RECENT RESULTS AND FUTURE PLANS OF COMPASS

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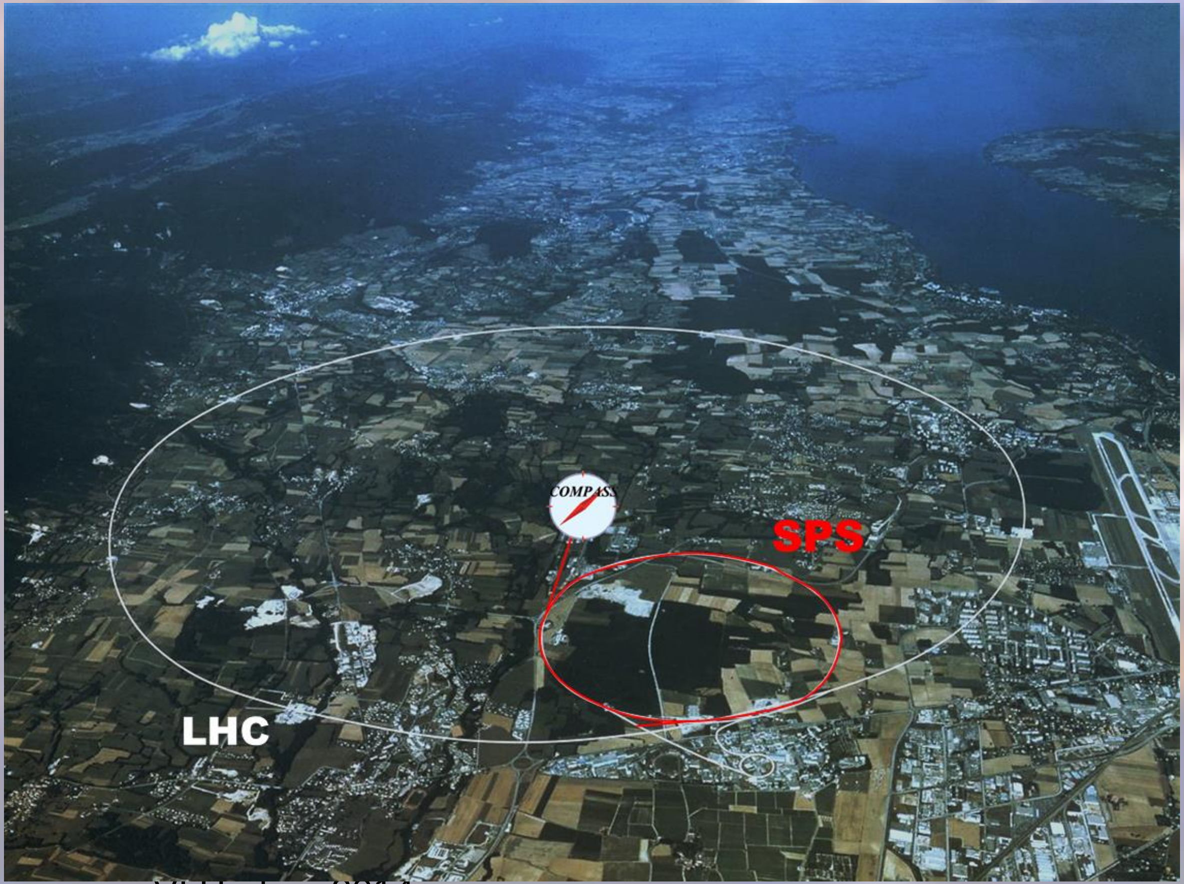
THE SIXTH WORKSHOP ON HADRON PHYSICS IN CHINA AND OPPORTUNITIES IN THE US

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

Collaboration
~ 250 physicists
from 24 Institutions
of 13 Countries

- **fixed target**
- **experiment**
- **at the CERN SPS**

data taking: since 2002



COMPASS Collaboration

Дубна (LPP and LNP),
Москва (INR, LPI, State University),
Протвино

CERN

Bochum, Bonn (ISKP & PI),
Erlangen,
Freiburg, Mainz,
München TU

Warsawa (NCBJ),
Warsawa (TU)
Warsawa (U)

Yamagata

USA (UIUC)

Praha (CU/CTU)

Liberec (TU)

Brno (ISI-ASCR)

Lisboa/Aveiro

Saclay

Calcutta (Matrivian)

Tel Aviv

Torino (University,INFN),
Trieste (University,INFN)

Taipei (AS)

COMPASS

- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer

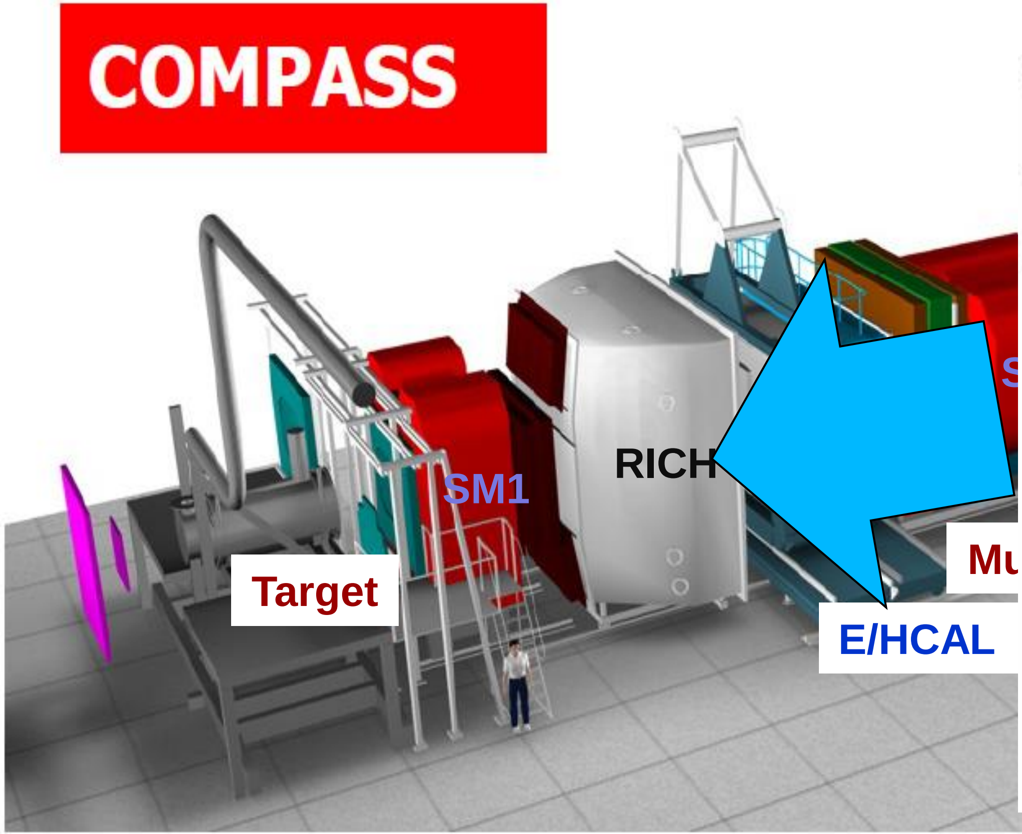
Large Angle Spectrometer (SM1)

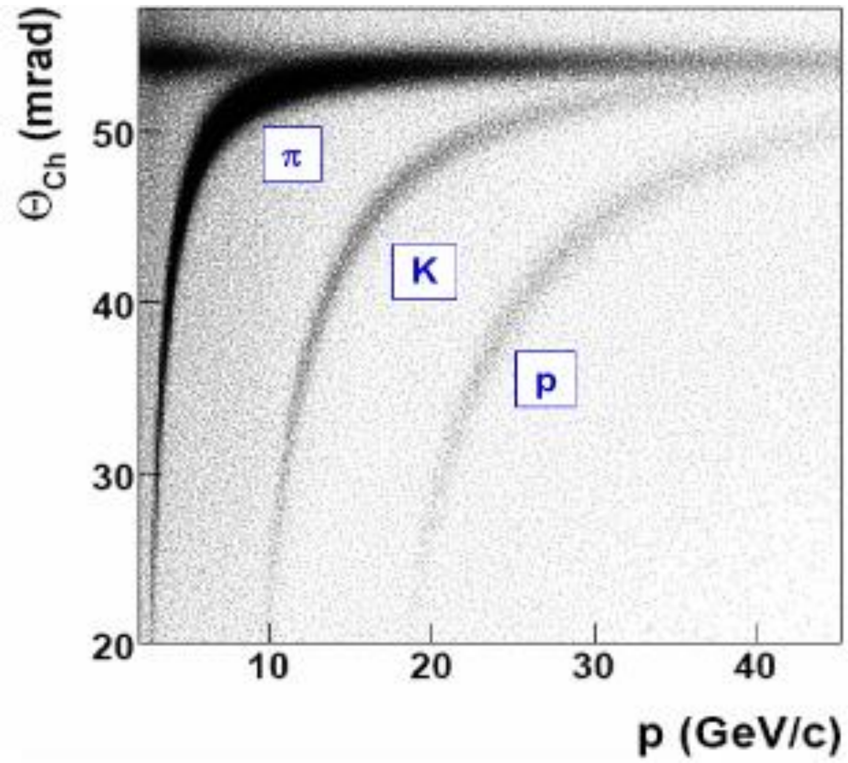
Small Angle Spectrometer (SM2)

radiator C_4F_{10}

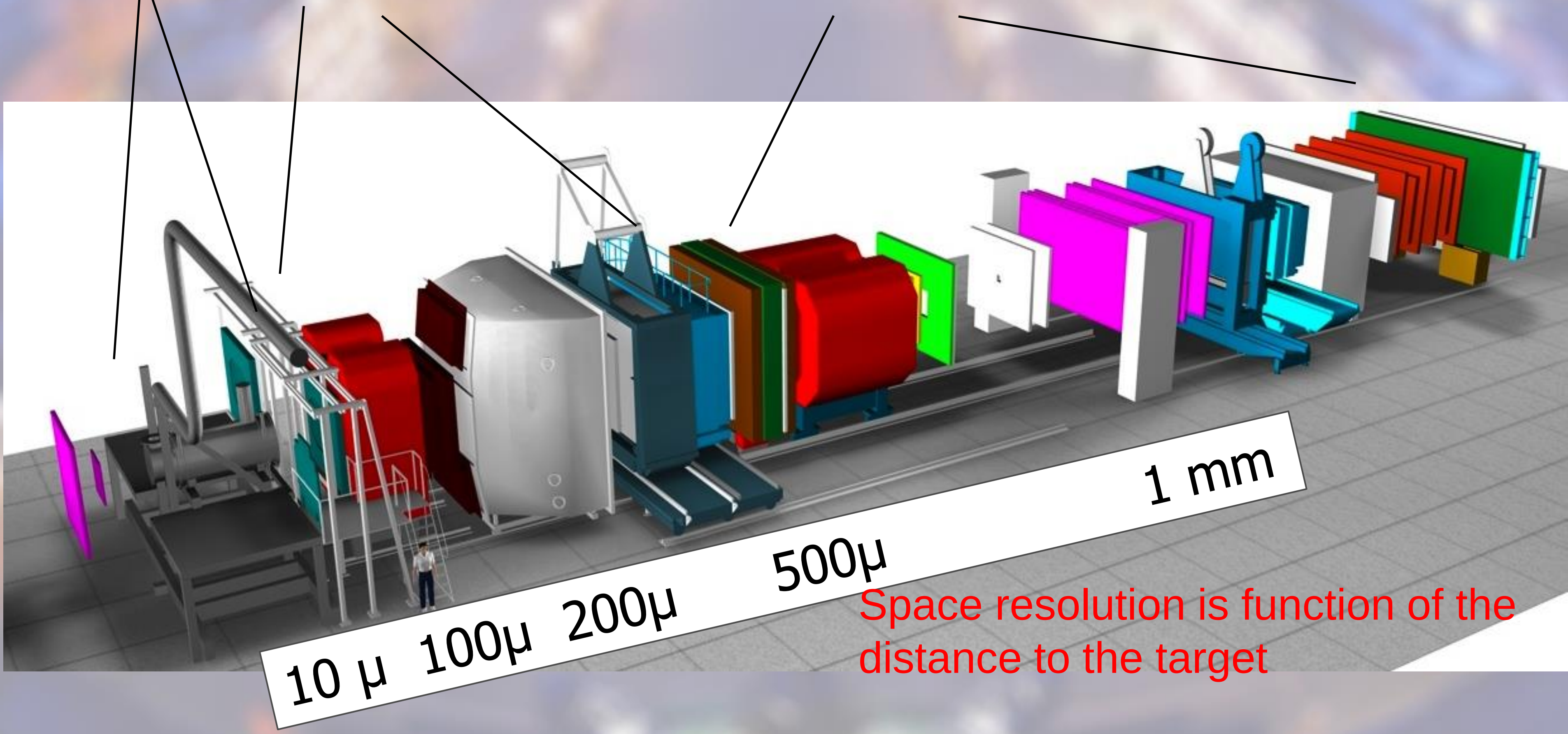
threshold: π ~2 GeV/c

K ~ 10 GeV/c





Space resolution



Target region

Large Angle Spectrometer

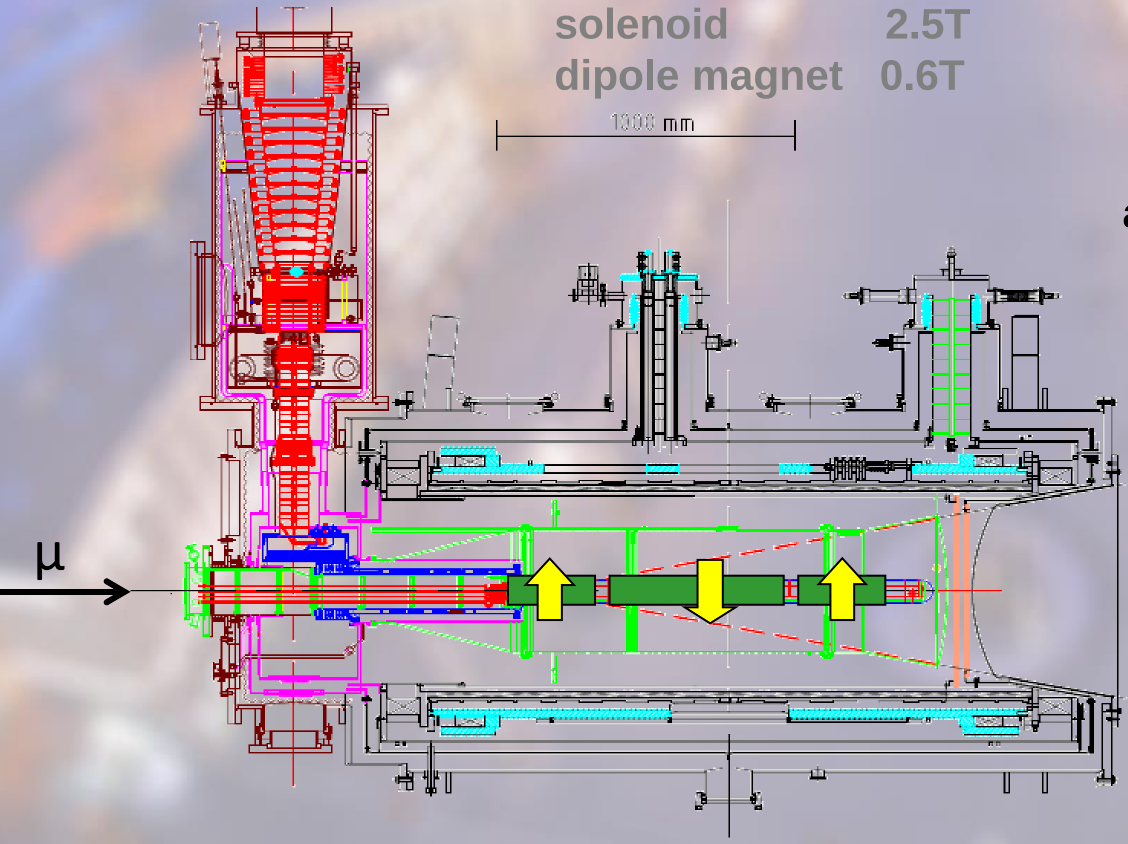
Small Angle Spectrometer

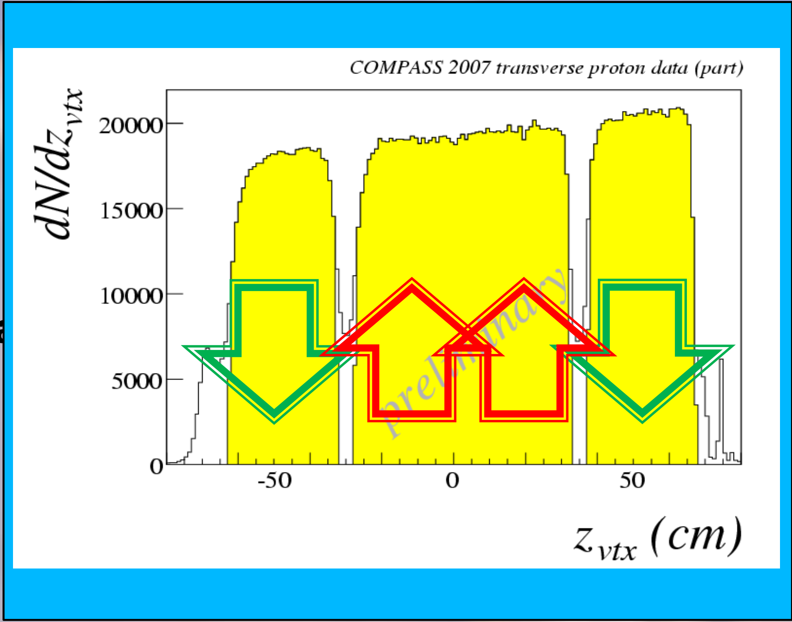
Space resolution is function of the distance to the target

the polarized target system (>2005)

^3He – ^4He dilution refrigerator (T~50mK)

solenoid 2.5T
dipole magnet 0.6T





opposite polarisation

	d (^6LiD)	p (NH_3)
polarization	50%	90%
dilution factor	40%	16%

no evidence for relevant nuclear effects *(160 GeV)*

COMPASS – some facts

- Located at CERN North Area beam line
  - Possible beams: μ^+, μ^-, π^+, π^-, K → Several physics programs

- Experiments with muon beam
- Experiments with hadron beams

COMPASS - I (2002 – 2011)

- Spin structure, Gluon polarization
- Flavor decomposition
- Transversity
- Transverse Momentum-dependent PDF

- Pion polarizability
- Diffractive and Central production
- Light meson spectroscopy
- Baryon spectroscopy

COMPASS - II (2012 – 2017)

- DVCS and HEMP
- Unpolarized SIDIS and TMDs

- Pion and Kaon polarizabilities
- Drell-Yan studies

COMPASS – some facts

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- Experiments with muon beam
- Experiments with hadron beams

COMPASS - I (2002 – 2011)

- Spin structure
- p, d polarized target (L & T)

- Hadron spectroscopy
- Small LH_2 or nuclear targets

COMPASS - II (2012 – 2017)

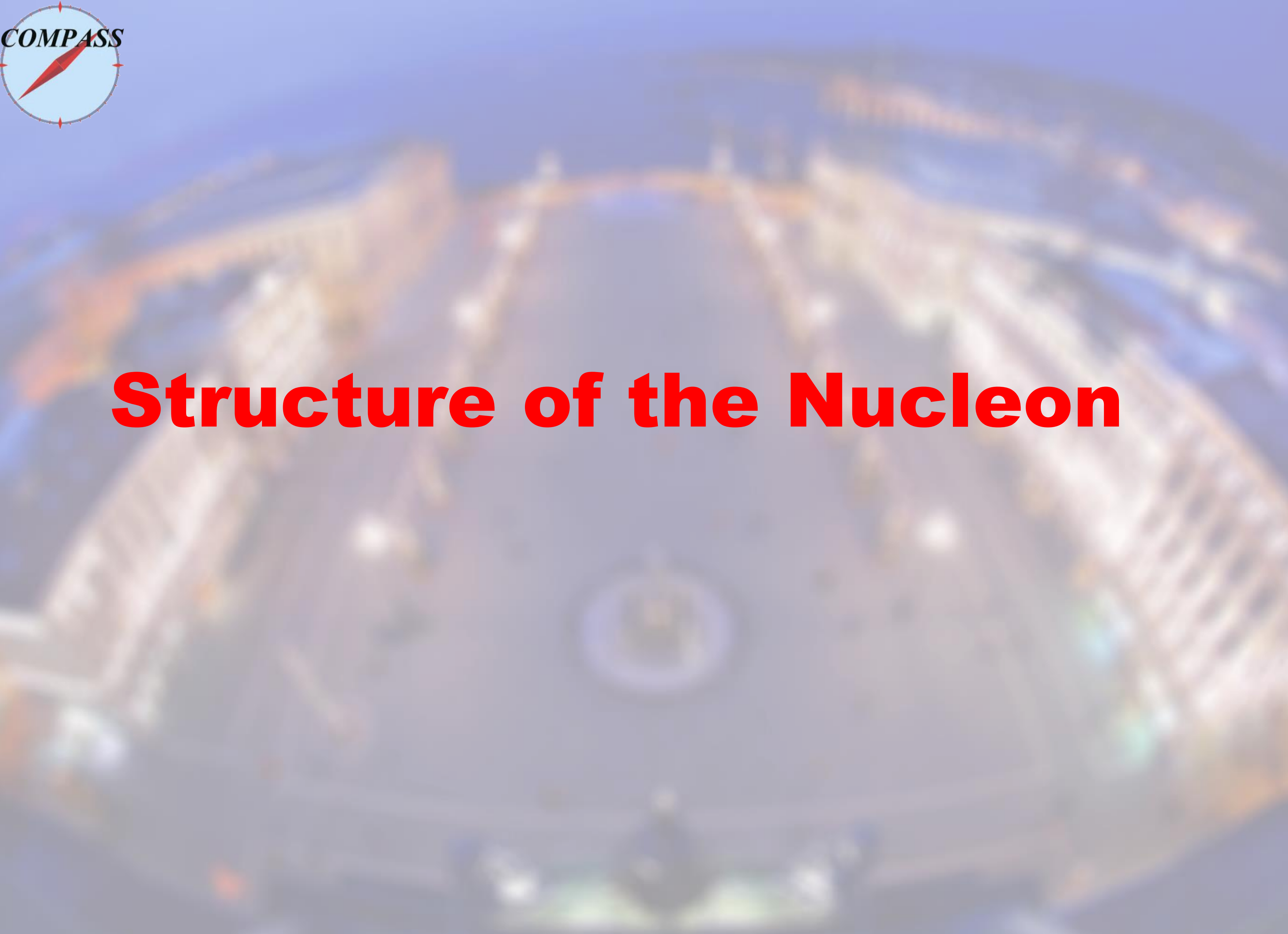
- DVCS/Unpol SIDIS
- Long LH_2 target

- Drell-Yan studies
- Polarized target (T)

Reconfigurable target region - versatile experimental setup!

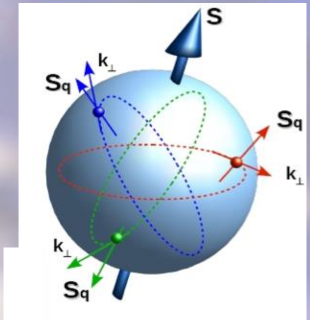
Key COMPASS measurements

$g_1^d(x)$, $\int g_1^d(x)dx$	Confirmation of SMC result on d (at variance with E142 claims)
$\Delta g/g$	first hint that Δg is small, at variance with predictions
$A_{Col,d}^h$	first measurement of transversity on deuteron $h_1^u \simeq -2h_1^d \quad H_{1,fav}^\perp \simeq -H_{1,unf}^\perp$
$A_{p,d}^{2h}$	Only polarimeter for transversity extraction from 2h asymmetries transversity extracted directly from the data, following Pavia group
$A_{Siv,p}^h$	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



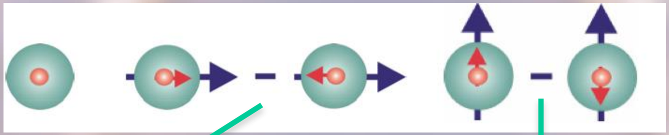
Structure of the Nucleon

The spin of the nucleon



Three twist-2 quark DF's in collinear approximation ($\int dk_\perp$)

$$F^{Tw-2}_{Coll}(x) = \frac{1}{2}\left\{ q(x) + S_L\gamma_5 \Delta q(x) + S_T\gamma_5\gamma^1 \Delta_T q(x) \right\} n^+$$



helicity

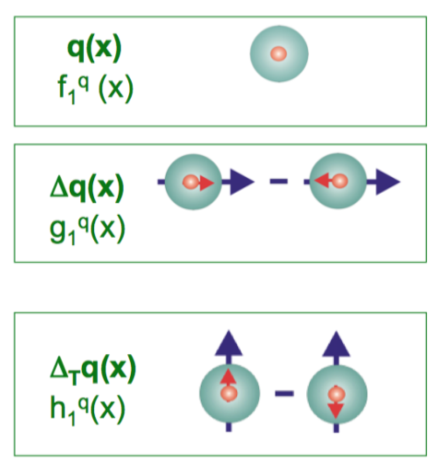
transversity

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

NR limit

[boost, rotat.]=0

➡ $\Delta_T q(x,Q^2) = \Delta q(x,Q2)$



q(x)

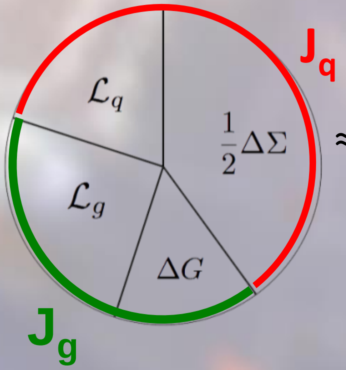
$f_1^q(x)$

Δq(x)

$g_1^q(x)$

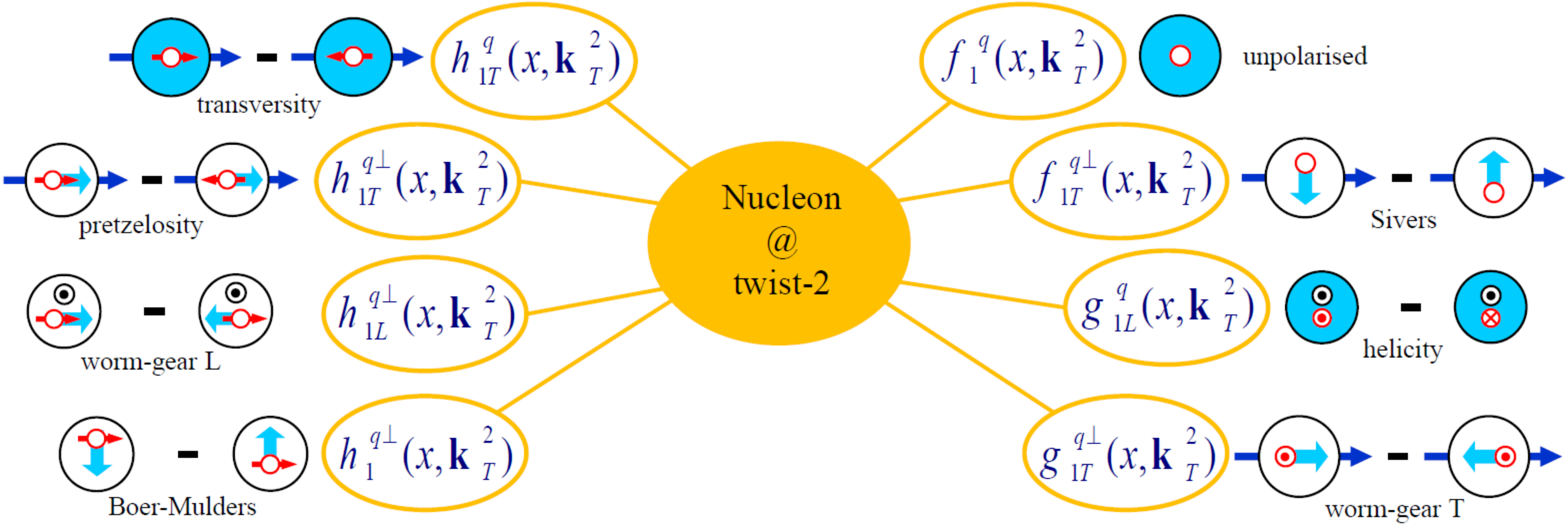
Δ_Tq(x)

$h_1^q(x)$



≈30% : **Spin puzzle**

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

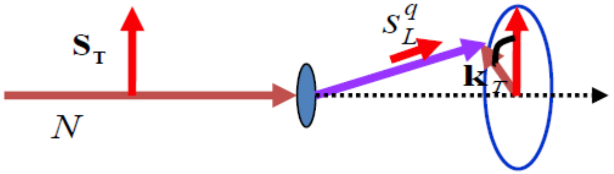
$g_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ worm-gear T

nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

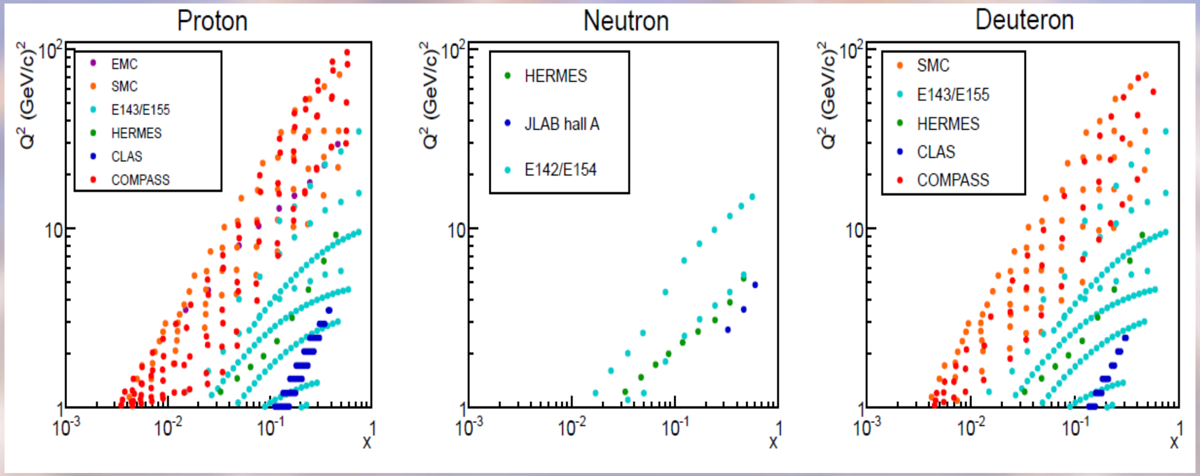
Proton goes out of the screen. Photon goes into the screen



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

Global NLO QCD fits to world data on g_1

- 138 out of 679 points are from COMPASS



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

$\Delta q_S = \Delta u + \Delta d + \Delta s$; 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

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

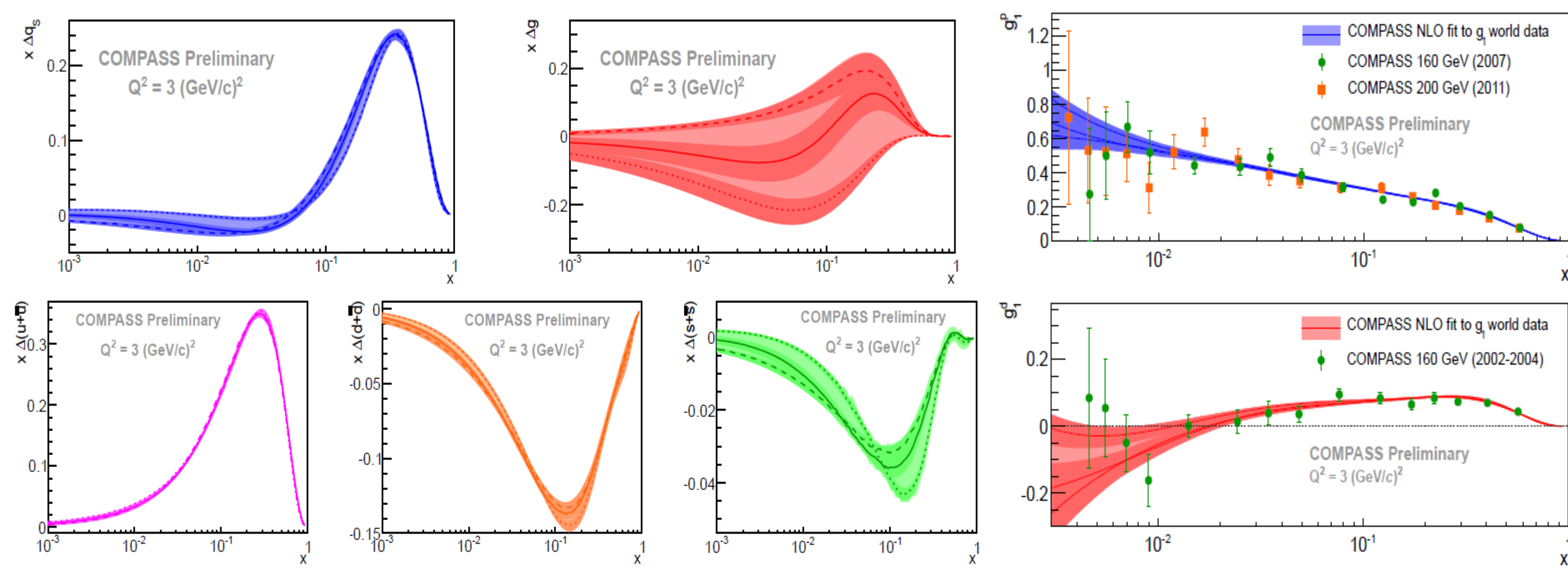
$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta q_S\\ \Delta g\end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{pmatrix}\Delta P_{qq} & 2n_f\Delta P_{qg}\\ \Delta P_{qg} & \Delta P_{gg}\end{pmatrix}\otimes\begin{pmatrix}\Delta q_S\\ \Delta g\end{pmatrix}$$

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.



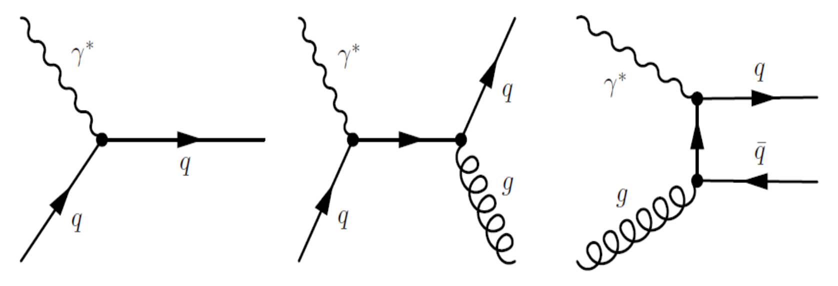
Distribution	First moment at $Q^2 = 3\ (\mathrm{GeV}/c)^2$
$\Delta\Sigma$	[0.25 , 0.34]
$\Delta u + \Delta\bar{u}$	[0.82 , 0.85]
$\Delta d + \Delta\bar{d}$	[−0.45 , −0.42]
$\Delta s + \Delta\bar{s}$	[−0.11 , −0.08]

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

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

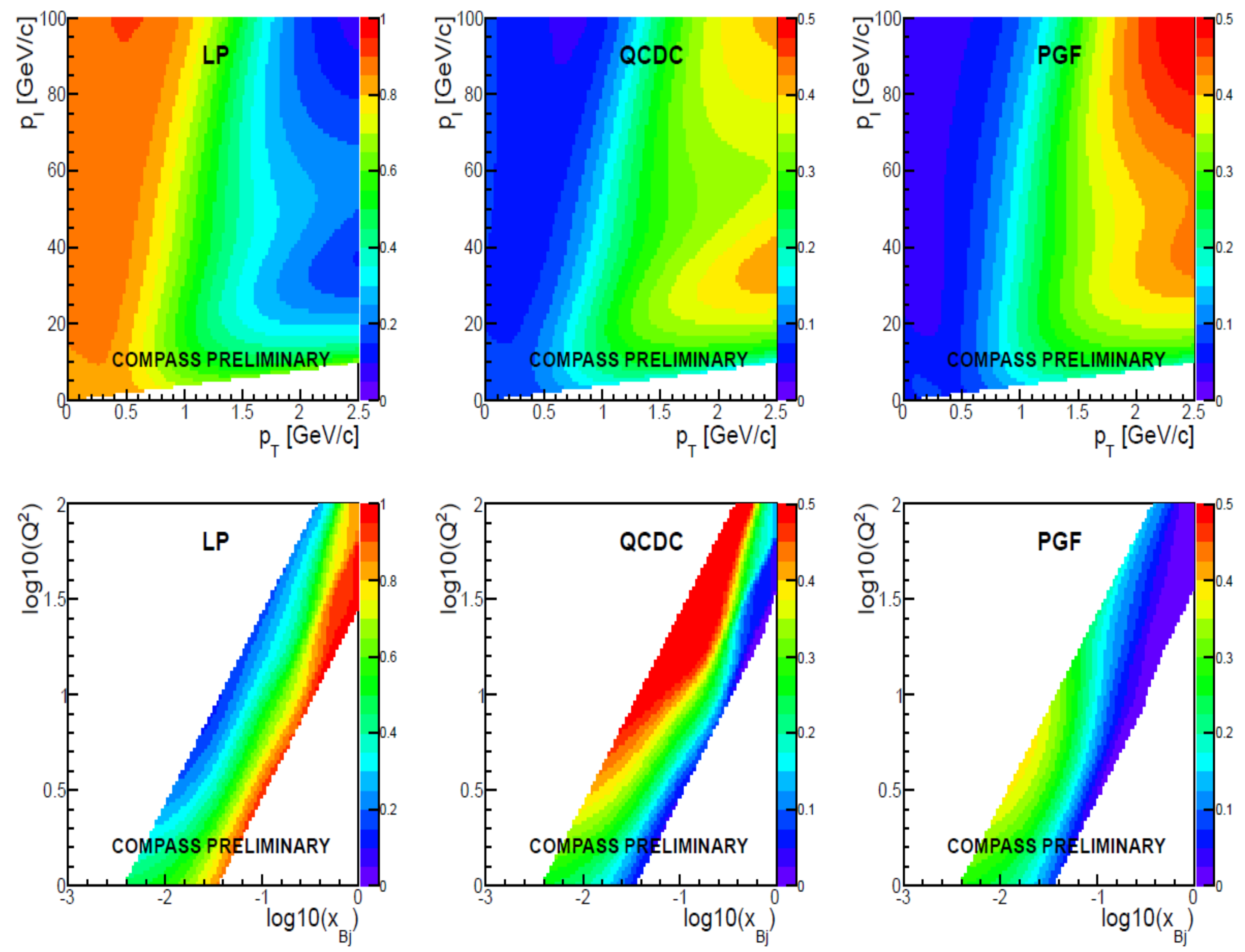
- The main goal is to improve the extraction by removing few sources of systematic effects.
- However, also a considerable reduction of the statistical error of $\Delta g/g$ was achieved.
- Three processes contribute to the cross-section

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

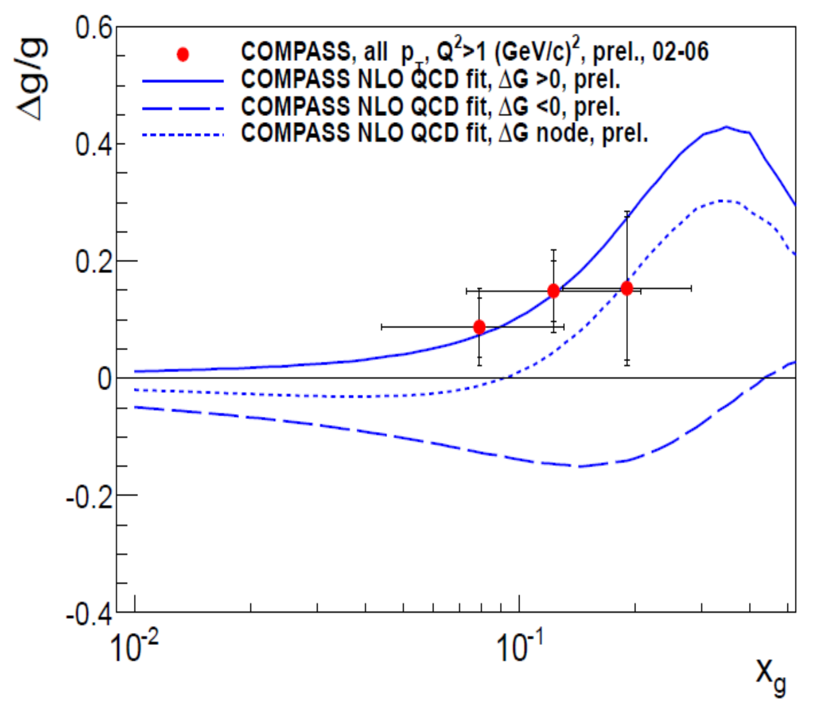


- Simultaneous extraction of $\Delta g/g$, and A_1^{LO}
- Extraction based on effective Monte Carlo description of all processes giving the relative weights (R_i) and analyzing powers (a_{LL}^{i})
- Process weights depends on p_T (at small p_T LO contribution is > 0.95)

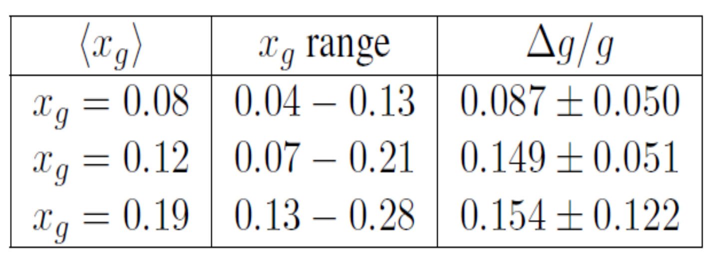
$\Delta g/g$ “all p_T” : correlations



$\Delta g/g$ “all p_T” : results



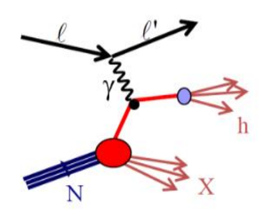
$$\Delta g/g\Big|_{\langle x_g\rangle=0.10} = 0.113 \pm 0.038 \pm 0.035$$



$\langle x_g \rangle$	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

Accessing TMD PDFs

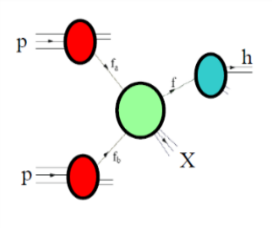
- SIDIS off polarized p, d, n targets



HERMES
COMPASS
JLab
*future: **eN colliders?***

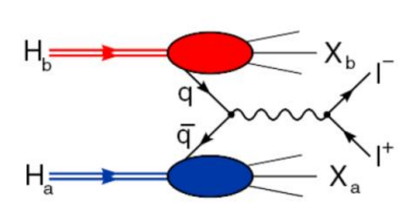
$$\sigma(\ell p \to \ell' hX) \sim q(x) \otimes \hat{\sigma}^{\gamma q \to q} \otimes D_q^h(z)$$

- hard polarised pp scattering



RHIC

- polarised Drell-Yan

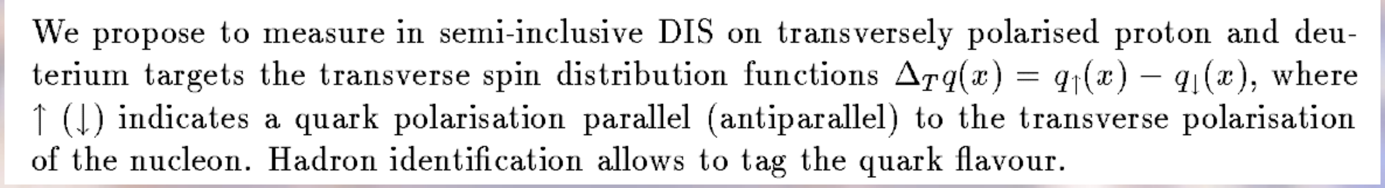


COMPASS
RHIC
FNAL
*future: **FAIR, JPark, NICA***

$$\sigma(\pi p \to \mu\mu) \sim \bar{q}_\pi(x_1) \otimes q_p(x_2) \otimes \hat{\sigma}^{\bar{q}q \to \mu\mu}(\hat{s})$$

Few facts:

- The measurement of transversity was in the COMPASS 1996 proposal



We propose to measure in semi-inclusive DIS on transversely polarised proton and deuterium targets the transverse spin distribution functions $\Delta_T q(x) = q_{\uparrow}(x) - q_{\downarrow}(x)$, where $\uparrow$ ($\downarrow$) indicates a quark polarisation parallel (antiparallel) to the transverse polarisation of the nucleon. Hadron identification allows to tag the quark flavour.

- The measurement of the Sivers PDF was added to the program soon after … the other TMD with the developments over the years
- Measurements started in 2002 by HERMES (p) and COMPASS (d)
- This field has grown considerably in the last years and comes one of high priority measurements for the JLab12 program

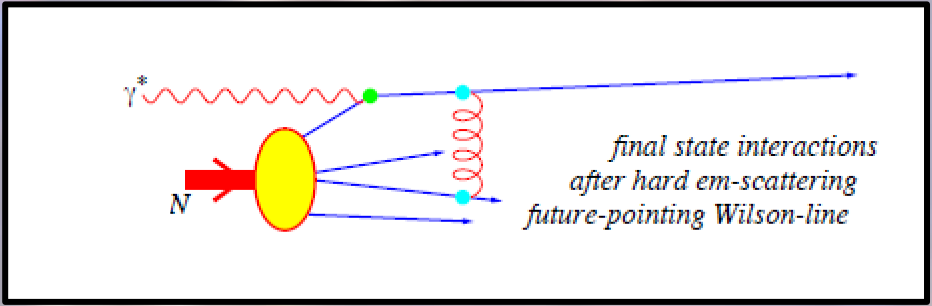
Results:

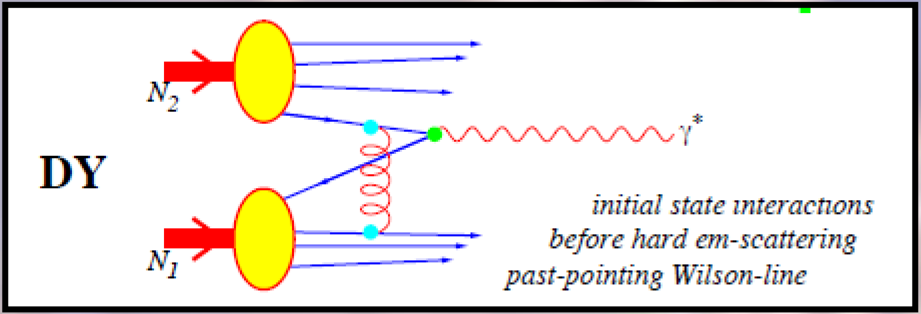
Year		
2005	$A_{Siv,d}^{h}, A_{Col,d}^{h}$	First ^{6}LiD data
2006	$A_{Siv,d}^{h}, A_{Col,d}^{h}$	Full ^{6}LiD statistics
2009	$A_{Siv,d}^{\pi^\pm,K^\pm,K_S^0}, A_{Col,d}^{\pi^\pm,K^\pm,K_S^0}$	Full ^{6}LiD statistics
2010	$A_{Siv,p}^{h}, A_{Col,p}^{h}$	2007 NH_3 data
2012	$A_{UT,d}^{sin\phi_{RS}}, A_{UT,p}^{sin\phi_{RS}}$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

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

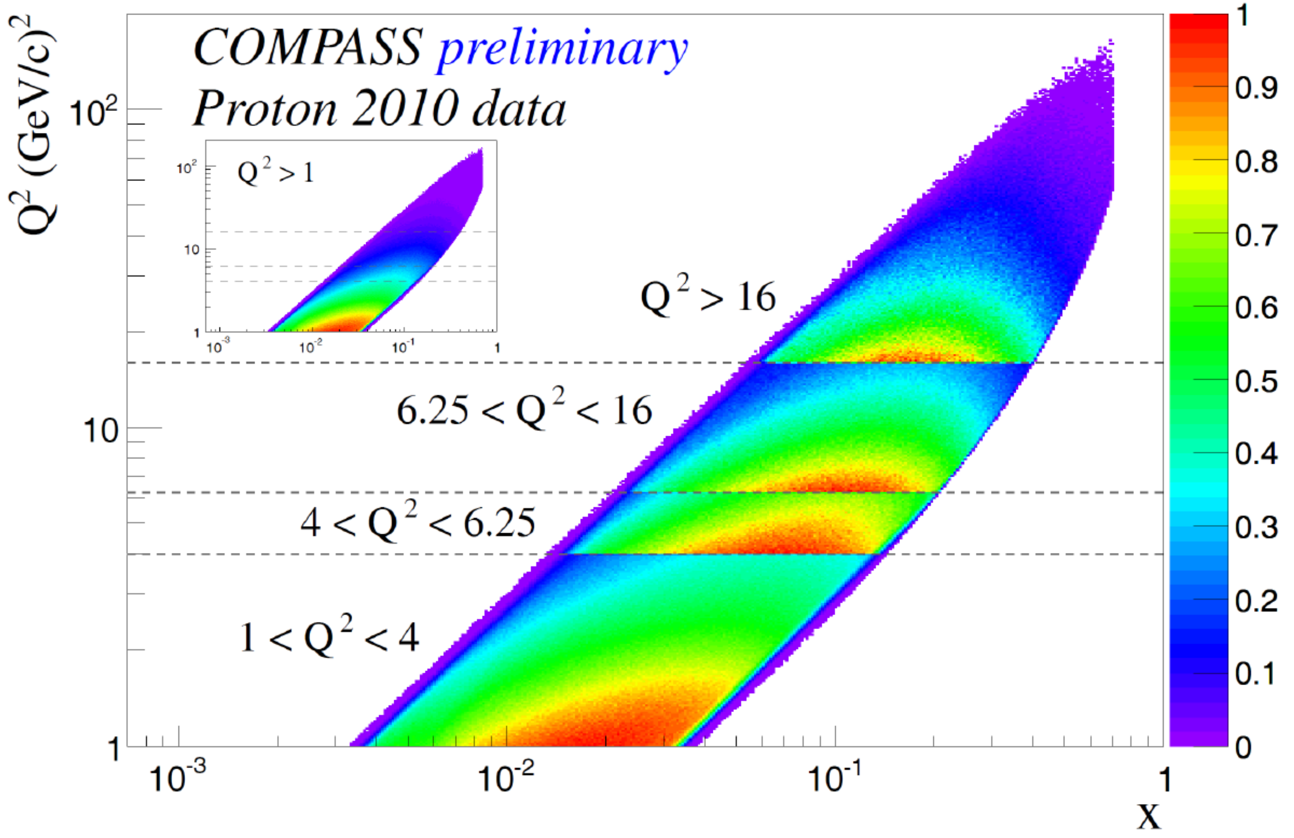
Boer-Mulders

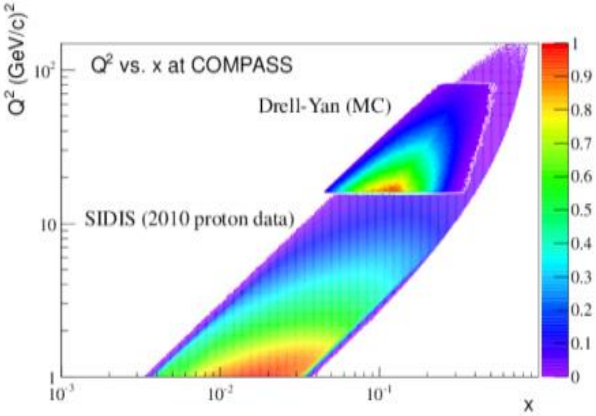
$$\boxed{h_1^{\perp}(SIDIS) = -h_1^{\perp}(DY)}$$

Sivers

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

Q^2 vs x phase space at COMPASS

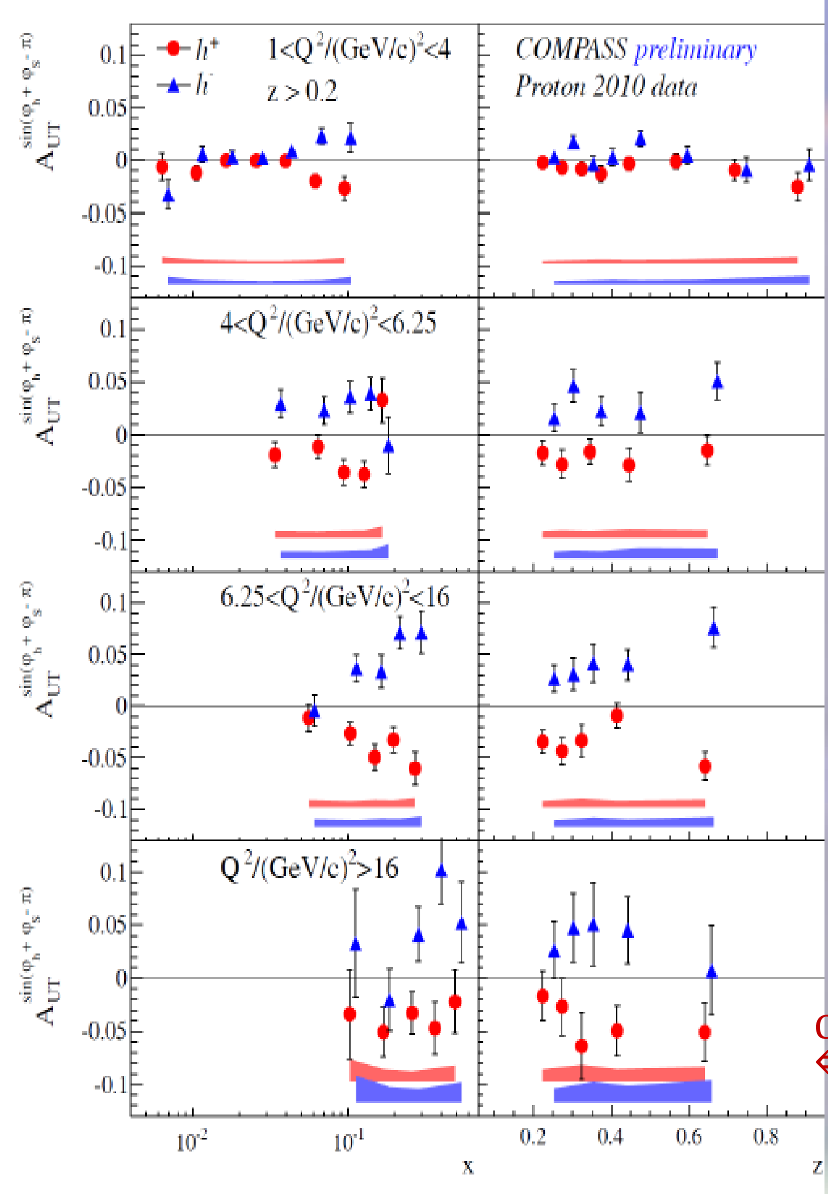




The phase spaces of the two processes overlap at COMPASS

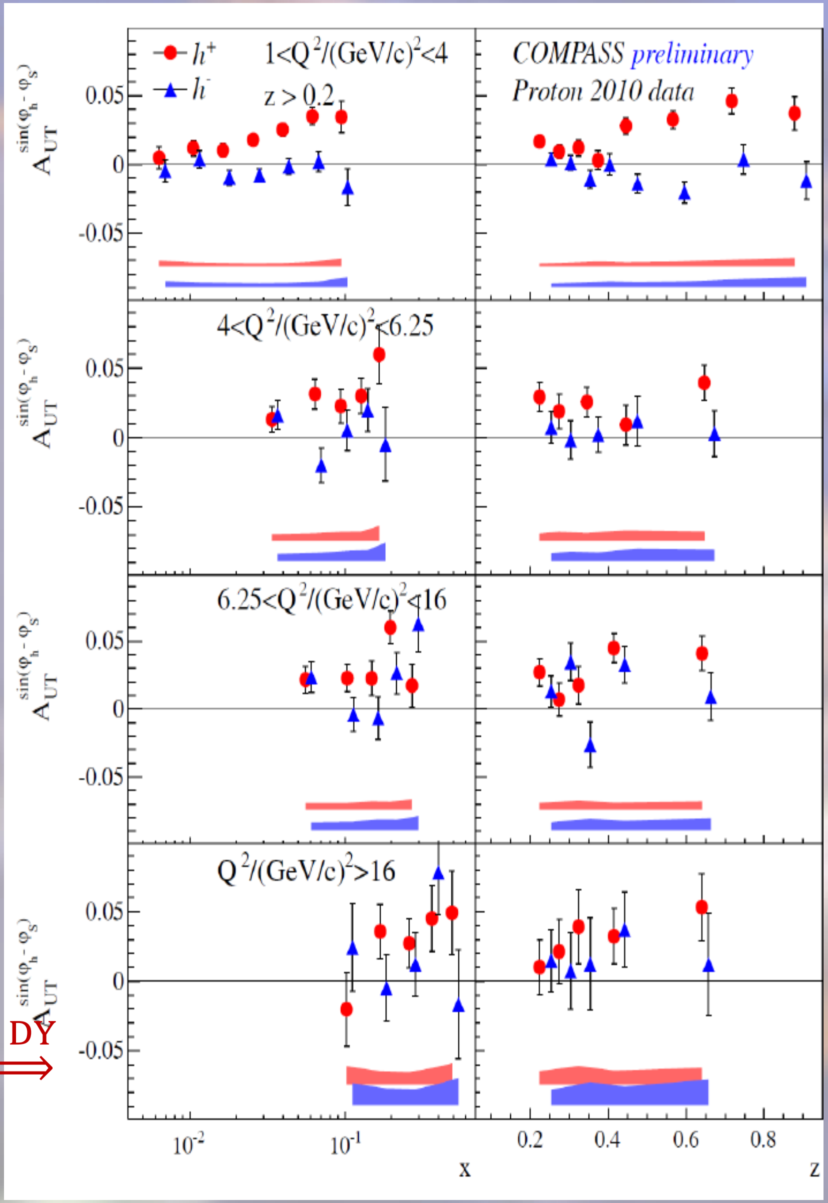
→ Consistent extraction of TMD DPFs in the same region

Collins and Sivers for different Q^2 ranges

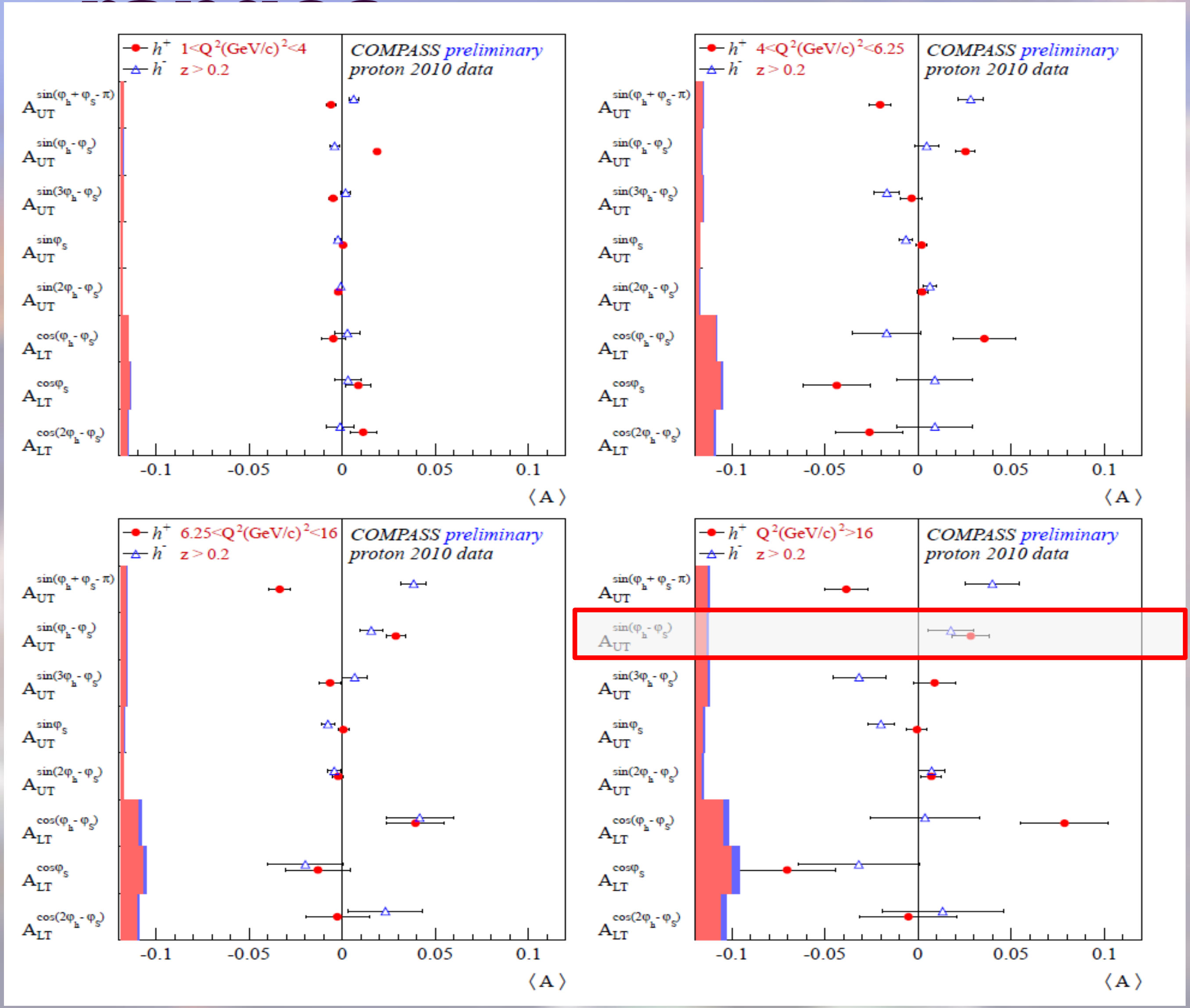


COMPASS DY

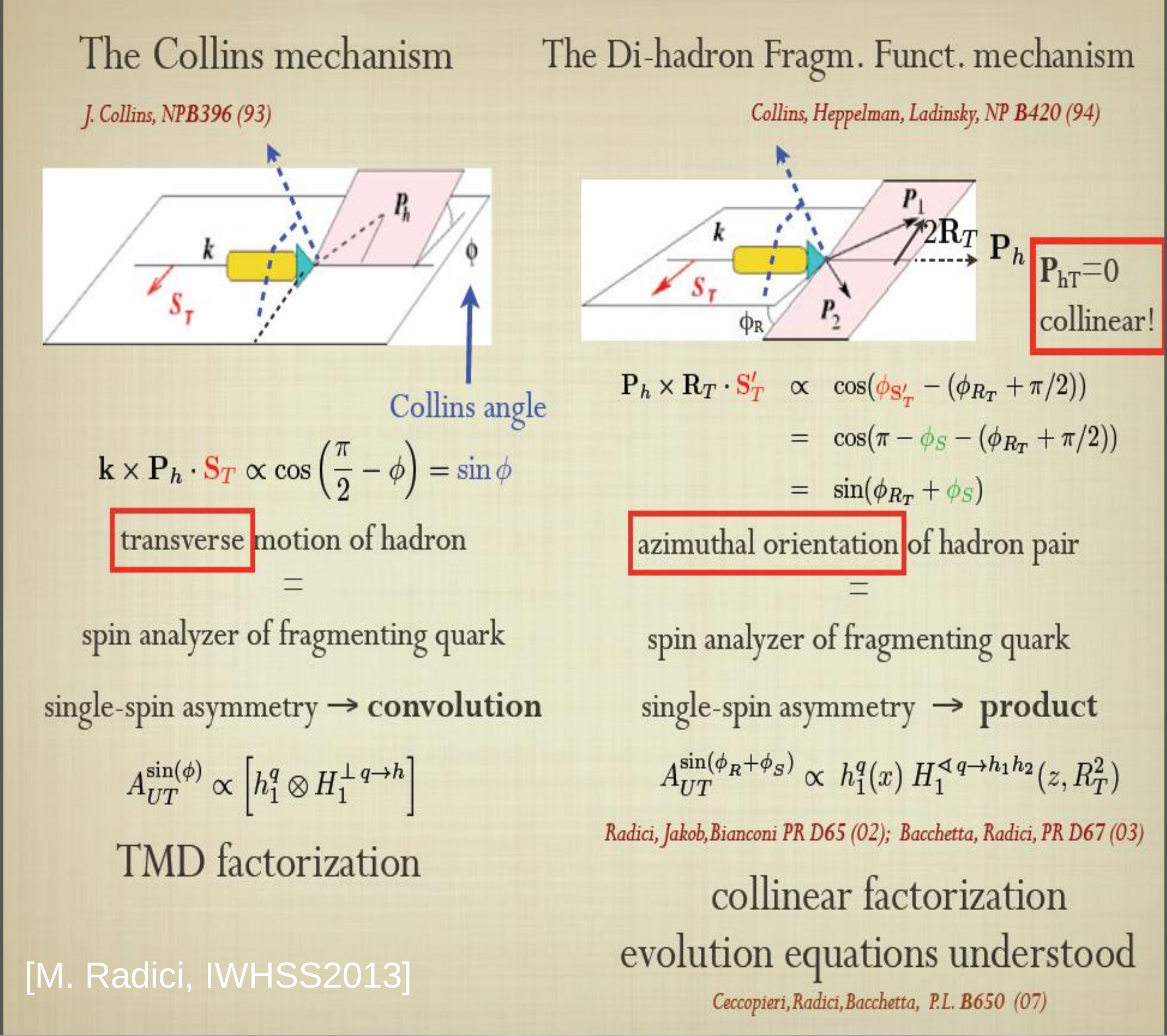
$\Longleftrightarrow$



Mean TMD SSA for the four Q^2



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

[M. Radici, IWHSS2013]

The Di-hadron Fragm. Funct. mechanism

Collins, Heppelman, Ladinsky, NP B420 (94)

$\mathbf{P}_{hT}$=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**

$$A_{UT}^{\sin(\phi_R+\phi_S)} \propto h_1^q(x)\, H_1^{\sphericalangle\, q\to h_1h_2}(z,R_T^2)$$

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

collinear factorization

evolution equations understood

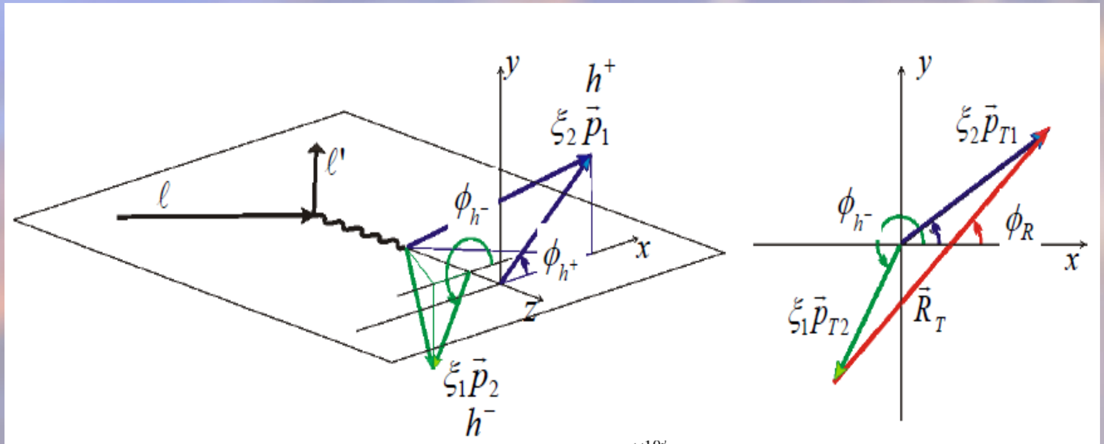
Ceccopieri, Radici, Bacchetta, P.L. B650 (07)

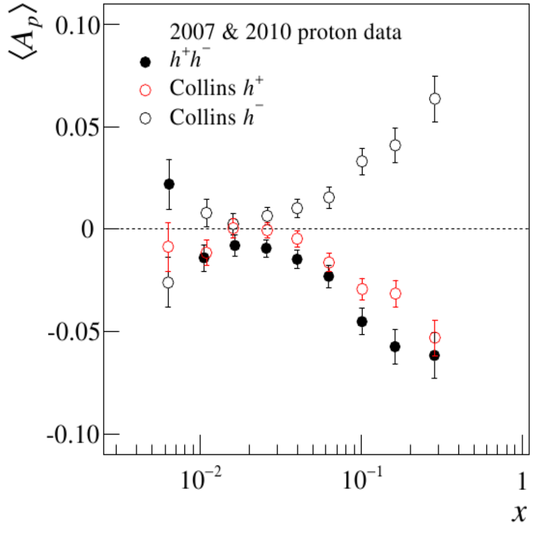
Interplay between Collins and IFF asymmetries

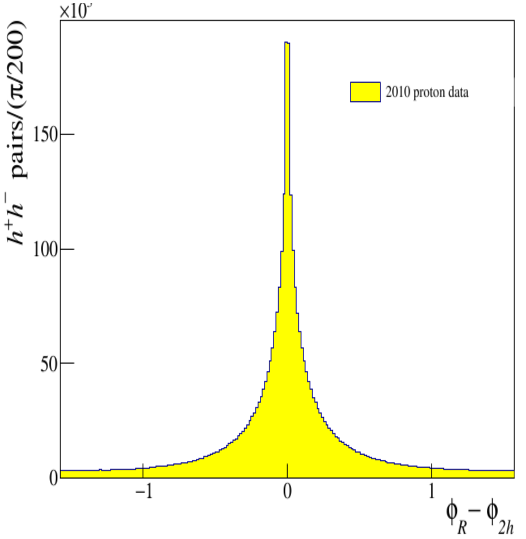
common hadron sample for Collins and 2h analysis

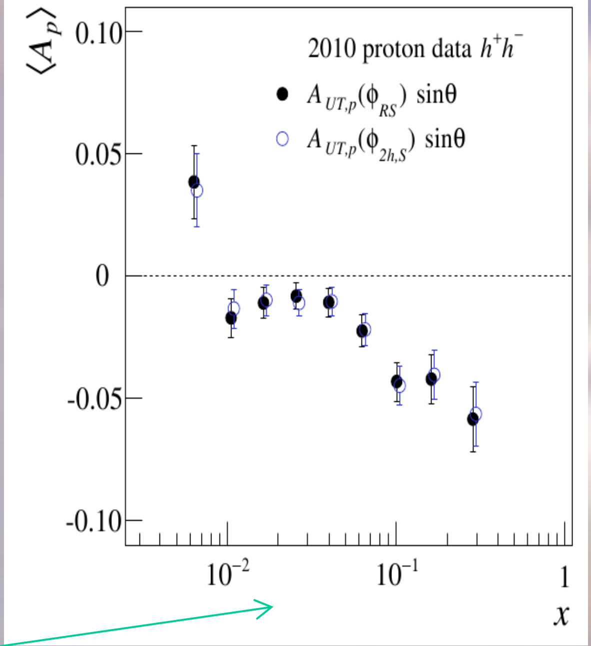
ϕ_{2h} azimuthal angle of $\vec{R}_N = \hat{p}_{T,h^+} - \hat{p}_{T,h^-}$

ϕ_R azimuthal angle of $\vec{R}_T$





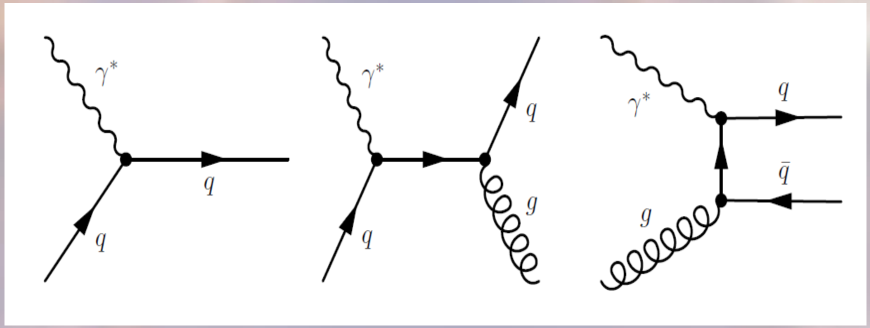




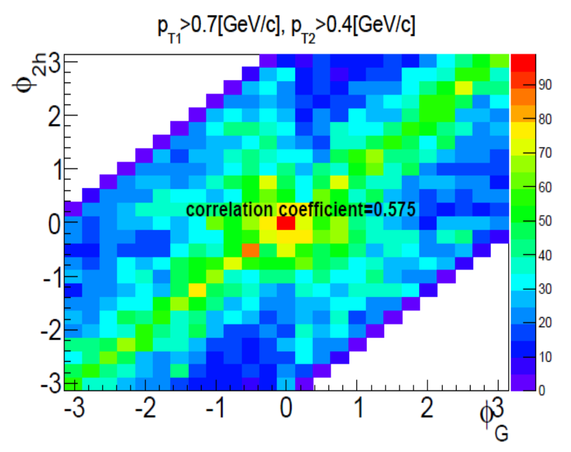
Hint to a at a common physical origin for the $H_1^{\perp}$ and the $H_1^{\sphericalangle}$ as suggested by different models

Sivers asymmetry on deuteron for Gluons

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

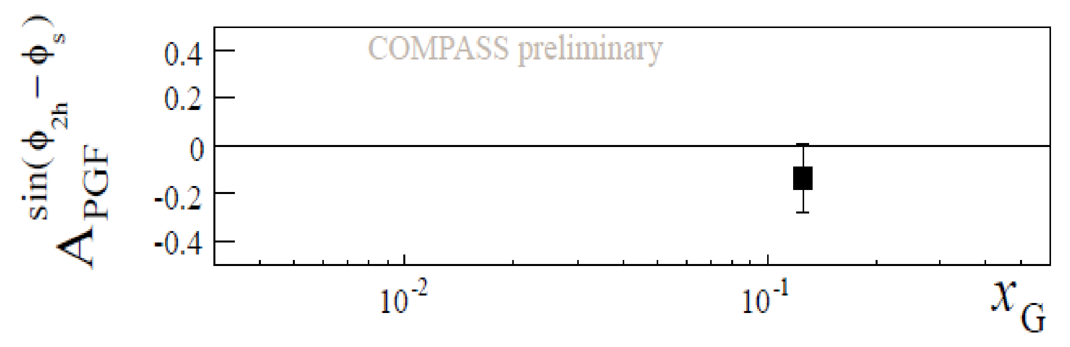


Correlation between azimuthal angle of the gluon ϕ_g and azimuthal angle of the two hadrons ϕ_{2h} (assumption $\vec{p}_g \approx \vec{p}_{h1} + \vec{p}_{h2}$)



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

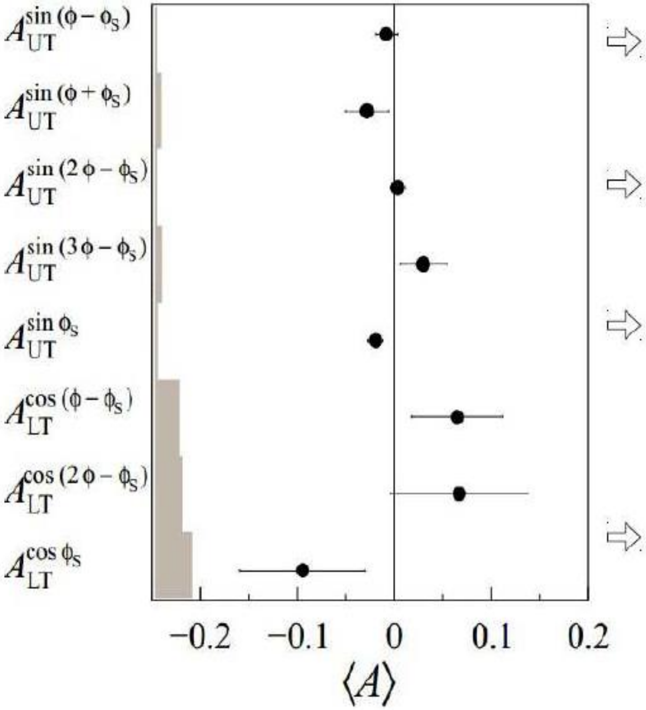
- Based on deuteron COMPASS data, Brodsky and Gardner [Phys.Lett.B643:22-28,2006] foresaw gluon Sivers $f_{1T,g}^{\perp} = 0$
- From the analysis of PHENIX data at mid rapidity, Anselmino et al. [Phys.Rev.D74:094011,2006] put constrains to $f_{1T,g}^{\perp}$ at small x

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

Physics from hadron beam

Rich program on hadron spectroscopy at COMPASS,
search for exotic mesons

- Diffractive resonance production
- Central production

π, K, p beams - 190 GeV : large energy transfer spectrum t
Spectrometer : flat acceptance, ECALs/ HCALs, RICH id.
charged & neutral channels

Huge statistics

Major progress on analysis
Potential for discovery of small intensity new states

Selected results

- Diffractive processes $\pi^- p \rightarrow \pi^-\pi^+\pi^- p_{recoil}$
- Pion polarisability π^- Ni → π^- Ni γ - (2009 Primakoff)

MENU 2013

13th International Conference
Meson-Nucleon Physics and the Structure of the Nucleon
September 30th - October 4th 2013, Rome, Italy

Topics:
- Meson-Nucleon Interactions
- Hadron Spectroscopy
- Nucleon Structure
- Few-Body Systems
- Fundamental Symmetries
- Electroweak Probes
- Future Facilities and Directions

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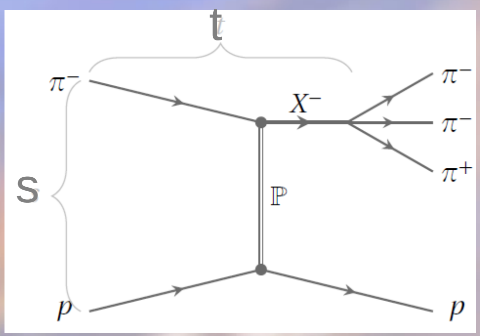
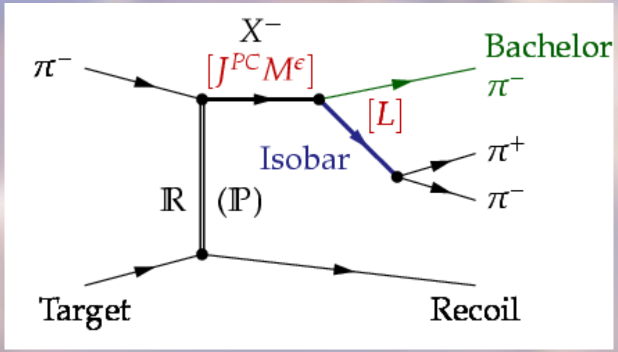
Diffractive resonance production in $\pi^- p \rightarrow \pi^-\pi^+\pi^- p_{recoil}$





Isobar model

Partial waves :

J^{PC} M^ε [isobar] L

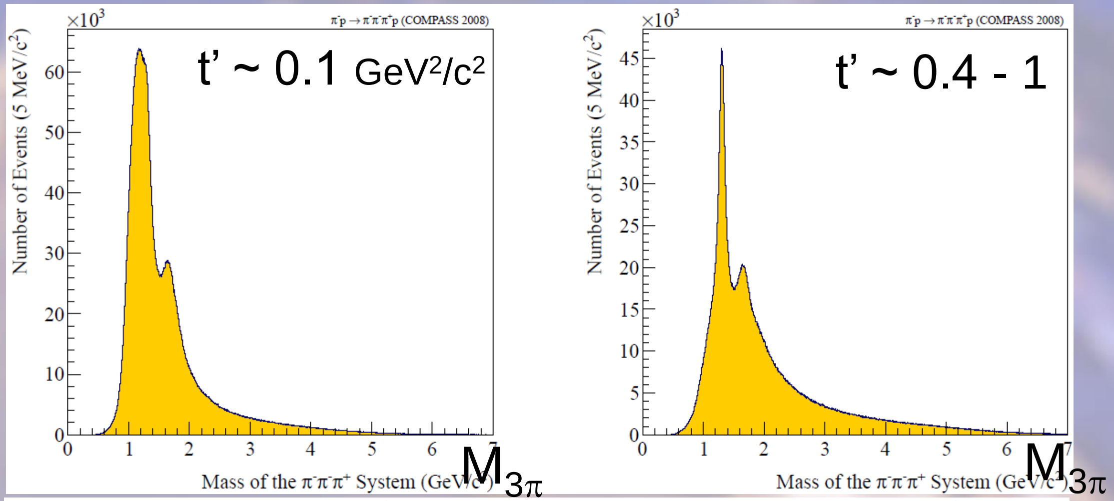
J^{PC}**-exotic** mesons

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

Shape of mass in 2 t' bins

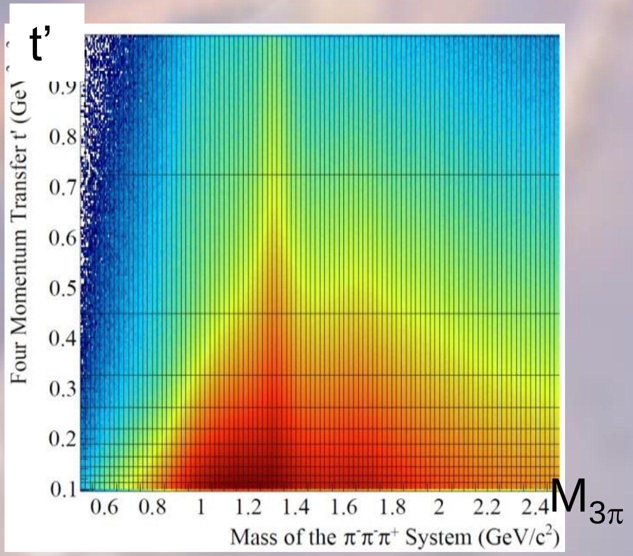


t' ~ 0.1 GeV^2/c^2

t' ~ 0.4 - 1

$M_{3\pi}$

$M_{3\pi}$

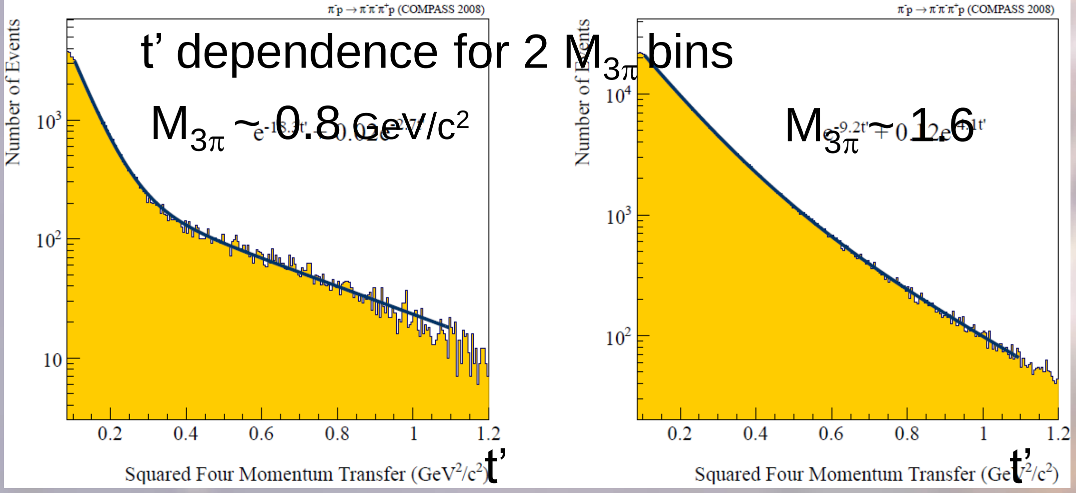


t'

$M_{3\pi}$

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

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



$M_{3\pi}$ ~ 0.8 GeV/c^2

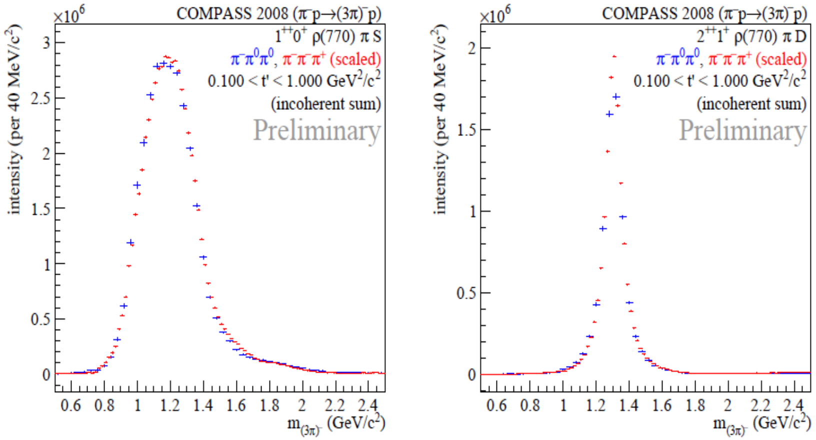
$M_{3\pi}$ ~ 1.6

t'

t'

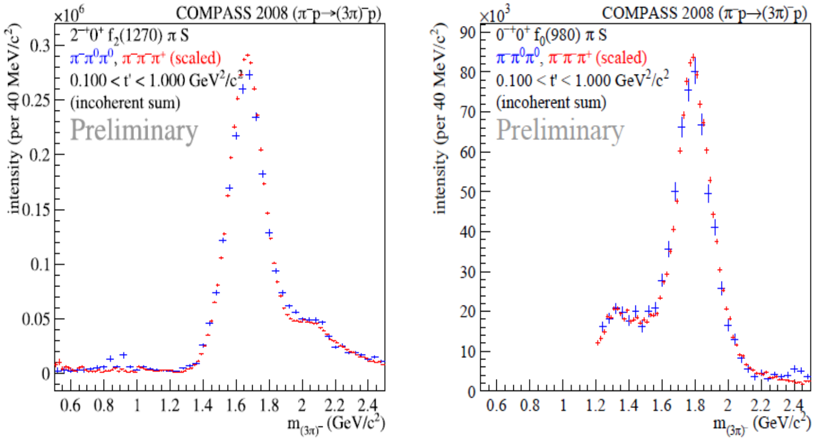
A look to major waves

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



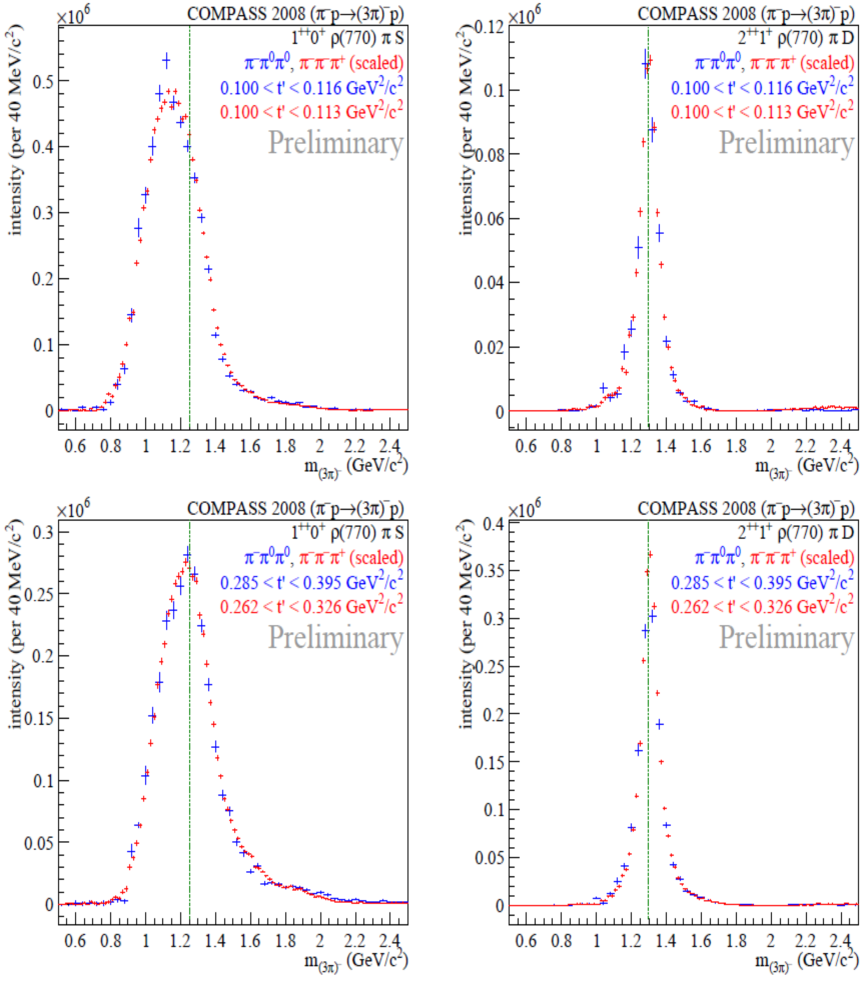
(a) $1^{++}0^+$ $\rho\pi$ S wave with the $a_1(1260)$ peak.

(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.



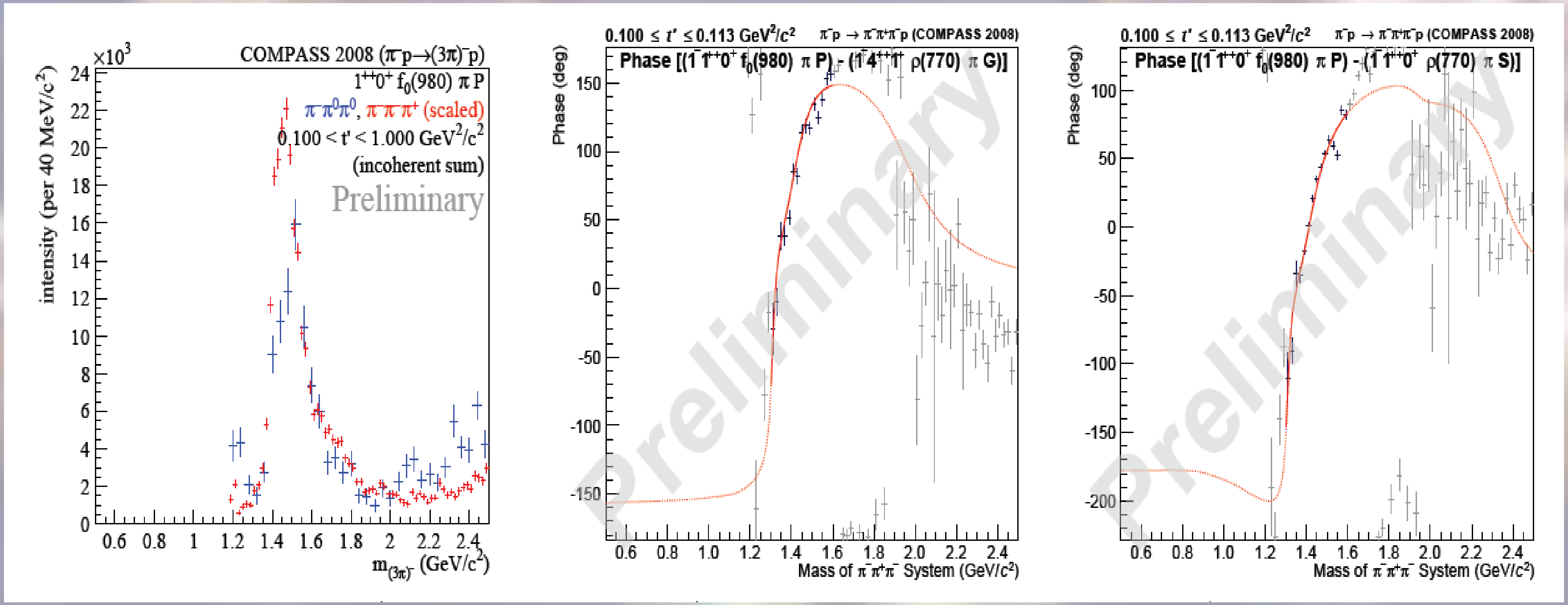
(a) $1^{++}0^+$ $\rho\pi$ S wave with the $a_1(1260)$ peak.

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

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).



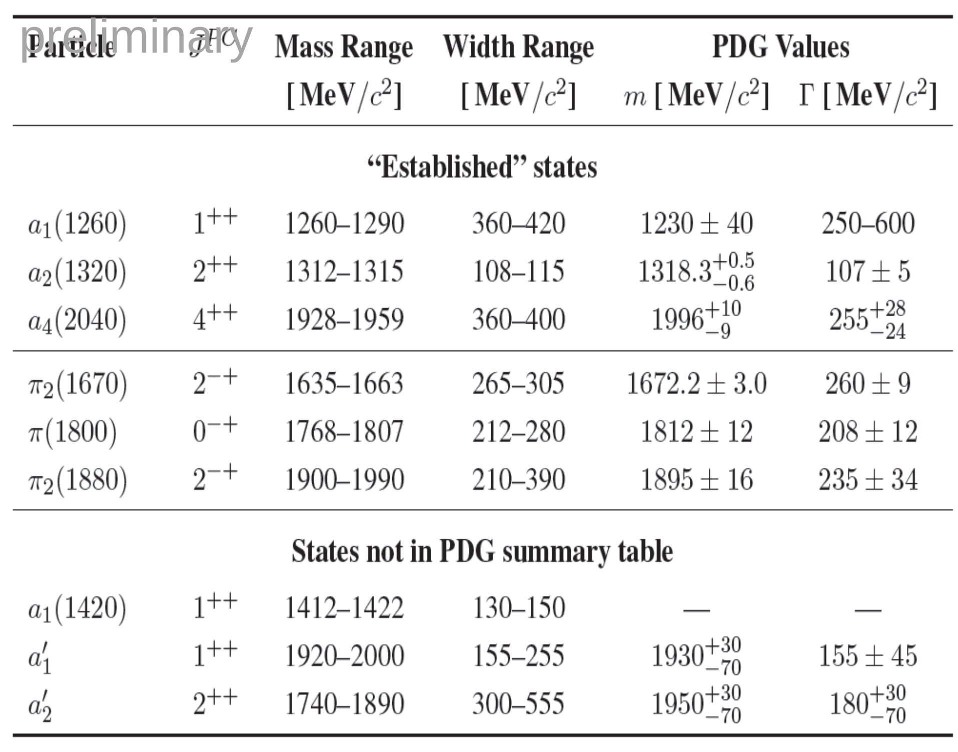
Interpretation

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 $K\bar{K}^*$.



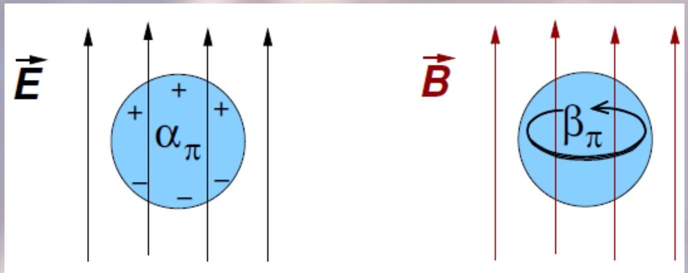
preliminary

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}

Pion polarisabilities - Primakoff 2009 data

Polarisabilities: deviation from pointlike particle

electric (α) and magnetic (β)



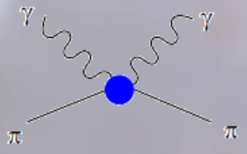
Predictions from Ch PT:

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

Experiments inconclusive:

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

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 $\pi Z \rightarrow \pi Z \gamma$

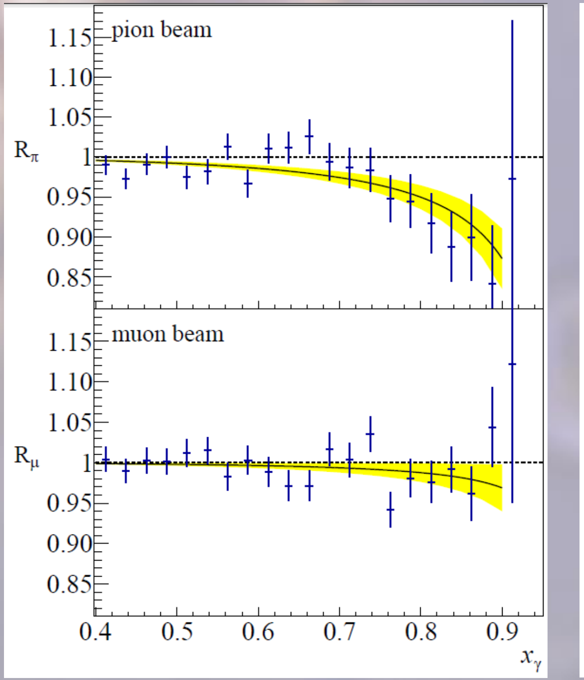
Pion polarisability - result

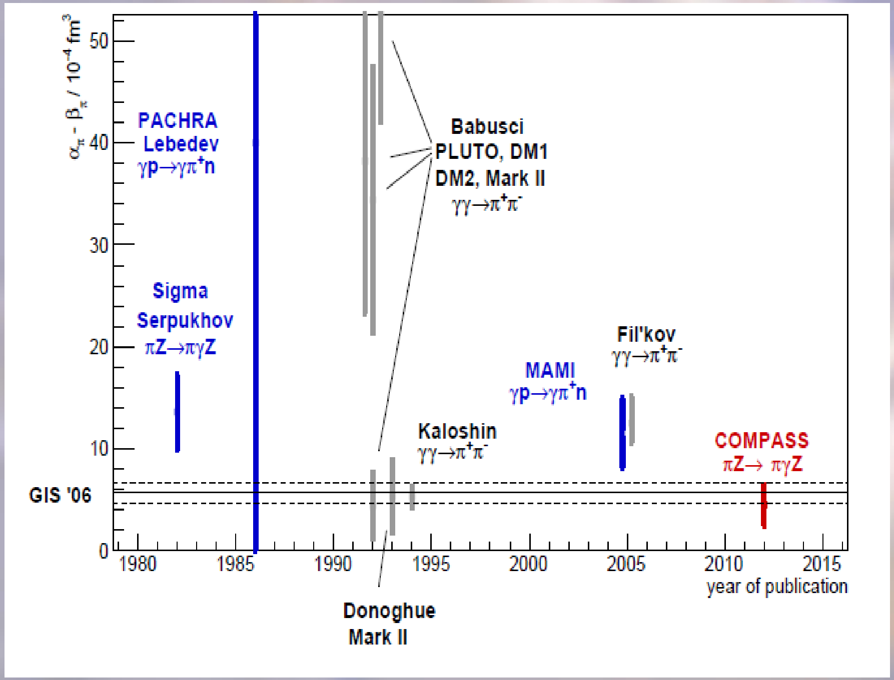
2009 data $\pi^- Ni \rightarrow \pi^- Ni\ \gamma$ exclusive reaction

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

$\alpha_\pi - \beta_\pi$ extracted from comparison of data to MC(pointlike)

Ratio:
data/MC
(pointlike)





α_π $= (2.0 \pm 0.6_{stat} \pm 0.7_{sys}) \times 10^{-4}\ \mathrm{fm}^3$ (assuming $\alpha_\pi + \beta_\pi = 0$)

FUTURE

Near COMPASS future is defined:

- 2014-2015: Transversely polarized DY to check pseudo-universality $([f_{1T}^{\perp}(x,Q^2)]_{DY} \approx -[f_{1T}^{\perp}(x,Q^2)]_{SIDIS})$
- 2016-2017: Unpolarised DVCS/HVMP

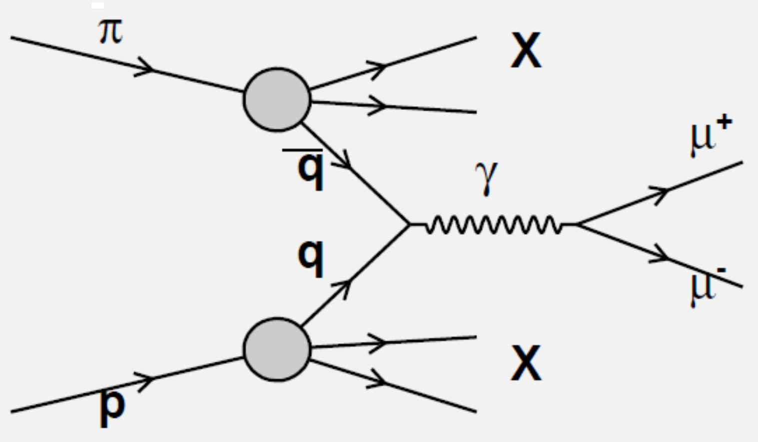
  (B slope and GPD H)

  and unpolarised SIDIS on LH_2

  $dn^h/(dN^\mu dz\, dp_T^2)$ i.e. p_T dependent multiplicities, and $h_{1T}^{\perp}$ Boer-Mulders TMD PDF
- 2018 to be discussed having in hand the performances in the previous years

After SIDIS, polarized Drell-Yan to study TMDs

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



Cross sections:

In SIDIS: convolution of a TMD with a fragmentation function

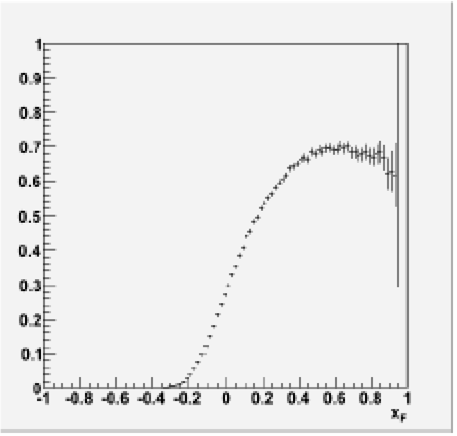
In DY: convolution of 2 TMDs $\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f_{u|p}$

→ complementary information and universality test

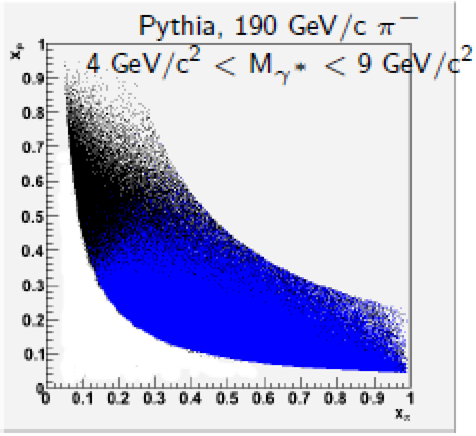
Why DY $\pi p^{\uparrow}$ is very favourable at COMPASS?

σ^{DY} dominated by the annihilation of a valence anti-quark from the pion and a valence quark from the polarised proton

$$\boxed{\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f_{u|p}}$$



x_F acceptance plot



x_p vs x_π scatter plot: in black all generated events, in blue events in acceptance

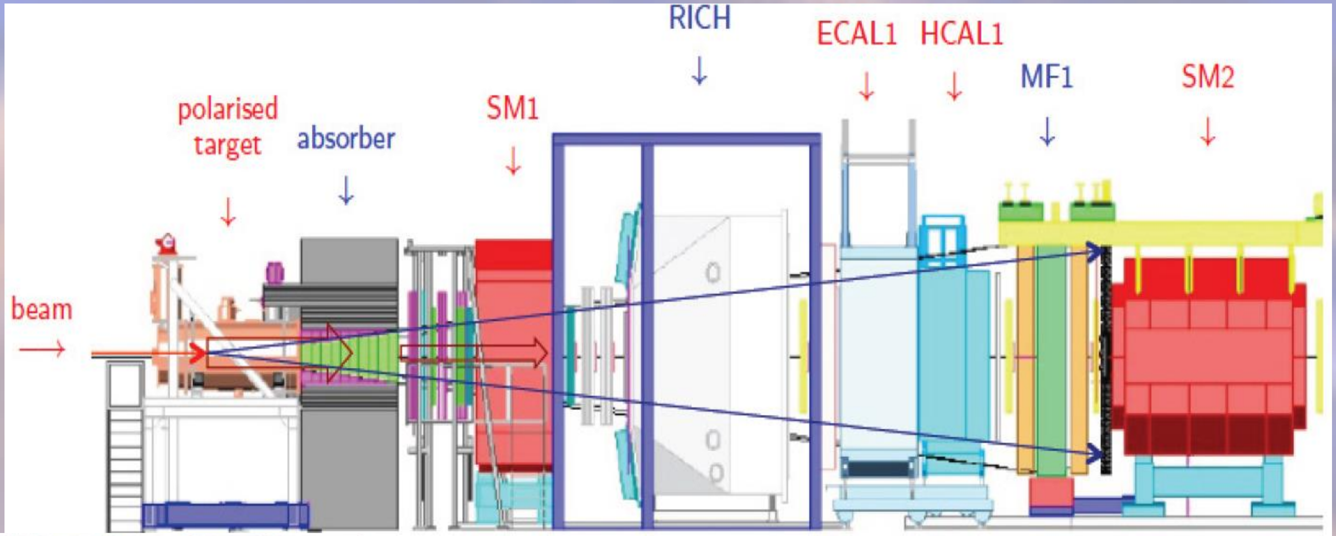
Competitive experiments at

RHIC (STAR, PHENIX) collider	$p^{\Uparrow} p$
Fermilab fixed target	$p^{\Uparrow\Rightarrow} H,\ pH^{\Uparrow\Rightarrow}$
J-PARC fixed target	$pp^{\Uparrow},\ \pi p^{\Uparrow}$
FAIR (PAX) collider	$\bar{p}^{\Uparrow} p^{\Uparrow}$
NICA collider	$p^{\Uparrow} p^{\Uparrow},\ d^{\Uparrow} d^{\Uparrow}$

large acceptance of COMPASS
in the valence quark region for p and π
where SSA are expected to be larger

COMPASS has the chance to be the first experiment to collect single polarized DY

Drell-Yan setup



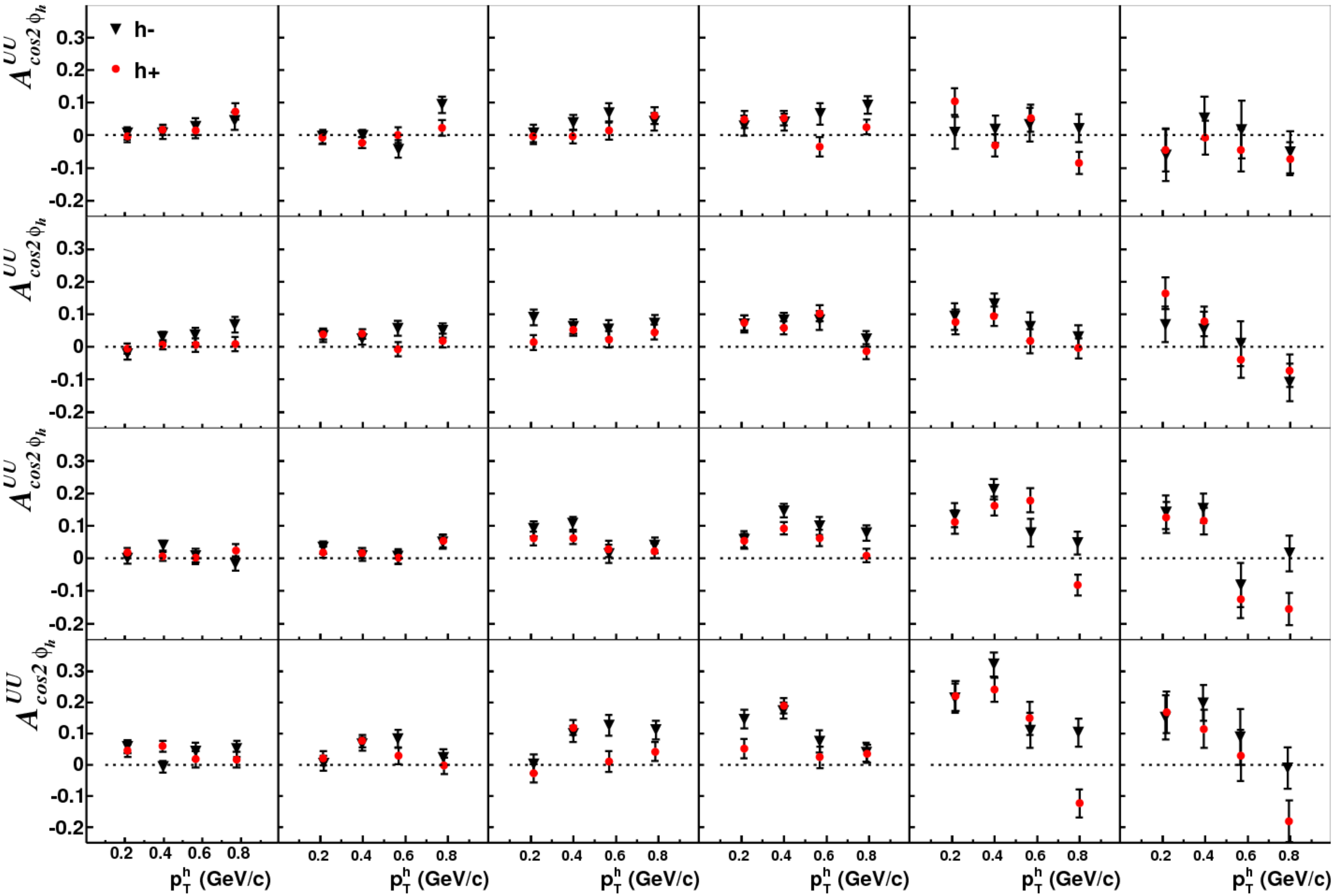
Importance of unpolarized SIDIS For TMDs

- The cross-section dependence from p_T^h results from:
  - intrinsic k_T of the quarks
  - $p_\perp$ generated in the quark fragmentation
- The azimuthal modulations in the unpolarized cross-sections comes from:
  - Intrinsic k_T of the quarks
  - The Boer-Mulders PDF

These are difficult measurements requiring to take into account apparatus acceptance

- COMPASS has
  - results on ^6LiD $(\sim d)$ from 2004/6 data
  - No measurements on p since on NH_3 $(\sim p)$ nuclear effects may be important
- ⇒COMPASS-II, measurements on LH_2 in parallel with DVCS

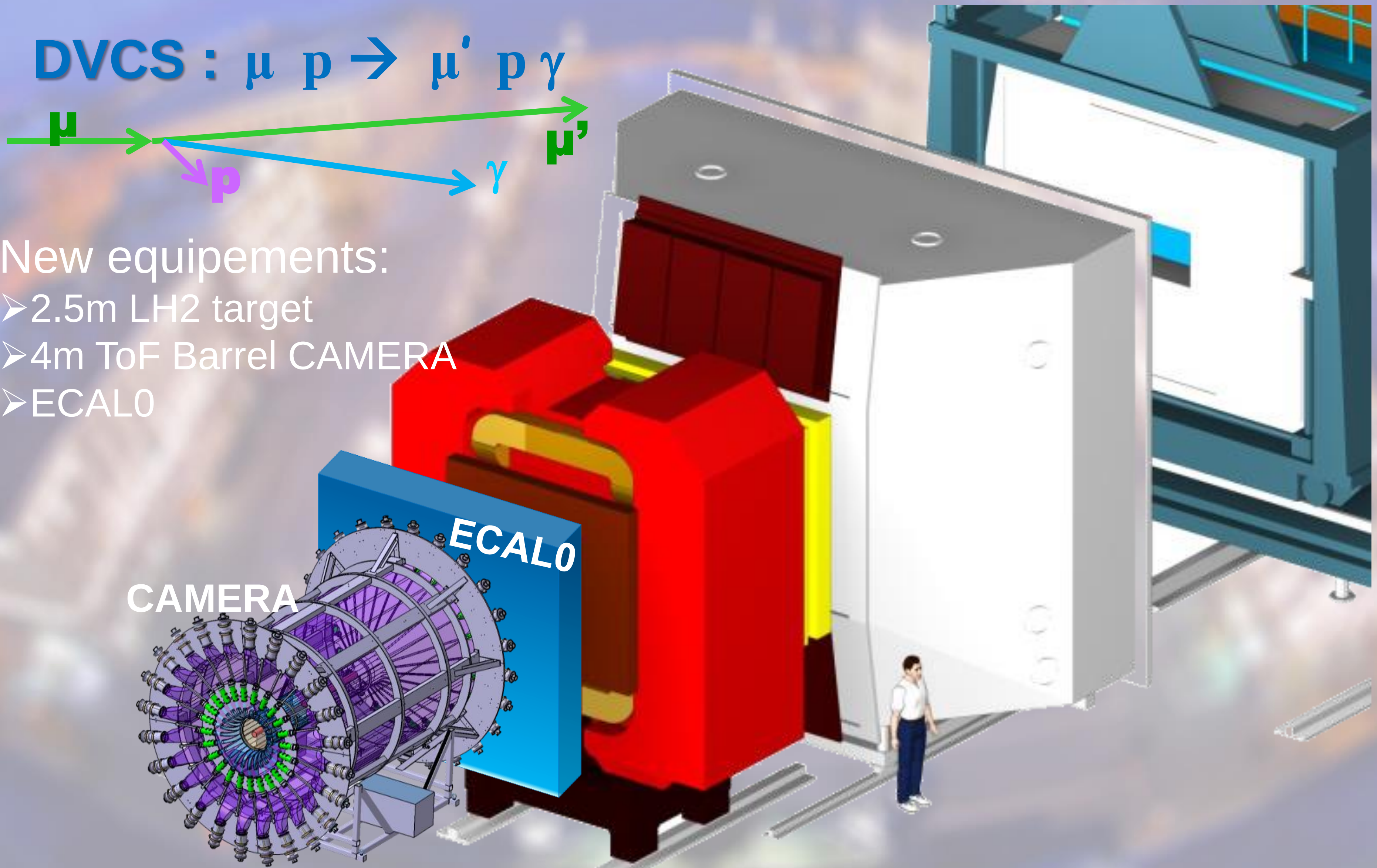
COMPASS ^{6}LiD (25% of 2004 data) preliminary



→many data collected and still to be collected in SIDIS with GPD program

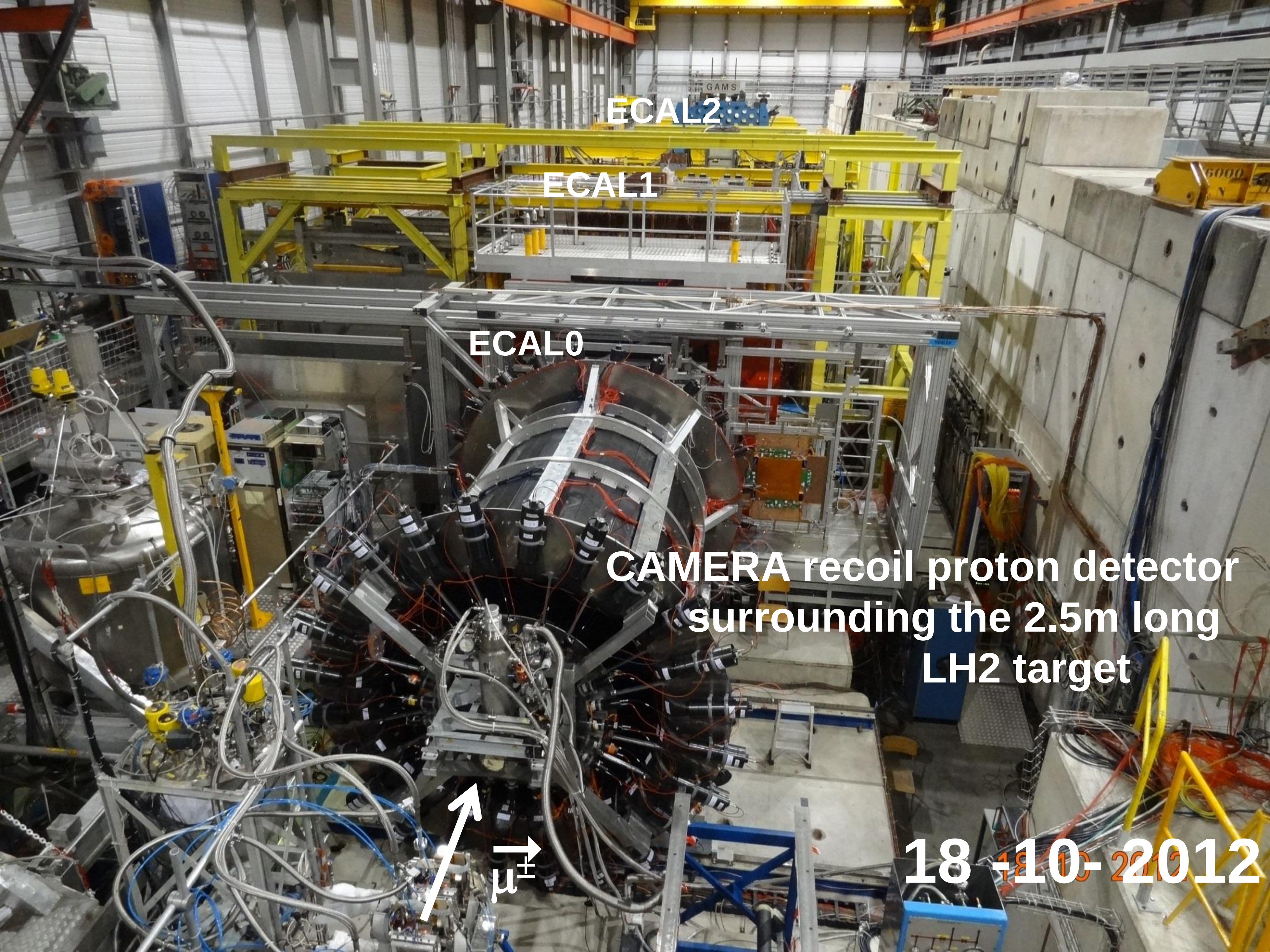
Upgrades of the COMPASS spectrometer

DVCS : μ p → μ' p γ



New equipements:

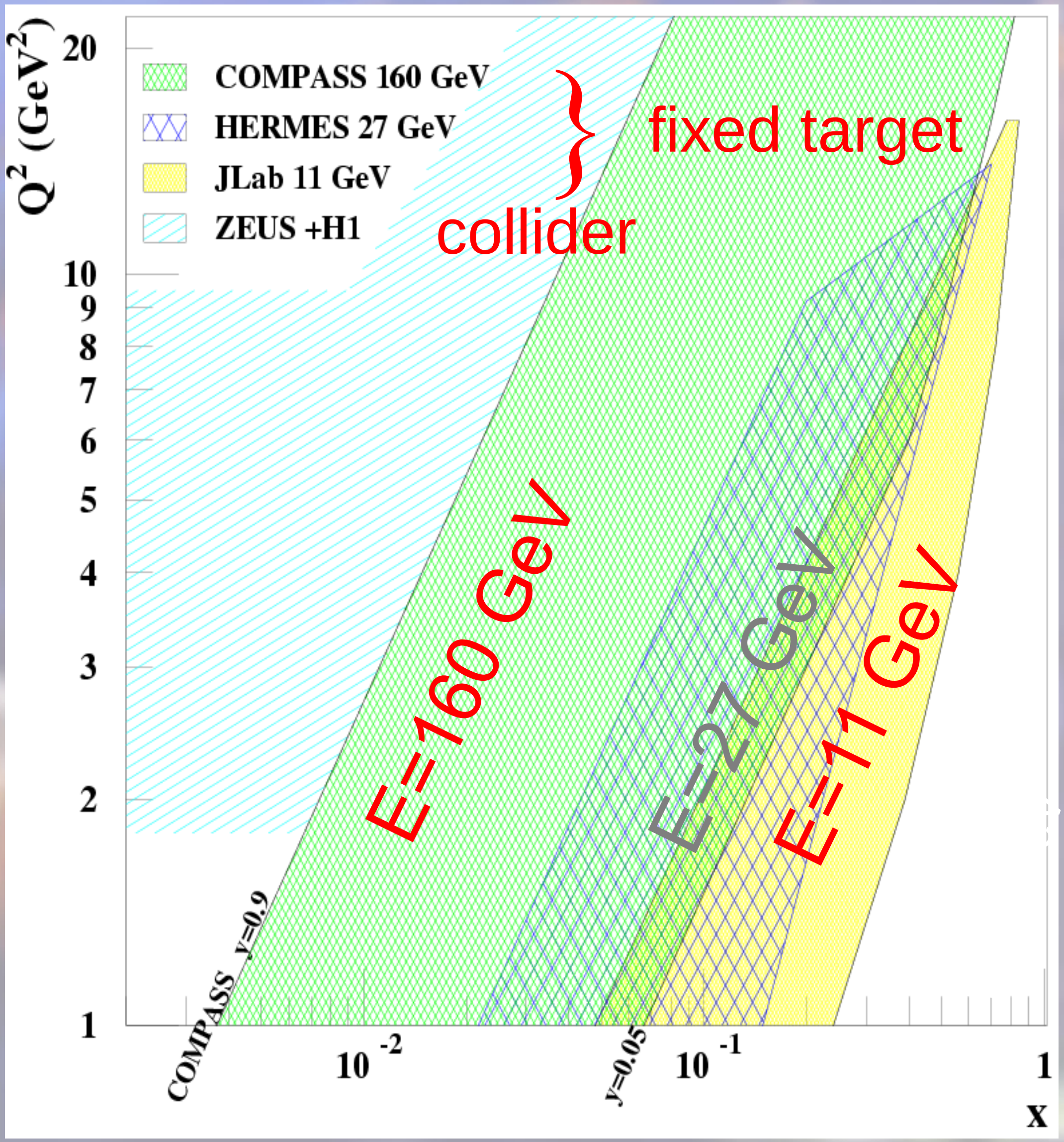
- 2.5m LH2 target
- 4m ToF Barrel CAMERA
- ECAL0



CAMERA recoil proton detector surrounding the 2.5m long LH2 target

18 -10- 2012

Kinematic domain (Q^2, x_B) for GPDs



COMPASS unique for GPDs

CERN High energy muon beam

- ✓ **100 - 190 GeV**
- ✓ **$\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ available**
- ✓ **80% Polarisation with opposite polarization**

✓ **4.6 10^8 μ^+**

➔ **Lumi= 10^{32} cm^{-2} s^{-1} with 2.5m LH2 target**

- ➢ Explore the intermediate x_{Bj} region
- ➢ Uncovered region between ZEUS+H1 & HERMES **+ Jlab** before new colliders may be available

It's time to show the impact of COMPASS
=> goal of the 2012 DVCS pilot run

Deeply Virtual Compton Scattering

$$d\sigma_{(\mu p\rightarrow\mu p\gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \cancel{P_\mu\, d\sigma^{DVCS}}_{pol}$$

$$+ \cancel{e_\mu}\, a^{BH}\, \mathcal{Re}\, A^{DVCS} + e_\mu\, P_\mu\, a^{BH}\, \mathcal{Im}\, A^{DVCS}$$

Phase 1: the transverse imaging

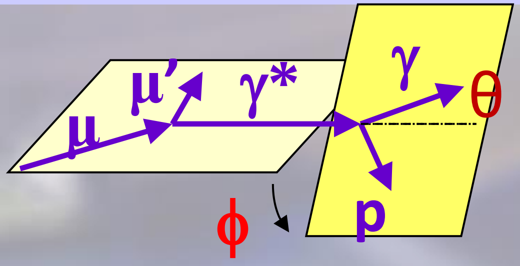
with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam + unpolarized 2.5m long LH2 (proton) target

$$S_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + K \cdot s_1^{Int} \sin\varphi$$

$$\downarrow$$

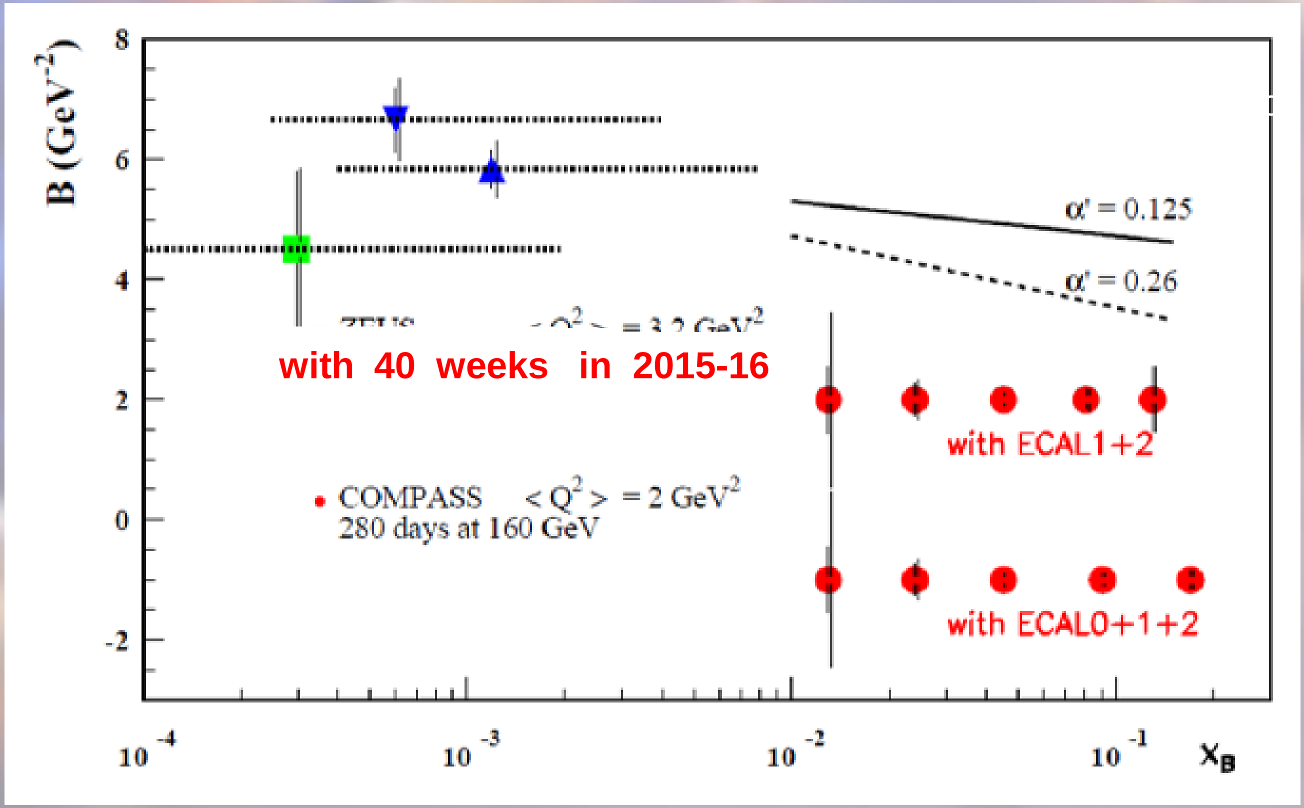
Using $S_{CS,U}$ and BH subtraction
and integration over ϕ

$$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$$



Transverse imaging

$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$



2 years of data
160 GeV muon beam
2.5m LH_2 target
$\varepsilon_{global} = 10\%$

ansatz at small x_B
inspired by
Regge Phenomenology:

$B(x_B) = b_0 + 2\,\alpha' \ln(x_0/x_B)$

α' slope of Regge traject

Deeply Virtual Compton Scattering

$$d\sigma_{(\mu p\to\mu p\gamma)} = \cancel{d\sigma^{BH}} + \cancel{d\sigma^{DVCS}}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol}$$

$$+\, e_\mu\, a^{BH}\, \mathcal{R}e\, A^{DVCS} \qquad + e_\mu\, \cancel{P_\mu\, a^{BH}}\, \mathcal{I}m$$

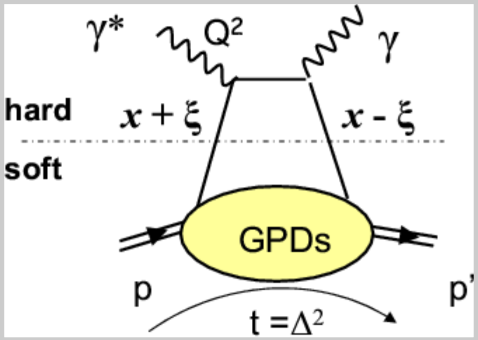
Phase 1: DVCS experiment to constrain GPD H

with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam + unpolarized 2.5m long LH2 (proton) target

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto \boxed{c_0^{Int} + c_1^{Int}\cos\phi} \text{ and } c_{0,1}^{Int} \sim \mathcal{R}e(F_1\mathcal{H})$$

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto \boxed{d\sigma^{BH} + c_0^{DVCS} + K\cdot s_1^{Int}\sin\varphi} \text{ and } s_1^{Int} \sim \mathcal{I}m(F_1\mathcal{H})$$

Note: dominance of **H** at COMPASS kinematics



$\xi \sim x_B / (2-x_B)$

$$\mathcal{I}m\,\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$$

$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, \frac{H(x,\xi,t)}{x-\xi} = \mathcal{P}\int dx\, \frac{H(x,x,t)}{x-\xi} + D(t)$$

Re part of the *Compton Form Factors* linked to the *D term*

Summary for GPD @ COMPASS

GPDs investigated with Hard Exclusive Photon and Meson Production

COMPASS-II 2016-17: **with LH_2 target + RPD (phase 1)** $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ **160 GeV**

✓ the t-slope of the DVCS and HEMP cross section
→ transverse distribution of partons

✓ the Beam Charge and Spin Sum and Difference
→ $\mathcal{R}e\,T^{DVCS}$ and $\mathcal{I}m\,T^{DVCS}$ for the GPD H determination

✓ Vector Meson $\rho^0, \rho^+, \omega, \Phi$

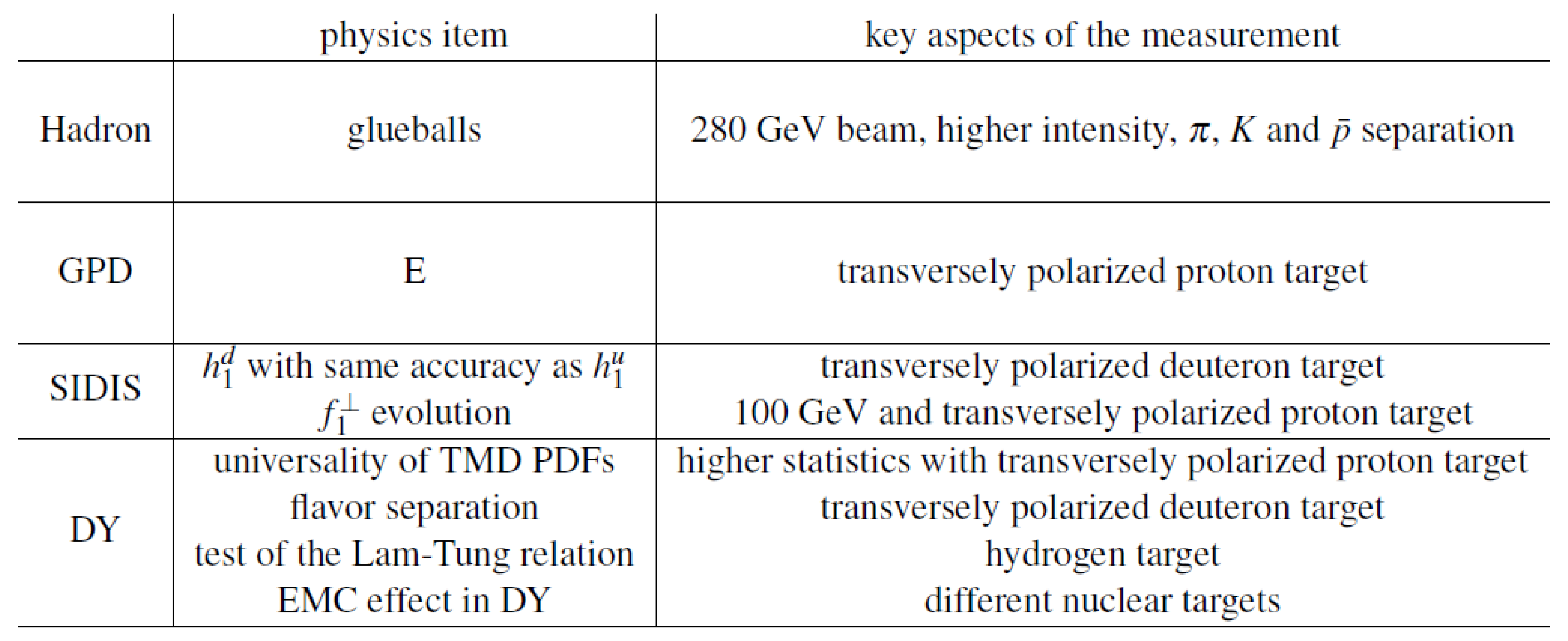
✓ Pseudo-saclar π^0

Using the 2007-10 data: **transv. polarized NH_3 target without RPD**

In a future addendum > 2017: **transv. polarised NH_3 target with RPD (phase 2)**

✓ the Transverse Target Spin Asymm
→ GPD E and chiral-odd (transverse) GPDs

More in the FUTURE:



	physics item	key aspects of the measurement
Hadron	glueballs	280 GeV beam, higher intensity, π, K and $\bar{p}$ separation
GPD	E	transversely polarized proton target
SIDIS	h_1^d with same accuracy as h_1^u $f_{1T}^{\perp}$ evolution	transversely polarized deuteron target 100 GeV and transversely polarized proton target
DY	universality of TMD PDFs flavor separation test of the Lam-Tung relation EMC effect in DY	higher statistics with transversely polarized proton target transversely polarized deuteron target hydrogen target different nuclear targets

For the next 10 years

- before any collider is available,
- and complementary to Jlab 12 GeV

COMPASS@CERN can be a major player in QCD physics using its unique high energy both:

- hadron beam and
- positive and negative muon beams

Looking even further…a polarized lepton-nucleon collider well be a mandatory tool

Thank You

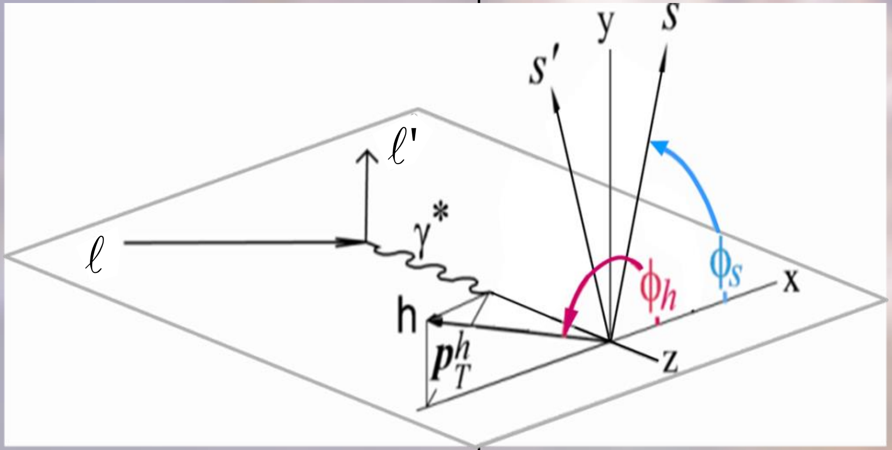
SIDIS x-Section

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

$$\varepsilon = \frac{1 - y - \frac{1}{4}y^2\gamma^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}y^2\gamma^2}, \quad \gamma = \frac{2xM}{Q}$$

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

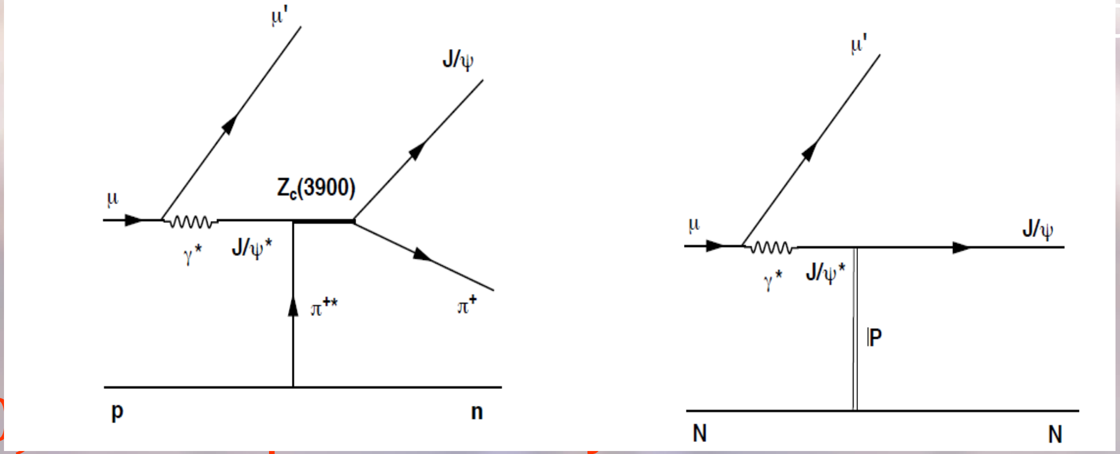
$$\left\{\begin{array}{l}
1 + \cos\varphi_h \times \sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h} + \cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)} + \lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h} + \\
S_L\left[\sin\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\varphi_h}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



The search for $Z_C(3900)$

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

CE

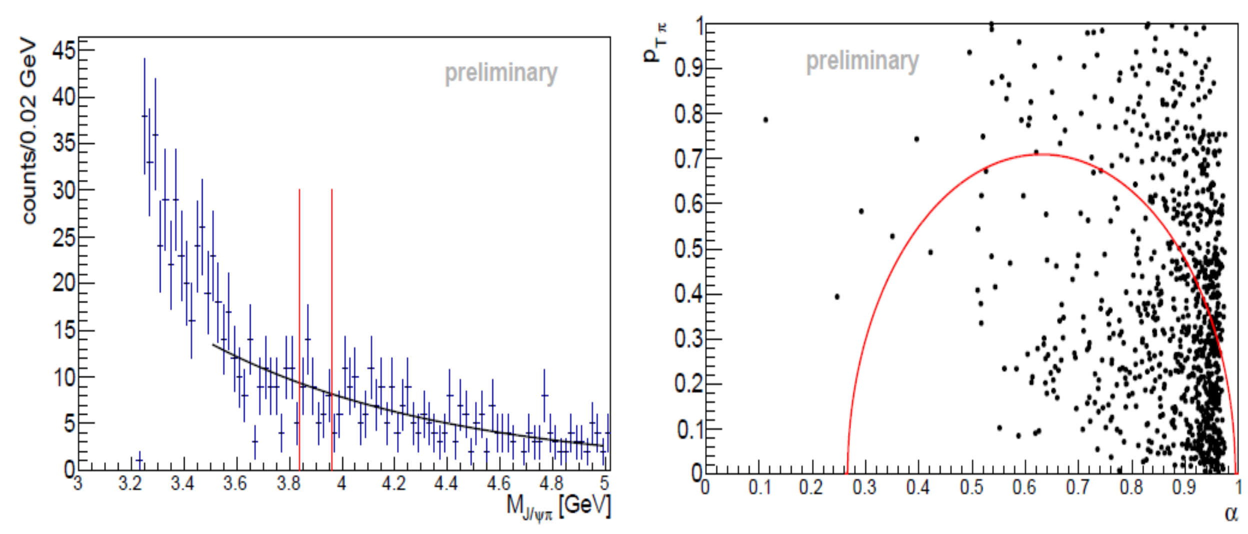


- $Z_C(3900$ an incoming photon with a virtual charged pion provided by the target nucleon (expected $\sigma \sim 50 \div 100$ nb in kinematic region close to COMPASS)

Limits on $Z_C(3900)$ in COMPASS

- Expected mass resolution $\sim 15\ \mathrm{MeV}/c^2$ (as for $\psi(2S)$ in the spectra of $\mathrm{J}/\psi\pi^+\pi^-$)
- Upper limit for $N^{UL}_{Z_C} = 13$, while for the reference process we counted $N_{J/\psi} = 11.6 \times 10^3$

$$\frac{\sigma_{\gamma N \to Z_C^{\pm}(3900)N} \times BR(J/\psi\pi)}{\sigma_{\gamma N \to J/\psi N}} = \frac{1}{0.5} \cdot \frac{N^{UL}_{Z_C}}{N_{\frac{J/\psi}{\psi}}} < 2.2 \times 10^{-3} \quad \text{or} \quad \sigma_{\gamma N \to Z_C^{\pm}(3900)N} \times BR(J/\psi\pi) < 31\ \mathrm{pb}$$

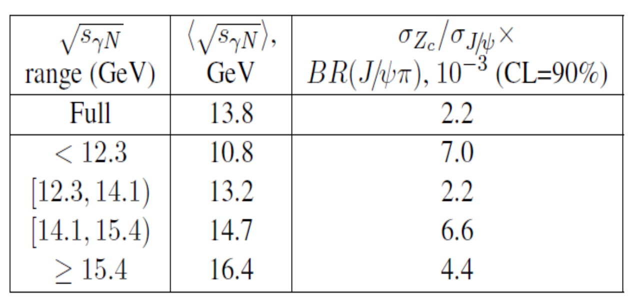


$\Gamma_{J/\psi\pi} < 1.8\ \mathrm{MeV}/c^2$

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

LO content

SIDIS

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

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \frac{1}{Q}\left(f_1^q \otimes D_{1q}^h + \cdots \right)$$

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

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

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

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

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

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

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

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

DY

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

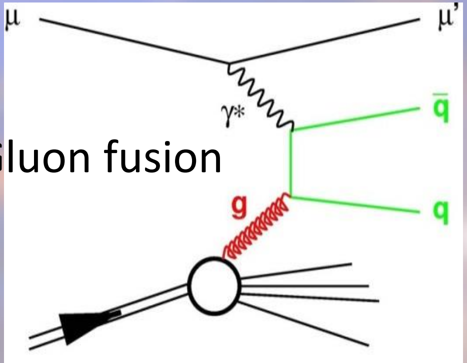
$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_1^q$$

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

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

Gluon polarization via PGF: open charm

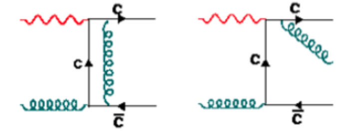
Photon-Gluon fusion

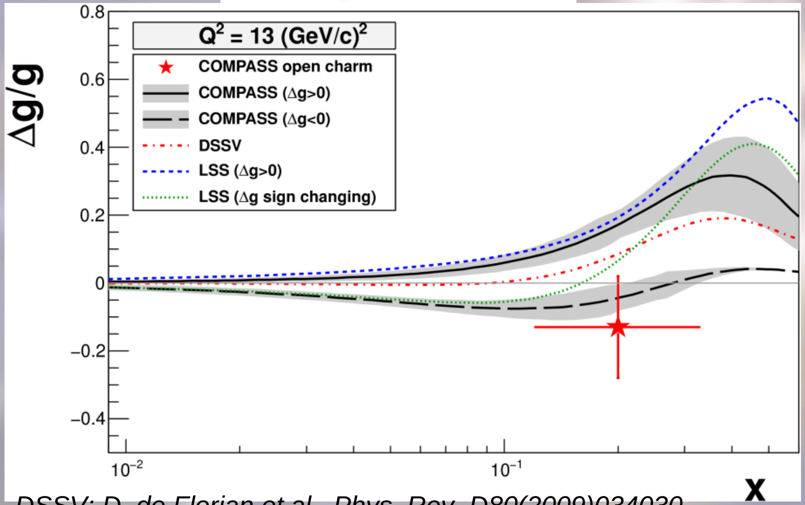


$$A_{LL}^{\mu N(LO)} = R^{PGF} a_{LL}^{PGF} \frac{\Delta g}{g}(x)$$

- **Open Charm production**
  - $\gamma^* g \rightarrow c\bar{c}$ ⇒ reconstruct D^0 mesons
  - Hard scale: M_c^2
  - No intrinsic charm in COMPASS kinematics
  - No physical background
  - Weakly Monte Carlo dependent
  - Low statistics

NLO





DSSV: D. de Florian et al., Phys. Rev. D80(2009)034030
LSS: E. Leader, A.V. Sidorov, D.B. Stamenov, arXiv 1010.5742(2010)

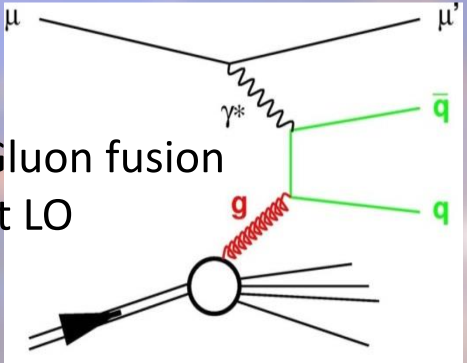
- First extraction of **ΔG at NLO**
- **Constrains ΔG at larger x**
- **Charm result can be included in global NLO fits:** model independent asymmetries $A_{LL}(p_T, E_D)$ available

PRD 87 (2013) 052018 New

ΔG/G(x=0.2) = -0.13 ± 0.15 ± 0.15

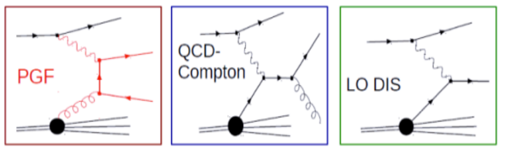
Gluon polarization via PGF: high p_T

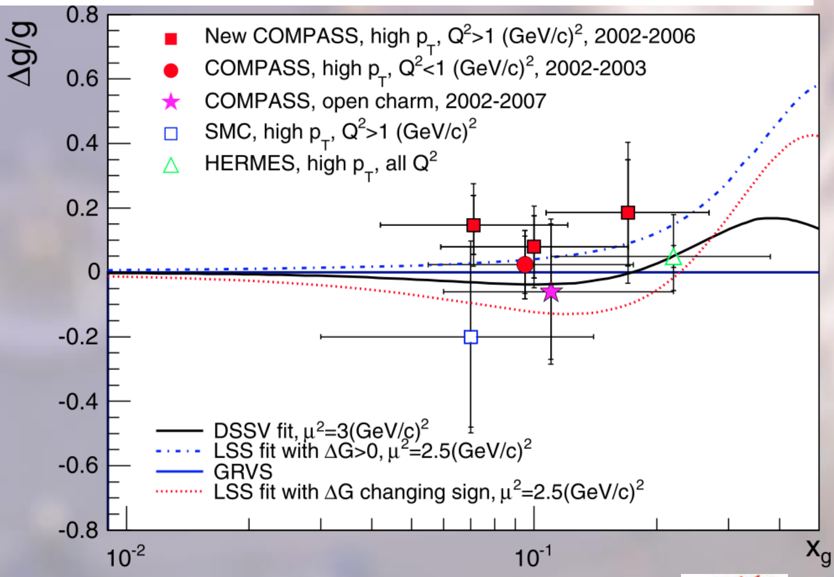
Photon-Gluon fusion
at LO



$$A_{LL}^{\mu N(LO)} = R^{PGF} a_{LL}^{PGF} \frac{\Delta g}{g}(x) + ...$$

- **High-p_T hadron pairs**
  - $\gamma^* g \rightarrow q\bar{q}$ ⇒ reconstruct 2 jets or h^+h^-
  - Hard scale: Q^2 or Σp_T^2 $[Q^2 > 1$ or $Q^2 < 1\ (\mathrm{GeV/c})^2]$
  - High statistics
  - Physical background
  - Strongly Monte Carlo dependent





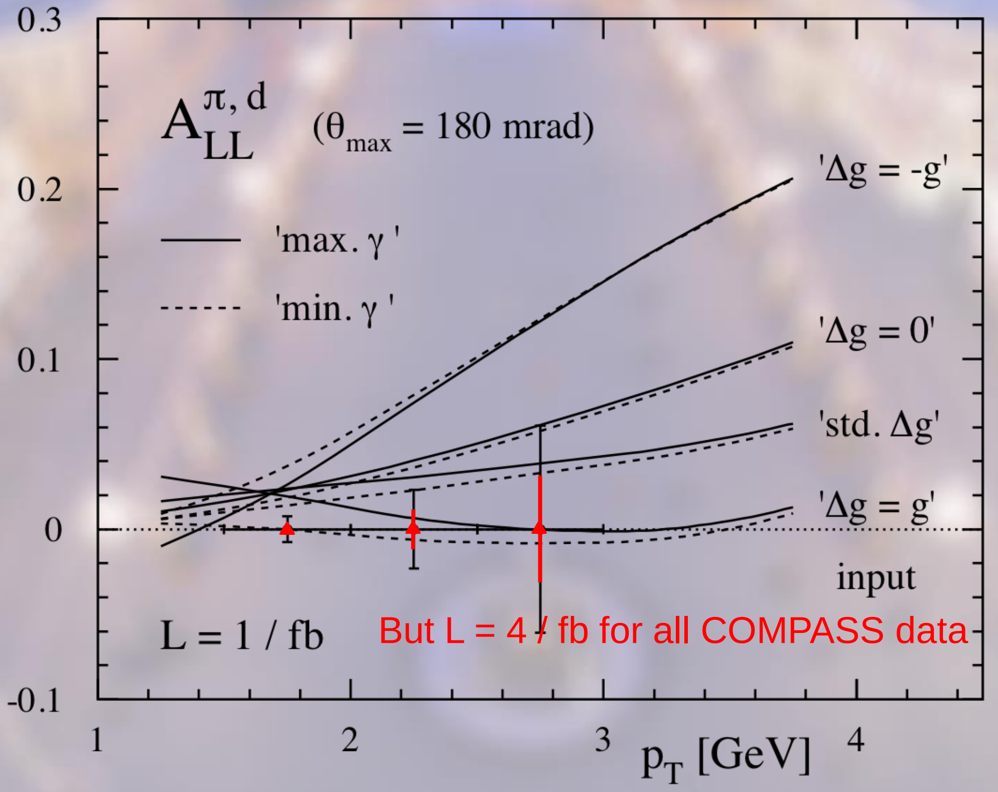
Phys. Lett. B 718 (2013) 922

Caveat:

- LO extractions of $\Delta G/G(x)$
- Can not directly be compared to NLO fits
- Need for reliable NLO for high p_T
  in COMPASS c.m. energy range…
- $A_{LL}^{2h}/D(x,p_T)$ available for $Q^2>1$ data

$A_{LL}^{1h}(p_T)$:polarized hadron γ-production

Projections by Jäger et al. for COMPASS with 1 fb^{-1} (=1/4 COMPASS stat.)



Jäger, Stratmann & Vogelsang: ***EPJ C44 (2005) 533***

So far, only NLO pQCD for polarized case (no resum.)

In perspective: constraining ΔG by $A_{LL}^{1h}(p_T)$ (**working on**)

Collins and Sivers asym.

- T polarized target, SIDIS:
- Measure azimuthal asymmetries:

$\mu\, p^{\uparrow} \rightarrow \mu\, p\, h^{+/-}$

Collins: Outgoing hadron direction & quark transverse spin

Sivers: Nucleon spin & quark transverse momentum k_T

at LO:

Collins

$\Delta_T q$ transverse spin distr.

Collins fragmentation function, depends on spin

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

Sivers

TMD

Quark fragmentation function

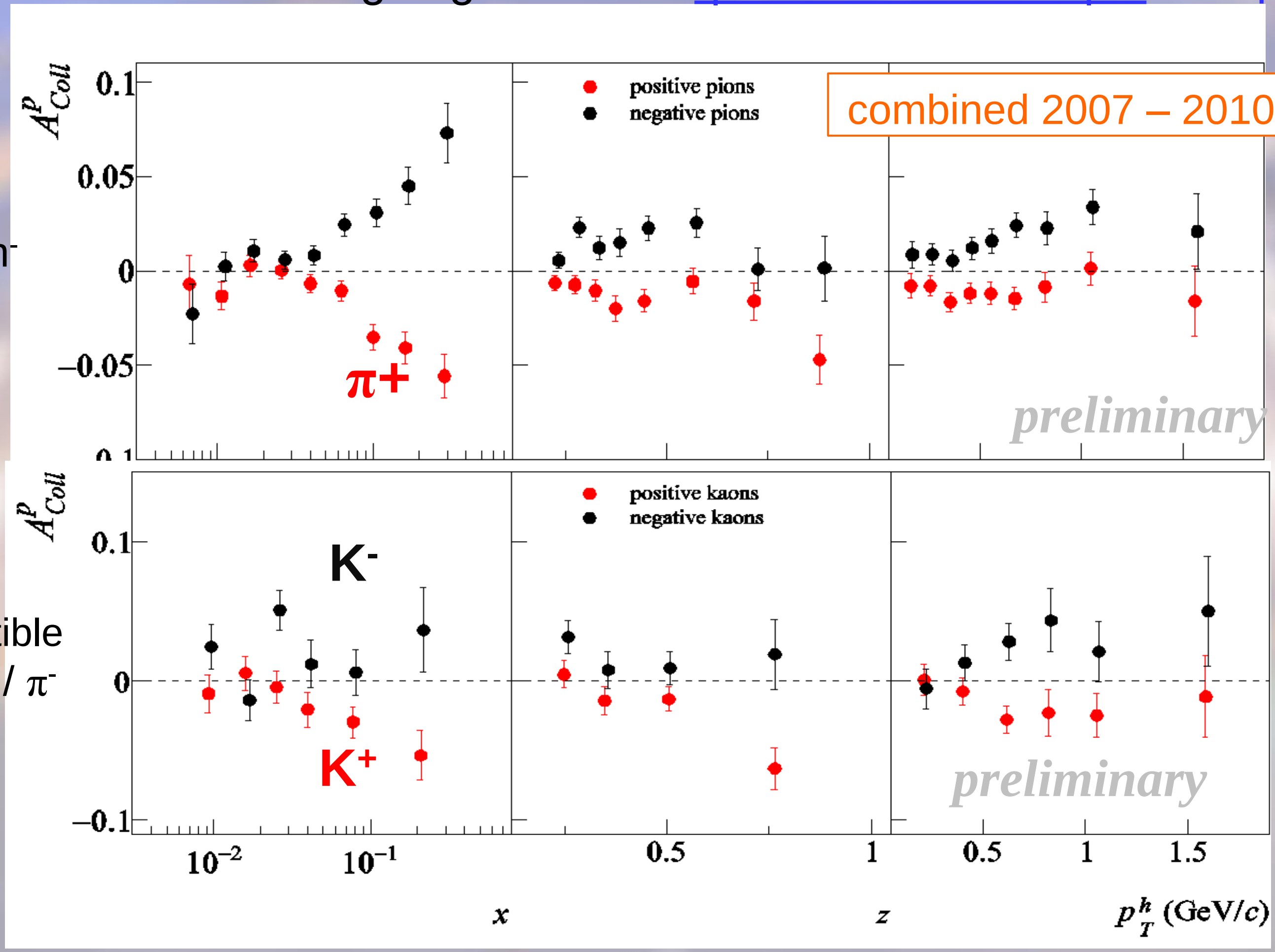
$$A_{Siv} = \frac{\sum_q e_q^2 f_{1Tq}^{\perp} \otimes D_q^h}{\sum_q e_q^2 q \otimes D_q^h}$$

note: $\Delta_T q$ also measured using
''Two hadron'' fragmentation function

Collins Asymmetry on p - π, K id.

Correlation between outgoing hadron & quark transverse spin → $\Delta_T u$ & $\Delta_T d$

combined 2007 – 2010 results



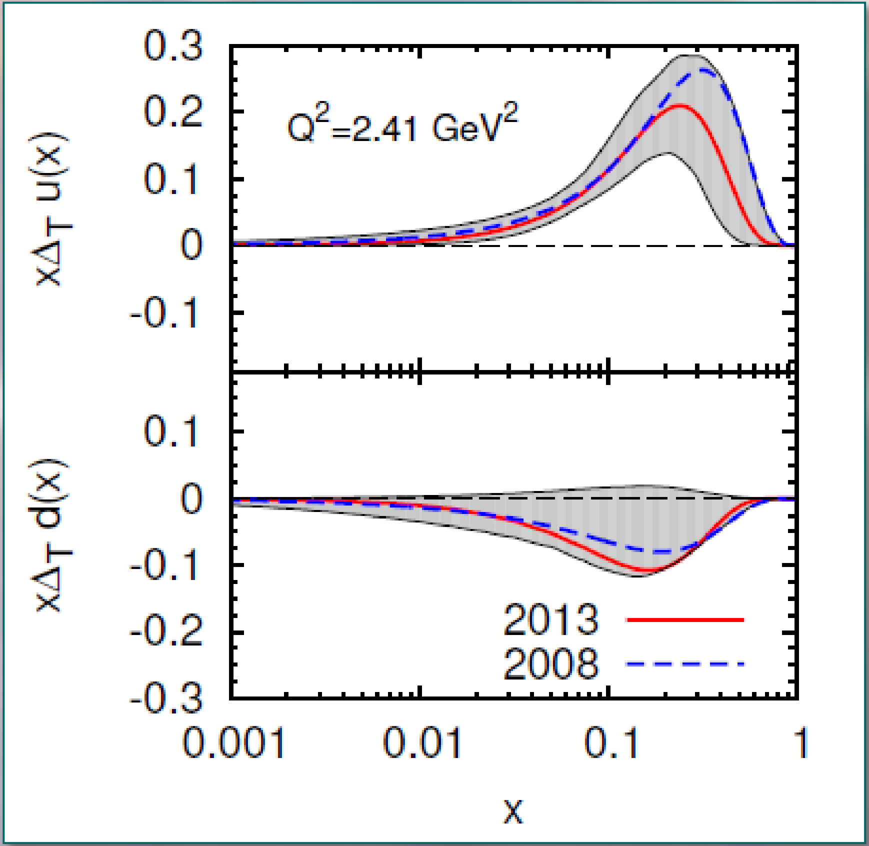
~ h^+ / h^-

compatible with π^+ / π^-

- **Agreement HERMES/COMPASS (not shown)** → **no Q^2 dependence seen** (factor of ~3 inQ^2)
- **Now also produced in bins of z and y**

Transversity from Collins

Combined analyses of **HERMES, COMPASS** and **BELLE fragm.fct.** data



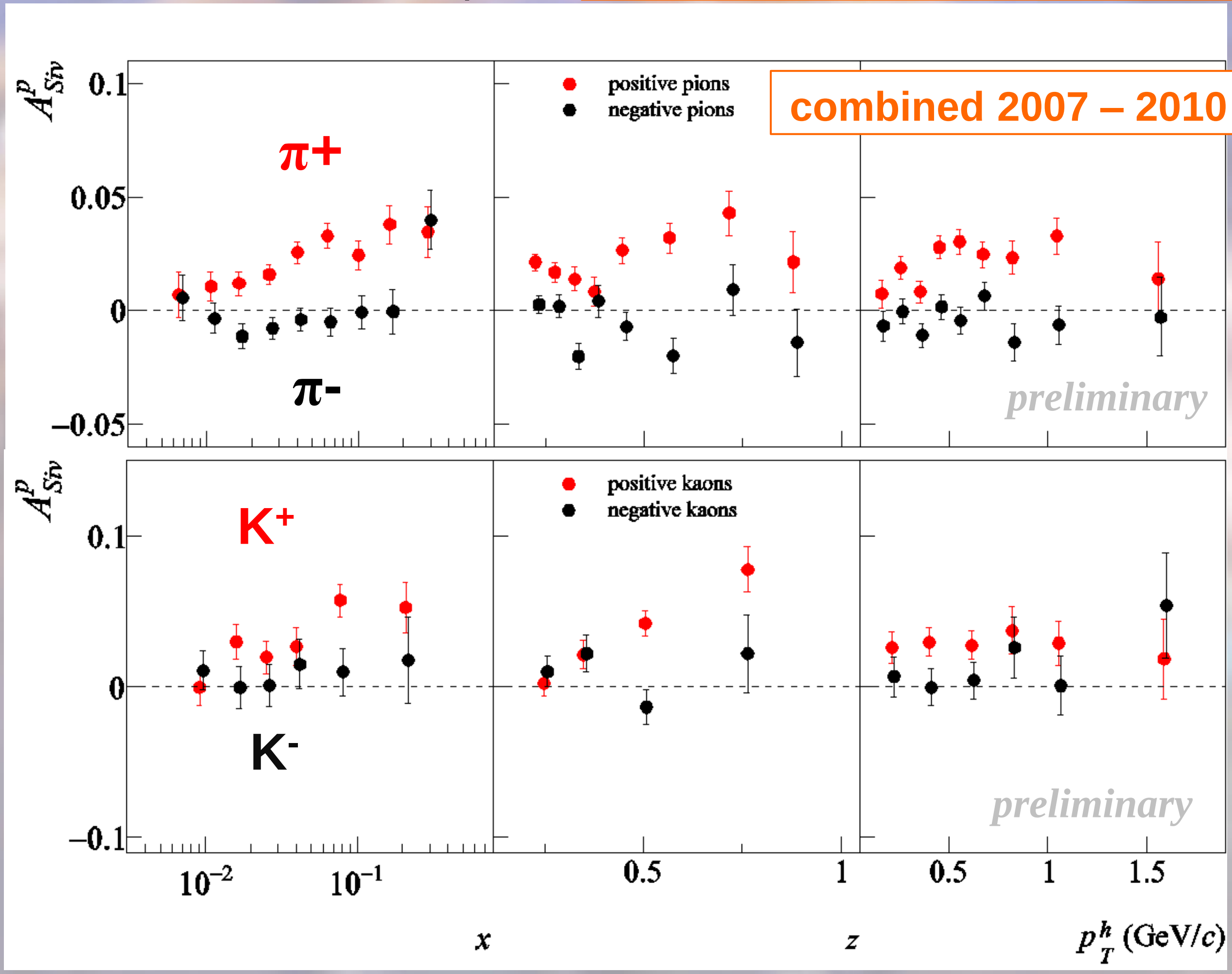
Anselmino et al. arXiv: 1303.3822

Sivers Asymmetry on p - π, K id.

Correlation between nucleon spin & quark transverse momentum k_T

~ h^+ / h^-

larger than for π^+



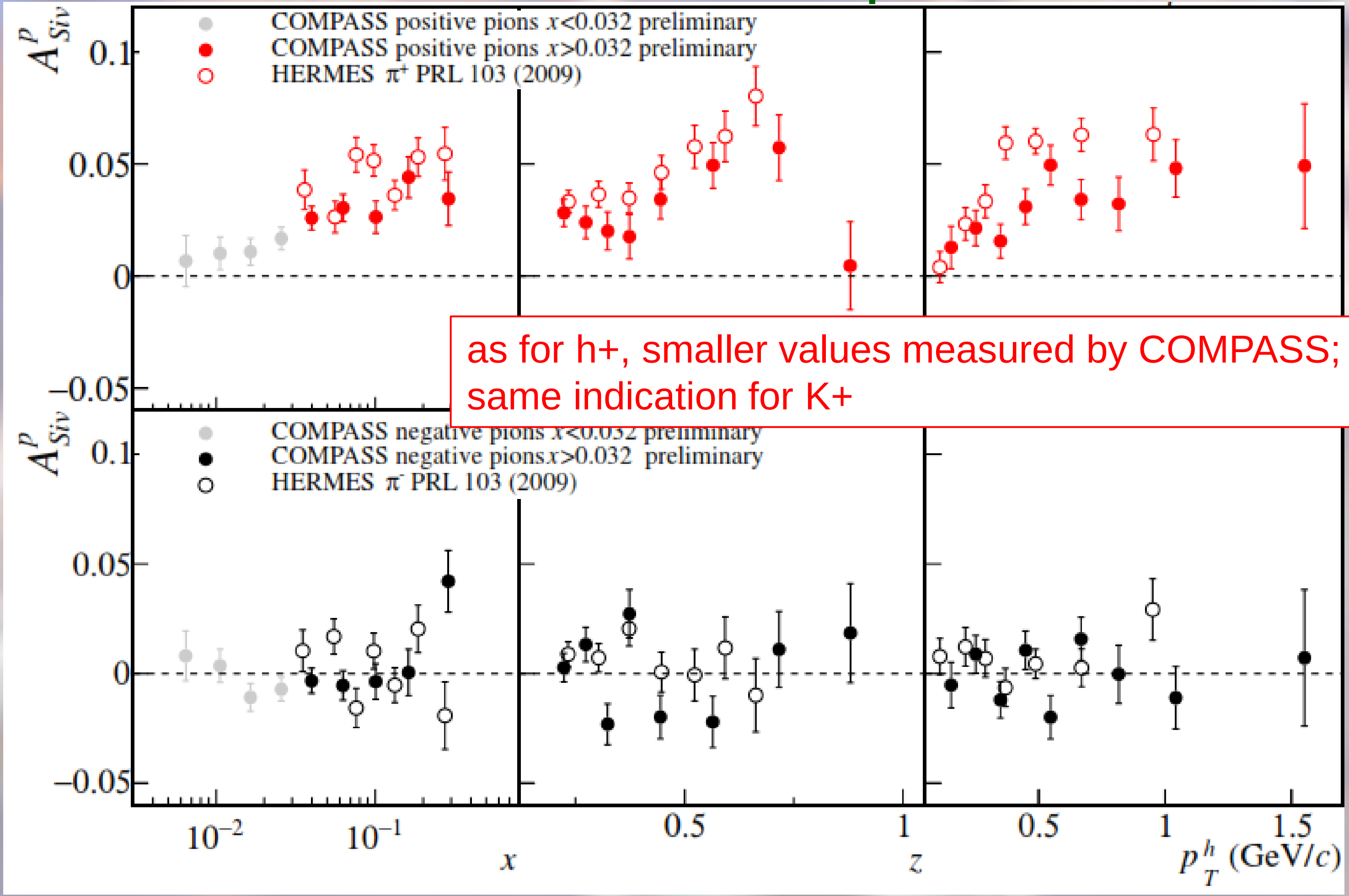
combined 2007 – 2010 results

- **In region of overlap, agreement with HERMES, but smaller strength**
- **Now also produced in separate bins of z and y.**

Sivers asymmetry on p, $x > 0.032$

charged pions (and kaons), 2010 data

comparison with HERMES results



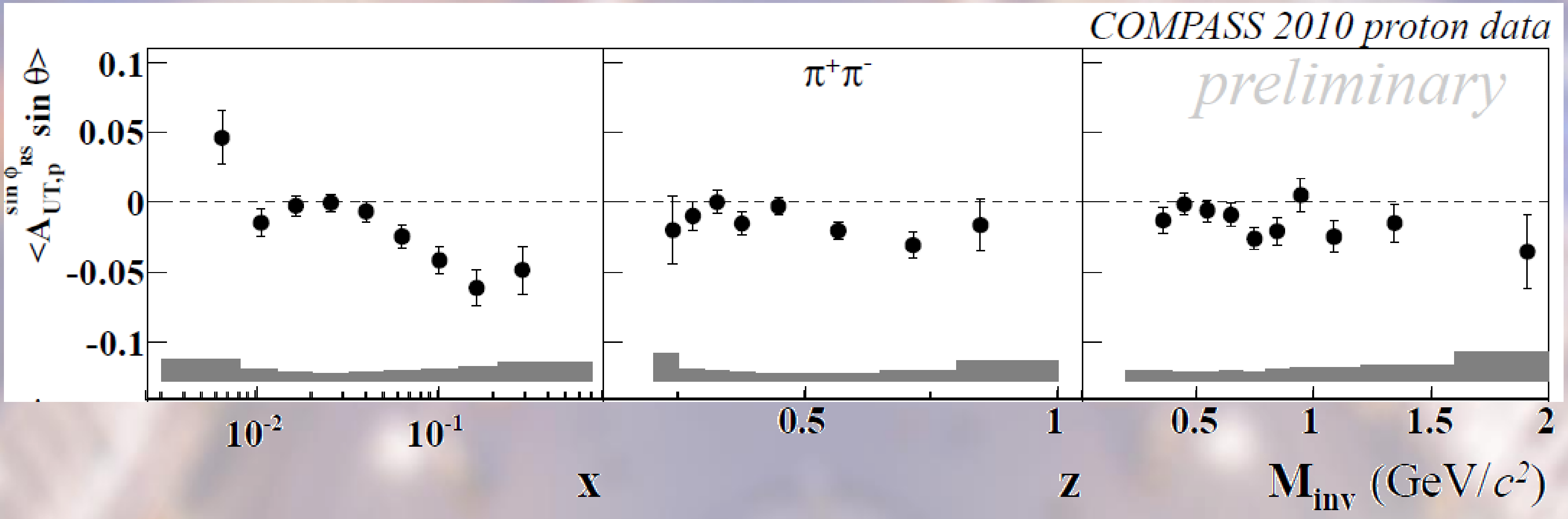
as for h+, smaller values measured by COMPASS; same indication for K+

$\pi+$
● COMPASS
○ hermes

$\pi-$
● COMPASS
○ hermes

2-hadron asymmetries

Another access to transversity h_1



$$A_{RS} = \frac{1}{f \cdot P_T \cdot D} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{\angle}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, M_h^2)}$$

- **h_1^u & h_1^d extraction**
- **Also measured for the first time for K^+K^- , π^+K^- and $K^+\pi^-$ pairs**

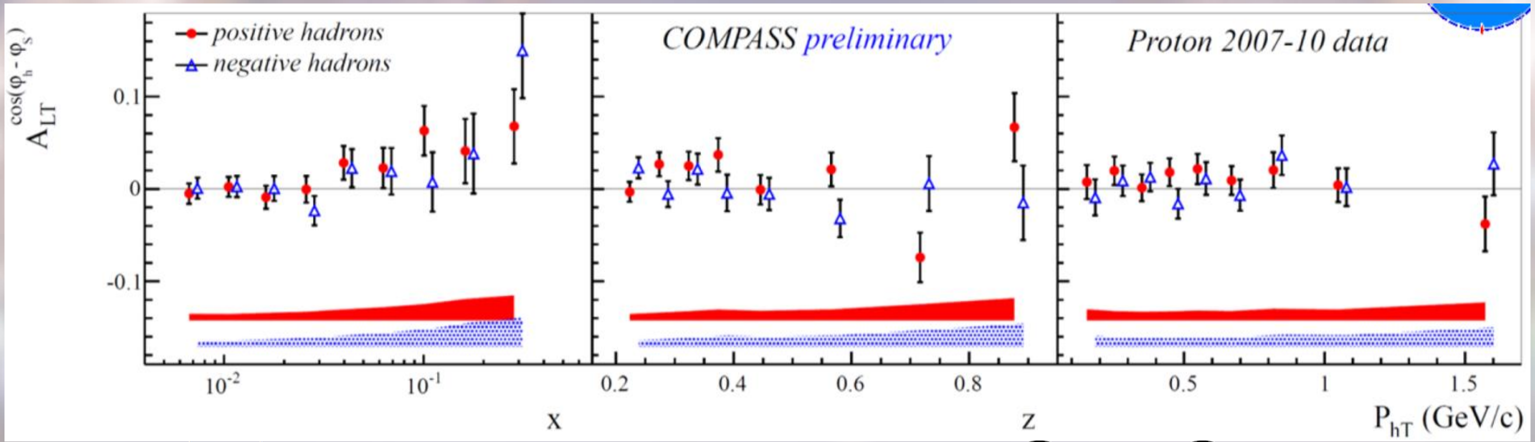
Other Transverse Target spin asymmetries

k_T effects → modulations in SIDIS cross-section

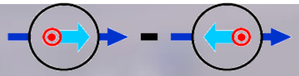
$\mu p^{\uparrow} \rightarrow \mu p h^{+/-}$

- **Major progress in TMD measurement**
- **Powerful tool to understand correlations**

$A_{LT}^{\cos(\varphi_h-\varphi_s)}$ shown as example

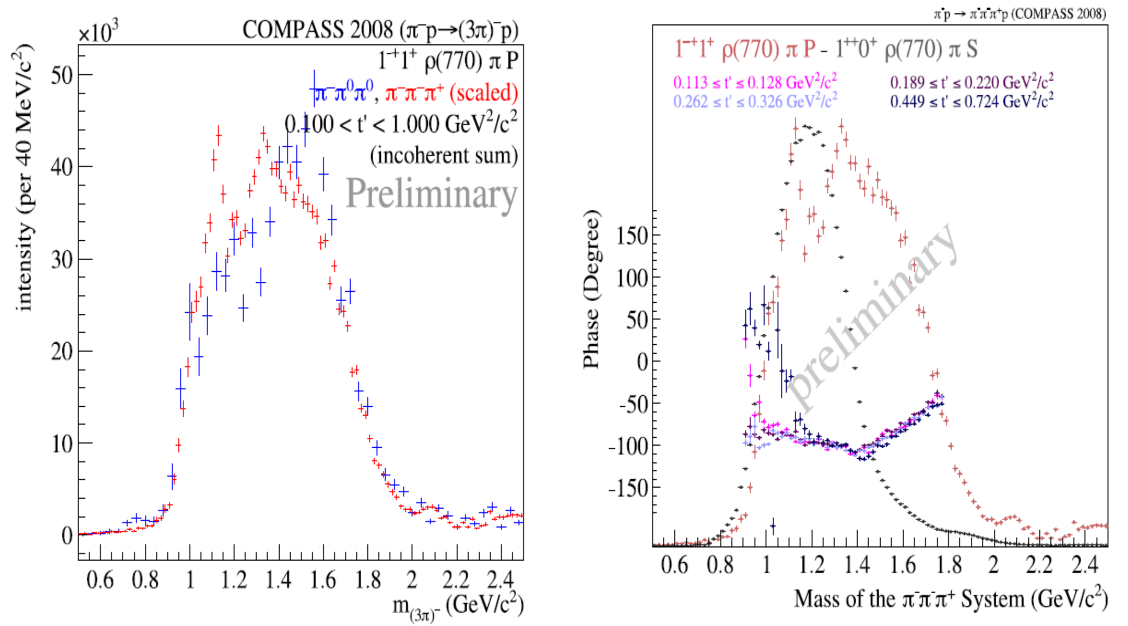


$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$, "Worm Gear" PDF g_{1T}^q :



In agreement with HERMES prelim., and with theoretical predictions

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.

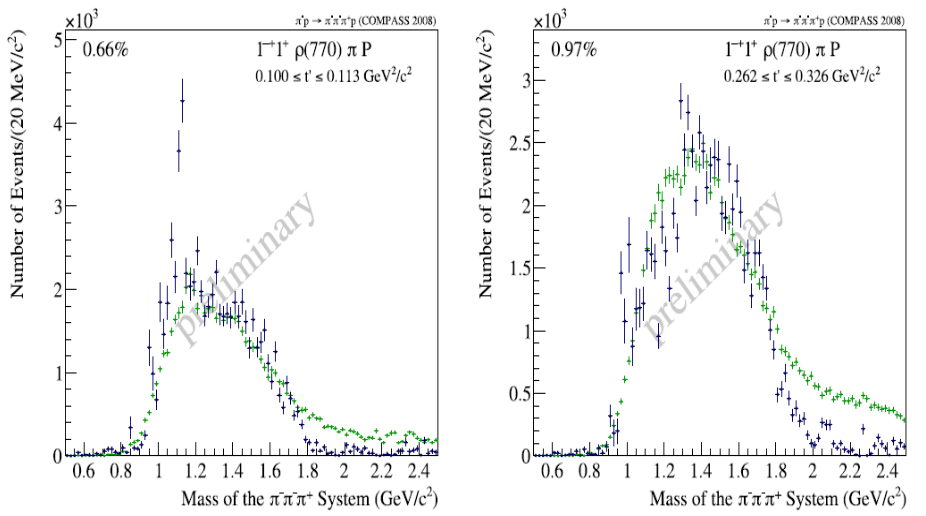
Spin exotics $J^{PC} = 1^{-+}$

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

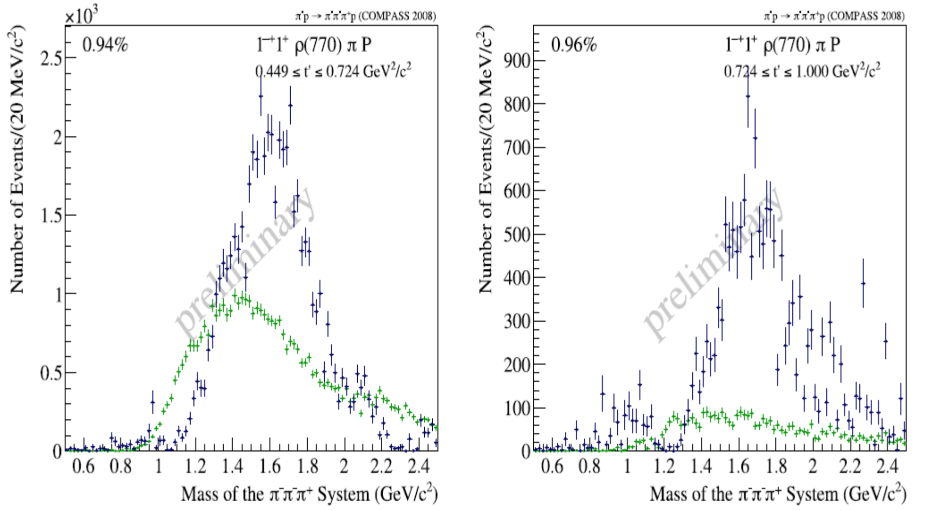
- low t' the wave exhibits a broad intensity distribution
- Increasing t' the intensity shifts towards higher masses leaving a narrower peak at about 1.6 GeV/c^2

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



140 days Drell-Yan at COMPASS