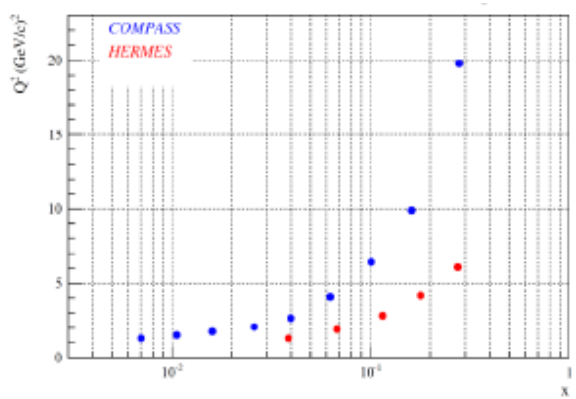


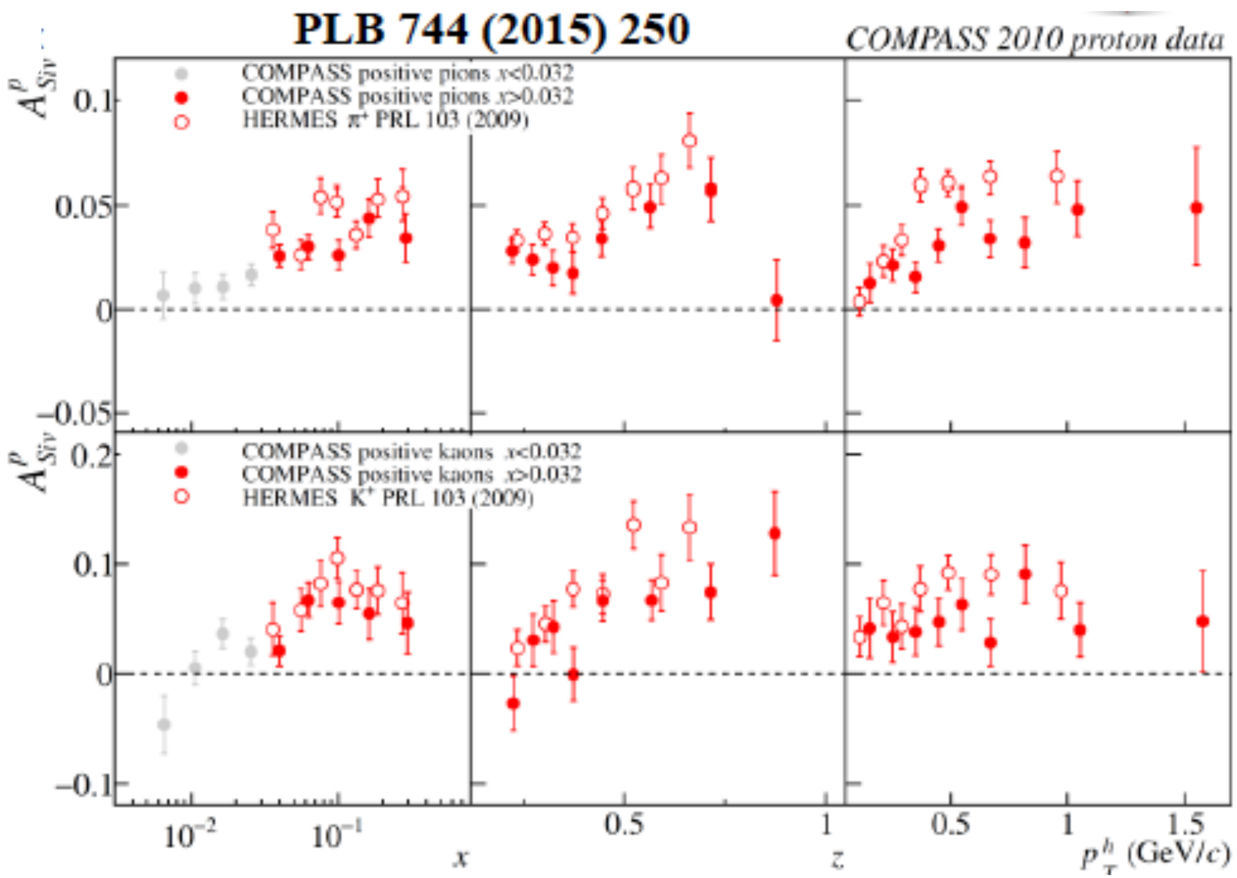
Flavour separation is essential

COMPASS ←→Hermes proton data
COMPASS Sivers is smaller – QCD evolution eff.?

Even if exist evolution has to be rather slow







Unpolarised SIDIS

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

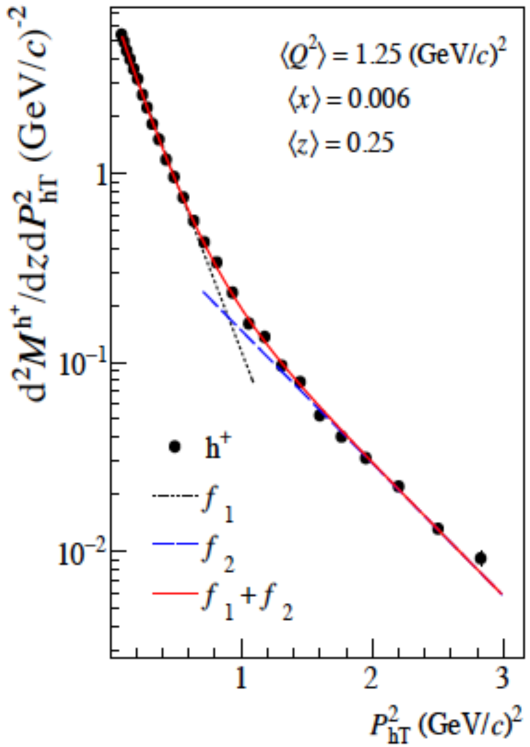
^{6}LiD (deuteron) isoscalar target

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

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

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

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

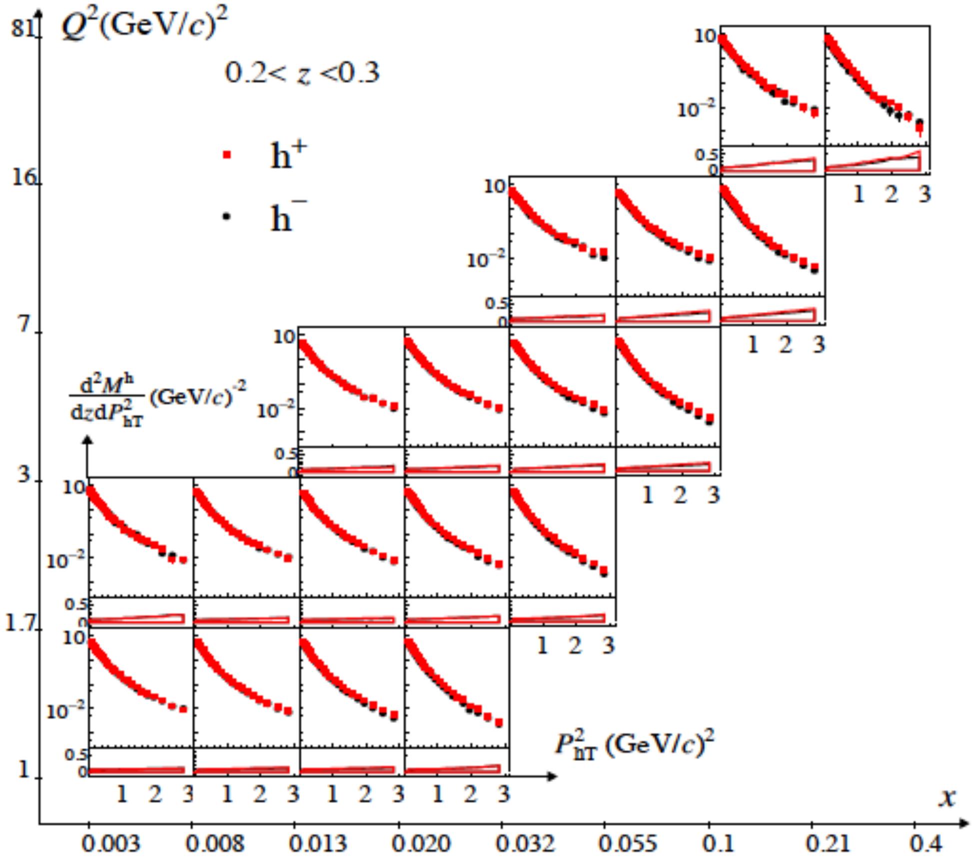


The small P^2_{hT} region (< 1 $(GeV/c)^2$) - hadron transverse momenta are expected to arise from non-perturbative effects

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

NEW!! TMD hadron multiplicities in SIDIS (multidimensional)

arXiv:1709.07374v1



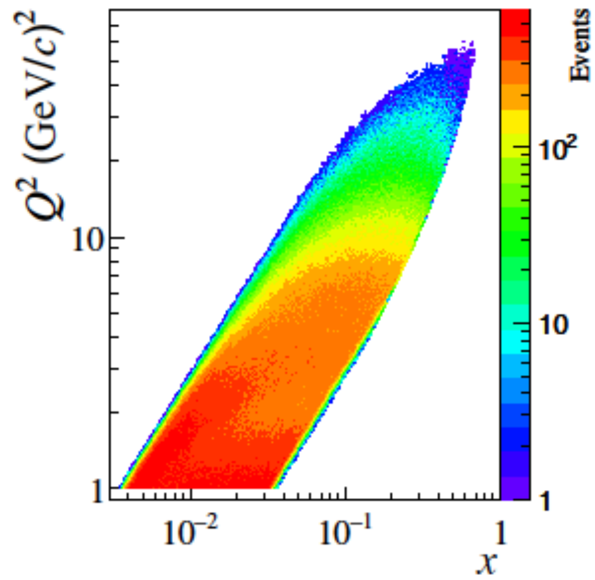


Fig. 5: Multiplicities of positively (full squares) and negatively (full circles) charged hadrons as a function of P^2_{hT} in (x, Q^2) bins for $0.2 < z < 0.3$. Error bars on the points correspond to the statistical uncertainties. The systematic uncertainties (σ_{sys}/M^h) are shown as bands at the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

NEW!! TMD hadron multiplicities in SIDIS (multidimensional)

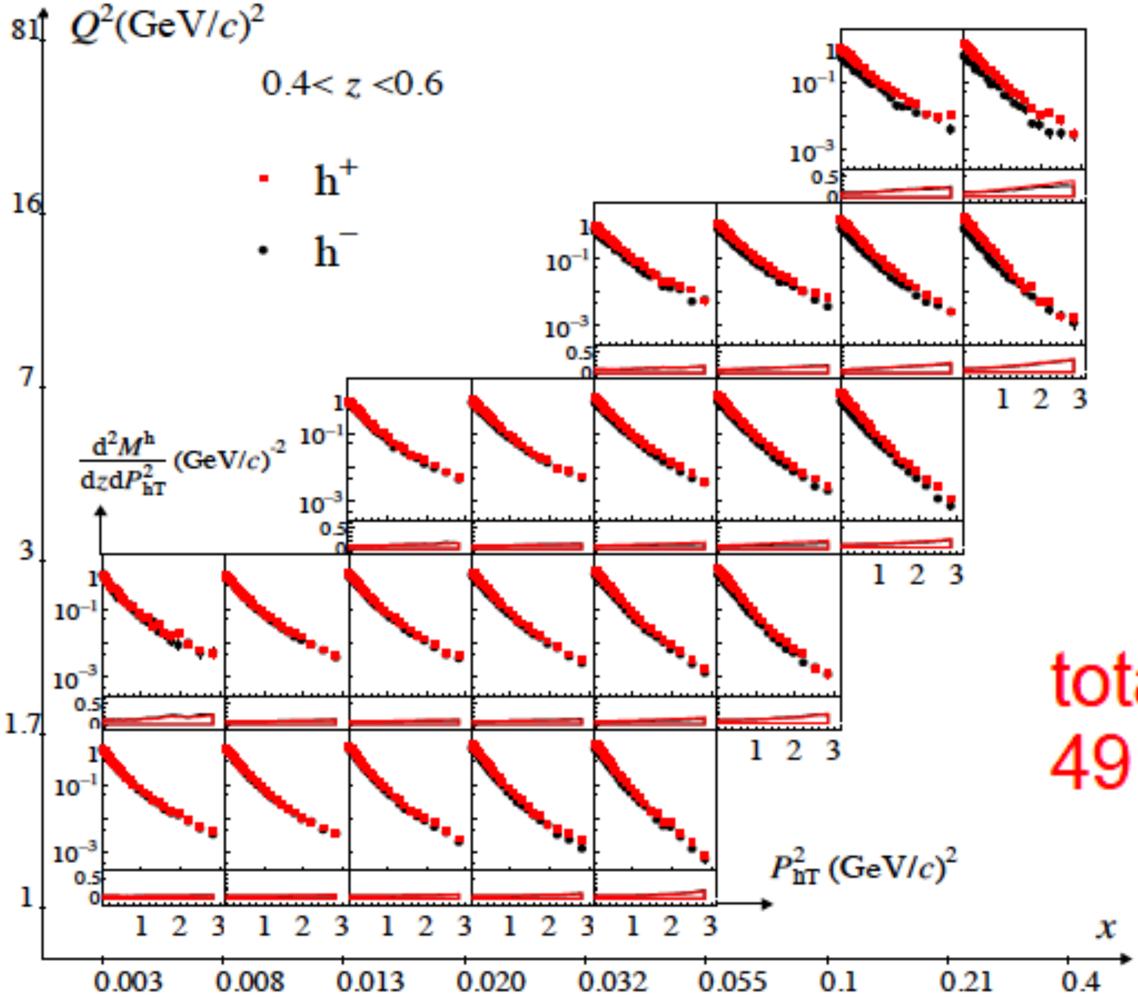
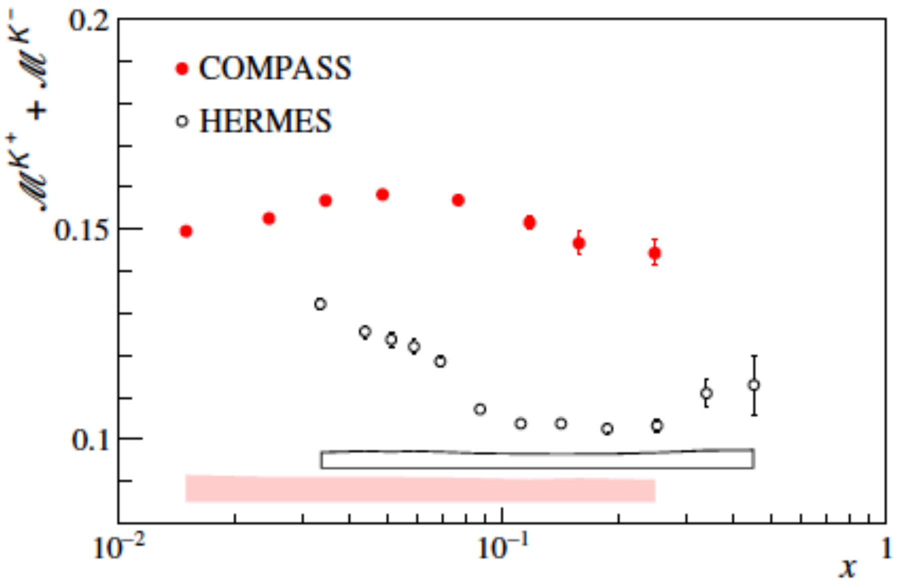


Fig. 7: Same as Fig. 5 for $0.4 < z < 0.6$.

total:
4918 data points

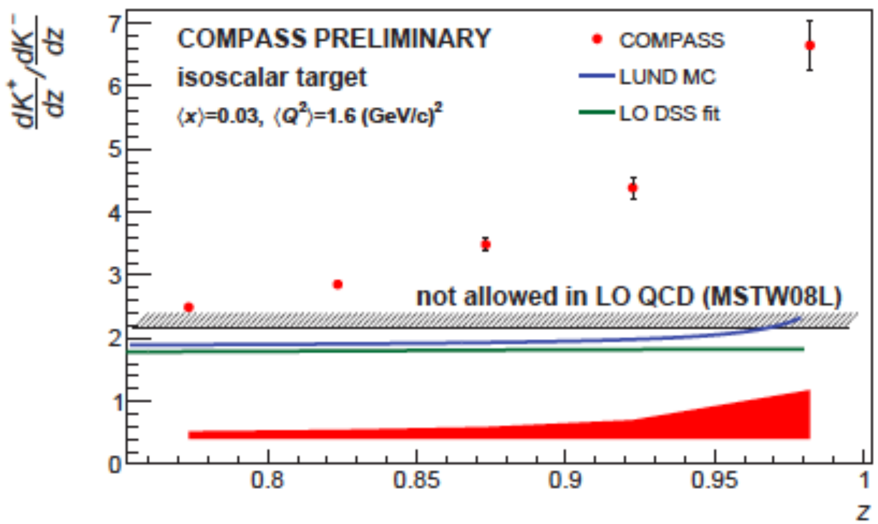
SIDIS (kaon) multiplicities

Charged kaon multiplicities (2006 160 GeV ^{6}LiD) – 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.

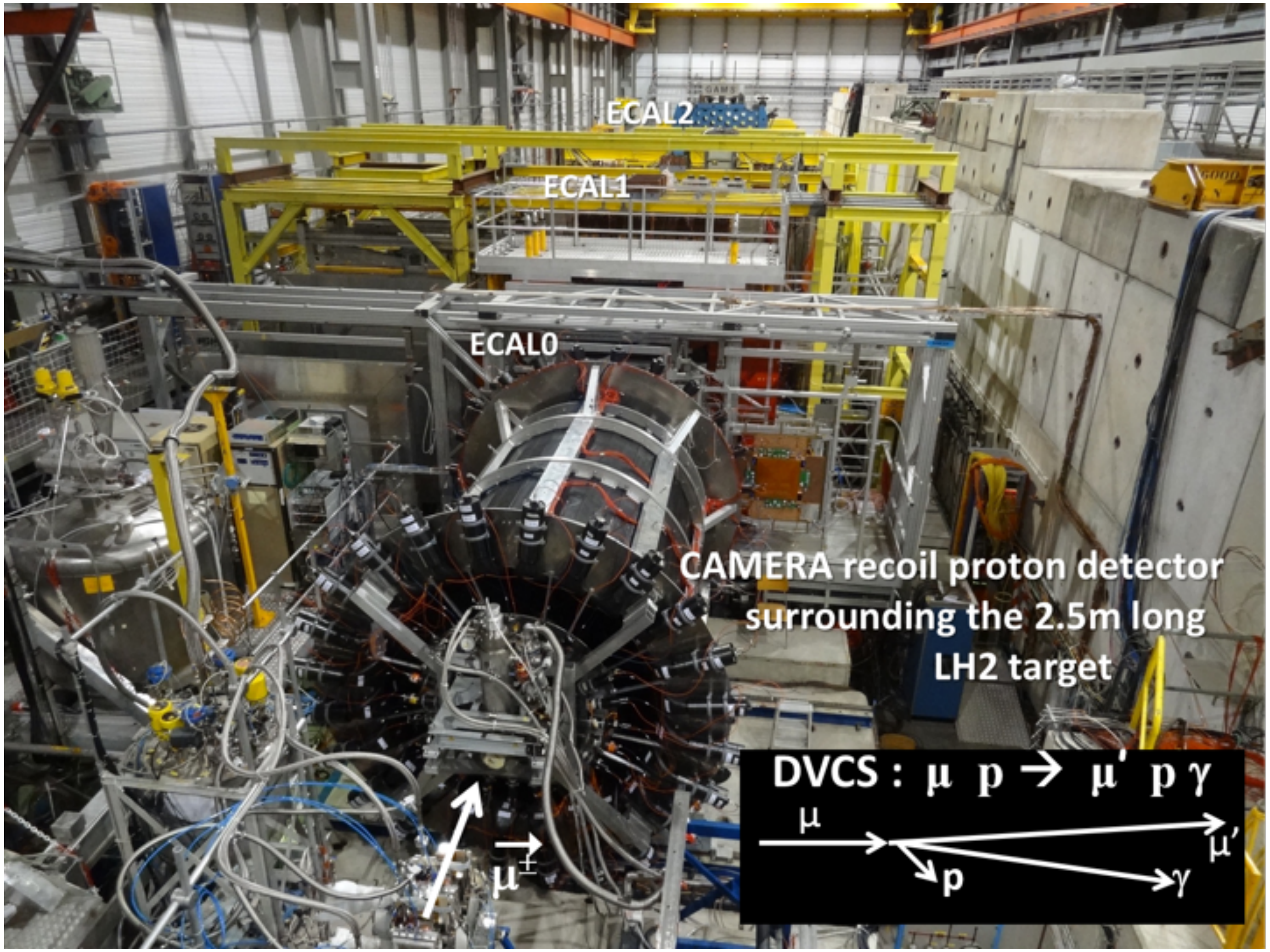


Important message – HERMES and COMPASS data are in tension.
Can not be explained only by different Q^2 range, the discussion is going on.

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)/(ū+đ) 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.

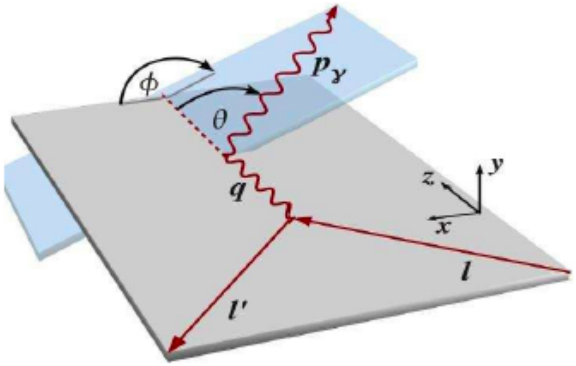


DVCS 2012 I



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

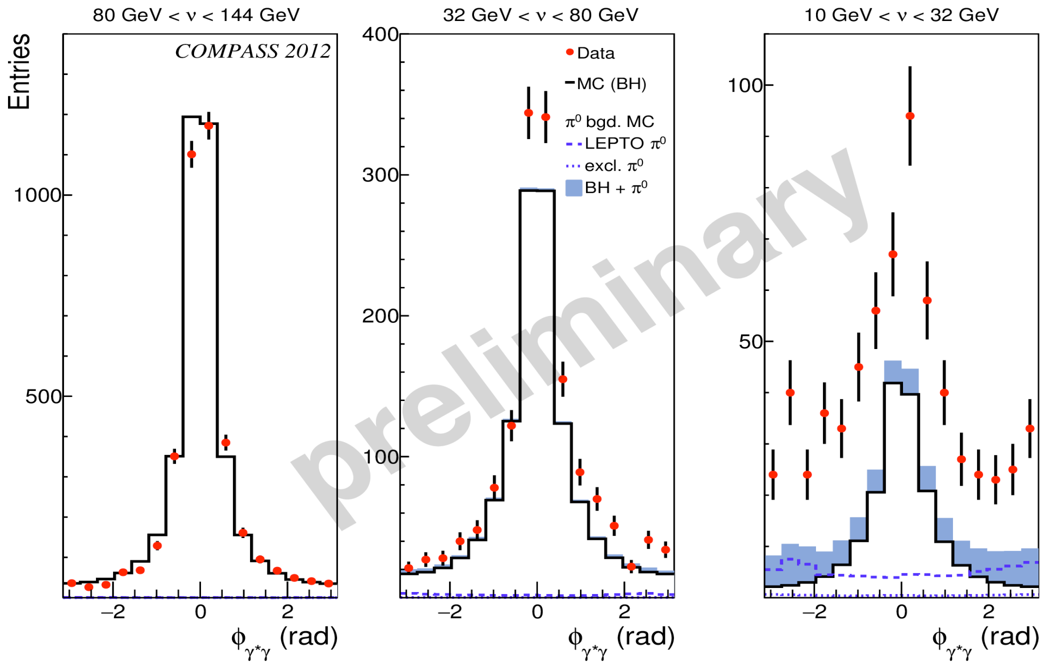
DVCS 2012 II



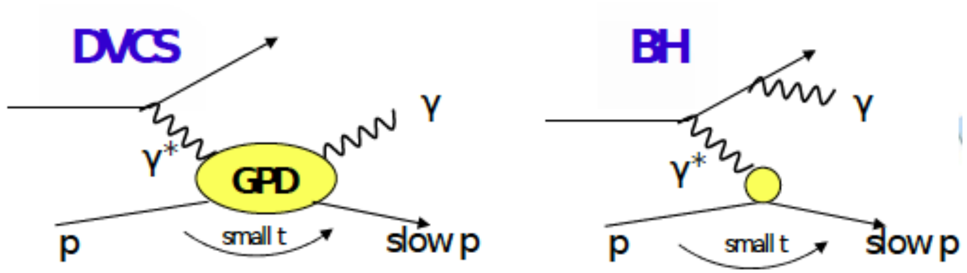
t-dependence of DVCS x-section

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

$\Downarrow$

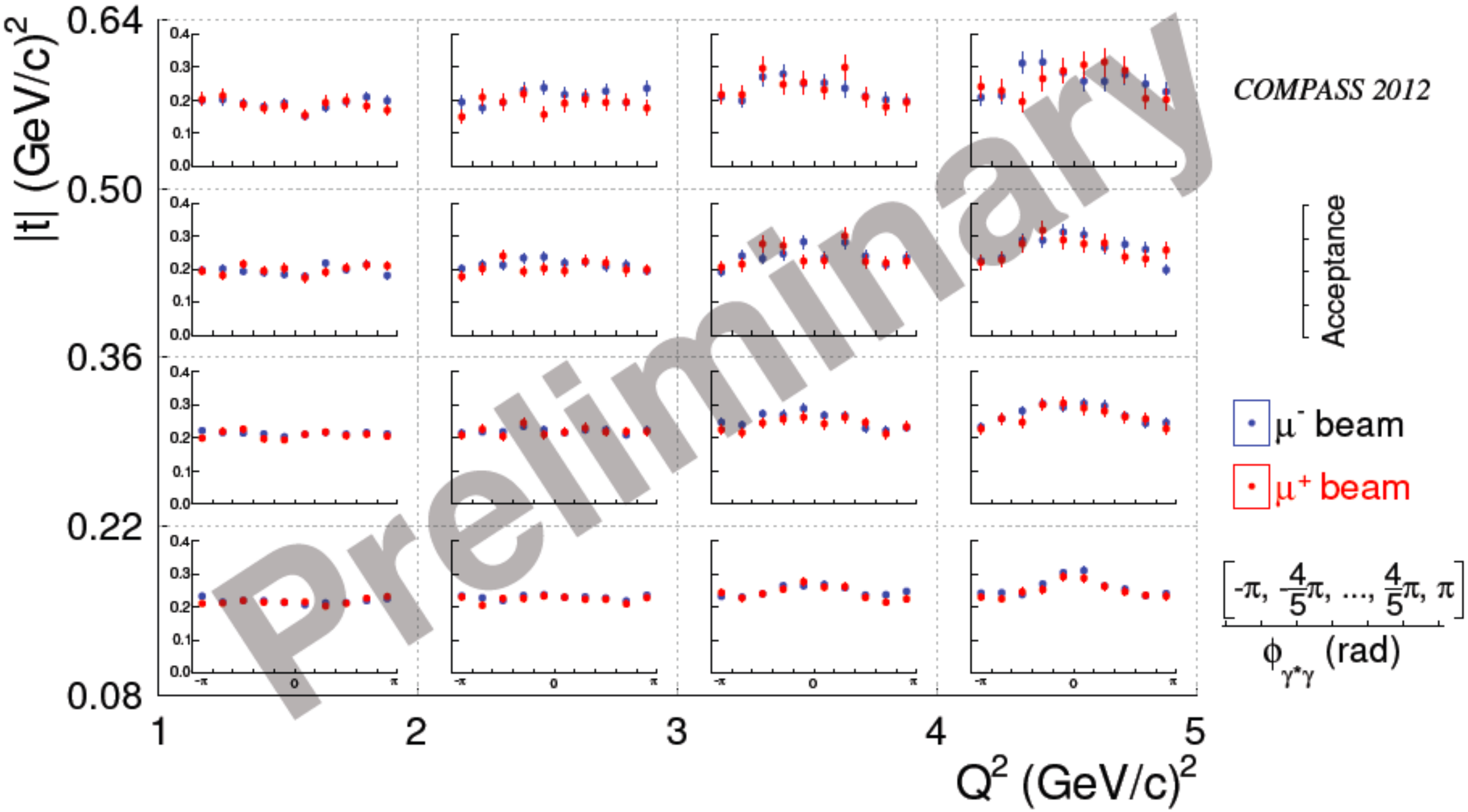


Two competing processes (Bethe-Heitler and DVCS)
Contribute differently in the different *x(v)*-ranges



DVCS 2012 III

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

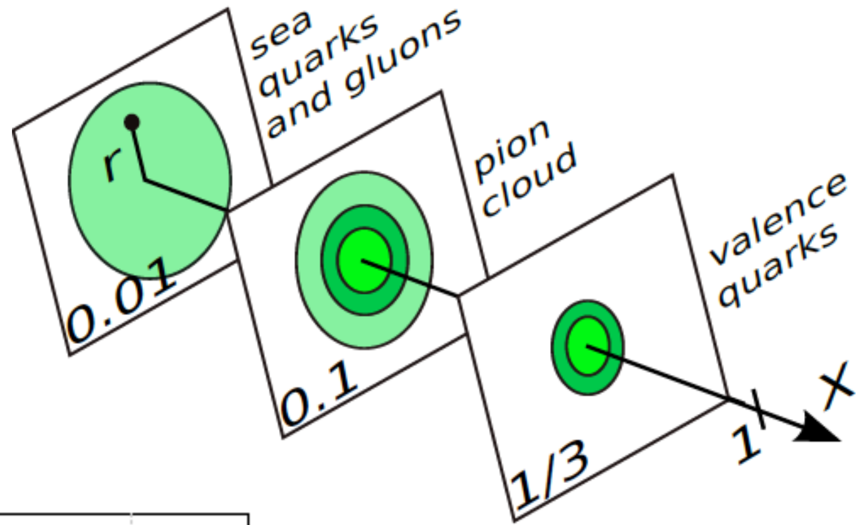


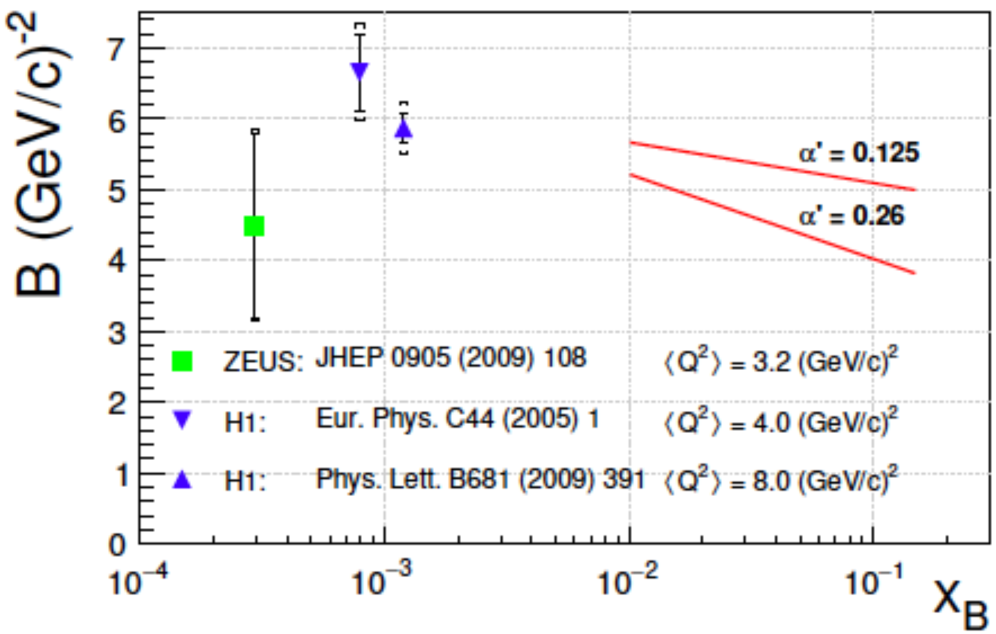
DVCS 2012 IV: t-slope

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

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

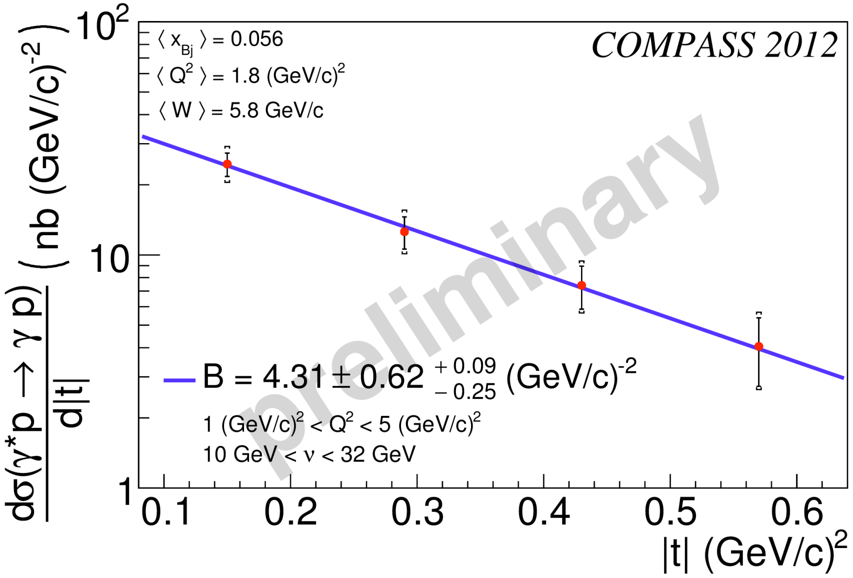
at small x_{Bj}

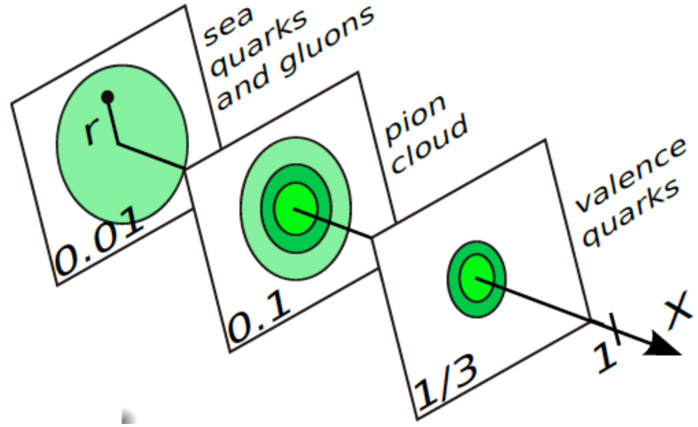




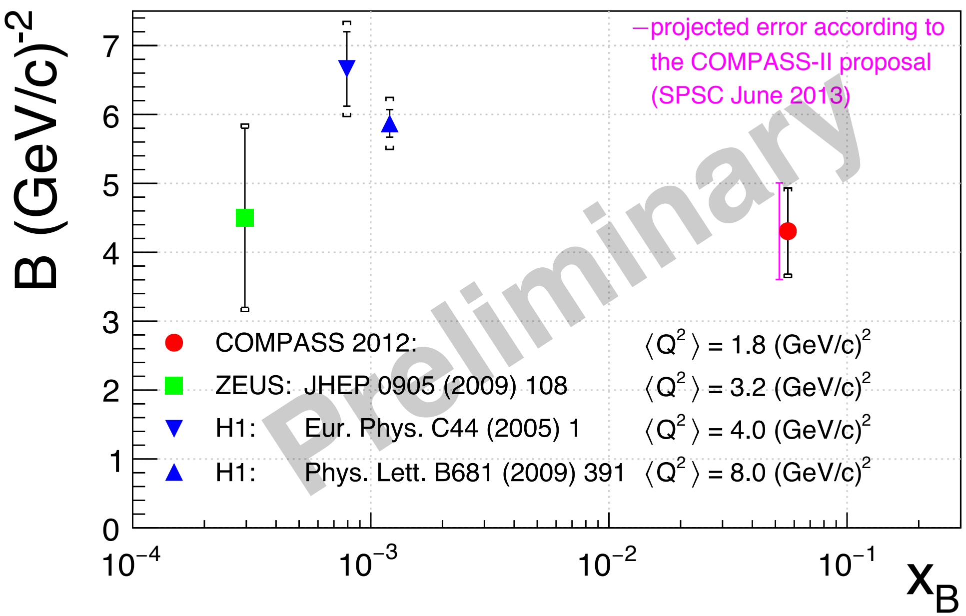
$$B(x_B) = B_0 + 2\,\alpha' \log(\frac{x_0}{x_B})$$

DVCS 2012 V: *t*-slope



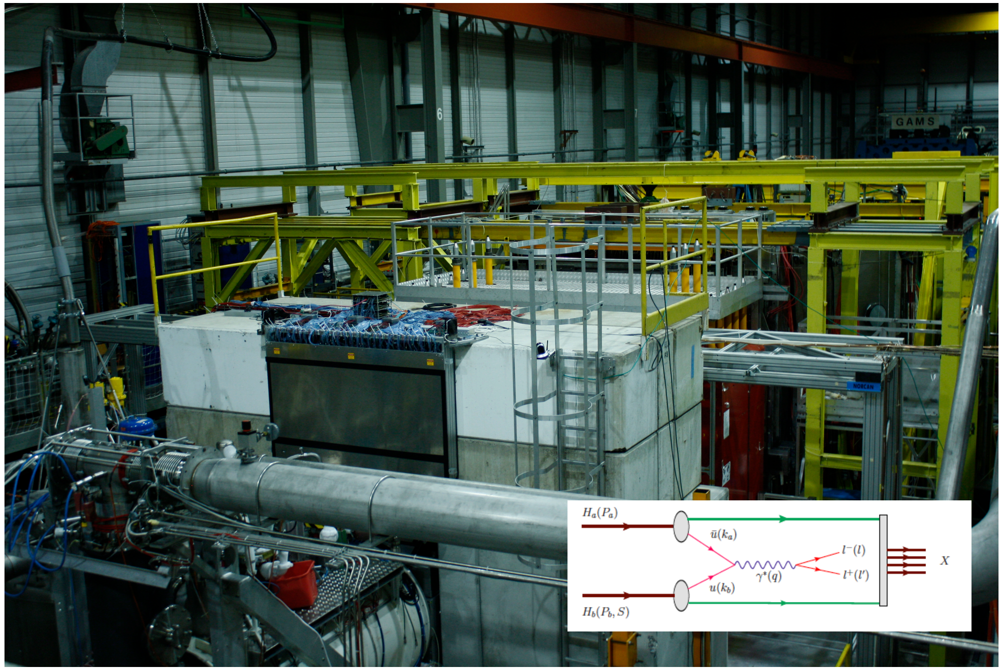


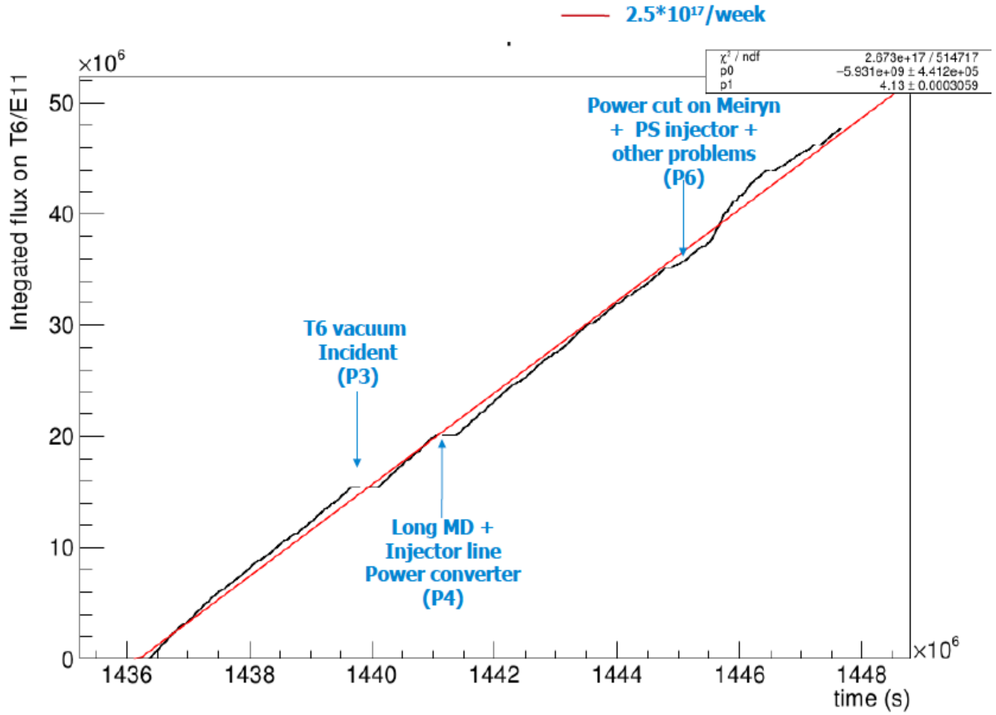
$$B \; = \; 4.31 \, \pm \, 0.62 \,^{+0.09}_{-0.25} \; (\mathrm{GeV}/c)^{-2}$$



COMPASS Drell-Yan Run 2015 I

First ever polarised Drell-Yan data set successfully collected





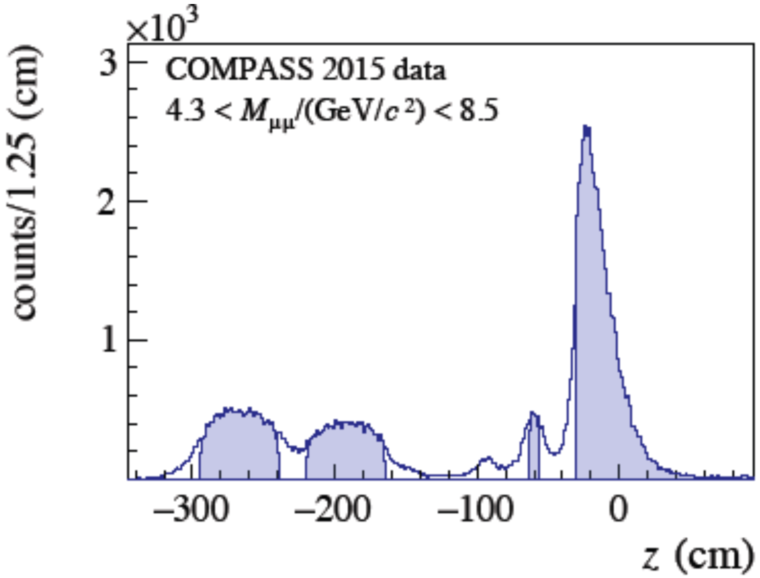
The final statistics penalised by late start (08/07/2015) because of the PT magnet and spectrometer commissioning.

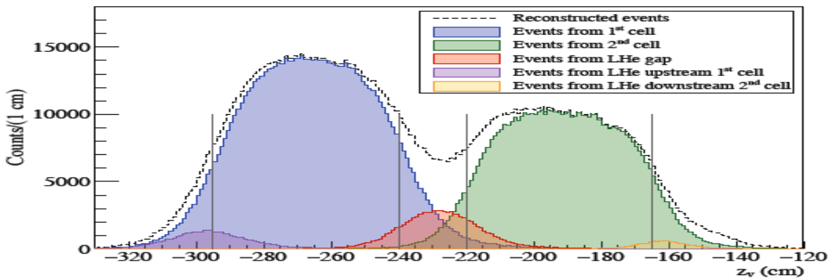
9 periods are collected (~2 weeks long each, polarisation is inverted after first week)

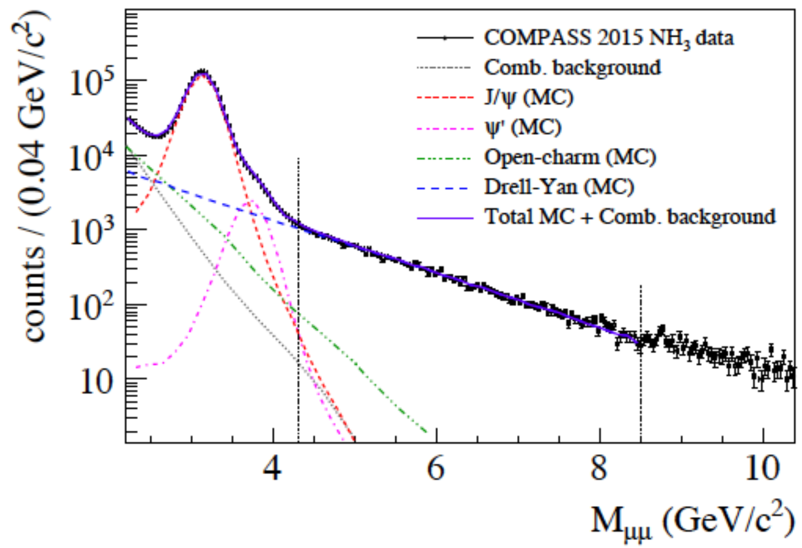
Good machine performance: on average 84%
Good spectrometer availability: ~80%

COMPASS Drell-Yan Run 2015 results II

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





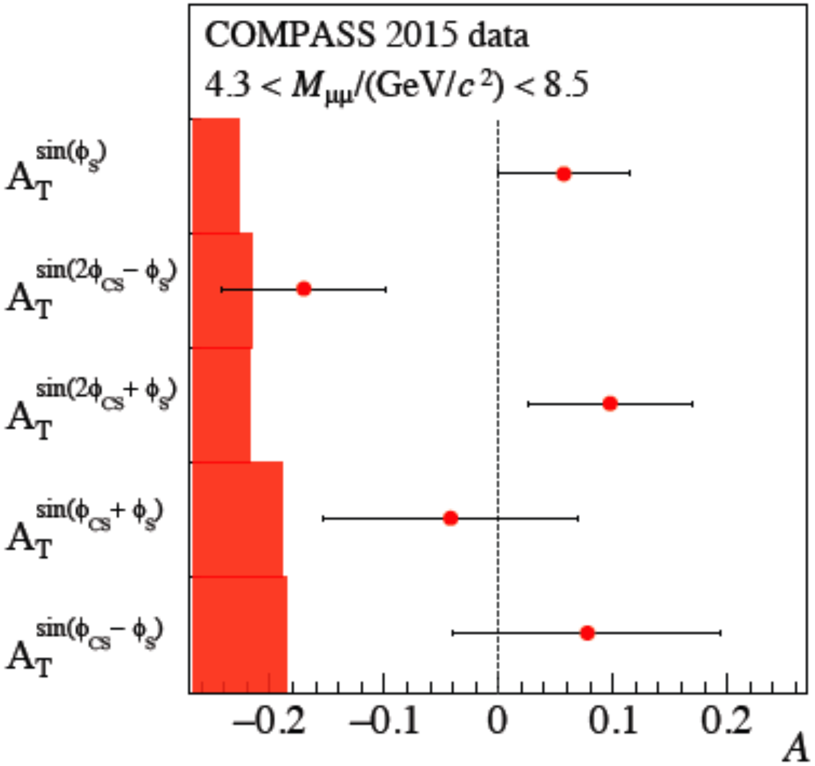


Total number of J/ψ (NH_3) is **~ 1.500.00**

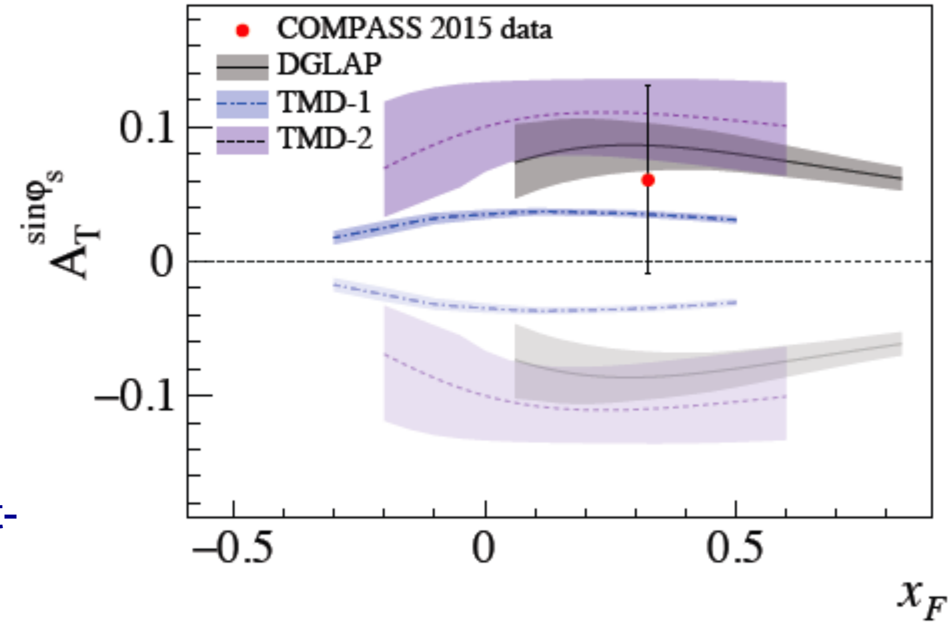
Total number of HM DY (4.3 GeV/c^2 < $M_{\mu\mu}$ < 8.5 GeV/ c^2) (NH_3) is **~35.000**

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.

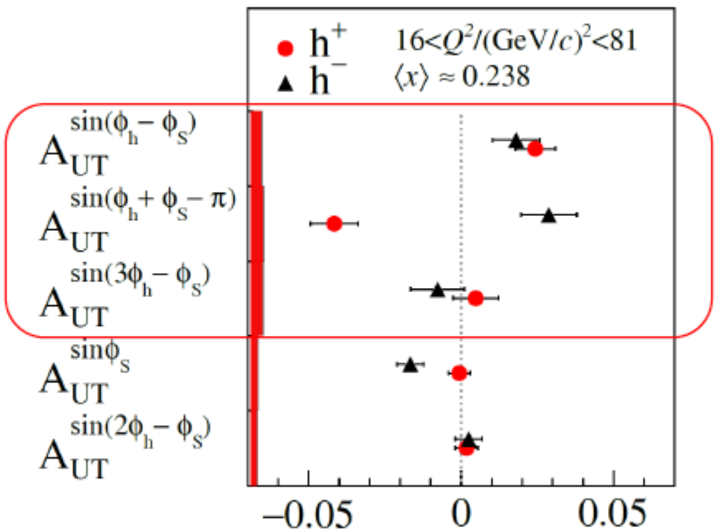


The measured mean Sivers asymmetry and the theoretical predictions for different Q^2 evolution schemes from Anselmino (DGLAP), Echevarria (TMD1) and Sun (TMD2). The dark-shaded (light-shaded) predictions are evaluated with (without) the sign-change hypothesis.

NEW!! TSAs in Drell-Yan compared to SIDIS

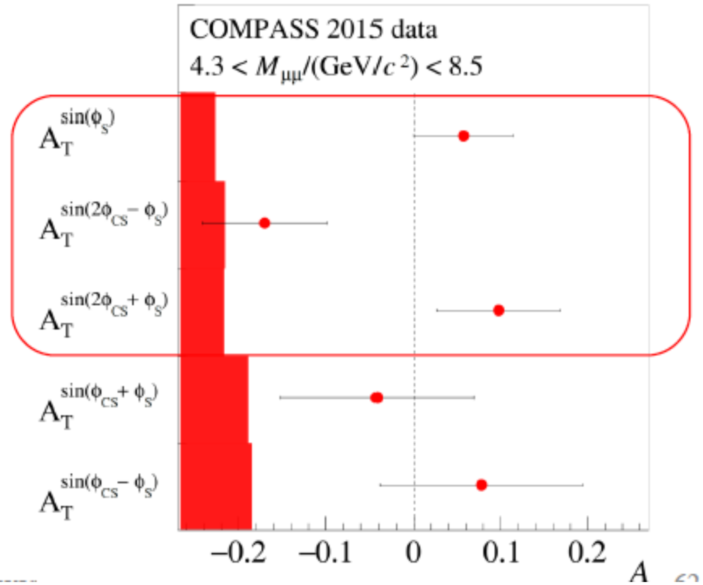
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\ldots + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S) \end{array} \right] \right\}$$

COMPASS PLB 770 (2017) 138



$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right)\left\{ 1+\ldots + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S}\sin\varphi_S \\ +D_{[\sin^2\theta_{CS}]}\left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S) \\ +\ A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\varphi_S) \end{array}\right) \\ +D_{[\sin 2\theta_{CS}]}\left(\begin{array}{l} A_T^{\sin(\varphi_{CS}-\varphi_S)}\sin(\varphi_{CS}-\varphi_S) \\ +\ A_T^{\sin(\varphi_{CS}+\varphi_S)}\sin(\varphi_{CS}+\varphi_S) \end{array}\right) \end{array} \right] \right\}$$

COMPASS arXiv:1704.00488 [hep-ex]



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 factro ~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

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

222-R-001 (CERN)

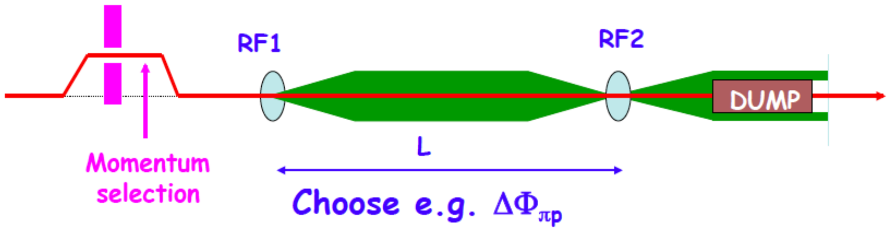
Description The goal of the workshop is to explore hadron physics opportunities for fixed-target COMPASS-like experiments at CERN beyond 2020 (CERN Long Shutdown 2 2019-2020). The programme comprises

- 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



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

"Normal" h^- beam composition:
~97% (π) ~2.5%(K) ~0.5% (pbar)

Assumptions:

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

Antiprotons RF separated beam: 3.2 x 10^7 /s - Gain is a factor of 50 compared to the standard h^- beam for Drell-Yan experiment (~1% of h^- beam 6x10^7 /s dominated by π^-)

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

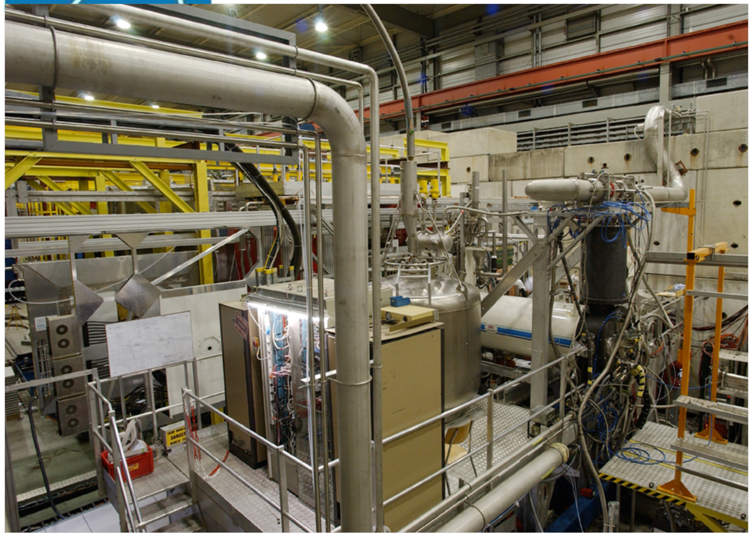
High intensity RF separated beam will provide unique opportunities for Hadron Spectroscopy and Drell-Yan physics

Short term COMPASS future

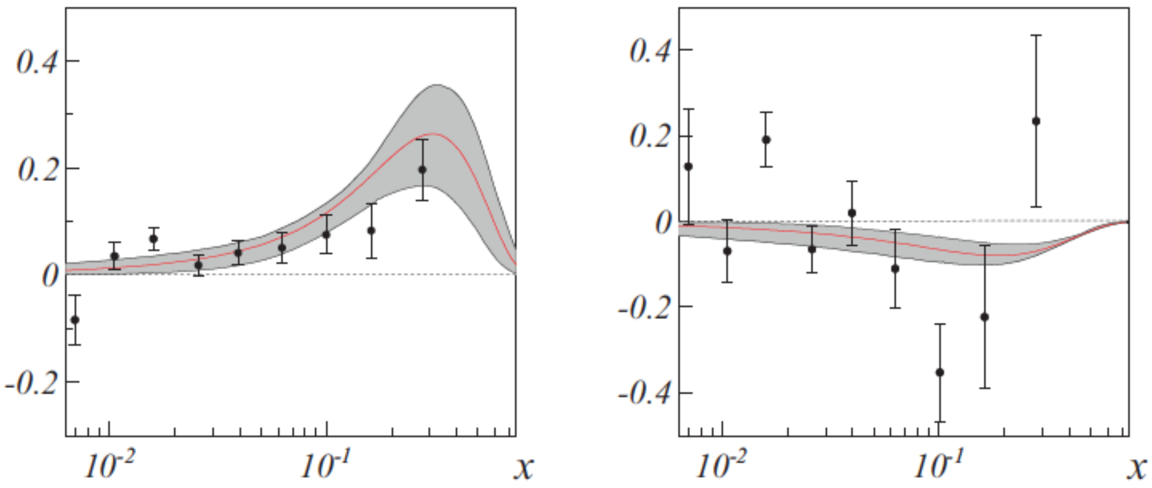
Short term future COMPASS Proposal (extension of the COMPASS-II experiment) was submitted to the SPSC ~1 month ago. The goal is to ensure COMPASS running after Long Shutdown II (2019-2020) for at least one year to keep collaboration going on and to provide an access to fresh funds.

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

Short term COMPASS future I :
SIDIS – transversely polarised Deuteron Target (^6LiD)



- TMD PDFs and Transversity $h_1(x)$ are flavour dependent.
- Flavour separation ➔ data on both proton (NH_3) and deuteron (^6LiD) 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 (^6LiD) and CLAS (^3He) targets).



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

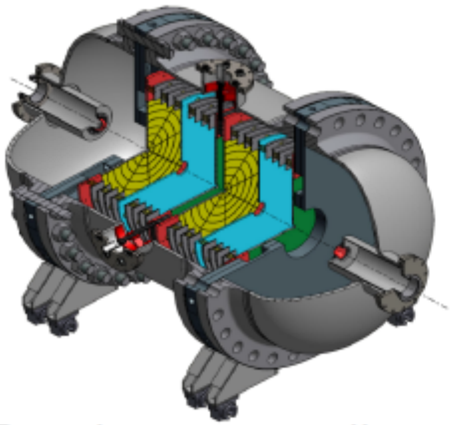
Fig. 6: $xh_1^u(x)$ (left) and $xh_1^d(x)$ (right) from the 'two hadron' asymmetries of 2010 proton and of 2002-2004 deuteron data (from[30]). The curves show the transversity PDFs obtained from a fit of Collins asymmetries [29]

Short term COMPASS future I : Proton radius measurement in elastic mu-p scattering

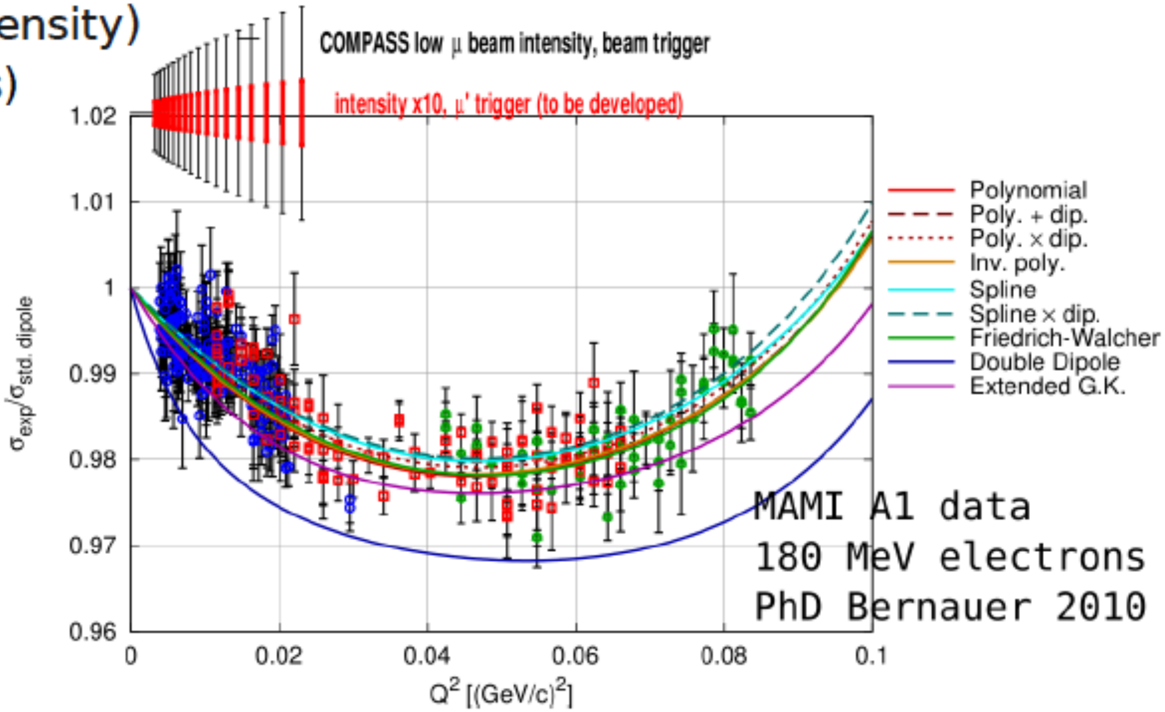
- 100 GeV SPS muon beam (M2)
- Hydrogen high-pressure active TPC target cell (PNPI development)
- Measure the cross-section (shape) over broad Q^2 range 10^{-4} … 10^{-1}
- From 10^{-3} … $2*10^{-2}$ fit the proton radius (slope of electric form factor)
  - Precision 0.03 fm with conservative beam trigger (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



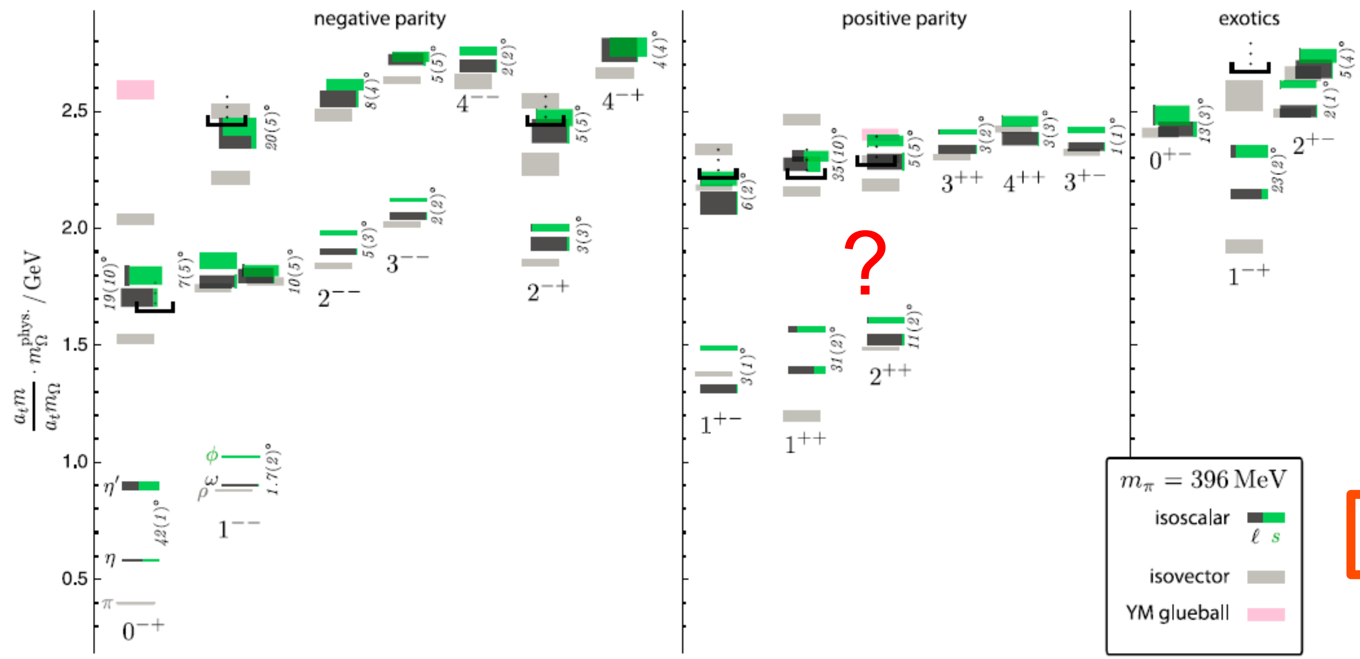
Long term COMPASS future

Long term future COMPASS-like experiment LoI (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)

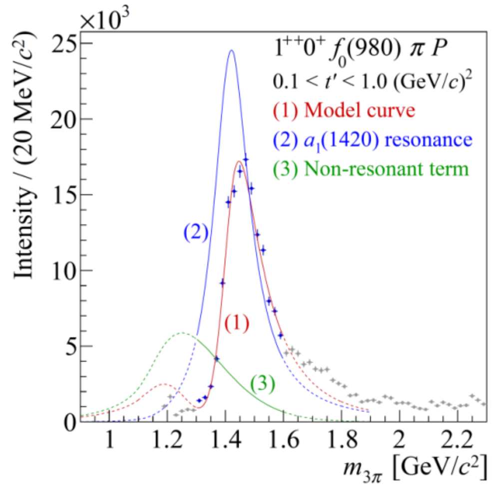
Light Meson Sector & COMPASS contribution



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

Good illustration or 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)

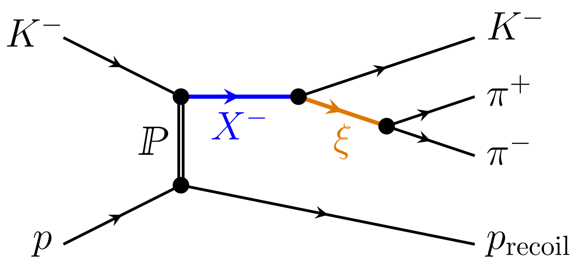
Light and Strange Meson Spectrum

RF separated kaon beam ~ 8 x 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 - ~10^5 /s, low momenta kaons

JLab - ~10^4 /s, K^0 long beam, lower momenta

Unique opportunity

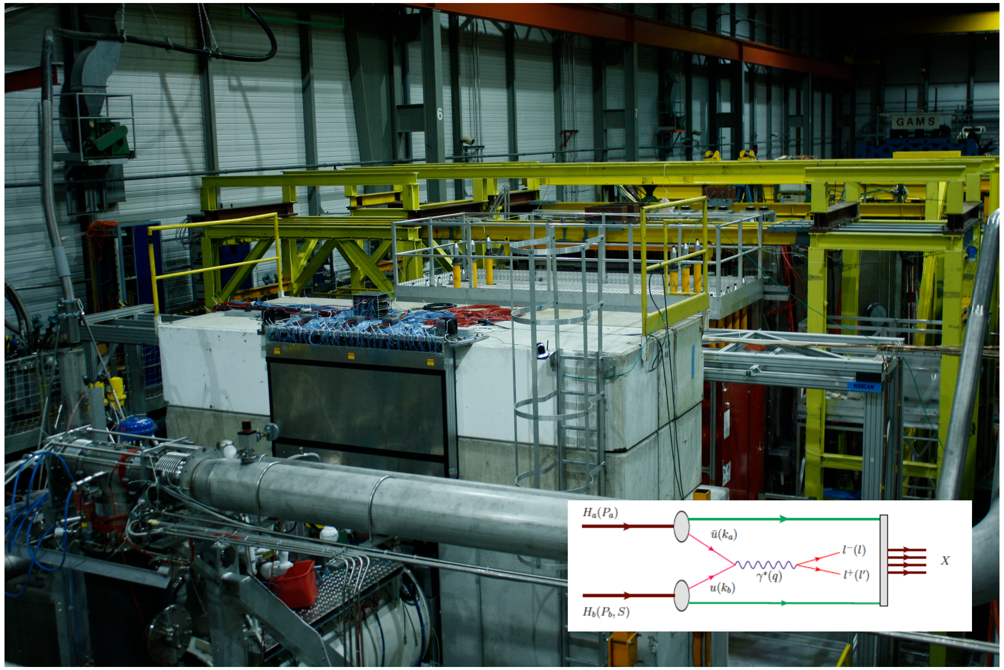
Running/planed Drell-Yan experiments, COMPASS (π^- beam on $p^\uparrow$) – unique experiment

Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2}\ s^{-1}$)		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 x 10^{33}	0.14	P_t = 80% f = 0.22	1.0 x 10^{-3}	2014-2015, 2018
PANDA (GSI)	pbar + $p^\uparrow$	15 GeV $\sqrt{s}$ = 5.5	x_t = 0.2 – 0.4	2 x 10^{32}	0.07	P_t = 90% f = 0.22	1.1 x 10^{-4}	>2025
AFTER	$p^\uparrow$ + p	7 TeV $\sqrt{s}$ = 120	x_b = 0.1 – 0.9	2 x 10^{32}	0.06	P_b = 100%?	2.3 x 10^{-5}	>2020
NICA (JINR)	$p^\uparrow$ + p	collider $\sqrt{s}$ = 26	x_b = 0.1 – 0.8	1 x 10^{32}	0.04	P_b = 70%	6.8 x 10^{-5}	>2023
PHENIX/STAR (RHIC)	$p^\uparrow + p^\uparrow$	collider $\sqrt{s}$ = 510	x_b = 0.05 – 0.1	2 x 10^{32}	0.08	P_b = 60%	1.0 x 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 x 10^{31} 6 x 10^{32}	0.08	P_b = 60% P_b = 50%	4.0 x 10^{-4} 2.1 x 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 x 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 x 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 x 10^{35}	0.04	P_b = 60%	1	2020

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

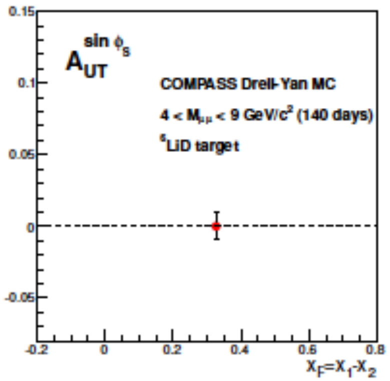
**not constrained by SIDIS data* / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams, f=0.22 for π^- beam on NH_3)

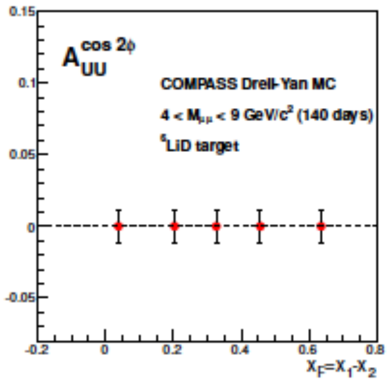
COMPASS pion-induced Drell-Yan (LH_2, ^{6}LiD, Ni…)

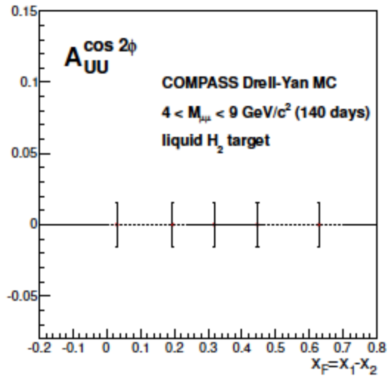


The same arguments as for SIDIS TMDs flavour separated extraction valid as well for our Drell-Yan data, both TMDs and "normal" pion PDFs.

- 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}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 ~3-4x10^7 /s can be reached (antiprotons) and ~8x10^6 /s (kaons)

Assuming flux of 1x10^7 /s for kaon/antiproton,
background free high mass range $4 < M_{\mu\mu} < 9\ GeV/c^2$ 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 LH_2, 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

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

NA10 $\pi^- W$

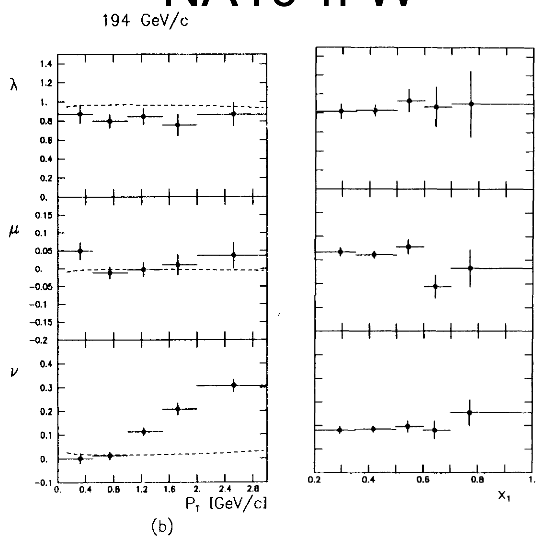
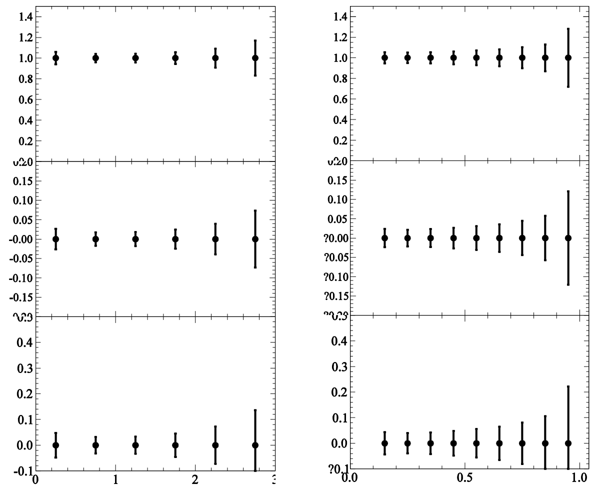
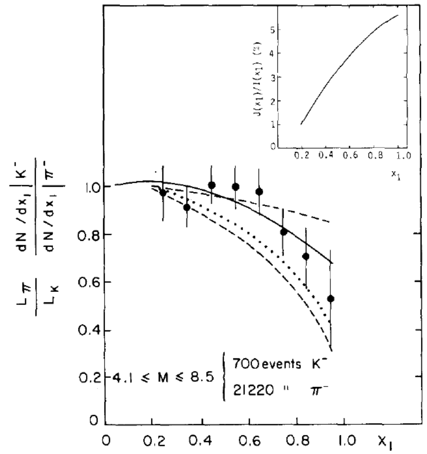


Fig. 3

COMPASS $K^- W$



p_T (GeV/c) *X_1*

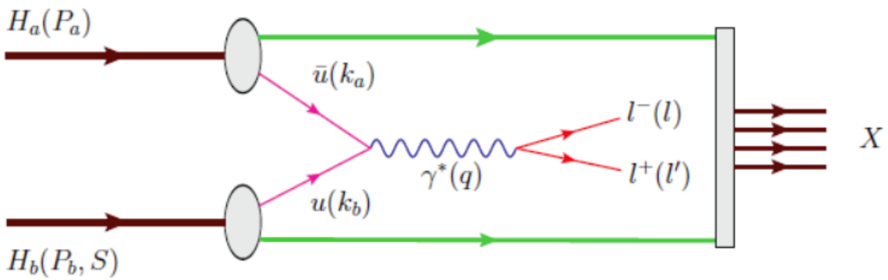


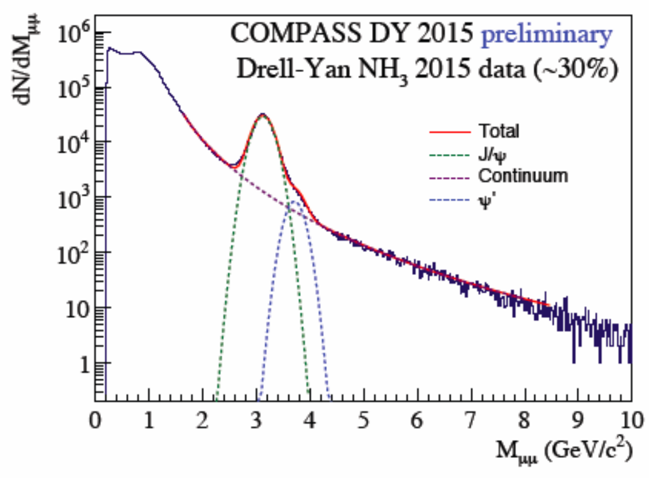
NA3 Collaboration, PLB 93, 354 (1980

No competitors, unique data

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

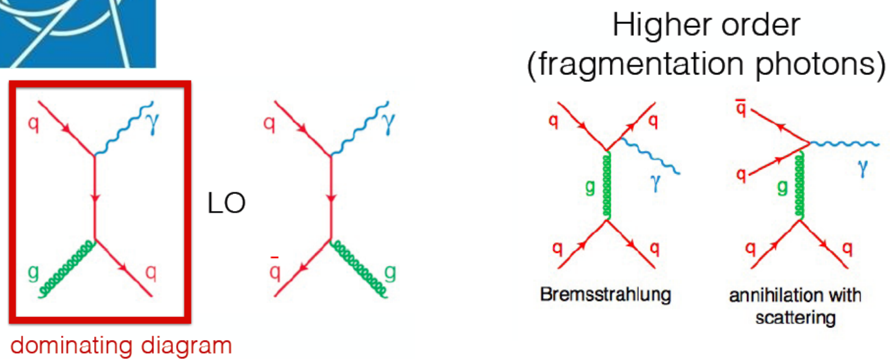
- Antiproton-induced polarised DY makes **TMD's extraction model independent**
- Allows to profit from good knowledge of proton PDFs (from SIDIS) and as alternative probe permits to test TMDs universality
- New data on all TMDs induced asymmetries in both High Mass and *J/Ψ* regions:
  1. Model independent 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





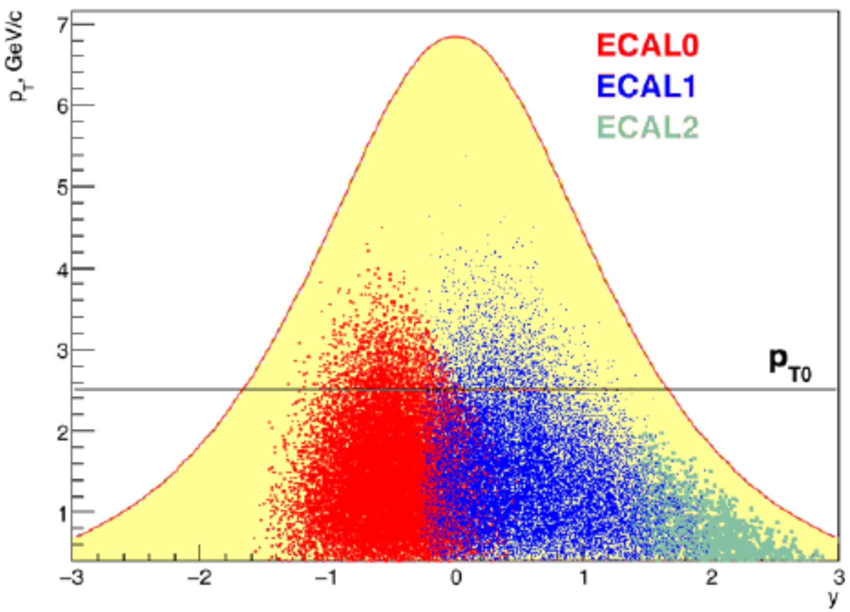
No competitors, unique data

Kaon structure study via prompt photons



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

access to gluon distributions in hadrons

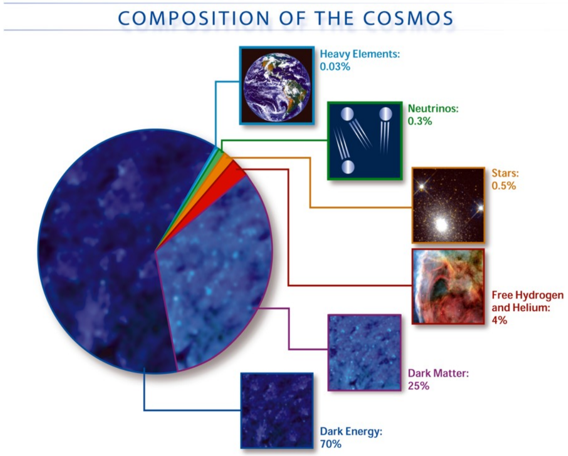


Gluon structure of the kaon in completely unknown while gluon contribution to its mass is especially important for understanding of the nature of the kaon. Some models conclude about much smaller gluon contribution in the kaon rather than in the pion while opposite arguments based on the experimental 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

Astrophysics – search for dark matter,
contribution from COMPASS



- 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)

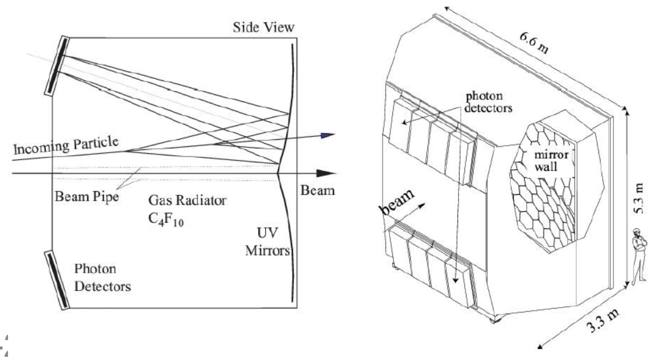
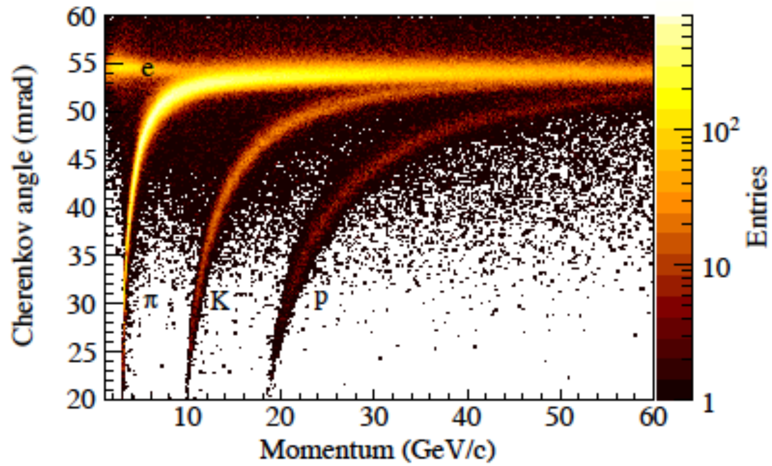


Figure 34. COMPASS RICH-1: principle and artistic view.



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, atticipate 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 LoI is in preparation, will be made public at the beginning of 2018

Thank you!