Polarization of valence, non-strange and strange quarks in the nucleon determined by COMPASS

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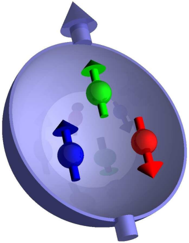
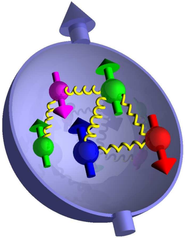
The spin of the nucleon

Angular momentum conservation

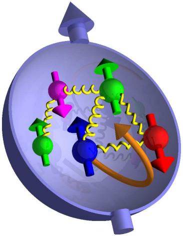
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



Constituent (naive) parton model: $\Delta\Sigma = \Delta u_v + \Delta d_v = 1$



Is contribution from gluons important as in unpolarized case?

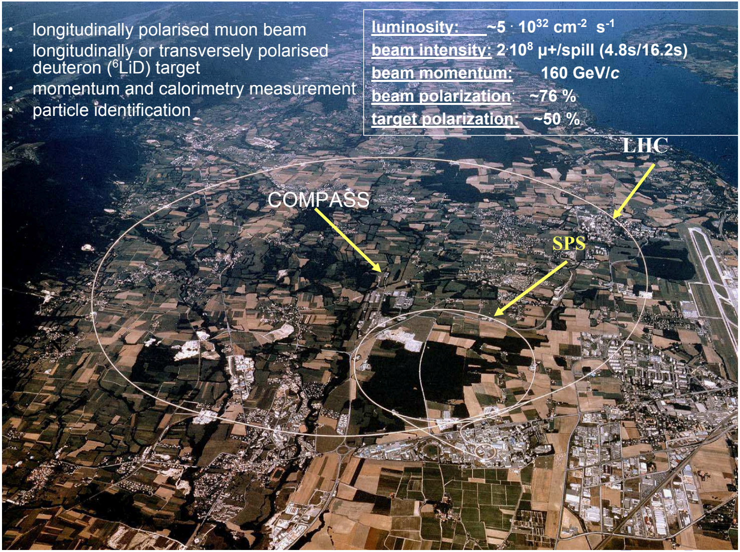


Full description should take into account orbital angular momenta

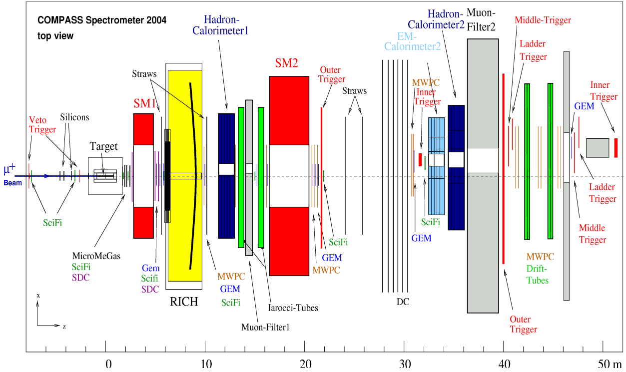
Outline

1. COMPASS experiment
2. First moment of g_1
3. Semi-inclusive asymmetries
4. Flavour separation
5. Summary

COMPASS experiment at CERN

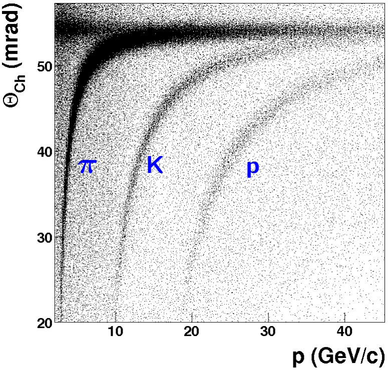


COMPASS spectrometer



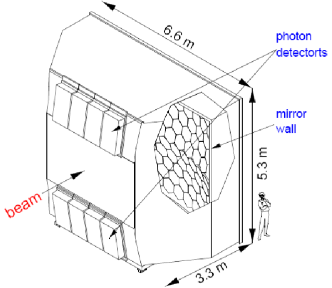
- Two parts of spectrometer (60m length in total)
- About 350 detector planes of different type
- Polarized beam: μ^+ (P_B=76% at 160GeV)
- Polarized target: ^{6}LiD (P_T=50%) and NH_3 (P_T=90%)
- Particle identification by RICH, ECALs, HCALs and μ-filter

Ring Imaging CHerenkov detector

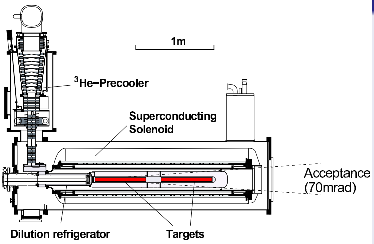


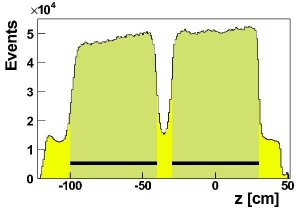
RICH features

- π, K, p separation from 2, 9, 18 GeV up to 50 GeV
- 116 spherical mirrors (21 m^2)
- 80 m^3 C_4F_{10}, n=1.00153
- $< n > = 15$



The polarized target

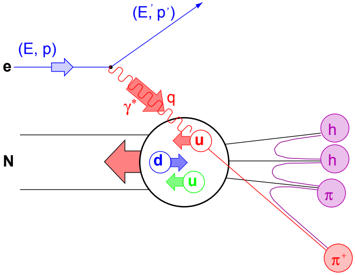




Target features

- target material: ^{6}LiD, NH_3
- Dynamic Nuclear Polarization technique
- polarization: 50%, 90%
- acceptance: 70 mrad, 180 mrad
- solenoid field: 2.5T
- temperature: 50mK
- two (three) cells with opposite polarization
- target length: 120 cm in total
- dilution factor $\approx$ 0.4, 0.2

Deep inelastic scattering



Kinematical variables:

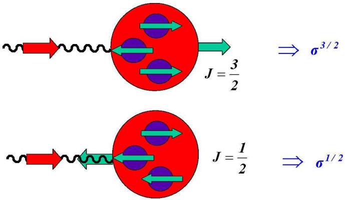
- $Q^2 = -q^2$
- $\nu = E - E'$
- $x = Q^2/2M\nu$
- $y = \nu/E$
- $z = E_h/\nu$

Inclusive cross-section

$$\frac{d^2\sigma}{dxdQ^2} = c_1 F_1(x, Q^2) + c_2 F_2(x, Q^2) + c_3 g_1(x, Q^2) + c_4 g_2(x, Q^2)$$

where g_1, g_2 and F_1, F_2 are spin dependent and spin independent structure functions.

Polarized deep inelastic scattering



Quark densities in QPM:

- $q(x) = q^{+}(x) + q^{-}(x)$
- $\Delta q(x) = q^{+}(x) - q^{-}(x)$

$q^{+}(x), q^{-}(x)$: quarks polarized parallel (antiparallel) to nucleon spin

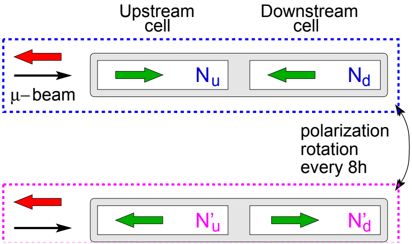
- Inclusive asymmetry:

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1}{F_1} = \frac{2x(1+R)}{F_2} g_1 \stackrel{QPM}{=} \frac{\sum_q e_q^2 \Delta q}{\sum_q e_q^2 q}$$

- Semi-inclusive asymmetry:

$$A_1^h = \frac{\sigma^h_{1/2} - \sigma^h_{3/2}}{\sigma^h_{1/2} + \sigma^h_{3/2}} \stackrel{QPM}{=} \frac{\sum_q e_q^2 \Delta q D_q^h}{\sum_q e_q^2 q D_q^h}, \qquad A_{\parallel} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \approx D A_1$$

Experimental asymmetry



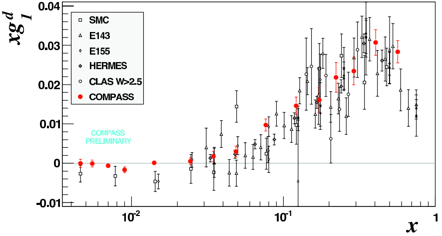
- Target cells polarized in opposite direction
- Acceptance for cells is not the same
- Polarization reversed

Experimental asymmetry:

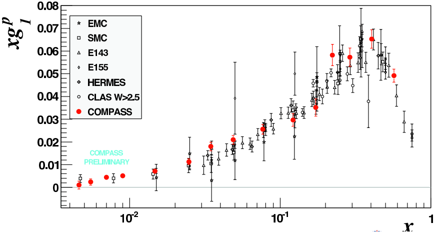
$$A_{exp} = \frac{1}{2}\left(\frac{N_u - N_d}{N_u + N_d} + \frac{N'_d - N'_u}{N'_d + N'_u}\right) = fP_B P_T A_{\parallel}$$

P_B, P_T - beam and target polarization
f - dilution factor

Structure functions g_1^d, g_1^p



Very good agreement between experiments



NLO QCD analysis

- Spin dependent structure function g_1:

$$g_1^d(x,Q^2)=\frac{1}{2}\langle e^2\rangle\left[C_q^S\otimes\Delta\Sigma+C_q^{NS}\otimes\Delta q^{NS}+2n_f C_G\otimes\Delta G\right]$$

$$\Delta\Sigma=\Delta u+\Delta d+\Delta s,\quad \Delta q_3=\Delta u-\Delta d,\quad \Delta q_8=\Delta u+2\Delta d-\Delta s$$

- DGLAP equations:

$$\frac{\mathrm{d}}{\mathrm{d}t}\Delta q^{NS}=\frac{\alpha_s(t)}{2\pi}P_{qq}^{NS}\otimes\Delta q_{NS},\quad t=\log\left(\frac{Q^2}{\Lambda^2}\right)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix}=\frac{\alpha_s(t)}{2\pi}\begin{pmatrix}P_{qq}^S & 2n_f P_{qG}^S\\ P_{Gq}^S & P_{GG}^S\end{pmatrix}\otimes\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix}$$

- Input parametrization at fixed Q_0^2:

$$(\Delta\Sigma,\Delta q_3,\Delta q_8,\Delta g)=\eta\frac{x^\alpha(1-x)^\beta(1+\gamma x)}{\int_0^1 x^\alpha(1-x)^\beta(1+\gamma x)\mathrm{d}x}$$

- Minimization routine:

$$\chi^2=\sum_{i=1}^{N}\frac{\left[g_1^{calc}(x,Q^2)-g_1^{exp}(x,Q^2)\right]^2}{\left[\sigma_{stat}^{exp}(x,Q^2)\right]^2}$$

First moment of g_1

- **Quark polarization from the fit ($Q^2 = 3$ GeV^2)**

$$\eta_\Sigma = 0.30 \pm 0.01(stat) \pm 0.02(syst)$$

- **First moment (average nucleon) (Phys. Lett. B 647 (2007) 8)**

$$\Gamma_1^N(Q^2 = 3\mathbf{GeV/c})^2 = \int_0^1 g_1^N(x)dx = 0.0502 \pm 0.0028(stat) \pm 0.0020(evol) \pm 0.0051(syst)$$

- **Contribution from unmeasured region about 4%**
- **Extracting a_0 from the first moment of g_1^N**

$$\Gamma_1^N(Q^2) = \frac{1}{9}\left(1 - \frac{\alpha_s(Q^2)}{\pi} + \mathcal{O}(\alpha_s^2)\left(a_0(Q^2) + \frac{1}{4}a_8\right)\right)$$

- **From hyperons β decays assuming SU(3)$_f$**

$$a_8 = 0.585 \pm 0.025$$ **(Y. Goto at al., PRD 62 (2000)034017)**

$$\Rightarrow a_0 = 0.35 \pm 0.03(stat) \pm 0.05(syst)$$

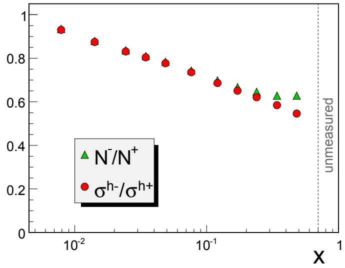
- **Quark polarization at $Q^2 = 3$ GeV^2**

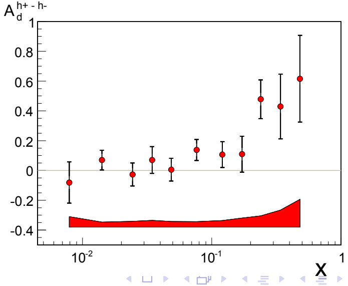
$$\hat{a}_{0(Q^2 \to \infty)} = \Delta\Sigma = 0.35 \pm 0.03(stat) \pm 0.05(syst)$$

$$(\Delta s + \Delta\bar{s}) = \frac{1}{3}(\hat{a}_0 - a_8) = -0.08 \pm 0.01(stat) \pm 0.02(syst)$$

Difference asymmetry

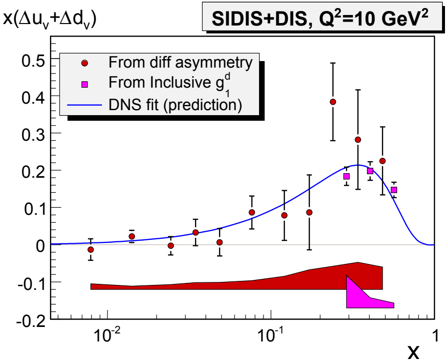
- Definition: $A^{h^+-h^-} = \frac{(\sigma^{h+}_{\uparrow\downarrow}-\sigma^{h-}_{\uparrow\downarrow})-(\sigma^{h+}_{\uparrow\uparrow}-\sigma^{h-}_{\uparrow\uparrow})}{(\sigma^{h+}_{\uparrow\downarrow}-\sigma^{h-}_{\uparrow\downarrow})+(\sigma^{h+}_{\uparrow\uparrow}-\sigma^{h-}_{\uparrow\uparrow})}$
- In LO FF cancel out. For a deuteron target:
$$A_d^{\pi^+-\pi^-}(x) = A_d^{K^+-K^-}(x) = \frac{\Delta u_v(x)+\Delta d_v(x)}{u_v(x)+d_v(x)}$$
- $A^{h^+-h^-}$ calculated from A^{h+} and A^{h-}:
$$A^{h^+-h^-} = \frac{1}{1-r}(A^{h+} - rA^{h-}),\ r = \frac{\sigma^{h-}_{\uparrow\downarrow}+\sigma^{h-}_{\uparrow\uparrow}}{\sigma^{h+}_{\uparrow\downarrow}+\sigma^{h+}_{\uparrow\uparrow}} = \frac{\sigma^{h-}}{\sigma^{h+}} = \frac{N^-/a^-}{N^+/a^+}$$





Valence quark distribution

$$x(\Delta u_v(x)+\Delta d_v(x))= \frac{x(u_v(x)+d_v(x))}{(1+R(x))(1-1.5\omega_D)} A^{h^+-h^-}(x), \quad \omega_D=0.05\pm0.01$$

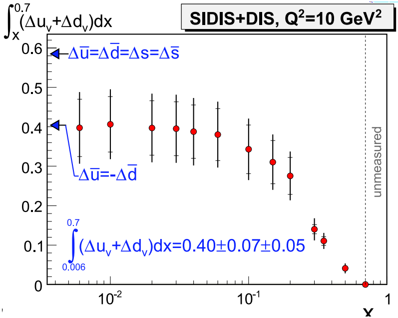


- evolved to $Q^2 = 10\ (\mathrm{GeV}/c)^2$
- using LO DNS parameterization (PRD 71(2005)094018)
- DNS predicts COMPASS data
- for $u_v + d_v$ MRST04(LO) used

sea very small at large x, with inclusive asymmetry much better precision

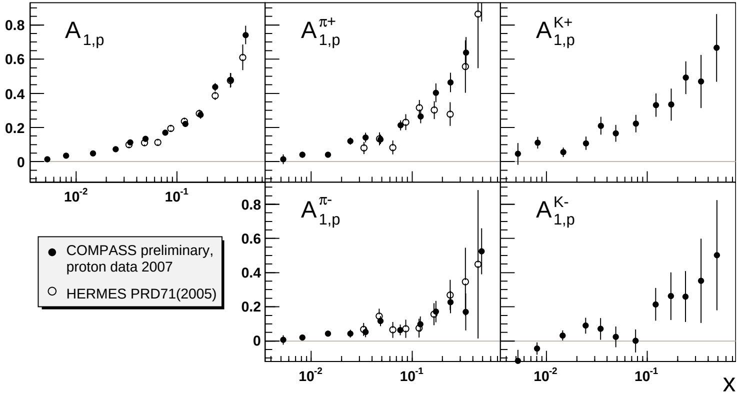
$$\Delta u_v + \Delta d_v = \frac{36}{5}\frac{g_1^d(x,Q^2)}{(1-1.5\omega_D)} - \left[2(\Delta\bar{u}+\Delta\bar{d}) + \frac{2}{5}(\Delta s + \Delta\bar{s})\right]$$

Valence quark distribution - first moment

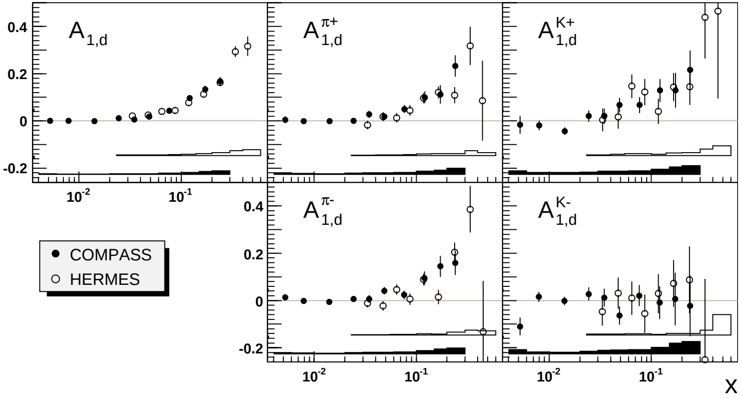


- First moment $\Gamma_v = \int_0^1 (\Delta u_v(x) + \Delta d_v(x))dx$
- Contribution from $x > 0.7$ about 0.004 (DNS fit)
- Γ_v (DIS+SIDIS) is $2.5\sigma_{stat}$ away from the symetric sea scenario, asymmetric sea favoured

Proton asymmetries



Deuteron asymmetries



The method of PDF extraction in LO

Asymmetries in LO

$$A_{1,d} = \frac{5(\mathbf{\Delta u} + \mathbf{\Delta d}) \;+\; 5(\mathbf{\Delta \bar{u}} + \mathbf{\Delta \bar{d}}) \;+\; 4\mathbf{\Delta s}}{5(u+d) + 5(\bar{u}+\bar{d}) + 2(s+\bar{s})}$$

$$A_d^h = \frac{(4D_u^h + D_d^h)(\mathbf{\Delta u} + \mathbf{\Delta d}) \;+\; (4D_{\bar{u}}^h + D_{\bar{d}}^h)(\mathbf{\Delta \bar{u}} + \mathbf{\Delta \bar{d}}) \;+\; 2(D_s^h + D_{\bar{s}}^h)\mathbf{\Delta s}}{(4D_u^h + D_d^h)(u+d) + (4D_{\bar{u}}^h + D_{\bar{d}}^h)(\bar{u}+\bar{d}) + 2(D_s^h s + D_{\bar{s}}^h \bar{s})}$$

$$A_{1,p} = \frac{4(\mathbf{\Delta u} + \mathbf{\Delta \bar{u}}) \;+\; (\mathbf{\Delta d} + \mathbf{\Delta \bar{d}}) \;+ 2\mathbf{\Delta s}}{4(u+\bar{u}) + (d+\bar{d}) + (s+\bar{s})}$$

$$A_{1,p}^h = \frac{4(D_u^h \mathbf{\Delta u} + D_{\bar{u}}^h \mathbf{\Delta \bar{u}}) \;+\; (D_d^h \mathbf{\Delta d} + D_{\bar{d}}^h \mathbf{\Delta \bar{d}}) \;+\; (D_s^h + D_{\bar{s}}^h)\mathbf{\Delta s}}{4(D_u^h u + D_{\bar{u}}^h \bar{u}) + (D_d^h d + D_{\bar{d}}^h \bar{d}) + (D_s^h s + D_{\bar{s}}^h \bar{s})}$$

$$\vec{A}(x) = B(x)\,\Delta\vec{q}(x), \qquad \Delta\vec{q} = (\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta s)$$

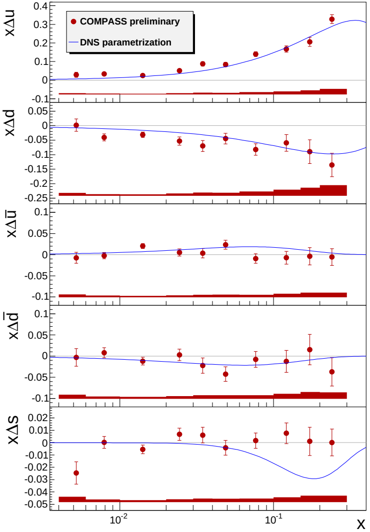
$$\chi^2 = (\vec{A} - \mathrm{B}\Delta\vec{q})^T \mathrm{Cov}_A^{-1} (\vec{A} - \mathrm{B}\Delta\vec{q}).$$

$$\Delta\vec{q} = (\mathrm{B}^T \mathrm{Cov}_A^{-1} \mathrm{B})^{-1} \mathrm{B}^T \mathrm{Cov}_A^{-1} \vec{A}$$

Error propagation:

$$\mathrm{Cov}_q = (\mathrm{B}^T \mathrm{Cov}_A^{-1} \mathrm{B})^{-1}$$

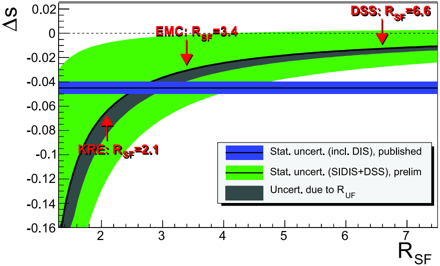
Polarized Quarks Distributions



First moments, x-range 0.004-0.3, MRST04 LO, DSS

- $\Delta u = 0.45 \pm 0.02 \pm 0.03$
- $\Delta d = -0.25 \pm 0.03 \pm 0.02$
- $\Delta \bar{u} = 0.01 \pm 0.02 \pm 0.004$
- $\Delta \bar{d} = -0.04 \pm 0.03 \pm 0.01$
- $\Delta s = \Delta \bar{s} = -0.01 \pm 0.01 \pm 0.02$

Quark valence distribution - FF dependence



$$R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$$

$$R_{UF} = \frac{\int D_d^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$$

- R_{UF} fixed at 0.14 from the DSS fragmentation functions
- Large statistical uncertainty due to R_{SF}
- If $R_{SF} > 5 \Delta s$ (SIDIS) $> \Delta s$ (DIS) and $\Delta s < 0$ for $x < 0.004$

Summary

- Analysis of 2002-2007 data has been presented
- From the first moment of g_1 we obtained quark contibution to the nucleon spin:

$$\Delta\Sigma = 0.33 \pm 0.03 \pm 0.05$$
$$(\Delta s + \Delta\bar{s}) = -0.08 \pm 0.01(stat) \pm 0.02$$

- Method of difference asymmetries gives

$$\Delta u_v + \Delta d_v = 0.40 \pm 0.07 \pm 0.05$$

- Proton data allows to perform full flavor separation
  - $\Delta u = 0.45 \pm 0.02 \pm 0.03$
  - $\Delta d = -0.25 \pm 0.03 \pm 0.02$
  - $\Delta\bar{u} = 0.01 \pm 0.02 \pm 0.004$
  - $\Delta\bar{d} = -0.04 \pm 0.03 \pm 0.01$
  - $\Delta s = \Delta\bar{s} = -0.01 \pm 0.01 \pm 0.02$
- Determination of fragmentation function is under study