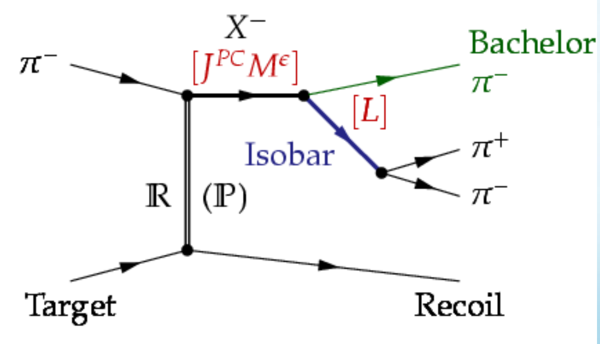
2014 COMPASS STATUS REPORT

Outline

- Analysis and results of hadron beam data
  - PWA of the $\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ final states and observation of a new iso-vector meson
  - Search for the $Z_c(3900)$ in COMPASS
- Analysis and results of muon beams data
  - Global NLO QCD fit to world data on g_1
  - Determination of $\Delta g/g$ using “all-p_T” events
  - Sivers/Collins asymmetries in the Drell-Yan $x - Q^2$ region
  - Interplay between the dihadron asymmetry and the Collins asymmetry
  - The gluon Sivers asymmetry
  - Pion multiplicities and fragmentation function
- Hardware preparation for the 2014 short Drell-Yan run

Hadron beam analysis

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



Isobar model

Partial waves :

J^{PC} M^ε [isobar] L

J^{PC}-**exotic** mesons

2008 ℓH_2 data, 4×10^7 $\pi^- p \longrightarrow \pi^- \pi^+ \pi^- p$ and 3.6×10^6 $\pi^- p \longrightarrow \pi^- \pi^0 \pi^0 p$: large statistics

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,

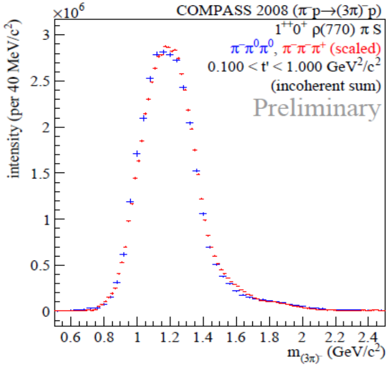
combined fit of t' bins

(same mass, width; different background and couplings)

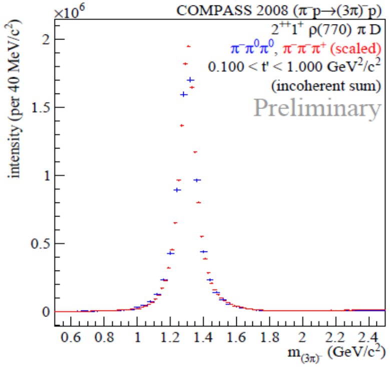
Extract resonance parameters

A look to major waves

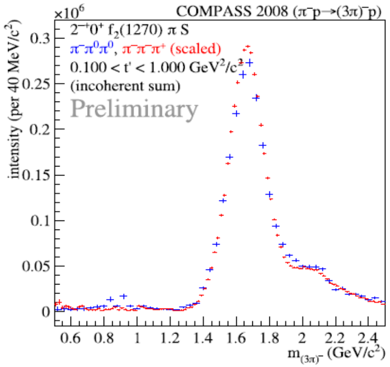
Good agreement between charged $\pi^-\pi^+\pi^-$ and mixed $\pi^-\pi^0\pi^0$ final states



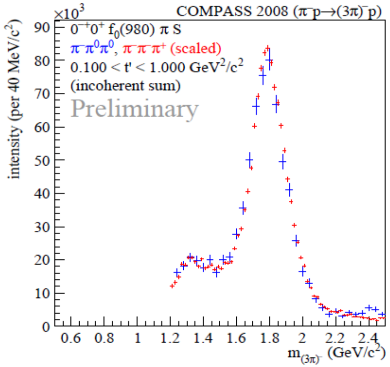
(a) $1^{++}\,0^+\,\rho\pi\,S$ wave with the $a_1(1260)$ peak.



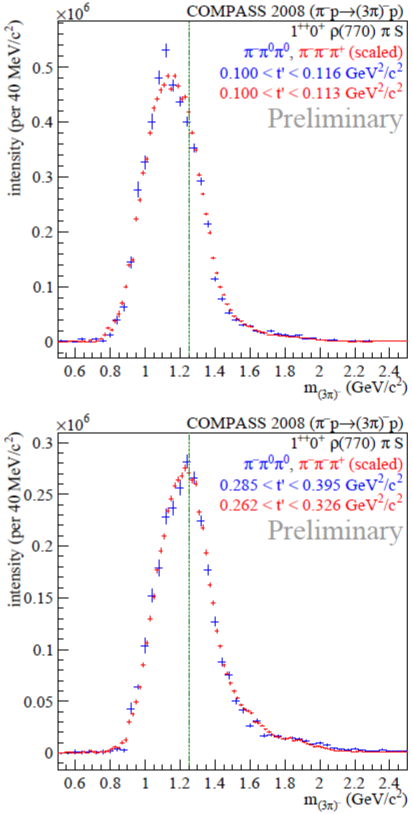
(b) $2^{++}\,1^+\,\rho\pi\,D$ wave with the $a_2(1320)$ peak.



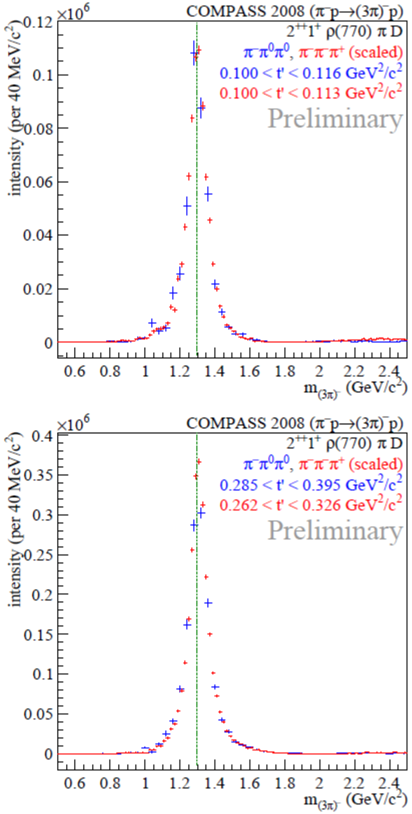
(c) $2^{-+}\,0^+\,f_2(1270)\,\pi\,S$ wave with the $\pi_2(1670)$ peak.



(d) $0^{-+}\,0^+\,f_0(980)\,\pi\,D$ wave with the $\pi(1800)$ peak.

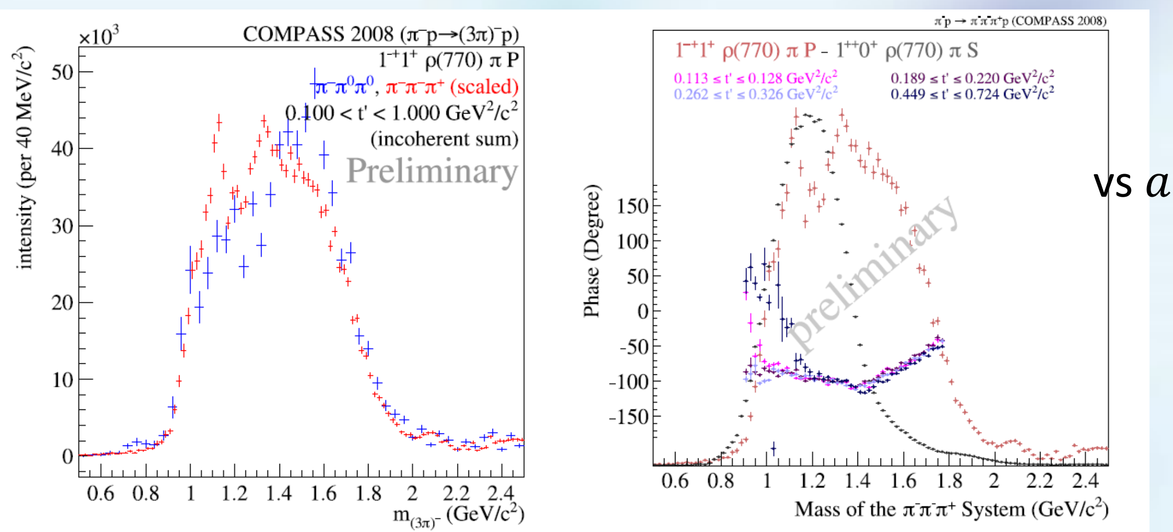


(a) $1^{++}\,0^+\,\rho\pi\,S$ wave with the $a_1(1260)$ peak.



(b) $2^{++}\,1^+\,\rho\pi\,D$ wave with the $a_2(1320)$ peak.

Spin exotics $J^{PC} = 1^{-+}$



vs $a_1(1260)$

- Both analyses show a broad intensity distribution without a clear peak at 1.6 GeV/c^2.
- However, slow phase motions of about 50 are observed
- The region around 1.1 GeV/c^2 (no resonances expected), exhibits fit instabilities.

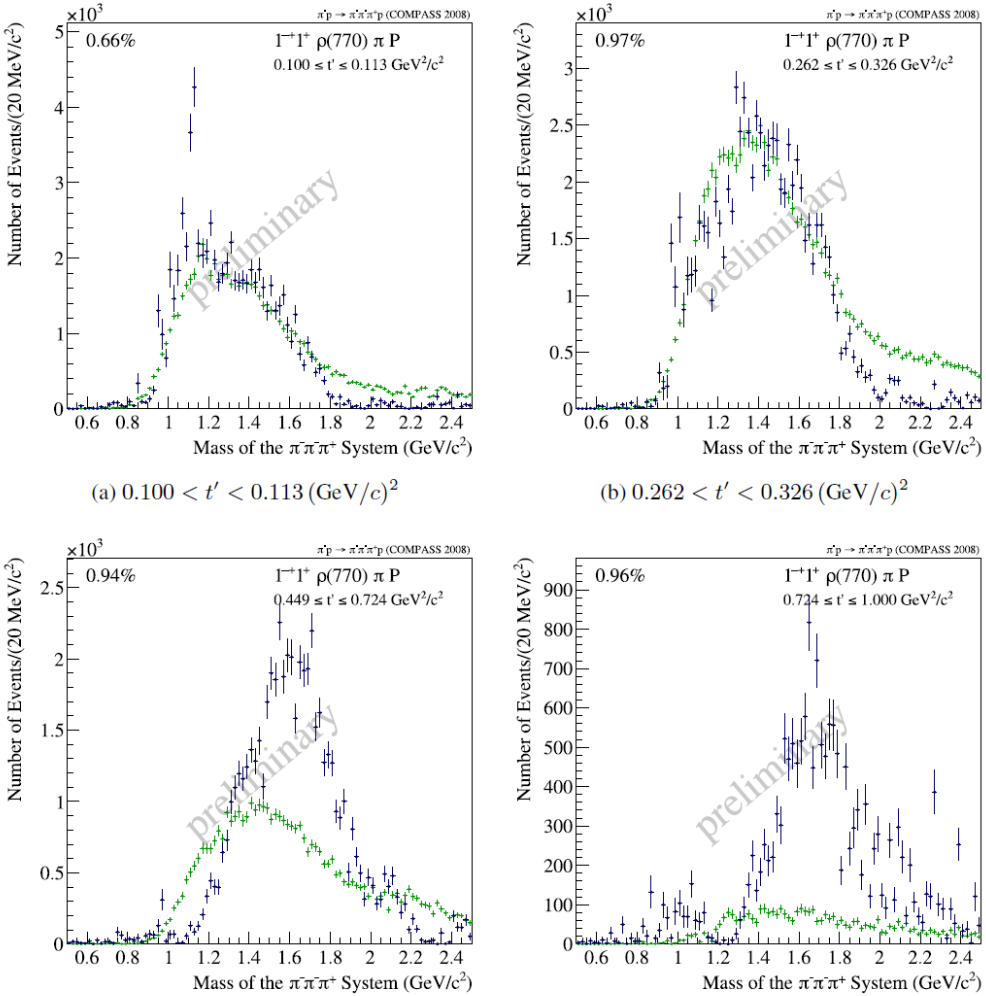
Spin exotics $J^{PC} = 1^{-+}$

Striking t' dependence of $J^{PC} = 1^{-+}$ $\rho\pi P$ spectrum.

- low t' the wave exhibits a broad intensity distribution
- Increasing t' the intensity shifts towards higher masses leaving a narrower peak at about 1.6 GeV/c^2

i.e. spin-exotic influenced by non-resonant contributions (interpretation depends on non-resonant terms modelling)

Green points; modelling of Deck effect



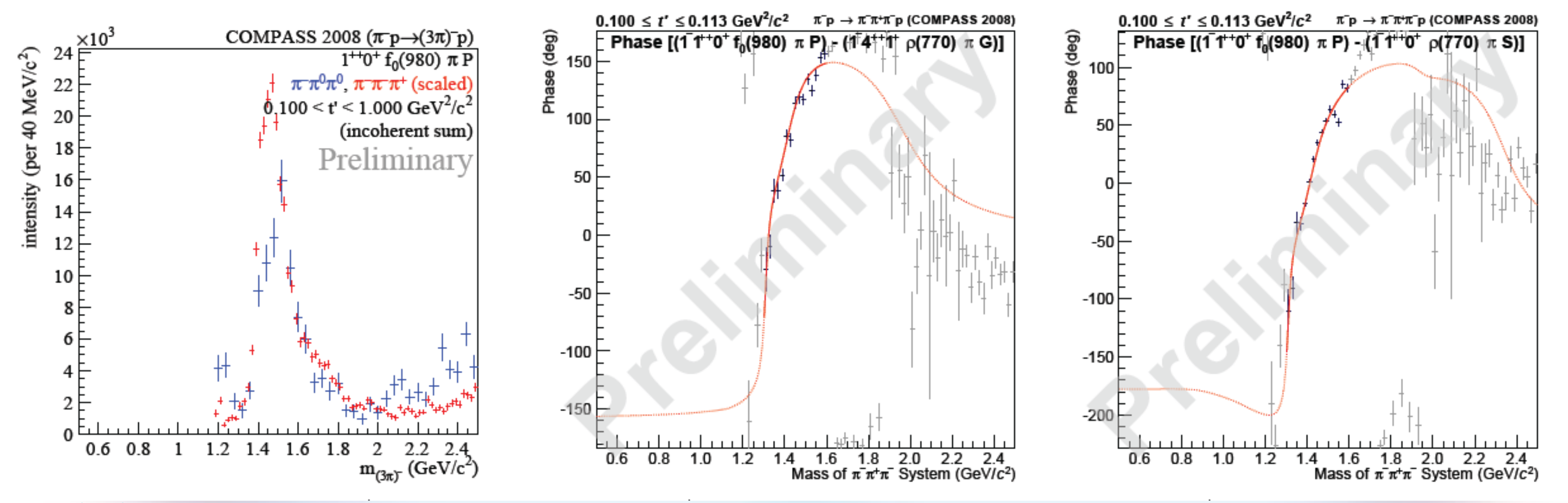
(a) $0.100 < t' < 0.113\,(\mathrm{GeV}/c)^2$

(b) $0.262 < t' < 0.326\,(\mathrm{GeV}/c)^2$

New iso-vector meson $a_1(1420)$

We have identified a new iso-vector axial-vector meson with of $J^{PC} = 1^{++}$, the $a_1(1420)$:

- mass of $1420\ \mathrm{MeV}/c^2$, a (rather small) width of $140\ \mathrm{MeV}/c^2$.
- Exotic (non-$q\bar{q}$) features since only decay as $f_0(980)\pi$ ($f_0(980)$ superposition of $q\bar{q}$ and $s\bar{s}$ states).

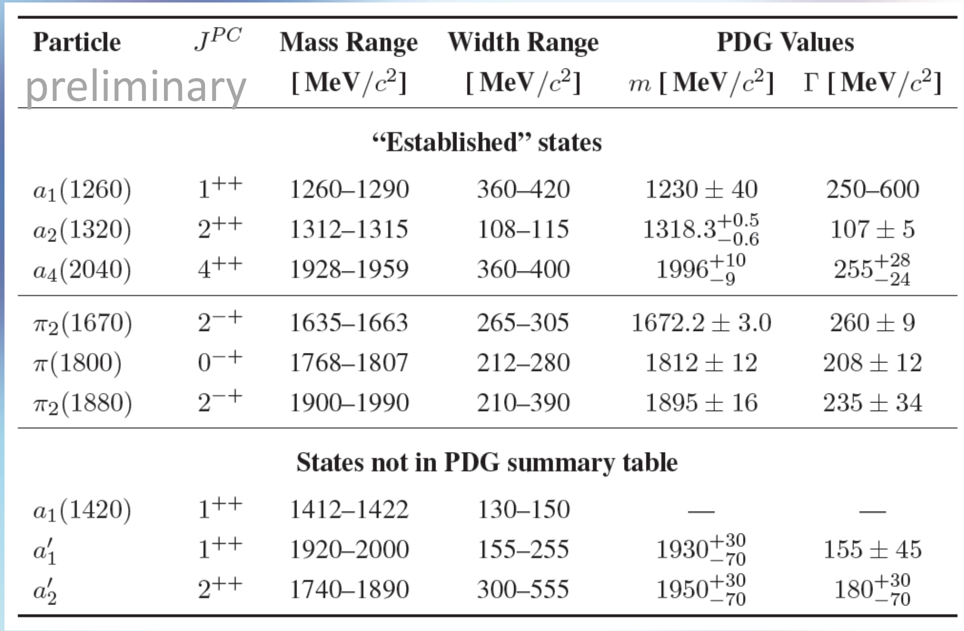


Interpretation

The $a_1(1420)$ signal inside the $1^{++}0^{+}f_0(980)\pi P$ wave has a strength about 100 times less than the main wave, $1^{++}0^{+}\rho\pi S$ (it can be the reason why escaped detection in previous experiments).

Still unclear the origin; possible explanations:

- It can 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 an isospin partners of exotic states were discovered).
- Another possibility is a dynamic generation through the strong coupling of the systems $a_1(1420)$, $f_0(980)\pi$, and $K\bar{K}^*$.



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}

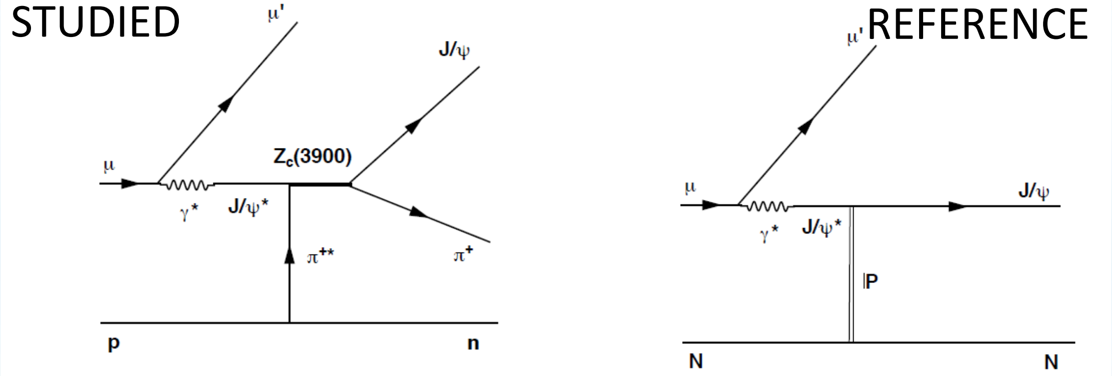
Conclusions

- A large effort in view of publication:
  - Three publications foreseen in 2014.
    - A short letter on the finding of $a_1(1420)$ state
    - The results from the partial-wave decomposition in mass and t' bins (details of analysis)
    - A long paper will present more detailed results on the parameters and t' dependencies of various resonances.

All three papers are currently in the drafting stage

The search for $Z_C(3900)$

- $Z_C(3900)$ was recently discovered by the BES-III and Belle Collaborations in $e^+e^- \longrightarrow \left(Z_C^\pm \to J/\psi\,\pi^\pm\right)\pi^\mp$ at $\sqrt{s} = 4.26$ GeV

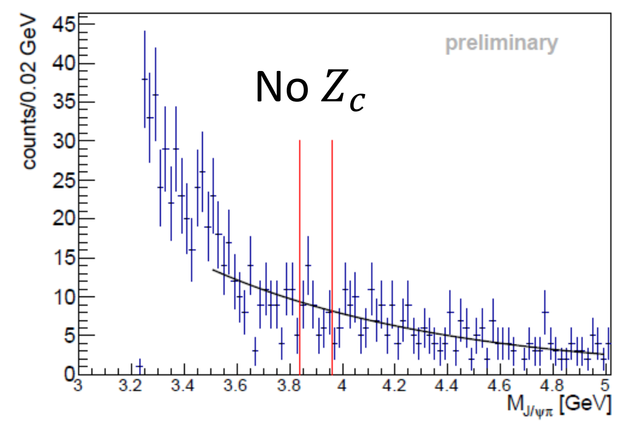


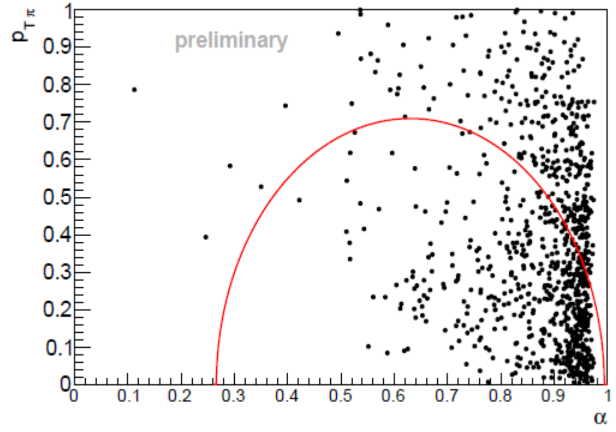
- $Z_C(3900)$ can be produced by the interaction of an incoming photon with a virtual charged pion provided by the target nucleon (expected $\sigma \sim 50 \div 100$ nb in kinematic region close to COMPASS)

Limits on $Z_C(3900)$ in COMPASS

- Expected mass resolution $\sim 15\ \mathrm{MeV}/c^2$ (as for $\psi(2S)$ in the spectra of $J/\psi\pi^+\pi^-$)
- Upper limit for $N_{Z_C}^{UL} = 13$, while for the reference process we counted $N_{J/\psi} = 11.6\times10^3$

$$\frac{\sigma_{\gamma N\to Z_C^{\pm}(3900)N}\times BR(J/\psi\pi)}{\sigma_{\gamma N\to J/\psi N}} = \frac{1}{0.5}\cdot\frac{N_{Z_C}^{UL}}{N_{J/\psi}} < 2.2\times10^{-3}$$ or $\sigma_{\gamma N\to Z_C^{\pm}(3900)N}\times BR(J/\psi\pi) < 31\ \mathrm{pb}$



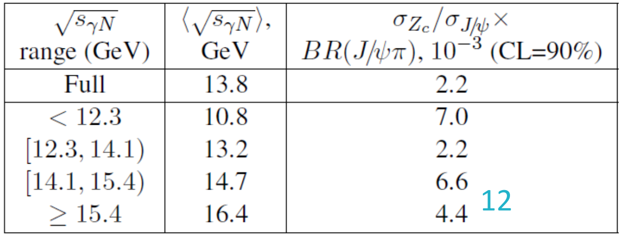


$\Gamma_{J/\psi\pi} < 1.8\ \mathrm{MeV}/c^2$

since

$\Gamma_{\mathrm{tot}} = 46\ \mathrm{MeV}/c^2$

What is the main decay mode?

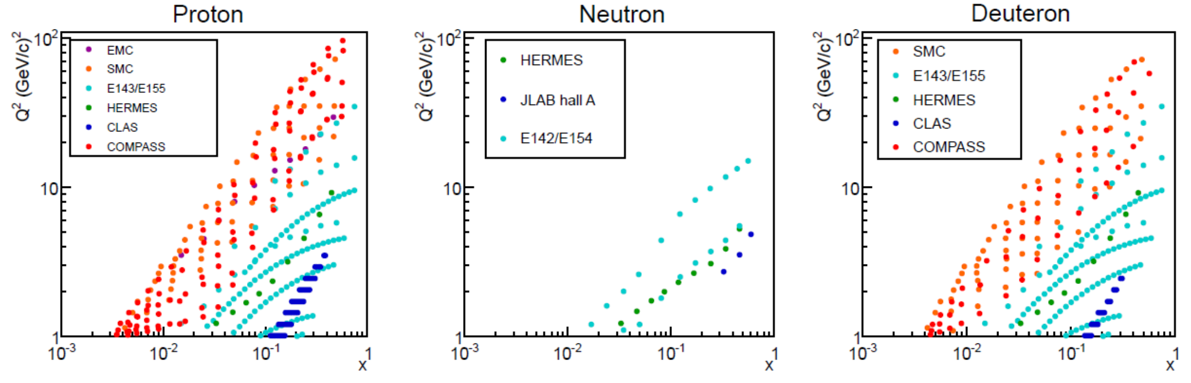


$\sqrt{s_{\gamma N}}$ range (GeV)	$\langle\sqrt{s_{\gamma N}}\rangle$, GeV	$\sigma_{Z_c}/\sigma_{J/\psi}\times BR(J/\psi\pi)$, 10^{-3} (CL=90%)
Full	13.8	2.2
< 12.3	10.8	7.0
[12.3, 14.1)	13.2	2.2
[14.1, 15.4)	14.7	6.6
≥ 15.4	16.4	4.4

Muon beam analysis

Global NLO QCD fits to world data on g_1

- 138 out of 679 points are from COMPASS



$$g_1 = \frac{1}{2}\langle e^2\rangle(C^S(\alpha_s)\otimes\Delta q_S + C^{NS}(\alpha_s)\otimes\Delta q_{NS} + C^g(\alpha_s)\otimes\Delta g)$$

$\Delta q_S = \Delta u + \Delta d + \Delta s$; Δq_{NS} is a combination of $\Delta q_3 = \Delta u - \Delta d$ and $\Delta q_8 = \Delta u + \Delta d - 2\Delta s$

Evolving as

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

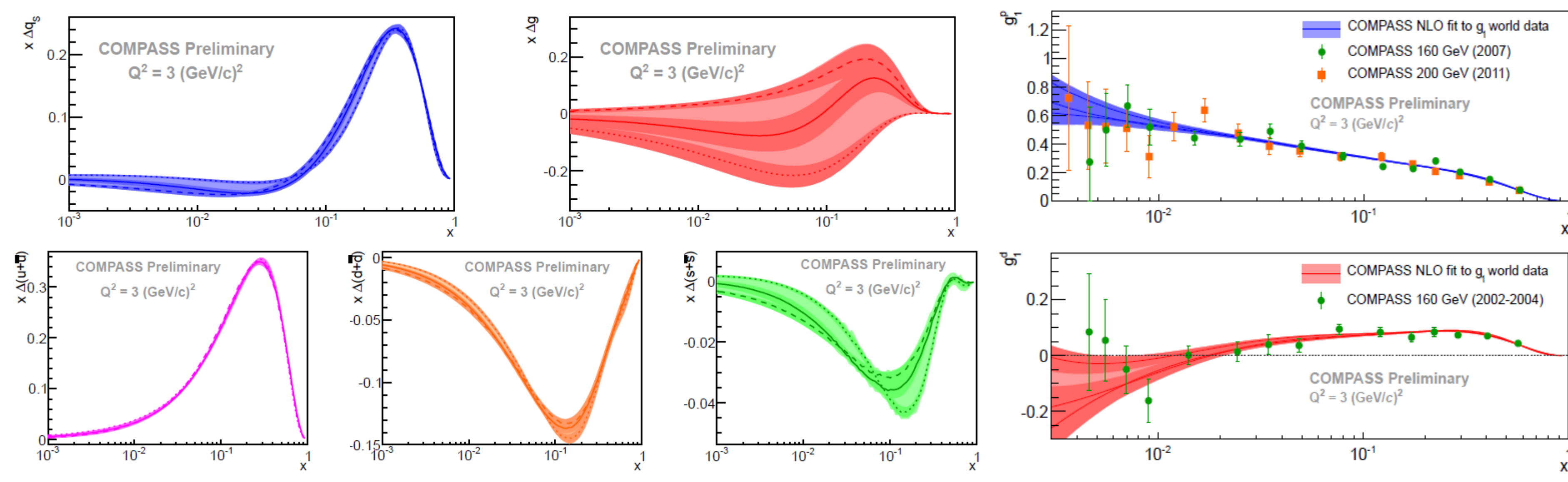
$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta q_S\\ \Delta g\end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{pmatrix}\Delta P_{qq} & 2n_f\Delta P_{qg}\\ \Delta P_{qg} & \Delta P_{gg}\end{pmatrix}\otimes\begin{pmatrix}\Delta q_S\\ \Delta g\end{pmatrix}$$

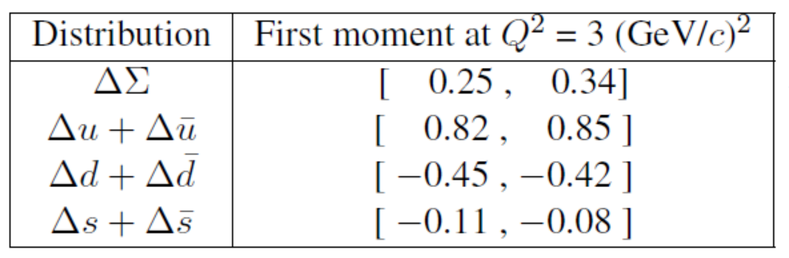
First moments of Δq_3 and Δq_8 fixed by baryon decay constants $(F+D)$ and $(3F-D)$ assuming $SU(2)_f$ and $SU(3)_f$ symmetries.

$$\Delta f_k(x) = \Delta q_k\frac{x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x+\rho\sqrt{x})}{\int_0^1 x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x+\rho\sqrt{x})}$$

Results

3 initial Δg shapes; positive, negative with node.





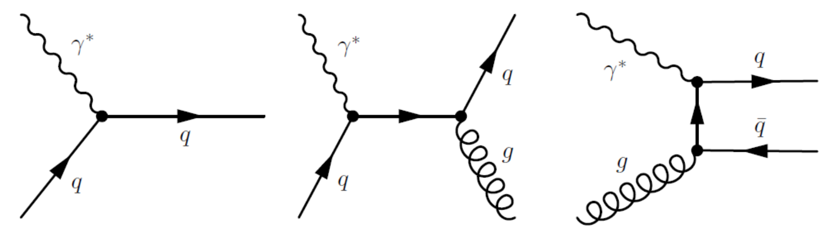
Distribution	First moment at $Q^2 = 3\ (\mathrm{GeV}/c)^2$
$\Delta\Sigma$	[0.25 , 0.34]
$\Delta u + \Delta\bar{u}$	[0.82 , 0.85]
$\Delta d + \Delta\bar{d}$	[−0.45 , −0.42]
$\Delta s + \Delta\bar{s}$	[−0.11 , −0.08]

Range in $\Delta\Sigma$ driven by uncertainty on initial Δg shape

$\Delta g/g$ using “all p_T” events

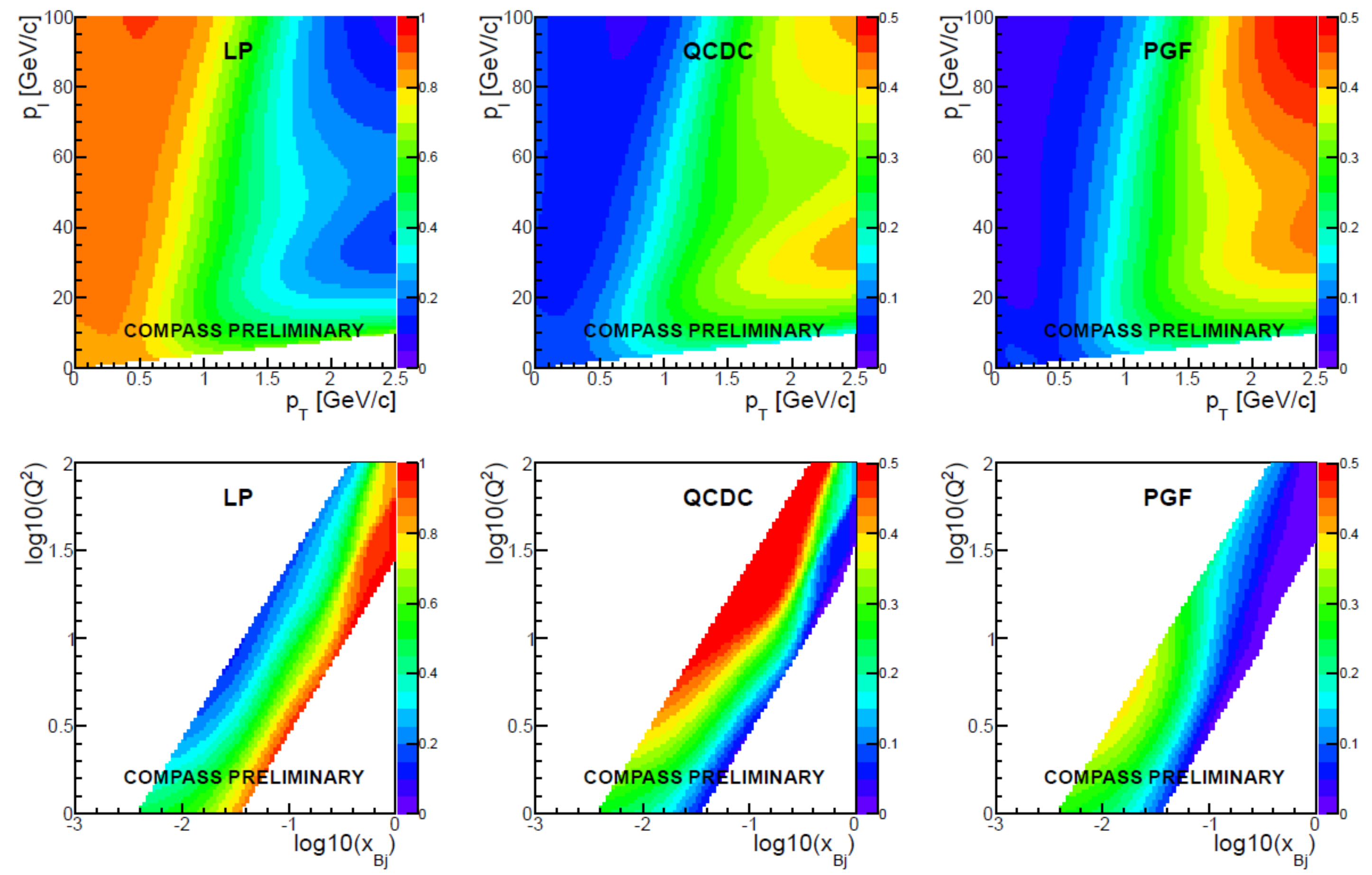
- The main goal is to improve the extraction by removing few sources of systematic effects.
- However, also a considerable reduction of the statistical error of $\Delta g/g$ was achieved.
- Three processes contribute to the cross-section

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

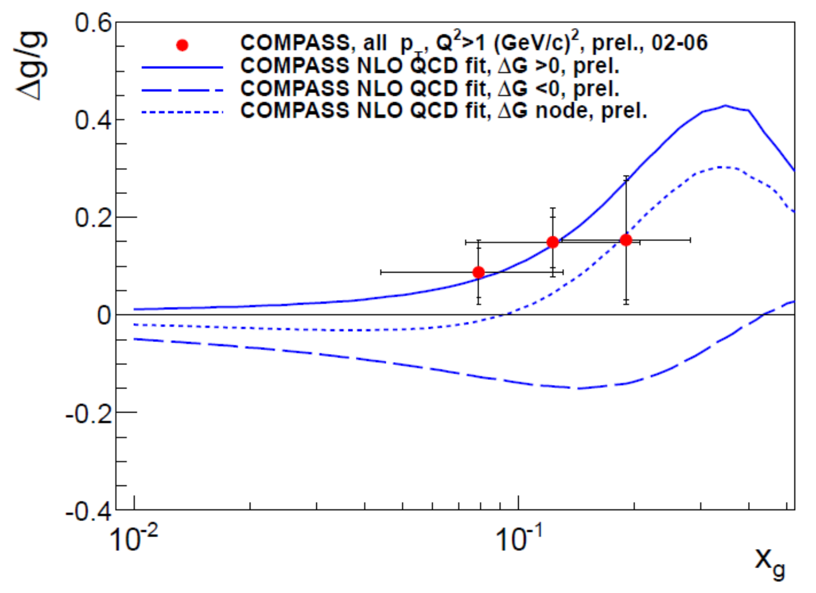


- Simultaneous extraction of $\Delta g/g$, and A_1^{LO}
- Extraction based on effective Monte Carlo description of all processes giving the relative weights (R_i) and analyzing powers (a_{LL}^{i})
- Process weights depends on p_T (at small p_T LO contribution is > 0.95)

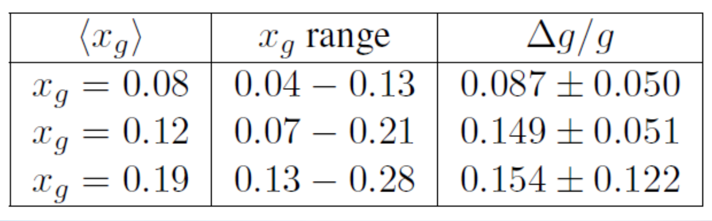
$\Delta g/g$ using "all p_T" events: correlations



$\Delta g/g$ using “all p_T” events: results



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

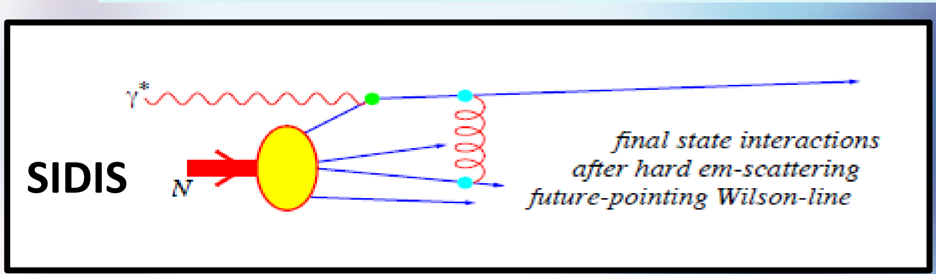


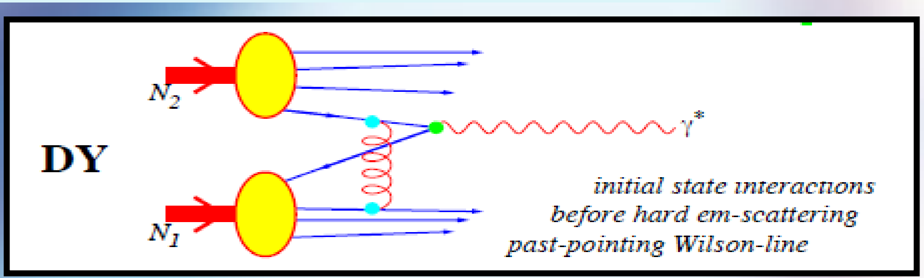
$\langle x_g\rangle$	x_g range	$\Delta g/g$
$x_g = 0.08$	$0.04 - 0.13$	0.087 ± 0.050
$x_g = 0.12$	$0.07 - 0.21$	0.149 ± 0.051
$x_g = 0.19$	$0.13 - 0.28$	0.154 ± 0.122

Test of universality

T-odd character of the Boer-Mulders and Sivers functions

In order not vanish by time-reversal invariance T-odd SSA require an interaction phase generated by a rescattering of the struck parton in the field of the hadron remnant





these functions are process dependent, they change sign to provide the gauge invariance

Time reversal

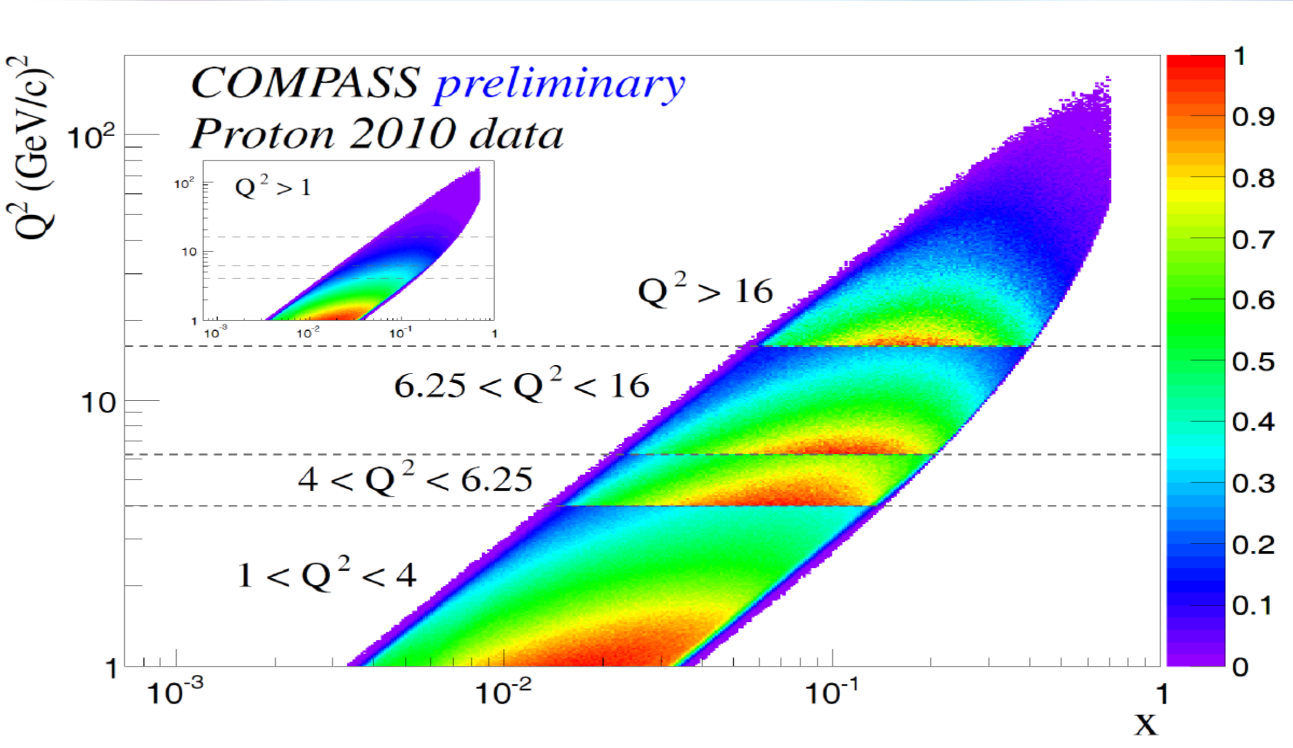
Boer-Mulders

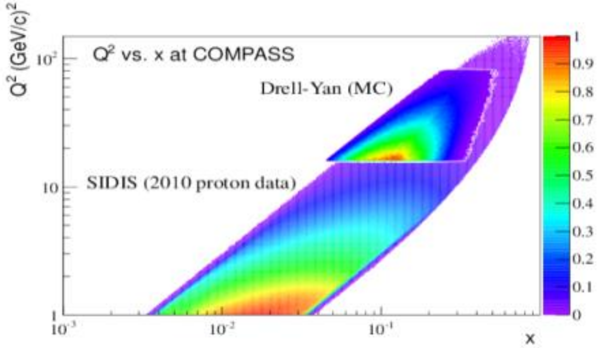
$$\boxed{h_1^\perp(SIDIS) = -h_1^\perp(DY)}$$

Sivers

$$\boxed{f_{1T}^\perp(SIDIS) = -f_{1T}^\perp(DY)}$$

Q^2 vs x phase space at COMPASS

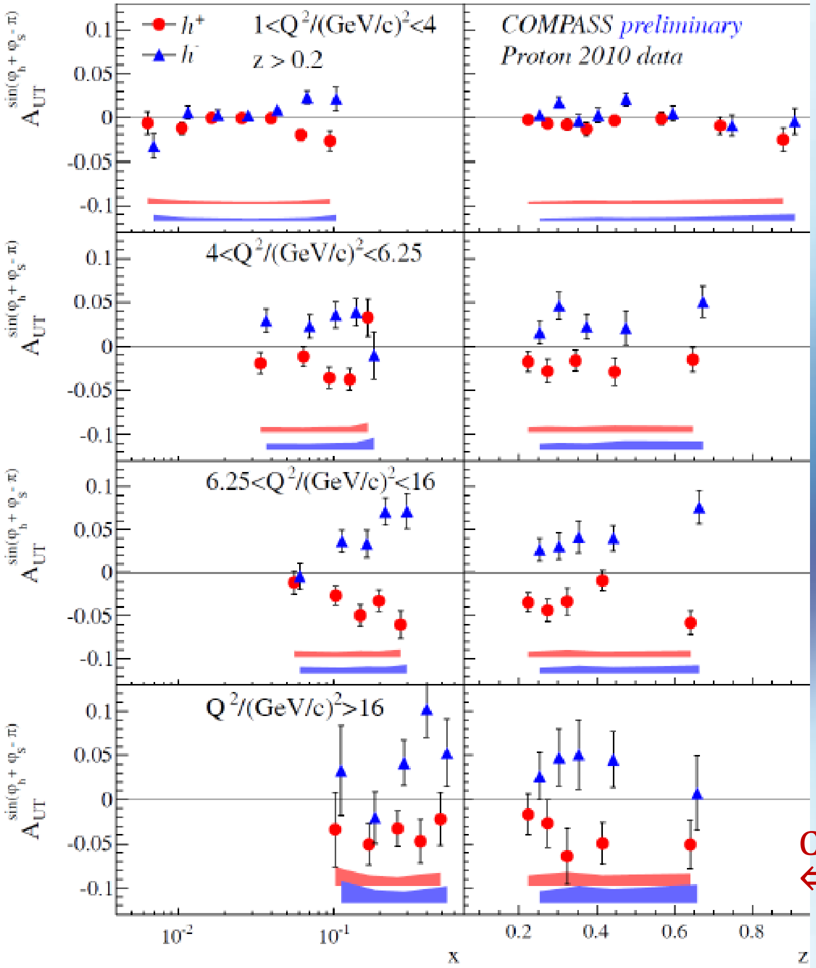




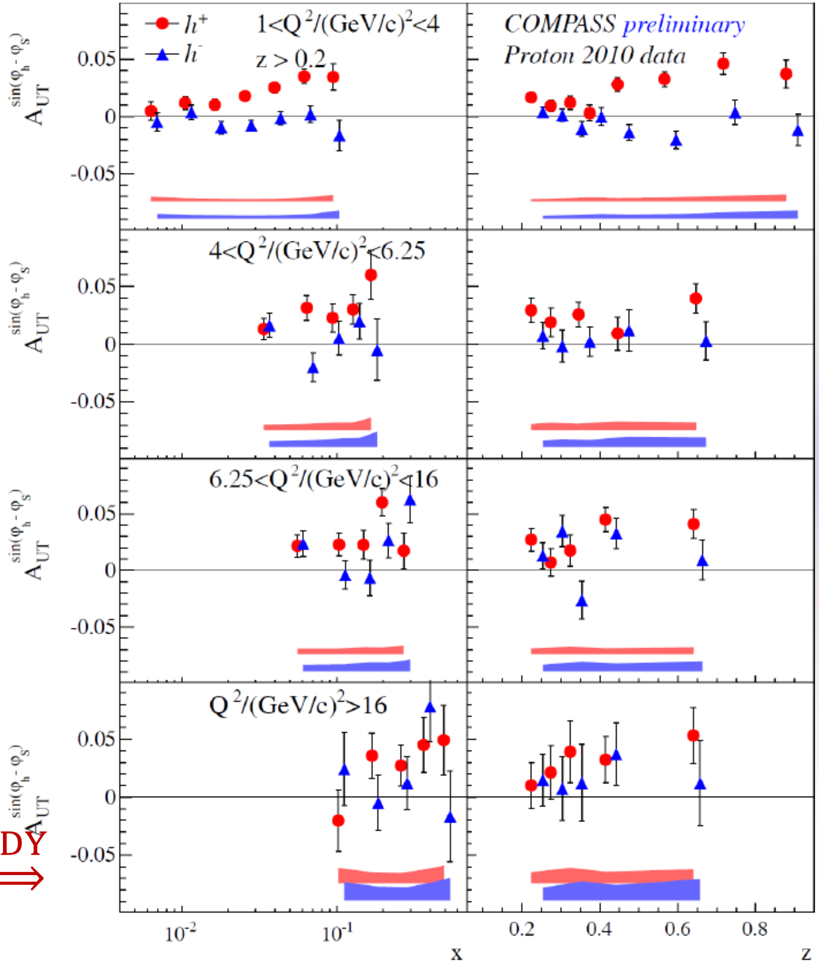
The phase spaces of the two processes overlap at COMPASS

➔ Consistent extraction of TMD DPFs in the same region

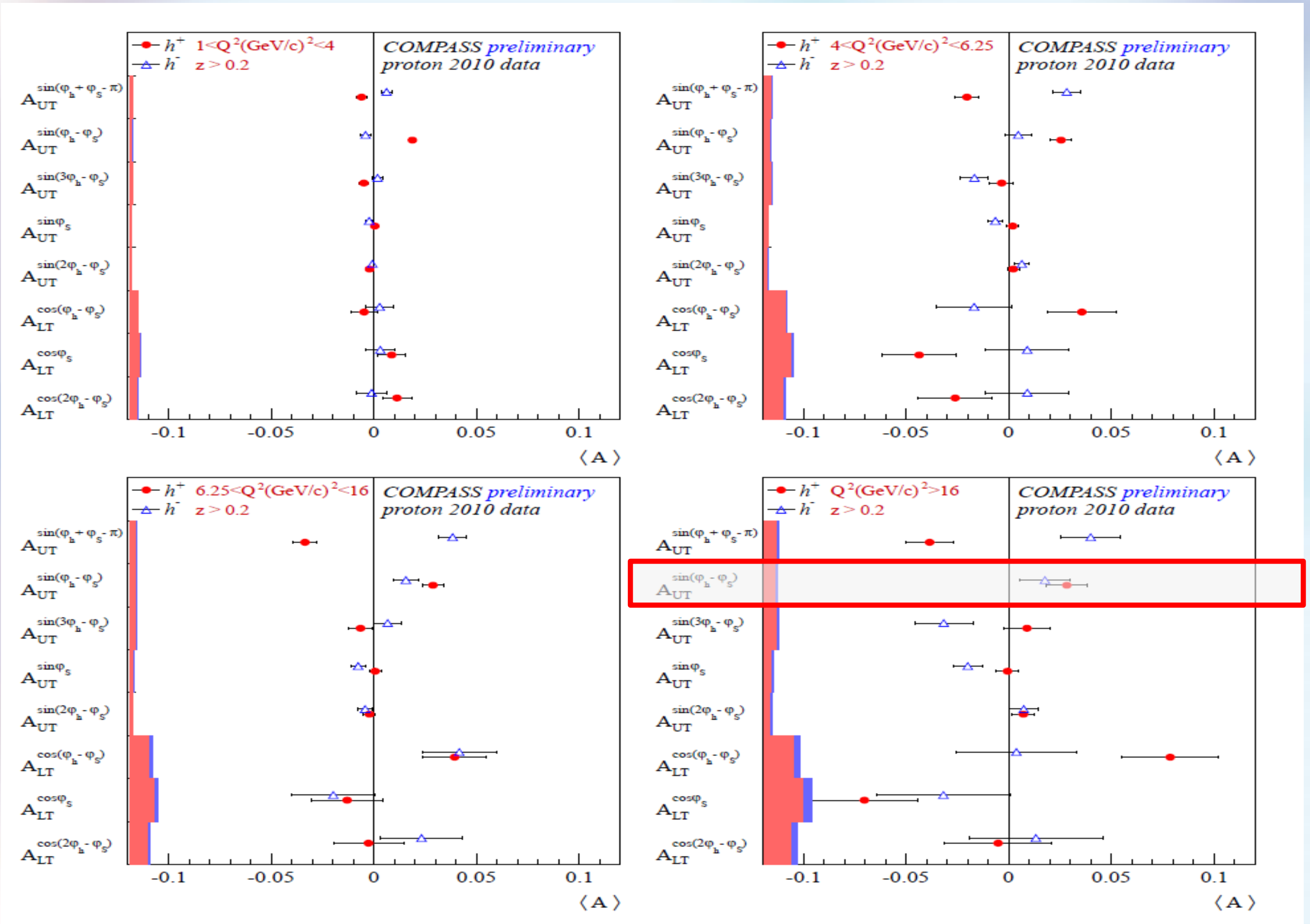
Collins and Sivers for different Q^2 ranges



COMPASS DY



Mean TMD SSA for the four Q^2 ranges

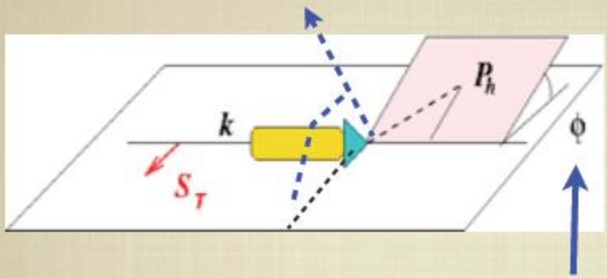


COMPASS DY

⟸

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

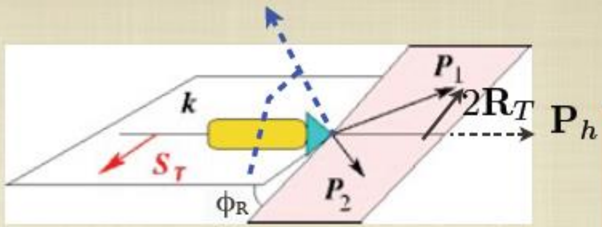
single-spin asymmetry → **convolution**

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

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**

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

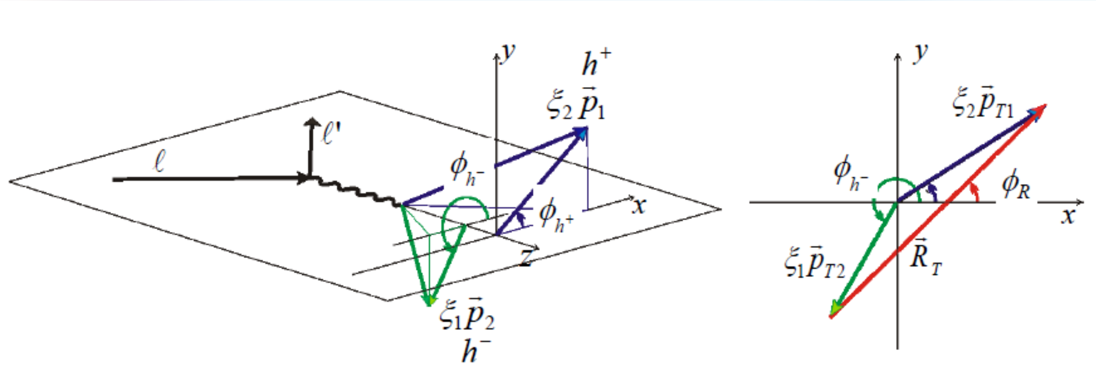
Radici, Jakob, Bianconi PR D65 (02); Bacchetta, Radici, PR D67 (03)

collinear factorization
evolution equations understood

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

[M. Radici, IWHSS2013]

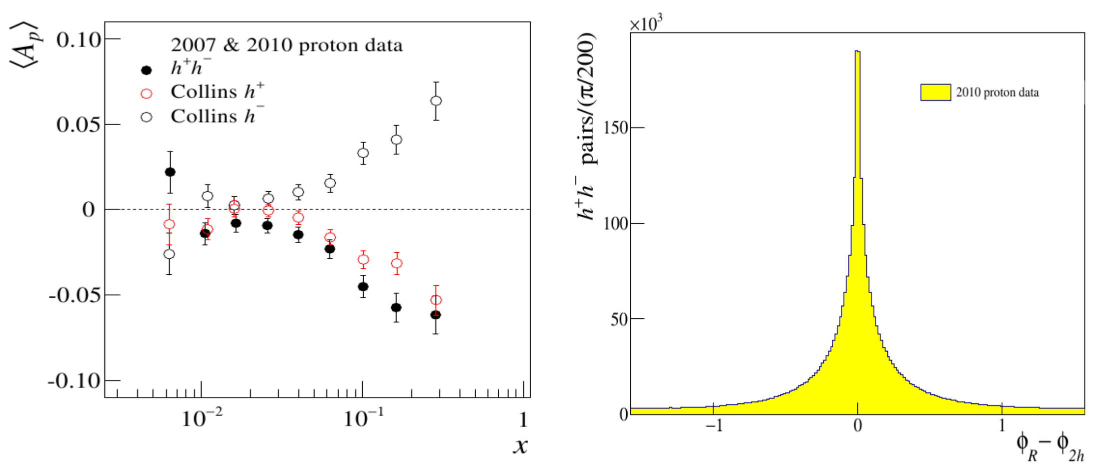
Interplay between Collins and IFF asymmetries

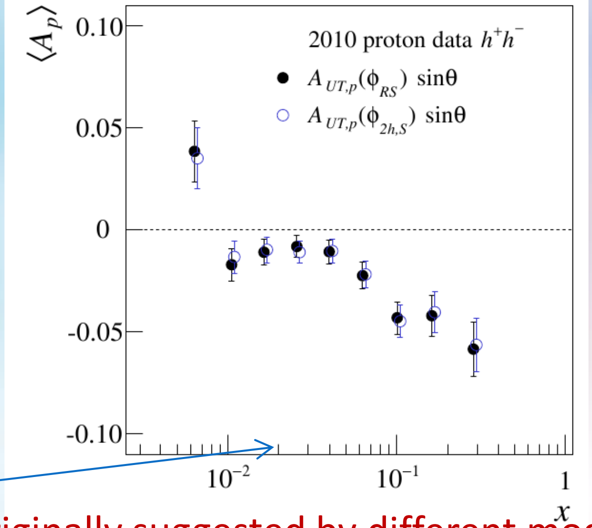


common hadron sample for Collins and 2h analysis

ϕ_{2h} azimuthal angle of $\vec{R}_N = \hat{p}_{T,h^+} - \hat{p}_{T,h^-}$

ϕ_R azimuthal angle of $\vec{R}_T$

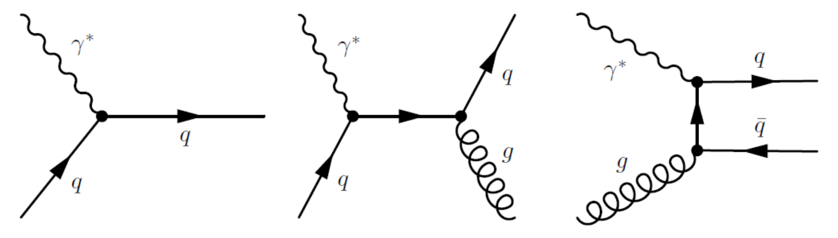




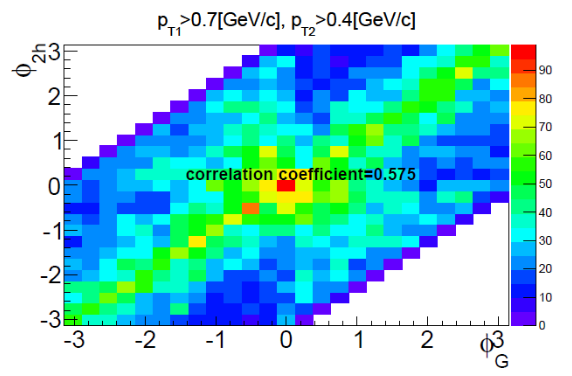
Hint to a at a common physical origin for the $H_1^{\perp}$ and the $H_1^{\sphericalangle}$ as originally suggested by different models

Sivers asymmetry on deuteron for Gluons

$$A_{UT}^{\sin(\phi_{2h}-\phi_S)}(x) = R_{LO}A_{LO}^{\sin(\phi_{2h}-\phi_S)}(x) + R_{QCDC}A_{QCDC}^{\sin(\phi_{2h}-\phi_S)}(x_C) + R_{PGF}\,A_{PGF}^{\sin(\phi_{2h}-\phi_S)}(x_g)$$

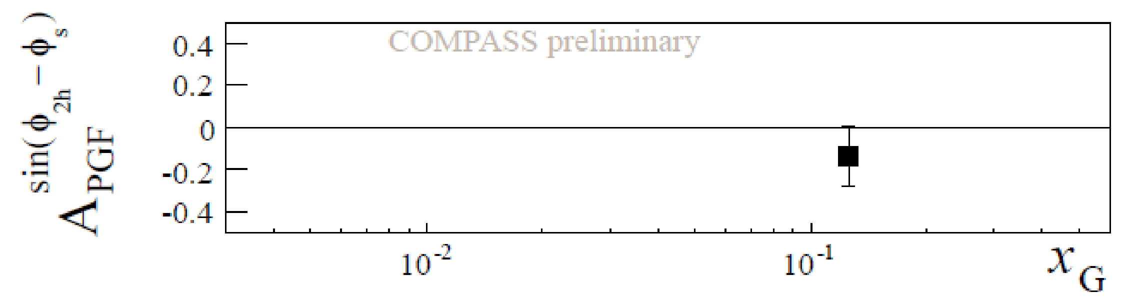


Correlation between azimuthal angle of the gluon ϕ_g and azimuthal angle of the two hadrons ϕ_{2h} (assumption $\vec{p}_g \approx \vec{p}_{h1} + \vec{p}_{h2}$)



Sivers asymmetry on deuteron for Gluons

First extraction of the Sivers function for gluons



$$A_{PGF}^{\sin(\phi_{2h}-\phi_S)}(x_g \approx 0.126) = -0.14 \pm 0.15 \pm 0.06$$

Measured asymmetry is small in agreement with expectations

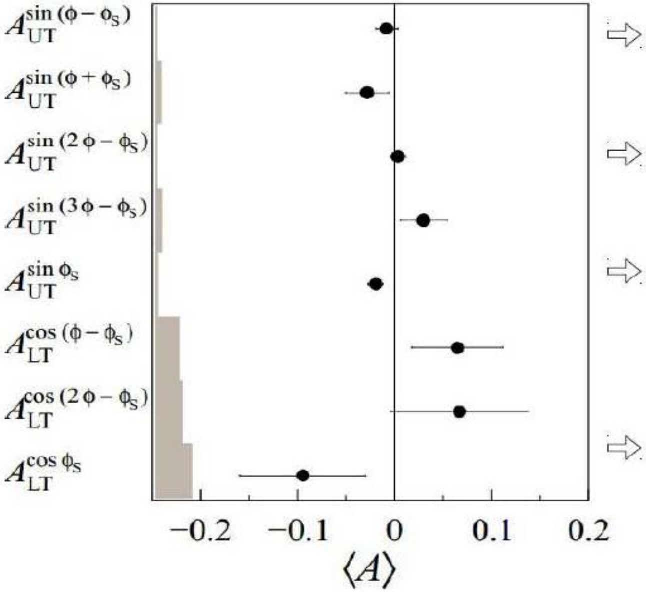
- Based on deuteron COMPASS data, Brodsky and Gardner [Phys.Lett.B643:22-28,2006] foresaw gluon Sivers $f_{1T,g}^{\perp} = 0$
- From the analysis of PHENIX data at mid rapidity, Anselmino et al. [Phys.Rev.D74:094011,2006] put constrains to $f_{1T,g}^{\perp}$ at small x

Exclusive ρ^0 production on $p\uparrow$

new

- **COMPASS**, PLB 731 (2014)

asymmetries published also as functions of x_{Bj}, Q^2 and $p_T{}^2$



$$\Rightarrow A_{UT}^{\sin(\varphi-\varphi_s)}\sigma_0=-2\,Im[\epsilon\overset{\sim E}{M^*_{0-,0+}}\overset{\sim H}{M_{0+,0+}}+\overset{\sim E}{M^*_{+-,++}}\overset{\sim H}{M_{++,++}}+\frac{1}{2}\overset{\sim H_T}{M^*_{0-,++}}\overset{\sim \bar{E}_T}{M_{0+,++}}]$$

$$\Rightarrow A_{UT}^{\sin(2\varphi-\varphi_s)}\sigma_0=-Im[\overset{\sim \bar{E}_T}{M^*_{0+,++}}\overset{\sim E}{M_{0-,0+}}]$$

$$\Rightarrow A_{UT}^{\sin(\varphi_s)}\sigma_0=-Im[\overset{\sim H_T}{M^*_{0-,++}}\overset{\sim H}{M_{0+,0+}}-\overset{\sim \bar{E}_T}{M^*_{0+,++}}\overset{\sim E}{M_{0-,0+}}]$$

$$\Rightarrow A_{LT}^{\cos(\varphi_s)}\sigma_0=-Re[\overset{\sim H_T}{M^*_{0-,++}}\overset{\sim H}{M_{0+,0+}}-\overset{\sim \bar{E}_T}{M^*_{0+,++}}\overset{\sim E}{M_{0-,0+}}]$$

M_{Vp',γ^*p} helicity amplitudes
σ_0 unpolarised cross section
$H_T(x, 0, 0) = h_1(x)$
$\bar{E}_T = 2\widetilde{H}_T - E_T$

- asymmetries small, compatible with 0, except

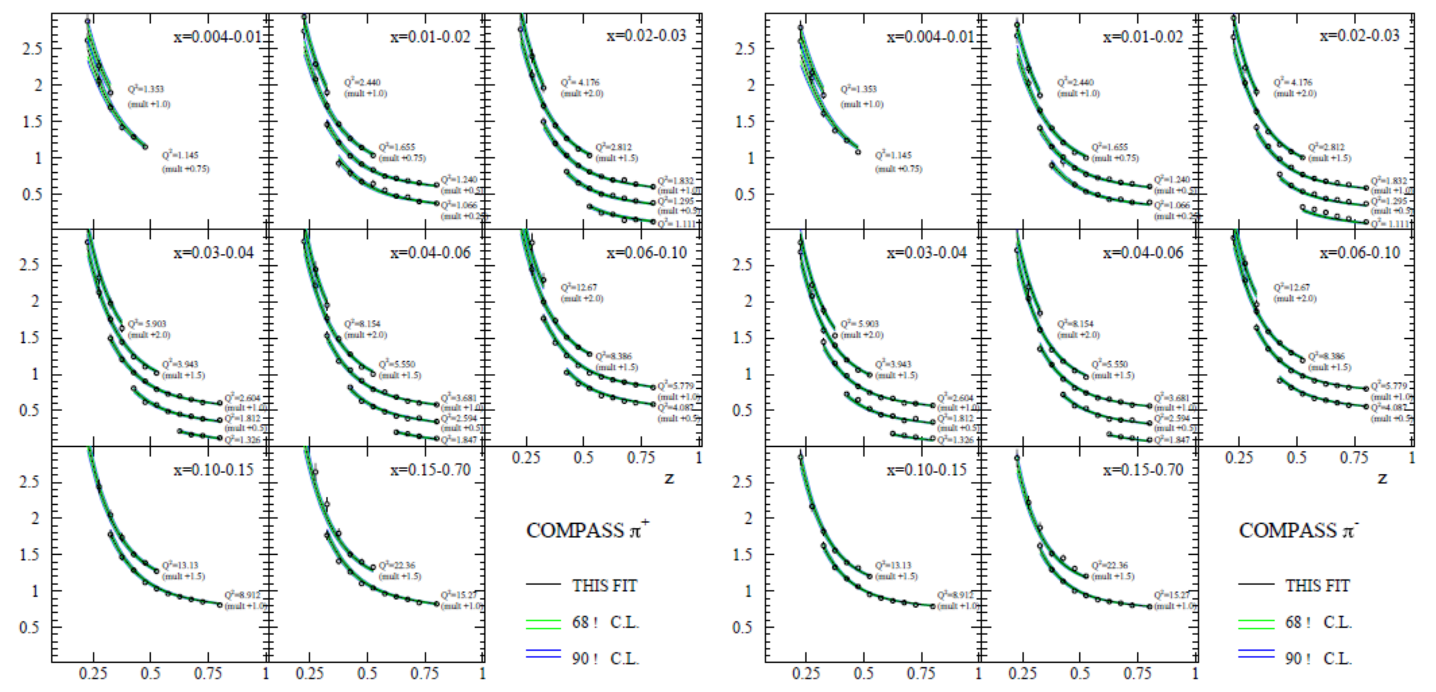
$$A_{UT}^{\sin\varphi_s}=-0.019\pm0.008\pm0.003$$

- indication of H_T, 'transversity' GPD, contribution
- larger effects for some asymmetries expected for exclusive ω production, ongoing analysis

Pion multiplicities $(\mu d \longrightarrow \mu\pi^{\pm}X)$

- Multiplicities are defined as the differential cross section for hadron production normalized to the inclusive DIS cross section.

$$M^h = \frac{d^3\sigma^h(x,\ \ Q^2,\ \ z)/dxdQ^2dz}{d^2\sigma^{DIS}(x,\ \ Q^2)/dxdQ^2} = \frac{\Delta x \Delta Q^2}{N^{DIS}(x,\ \ Q^2)} \cdot \frac{N^h(x,\ \ Q^2,\ \ z)}{\Delta x \Delta Q^2 \Delta z} = \frac{\sum_q e_q^2\, q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2\, q(x,Q^2)}$$



NLO fit of DSS
[PRD76:074033 2007]

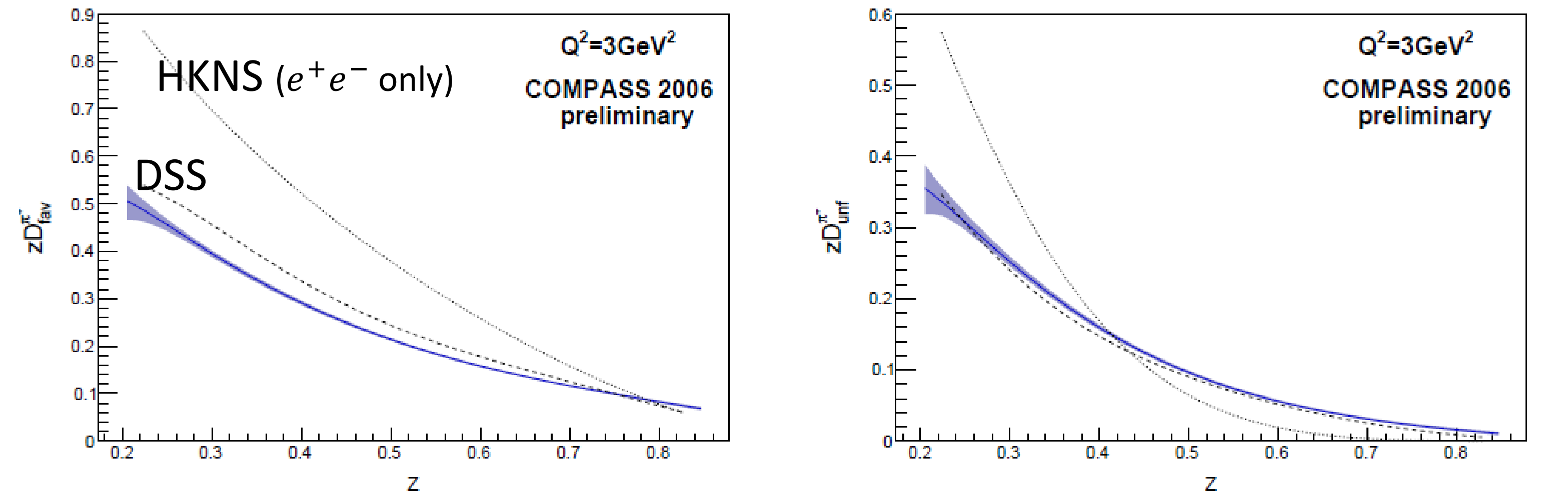
Pion analysis is finished,
Now kaons!

Quark FF from pion multiplicities

- LO fit performed (MSTW08 for PDFs)
  - Imposing isospin and charge symmetry
  - Assuming $D_s^{\pi^\pm} = D_{\bar{u}}^{\pi^\pm}$

$$D^i(z, Q_0^2) = N_i z^{\alpha_i}(1-z)^{\beta_i}[1 + \gamma_i(1-z)^{\delta_i}]$$

Only two pion fragmentation functions remain $D_{\text{fav}}^{\pi^\pm}$ and $D_{\text{unfav}}^{\pi^\pm}$

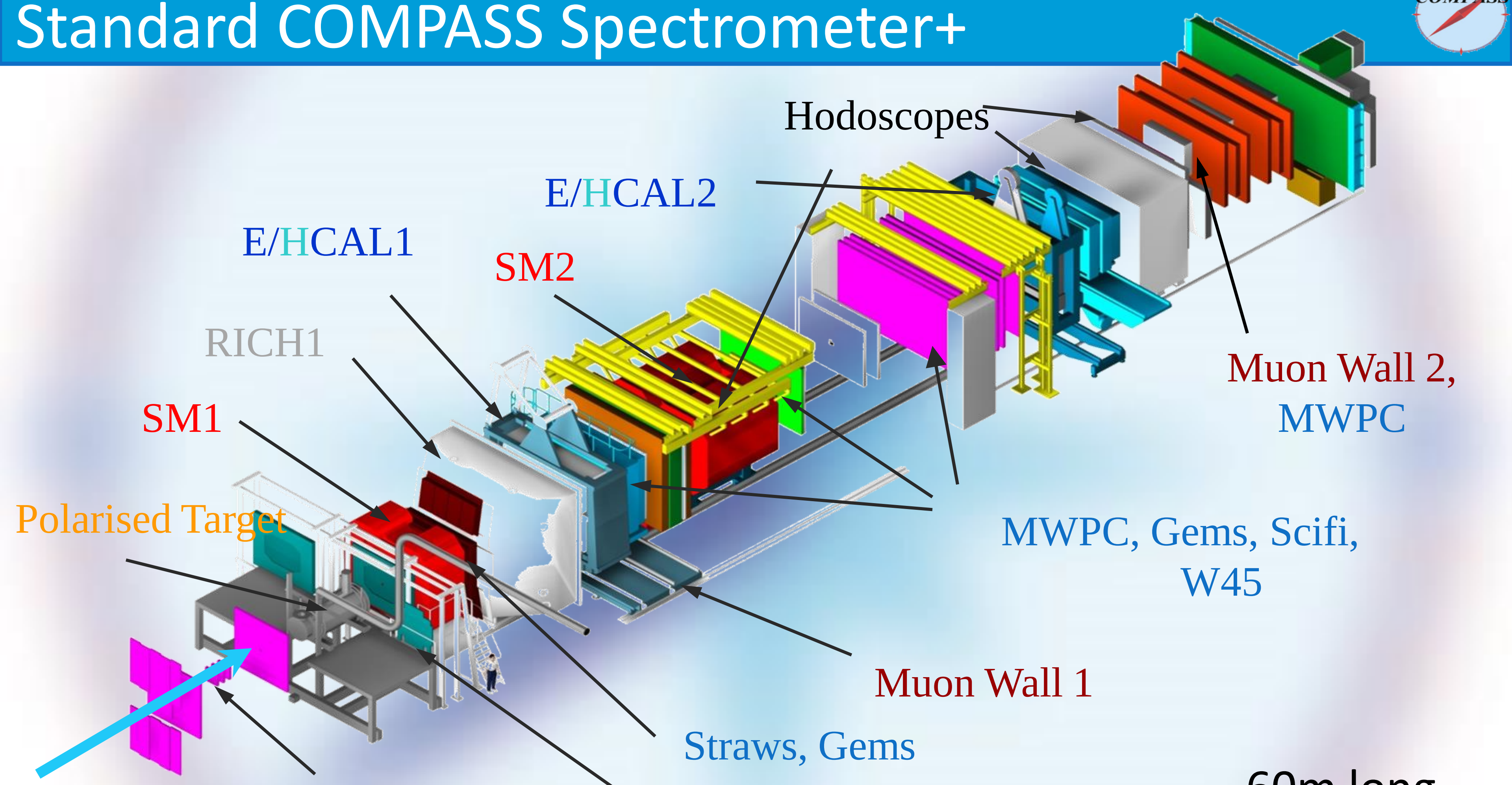


Conclusions

- Progress in the analysis of longitudinal, transverse and unpolarized data.
- Moving from single to multidimensional analysis of the data to take into account of the large dynamics and correlations shown

PREPARATION FOR THE SHORT DY RUN

Standard COMPASS Spectrometer+



Hodoscopes

E/HCAL2

E/HCAL1

SM2

RICH1

SM1

Polarised Target

Muon Wall 2,
MWPC

MWPC, Gems, Scifi,
W45

Muon Wall 1

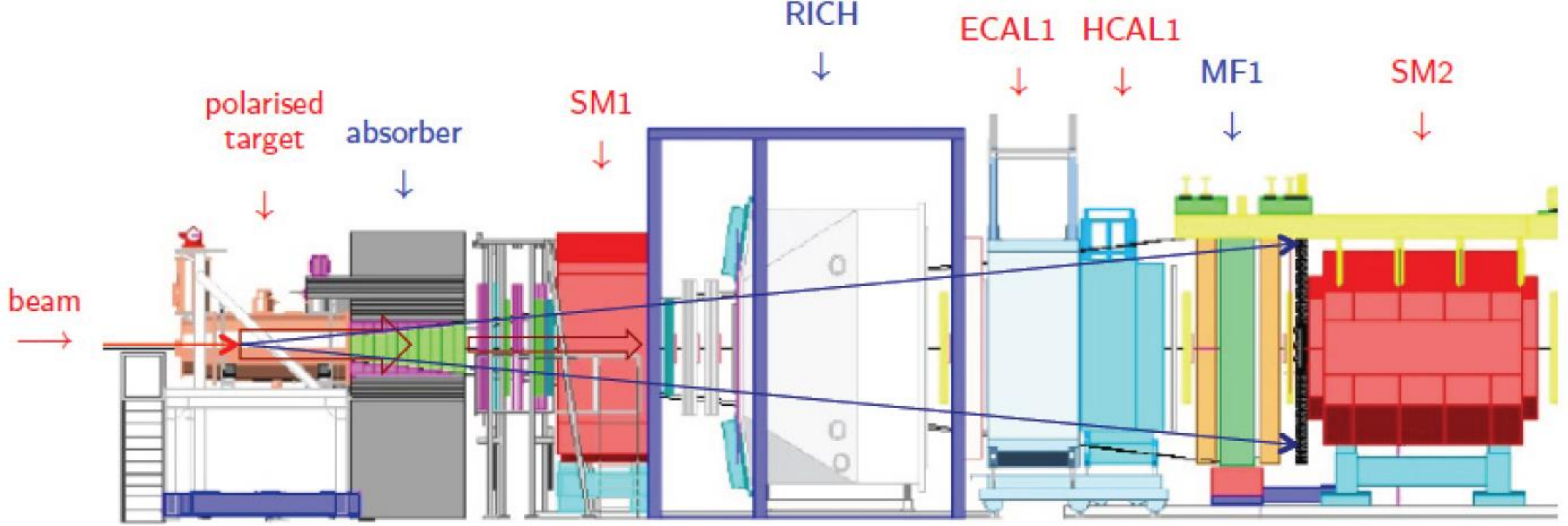
Straws, Gems

Micromegas, DC, Scifi

Scifi, Silicon

60m long

Hadron beam: Drell-Yan setup

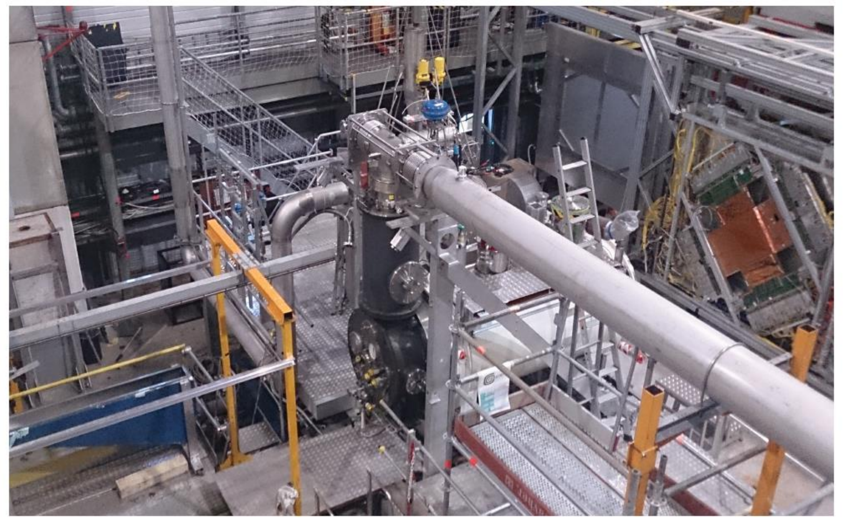


Major activities

- Magnet repair and installation of the PT target
- New DAQ preparation
- DC5 construction and installation
- Absorber construction and installation
- Sci-Fi vertex detector for the DY

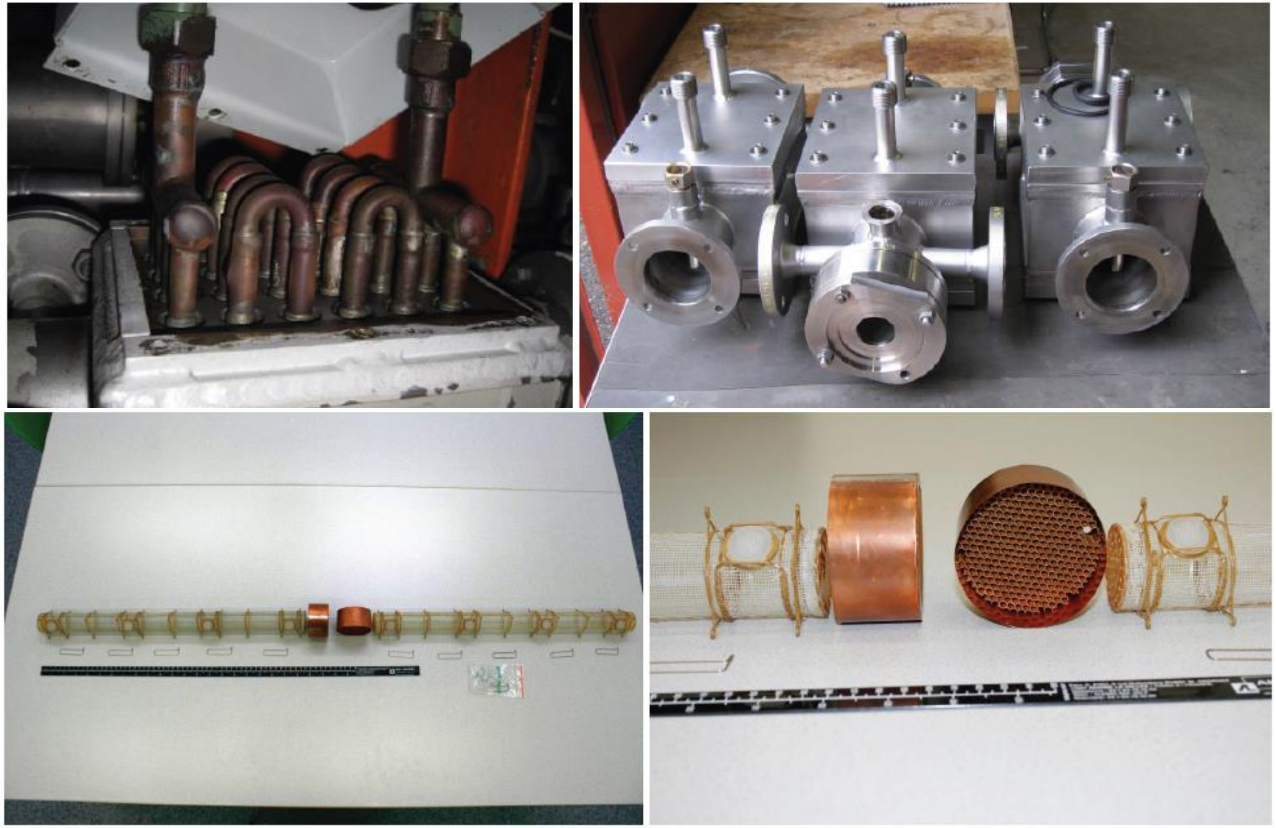
Magnet repair and installation

- After repair and consolidation a power test at full current was performed successfully by the end of March
- The magnet was moved to 888 by the end of April and presently the work for reinstalling it is ongoing



Target preparation

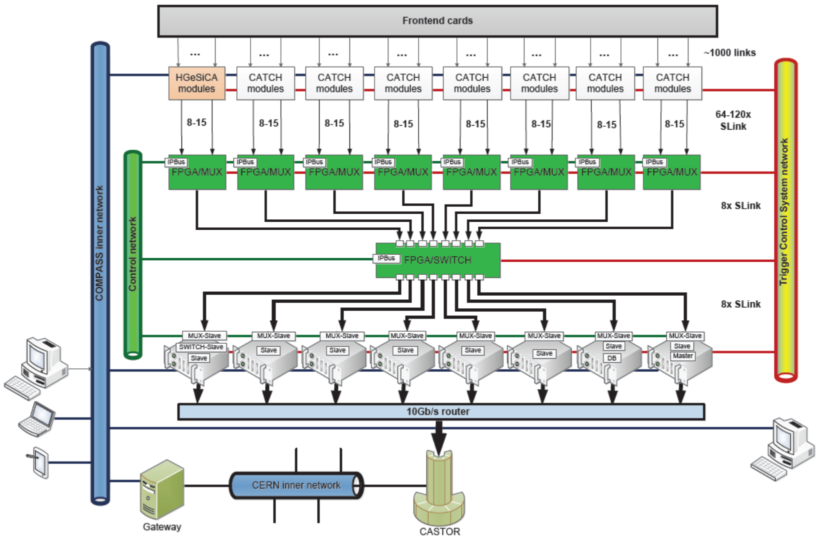
- Preparation of a two-cell target
- Consolidation of the ^{3}He pump system

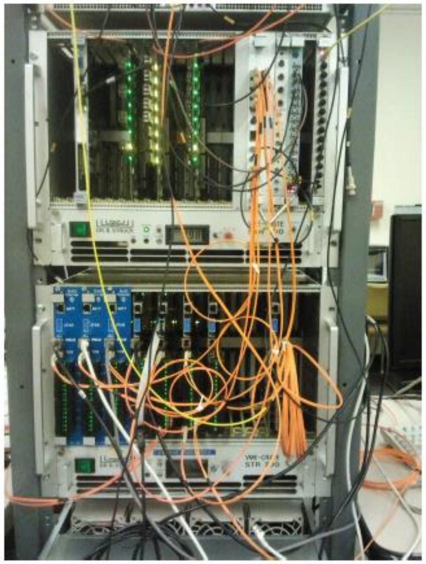


Ongoing as planned

New DAQ preparation

- Ageing of DATE and no revision foreseen for SLC6
- New custom made DAQ system based on hardware event builder together with a set of software packages for control and monitoring.
- The event builder is implemented in nine FPGA modules
  - Eight modules perform data concentration by merging sub events from up to 15 front-end modules.
  - The ninth module receives assembled sub-events from the first eight modules, completes the event building, and distributes them to up to eight online computers

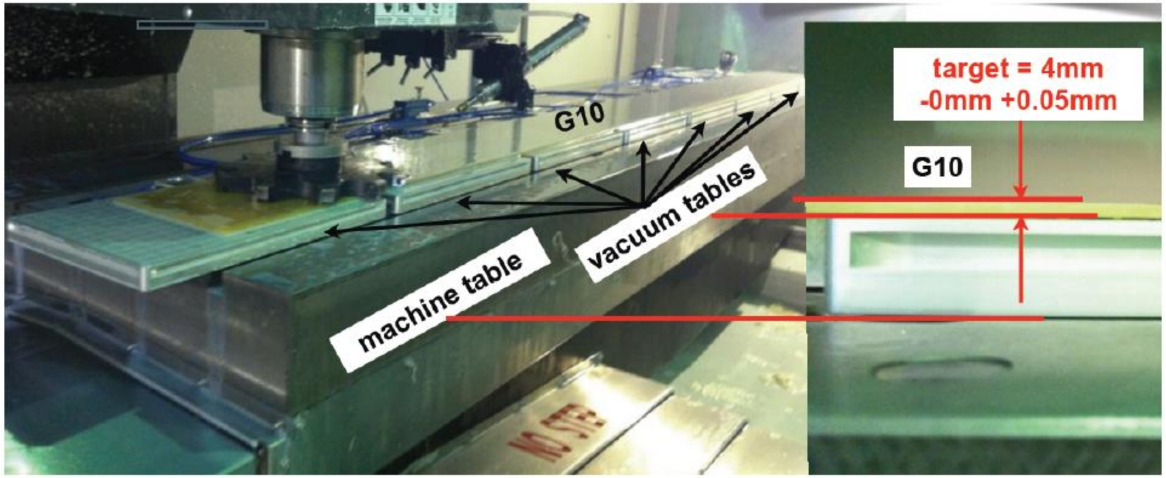




Sustained system bandwidth is 1.5 GBytes/s

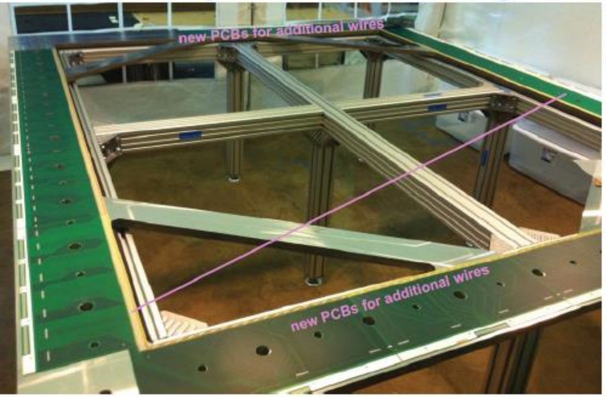
DC5 construction and installation

Work progressing at full speed but schedule is tight. Decision on installation planned for middle of July

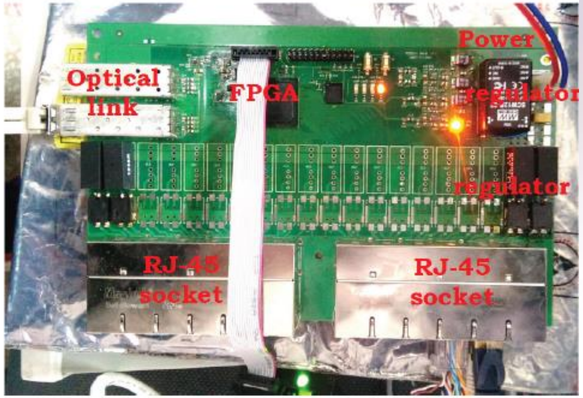


FEM

PCBs of the U-plane on the stiffening frame

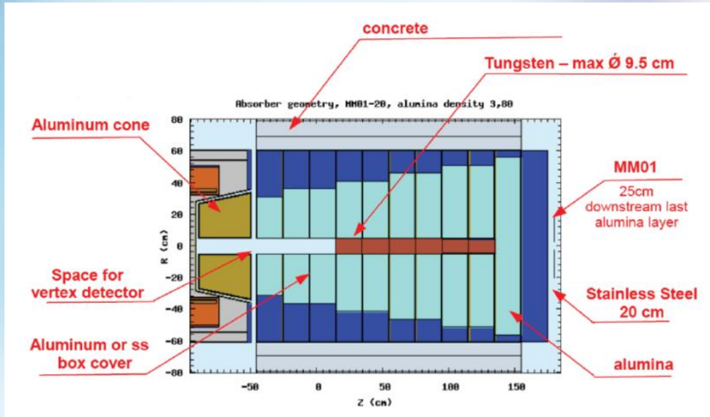


DCM



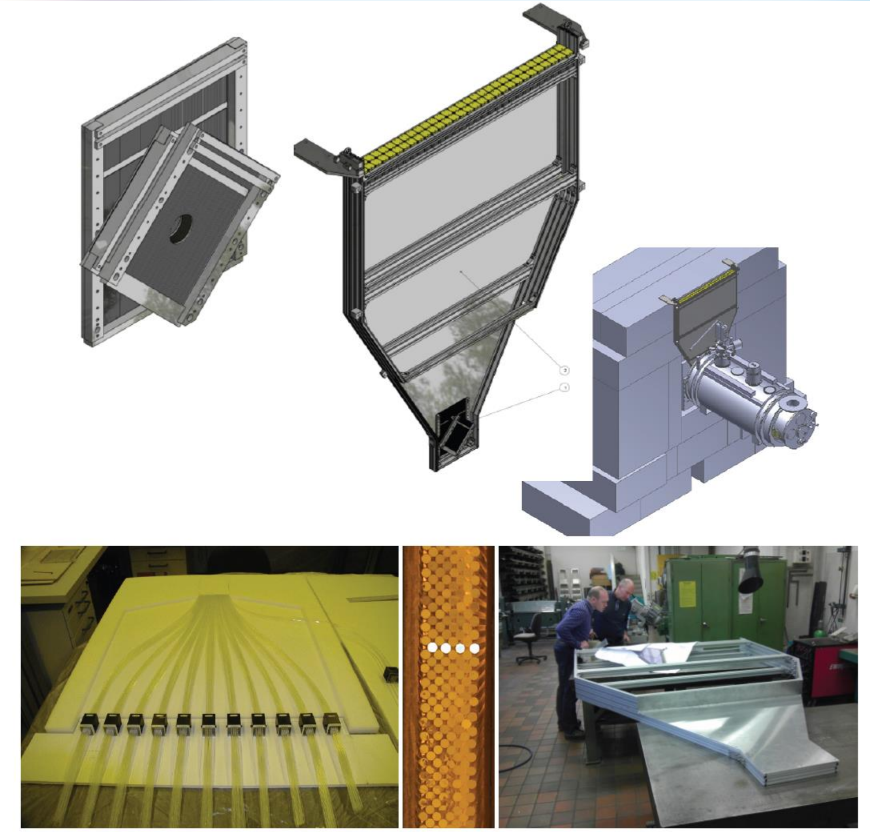
Absorber construction and installation

- Tungsten core to absorb the uninteracting beam
- Alumina body ($\mathrm{Al_2O_3}$) to absorb hadrons from pion interactions in the target, while minimizing muons (from DY $\pi^- p \rightarrow \mu^+ \mu^+ X$) multiple scattering

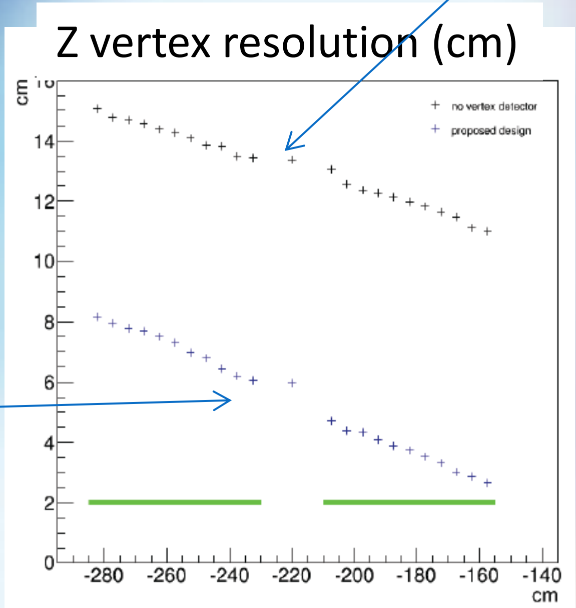


Sci-Fi vertex detector

- Ready for installation when shielding around the absorber installed



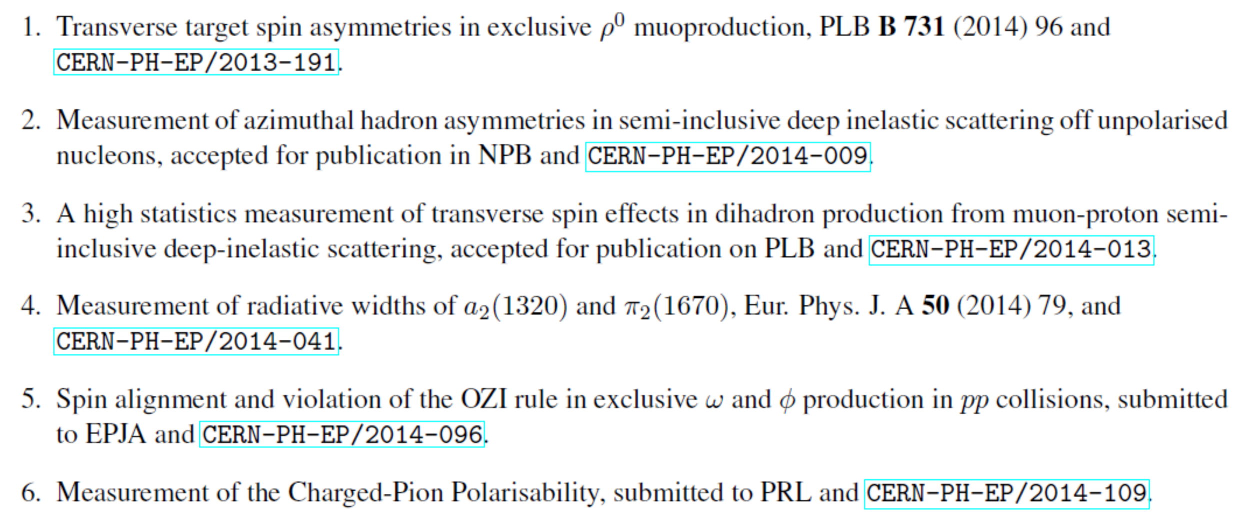
No vertex detector



vertex detector

Publications and talks at conferences

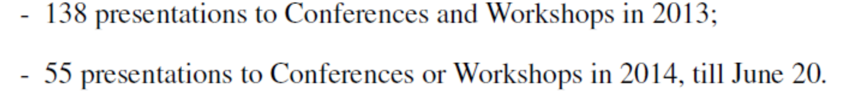
- Publications last 12 months



1. Transverse target spin asymmetries in exclusive ρ^0 muoproduction, PLB **B 731** (2014) 96 and `CERN-PH-EP/2013-191`.
2. Measurement of azimuthal hadron asymmetries in semi-inclusive deep inelastic scattering off unpolarised nucleons, accepted for publication in NPB and `CERN-PH-EP/2014-009`.
3. A high statistics measurement of transverse spin effects in dihadron production from muon-proton semi-inclusive deep-inelastic scattering, accepted for publication on PLB and `CERN-PH-EP/2014-013`.
4. Measurement of radiative widths of $a_2(1320)$ and $\pi_2(1670)$, Eur. Phys. J. A **50** (2014) 79, and `CERN-PH-EP/2014-041`.
5. Spin alignment and violation of the OZI rule in exclusive ω and ϕ production in pp collisions, submitted to EPJA and `CERN-PH-EP/2014-096`.
6. Measurement of the Charged-Pion Polarisability, submitted to PRL and `CERN-PH-EP/2014-109`.

  - Three more papers in the final circulation + other drafting close to finish

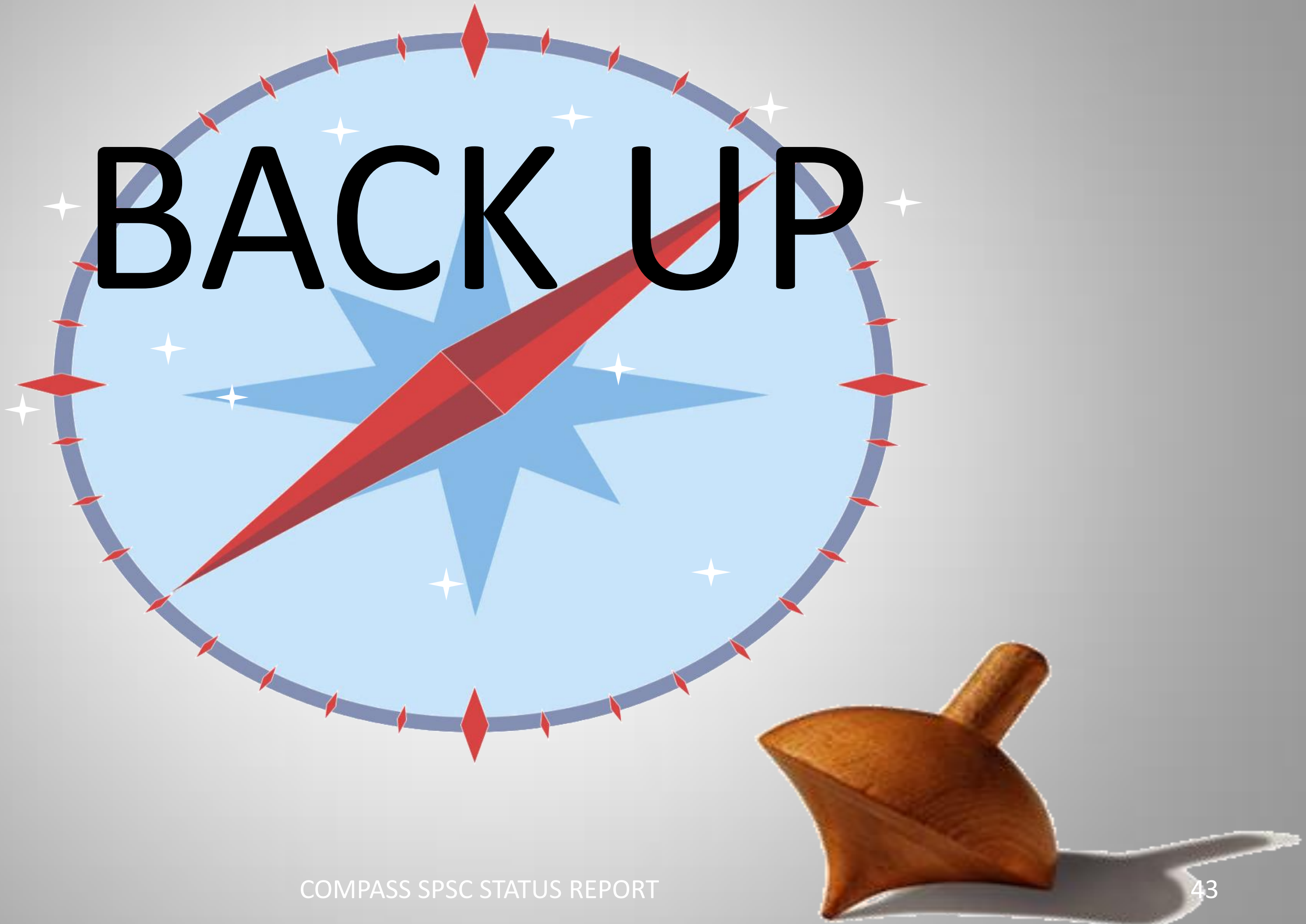
- Talks at conferences



- 138 presentations to Conferences and Workshops in 2013;
- 55 presentations to Conferences or Workshops in 2014, till June 20.

THANK YOU

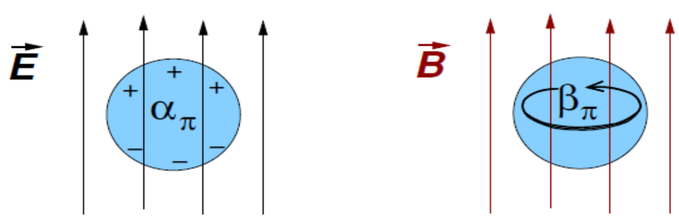
BACK UP



Pion polarisabilities - Primakoff 2009 data

Polarisabilities: deviation from pointlike particle

electric (α) and magnetic (β)



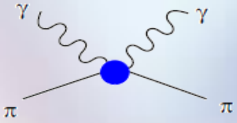
Predictions from Ch PT:

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

Experiments inconclusive:

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

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



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

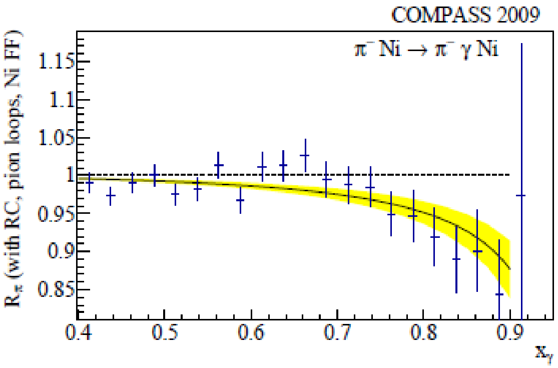
$\pi\ \gamma \rightarrow \pi\ \gamma$ measured via $\pi\ Z \rightarrow \pi\ Z\ \gamma$

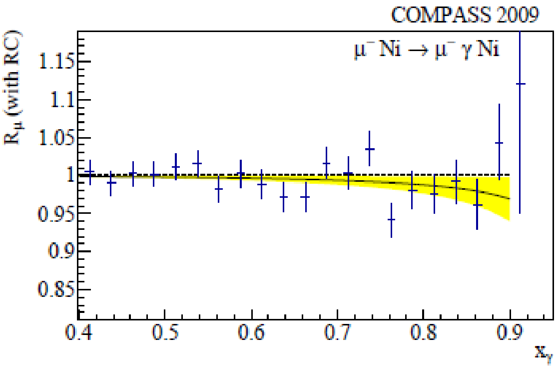
Pion polarisability - result

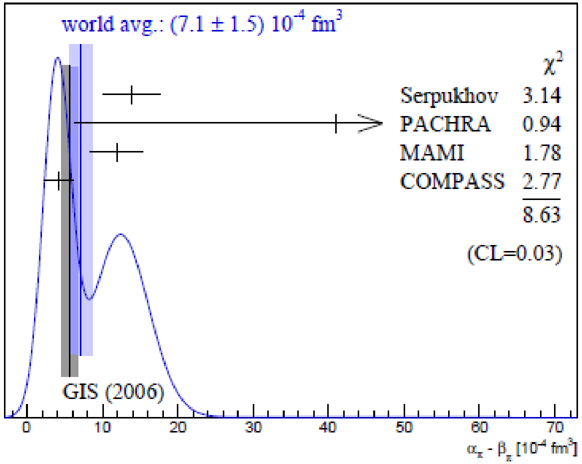
2009 data $\pi^- \mathrm{Ni} \rightarrow \pi^- \mathrm{Ni}\ \gamma$ exclusive reaction

- high resolution vertexing, precise calorimetry, calibrations, alignment
- precise MC description of spectrometer performance,

α_π extracted from comparison of data to MC(point-like)







$$\alpha_\pi = \left(2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}\right) \times 10^{-4}\ \ \mathrm{fm}^3$$

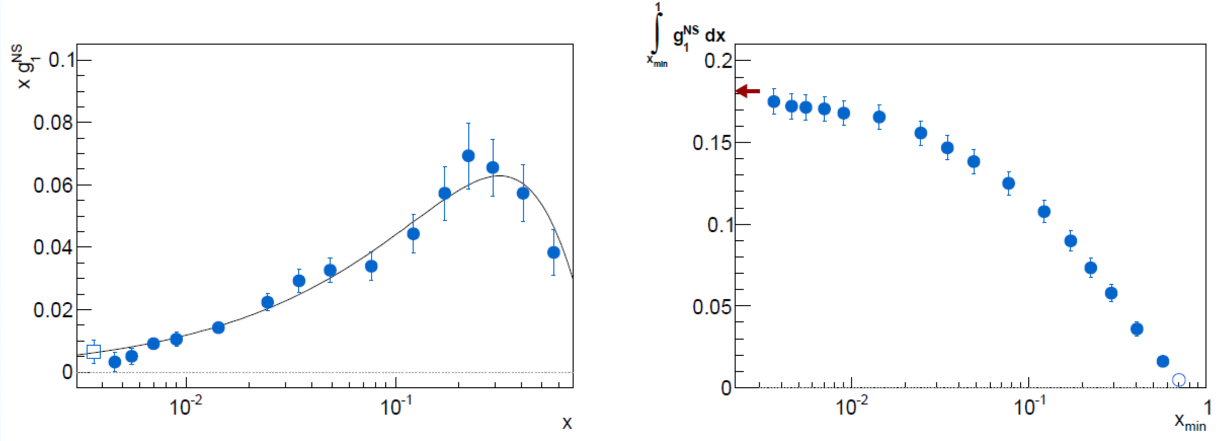
Bjorken sum rule

- The new proton data allow to improve the test of the Bjorken sum rule performed by using COMPASS data alone.

$Q^2 = 3$ GeV/c

$$\Gamma_1^{NS}(Q^2) = \int_0^1 g_1^{NS}(x,Q^2)dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$

$$g_1^{NS}(x,Q^2) = g_1^{p}(x,Q^2) - g_1^{n}(x,Q^2)$$



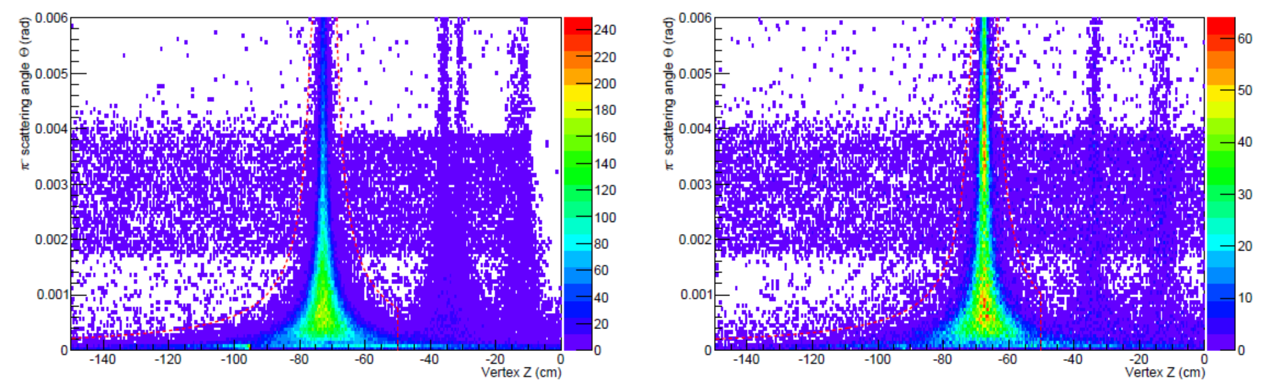
$$\Gamma_1^{NS}(Q^2) = 0.190 \pm 0.009_{\text{stat}} \pm 0.015_{\text{syst}}$$

Bjorken sum rule validated within 4%

2012 data analysis – Primakoff run

In progress:

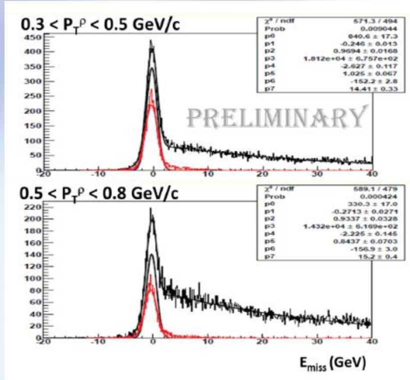
- Data production delayed by finalization of 2009 analysis
- Improvements of ECAL signal treatment introduced and data being processed
- Good vertex resolution achieved



(a) 2009 data.

(b) 2012 data.

2012 data analysis – DVCS run



Many improvements:

- Characterization of CAMERA RPD well advanced
  - Time/Position calibrations
  - Efficiency according to expectations
  - Impact of exclusive reactions selection as expected
  - We do not necessarily foresee the exchange of the ring A slabs, provided that beam detector allows to reach the expected accuracy.
- ECALs characterization
  - $\mathrm{ECAL0}_{1/4}$, ECAL1 and ECAL2 calibrated
  - Improved time/amplitude extraction for noisy part of ECAL1, allowing to lower the thresholds closed to the expected value of 300 MeV [PS: noisy bases have been replaced in the meanwhile
- Flux determination under study. Progress but 3% not yet reached.

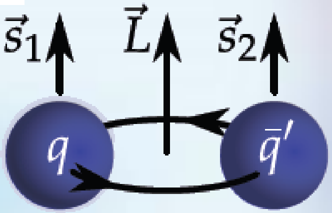
2012 data analysis – DVCS run

Next steps:

- Production of MC data with LEPTO and HEPGEN for DIS, SIDIS and exclusive events for acceptance corrections.
- Determination of DIS cross section using both $\mu^+$and μ^- data.
- Determination of the BH, DVCS and π^0 cross sections as a function of x.
- Study of the t-dependence of the sum of the DVCS cross sections induced with $\mu^+$and μ^- beams

Mesons quantum numbers in CQM

$$S = 0, 1; \;\; \vec{J} = \vec{L} + \vec{S}; \;\; P = (-1)^{L+1}; \;\; C = (-1)^{L+S}$$



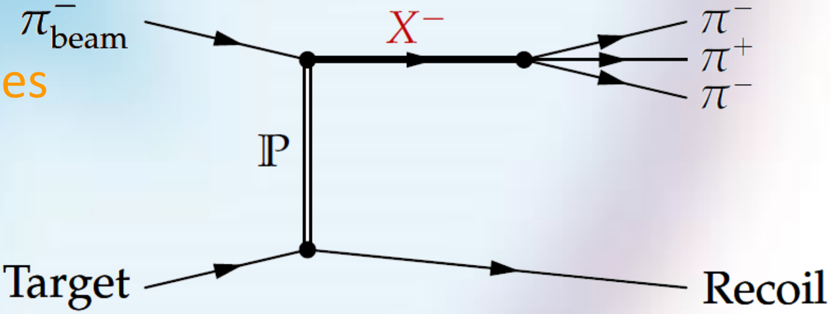
- forbidden (exotic QN's)

$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$$

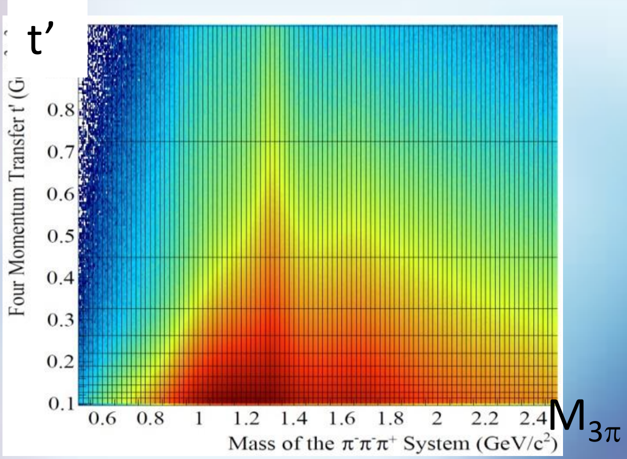
$|q\bar{q}g\rangle$ $|gg\rangle$ $|q^2\bar{q}^2\rangle$

- more states in QCD:
  hybrids , glueballs , multiquark states

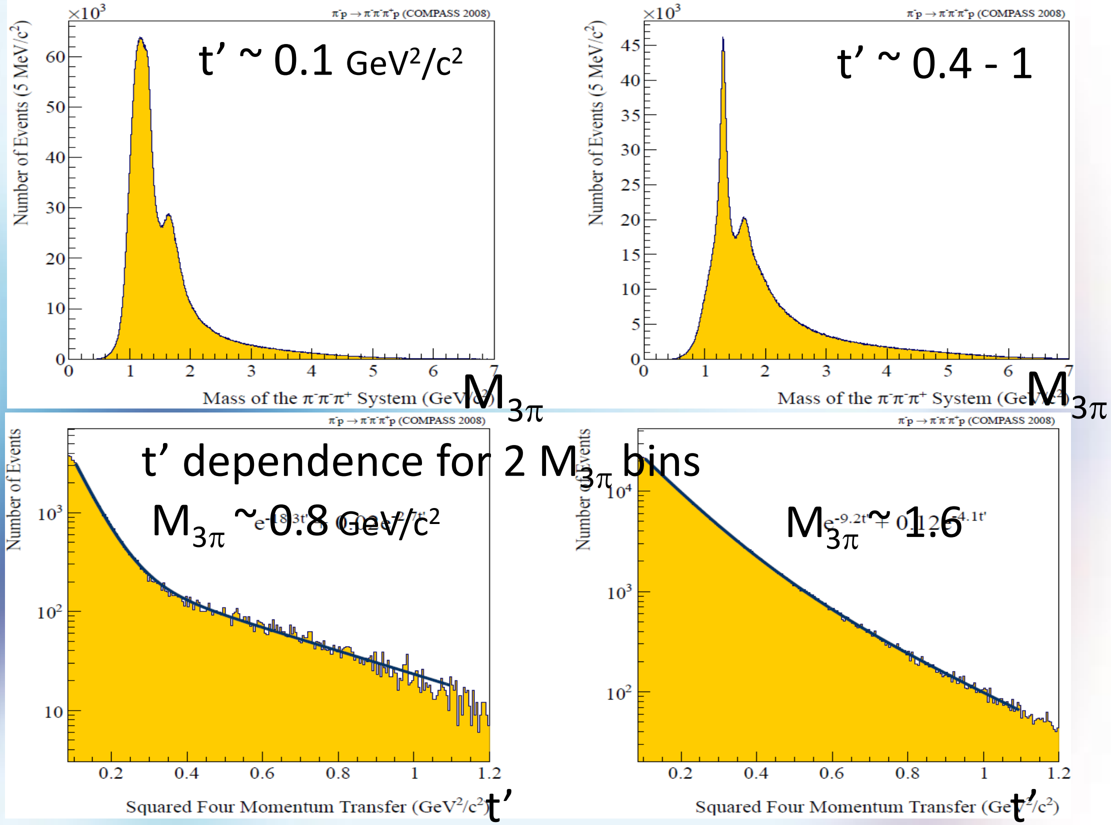
- Diffractive dissociation:



Shape of mass in 2 t' bins



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



$t' \sim 0.1$ GeV²/c²

$t' \sim 0.4 - 1$

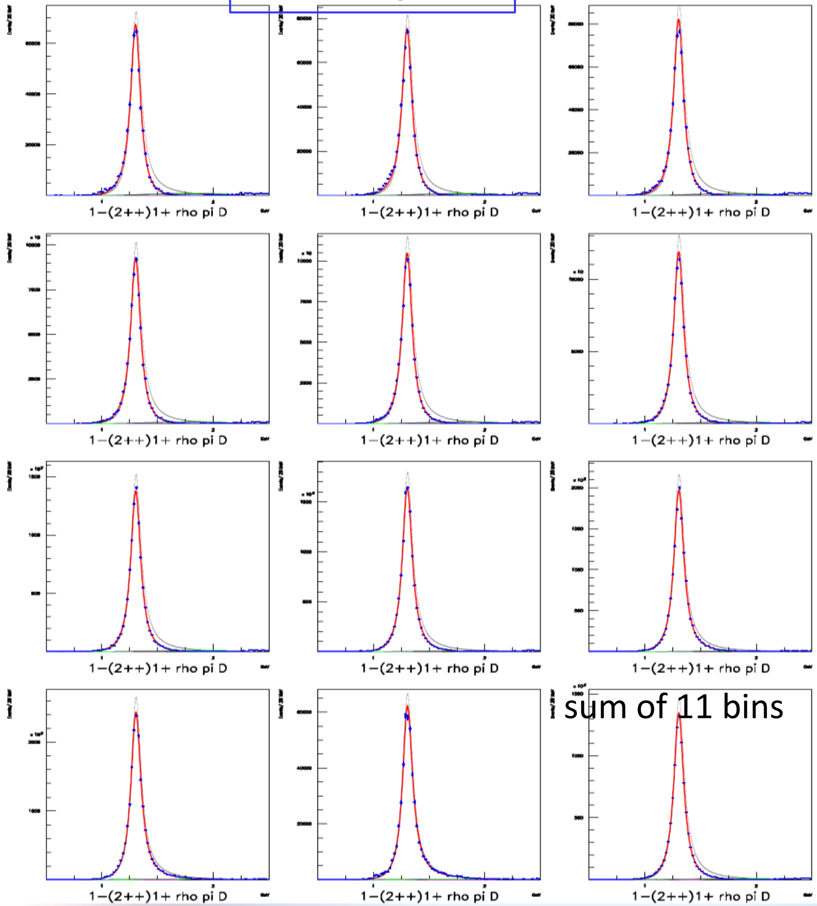
t' dependence for 2 $M_{3\pi}$ bins

$M_{3\pi} \sim 0.8$ GeV/c²

$M_{3\pi} \sim 1.6$

PWA M$_{3\pi}$ dependent fit, ex: 2++

2++ 1+[ρπ]D

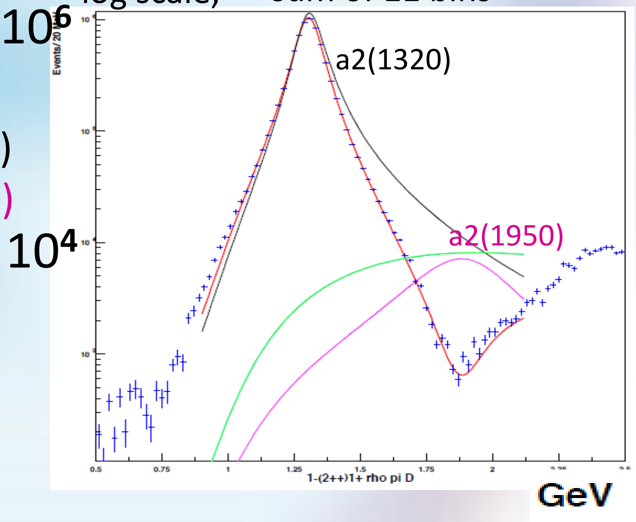


- Mass dependent fits for 5 selected waves, using a model for 3π resonance + bkgd.
- 11 t’ bins

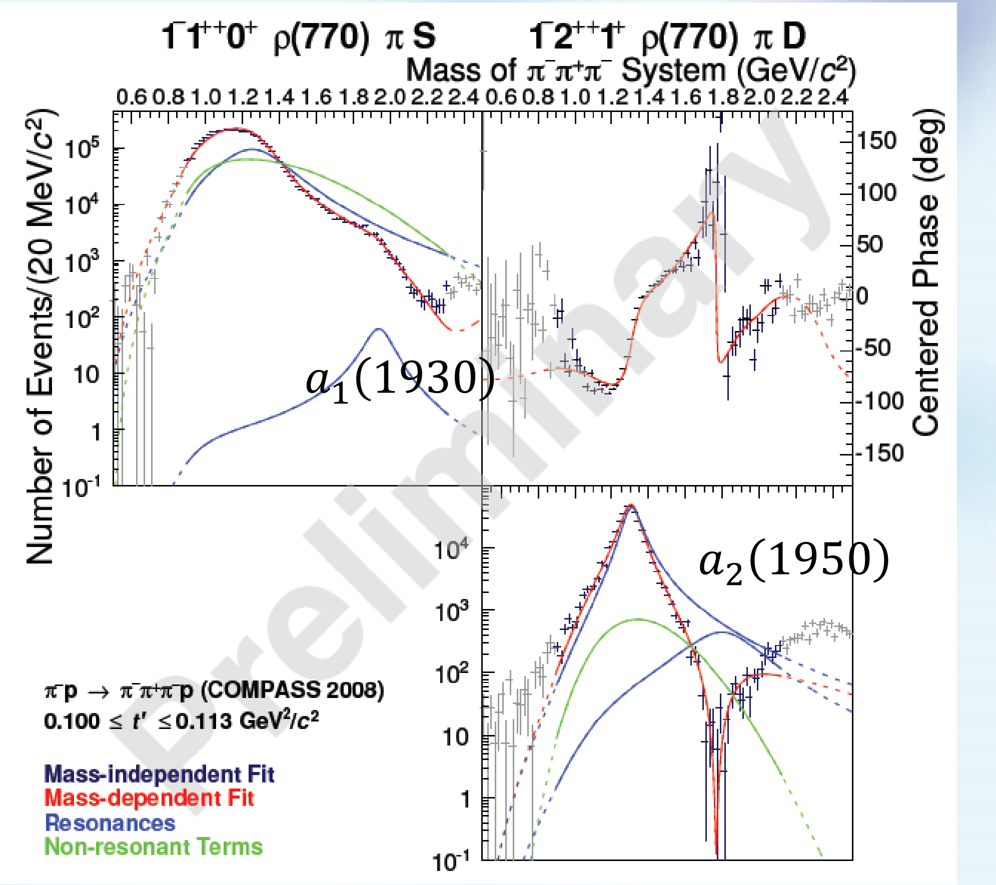
- data

--- model :
BW-a2 (1320)
+ BW-a2 (1950)
+ Bkgd

log scale, sum of 11 bins

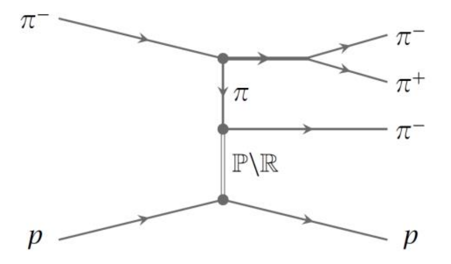


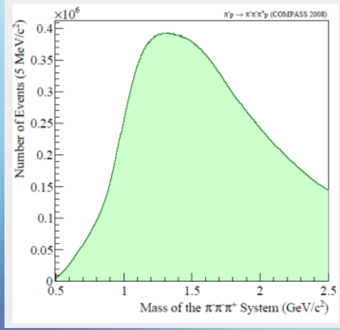
Need of a a_1' and a_2'

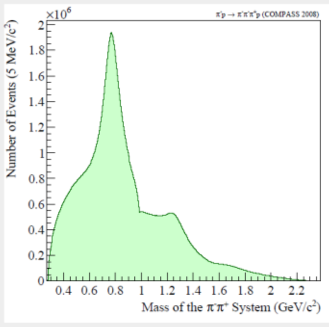


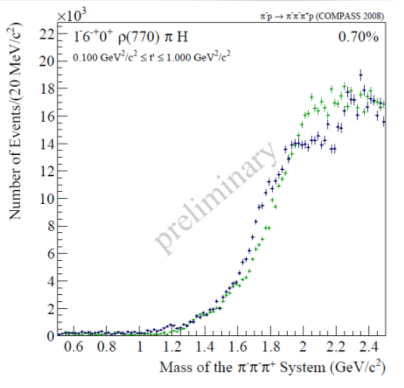
Deck effect

- Additional production mechanism for the same final state → non-resonant contribution
- An incident beam pion dissociates into a ρ or f_2 and a virtual π. The virtual π scatters diffractively from the target proton (via Pomeron) into a real state.









- Amplitude parametrisation:

$$\psi(\mathcal{M}_{\pi\pi}, t_\pi, t') = \frac{A_{\pi\pi}(\mathcal{M}_{\pi\pi}, t_\pi) \cdot A_{\pi p}\left(S_{\pi p}, t\right)}{m_\pi^2 - t_\pi}$$

with $A_{\pi\pi}$ scattering amplitude trough the ρ and/or f_2

$A_{\pi p}$ $\pi^- p$ elastic scattering amplitude

$\pi^- p \longrightarrow \pi^- \pi^+ \pi^- p$

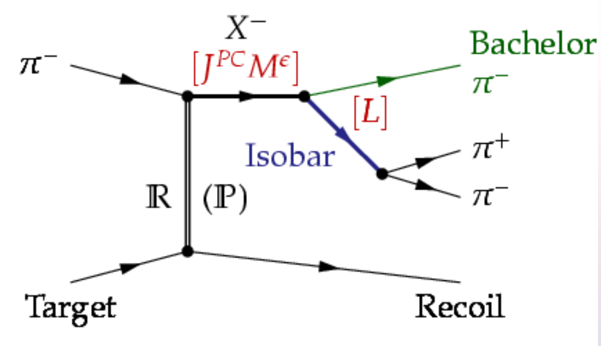
3 pions, $I^G = 1^-$, Pomeron isoscalar

$b = b_0 + 4\alpha'_{\mathbb{P}} \ln \sqrt{\frac{s}{s_0}}$ $\frac{d\sigma}{dt} \propto e^{-bt'}$

$$0^{-+}(\pi^-) + 2^{++}(\text{Pomeron}) \longrightarrow \begin{array}{r} (2^{-+})_{L=0} \oplus \\ (1^{++}, 2^{++}, 3^{++})_{L=1} \oplus \\ (0^{-+}, 1^{-+}, 2^{-+}, 3^{-+}, 4^{-+})_{L=2} \oplus \\ (1^{++}, 2^{++}, 3^{++}, 4^{++}, 5^{++})_{L=3} \oplus \\ (1^{-+}, 2^{-+}, 3^{-+}, 4^{-+}, 5^{-+}, 6^{-+})_{L=4} \cdots \end{array}$$

$\pi^- p \longrightarrow \pi^-\pi^+\pi^- p$

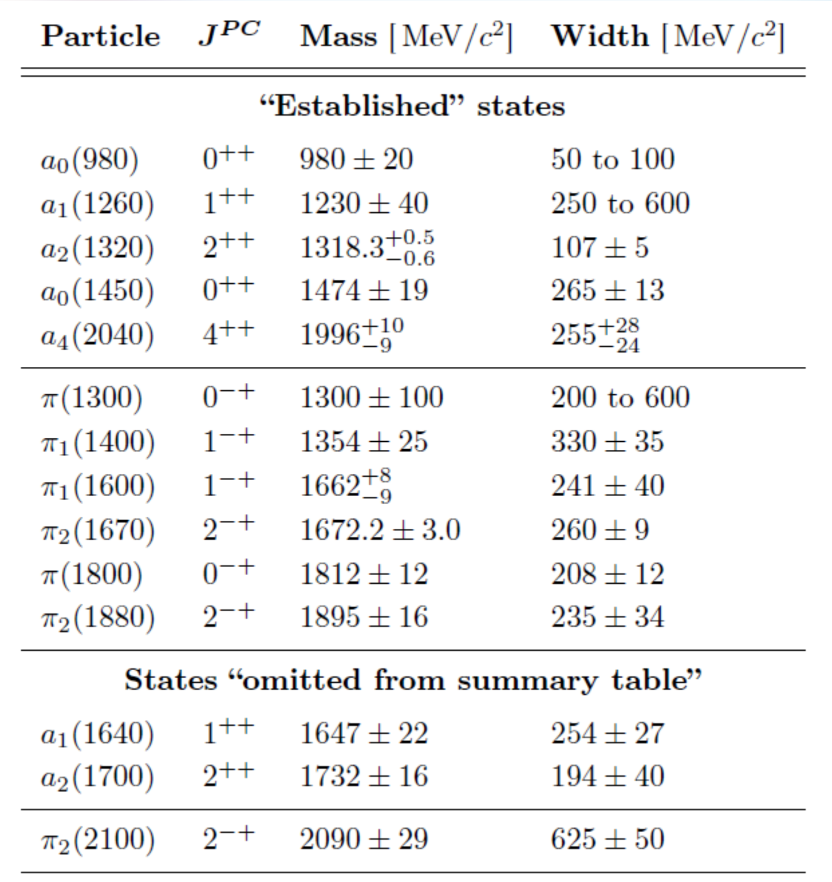
Assumption: resonances dominates the intermediate $X^-[J^{PC}M^{\epsilon}]$ state: this means that the amplitude can be Factorized in two terms (production of a particular X^- And decay to a particular $\pi^-(\pi^+\pi^-)_L$ state



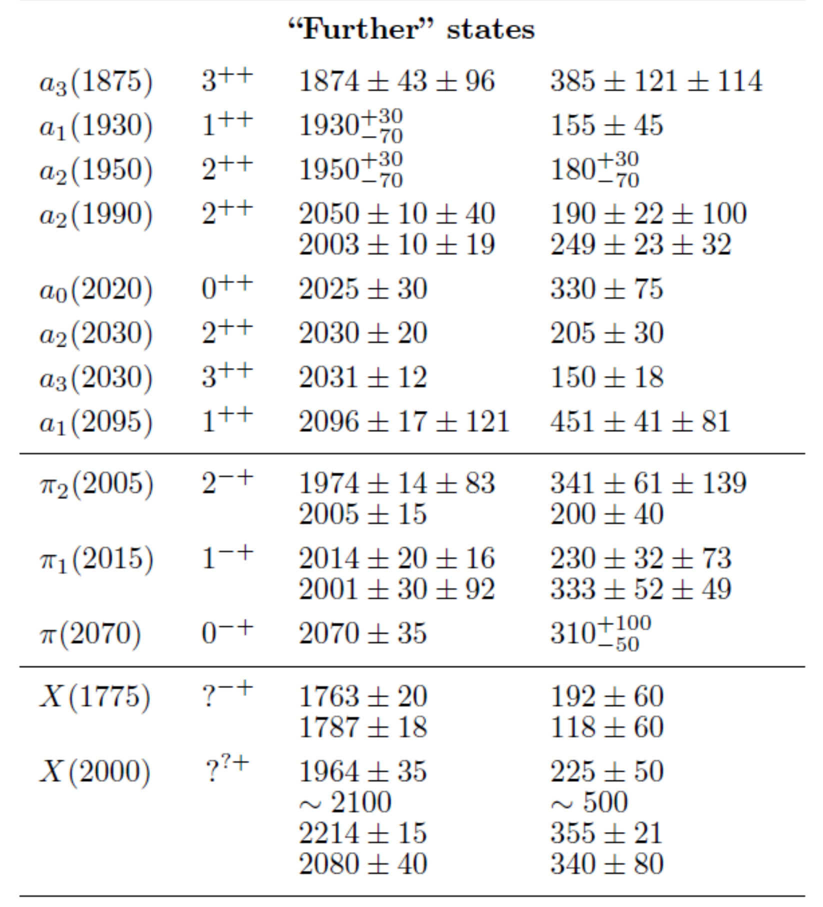
$$\mathcal{I}(m_X, t', \tau) \quad = \sum_{i,k} \tilde{T}_i(m_X, t')\tilde{T}_k^*(m_X, t') \sum_{j,l} \psi_{i,j}(m_X, \tau)\psi_{k,l}^*(m_X, \tau)$$

$$\equiv \sum_{i,k} \rho_{ik}(m_X, t') \sum_{j,l} \psi_{i,j}(m_X, \tau)\psi_{k,l}^*(m_X, \tau)$$

$\pi^- p \longrightarrow \pi^- \pi^+ \pi^- p$



Particle	J^{PC}	**Mass** [MeV/c^2]	**Width** [MeV/c^2]
		"Established" states	
$a_0(980)$	0^{++}	980 ± 20	50 to 100
$a_1(1260)$	1^{++}	1230 ± 40	250 to 600
$a_2(1320)$	2^{++}	$1318.3^{+0.5}_{-0.6}$	107 ± 5
$a_0(1450)$	0^{++}	1474 ± 19	265 ± 13
$a_4(2040)$	4^{++}	1996^{+10}_{-9}	255^{+28}_{-24}
$\pi(1300)$	0^{-+}	1300 ± 100	200 to 600
$\pi_1(1400)$	1^{-+}	1354 ± 25	330 ± 35
$\pi_1(1600)$	1^{-+}	1662^{+8}_{-9}	241 ± 40
$\pi_2(1670)$	2^{-+}	1672.2 ± 3.0	260 ± 9
$\pi(1800)$	0^{-+}	1812 ± 12	208 ± 12
$\pi_2(1880)$	2^{-+}	1895 ± 16	235 ± 34
		States "omitted from summary table"	
$a_1(1640)$	1^{++}	1647 ± 22	254 ± 27
$a_2(1700)$	2^{++}	1732 ± 16	194 ± 40
$\pi_2(2100)$	2^{-+}	2090 ± 29	625 ± 50



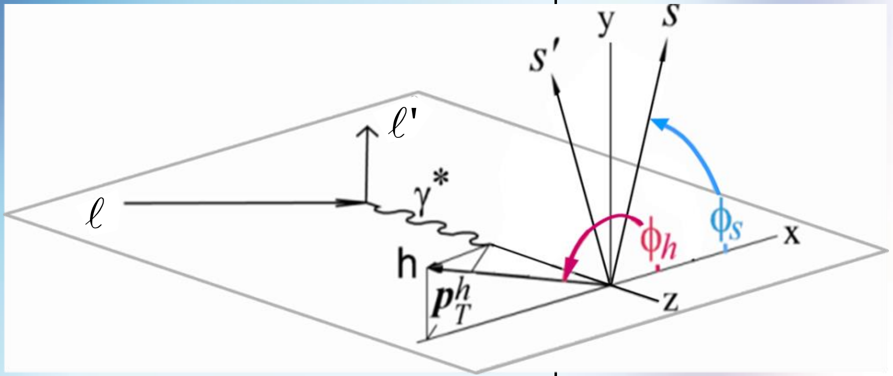
		"Further" states	
$a_3(1875)$	3^{++}	$1874 \pm 43 \pm 96$	$385 \pm 121 \pm 114$
$a_1(1930)$	1^{++}	1930^{+30}_{-70}	155 ± 45
$a_2(1950)$	2^{++}	1950^{+30}_{-70}	180^{+30}_{-70}
$a_2(1990)$	2^{++}	$2050 \pm 10 \pm 40$ $2003 \pm 10 \pm 19$	$190 \pm 22 \pm 100$ $249 \pm 23 \pm 32$
$a_0(2020)$	0^{++}	2025 ± 30	330 ± 75
$a_2(2030)$	2^{++}	2030 ± 20	205 ± 30
$a_3(2030)$	3^{++}	2031 ± 12	150 ± 18
$a_1(2095)$	1^{++}	$2096 \pm 17 \pm 121$	$451 \pm 41 \pm 81$
$\pi_2(2005)$	2^{-+}	$1974 \pm 14 \pm 83$ 2005 ± 15	$341 \pm 61 \pm 139$ 200 ± 40
$\pi_1(2015)$	1^{-+}	$2014 \pm 20 \pm 16$ $2001 \pm 30 \pm 92$	$230 \pm 32 \pm 73$ $333 \pm 52 \pm 49$
$\pi(2070)$	0^{-+}	2070 ± 35	310^{+100}_{-50}
$X(1775)$	$?^{-+}$	1763 ± 20 1787 ± 18	192 ± 60 118 ± 60
$X(2000)$	$?^{?+}$	1964 ± 35 ~ 2100 2214 ± 15 2080 ± 40	225 ± 50 ~ 500 355 ± 21 340 ± 80

SIDIS 1h x-section

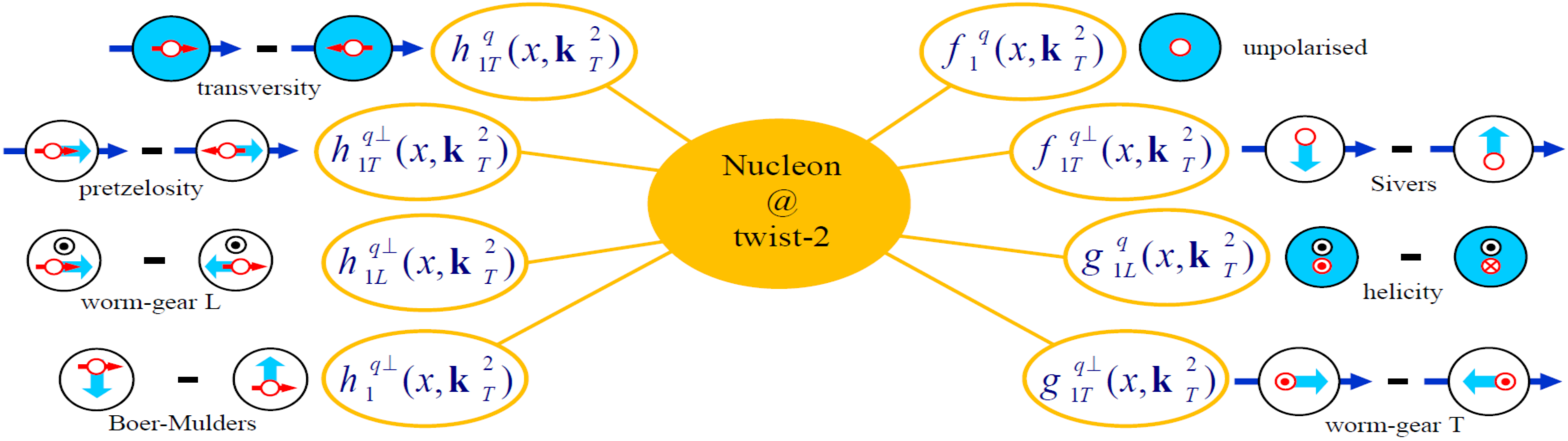
$$A_{U(L),T}^{w(\varphi_h,\varphi_S)} = \frac{F_{U(L),T}^{w(\varphi_h,\varphi_S)}}{F_{UU,T}+\varepsilon F_{UU,L}}$$

$$\frac{d\sigma}{dxdydzdP_{h\perp}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times \qquad \varepsilon = \frac{1-y-\frac{1}{4}y^2\gamma^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}y^2\gamma^2},\quad \gamma = \frac{2xM}{Q}$$

$$\left\{\begin{array}{l}
1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}+\cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)}+\lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h}+\\
S_L\left[\sin\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\varphi_h}+\sin(2\varphi_h)\times\varepsilon A_{UL}^{\sin(2\varphi_h)}\right]+\\
S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\cos\varphi_h\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h}\right]+\\
\mathbf{S}_T\left[\begin{array}{l}
\sin\varphi_S\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+\\
\sin(\varphi_h-\varphi_S)\times\left(A_{UT}^{\sin(\varphi_h-\varphi_S)}\right)+\\
\sin(\varphi_h+\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}\right)+\\
\sin(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}\right)+\\
\sin(3\varphi_h-\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)
\end{array}\right]+\\
\mathbf{S}_T\lambda\left[\begin{array}{l}
\cos\varphi_S\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}\right)+\\
\cos(\varphi_h-\varphi_S)\times\left(\sqrt{(1-\varepsilon^2)}A_{UT}^{\cos(\varphi_h-\varphi_S)}\right)+\\
\cos(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{UT}^{\cos(2\varphi_h-\varphi_S)}\right)
\end{array}\right]
\end{array}\right\}$$



TMD Distribution Functions



Nucleon @ twist-2

$h_{1T}^{q}(x,\mathbf{k}_T^2)$ transversity

$h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ pretzelosity

$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$ worm-gear L

$h_{1}^{q\perp}(x,\mathbf{k}_T^2)$ Boer-Mulders

$f_{1}^{q}(x,\mathbf{k}_T^2)$ unpolarised

$f_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ Sivers

$g_{1L}^{q}(x,\mathbf{k}_T^2)$ helicity

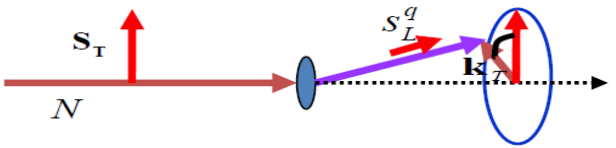
$g_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ worm-gear T

nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

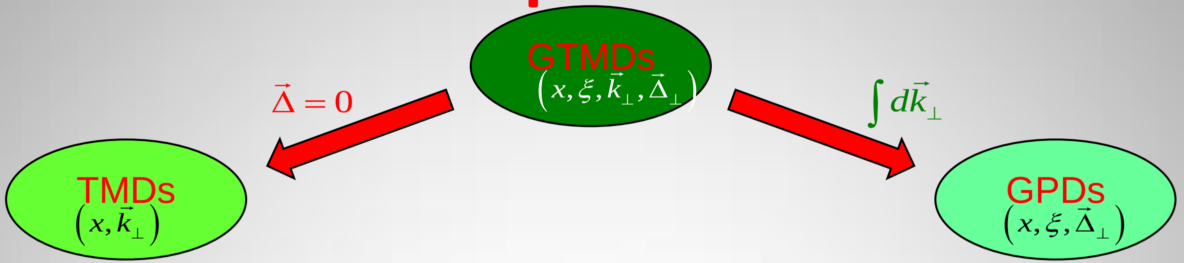
parton transverse momentum

Proton goes out of the screen. Photon goes into the screen



$\mathbf{k}_T$ — intrinsic transverse momentum of the quark

Top→Bottom



Nucleon polarization

Parton polarization

	U	T	L
U	f_1	$h_1^\perp$	
T	$f_{1T}^\perp$	$h_1, h_{1T}^\perp$	g_{1T}
L		$h_{1L}^\perp$	g_{1L}

Nucleon polarization

Parton polarization

	U	T	L
U	H	$\mathcal{E}_T$	
T	E	$H_T, \widetilde{H}_T$	$\widetilde{E}$
L		$\widetilde{E}_T$	$\widetilde{H}$

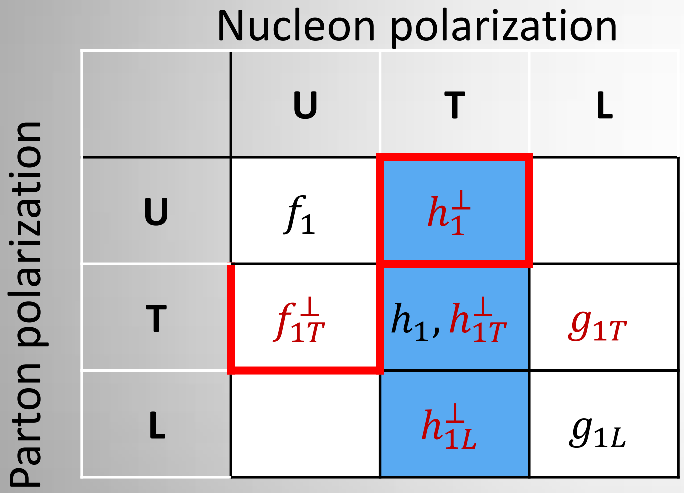
- distributions in red vanish if there is no quark orbital angular momentum
- quark GPDs (at ξ=0) and TMDs given by the same overlap of LCWFs but in different kinematics
  - each distribution contains unique information
  - no model-independent relations between GPDs and TMDs

SIDIS access to TMDs

$$\sigma(\ell p \to \ell' h X) \sim q(x) \otimes \hat{\sigma}^{\gamma q \to q} \otimes D_q^h(z)$$

TMDs $\left(x, \vec{k}_\perp\right)$

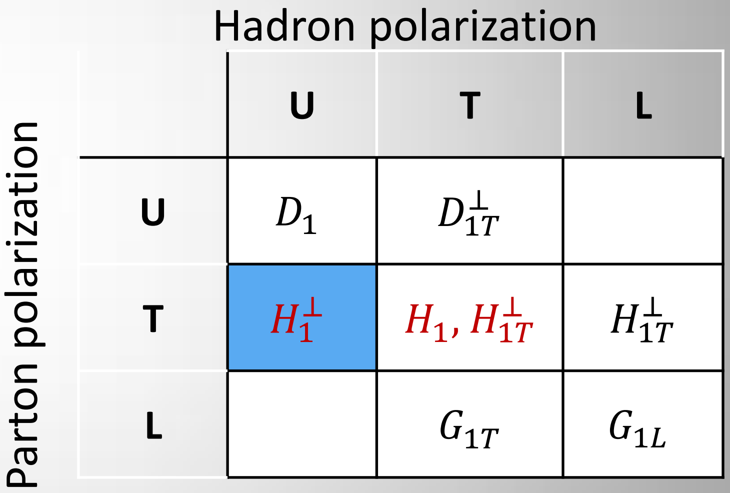
FFs $\left(z, \vec{p}_\perp\right)$



Nucleon polarization

Parton polarization

	U	T	L
U	f_1	$h_1^\perp$	
T	$f_{1T}^\perp$	$h_1, h_{1T}^\perp$	g_{1T}
L		$h_{1L}^\perp$	g_{1L}



Hadron polarization

Parton polarization

	U	T	L
U	D_1	$D_{1T}^\perp$	
T	$H_1^\perp$	$H_1, H_{1T}^\perp$	$H_{1T}^\perp$
L		G_{1T}	G_{1L}

🟥 T odd

🟦 chiral odd

Factorisation (Collins & Soper, Ji, Ma, Yuan, Qiu & Vogelsang, Collins & Metz...)

Key COMPASS measurements

$g_1^d(x), \quad \int g_1^d(x)dx$	Confirmation of SMC result on d (at variance with E142 claims)
$\Delta g/g$	first hint that Δg is small, at variance with predictions
$A^h_{Col,d}$	first measurement of transversity on deuteron $h_1^u \simeq -2h_1^d \quad H^{\perp}_{1,fav} \simeq -H^{\perp}_{1,unf}$
$A^{2h}_{p,d}$	Only polarimeter for transversity extraction from 2h asymmetries transversity extracted directly from the data, following Pavia group
$A^h_{Siv,p}$	Evolution of Sivers
$\pi_1(1600)$	Hint for an exotic state
$a_1(1420)$	New state
Radiative width of $a_2(1320)$ and $\pi_2(1670)$	Confirmation of VMD model, EPJ highlight

Results:

Year		
2005	$A^h_{Siv,d}, A^h_{Col,d}$	First ^{6}LiD data
2006	$A^h_{Siv,d}, A^h_{Col,d}$	Full ^{6}LiD statistics
2009	$A^{\pi^\pm, K^\pm, K^0_S}_{Siv,d}, A^{\pi^\pm, K^\pm, K^0_S}_{Col,d}$	Full ^{6}LiD statistics
2010	$A^h_{Siv,p}, A^h_{Col,p}$	2007 NH_3 data
2012	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full ^{6}LiD and NH_3statistics
2012	$A^h_{Siv,p}, A^h_{Col,p}$	Full NH_3statistics
2012	$A^{sin(\phi_\rho-\phi_S)}_{UT,d}, A^{sin(\phi_\rho-\phi_S)}_{UT,p}$	Exclusive ρ^0 production– Full ^{6}LiD and NH_3statistics
2013	$dn^h/(dN^\mu dz\, dp_T^2)$	Unpolarized multiplicities on d
2014	$A^{\sin\phi_h}_{UU,d}, A^{\cos\phi_h}_{UU,d}, A^{\cos 2\phi_h}_{UU,d}$ $A^{sin\phi_S}_{UT,p}, A^{cos\phi_S}_{LT,p}, A^{sin(2\phi_\rho-\phi_S)}_{UT,p}$ … $A^g_{Siv,d}$	Unpol. azimuthal asymm.s Excl. ρ^0 production on NH_3 preliminary

LO content

SIDIS

$$A_{UU}^{\cos\phi_h} \propto \frac{1}{Q}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \cdots \right)$$

$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \frac{1}{Q}(f_1^q \otimes D_{1q}^h +$ [redacted]

$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^q \otimes D_{1q}^h$$

$A_{UT}^{\sin(2\phi_h-\phi_S)} \propto \frac{1}{Q}(h_1^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \cdots$

$$A_{LT}^{\cos\phi_S} \propto \frac{1}{Q}\left(g_{1T}^q \otimes D_{1q}^h + \cdots \right)$$

$$A_{LT}^{\cos(2\phi_h-\phi_S)} \propto \frac{1}{Q}\left(g_{1T}^q \otimes D_{1q}^h + \cdots \right)$$

DY

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_1^q$$

$$A_T^{\sin\varphi_{CS}} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

Sivers Asymmetry

Sivers: correlates nucleon spin & quark transverse momentum k_T /T-ODD

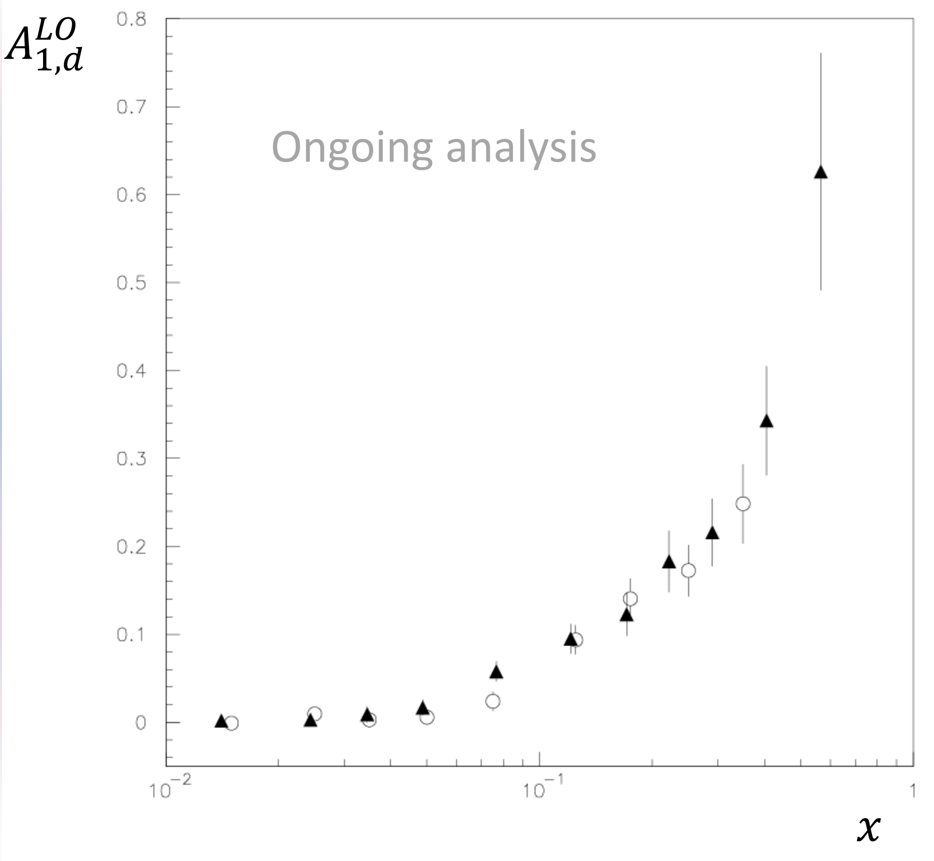
at LO:

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

$$\boxed{\mu p^{\uparrow} \rightarrow \mu X h^{\pm}}$$

The Sivers PDF	
1992	Sivers proposes $f_{1T}^{\perp}$
1993	J. Collins proofs $f_{1T}^{\perp} = 0$ for T invariance
2002	S. Brodsky, Hwang and Schmidt demonstrate that $f_{1Tq}^{\perp}$ may be $\neq 0$ due to FSI
2002	J. Collins shows that $(f_{1T}^{\perp})_{DY} = -(f_{1T}^{\perp})_{SIDIS}$
2004	HERMES on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$
2004	COMPASS on d: $A_{Siv}^{\pi^+} = 0$ and $A_{Siv}^{\pi^-} = 0$
2008	COMPASS on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$

$A_{1,d}^{LO}$ from standard analysis and all-p_T



Triangles: [PLB 647 (2007) 8–17]

Circles: all-p_T

A_{LL} for single hadron photoproduction at high-p_T

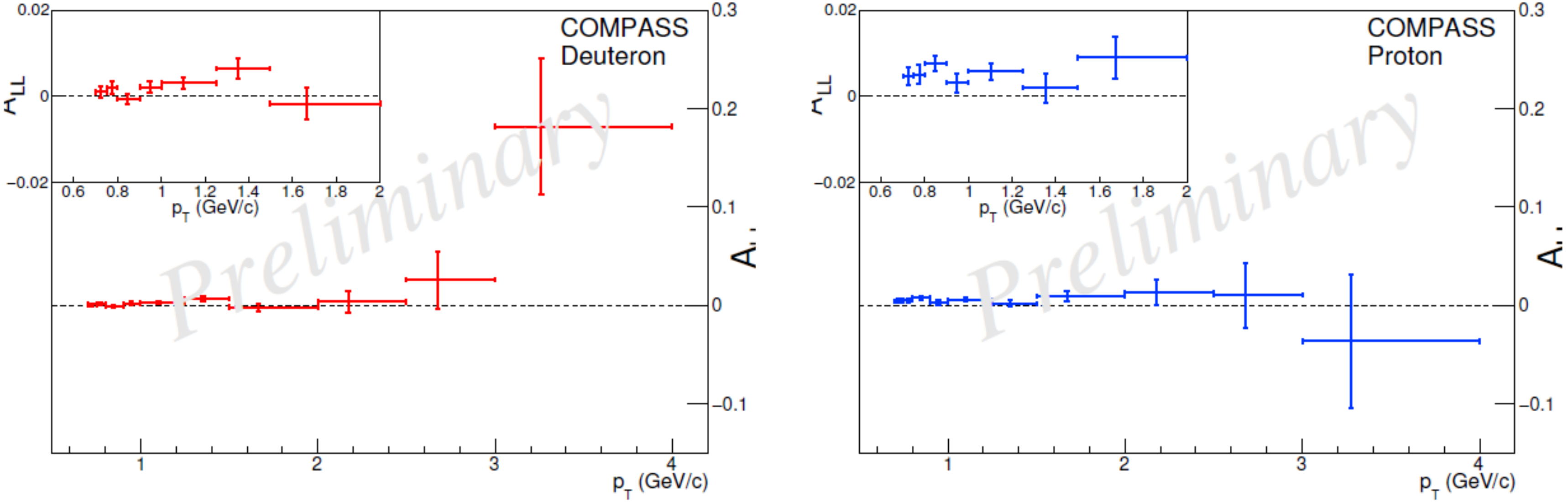


Fig. 26: A_{LL} asymmetries for the full COMPASS statistics on polarized deuteron and proton targets.

Data will be compared to calculations including the resummation of soft gluons, when they are available. The final goal is to include the data in a
global fit of pPDFs to world spin-dependent data.