COMPASS Review on PDF observables

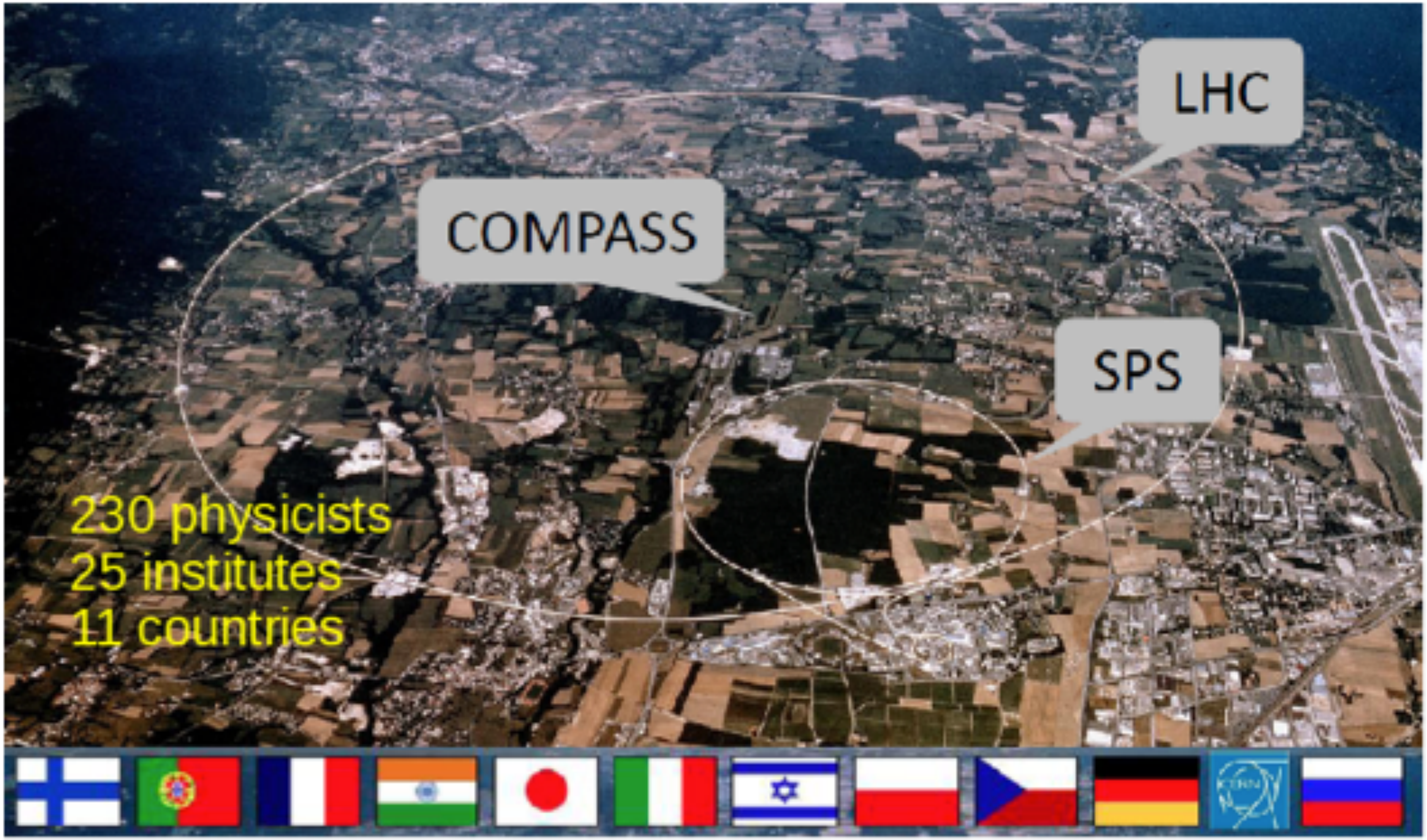
Nour Makke for COMPASS Collaboration

University of Trieste and INFN section of Trieste

Probing strangeness in hard processes

Laboratori Nazionale di Frascati
November 11-13

The COMPASS Experiment
Common Muon and Proton Apparatus for Structure and Spectroscopy



The COMPASS Experiment

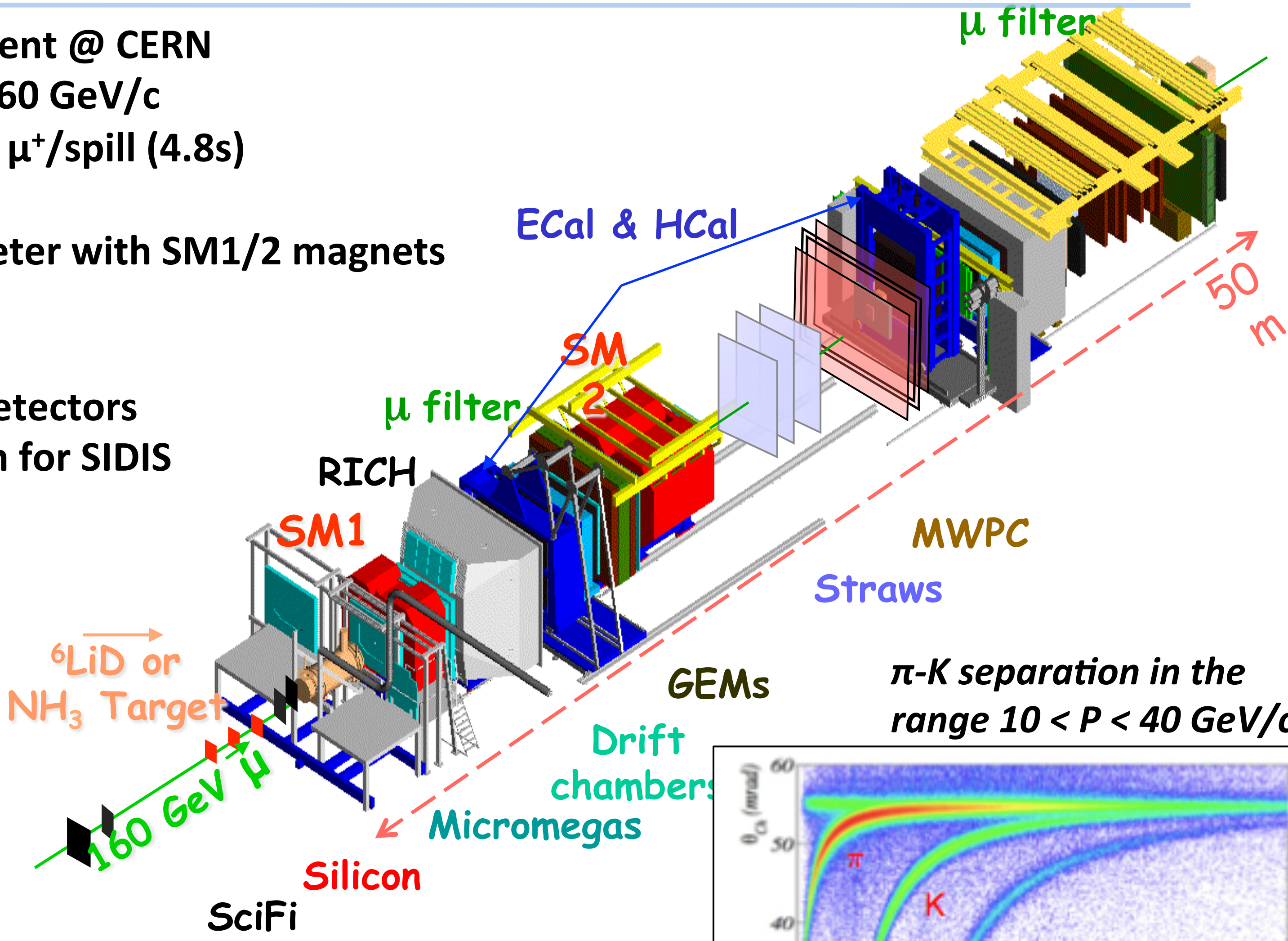
Common Muon and Proton Apparatus for Structure and Spectroscopy

Fixed target experiment @ CERN
High energy beam: 160 GeV/c
Beam intensity 2.10^8 μ^+/spill (4.8s)

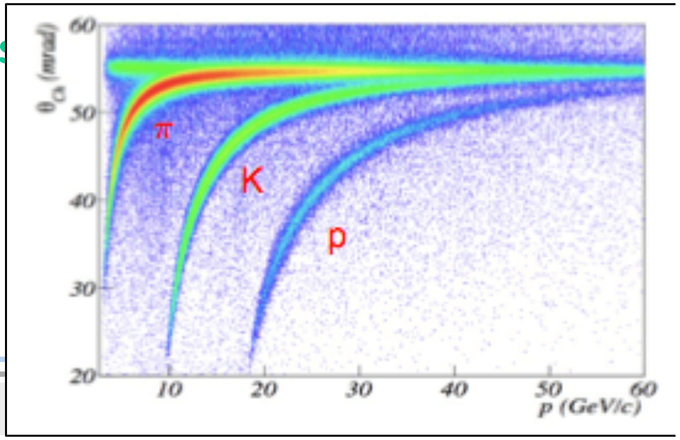
Two stage spectrometer with SM1/2 magnets

Muon identification
Variety of tracking detectors
Hadron identification for SIDIS

Polarized target
2002-2006: ^{6}LiD
2007,2011: NH_3



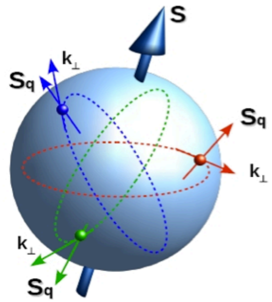
π-K separation in the range 10 < P < 40 GeV/c



The spin of the nucleon

Longitudinal spin decomposition

$$\frac{S_z^N}{\hbar} = \frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{in this talk}} + \Delta G + L_z^q + L_z^g$$



Deep Inelastic Scattering cross-section

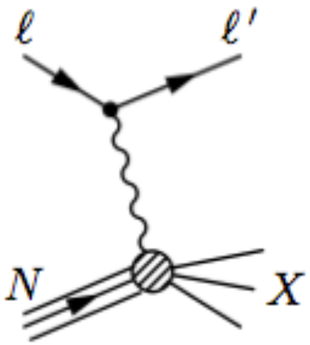
Inclusive Deep Inelastic scattering cross-section

- Structure functions

unpolarised $\mathbf{F_1}(x,Q^2)$, $\mathbf{F_2}(x,Q^2)$ → unpol . PDFs q(x)

Polarised $\mathbf{g_1}(x,Q^2)$, $\mathbf{g_2}(x,Q^2)$ → pol. PDFs Δq(x)

$$\ell N \to \ell' (X)$$



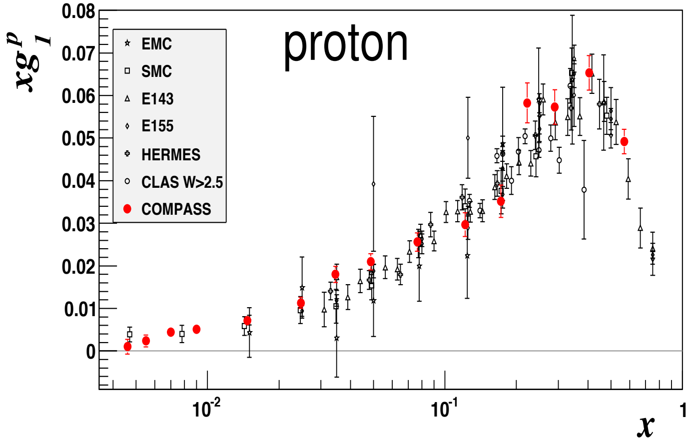
From Longitudinal double-spin asymmetry:

$$A = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \Rightarrow g_1(x, Q^2)$$

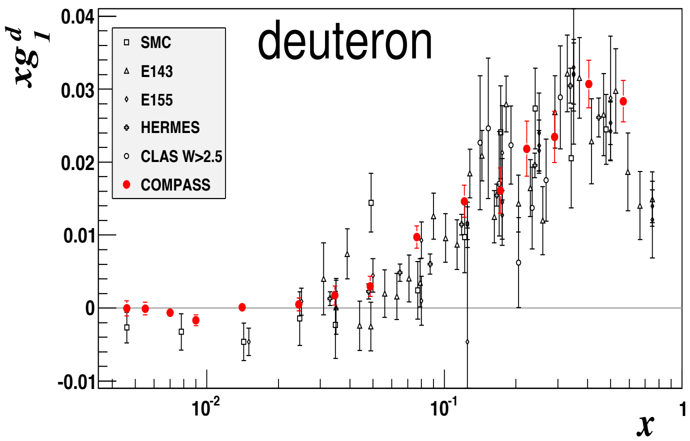
$$\longrightarrow \Gamma_1 = \int_0^1 dx\, g_1(x) = \frac{1}{2} \sum_q e_q^2 \underbrace{\int_0^1 dx\, (\Delta q(x) + \Delta \bar{q}(x))}_{\equiv \Delta q}$$

New $A_1^p(x)$ & $g_1^p(x)$ from 2011 200 GeV data

Phys. Lett. B 690 (2010) 466

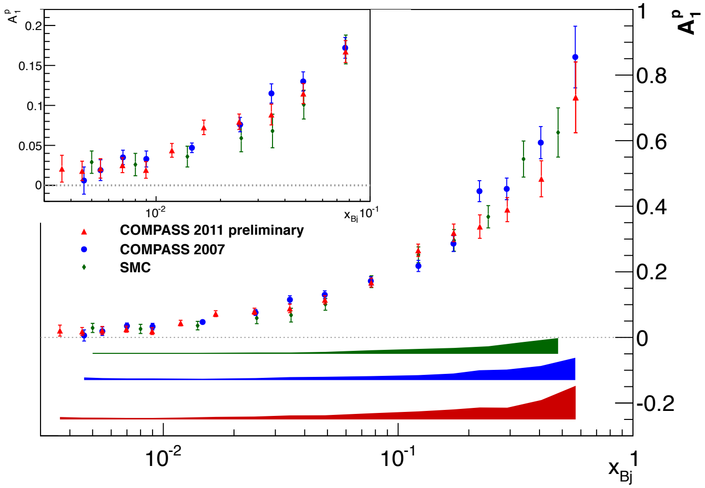


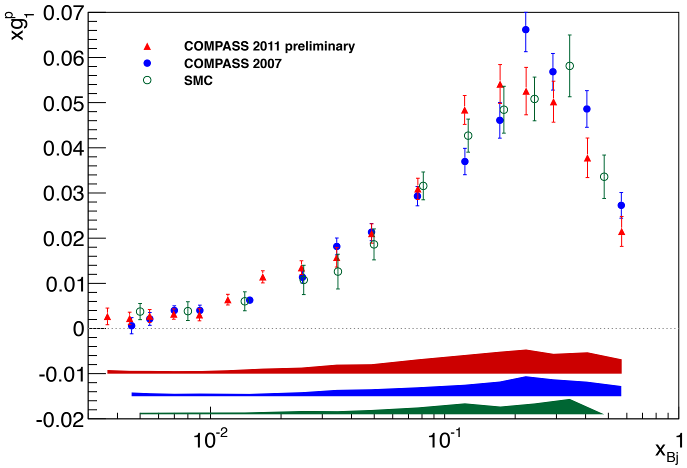
Phys. Lett. B 647 (2007) 8



***NEW** 2011 COMPASS proton data with 200 GeV muon beam*

DIS2013

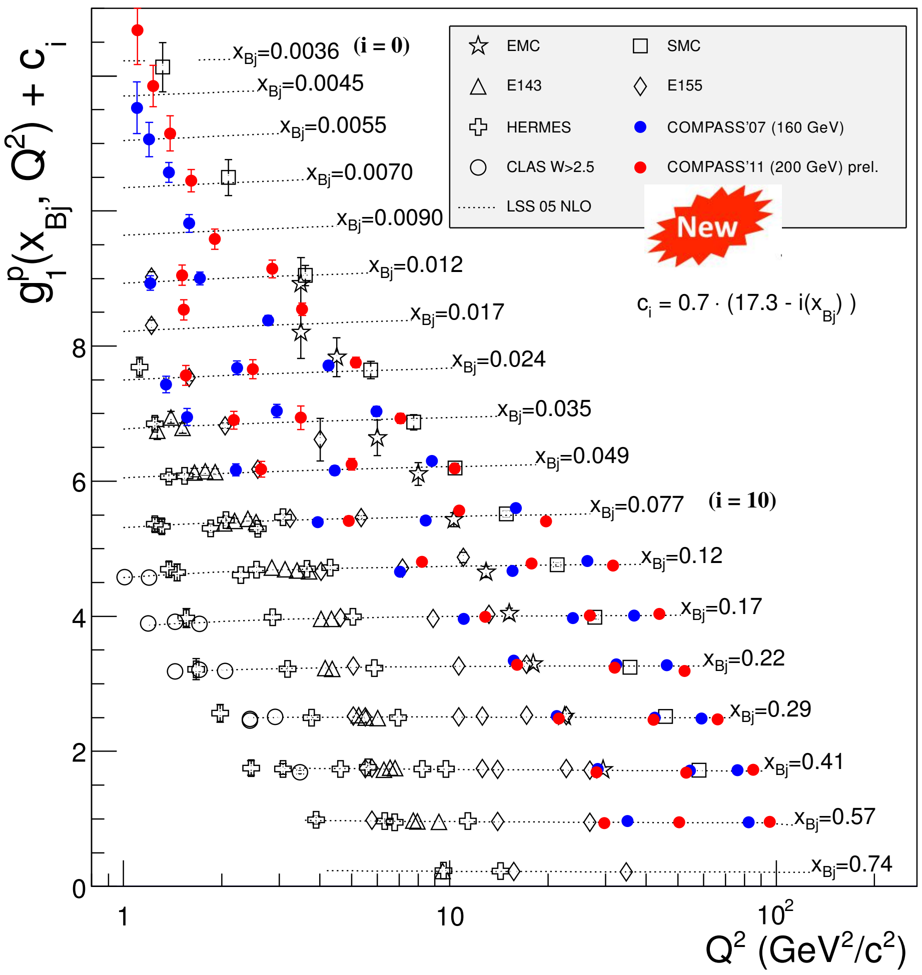


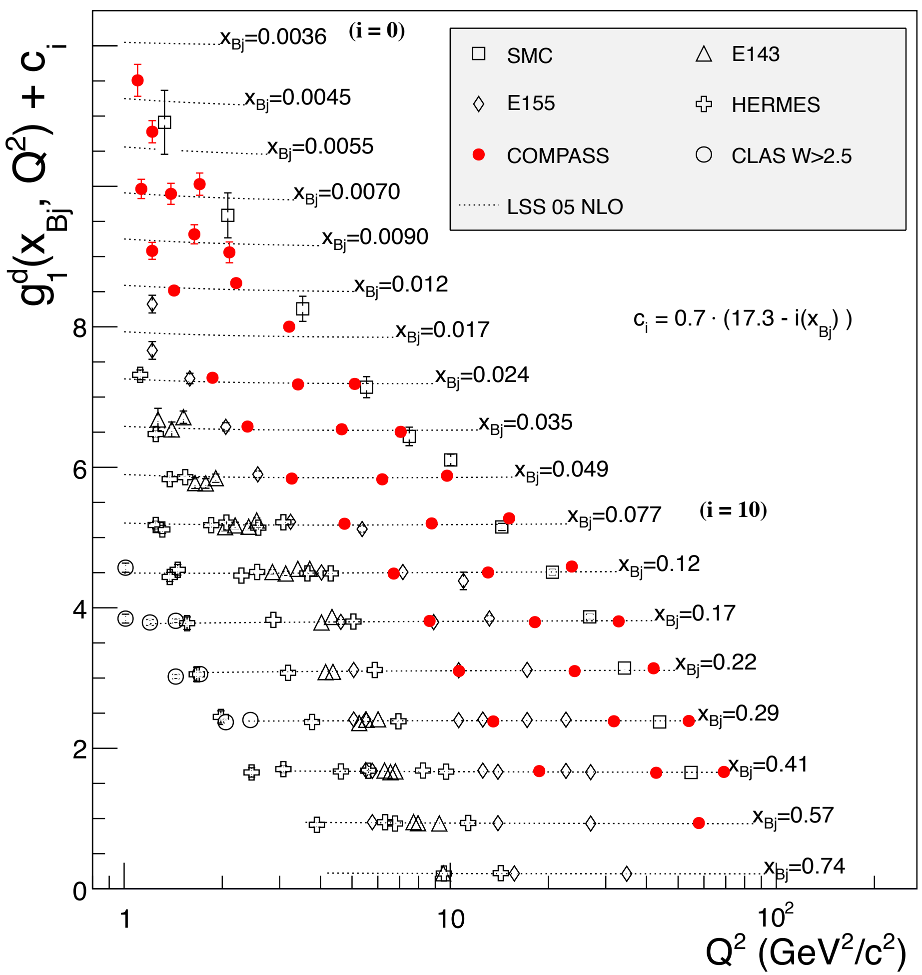


→ *Lower x, higher Q^2*

→ *Improve statistics on proton target*

COMPASS data on $g_1^{p,d}(x,Q^2)$





Polarised Structure functions

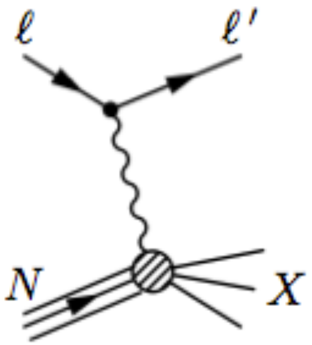
Inclusive Deep Inelastic scattering cross-section

- Structure functions

unpolarised $F_1(x,Q^2)$, $F_2(x,Q^2)$ → unpol . PDFs $q(x)$

Polarised $g_1(x,Q^2)$, $g_2(x,Q^2)$ → pol. PDFs $\Delta q(x)$

$\ell N \rightarrow \ell' (X)$



From Longitudinal double-spin asymmetry:

$$A = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \Rightarrow g_1(x, Q^2)$$

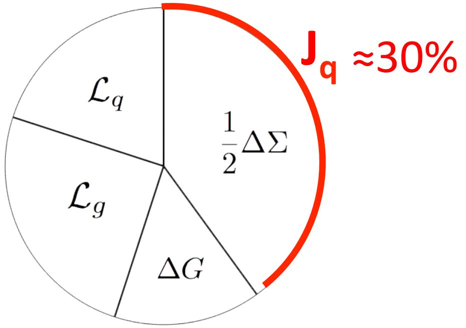
$$\longrightarrow \Gamma_1 = \int_0^1 dx\, g_1(x) = \frac{1}{2} \sum_q e_q^2 \underbrace{\int_0^1 dx\, (\Delta q(x) + \Delta \bar{q}(x))}_{\equiv \Delta q}$$

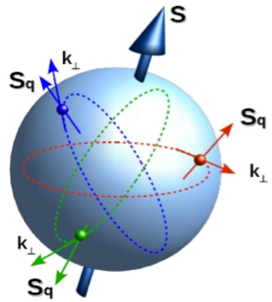
$$\longrightarrow \Delta\Sigma(Q^2 = 3(GeV/c)^2) = 0.30 \pm 0.01_{\text{stat}} \pm 0.02_{\text{evol}}$$

The spin of the nucleon

Longitudinal spin decomposition

$$\frac{S_z^N}{\hbar} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$





How do different flavors contribute ?

The spin of the nucleon

Longitudinal spin decomposition

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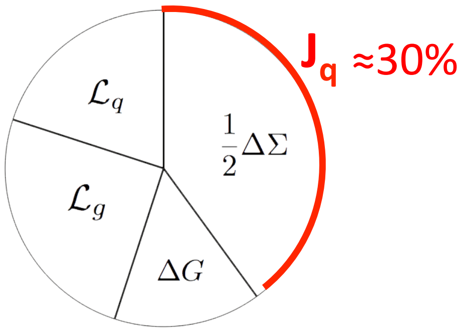
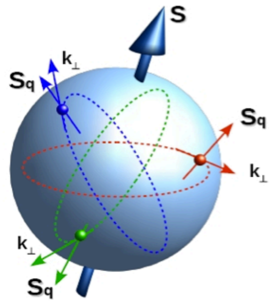
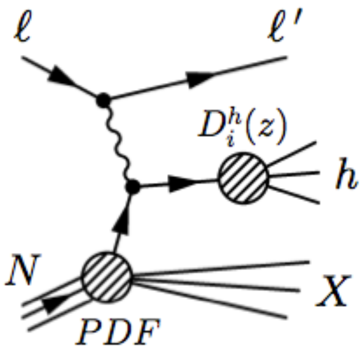




How do different flavors contribute ?

Contributions determinable in Semi-inclusive DIS



$\longrightarrow$

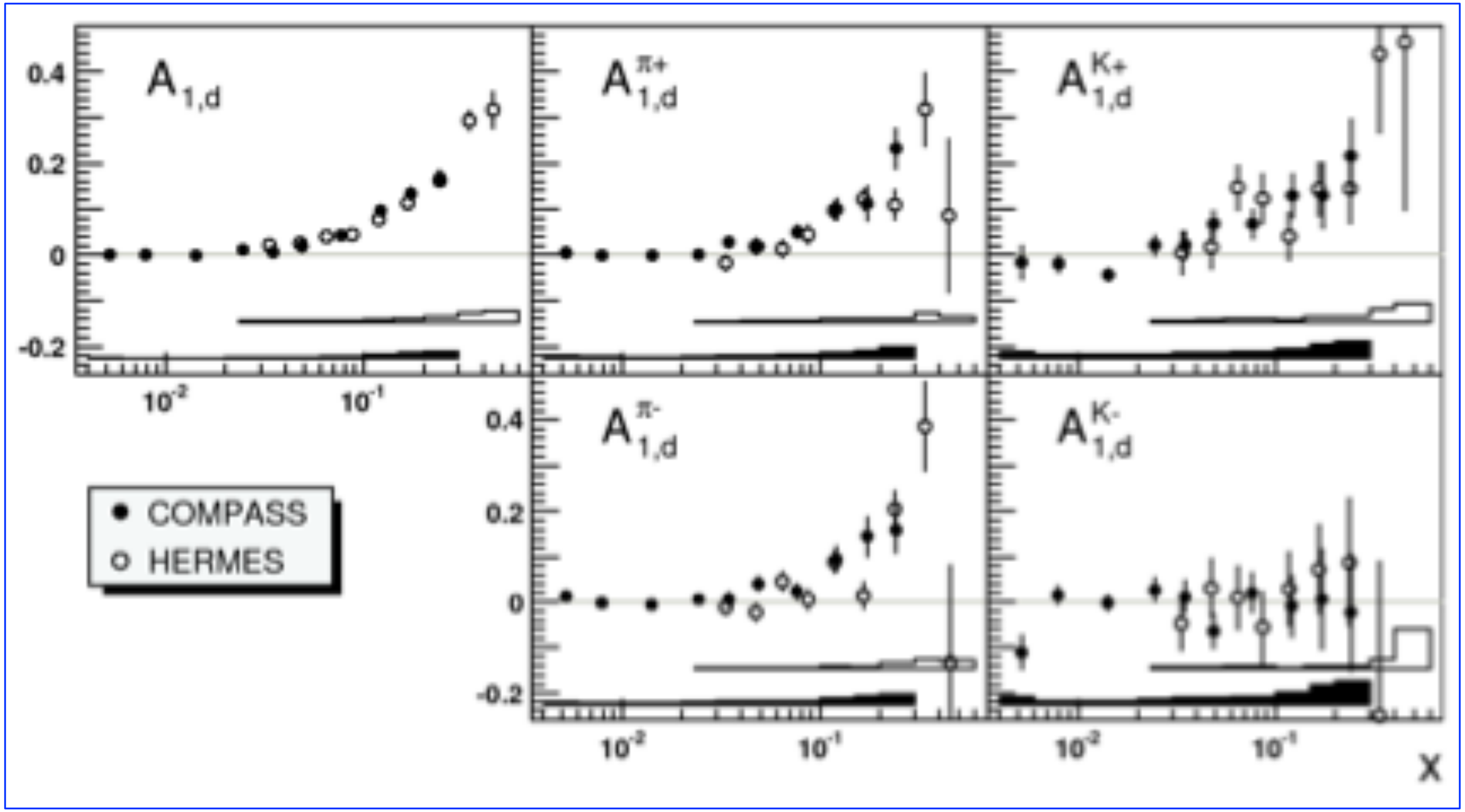
$$A^h(x,z) = \frac{\sigma_h^{\uparrow\uparrow} - \sigma_h^{\uparrow\downarrow}}{\sigma_h^{\uparrow\uparrow} + \sigma_h^{\uparrow\downarrow}} \quad (z = E_h/E_\gamma)$$

$$= \frac{\sum_q e_q^2 \left(\Delta q(x) D_q^h(z) + \Delta \bar{q}(x) D_{\bar{q}}^h(z)\right)}{\sum_q e_q^2 \left(q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z)\right)}$$

Hadron Asymmetries in SIDIS

PLB 680 (2009) 217-224

Deuteron



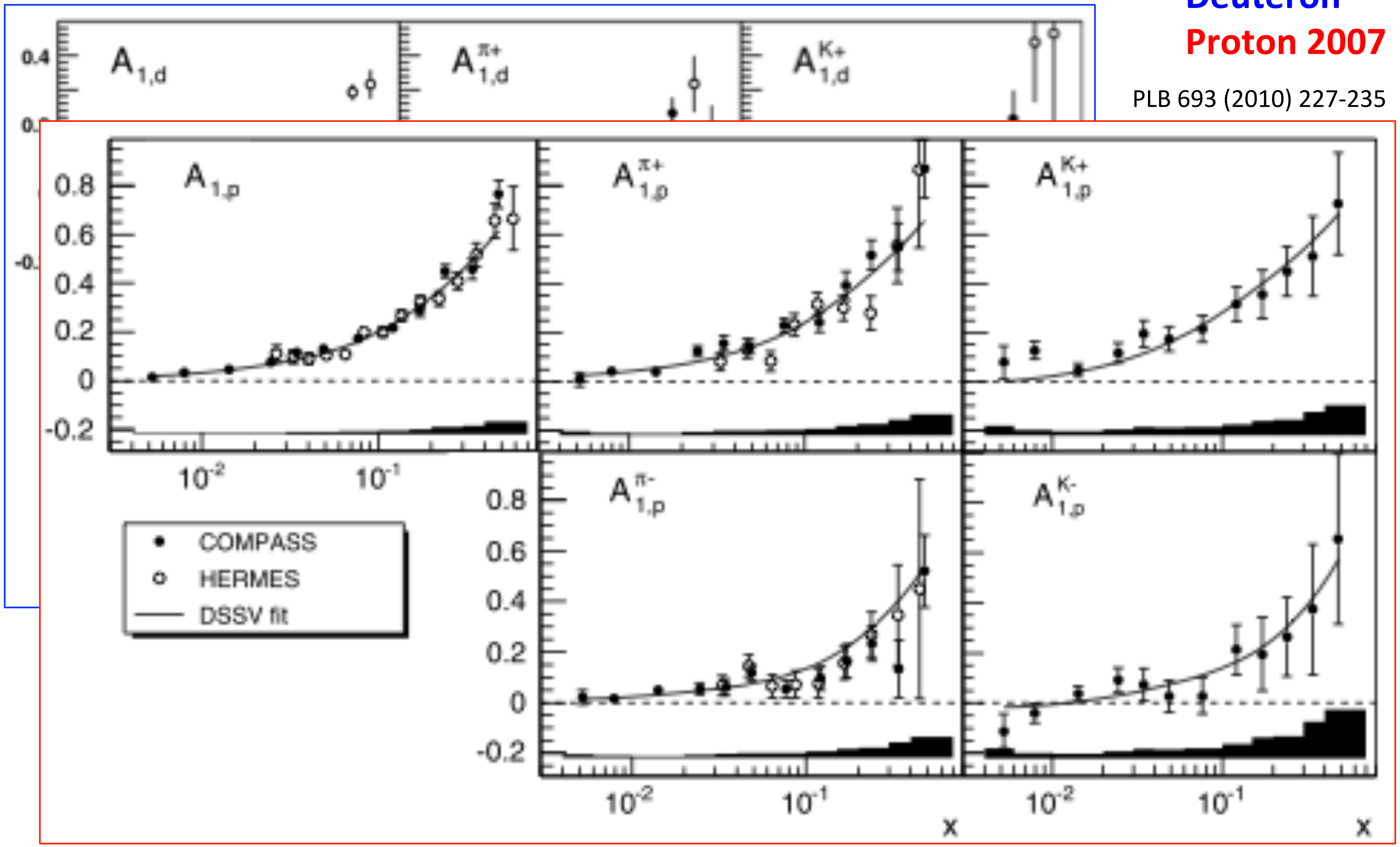
Hadron Asymmetries in Semi-Inclusive DIS

PLB 680 (2009) 217-224

Deuteron

Proton 2007

PLB 693 (2010) 227-235

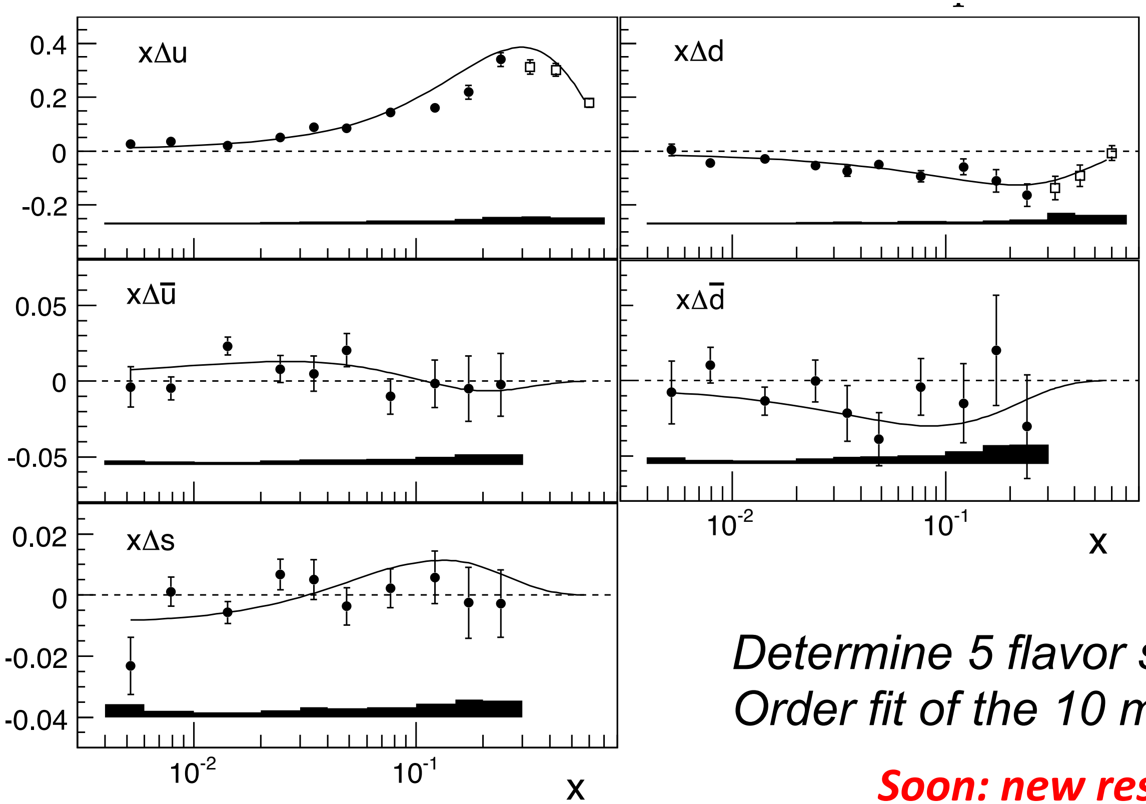


→ *First Kaon SIDIS asymmetries on a proton target*

Soon: new results on 2011 proton data

Polarized PDFs from Semi-inclusive DIS

$$A^h(x,z) = \frac{\sum_q e_q^2 \left(\Delta q(x) D_q^h(z) + \Delta\bar{q}(x) D_{\bar{q}}^h(z)\right)}{\sum_q e_q^2 \left(q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z)\right)}$$



Using:

- MRST unpolarised PDF $\Delta q(x,Q^2)$ (Phys. Lett. B636 (2006) 259)
- DSS fragmentation functions (Phys. Rev. D75 (2007) 114010)
- $\Delta s = \Delta sb$

Determine 5 flavor separated PDFs from Leading Order fit of the 10 measured asymmetries

Soon: new results on 2011 proton data

Good agreement between COMPASS data and DSSV parametrization, but what about Δs ?

The ΔS PUZZLE

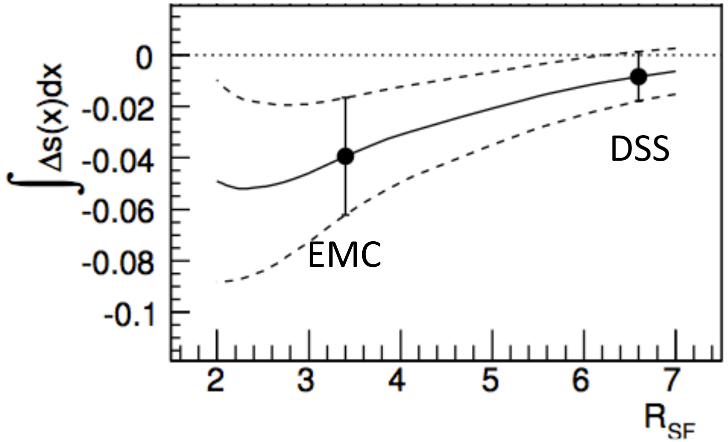
$$\int_0^1 \Delta s(x) + \Delta\bar{s}(x)dx = 2\Delta S$$

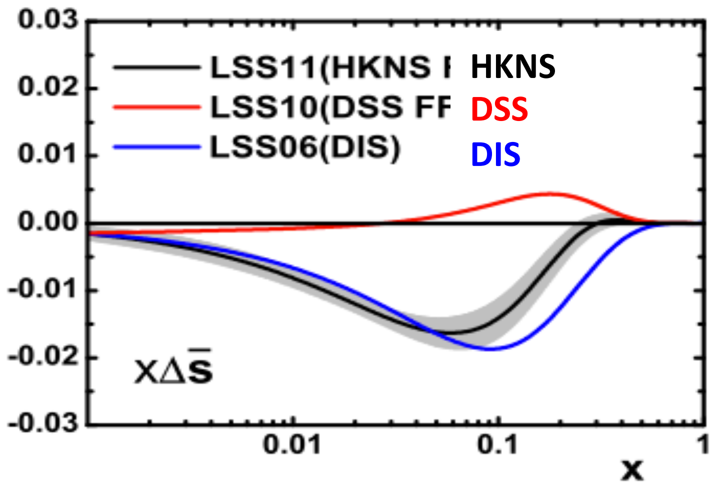
- **Inclusive DIS ($\int g_1(x)dx$, SU(3) flavor symmetry + axial charged of baryons)**

  $2\Delta S = -0.08 \pm 0.01_{stat.} \pm 0.02_{syst.}$ *PLB 647(2007) 8-17*

- **Semi-Inclusive DIS** $2\Delta S = -0.02 \pm 0.02_{stat.} \pm 0.02_{syst.}$ *PLB 693 (2010) 227-235*

→ *Strong dependence on the choice of fragmentation functions $R_{SF} = D_{str}^K/D_u^K$*



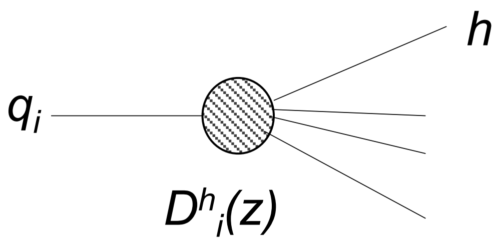


Large sensitivity of ΔS to strange to favored FF ratio
→ *Try to extract from Kaon multiplicities*

Fragmentation Functions

- Describe the collinear transition of a parton i into a final-state hadron *h* carrying momentum fraction *z*

- $D^h_{i(q,g)}$ *gives the density of hadrons produced after partons hard scattering*



- Relevant any time a hadron is emitted in a high energy collision
  - flavor separation of polarised parton distribution
  - extraction of polarised gluon density
  - Key role in single spin asymmetries, transversity
  - Heavy ion studies of QGP

- **Universal** ⇔ Determinable from global fits on different observables/reactions
- Depend on ***energy fraction*** of the fragmenting parton transferred to the hadron

$$z = E_h / E_i$$

- Energy conservation sum rule: $\sum_h \int_0^1 z D_i^h(z, Q^2) dz = 1$

Fragmentation Functions

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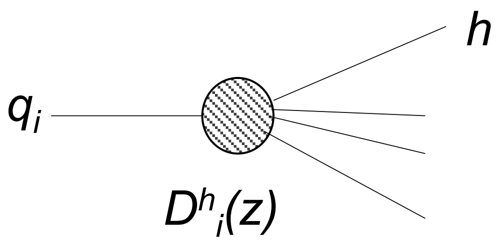


- Relevant any time a hadron is emitted in a high …
  - flavor separation of …

Several global NLO QCD analyses exist (HKNS, DSS, LSS, KRE, KKP, AKK, …)
→ Use different data sets & assumptions BUT significantly disagree

… on different observables/reactions

… *fraction* of the fragmenting parton transferred to the hadron

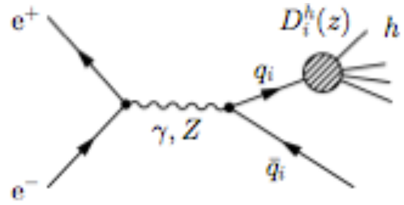
$$z = E_h / E_i$$

- Energy conservation sum rule: $\sum_h \int_0^1 z D_i^h(z, Q^2) dz = 1$

Access to FFs via high-energy reactions

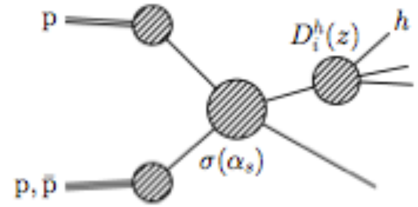
e+e- annihilation into hadrons

- Precise data from LEP (+ new prel. Results from BELLE & BABAR)
- Clean process (sole dependence on FFs)
- Narrow scale coverage (far from target scales)
- Only sensitive to singlet combination ($D_u + D_d + D_s + \dots$)



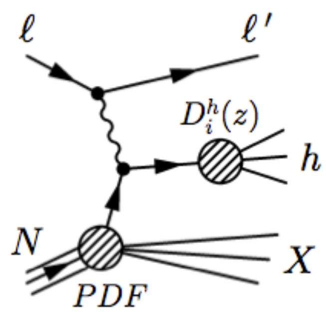
Hadron-hadron collisions

- Large sensitivity to gluon FF
- Larger theoretical uncertainties
- Strong dependence on PDFs



Semi-inclusive DIS, *ℓN -> ℓ' h X*

- Allows flavor/charge separation
- Wider scale coverage
- Access to larger z
- Non-negligible dependence on PDFs
- Poorly known strange parton distribution
- study the hadronisation process in nuclear medium (using different targets)



Hadron multiplicities in SIDIS

Relevant observables: **Hadron Multiplicities**

$$M^h(x,Q^2,z) \equiv \frac{dN^h/dz}{N_{\mathrm{DIS}}} = \frac{\sum_q e_q^2 \left[q(x,Q^2)D_q^h(z,Q^2) + \bar{q}(x,Q^2)D_{\bar{q}}^h(z,Q^2)\right]}{\sum_q e_q^2 \left[q(x,Q^2) + \bar{q}(x,Q^2)\right]}$$

Knowledge of unpolarised PDFs <u>essential</u>

- u(x), d(x) well known
- ***s(x) poorly known ⇔ can be accessed from hadron multiplicities***

Kinematic dependence on x, Q^2, z:
→ Binning in x, Q^2, z required
→ High statistics needed

Flavor separation:
→ Particle identification required

Requirements fulfilled by COMPASS

in the kinematic domain

$Q^2 > 1$ GeV^2, W > 5 GeV, $0.1 < y < 0.7$, $0.004 < x < 0.7$, $0.2 < z < 0.85$

Multiplicity measurement

$$M = \frac{N^h}{N_{\rm DIS}\,\Delta z}$$

Acceptance correction

- Simulate DIS events with physics generator (LEPTO) => M_{gen}
- Simulate the detector response using GEANT toolkits and reconstruct data => M_{rec}
- Estimate acceptance correction factor for limited geom. and reconstruction efficiency $a = M_{rec}/M_{gen}$
- Correct real data:

$$M_{\rm cor} = \frac{M_{\rm raw}}{a}$$

Particle identification

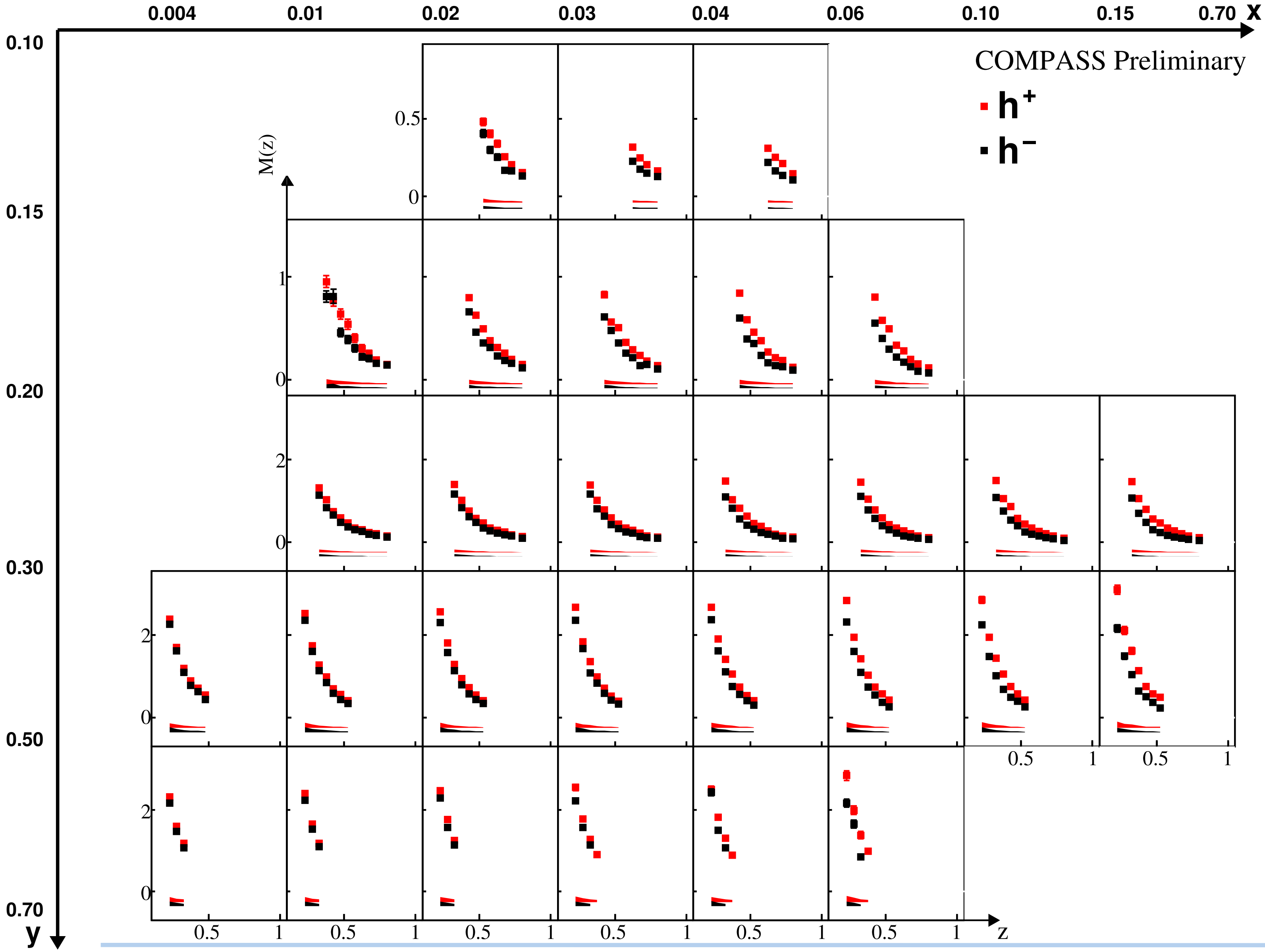
- Measure identif./misidentif. Probability matrix

$$\begin{pmatrix} I_\pi \\ I_{\rm K} \\ I_{\rm p} \end{pmatrix} = \underbrace{\begin{pmatrix} P^{\pi\to\pi} & P^{\rm K\to\pi} & P^{\rm p\to\pi} \\ P^{\pi\to\rm K} & P^{\rm K\to K} & P^{\rm p\to K} \\ P^{\pi\to\rm p} & P^{\rm K\to p} & P^{\rm p\to p} \end{pmatrix}}_{=P} \begin{pmatrix} T_\pi \\ T_{\rm K} \\ T_{\rm p} \end{pmatrix}$$

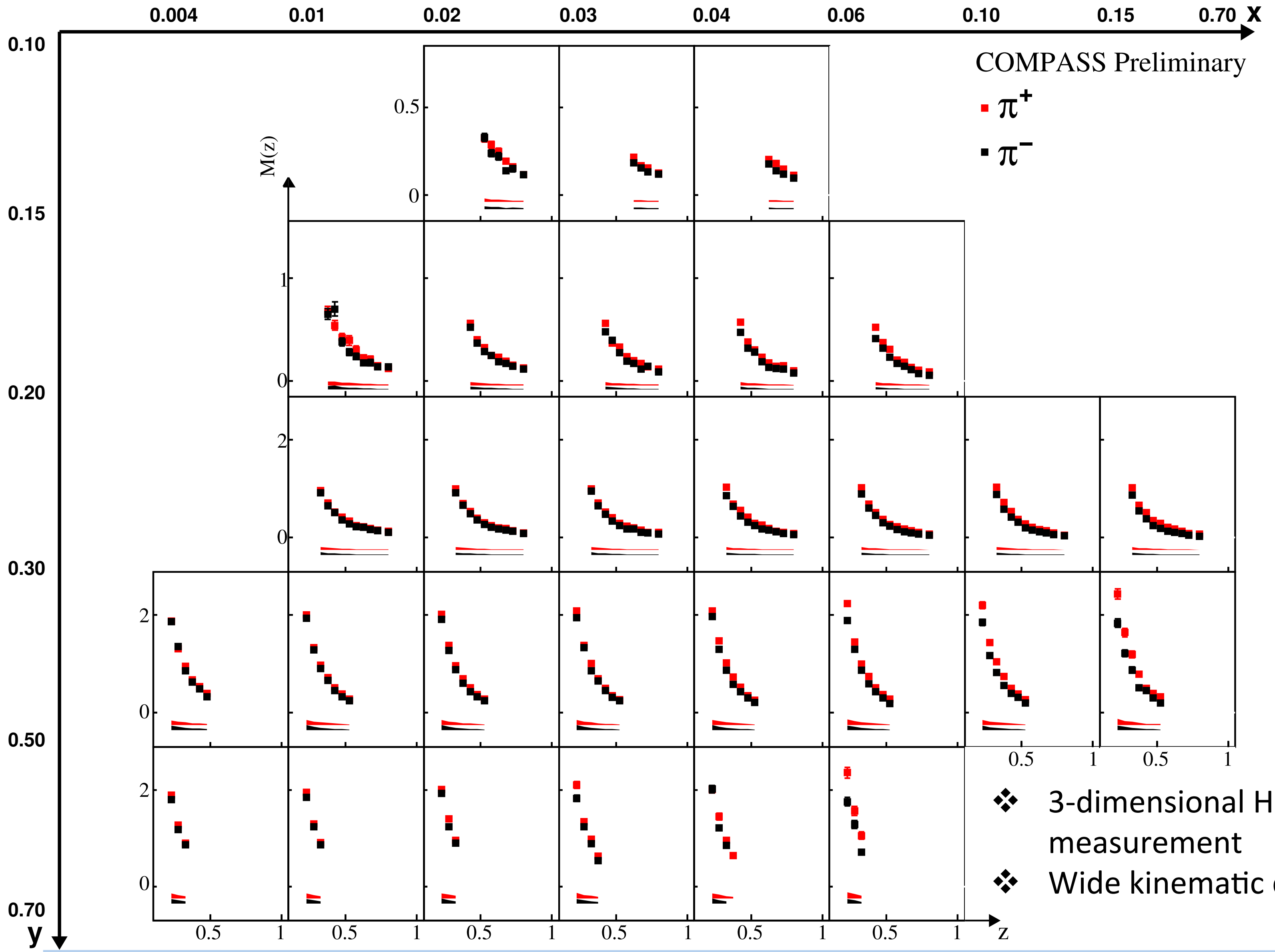
And unfold data :

$$\boxed{\vec{T} = P^{-1}\vec{I}}$$

Unidentified hadron multiplicities

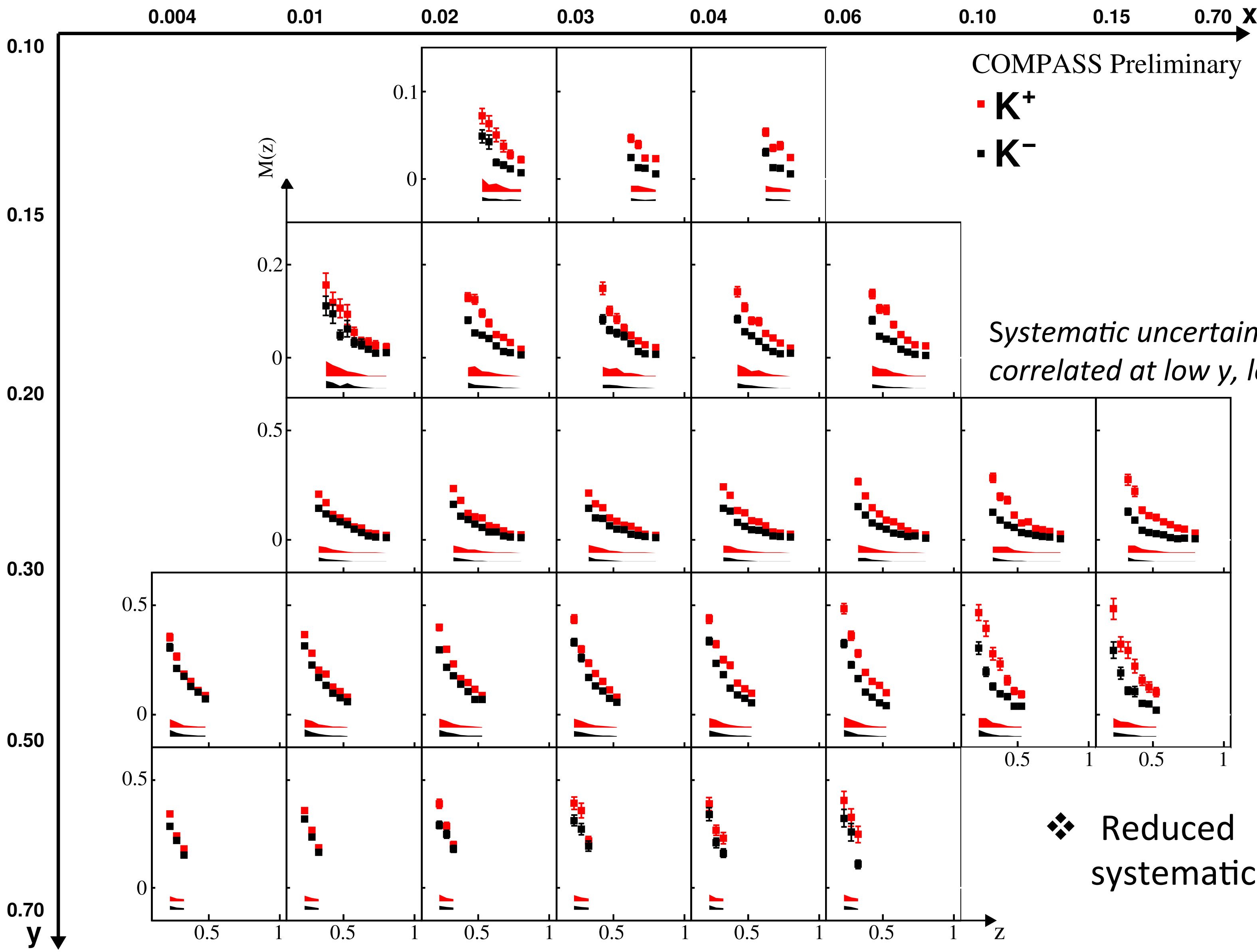


Charged pion multiplicities



- 3-dimensional High precision measurement
- Wide kinematic domain

Charged kaon multiplicities



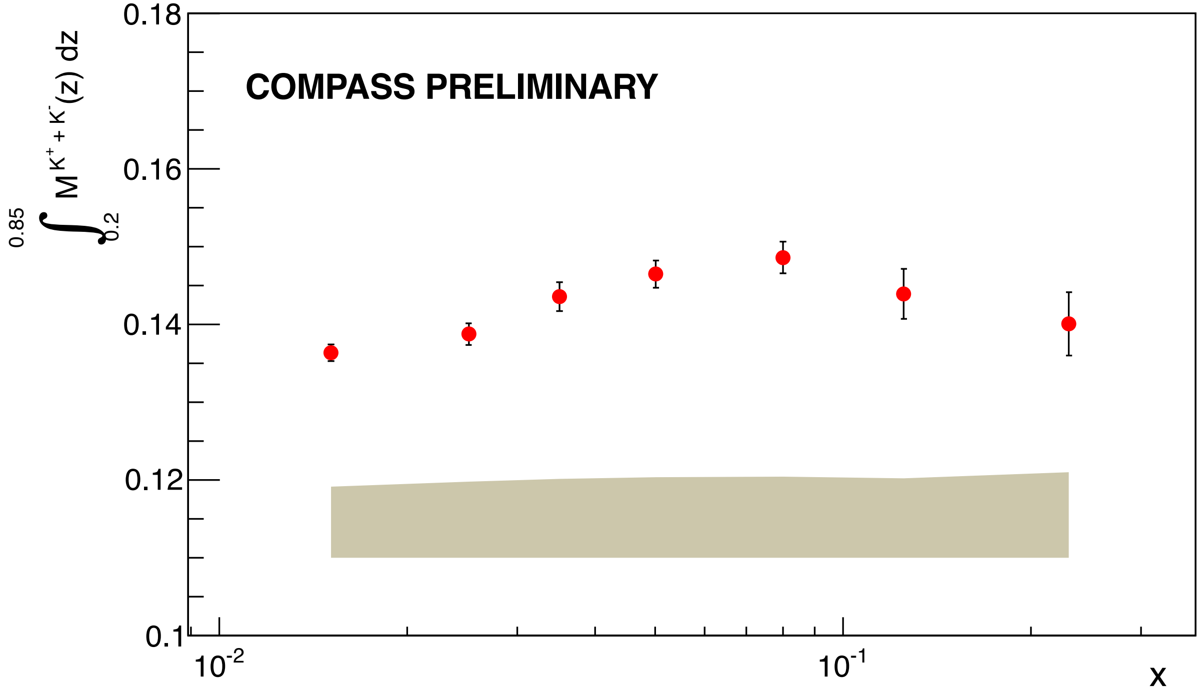
Systematic uncertainty fully correlated at low y, low z

- Reduced systematic errors

Kaon multiplicity sum $M^{K+ + K-}$

$$\int_{0.2}^{0.85} M^{K^+ + K^-}(x,z)dz = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz}{5Q(x)+2S(x)}$$

$$\xrightarrow{2S(x) \ll 5Q(x)} \int_{0.2}^{0.85} M^{K^+ + K^-}(x,z)dz = \frac{1}{5}\left(\int D_Q^K(z)dz + \frac{S(x)}{Q(x)}\int D_S^K(z)dz\right)$$



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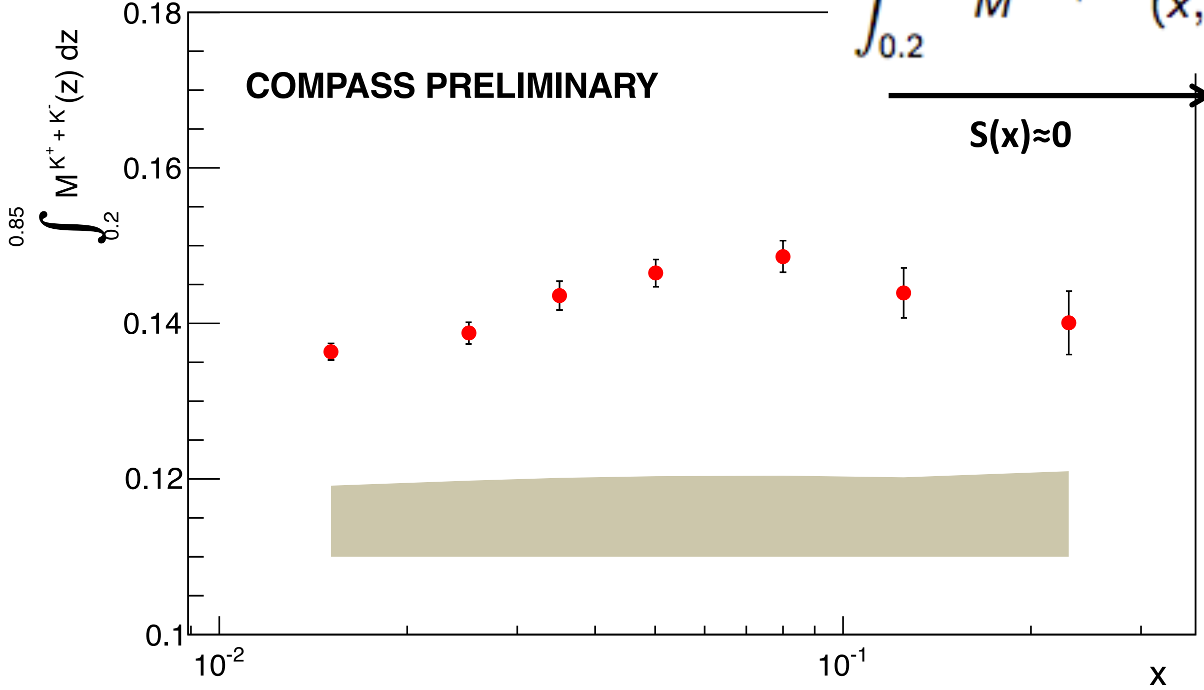
$\xrightarrow{2S(x) << 5Q(x)}$

$$\int_{0.2}^{0.85} M^{K^+ + K^-}(x,z)dz = \frac{1}{5}\left(\int D_Q^K(z)dz + \frac{S(x)}{Q(x)}\int D_S^K(z)dz\right)$$



$\xrightarrow{S(x)\approx 0}$

$$\int_{0.2}^{0.85} M^{K^+ + K^-}(x,z)dz = \frac{1}{5}\int D_Q^K(z)dz$$

x-independent distribution ✔

Kaon multiplicity sum $M^{K+ + K-}$

$$\int_{0.2}^{0.85} M^{K^++K^-}(x,z)dz = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz}{5Q(x)+2S(x)}$$

$\longrightarrow$ 2S(x)<<5Q(x)

$$\int_{0.2}^{0.85} M^{K^++K^-}(x,z)dz = \frac{1}{5}\left(\int D_Q^K(z)dz + \frac{S(x)}{Q(x)}\int D_S^K(z)dz\right)$$

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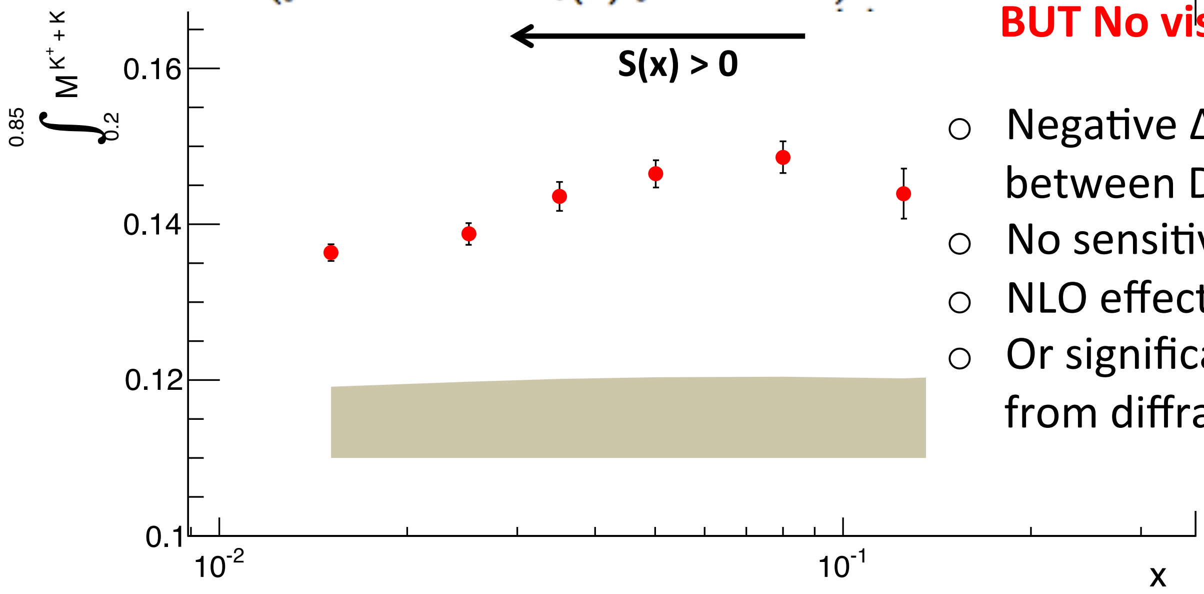


BUT No visible x dependence

- Negative ΔS ? Solves tension between DIS and SIDIS…
- No sensitivity to strangeness ?
- NLO effects ?
- Or significant contributions from diffractive production ?

Ongoing studies to reduce systematics and increase high x bins

Hadron Multiplicities vs p_T^2

(cf. A. Martin's talk)

Differential SIDIS cross-section

$$\left.\frac{d^2 n^{h\pm}(z, p_T^2, x_{Bj}, Q^2)}{dz\,dp_T^2}\right|_{\Delta x_{Bj}\Delta Q^2} \approx \frac{\Delta^4 N^{h\pm}(z, p_T^2, x_{Bj}, Q^2)/(\Delta z \Delta p_T^2 \Delta x_{Bj} \Delta Q^2)}{\Delta^2 N^{\mu}(x_{Bj}, Q^2)/(\Delta x_{Bj} \Delta Q^2)}$$

SIDIS data collected in 2004 with ^{6}LiD target

Kinematic range

- $Q^2 > 1$ GeV^2
- $0.1 < y < 0.9$
- W > 5 GeV

Multi-dimensional analysis:

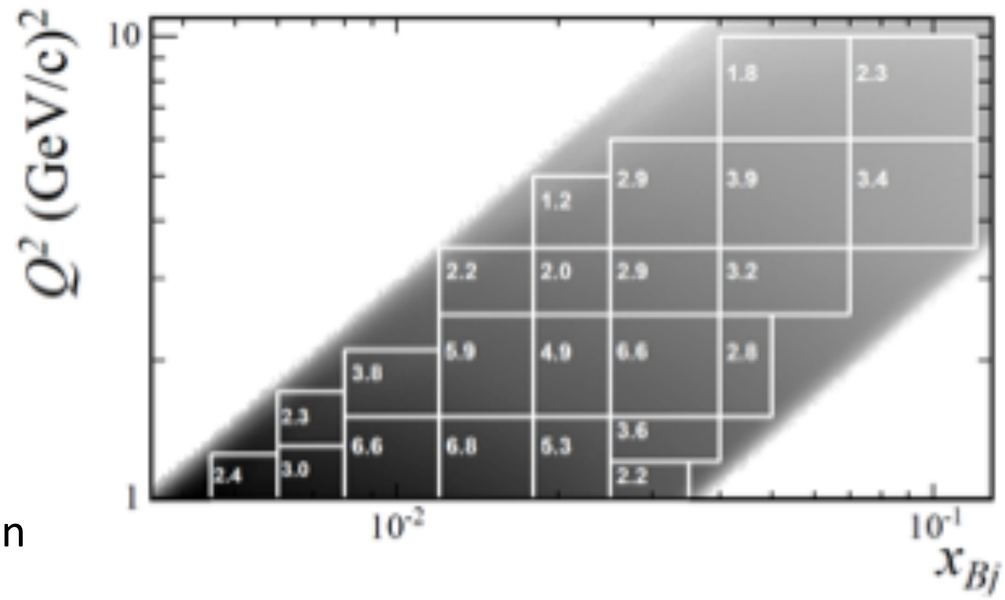
23 x, Q^2 intervals

8 z bins and 40 p_T^2 bins

4-dimensional acceptance correction

5% systematic uncertainties

23 x, Q^2 intervals



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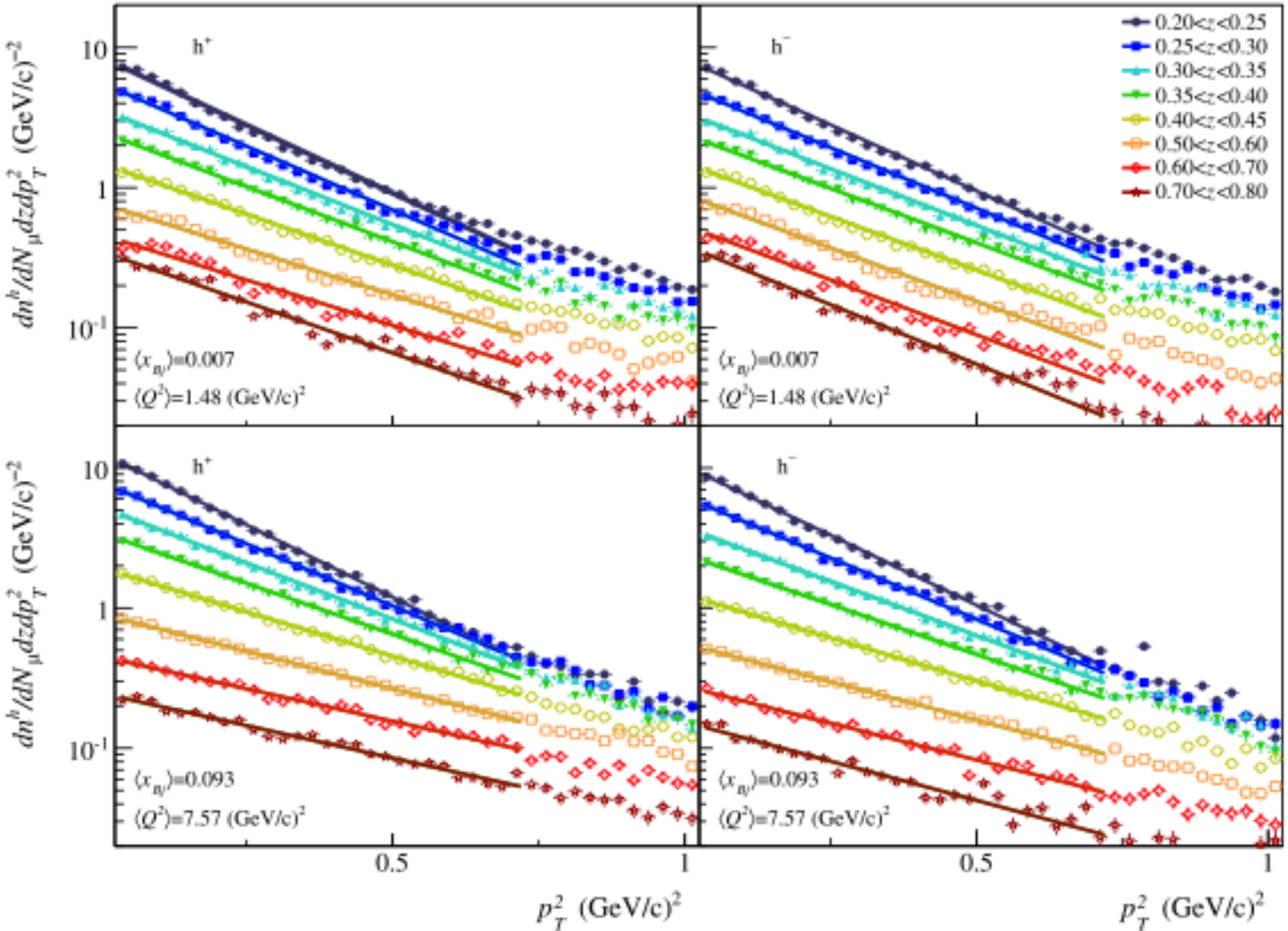
(cf. A. Martin's talk)



Work ongoing to extract same observables from 2006 data with Particle identification

Hadron pair multiplicities

Main motivation:

transversity from hadron pair transverse spin asymmetry (measured at COMPASS)

Interference fragmentation functions

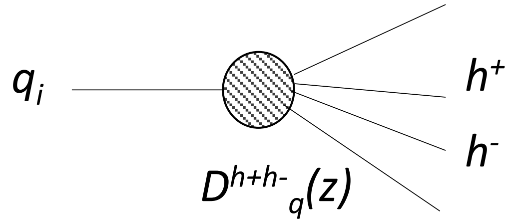
$$A_{UT}^{\sin\phi_{RS}} = \frac{|\mathbf{p_1} - \mathbf{p_2}|}{2M_{inv}} \frac{\sum_q e_q^2 \, h_1^q(x) \, H_1^{\sphericalangle,q}(z, M_{inv}^2, \cos\theta)}{\sum_q e_q^2 \, f_1^q(x) \, D_1^q(z, M_{inv}^2, \cos\theta)}$$

Experimentally measured asymmetries

Unpolarised di-hadron fragmentation functions

Dihadron Fragmentation Functions (DiFFs)

- Describe the probability that a quark of given flavor (q_f) fragments into a final-state hadron pair



- First introduced in the late 1970's to study the hadron structure of jets
  Konishi, Ukawa and Veneziano, Phys. Lett. B ***78****, 243 (1978)*

- Needed in NLO calculations in α_S for hadron pair production in e^+e^- annihilation
  Phys. Lett. B ***578****, 139 (2004)*

- Useful to investigate the in-medium effects in heavy ion collisions
  Phys. Lett. L ***99****, 152301 (2007)*

- Key element to access transversity distribution of the nucleon (h_1) in SIDIS

DiFFs needed in several high energy processes with final state hadrons

BUT no measurements !

Hadron pair multiplicities

Main motivation:

transversity from hadron pair transverse spin asymmetry (measured at COMPASS)

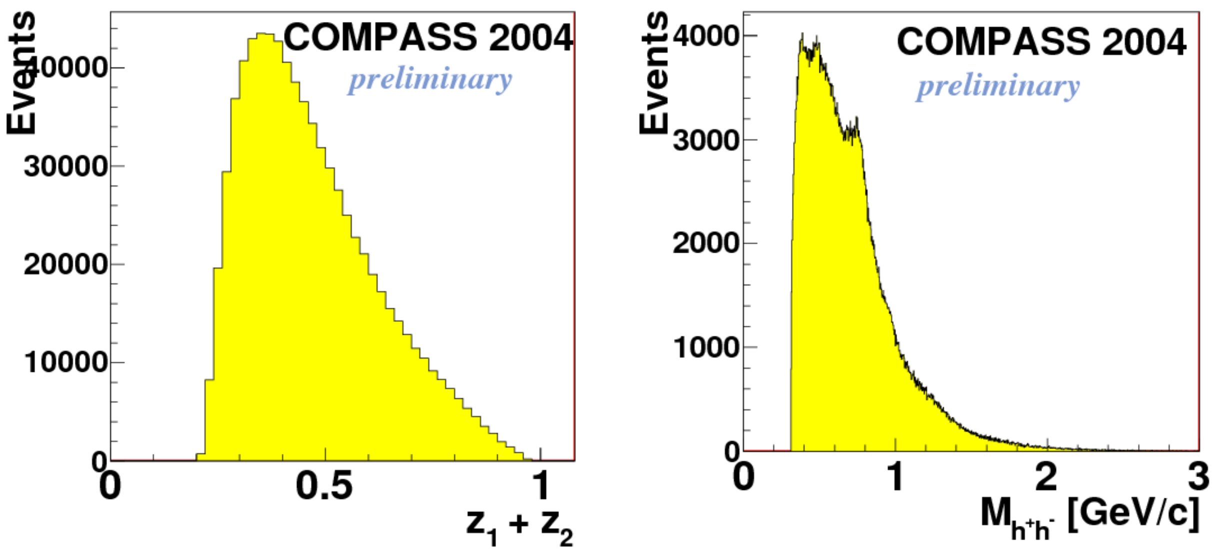
Based on SIDIS data collected in 2004

Event selection

- $Q^2 > 1$ GeV^2
- $0.1 < y < 0.9$
- W > 5 GeV

Hadron selection

- $z_{1,2} > 0.1$
- $x_{\mathcal{F}1,2} > 0.1$
- $E_{miss} > 3$ GeV
- $R_T > 0.07$



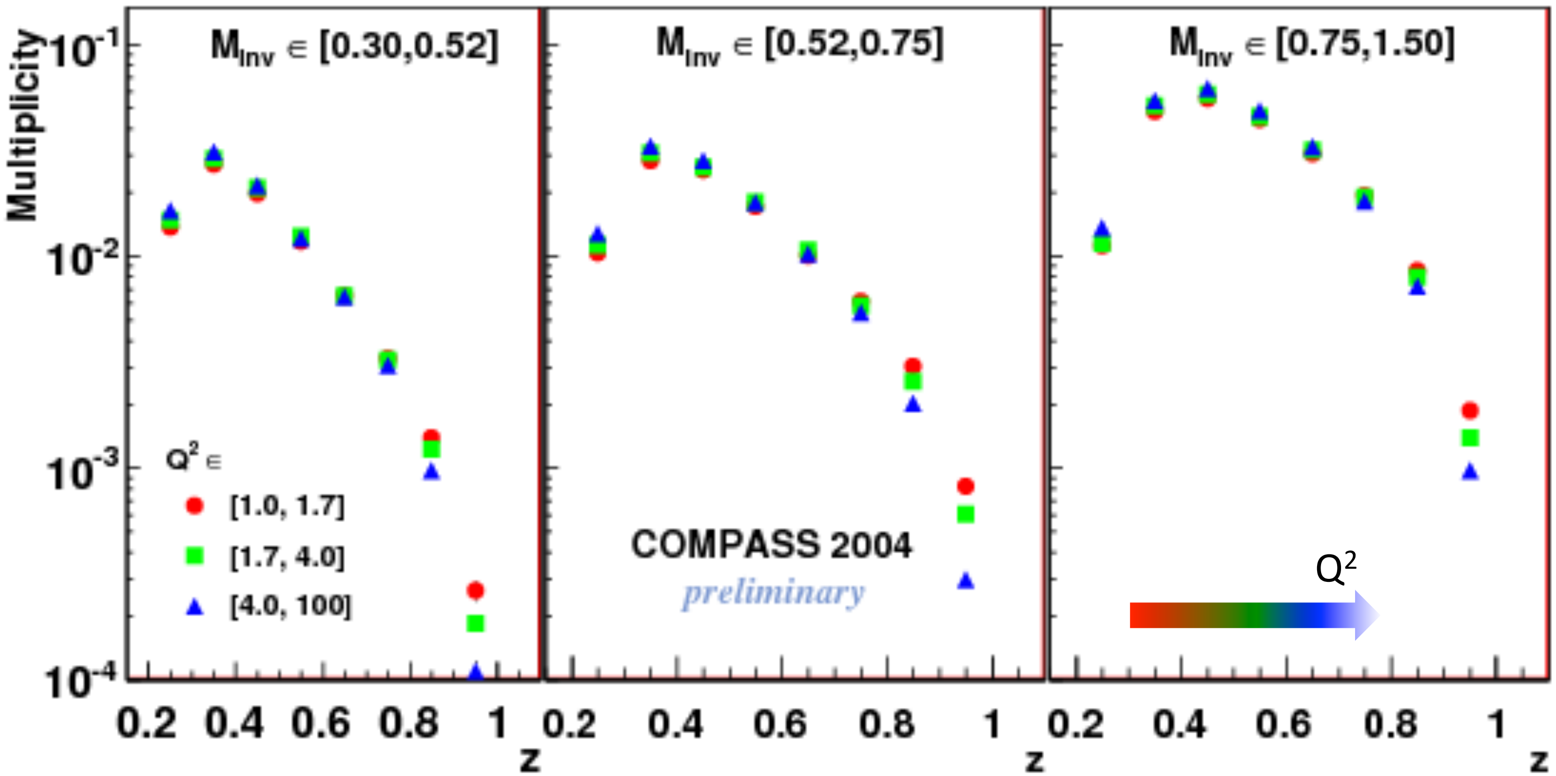
Hadron pair multiplicities

Main motivation:

transversity from hadron pair transverse spin asymmetry

First measurements in M_{inv}, $z = z_1 + z_2$, Q^2 bins

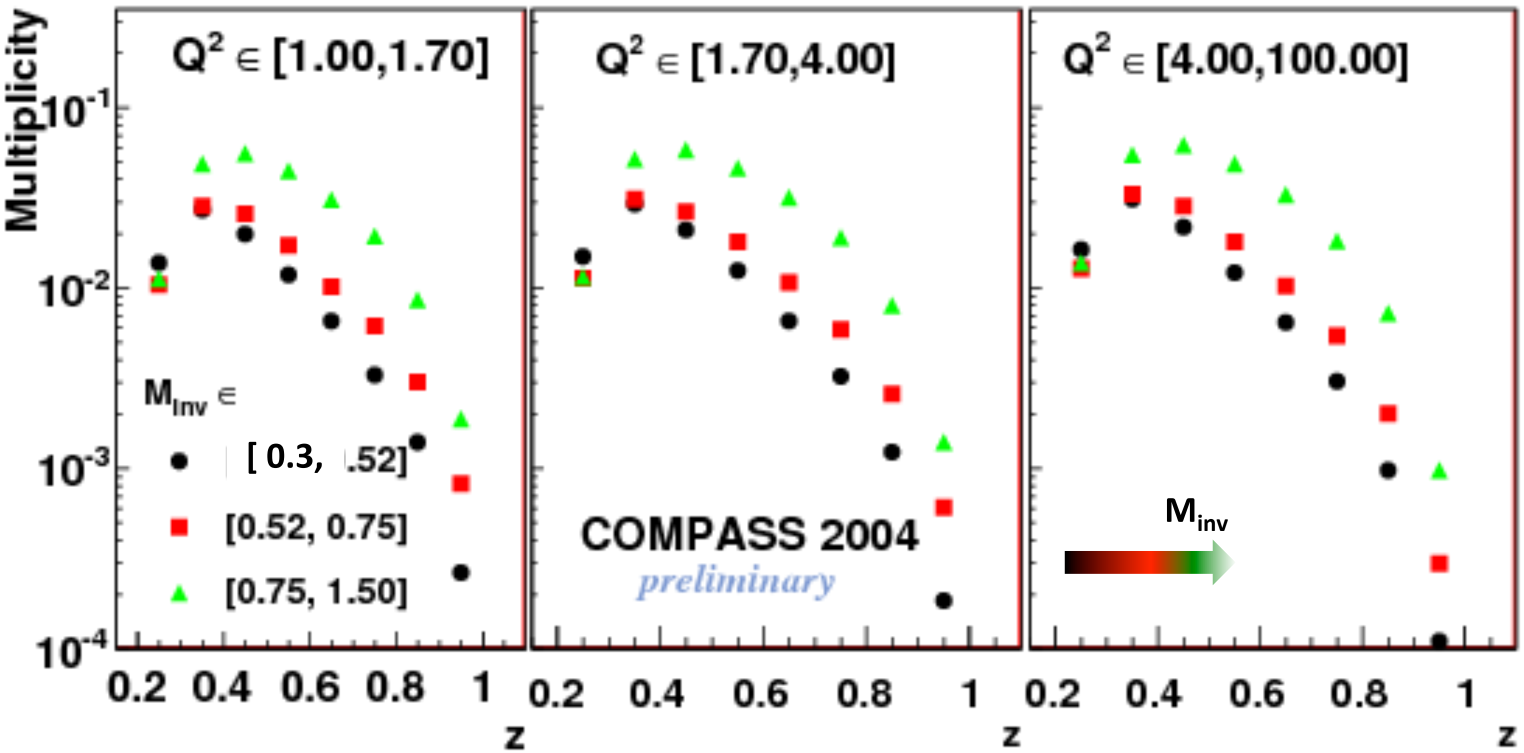
SPIN2012



Weak Q^2 dependence

Hadron pair multiplicities

First measurements in M_{inv}, $z=z_1+z_2$, Q^2 bins



Significant M_{inv} and $z=z_1+z_2$ dependences (as expected)
Trend and shape reproduced by LEPTO (no parametrizations yet exist)

Summary

- Preliminary results on hadron multiplicities
  - Broad kinematical ranges
  - 3-Multidimensional binning
  - Identified pions and kaons

- Improved kaon identification with reduced systematic errors
  with ongoing studies to reduce systematics

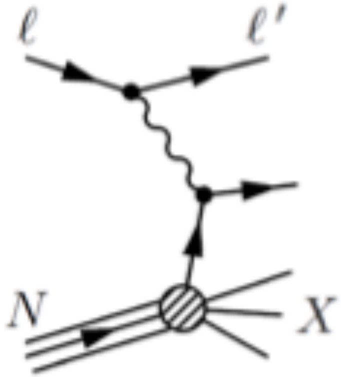
- First measurement of unidentified hadron pair multiplicities for the perspective of extracting Dihadron fragmentation functions

- More high precision measurement on the list
  - P_T^2 dependent pion and kaon multiplicities in (x,Q^2,z) bins
  - Identified hadron pair multiplicities in (z,Q^2,M_{inv}) bins

$g_1^{p,d}$ and related sume rules

$$\boxed{\ell\, N \to \ell'\,(X)}$$ $Q^2 > 1$ GeV^2 (hard scale)

⇒ Scattering on quasi free partons (Factorisation + pQCD ⇒ parton model)



Relation with axial charges of baryons

(SU(3) flavour symmetry)

$$\Gamma_1^N \equiv \frac{1}{2}\left(\Gamma_1^p + \Gamma_1^n\right) = \frac{1}{9} C_1^S(Q^2)\, a_0 + \frac{1}{36} C_1^{NS}(Q^2)\, a_8$$

- $C_1^{S,NS}$ calculable in pQCD
- $a_8 = 0.585 \pm 0.025$ from hyperon beta decay
- $a_0 = \Delta\Sigma$ in the $\overline{\text{MS}}$ scheme

$$\Rightarrow \Delta\Sigma(Q^2 = 3(GeV/c)^2) = 0.30 \pm 0.01_{\text{stat}} \pm 0.02_{\text{evol}}$$

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$g_1^{p,d}$ and related sume rules

$$g_1^p = \frac{1}{2}\left[\frac{4}{9}\left(\Delta u + \Delta\bar{u}\right) + \frac{1}{9}\left(\Delta d + \Delta\bar{d}\right) + \frac{1}{9}\left(\Delta s + \Delta\bar{s}\right)\right]$$

$$g_1^d = \frac{1}{2}\left[\frac{1}{9}\left(\Delta u + \Delta\bar{u}\right) + \frac{4}{9}\left(\Delta d + \Delta\bar{d}\right) + \frac{1}{9}\left(\Delta s + \Delta\bar{s}\right)\right]$$

$$Singlet : \Delta\Sigma = \left[(\Delta u + \Delta\bar{u}) + +(\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s})\right]$$

$$NS : \Delta q_3 = \left[(\Delta u + \Delta\bar{u}) - (\Delta d + \Delta\bar{d})\right]$$

$$NS : \Delta q_8 = \left[(\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) - 2(\Delta s + \Delta\bar{s})\right]$$

$\int g_1 dx$ $\quad \Gamma_1^p = \int_0^1 g_1^p(x)dx;\ \Gamma_1^d = \int_0^1 g_1^p(x)dx$

➥ **Moments** $\Gamma_1^p - \Gamma_1^d = \frac{a_3}{6}(1+\alpha^2 corr)\ \ (Bjorken\ SR)$

+ $a_3 = \Delta\Sigma_u - \Delta\Sigma_d = F + D = 1.267,$

$a_8 = \Delta\Sigma_u + \Delta\Sigma_d - 2\Delta\Sigma_s = 3F - D \approx 0.58$

from neutron and hyperon decays

$6(\Gamma_1^p - \Gamma_1^n)/(1+\alpha^2\ corr) = g_A/g_V = 1.28 \pm 0.07 \pm 0.10$

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$\Delta\Sigma = a_0 = 0.30 \pm 0.01 \pm 0.02$

$(\Delta s + \Delta\bar{s}) = 1/3(a_0 - a_8) = -0.09 \pm 0.01 \pm 0.02$

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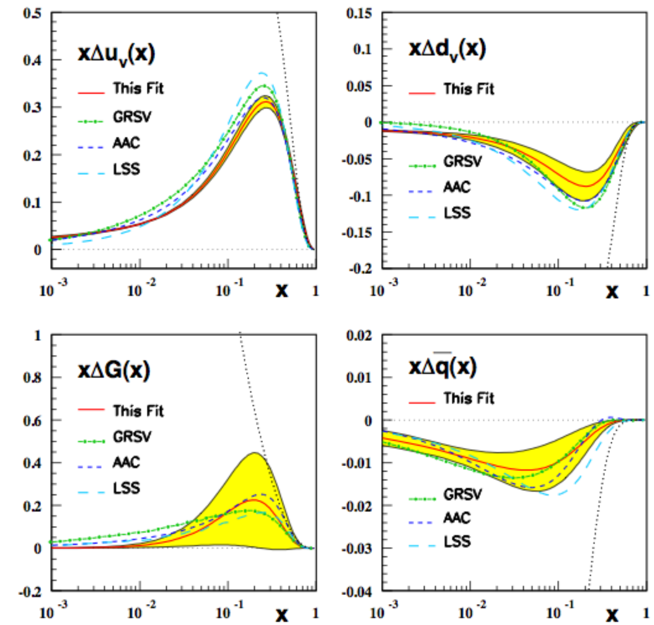
NLO: DGLAP links q and g

$$\frac{d}{d\ln Q^2}\Delta q_{NS}(x,Q^2) = \frac{\alpha_S(Q^2)}{2\pi} P_{qq}^{NS} \otimes \Delta q_{NS}$$

$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix} = \frac{\alpha_S(Q^2)}{2\pi}\begin{pmatrix}Pqq & P_{qg} \\ P_{gq} & P_{gg}\end{pmatrix} \otimes \begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix}$$

Assume SU(3) flavor symmetry: $\Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s} = \Delta s$



Blümlein, Böttcher arXiv 1101.0052