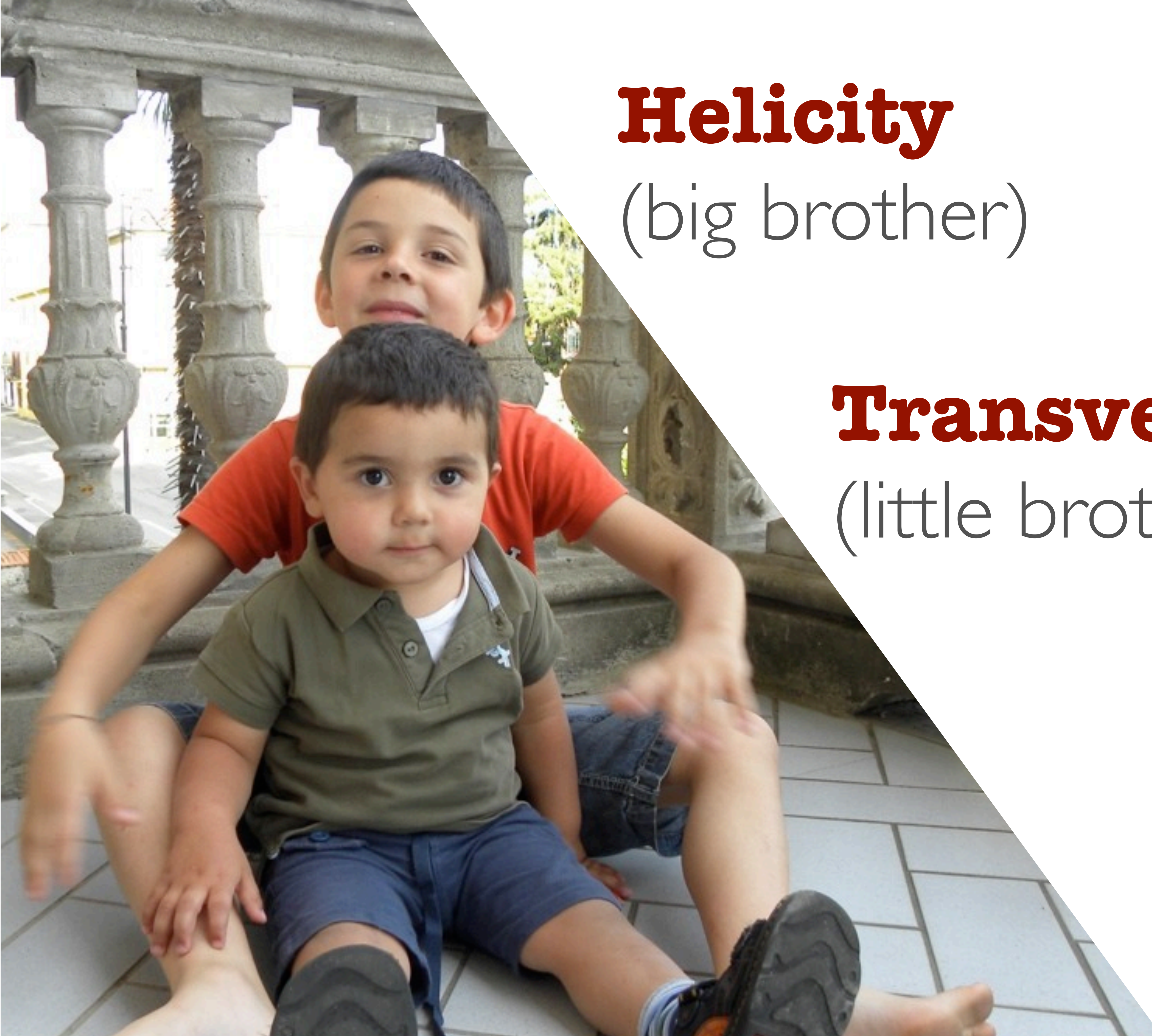
Overview of transversity

Alessandro Bacchetta
Pavia University and INFN, Pavia



Helicity
(big brother)

Transversity
(little brother)

2002: no data on transversity

2002: no data on transversity

2012: about 100 data points, first extractions

2002: no data on transversity

2012: about 100 data points, first extractions

2022: hope we will be able to give the same kind of talk as Werner and Marcin

Theory:
general remarks

One slide on TMDs

quark pol.

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

Twist-2 TMDs

One slide on TMDs

quark pol.

nucleon pol.

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

Twist-2 TMDs

talks by N. Makins, B. Pasquini, N. Makins, C. Lorcé, A. Prokudin

One slide on TMDs

quark pol.

nucleon pol.

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

Twist-2 TMDs

transversity

talks by N. Makins, B. Pasquini, N. Makins, C. Lorcé, A. Prokudin

Integrated on transv. momentum

quark pol.

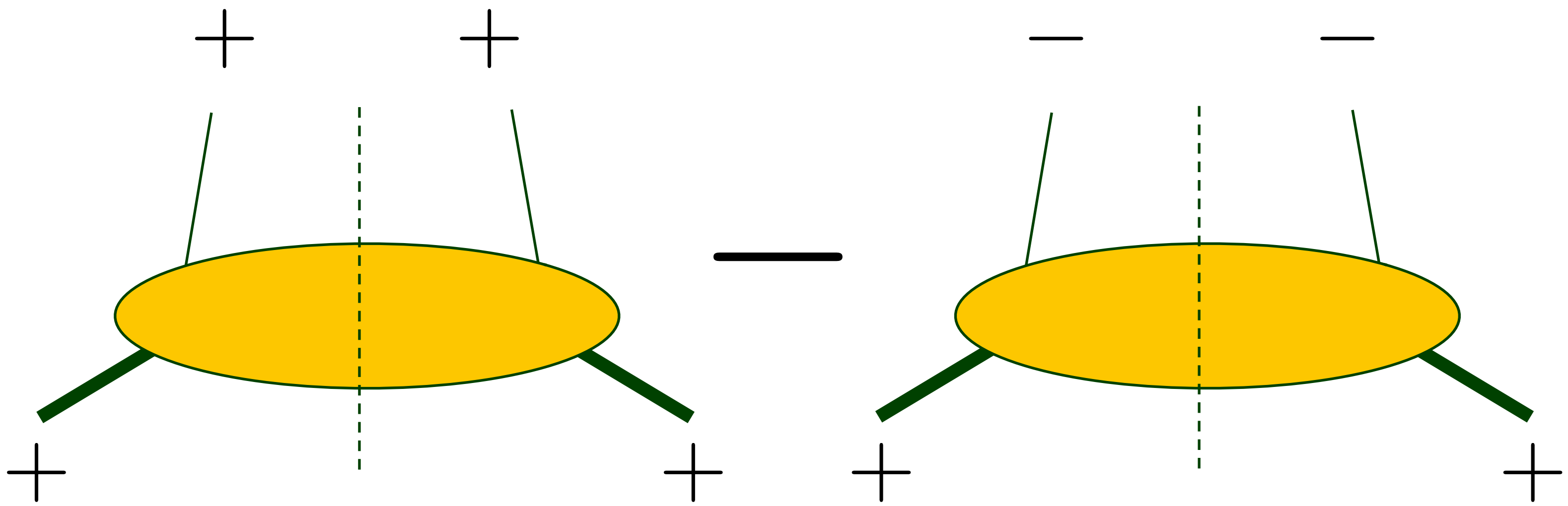
nucleon pol.

	U	L	T
U	f_1		
L		g_{1L}	
T			h_1

transversity

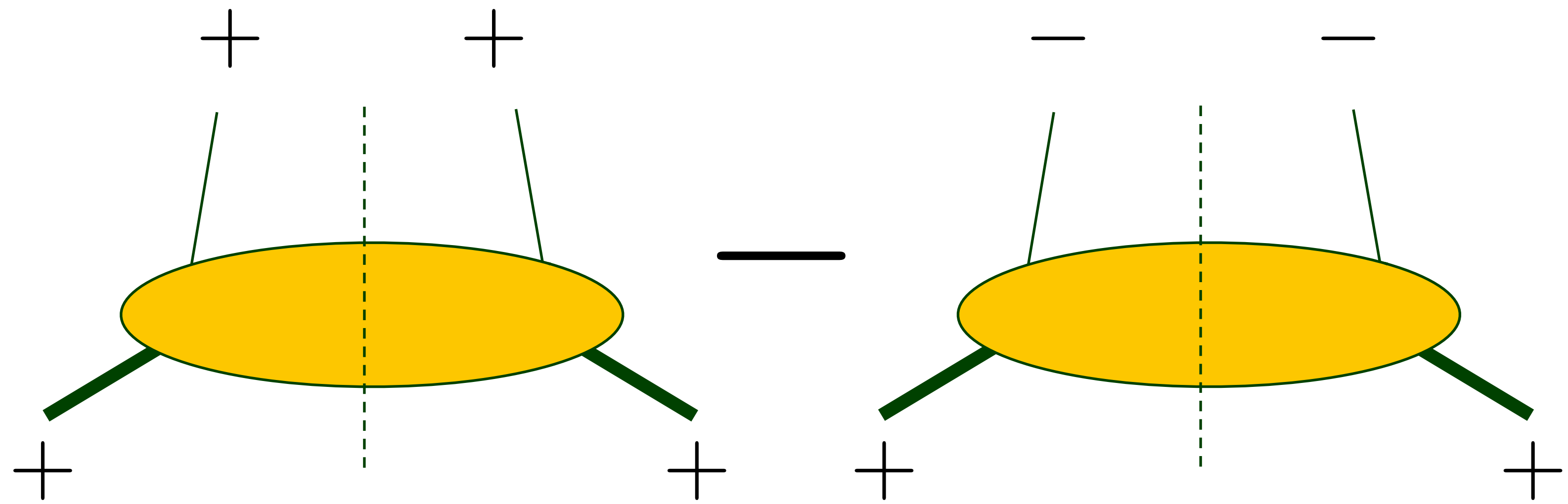
Twist-2 collinear PDFs

Helicity g_1



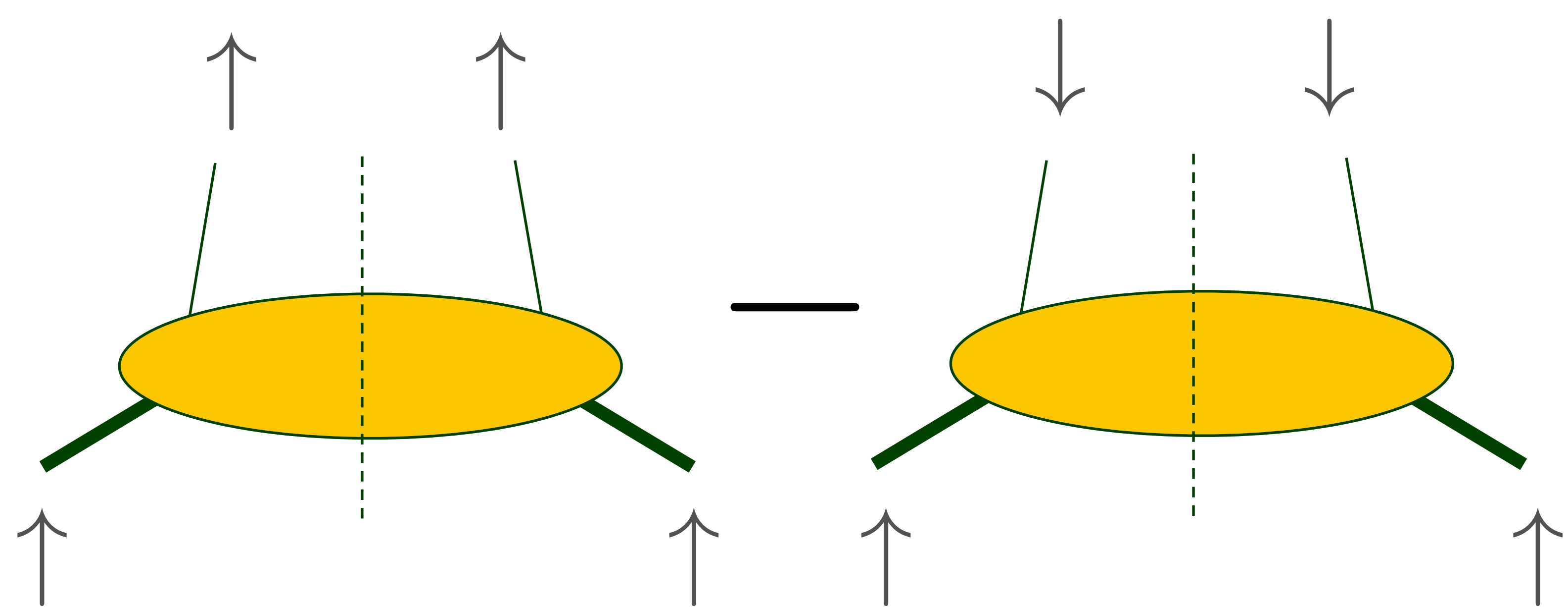
talks by Werner Vogelsang, Marcin Stolarski

Helicity g_1

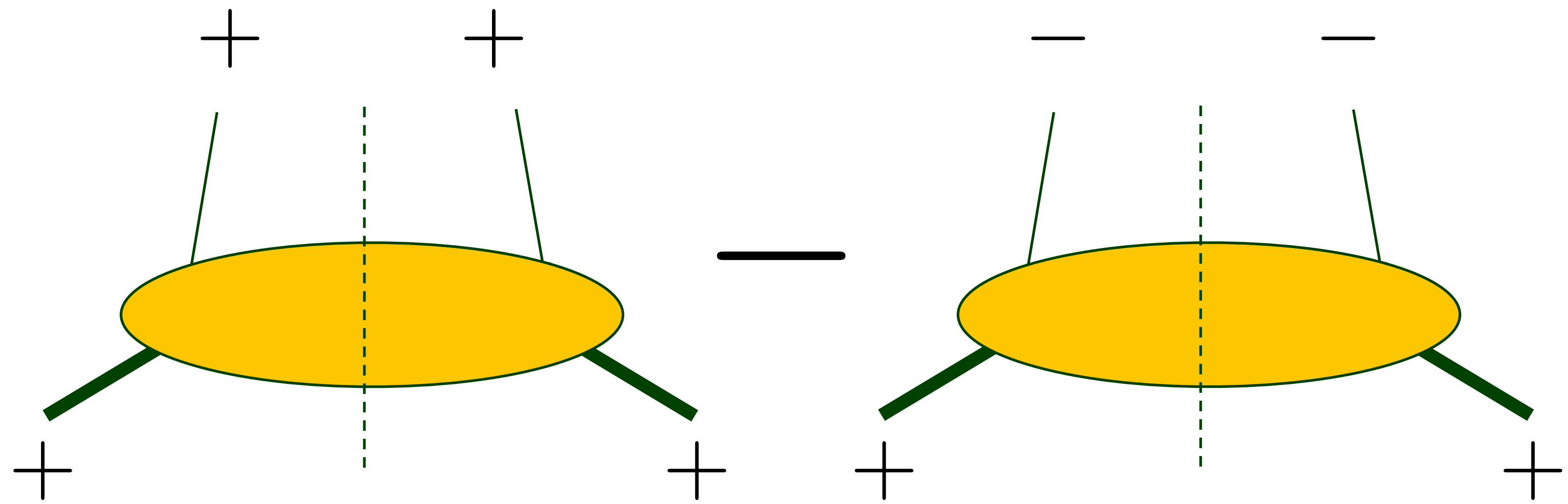


talks by Werner Vogelsang, Marcin Stolarski

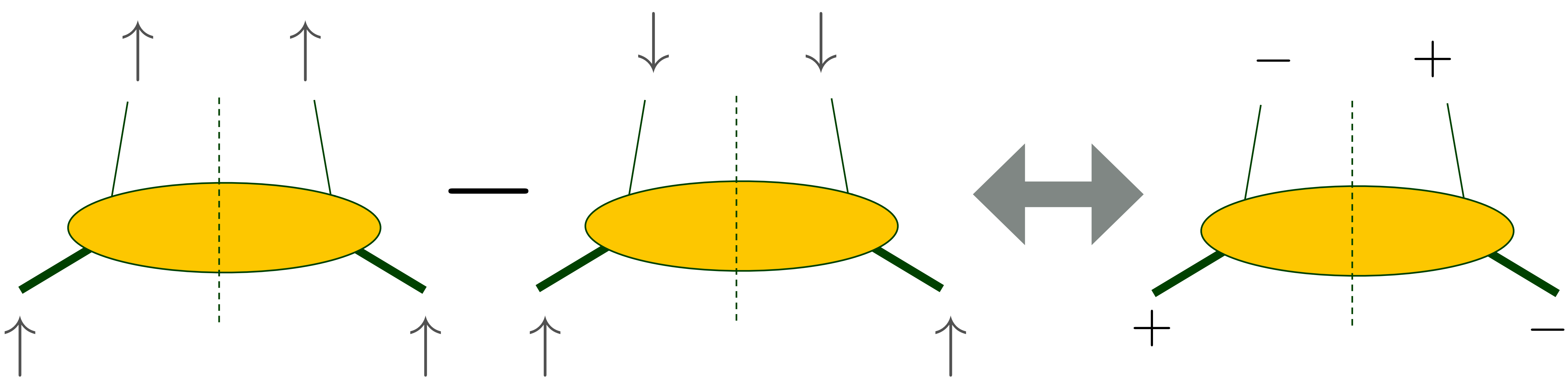
Transversity h_1



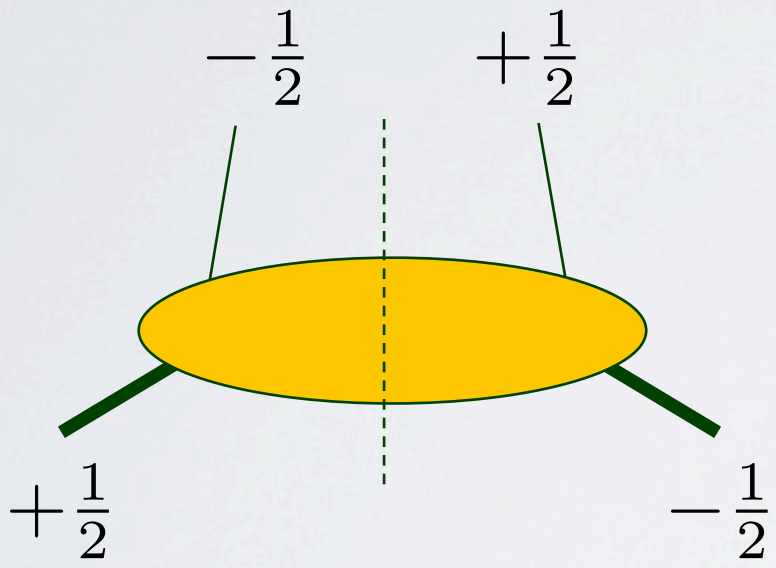
Helicity g_1



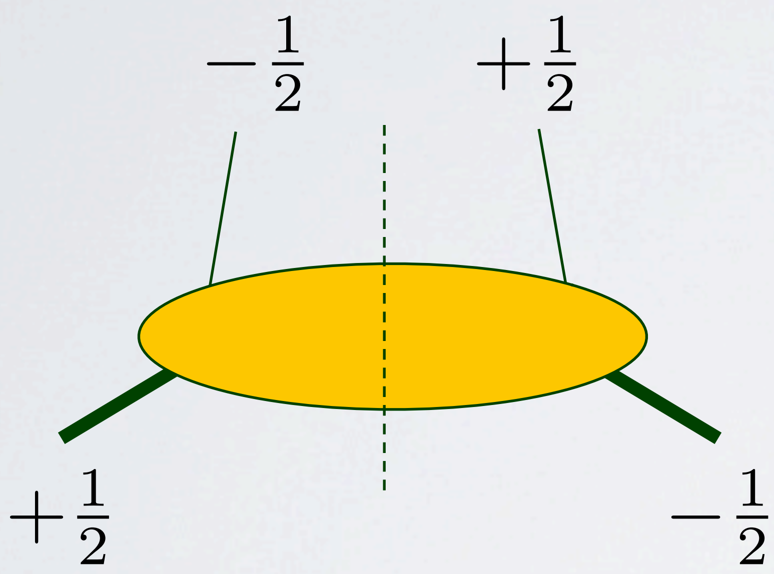
Transversity h_1

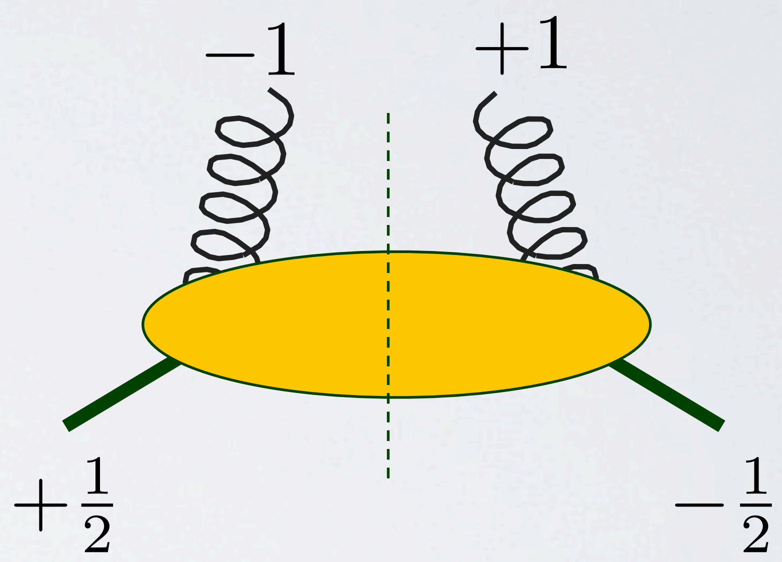


Gluons...

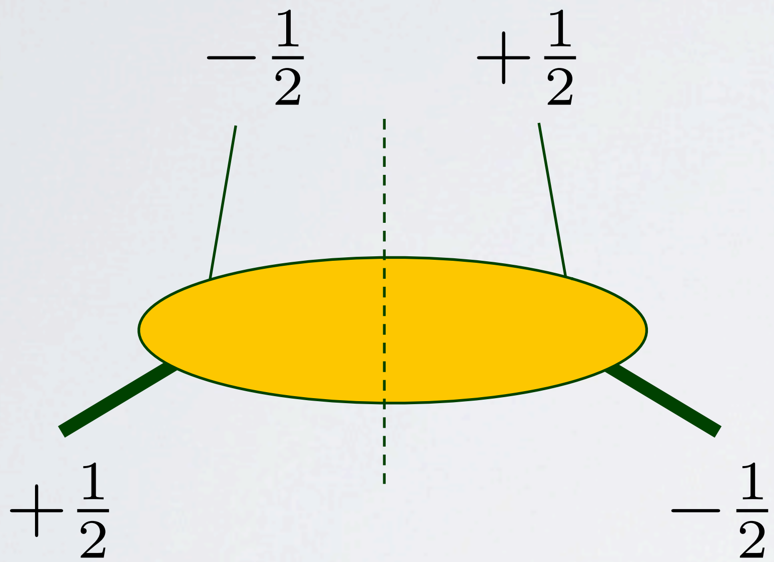


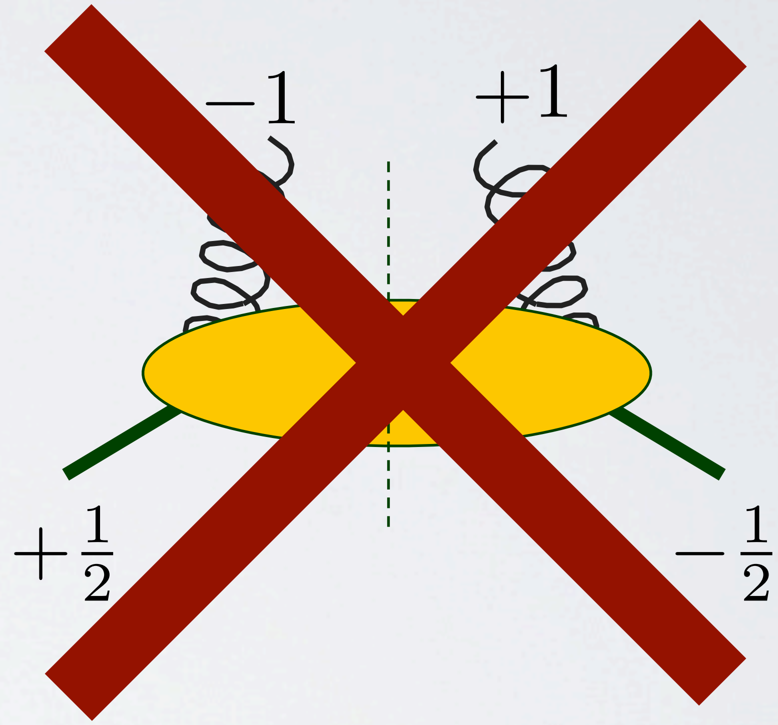
Gluons...



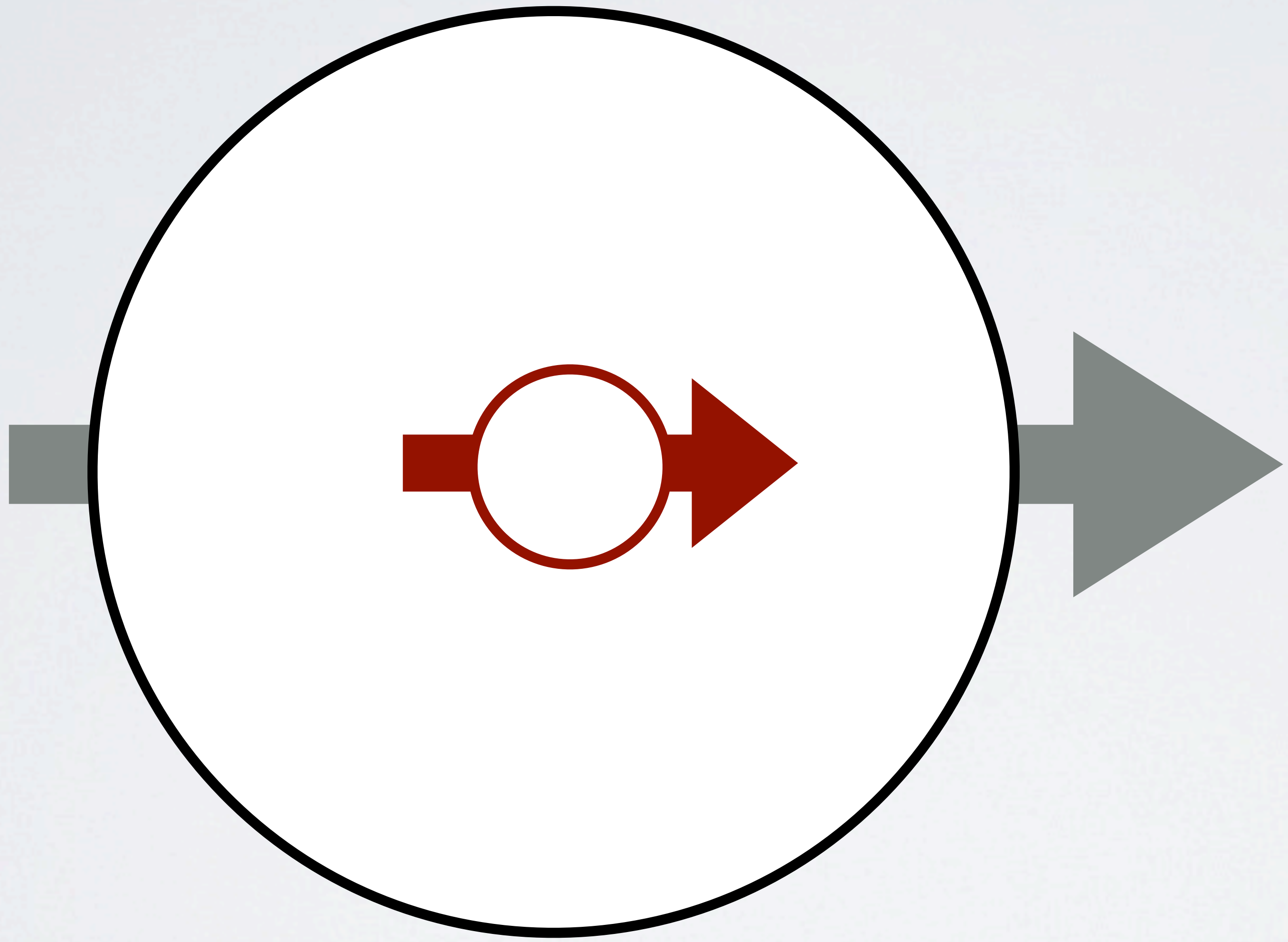


Gluons...

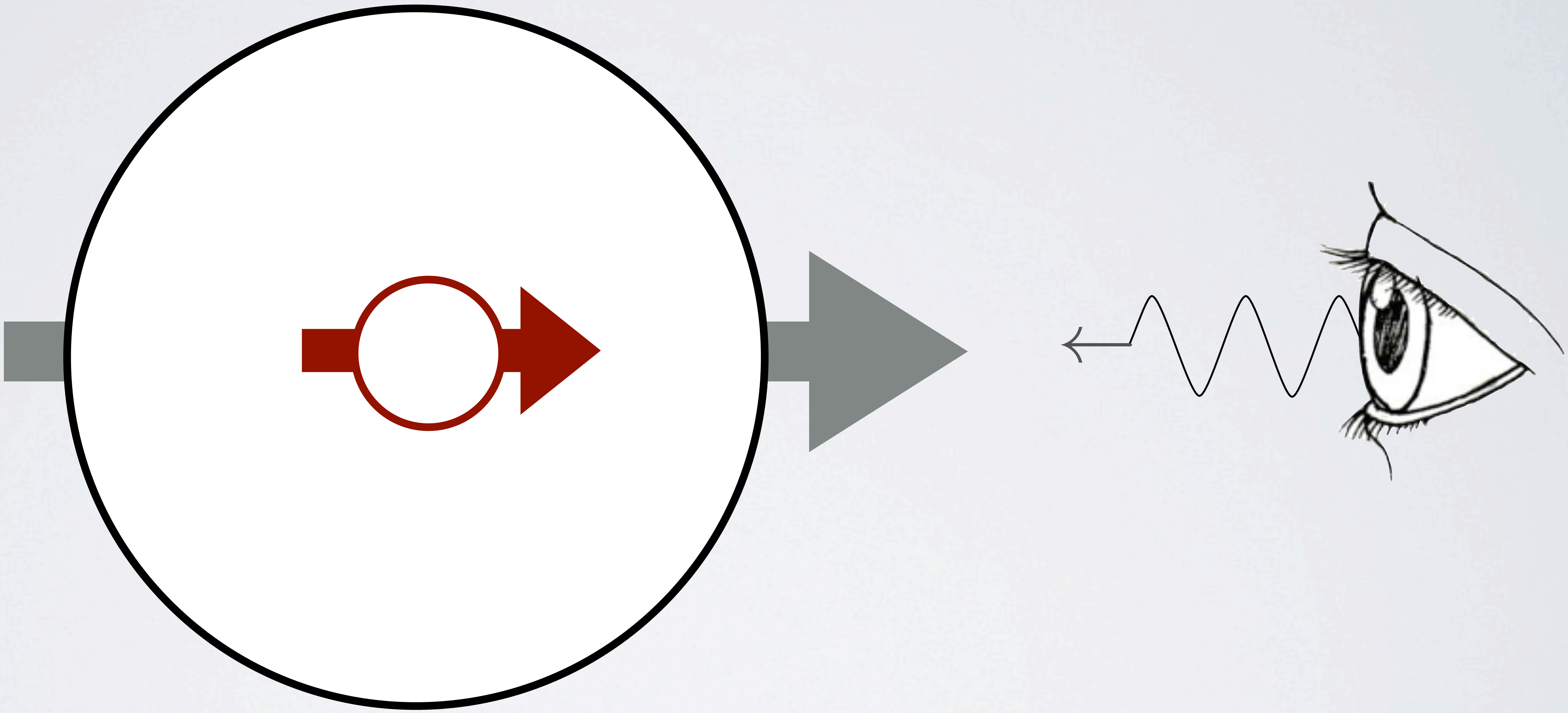




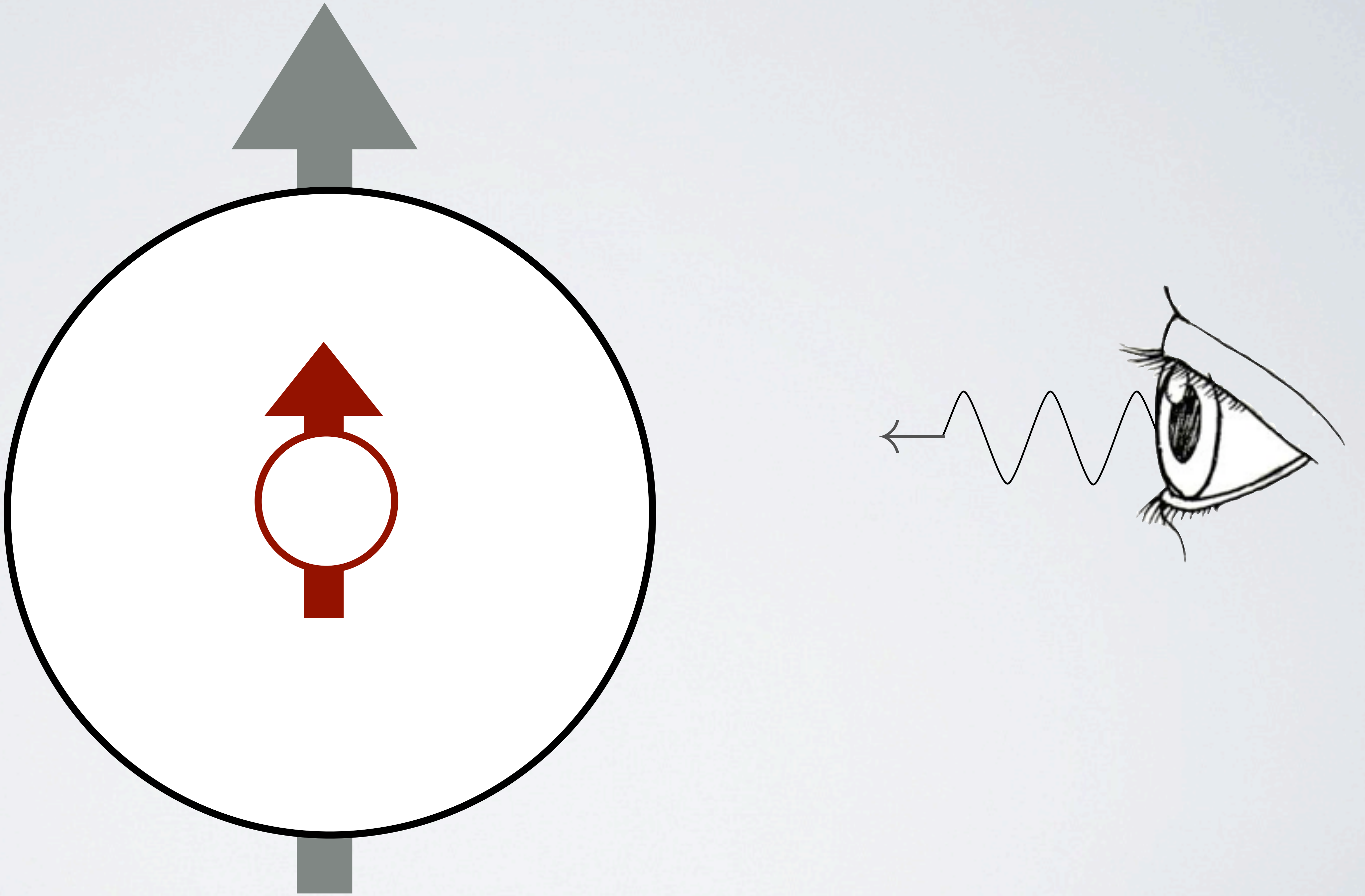
Helicity



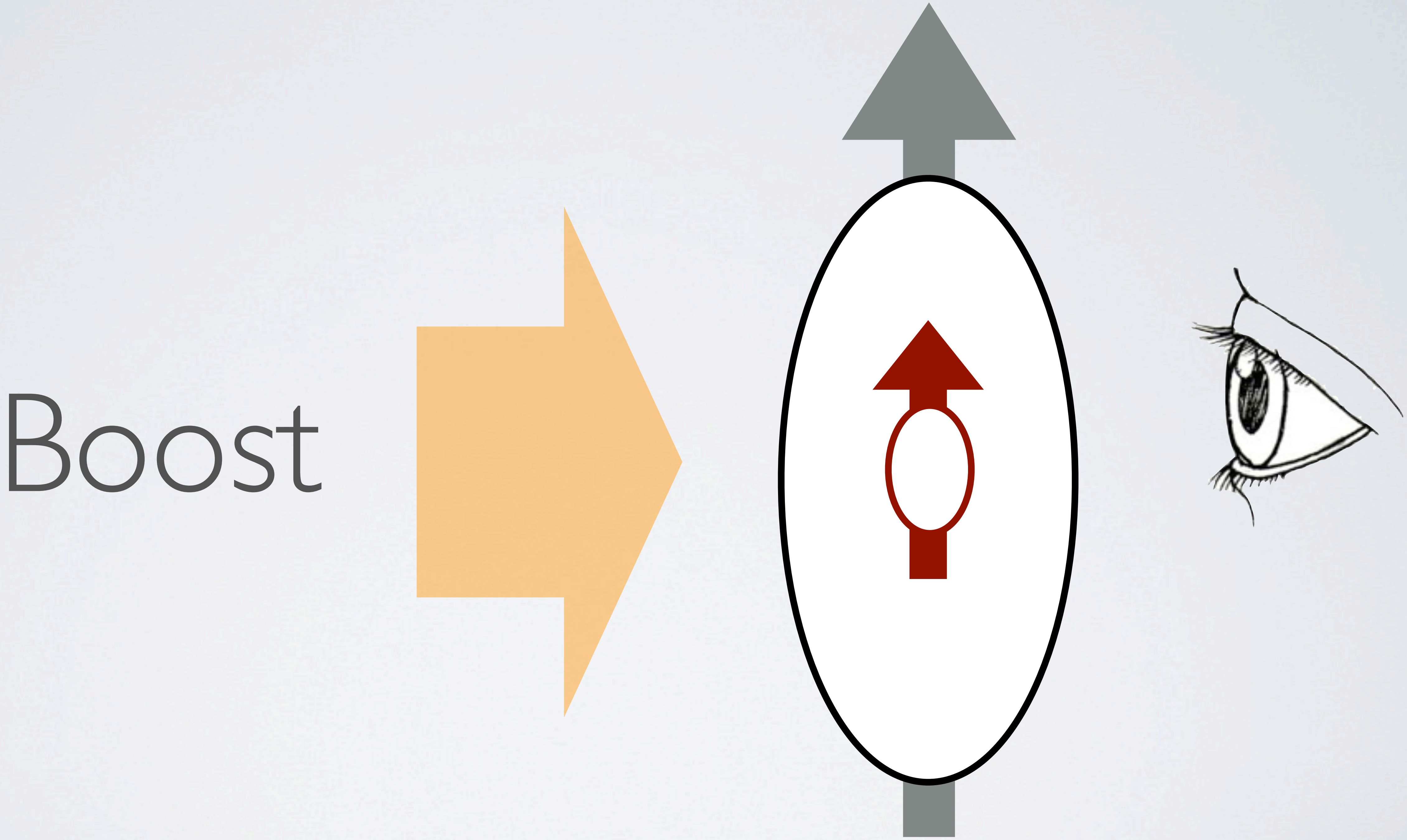
Helicity



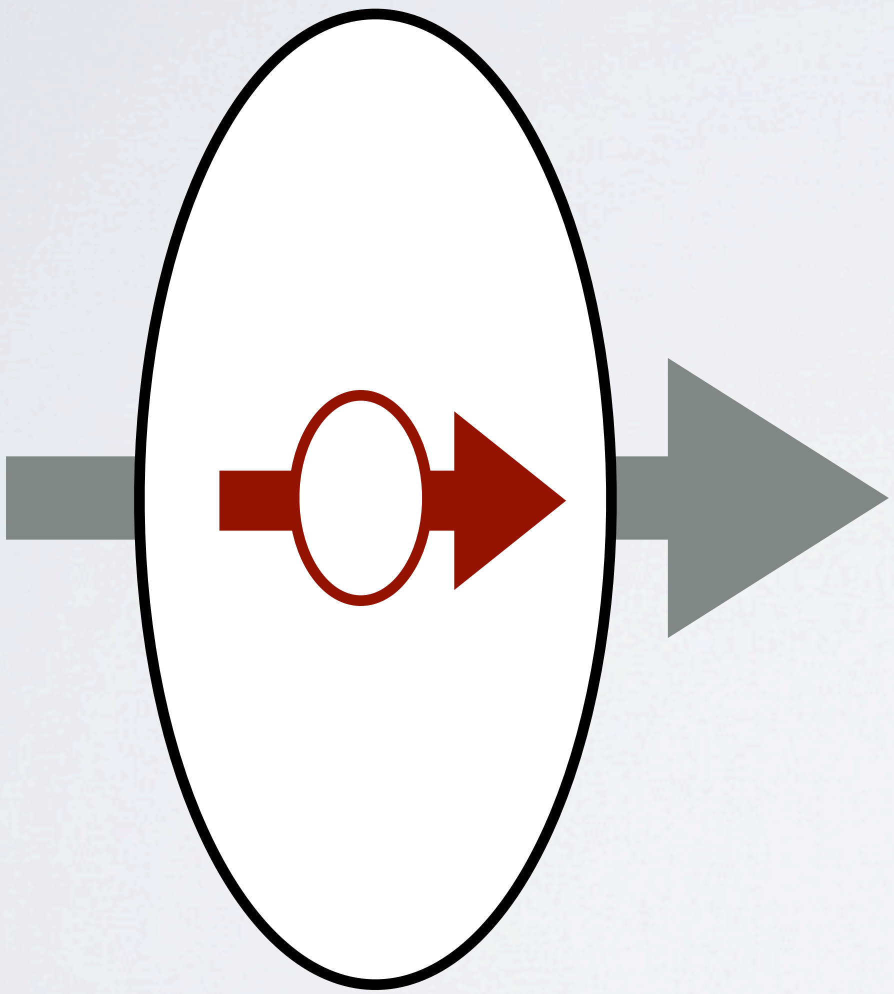
Transversity



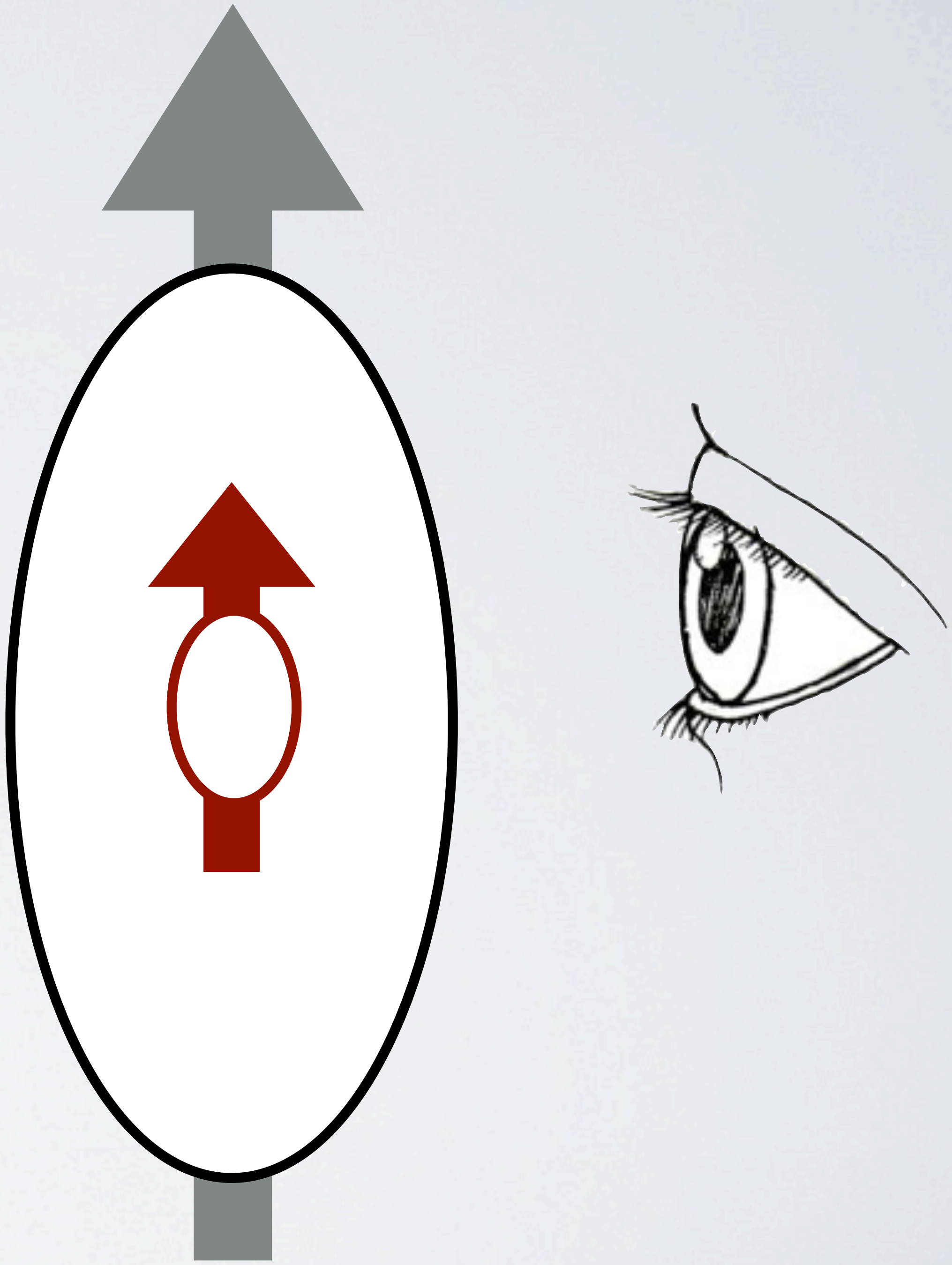
Transversity



Helicity



Transversity



- Difference transversity/helicity: relativistic effect

pQCD framework

- HELICITY: solid pQCD framework

see talk by Werner Vogelsang

pQCD framework

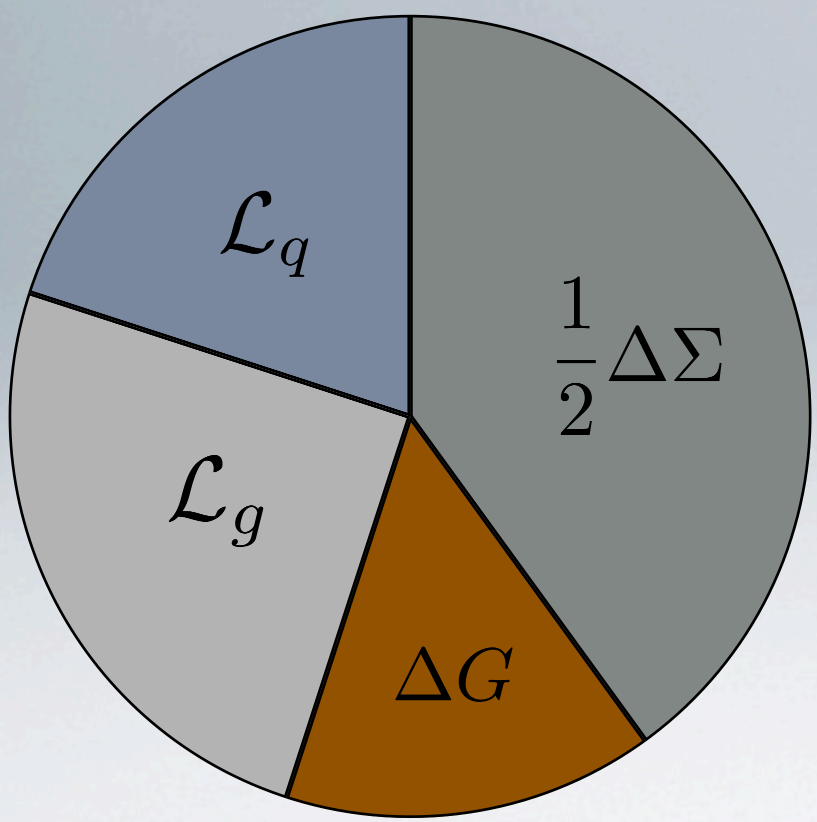
- HELICITY: solid pQCD framework

- TRANSVERSITY: solid pQCD framework for collinear factorization, TMD factorization needs some work.

see talk by Werner Vogelsang

Spin sum rules

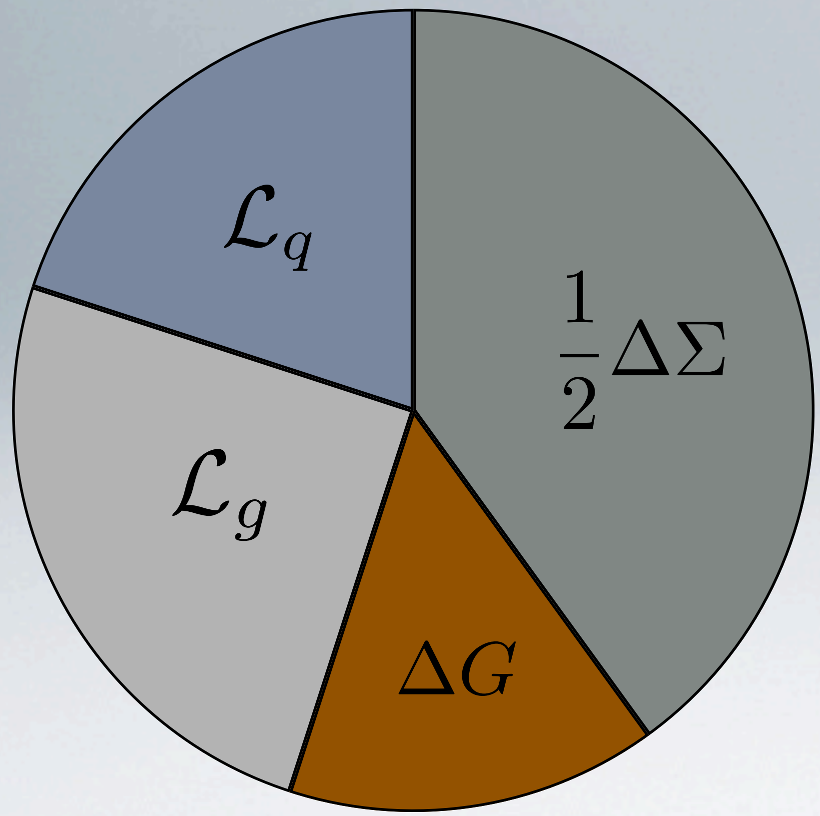
Helicity



see talks by
Wakamatsu, Lorcé, Pasquini

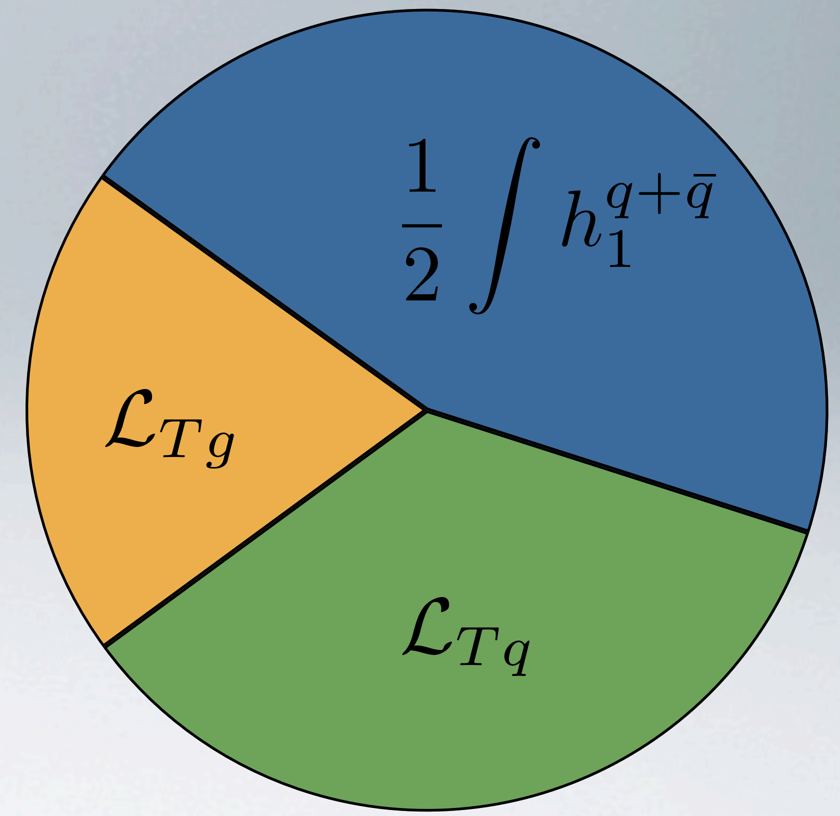
Spin sum rules

Helicity



see talks by Wakamatsu, Lorcé, Pasquini

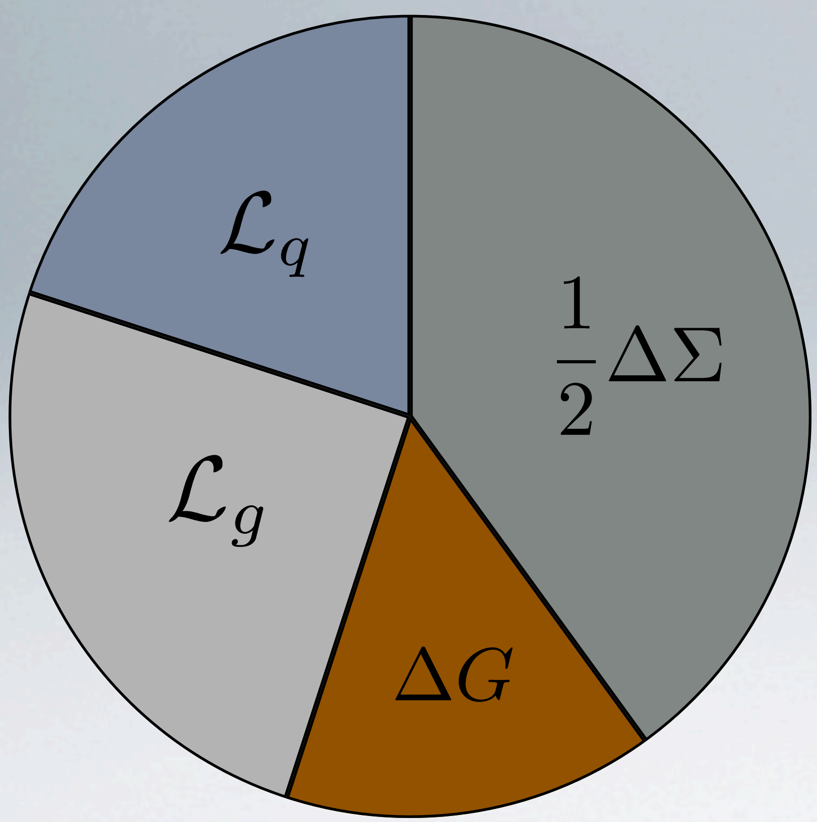
Transversity



Bakker, Leader, Trueman, PRD 70 (04)

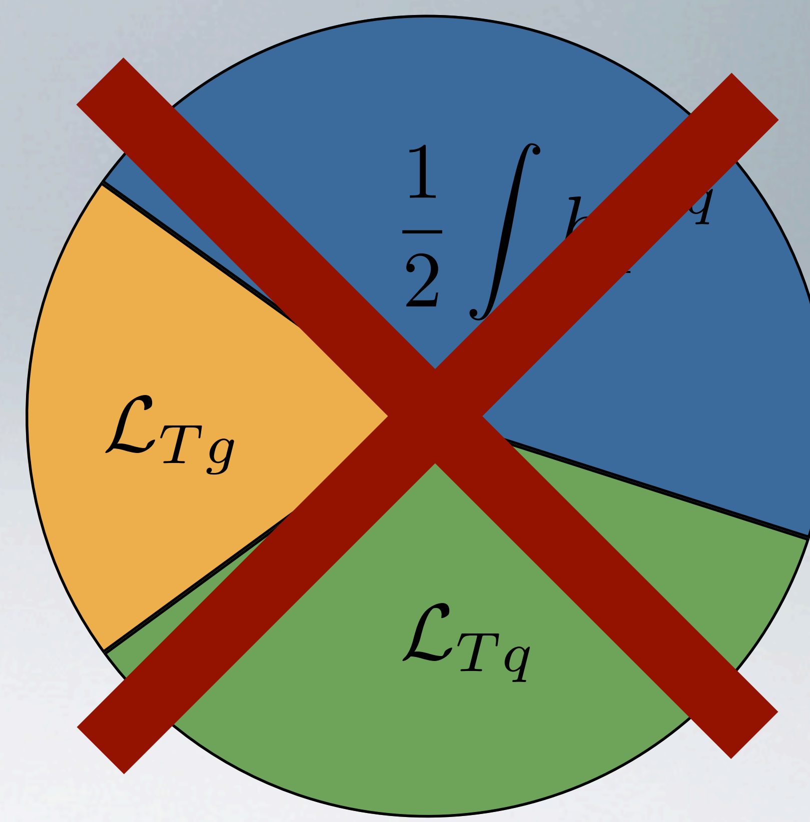
Spin sum rules

Helicity



see talks by Wakamatsu, Lorcé, Pasquini

Transversity



Bakker, Leader, Trueman, PRD 70 (04)


PORTUGAL


50
EURO
CENT

Helicity

Transversity

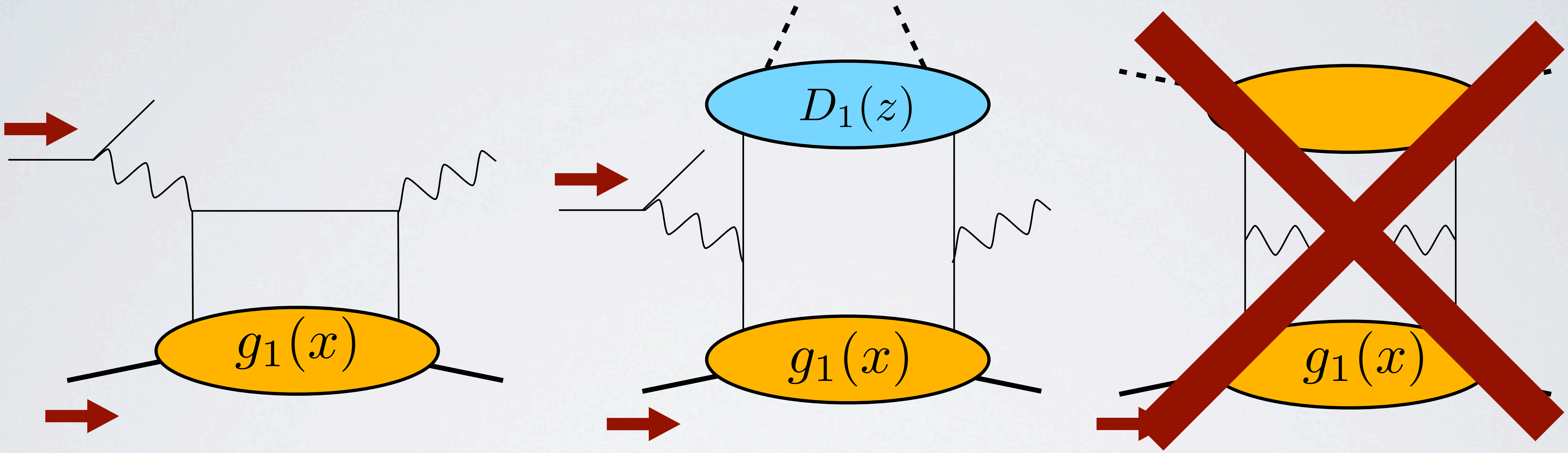
Helicity

Transversity

It is important to look at the proton's spin from two different sides

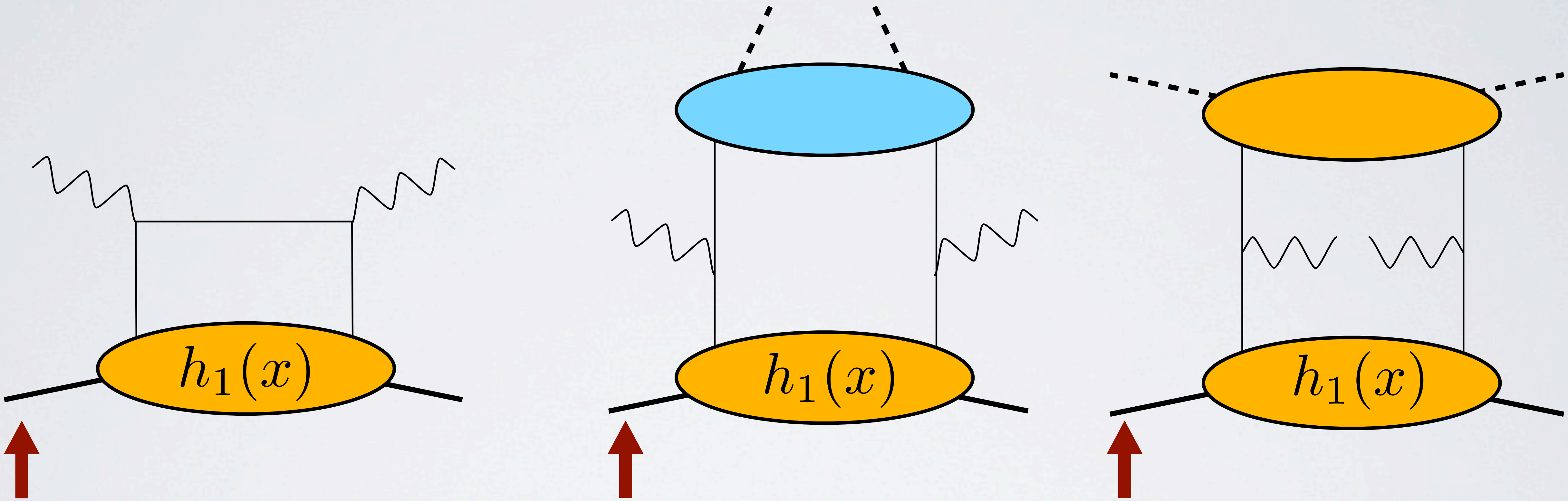
Phenomenology: general remarks

Observables: helicity



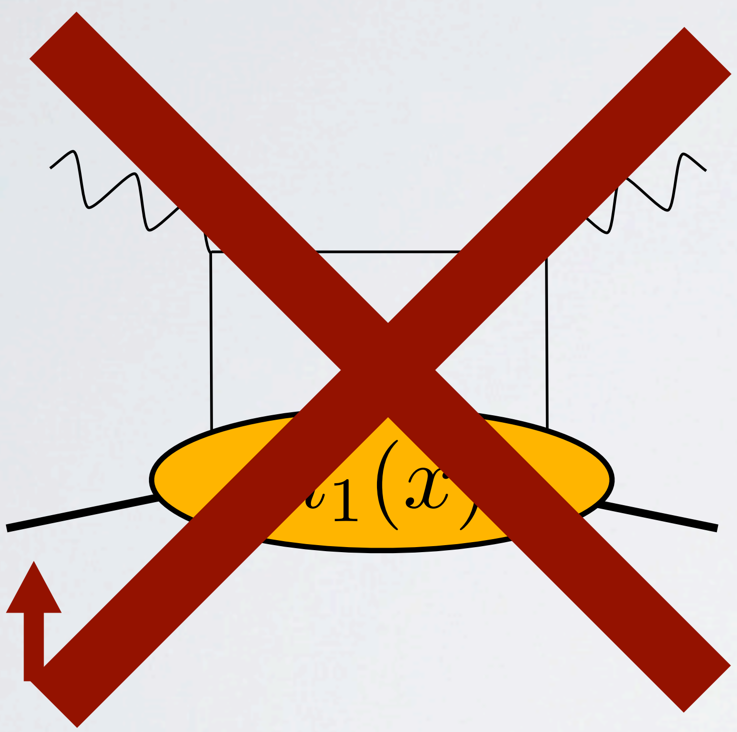
DIS SIDIS πp Drell-Yan

Observables: transversity

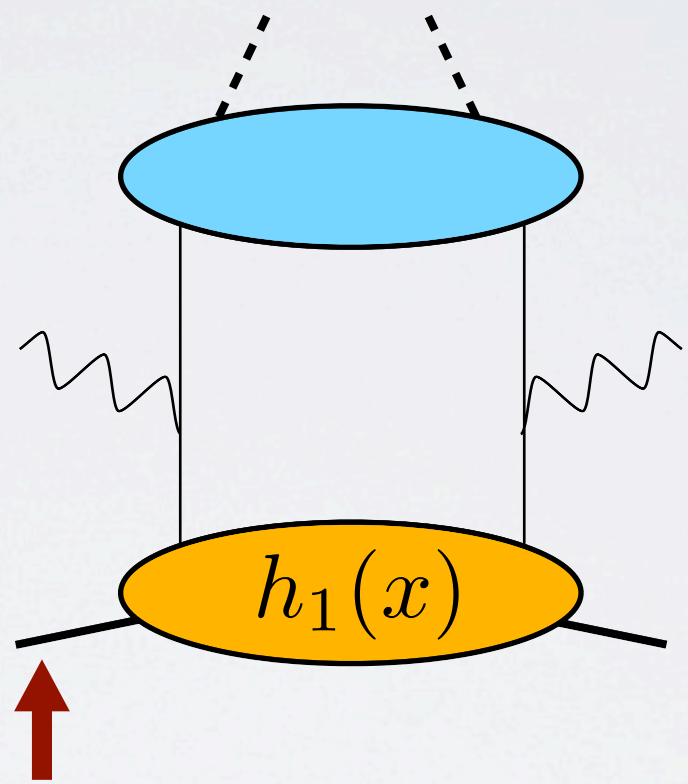


DIS　　SIDIS　　πp Drell-Yan

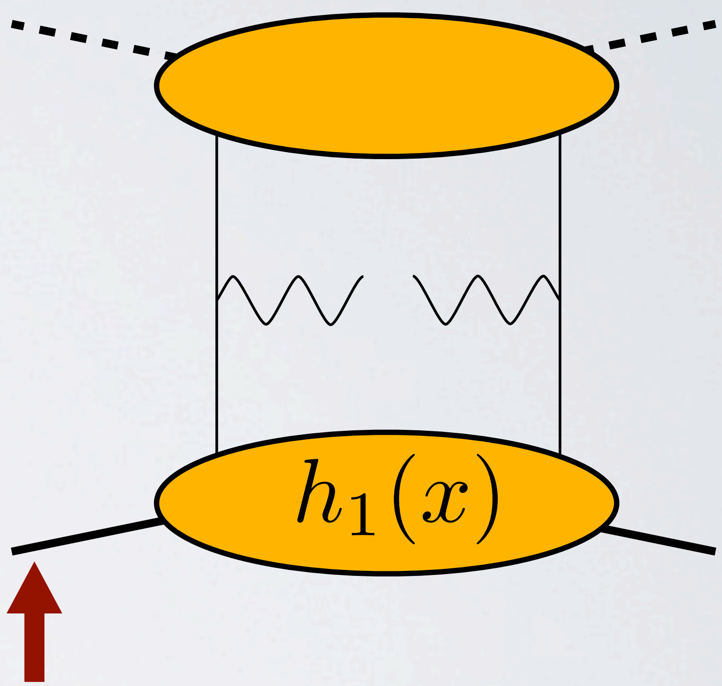
Observables: transversity



DIS



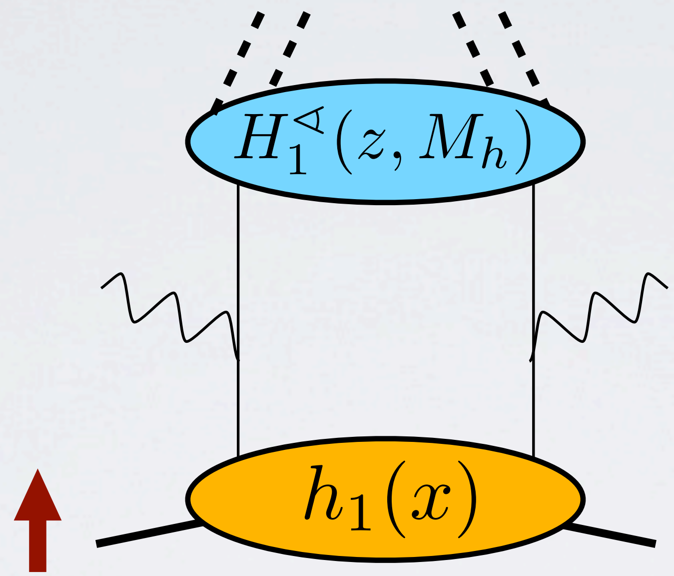
SIDIS



πp Drell-Yan

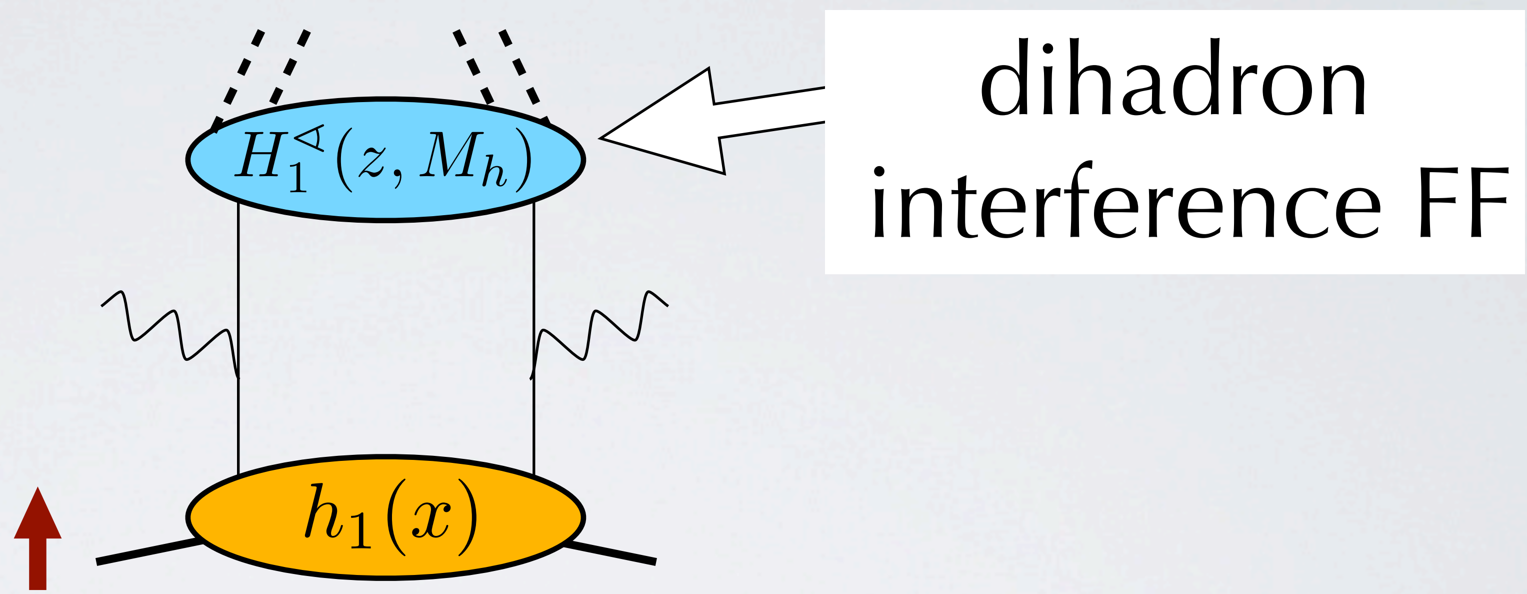
Observables: transversity

Collinear factorization



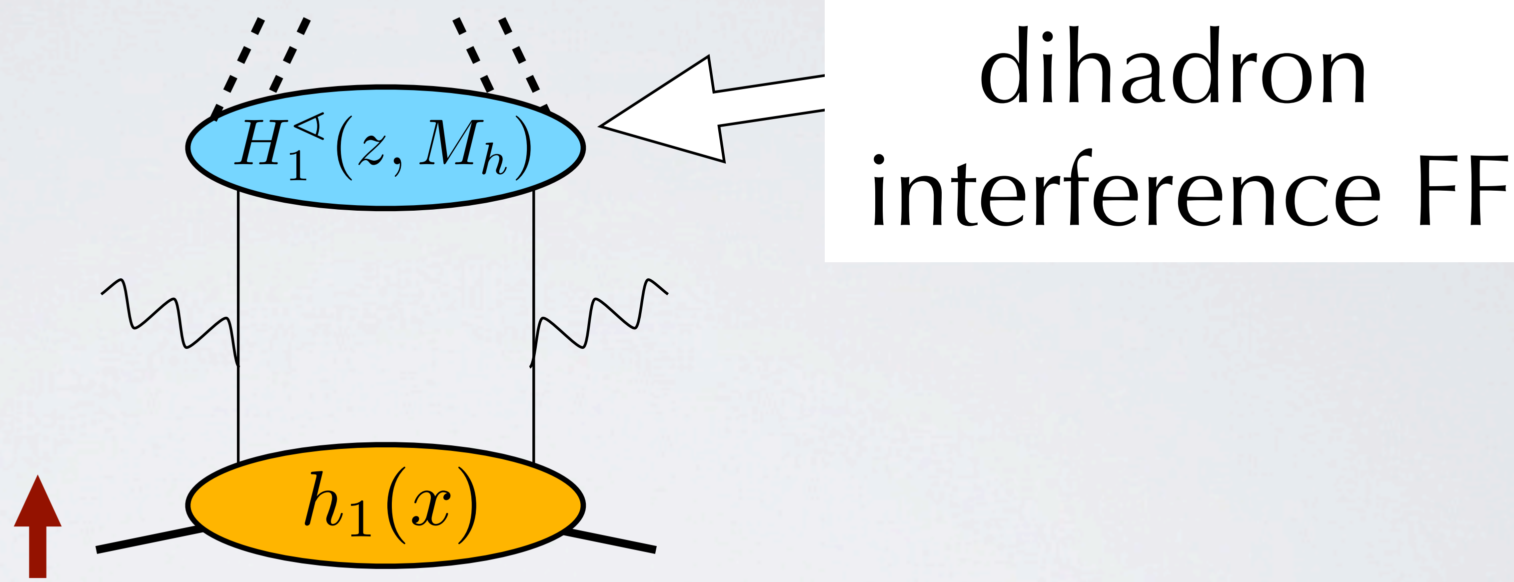
Observables: transversity

Collinear factorization

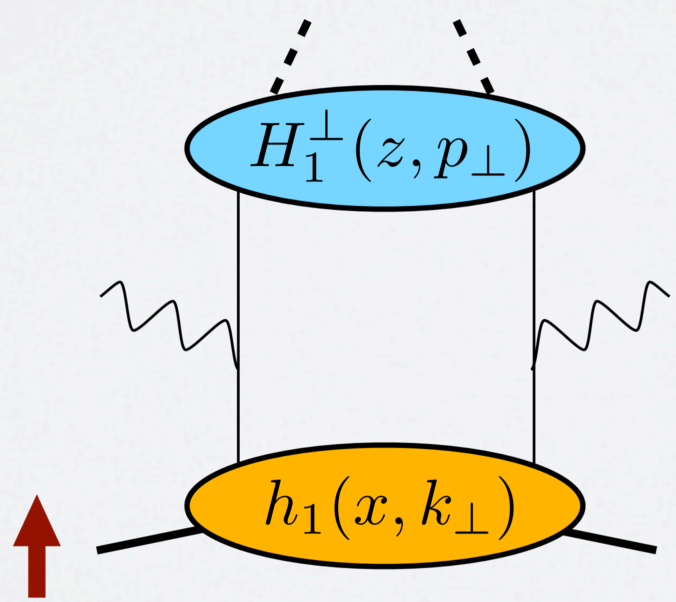


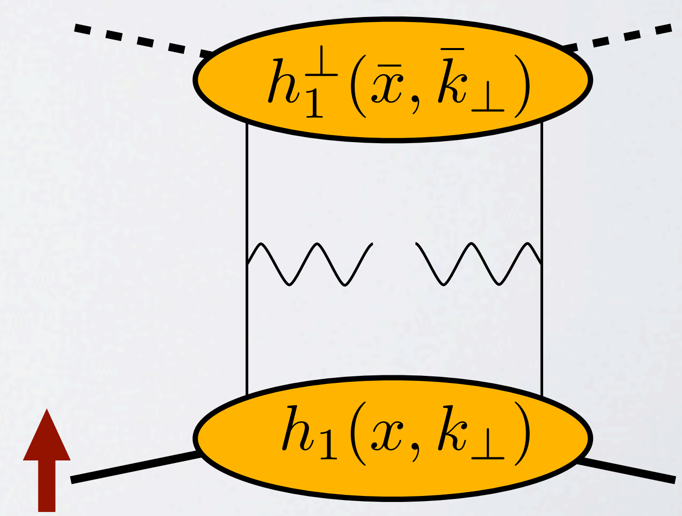
Observables: transversity

Collinear factorization



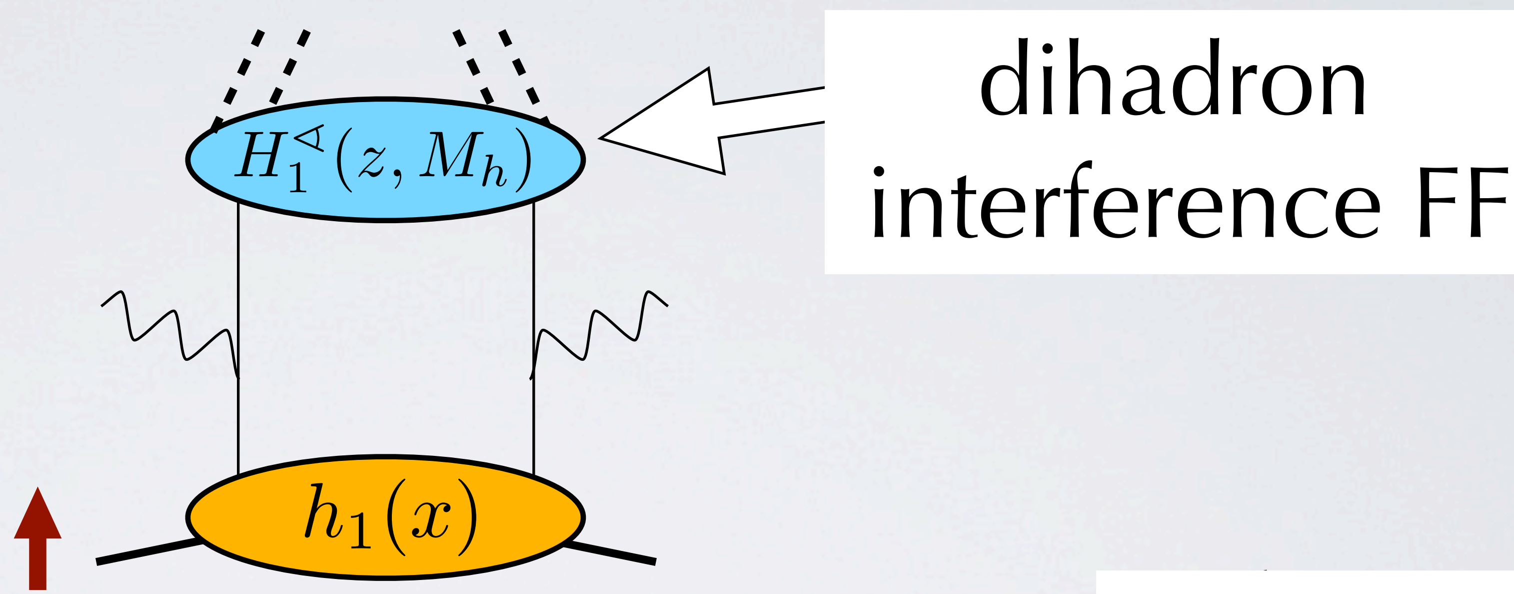
TMD factorization



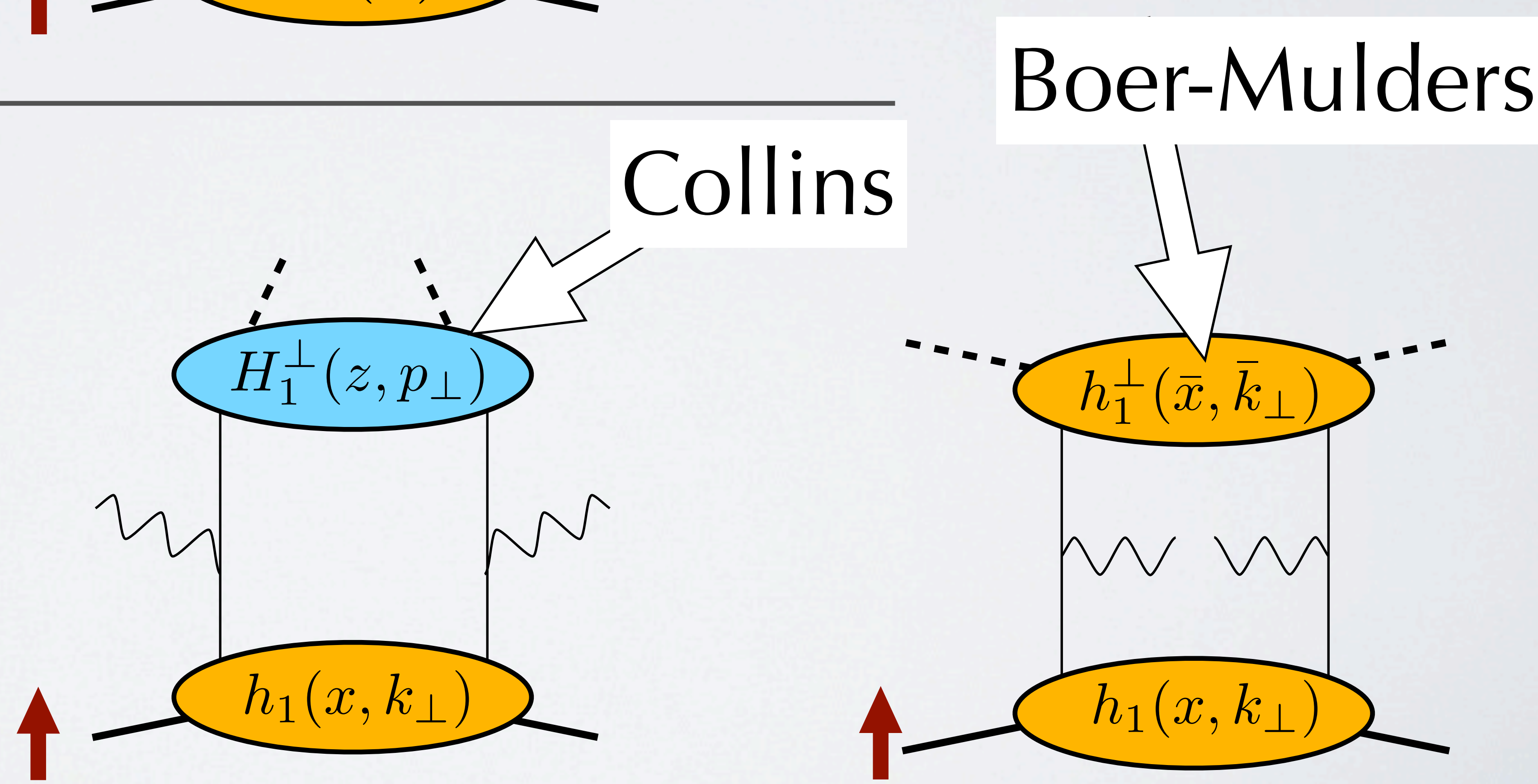


Observables: transversity

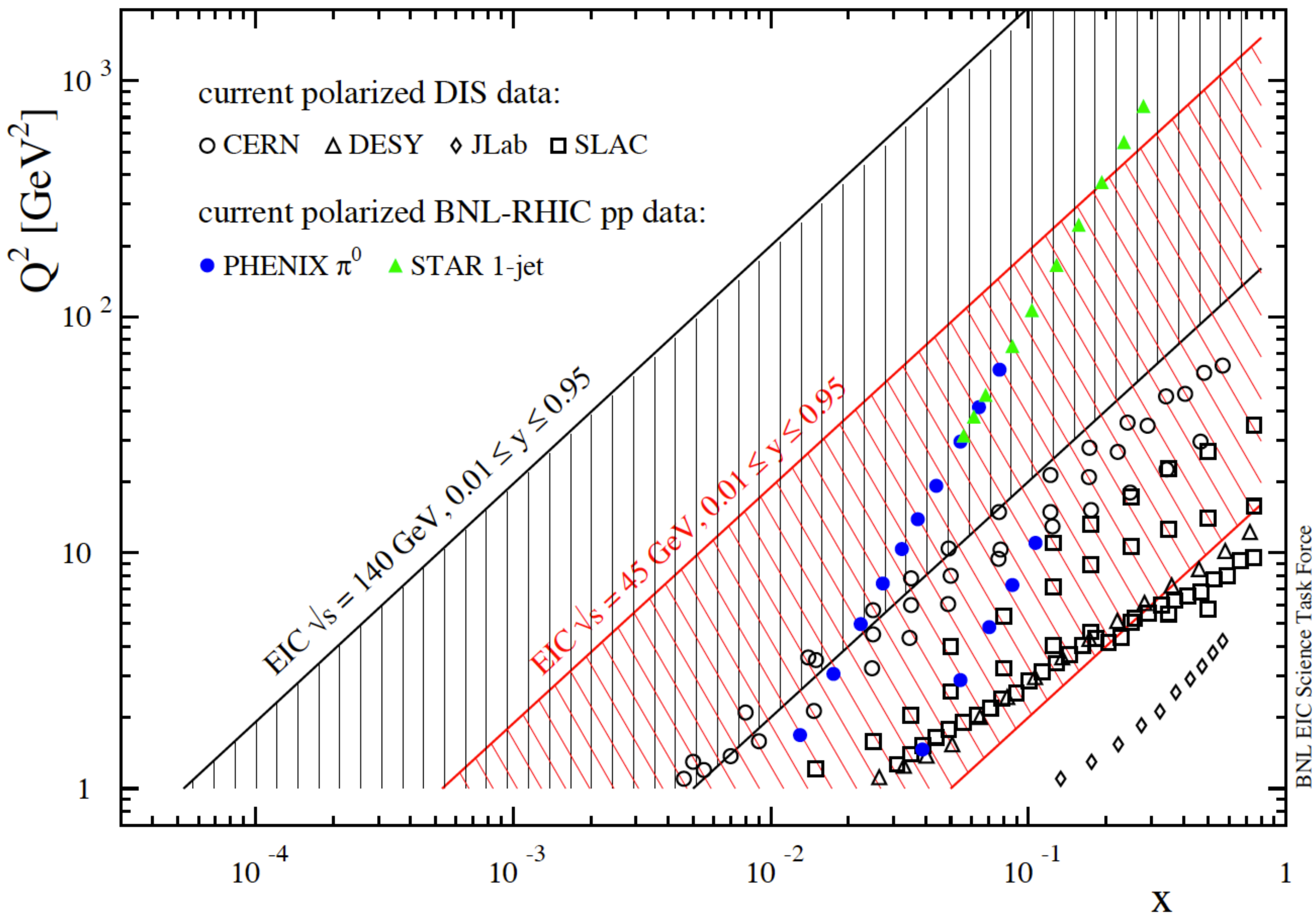
Collinear factorization



TMD factorization

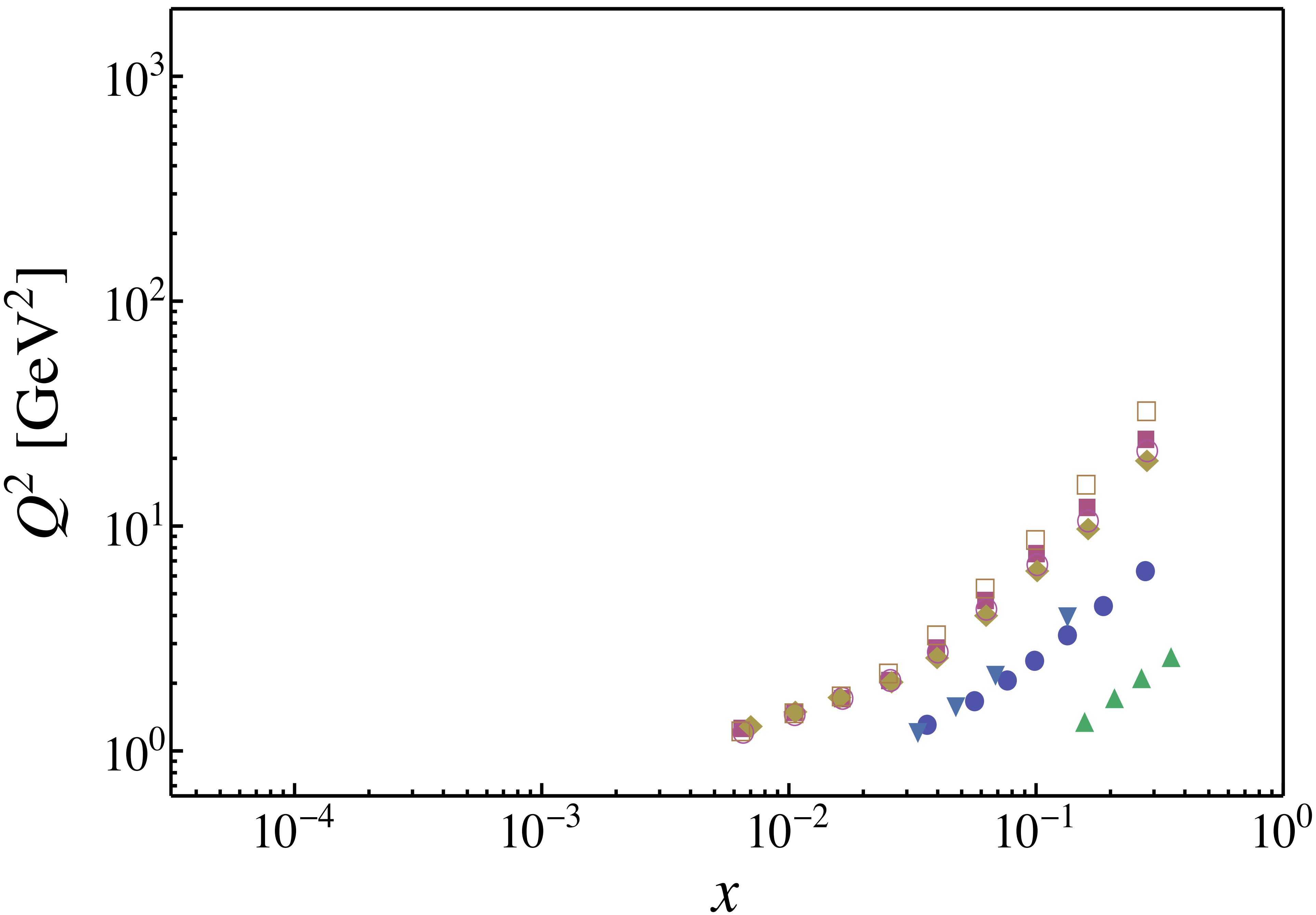


x-Q^2 coverage: helicity

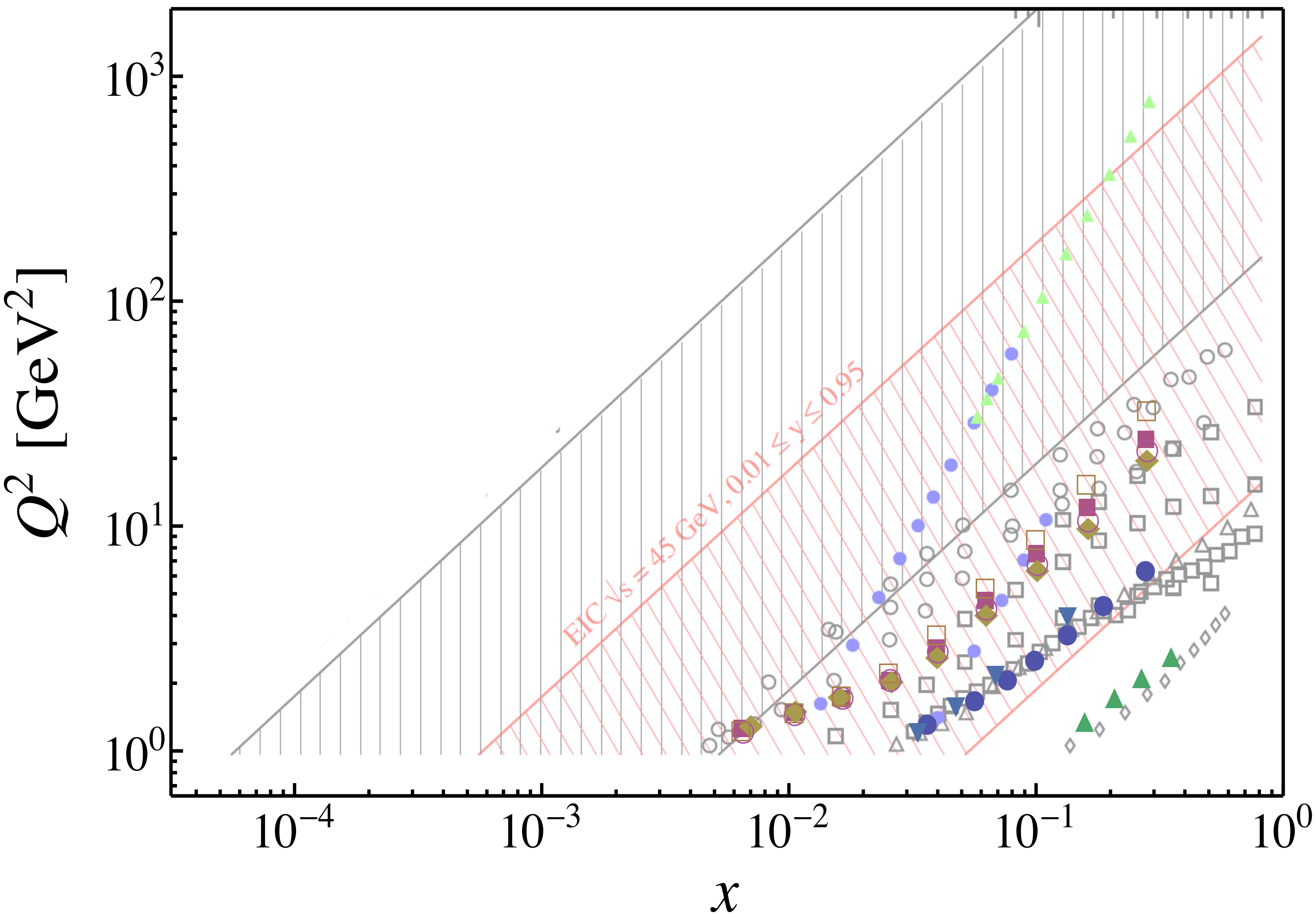


M. Stratmann, talk at DIS2012

x-Q^2 coverage: transversity



x-Q^2 coverage: transversity



Data points: helicity

experiment	process	$N_{\rm data}$
EMC [2]	DIS (p)	10
SMC [3]	DIS (p)	12
SMC [3]	DIS (d)	12
COMPASS [4]	DIS (d)	15
E142 [5]	DIS (n)	8
E143 [6]	DIS (p)	28
E143 [6]	DIS (d)	28
E154 [7]	DIS (n)	11
E155 [8]	DIS (p)	24
E155 [9]	DIS (d)	24
HERMES [10]	DIS (He)	9
HERMES [11]	DIS (p)	15
HERMES [11]	DIS (d)	15
HALL-A [12]	DIS (n)	3
CLAS [13]	DIS (p)	10
CLAS [13]	DIS (d)	10
SMC [14]	SIDIS (p, h^+)	12
SMC [14]	SIDIS (p, h^-)	12
SMC [14]	SIDIS (d, h^+)	12
SMC [14]	SIDIS (d, h^-)	12
HERMES [15]	SIDIS (p, h^+)	9
HERMES [15]	SIDIS (p, h^-)	9
HERMES [15]	SIDIS (d, h^+)	9
HERMES [15]	SIDIS (d, h^-)	9
HERMES [10]	SIDIS (He, h^+)	9
HERMES [10]	SIDIS (He, h^-)	9
HERMES [15]	SIDIS (p, π^+)	9
HERMES [15]	SIDIS (p, π^-)	9
HERMES [15]	SIDIS (d, π^+)	9
HERMES [15]	SIDIS (d, π^-)	9
HERMES [15]	SIDIS (d, K^+)	9
HERMES [15]	SIDIS (d, K^-)	9
HERMES [15]	SIDIS $(\mathrm{d}, K^+ + K^-)$	9
COMPASS [16]	SIDIS (d, h^+)	12
COMPASS [16]	SIDIS (d, h^-)	12
PHENIX [22]	pp $(200\,\mathrm{GeV}, \pi^0)$	10
PHENIX [23]	pp $(200\,\mathrm{GeV}, \pi^0)$	10
PHENIX [24]	pp $(62\,\mathrm{GeV}, \pi^0)$	5
STAR [25]	pp (200 GeV, jet)	10
STAR (prel.) [26]	pp (200 GeV, jet)	9
TOTAL:		467

DSSV08, PRD 80 (09)

Data points: helicity

experiment	process	$N_{\rm data}$
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SMC [3]	DIS (p)	12
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E143 [6]	DIS (p)	28
E143 [6]	DIS (d)	28
E154 [7]	DIS (n)	11
E155 [8]	DIS (p)	24
E155 [9]	DIS (d)	24
HERMES [10]	DIS (He)	9
HERMES [11]	DIS (p)	15
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SMC [14]	SIDIS (d, h^-)	12
HERMES [15]	SIDIS (p, h^+)	9
HERMES [15]	SIDIS (p, h^-)	9
HERMES [15]	SIDIS (d, h^+)	9
HERMES [15]	SIDIS (d, h^-)	9
HERMES [10]	SIDIS (He, h^+)	9
HERMES [10]	SIDIS (He, h^-)	9
HERMES [15]	SIDIS (p, π^+)	9
HERMES [15]	SIDIS (p, π^-)	9
HERMES [15]	SIDIS (d, π^+)	9
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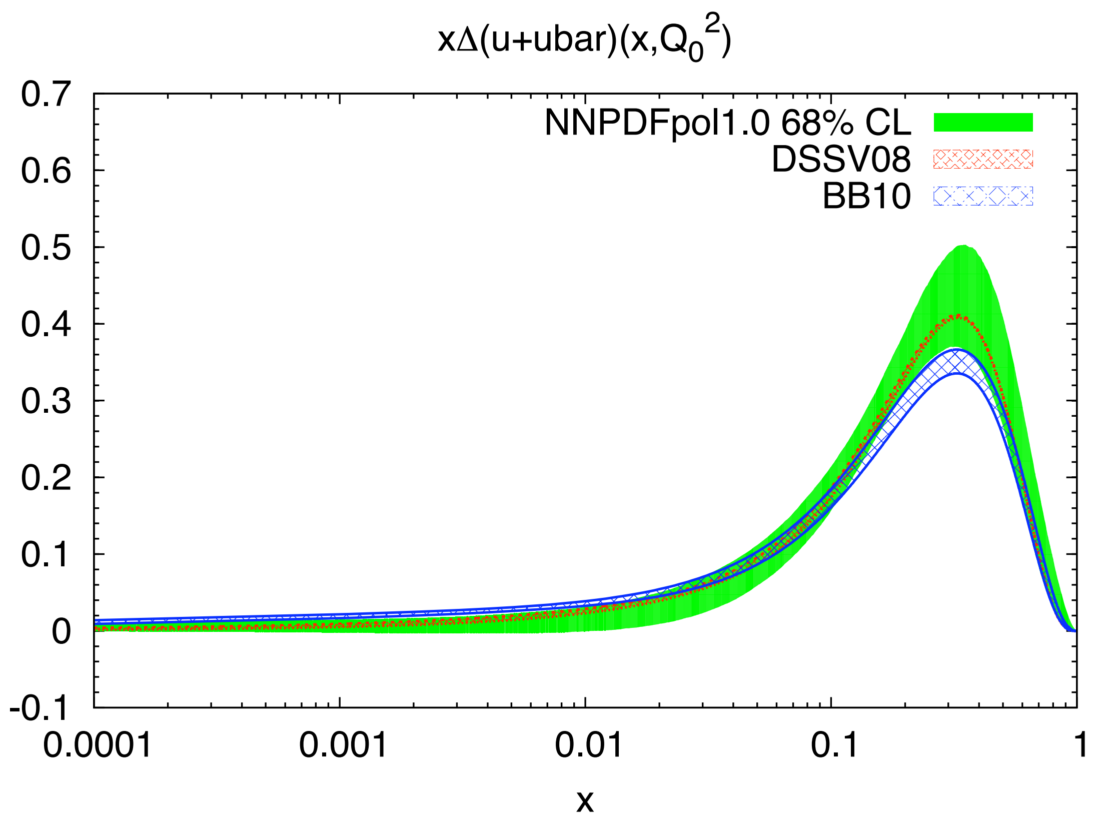
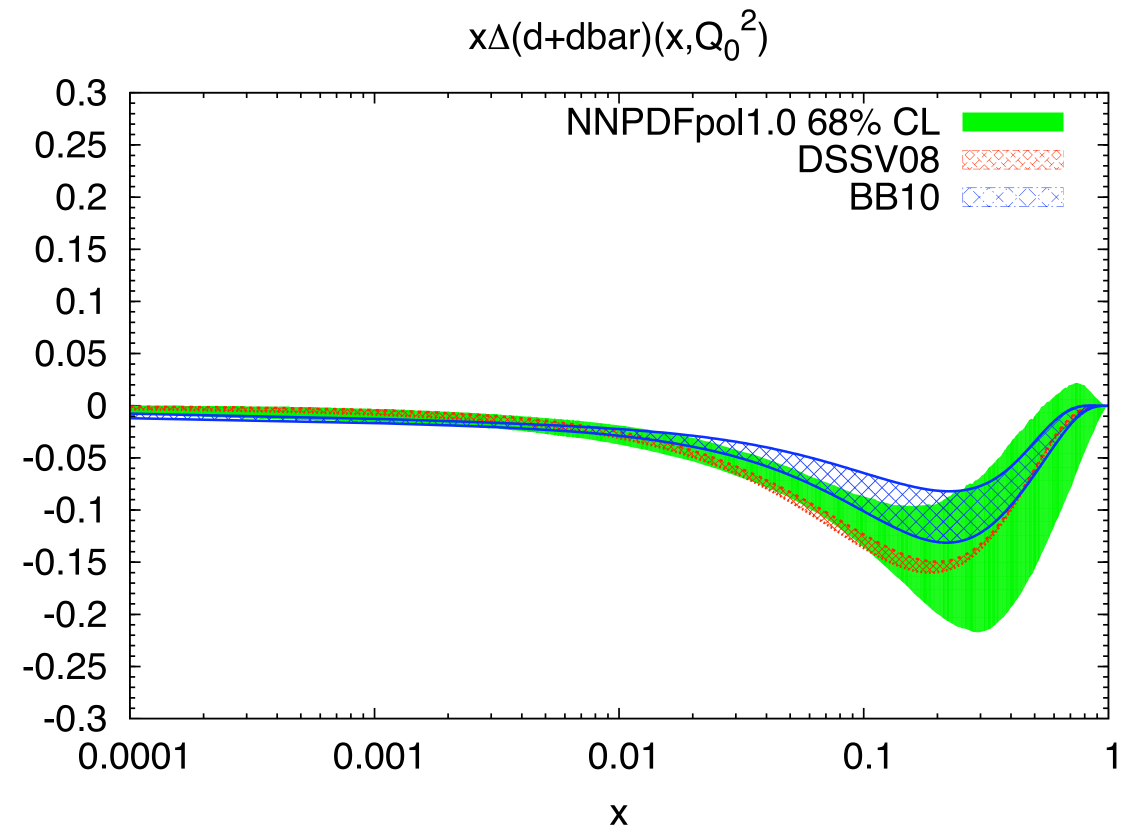
467

DSSV08, PRD 80 (09)

Extractions: helicity





- DSSV08, arXiv:0904.3821 (467 points -- DIS, SIDIS, pp)
- LSS10, arXiv:1010.0574 (1043 -- DIS,SIDIS)
- BB10, arXiv:1005.3113 (1385 -- DIS)
- AAC, arXiv:0808.0413 (451 points -- DIS, SIDIS, pp)
- COMING SOON: Neural Network PDFs, talk by E. Nocera at DIS2012

Data points: transversity

	Hadron	N. Points
HERMES	π^+	7
	π^-	7
	π^0	7
	K^+	7
	K^-	7
COMPASS *d*	π^+	9
	π^-	9
	K^+	9
	K^-	9
	$h^+ h^-$	9
COMPASS *p* 2007	h^+	9
	h^-	9
	$h^+ h^-$	9
JLab Hall A	π^+	4
	π^-	4
Total		*115*

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	π^-	7
	π^0	7
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	π^-	9
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	K^-	9
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COMPASS *p* 2007	h^+	9
	h^-	9
	$h^+ h^-$	9
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115

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HERMES	π^+	7
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	π^0	7
	K^+	7
	K^-	7
COMPASS *d*	π^+	9
	π^-	9
	K^+	9
	K^-	9
	$h^+ h^-$	9
COMPASS *p* 2007	[illegible]	[illegible]
	h^-	9
	$h^+ h^-$	[illegible]
JLab Hall A	π^+	4
	π^-	4
Total		*115*

115

… and counting

see talk by Federica Sozzi

Transversity from Collins asymmetry

Single hadron

SIDIS

$$A_{DIS}(x,z,P_{h\perp}^2) = -\langle C_y\rangle \frac{\sum_q e_q^2\, h_1^q(x,p_T^2) \otimes_C H_{1,q}^{\perp}(z,k_T^2)}{\sum_q e_q^2\, f_1^q(x,p_T^2) \otimes D_{1,q}(z,k_T^2)}$$

Single hadron

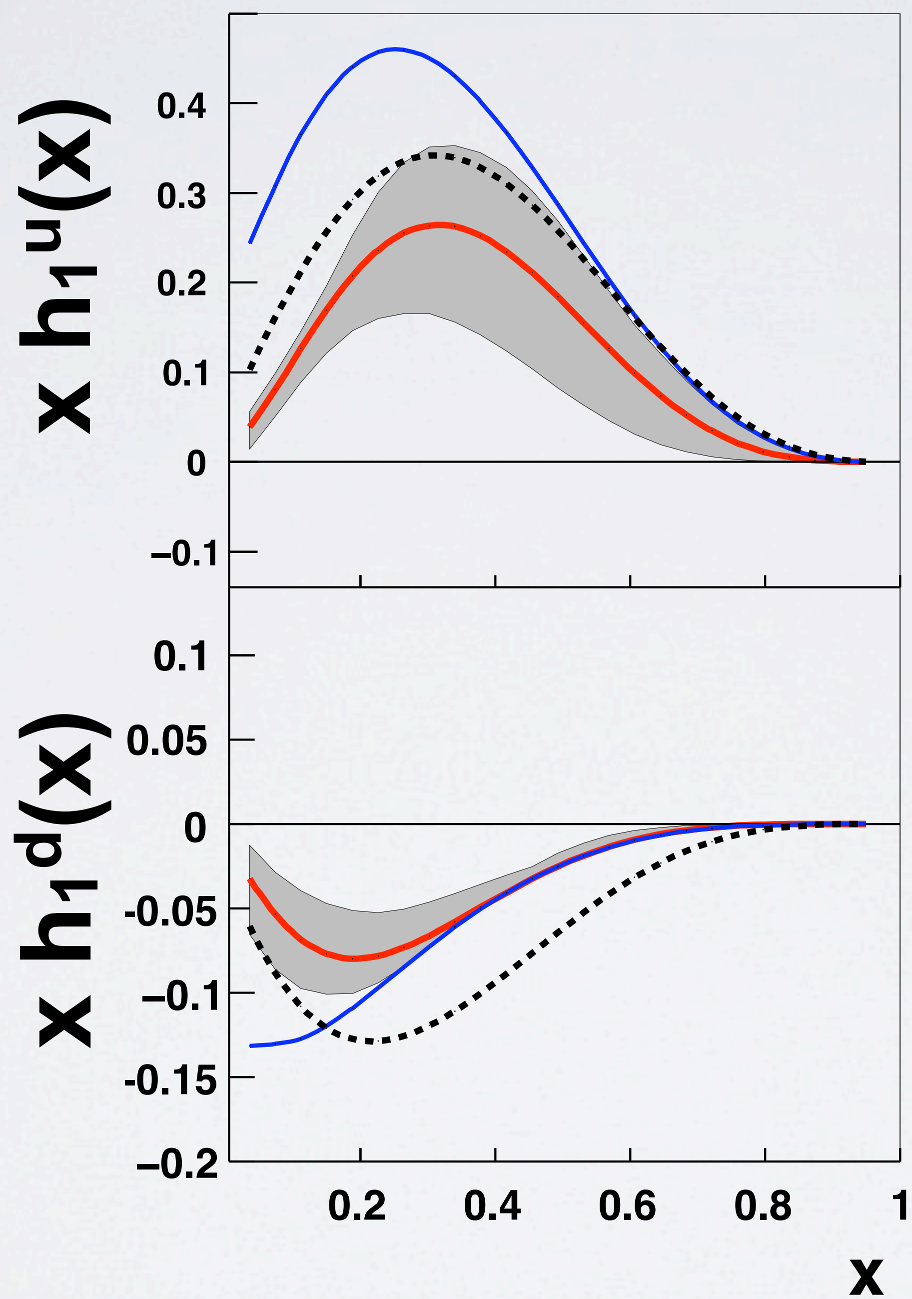
SIDIS

$$A_{DIS}(x,z,P_{h\perp}^2) = -\langle C_y \rangle \frac{\sum_q e_q^2\, h_1^q(x,p_T^2) \otimes_C H_{1,q}^{\perp}(z,k_T^2)}{\sum_q e_q^2\, f_1^q(x,p_T^2) \otimes D_{1,q}(z,k_T^2)}$$

e^+e^-

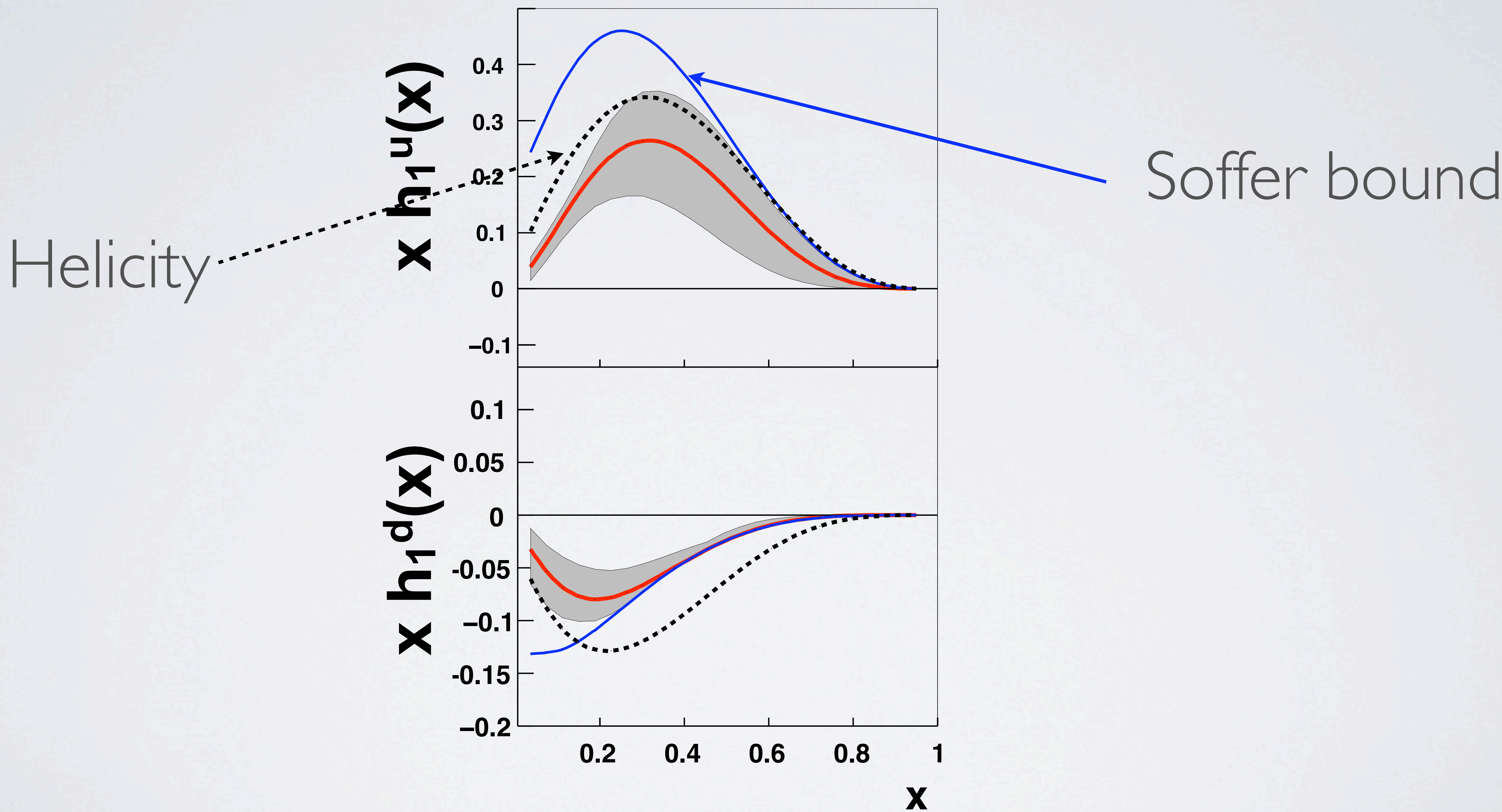
$$A_{e+e-}(z,\bar{z},Q_T^2) = -\frac{\langle \sin^2\theta_2 \rangle}{\langle 1+\cos^2\theta_2 \rangle} \frac{\sum_q e_q^2\; H_{1,q}^{\perp}(z,k_T^2) \otimes_C' H_{1,\bar{q}}^{\perp}(\bar{z},\bar{k}_T^2)}{\sum_q e_q^2\, D_{1,q}(z,k_T^2) \otimes' D_{1,\bar{q}}(\bar{z},\bar{k}_T^2)}$$

Torino's transversity



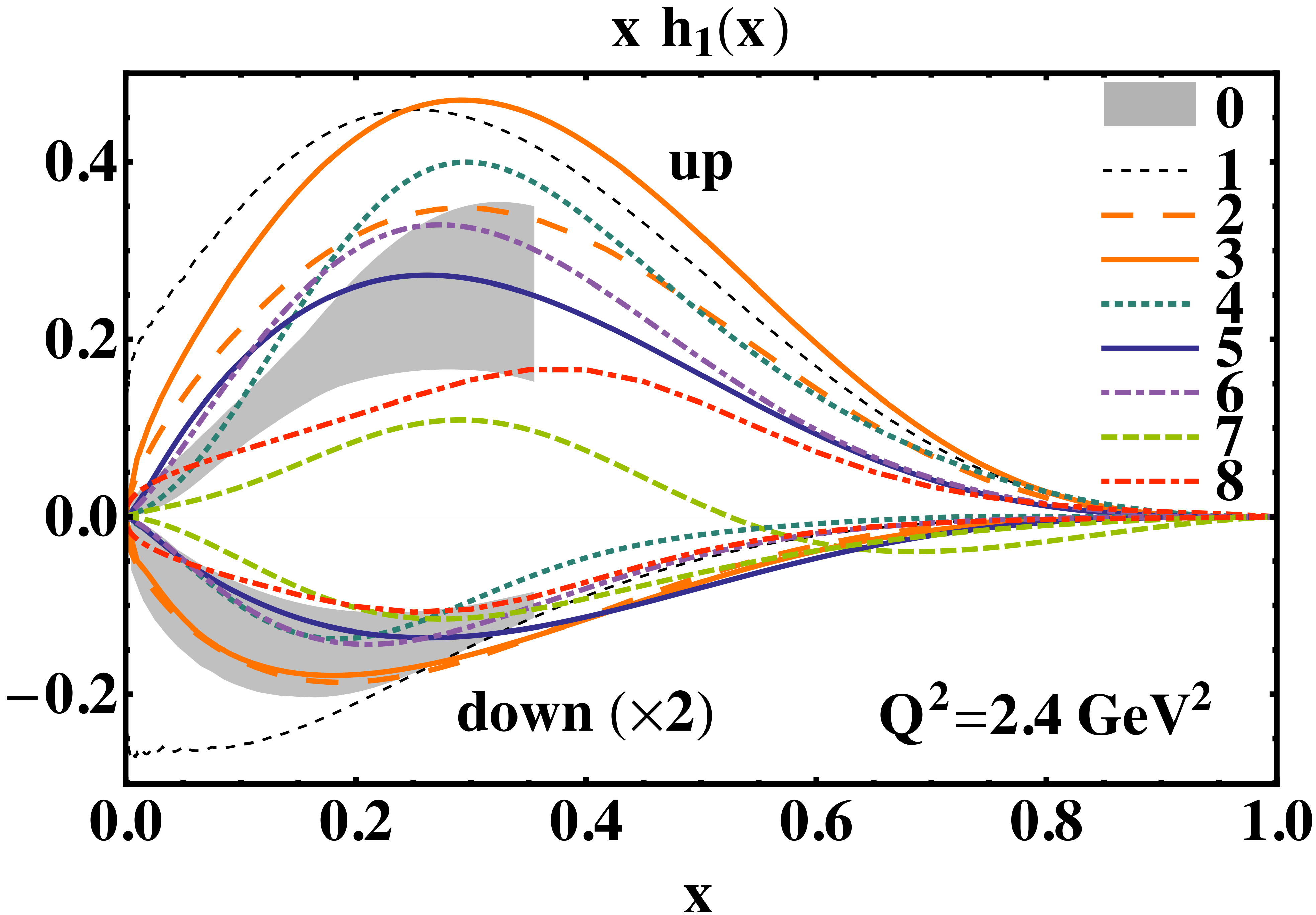
Anselmino et al. , arXiv:0812.4366, ask A. Prokudin for more details

Torino's transversity



Anselmino et al. , arXiv:0812.4366, ask A. Prokudin for more details

Comparison with models



Axial and tensor charges

$$\Delta\Sigma_q = \int_0^1 dx \; g_1^{q+\bar{q}} \qquad \delta\Sigma_q = \int_0^1 dx \; h_1^{q-\bar{q}}$$

Axial and tensor charges

$$\Delta\Sigma_q = \int_0^1 dx\ g_1^{q+\bar{q}} \qquad \delta\Sigma_q = \int_0^1 dx\ h_1^{q-\bar{q}}$$

	Axial	Tensor

Axial and tensor charges

$$\Delta\Sigma_q = \int_0^1 dx \; g_1^{q+\bar{q}} \qquad \delta\Sigma_q = \int_0^1 dx \; h_1^{q-\bar{q}}$$

	Axial		Tensor	
	Lattice (1.4 GeV)	DSSV (1 GeV)	Lattice (1.4 GeV)	Ans (0.9 GeV)
u	0.64	0.82	0.84	0.54
d	-0.35	-0.45	-0.23	-0.23
s	-0.11	-0.11	-0.05	0
Sum	**0.18**	**0.26**	**0.56**	**0.39**

S.Aoki et al., PRD 56 (1997)

see also M. Göckeler et al. [QCDSF/UKQCD], PLB (05)

Charge Errors

	Anselmino
$\delta\Sigma_u$	$0.54^{+0.09}_{-0.22}$
$\delta\Sigma_d$	$-0.23^{+0.09}_{-0.16}$

	DSSV08
$\Delta\Sigma_u$	$0.793^{+0.028}_{-0.034}$
$\Delta\Sigma_d$	$-0.416^{+0.035}_{-0.025}$

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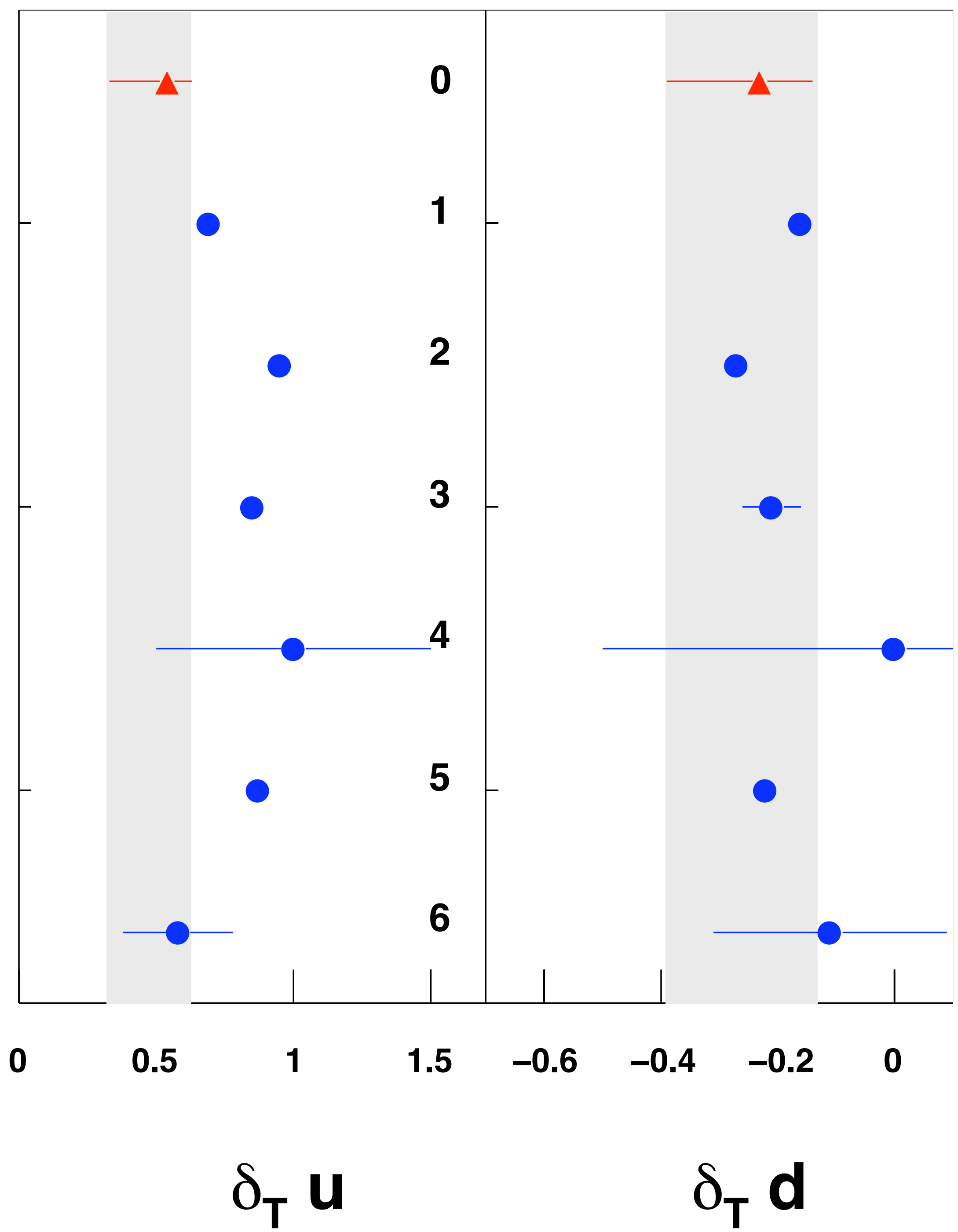
The error is large, but probably still largely underestimated

	$\mathrm{NNPDF}_{\mathrm{pol1.0}}$	DSSV08
$\Delta\Sigma$	0.32 ± 0.11	0.26 ± 0.03

Example of Neural Network results

talk by E. Nocera at DIS2012



[0] Anselmino et al. , arXiv:0812.4366

[1] Diquark spectator model,
Cloet, Bentz, Thomas, PLB 659 (08)

[2] Chiral quark soliton model,
Wakamatsu, PLB 653 (07)

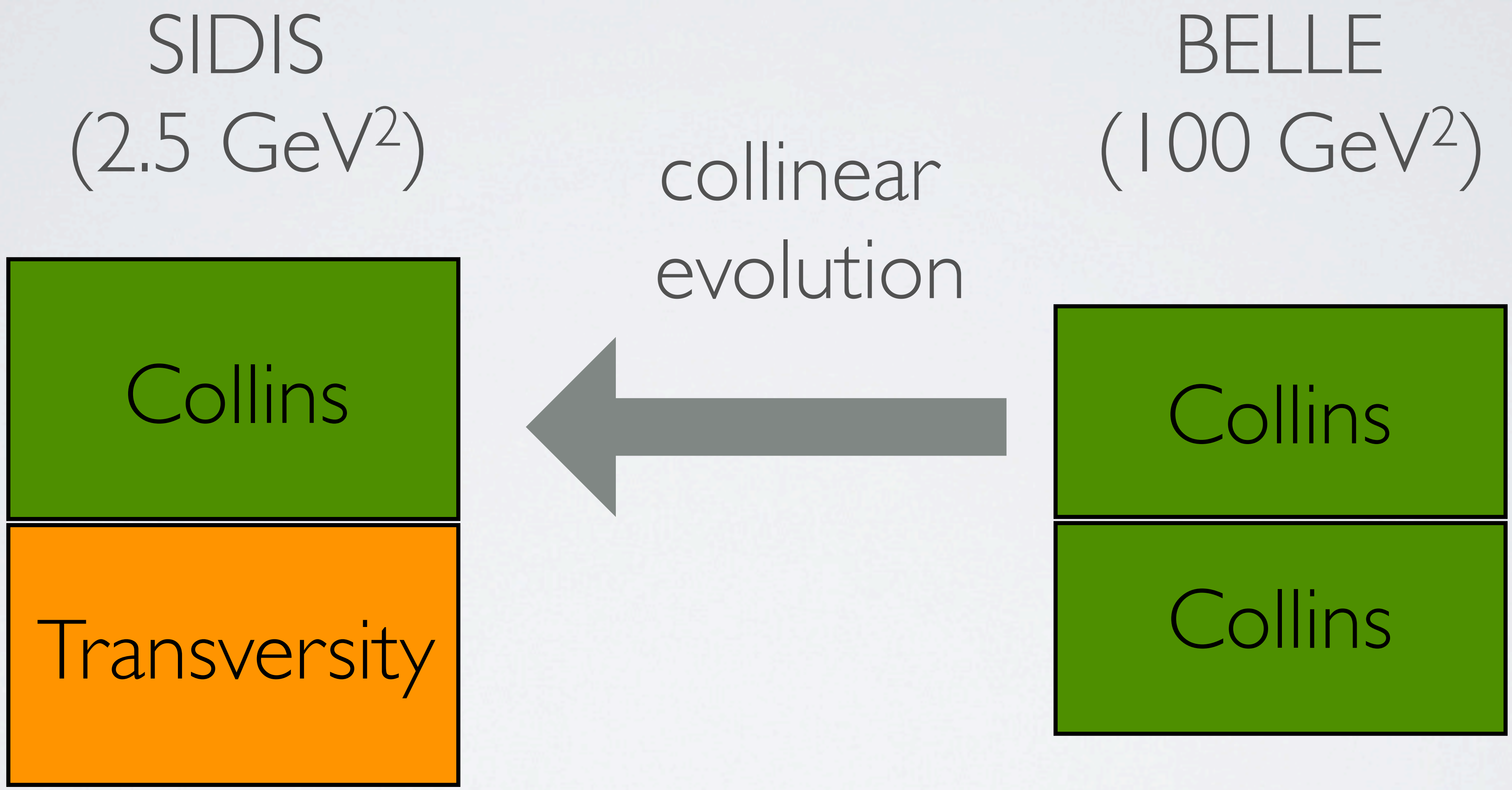
[3] Lattice QCD, Goekeler et al. PLB 627 (05)

[4] QCD sum rules, He, Ji, PRD 52 (95)

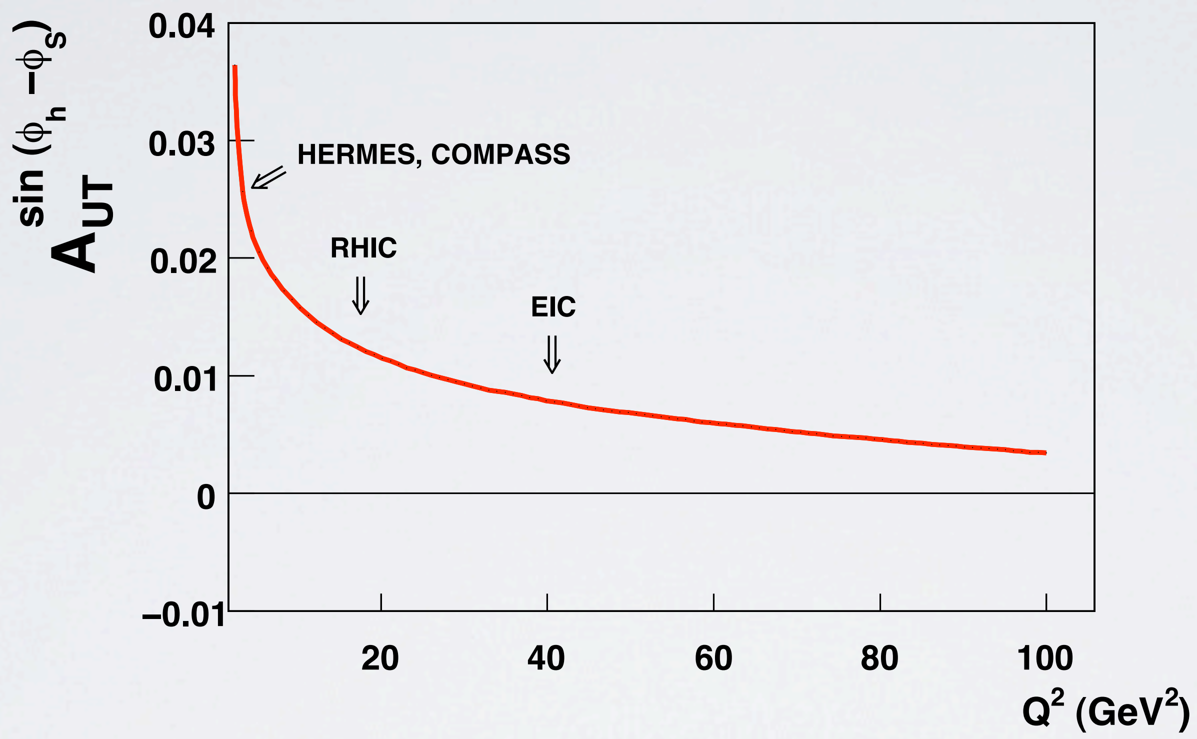
[5] Const. quark model, Pasquini et al. PRD 76 (07)

[6] SU(6) spin-flavor symmetry, Gamberg, Goldstein, PRL 87 (01)

The problem of evolution



Effects of TMD evolution

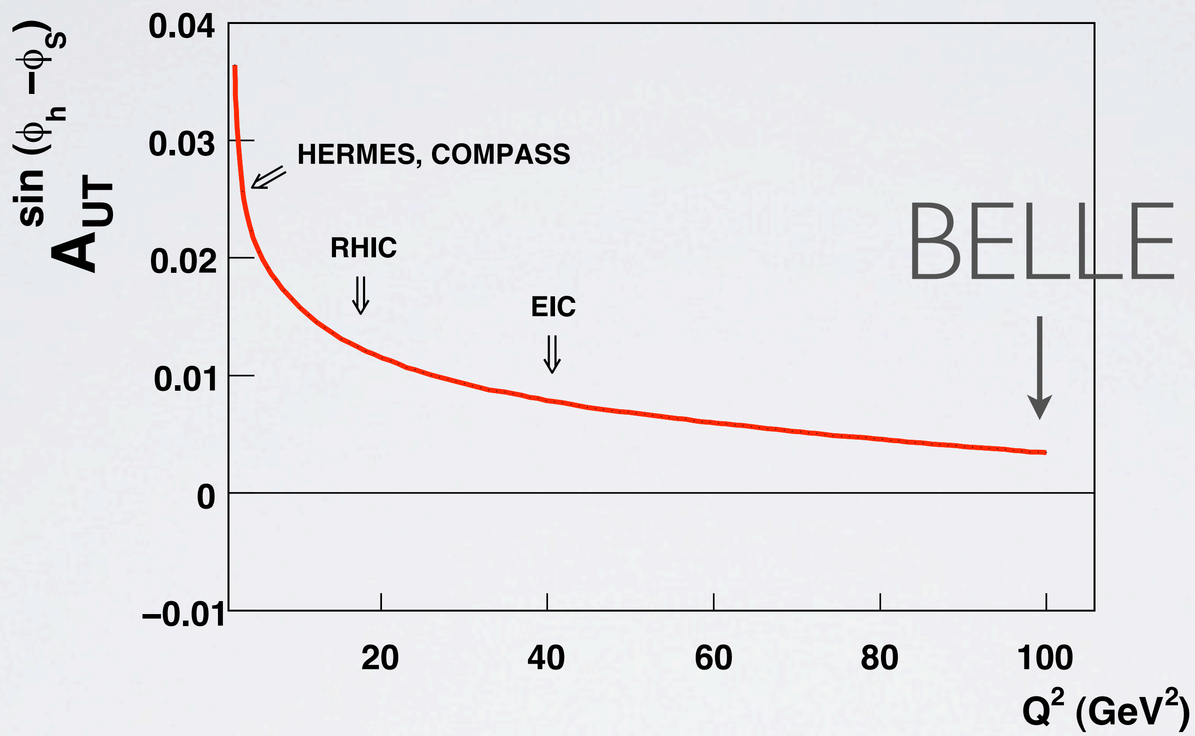


NEW and very important. Only done for SIVERS

Aybat, Rogers, PRD 85 (2012)
Aybat, Prokudin, Rogers, arXiv:1112.4423

see Alexei Prokudin's talk

Effects of TMD evolution



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Aybat, Prokudin, Rogers, arXiv:1112.4423
see *Alexei Prokudin's talk*

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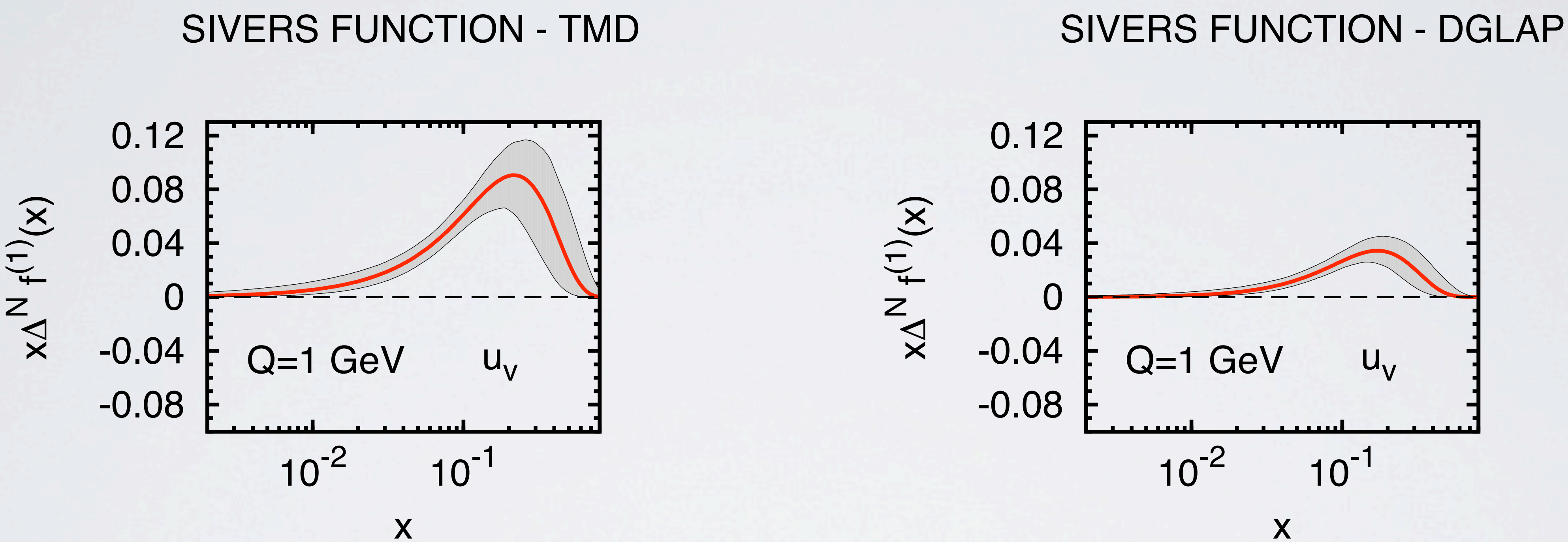
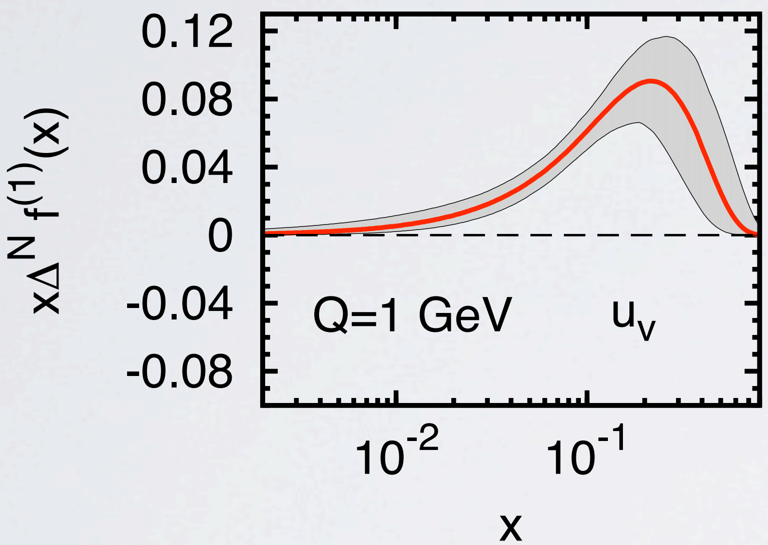


Anselmino, Boglione, Melis, arXiv:1204.1239

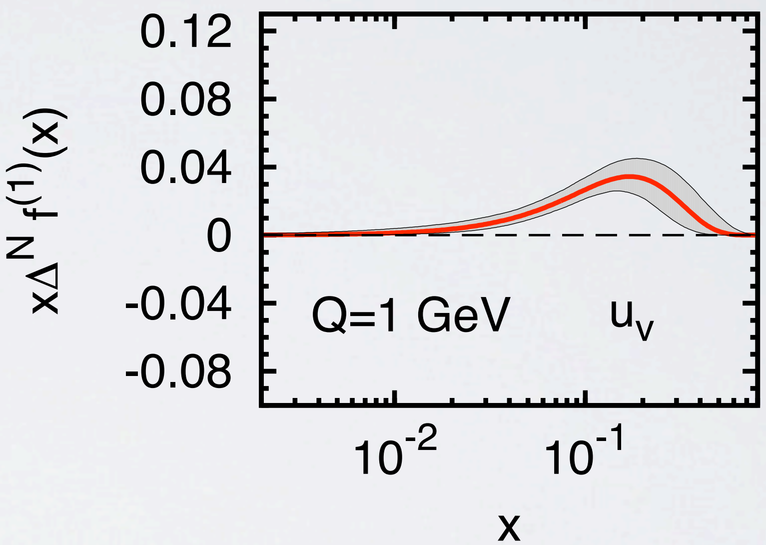
see Alexei Prokudin's talk

Effects of TMD evolution

SIVERS FUNCTION - TMD



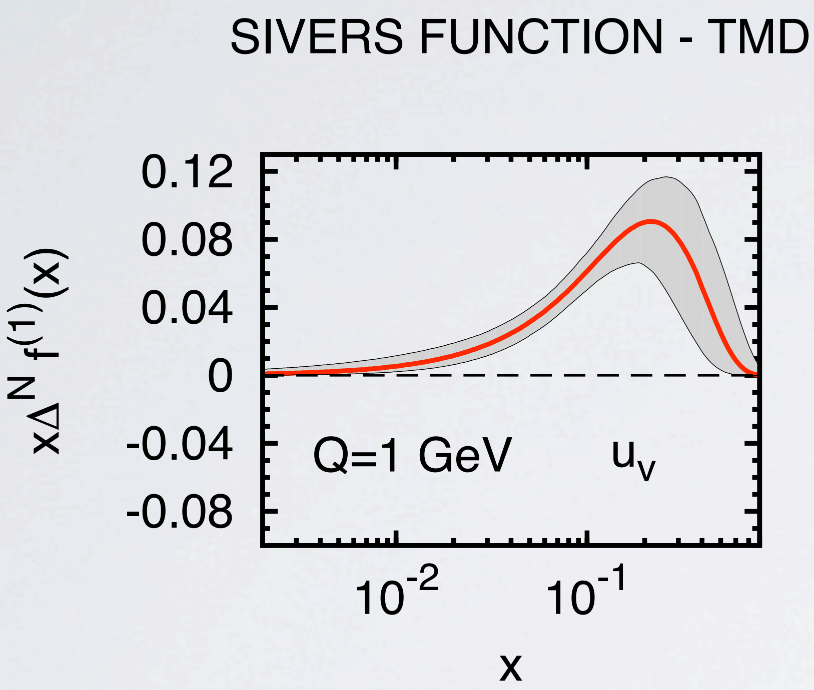
SIVERS FUNCTION - DGLAP

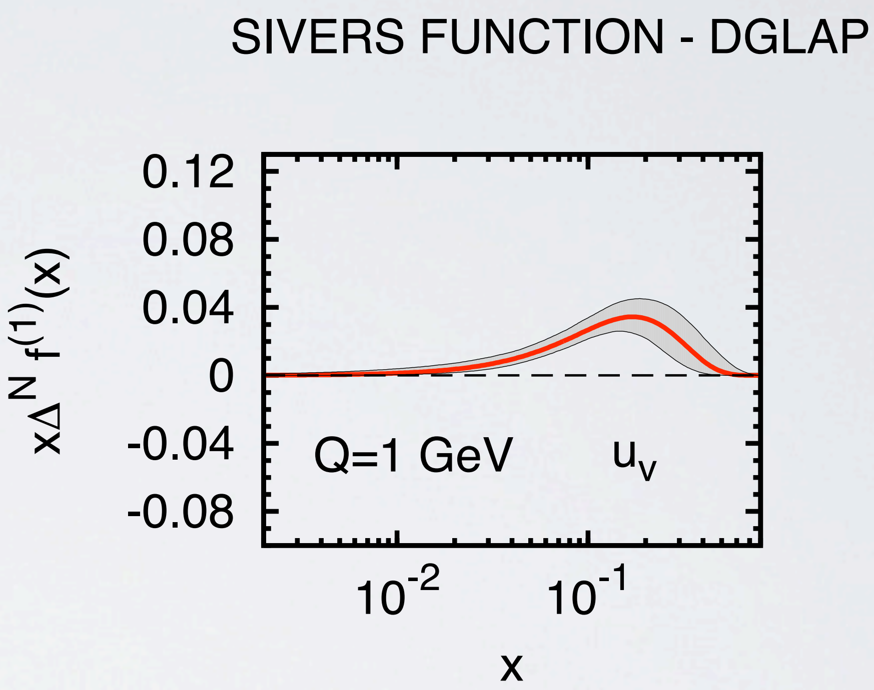


Sivers becomes BIGGER at low Q

Anselmino, Boglione, Melis, arXiv:1204.1239
see *Alexei Prokudin's talk*

Effects of TMD evolution



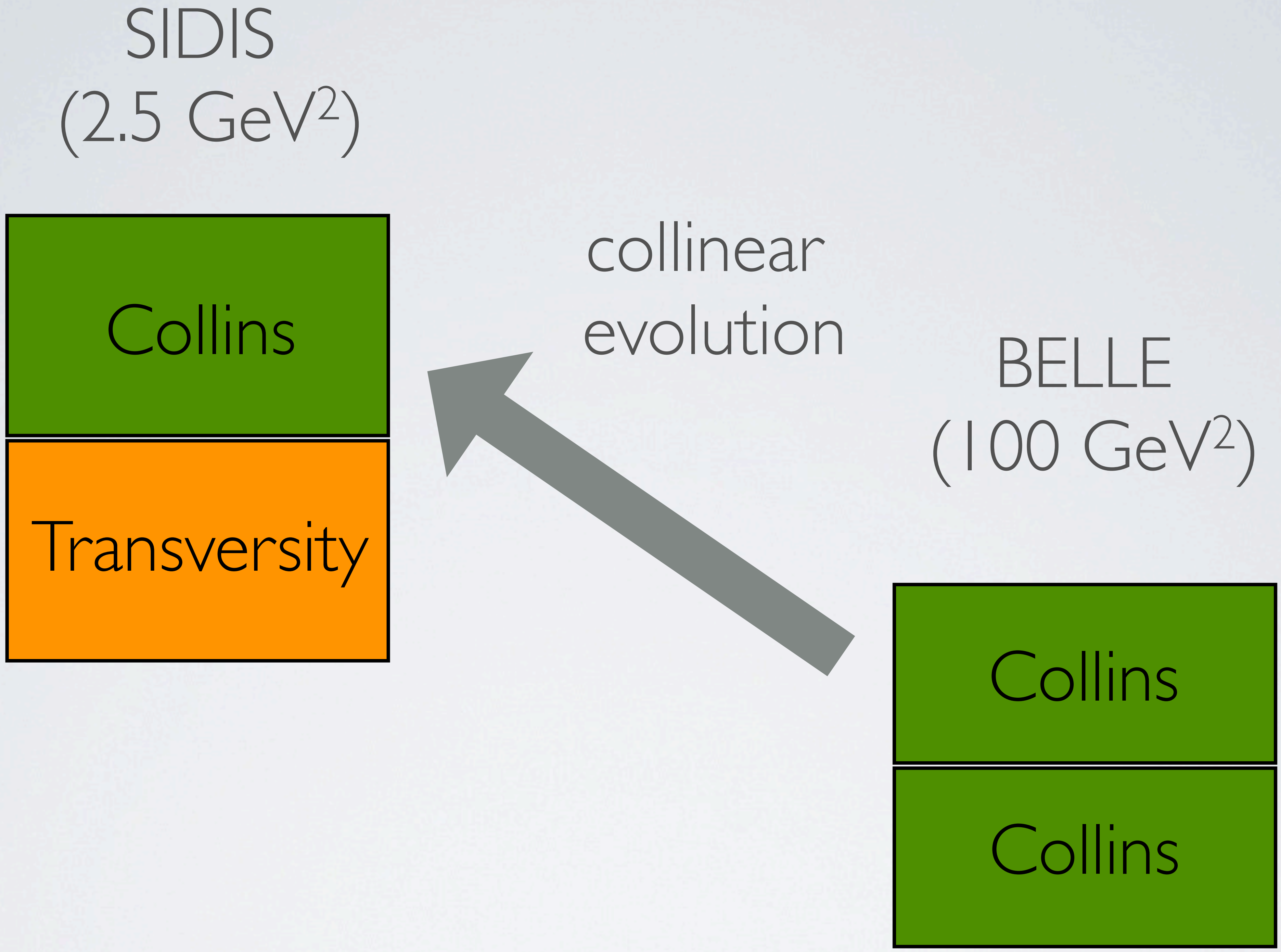


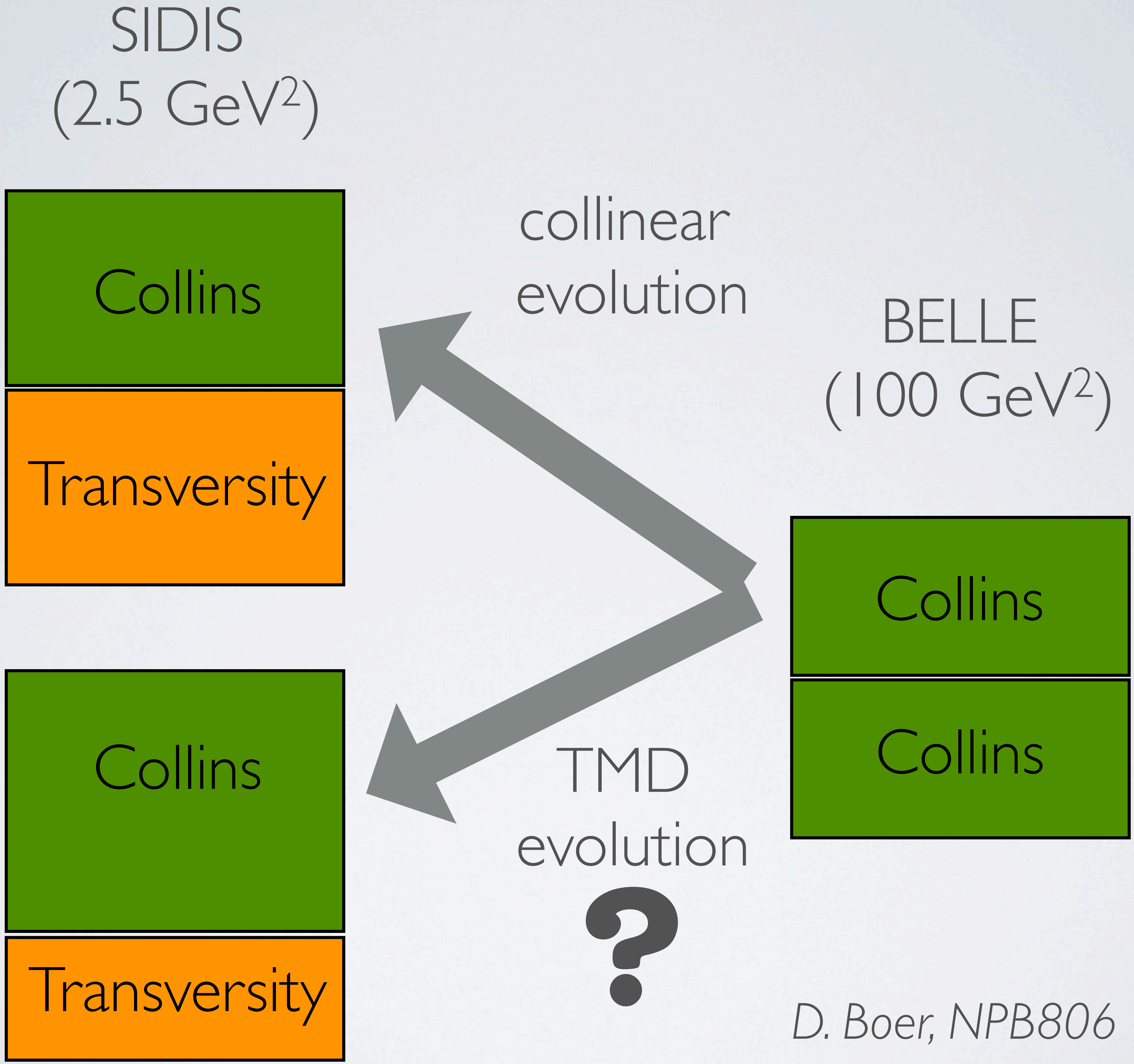
Sivers becomes BIGGER at low Q

Is it similar for Collins?

Anselmino, Boglione, Melis, arXiv:1204.1239

see Alexei Prokudin's talk


SIDIS
(2.5 GeV²)
Collins
Transversity
collinear
evolution
BELLE
(100 GeV²)
Collins
Collins



D. Boer, NPB806 (09)

Transversity from dihadron interference FF


IWHSS 2011
The
dihadron way
to transversity is opening


IWHSS 2012
The
dihadron way
to transversity HAS OPENED

Two hadrons

SIDIS

$$A_{DIS}(x, z, M_h^2) = -\langle C_y \rangle \frac{\sum_q e_q^2 \, h_1^q(x) \, \frac{|\boldsymbol{R}|}{M_h} H_{1,q}^{\sphericalangle}(z, M_h^2)}{\sum_q e_q^2 \, f_1^q(x) \, D_{1,q}(z, M_h^2)}$$

Two hadrons

SIDIS

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e^+e^-

$$A_{e+e-}(z,M_h^2,\bar{z},\bar{M}_h^2) = -\frac{\langle \sin^2\theta_2\rangle\langle\sin\theta\rangle\,\langle\sin\bar{\theta}\rangle}{\langle 1+\cos^2\theta_2\rangle}\, \frac{\sum_q e_q^2\, \frac{|\boldsymbol{R}|}{M_h}\, H_{1,q}^{\sphericalangle}(z,M_h^2)\, \frac{|\bar{\boldsymbol{R}}|}{\bar{M}_h}\, H_{1,\bar{q}}^{\sphericalangle}(\bar{z},\bar{M}_h^2)}{\sum_q e_q^2\, D_{1,q}(z,M_h^2)\, D_{1,\bar{q}}(\bar{z},\bar{M}_h^2)}$$

Simplified expressions

$$\frac{n_u^{\uparrow}}{n_u} = \frac{\iint \frac{|\boldsymbol{R}|}{M_h} H_{1,u}^{\sphericalangle}(z, M_h^2)}{\iint D_{1,u}(z, M_h^2)}$$

SIDIS (proton, $\pi^- \pi^+$)

$$A_{DIS}(x) \approx -\langle C_y \rangle \, \frac{(h_1^{u_v}(x) - h_1^{d_v}(x)/4)}{(f_1^{u+\bar{u}}(x) + f_1^{d+\bar{d}}(x)/4)} \frac{n_u^{\uparrow}}{n_u}$$

Simplified expressions

$$\frac{n_u^{\uparrow}}{n_u} = \frac{\int\int \frac{|\boldsymbol{R}|}{M_h} H_{1,u}^{\sphericalangle}(z, M_h^2)}{\int\int D_{1,u}(z, M_h^2)}$$

SIDIS (proton, π^- π^+)

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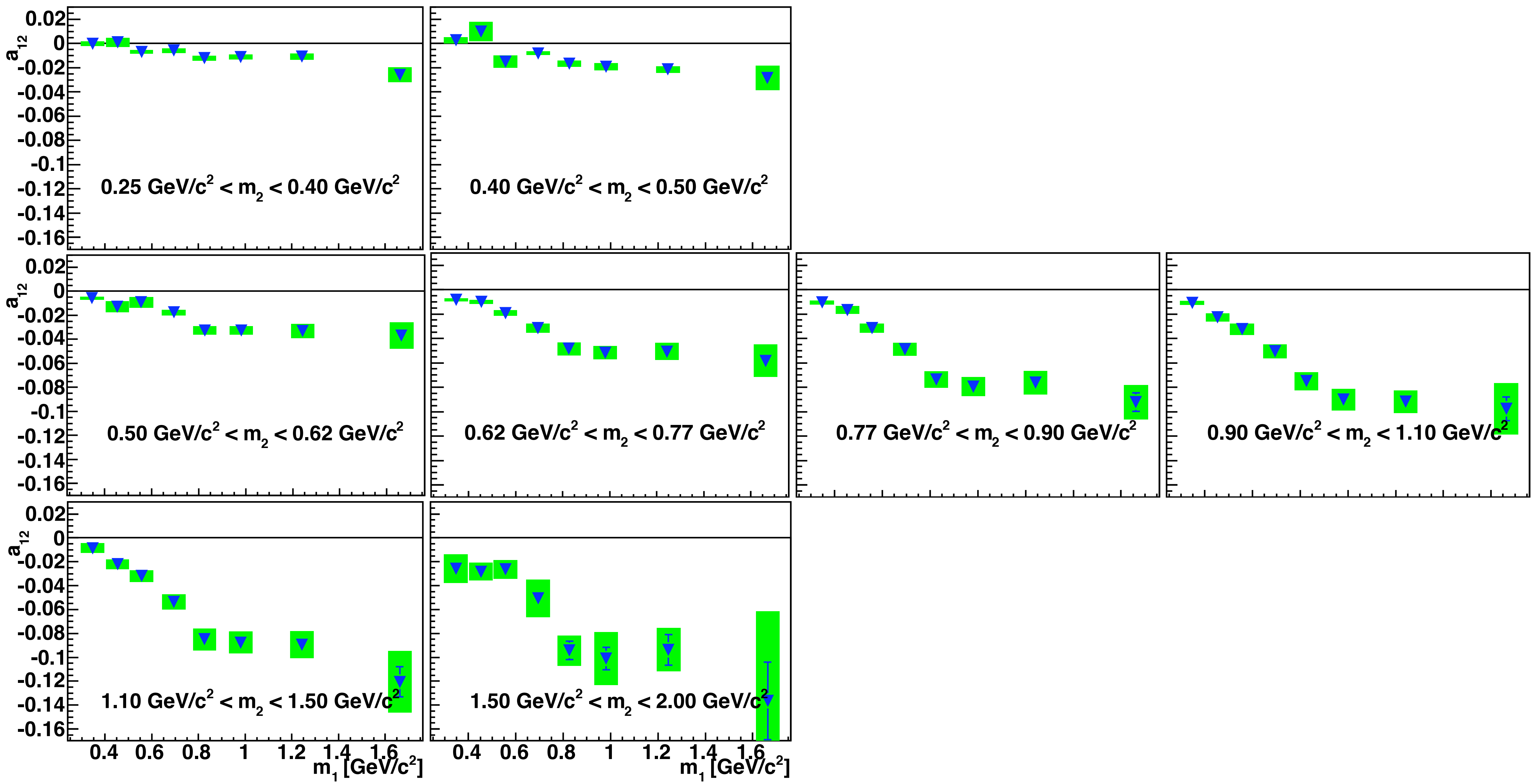
From BELLE: $\frac{n_u^{\uparrow}}{n_u} =$ -21±2% at COMPASS

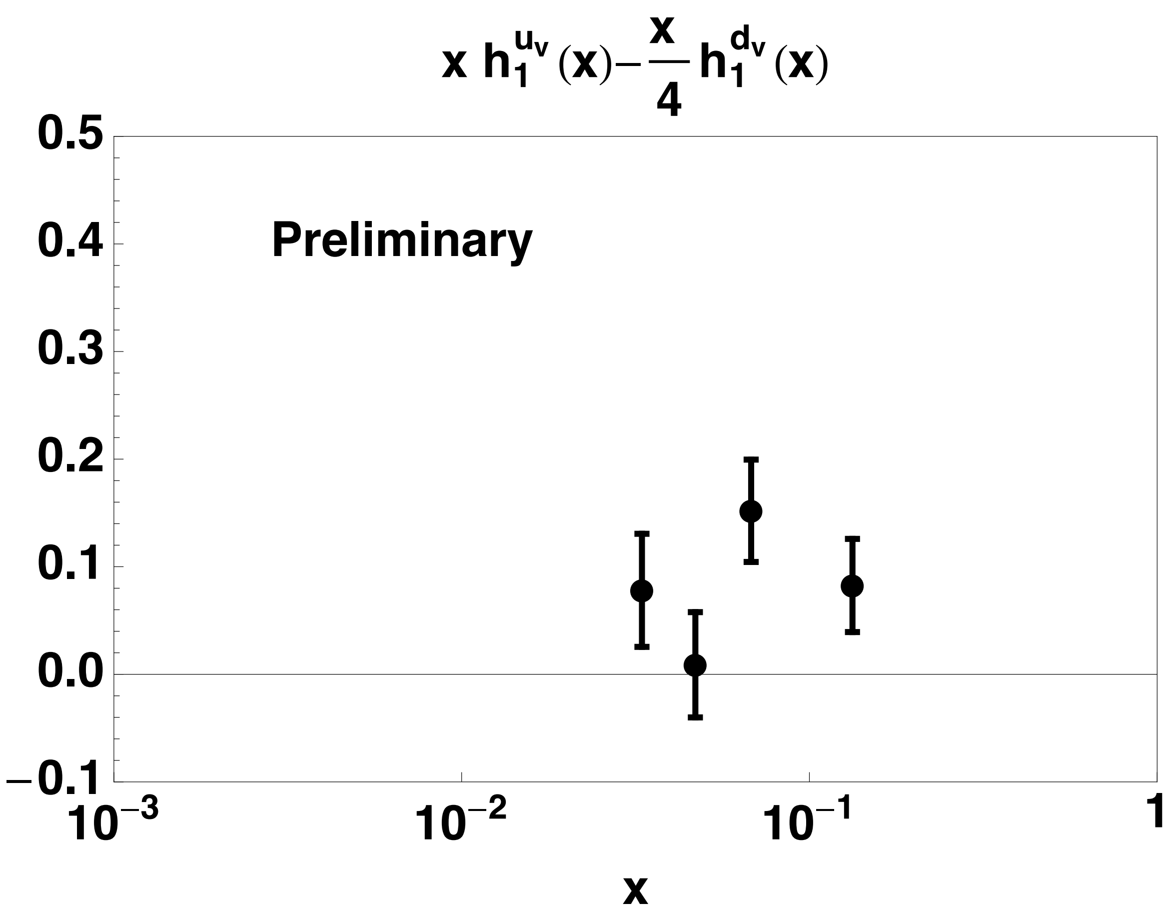
see Courtoy, Bacchetta, Radici, Bianconi, arXiv:1202.0323 [hep-ph]

BELLE data



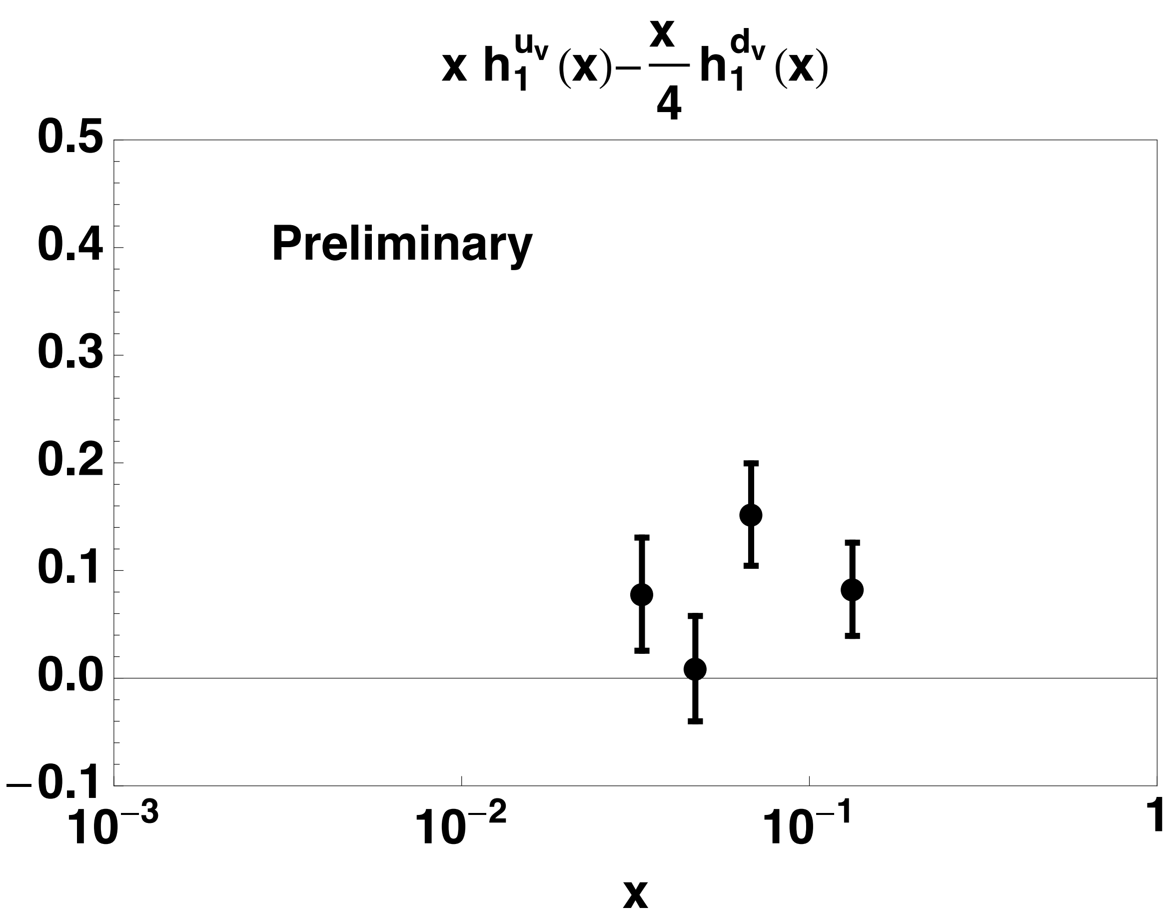
Vossen, Seidl et al. (Belle), PRL 107 (2011)

Extraction 2011



Bacchetta, Courtoy, Radici, PRL 107 (2011)

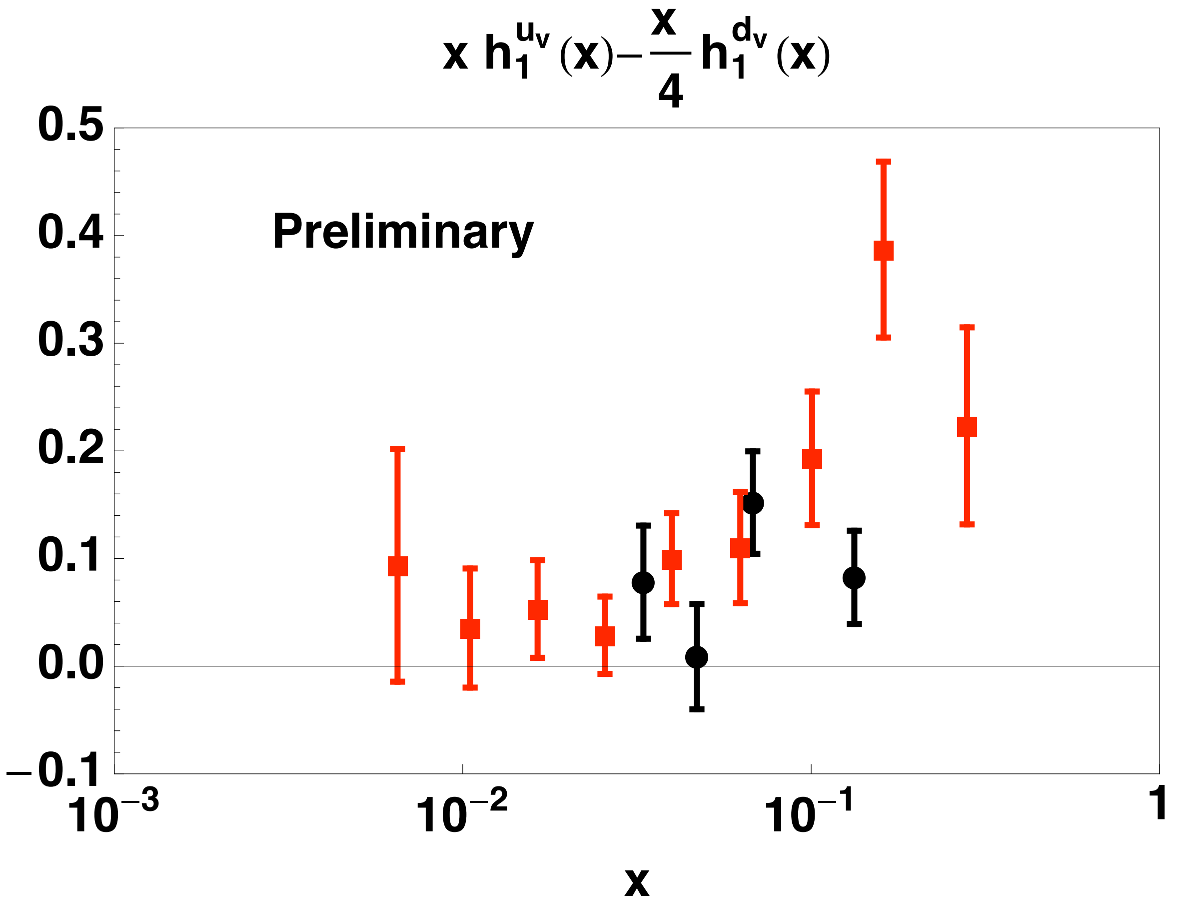
Extraction 2011



Bacchetta, Courtoy, Radici, PRL 107 (2011)

NEW extraction

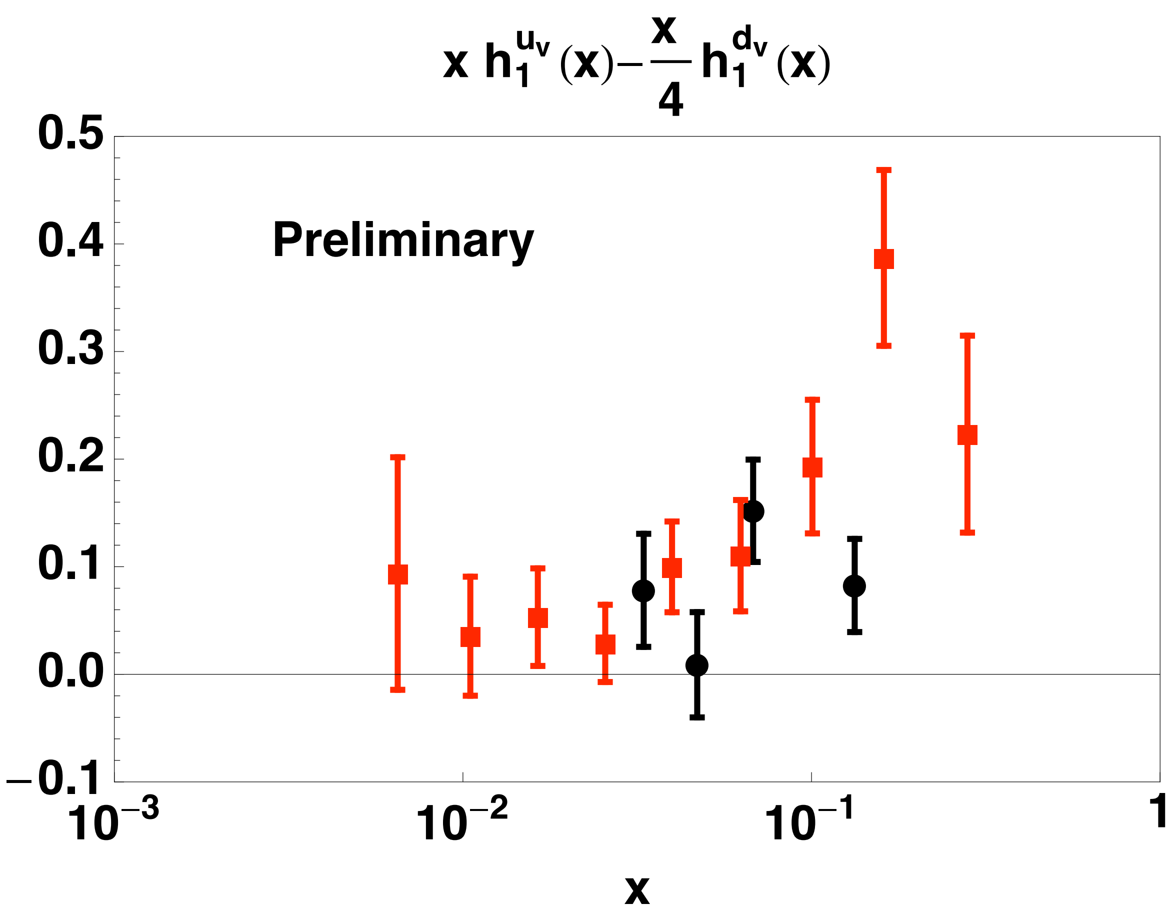
from proton



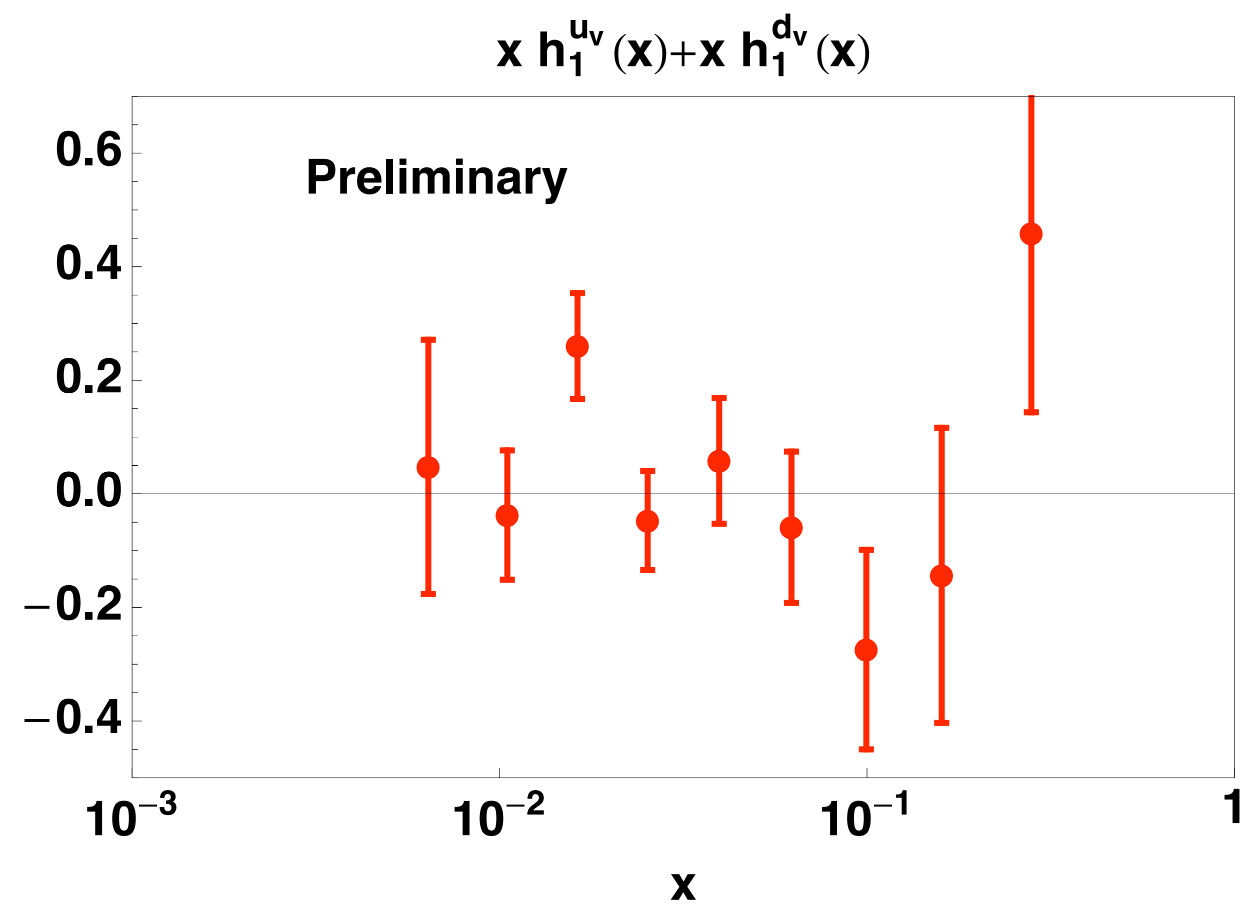
Based on freshly published: arXiv:1202.6150 [hep-ex]

NEW extraction

from proton

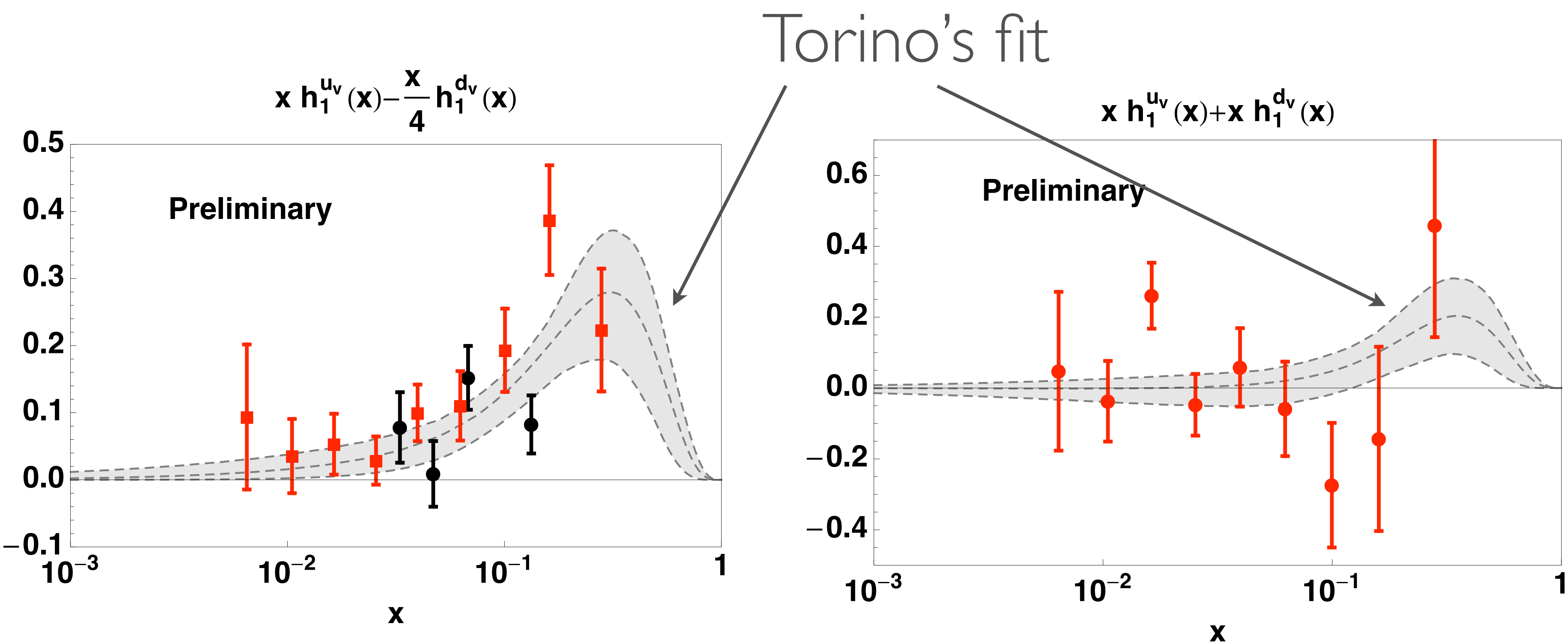


from deuteron



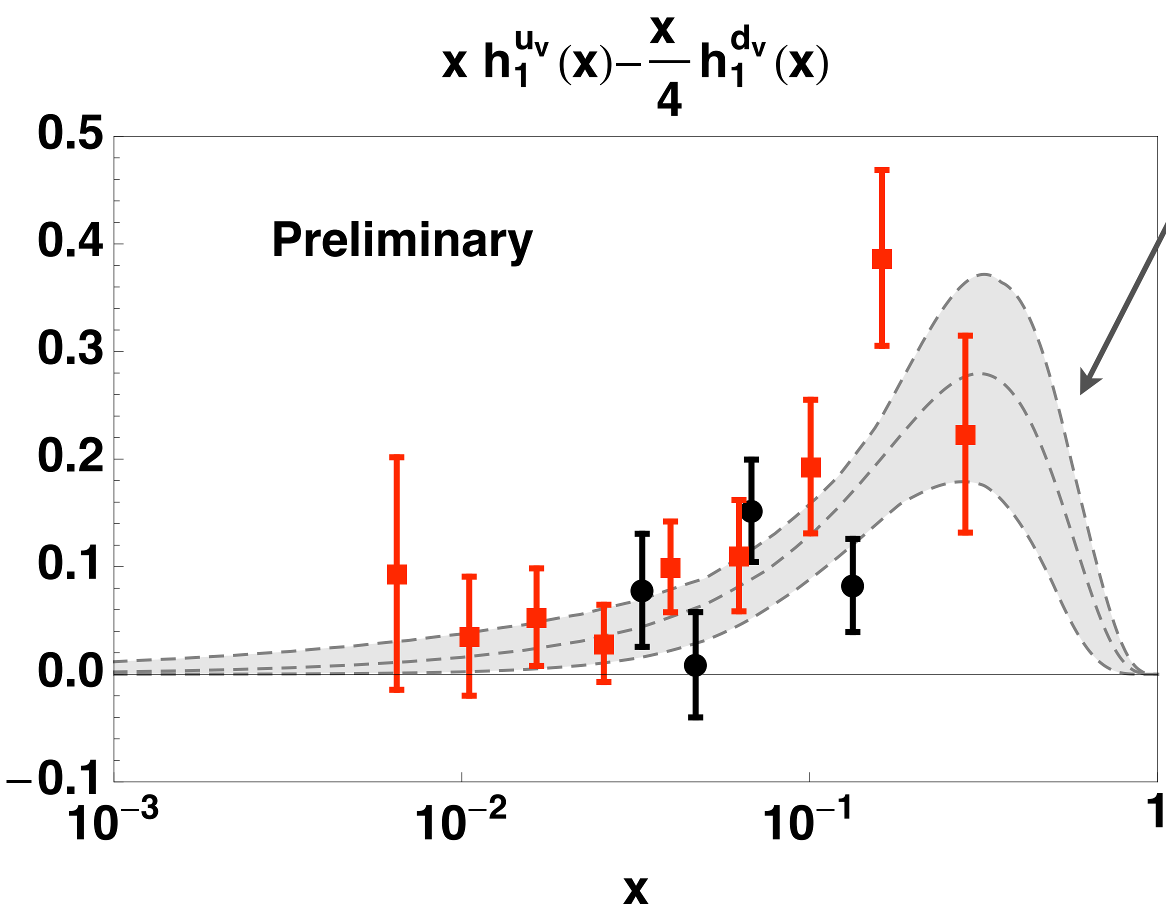
Based on freshly published: arXiv:1202.6150 [hep-ex]

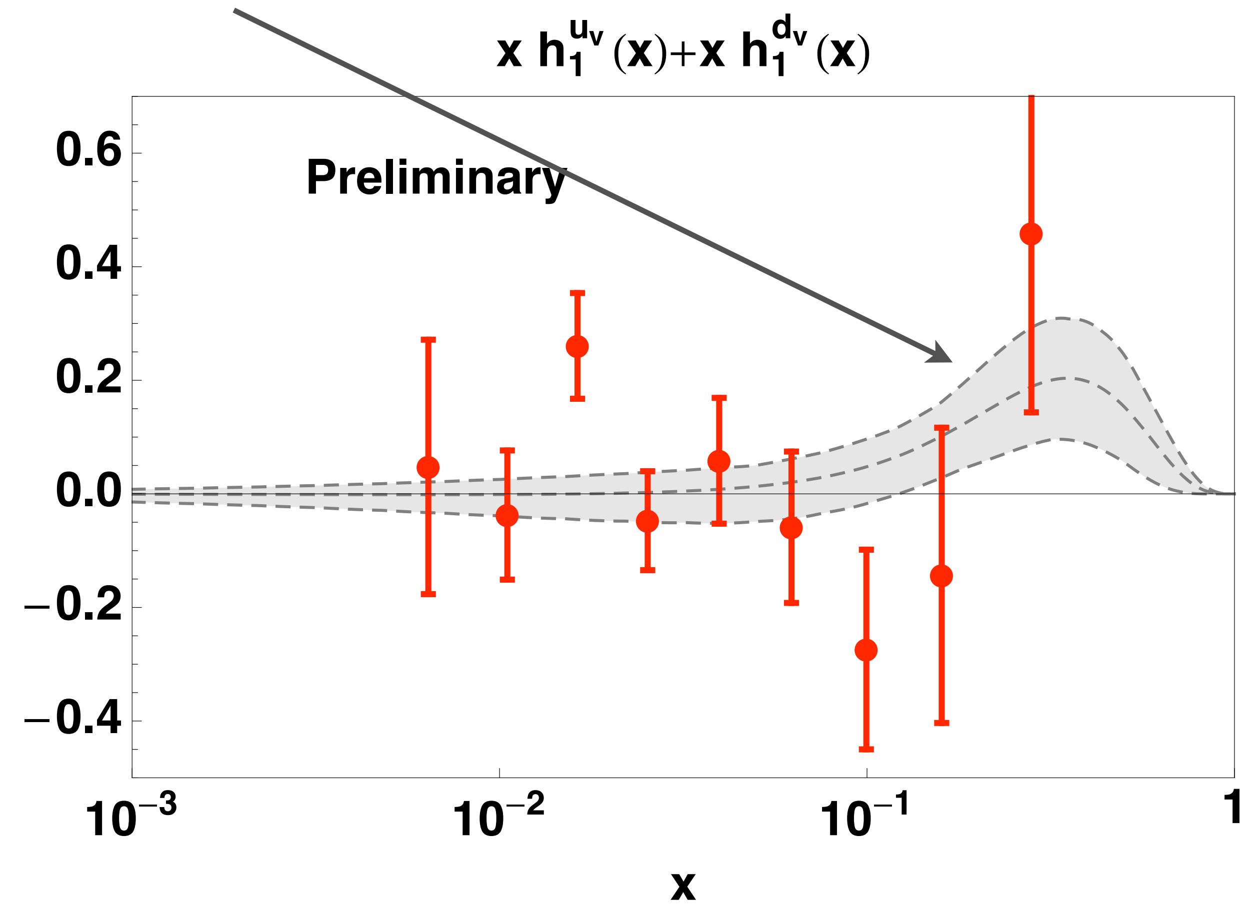
NEW extraction



NEW extraction

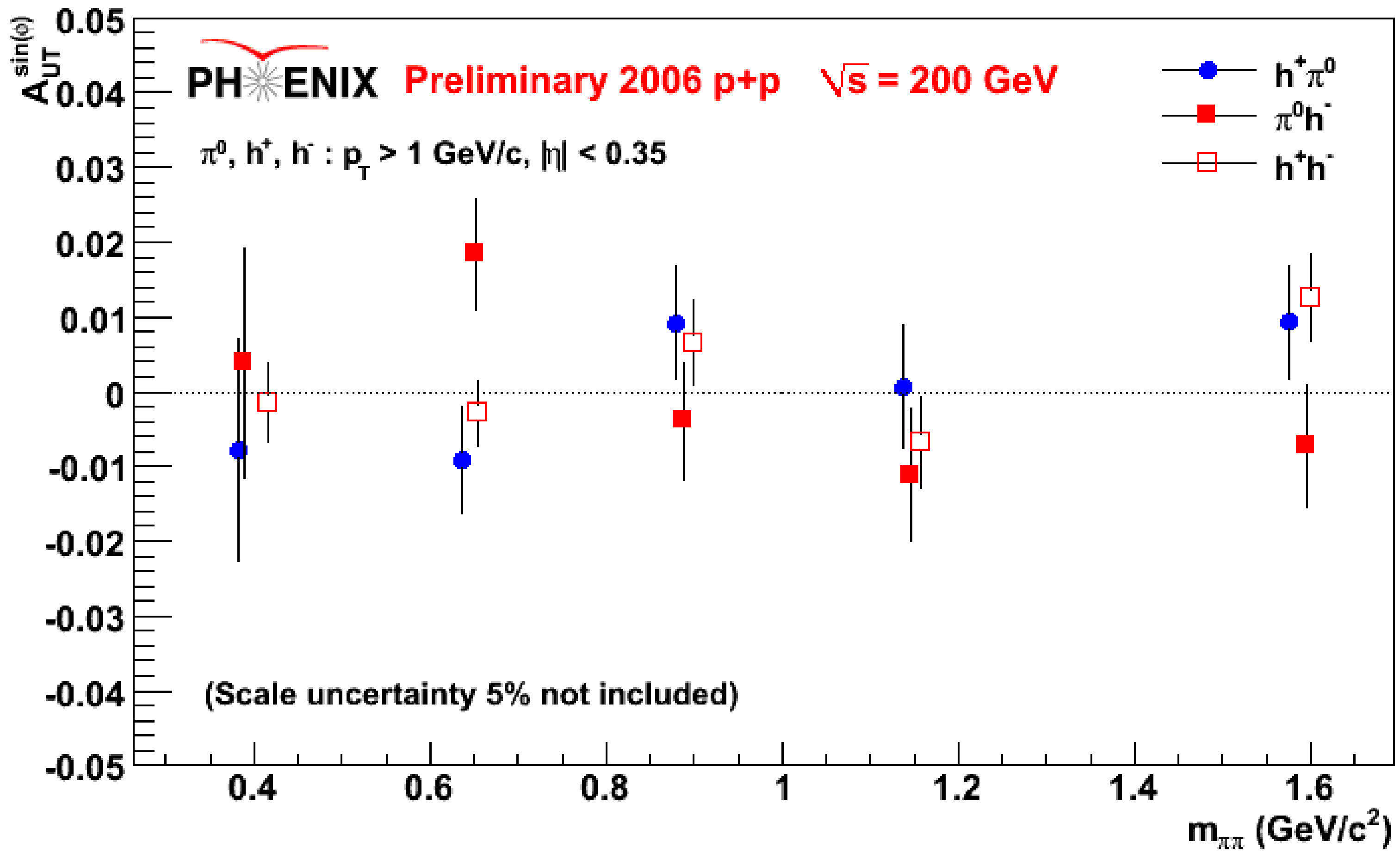
Torino's fit





Our extraction does not contradict Torino's

Also from *pp* collisions



R. Yang, Beijing Transversity Workshop, 2008

Status of transversity studies