COMPASS legacy results concerning longitudinal spin structure of the nucleon

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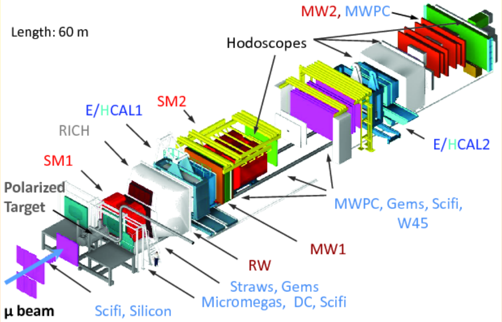
COmmon Muon and Proton Apparatus for Structure and Spectroscopy

COMPASS

TARGET:

120 cm total length
2 or 3 cells, oppositely polarised
material: ^{6}LiD or NH_3
polarisation: about 50% or 90%
2.5 T solenoid field



Polarised BEAM: about 80%

μ^+ at 160 (200) GeV/c

FEATURES

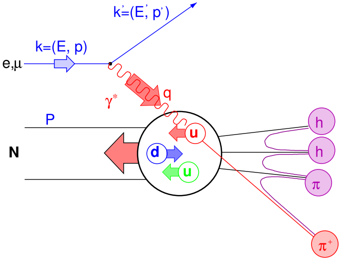
angular acceptance: ± 180 mrad
track reconstruction:
$p > 0.5$ GeV/c
h, e, μ identification: calorimeters and muon filters
π, K, p identification (RICH);
$p > 2$, 9, 18 GeV/c, respectively

DETECTOR

two stage spectrometer
60 m lenght
about 350 detector planes

COMPASS spectrometer for muon run, NIMA 577 (2007) 455

Nucleon spin structure in DIS: $\mu + N \to \mu' + X$

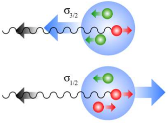


- $$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2Mq^4}\frac{E'}{E} L_{\mu\nu}W^{\mu\nu}$$
- Symmetric part of $W^{\mu\nu}$ – unpolarised DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2}$, $q(x, Q^2) \longrightarrow g_{1,2}$, $\Delta q(x, Q^2)$ where $q = q^+ + q^-$, $\Delta q = q^+ - q^-$, but...
- ...anomalous gluon contribution to $g_1(x, Q^2)$
- ...$g_2(x, Q^2)$ has no interpretation in terms of partons.

Definitions of DIS variables...

$Q^2 = -q^2$	γ^* virtuality
$x = Q^2/(2Pq)$	Bjorken variable
$y = Pq/(Pk)$	relative γ^* energy
$W = P + q$	γ^*-N cms energy

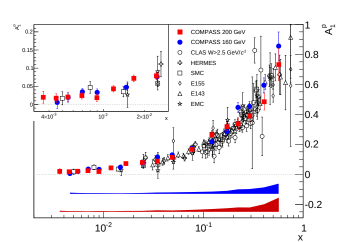
...and of the γ^*-N asymmetry (e.g. for γ^*-p):

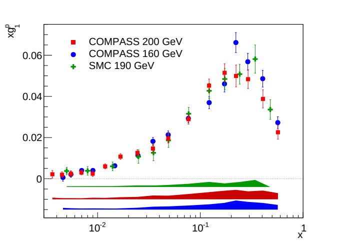


$$A_1(x, Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

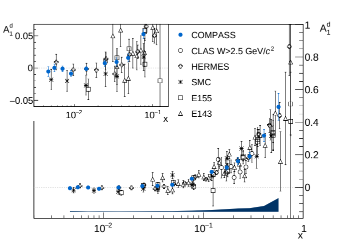
slide from B. Badelek, "Low x 2017"

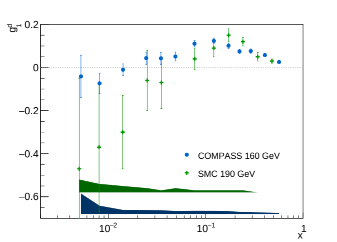
Results on $A_1(x)$ and $g_1(x)$ at the measured values of Q^2





Phys.Lett.B 753 (2016) 18

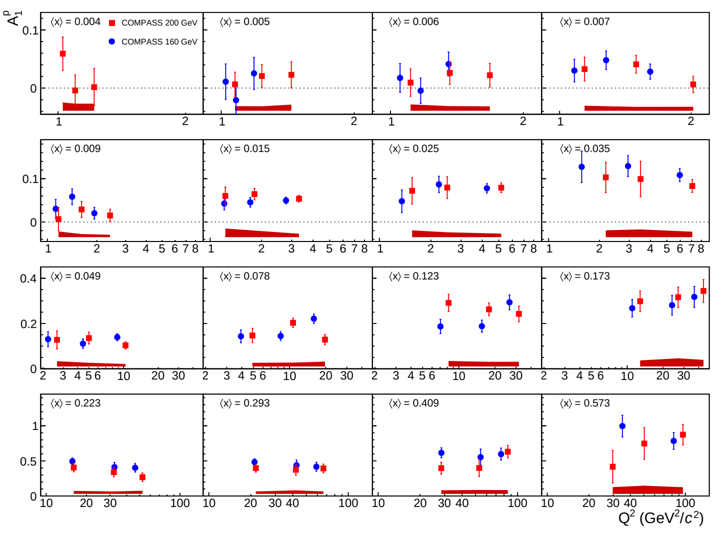




Phys.Lett.B 769 (2017) 034

- Good agreement of new COMPASS $A_1(x)$ and $g_1(x)$ with world data
- $g_1^p(x)$ clearly positive at lowest measured x; $g_1^d(x)$ compatible with zero

The asymmetry A_p^1 as a function of Q^2 in bins of x



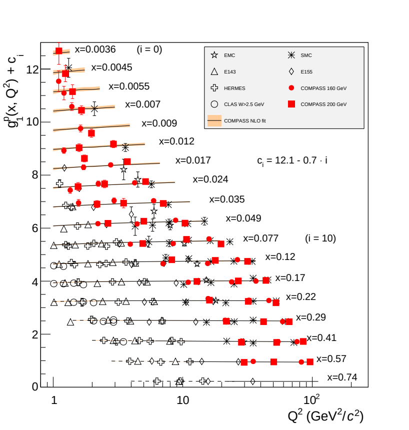
In none of the x bins, a significant Q^2 dependence is observed.

Phys.Lett.B 753 (2016) 18

World data on g_1^p and g_1^d, $Q^2 > 1\ (\text{GeV}/c)^2$

COMPASS

Continuous line: COMPASS NLO QCD fit to the world data, $W^2 > 10\ (\text{GeV}/c^2)^2$
Dashed line: extrapolation to $W^2 < 10\ (\text{GeV}/c^2)^2$



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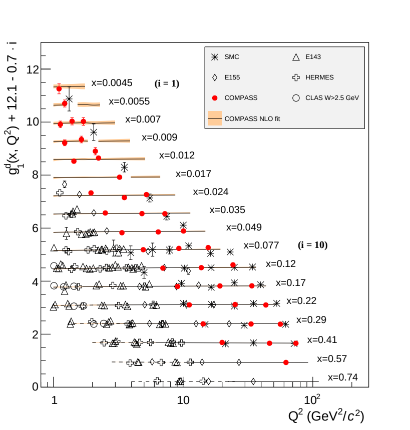
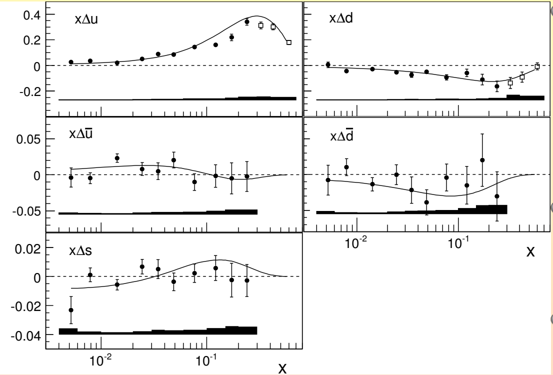


Phys. Lett. B 769 (2017) 034

Data little sensitive to Δg

Flavour separation using SIDIS data



COMPASS, Phys. Lett. B 693 (2010) 227
DSSV, Phys. Rev. D 80 (2009) 034030

- SIDIS permits to separate q and $\bar{q}$ distributions, in LO:

$$A_1^h = \frac{\sum_q e_q^2 \Delta q(x) \int D_q^h(z)dz}{\sum_q e_q^2 q(x) \int D_q^h(z)dz}$$

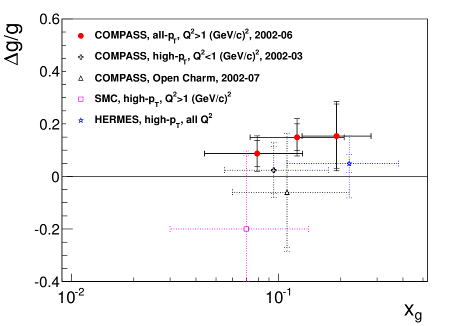
- COMPASS: measured on both proton and deuteron targets for π^+, π^-, K^+, K^-
- COMPASS: LO DSS FFs and LO unpolarised MRST assumed
- NLO parametrisation of DSSV describes the data well

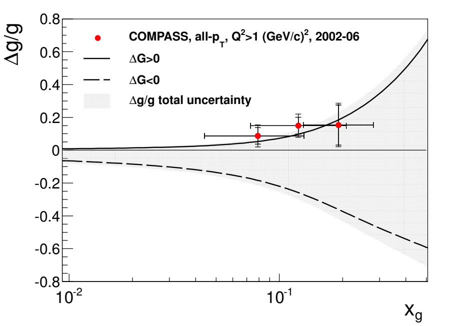
$\Delta S = \int_0^1 (\Delta s(x) + \Delta\bar{s}(x))dx = -0.09 \pm 0.01 \pm 0.02$ from DIS + SU(3), while from SIDIS it is compatible with zero but depends upon chosen FFs

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

Direct measurements of $\Delta g(x)$

Direct measurements via the cross section asymmetry for the photon-gluon fusion (PGF) with subsequent fragmentation into $c\bar{c}$ (LO, NLO) or $q\bar{q}$ (high p_T hadron pair (LO)): $A_{\gamma N}^{PGF} \approx \langle a_{LL}^{PGF} \rangle \frac{\Delta g}{g}$





COMPASS, EPJC 77 (2017) 209

COMPASS from SIDIS on d for any $(p_T)_h$ and at LO:

$\Delta g/g = 0.113 \pm 0.038(stat.) \pm 0.036(syst.)$ at $\langle Q^2 \rangle \approx 3(\text{GeV}/c)^2$, $\langle x_g \rangle \approx 0.1$

clearly positive gluon polarisation!

Fragmentation functions (FFs, D_q^h)

- FFs describe parton fragmentation into hadrons
- FFs are needed in analysis which deals with a hadron(s) in the final state
- In Leading Order QCD, D_q^h describes probability density for a quark of flavour q to fragment into hadron of type h
- The cleanest way to access FFs is in e^+e^- annihilaton. However,
  - only sensitive to the sum of $q + \bar{q}$ fragmentation
  - flavour separation possibilities are limited
- In SIDIS data, FFs are convoluted with PDFs. However,
  - possibility to separate fragmentation from q and $\bar{q}$
  - full flavour separation possible
- By studying pp collisions with a high p_T hadrons, access to gluon fragmentation functions
- SIDIS data are crucial to understand quark fragmentation process

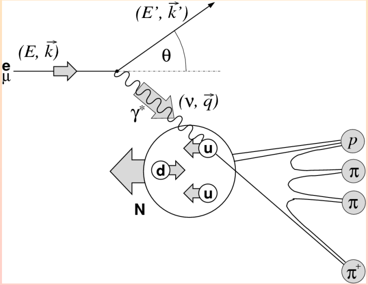
Multiplicity measurement

- Hadron multiplicities are defined as number of observed hadrons in a number of DIS events, in LO

$$\frac{dM^h(x,z,Q^2)}{dz} = \frac{d^3\sigma^h(x,z,Q^2)/dxdQ^2dz}{d^2\sigma^{DIS}(x,Q^2)/dxdQ^2}$$

where z is a fraction of the virtual photon energy carried by a hadron

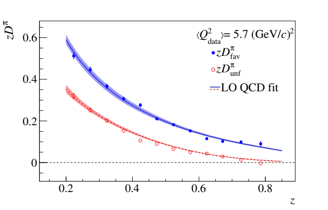
- Experimentally measured hadron multiplicities need to be corrected for various effects, e.g.
  - spectrometer acceptance and reconstruction program efficiency
  - RICH efficiency and purity (for π and K)
  - radiative corrections
  - diffractive vector meson production

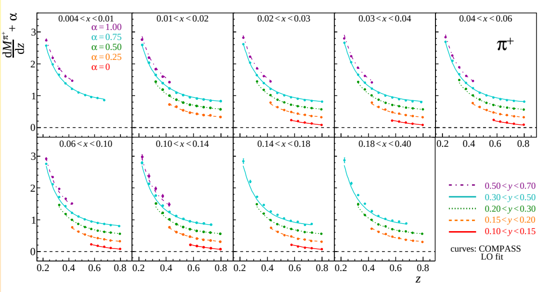


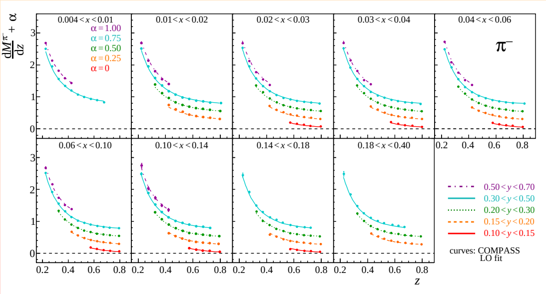
Multiplicities of $\pi^{\pm}$ on isoscalar target

COMPASS

- Results published in PLB 764 (2017) 001
- Some preliminary data were used in DSS+ fit
- COMPASS performed LO fit, using HKNS FF program
- Results agree with world FFs. As expected $D_{fav} > D_{unf}$



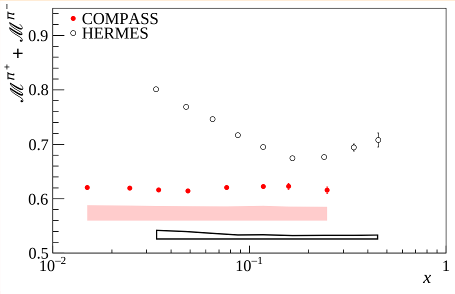


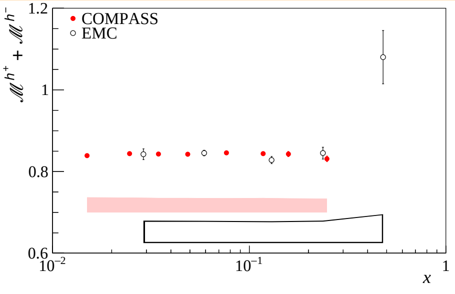


The π multiplicity sum   PLB 764 (2017) 001

For iso-scalar target:

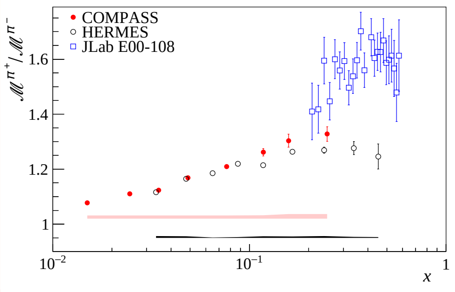
- $\frac{dM^{\pi^+}}{dz} + \frac{dM^{\pi^-}}{dz} = D_{fav} + D_{unf} - \frac{2S}{5Q+2S}(D_{fav} - D_{unf}) \approx D_{fav} + D_{unf}$
  - $Q = u + \bar{u} + d + \bar{d}$; $S = s + \bar{s}$
  - $D_{fav} = D_q^h$ where q is a valence quark of h
  - $D_{unf} = D_q^h$ where q is NOT a valence quark of h
  - $D(Q^2, z) \rightarrow$ obtained multiplicity sum is effectively independent of x
  - in fixed target experiment x and Q^2 are correlated, but Q^2 dependence of z integrated FF is weak
- $\mathscr{M}^{\pi^+} + \mathscr{M}^{\pi^-} = \int_{0.2}^{0.85}(\frac{dM^{\pi^+}}{dz} + \frac{dM^{\pi^-}}{dz})dz$ vs. x should be almost flat

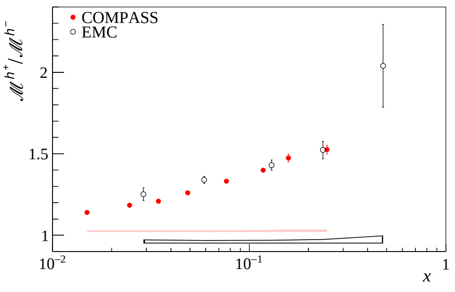




The π^+/π^- multiplicity ratio PLB 764 (2017) 001

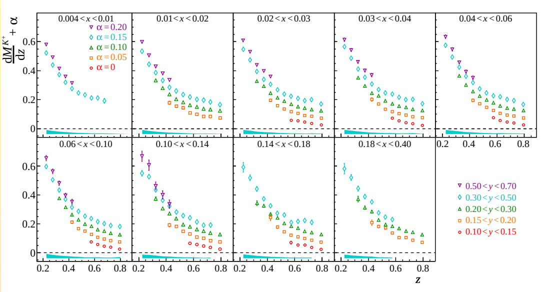
- Significant cancellation of experimental systematic errors
- A good agreement between HERMES and COMPASS
- Difference between HERMES and JLab likely explained by different W
- A good agreement between COMPASS and EMC data for unidentified hadrons

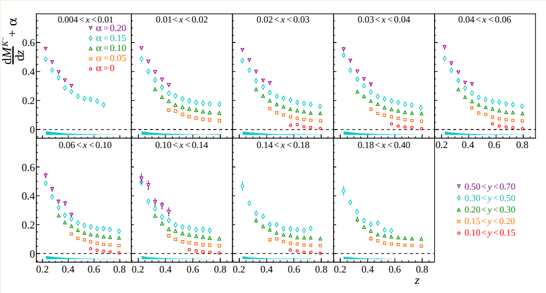




Multiplicities of $K^{\pm}$ on isoscalar target

- More than 620 data points
- Results published in PLB 767 (2017) 133



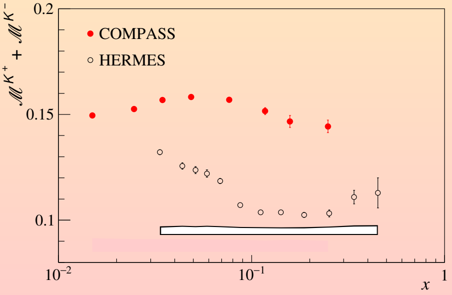


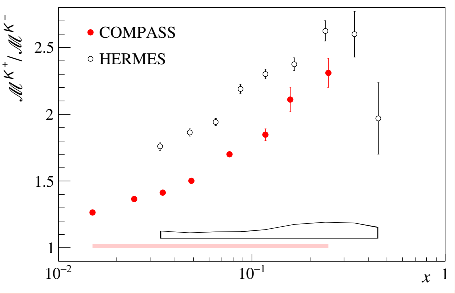
Kaon multiplicity sum and ratio PLB 767 (2017) 133

For iso-scalar target:

- $5(\frac{dM^{K^+}}{dz} + \frac{dM^{K^-}}{dz}) =\approx D_Q^K + S/QD_S^K \approx 4D_{fav}^K + 6D_{unf}^K + S/QD_S^K$

- There are large difference observed between COMPASS and HERMES
  - shape of the distribution at low x
  - the value of $\mathscr{M}^{K^+} + \mathscr{M}^{K^-}$ at high $x \to \int D_Q$
  - $\mathscr{M}^{K^+}/\mathscr{M}^{K^-}$ multiplicity ratio (while agrees for π case)



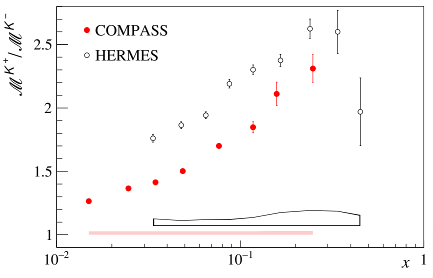


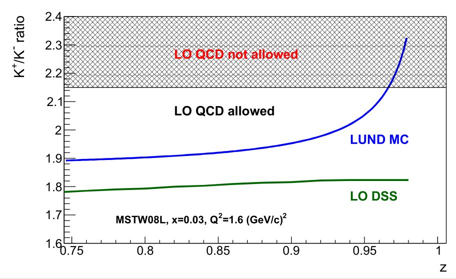
Kaon multiplicity ratio at high z: physics motivation

- There are e^+e^- measurements of multiplicities up to $z = 0.98$
- So far, region $z > 0.85$ was not investigated in SIDIS
- In LO QCD + independent fragmentation and proton target
  $\frac{dM^{K^+}}{dz}\frac{dz}{dM^{K^-}} = \frac{4uD_{fav}+(4\bar{u}+d+\bar{d}+s)D_{unf}+\bar{s}D_{str}}{4\bar{u}D_{fav}+(4u+d+\bar{d}+\bar{s})D_{unf}+sD_{str}}$
- So far, all the studies show that $D_{unf} \approx 0$ for $z \approx 0.5$
  $\Rightarrow$ for data with $z > 0.75$, one can neglect it
  $\frac{dM^{K^+}}{dz}\frac{dz}{dM^{K^-}} = \frac{4uD_{fav}+\bar{s}D_{str}}{4\bar{u}D_{fav}+sD_{str}}$, or $\frac{dM^{K^+}}{dz}\frac{dz}{dM^{K^-}} < \frac{u}{\bar{u}}$
- For isoscalar target: $\frac{dM^{K^+}}{dz}\frac{dz}{dM^{K^-}} < \frac{u+d}{\bar{u}+\bar{d}}$

Kaon multiplicity ratio at high z: physics motivation

- Typical ratio $(u+d)/(\bar{u}+\bar{d})$ at $Q^2 = 1.6$ (GeV$/c)^2$ and $x = 0.03$:
  - 2.15 (MSTW08 LO), or 2.05 (MRST04L)
  - 1.90 ± 0.10 (NNPDF3.0L), or 2.35 ± 0.20 (NNPDF2.3)
  - $2.12 - 2.38$ (NLO)
- Note, that in NLO the cross section formula is more complex ($\sim \alpha_S/2\pi$)
- In Lund string model the kaon multiplicity ratio goes (almost) in the LO QCD allowed region





Phys. Lett. B 767 (2017) 133

Kaon multiplicity ratio at high z from COMPASS

- High z region is free from kaons coming from decays of diffractively produced ϕ

- Why ratio?
  - radiative corrections largely cancel
  - experimental systematic uncertainties are also mostly canceled out
  - DIS sample is not needed

- COMPASS can and DID measure kaon multiplicity ratio at high z

Kaon multiplicity ratio at high z from COMPASS

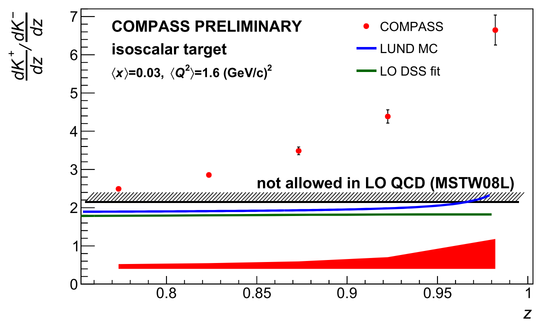
Analysis

- We try to keep all the cuts as in the published kaon paper, but
  - z range was extended above 0.85
  - stricter cuts on K/π separation were applied
  - improved method of acceptance corrections was used
  - 4 times more data was used than in PLB 767 (2017) 133
- Here we concentrate in region of $x < 0.05$
  - $\langle x \rangle = 0.03$
  - $\langle Q^2 \rangle = 1.6$ (GeV$/c)^2$
  - 40000 K^+ and K^- analysed for $z > 0.75$

Kaon multiplicity ratio at high z from COMPASS

Results

- Observe clear discrepancy between LO QCD expectation and data
- This discrepancy is even larger than presented in figure because of the z smearing
- Obtained result may indicate that factorisation and/or universality of FF does not hold in the studied region
- Further calculations are welcome, also at higher orders

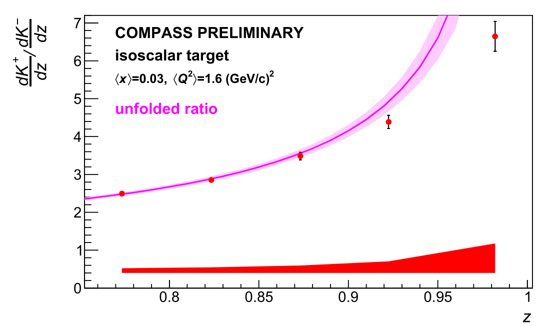


No z unfolding, which would futher increase the ratio

Kaon multiplicity ratio at high z from COMPASS

z unfolded kaon multiplicity ratio

- A "hybrid method" was used consisting of
  - smearing matrix $z_{generated}$ vs. $z_{reconstructed}$ from MC
  - functional form assumed for the K^+, K^- yields: $\alpha e^{(-\beta z)}(1-z)^{\gamma}$
- As expected, unfolding procedure further increases the ratio K^+/K^-
- However, for $z < 0.95$ the unfolding impact is not that dramatic



Summary

DIS gave and is giving fundamental contributions to the study of the nucleon structure. The COMPASS contribution is remarkable:

- Structure functions g_1^d and g_1^p (PLB 753 (2016) 18, and PLB 769 (2017) 034)
- Helicity PDFs (PLB 693 (2010) 227, and EPJC 77 (2017) 209)
- $h^{\pm}$, $\pi^{\pm}$, and $K^{\pm}$ multiplicities from DIS on an isoscalar target
  - Large sample of precise data vs. (x, y, z) covering a wide kinematical range, constitute an important input for future FF global analysis
  - PLB 764 (2017) 001, and PLB 767 (2017) 133
- Preliminary results for the kaon multiplicity ratio K^+/K^- at high z were shown
  - Results are inconsistent with prediction of (N)LO pQCD
  - They may indicate that factorisation and/or universality of FF does not hold in the studied region
  - Hints of the problem can already be noticed in the published data
  - More calculations are needed, possibly also at higher orders