WG6 – Spin Physics
Summary Talk

WG6 Conveners:

Salvatore Fazio (BNL)

Emanuele R. Nocera (Oxford)

Silvia Pisano (LNF-INFN)

Erin Seder (CEA-Saclay)

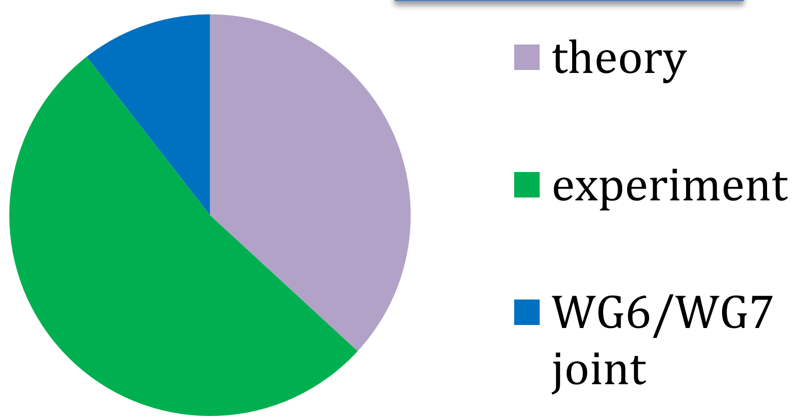
Thanks to all speakers!

TMDs & FFs
Piet Mulders
Mariaelena Bolgione
Osvaldo Gonzalez Hernandez
Wim Cosyn
Erin Seder
Kiyoshi Tanida
Christopher Dilks
Salvatore Fazio
Harut Avagyan
Charlotte Van Hulse
Andrea Bressan
Marcia Quaresma
Adam Szabelski

Twist 3
Shinsuke Yoshida
Yuji Koike
Kenta Yabe

Longitudinal
Nobuo Sato
Claudia Uebler
Malte Wilfert
Ana Sofia Nunes
Ralf Seidl
Suvarna Ramachandran
Bernd Surrow

34+4 talks

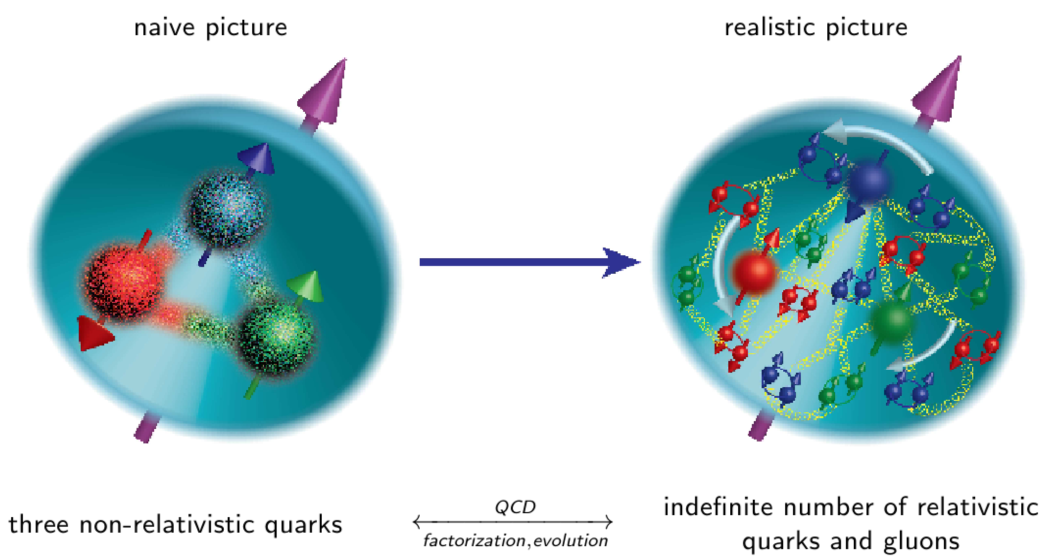


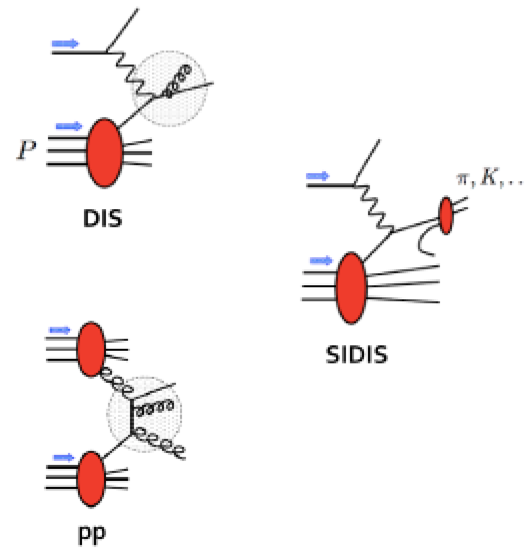
GPDs
Dieter Muller
Gary Goldstein
Renaud Boussarie
Christian Wiese
Silvia Niccolai
Kyungseon Joo
Philipp Jorg
Sergey Manaenkov

Future experiments (WG6/WG7 joint session)
Jean-Philippe Lansberg
Elke Aschenauer
Rolf Ent
Tianbo Liu

Apologies where we omitted your favourite topic

A (multi-D) QCD picture of the proton





A (multi-dimensional) mapping of the nucleon structure in terms of its elementary degrees of freedom (quarks and gluons) which combines spin with QCD dynamics

How is the nucleon spin carried by quark and gluon spins and orbital momenta?

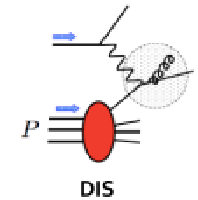
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu^2) + \Delta G(\mu^2) + \mathcal{L}_q(\mu^2) + \mathcal{L}_g(\mu^2)$$

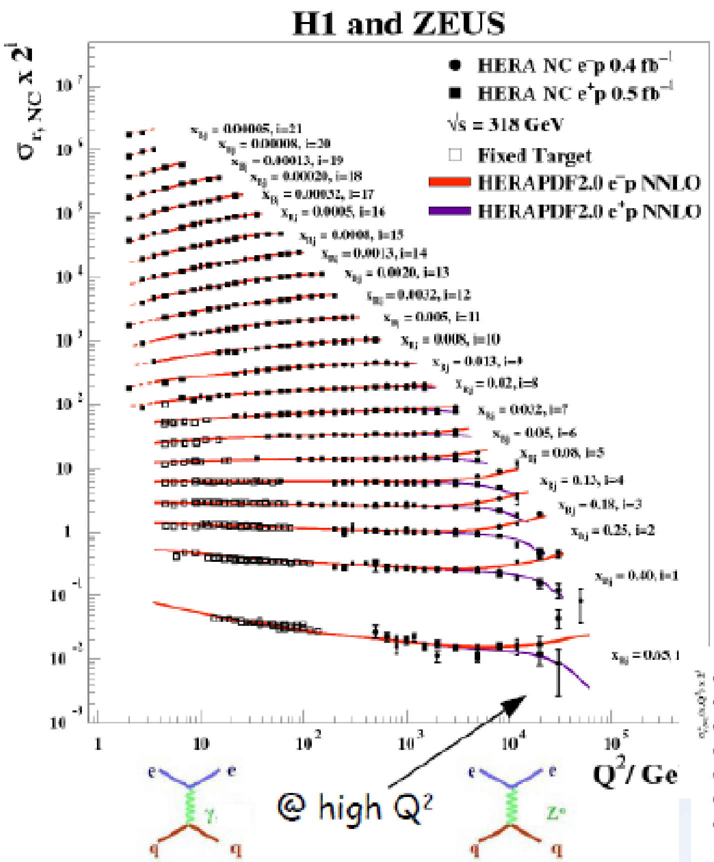
What is the role of spin in QCD?

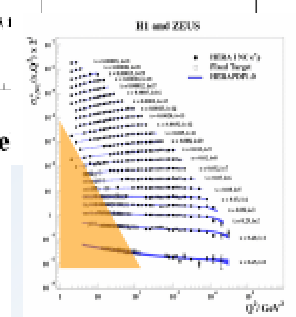
WG6 – Spin Physics Summary Talk

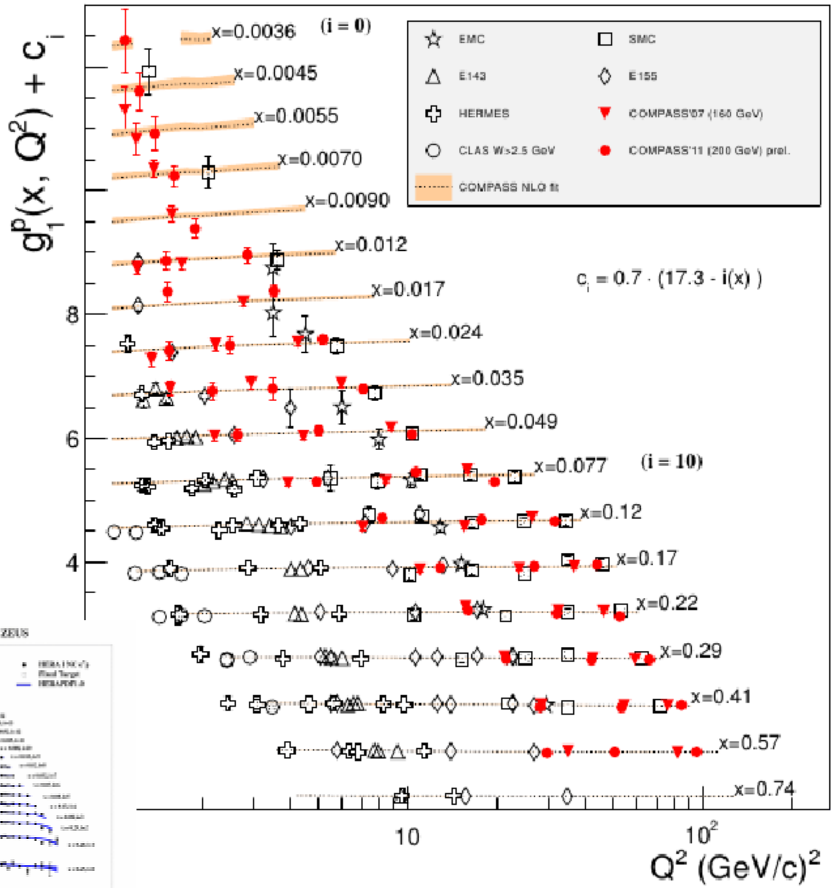
Inclusive DIS

[P. Nadolsky and R. Seidl, plenary]





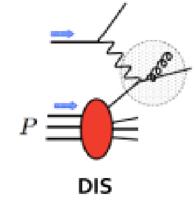




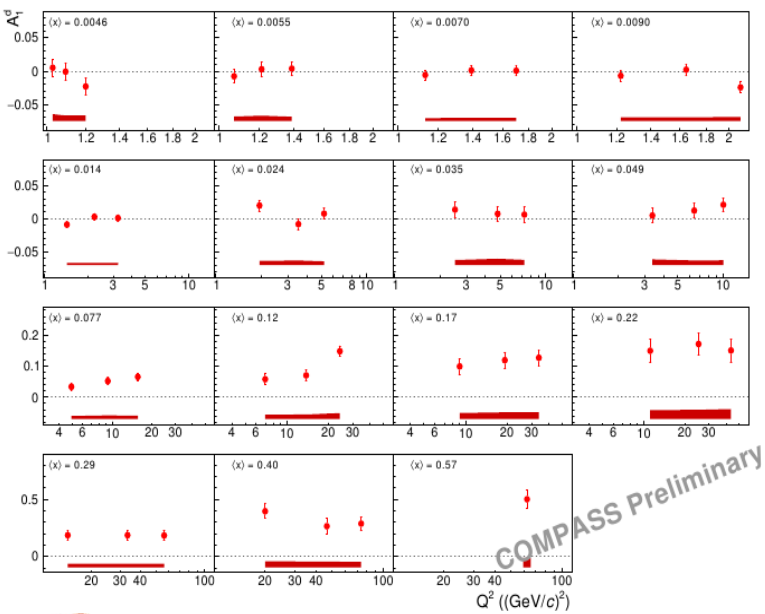
WG6 – Spin Physics Summary Talk

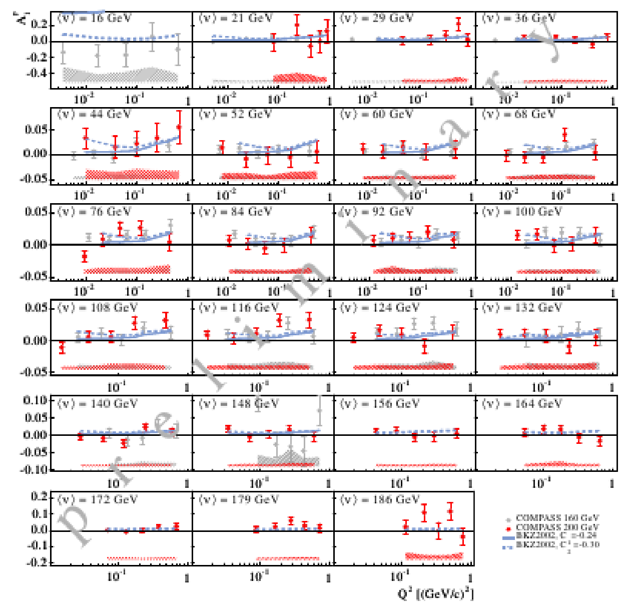
Inclusive DIS

[M. Wilfert and A.S. Nunes]



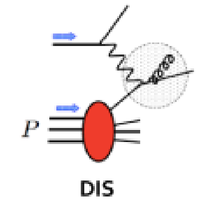
- Final results on A_1 and g_1 on deuteron from the 2002-2006 COMPASS run (~2 times more data with a precision improvement w.r.t. 2002 data only)
- Results for A_1 and g_1 on proton at low Q and low x in two-dimensional bins (transition from the photoproduction regime to the pQCD regime) (evidence of positive spin effects at very low x, no dipendence on kinematics)

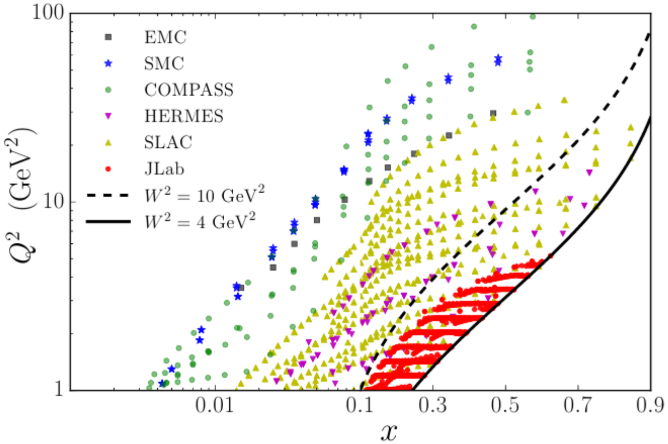


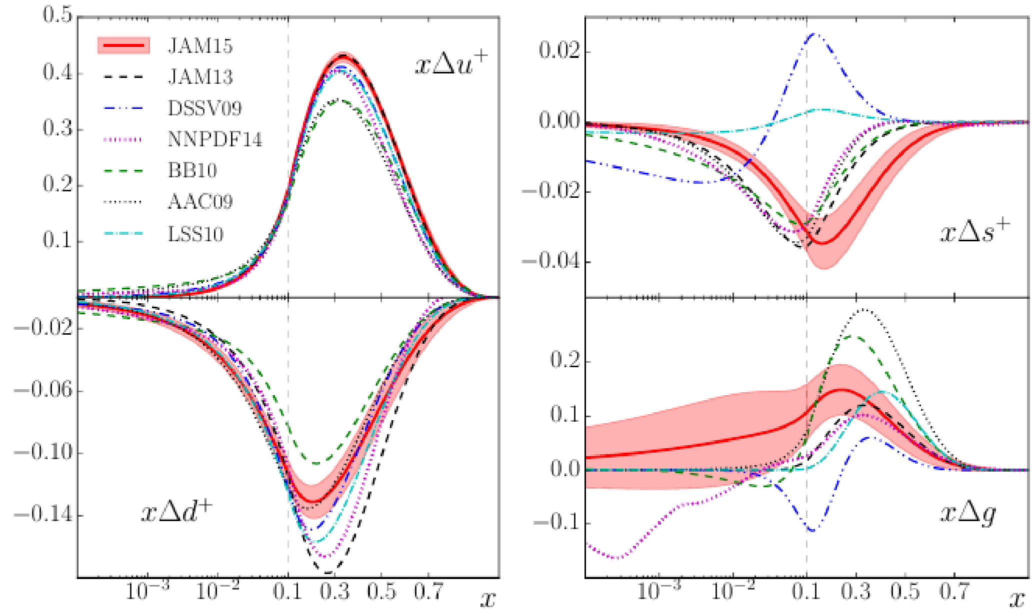


Polarized PDFs from DIS

[N. Sato]





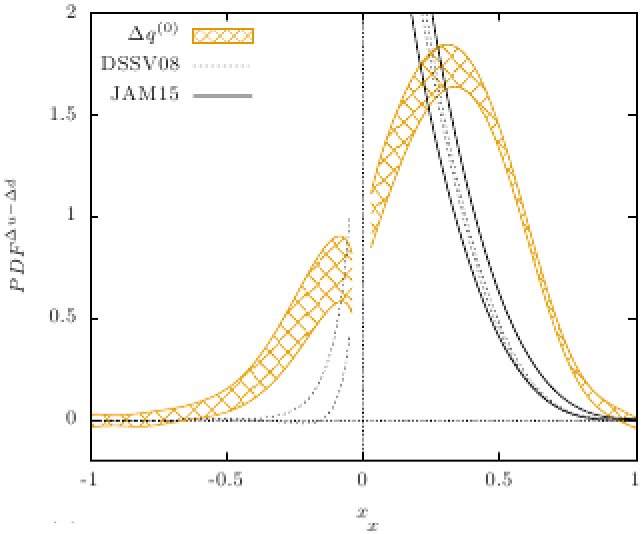


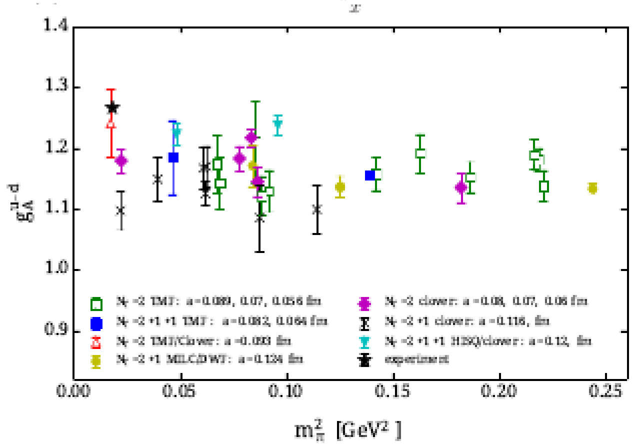
moment	truncated	full
Δu^+	0.82 ± 0.01	0.83 ± 0.01
Δd^+	-0.42 ± 0.01	-0.44 ± 0.01
Δs^+	-0.10 ± 0.01	-0.10 ± 0.01
$\Delta\Sigma$	0.31 ± 0.03	0.28 ± 0.04
ΔG	0.5 ± 0.4	1 ± 15
d_2^p	0.005 ± 0.002	0.005 ± 0.002
d_2^n	-0.001 ± 0.001	-0.001 ± 0.001
h_p	-0.000 ± 0.001	0.000 ± 0.001
h_n	0.001 ± 0.002	0.001 ± 0.003

- Non-zero twist 3 quark distribution
- Twist-4 contribution to g_1 consistent with zero
- Negative total strangeness
- Large uncertainties on the gluon

Proton spin from the lattice

[C. Wiese]

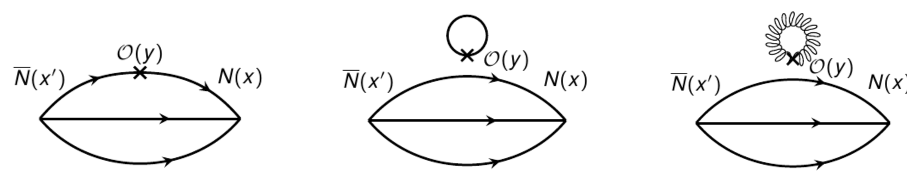




An additional non-perturbative ab initio prediction
Two options viable:

- direct computation of helicity PDFs ([F. Steffens, WG1])
- compute proton form factors from matrix elements of local operators

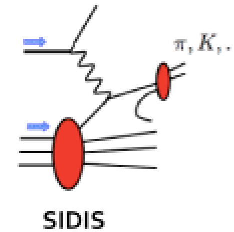
$$\langle P|\overline{q}\gamma^\mu\gamma^5 q|P\rangle = \overline{U}(P)G_A^q(0)U(P)$$



$\Delta\Sigma$	up	down	strange	combined
connected	0.897(23)	-0.314(12)	-	0.583(24)
disconnected	-0.060(10)	-0.060(10)	-0.045(10)	-0.165(17)
combined	0.837(25)	-0.374(16)	-0.045(10)	0.418(29)

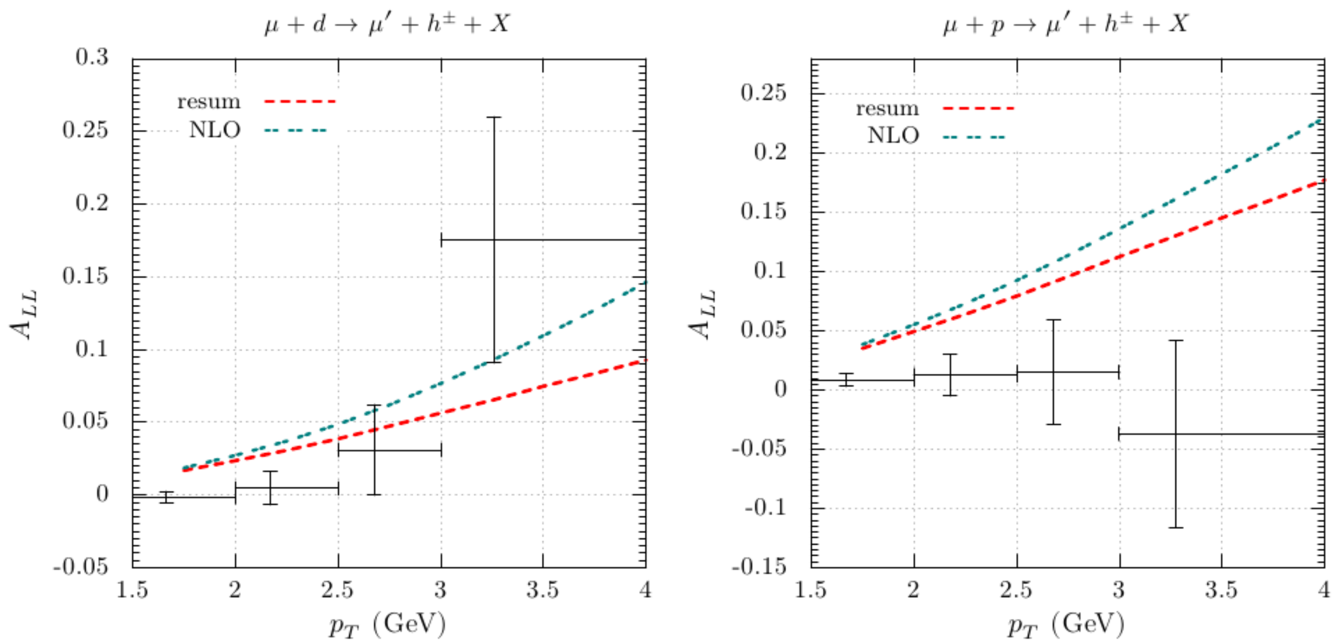
High-p_T hadroproduction

[C. Uebler]



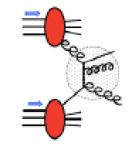
High p_T hadron production (sensitive to the gluon polarization)
Resummation of log threshold corrections by soft/collinear gluon emission at NLL

- Predictions for A_{LL} decrease when resummations effects are taken into account
- Discrepancy between data and theoretical predictions (theory predict a large ALL for protons than for deuterons, in contrast to the data)



[Phys.Rev.D92,094029]

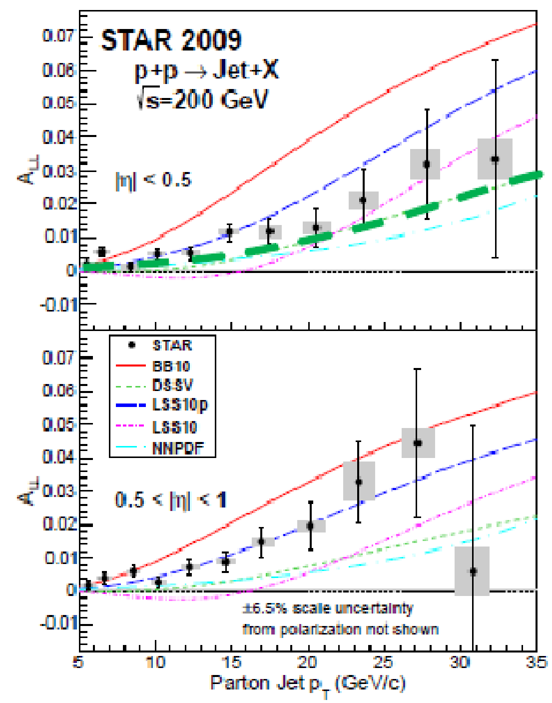
Gluon helicity at RHIC



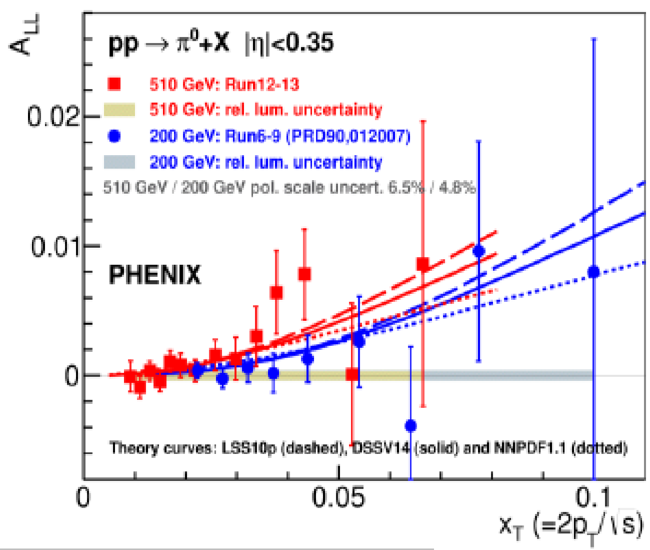
Inclusive jets and pions (new) **[R. Seidl]**

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \mathrm{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \mathrm{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	

STAR: arXiv:1405.5134

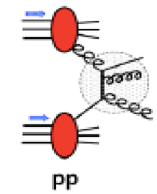


PHENIX PRD 93 (2016) 011501



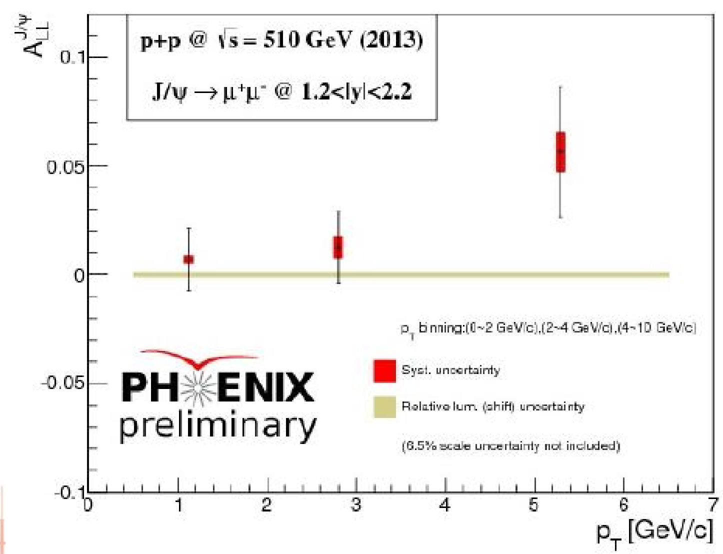
First nonzero pion double spin asymmetries confirm a sizeable positive gluon spin contribution
Sensitivity extended at 510 GeV down to ~0.01

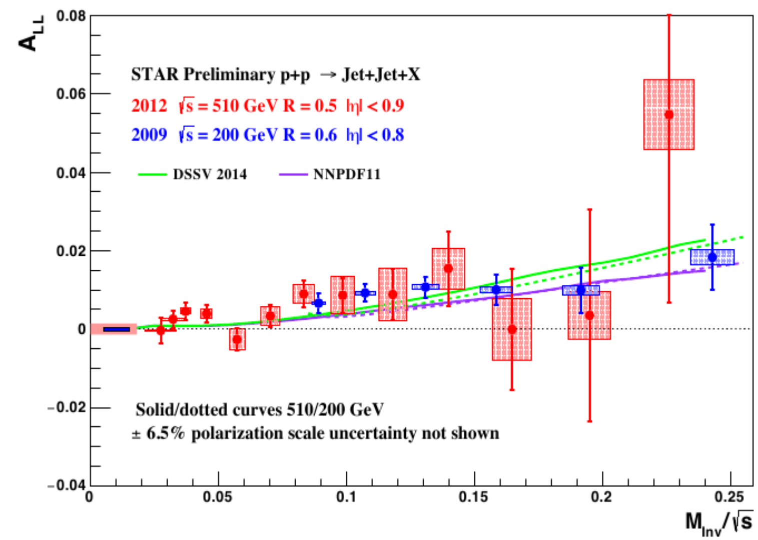
Gluon helicity at RHIC



J/Psi and dijets **[R. Seidl and S. Ramachandran]**

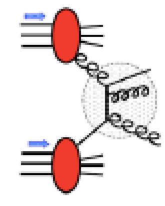
- Forward J/Psi asymmetry down to x~0.001 with a slightly positive asymmetry (potential strong impact if production mechanism known)
- First dijet measurements at 510 GeV complete the measurement at 200 GeV (will extend the knowledge of the gluon helicity below x~0.05) (in 2013 STAR collected ~3 times more data at 510 GeV)



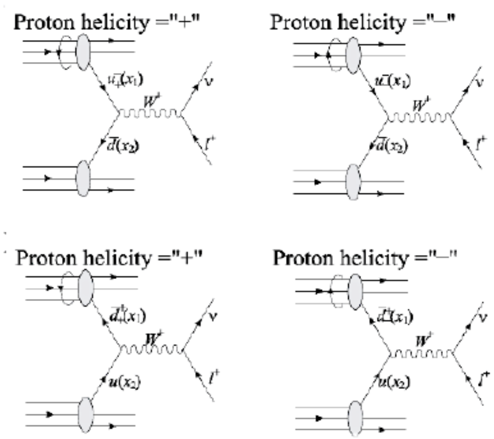


Sea quarks at RHIC

[B. Surrow]

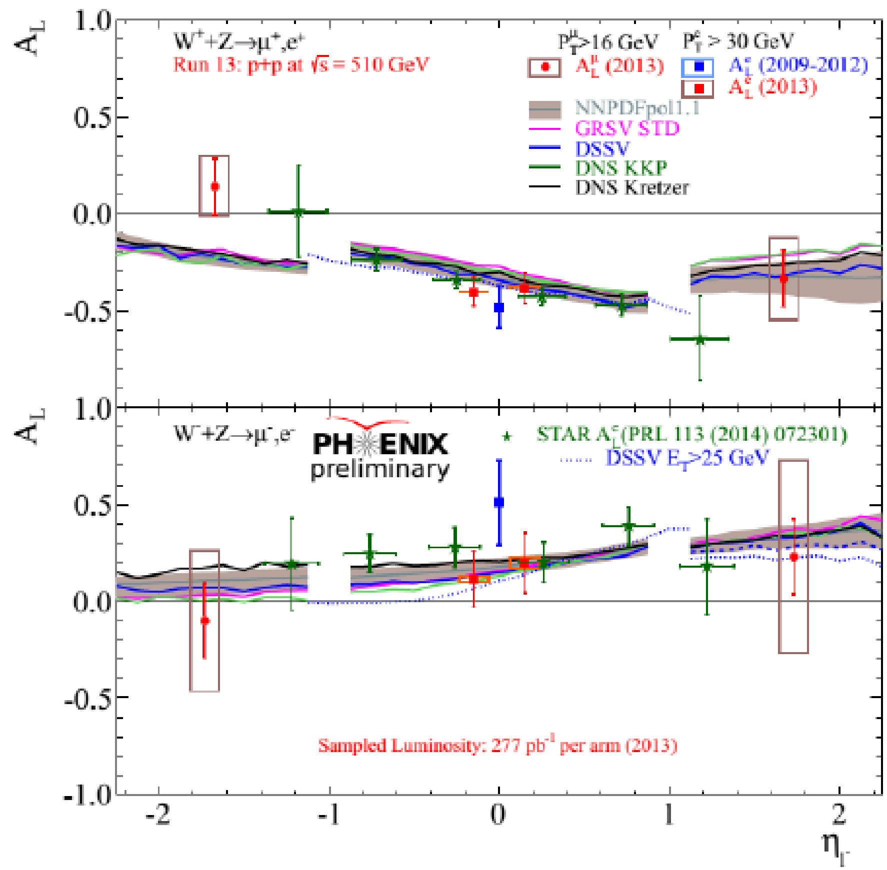


Forward rapidity (STAR) and mid-rapidity (new, PHENIX) results (run 11/12)
(results suggest a sizable anti-u quark polarization along with broken polarized sea)

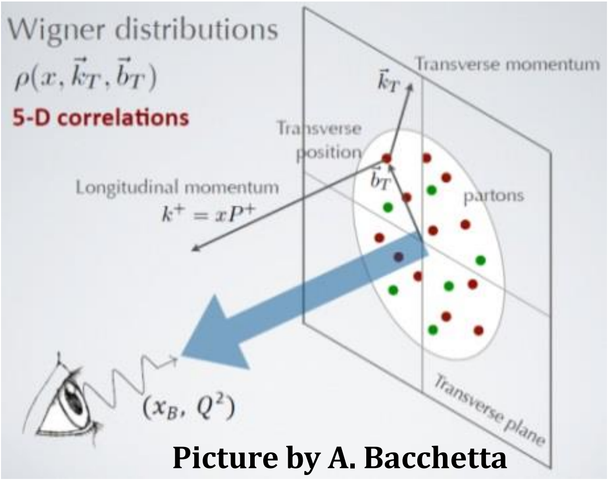


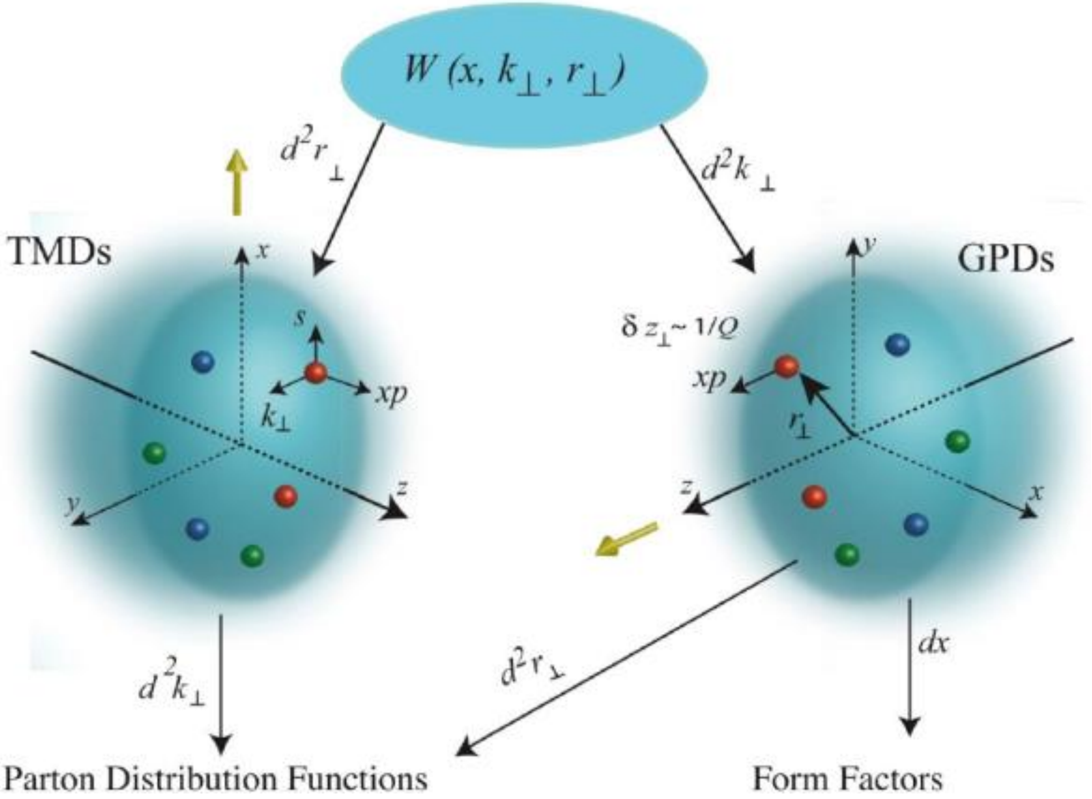
$$A_L^{W^-} \sim \frac{\Delta \bar{u}_{x_1} d_{x_2} (1-\cos\theta)^2 - \Delta d_{x_1} \bar{u}_{x_2} (1+\cos\theta)^2}{\bar{u}_{x_1} d_{x_2} (1-\cos\theta)^2 - d_{x_1} \bar{u}_{x_2} (1+\cos\theta)^2}$$

backward lepton rapidity   forward lepton rapidity



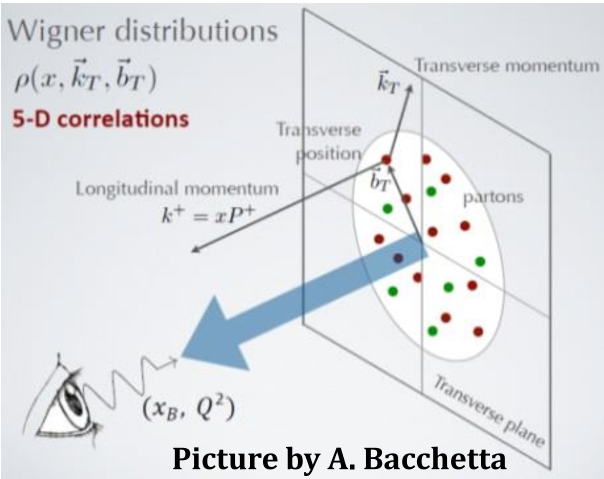
From 1D to 3D





- how charges are distributed inside the nucleon
- macroscopic nucleon properties in terms of elementary degrees of freedom

From 1D to 3D



- how charges are distributed inside the nucleon
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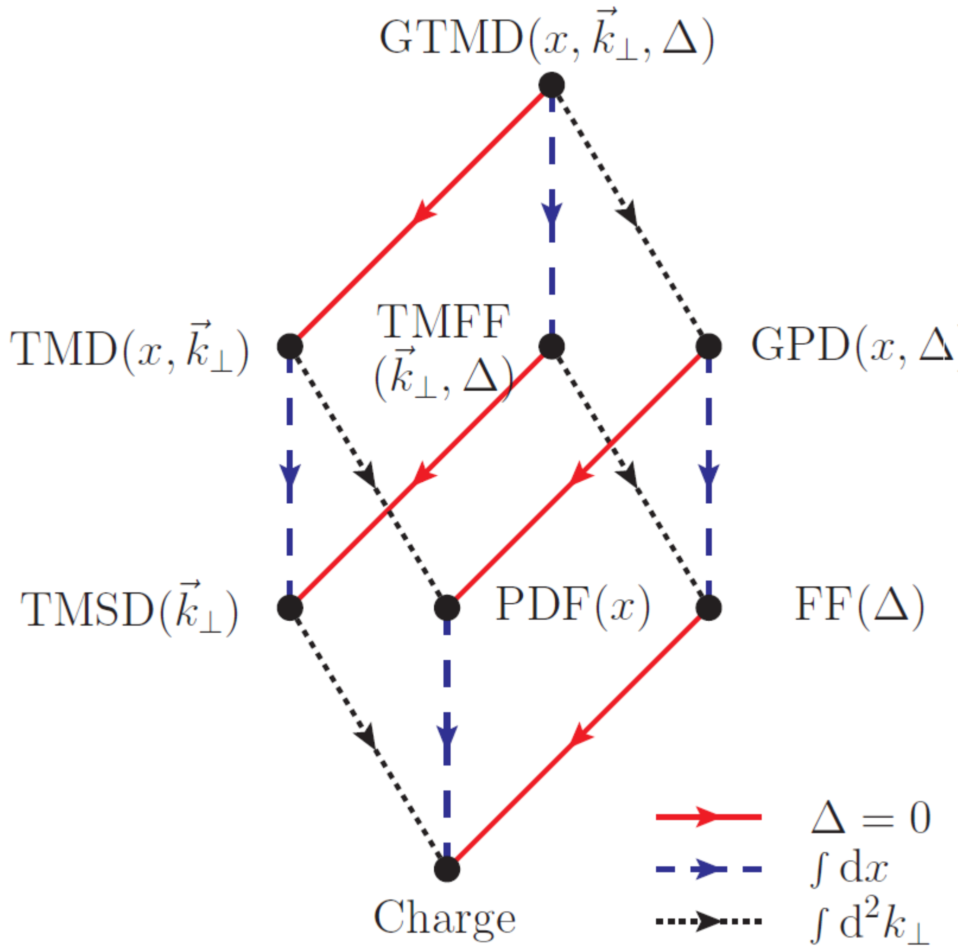
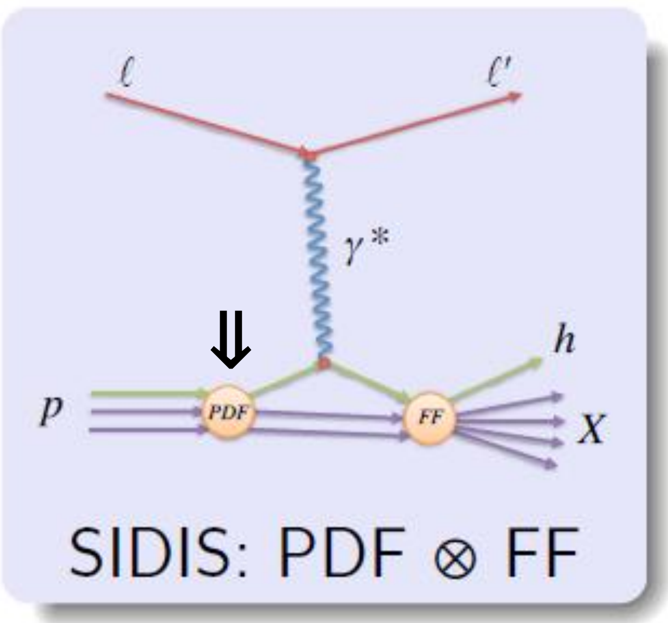


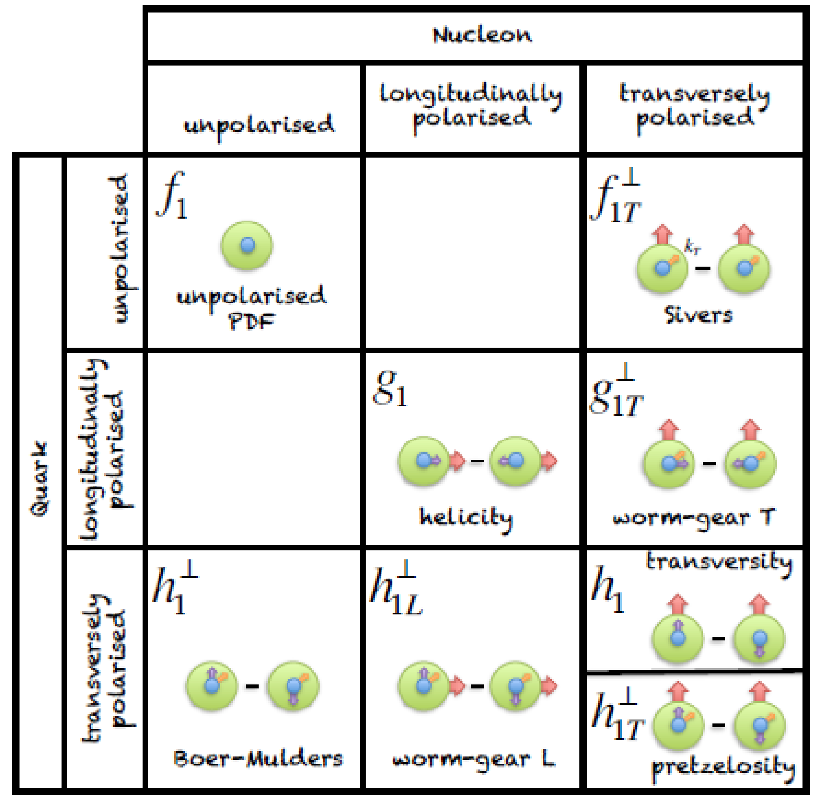
Lorcé et al., JHEP05 (2011) 041

3D nucleon mapping in the momentum space

Tranverse Momentum Dependent distributions map the nucleon in the momentum space

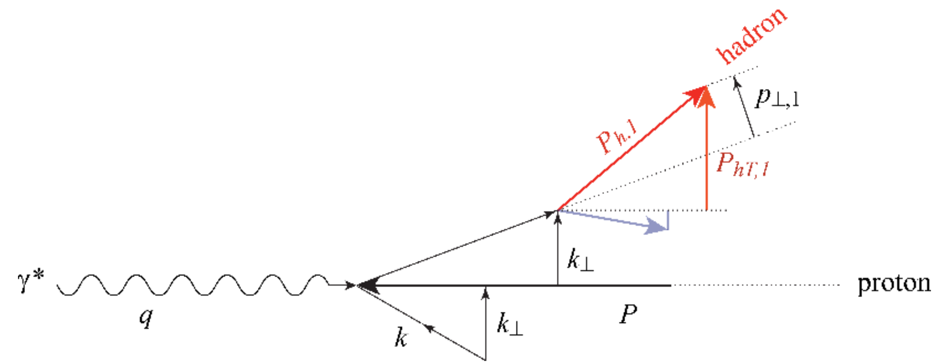
Accessed through Semi-Inclusive DIS

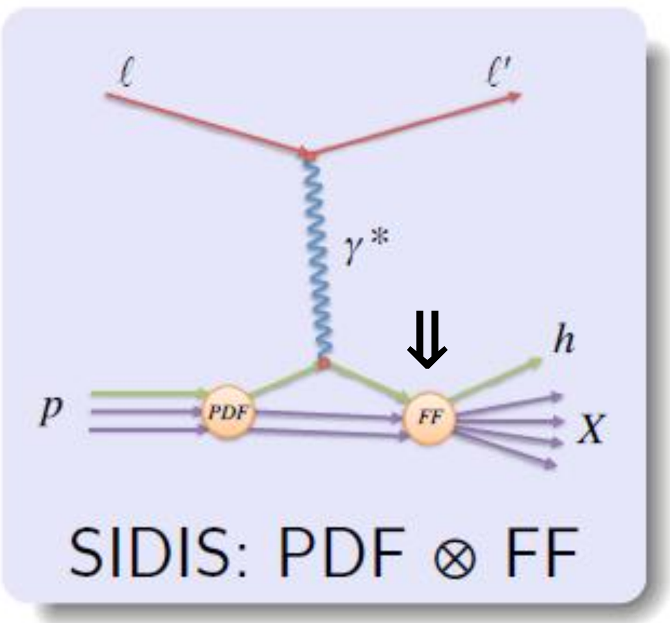




3D nucleon mapping in the momentum space

Fragmentation functions describe the hadronization, *i.e.* the **transition from elementary to hadron degrees of freedom**





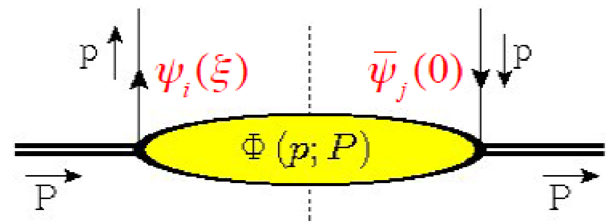
q/H	U	L	T
U	$\boldsymbol{D_1}$		$H_1^\perp$
L		$\boldsymbol{G_{1L}}$	$H_{1L}^\perp$
T	$H_1^\perp$	G_{1T}	$\boldsymbol{H_1}, H_{1T}^\perp$

Gauge links and process dependence

[P. Mulders]

Non perturbative bound states implemented through correlators.
Gauge links accounts for non locality & color gauge invariance

$$\Phi_{ij}(x,p_T;n) = \int \frac{d\,\xi{\cdot}P\,d^2\xi_T}{(2\pi)^3}\,e^{ip\cdot\xi}\langle P,S|\overline{\psi}_j(0)\,\psi_i(\xi)|P,S\rangle\,\Big|_{\xi\cdot n=0}$$



⇒ Gauge links are process dependent, **universality is lost**

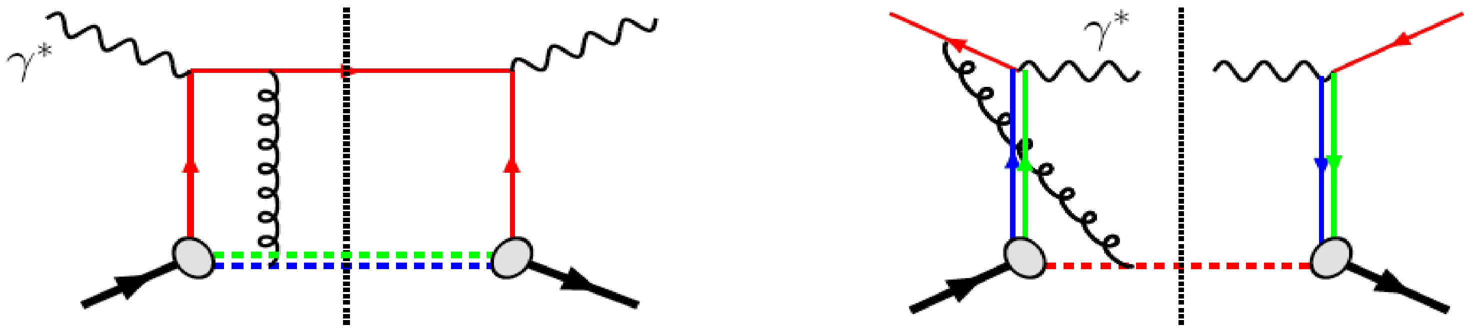
$$\Phi_{ij}^{q[C]}(x,p_T;n) = \int \frac{d(\xi.P)d^2\xi_T}{(2\pi)^3}\,e^{ip.\xi}\left\langle P\middle|\bar{\psi}_j(0)U_{[0,\xi]}^{[C]}\psi_i(\xi)\middle|P\right\rangle_{\xi.n=0}$$

path dependent gauge link

Testing QCD: Sivers sign change

[S. Fazio, E. Aschenauer]

Fundamental prediction from the **Gauge Invariance** of QCD



Sivers (DIS) = - Sivers (DY or W or Z)

Test through Drell-Yan process: COMPASS (CERN), SeaQuest (proposed at FermiLab)

- strong background suppression, high luminosity
- @STAR in 2017

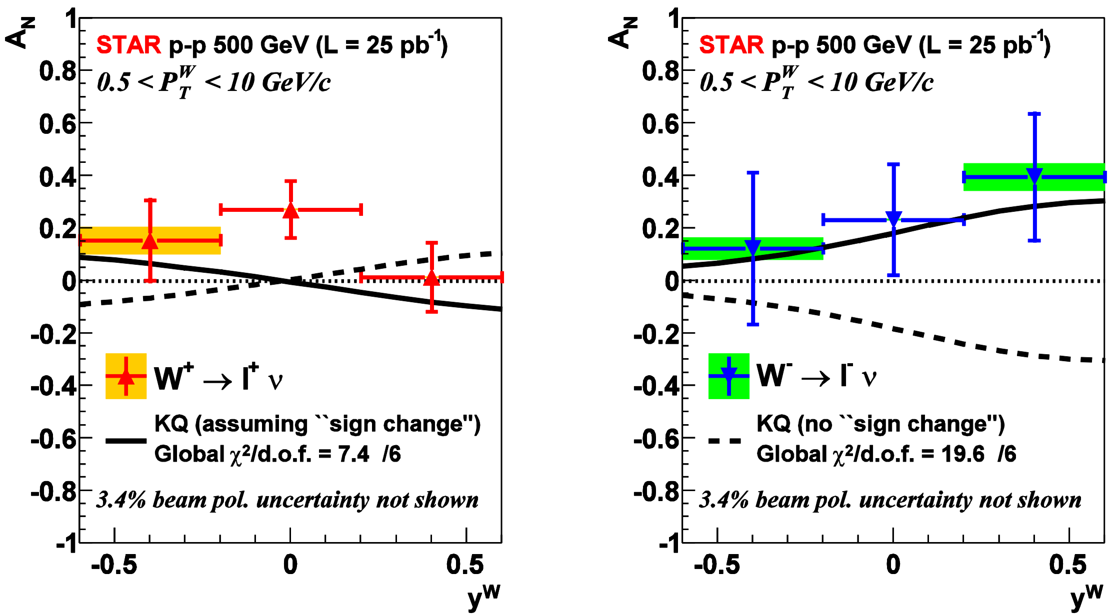
Polarized weak boson production

- very low background
- Very-high Q^2 scale (W/Z mass)

Sivers sign change@STAR

[S. Fazio , E. Aschenauer]

No TMD evolution effects included



- **solid line:** assumption of a <u>sign change</u> $\to$ $\chi^2(/dof) = 7.4/6$
- **dashed line:** assumption of <u>no sign change</u> $\to$ $\chi^2(/dof) = 19.6/6$

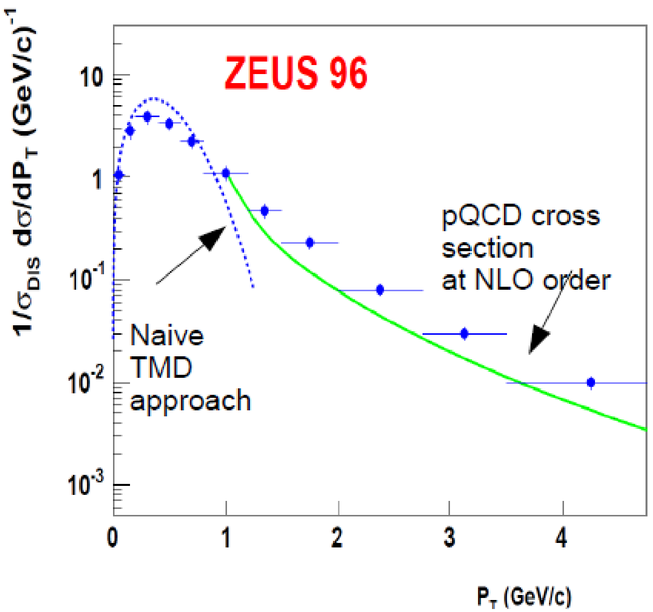
PRL 116 132301 (2016) editor's suggestion

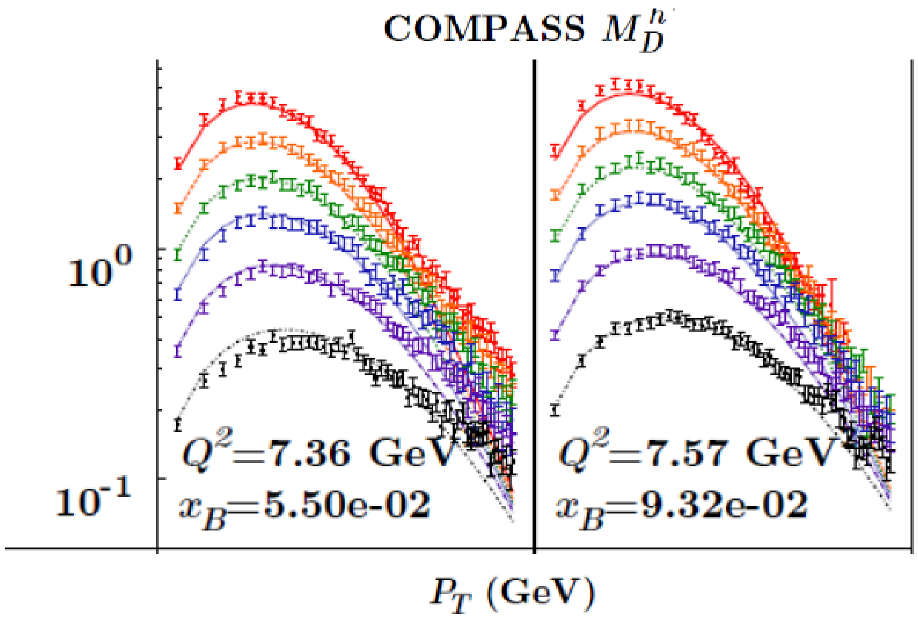
$25pb^{-1}$ pilot sample $\to$ proof of principle
New Run 17 next year: integrated delivered luminosity of $400pb^{-1}$

If there are not evolution effect, data favor Sivers change of sign hypothesis
Same test done by including the largest predicted evolution effect

Hadronization & fragmentation

[M. E. Boglione]





Calculating a cross section which describes a hadronic process over the whole q_T range is a highly non-trivial task

Fixed-order pQCD fails to describe SIDIS data at low q_T

Cross-section tail at large q_T clearly not-Gaussian

Hadronization & fragmentation

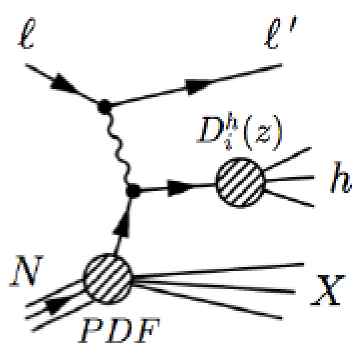
[E. Seder]

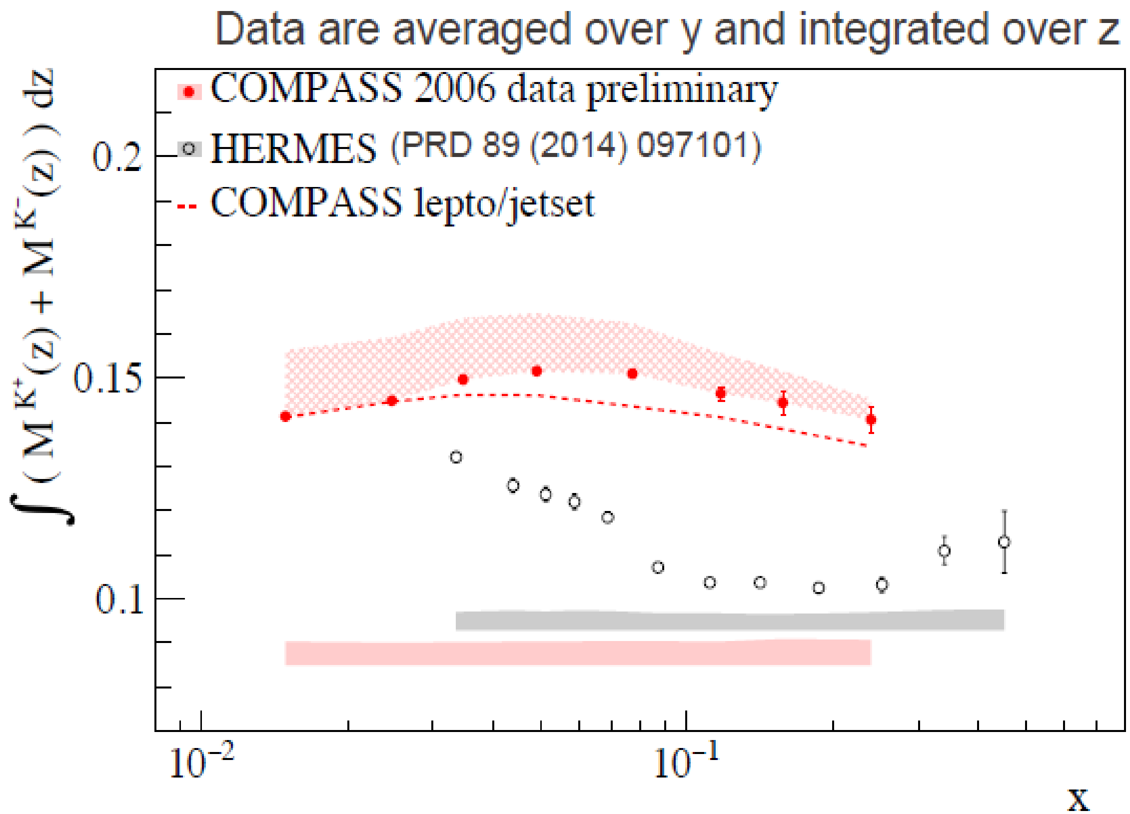
SIDIS constitutes an alternative approach to extract quark spin contribution to proton's

$\Delta S_{hyp\ \beta\ dec} = -0.08 \pm 0.01 \pm 0.02$

$\Delta S_{SIDIS} = -0.01 \pm 0.01 \pm 0.01$

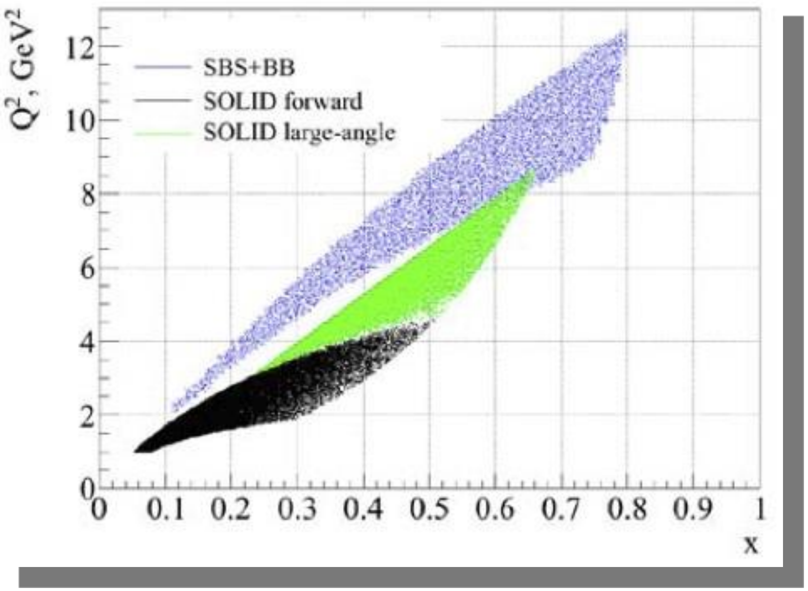
In SIDIS enters fragmentation.

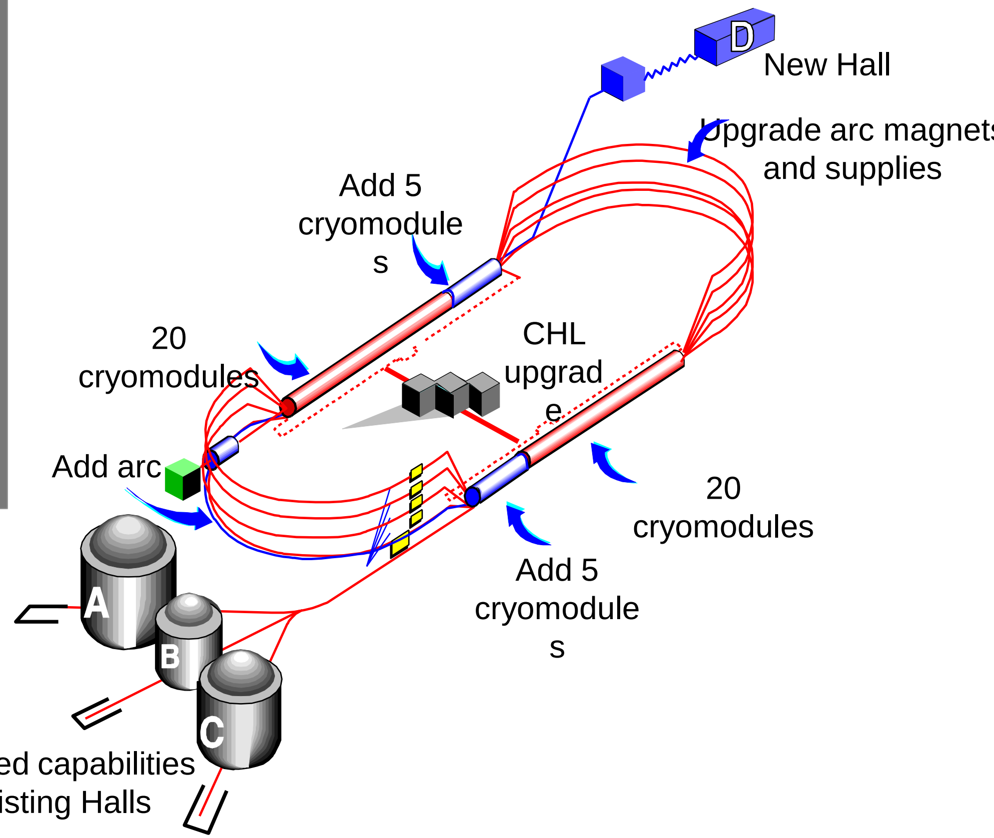




Hadronization & fragmentation

[T. Liu, R. Ent]



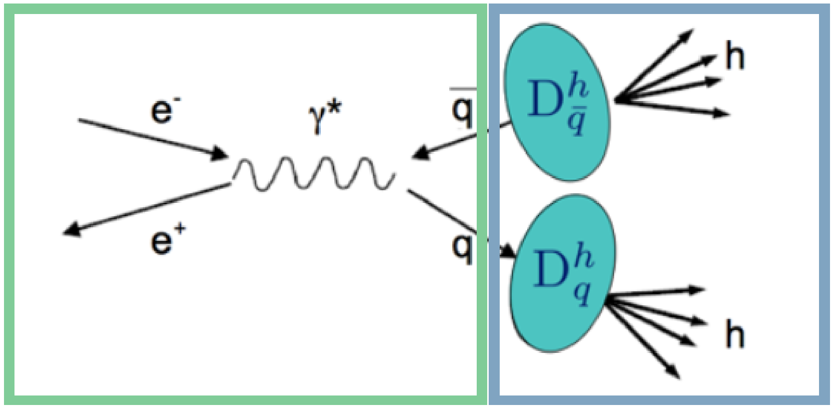


significant extension of fragmentation (pions, kaons) to the **valence region** with the 12 GeV upgrade of Jefferson

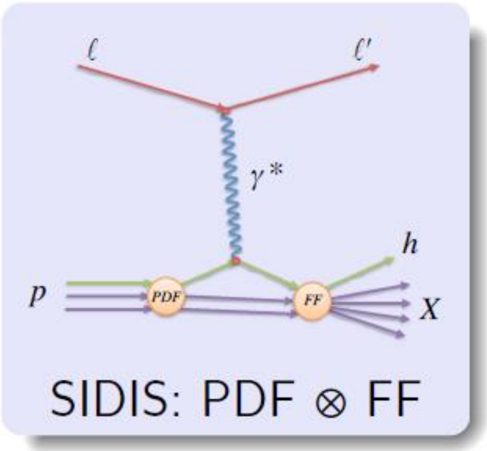
Accessing fragmentation functions

[C. Van Hulse]

calculable



non-perturbative



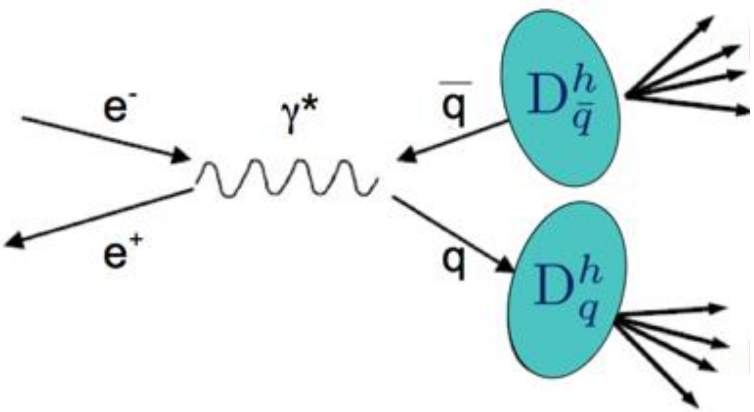
cleanest access to FF through e^+e^-collisions

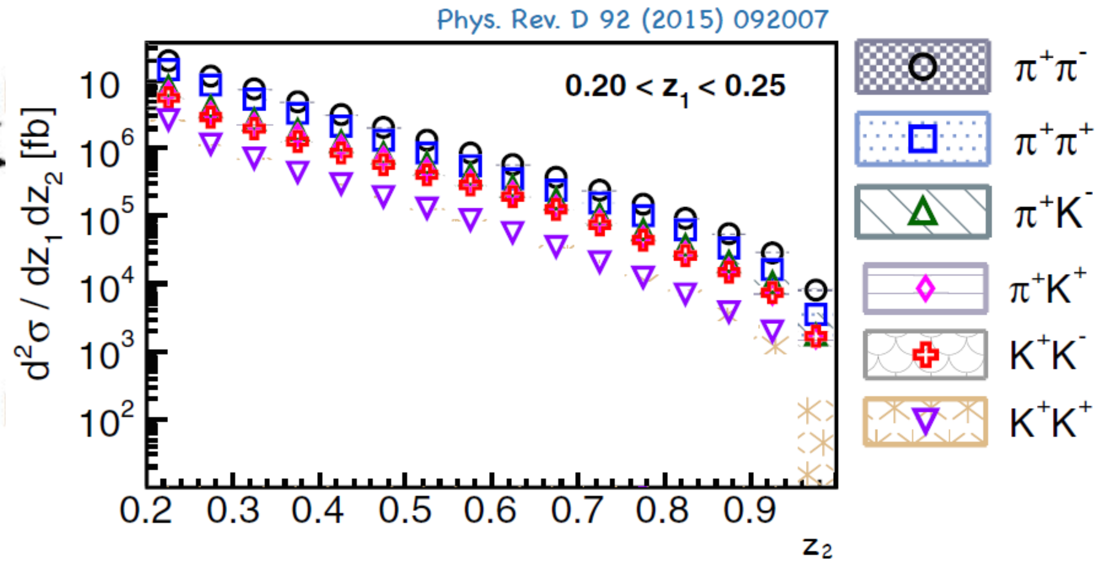
Universality of FF: used in nucleon structure analysis in SIDIS processes

global analysis needed to access flavor discrimination ⇒ pp, SIDIS data

Accessing fragmentation functions

[C. Van Hulse]





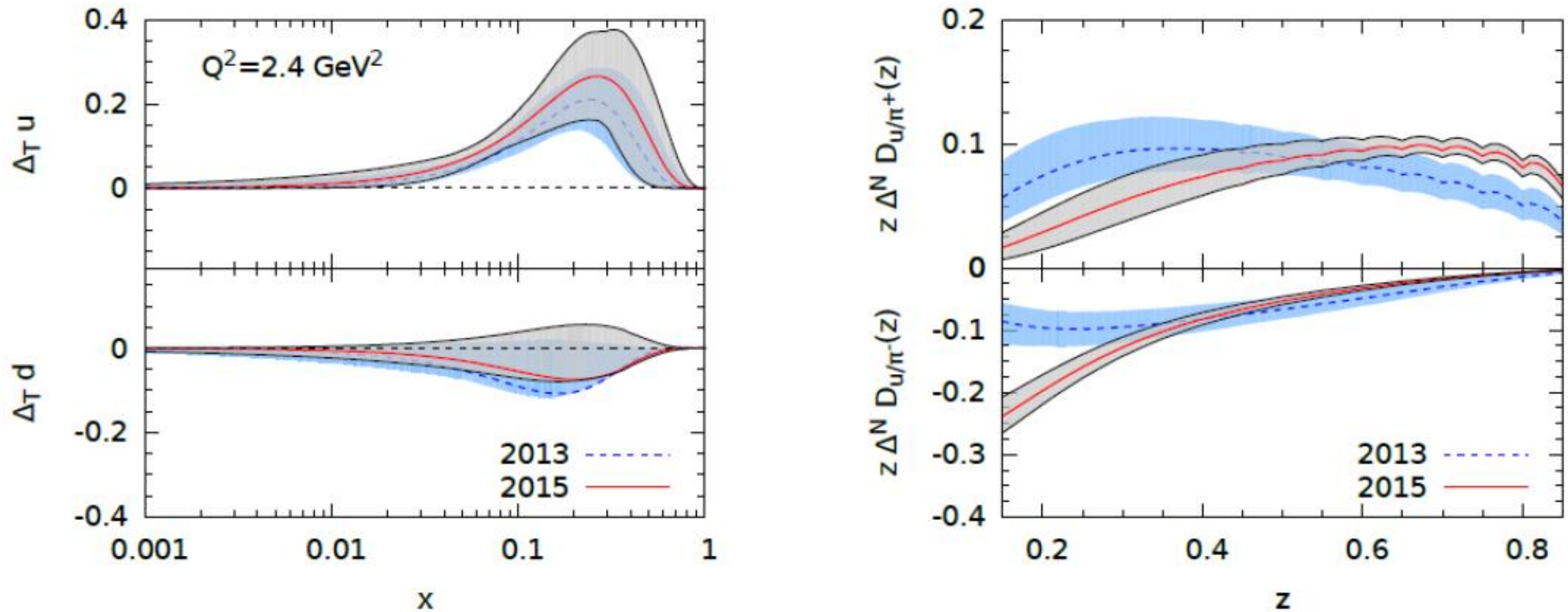
Universality of FF: used in nucleon structure analysis in SIDIS processes

global analysis needed to access flavor discrimination ⇒ pp, SIDIS data

Accessing fragmentation functions

[O. G. Hernandez]

Collins extraction from e^+e^- data



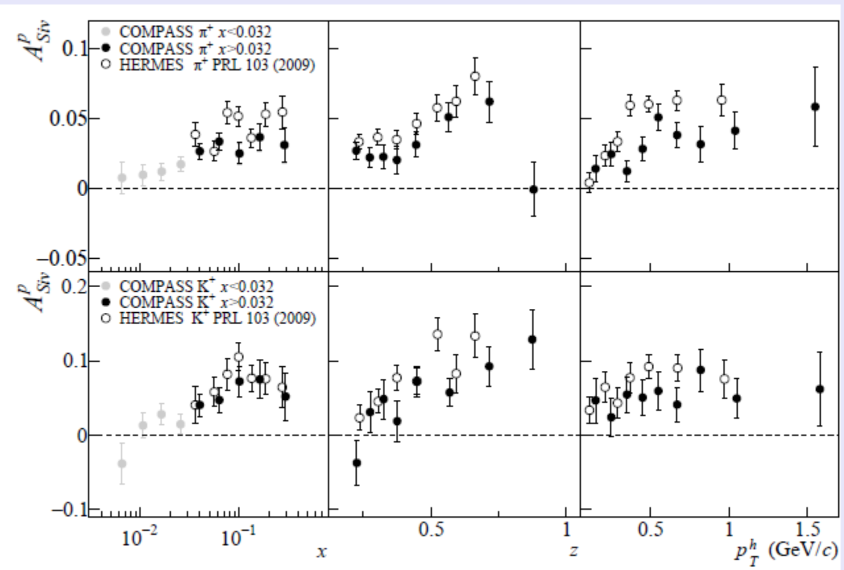
Universality of FF: used in nucleon structure analysis in SIDIS processes

global analysis needed to access flavor discrimination ⇒ pp, SIDIS data

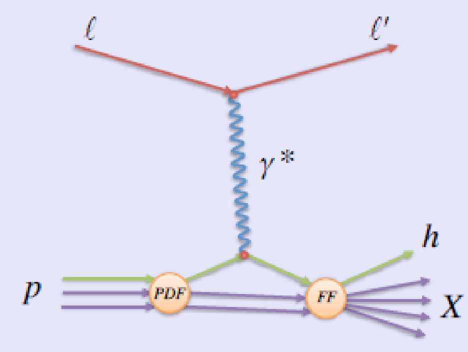
Sivers through SIDIS – COMPASS & HERMES

COMPASS SIDIS proton data from 2007 and 2010
(*PLB 744 (2015) 250*)

[A. Bressan, C. Van Hulse]



- ● COMPASS: $\langle Q^2 \rangle = 8.7\ \mathrm{GeV}/c^2$
- ○ HERMES: $\langle Q^2 \rangle = 2.4\ \mathrm{GeV}/c^2$



SIDIS: PDF ⊗ FF

possible evolution effects can be present while analyzing data from different Q^2

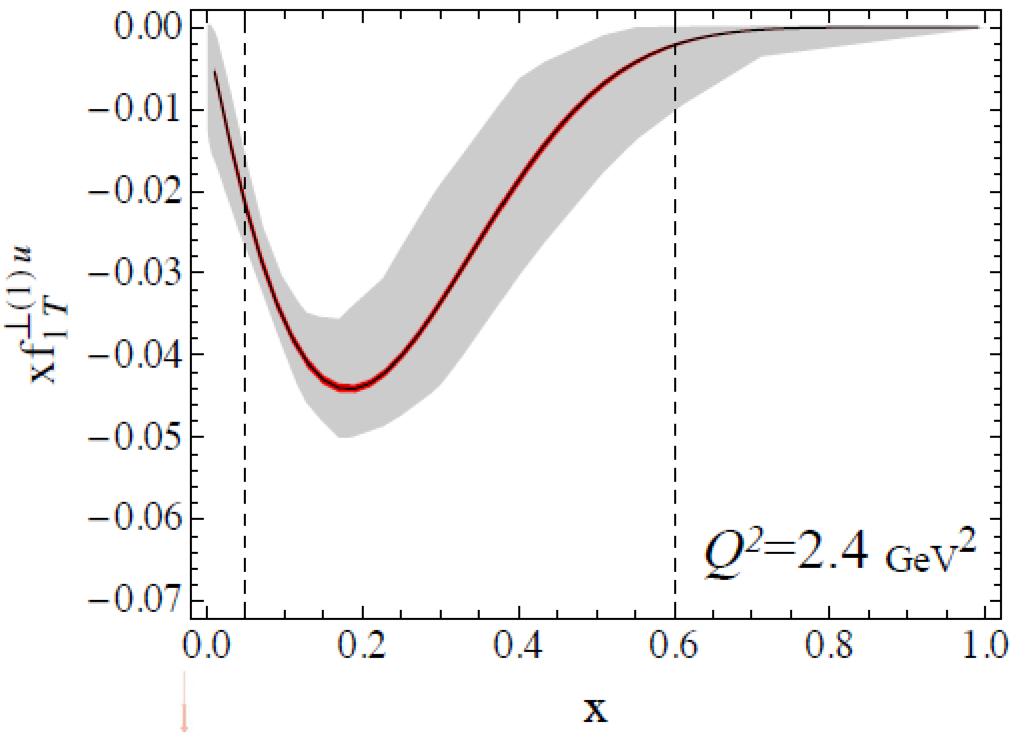
⇒ important to cover an extended Q^2 region

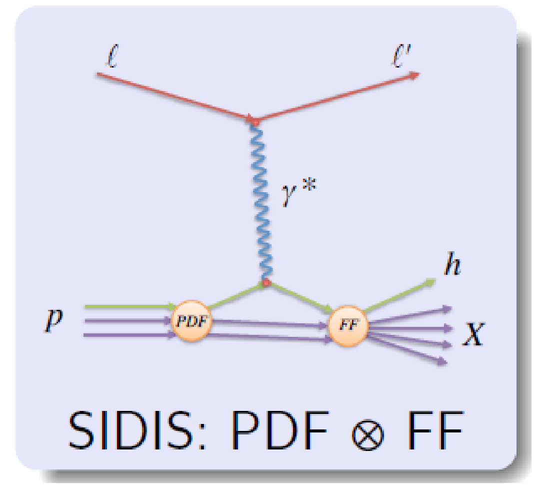
Sivers through SIDIS – SoLID & Hall-B@JLab

[T. Liu, R. Ent]

parametrization by M. Anselmino *et al.*, EPJ A 39, 89 (2009).

SoLID projection with transversely polarized neutron and proton data.



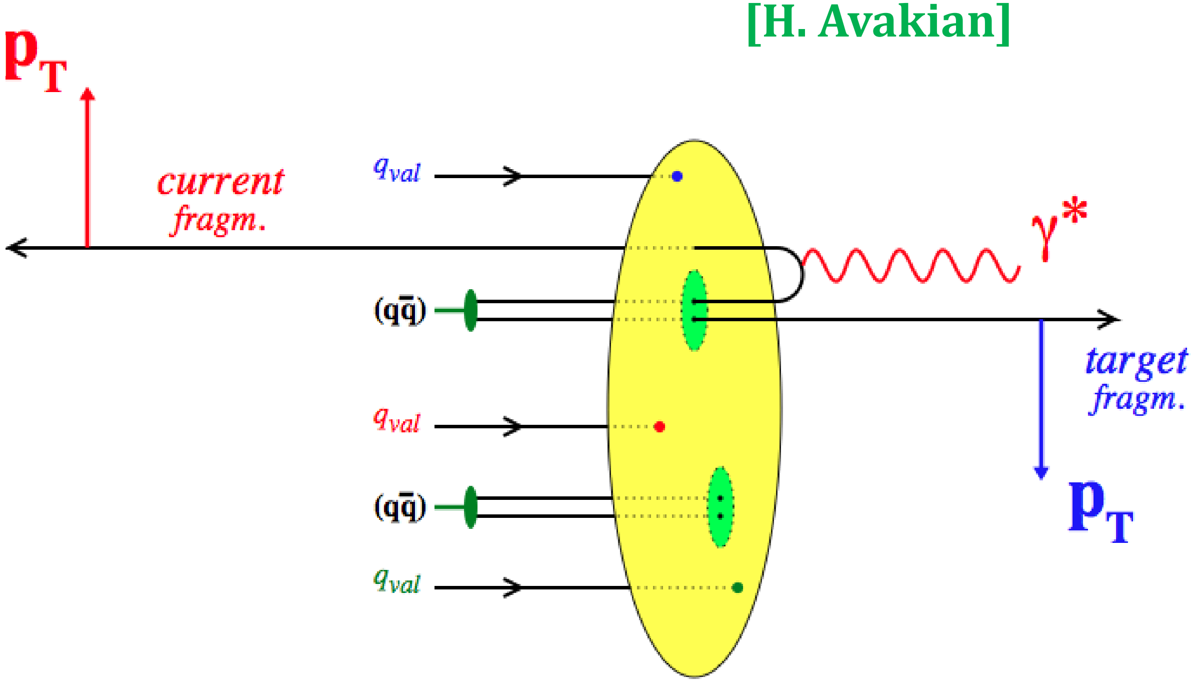


- JLab data will cover the valence region
- extended lever arm in Q^2 to test evolution

Correlated quark pairs in the nucleon

- how the remnant system dresses itself up to become a full-fledged hadron?
- control the flavor content of the final state hadron in current fragmentation (detecting the target hadron)
- access quark short-range correlations and χSB (*Schweitzer et al*)

[H. Avakian]



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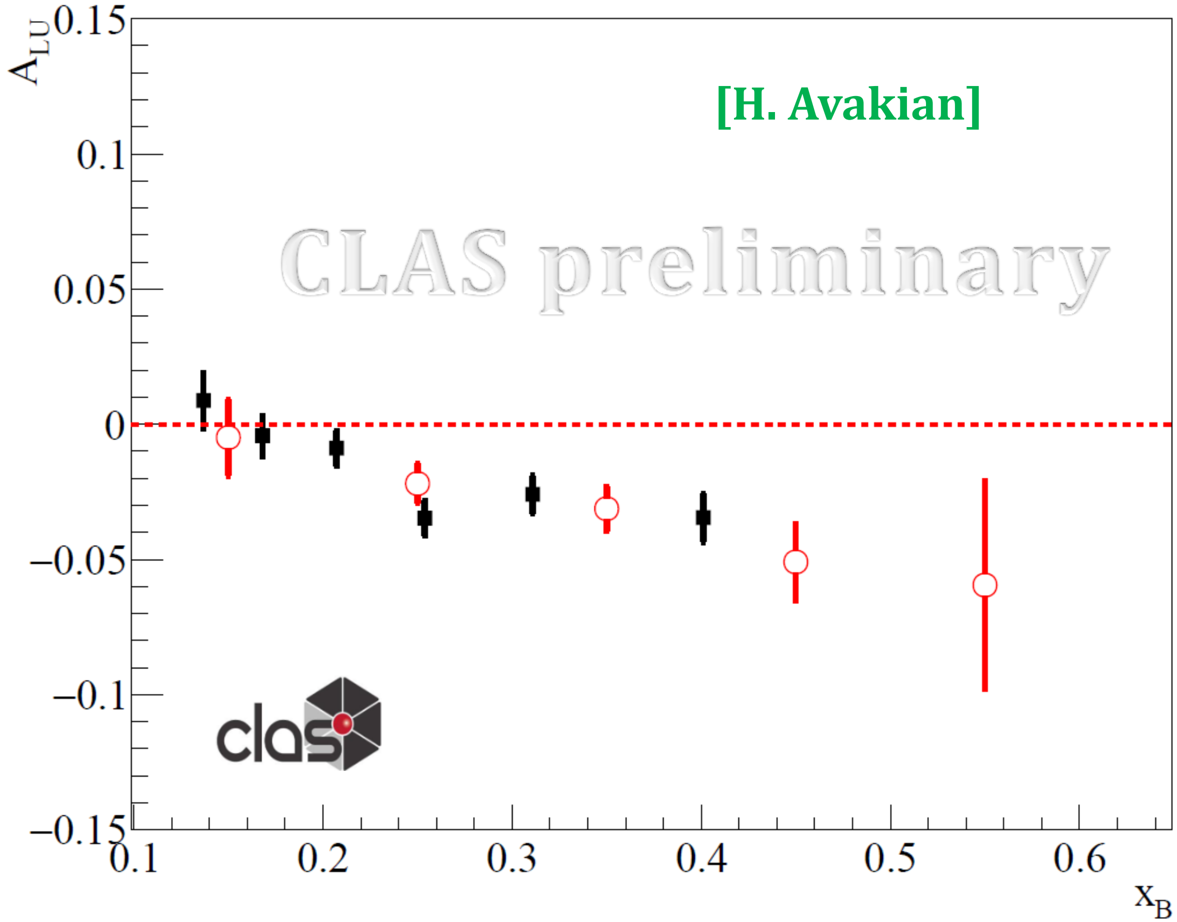
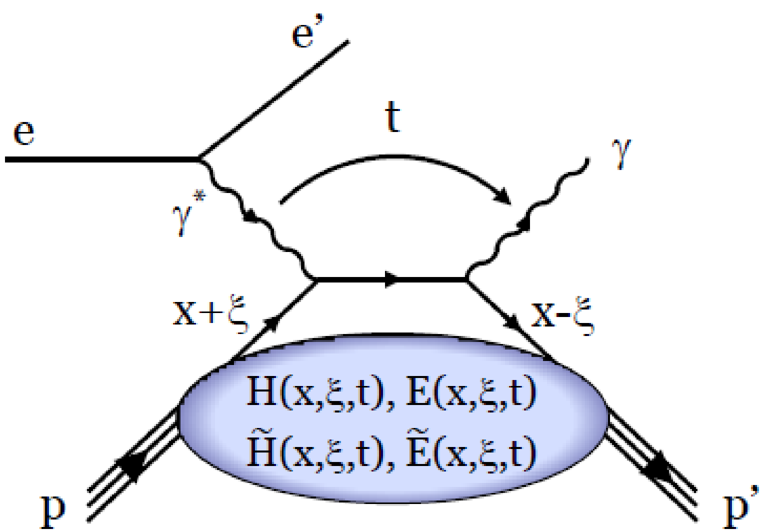


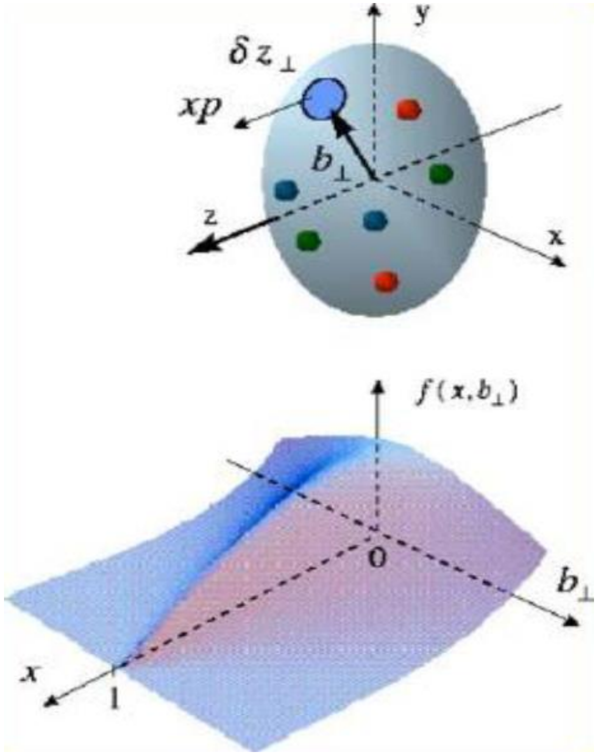
Generalized Parton Distributions

[G. Goldstein, D. Mueller]

GPDs ⇒ (2 + 1)D description of the nucleon

Relate parton tranverse position to its momentum fraction (combining 1D PDF to electromagnetic form factors)



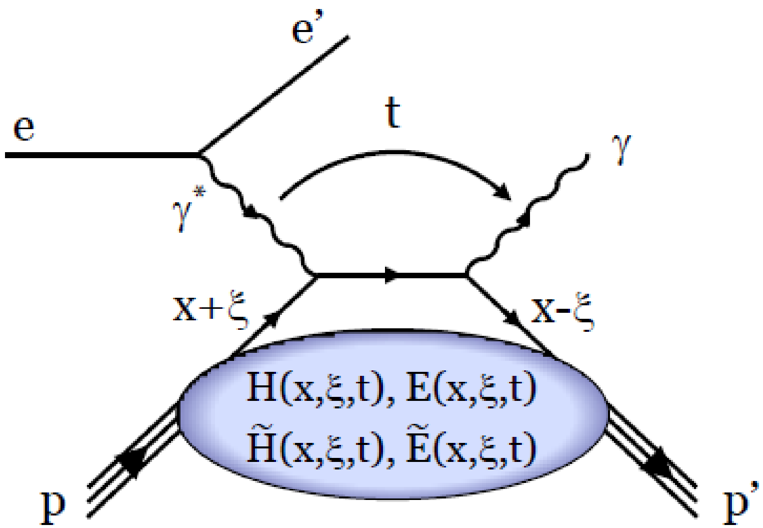


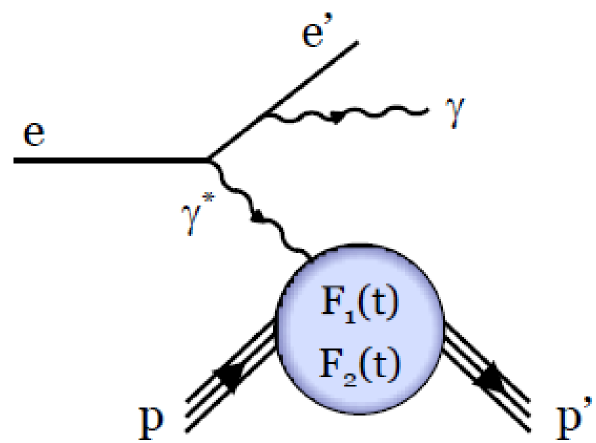
Generalized Parton Distributions

[G. Goldstein, D. Mueller]

Accessed through Deeply-Virtual Compton Scattering

Single/double spin asymmetries give access to different GPDs





Different GPDs correspond to specific polarization degrees of freedom (different charges)

Nucleon transverse size – GPD's $-t$ dependence

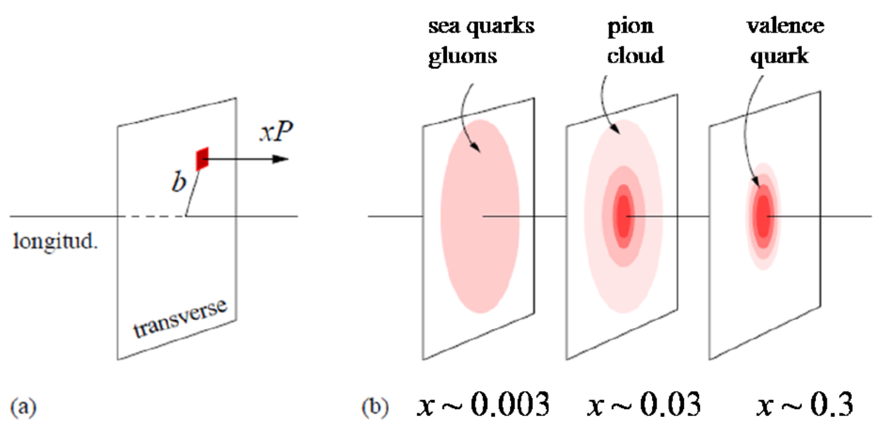
[P. Jörg]

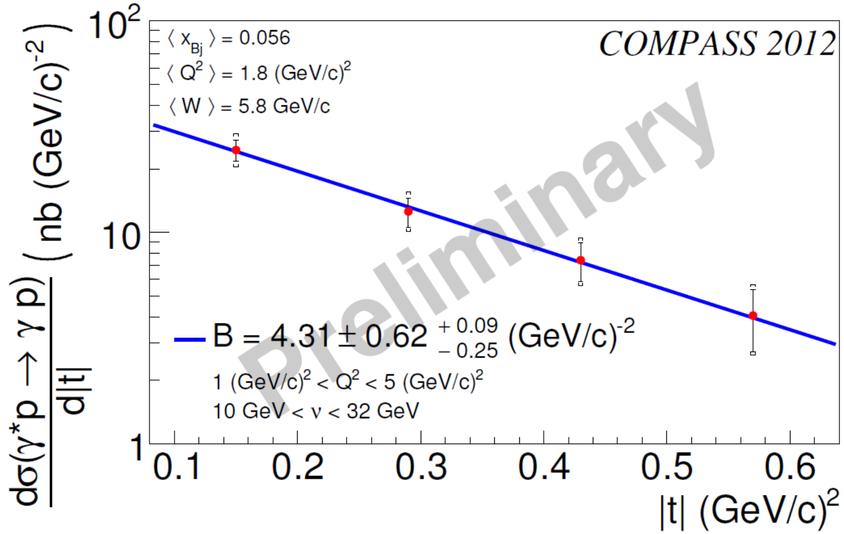
The distance $\langle r_\perp{}^2 \rangle$ between the struck quark and the spectator c.m. is given by the t-slope of the DVCS cross-section.

$$\frac{d\sigma_0{}^{DVCS}}{dt} \propto exp(-B(x_B)|t|)$$

Extracting it for different x_B values provides a tomographic picture of the nucleon, *i.e.* how its shape changes with x_B

$$B(x_B) = B_0 + 2\alpha' log\left(\frac{x_0}{x_B}\right)$$





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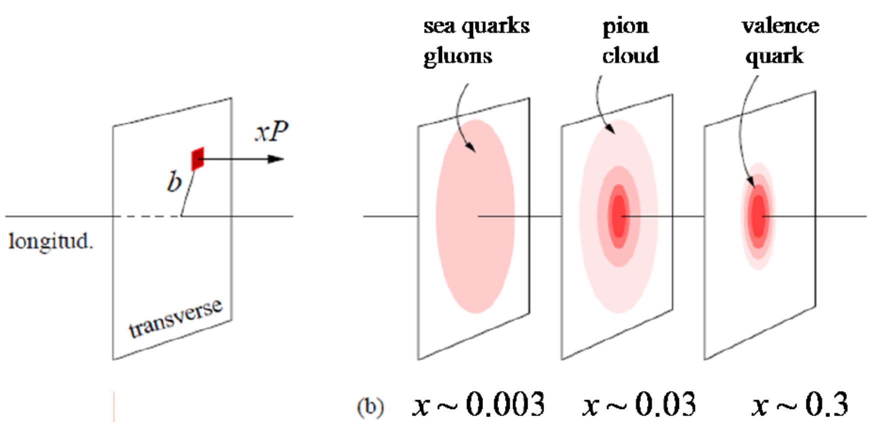
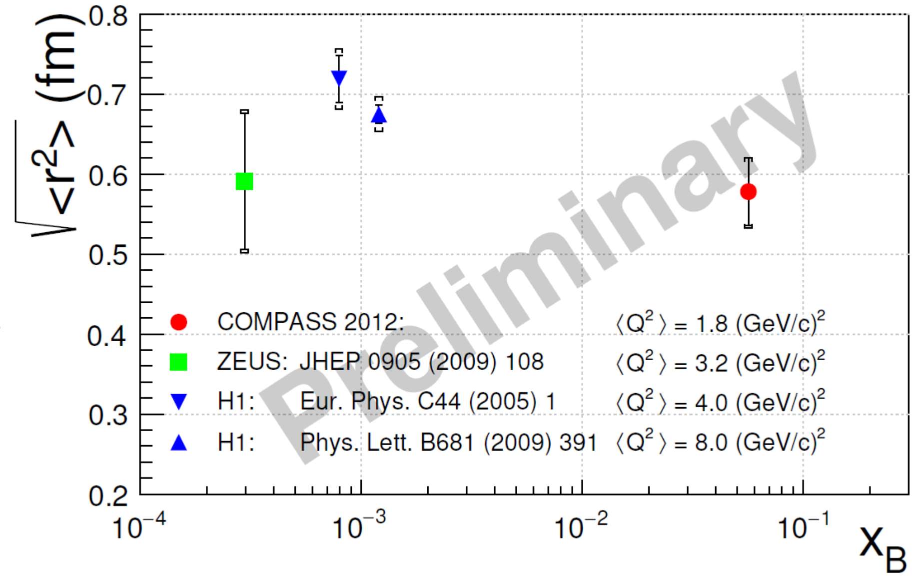
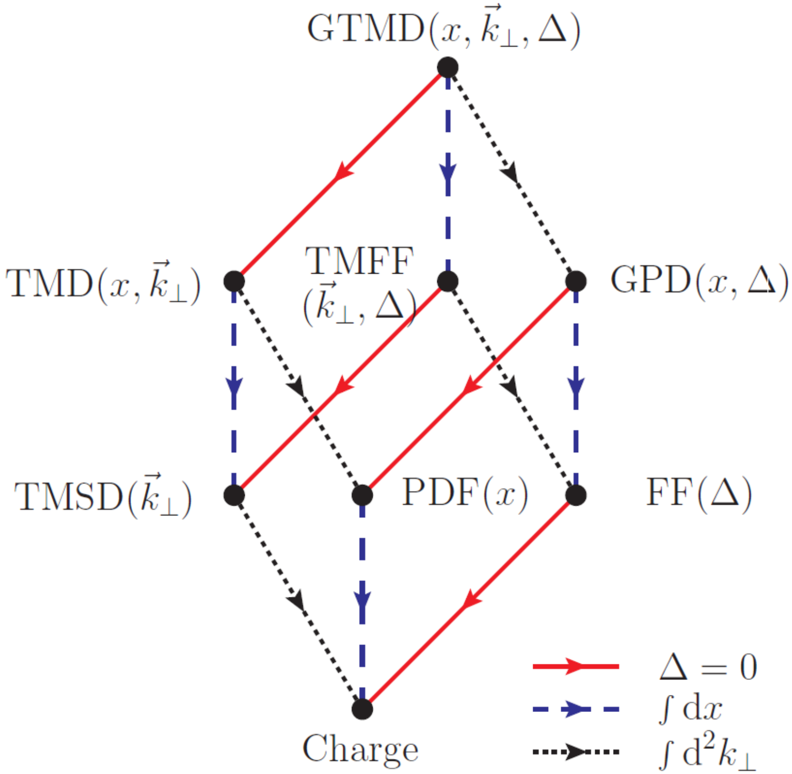
combining HERA data with the expected ones from COMPASS, JLab12 will allow to cover a wide region **from sea to valence**



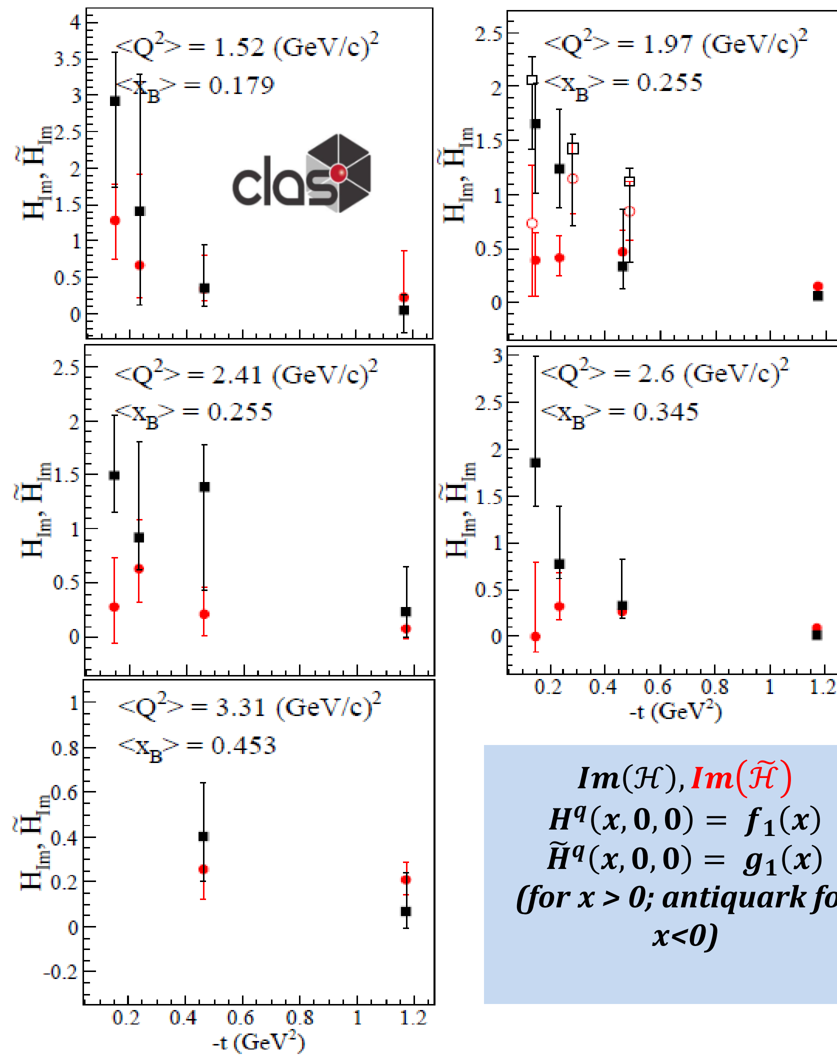


Charges in the nucleon

[S. Niccolai, K. Joo]



→ axial charge is more concentrated in the nucleon centre than the electric charge



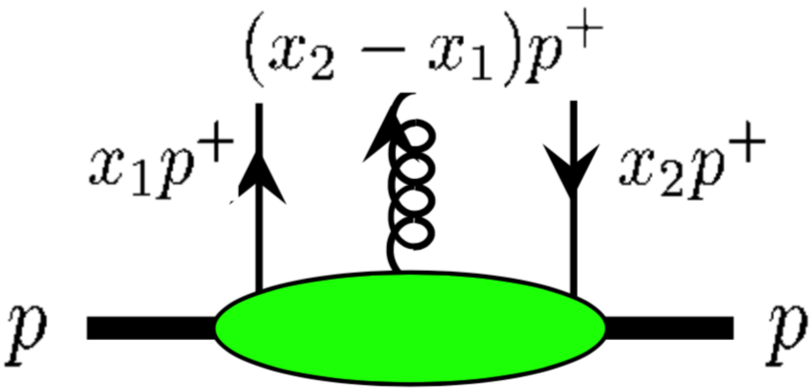
$Im(\mathcal{H})$, $Im(\tilde{\mathcal{H}})$
$H^q(x,0,0) = f_1(x)$
$\tilde{H}^q(x,0,0) = g_1(x)$
(for x > 0; antiquark for x<0)

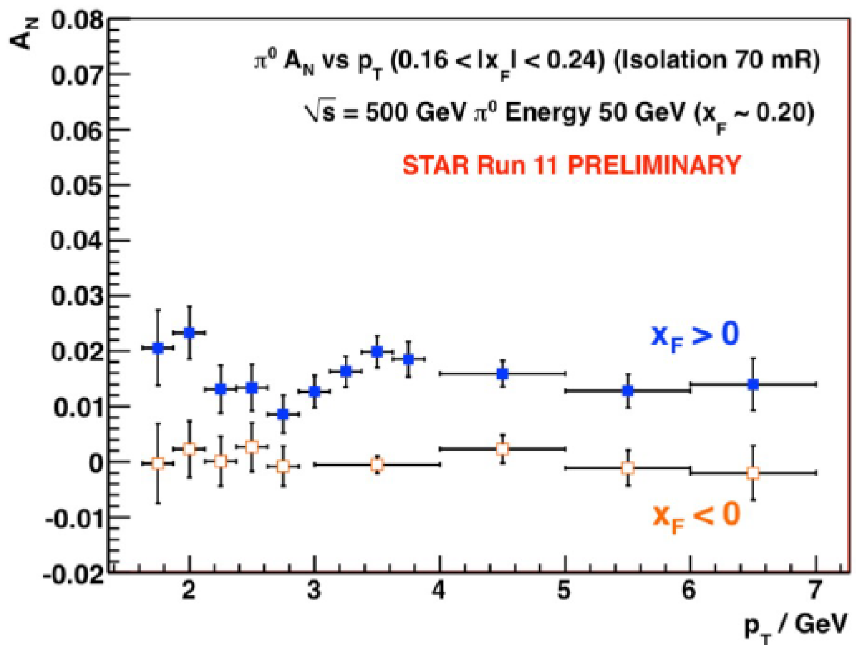
PRL 114 (2015) 032001
PRD 91, 052014 (2015)

Beyond leading twist

[C. Dilks,
C. Van Hulse]

Twist-3 asymmetries already observed in some experiments





Single-spin asymmetries can also be generated in a fully collinear framework using higher-twist functions

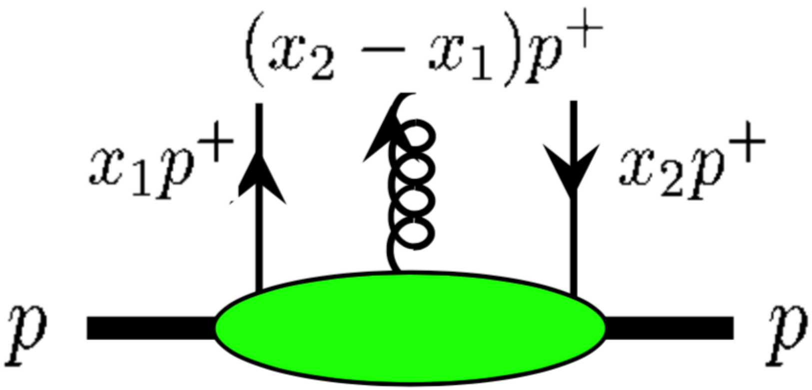
[Y. Koike,
S. Yoshida,
K. Yabe]

Collins, Sivers, Twist-3 suggest $1/p_T$
Flat dependence observed

Beyond leading twist

**[C. Dilks,
C. Van Hulse]**

Twist-3 asymmetries already observed in some experiments



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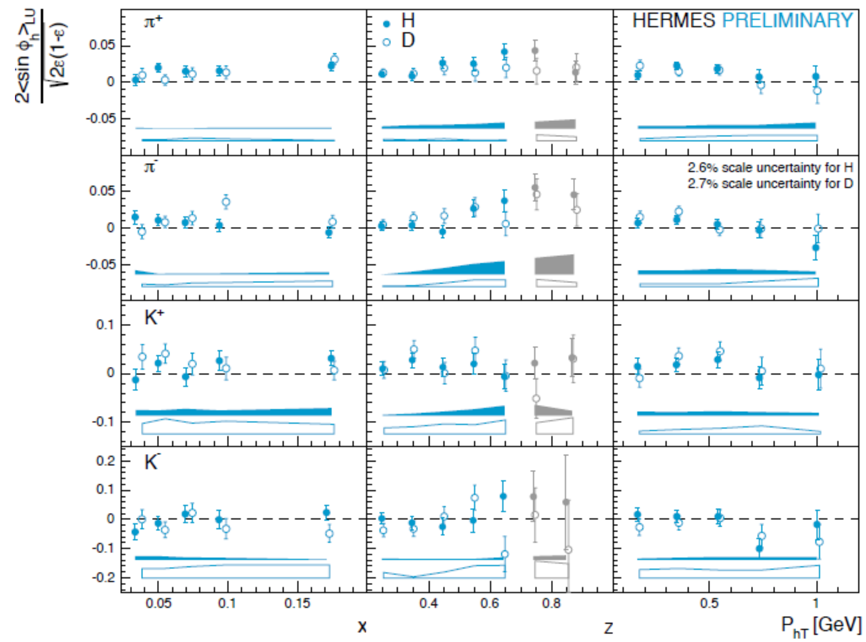
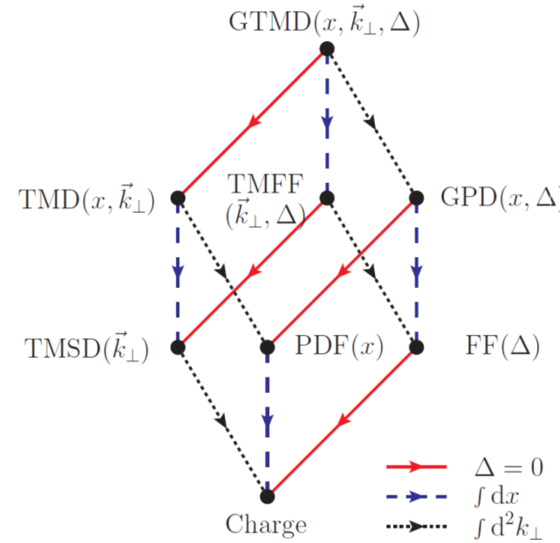


Collins, Sivers, Twist-3 suggest $1/p_T$
Flat dependence observed

A path toward a 5D mapping

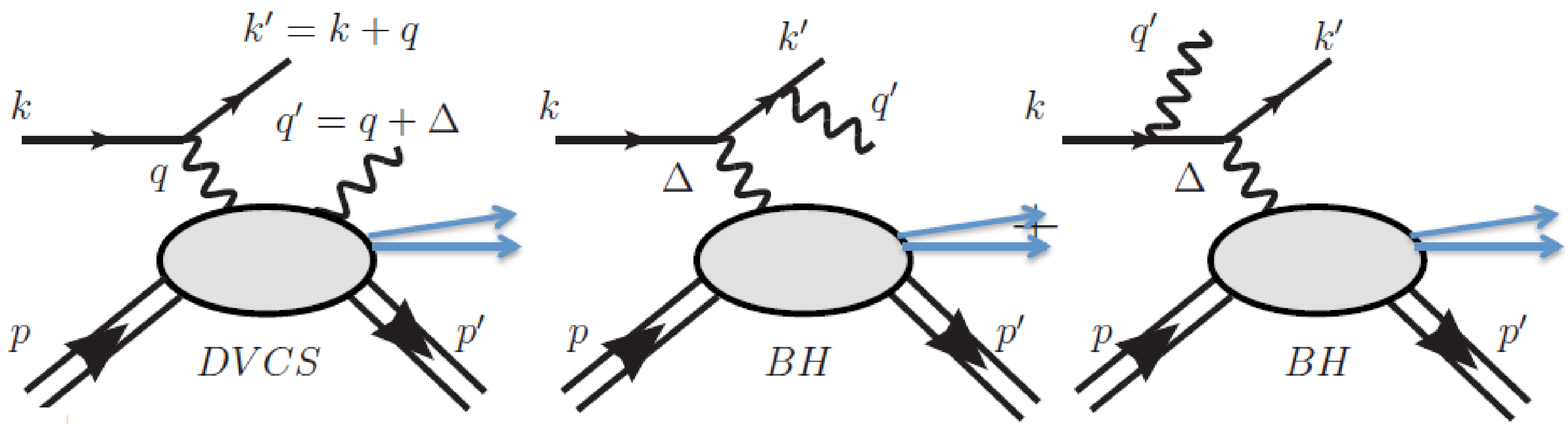


We are looking for suitable processes to go beyond the 3D description

Multi-particle final states

Large acceptance detectors, high statistics

[G. Goldstein, R. Ent, E. Ashenauer]



WG6 – Spin Physics Summary Talk

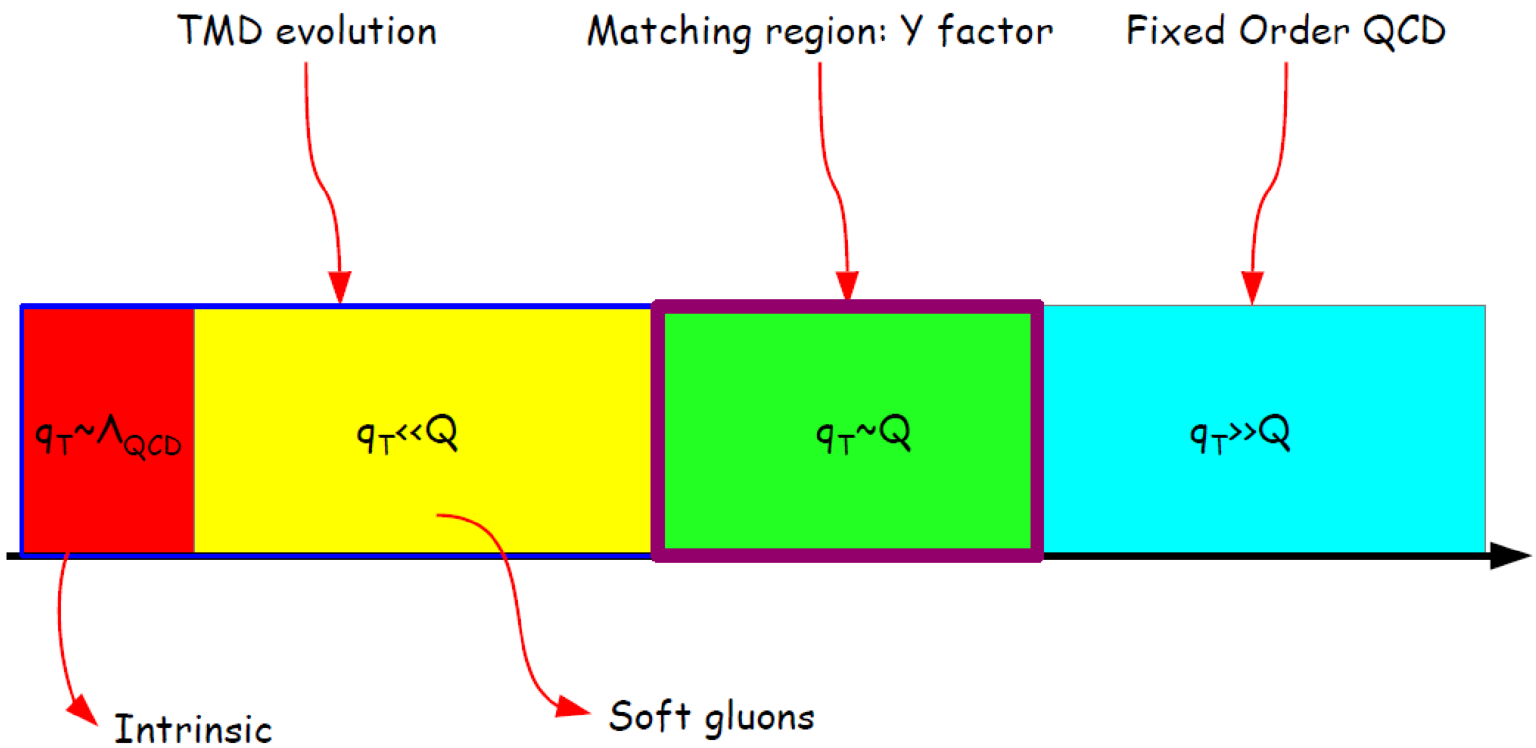
Conclusions

To understand hadronic bound states we need to look in the non-perturbative mess inside the proton

credits to H. Avakian for this parable

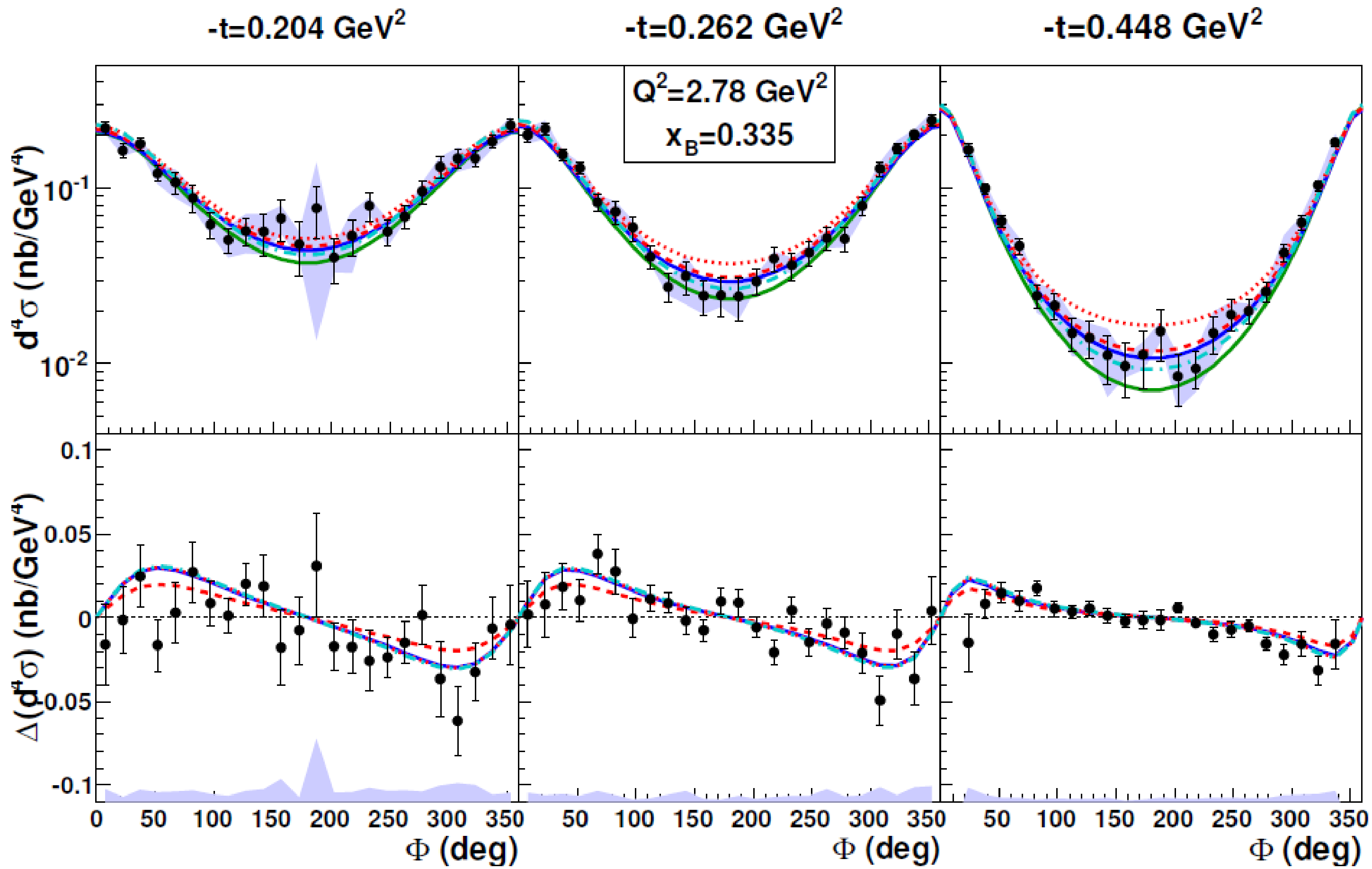
backup

TMD regions

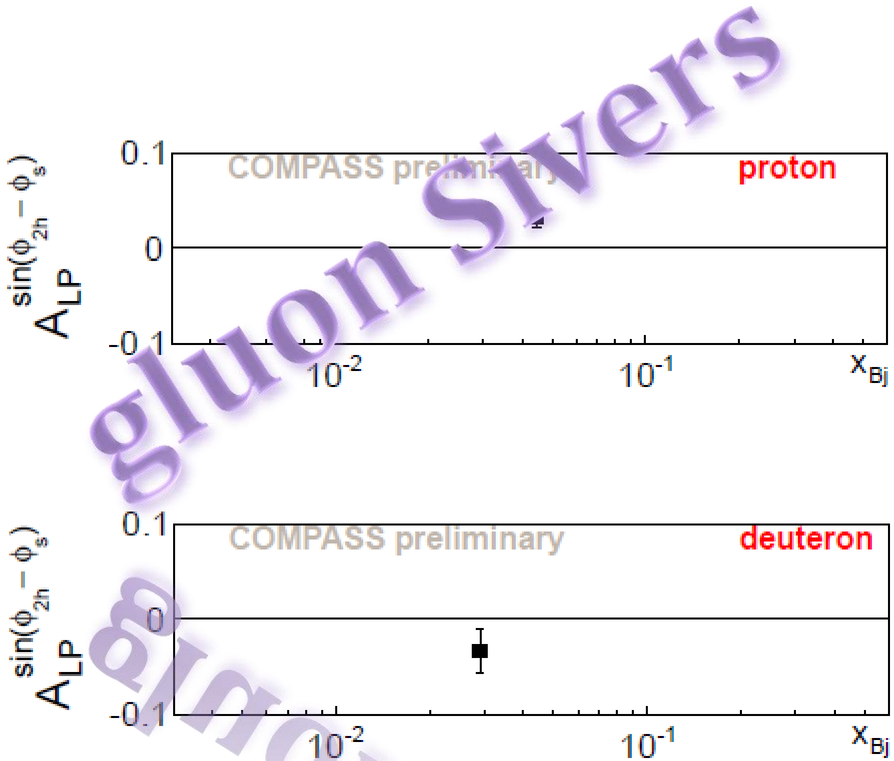


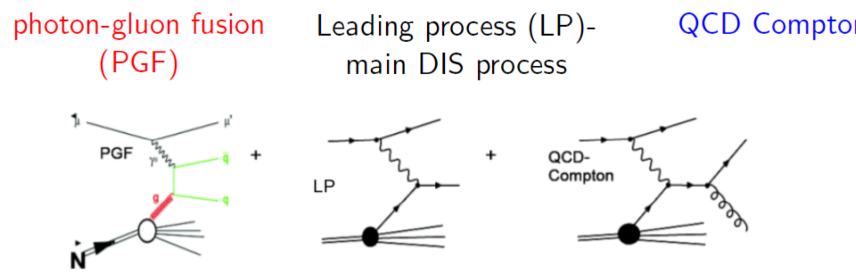
TMD evolution
Matching region: Y factor
Fixed Order QCD
$q_T \sim \Lambda_{QCD}$
$q_T \ll Q$
$q_T \sim Q$
$q_T \gg Q$
Intrinsic
Soft gluons

DVCS@Hall-B, JLab



Sivers through SIDIS – COMPASS & HERMES



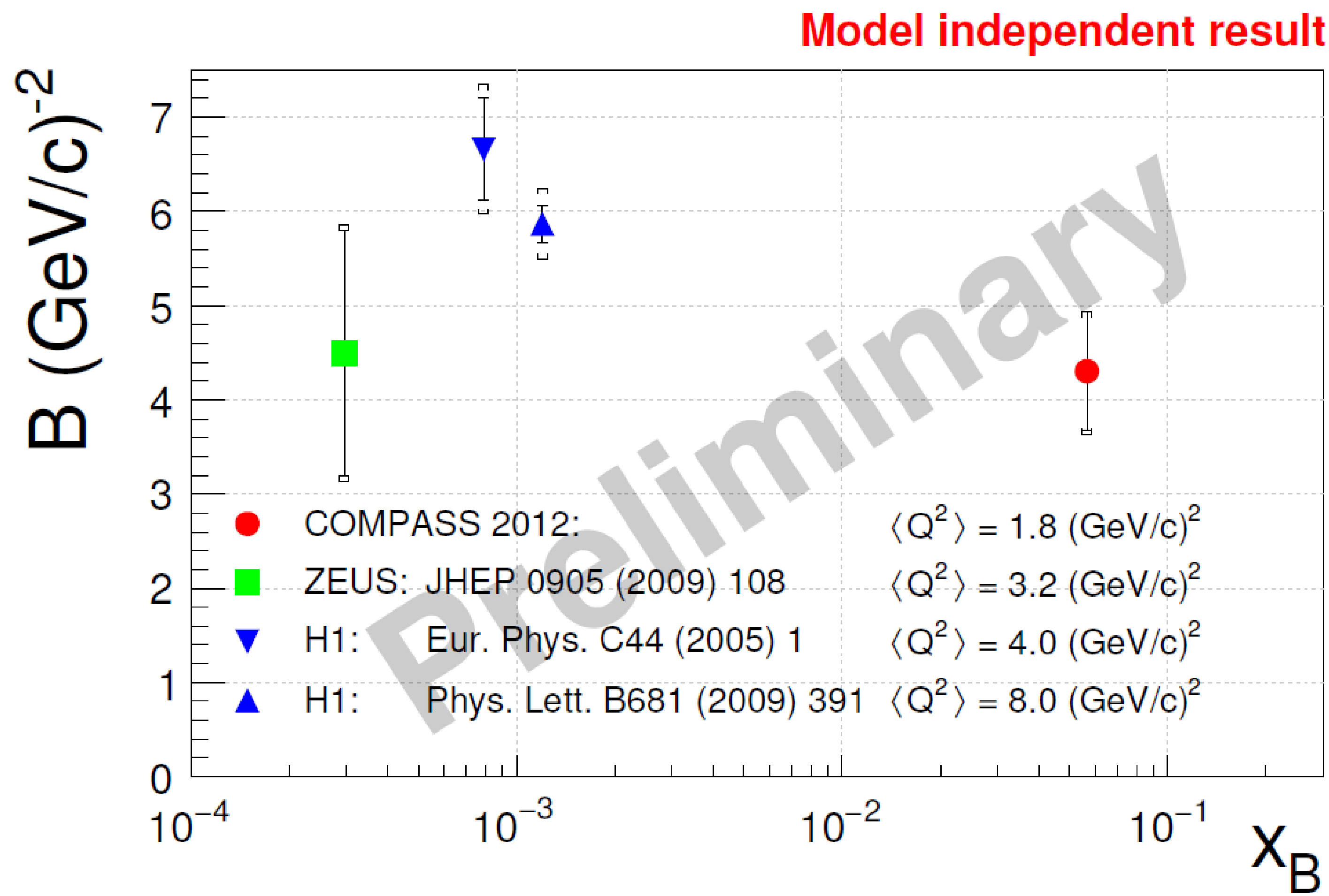


- Also gluon Sivers is being test @COMPASS, both on proton and deuteron
- two different mechanisms exploited: J/ψ production & high-p_T hadron pair production

results on deuteron compatible with zero

2010 proton data: negative value@3σ

DVCS cross-section: $-t$ dependence



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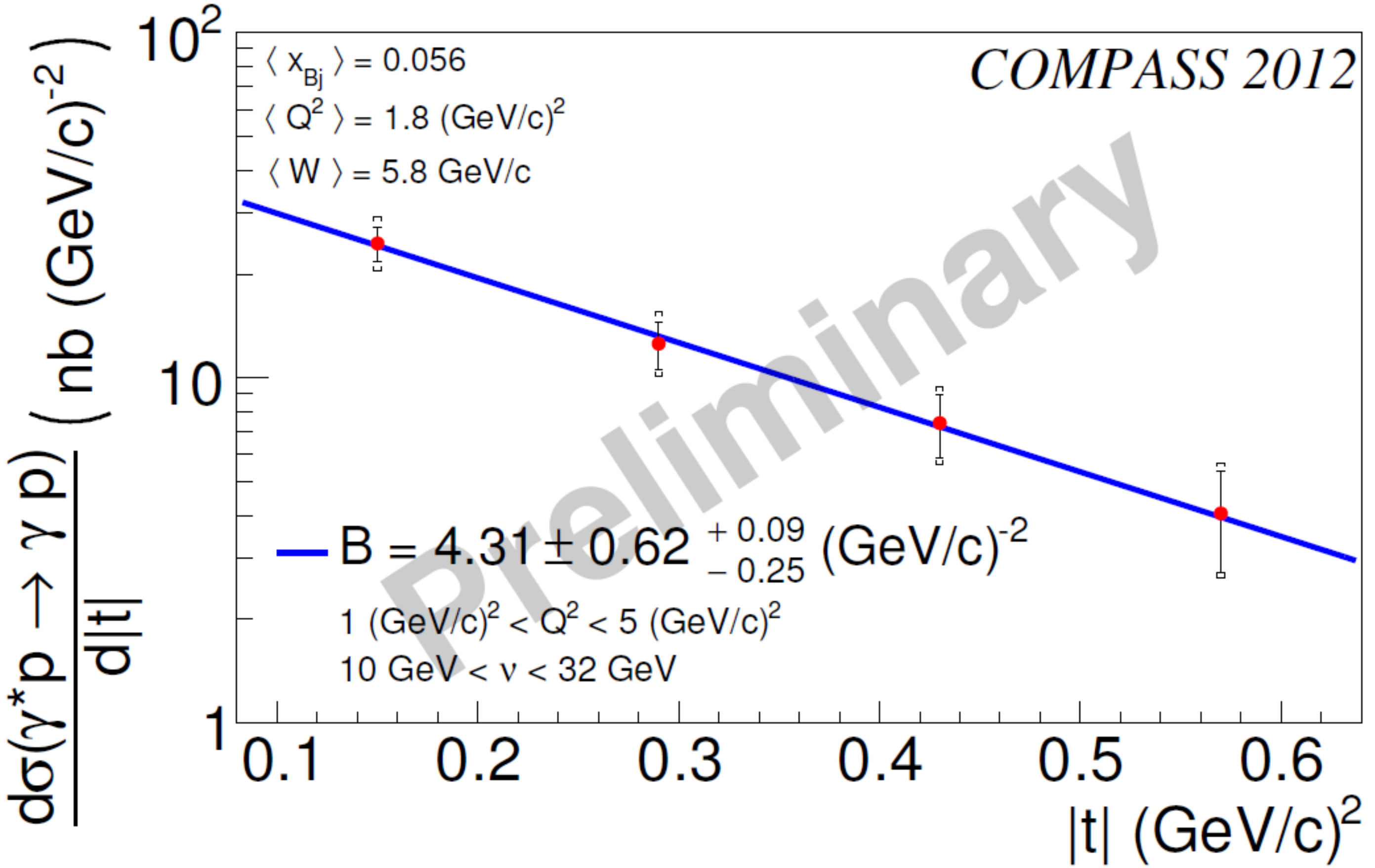
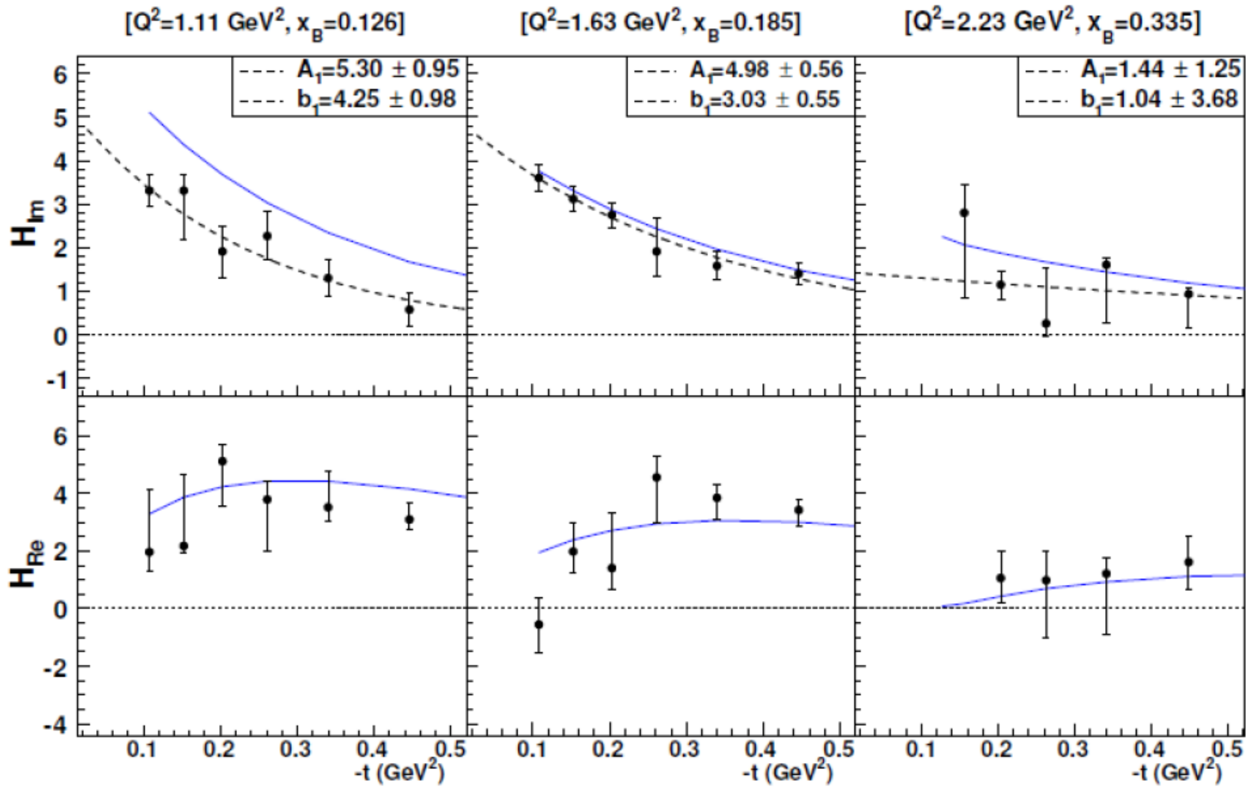


DVCS jlab – cross-section



- VGG model
- Ae^{bt}

A, b increases with x_B

→ the partonic content of the nucleon increases when probing smaller x_B