Study of $\Sigma(1385)$ and $\Xi(1321)$ hyperon and antihyperon production in DIS

Natalia Rossiyskaya (JINR Dubna)

on behalf of the COMPASS collaboration

Hadron Structure and QCD 2014

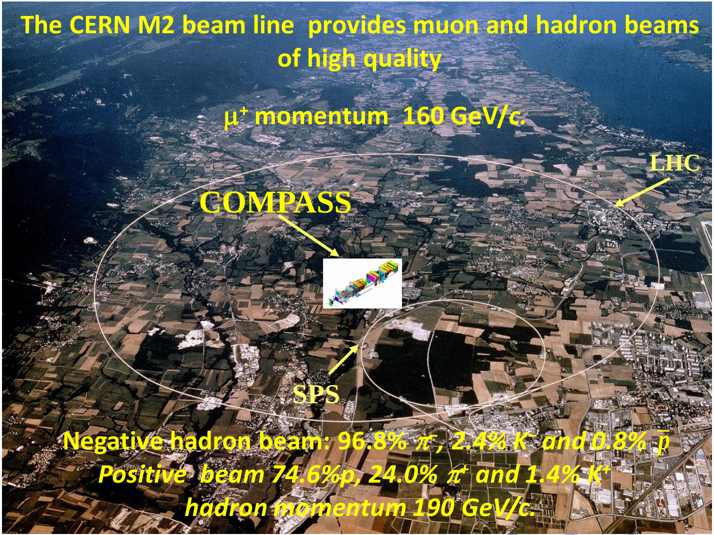
Gatchina, 4 July 2014

Physics motivation

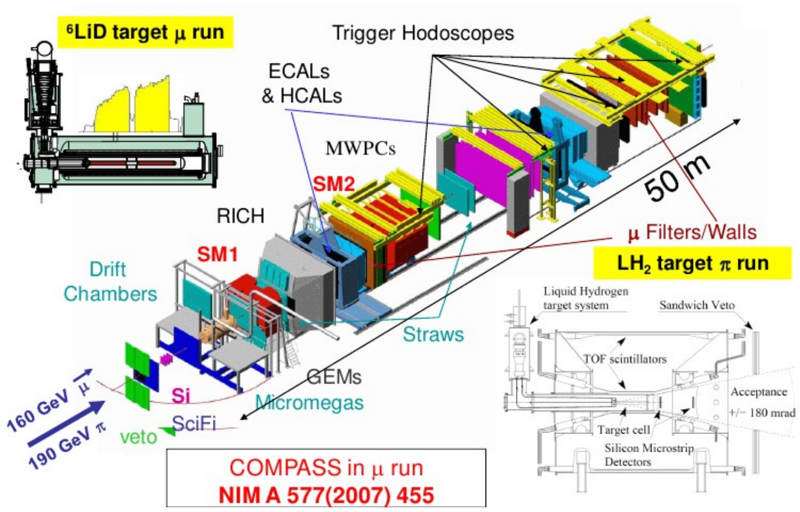
- Understanding the production mechanism of heavy hyperons and antihyperons in lepton DIS. No measurements of the heavy antihyperon yields were done before this work.
- Role of heavy hyperons decays in the production and polarization of Λ and $\bar{\Lambda}$.
- Determination the relative proportion of $\Lambda(\bar{\Lambda})$ originating directly (from primary vertex) and indirectly (from heavy hyperons decays).
- Tuning the LEPTO generator parameters according to your measurements of heavy hyperons yields ($\Sigma^{\pm}(1385)/\Lambda$, $\bar{\Sigma}^{\pm}(1385)/\bar{\Lambda}$, $\Xi^{-}(1321)/\Lambda$, $\bar{\Xi}^{+}(1321)/\bar{\Lambda}$).

COMPASS spectrometer

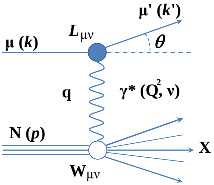
COmmon Muon Proton Apparatus for Structure and Spectroscopy



COMPASS set-up



The most important kinematic variables of DIS



$k = (E, \vec{k})$ – four vector of incoming lepton;
$k' = (E', \vec{k}')$ – four vector of outgoing lepton;
$p = (M, \vec{0})$ – four vector of nucleon;
E – energy of incoming lepton in laboratory system;
E' – energy of outgoing in laboratory system;
M – nucleon mass.

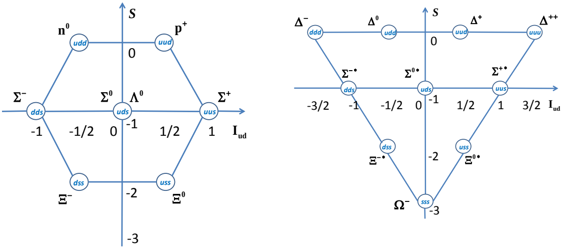
variable	inclusive DIS $\mu^+ + d \to \mu^{+'} + X$
$q = k - k'$	four momentum transfer
$Q^2 = -q^2$	four momentum squared of the virtual photon
$y = \frac{E-E'}{E}$	relative energy transfer in laboratory system $(0 < y < 1)$
$x = \frac{Q^2}{2M(E-E')}$	Bjorken variable (0<x<1)
$W^2 = (p+q)^2$	mass of hadronic final state squared
	semi-inclusive DIS $\mu^+ + d \to \mu^{+'} + h + X$
$z = \frac{E_h}{(E-E')}$	fraction of virtual photon energy carried by the hadron h
p_T	transverse momentum of hadron relative to the photon γ^*
$x_F \cong \frac{2p_L}{W}$	Feynman variable (-1<x_F<1)

For 2003 and 2004: $2.58 \cdot 10^{10}$ events, $3.12 \cdot 10^8$ of them are in DIS.
DIS events are selected by cuts: $Q^2 > 1$ $(\text{GeV}/c)^2$ and $0.2 < y < 0.9$.

Λ and heavier hyperons

Decay of heavy hyperons (antihyperons) is one of the sources Λ ($\bar{\Lambda}$).

Baryon octet and decuplet



Heavy hyperons decay

$\mathrm{Br}(\Sigma(1385) \to \Lambda\pi) = 0.87 \pm 0.02$

$\mathrm{Br}(\Xi(1321)^- \to \Lambda\pi) = 1.00 \pm 0.04$

$\mathrm{Br}(\Sigma(1192)^0 \to \Lambda\gamma) = 1$

$\mathrm{Br}(\Xi(1314)^0 \to \Lambda\pi^0) = 1.00 \pm 0.01$

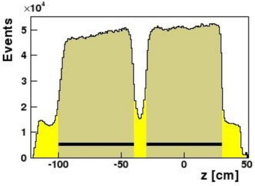
$\mathrm{Br}(\Omega(1672)^- \to \Lambda K^-) = 0.68 \pm 0.01$

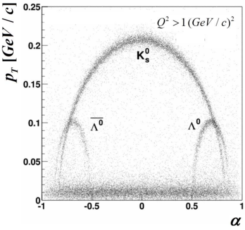
- High statistics for Λ and $\bar{\Lambda}$ hyperons is 69500 and 41600, respectively.
  COMPASS Collaboration, M. Alekseev et al., *Eur. Phys. J.* **64** (2009) 171.
- Σ^0 and Ξ^0 were not studied because during these years the electromagnetic calorimeters were not yet included in the spectrometer set-up.
- This analysis is based on the decays of charged Σ and Ξ hyperons.

Selection criteria Λ and $\bar{\Lambda}$ hyperons

2003 - 2004 data were used for this analysis.

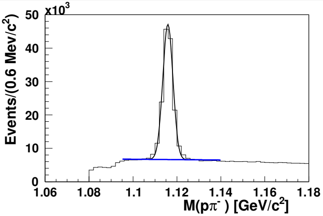
- The DIS cuts were $Q^2 > 1\ (\mathrm{GeV}/c)^2$ and $0.2 < y < 0.9$.
- Primary vertex inside the target.
- Secondary vertex: 5 cm downstream of the last target cell.
- The χ^2/ndf value of the secondary vertex fit is $\chi^2 < 2$.
- $p_t > 23$ MeV/c – to reject e^+e^- pairs from the γ conversion.
- $p_\pm > 1$ GeV/c.
- The current fragmentation region ($x_F > 0.05$).

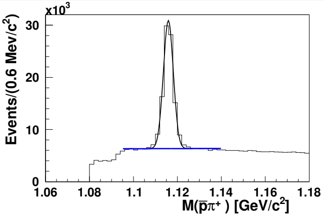




$$\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$$

Distributions of $p\pi^-(\Lambda)$ and $\bar{p}\pi^+(\bar{\Lambda})$ invariant mass





	N	m(RD), MeV	m(PDG), MeV	σ(RD), MeV
Λ	112449±418	1115.85 ± 0.01	1115.683 ± 0.006	2.22 ± 0.01
$\bar{\Lambda}$	66685±350	1115.84 ± 0.02	1115.683 ± 0.006	2.21 ± 0.02

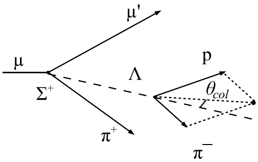
The total numbers of Λ and $\bar{\Lambda}$ hyperons, represent an improvement of an order of magnitude with respect to previous experiments.

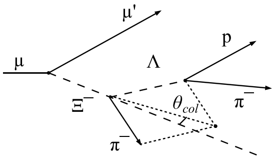
	N(Λ)	N($\bar{\Lambda}$)
E665	750	650
NOMAD	8087	649
HERMES	7300	1687
STAR	30000	24000
COMPASS	112000	67000

Heavy hyperon and antihyperon selection

$\Sigma(1385)$ and $\bar{\Sigma}(1385)$
decay via
strong interaction

$\Xi(1321)$ and $\bar{\Xi}(1321)$
decay via
weak interaction





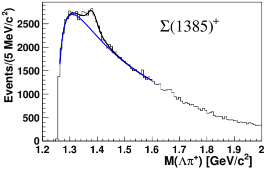
- Events with a $p\pi^-(\bar{p}\pi^+)$ invariant mass within a $\pm 2\ \sigma$ interval from the mean value of the Λ $(\bar{\Lambda})$ peak are taken.

- $\theta_{col_\Lambda} < 0.01$ rad.
  This cut selects Λ
  with the momentum pointing
  to the primary vertex.
- Selected $\Lambda((\bar{\Lambda})$ candidates were then combined with each charged track associated to the primary vertex which is assumed to be a pion.

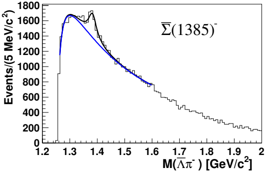
- $\theta_{col_\Xi} < 0.02$ rad.
  This cut selects Ξ
  with the momentum pointing
  to the primary vertex.
- Selected $\Lambda((\bar{\Lambda})$ candidates were then combined with each charged track not associated to the primary vertex which is assumed to be a pion.
- Procedure of the *CDA* (Closest Distance of Approach)

Distributions of $\Lambda\pi^{\pm}$ and $\bar{\Lambda}\pi^{\pm}$ invariant mass

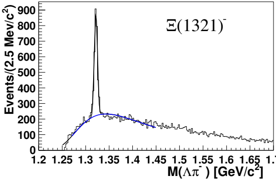
$N(\Sigma^{*+}) = 3631 \pm 333$



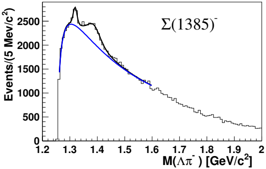
$N(\bar{\Sigma}^{*-}) = 2173 \pm 222$



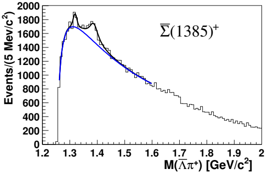
$N(\Xi^{-}) = 1634 \pm 52$



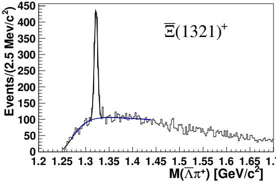
$N(\Sigma^{*-}) = 2970 \pm 490$



$N(\bar{\Sigma}^{*+}) = 1889 \pm 265$



$N(\bar{\Xi}^{+}) = 1054 \pm 44$



Fitting function for the signal Σ $\quad S(x) = \frac{\Gamma}{(2\pi)^{3/2}} \int \frac{N e^{-\frac{1}{2}(\frac{t-x}{\sigma})^2}}{(t-M)^2+(\frac{\Gamma}{2})^2} dt$

for the signal Ξ $\quad G(x) = \frac{N}{\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{t-x}{\sigma})^2}$

for the background function $\quad B(x) = a\,(x - M_{th})^b\, e^{-c\,(x-M_{th})^d}$

Yields of heavy hyperons and antihyperons

For the first time the relative yields of heavy hyperons and antihyperons were measured in lepton DIS:

The relative yields	COMPASS
Σ^{*+}/Λ	$0.055 \pm 0.005(\text{stat}) \pm 0.005(\text{syst})$
$\bar{\Sigma}^{*-}/\bar{\Lambda}$	$0.047 \pm 0.006(\text{stat}) \pm 0.006(\text{syst})$
Σ^{*-}/Λ	$0.056 \pm 0.009(\text{stat}) \pm 0.007(\text{syst})$
$\bar{\Sigma}^{*+}/\bar{\Lambda}$	$0.039 \pm 0.006(\text{stat}) \pm 0.006(\text{syst})$
Ξ^{-}/Λ	$0.038 \pm 0.003(\text{stat}) \pm 0.002(\text{syst})$
$\bar{\Xi}^{+}/\bar{\Lambda}$	$0.043 \pm 0.004(\text{stat}) \pm 0.002(\text{syst})$

- These ratios were corrected for acceptance.
- These ratios were used to tune the LEPTO generator parameters.

Comparison with NOMAD experiment

Previously the yields of the heavy hyperons were measured by the NOMAD collaboration in neutrino DIS.

The average neutrino energy of charged current interactions was 45.3 GeV.

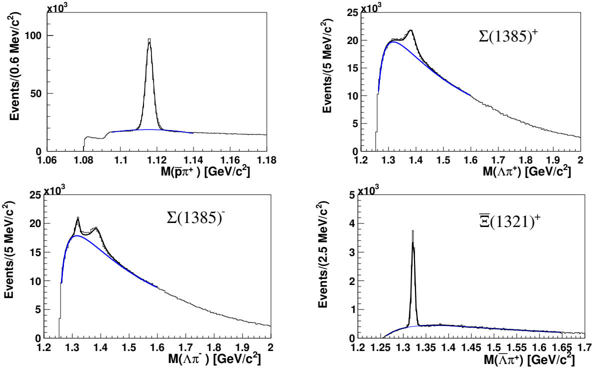
Ratios	Present data	NOMAD
Σ^{*+}/Λ	0.055 ± 0.005	0.025 ± 0.019
$\bar{\Sigma}^{*-}/\bar{\Lambda}$	0.047 ± 0.006	-
Σ^{*-}/Λ	0.056 ± 0.009	0.037 ± 0.015
$\bar{\Sigma}^{*+}/\bar{\Lambda}$	0.039 ± 0.006	-
Ξ^{-}/Λ	0.038 ± 0.003	0.007 ± 0.007
$\bar{\Xi}^{+}/\bar{\Lambda}$	0.043 ± 0.004	-

- The large experimental uncertainties in the NOMAD measurements prevent us from drawing conclusions about heavy hyperon production in charged lepton DIS as compared to neutrino DIS.

The full kinematic range Q^2 and y

- $Q^2 > 0\ (\mathrm{GeV}/c)^2$ and $0 < y < 1$

Hyperon	Full range Q^2 and y
Λ	1200000 ± 1300
$\bar{\Lambda}$	650000 ± 1000
Σ^{*+}	44000 ± 1300
$\bar{\Sigma}^{*-}$	37000 ± 1400
Σ^{*-}	23000 ± 900
$\bar{\Sigma}^{*+}$	20000 ± 1100
Ξ^{-}	20500 ± 200
$\bar{\Xi}^{+}$	11500 ± 100



- The resulting $\Lambda(\bar{\Lambda})$ and heavy hyperon statistics are about ten times bigger that those obtained using DIS cuts.

The ratios of the hyperon yields for the events without and with the DIS cuts

Σ/Λ (no cut)/Σ/Λ (DIS cut)	
Σ^+/Λ	1.03 ± 0.08
$\bar{\Sigma}^-/\bar{\Lambda}$	0.97 ± 0.11
Σ^-/Λ	1.03 ± 0.16
$\bar{\Sigma}^+/\bar{\Lambda}$	0.97 ± 0.13
Ξ/Λ (no cut)/Ξ/Λ (DIS cut)	
Ξ^-/Λ	1.06 ± 0.09
$\bar{\Xi}^+/\bar{\Lambda}$	1.06 ± 0.09

DIS cuts: $\langle Q^2 \rangle = 3.58 (\mathrm{GeV}/c)^2$

Without DIS cuts: $\langle Q^2 \rangle = 0.47\, (\mathrm{GeV}/c)^2$

- No strong Q^2 dependence of these ratios was found within the statistical accuracy.

Tuning the Monte Carlo parameters

In order to reproduce better the measured ratios the LEPTO/ JETSET 7.4 parameters related to the production yields of strange baryons were tuned.

Ratios	LEPTO Default	Experimental data	LEPTO COMPASS
$\Lambda/\bar{\Lambda}$	1.22 ± 0.01	1.71 ± 0.02	1.72 ± 0.01
K/Λ	6.06 ± 0.01	6.21 ± 0.05	6.22 ± 0.01
Σ^+/Λ	0.082 ± 0.001	0.055 ± 0.005	0.052 ± 0.001
$\bar{\Sigma}^-/\bar{\Lambda}$	0.074 ± 0.001	0.047 ± 0.006	0.038 ± 0.001
Σ^-/Λ	0.084 ± 0.001	0.056 ± 0.009	0.067 ± 0.001
$\bar{\Sigma}^+/\bar{\Lambda}$	0.060 ± 0.001	0.039 ± 0.006	0.037 ± 0.001
Ξ^-/Λ	0.051 ± 0.0008	0.034 ± 0.003	0.029 ± 0.001
$\bar{\Xi}^+/\bar{\Lambda}$	0.056 ± 0.0008	0.039 ± 0.004	0.040 ± 0.001

- In the COMPASS experiment simulation with LEPTO default parameters shows that indirect production contribution is about 58% for Λ and 54% for $\bar{\Lambda}$. With tuned LEPTO parameters the fractions of the indirectly produced Λ and $\bar{\Lambda}$ are reduced to 37% and 32%, respectively.

Conclusion

- For the first time the yields of heavy hyperons and antihyperons in lepton DIS were measured:

$$\begin{aligned}
\Sigma^{*+}/\Lambda &= 0.055 \pm 0.005(\text{stat})\pm 0.005(\text{syst})\\
\bar{\Sigma}^{*-}/\bar{\Lambda} &= 0.047 \pm 0.006(\text{stat})\pm 0.006(\text{syst})\\
\Sigma^{*-}/\Lambda &= 0.056 \pm 0.009(\text{stat})\pm 0.007(\text{syst})\\
\bar{\Sigma}^{*+}/\bar{\Lambda} &= 0.039 \pm 0.006(\text{stat})\pm 0.006(\text{syst})\\
\Xi^{-}/\Lambda &= 0.038 \pm 0.003(\text{stat})\pm 0.002(\text{syst})\\
\bar{\Xi}^{+}/\bar{\Lambda} &= 0.043 \pm 0.004(\text{stat})\pm 0.002(\text{syst})
\end{aligned}$$

- No strong Q^2 dependence of these ratios was found within the statistical accuracy
- The LEPTO generator parameters have been tuned to reproduce the measurement yields
- Using the tuned LEPTO parameters, the fractions of indirectly produced Λ and $\bar{\Lambda}$ hyperons were found to be 37% and 32%, respectively.

Tuning the Monte Carlo

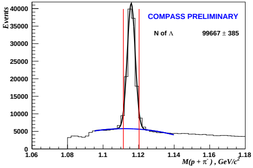
In Table a comparison between the default LEPTO parameters and the NOMAD tuned ones is given. The results of the COMPASS tuning are given in the last column.

Parameters	Default	COMPASS tuning
PARJ(1)	0.1	0.03
PARJ(2)	0.3	0.45
PARJ(3)	0.4	0.175
PARJ(4)	0.05	0.078
PARJ(5)	0.5	3.0
PARJ(7)	0.5	0.13

PARJ(1) is $P(qq)/P(q)$, the suppression of diquark-antidiquark pair production in the colour field, compared with quark(antiquark) production;
PARJ(2) is P(s)/P(u), the suppression of s quark pair production in the field compared with u- or d- pair production;
PARJ(3) is (P(us)/P(ud))/(P(s)/P(d)), the extra suppression of strange diquark production compared with the normal suppression of strange quarks;
PARJ(4) is $(1/3)P(ud_1)/P(ud_0)$, the suppression of spin 1 diquarks compared with spin 0 ones (excluding the factor 3 coming from spin counting);
PARJ(5) is parameter determining relative occurence of baryon production by $BM\bar{B}$ and by $B\bar{B}$ configurations in the popcorn baryon production model, roughly $P(BM\bar{B})/(P(B\bar{B}) + P(BM\bar{B}))$ = PARJ(5)/(0.5+PARJ(5));
PARJ(7) is extra suppression for having a strange meson M in a $BM\bar{B}$ configuration.

Estimation of the systematic effects

- **Selection cut:**
  To estimate the systematic error related to the particular choice of the selection cut of the Λ ($\bar{\Lambda}$) sample we change the width of the central band from $\pm 2\,\sigma$ to ± 2.5 and $\pm 1.5\,\sigma$.



- **Background shape:**
  To estimate this effect we evaluate the background using mixed event method, in which the shape of the background distribution in the $\Lambda\pi$ invariant mass was determined combining Λ and π from different events of the same topology.