CONCLUDING REMARKS

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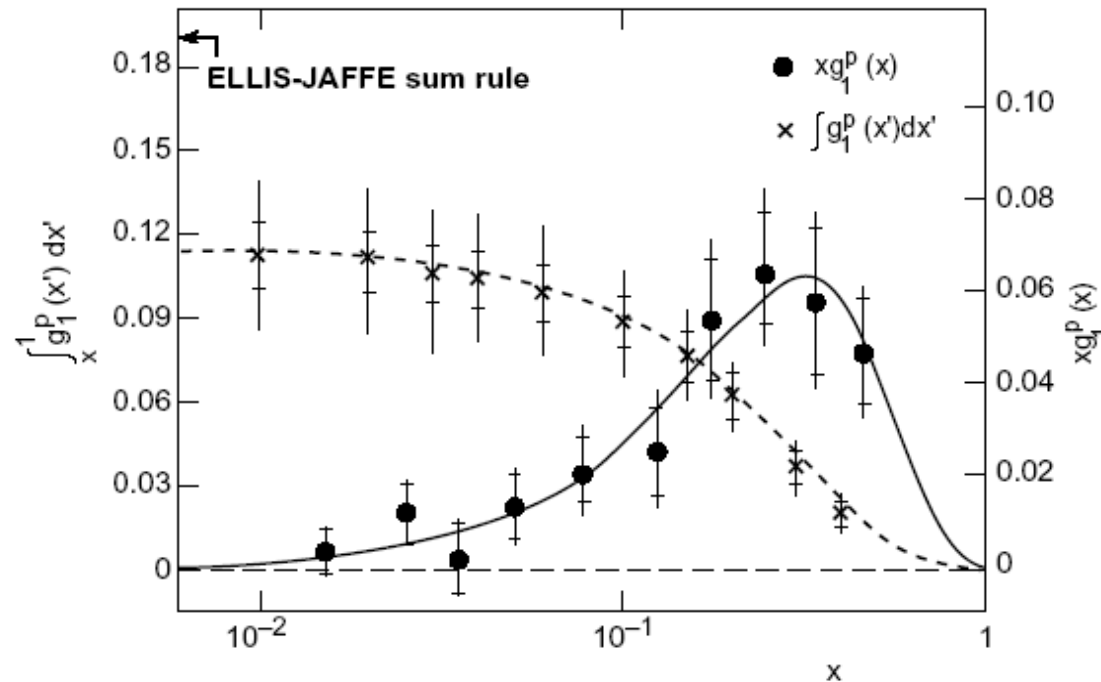
Structure of Nucleons and Nuclei

Como

June 14, 2013

The Quark Contribution to the Nucleon Spin

EMC   1988

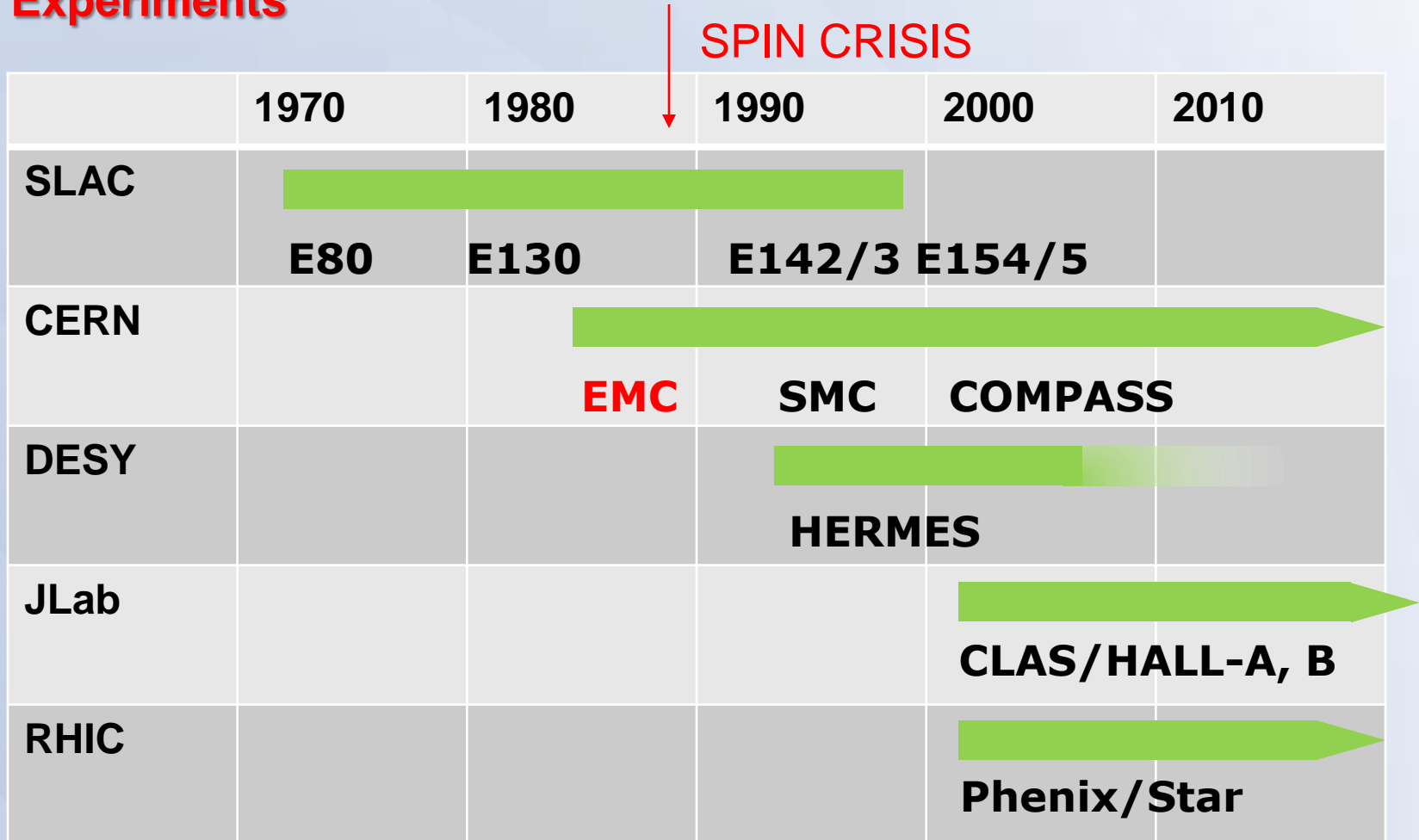$\Gamma_1^p = 0.123 \pm 0.013 \pm 0.019$ $\Delta\Sigma = 0.12 \pm 0.17$

➔ **SPIN CRISIS**

25 years !

Franco Bradamante

A worldwide effort since decades

Experiments

SPIN CRISIS

	1970	1980	1990	2000	2010
SLAC	E80	E130	E142/3 E154/5		
CERN		EMC	SMC	COMPASS	
DESY			HERMES		
JLab				CLAS/HALL-A, B	
RHIC				Phenix/Star	

and Theory

Spin Physics

many unresolved puzzles even before

transverse spin effects:

- **Hyperon polarization**
- **E704**
- **Krisch effect**

push in US for a polarized proton collider

but undoubtedly the EMC result caused a phase transition
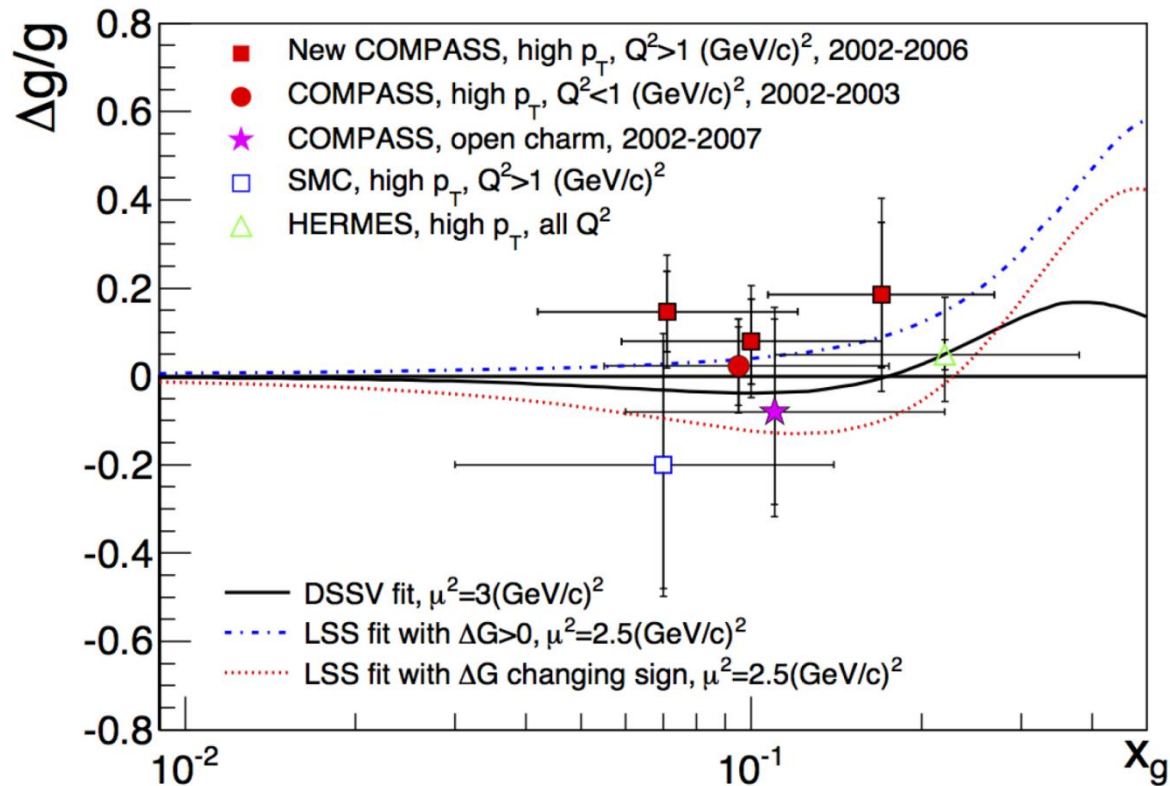
record number of citations

sum rules

!!!   QCD   !!!

spin sum-rule
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta\mathbf{G} + <\mathbf{L_z}>$$
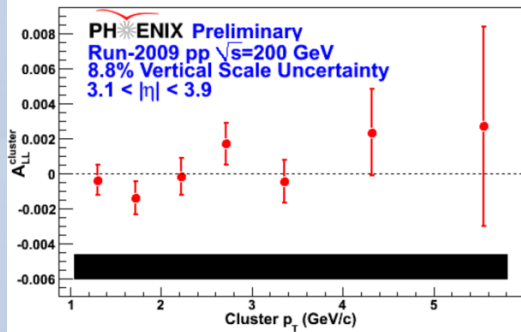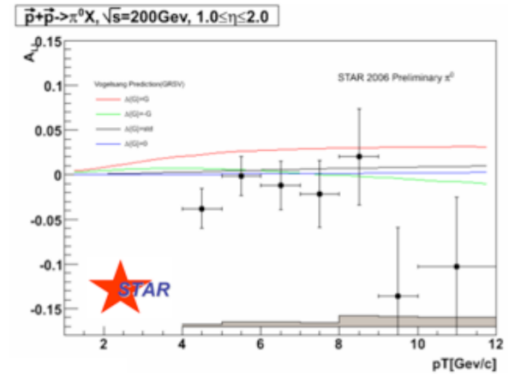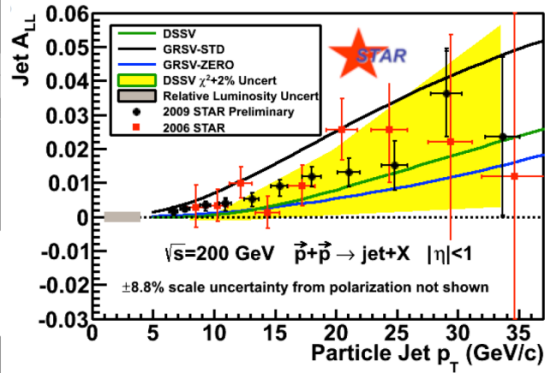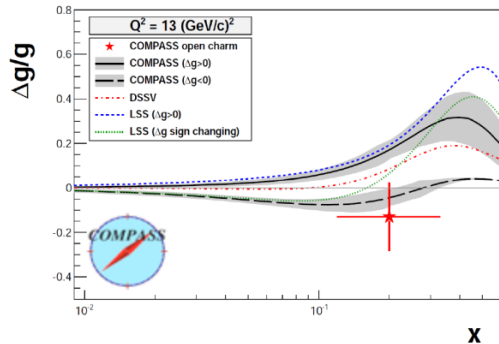
measurements of Gluon Helicity

Physics Letters B 718 (2013) 922–930

**HERMES and COMPASS gave their contribution
the ball is on the RHIC side**

measurements of Gluon Helicity

Gluon helicity
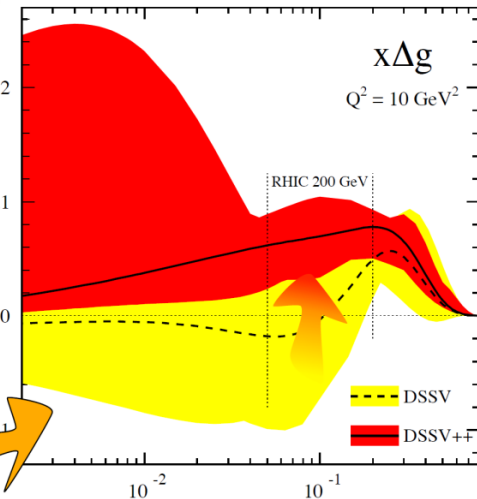
Including part of the Phenix and Star data

F. Giordano, A. Bacchetta, M. Contalbrigo, M. Stolarski

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measurements of $\Delta\Sigma$

spin sum-rule
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + <L_z>$$

$$g_1(x, Q^2) = \frac{1}{2}\langle e^2 \rangle \left[C_q^S \otimes \Delta\Sigma + C_q^{NS} \otimes \Delta q^{NS} + 2n_f C_G \otimes \Delta G \right]$$

$\Delta\Sigma = \Delta u + \Delta d + \Delta s,$ $\Delta q_3 = \Delta u - \Delta d,$ $\Delta q_8 = \Delta u + \Delta d - 2\Delta s$

DGLAP equations:

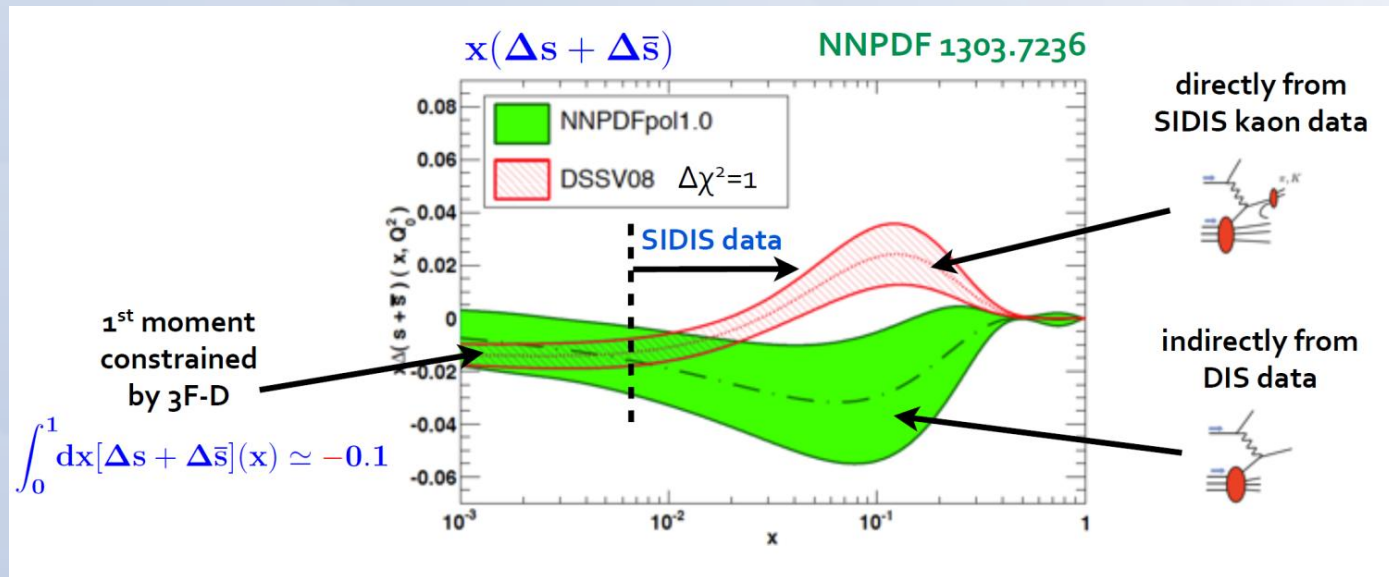$$\frac{d}{dt}\Delta q^{NS} = \frac{\alpha_s(t)}{2\pi} P_{qq}^{NS} \otimes \Delta q^{NS}$$

$$\frac{d}{dt}\begin{pmatrix} \Delta\Sigma \\ \Delta G \end{pmatrix} = \frac{\alpha_s(t)}{2\pi} \begin{pmatrix} P_{qq}^S & 2n_f P_{qG}^S \\ P_{Gq}^S & P_{GG}^S \end{pmatrix} \otimes \begin{pmatrix} \Delta\Sigma \\ \Delta G \end{pmatrix}, \quad t = \log\left(\frac{Q^2}{\Lambda^2}\right)$$

$\Delta\Sigma$ **OK**

but   **$\Delta s = 0.08$ incompatible with SIDIS measurement**

strange helicity puzzle

remarks/caveats:

- SIDIS analysis depends on s->K fragmentation
- DSSV global fit finds no tension between DIS and SIDIS
- NNPDF allows for 30% error on 3F-D -> no big impact
- how well do we know the unpolarized s(x)?
- lattice finds small strangeness $\int_0^1 dx[\Delta s + \Delta \bar{s}](x) \simeq -0.020(10)(1)$
  <-> large breaking of 3F-D relation
  Bali et al. 1112.3354

priority issue: multiplicities
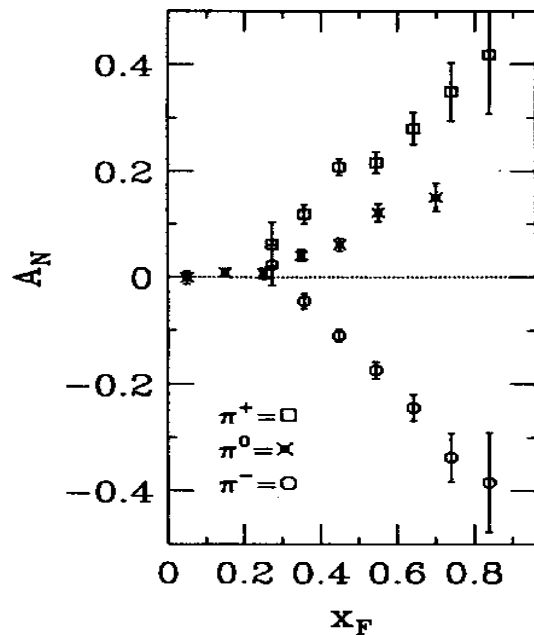
TRANSVERSE SPIN !

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Transverse Spin

Since many years intriguing evidence of large transverse spin effects at high energy

- hyperon polarization
- high p_t effects in hadronic interactions
- asymmetries in hadron production

US: pp collider

Europe: HELP at LEP

HERMES   COMPASS

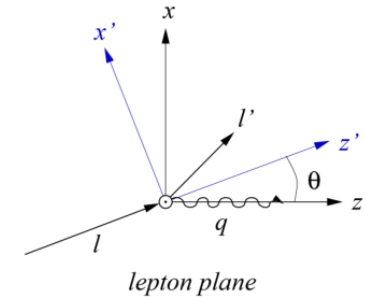# Collins asymmetry
Sivers asymmetry

and,
shortly
after :

unpolarised SIDIS cross-section
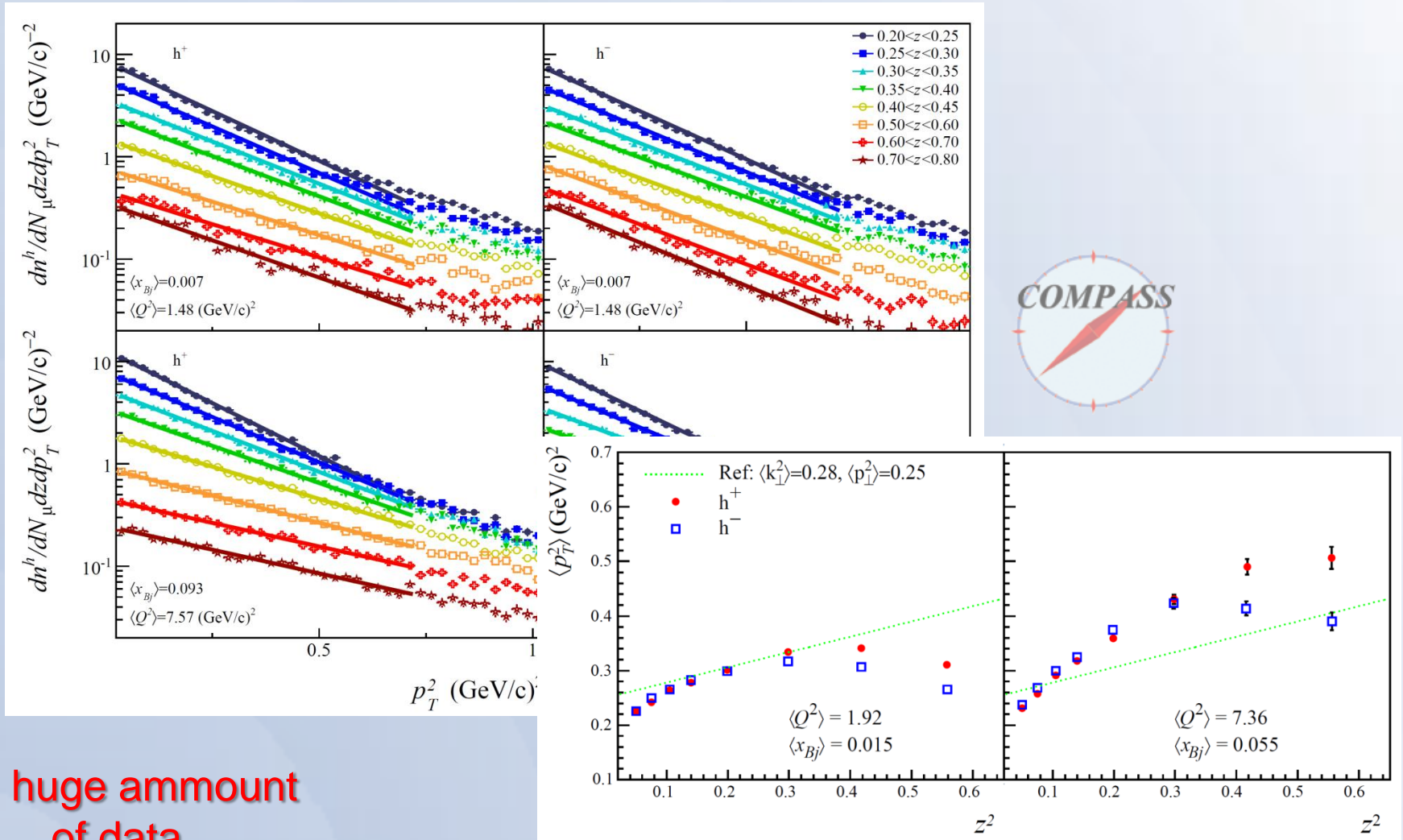
**huge ammount
of data
from HERMES and COMPASS**

azimuthal asymmetries - cos ϕ

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

COMPASS

x

$A^{UU}_{cos\,\phi_h}$

- ▼ h-
- ● h+

0.130

0.038

0.020

0.012

0.003

P^h_T [GeV/c]

0.20   0.25   0.32   0.40   0.55   0.70   0.85

z
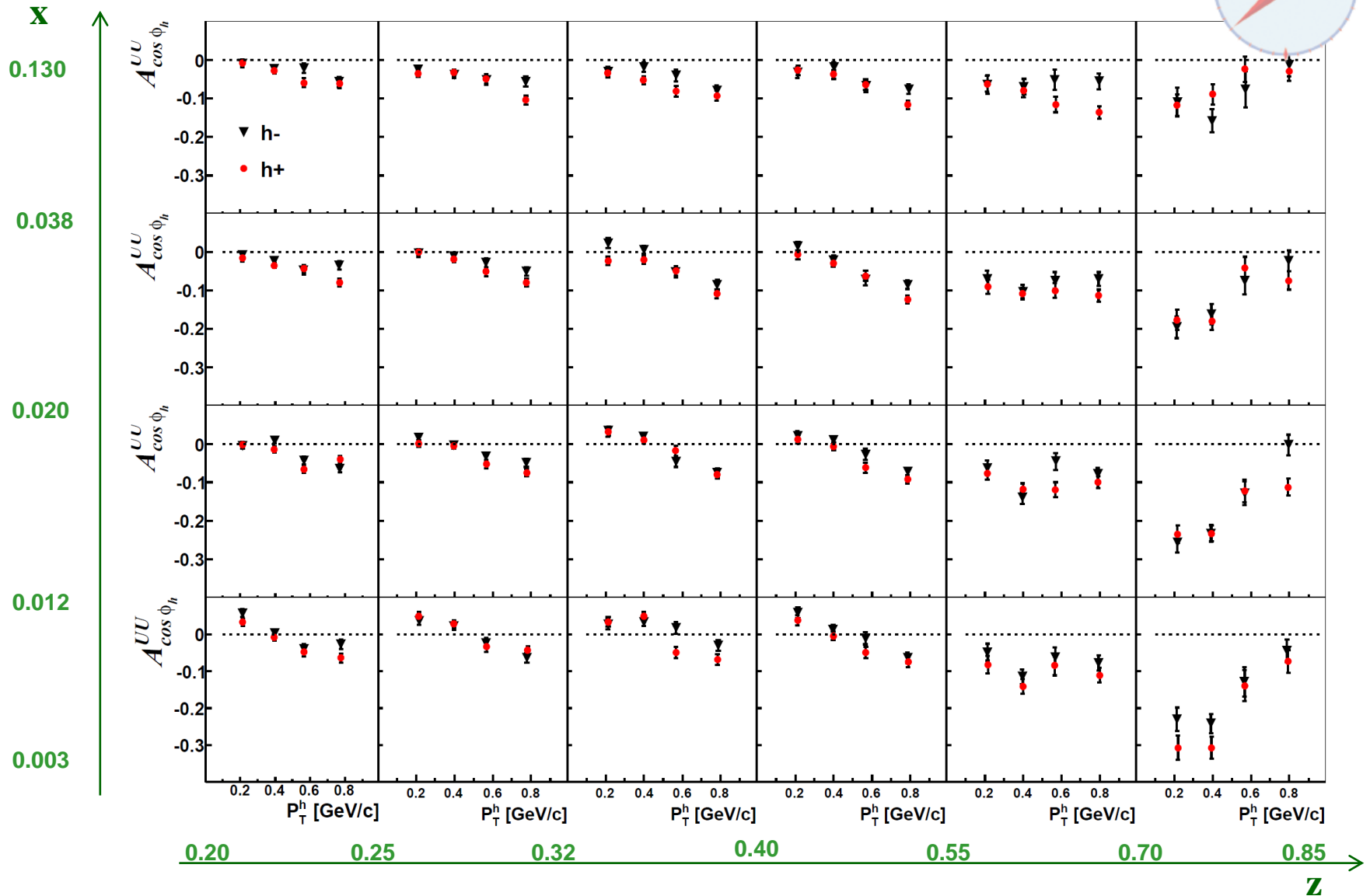
azimuthal asymmetries - cos 2ϕ

COMPASS ^{6}LiD (25% of 2004 data)   preliminary
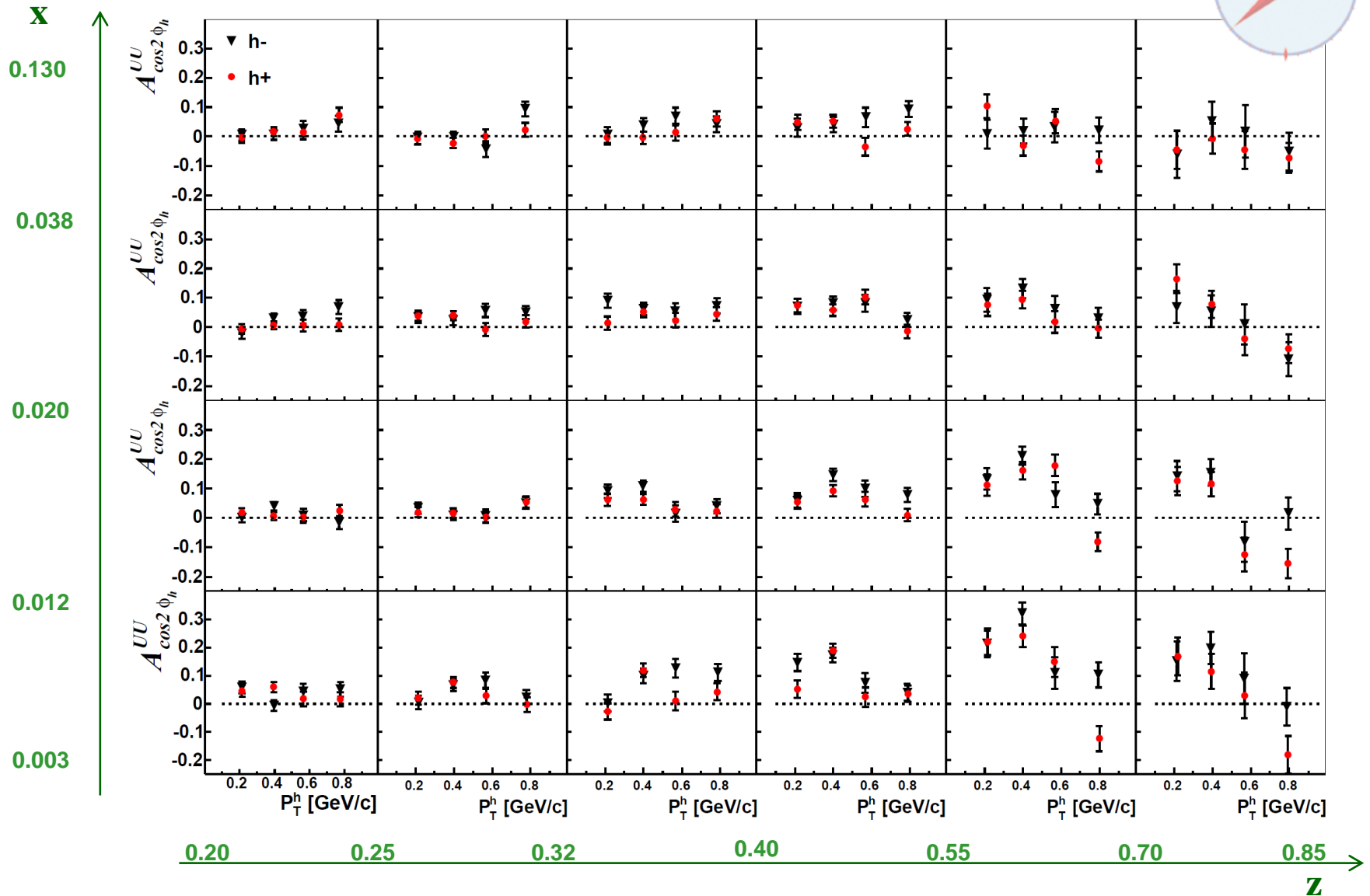
(transverse) spin dependent asymmetries

Sivers asymmetry

Anselmino, Boglione, Melis, Phys. Rev. D86 (2012) 014028

HERMES PROTON — COMPASS PROTON

hermes
$\langle Q^2 \rangle = 2.4$ GeV^2
Q^2 in the range [1.3 – 6.2] GeV^2

COMPASS
$\langle Q^2 \rangle = 3.8$ GeV^2
Q^2 in the range [1.3 – 20.5] GeV^2
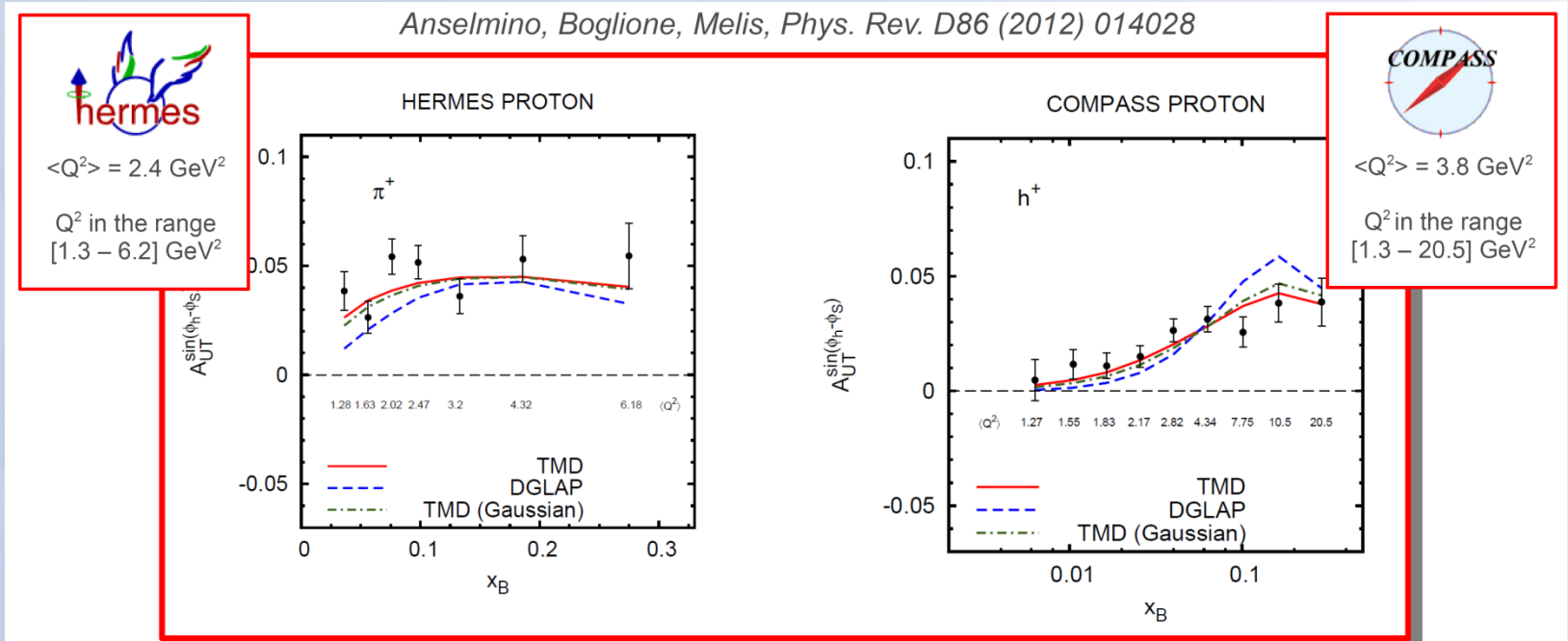
A. Airapetian et al., Phys. Rev. Lett. 103, (2009) 152002

C. Adolph et al., Phys. Lett. B717 (2012) 383

studies of Q² evolution

(transverse) spin dependent asymmetries

Transversity

Simultaneous extraction of transversity and the Collins function

Standard.
param.
of the
Collins
function

Polynom.
param.
of the
Collins
function
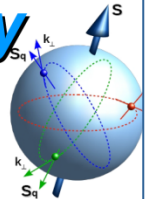
Old data:

BELLE : 2008 new analy

HERMES : 2005 data, A.
2007 release.

COMPASS – d : 2007 da
2008 rel
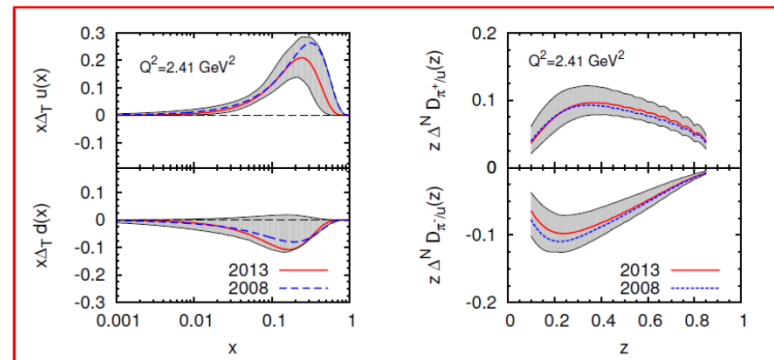
New data:

BELLE :   2012 erratum,

HERMES : 2010 data, Ph

COMPASS – p : two runs
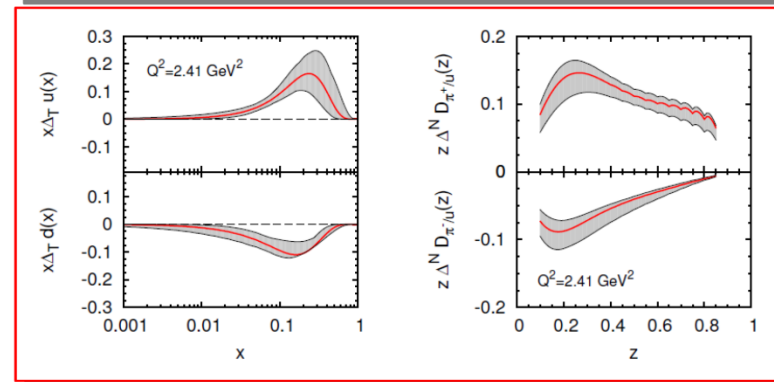
11/6/2013   Elena Boglione - Structure of Nucleons and Nuclei - COMO

2013

(transverse) spin dependent asymmetries

Transversity

PROTON

$x\, h_1^{u_V}(x) - x\, h_1^{d_V}(x)/4$

fit

data HERMES

data COMPASS

flexible functional form

DEUTERON

$x\, h_1^{u_V}(x) + x\, h_1^{d_V}(x)$

fit

data COMPASS
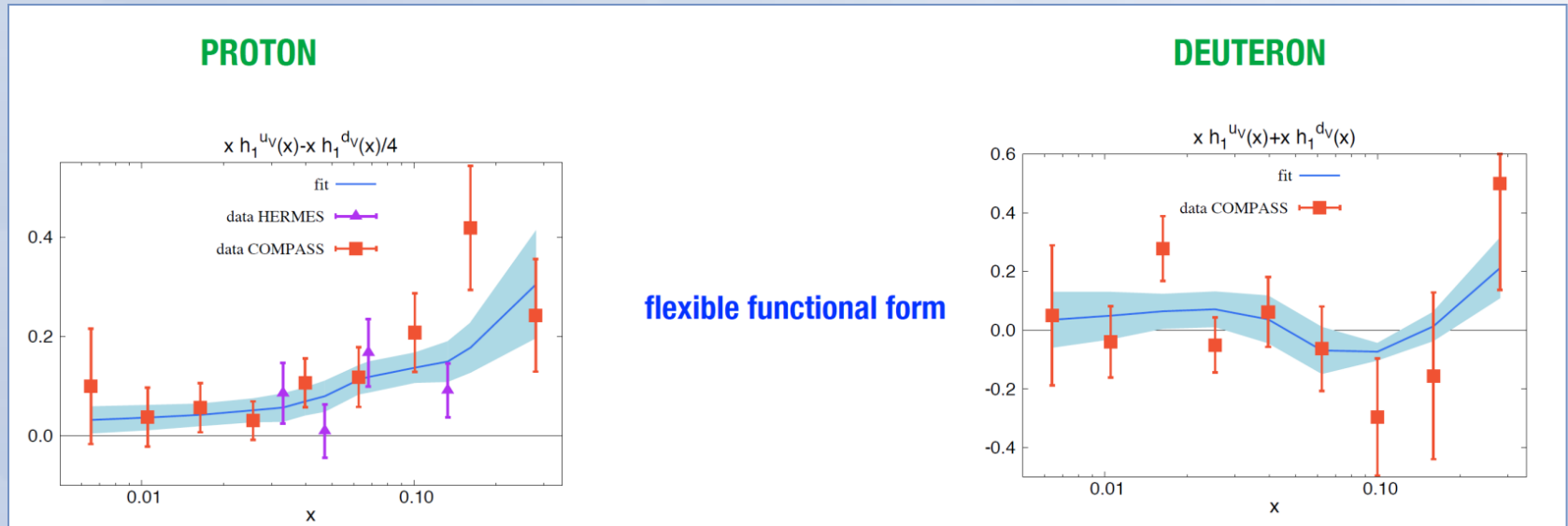
M. Radici

INTERPLAY BETWEEN
COLLINS ASYMMETRY AND TWO-HADRON ASYMMETRY
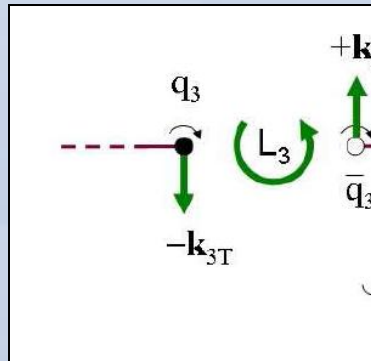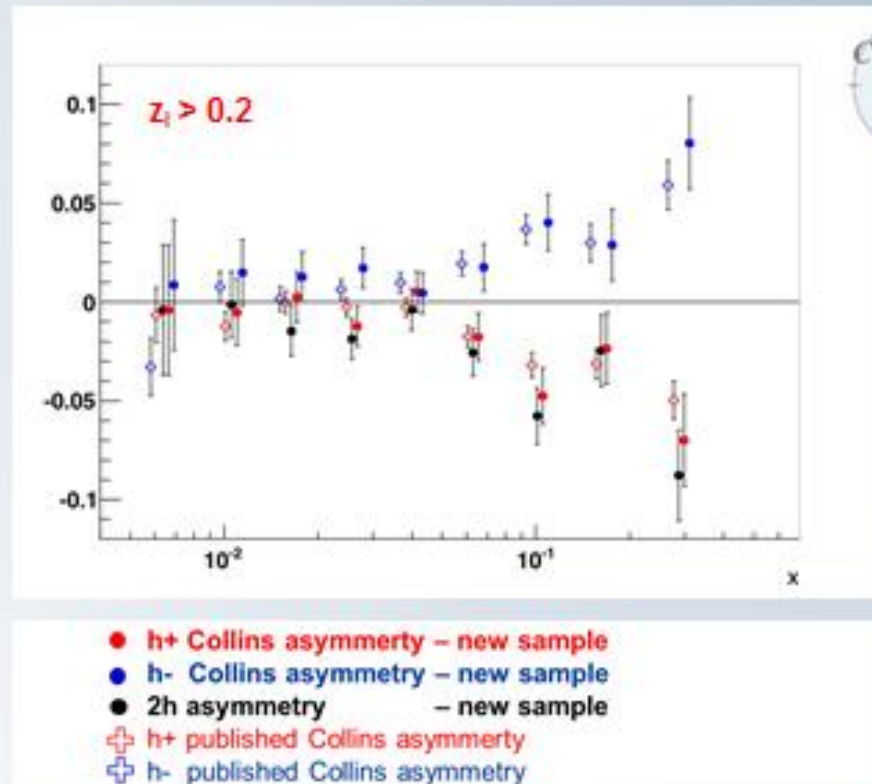
and HERMES (L. Pappalardo)

test of pseudo-universality of T-odd TMD PDFs

measurement of polarised Drell-Yan

COMING SOON !

Facility	type	s (GeV^2)	timeline
RHIC (STAR, PHENIX)	collider, $p^\uparrow p$	200^2	> 2016
J-PARC	fixed target, $p^{\rightarrow\uparrow} D$	60 – 100	> 2018
FAIR (PAX)	collider, $\bar{p}^\uparrow p^\uparrow$	200	> 2018
NICA	collider, $p^\uparrow p^\uparrow$, $D^\uparrow D^\uparrow$	676, 144	> 2018
COMPASS	fixed target, $\pi^\pm H^{\rightarrow\uparrow}$, $\pi^\pm D^{\rightarrow\uparrow}$	357	2014

more on theory …

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Where do we stand with TMDs (schematic)

- Collinear high-energy processes:

$$\sigma(x_1, x_2, z) = \Phi^i(x_1)\Phi^j(x_2) f_C \hat{\sigma}^C_{ij \to k \ldots}(x_1, x_2, z)\Delta^k(z)$$

- Convoluted azimuthal dependences:

$$\sigma(x_1, x_2, z, q_T) = f_C^{[U_1 U_2]} \Phi^{i[U_1(C)]}(x_2, p_{2T}) \otimes \Phi^{j[U_2(C)]}(x_1, p_{1T}) \hat{\sigma}^{[C]}_{ij \to k \ldots}(x_1, x_2, z)\Delta^k(z, k_T)$$

$$\Phi^{i[U]}(x, p_T) = \Phi^i(x, p_T^2) + p_T^\alpha \tilde{\Phi}^{i\alpha}_\partial(x, p_T^2) + C_G^{[U]} p_T^\alpha \Phi_G^{i\alpha}(x, p_T^2) + C_{GG}^{[U]} p_T^{\alpha\beta} \Phi_{GG}^{i\alpha\beta}(x, p_T^2) + \ldots$$

$$\Delta^{k[U]}(x, k_T) = \Delta^k(z, k_T^2) + k_T^\alpha \tilde{\Delta}^{k\alpha}_\partial(x, k_T^2) + k_T^{\alpha\beta} \tilde{\Delta}^{k\alpha\beta}_{\partial\partial}(z, k_T^2) + \ldots$$
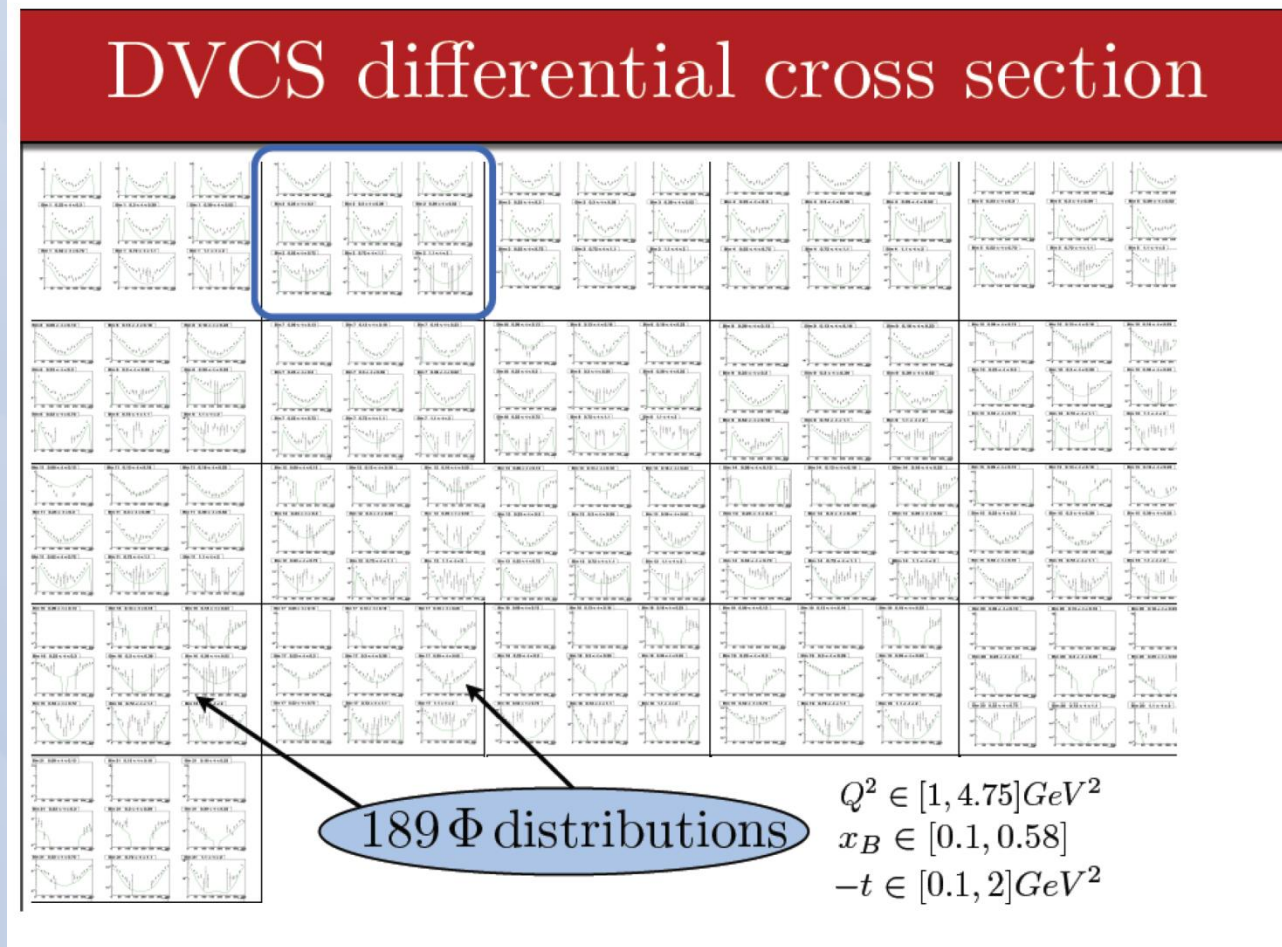
- Deconvoluted azimuthal dependence

$$\sigma(x_1, x_2, z, q_T) = f_C^{[U_1 U_2]} \Phi^{i[U_1(C)]}(x_1, b_T) \otimes \Phi^{j[U_2(C)]}(x_2, b_T) \hat{\sigma}^{[C]}_{ij \to k \ldots}(x_1, x_2, z)\Delta^k(z, b_T)$$
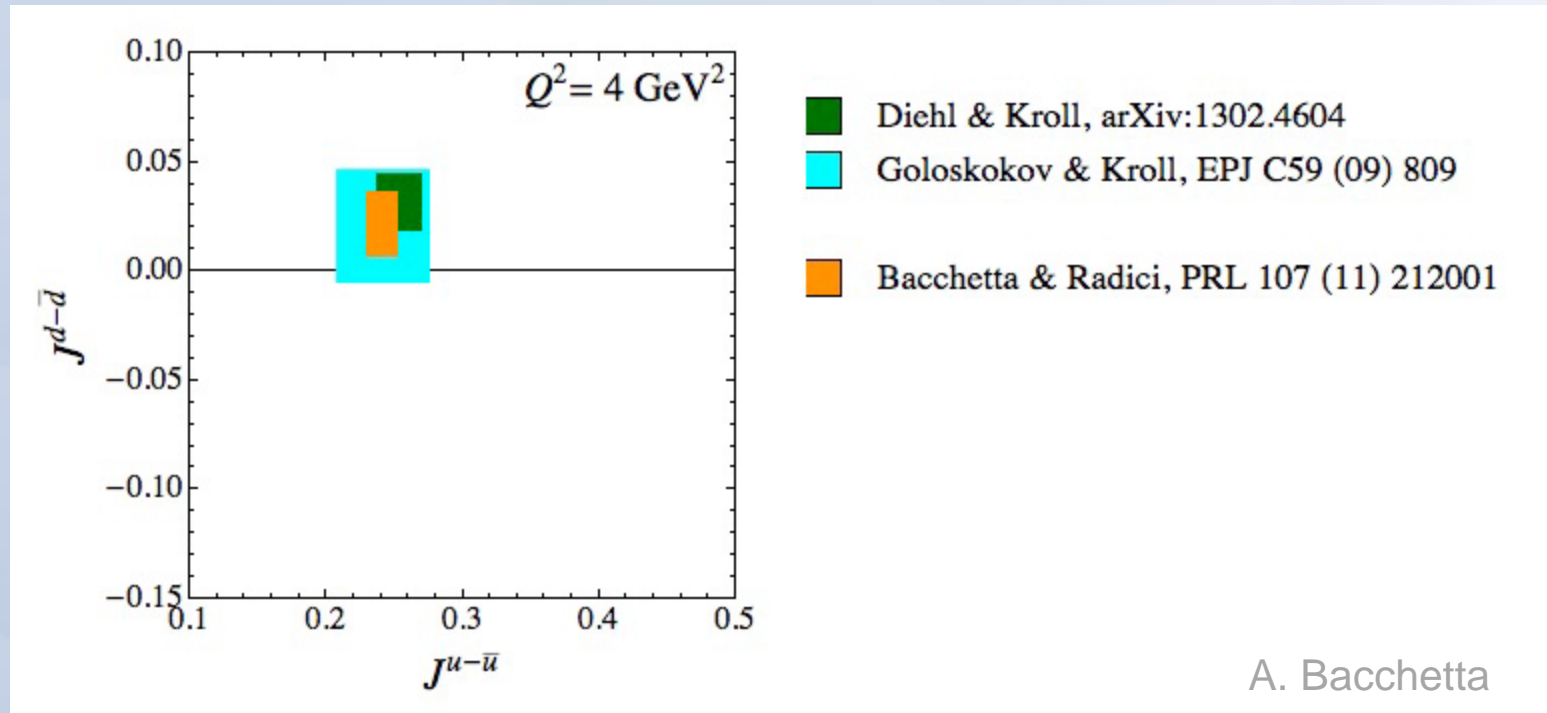
gauge-link process-dependent color factors

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GPDs

❖ *GPDs: Fiction, Excitement, and Calming Down*
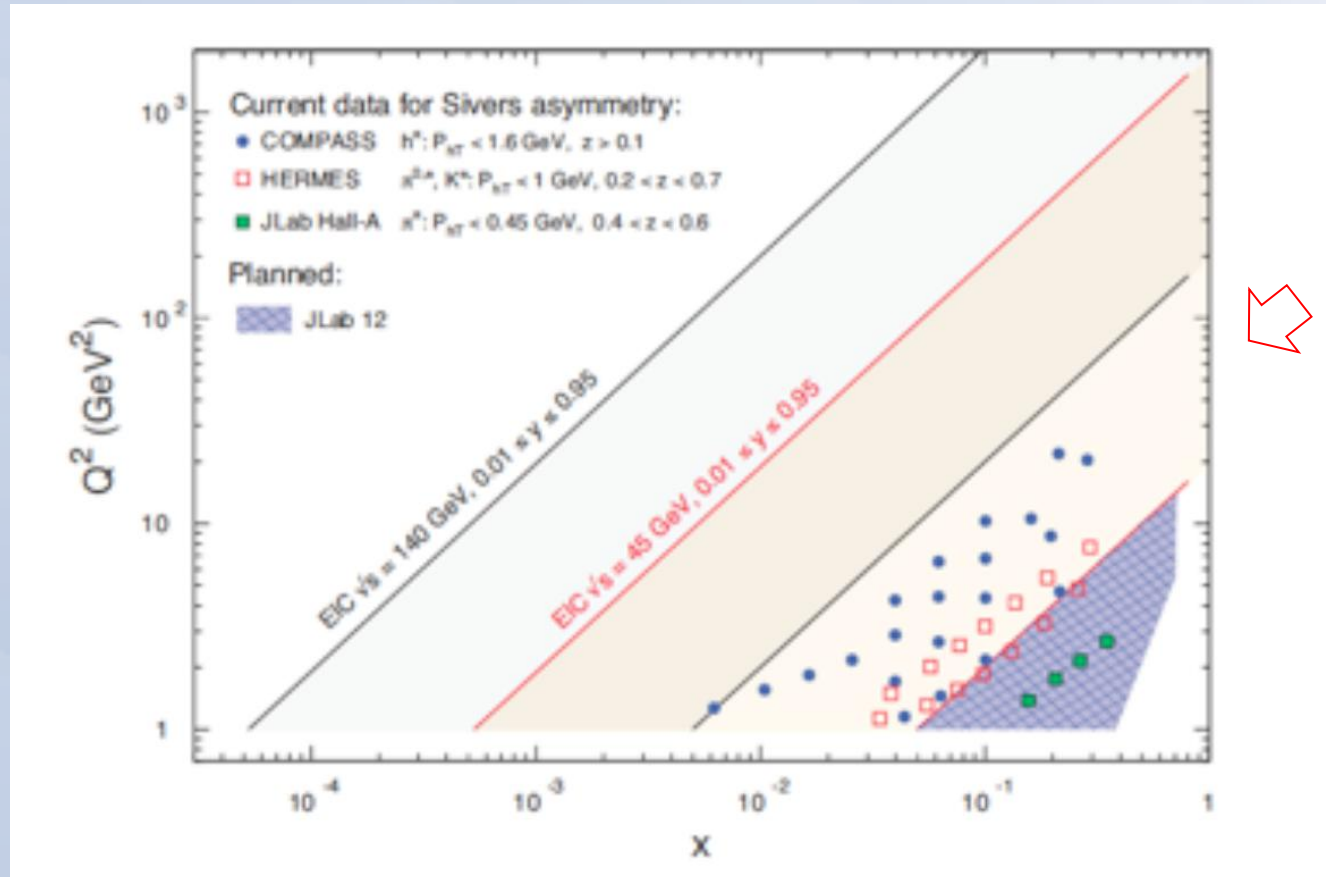

and hard work !

OAM

$Q^2 = 4 \text{ GeV}^2$

■ Diehl & Kroll, arXiv:1302.4604
□ Goloskokov & Kroll, EPJ C59 (09) 809

■ Bacchetta & Radici, PRL 107 (11) 212001

A. Bacchetta

TMDs ←── lensing ──→ **GPDs**

FUTURE

message to the community

today:

a lot of results / data from

HERMES
COMPASS
JLab6

to-morrow:

COMPASS-II
JLab12

still time to extract valuable physics from existing data

but hurry up, don't wait too long!

make specific suggestions

second message to the community

from

THE INTERNATIONAL WORKSHOP ON TRANSVERSE POLARISATION PHENOMENA IN HARD PROCESSES (TRANSVERSITY 2005)

Villa Olmo (Como), 7−10th. September 2005

to …

… Transversity 2014 !

The Next Transversity Workshop

Baia Chia – Sardinia

June 2014
(first or second week)