Latest results from COMPASS

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On behalf of the COMPASS Collaboration

- Chiral Perturbation Theory - Pion polarisability
- Light meson spectroscopy
- Nucleon spin longitudinal and transverse
- Quark fragmentation functions
- Outlook

COMPASS at CERN

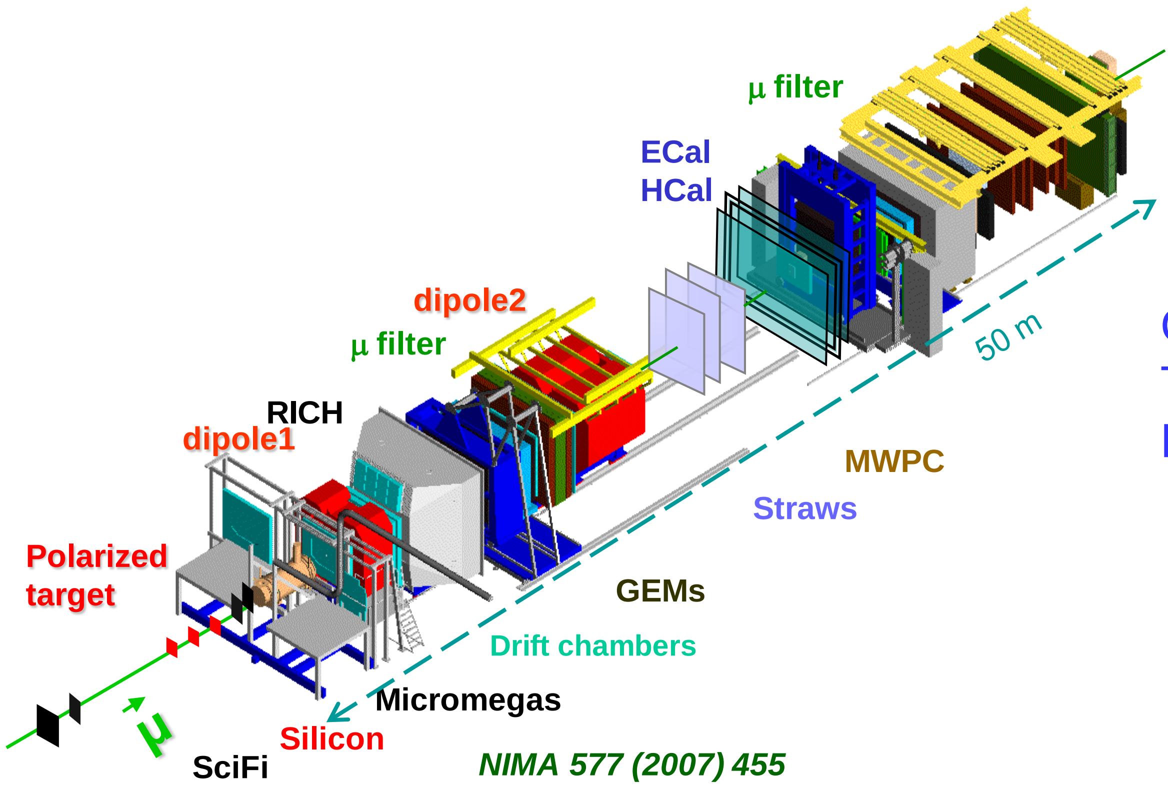
Fixed target
Secondary 200 GeV muon and hadron beams from CERN SPS
→ Multipurpose setup

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

Physics with hadron beams

Selected results

- Pion polarisability $\pi^- Ni \rightarrow \pi^- Ni \gamma$ Chiral PT

CERN press release Feb.2015

- Diffractive processes $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{recoil}$ Search for exotic mesons & hybrids

New a1(1420)

π, K, p beams - 200 GeV:

Broad spectrum in energy transfer t
Charged & neutral channels
Huge statistics
Potential for discovery of small intensity possible new states

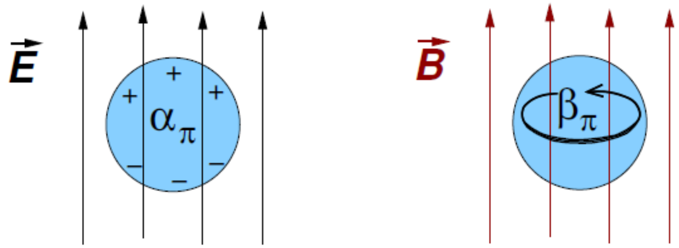
Pion polarisability – Theoretical context

- To describe forces that determine substructure of hadrons
- **Low energy QCD**
  Chiral Perturbation Theory, ChPT , effective field theory,
  Pions π^+, π^- π^0: Goldstone bosons associated to spontaneous breaking of chiral symmetry.
- **Pion** : the simplest and lightest bound state of QCD (quark - anti quark)
- Testing properties and interactions of the pion

→ Testing if ChPT is a correct representation of QCD at low energy

Pion polarisabilities

Polarisabilities: deviation from pointlike particle
= deformation in an electric (α) and magnetic (β) field



Precise predictions from Chiral Perturbation theory (Ch PT)

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

Measurements difficult: tiny quantities,
Previous experiments to measure α_π since 1980: not conclusive

Measurement of pion polarisability

- **Measure pion Compton cross-section $\gamma\pi \rightarrow \gamma\pi$**
  At LO, it is proportional to $\alpha_\pi - \beta_\pi$
  and following ChPT result, one can assume $\alpha_\pi + \beta_\pi \sim 0$.

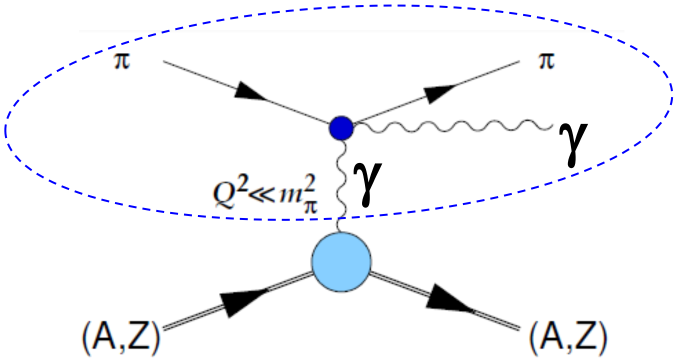
- **Compare it to cross-section expected for pointlike particle** by ChPT
  Observe reduction of ratio due to polarisability α_π

$$R_\pi = \left(\frac{d\sigma_{\pi\gamma}}{dx_\gamma}\right) \Big/ \left(\frac{d\sigma^0_{\pi\gamma}}{dx_\gamma}\right) = 1 - \frac{3}{2} \cdot \frac{m_\pi^3}{\alpha} \cdot \frac{x_\gamma^2}{1-x_\gamma} \alpha_\pi$$

- Difficulty: no pion target.
  In ChPT, factorization of the $\pi\gamma$ cross section in the πZ one, in the 'Equivalent Photon Approximation (EPA)'
  → Use the πZ reaction

The measurement… embedded in a nucleus

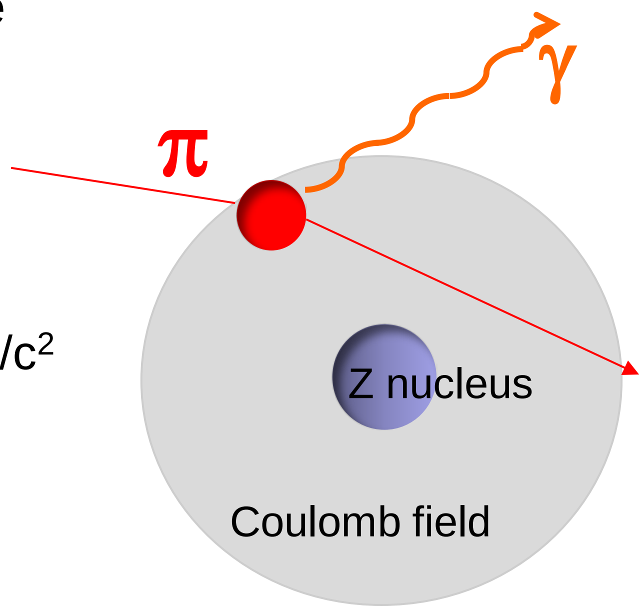
Measure $\pi\,\gamma \rightarrow \pi\,\gamma$
via $\pi\,Z \rightarrow \pi\,Z\;\gamma$



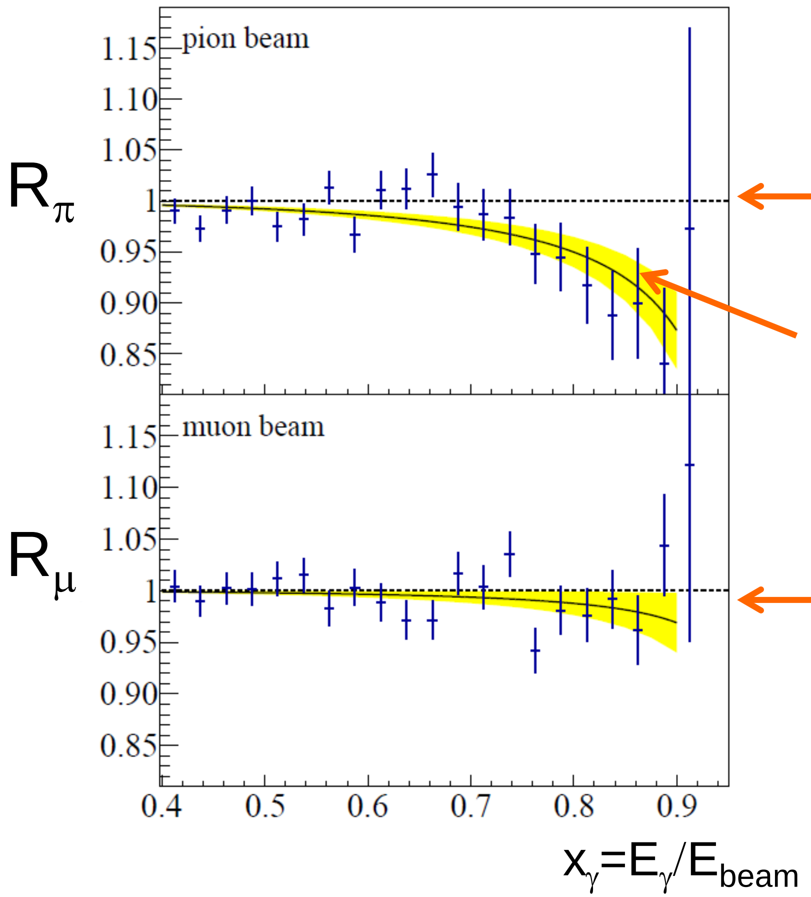
- The charged **pion**, diameter ~0.6 fm, crosses the **electric field** of a nucleus
  Typical field at r=5 R_{Ni} : **E ~ 300 kV/fm**

- Bremsstrahlung emission:
  'Equivalent photon'
  Very small momentum transfer $\mathbf{Q^2 \sim 10^{-5}}$ GeV^2/c^2
  → Quasi real pion Compton scattering

- Polarisability effect:
  Reduction of cross section



Pion polarizability - result



Ratio of measured cross section to cross section for pointlike particle
2009 data, ~ 2 weeks, 63000 pions

COMPASS: 190 GeV π beam, Nickel target

Expected value for point like particle

pion measurement: reduction of cross section due to polarizability

$\alpha_\pi = (2 \pm 0.6 \pm 0.7) \times 10^{-4}\ \mathrm{fm}^3$ $(\alpha_\pi+\beta_\pi=0)$

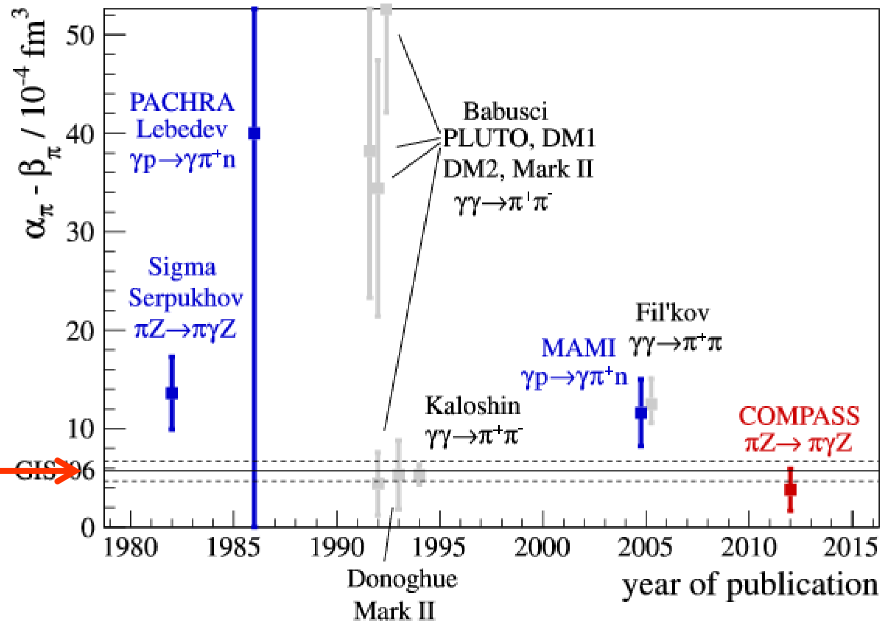
muon control measurement

Phys. Rev. Lett. 114 (2015) 062002

CERN press release, Feb.2015

Pion polarizability – world data

ChPT

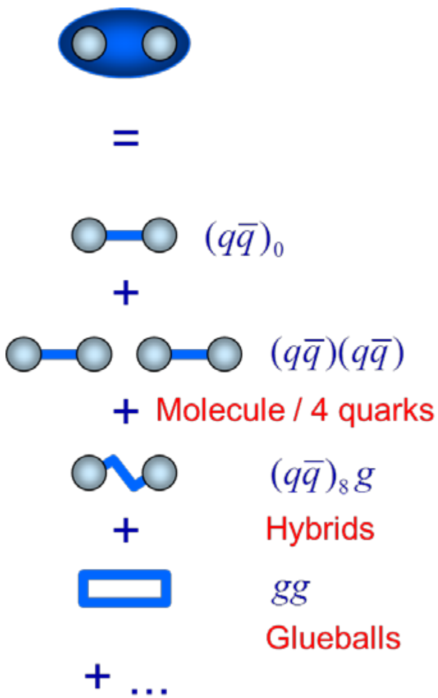


COMPASS result:

- **in agreement with ChPT,**
- **contradicts some previous measurements**

Next steps: more statistics to come using 2012 data: α_π, β_π, some insight also into kaon polarisability

Light meson spectroscopy



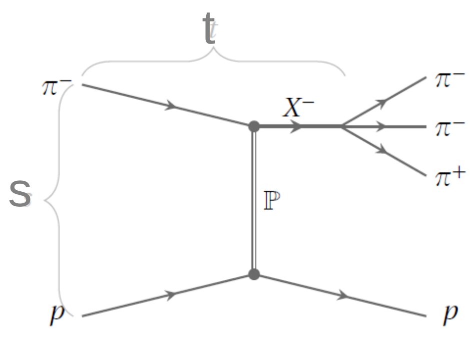
Allowed combinations

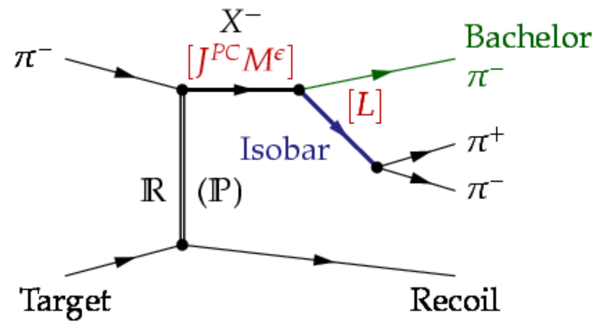
$$J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$$

“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 :

$J^{PC} M^{\varepsilon}$ [isobar] L

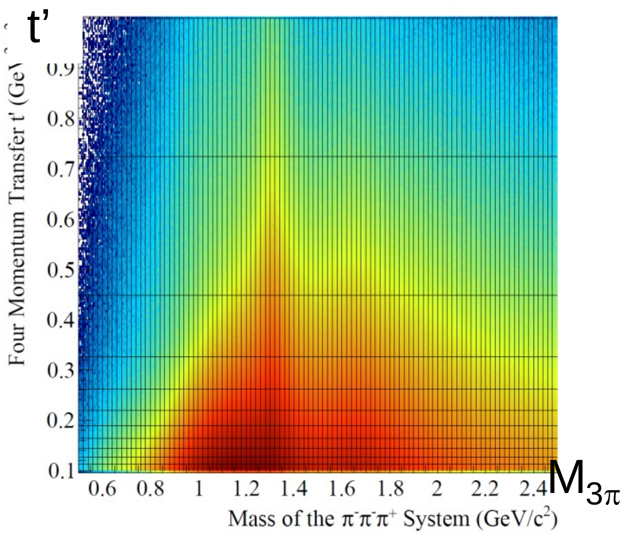
J^{PC}-exotic mesons

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

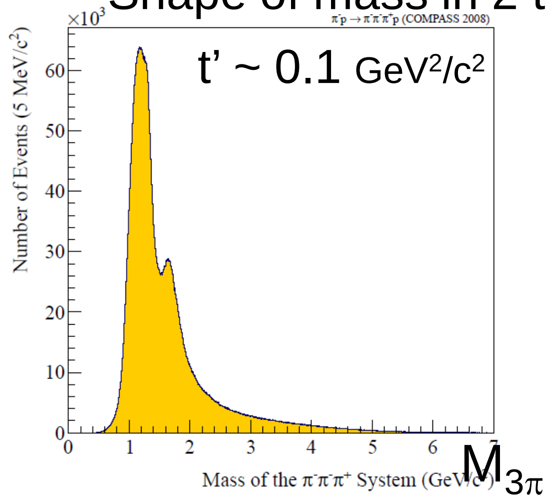
3π final state $\pi^- p \rightarrow \pi^-\pi^+\pi^- p_{recoil}$

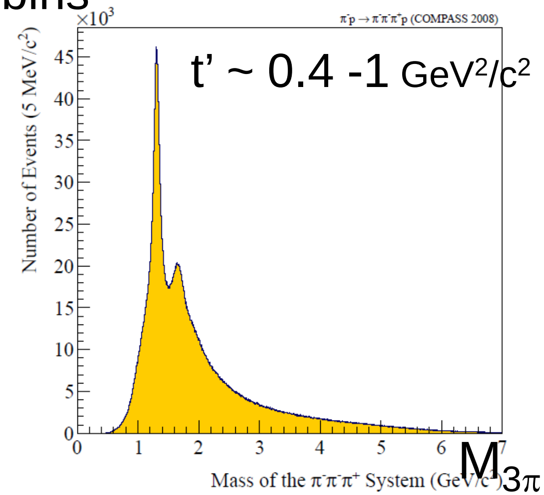


50 M events

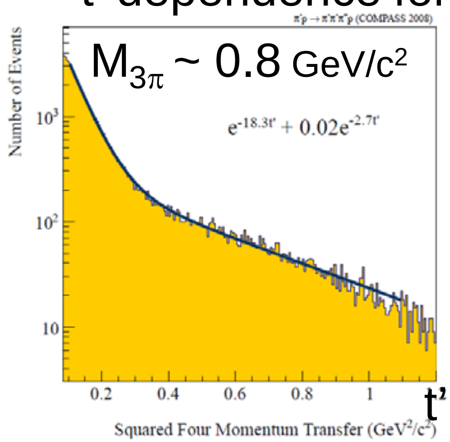
11 x 100 (t',$M_{3\pi}$) bins

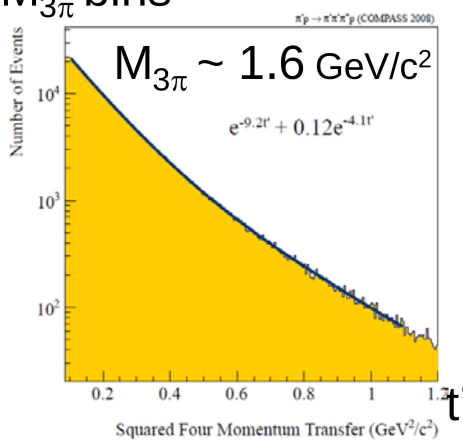
Shape of mass in 2 t' bins





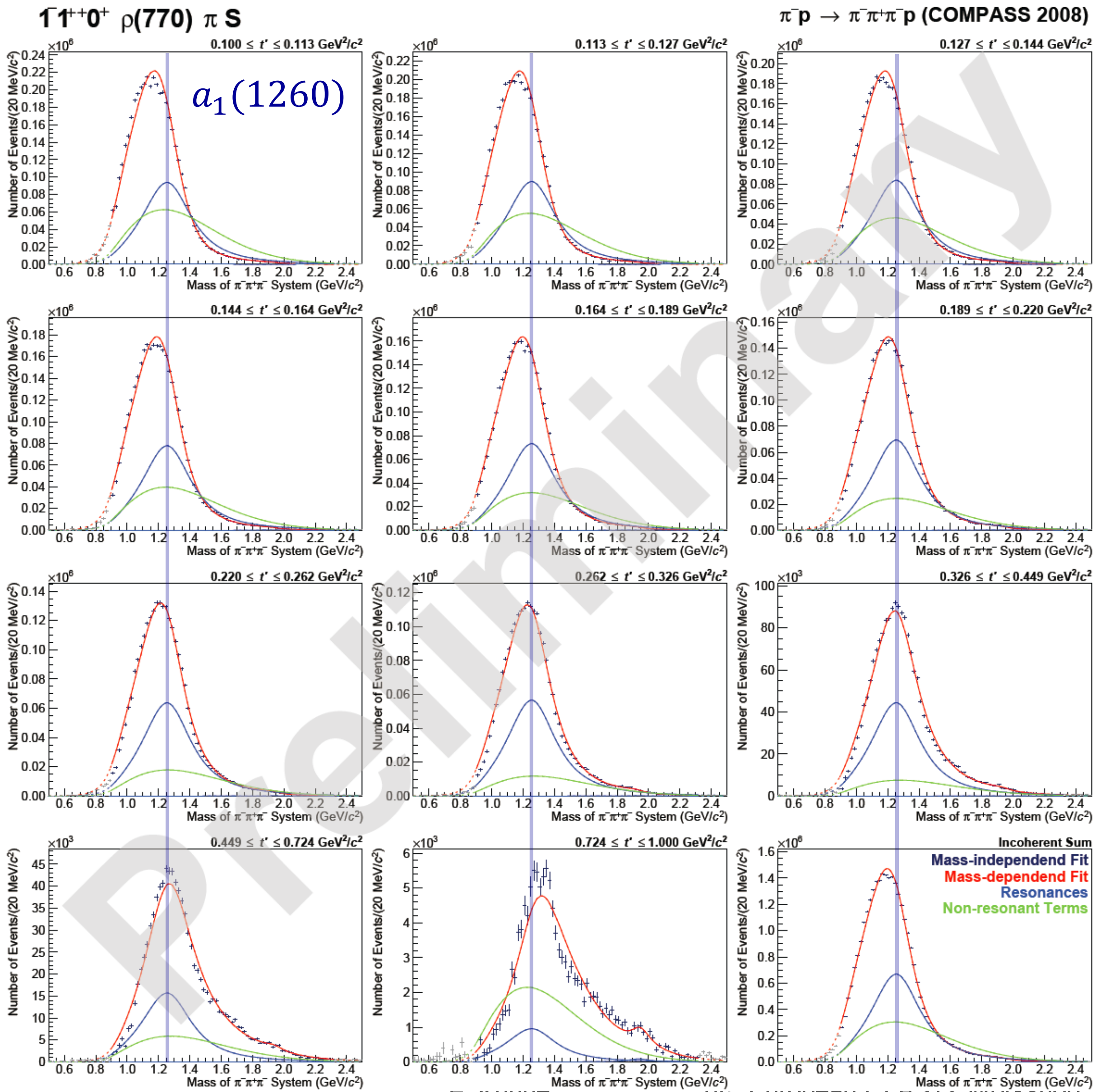
t' dependence for 2 $M_{3\pi}$ bins





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

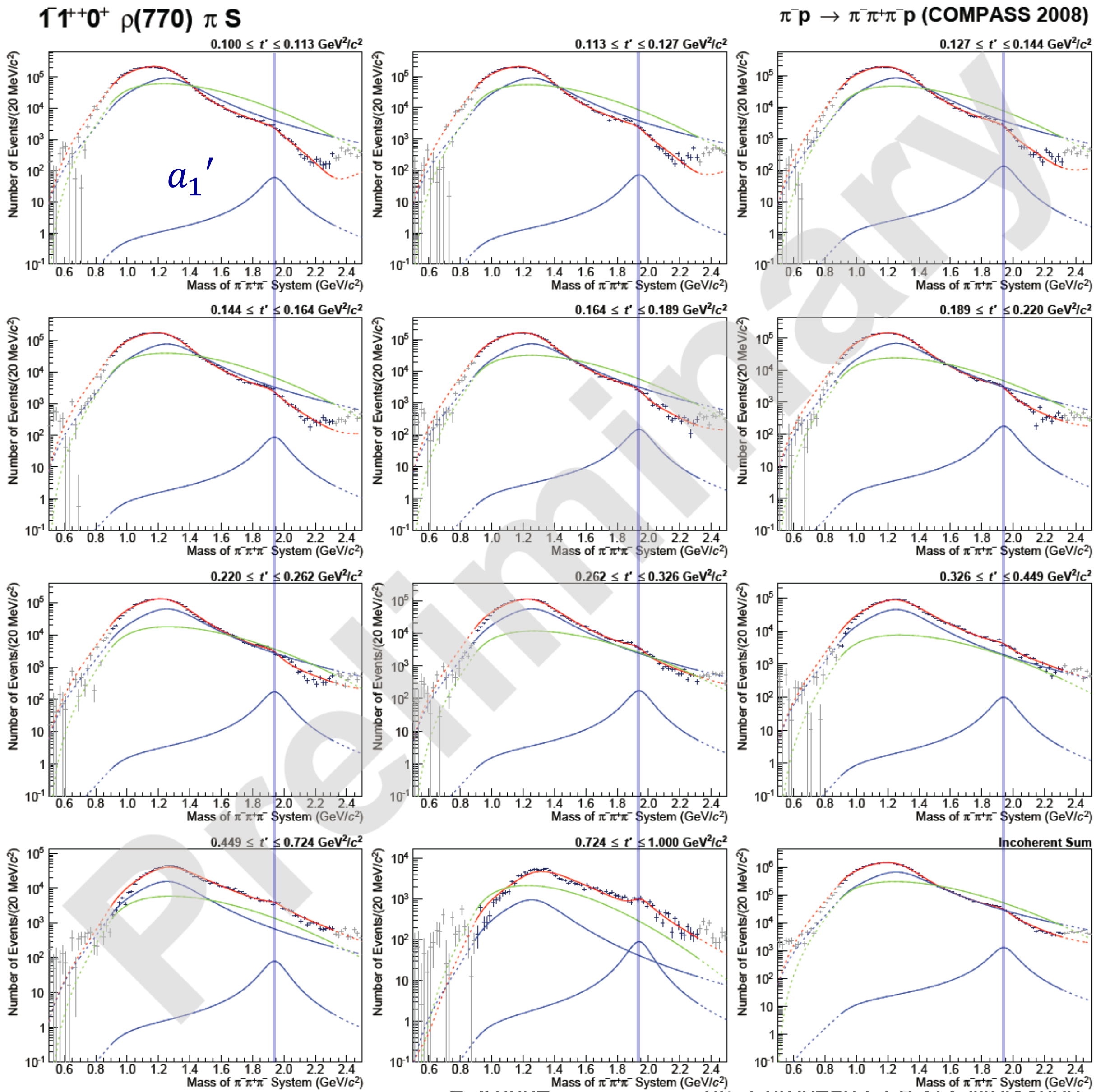
11 t' slices



Incoherent sum

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

11 t' slices



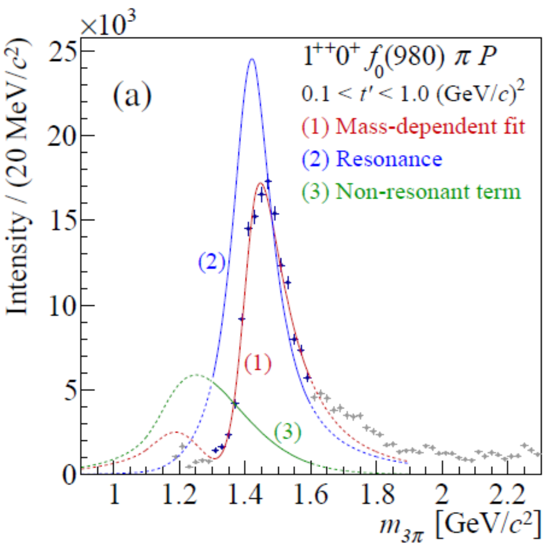
Incoherent sum

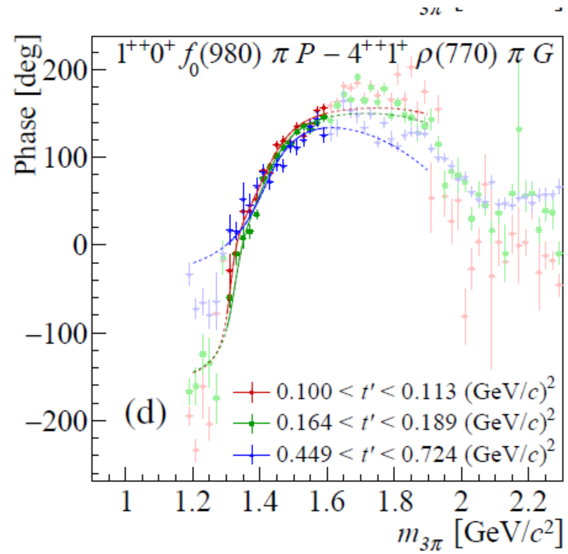
New a_1 (1420) - $1^{++}0^{+}$ $f_0(980)\pi$ P

New meson identified, $J^{PC} = 1^{++}$

a_1 (1420)
Mass= 1414 MeV/c^2
Γ = 150 MeV/c^2

Exotic (non-$q\bar{q}$) features since only decays into $f_0(980)\pi$ ($f_0(980)$ superposition of $q\bar{q}$ and $s\bar{s}$ states).





arXiv1501.05732
Submitted to PRL

- Seen in charged and neutral channels
- Accessible thanks to high statistics (1% of main signal)

Interpretations

Origin unclear, possible explanations:

- Could be **associated with the $f_1(1420)$**, an iso-scalar resonance **with strong coupling to $K\bar{K}^*$** final state, often interpreted as a molecular state: almost equal masses and similar narrow widths (first time that isospin partners of exotic states discovered).
- Another possibility is a dynamic generation through **the strong coupling of the systems $a_1(1420)$, $f_0(980)\pi$, and $K\bar{K}^*$**
- See also:
  B. Ketzer et al. http://arxiv.org/abs/1501.07023

  Basdevant et al. http://arxiv.org/pdf/1501.04643.pdf

Physics with muon beams

- Gluon and quark polarization
- Hadronization
- Transversity

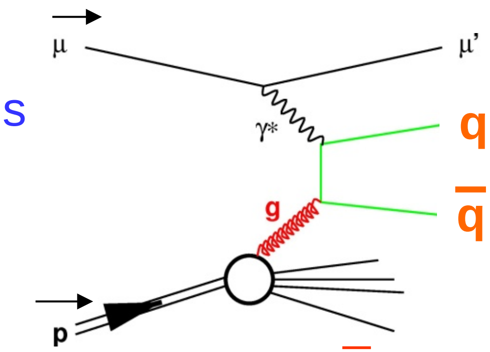
Gluon polarization $\Delta G/G$ from $\vec{\mu}\vec{N}$ scattering

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 $c \rightarrow D^0 \rightarrow K\pi$
Clean signature of PGF
Limited statistics & large combinatorial background

COMPASS :1 point

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

COMPASS : 4 points + HERMES &SMC

→ Prelim. result reanalysis 'all p_T' method

$\Delta g/g$ from hadron muon production using "all p_T" events

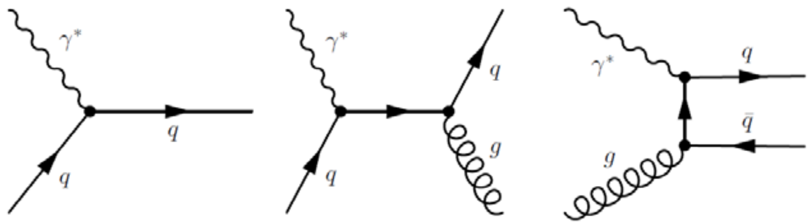
M. Stolarski , DIS-2014

Main goal of this new analysis : improve the extraction of ΔG, by removing some sources of systematic effects affecting the previous "2 high p_T hadron" analysis

In addition, a significant reduction of the statistical error of $\Delta g/g$ is also obtained.

Three processes contribute to the cross-section

$$A_{LL}^{h}(x) = R_{LO}\, D\, A_1^{LO}(x) + R_{PQCD}\, a_{LL}^{QCDC}\, A_1^{LO}(x_C) + R_{PGF}\, a_{LL}^{PGF} \frac{\Delta g}{g}(x_g)$$



Simultaneous extraction of $\Delta g/g$, and A_1^{LO}

Extraction based on Monte Carlo description of all processes with relative weights (R_i) and analyzing powers (a_{LL}^{i})

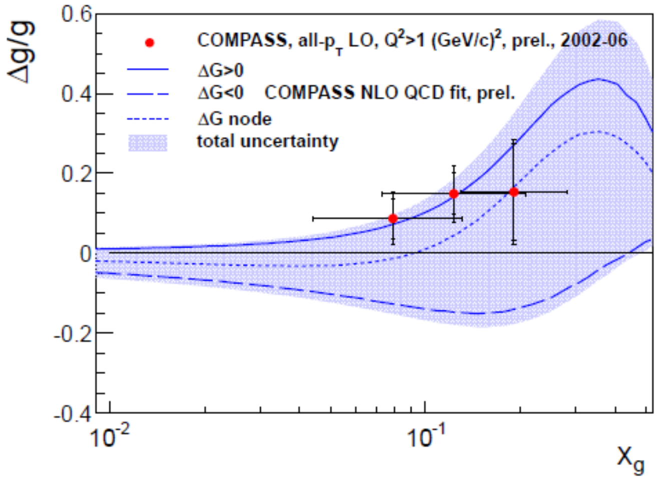
Process weights depends on p_T (at small p_T LO contribution is > 0.95)

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

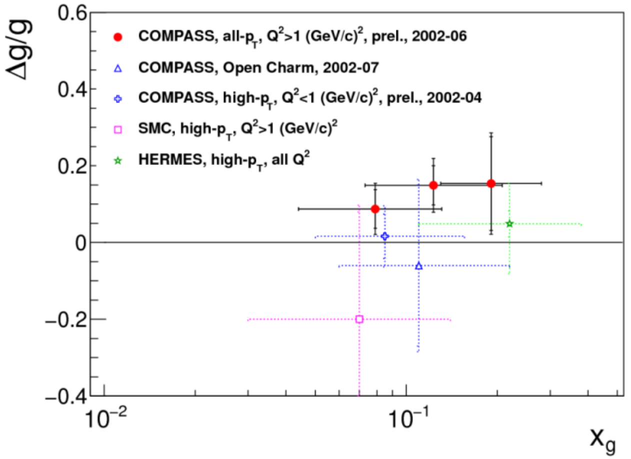
New ΔG/G extraction at LO, in 3 x-bins

M. Stolarski , DIS-2014

Data compared to the 3 solutions from COMPASS NLO QCD fit of g_1 world data (discussed later)



Results compared to other extractions of ΔG at LO



- **Most precise direct measurement of ΔG/G at LO**
- **Data suggest positive value (2σ)**

$$\Delta g/g\Big|_{\langle x_g\rangle=0.10} = 0.113 \pm 0.038 \pm 0.035$$

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

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

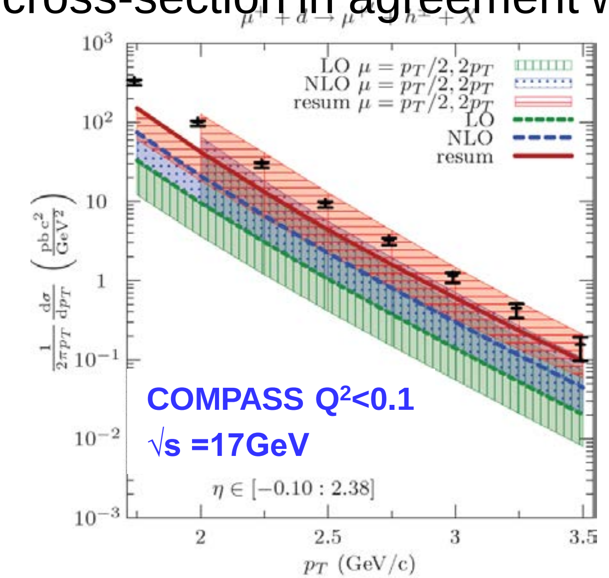
Method 'à la RHIC': $\mu\, d \rightarrow \mu'\, h^{+/-}\, X$

Measure $A_{LL}(p_T)$

Compare to theoretical calculations with various assumptions for ΔG(x)

No direct extraction, no model needed

Absolute cross-section in agreement with pQCD calculations, with 'resummations'



COMPASS, PRD 88 (2013) 091101

--- Resummation 'all orders'

--- NLO

--- LO

De Florian, Pfeuffer, Schaefer, Vogelsang, PRD 88 (2013)

→ Sets 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

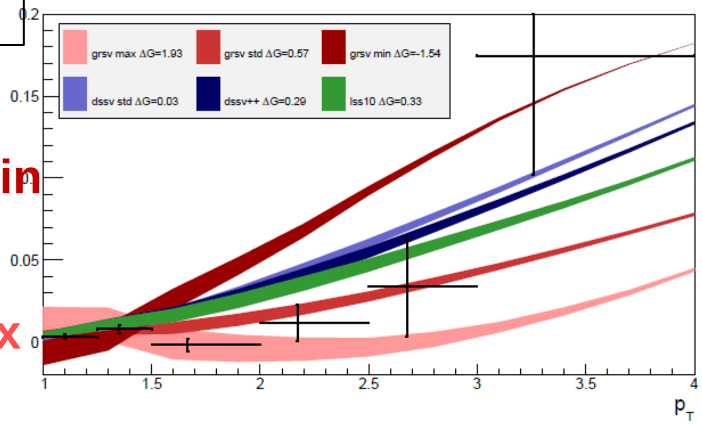
M. Levillain, DIS-2014

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

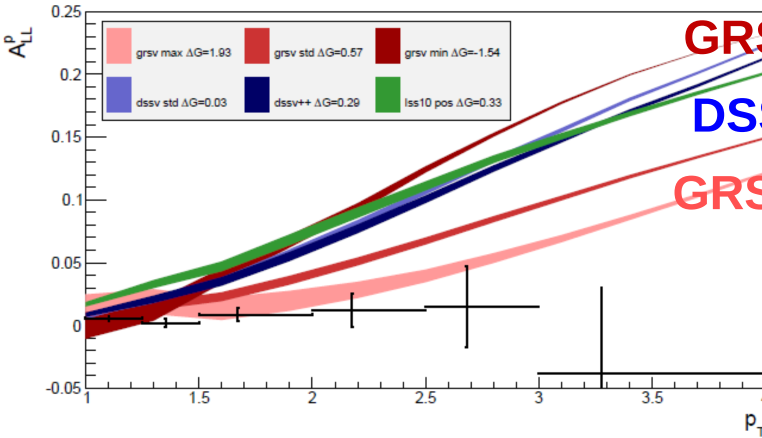
Comparison to theory… but only NLO available for polarized case:

$A_{LL}(p_T)$

Deuteron



Proton



$\Delta G > 0$ favoured

However, need full calculation with 'threshold resummations' before concluding

New COMPASS proton data on g_1 – 200 GeV

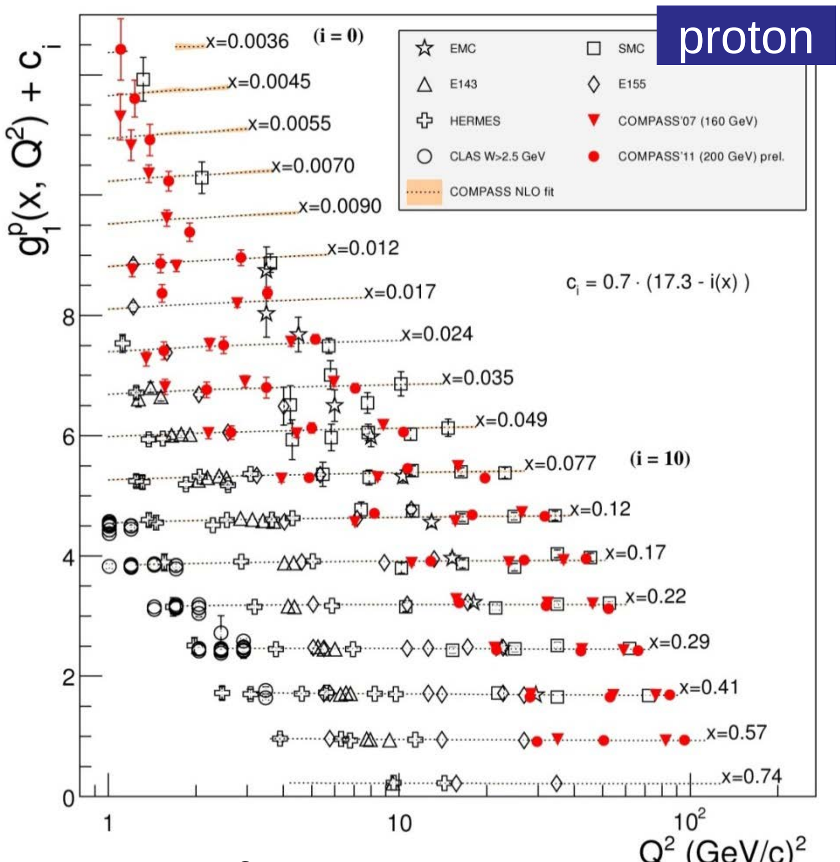
Spin structure functions g_1
Pol. Deep Inelastic Scattering

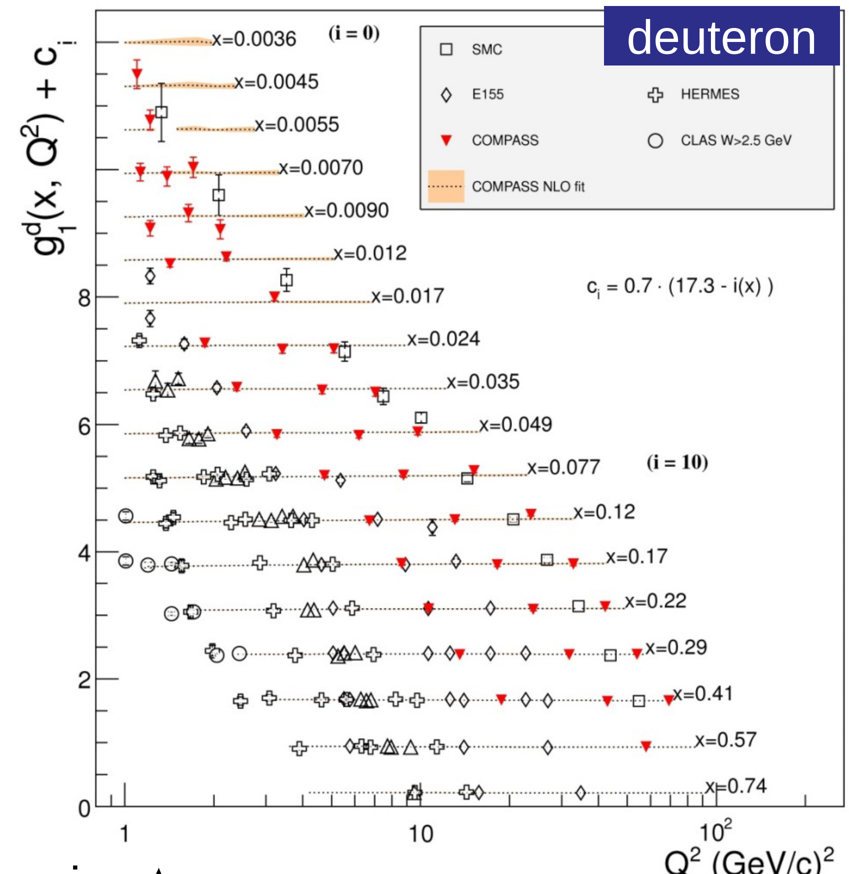
$$A_1^{DIS} \propto g_1 f(x) \propto \frac{1}{2}\Sigma_q e_q^2 \left(\Delta q(x) + \Delta\bar{q}(x)\right)$$

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

Low x and high Q^2

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





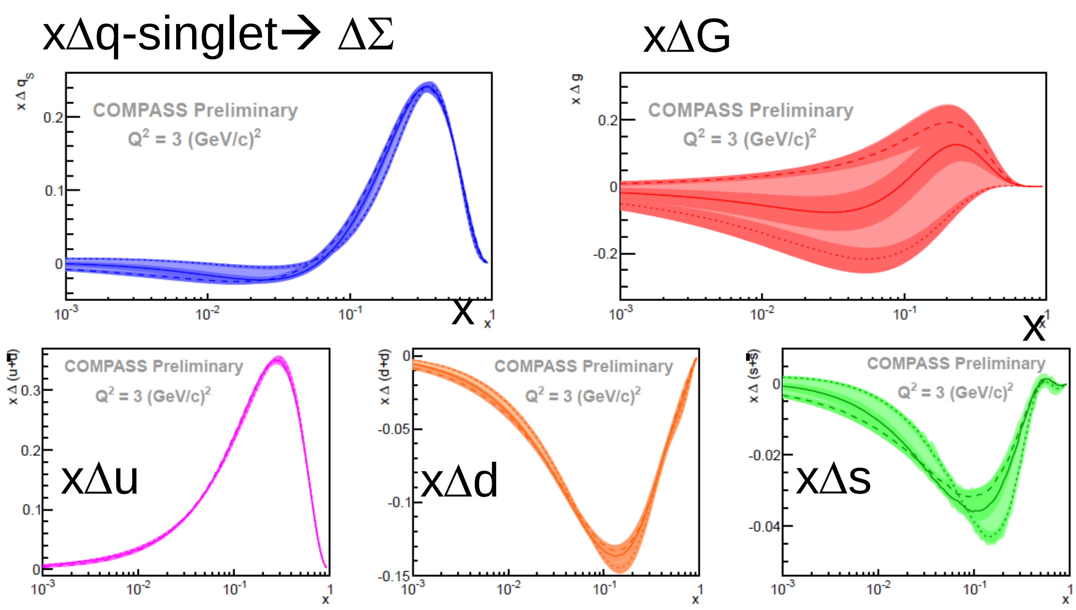
x and Q^2 coverage not yet sufficient for precise Δg
Would need to use constraint from pp data (as DSSV, NNPDF)

M. Andrieux at DIS-2013

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

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.

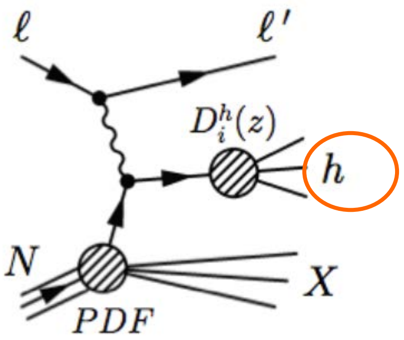
Data exist from e^+e^- and pp reactions, but unsufficient and at too high Q^2

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

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

PDFs FFs

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



→ **Provide inputs to global QCD analyses to extract quark FF**

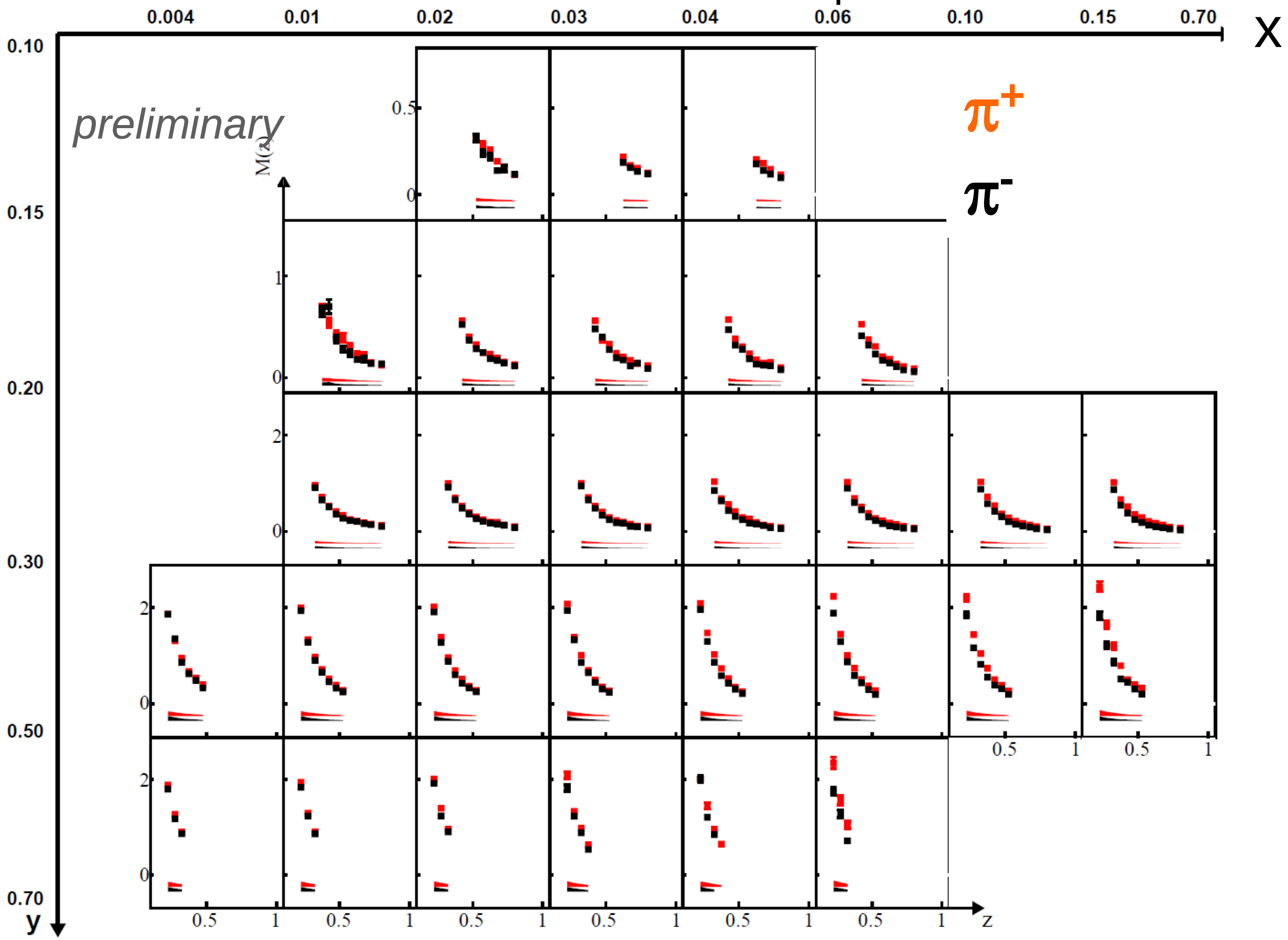
Fine binning in x, z, Q^2

PDFs depend on x, while FFs depend on z.

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

COMPASS prelim. DIS-2013, N.Makke

~400 data points for π



NB- Also measured: kaon multiplicities, 2h multiplicities.
and p_T dependence

Quark FFs into π, from COMPASS fits

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

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

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

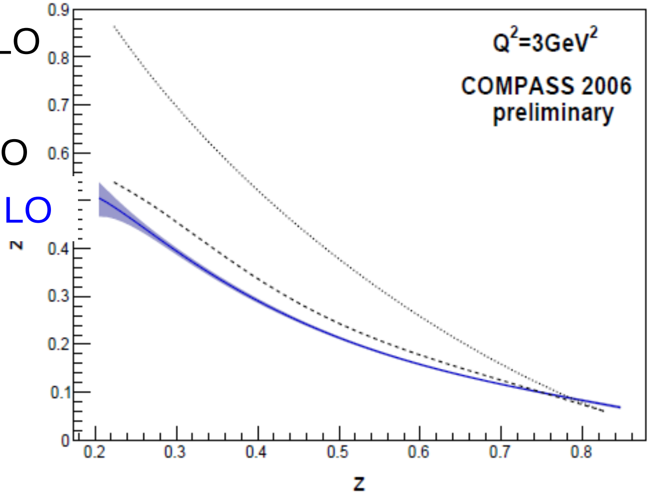
And assuming $D_{unf}^{\pi+} = D_s^{\pi+} = D_s^{\pi-}$

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

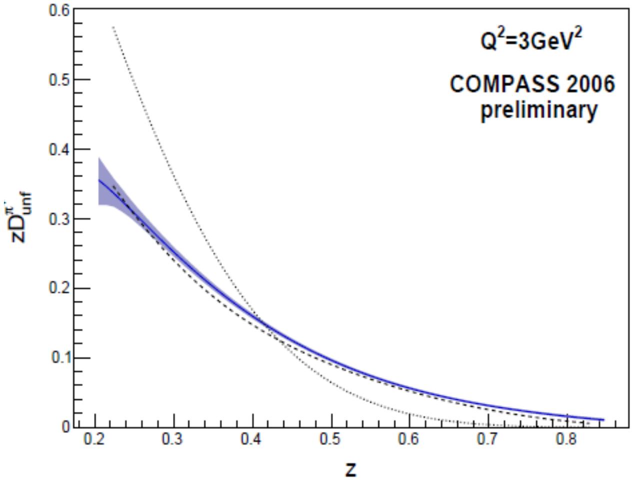
HNKS NLO

DSS NLO

COMPASS LO



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



COMPASS LO

….. DSS NLO

----- HNKS NLO

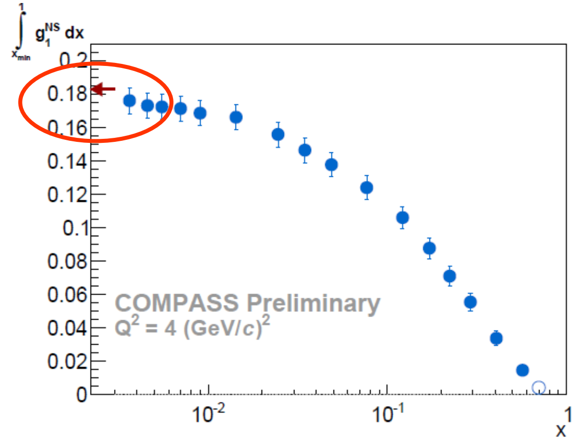
Next step: Fragmentation functions into kaons D_s^{K+} and D_s^{K-} starting from kaon multiplicities

Results for Bjorken sum rule from g_1 COMPASS data

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

M. Wilfert, DIS-2014

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



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

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

→ Bjorken sum rule verified within 9% uncertainty

Better statistics and systematics studies compared to previously

Hint for higher orders: obtain $(g_A/g_V)_{\text{"N"NLO}} = 1.251 \pm 0.053(\mathrm{stat.}) \pm 0.097(\mathrm{syst.})$

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

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** **Sivers**

q transverse spin distr.

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

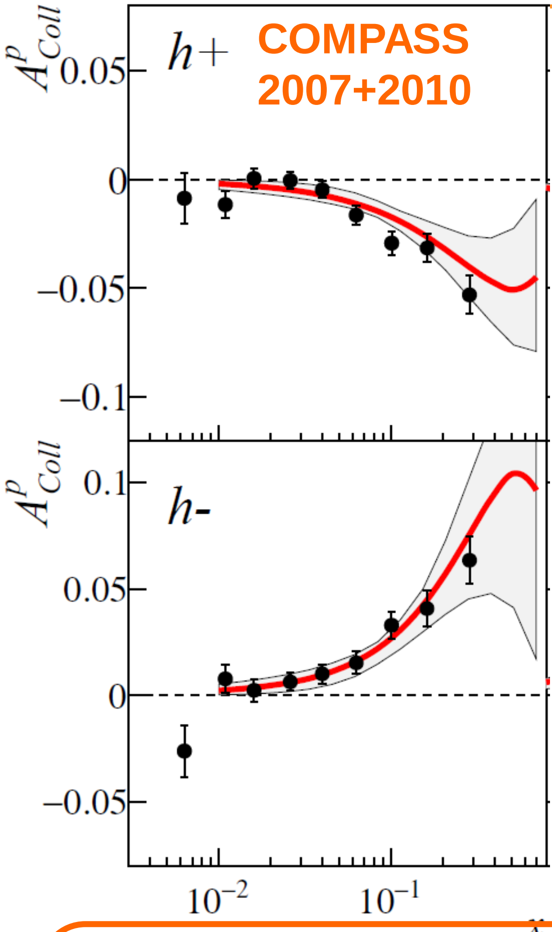
Collins fragmentation function, depends on spin

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

Usual quark fragmentation function

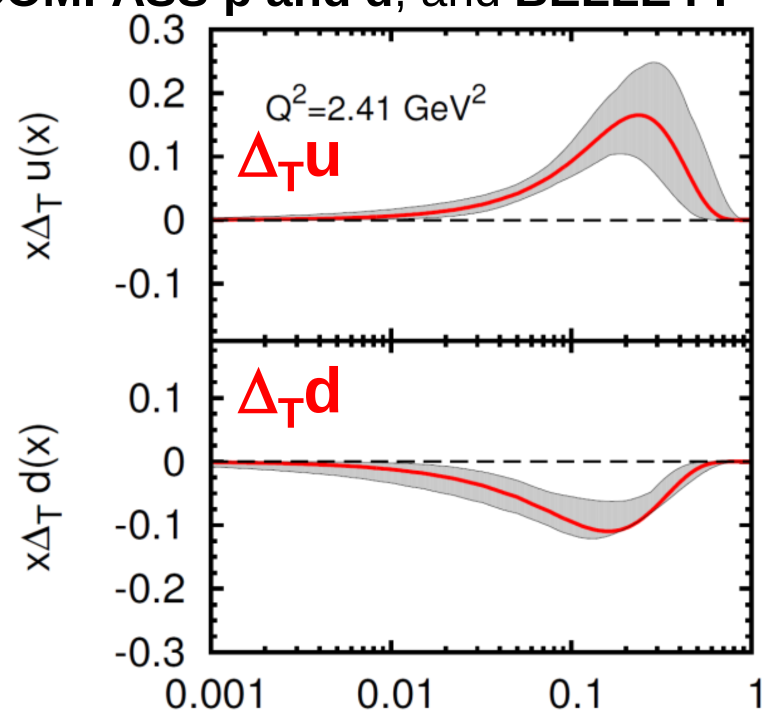
note: **$\Delta_T q$ also measured in SIDIS using di-hadron fragmentation function**

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**



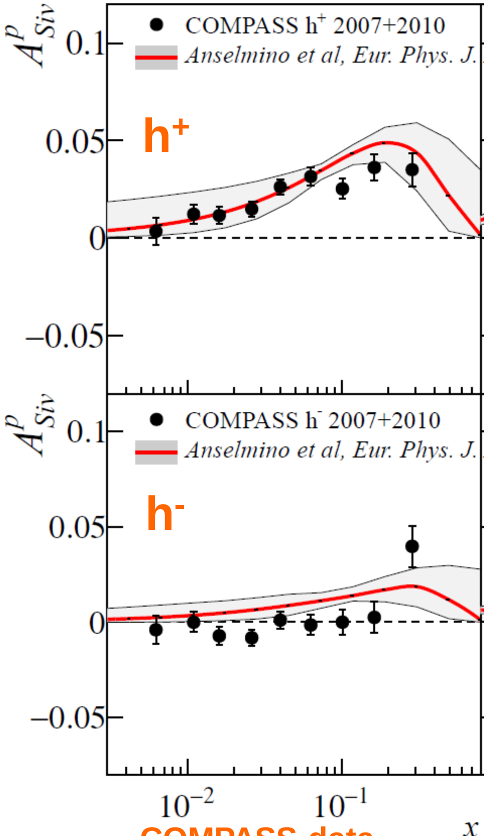
M. Anselmino et al., PRD87 (2013) 094019

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

Nb: Asymmetry also measured for π and K
hep-ex/1408.4405 subm. to PLB

Sivers asymmetry → Sivers function

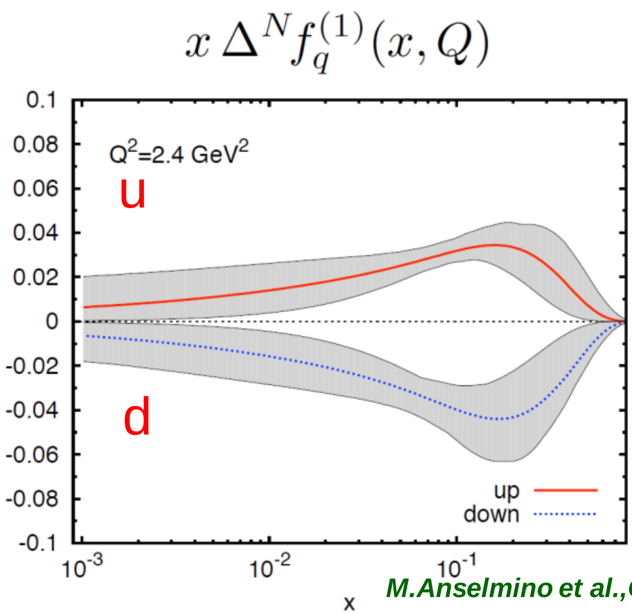
Correlation between Nucleon spin & quark transverse momentum k_T



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

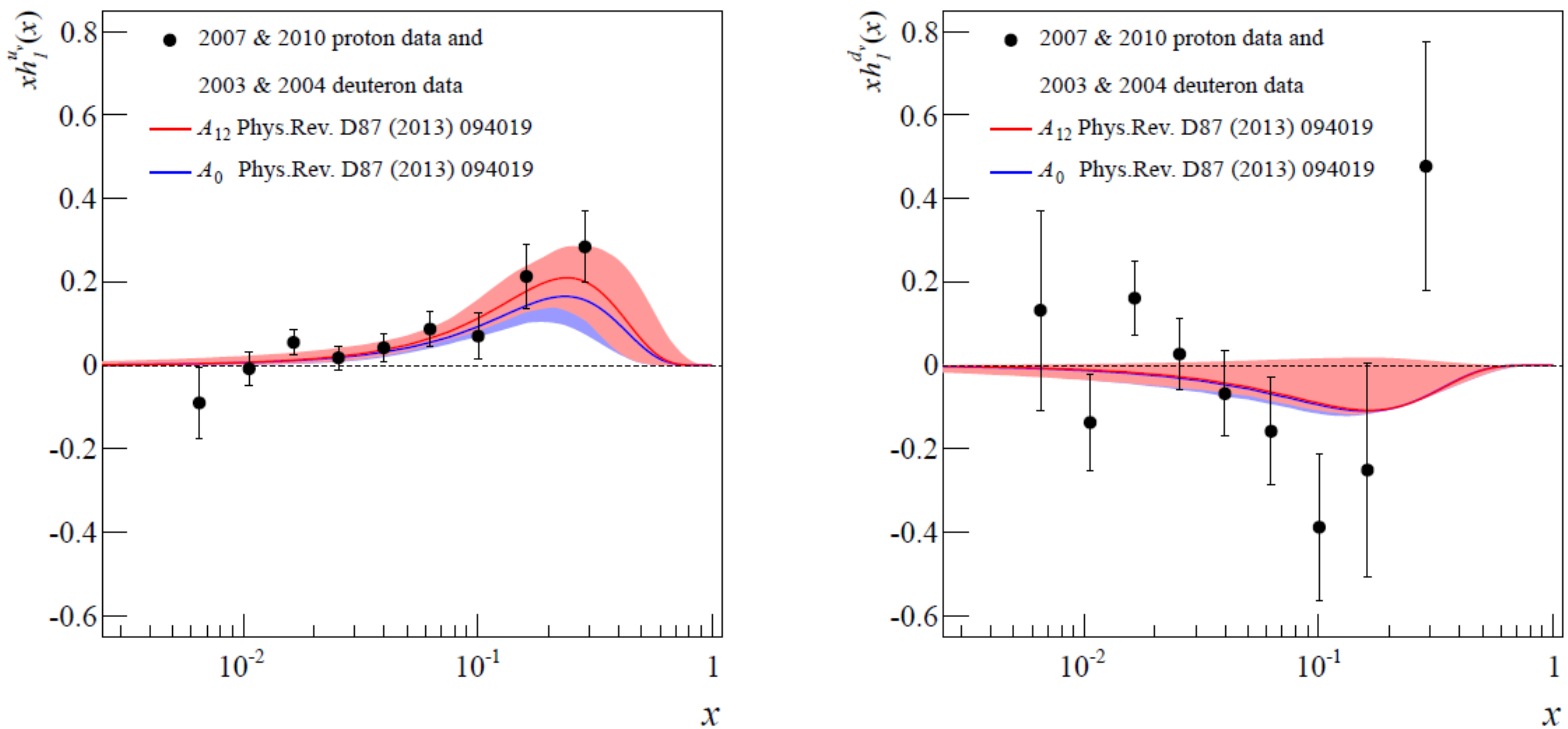
Nb: Asymmetry also measured for π and K hep-ex/1408.4405 subm. to PLB

Transversity from dihadrons – Extraction of h1

using :

- COMPASS proton and deuteron data on dihadron azimuthal asymmetries (different analysis from Collins)
- dihadron FF + Q^2 evolution from Bacchetta et al. ***JHEP03 (2013) 119***

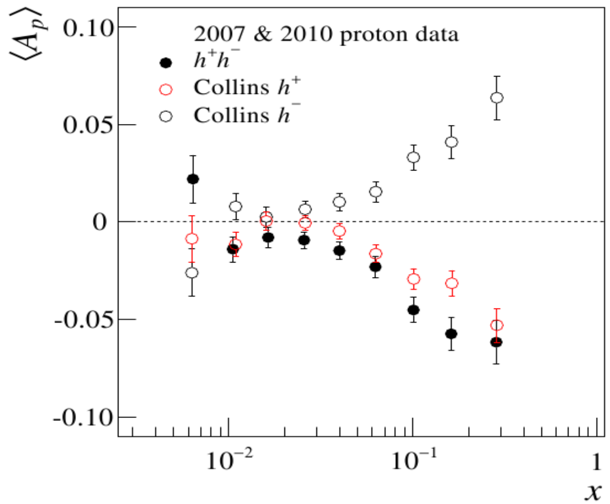
h_1^{uv} h_1^{dv}



Comparison with Anselmino et al. (global fits of single hadron Collins asymmetries and FFs):

Very good agreement for u quark, and fair agreement for d quark transversity.

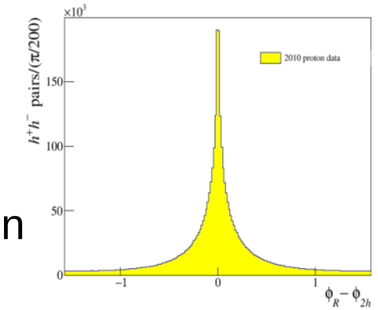
Transversity - dihadrons. Interplay with Collins



Observe:

- **Mirror symmery of Collins h+ and Collins h-**
- **Asymmetry for di-hadron somewhat larger**

strong correlation between relevant angles



Hint at common physical origin for Collins mechanism and polarized dihadron fragmentation function as originally suggested by different models

F. Bradamante [COMPASS], Como 2013, D-SPIN 2013
C. Adolph et al. [COMPASS], Phys. Lett. B 736 (2014) 124

- **The h^+ and h^- Collins asymmetries are mirror symmetric**
- **The h^+ and h^- asymmetries are entangled**
- **The 2h asymmetry can also be derived from the h+ asymmetry**
- **Sivers-like asymmetries also entangled, but no mirror symmetry**

F. Bradamante [COMPASS], SPIN-2014, Beijing

COMPASS 2015 - 2018:

- **2015: Polarized Drell-Yan** $\pi^- p\uparrow \rightarrow \mu^+\mu^- X$

  First time ever
  → Fundamental test of universality of TMDs (Sivers, Boer-Mulders…)
  Expect change of sign in **Drell-Yan** vs **SIDIS**

- **2016-2017: GPDs** $\mu\ p \rightarrow \mu\ p\ \gamma$

(Generalized Parton Distributions) via Deep Virtual Compton Scatt.

- PDFs and FFs strange quarks (in parallel to GPDs)

Summary

Pion polarisability

α_π-β_π measurement in agreement with Ch PT

Light meson spectroscopy

Huge statistics in diffractive production, 3π channel, PWA

New resonance $a_1(1420) \rightarrow f_0(980)\ \pi$

Gluon and quark contribution to nucleon spin

Gluon $\Delta G/G$: Latest extraction in 3 x bins ('all p_T'), positive contribution.

Quarks : Sum $0.26 < \Delta\Sigma < 0.34$ from global QCD fit at NLO

Extraction for all flavours from SIDIS measurements, 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 $\Delta d_T(x)$

Interplay Collins effect / di hadron

Much progress on all azimuthal asymmetries for TMDs (not shown)

Future 2015-2018:

TMDs via polarized Drell-Yan $\pi\ p\uparrow \rightarrow \mu\ \mu$

GPds via Deep Virtual Compton Scattering $\mu\ p \rightarrow \mu\ p\ \gamma$

Spares

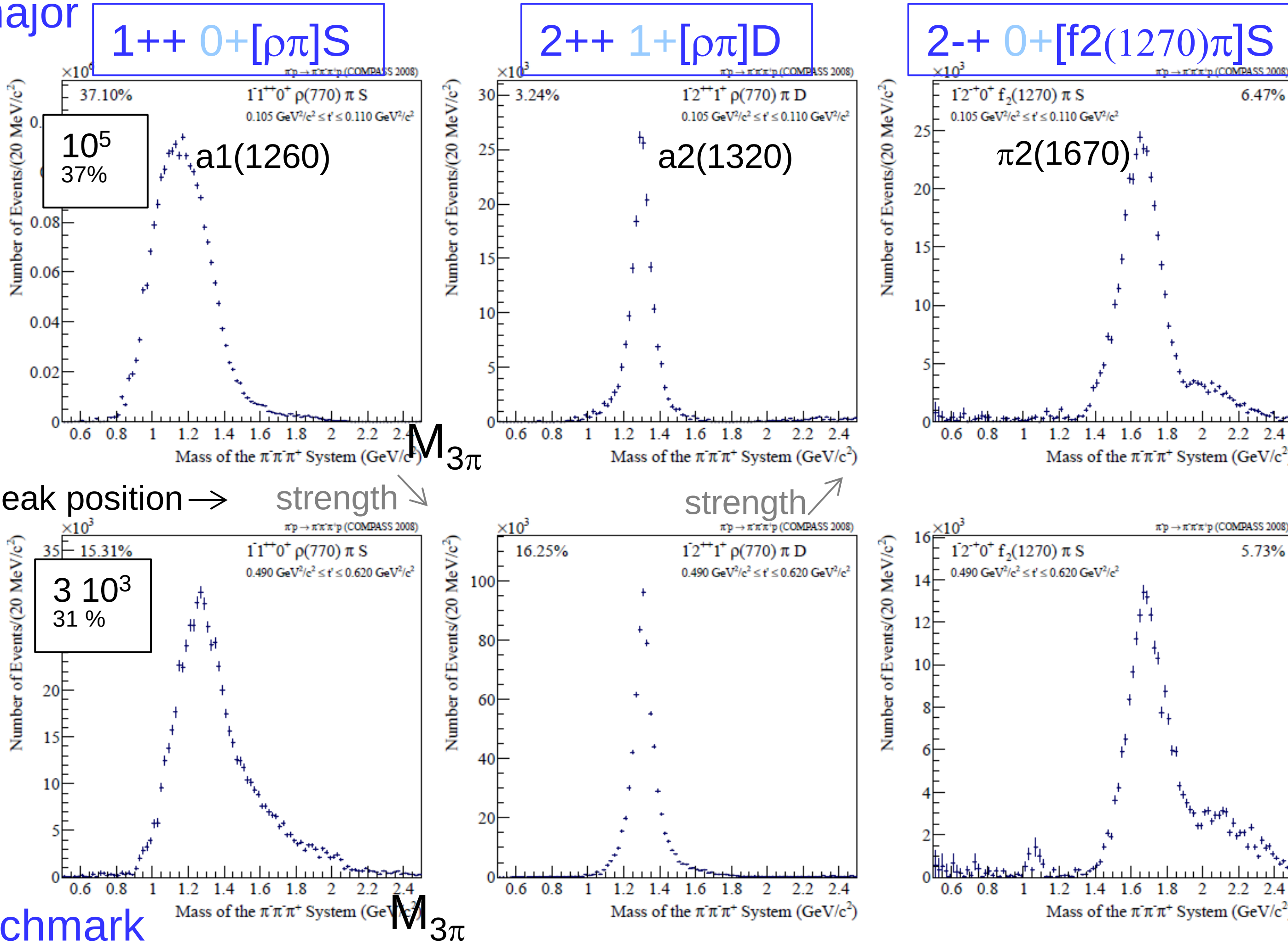
Step 1: PWA in (M, t’) bins

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

t’~0.1 GeV²/c²

100 $M_{3\pi}$ bins

t’~0.5 GeV²/c²



- a_1 as benchmark
- Possibility of separation of resonant and non resonant content

  high statistics & fine binning

Diffractive resonance production - conclusion

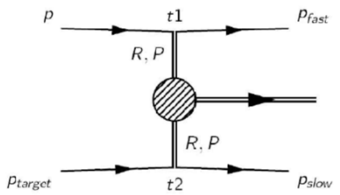
• **Mass dependent PWA of 3π charged channel**,
Huge statistics , 50 M events, 10 times more than previous expts
11 t' bins

• Precise determination of resonance parameters

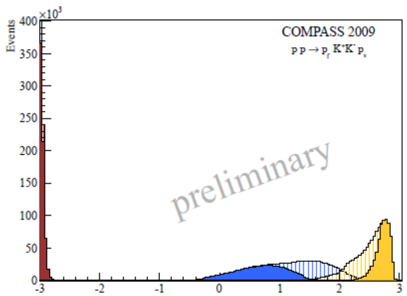
• Analysis proves the potential for establishing new small waves with firm grounds

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

Central production p p→ pK⁺K⁻p

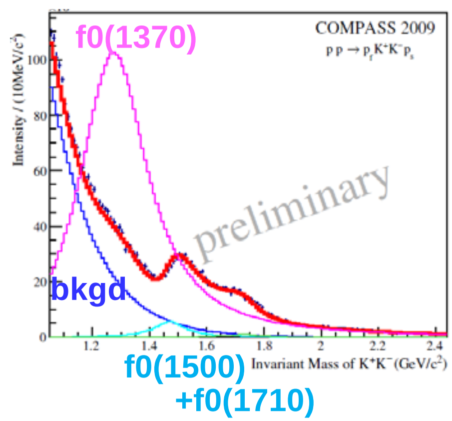


Double Pomeron exchange → glue rich environment
Production of non q-$\bar{q}$ meson (glueballs, hybrids) at central rapidities

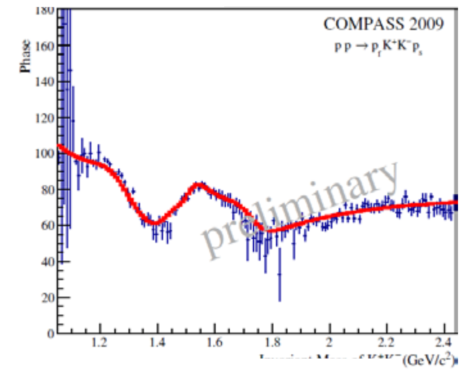


pK+K-p channel
Selection of central production
Cut on p(p_{fast}) >140 GeV;
K id (RICH)

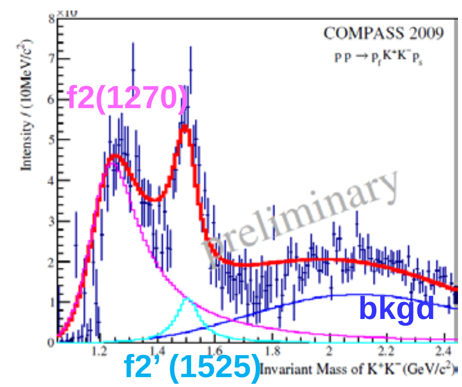
Intensity of S wave



Phase S-D



Intensity of D wave

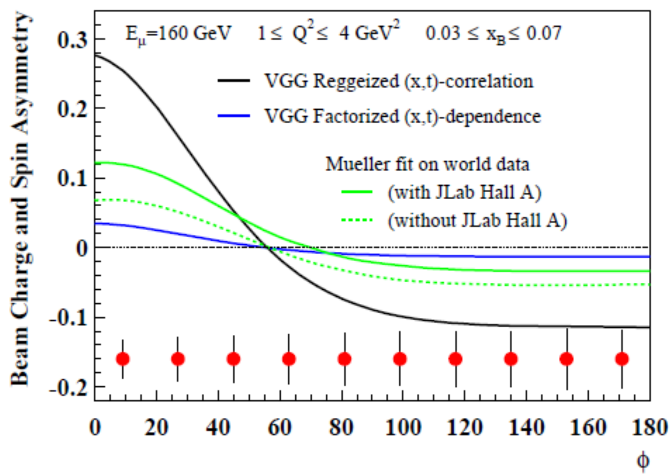


Mass dependent PWA

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

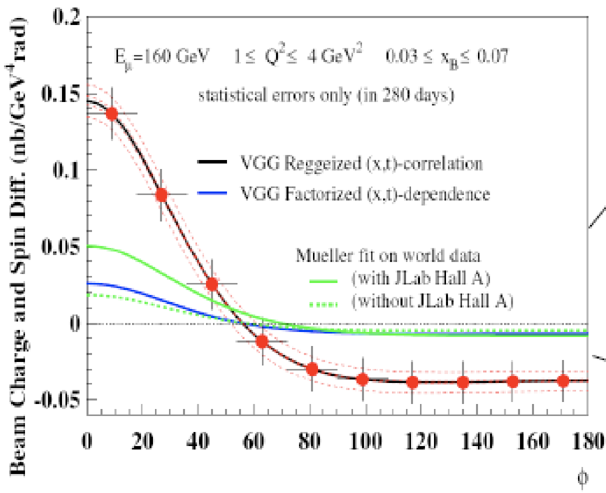
DVCS - Examples of COMPASS projections

Beam-charge asymmety

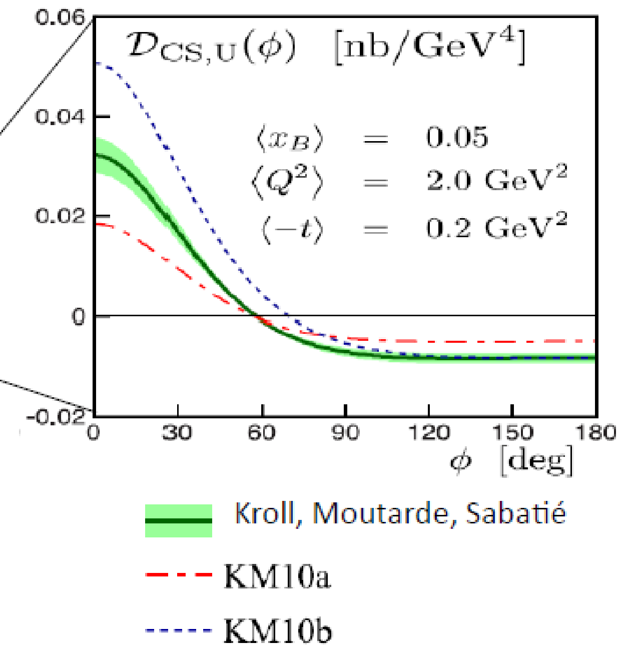


$c_1^I \propto \mathrm{Re}(F_1 \mathcal{H})$

Beam-charge difference



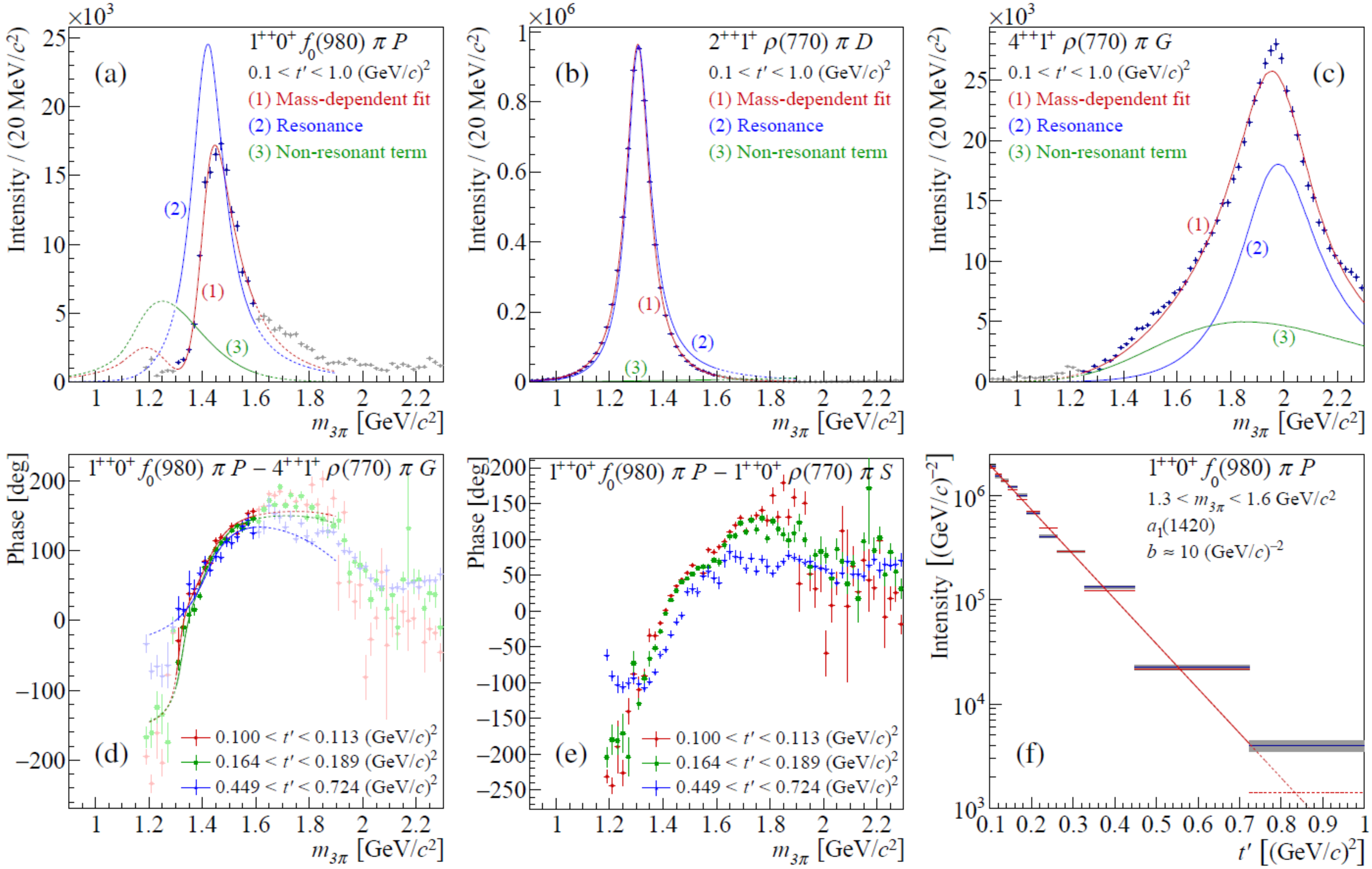
New predictions
by Kroll, Moutarde and Sabatié



a1 (1420)

mass $(1414^{+15}_{-13})\,\mathrm{MeV}/c^2$

width $(153^{+8}_{-23})\,\mathrm{MeV}/c^2$.

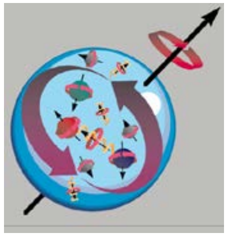


Nucleon spin

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 $g_1 + SU_f(3)$ $a_0 = \Delta\Sigma \sim 0.3$

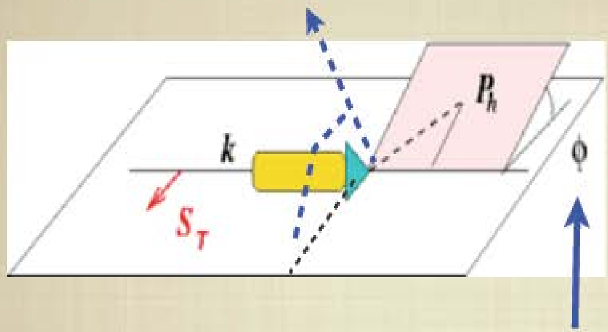
First results from Lattice QCD on $\Delta\Sigma_{u,d}$ and $L_{u,d}$

Large experimental effort on ΔG measurement

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

The Collins mechanism

J. Collins, NPB396 (93)



Collins angle

$$\mathbf{k} \times \mathbf{P}_h \cdot \mathbf{S}_T \propto \cos\left(\frac{\pi}{2} - \phi\right) = \sin\phi$$

transverse motion of hadron

=

spin analyzer of fragmenting quark

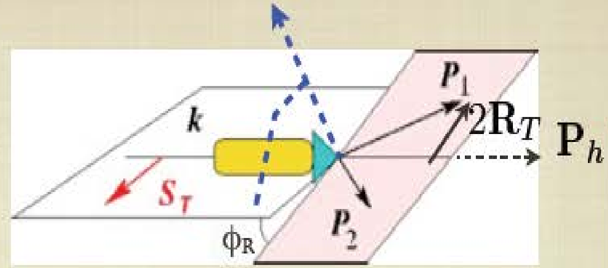
single-spin asymmetry → **convolution**

$$A_{UT}^{\sin(\phi)} \propto \left[h_1^q \otimes H_1^{\perp\, q\to h}\right]$$

TMD factorization

The Di-hadron Fragm. Funct. mechanism

Collins, Heppelman, Ladinsky, NP B420 (94)



$P_{hT}=0$ collinear!

$$\begin{aligned} \mathbf{P}_h \times \mathbf{R}_T \cdot \mathbf{S}'_T &\propto \cos(\phi_{S'_T} - (\phi_{R_T} + \pi/2)) \\ &= \cos(\pi - \phi_S - (\phi_{R_T} + \pi/2)) \\ &= \sin(\phi_{R_T} + \phi_S) \end{aligned}$$

azimuthal orientation of hadron pair

=

spin analyzer of fragmenting quark

single-spin asymmetry → **product**

$$A_{UT}^{\sin(\phi_R+\phi_S)} \propto h_1^q(x)\, H_1^{\sphericalangle\, q\to h_1 h_2}(z, R_T^2)$$

Radici, Jakob, Bianconi PR D65 (02); Bacchetta, Radici, PR D67 (03)

collinear factorization

evolution equations understood

Ceccopieri, Radici, Bacchetta, P.L. B650 (07)

[M. Radici, IWHSS2013]

3π diffractive-Observation of new state a1(1420)

preliminary

Particle	J^{PC}	Mass Range [MeV/c^2]	Width Range [MeV/c^2]	PDG Values m [MeV/c^2]	Γ [MeV/c^2]
"Established" states					
$a_1(1260)$	1^{++}	1260–1290	360–420	1230 ± 40	250–600
$a_2(1320)$	2^{++}	1312–1315	108–115	$1318.3^{+0.5}_{-0.6}$	107 ± 5
$a_4(2040)$	4^{++}	1928–1959	360–400	1996^{+10}_{-9}	255^{+28}_{-24}
$\pi_2(1670)$	2^{-+}	1635–1663	265–305	1672.2 ± 3.0	260 ± 9
$\pi(1800)$	0^{-+}	1768–1807	212–280	1812 ± 12	208 ± 12
$\pi_2(1880)$	2^{-+}	1900–1990	210–390	1895 ± 16	235 ± 34
States not in PDG summary table					
$a_1(1420)$	1^{++}	1412–1422	130–150	—	—
a_1'	1^{++}	1920–2000	155–255	1930^{+30}_{-70}	155 ± 45
a_2'	2^{++}	1740–1890	300–555	1950^{+30}_{-70}	180^{+30}_{-70}

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**
- **Δq(x) = q⇉- q⇆** : longitudinal polarization or **helicity distribution**
- **Δ_Tq(x) = q↑↑- q↓↑** : transverse polarization or **transversity distribution**

All 3 of equal importance

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

All measured in COMPASS in SIDIS

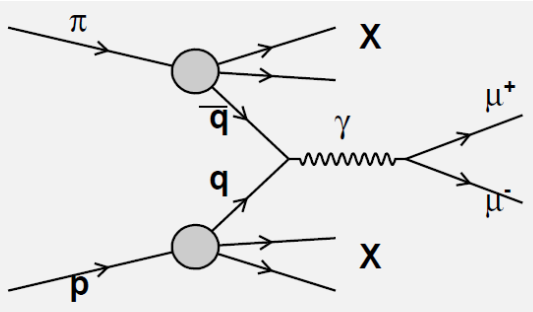
Among them, the **Sivers** function.

Polarized Drell-Yan

5-month run in 2015 with π beam and transversely polarized target(NH3)

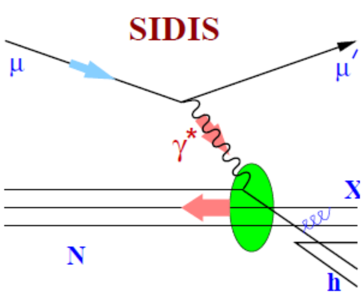
$\pi^- p\uparrow \rightarrow \mu^+\mu^- X$

→ Measure TMDs, Sivers & Boer-Mulders

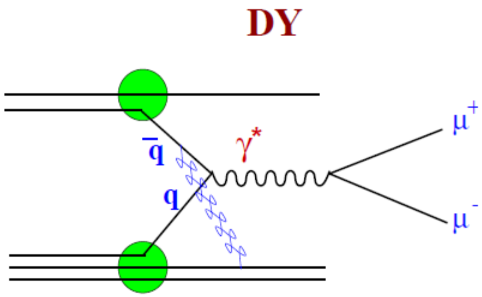


Drell-Yan: TMD x TMD
SIDIS: TMD x FF

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



Final State Interactions



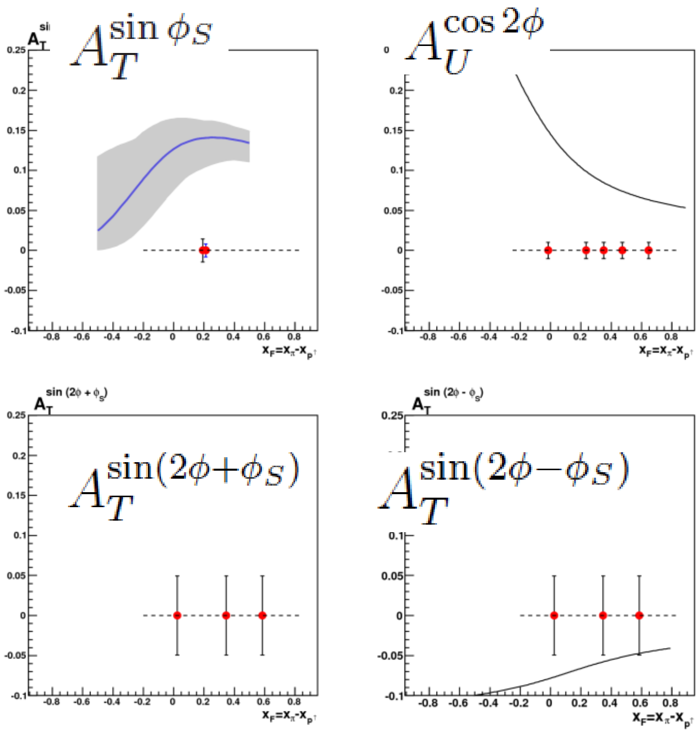
Initial State Interactions

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)

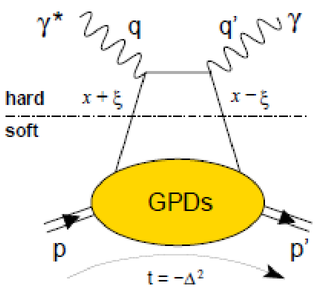
Sivers, Boer-Mulders… via Polarized Drell-Yan

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:

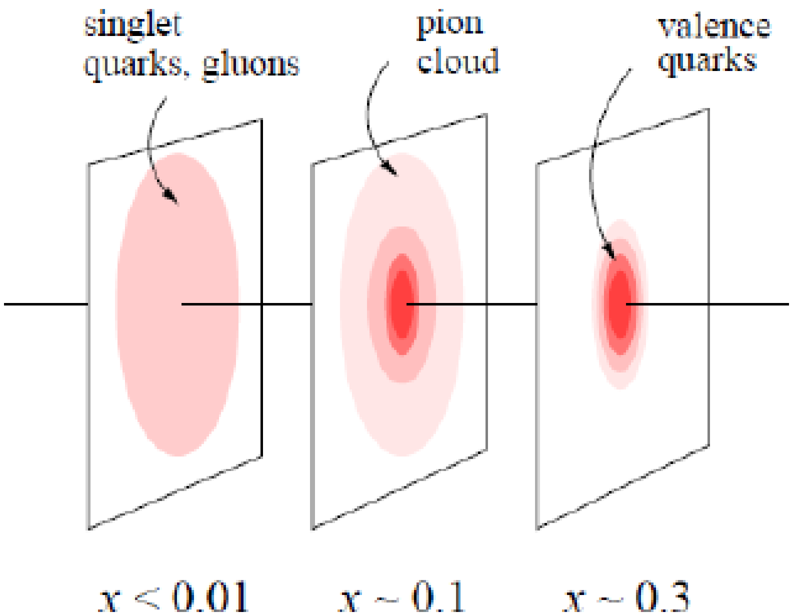
$$J^f = \frac{1}{2} \lim_{t\to 0} \int_{-1}^{1} dx\ x\ \left[H^f(x,\xi,t) + E^f(x,\xi,t)\right]$$

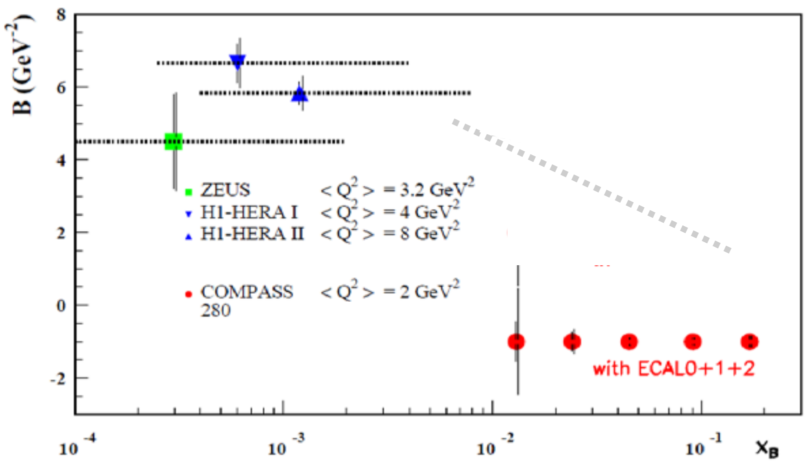
GPD **H** : accessible with unpolarized H target
GPD **E** : transversely polarized target

DVCS ex: Projection for t-slope

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

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





Also accessed via meson production ρ, ω, ϕ