TRANSVERSITY
theory and phenomenology

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DIFFRACTION 2012

INTERNATIONAL WORKSHOP ON
DIFFRACTION IN HIGH-ENERGY PHYSICS

Outline

- **Theory: definition, properties, importance/interest**
- **Accessing it: Double and Single spin asymmetries**
  Collinear vs. TMD approach
- **Phenomenology**
- **Open issues and perspectives**

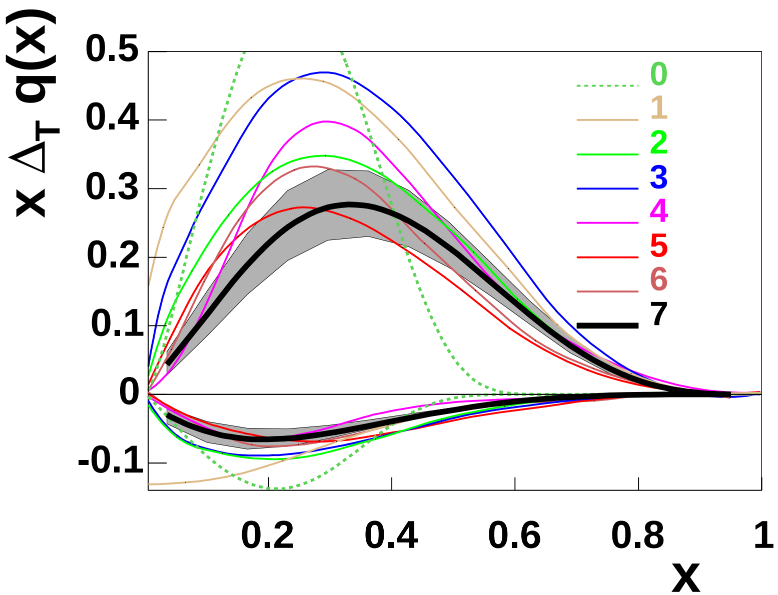
Three parton distributions characterize completely the structure of a nucleon:

$q(x)$: **momentum distribution** *very well known*

$\Delta q(x)$: **helicity distribution** *quite well known*

The third one?

- **escaped notice until 1979: Drell-Yan spin asymmetries (Ralston & Soper)**
- **computed in a large class of models**
- **extracted only recently**



0 Barone et al. 1997

1 Soffer et al. 2002

2 Korotkov et al. 2001

3 Schweitzer et al. 2001

4 Wakamatzu 2007

5 Pasquini et al. 2005

6 Cloet et al. 2008

7 phen. extraction 2007

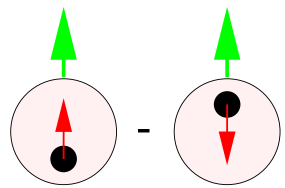
Basics

- **notation:** $h_1^q(x)$, $\Delta_T q(x)$ **(plus others)**

- **probabilistic interpretation:**

distribution of transversely polarized quarks inside a transversely polarized nucleon

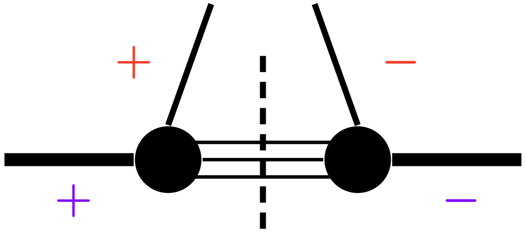
$$\Delta_T q(x) = q_{\uparrow/\uparrow}(x) - q_{\downarrow/\uparrow}(x)$$



- **formal definition:** *hadronic matrix element of a nonlocal operator*

$$\int \frac{d\xi^-}{4\pi} e^{ixP^+\xi^-} \langle PS_T | \bar{\psi}(0) i\sigma^{1+}\gamma_5 \psi(0,\xi^-,0_\perp) | PS_T \rangle$$

- **No gluon transversity** $\rightarrow$ **Non-singlet Q^2-evolution, h_1^q suppressed at low x**



Forward quark-nucleon amplitudes ($N \to qX$)

- $\Delta_T q(x) = q_{\uparrow/\uparrow} - q_{\downarrow/\uparrow} = F^{+-}_{+-}$

Off-diagonal in the helicity basis $\to$ a chiral-odd quantity!

To be compared with the chiral-even

- **unpolarized parton distribution:** $q(x) = q_{+/+} + q_{-/+} = F^{++}_{++} + F^{--}_{++}$
- **longitudinally polarized distribution:** $\Delta q(x) = q_{+/+} - q_{-/+} = F^{++}_{++} - F^{--}_{++}$

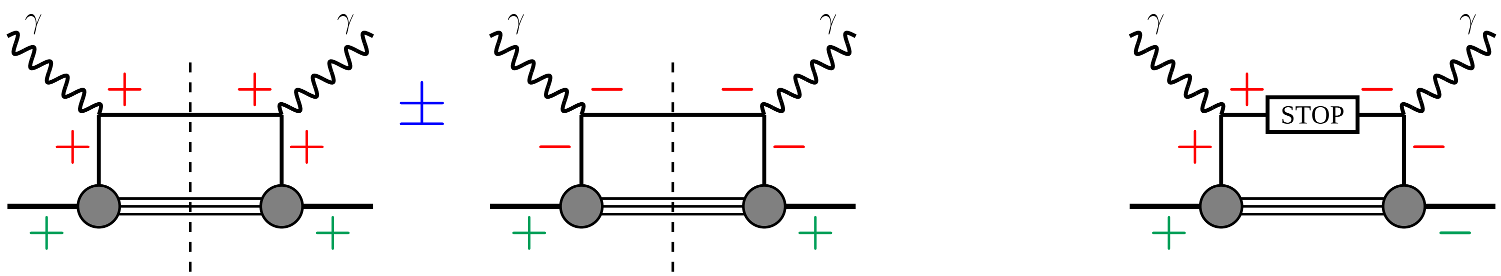
First remarks:

- in a collinear picture: $p_q = xP_N$

q, Δq and $\Delta_T q$ for a complete description of quark momentum and spin!

but $\Delta_T q$ harder to measure and escaped for a long time. Why?

Not accessible via inclusive DIS



$$F^{++}_{++} \quad \pm \quad F^{--}_{++} \qquad\qquad \cancel{F^{+-}_{+-}}$$

$\Rightarrow$ **needs a χ-odd partner**

Importance and interest

- $\Delta_T q \neq \Delta q$ for relativistic quarks

- it is the **only source** of information on the tensor charge: δq

vector charge	axial charge	tensor charge	[all fundamental]
$\langle \, \|\gamma^\mu\| \, \rangle$	$\langle \, \|\gamma^\mu\gamma_5\| \, \rangle$	$\langle \, \|\sigma^{\mu\nu}\gamma_5\| \, \rangle$	
$\int dx(q-\bar{q})$	$\int dx(\Delta q + \Delta\bar{q})$	$\int dx(\Delta_T q - \Delta_T \bar{q})$	

- Angular momentum sum rule:

$$\frac{1}{2} = \frac{1}{2}\int dx(\Delta_T q + \Delta_T \bar{q}) \qquad + L_T^q + L_T^g$$

Bakker-Leader-Trueman '04

but: $\Delta_T q$ information on transverse polarization NOT on transverse spin

[$\Pi_T \sim \gamma_0 \Sigma_T$ (**conserved**) vs. $\Sigma_T = \gamma_5\gamma_0\gamma_T$ (**non conserved**)]

- energy **scale dependence**: very different from that of helicity distribution

- various model (and lattice) calculations give $\delta u \simeq 1$ and $\delta d \simeq -0.2$

- obeys a **nontrivial bound**: $|\Delta_T q(x)| \leq \frac{1}{2}[q(x) + \Delta q(x)]$ [*Soffer '95*]
preserved under evolution, strictly true at LO [*Barone '97, Bourrely et al. '98*];
with some care at NLO [*Vogelsang '98*]

How to measure it?

We need a **chiral-odd partner**, that is at least **two hadrons!**

Let's start with the *simplest* [theory side] case:

Double transverse-spin asymmetries

χ-odd partner in INITIAL hadron

- **requires a second polarized beam**
- **$(h_1^q)^2$ observables $\longrightarrow$ self-sufficient!**

χ-odd partner in FINAL hadron

- **requires only one polarized beam**
- **extra unknowns**

χ-odd partner in INITIAL hadron

- **A_{TT} in Drell-Yan processes: $p^{\uparrow}p^{\uparrow} \to \ell^+\ell^- X$** [*Ralston-Soper '79*]

$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} \sim \sum_q e_q^2 \left[h_1^q(x_1)\, h_1^{\bar{q}}(x_2) + h_1^{\bar{q}}(x_1)\, h_1^q(x_2)\right]$$

- feasible @ RHIC [large $\sqrt{s}$ (200 GeV)], small NLO QCD corrections

- small x (AND no gluon in evolution), small h_1 for antiquark

$\Rightarrow$ $A_{TT} \sim$ 1-2% [upper bound] [*Martin et al. '99*]

• **IDEA, (PAX @ GSI): DY with polarized antiprotons**

$$A_{TT}^{p\bar{p}} \sim \sum_q e_q^2 \left[h_1^q(x_1)\, h_1^q(x_2) + h_1^{\bar{q}}(x_1)\, h_1^{\bar{q}}(x_2)\right]$$

- **product of two quark h_1 and moderate $\sqrt{s}$ [valence region] $\Rightarrow$ large A_{TT}**
- **polarization of antiprotons, low rates**

★ **Higher rates: J/ψ peak (gain 2 order of magnitudes) [*Anselmino et al. '04*]**

other DSAs:

• $p^{\uparrow} p^{\uparrow} \to \gamma(\pi, \mathrm{jet}) + X$

- **high rates**
- **gluon dominance in $d\sigma^{\mathrm{unp}} \to$ small A_{TT} @ RHIC**
- **with polarized $\bar{p}$ @ PAX: $A_{TT} \sim$ 2-5% [*Mukherjee-Stratmann-Vogelsang '05*]**

χ-odd partner in FINAL hadron

- $\ell p^\uparrow \to \ell' \Lambda^\uparrow X$ or $p^\uparrow p \to \Lambda^\uparrow X$: Λ as a polarimeter

- Λ self-analyzing through its parity violating decay
- spin transfer $D_{NN} \simeq h_1^q \otimes H_1^q$
- $q^\uparrow \to \Lambda^\uparrow$ unknown, i.e. H_1^q unknown
- u quark dominated (charge and nucleon content) but $s^\uparrow \to \Lambda^\uparrow$

- help from $e^+e^- \to \Lambda^\uparrow \bar{\Lambda}^\uparrow X$: $H_1^q \otimes H_1^q$ [*Contogouris et al. '95*]

$\Delta_T q$ via Single spin asymmetries (SSAs):

1. $k_\perp$-dependent functions (TMDs)
   (a) Initial hadron: $p^\uparrow p \to \ell^+ \ell^- X$, SSA in DY
   (b) Final hadron: $\ell p^\uparrow \to \ell' \pi X$, SSA in SIDIS
   (c) ...
2. dihadron fragmentation functions (diFF): $\ell p^\uparrow \to \ell' (\pi\pi) X$
3. higher twist functions, higher spin particles (ρ)
4. ...

All these cases involve extra unknown quantities

SSA in DY processes, $p^{\uparrow}p \to \ell^{+}\ell^{-}X$:

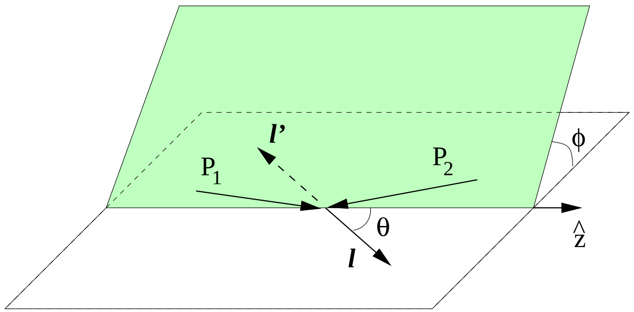
▶ $A_N \simeq \cdots + h_1^q \otimes h_1^{\perp q} \sin(\phi + \phi_{\uparrow})$

$h_1^{\perp q}(x, k_\perp)$: **Boer-Mulders function**

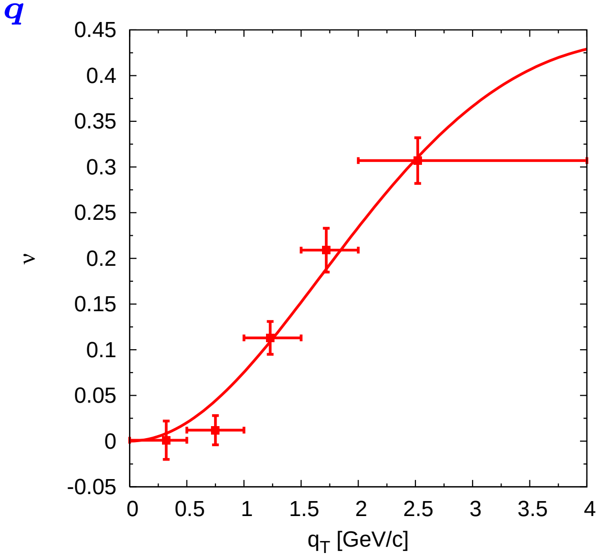
transversely polarized quarks inside an unpolarized nucleon [*Boer '99*]

$$d\sigma \simeq 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

large ν (NLO not sufficient) $\Rightarrow \nu \propto h_1^{\perp q} \otimes h_1^{\perp q}$



DY process in the lepton c.m. frame (CS).



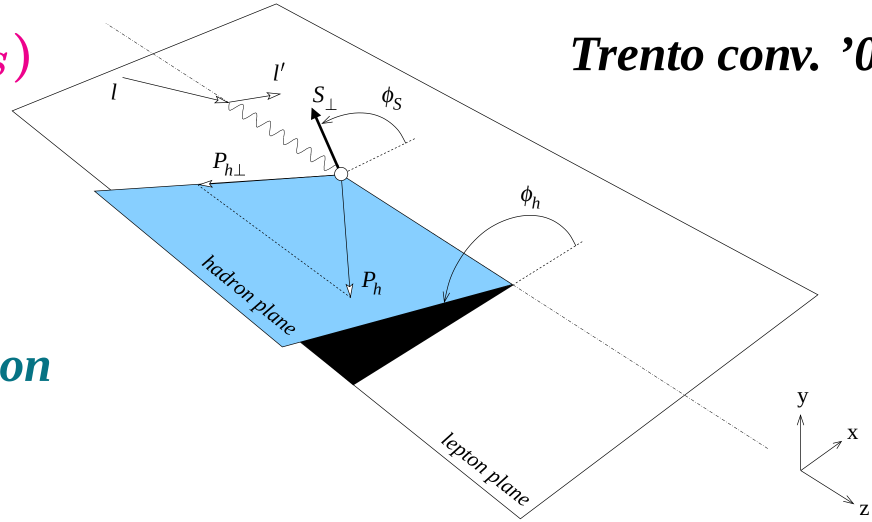
$\pi N \to \mu^+\mu^- X$ ***Boer '99***

SSA in SIDIS, $\ell p^{\uparrow} \to \ell' \pi X$

Focusing on the transversity contribution

▶ $A_{UT} \sim h_1^q \otimes H_1^{\perp q} \sin(\phi_h + \phi_S)$

Trento conv. '04



$H_1^{\perp q}$ [$\Delta^N D_{h/q^{\uparrow}}$]: Collins function

transversely polarized quark

fragmenting into an unpolarized hadron

[*Collins '93*]

Help from azimuthal correlations in $e^+e^- \to h_1 h_2 X$: $H_1^{\perp q} \otimes H_1^{\perp q}$

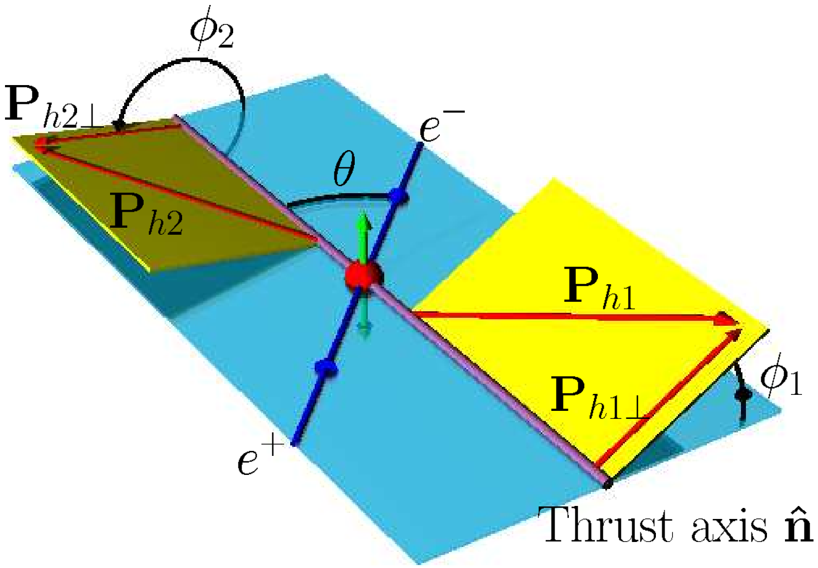
[@ B-factories: Belle, BaBar]

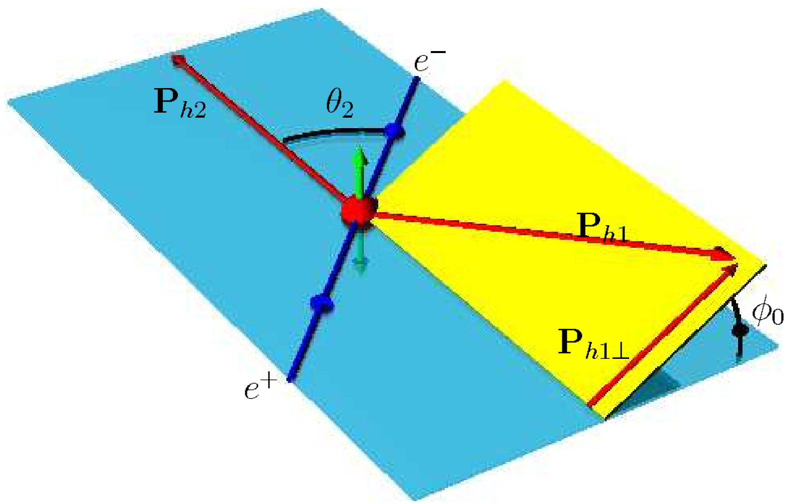
Two hadrons from opposite hemispheres in jetlike events

$e^+e^- \to q\bar{q} \to h_1 h_2 X$: [*Boer-Jacob-Mulders '97*]

$$d\sigma \simeq (1+\cos^2\theta)\, D_{h_1/q}\, D_{h_2/\bar{q}} + \sin^2\theta\, \Delta^N D_{h_1/q^\uparrow}\;\; \Delta^N D_{h_2/\bar{q}^\uparrow}$$

$\times\cos(\phi_1+\phi_2)$ $\times\cos(2\phi_0)$





Thrust axis Products: no models **No thrust axis convolutions: models**

Important issues related to TMD factorization (in SIDIS, DY, e^+e^-).

In general for a SIDIS cross section beyond tree level [*Ji et al. '04*]

$$d\sigma \simeq w(k_\perp, P_T, p_\perp) \otimes f(x, k_\perp) \otimes D(z, p_\perp) \otimes U(l_\perp^2)$$

U: soft factor [*Collins-Soper-Sterman '81*]

- **dilution of the asymmetry at large Q^2**
- **increasing effect with Q^2 (Sudakov suppression)** [*Boer '01,'09*]
- **recent developments** [*Collins '11, Aybat-Rogers '11, Aybat et al. '12, Anselmino-Boglione-Melis '12, Echevarría et al. '12*] **(Scimemi talk)**
- **under study for χ-odd TMDs and not implemented in their phenomenology**

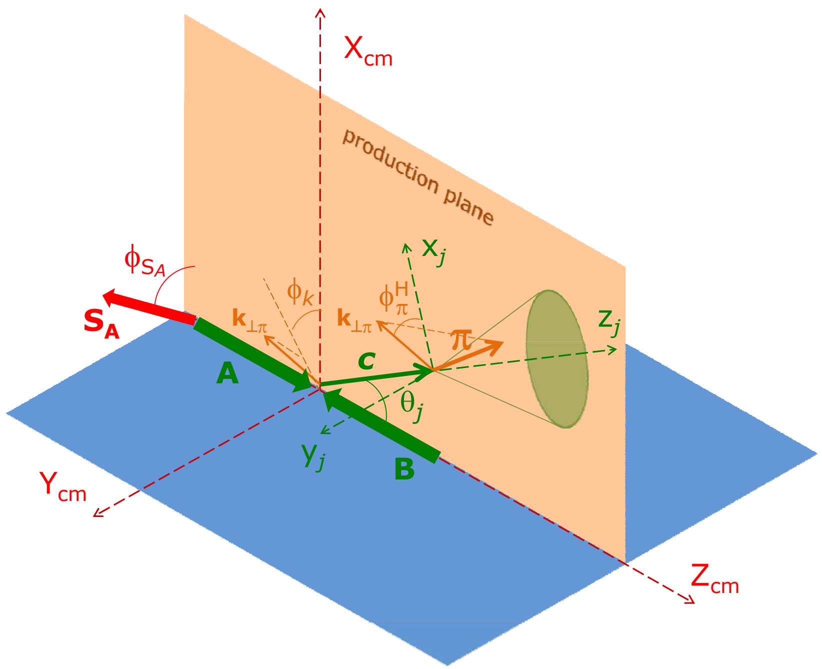
Still in a TMD scheme

SSA in $p^{\uparrow}p \to \text{jet}\,\pi X$

▶ $A_N \sim \cdots + h_1^q \otimes H_1^{\perp q} \sin(\phi_S - \phi_\pi^H)$

azimuthal distribution of pions inside a jet

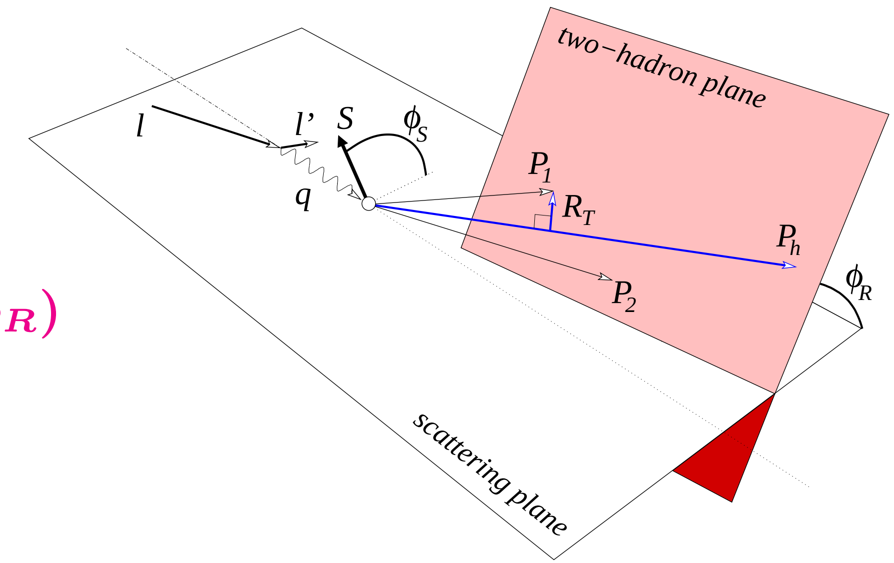
[***Yuan '08, UD-Murgia-Pisano '11***]



At variance with the inclusive process
$pp \to \pi X$, **here TMD effects ARE separable**

DiFF approach

SSA in $\ell p^{\uparrow} \to \ell'(\pi\pi)X$



▶ $A_{UT} \sim h_1^q \otimes H_1^{\sphericalangle q} \sin(\phi_S + \phi_R)$

Dihadron fragmentation function:

$q^{\uparrow} \to \pi(P_1)\pi(P_2)$

interference between different partial waves of the (ππ) system

Ji '94, Jaffe-Jin-Tang '98, Bianconi-Jacob-Radici '02

again help from $e^+e^- \to (\pi\pi)_1\,(\pi\pi)_2\,X \Rightarrow H_1^{\sphericalangle q} \otimes H_1^{\sphericalangle q}$ **[*Artru-Collins '96*]**

• **Collinear factorization and same evolution as for** H_1^q

Experimental data

Collins asymmetries

- SIDIS

HERMES: $p^{\uparrow}$, *'05, '07, '10* **FIRST EVIDENCE!!!**

COMPASS: $D^{\uparrow}$, *'05, '07, '08* | $p^{\uparrow}$, *'09, '10*

JLab: $(^3He)^{\uparrow}$, *'11*

- e^+e^-

Belle: *'06, '08*

BaBar: *'12* **(prelim.)**

DiFF asymmetries

- SIDIS: HERMES $p^{\uparrow}$ *'08* | **COMPASS** $p^{\uparrow}$, $D^{\uparrow}$ *'12*

- e^+e^-**: Belle** *'11*

- pp**: PHENIX** *'09*

Phenomenology

$\Delta_T q$ extraction via TMDs (Collins effect)

1) parametrization of $\Delta_T q$ (u, d) and $H_1^\perp$ (fav., unf.): $N x^a (1-x)^b$

2) factorized gaussian $k_\perp$-dependence

3) global fit of $ep^\uparrow \to e'\pi X$ and $e^+e^- \to \pi\pi X$ data (up to 2008)

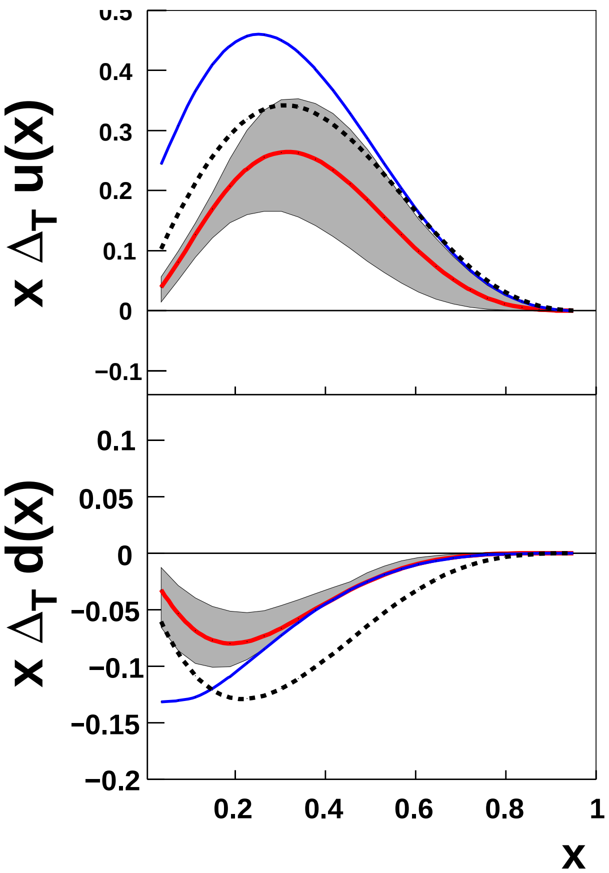
4) Q^2-evolution: h_1^q properly; $H_1^{\perp q}$ (unknown) same as D_q (also as H_1^q)

5) Universality of $H_1^{\perp q}$ [*Metz '02, Collins-Metz '04, Yuan '08*]

6) ongoing analysis: latest SIDIS data (HERMES, COMPASS) and e^+e^- (BaBar)

★ reanalysis(correction) of one Belle data set (2012) $\to$ no changes

Transversity



$Q^2 = 2.4$ GeV^2

$x > 0.3$ unconstrained

Soffer bound: $(q + \Delta q)/2$

helicity distribution: Δq **[GRSV2000]**

$|\Delta_T q| < |\Delta q|$: **relativistic effect**

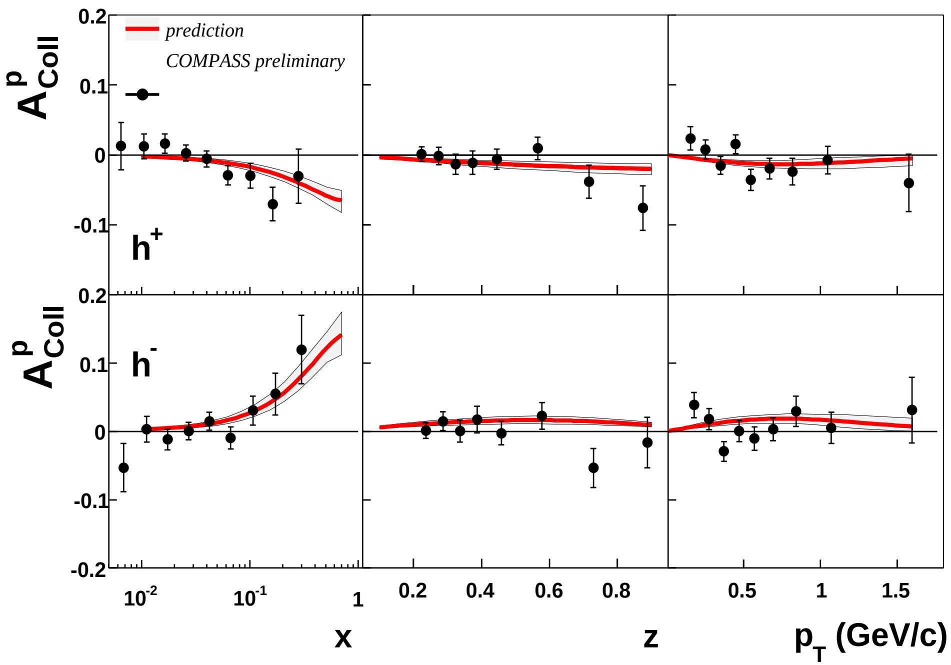
$\Delta_T u$ **via HERMES data**

$\Rightarrow \Delta_T d$ **via COMPASS** $A_{UT}|_D \sim 0$

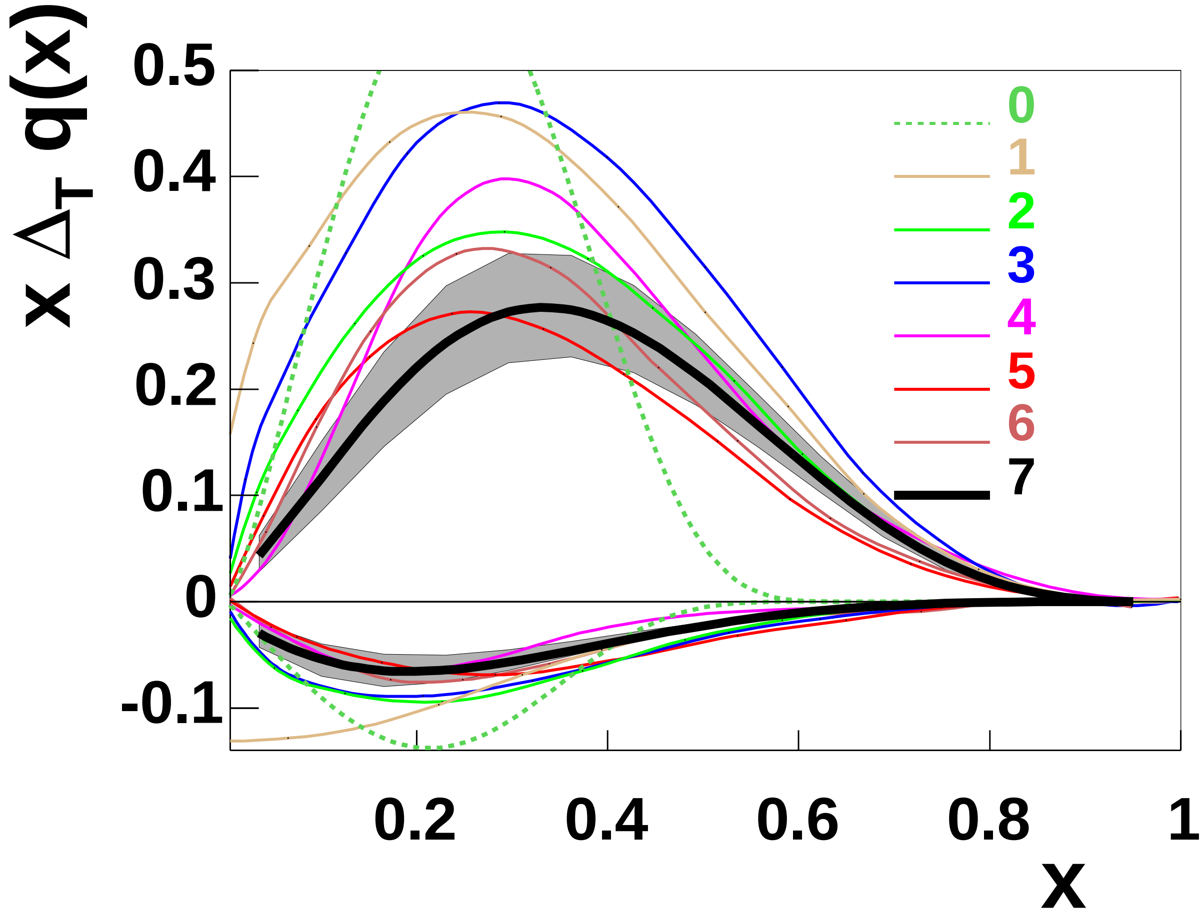
$\delta u = 0.54^{+0.07}_{-0.09} \quad \delta d = -0.23^{+0.04}_{-0.05}$

at $Q^2 = 0.8$ GeV^2

Predictions vs. COMPASS data (*Levorato '08*) for proton target



Comparison with model calculations

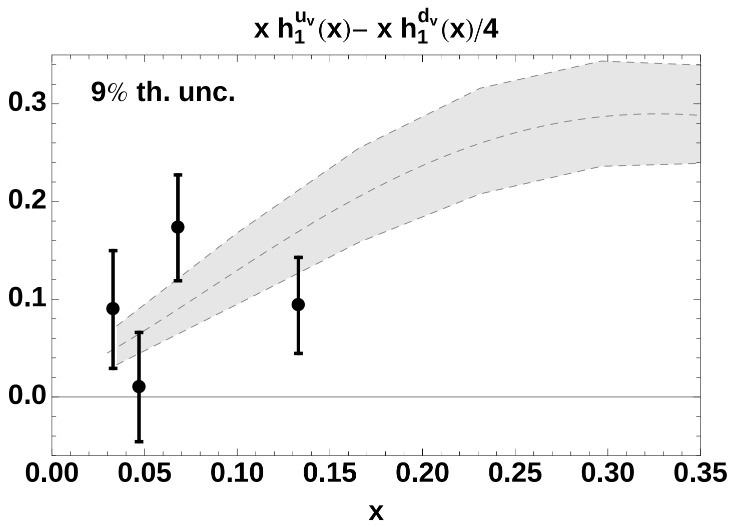


0 Barone et al. 1997
1 Soffer et al. 2002
2 Korotkov et al. 2001
3 Schweitzer et al. 2001
4 Wakamatzu 2007
5 Pasquini et al. 2005
6 Cloet et al. 2008
7 phen. extraction

h_1^q extraction via DiFF

[*Bacchetta-Courtoy-Radici '11*]

1) extraction of DiFFs from $e^+e^- \to (\pi^+\pi^-)\,(\pi^+\pi^-)\,X$ [*Belle '11*]
2) $H_1^{\triangleleft u} = -H_1^{\triangleleft d}$ + isospin sym. and no sea IFFs; z-integrated
3) unpolarized $D^{q\to\pi^+\pi^-}$ from PITHYA (no data !!!)
4) Q^2-evolution from 110 to 2.4 GeV^2
5) extraction of $(xh_1^u - xh_1^d/4)$ from $ep^\uparrow \to e'(\pi^+\pi^-)\,X$ [*HERMES '08*]
6) ongoing analysis: fit of COMPASS data on p and D $\to$ flavor separation

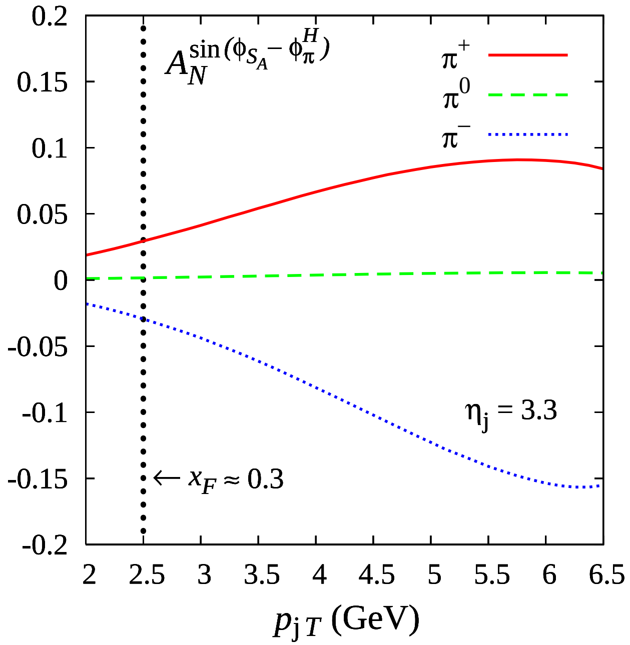


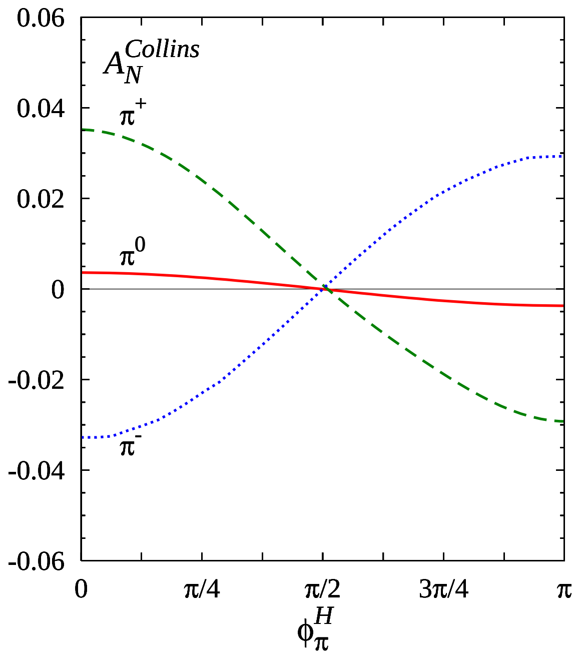
band: extraction via TMDs

[*Anselmino et al. '08*]

Predictions for Collins asymmetry in $p^{\uparrow} p \to \text{jet}\, \pi X \propto h_1^q \otimes H_1^{\perp q}$

STAR kinematics, $\sqrt{s} = 200$ GeV, forward rapidities





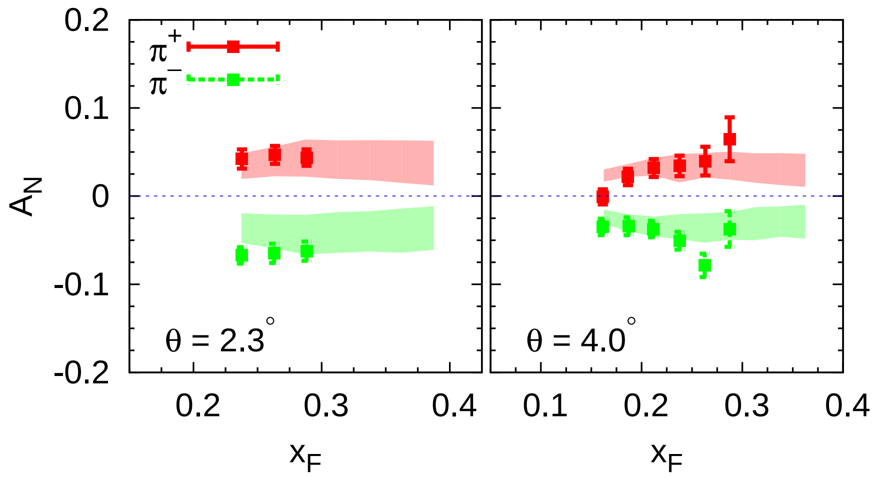
strong cancelation for π^0 (consistent with preliminary STAR data)

Role of Collins effect in A_N in $pp \to \pi X$: $h_1^q \otimes H_1^{\perp q}$

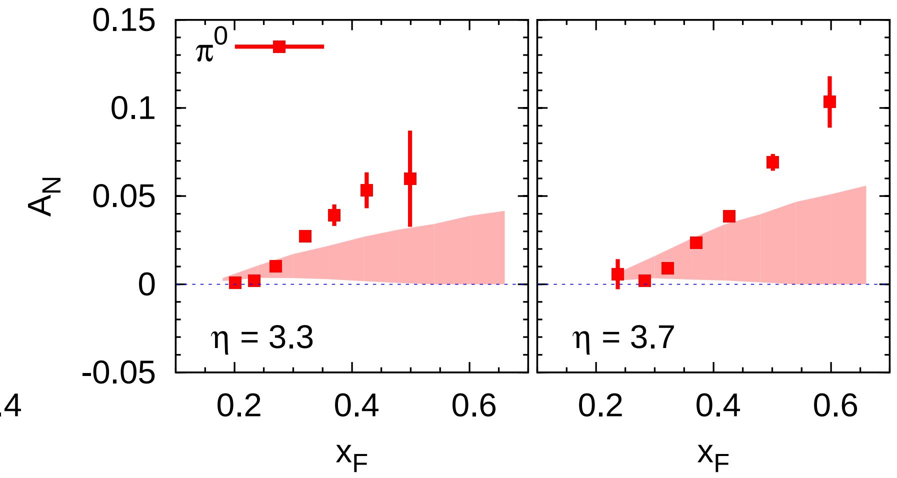
TMD factorization not proven; additional mechanisms potentially at work

Reanalysis based on SIDIS and e^+e^- data (PLUS sign correction)

Collins effect unsuppressed, but not sufficient at large x_F [*Anselmino et al. '12*]



BRAHMS data '07



STAR data '08

Open issues and perspectives

- h_1^q: **fundamental**; theoretically well known (like q and Δq)
- DSAs via D_{NN} still problematic: no information on H_1^q [$q^\uparrow \to \Lambda^\uparrow$]
- Drell-Yan: golden channel, self-sufficient, large A_{TT} at PAX, promising
- large x region still uncovered
- TMD strategy: first extraction

- Q^2-evolution of χ-odd TMDs: $H_1^{\perp q}$ and $h_1^{\perp q}$
- SIDIS: JLab at 12 GeV (large x, high luminosity, neutron transversity)
- azimuthal correlations in e^+e^-: $p_\perp$-dependence, BaBar [$H_1^{\perp q}$]
- A_N and unpol. cross sections in DY: PAX ($p^\uparrow \bar{p}$), COMPASS($\pi p^\uparrow$) [$h_1^{\perp q}$]

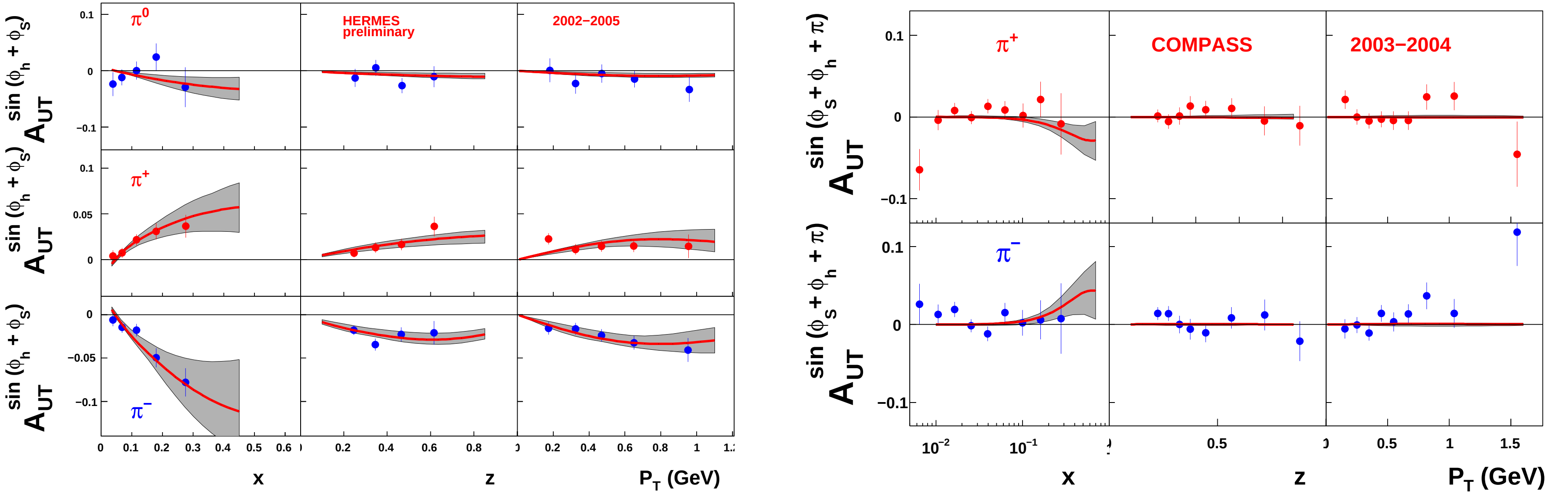
- DiFF strategy: started, consistent with the TMD extraction

- safe | more and more precise data needed

BACK-UP SLIDES

SIDIS

Anselmino et al. '08

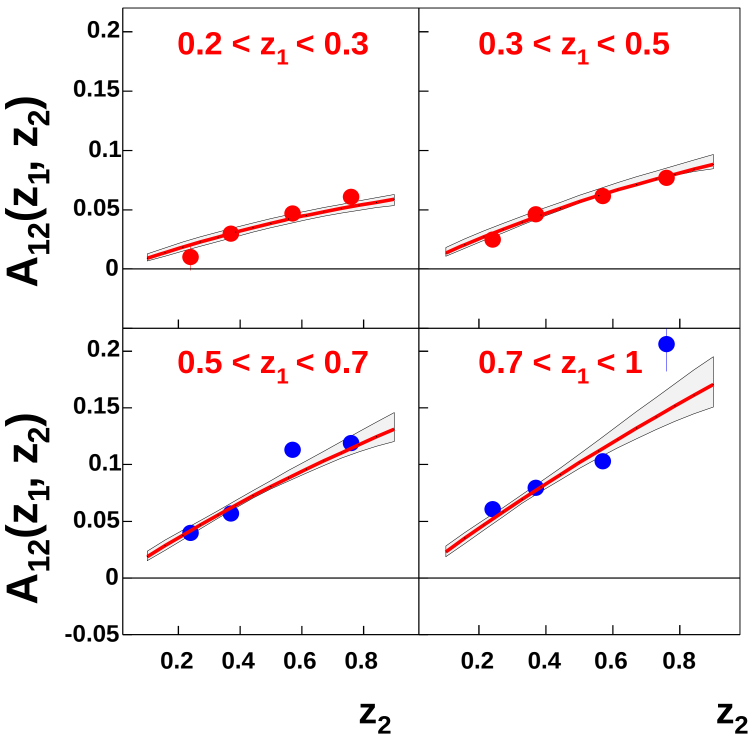


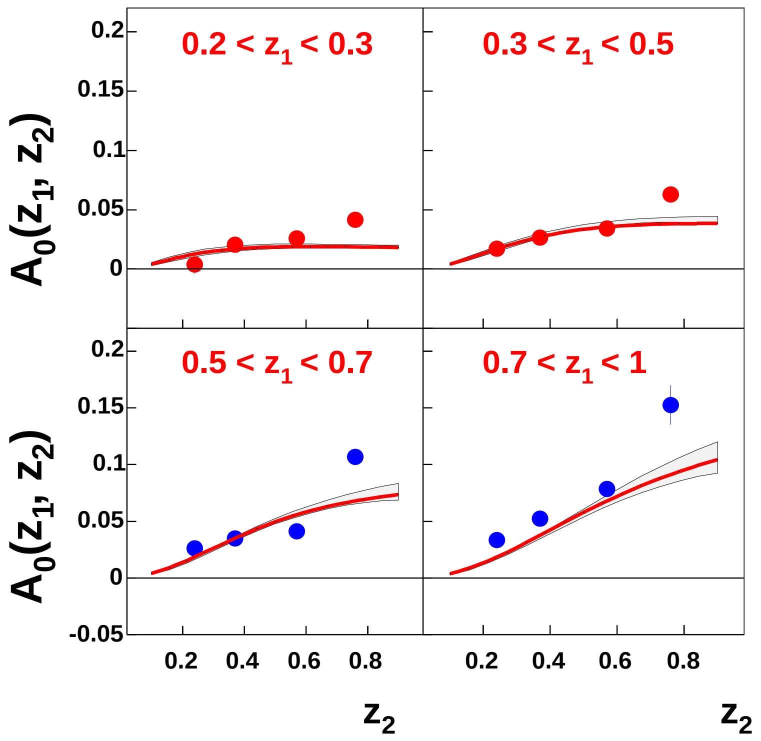
HERMES data on hydrogen [*Diefenthaler et al. '07*]

COMPASS data on deuterium [*Alekseev et al. '08*]

$e^+e^- \to \pi\pi X$

Anselmino et al. '08

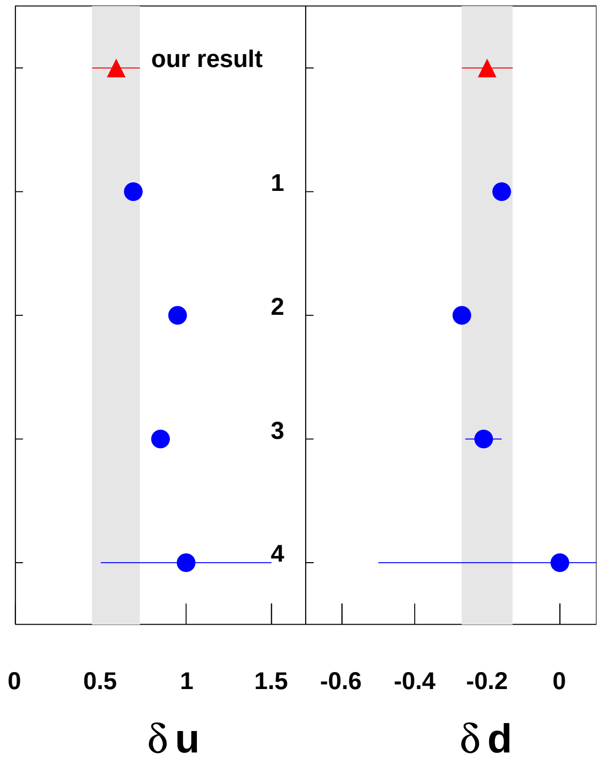




Fit of A_{12} and comparison with A_0 data. [Belle *Seidl et al. '08*].

Tensor charge: $\delta q = \int dx (\Delta_T q - \Delta_T \bar{q}) = \int dx \Delta_T q$

$\delta u = 0.54^{+0.07}_{-0.09}$ $\delta d = -0.23^{+0.04}_{-0.05}$ at $Q^2 = 0.8$ GeV^2



1 Quark-diquark model: ***Cloet et al. 2008***

2 CQSM: ***Wakamatzu 2007***

3 Lattice QCD: ***Goeckeler et al. 2005***

4 QCD sum rules: ***He & Ji 1995***

Caution! **[*Wakamatsu '08*]**

1) model results: evolution *arbitrary* low input scales (δq is scale dependent)

2) much safer the scale independent ratio $\delta d/\delta u$ (absence of gluon coupling)