“Spin physics at COMPASS-II and perspectives of the spin physics at JINR”

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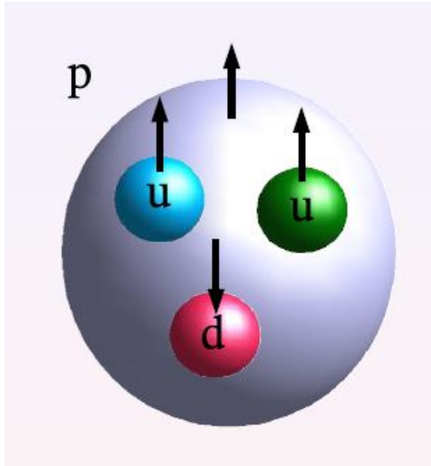
on behalf of the COMPASS collaboration

Plan

- **Introduction**
  - ***nucleon spin***
  - ***status of the problem***
- **Spin physics at COMPASS-II**
  - ***GPD (DVCS)***
  - ***TMD (SIDIS, Drell-Yan)***
- **Spin physics at JINR**
  - ***NICA facility***
  - ***spin physics program at NICA***

Nucleon spin

$$\Delta\Sigma = \Delta u + \Delta d = 1$$

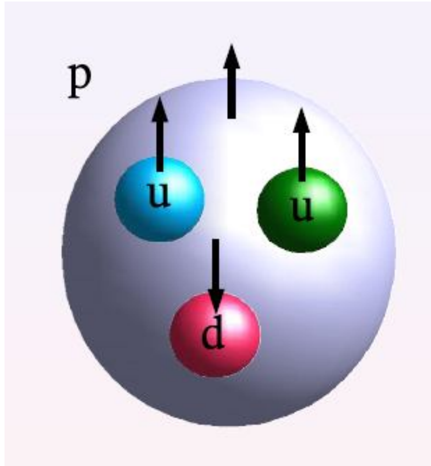


SQM: up and down quarks carry the nucleon spin!

EMC: Quarks spins contribute little (1987/88)

$\Delta\Sigma = 0.12$

Nucleon spin



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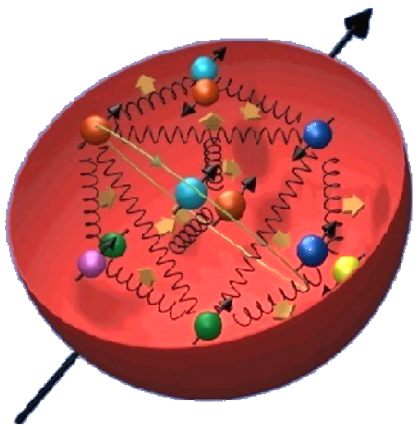
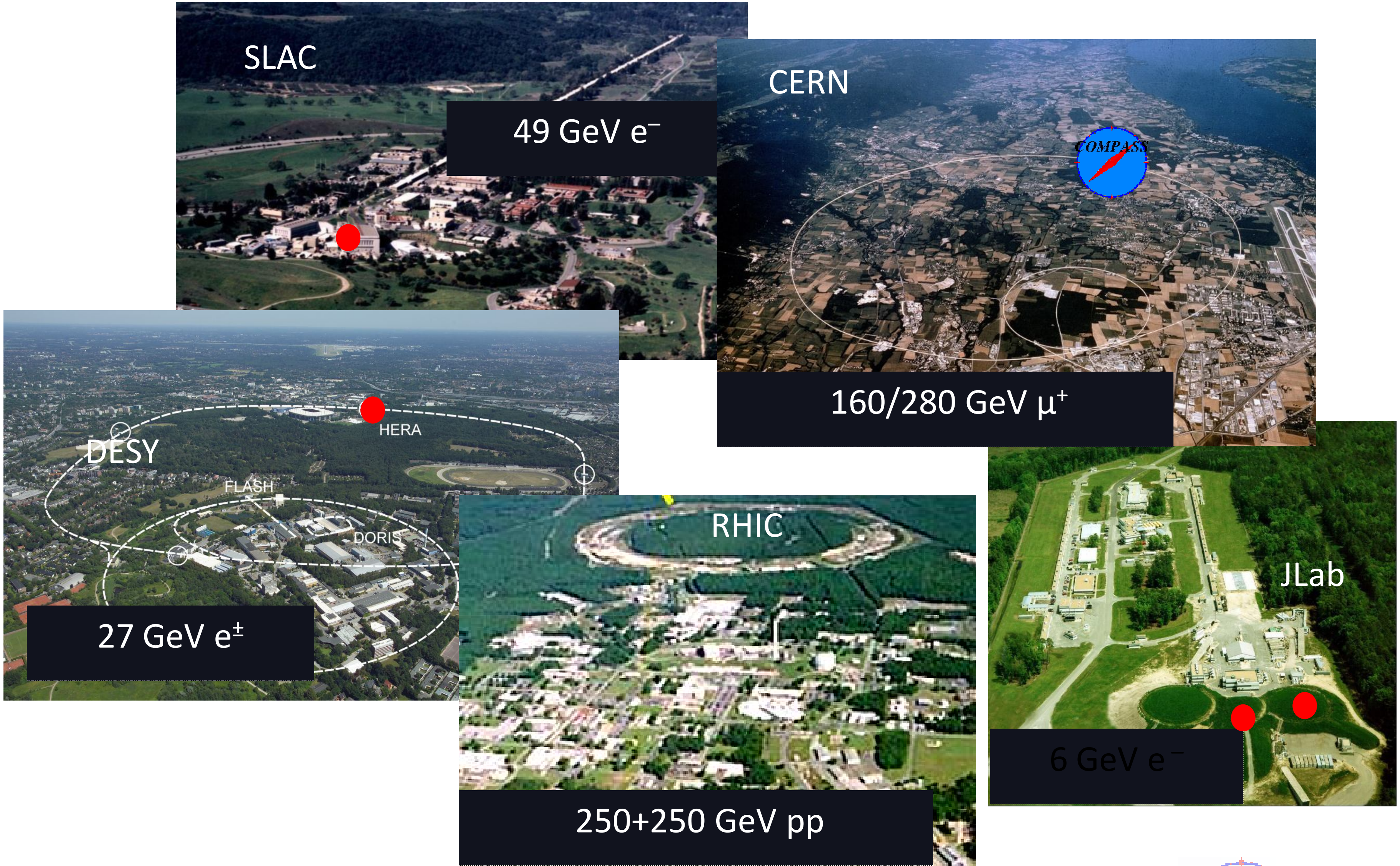


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

quarks	gluons	orbital
small ~0.15	Still poorly known	unknown

Laboratories &



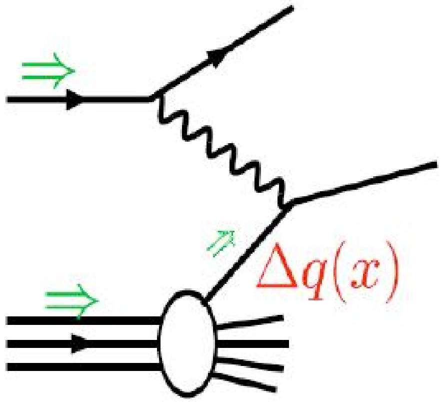
& Experiments

	1970	1980	1990	2000
SLAC	E80	E130	E142/3 E154/5	
CERN		EMC	SMC	COMPASS
DESY			HERMES	
JLab				CLAS/HALL-A
RHIC				Phenix/Star

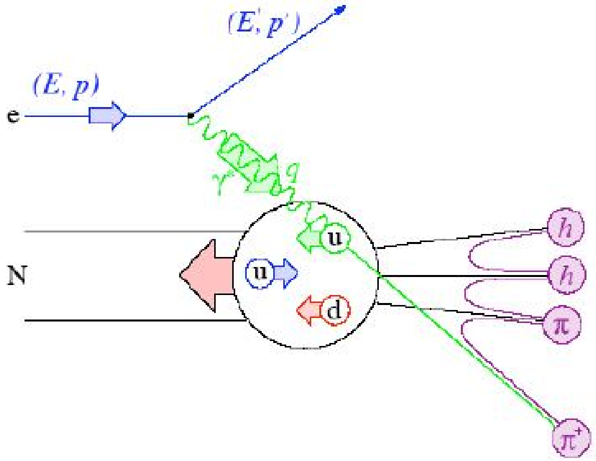
A worldwide effort since decades

Tools to study the spin structure

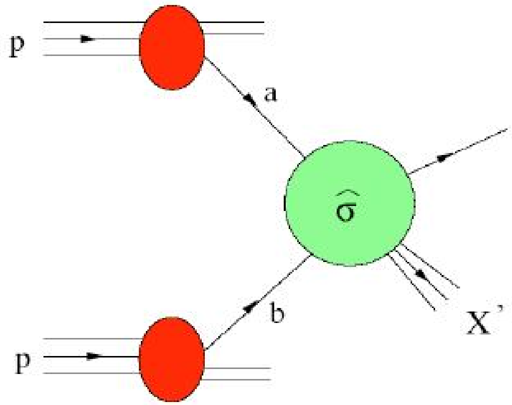
DIS



SIDIS

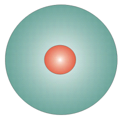


pp



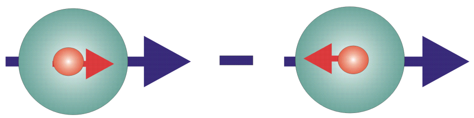
Parton Distribution Functions

$q(x)$
$f_1^q(x)$



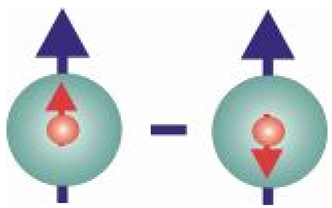
unpolarised PDF
quark with momentum *xP* in a nucleon
well known – unpolarized DIS

$\Delta q(x)$
$g_1^q(x)$



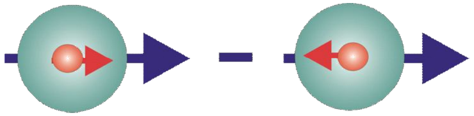
helicity PDF
quark with spin parallel to the nucleon spin in a longitudinally polarised nucleon
known – polarized DIS

$\Delta_T q(x)$
$h_1^q(x)$

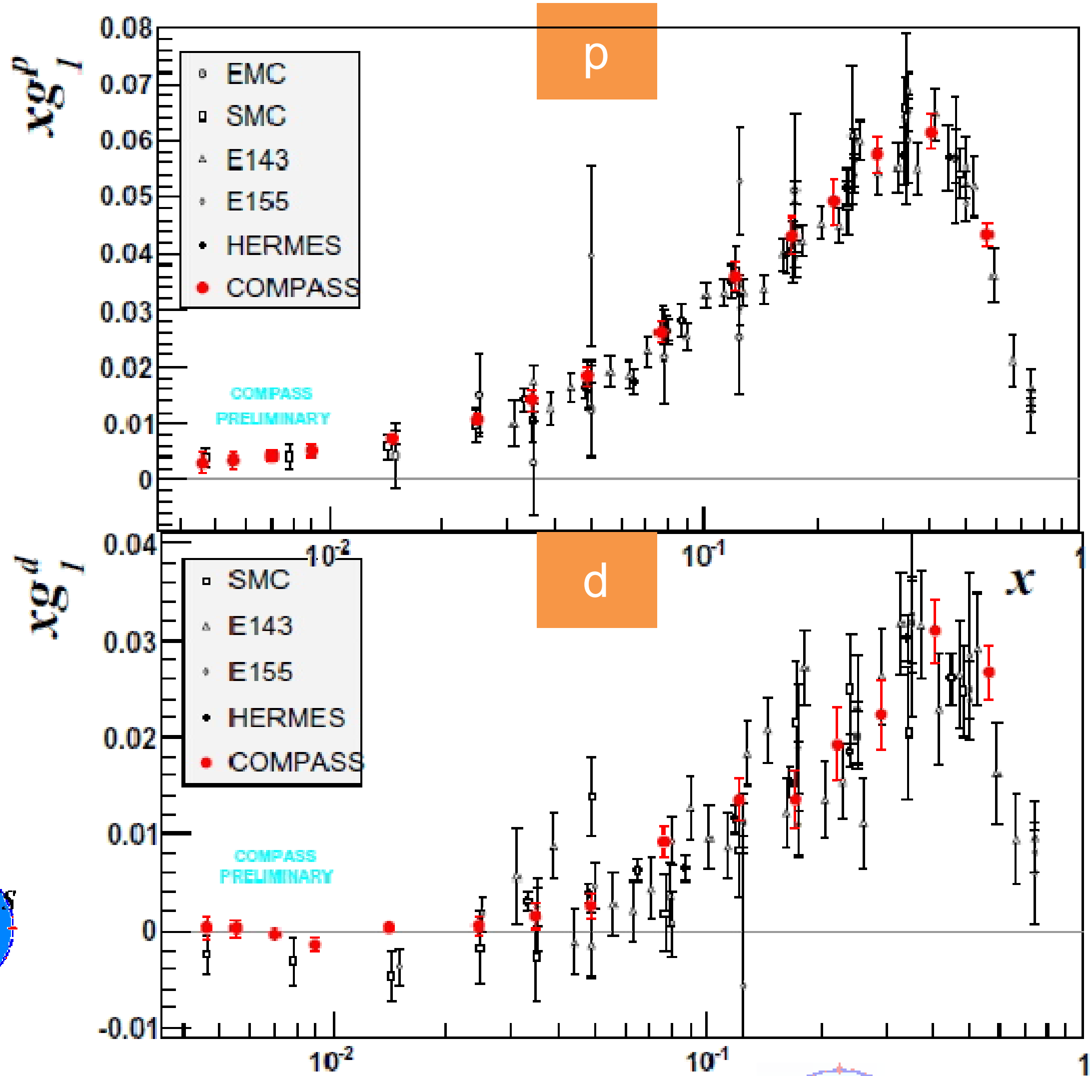


transversity PDF
quark with spin parallel to the nucleon spin in a transversely polarised nucleon
chiral odd, poorly known

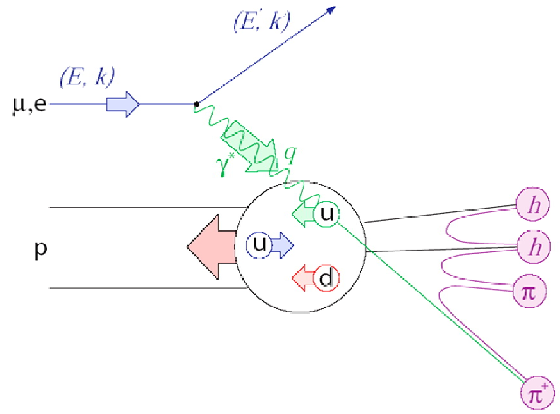
Structure function $g_1(x,Q^2)$



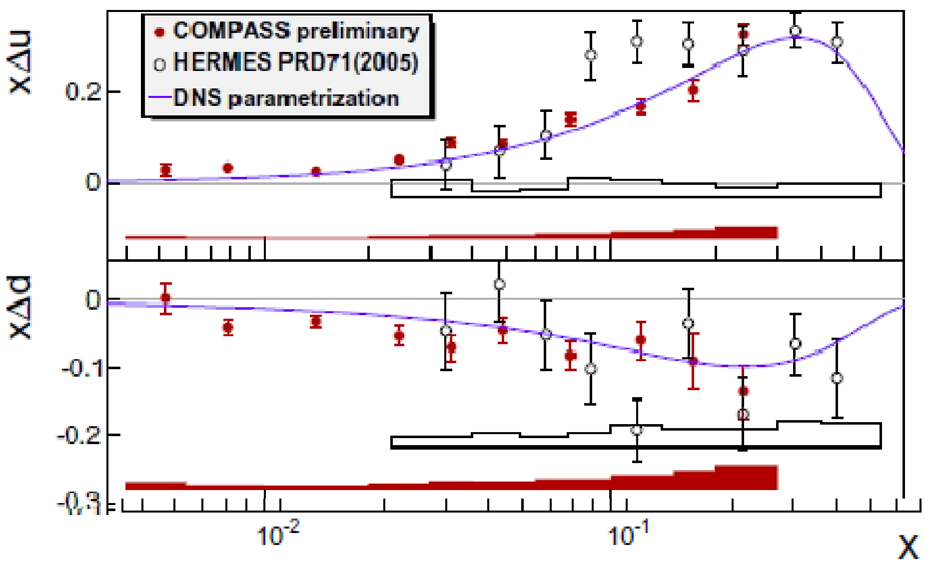
- very precise data
- only COMPASS for $x < 0.01$ ($Q^2 > 1$)
- deuteron data:
- $\Delta\Sigma = 0.33 \pm 0.03 \pm 0.05$
- $\Delta s + \Delta s =$
  $= -0.08 \pm 0.01 \pm 0.02$
- ($\Delta\Sigma = a_0$, evol. to $Q^2 = \infty$)

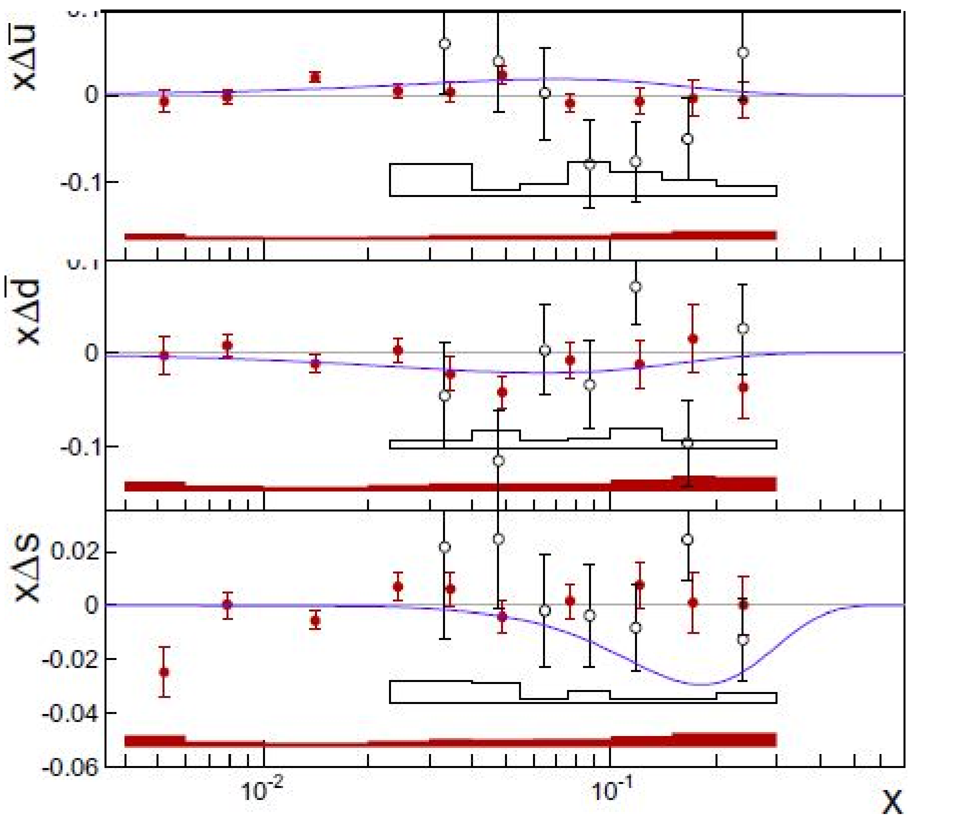


The quark flavours



- LO semi-inclusive data analysis

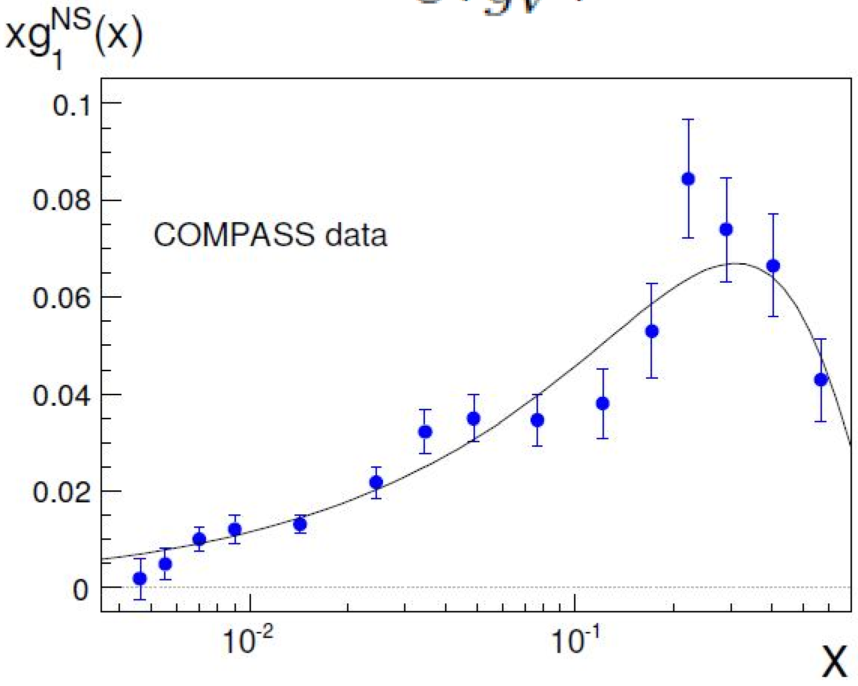


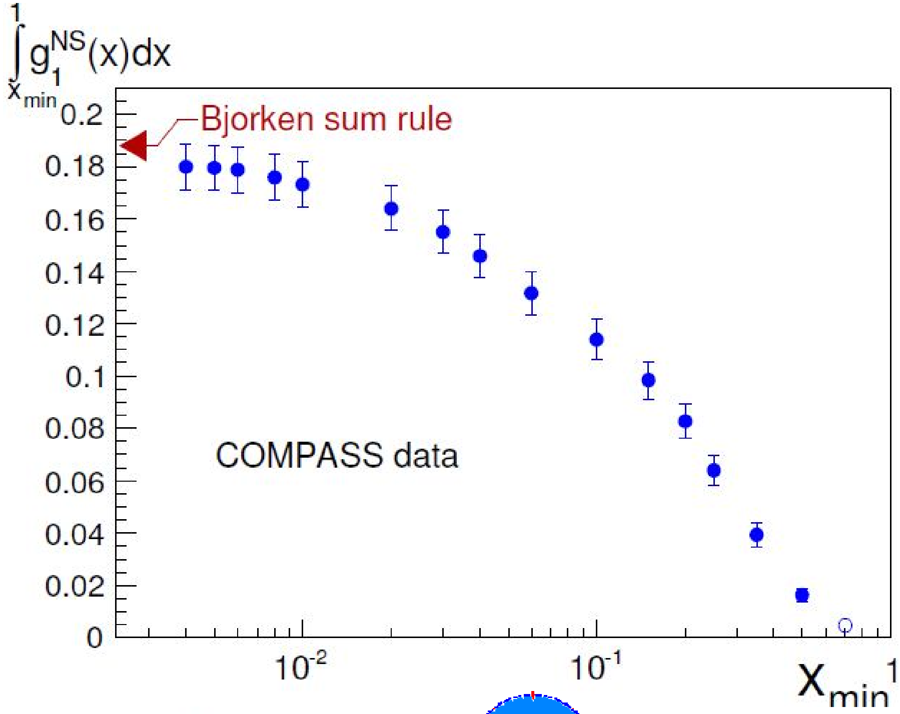


Bjorken sum rule

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

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

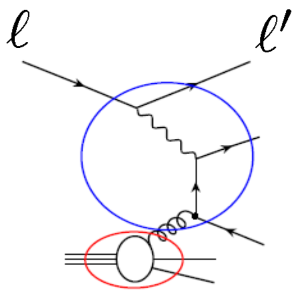




$$|g_A/g_V| = 1.28 \pm 0.07(\text{stat.}) \pm 0.10(\text{syst.})$$

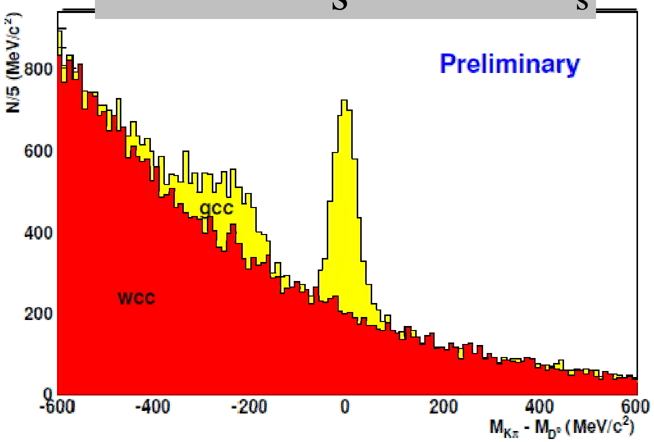
$$|g_A/g_V| = 1.269$$ from neutron β decay

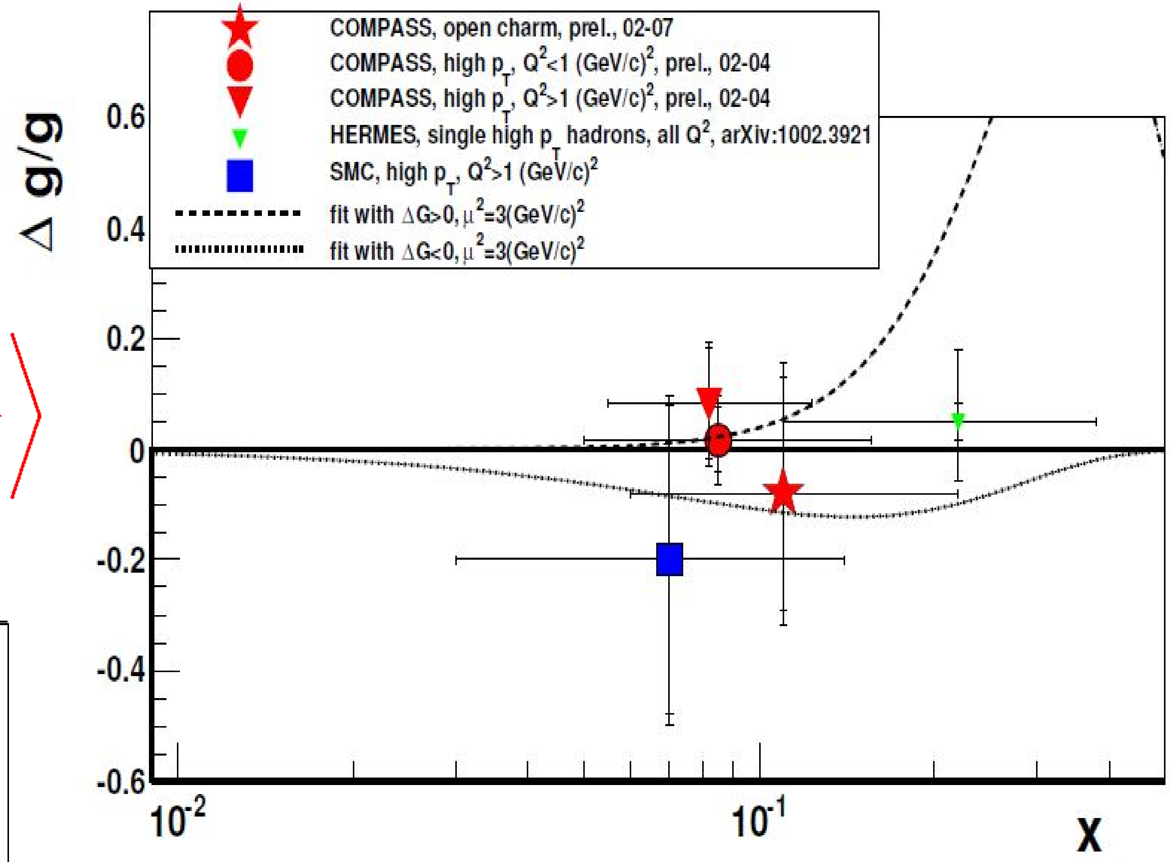
Gluon polarization from PGF



$$A_{||} = R_{pgf} \langle \hat{a}_{pdf} \rangle \left\langle \frac{\Delta g}{g} \right\rangle$$

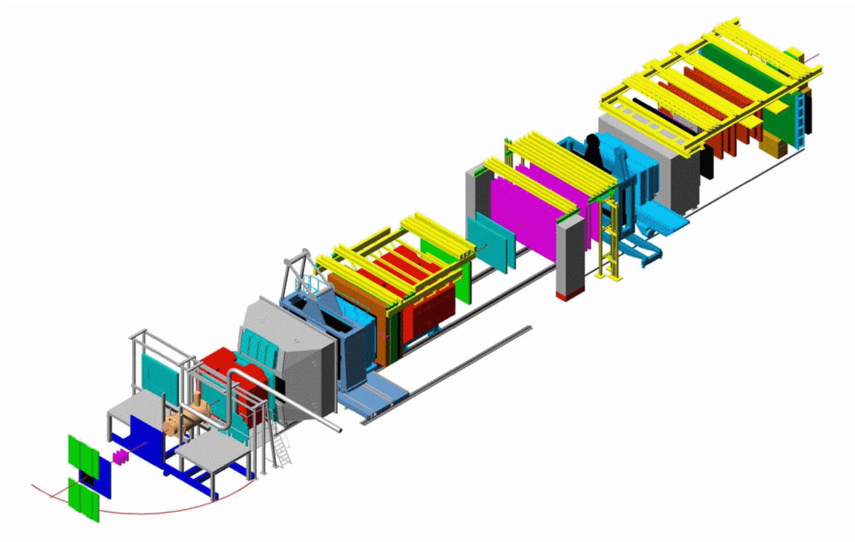
$$D^* \rightarrow D^0 + p_s \rightarrow K + p + p_s$$





Data not yet in global fits

What's next?



COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

Focus on transverse structure of the nucleon

- **Transverse size and orbital angular momentum (GPDs) →**
  → DVCS & DVMP with μ beams
- **Transv.Momentum Dependent PDFs:**
  Sivers, Boer-Mulders, sign change from SIDIS to DY, additional TMDs (pretzelozity, worm-gear) →
  → Drell-Yan with π beams

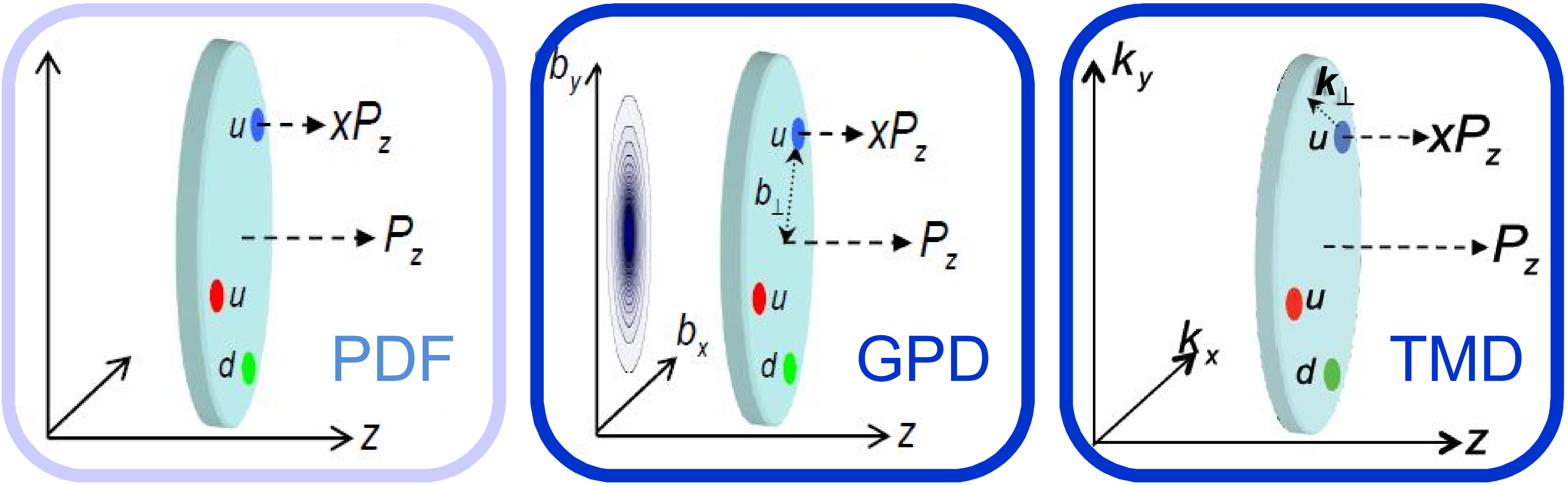
Exploring the 3-dimensional phase-space structure of the nucleon

From Wigner phase-space-distributions (Ji, PRL 2003, Belitsky, Ji, Yuan PRD 2004)
We can build « mother-distributions » (Meissner, Metz, Schlegel, JHEP 0908:056 2009)

$$\mathcal{W}(x, b_\perp, k_\perp)$$

and derive

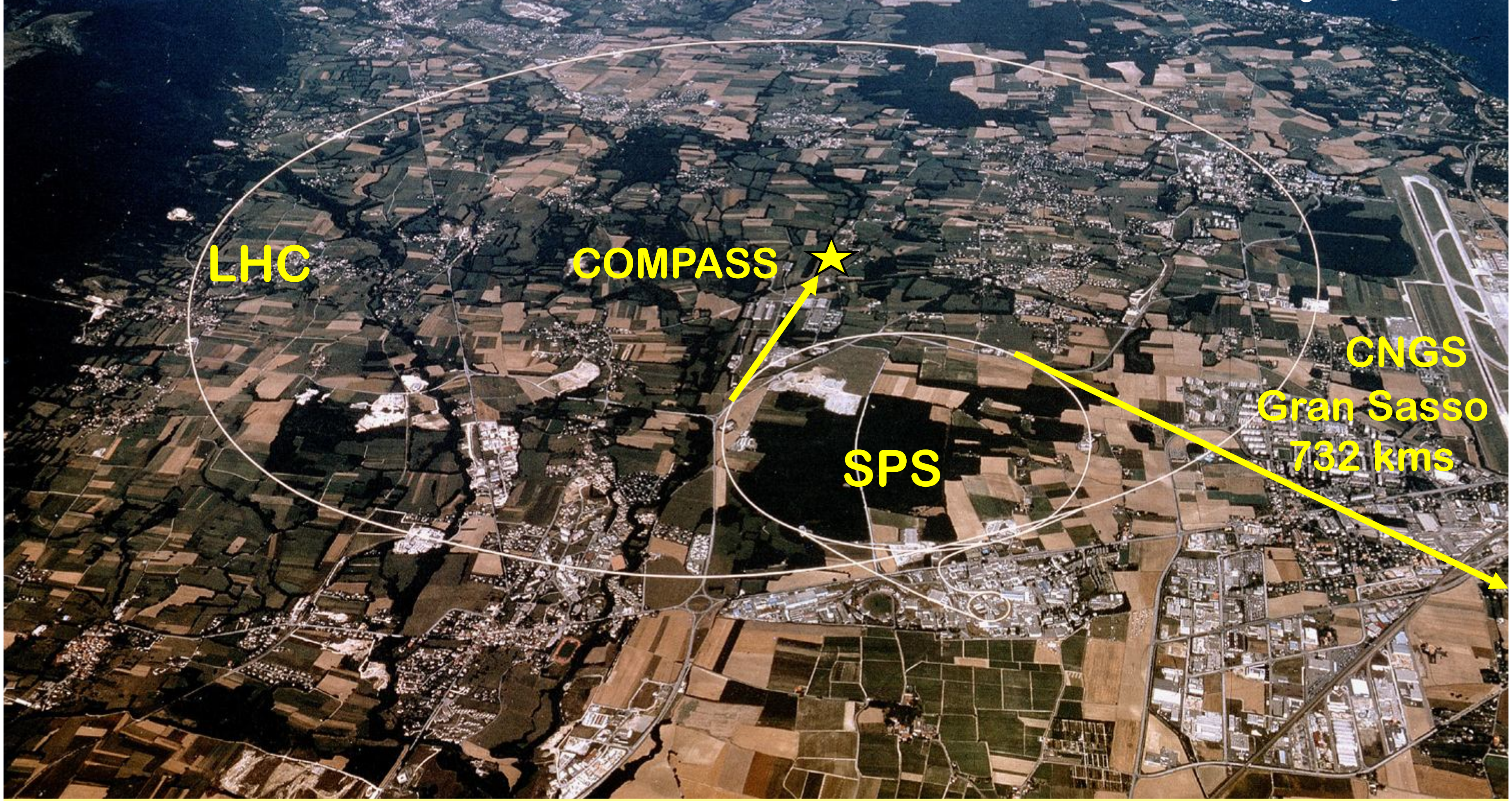
- **GPD: Generalised Parton Distribution (position in the transverse plane)**
- **TMD:Transverse Momentum Distribution (momentum in the transv. plane)**



- SPS proton beam: 2.6 10^{13}/spill of 9.6s each 48s, 400 GeV/c
- Secondary hadron beams (π, K, …): 6.10^{8} /spill, 50-200 GeV/c
- Tertiary muon beam (80% pol): 4.6$10^{8}$ /spill, 100-200 GeV/c

-> Luminosity ~ 10^{32} cm^{-2} s^{-1} GPD with μ^{+} and a 2.5m long LH target

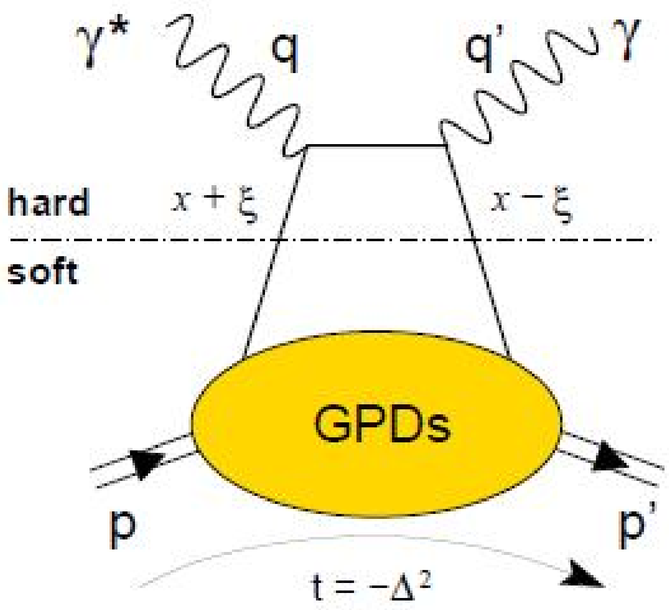
~1.2 10^{32} cm^{-2} s^{-1} DY with π^{-} and a 1.1m long NH_3 target



high energy beams, broad kinematic range, large angular acceptance

GPD Functions

- Allow for a unified description of form factors and parton distributions
- Allow for transverse imaging (nucleon tomography) and give access to the quark angular momentum (through E)



Total orbital momentum:

$$J^f(Q^2) = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \; x$$

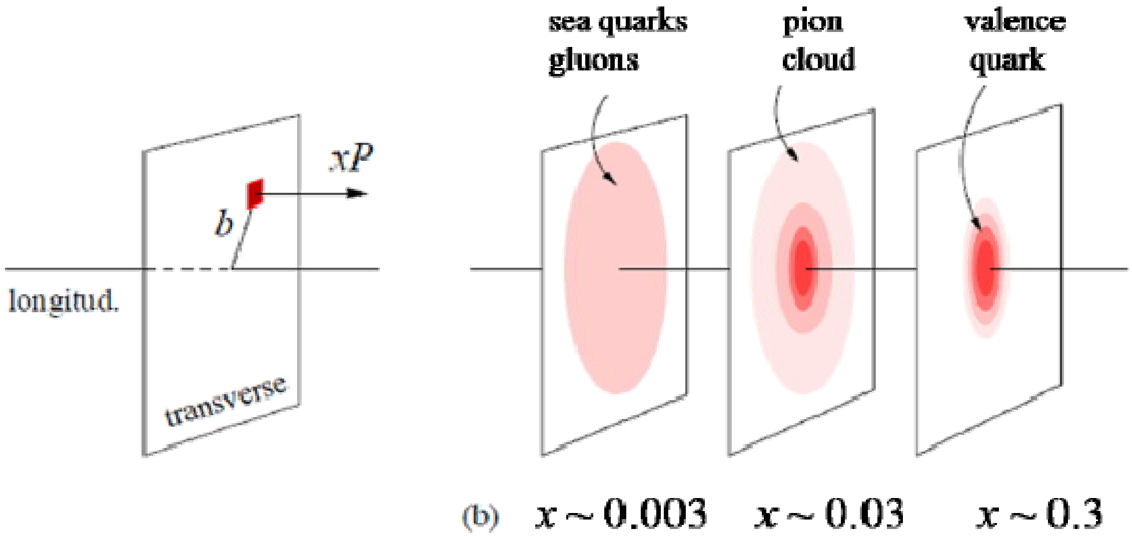
$$[H^f(x, \xi, t, Q^2) + E^f(x, \xi, t, Q^2)]$$

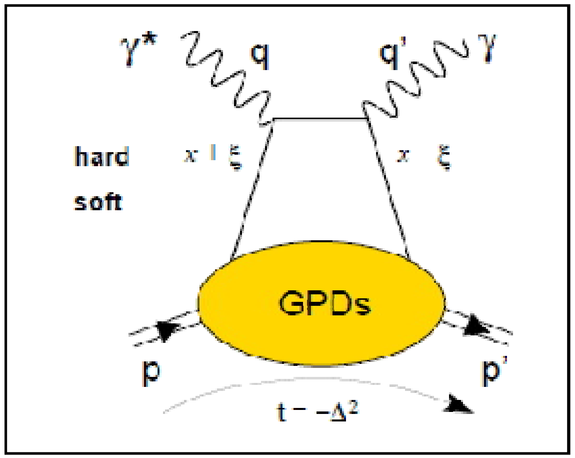
- X.-D. Ji, Phys. Rev. Lett. 78 (1997) 610

x **is not *x*-Bjorken** $\xi \sim x_B / (2-x_B)$

Tomographic image of the nucleon

- $t = -\Delta_T^2$





$$q^f(x, \boldsymbol{b}_\perp) = \int \frac{d^2 \boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{-i \boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} H^f(x, 0, -\boldsymbol{\Delta}_\perp^2)$$

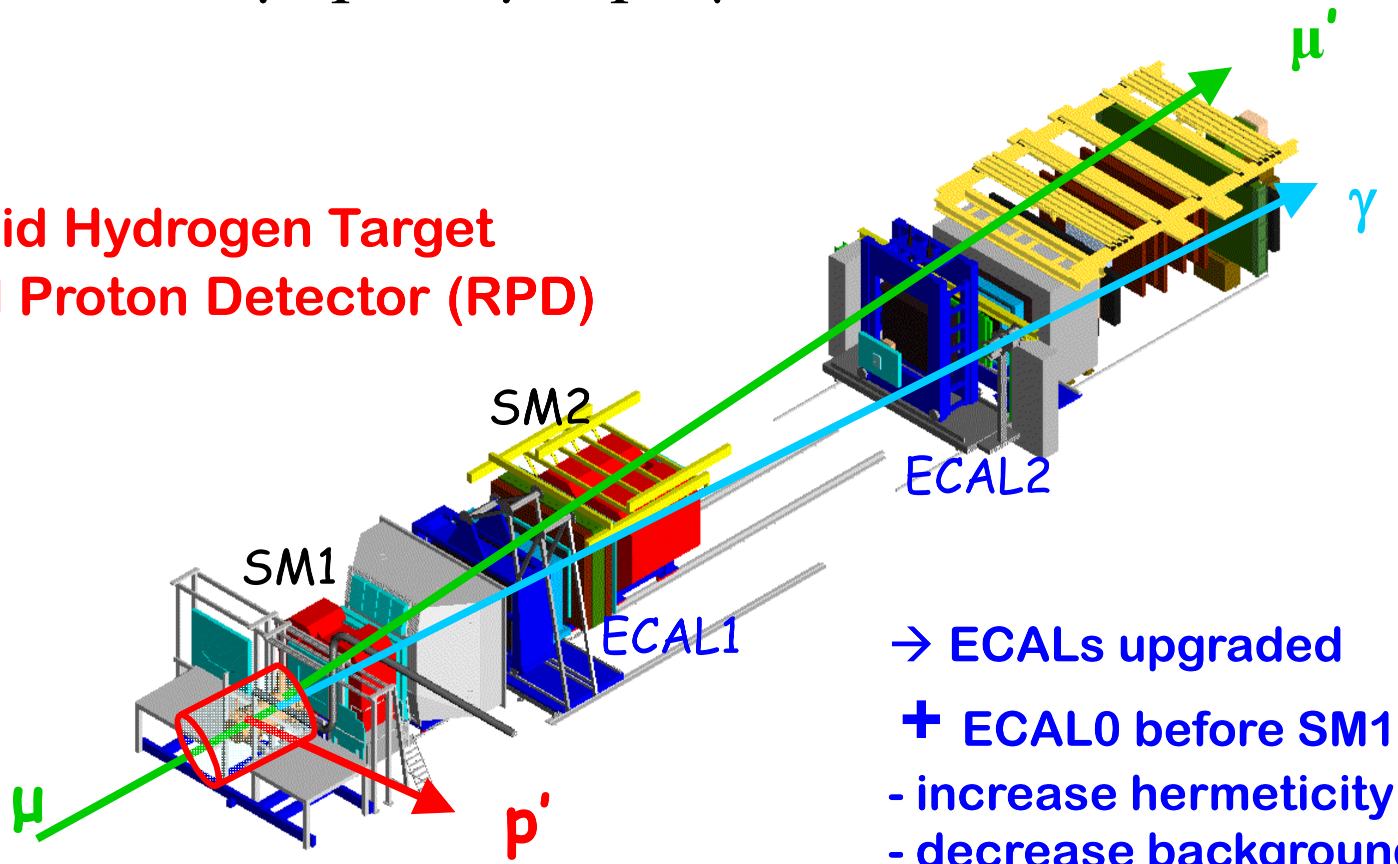
For fixed x GPD H describes the distribution of the transverse distance *b* of the constituent carried fraction *x* of the longitudinal momentum *p* from the center of the nucleon

Experimental requirements for DVCS

$\mu\ p \rightarrow \mu'\ p\ \gamma$

~ 2.5 m Liquid Hydrogen Target

~ 4 m Recoil Proton Detector (RPD)

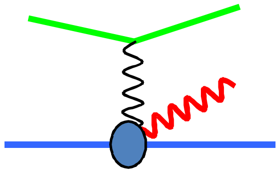


→ ECALs upgraded

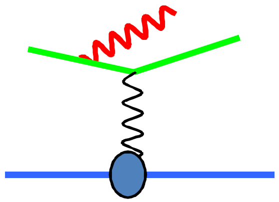
+ ECAL0 before SM1:

- **increase hermeticity**
- **decrease background**
- **enlarge acceptance**

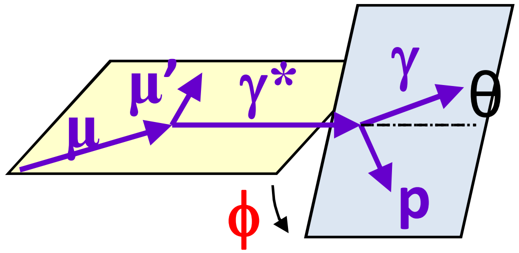
Contributions of DVCS and BH at E_μ=160 GeV



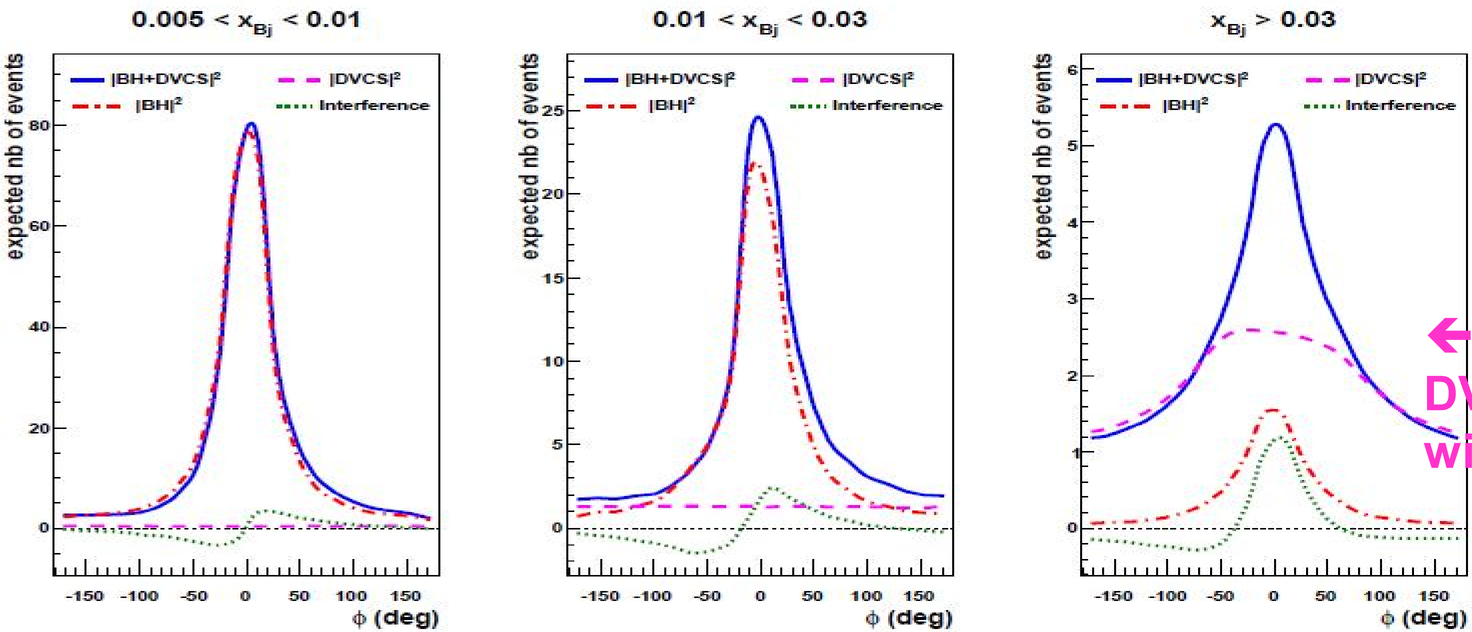
Deep VCS



Bethe-Heitler



$$d\sigma \ \alpha \ |T^{DVCS}|^2 + |T^{BH}|^2 + \text{Interference Term}$$



Monte-Carlo Simulation for COMPASS set-up with only ECAL1+2

← Missing DVCS acceptance without ECAL0

BH dominates

excellent reference yield

study of Interference

→ Re T^{DVCS}

or Im T^{DVCS}

DVCS dominates

study of $d\sigma^{DVCS}/dt$

→ Transverse Imaging

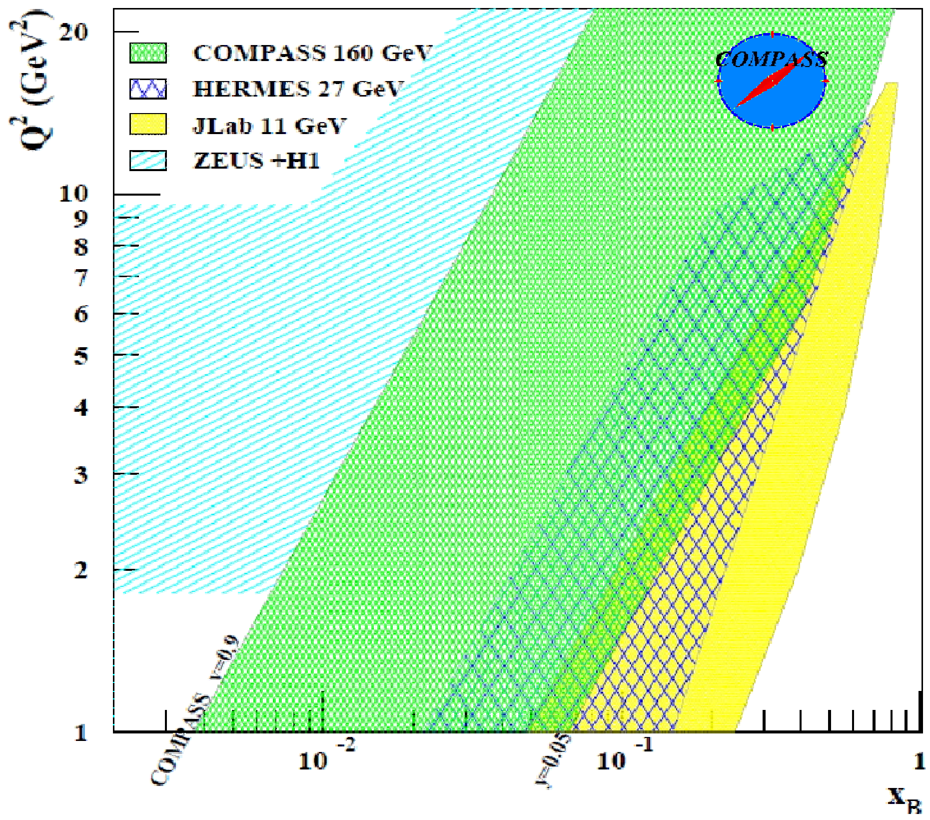
DVCS

- GPDs need a world-wide effort
- Global analysis over large kinematic range mandatory
- COMPASS-II: from HERA to JLAB 11 GeV kinematics
- The GPD H can be constrained by beam charge and spin ($\mu^+\mu^-$) combinations using an unpolarized proton target

$$\mathcal{D}_{CS,U} \equiv \mathrm{d}\sigma^{\overleftarrow{+}} - \mathrm{d}\sigma^{\overrightarrow{-}}$$

$$\mathcal{S}_{CS,U} \equiv \mathrm{d}\sigma^{\overleftarrow{+}} + \mathrm{d}\sigma^{\overrightarrow{-}}$$

- *E* GPDs require transversely pol. target (later)



Deeply Virtual Compton Scattering

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

- $\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + K.s_1^{Int} \sin\phi \sim Im(F_1\mathcal{H})$

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

$$\downarrow$$

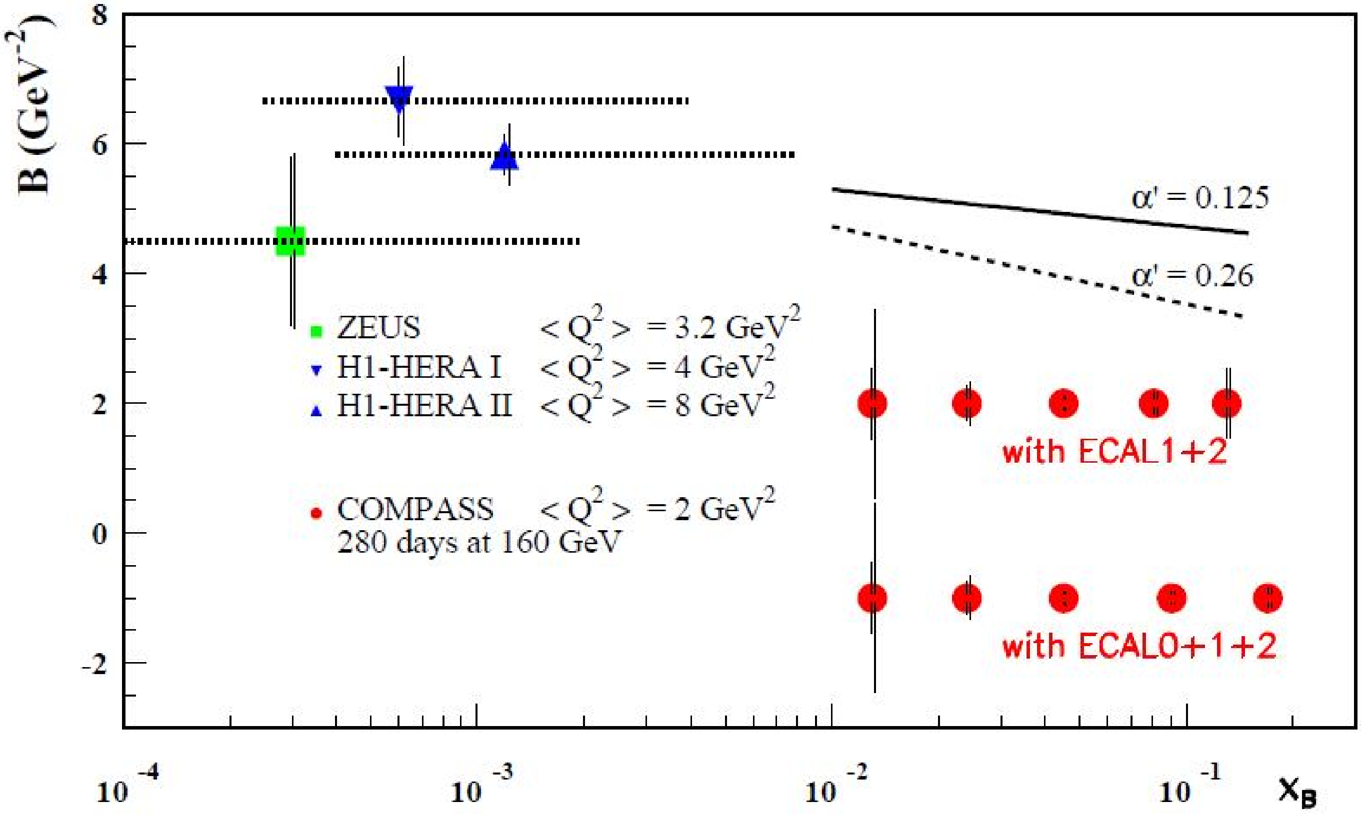
$$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$$

- $\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \sim \mathcal{R}e(F_1\mathcal{H})$

$$Re\,\mathbf{H}(\xi,t) = P\int dx\,\mathbf{H}(x,\xi,t)/(x-\xi)$$

$$Im\,\mathbf{H}(\xi,t) = \mathbf{H}(x=\xi,\xi,t)$$

Deeply Virtual Compton Scattering



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

α' slope of Regge traject

without any model we can extract $B(x_B)$

$B(x_B) = ½ < r_\perp^2 (x_B) >$

$r_\perp$ is the transverse size of the nucleon

Parton Distribution Functions

- **8 PDFs at LO**
- **Azimuthal asymmetries with different angular modulations in the hadron and spin azimuthal angles, Φ_h and Φ_s**

quark polarization \ nucleon polarization	U	L	T
U	f_1 number density		$f_{1T}^{\perp}$
L		g_1 helicity	g_{1T}
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 transversity $h_{1T}^{\perp}$

Boer–Mulders

Sivers

Transversity

aka

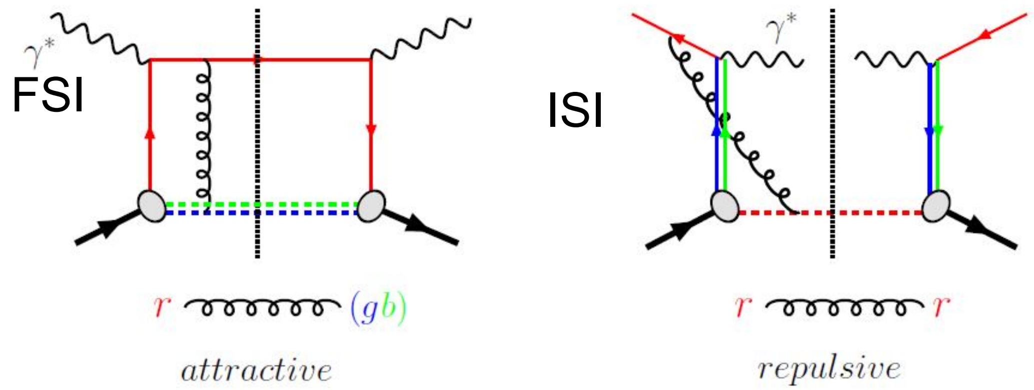
$\Delta_0^T q$

$\Delta_T q$

Experimental check of the change of sign of TMDs confronting Drell-Yan and SIDIS results

The T-odd character of the Boer-Mulders and Sivers function implies that these functions are process dependent

`gauge link changes sign for T-odd TMD', restricted universality of T-odd TMDs



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

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

Need experimental verification

Test of consistency of the approach

Polarised Drell-Yan

- **COMPASS-II: 190 GeV/*c* π^- beam on transversely pol. proton target**
- **π^- valence u-antiquark picks nucleon's u quark in valence region (u-quark dominance)**
- **Access to transversity , the T-odd Sivers and Boer-Mulders TMDs and `pretzelozity'**

The Drell-Yan process in $\pi^- p$

$$\frac{d\sigma^{DY}}{} \propto \Big(1 + \int d^2k_{1T}\, d^2k_{2T}\, \mathcal{W}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2) \otimes h_1^{\perp}(x_2,k_{2T}^2) \cos 2\phi \Big)$$

$$+ |S_T| \Big(\int d^2k_{1T}\, d^2k_{2T}\, \mathcal{X}(k_{1T},k_{2T})\, \bar{f}_1(x_1,k_{1T}^2) \otimes f_{1T}^{\perp}(x_2,k_{2T}^2) \sin \phi_S$$

$$+ \int d^2k_{1T}\, d^2k_{2T}\, \mathcal{Y}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2) \otimes h_{1T}^{\perp}(x_2,k_{2T}^2) \sin(2\phi + \phi_S)$$

$$+ \int d^2k_{1T}\, d^2k_{2T}\, \mathcal{Z}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2) \otimes h_1(x_2,k_{2T}^2) \sin(2\phi - \phi_S) \Big)$$

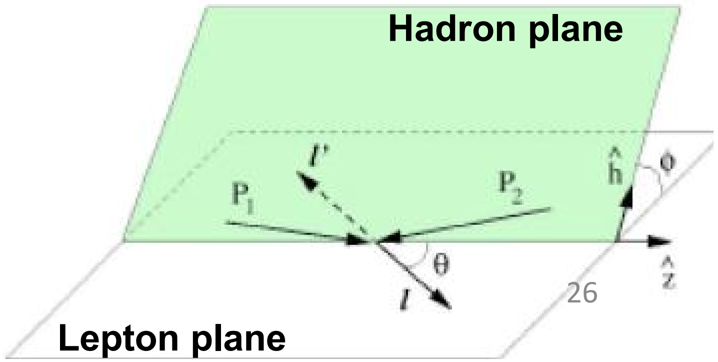
➔Access to TMDs for incoming pion ⊗ target nucleon
TMD as Transversity, Sivers, Boer-Mulders, pretzelosity

Collins-Soper frame (of virtual photon)

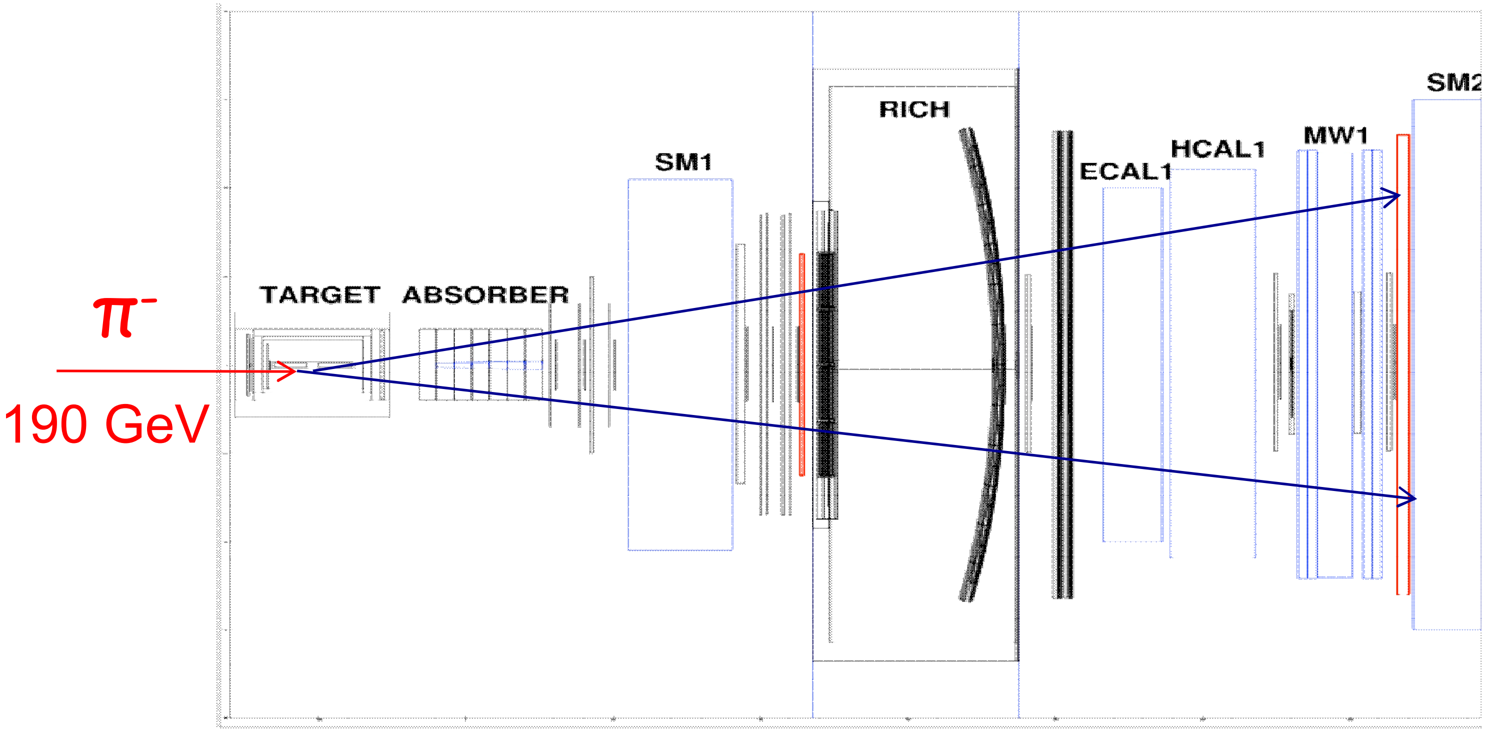
θ, ϕ lepton plane wrt hadron plane

target rest frame

ϕ_S target transverse spin vector /virtual photon



DY and COMPASS set-up



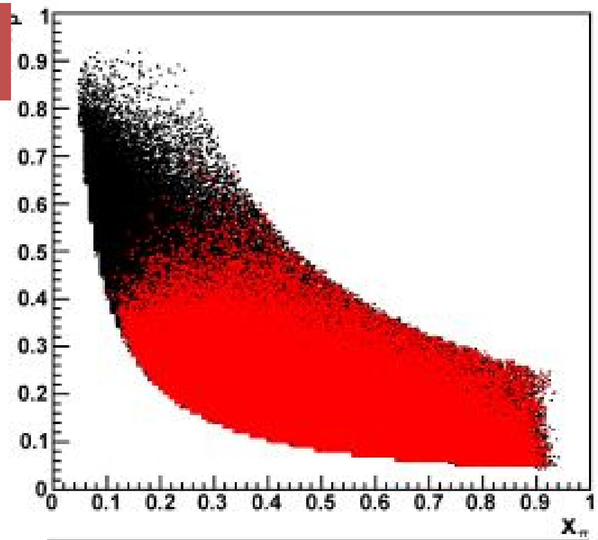
Key elements for a small cross section investigation at high luminosity

1. Absorber (lesson from 2007-8 tests) to reduce secondary particle flux
2. COMPASS Polarised Target
3. Tracking system and beam telescope
4. Muon trigger (LAS of particular importance - 60% of the DY acceptance)
5. RICH1, Calorimetry – also important to reduce the backgrou

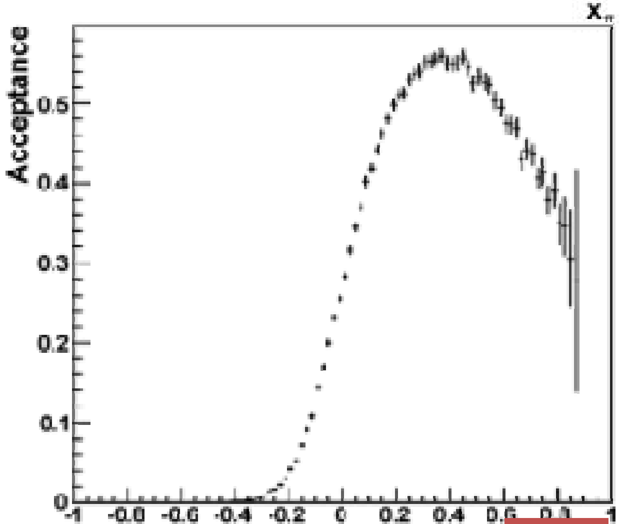
COMPASS polarized DY

dominated by the annihilation of a valence anti-quark from the pion and a valence quark from the polarised proton

x_p

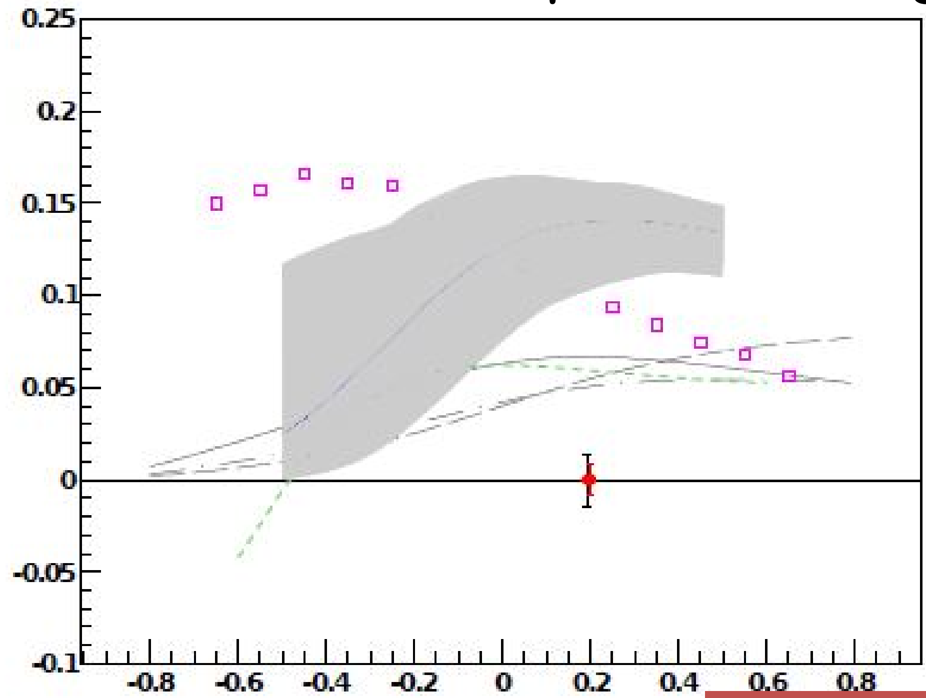


x_π



x_F

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



$x_F = x_\pi - x_p$

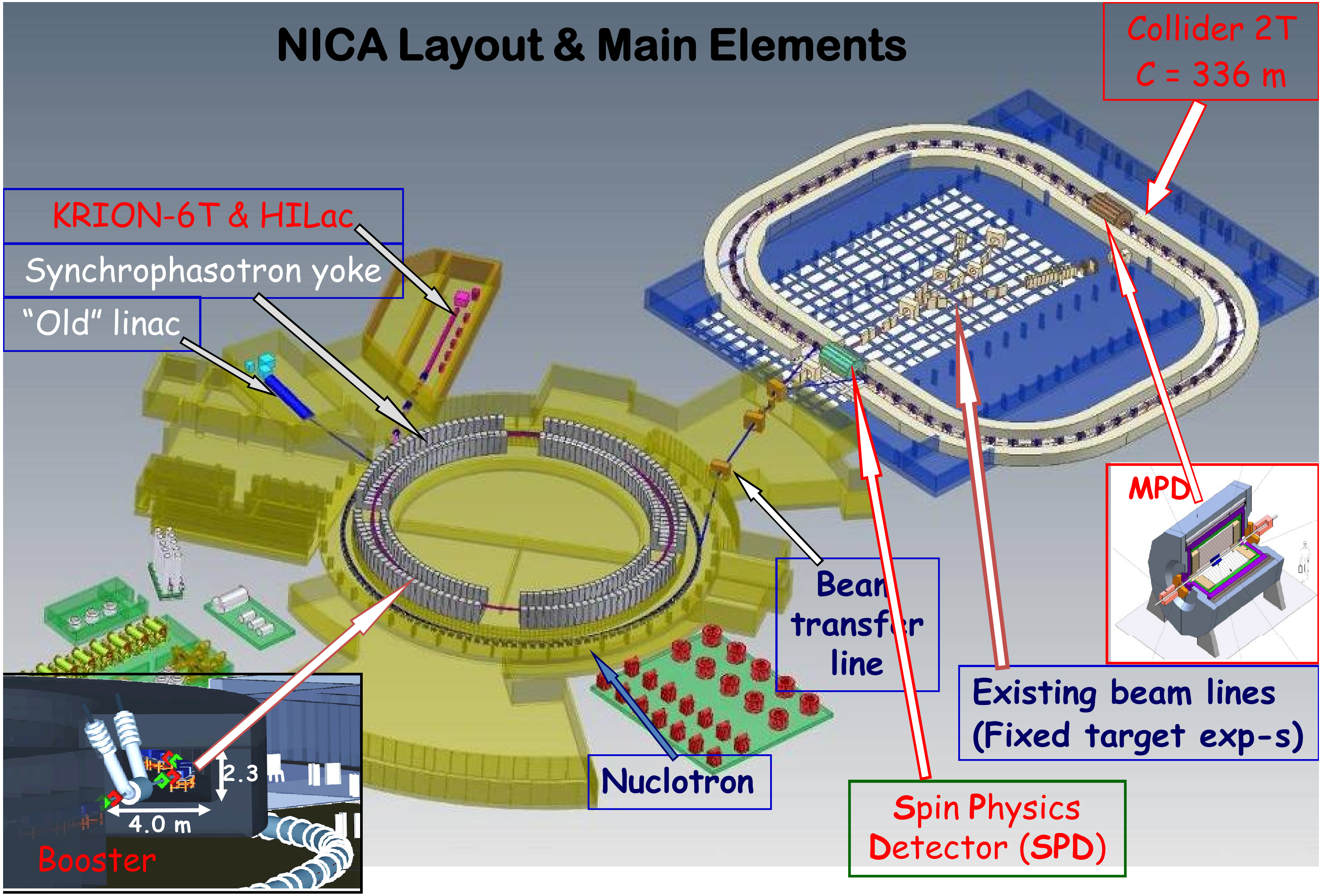
TMDs at Drell-Yan: road map

- **2010 – COMPASS polarised SIDIS data (Sivers, transversity via global data fit)**
- **2013 - 2016 COMPASS polarised Drell-Yan pi-p data – TMDs universality and T-odd TMDs sign change SIDIS←→DY**
- **2015 → …… RHIC, NICA pp (un)polarised DY data**
- **2020 → GSI antiproton data**

Future DY experiments

Facility		Type		s (GeV^2)	Time-line
[illegible]	[147]	collider,	$p^{\uparrow}p^{\uparrow}$	200^2, 500^2	> 2014
[illegible]	[148]	fixed target,	$p^{\uparrow}p^{\uparrow}$	500	> 2015
E906 (Fermilab)	[149]	fixed target,	pp,	226	> 2010
J-PARC	[150]	fixed target,	$pp^{\uparrow}$	$60 \div 100$	> 2015
[illegible]	[151]	collider,	$\bar{p}^{\uparrow}p^{\uparrow}$	200	> 2017
GSI (Panda)	[152]	fixed target,	$\bar{p}p$	30	> 2016
[illegible]	[153]	collider,	$p^{\uparrow}p^{\uparrow}$, $d^{\uparrow}d^{\uparrow}$	676	> 2014
[illegible]		fixed target,	[illegible]	$300 \div 400$	> 2012

NICA Layout & Main Elements



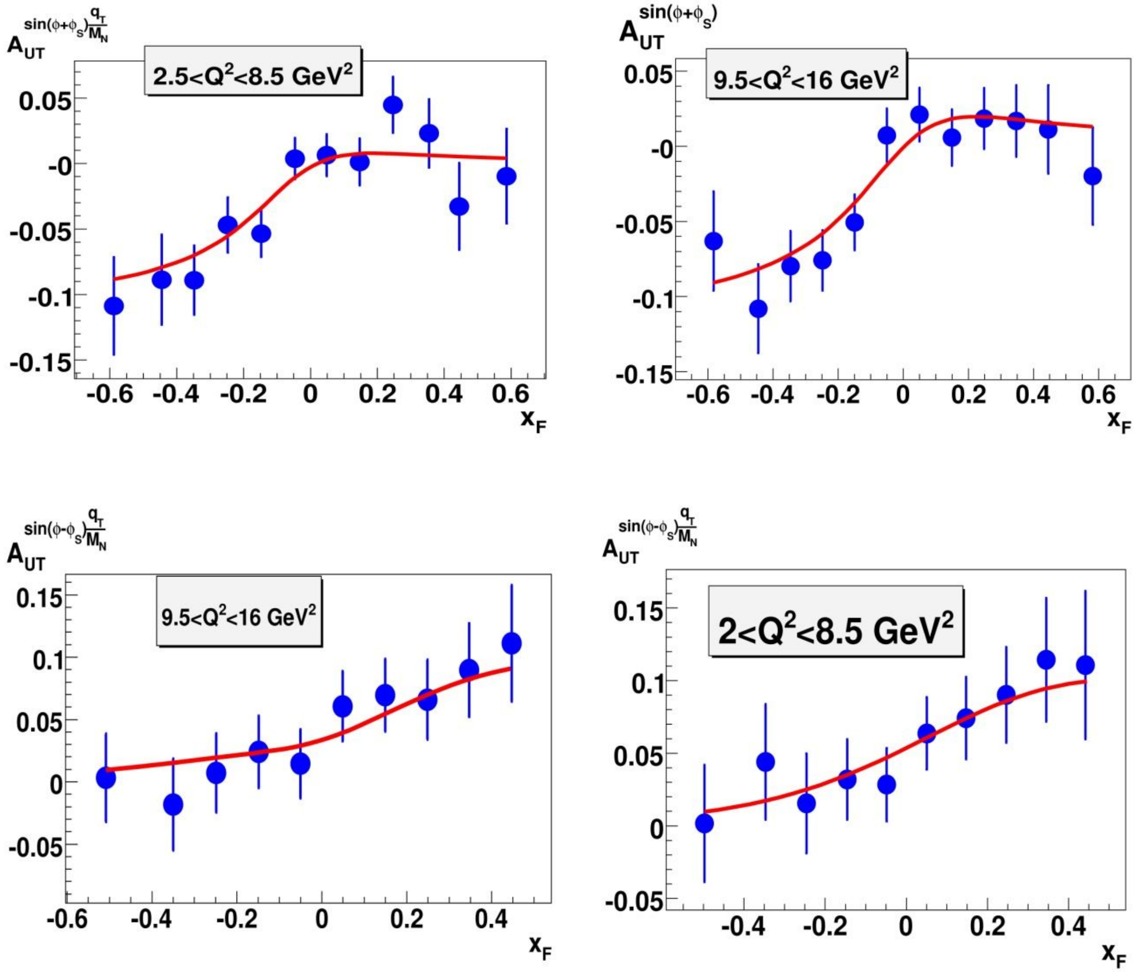
Spin Physics at NICA

The spin program at NICA is under preparation. The main topics are:

- **Studies of Drell-Yan processes with longitudinally and transversely polarized p and D beams. Extraction of unknown and poor known PDFs**
- **PDF from J/Ψ production processes**
- **Spin effects in baryon, meson and photon production**
- **Study of spin effects in various exclusive processes**
- **Diffractive processes studies**
- **Cross sections, helicity amplitudes and double spin asymmetries (Krisch effect) in elastic reactions**
- **Spectroscopy of quarkonium**

Spin Physics at NICA - polarized DY

From report by A. Nagaytsev, IWSS2010



The set of original software packages (MC simulation, generator etc.) were developed for the feasibility studies of DY polarized processes

The SSA asymmetries. Top:access to transversity and Boer-Mulders PDFs.
(Sissakian, Shevchenko, Nagaytsev,PRD 72 (2005), EPJ C46 (2006))

Bottom: access to Sivers PDFs
(Efremov,... PLB 612(2005), PRD 73(2006));

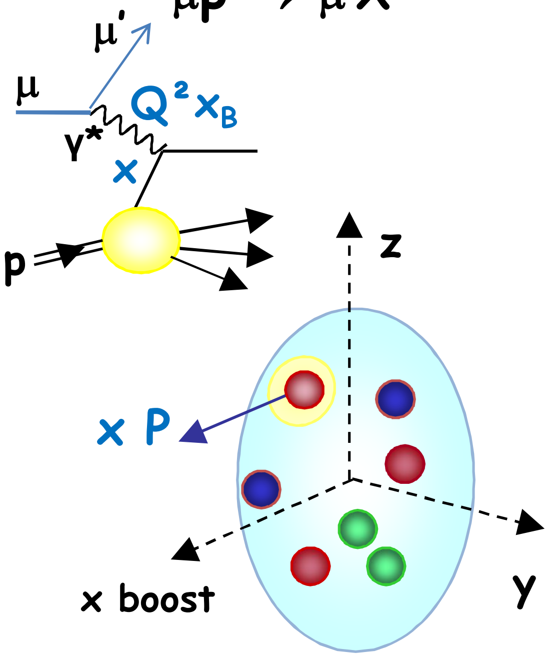
Asymmetries are estimated for 100 K DY events

Spare

From inclusive to exclusive reactions

Deep Inelastic Scattering

$\mu p \to \mu' X$

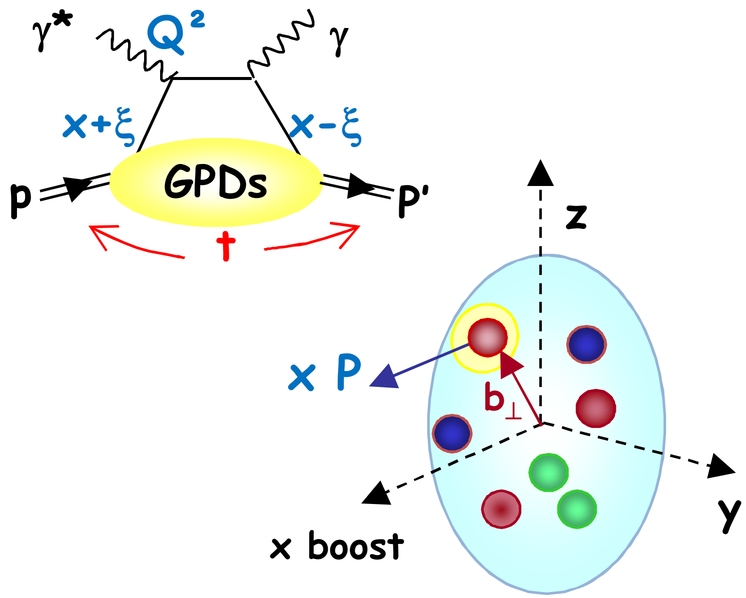


Distrib. de Partons q (x)

P_x

Deeply Virtual Compton Scattering

$\mu p \to \mu' p' \gamma$



Generalized Partons Distrib. $H(x, \xi, t)$

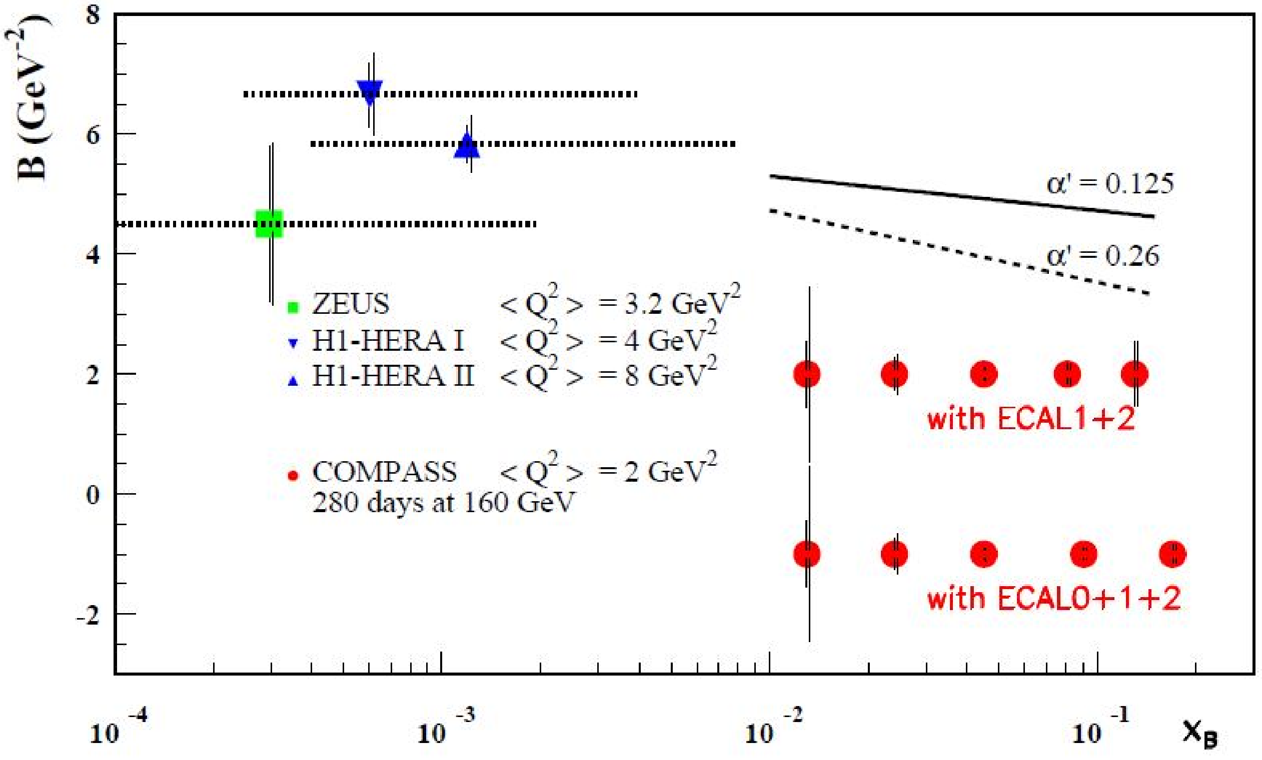
$(P_x, b_\perp)$

Observation of the Nucleon Structure

in 1 dimension — **in 1+2 dimensions**

DVCS: Transverse imaging at COMPASS

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



ansatz at small x_B
inspired by
Regge Phenomenology:

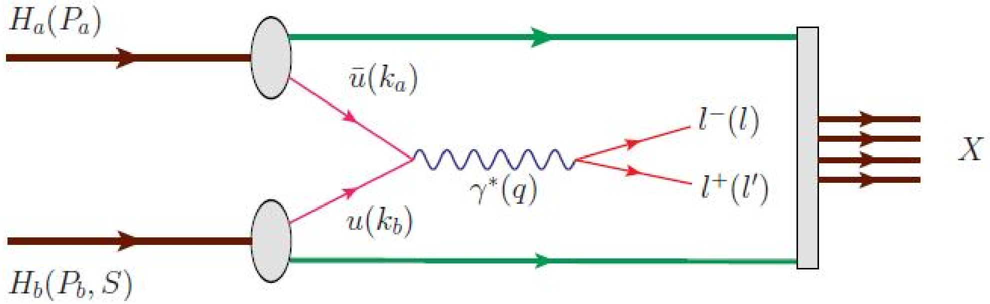
$B(x_B) = b_0 + 2\,\alpha' \ln(x_0/x_B)$

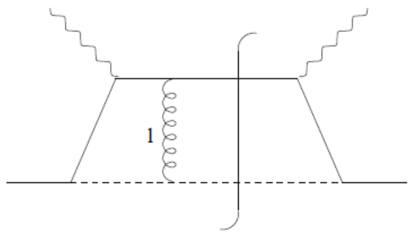
α' slope of Regge traject

with the projected uncertainties we can determine :

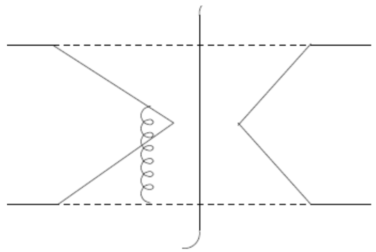
- B with an accuracy of 0.1 GeV^{-2}
- α' with an accuracy $\geq 2.5\,\sigma$
  if $\alpha' \geq$ **0.26** with ECAL1+2
  if $\alpha' \geq$ **0.125** with ECAL0+1+2

T-odd TMD in SIDIS and DY





SIDIS: FSI



DY:ISI

`gauge link changes sign for T-odd TMD', restricted universality of T-odd TMDs

- J.C. Collins, Phys. Lett. B536 (2002) 43

$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{DIS} \qquad \text{and} \qquad h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{DIS}$$

Single-polarised DY cross-section: Leading order QCD parton model, TMD PDFs universality

At LO the general expression of the DY cross-section simplifies to (Aram Kotzinian):

$$
\begin{aligned}
\frac{d\sigma^{LO}}{d^4q\,d\Omega} &= \frac{\alpha_{em}^2}{F\,q^2}\hat{\sigma}_U^{LO}\Big\{\Big(1 + D_{[\sin^2\theta]}^{LO}\,A_U^{\cos 2\phi}\cos 2\phi\Big) \\
&+ S_L D_{[\sin^2\theta]}^{LO}\,A_L^{\sin 2\phi}\sin 2\phi \\
&+ |\vec{S}_T|\Big[A_T^{\sin\phi_S}\sin\phi_S + D_{[\sin^2\theta]}^{LO}\Big(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S) \\
&+ \qquad A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\Big)\Big]\Big\},
\end{aligned}
$$

Thus the measurement of 4 asymmetries (modulations in DY cross-section):

- $A_U^{\cos 2\phi}$ gives access to the Boer-Mulders functions of the incoming hadrons,
- $A_T^{\sin\phi_S}$ – to the Sivers function of the target nucleon,
- $A_T^{\sin(2\phi+\phi_S)}$ – to the Boer-Mulders functions of the beam hadron and to $h_{1T}^{\perp}$, the pretzelosity function of the target nucleon,
- $A_T^{\sin(2\phi-\phi_S)}$ – to the Boer-Mulders functions of the beam hadron and h_1, the transversity function of the target nucleon.

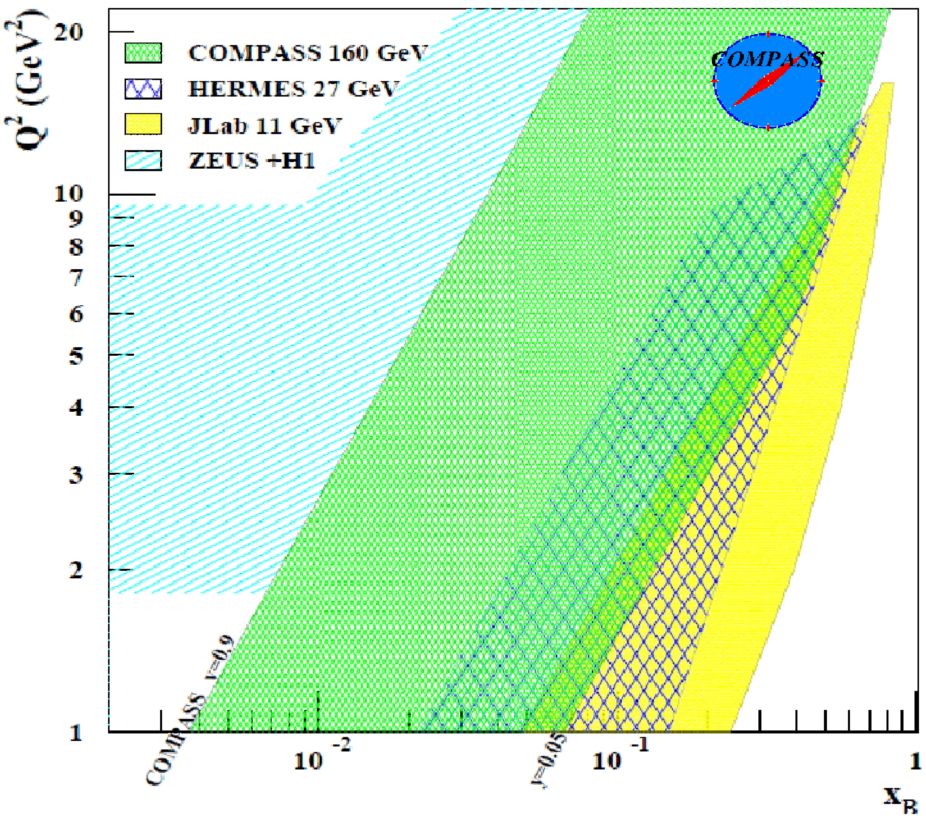
DVCS

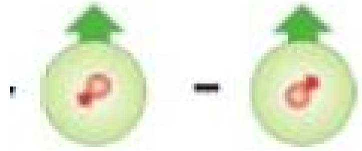
- GPDs need a world-wide effort
- Global analysis over large kinematic range mandatory
- COMPASS-II: from HERA to JLAB 11 GeV kinematics
- *H* GPDs can be separated from BH and constrained by beam charge & spin ($\mu^+\mu^-$) combinations

$$\mathcal{D}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}$$

$$\mathcal{S}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$$

- *E* GPDs require transversely pol. target (later)



Transversity PDF $\Delta_T q$ or h_1 

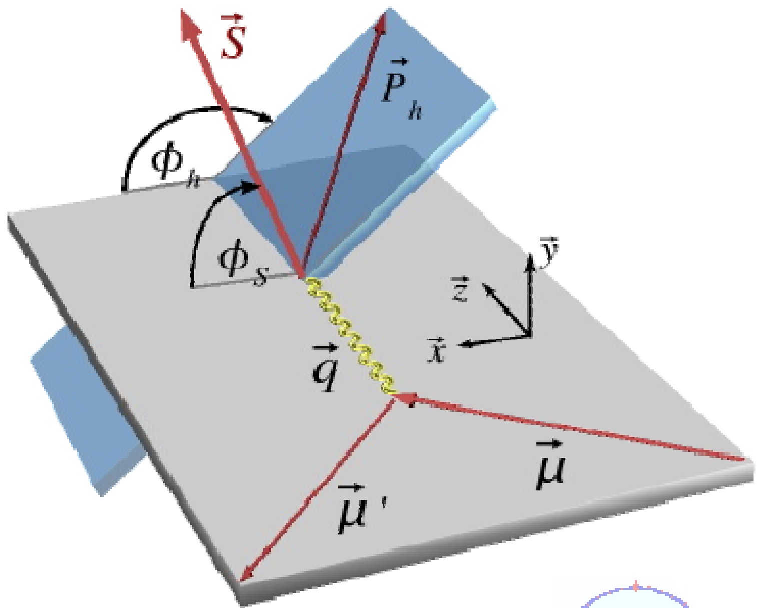
- Couple $\Delta_T q$ to chiral odd Collins FF $\Delta_T^0 D_q^h$

$$A_{Coll} = \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 q(x) D_q^h(z, p_T^h)}$$

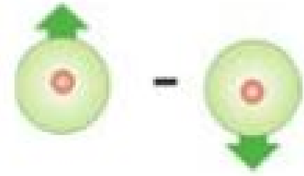
Azimuthal cross-section asymmetry:

$$\frac{\Delta\sigma}{\sigma} \propto A_{Coll} \sin \Phi_C$$

$$\Phi_C = \phi_h - \phi_s - \pi$$



Sivers function $\Delta_0^T q$ or $f_{1T}^{\perp}$

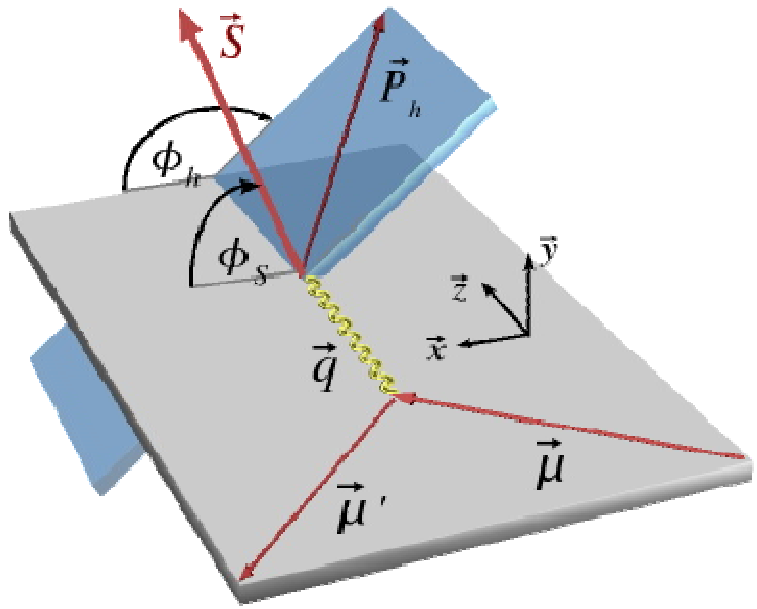


- Sivers Asymmetry:

$$A_{Siv} = \frac{\sum_q e_q^2 \Delta_0^T q(x, p_T^h/z) D_q^h(z)}{\sum_q e_q^2 q(x, p_T^h/z) D_q^h(z)}$$

$$\frac{\Delta\sigma}{\sigma} \propto A_{Siv} \sin \Phi_S$$

$$\Phi_S = \phi_h - \phi_S$$

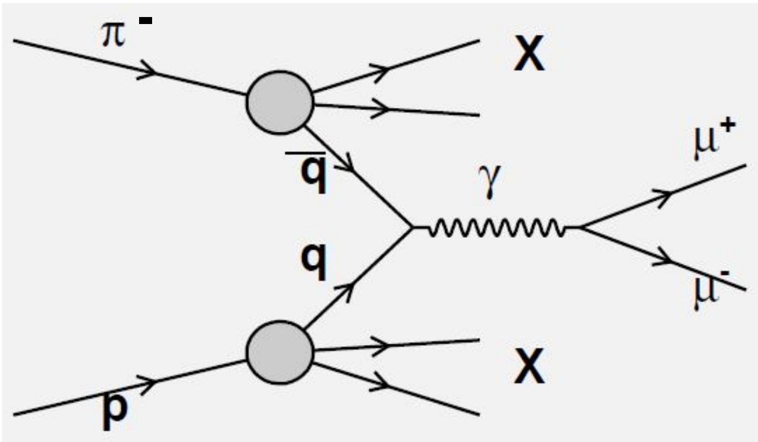


- proposed (1990, Sivers)
- thought to vanish (1993, Collins)
- resurrected (2002, Brodsky, Hwang, Schmitt)
- different sign in DY and SIDIS

SIDIS & Drell-Yan to study TMDs

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

with intense pion beam (up to 10^9 π/spill)
with the transversely polarised NH_3 target
with the COMPASS spectrometer equipped with an absorber



Cross sections:

In SIDIS: convolution of a TMD with a fragmentation function

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

→ **complementary information and universality test**