Final COMPASS Results on Hadrons, Pions and Kaons Multiplicities

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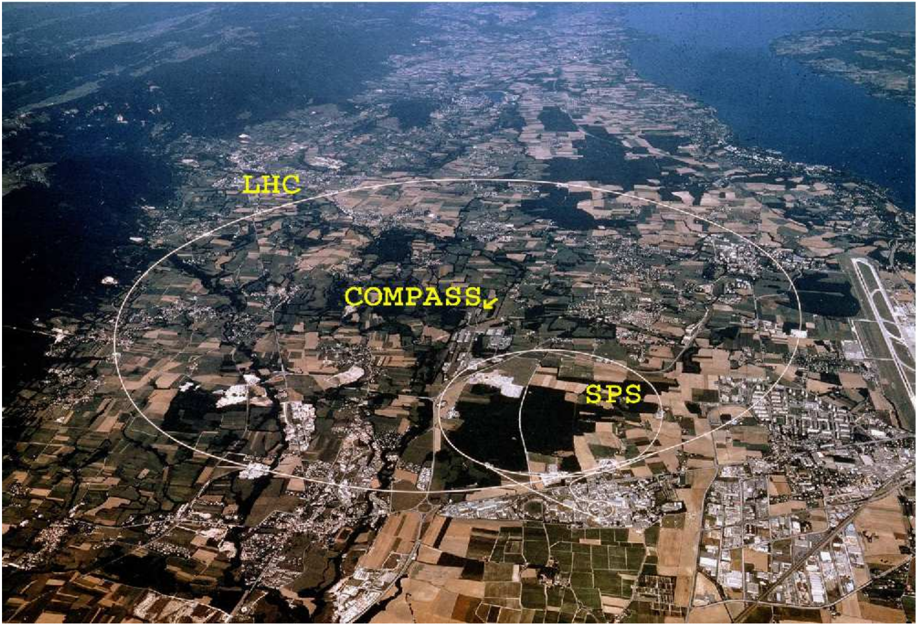
On behalf of the COMPASS Collaboration

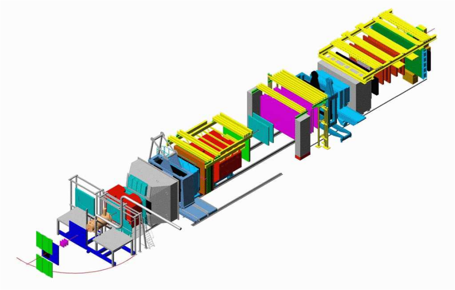
20-II-2018

Outline

COMPASS at CERN



COMPASS Spectrometer 2006



- COLLABORATION
  - about 210 physicists
  - 27 institutes
- DETECTOR
  - two stage spectrometer
  - 60 m length
  - about 350 detector planes
- TARGET
  - ^{6}LiD target
  - 3 cells (120 cm total length)
- BEAM
  - μ^{+} at 160 GeV/c
- FEATURES
  - angular acceptance: $\pm$180 mrad
  - track reconstruction: $p > 0.5$ GeV/c
  - identification h, e, μ: calorimeters and muon filters
  - identification: π, K, p (RICH) $p > 2, 9, 18$ GeV/c respectively

Motivation

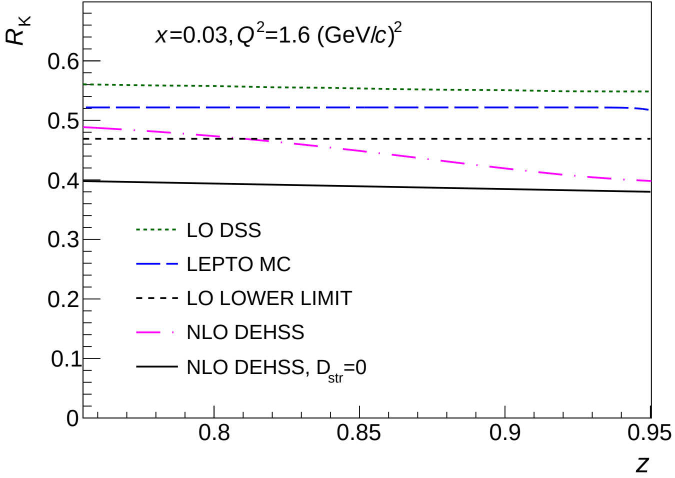
- Fragmentation functions (FF, D_q^h) describe parton fragmentation into hadrons
- FF are needed in analyses which deal with a hadron(s) in the final state
- In Leading Order QCD D_q^h describes probability density for a quark of flavour q to fragment into hadron of type h
- The cleanest way to access FFs is in e^+e^- annihilation. However,
  - only sensitive to the sum of $q + \bar{q}$ fragmentation
  - flavour separation possibilities are limited
- In the SIDIS data, FF 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

K^- over K^+ multiplicity ratio

- In the multiplicity ratio a lot experimental and theoretical uncertainties cancel
- In LO pQCD one can calculate a limit for the ratio
  - $R_K(x, Q^2, z) = \frac{\mathrm{d}M^{\mathrm{K}^-}(x,Q^2,z)/\mathrm{d}z}{\mathrm{d}M^{\mathrm{K}^+}(x,Q^2,z)/\mathrm{d}z} = \frac{4(\bar{\mathrm{u}}+\bar{\mathrm{d}})D_{\mathrm{fav}}+(5\mathrm{u}+5\mathrm{d}+\bar{\mathrm{u}}+\bar{\mathrm{d}}+\mathrm{s}+\bar{\mathrm{s}})D_{\mathrm{unf}}+(\mathrm{s}+\bar{\mathrm{s}})D_{\mathrm{str}}}{4(\mathrm{u}+\mathrm{d})D_{\mathrm{fav}}+(5\bar{\mathrm{u}}+5\bar{\mathrm{d}}+\mathrm{u}+\mathrm{d}+\mathrm{s}+\bar{\mathrm{s}})D_{\mathrm{unf}}+(\mathrm{s}+\bar{\mathrm{s}})D_{\mathrm{str}}}$
- D_{unf} is expected to be small at large z, thus can be neglected
  - $R_K = \frac{4(\bar{\mathrm{u}}+\mathrm{d})D_{\mathrm{fav}}+(\mathrm{s}+\bar{\mathrm{s}})D_{\mathrm{str}}}{4(\mathrm{u}+\mathrm{d})D_{\mathrm{fav}}+(\mathrm{s}+\bar{\mathrm{s}})D_{\mathrm{str}}}$
- since $(\mathrm{s}+\bar{\mathrm{s}})D_{\mathrm{str}}$ is positive, for the limit calculation it can be also neglected
  - $R_K > \frac{\bar{\mathrm{u}}+\bar{\mathrm{d}}}{\mathrm{u}+\mathrm{d}}$

Theory and Model Predictions

- Several expectations for R_K are presented together with LO pQCD limit.

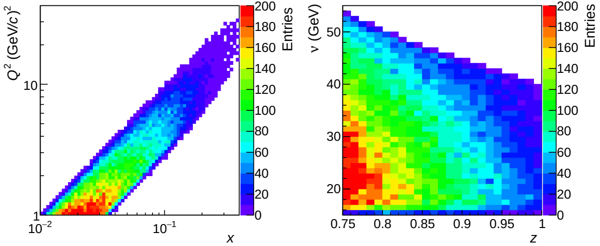


Multiplicity Measurement

- Hadron multiplicities are defined as number of observed hadrons in a number of DIS events
- $$\frac{dM^h(x,z,Q^2)}{dz} = \frac{d^3\sigma^h(x,z,Q^2)/dxdQ^2dz}{d^2\sigma^{DIS}(x,Q^2)/dxdQ^2}$$
- Experimentally measured hadron multiplicities need to be corrected for various effects e.g.
  - spectrometer acceptance & reconstruction program efficiency
  - RICH efficiency & purity (for π and K)
  - radiative corrections
  - diffractive vector meson production
  - kaon from c quarks

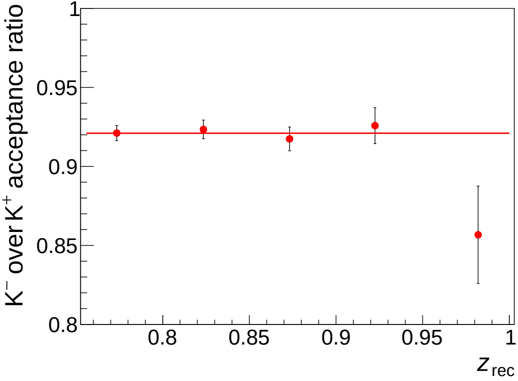
Data Selection

- Reconstructed μ and μ', $Q^2 > 1$ (GeV/c)^2 and $W > 5$ GeV/c^2
- $y > 0.1$
- There is a hadron candidate attached to the interaction vertex and $z_{rec} > 0.75$
- Hadron with momentum between 12 GeV/c and 40 GeV/c (RICH PID range)
- Particle is identified as a kaon (cf. infra.)
- The analysis is performed in two x bins, *i.e.* $x < 0.05$ and $x > 0.05$
- A few z-bins are used, with bin limits 0.75, 0.80, 0.85, 0.90, 0.95, 1.05
- In addition a binning in kaon momentum was done, using following bin limits in (GeV): 12, 16, 20, 25, 30, 35, 40
- Note that hadron momentum due to large z is strongly correlated with ν



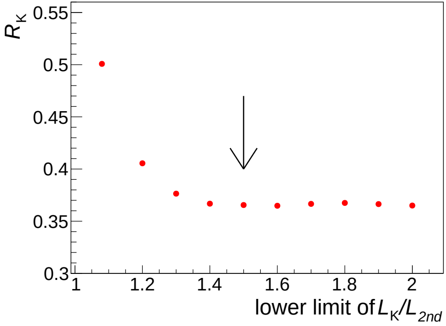
Acceptance Correction

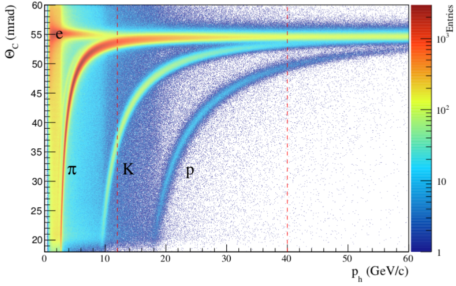
- The acceptance correction is split between x, Q^2 dependence and z dependence
- For (x, Q^2) we compute the ratio N^K_{rec}/N^K_{gen},
- The acceptance ratio is below 1.0, because of kaons re-interaction in the target.
- As for z, we use $z_{corr} = z^{data}_{rec} - (z^{MC}_{rec} - z^{MC}_{gen})$
- Example of the result with more sophisticated z treatment is discussed latter



Kaon identification by RICH

- The maximum likelihood method is used to test against π, K, e, μ, p and background hypotheses
- Kaon: kaon LH is the highest, and $L_K/L_{2nd} > 1.5$
- The selected sample is very pure, $\rightarrow$ simplifies unfolding
- R_K vs L_K/L_{2nd} for hadron with 35 GeV$< p <$40 GeV
- Note, that for lower momenta separation is much better



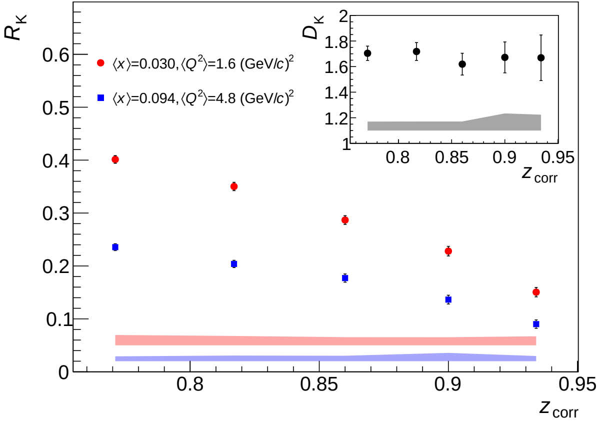


Kaons from VM and charm, Radiative Corrections

- Vector Mesons were simulated using HEPGEN generator
  - The high z region is free from $\phi -> K^+K-$
  - Heavier vectors mesons were not simulated, but their cross-section is smaller (about a factor 10) and dominant decay modes are multiparticle-ones, further reducing probability that a high z kaon is produced
- Kaons from charm decays were simulated for the PLB 767 (2017) 133, and already for z=0.2 their contribution was small, decreasing for higher z
- Radiative Corrections - In TERAD code, the correction is the same for K+ and K- thus it cancels in the ratio. (Note in COMPASS we cannot use RADGEN)

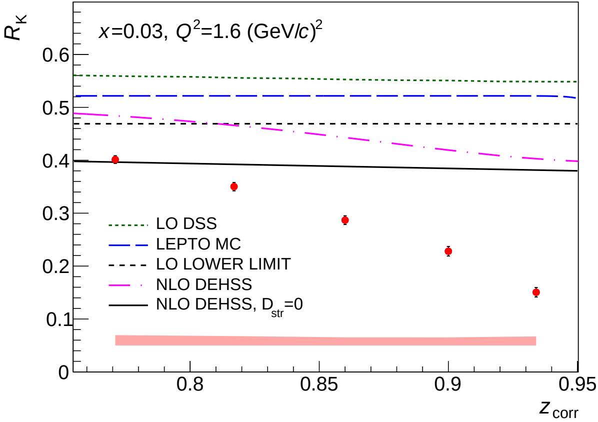
Results

- Results for $x < 0.05$ and $x > 0.05$
- R_K can be fit by a simple function form *e.g.* $(1 - z)^{\beta}$
- In the insert the double ratio of R_K in the two x-bins, D_R is flat within uncertainties.



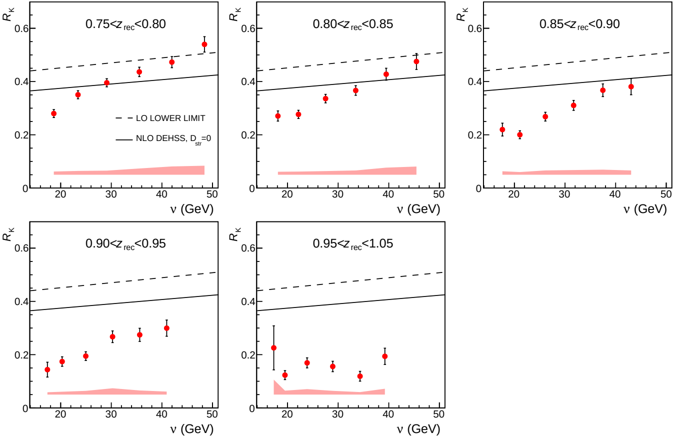
Results vs Predictions

- Clear disagreement with models and LO Limit is observed!
- Note, that non-zero contamination by kaon from decay products of V.M. or by pion misidentified as kaon, requires a correction with with further decreases the R_K value!, thus increasing tension with pQCD expectations.



R_K and ν dependence

- A ν dependence of R_K is observed
- With higher ν, the R_K is closer to pQCD expectation



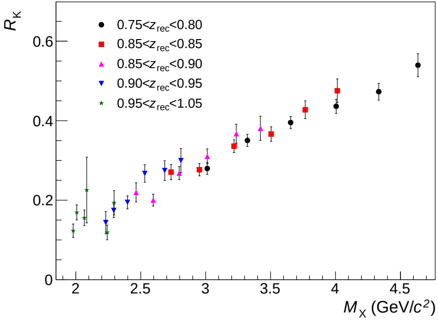
Confirmation of previous results!

- COMPASS successfully made LO QCD fit for the π case,
- unsuccessful kaon LO QCD fit, $\chi^2/ndf \approx 2-2.5$, thus the fit was even not included in the paper
- We have received private communication from LSS group, pointing to possible problem with our data especially at high z and low y

"In this analysis, the largest discrepancy between pQCD expectations and experimental results is observed in the region of large z and small y, $i.e.$ small ν. As exactly in this region the previously published COMPASS data PLB 767 (2017) 133 had shown the largest tension with the NLO pQCD fits of FFs, the present results provide additional evidence that this tension is of physical origin."

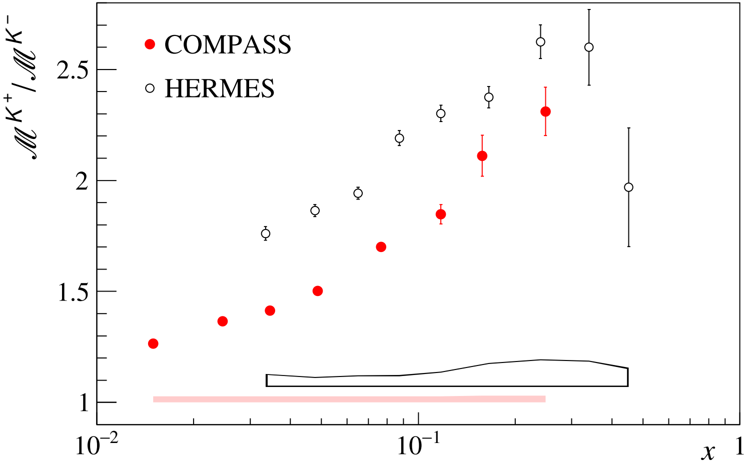
Missing Mass and R_K

- high-z kaon $\longrightarrow$ reduced phase space for other particles
- At the same time conservation laws needs to be fulfilled *e.g*. charge, baryon number and strangeness.
- Natural variable to study such events is a missing Mass, M_X
- $M_\mathrm{X} \approx \sqrt{M_\mathrm{p}^2 + 2M_\mathrm{p}\nu(1-z) - Q^2(1-z)^2}$
- Indeed R_K vs M_X shows a smooth trend!
- This suggests that a correction within the pQCD formalism is needed, to take into account the phase space available for the hadronisation of the target remnant.



R_K^{-1} and COMPASS vs HERMES discrepancy

- Figure from Phys. Lett. B 767 (2017) 133



R_K and COMPASS vs HERMES discrepancy

- We note that, the strong ν dependence of R_K may contribute to the observed disagreement between R_K presented by COMPASS and HERMES
- A direct comparison of the two results is possible at the only common kinematic 'point', *i.e.* $x \approx 0.035$, $z \approx 0.7$ and $\nu \approx 20$ GeV, where COMPASS and HERMES results agree
- In the neighbouring x bins, the average value of ν is smaller for HERMES than for COMPASS. In all these cases, the multiplicity ratio tends to be smaller for HERMES than for COMPASS.

Experiment	$\langle x \rangle$	$\langle Q^2 \rangle$ $(\mathrm{GeV}/c)^2$	$\langle z \rangle$	$\langle \nu \rangle$ (GeV)	R_K
COMPASS	0.035	1.3	0.69	20.8	0.412 ± 0.032
HERMES	0.033	1.2	0.69	19.0	0.392 ± 0.042
COMPASS	0.049	1.9	0.69	20.8	0.372 ± 0.028
HERMES	0.048	1.4	0.69	15.4	0.300 ± 0.028
COMPASS	0.077	3.0	0.69	20.8	0.355 ± 0.026
HERMES	0.076	1.6	0.69	11.6	0.266 ± 0.016
COMPASS	0.118	4.6	0.69	20.8	0.270 ± 0.027
HERMES	0.118	2.2	0.69	9.8	0.211 ± 0.017
COMPASS	0.158	6.1	0.69	20.8	0.227 ± 0.033
HERMES	0.166	3.2	0.69	10.2	0.202 ± 0.020

A more sophisticated z-unfolding...

- A smearing matrix z_{rec} vs. z_{gen} is obtained from MC
- A functional form is assumed in the 'true' phase space, with some free parameters
- This function is integrated over z-ranges, defined by the smearing matrix
- Obtained results are multiplied by the smearing matrix, and can be directly compared with kaon yield in z_{rec} phase space - *i.e.* χ^2 can be defined and optimal parameters can be found by its minimisation.
- Unfolding is not a reason of discrepancy between pQCD and COMPASS results!

bin	$z_{\rm min}$	$z_{\rm max}$	$R_{\rm K} \pm \delta R_{\rm K,\,stat.} \pm \delta R_{\rm K,\,syst.}$
1	0.75	0.80	$0.416 \pm 0.009 \pm 0.018$
2	0.80	0.85	$0.360 \pm 0.010 \pm 0.017$
3	0.85	0.90	$0.289 \pm 0.009 \pm 0.014$
4	0.90	0.95	$0.200 \pm 0.014 \pm 0.011$
5	0.95	1.00	$0.085 \pm 0.022 \pm 0.007$
$1'$	0.75	0.80	$0.237 \pm 0.006 \pm 0.011$
$2'$	0.80	0.85	$0.202 \pm 0.006 \pm 0.010$
$3'$	0.85	0.90	$0.165 \pm 0.006 \pm 0.009$
$4'$	0.90	0.95	$0.123 \pm 0.009 \pm 0.007$
$5'$	0.95	1.00	$0.068 \pm 0.016 \pm 0.005$

Summary

- COMPASS results for K^- over K^+ ratio were presented
- Large disagreement with pQCD limit (and model expectations) is observed
  - at high z
  - at low ν
  - smooth behaviour of M_X in our opinion suggest that:
- A correction within the pQCD formalism is needed, to take into account the phase space available for the hadronisation of the target remnant.