# COMPASS results on $g_1$ and quark fragmentation functions

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On behalf of the COMPASS Collaboration

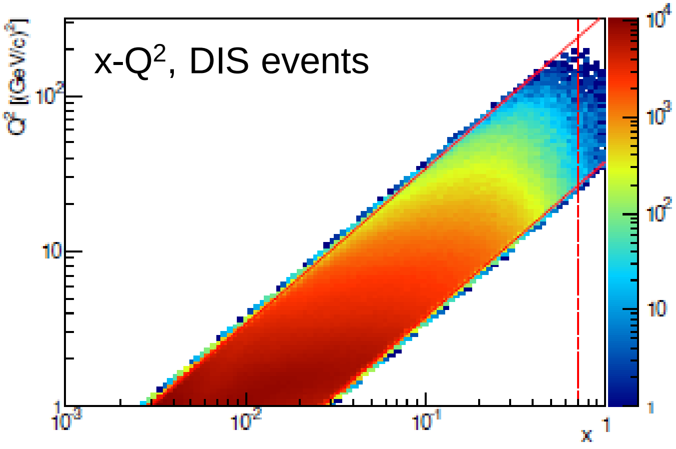
- **Longitudinal spin structure function**
  - **$g_1^p$ at 200 GeV**
  - **NLO QCD fit of $g_1$ world data**
  - **Test of Bjorken sum rule**
- **Quark fragmentation functions from SIDIS $\pi$ and K**

# Longitudinal spin asymmetry measurements at COMPASS

| Year | Pol.Target | Pol. μ beam | Status |
|---|---|---|---|
| 2002-2006 | d ($^6$LiD) | 160 GeV | PLB 612 (2005) 154<br>PLB 647 (2007) 8<br>PLB 647 (2007) 330 (low x, low $Q^2$)<br>PLB 660 (2008) 458 (SIDIS)<br>PLB 680 (2009) 171 (SIDIS) |
| 2007 | p ($NH_3$) | 160 GeV | PLB 690 (2010) 240<br>PLB 693 (2010) 227 (SIDIS) |
| 2011 | p ($NH_3$) | 200 GeV | to be published in PLB |

Goal of 200 GeV proton data:
improve precision at low x, access slightly higher $Q^2$:

- Enlarge x-$Q^2$ coverage for QCD fits ($\Delta G$, $\Delta\Sigma$)
- Improve precision of the integral of $g_1^p$ ($\Delta\Sigma$)
- Improve precision on semi-inclusive data at low x ($\Delta\bar{u}$, $\Delta\bar{d}$)
- Balance proton and deuteron statistics



# COMPASS at CERN

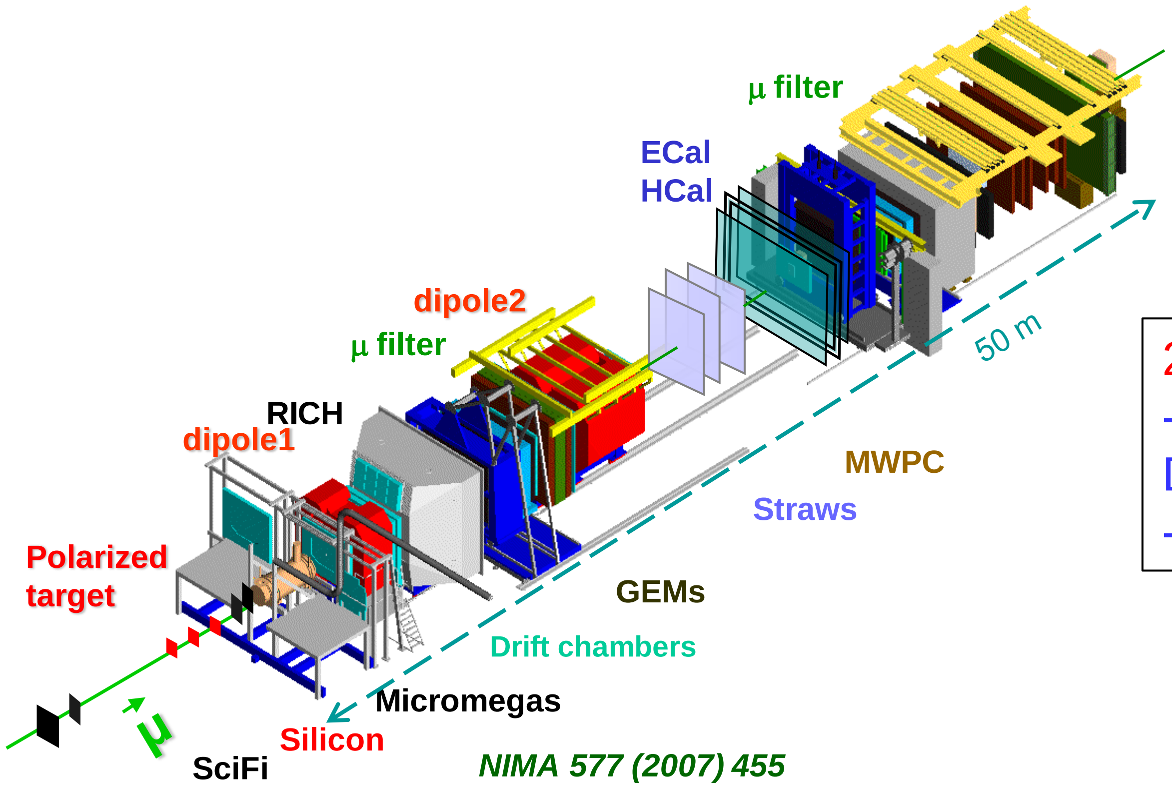
Fixed target
160-200 GeV muon and 190 GeV hadron beams from CERN SPS
→ Multipurpose setup

Polarized muon beam
& polarized target: d, p

Nucleon spin structure

Hadron beam $\pi$ / K / p
& $LH_2$ or nuclei

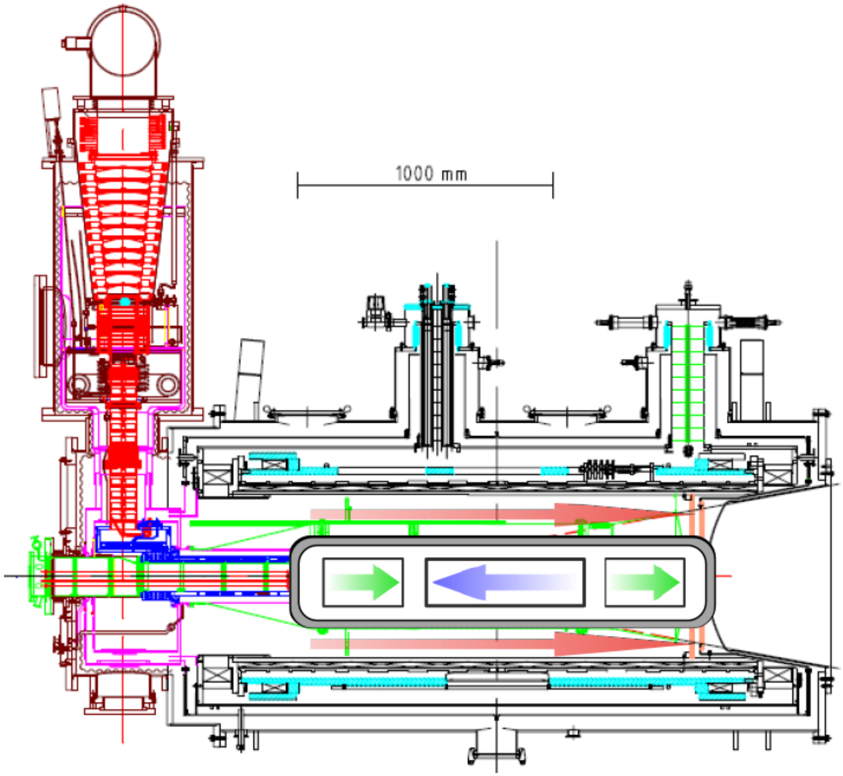
Meson spectroscopy
$\pi$, K polarisabilities




2015-2018:
- TMDs from Polarized Drell-Yan
- GPDs from DVCS

*NIMA 577 (2007) 455*

# Polarized target




- $NH_3$ material
- Dilution (15 ± 0.3) %
- Polarisation (80 ± 3)%

- Dynamic Nuclear Polarization
- Superconducting solenoid 2.5T

- 3 cells with opposite polarizations

  Nice balance of acceptance from the 2 spin states

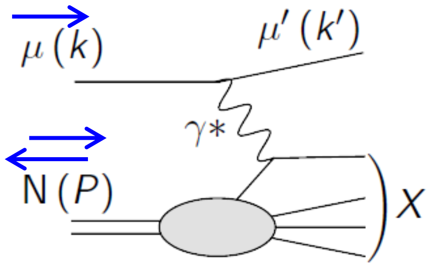
- Reversal of polarization by:

  - Adiabatic rotation of solenoid field
  - Different microwave settings

  → 4 measurements

→ Minimize systematics

# Measurement of $A_1^p$ and $g_1^p$




DIS events, $Q^2>1(GeV/c)^2$

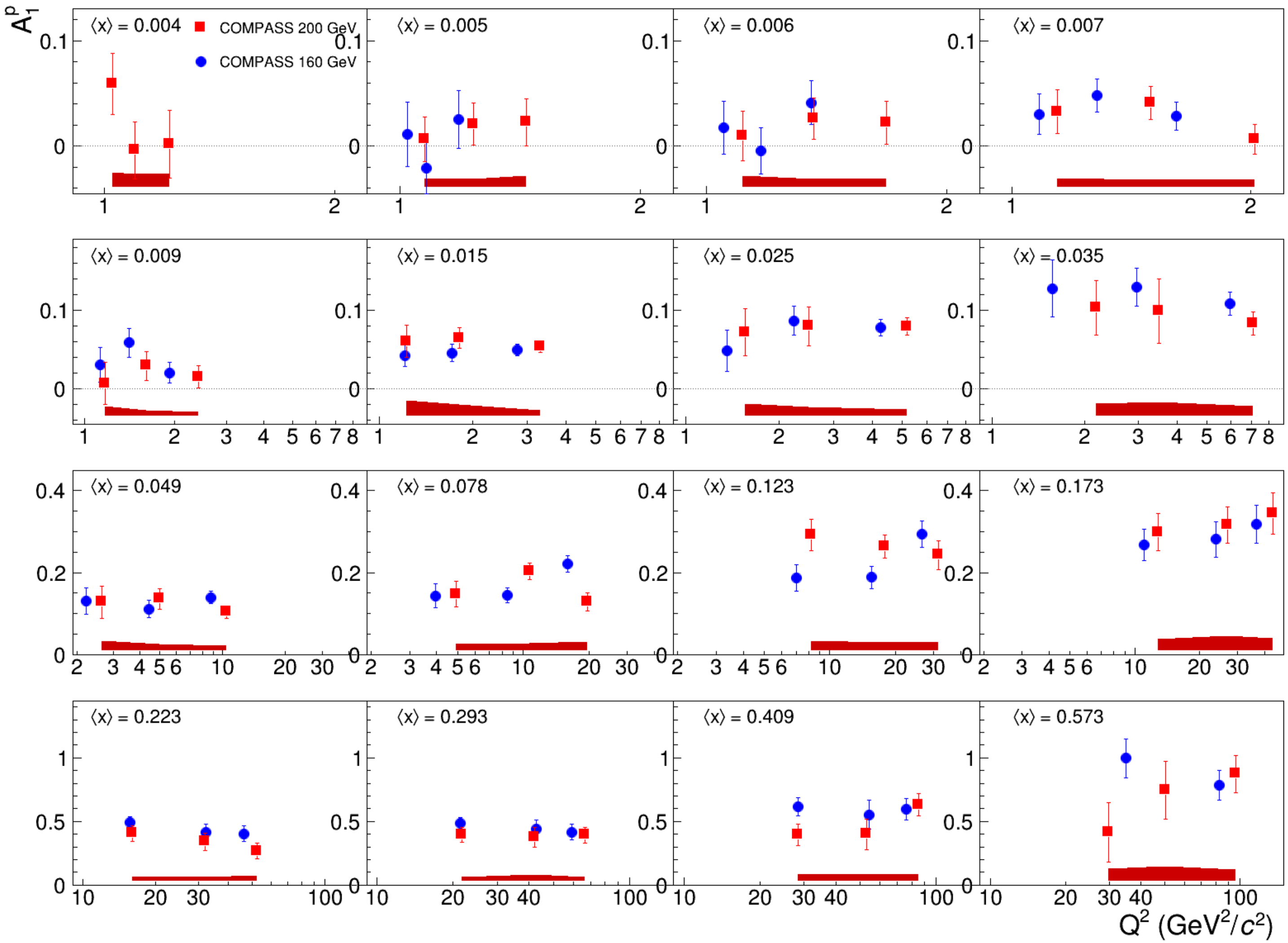
$$A_{\parallel} = \frac{d\sigma^{\rightleftarrows} - d\sigma^{\rightrightarrows}}{d\sigma^{\rightleftarrows} + d\sigma^{\rightrightarrows}} = D(A_1 + \eta A_2)$$

$$A_{\parallel} \approx D \cdot \frac{g_1}{F_1}$$

$$\frac{A_{\parallel}}{D} = \left\langle \frac{1}{2} \frac{1}{|P_B\, P_T|\, f\, D} \left( \frac{N^{\rightleftarrows} - N^{\rightrightarrows}}{N^{\rightleftarrows} + N^{\rightrightarrows}} + \frac{N^{\rightleftarrows} - N^{\rightrightarrows}}{N^{\rightleftarrows} + N^{\rightrightarrows}} \right) \right\rangle$$

f: target dilution
D: depolarization factor

# $A_1^p$ ($Q^2$) at various <x>

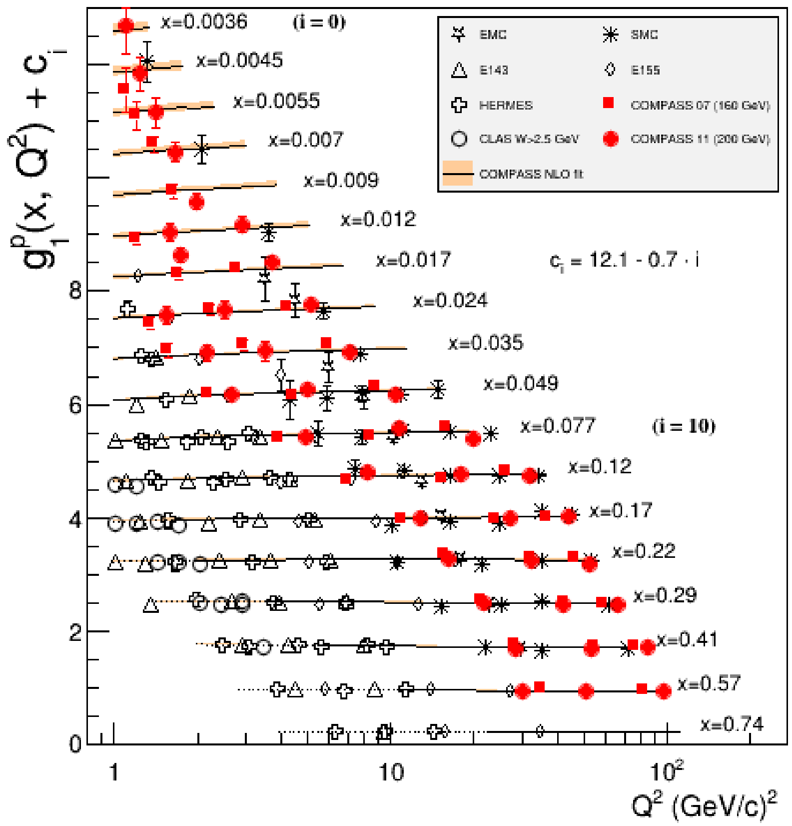



160 and 200 GeV data: no $Q^2$ dependence observed

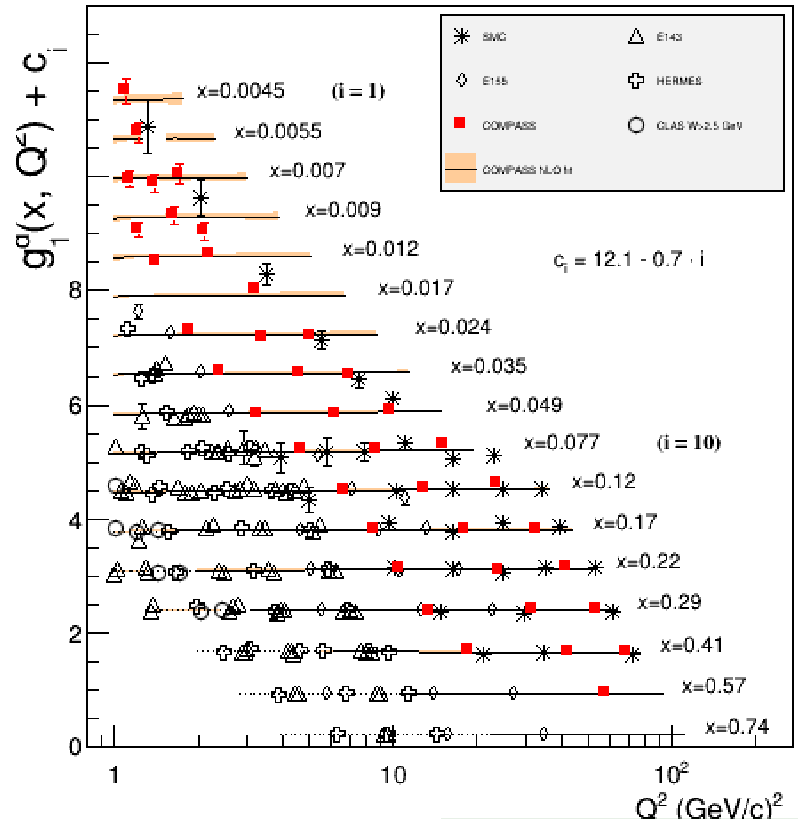
***hep-ex/1503.08935***
***to be published in PLB***

# World data on $g_1^{\,p}$ and $g_1^{\,d}$

**proton**




**deuteron**




- **200 GeV proton** data: lower x and higher $Q^2$

***hep-ex/1503.08935***
***to be published in PLB***

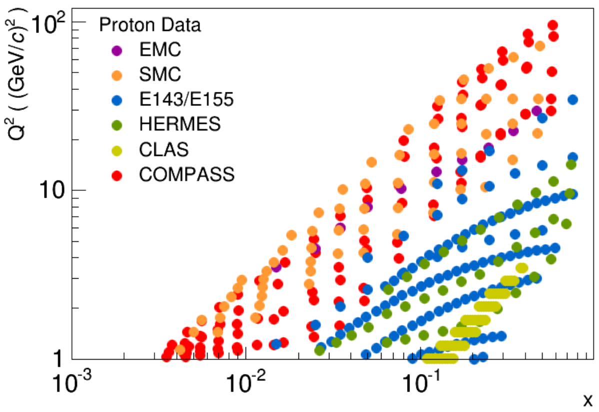
$g_1$ data as will be used in global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta G(x)$

$$\frac{d\, g_1}{d\, Log(Q^2)} \propto -\Delta g(x, Q^2)$$

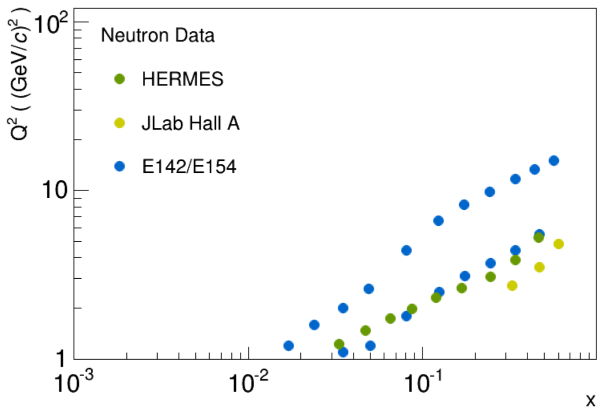
# Fit to proton, neutron and deuteron world data

x-$Q^2$ coverage of world data

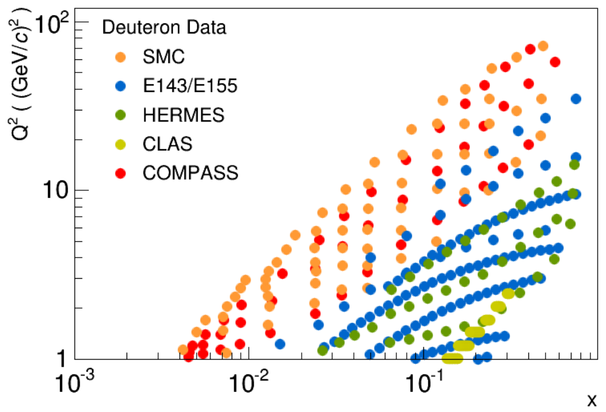
proton




neutron




deuteron




## NLO fit:

- Assume functional forms for $\Delta\Sigma$, $\Delta G$ and $\Delta q^{NS}$ at a reference $Q_0^2$ =1(GeV/c)$^2$

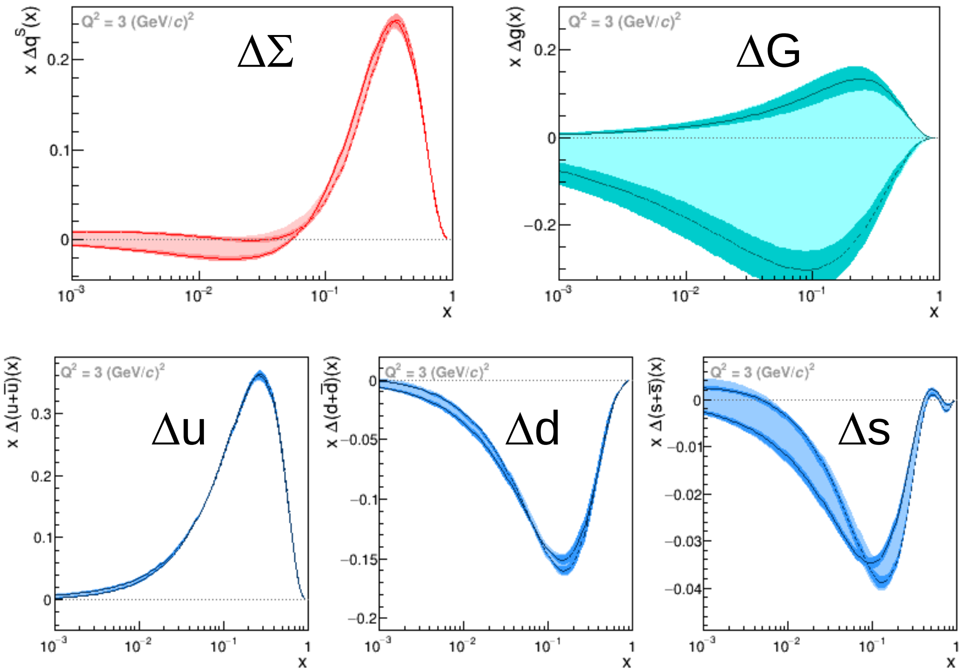
  e.g.: $\Delta q_{Si}(x|Q_0^2) = \eta_s x^{\alpha_s}(1-x)^{\beta_s}(1+\gamma_s x)/N_s$
- Assume $SU_3$
- Use DGLAP equations
- Fit world data

  495 points with W>10 GeV

  138 are from COMPASS, 11 free parameters.

# COMPASS NLO pQCD fit of $g_1$ world data

→ 2 classes of solutions, ΔG>0 and ΔG<0




***hep-ex/1503.08935***
***to be published in PLB***

- Quark spin contribution : 0.26 < ΔΣ < 0.36 at $Q^2$=3 $(\mathrm{GeV}/c)^2$

Largest uncertainty comes from the bad knowledge of functional forms.

Result in fair agreement with other global fits

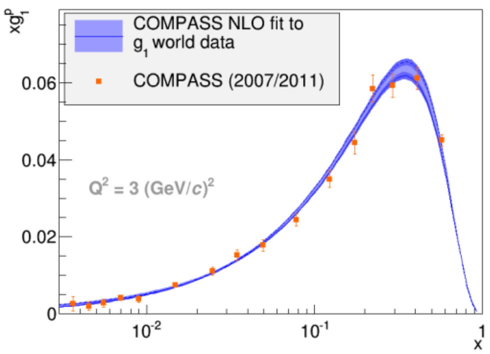
- Gluon spin contribution: ΔG not well constrained, even the sign, using DIS only
  Solution with ΔG>0 agrees with result from DSSV++ using RHIC pp data

# $g_1^p$ and $g_1^d$

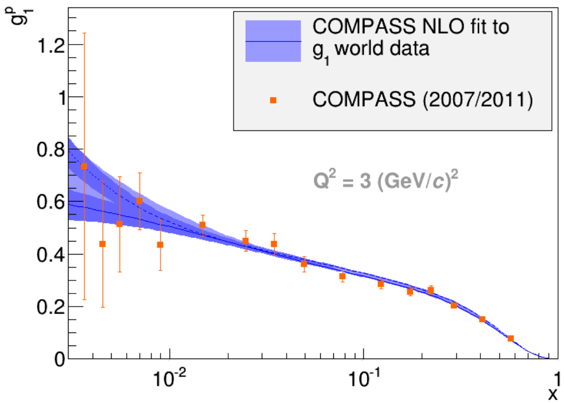
COMPASS data and NLO QCD fit to world data

- - - $\Delta G < 0$ solution
——— $\Delta G > 0$ solution

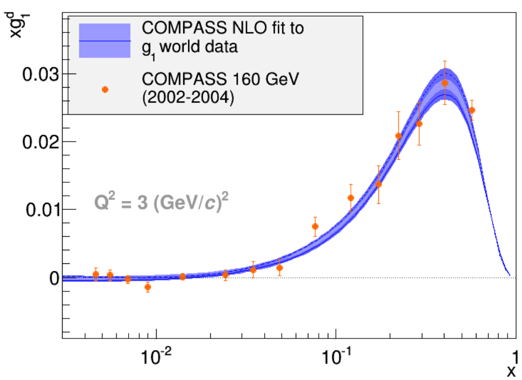
$xg_1^p$



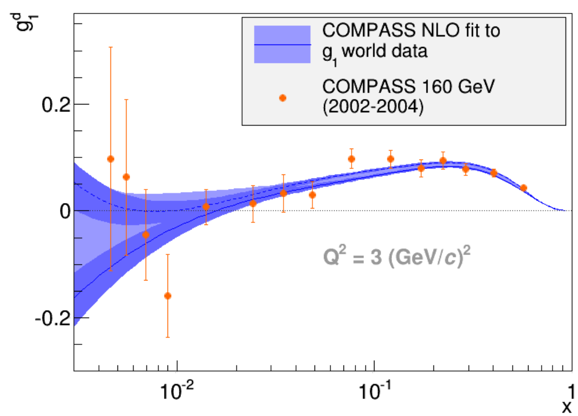

$g_1^p$




$xg_1^d$




$g_1^d$




- **$g_1^p$ positive at low x**
- **Lower x data needed for sensitivity to $\Delta G$**

# Results for Bjorken sum rule from $g_1$ COMPASS data

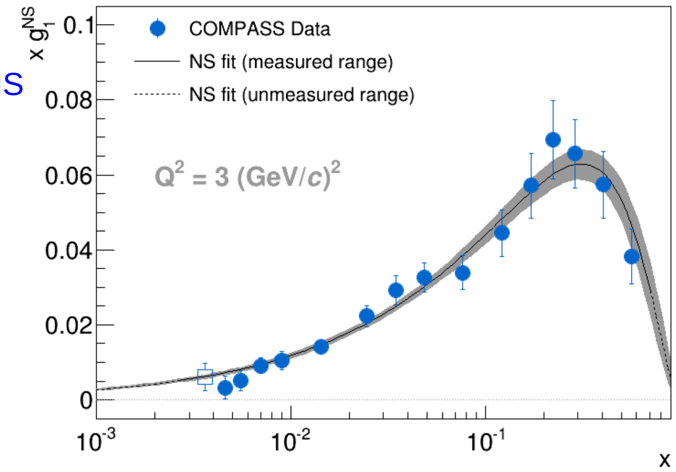
Fundamental QCD sum rule, which relates proton and neutron spin structure functions $g_1$. $\int_0^1 \left(g_1^p(x,Q^2) - g_1^n(x,Q^2)\right) dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C_1^{NS}(Q^2)$

Using COMPASS data alone:

- Non-singlet fit: independent from $\Delta G$
- Reduce systematics

94% of the sum is from the measured range

$xg_1^{NS}$




x

COMPASS $(g_A/g_V)_{NLO} = 1.219 \pm 0.052(\text{stat.}) \pm 0.095(\text{syst.})$

to be compared to: $\left| \frac{g_A}{g_V} \right| = 1.269 \pm 0.002$ obtained from neutron $\beta$-decay.

→ **Bjorken sum rule verified to 8%**

**Better statistics and extended systematics studies compared to past**

Note that experimental value increases from 1.22 to 1.25 when $C_1^{NS}$ at NNLO

# Summary for $g_1^p$

**$g_1^p$ :** Measurement down to <x>= 0.0035

Statistical precision improved by factor of ~3 compared to SMC

**NLO QCD fit of $g_1$ world data:**

$0.26 < \Delta\Sigma < 0.36$ Uncertainty dominated by initial functional forms

$\Delta G$ : Not constrained enough by DIS data alone

**Bjorken sum rule from COMPASS p and d data:** Verified to 8%

**Part II**

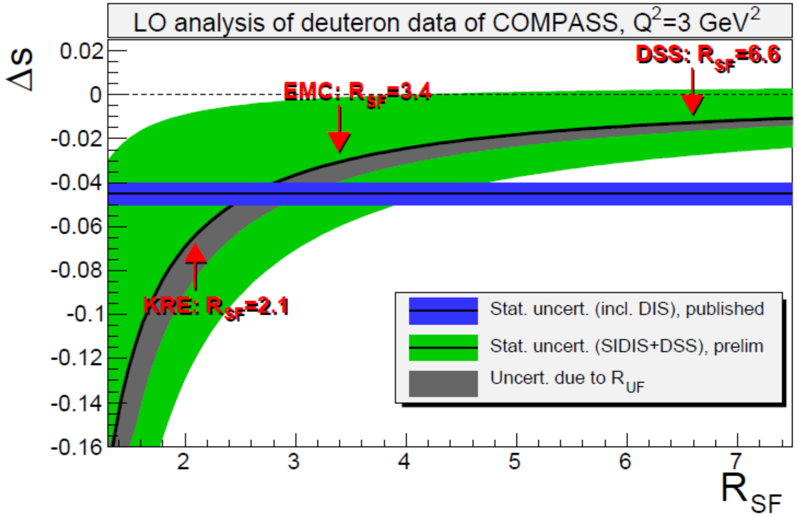
**Quark fragmentation functions from**

**$\pi$ and K mutiplicities in SIDIS**

# Quark Fragmentation Functions (FF)

- Non perturbative objects
- Process independent
- Needed to access strange quark polarization $\Delta s$ from polarized SIDIS.

strange quark FF = largest uncertainty in this extraction




*PLB 680 (2009) 217*

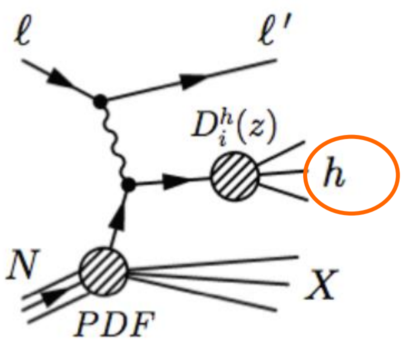
Data from $e^+e^-$ and pp reactions, unsufficient for good flavour separation and at too high $Q^2$

→ **extract FFs from COMPASS unpolarized SIDIS data**

# Quark FFs from SIDIS

Measurement of multiplicities of π, K, p in **SIDIS**

***$\mu^+ d \rightarrow \mu^+ h^\pm X$***




Hadron multiplicitiy = mean number of hadrons *h* per DIS event

$z = E_h / (E_\mu - E_\mu')$

PDFs FFs

$$\frac{dM^h(x, Q^2, z)}{dz} \underset{\text{at LO}}{=} \frac{\sum_q e_q^2 f_q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 f_q(x, Q^2)}$$

PDFs depend on *x*, while FFs depend on *z*

Data can be obtained in a fine binning in x, z, $Q^2$

**→ Constitute an input to global NLO QCD analyses to extract quark FFs**

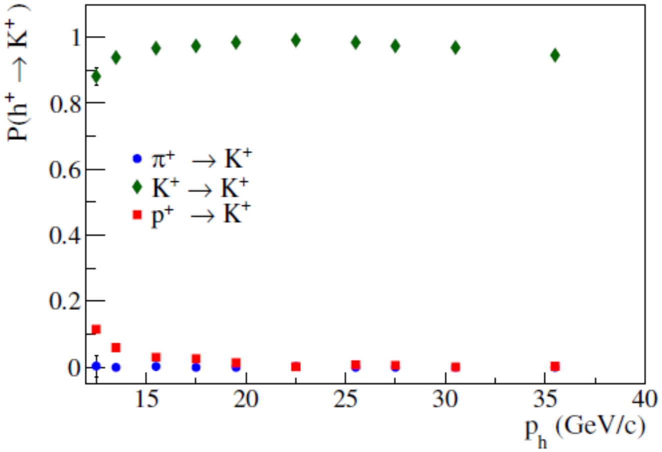
# Data analysis - hadron multiplicities

Isoscalar target $^6$LiD, 2006 data

$Q^2>1\ (GeV/c)^2$
$0.1 < y < 0.7$
$0.004 < x < 0.7$

$0.2 < z < 0.85$
Data cover $5 < W < 17$ GeV

$12 < p_h < 40$ GeV/c
for high RICH performance

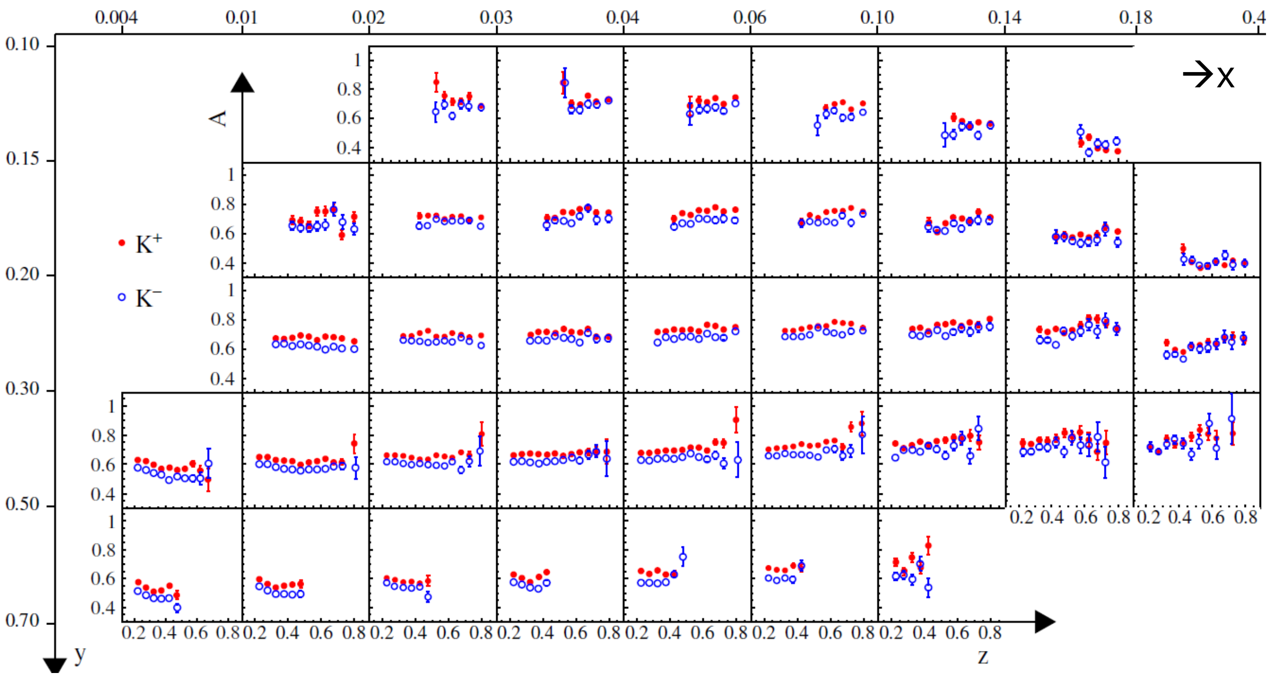


# Acceptance (x,y,z)

MC simulation, fine binning to avoid model dependence

→ A($z$) in ~30 ($x$-$y$) bins

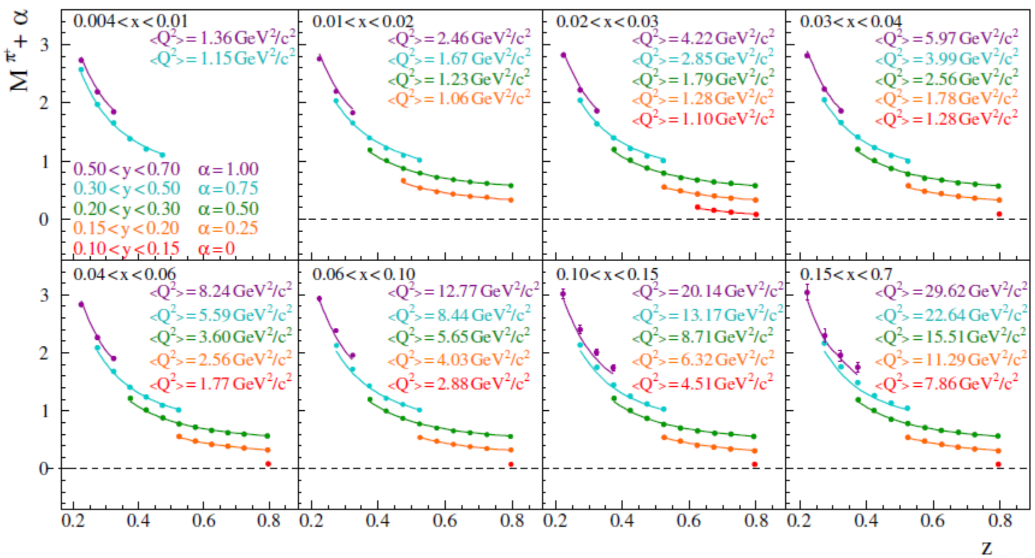
Use $y$ variable rather than $Q^2$, because of the $x$-$Q^2$ correlation




A(K+) ~ A(K-) ~ 0.6

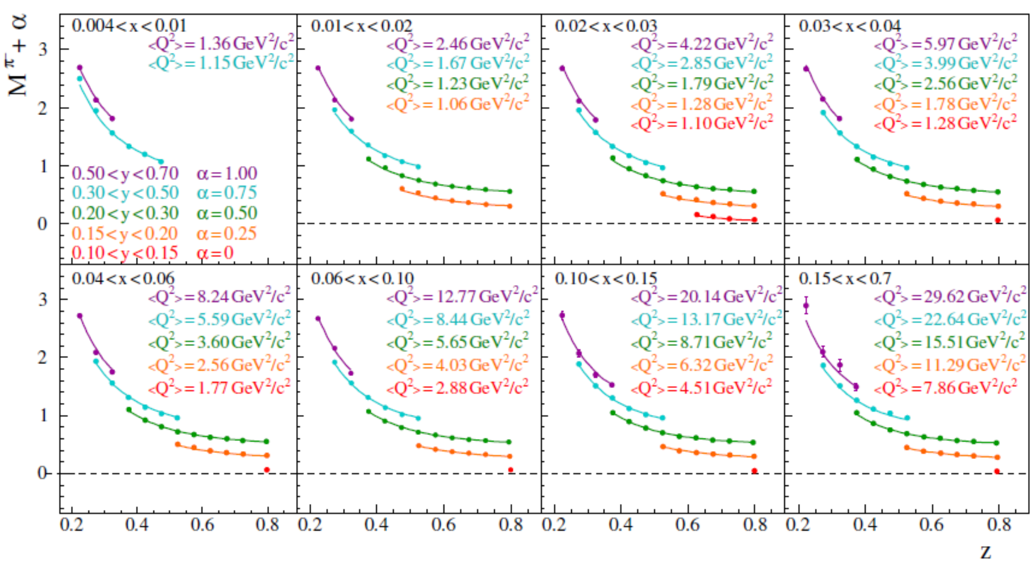
# $\pi^+$ and $\pi^-$ multiplicities vs z in (x,y) bins

$\pi^+$




- ~400 data points for $\pi$
- Strong z dependence
- $M\pi^+ \sim M\pi^-$

$\pi^-$




- Publication in preparation
- Some preliminary data already included in DSS++ NLO analysis
- All data included in COMPASS LO analysis (next slide)

NB- Also measured: $p_T$ dependence and 2h multiplicities

# Quark FFs into π, from COMPASS LO fits

Assume isospin and charge symmetry:

$$D_{\text{fav}}^{\pi+} = D_u^{\pi^+} = D_{\bar{d}}^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-}$$

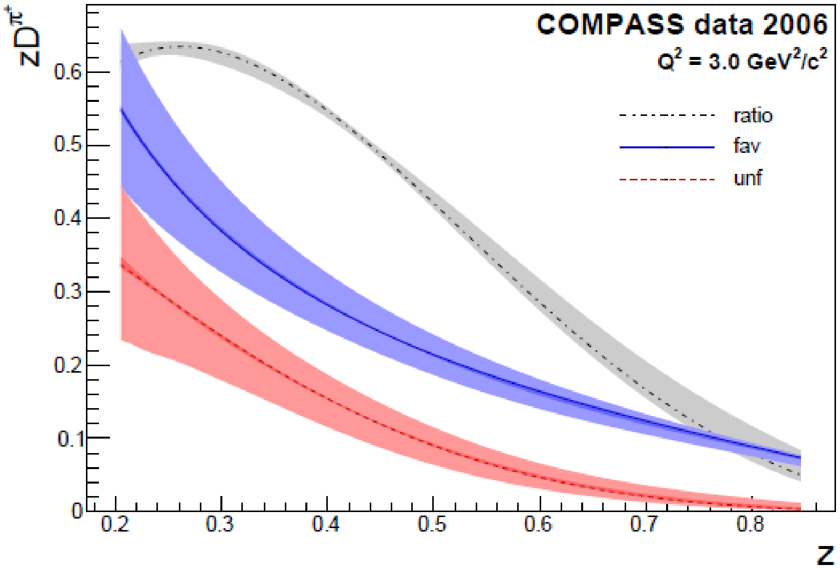
$$D_{\text{unf}}^{\pi+} = D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_u^{\pi^-} = D_{\bar{d}}^{\pi^-}$$

Assume also $D_s^{\pi+} = D_s^{\pi-} = D_{unf}^{\pi+}$

Choose functional forms for FFs (z); use DGLAP.
Fit $\pi^+$ and $\pi^-$ multiplicities and extract the 2 independent FFs:

$zD_{fav}^{\pi+}$

$zD_{unf}^{\pi+}$




- As expected, $D_{fav}$ > $D_{unf}$.
- Results in fair agreement with DSS and LSS NLO fits (not shown here)

# Sum of $z$ integrated multiplicities $\pi^+ + \pi^-$

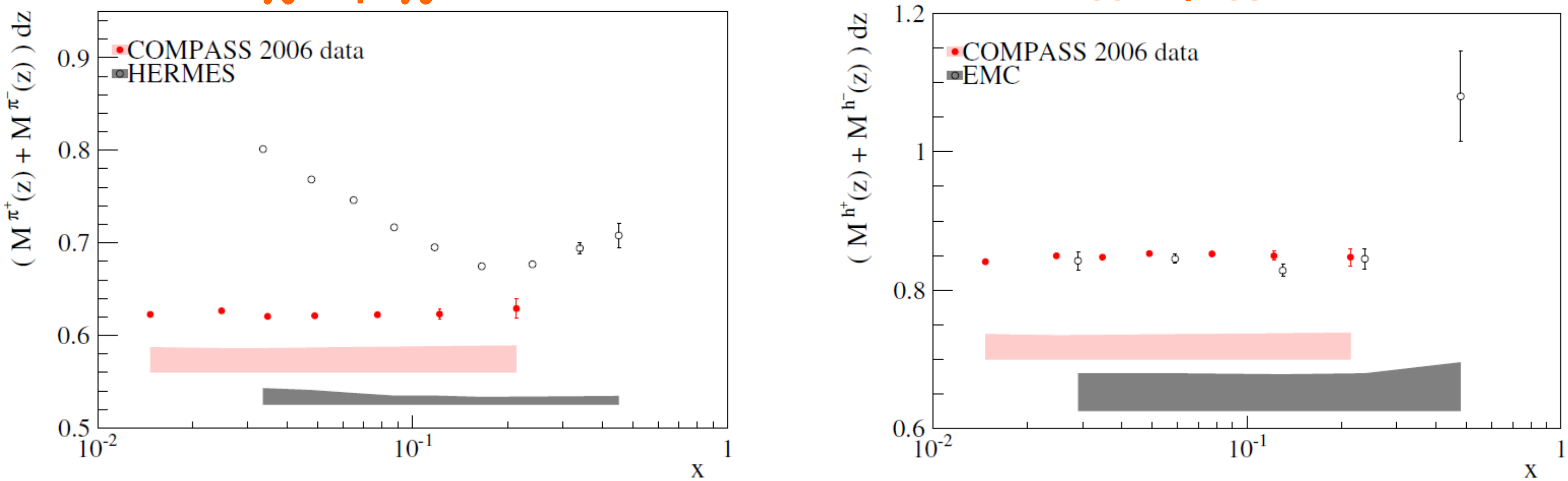
For isoscalar target, simple dependence on FFs:

$$M^{\pi^+ + \pi^-} = D_{fav} + D_{unf} + \frac{2S}{5Q+2S}(D_{unf} - D_{fav}) \approx D_{fav} + D_{unf}$$

$$\begin{cases} Q = u + \bar{u} + d + \bar{d}, \\ S = s + \bar{s}. \end{cases}$$

~ no $x$ dependence. Even if $x$-$Q^2$ are correlated, the $Q^2$ dependence of the $z$ integrated multiplicity is very weak

$\pi^+ + \pi^-$ $\quad$ $h^+ + h^-$

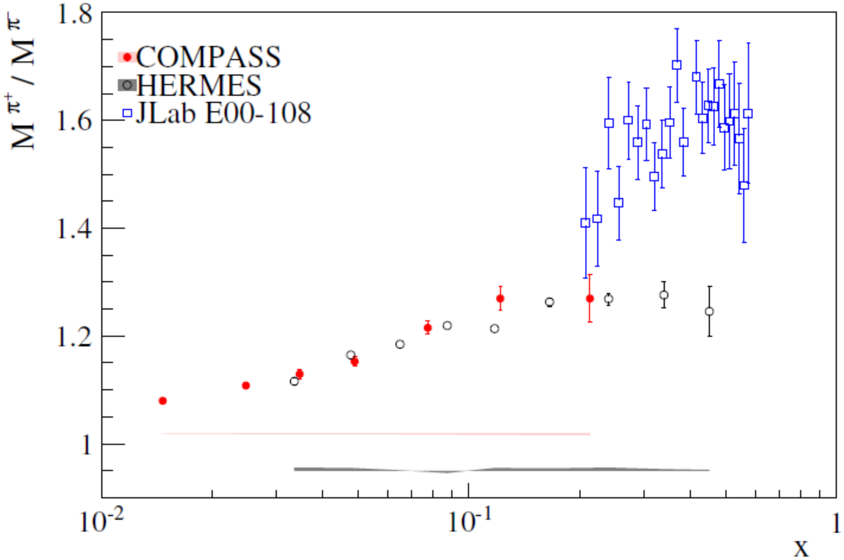



**Indeed, no x dependence observed in COMPASS nor in EMC data, at variance with HERMES data.**

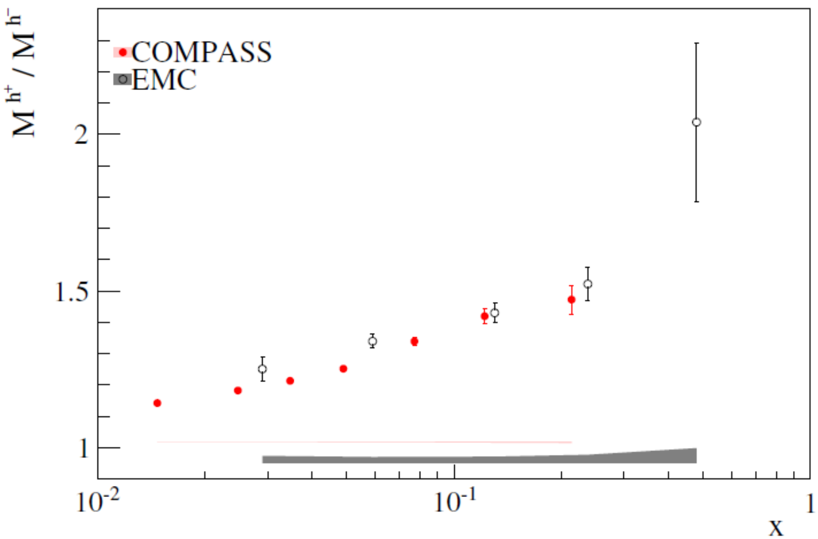
# Ratio of *z* integrated multiplicities $\pi^+ / \pi^-$

Interesting because many systematic errors cancel in the ratio

## $\pi^+ / \pi^-$




## $h^+ / h^-$




Pions:

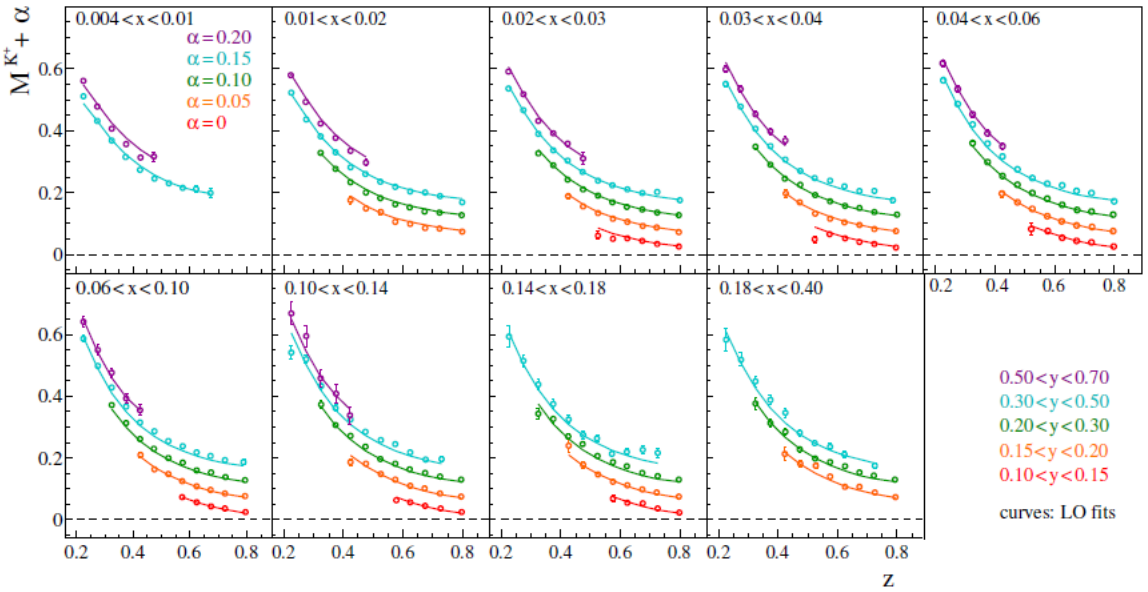
- Good agreement COMPASS-HERMES.
- Jlab data higher, but at lower W

Hadrons:

Good agreement COMPASS - EMC.

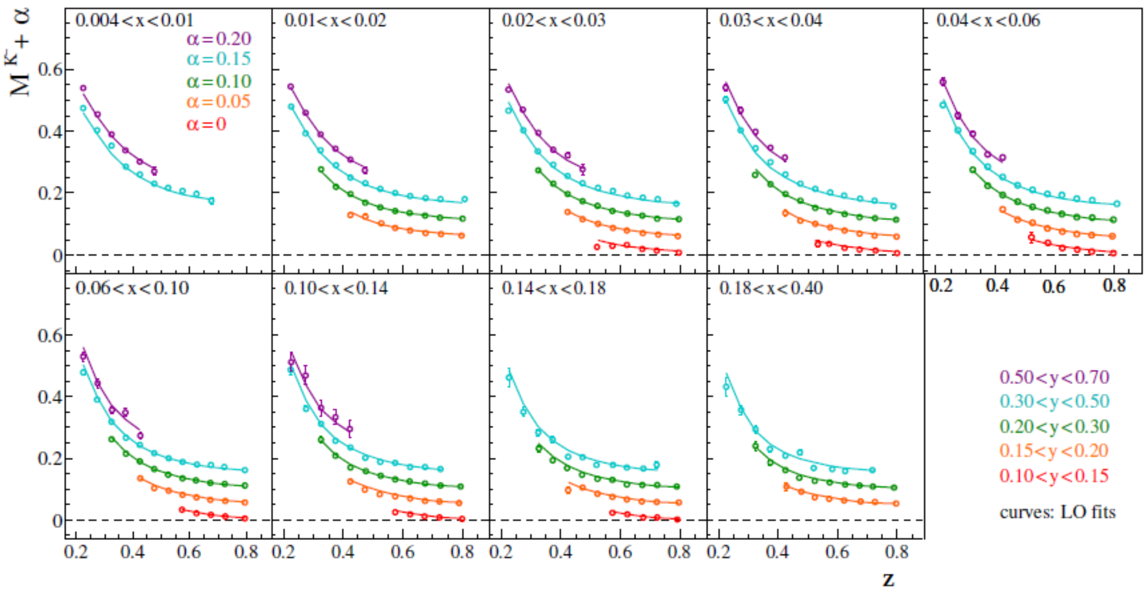
# $K^+$ and $K^-$ multiplicities vs z in (x,y) bins

$K^+$




~400 data points for K
Strong z dependance
$M^{K^+} > M^{K^-}$

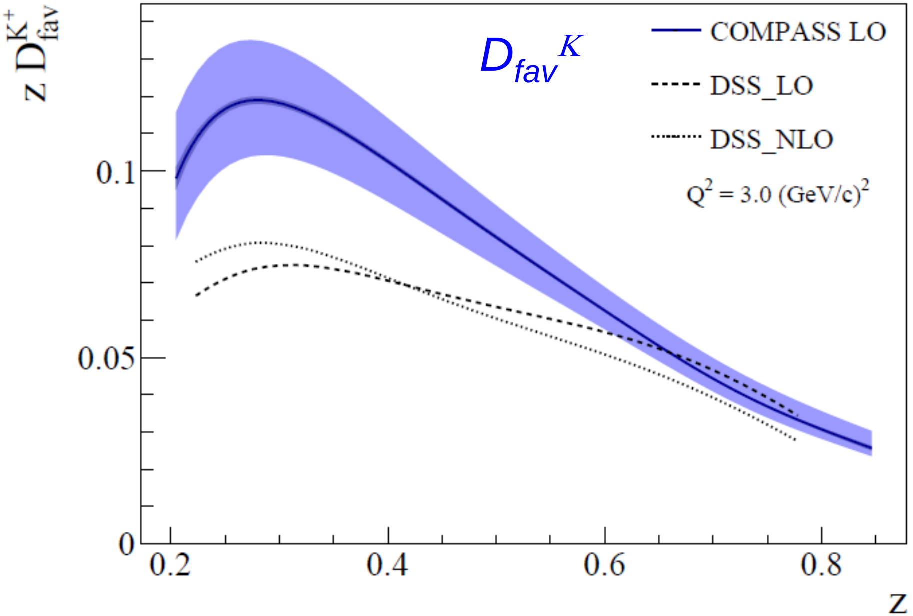
$K^-$

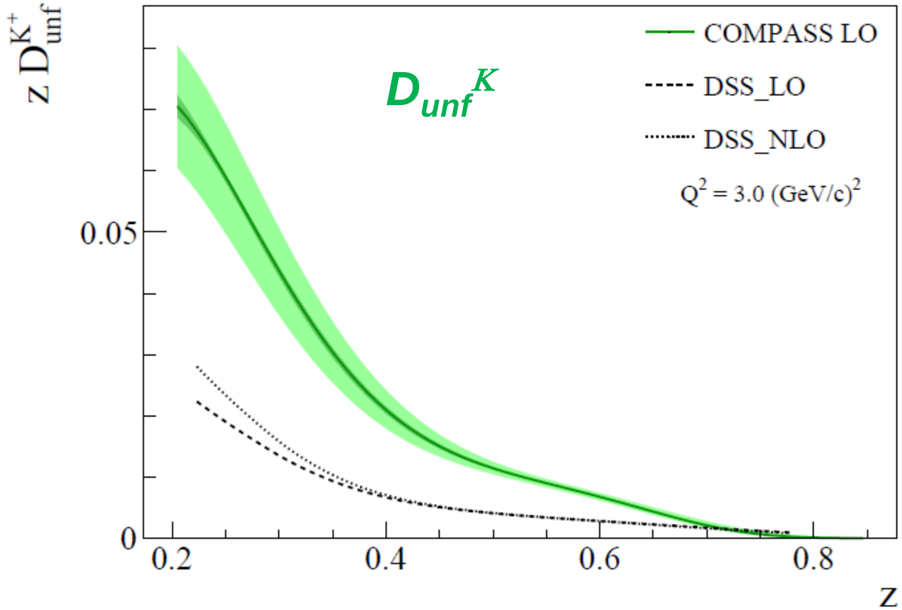


# Quark FFs into K,  from COMPASS LO fits

Assuming isospin symmetry, 3 independent quark FFs: $D_{fav}^{K}$ $D_{unf}^{K}$ $D_{str}^{K}$

LO fit to COMPASS kaon multiplicities:




- As expected, $D_{fav}$ > $D_{unf}$.
- $D_{fav}$ and $D_{unf}$ significantly larger than DSS and LSS NLO fits (which do not include these kaon data)
- Result for $D_{str}^{K}$ not shown. Unstable, depends on choice of functional form

# Sum of *z* integrated multiplicities K⁺ + K⁻

For an isoscalar target, the sum has a simple dependence on $D_{str}^{K}$:

$$5M^{K^+ + K^-} \approx \int D_Q^K + S/Q \int D_S^K$$

non-strange → Multiplicities at high x

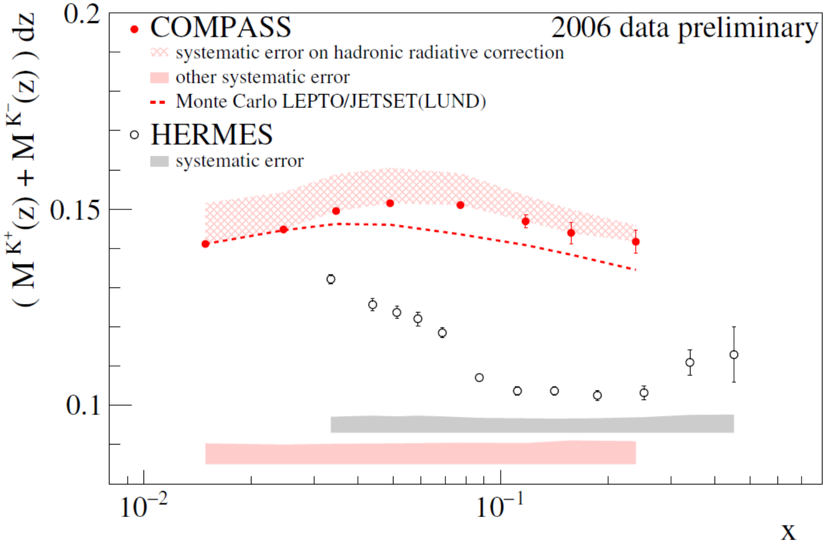
strange → Multiplicities at low x

$S/Q$ → 0 at high x

where:

$$\begin{cases} D_Q^K = 4D_{fav}^K + 6D_{unf}^K \\ Q = u + \bar{u} + d + \bar{d} \\ S = s + \bar{s} \end{cases}$$

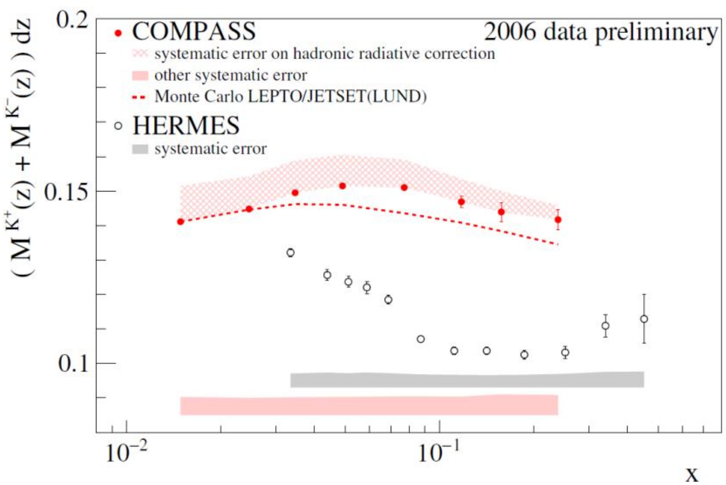
# Sum of *z* integrated multiplicities $K^+ + K^-$




**Conclusion I. COMPASS data :**

- **significantly above HERMES one**
- **agree rather well with MC simulation LEPTO+JETSET (LUND)**

# Sum of $z$ integrated multiplicities $K^+ + K^-$




**Conclusion II: Hints on fragmentation functions:**

$\int D_Q^K$

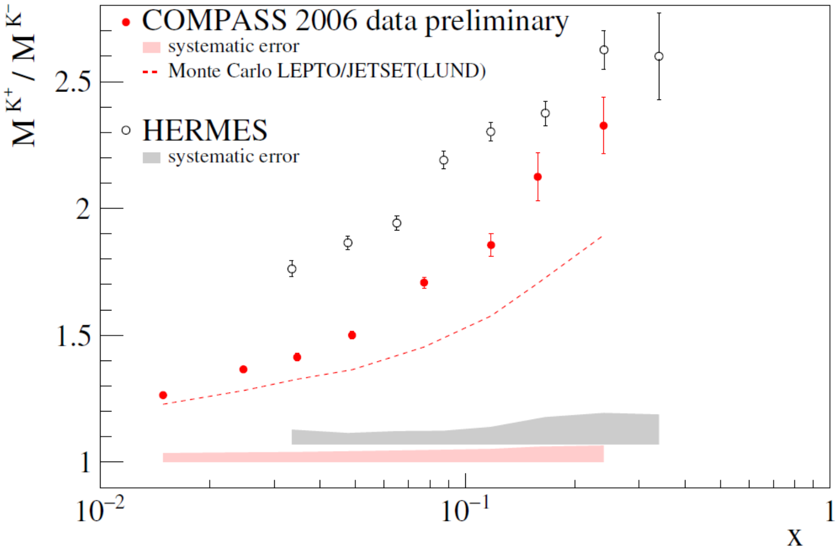
from these data at high x: **0.70**
from DSS analysis: **0.43**

***$D_Q^K$* COMPASS result >> DSS** one, as seen in LO fit where $D_{fav}$ and $D_{unfav}$ both larger for COMPASS than DSS

$S/Q \int D_S^K$

Low x data, agree well with MC/Lund
Do not show the rise expected from DSS from $D_{str}/D_{fav}$ ratio
→ **Suggest much lower $D_{str}$ than DSS**

# Ratio of *z* integrated multiplicities $K^+ / K^-$




Disagreement between HERMES and COMPASS for $K^+$ / $K^-$ ratio of multiplicities, while there was agreement for pions.

# Summary of quark FFs

**Multiplicities from isoscalar target, for** **$h^+$,h-, $\pi^+$, $\pi^-$, $K^+$,$K^-$**

in a fine binning of x,y,z; 5 < W < 17 GeV

Important input to global QCD fit of FFs at NLO

Large discrepancies with HERMES in the sum of integrated multiplicities

**Quark FF from LO fit of multiplicities**

$D_{fav}$ & $D_{unfav}(z,Q^2)$ for pions and for kaons

Promising results already at LO

**In progress**

Analyze data on $H_2$ target (2012) → more input for flavor separation

**Future**

2016-2017 : large set of proton data

(in parallel to GPD program: μ beam, $H_2$ target & upgraded RICH detector).

# Spares

# Systematic errors on $A_1$

- Multiplicative
- Additive

$$A_1^{1\gamma} = \frac{1}{fDP_BP_T}A^{raw} - \left(A_1^{RC} + \mathcal{O}(\frac{x}{Q}A_2) + \mathcal{O}(A_{False})\right)$$

Total of systematics always smaller than statistical error.
Dominant contributions:

- conservative limit put on possible false asymmetries (not seen)
- beam polarization at medium x

| Syst. uncertainties | | | |
|---|---|---|---|
| | Deuteron | Proton 07 | Proton 11 |
| Beam polarisation | 5% | | |
| Target polarisation | 5% | 2% | 3.5% |
| Depolarisation factor | 2% | 2% | 2% |
| Dilution factor | 2% | 1% | 2% |
| Combined(target, dep., dil.) | 6% | 3.6% | |

# NLO QCD fit

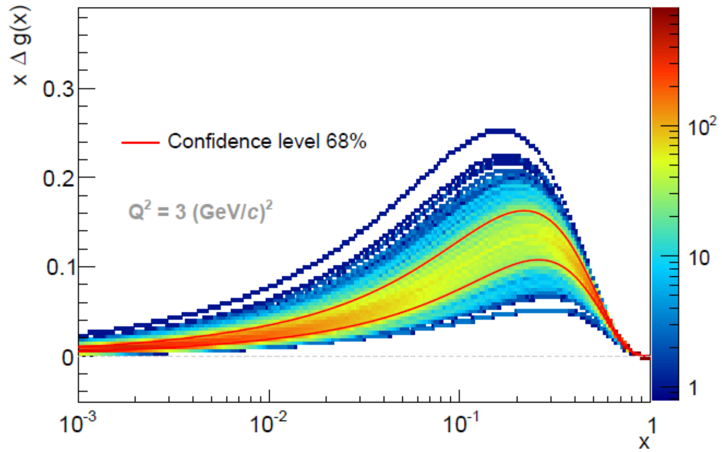



Figure 10: Illustration of the randomisation procedure. The results of 1,000 fits to the replicas are shown together with the two red curves which represent the border of the interval at 68% of confidence

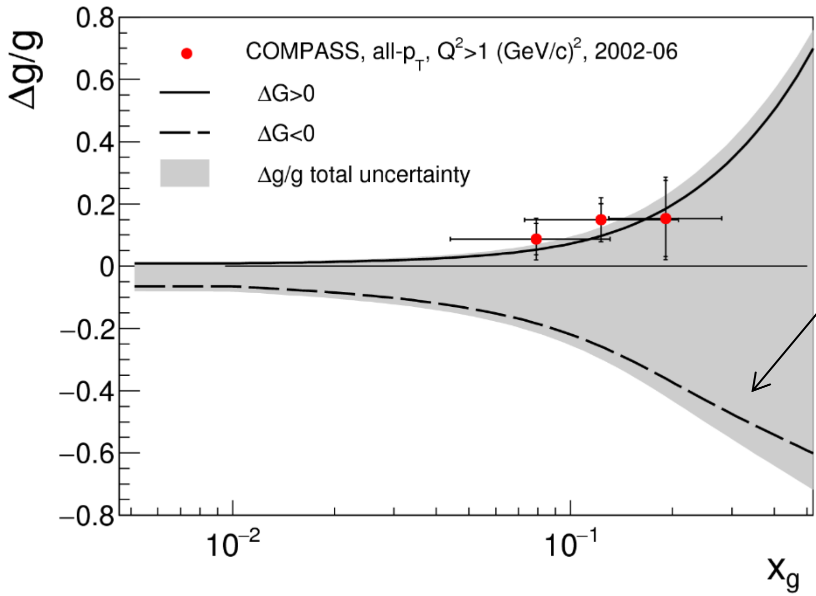
| $Q^2$ ((GeV/$c$)$^2$) | $\Delta\Sigma$ | $\Delta U$ | $\Delta D$ | $\Delta S$ |
|---|---|---|---|---|
| 1 | [0.27, 0.39] | [0.82, 0.86] | [−0.45, −0.41] | [−0.11, −0.06] |
| 3 | [0.26, 0.36] | [0.82, 0.85] | [−0.45, −0.42] | [−0.11, −0.08] |
| 10 | [0.26, 0.32] | [0.82, 0.84] | [−0.45, −0.43] | [−0.11, −0.09] |

Range of solution for the first moment of polarised parton distributions from the QCD fits

# ΔG/G from hadron prod. in DIS - (all-$p_T$)- PGF

New COMPASS results (better precision)

ΔG/G extracted at LO, in 3 x-bins




2 solutions from
COMPASS NLO QCD fit of $g_1$
world data

$\Delta g/g\ (x=0.10)$ = 0.113 ± 0.038 ± 0.036

# $\pi$ multiplicities -Systematic uncertainties

- Acceptance :
  - different sets of PDF in Lepto
  - different JETSET tunings

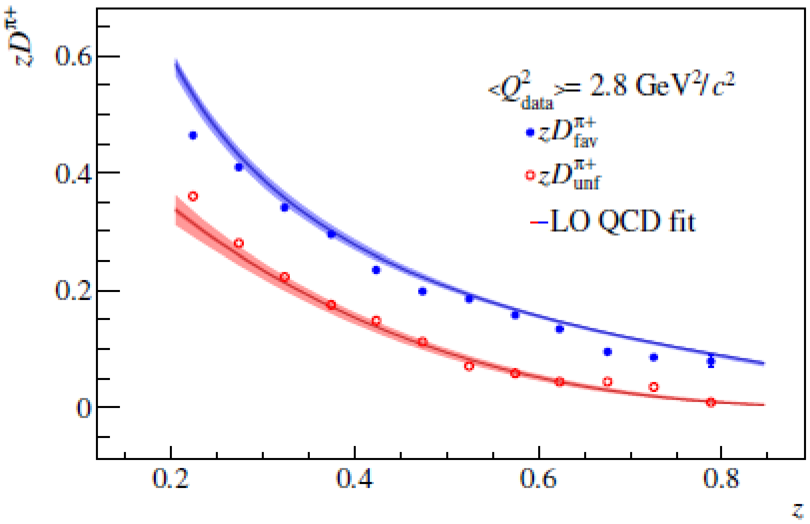
  } ≈ **5 %**

- RICH PID efficiency
  - pions : **1 % - 3 %**
  - kaons : **5 % - 10 %**

- Diff. $\rho^0$ and $\phi$ correction
  - 30 % theoretical uncertainty on HEPGEN cross-section
    - **12 %** max uncertainty on correction

- Electron correction
  - 25 % MC/data difference -> **50 %** conservative syst. error

# Pion FFs- Direct extraction and LO fit extraction




● ● Direct extraction of the 2 FFs in one of the x-y bins.

▬ ▬ LO Fit extraction of the 2 FFs.

Fit error bands: obtained using replica method

- Data with statistical error and uncorrelated syst. errors (dark band)
- Data with correlated systematic errors (light band)