Overview of COMPASS results

Fabienne KUNNE
CEA /IRFU Saclay, France

- **Nucleon spin**
  - **longitudinal: gluon and quark helicities**
  - **transversity**
- **Light meson spectroscopy**
- **Ch PT - Pion polarisability**
- **Outlook**

COMPASS at CERN

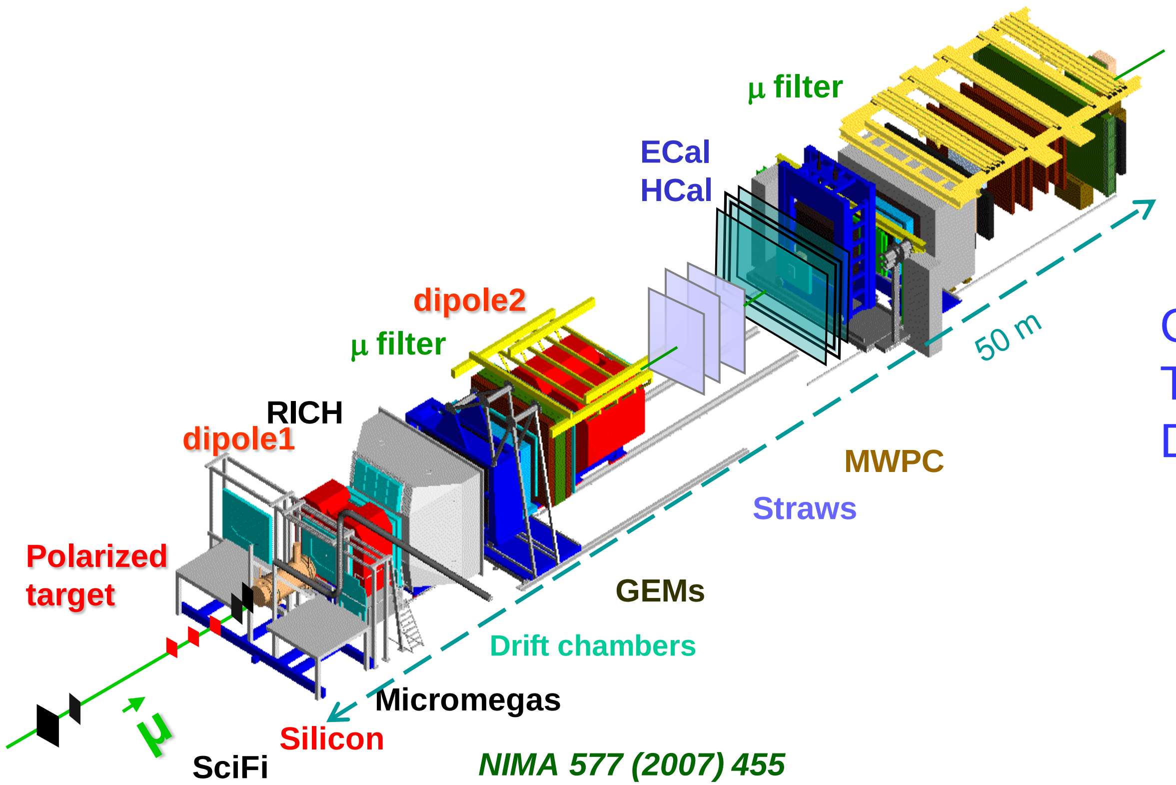
Fixed target
Secondary 200 GeV muon and hadron beams from CERN SPS
→ Multipurpose setup

Polarized muon beam
& polarized target: d, p

Nucleon spin structure

Hadron beam π / K / p
& LH_2 or nuclei

Meson spectroscopy
π, K polarisabilities



NIMA 577 (2007) 455

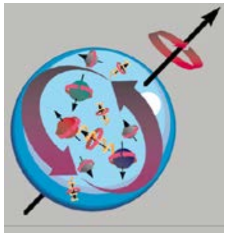
Future:
GPDs from DVCS
TMDs from Polarized Drell-Yan

Nucleon spin

How is the nucleon spin distributed among its constituents?

Nucleon Spin $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$

quark gluon orbital momentum



$\Delta\Sigma$: sum over u, d, s, $\bar{u}$, $\bar{d}$, $\bar{s}$

can take any value: superposition of several states

$\Delta q = \vec{q} - \overleftarrow{q}$

Parton spin parallel or anti parallel to nucleon spin

Past:

Theory: QPM estimations, with relativistic effects $\Delta\Sigma \sim 0.6$

Experiment: "Spin crisis" in 1988, when EMC measured $a_0 = \Delta\Sigma = 0.12 \pm 0.17$

$\overline{\text{MS}}$ scheme

Today:

Precise world data on polarized DIS $g_1 + SU_f(3)$ $a_0 = \Delta\Sigma \sim 0.3$

First results from Lattice QCD on $\Delta\Sigma_{u,d}$ and $L_{u,d}$

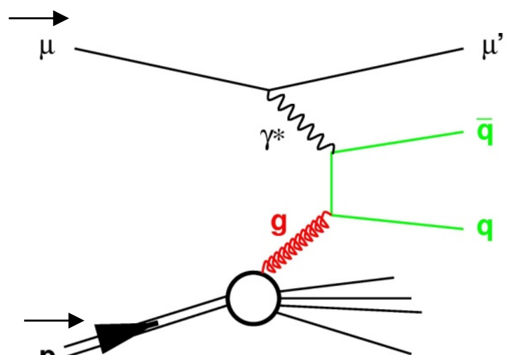
Large experimental effort on ΔG measurement

also because $a_0 = \Delta\Sigma - n_f (\alpha_s/2\pi) \Delta G$ (AB scheme)

Three ways to study gluon spin contribution ΔG

1. Lepton Nucleon

Photon Gluon Fusion

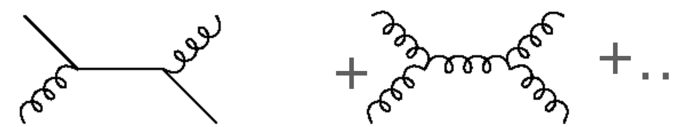


ΔG/G(x)

SMC, HERMES, COMPASS

2. Proton Proton collisions

Gluon-Quark + Gluon-Gluon +…



$$\frac{\Delta G}{G} \times \frac{\Delta q}{q} + \frac{\Delta G}{G} \times \frac{\Delta G}{G} + \ldots$$

A_{LL} (p_T)

RHIC : PHENIX & STAR

3. QCD Q^2 evolution of spin structure function $g_1(x,Q^2)$:
Indirect determination assuming a functional form ΔG(x).
Global fits include polarized DIS, SIDIS and pp data

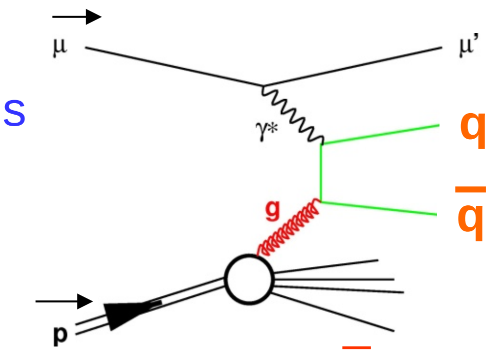
1. ΔG/G from $\overrightarrow{lepton}$ $\vec{N}$ scattering

Photon Gluon Fusion (PGF) process

Asymmetry of cross sections for longitudinal polarizations of beam and target, parallel and antiparallel

$$A_{LL} = R_{PGF} \langle a_{LL} \rangle \langle \Delta G/G \rangle + A_{background}$$

Fraction of process   Analyzing power



$$\gamma\, g \rightarrow q\bar{q}$$

Two signatures for PGF:

1/ q=c open charm c→ D^0 → K π
Clean signature of PGF
Limited statistics & large combinatorial background

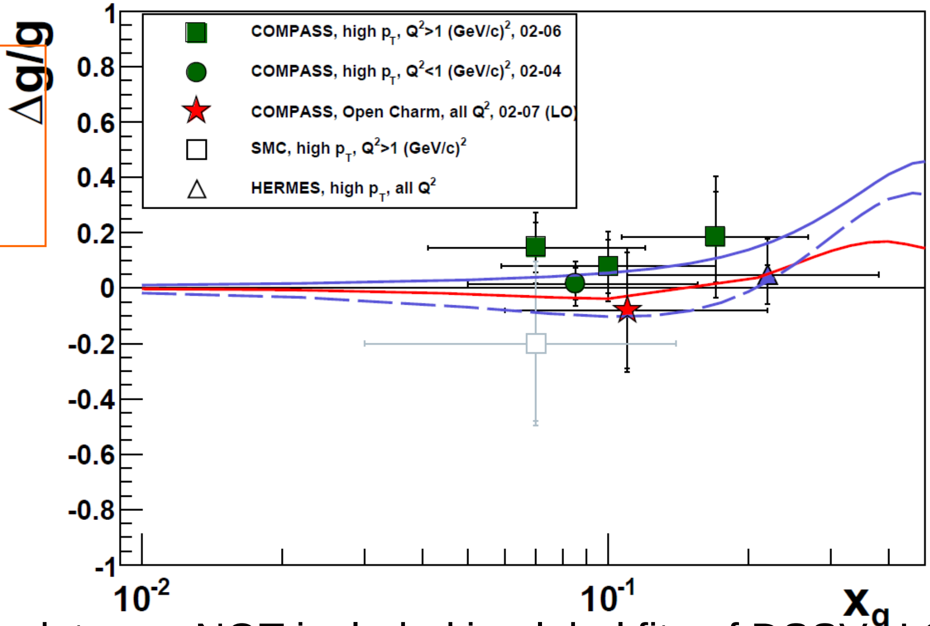
COMPASS :1 point

2/ q= u,d,s high p_T hadron pair q $\bar{q}$ → h h
High statistics
Physical background

COMPASS : 4 points + HERMES &SMC

Δ G/G at LO : SMC, HERMES and COMPASS

High p_T hadrons: Q^2~3
with model for physical background
Open charm: Q^2= 13



LSS10, ΔG~ + 0.32
LSS10, ΔG~ - 0.33 at Q^2= 4
DSSV, ΔG= 0.02 at Q^2=3

Note that these data are NOT included in global fits of DSSV, LSS or NNPDF

- **All direct measurements compatible with 0 or slightly >0**
- **ΔG measured only for 0.03 < x < 0.3**
- **Contribution to <ΔG> outside measured x range not excluded**
- **Results disfavour absolute value of the integral > ~ 0.3**
  i.e. ± 60% of the ½ nucleon spin

- **Results are in agreement with the latest fits NNPDF and DSSV++, using RHIC pp data, which give ΔG ~ 0.05 to 0.15 for 0.05 <x< 0.2**

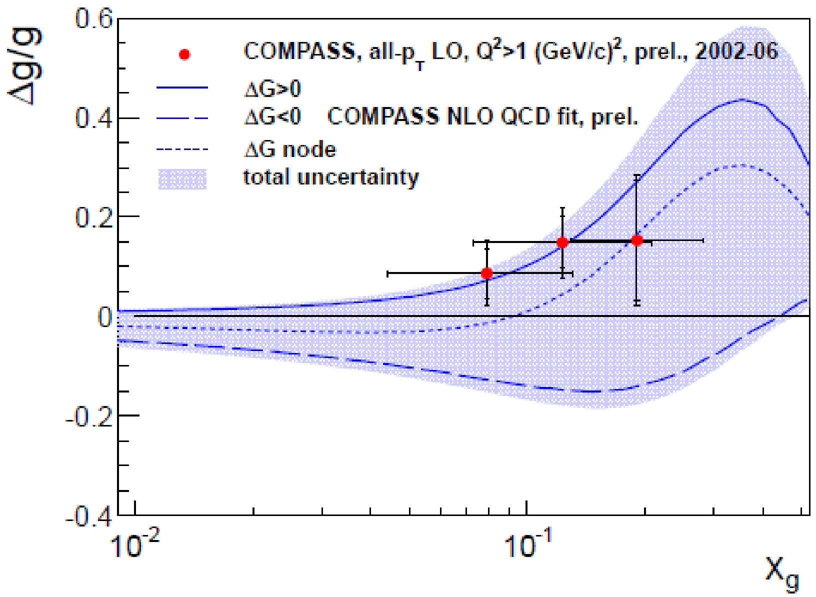
DSSV: De Florian, Sassot, Stratmann, Vogelsang ***LSS: Leader, Sidorov, Stamenov***

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

New: see M. Stolarski talk at DIS-2014 (last week)

New COMPASS results (better precision)

ΔG/G extracted at LO, in 3 x-bins



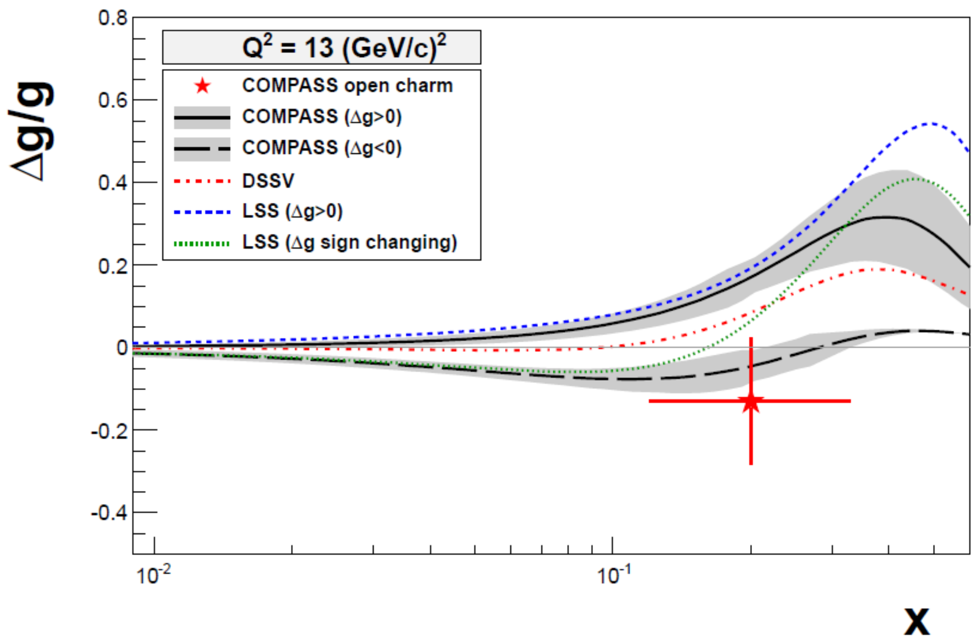
3 solutions from COMPASS NLO QCD fit of g_1 world data (discussed later)

Uncertainty on ΔG/G could be reduced if these results could be included in NLO fits

Δ G/G at NLO : charm channel

The only channel for which the analyzing power a_{LL} is calculated at NLO.

a_{LL} distribution shifted in x → Induces a change in **<ΔG>,** but also in the relative weight of events, hence a change in **<x>**



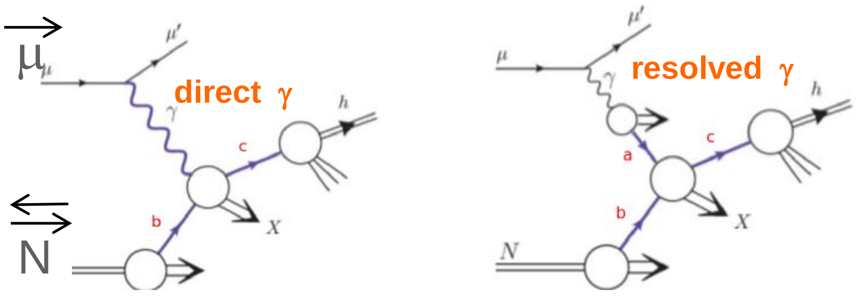
COMPASS PRD87(2013)052018

Value of ΔG still compatible with zero; higher <x > measured

ΔG from high p_T hadron photo production

- Measure spin asymmetry $A_{LL}(p_T)$
  Method 'à la RHIC': No direct extraction of ΔG → no model needed

- Compare to theoretical calculations with various assumptions for $\Delta G(x)$,



All processes taken into account: **γg** (PGF)
γq (QCD Compton) and all **resolved γ**.

First step: check agreement theory/experiment for unpolarized cross section

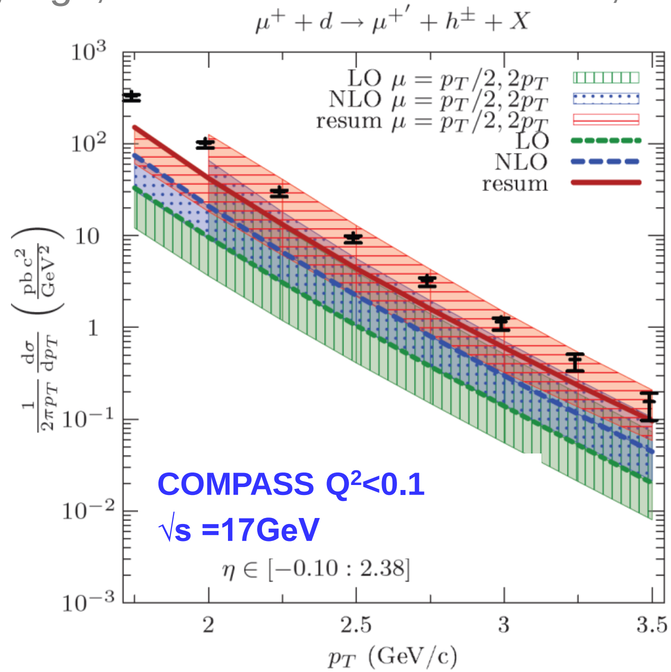
Stratmann, Jager, Vogelsang, EPJC 44(2005) 533

ΔG from $A_{LL}(p_T)$ high p_T hadron photo production

COMPASS absolute cross-section measurement $\mu\, d \rightarrow \mu'\, h^{+/-}\, X$

Compared to pQCD calculation with resummation 'all orders'

(soft gluons, leading logs; available for cross section, in progress for polarized case)



De Florian, Pfeuffer; Schaeffer, Vogelsang, PRD 88 (2013)

COMPASS, PRD 88 (2013) 091101

--- Resummation

--- NLO

--- LO

Bands= scale uncertainty

Data / theory in agreement over 4 orders of magnitude

→ Settles the theory framework for ΔG from high p_T events at this scale

Next step : Spin asymmetries $A_{LL}(p_T)$ for same events (next slide)

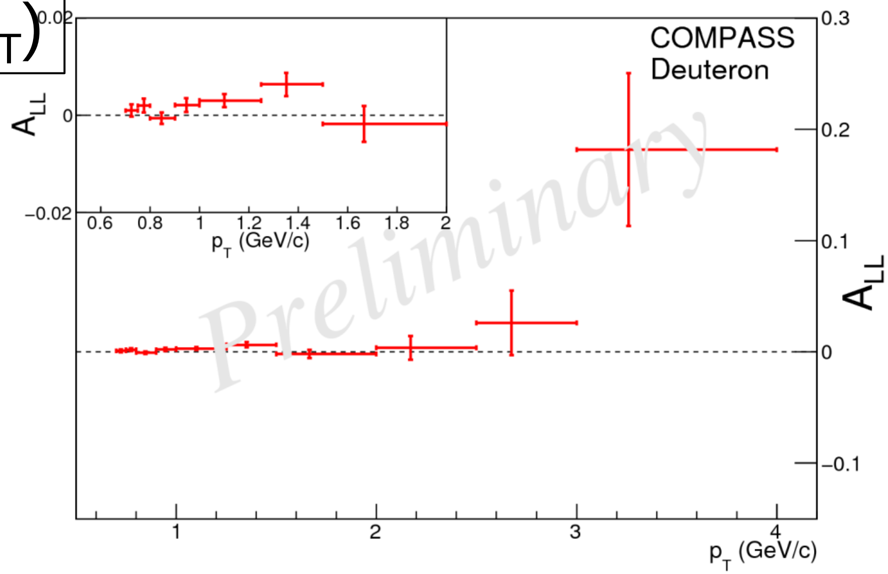
To be compared to calculations with ΔG hypotheses

ΔG from $A_{LL}(p_T)$ high p_T hadron photo production

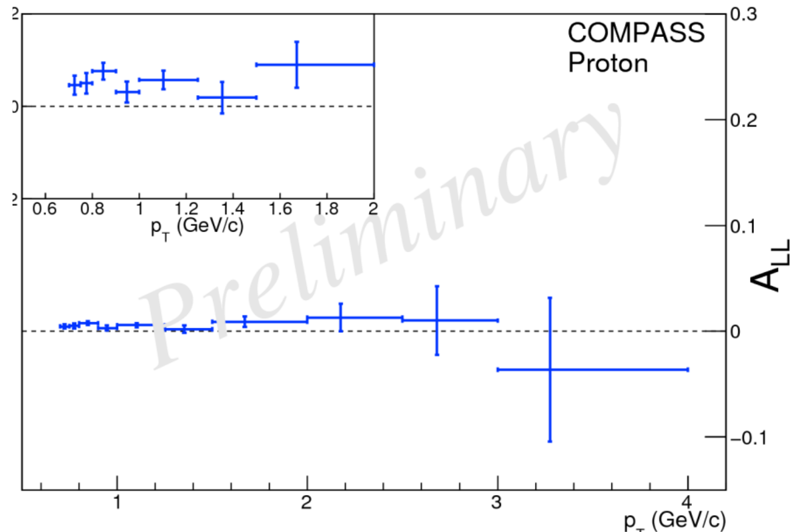
COMPASS preliminary results for the spin asymmetry $A_{LL}(p_T)$

$A_{LL}(p_T)$

Deuteron



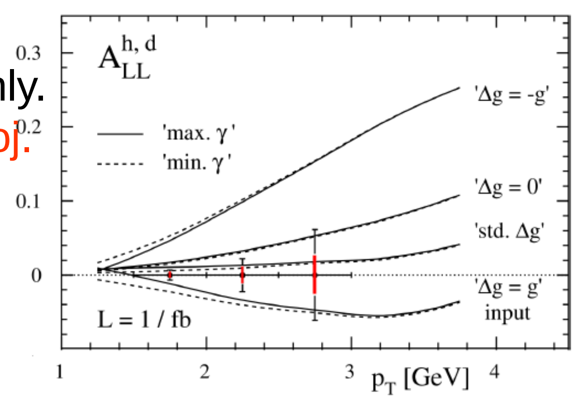
Proton

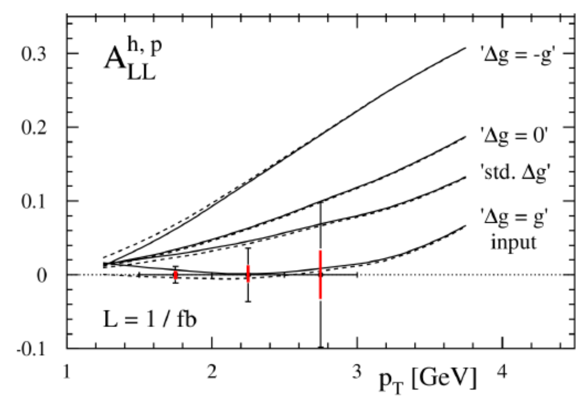


M. Levillain at DIS-2014

Need full calculation with resummations before concluding

Predictions
Jager (2005), NLO only.
In red: COMPASS proj.





ΔG from Q^2 evolution of g_1. Global QCD fits

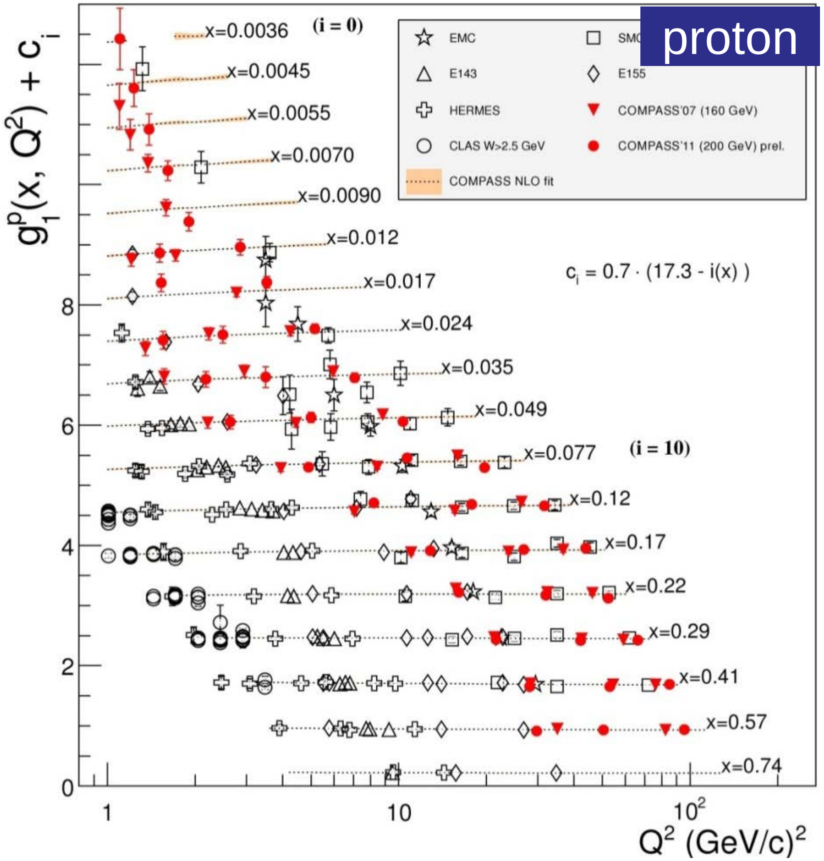
Pol. Deep Inelastic Scattering

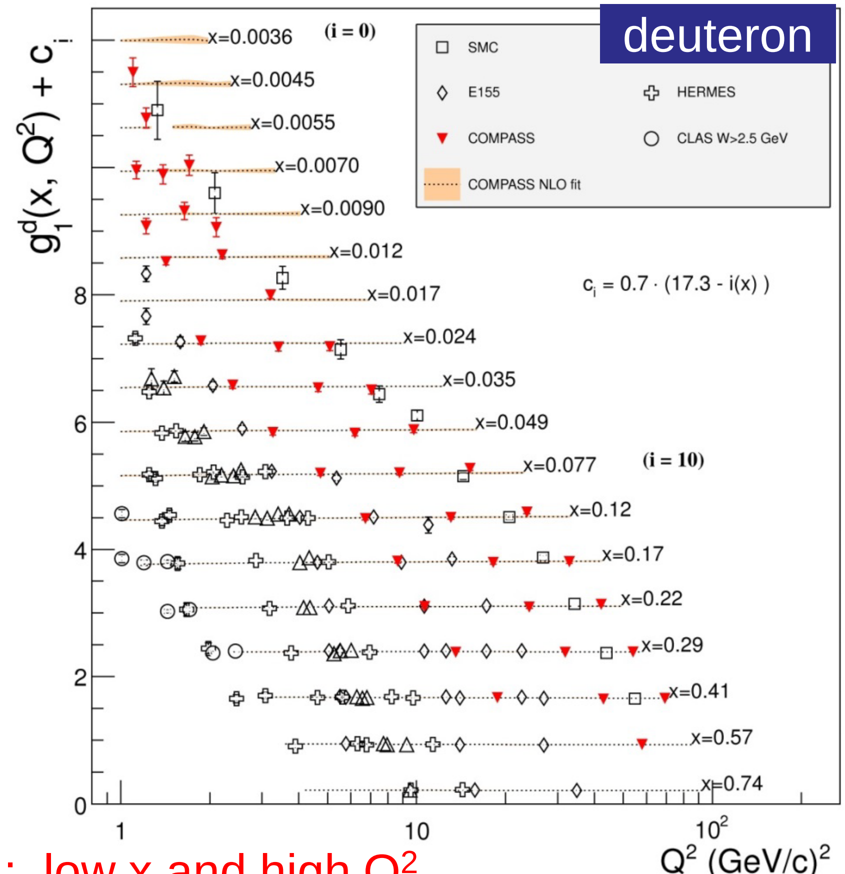
→ spin structure functions g_1

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

$$A_1^{DIS} \propto g_1(x) \propto \frac{1}{2}\Sigma e_q^2\left(\Delta q(x)+\Delta\bar{q}(x)\right)$$

→ g_1 as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta G(x)$





New data from COMPASS 200 GeV : low x and high Q^2

However x and Q^2 coverage not yet sufficient for precise ΔG

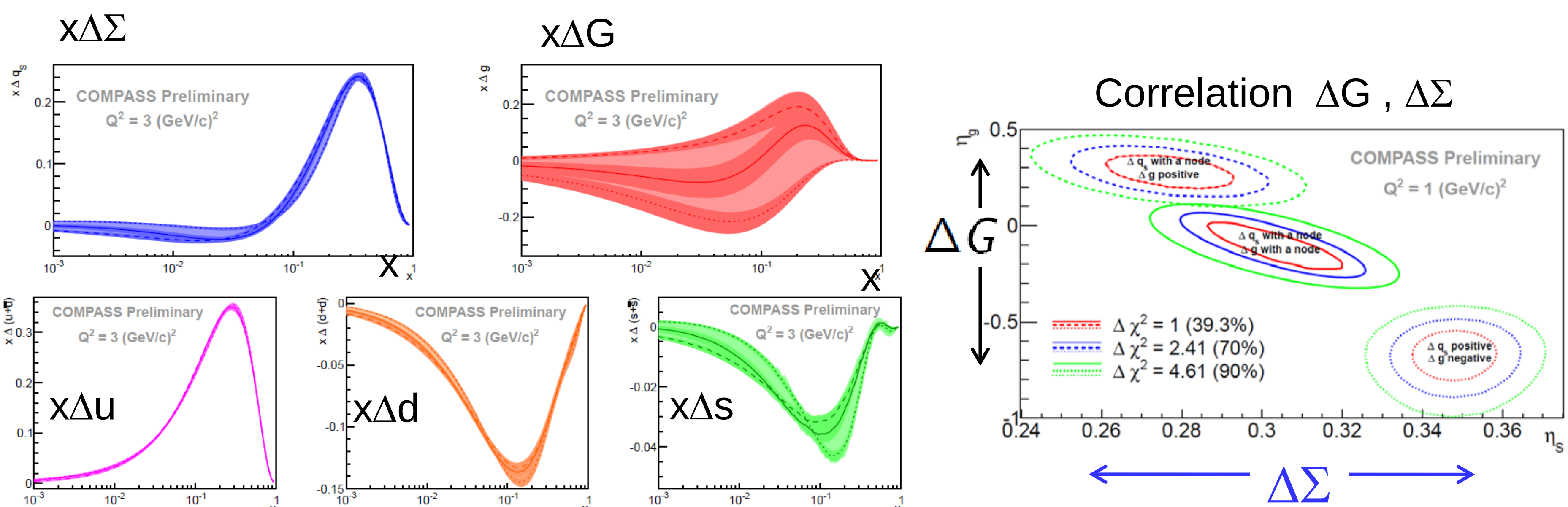
Use also constraint from pp data (DSSV)

M. Wielfert at DIS-2014

COMPASS NLO pQCD fit of g_1 world data

- Assume functional forms for $\Delta\Sigma$, ΔG and Δq^{NS} .   Assume SU3
- Use DGLAP equations, relating $\Delta\Sigma$, ΔG evolutions . Fit world data.

→ 3 classes of solutions, $\Delta G>0$, ΔG with a node, and $\Delta G<0$



- Quark spin contribution : $0.26 < \Delta\Sigma < 0.34$ at Q^2=3 $(GeV/c)^2$

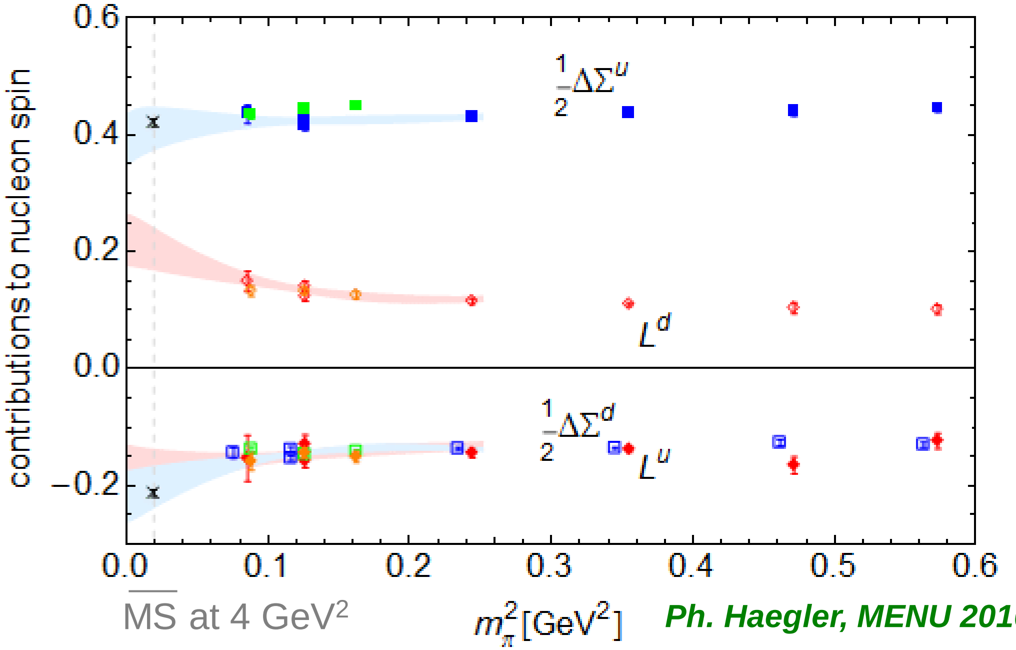
Largest uncertainty comes from the bad knowledge of functional forms (for $\Delta G(x)$).

Result in fair agreement with other global fits, and with Lattice QCD.

- Gluon spin contribution: ΔG not well constrained, even the sign, using DIS only

  Solution with node agrees with result from DSSV++ using RHIC pp data

Lattice : quark spin and angular momentum



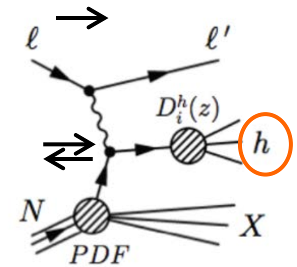
Ph. Haegler, MENU 2010

- **Impressive results from lattice QCD**
- **Agreement with measurements for quark spin**
- **Predictions for angular momentum**

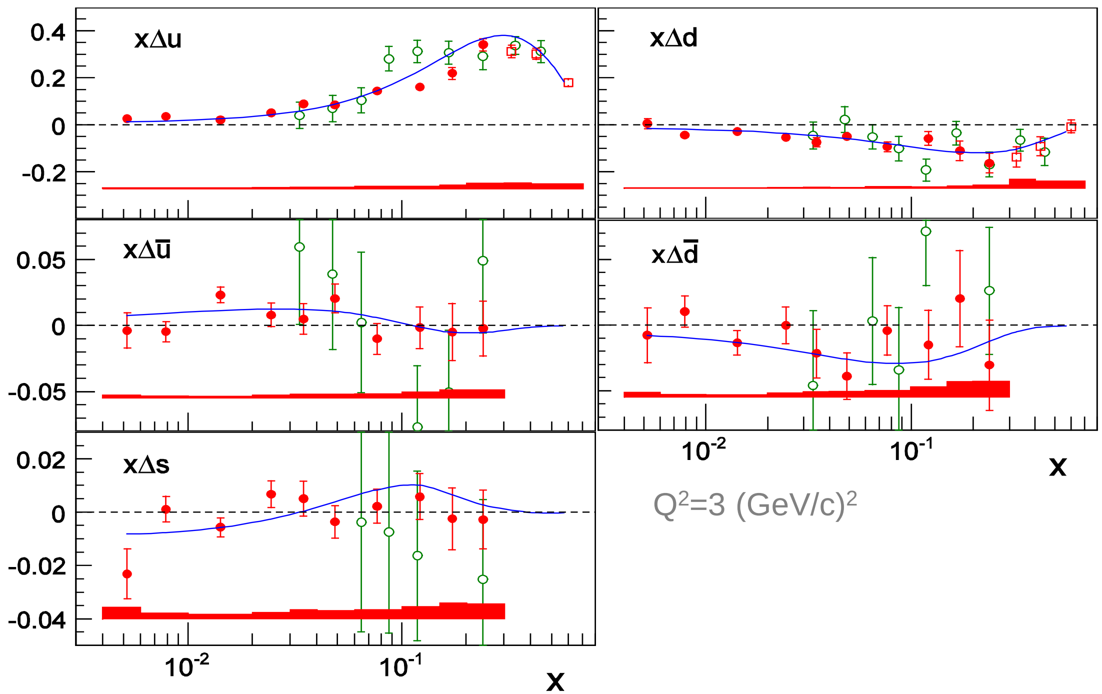
Quark helicities per flavor from SIDIS

$l^{\rightarrow} p^{\rightarrow} \rightarrow l\, h^{+/-}\, x$

Hadron tags quark flavor
(quark fragmentation functions)



Leading order extraction of quark helicities from spin asymmetries



- **COMPASS**
  PLB693(2010)227, using DSS quark FFs
- o **HERMES**
  PRD71(2005)012003
- __ DSSV at NLO

- **Full flavour separation → x~0.004**
- **Sea quark distributions ~ zero**
- **Good agreement with global fits**

Strange quark polarization – Δs puzzle

- **DIS data**: **Integral of Δs** is extracted from the integral of g_1 using two other inputs (n and hyperon decay) & SU(3)

  → $\int \Delta s + \Delta\bar{s} \approx 0.08$

- **SIDIS data**: **Δs(x)** measured from **kaon** spin asymmetries, using quark fragmentation functions, in particular D_s^K, (s quark fragmentation into K)

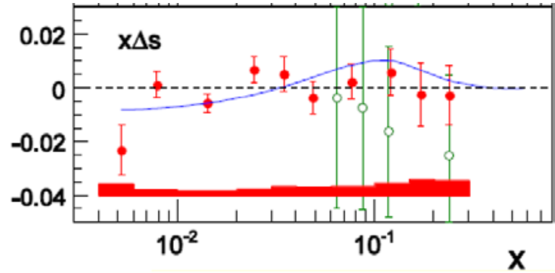
  → $\Delta s(x) \approx 0$

Several possible explanations to the discrepancy :

- Uncertainty on D_s^K
- Global fits (DSSV, LSS) suggest negative Δs at low x reconciles the two approaches
- SU(3) violation a_8 from 0.58 to 0.42

→ Δs=-0.02 *Bass &Thomas, PLB 684(2010)216*

COMPASS PLB 693(2010)227



To come: new data on quark fragmentation functions and data on Δs at low x **COMPASS 200 GeV**

Quark Fragmentation Functions (FF)

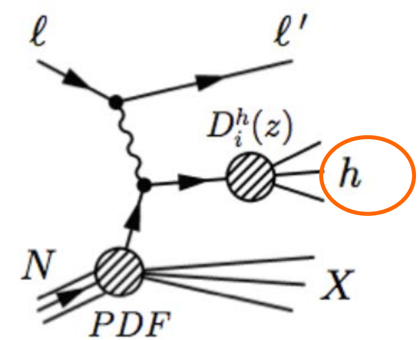
FFs : - Non perturbative, needed to describe various reactions

- Needed to access to strange quark polar. Δs measured in polar. SIDIS. strange quark FF= largest uncertainty in this extraction.

Data exist from e^+e^- and pp reactions, but unsufficient and at too high Q^2

Measure multiplicity of π, K, p in **SIDIS**

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



PDFs FFs

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

Input to global QCD analyses to extract quark FF

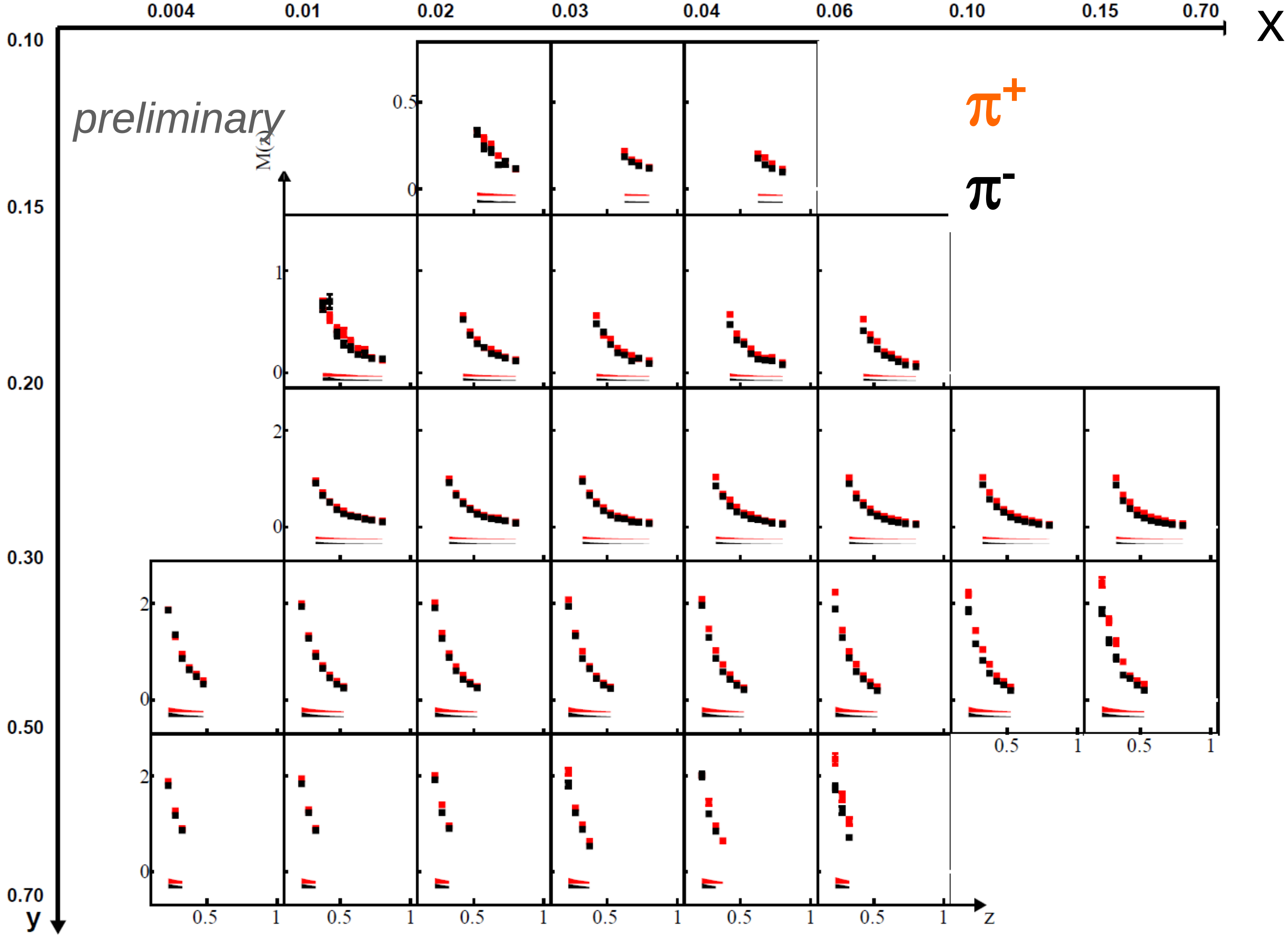
Fine binning in x, z, Q^2

PDFs depend on x, while FFs depend on z.

π^+ and π^- multiplicities vs z in (x,y) bins

COMPASS prelim. DIS-2013

~ 500 data points for π



NB- Also measured: kaon multiplicities, 2h multiplicities.

To come soon: k_T dependence

Quark FFs into π, from COMPASS fits

N.Dufresnes at DIS-2014 Starting from π multiplicities, extract 2 FFs.

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

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

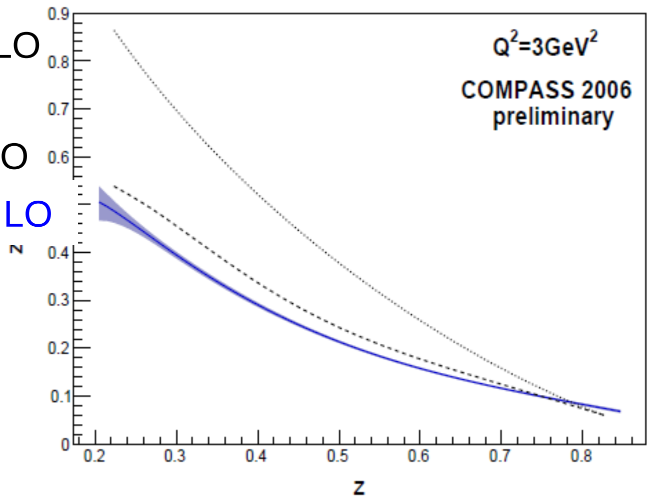
And assuming $D_{unf}^{\pi+} = D_s^{\pi+} = D_s^{\pi-}$

$z.D_{fav}^{\pi+}$

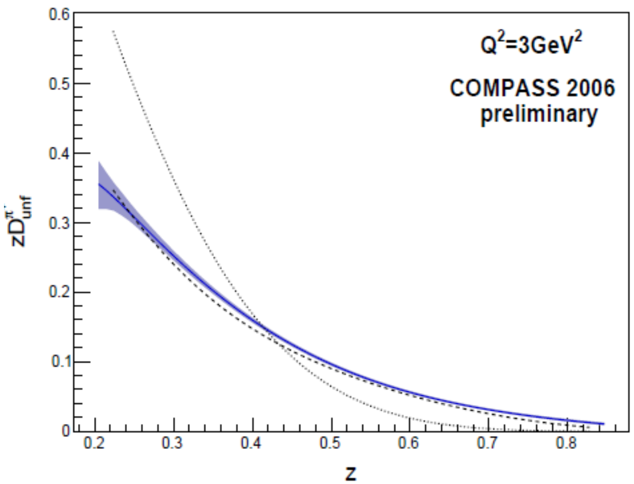
HNKS NLO

DSS NLO

COMPASS LO



$z.D_{unfav}^{\pi+}$



COMPASS LO

….. DSS NLO

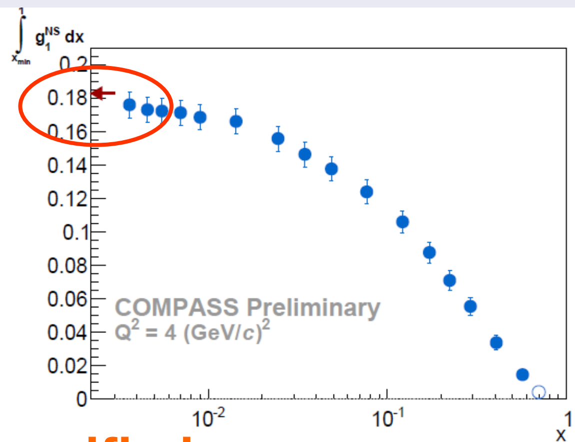
----- HNKS NLO

Next step: Fragmentation functions into kaons D_s^{K+} and D_s^{K-} starting from kaon multiplicities

Results for Bjorken sum rule from g_1 COMPASS data

Fundamental QCD sum rule, which relates proton and neutron spin structure functions g_1.

$$\int_0^1 \left(g_1^p(x,Q^2) - g_1^n(x,Q^2)\right) dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C_1^{NS}(Q^2)$$



- COMPASS result
- g_A from n β decay

M. Wielfert, DIS-2014

→ **Bjorken sum rule verified**

Better statistics and systematics studies compared to previously

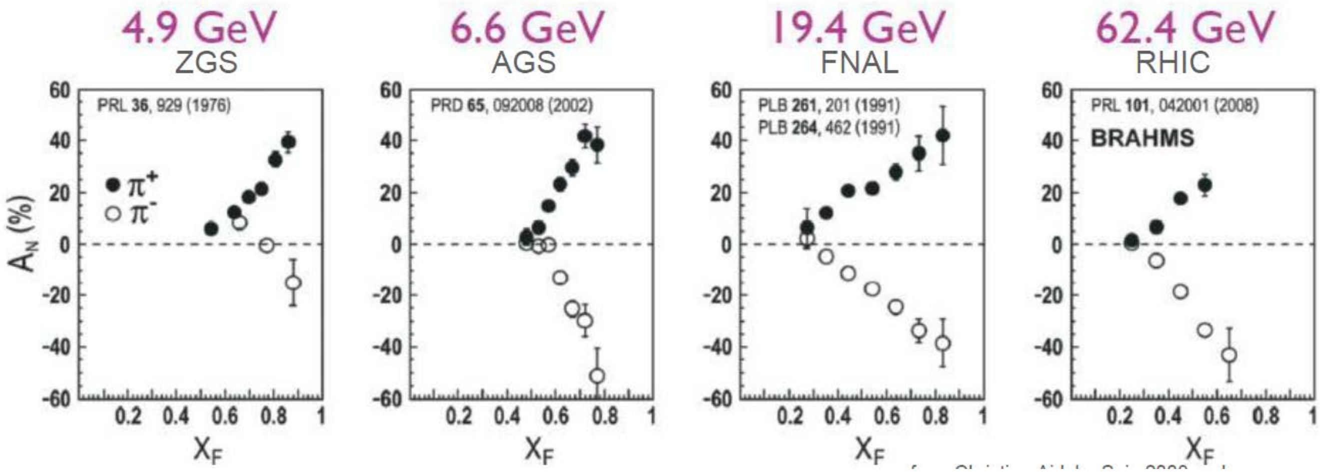
$$(g_A/g_V)_{NLO} = 1.219 \pm 0.052(\text{stat.}) \pm 0.095(\text{syst.})$$
$$(g_A/g_V)_{\text{"N"NLO}} = 1.251 \pm 0.053(\text{stat.}) \pm 0.097(\text{syst.})$$

Using NLO result for Γ_1^{NS} and C_1^{NS} in NNLO

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

Transverse spin

Where it all started from... (1978) $pp^{\uparrow} \rightarrow \pi X$ $\frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow}$ large p_T

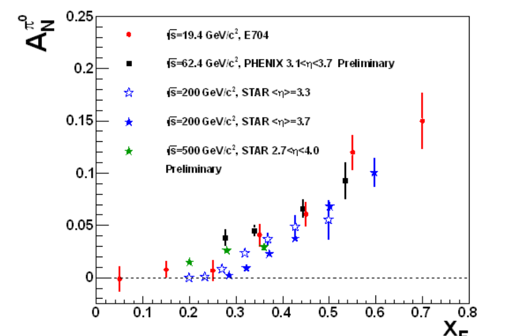


Unexpected large single spin asymmetry

Attributed to correlations between nucleon spin, orbital angular momentum, transverse momentum k_T of partons…

200 GeV

$pp^{\uparrow} \rightarrow \pi^0 X$



FNAL E704… and latest RHIC results from PHENIX and STAR on π^0.

Transversity

Three distribution functions are necessary to describe the structure of the nucleon at LO in the collinear case:

- **q(x) :** number density or **unpolarised distribution**
- **$\Delta q(x) = q^{\rightrightarrows} - q^{\leftrightarrows}$** : longitudinal polarization or **helicity distribution**
- **$\Delta_T q(x) = q^{\uparrow\uparrow} - q^{\downarrow\uparrow}$** : transverse polarization or **transversity distribution**

All 3 of equal importance

Further distributions exist, Transverse Momentum Dependent (**TMD**) , revealing correlations between **nucleon spin, quark spin** and **quark transverse momentum k_T**.

All measured simultaneously in SIDIS.

Among them, the **Sivers** function.

See talk of H. Avakian

Transversity- Collins and Sivers asymmetries

- Access via **SIDIS**, transversely polarized target $l\ p^{\uparrow} \rightarrow l\ h^{+/-}\ X$

- Measure simultaneously several azimuthal asymmetries, out of which :

  - Collins: Outgoing hadron direction & quark transverse spin
  - Sivers: Nucleon spin & quark transverse momentum k_T

at LO: **Collins**

q transverse spin distr.

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q \otimes \Delta_T{}^{\circ} D_q^h}{\sum_q e_q^2 \cdot q \otimes D_q^h}$$

Collins fragmentation function, depends on spin

Sivers

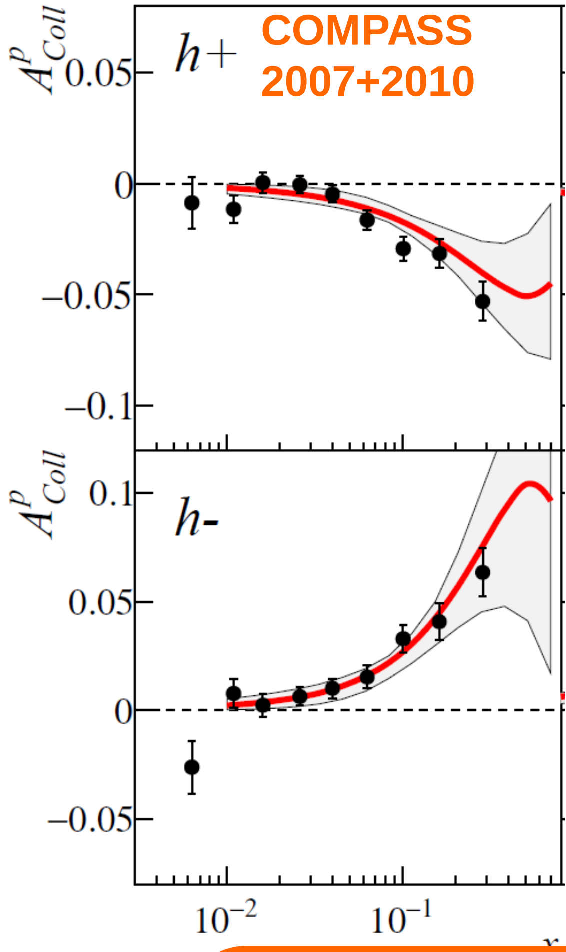
Usual quark fragmentation function

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot f_{1Tq}^{\perp} \otimes D_q^h}{\sum_q e_q^2 \cdot q \otimes D_q^h}$$

note: $\Delta_T q$ also measured in SIDIS using
- ''Two hadron'' fragmentation function
- lambda Transverse Polarization

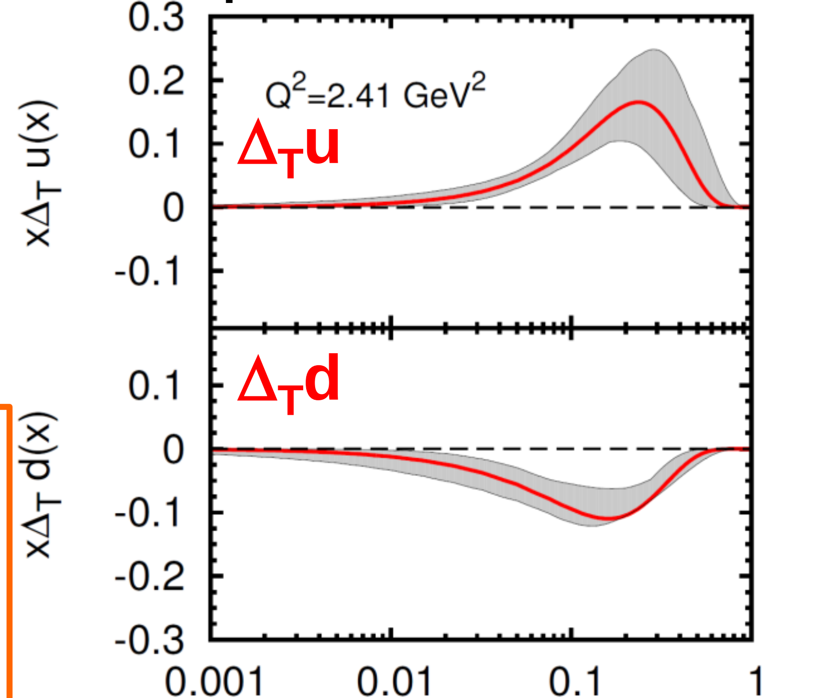
Also accessed in pp

Collins asymmetry → Transversity $\Delta_T u$ $\Delta_T d$



- **Large signal with proton target.**
  (Is zero with deuteron target)
- **Same signal strength seen by HERMES and COMPASS, although different Q^2 (times 4)**

Several combined analyses of polarized SIDIS data **HERMES p, COMPASS p and d**, and **BELLE FF**



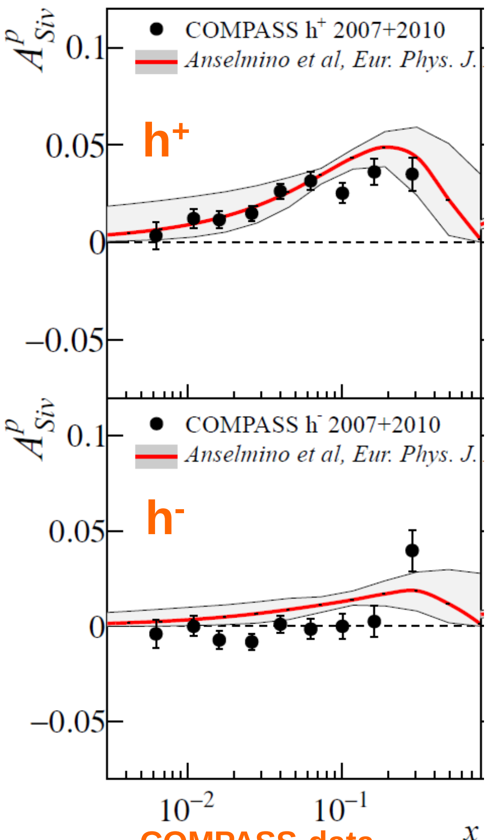
M. Anselmino et al., PRD87 (2013) 094019

- **$\Delta_T u > 0$ and $\Delta_T d < 0$**
- Do not saturate Soffer bound
- Smaller than helicity
- Derived also from di-hadron (not shown here)

F. Kunne

Sivers asymmetry → Sivers function

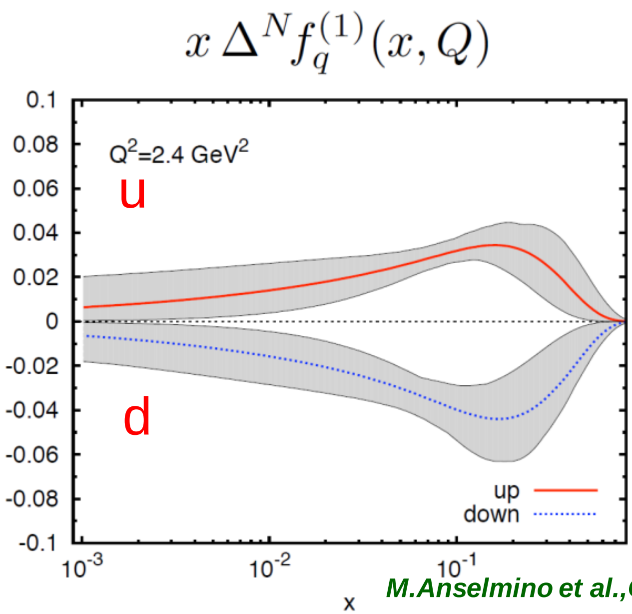
Correlation between Nucleon spin & quark transverse momentum k_T



COMPASS data
With Anselmino
et al. global analysis

Large signal with proton target and h+
Was measured to be zero on deuteron

Smaller strength at larger Q^2



M.Anselmino et al.,QNP2012

→ u and d quark Sivers function opposite

Physics with hadron beams

Physics with hadron beams

π, K, p beams - 200 GeV : broad spectrum in energy transfer t
Charged & neutral channels
Huge statistics
Potential for discovery of small intensity eventual new states

Selected results

- Diffractive processes $\pi^- p \rightarrow \pi^-\pi^+\pi^- p_{recoil}$ Search for exotic mesons & hybrids
- Central production $p\, p \rightarrow p K^+ K^- p$ Search for glueballs
- Pion polarisability π^- Ni $\rightarrow \pi^-$ Ni γ Chiral PT

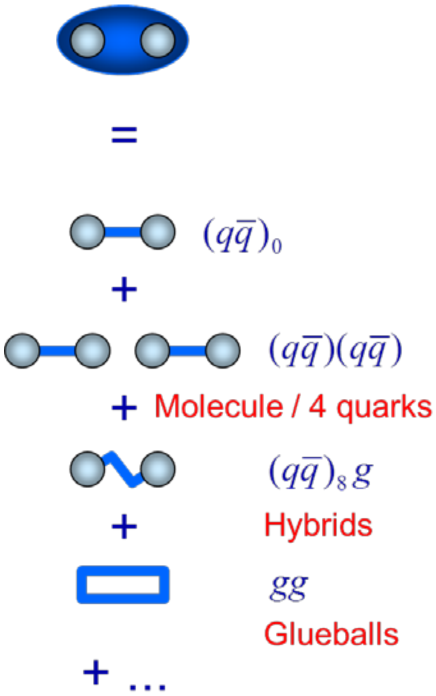
Light mesons

Allowed combinations

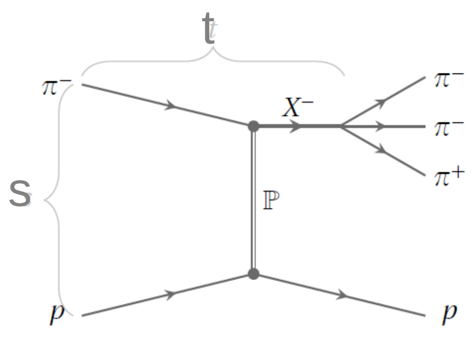
$$J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$$

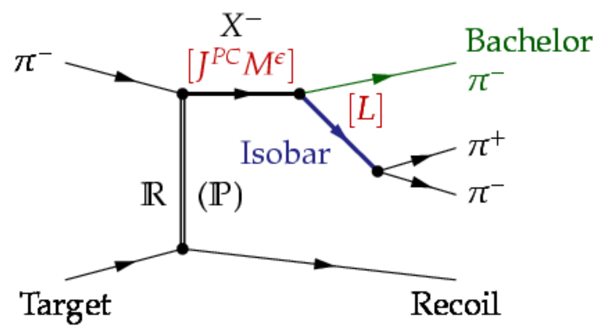
"Forbidden" combinations

$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$$



Diffractive resonance production in $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{recoil}$





Isobar model

Partial waves :

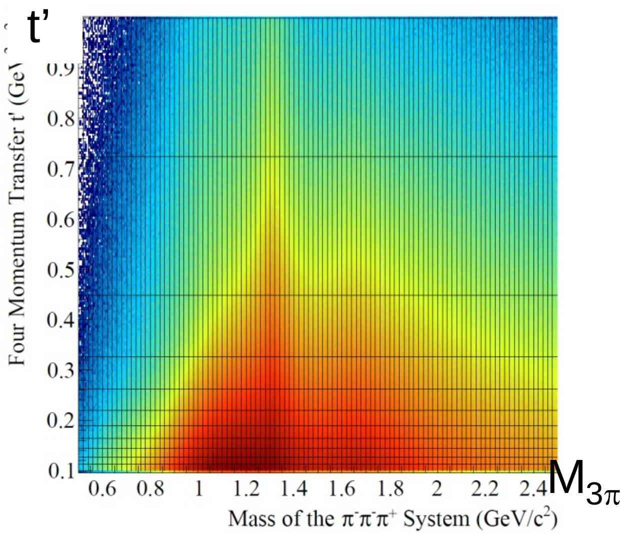
J^{PC} M^{ε} [isobar] L

J^{PC}-exotic mesons

Partial Wave Analysis (PWA):

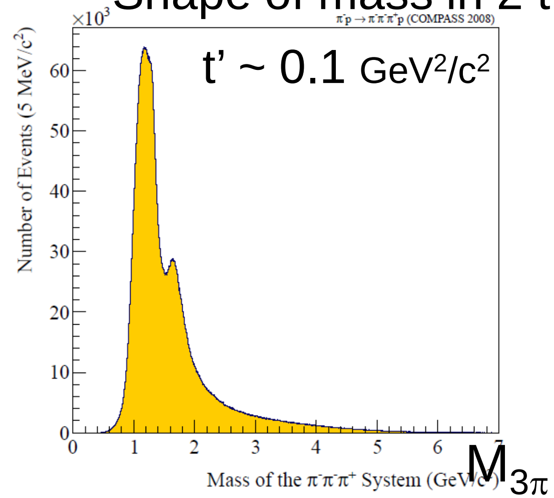
Step 1: In ($M_{3\pi}$, t') bins, 88 PW, (27 with thresholds)
Impose isobar description

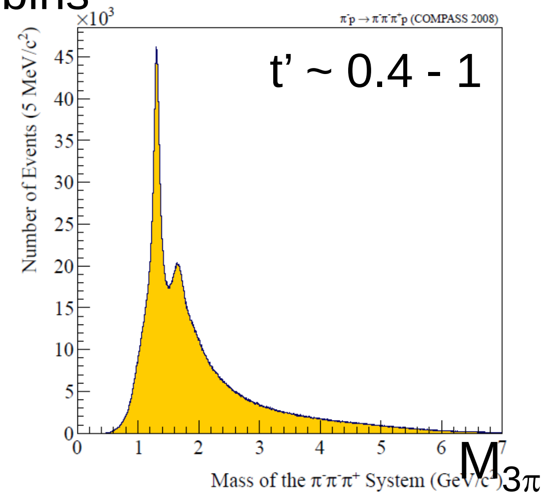
Step 2: $M_{3\pi}$ dependent fits on selected waves,
combined fit of t' bins
(same mass, width; different background and couplings)
Extract resonance parameters



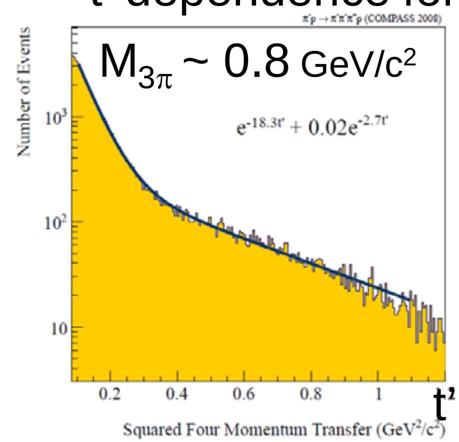
11 x 100 (t',$M_{3\pi}$) bins

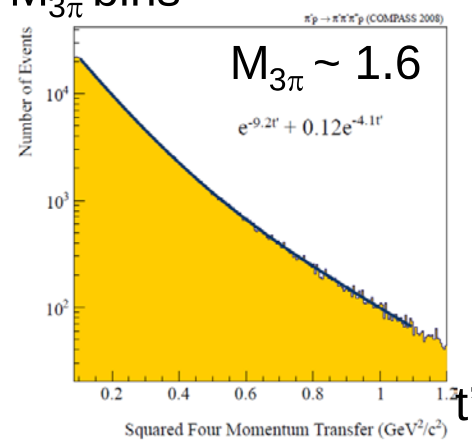
Shape of mass in 2 t' bins





t' dependence for 2 $M_{3\pi}$ bins





Step 1: PWA in (M, t') bins

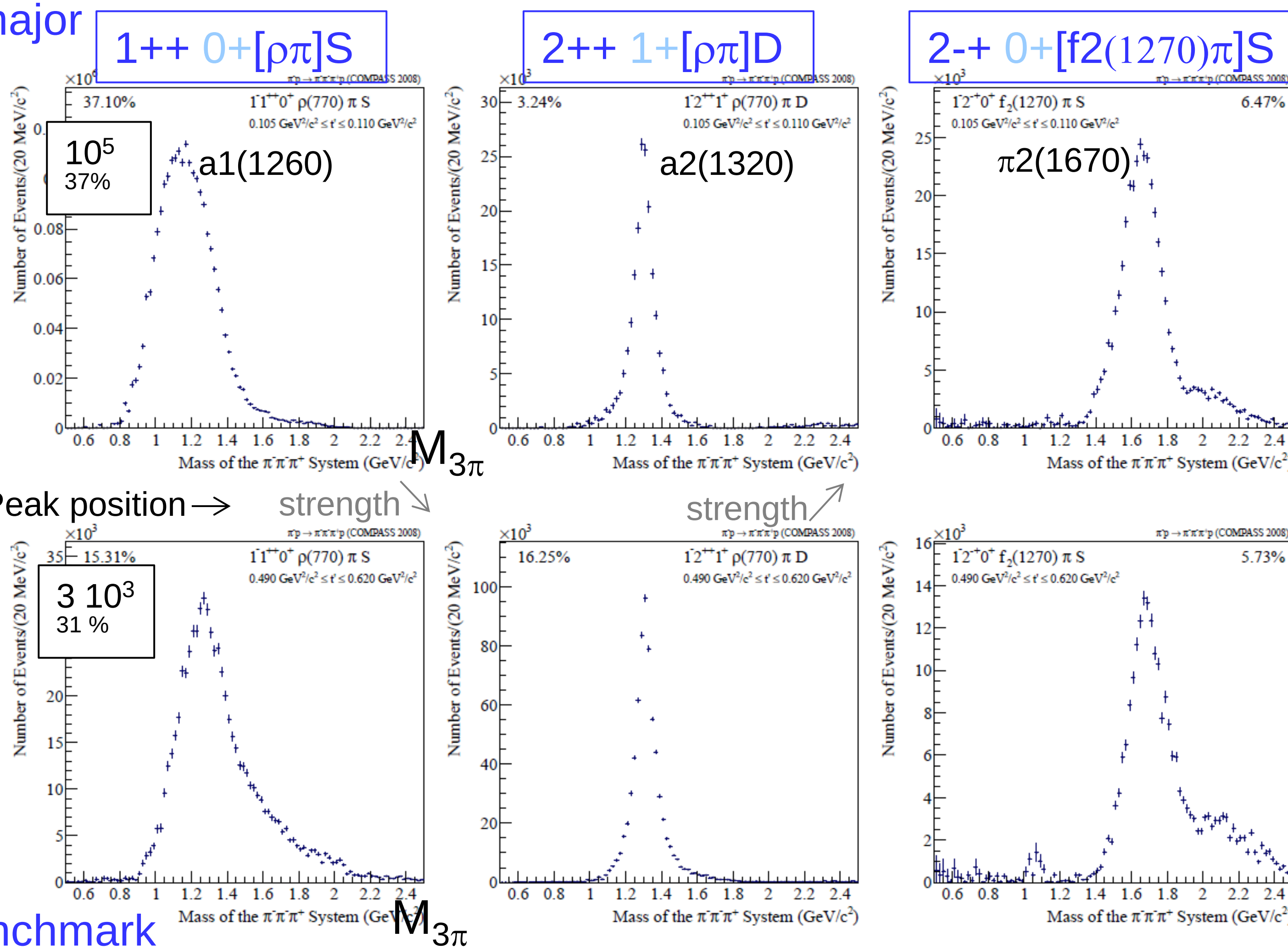
Intensities for 3 major waves vs $M_{3\pi}$

t'~0.1

(GeV^2/c^2)

100 $M_{3\pi}$ bins

t'~0.5

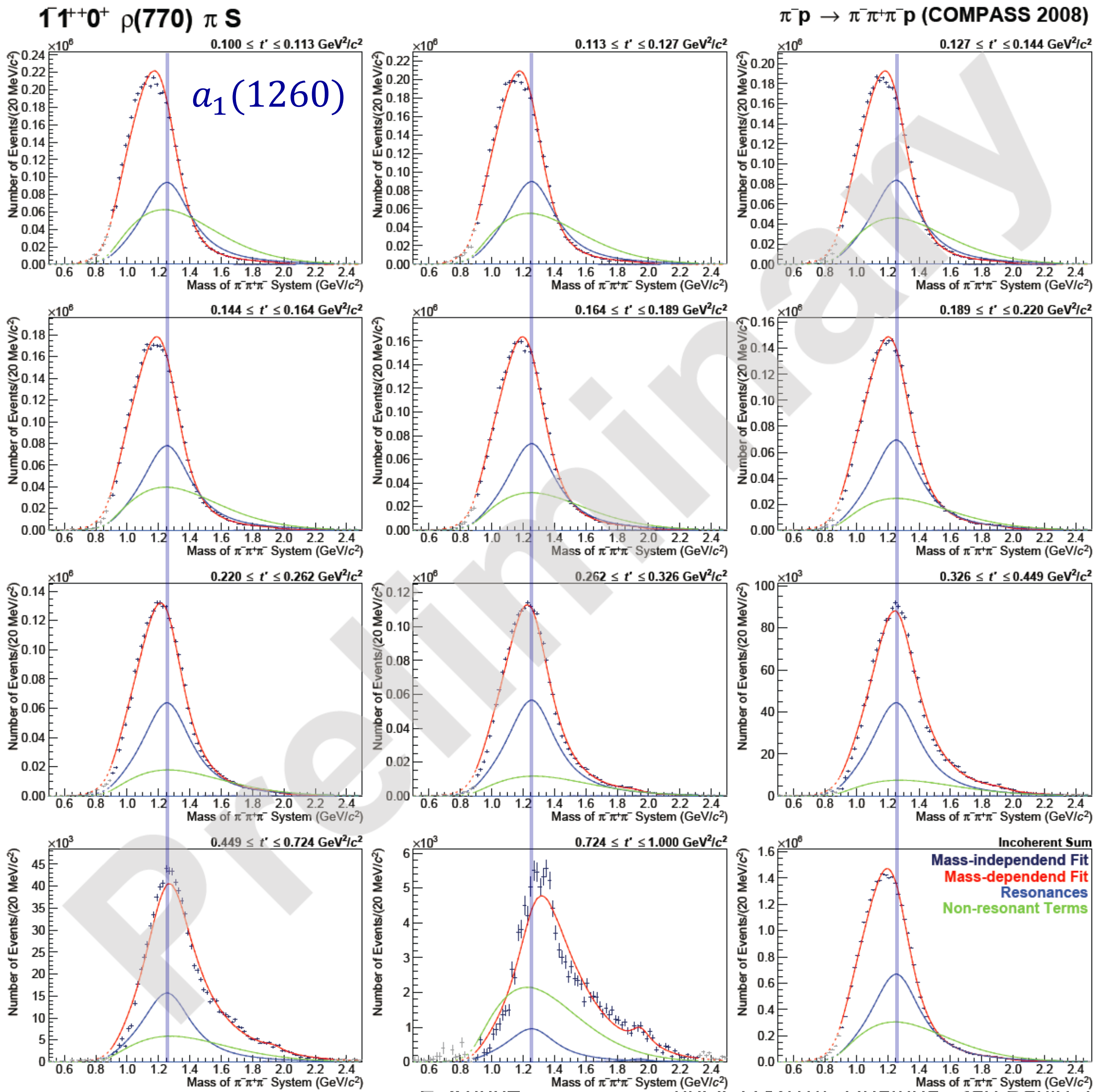


- a1 as benchmark
- Possibility of separation of resonant and non resonant content

  high statistics & fine binning

Step 2 : PWA M dependent fit, ex: $1^{++}0^{+}$ $\rho(770)\pi$ S

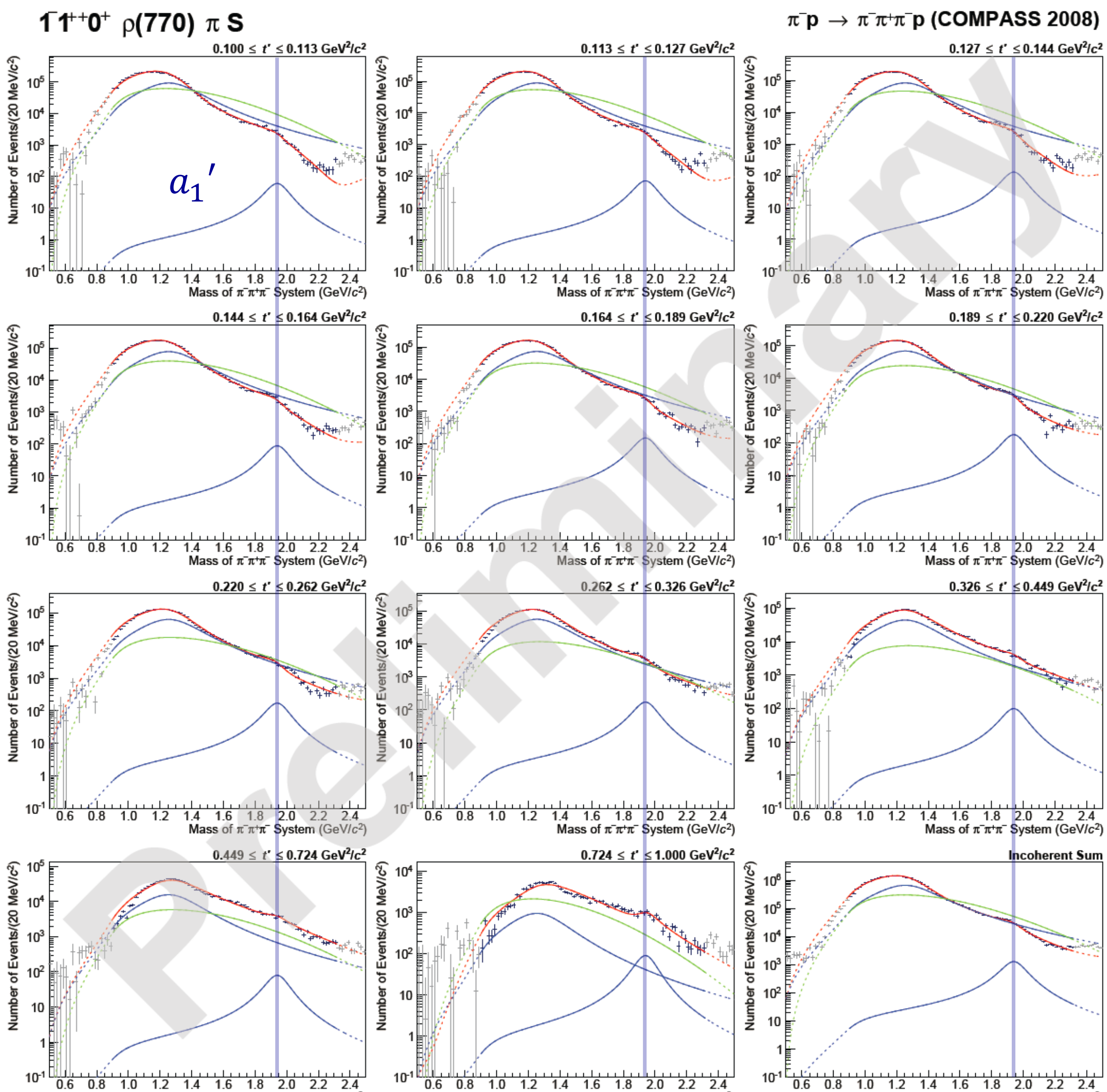
11 t' slices



Incoherent sum

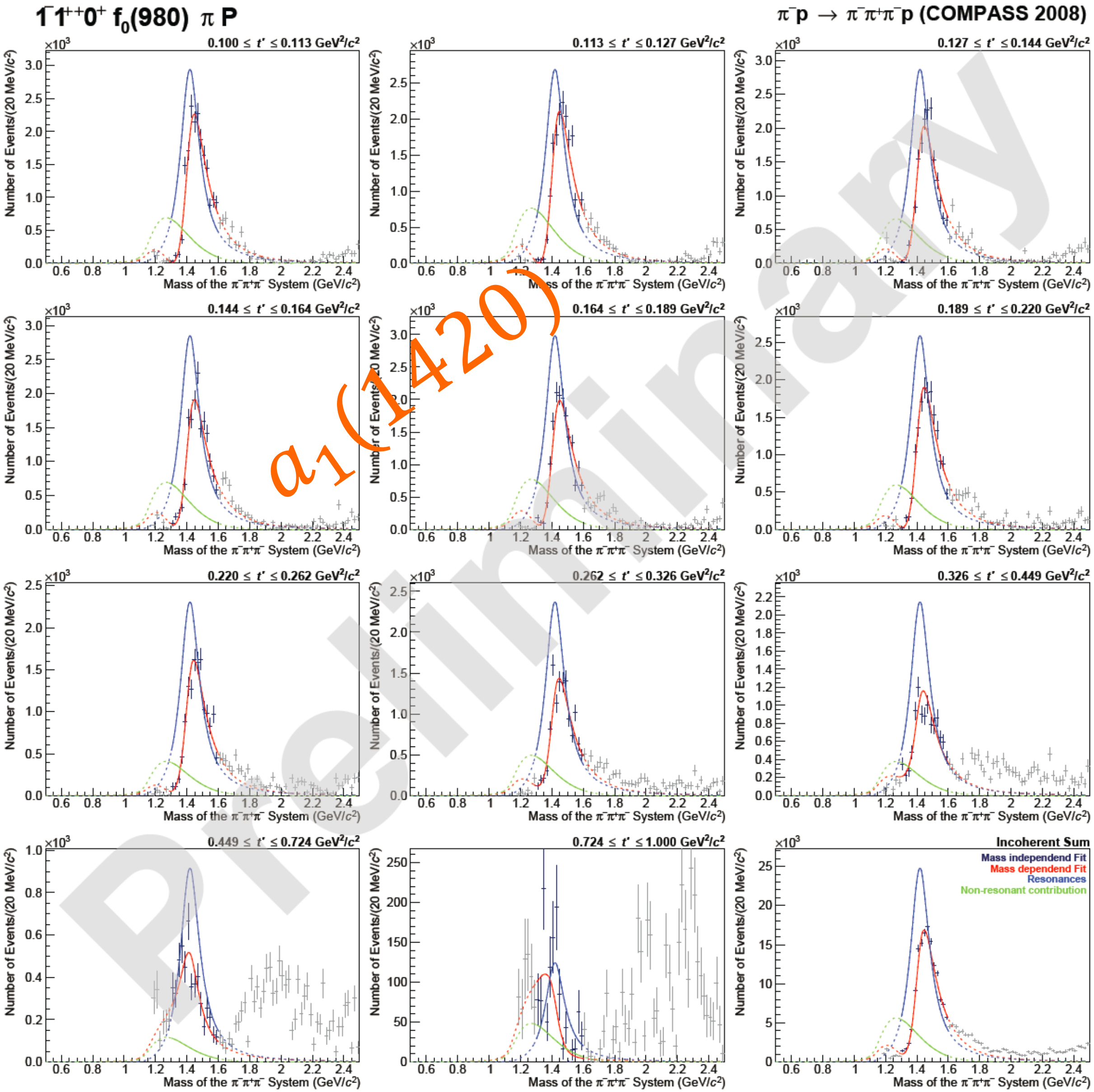
Same wave $1^{++}0^{+}$ $\rho(770)\pi$ S log scale

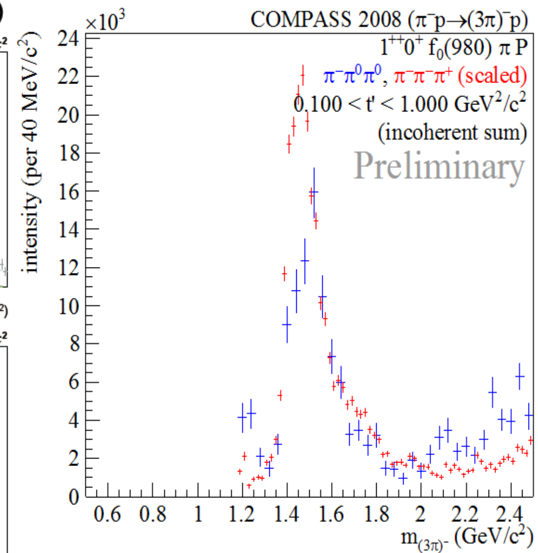
11 t' slices



Incoherent sum

New a_1 (1420) - $1^{++}0^+$ $f_0(980)\pi$ P





- Seen in charged and neutral channels
- Accessible thanks to high statistics

Γ = 130-150 MeV

Diffractive resonance production - conclusion

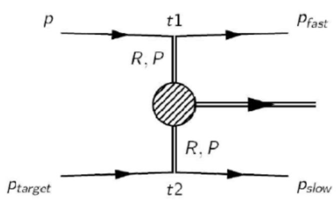
- **Mass dependent PWA of 3π charged channel**,
Huge statistics , 50 M events, 10 times more than previous expts
11 t' bins

- Precise determination of resonance parameters

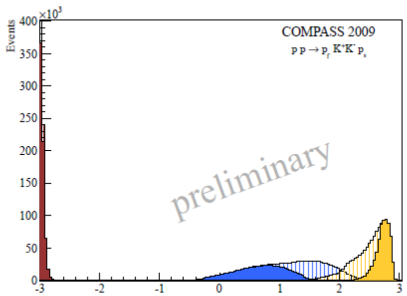
- Analysis proves the potential for establishing new small waves with firm grounds

- **New $a_1(1420) \rightarrow f_0(980)\,\pi$**

Central production p p→ pK⁺K⁻p



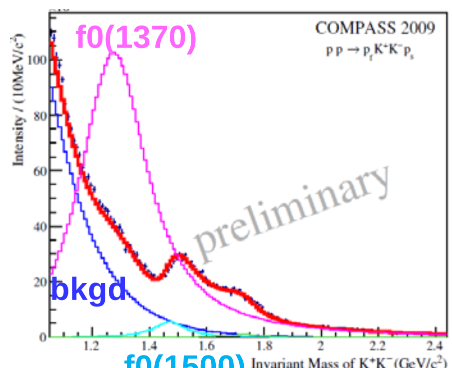
Double Pomeron exchange → glue rich environment
Production of non q-$\bar{q}$ meson (glueballs, hybrids) at central rapidities



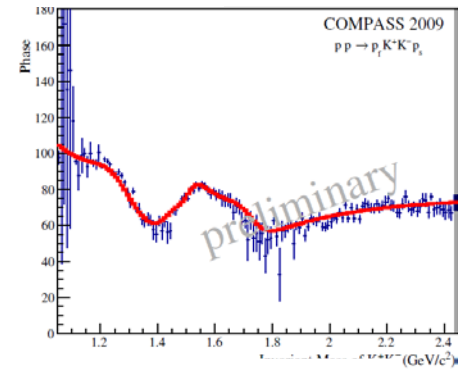
rapidities

pK+K-p channel
Selection of central production
Cut on p(p_{fast}) >140 GeV;
K id (RICH)

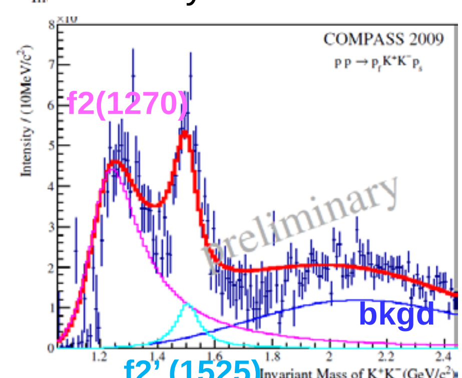
Intensity of S wave



Phase S-D



Intensity of D wave



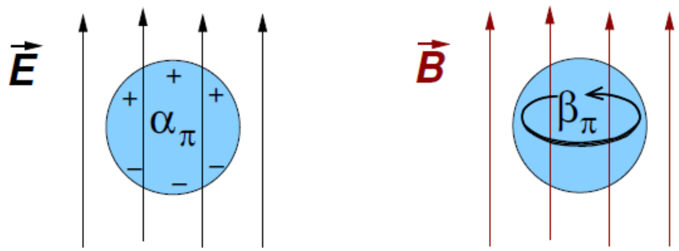
Mass dependent PWA

- Preliminary fit requires strong f_0(1370) signal
- Strong background (non resonant contributions at low mass)

Ch PT - Pion polarisabilities

Polarisabilities: deviation from pointlike particle

electric (α) and magnetic (β)



Predictions from Ch PT:

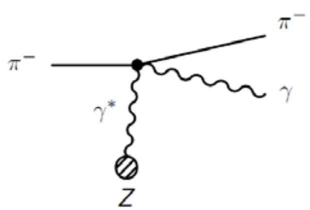
$$\alpha_\pi + \beta_\pi = (0.2 \pm 0.1) \cdot 10^{-4} \mathrm{fm}^3$$
$$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \cdot 10^{-4} \mathrm{fm}^3$$
$$\alpha_\pi = (2.9 \pm 0.5) \cdot 10^{-4} \mathrm{fm}^3$$

Experiments inconclusive:

$\alpha_\pi - \beta_\pi$ = 4 -14 . 10^{-4}

assuming ($\alpha_\pi+\beta_\pi$ =0)

At LO. Compton cross section is proportional to $\alpha_\pi - \beta_\pi$

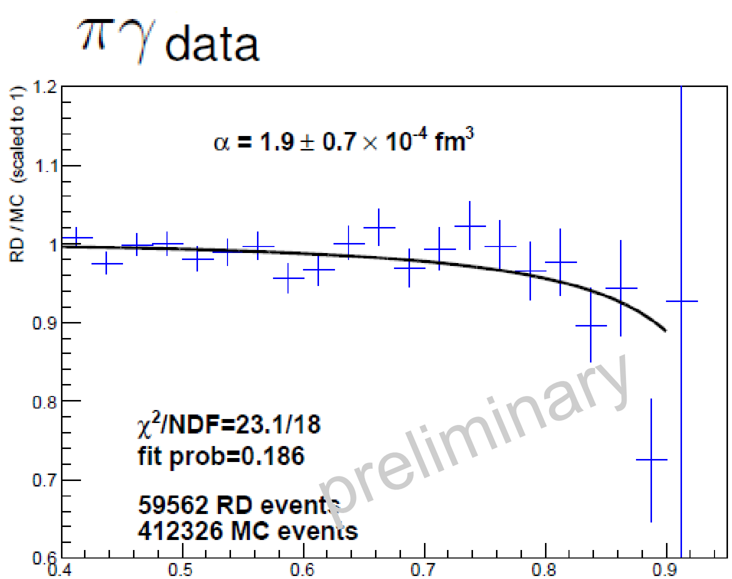


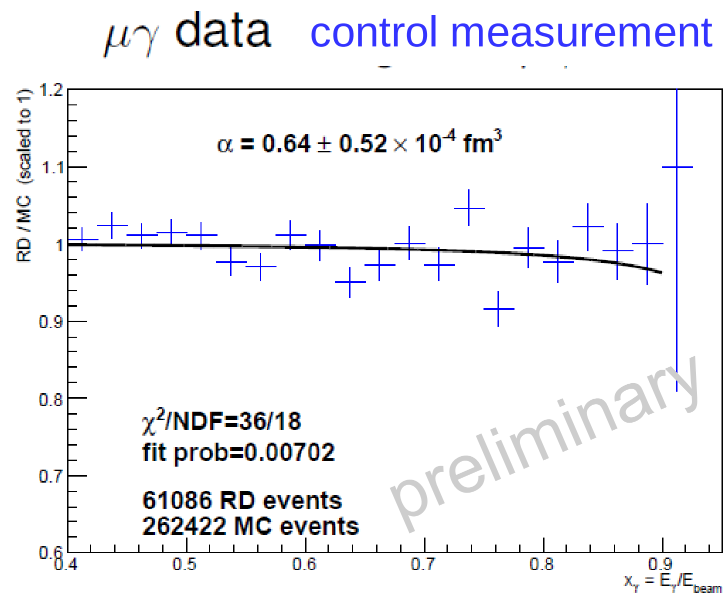
$\pi\,\gamma \rightarrow \pi\,\gamma$ measured via $\pi\,Z \rightarrow \pi\,Z\,\gamma$

Primakoff reaction π on nucleus (Ni)

Charged pion polarisability

Ratio of measured cross-section (Raw Data) to expected cross-section (Monte Carlo) calculated for point like particle, vs $E\gamma / E\mu$.





$\alpha_\pi - \beta_\pi = (3.8 \pm 1.4) \times 10^{-4}\ \mathrm{fm}^3$

$\alpha_\pi = (1.9 \pm 0.7) \times 10^{-4}\ \mathrm{fm}^3$ (assuming $\alpha_\pi + \beta_\pi = 0$)

COMPASS prelim. result :

in agreement with ChPT expectation,

does not confirm other dedicated measurements

Radiative widths of a_2 and π_2

Theory: **Values (keV)**

- $\Gamma(a_2(1320) \rightarrow \pi\gamma)$
  - VMD model: $\mathbf{375 \pm 50}$
  - Relativistic quark model: $\mathbf{324}$
  - Covariant oscillator quark model : $\mathbf{235 - 237}$
- $\Gamma(\pi_2(1670) \rightarrow \pi\gamma)$
  - Covariant oscillator quark model : $\mathbf{335 - 521}$

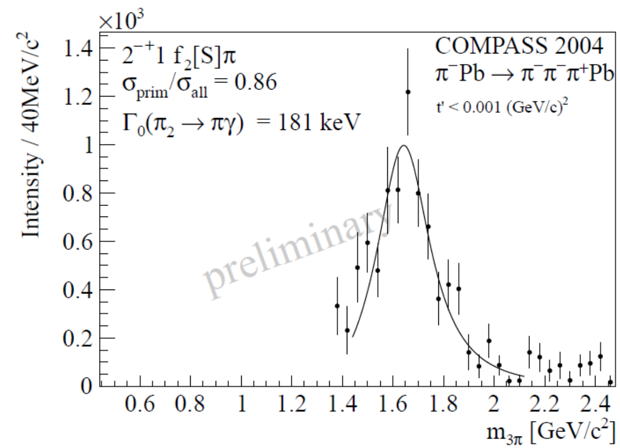
Previous experiments:

- $\Gamma(a_2(1320) \rightarrow \pi\gamma)$
  - May et al. **460 ±110**
  - E272: $\mathbf{265 \pm 60}$
  - SELEX **284±25 ± 25**

COMPASS results:

- $\Gamma(a_2(1320) \rightarrow \pi\gamma)$ **358±6 ± 42**
- $\Gamma(\pi_2(1670) \rightarrow \pi\gamma)$ **181 ± 11 ± 27 (0.56/BR $_{f2\pi}$)**

→ First measurement for π_2



COMPASS, EPJA, May 2014, Highlights

COMPASS future 2015-2018:

- **TMDs** **(Transverse Momentum Dependent distributions)**

  via spin dependent Drell-Yan

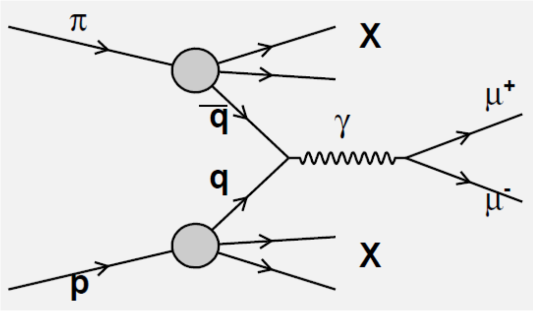
- **GPDs** **(Generalized Parton Distributions)**
  via Deep Virtual Compton Scattering

- **PDFs and FFs** **strange quarks**

COMPASS Future : Polarized Drell-Yan

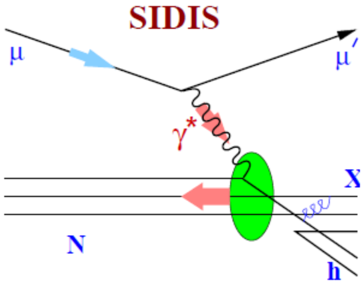
Polarized Drell-Yan $\pi^- p\uparrow \rightarrow \mu^+\mu^- X$

→ TMDs, Sivers & Boer-Mulders

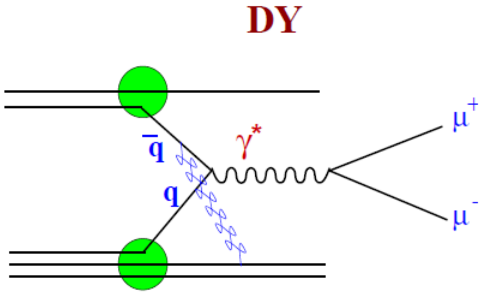


Drell-Yan: TMD x TMD
SIDIS: TMD x FF

→ Fundamental test of universality of TMDs
Expect change of sign in **Drell-Yan** vs **SIDIS**



Final State Interactions



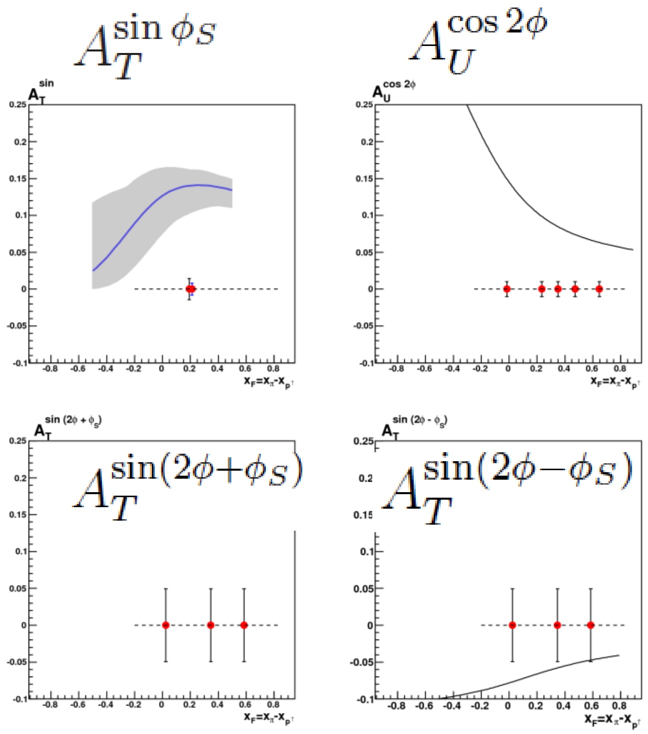
Initial State Interactions

Pion induced Drell-Yan:

- π as alternative probe to test nuclear models and meson structure (not accessible in DIS)
- flavor dependence (specific q-qbar compound)

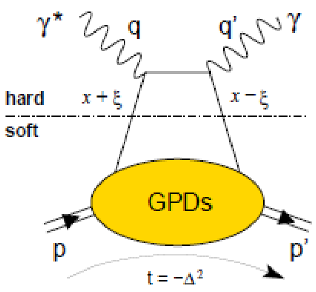
Sivers, Boer-Mulders… via Polarized Drell-Yan

Examples of COMPASS projections in mass region above J/ψ peak:
4 azimuthal asymmetries



- **Will probe 3 TMDs: Sivers, Boer-Mulders and Pretzelosity, in overlapping kinematic region for Drell-Yan and SIDIS**
- **Needed to test the change of sign, and check magnitude of signals.**

Generalized parton distributions



x, ξ : quark momentum fraction
t : transfer to proton
H(x,ξ,t) : Gen. Parton distribution

Study correlation between longitudinal quark momentum and transverse position

Deep virtual Compton scattering (DVCS)
A process which interferes with Bethe-Heitler(BH)
→ Can be studied in the interference regime (Jlab and COMPASS) and at high energy where BH smaller (COMPASS)

Also accessible via Hard Exclusive Meson
→ flavor decomposition

Should also compare first moments to lattice QCD

Link to angular momentum - Ji sum rule:

For a quark f:

$$J^f = \frac{1}{2} \lim_{t\to 0} \int_{-1}^{1} \mathrm{d}x \; x \; \left[\mathrm{H}^f(x,\xi,t) + \mathrm{E}^f(x,\xi,t)\right]$$

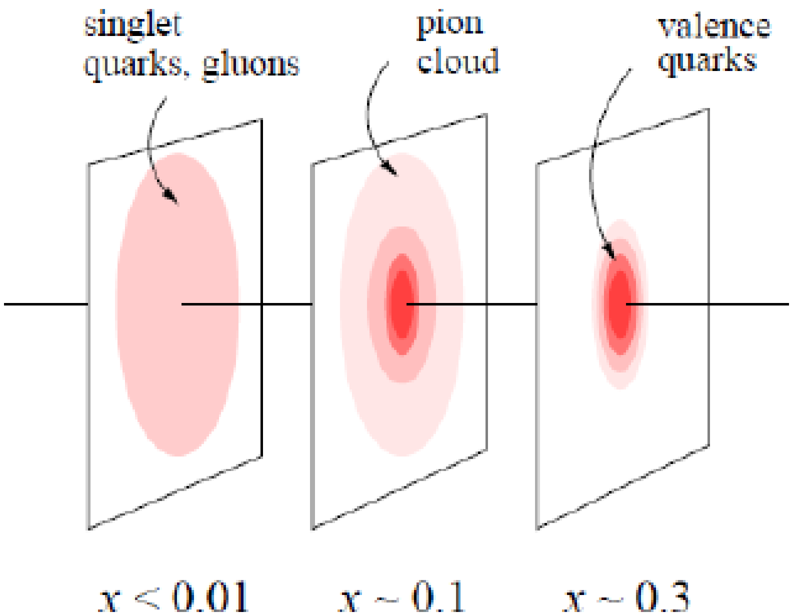
GPD **H** : accessible with unpolarized H target
GPD **E** : transversely polarized target

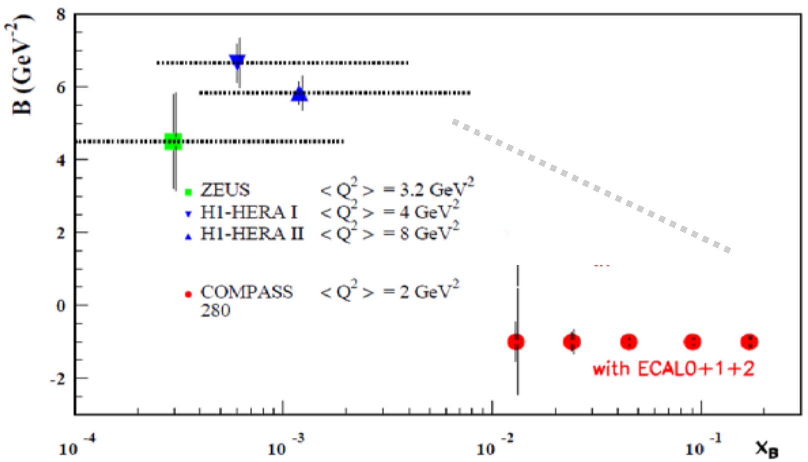
See talk of H.Moutarde

DVCS ex: Projection for t-slope

$\mu\ p \rightarrow \mu\ p\ \gamma$ x dependence of transverse size of the nucleon

$\sigma^{DVCS}/dt \sim \exp^{-B|t|}$ $B(x_B) = \frac{1}{2} < r_\perp^2 (x_B) >$





Also accessed via meson production ρ, ω, ϕ

Summary

Gluon and quark contribution to nucleon spin

Gluon $\Delta G/G$: Direct measurements point to zero or small contribution.
Only $0.05 < x < 0.2$ probed. Need lower x data to constrain the sum.
Quarks : Sum $0.26 < \Delta\Sigma < 0.34$ from global QCD fit at NLO
Extraction for all flavours from SIDIS, down to x ~ 0.004.
Towards agreement with Lattice QCD calculation

Transversity and Transverse Momentum Dependent distributions

Precise results on Collins and Sivers: gives $\Delta u_T(x)$ and $\Delta d_T(x)$
Much progress on all azimuthal asymmetries for TMDs

Light meson spectroscopy

Huge statistics in diffractive production, 3π channel, PWA
New resonance $a_1(1420) \rightarrow f_0(980)\ \pi$

Pion polarisability

$\alpha_\pi - \beta_\pi$ measurement in agreement with Ch PT

Future

TMDs via polarized Drell-Yan $\pi\ p\uparrow \rightarrow \gamma\ \gamma$
GPds via Deep Virtual Compton Scattering $\mu\ p \rightarrow \mu\ p\ \gamma$