ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
Institutional Member of the European Expert Committee NUPECC

Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum, London

Partons Transverse Momentum Distribution at Large x: A Window into Partons Dynamics in Nucleon Structure within QCD

Trento, April 11-15, 2016

Main Topics

Recent Progress in Transverse Momentum Dependent (TMD) Distributions
Transversity Distribution and Tensor Charge of the Nucleon
Quarks Orbital Angular Momentum in the Nucleon
Evolution Global Extractions and Model Calculations of TMDs
Lattice Calculations and TMDs
Experimental Programs of TMDs including the SoLID detector at Jefferson Lab

Key-note participants

Mauro Anselmino (*Torino University and INFN*), Hai-Bo Li (*Institute of High energy Physics, Beijing China*), Ian Clöet (*Argonne National Lab*), Michela Chiosso (*Torino University*), Marco Contalbrigo (*INFN Ferrara*), Michael Engelhardt (*New Mexico State University, El Paso, NM*), Leonard Gamberg (*Pen State-Berks, Pennsylvania*), Simonetta Liutti (*University of Virginia, Charlottesville, USA*), Wolfgang Lorenzon (*University of Michigan, Michigan USA*), Piet Mulders (*Nikhef/VU, Amsterdam*), Barbara Pasquini (*University of Pavia*), Marco Radici (*University of Pavia, Italy*), Ted Rogers (*Old Dominion University, Virginia, USA*), Peter Schweitzer (*U. of Connecticut, USA*), Jacques Soffer (*Temple University, Philadelphia, USA*), Giancarlo Ferrara (*INFN, Milano*)

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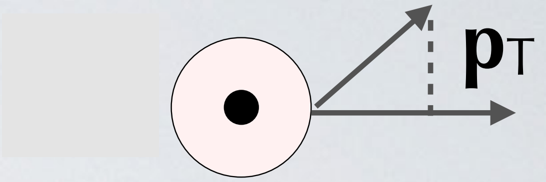
Transversity Tensor Charge overview

Marco Radici
INFN - Pavia

leading-twist TMD map



quark polarization

nucleon polarization

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

leading-twist TMD map → PDF map

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U	**f_1**		$h_1^\perp$
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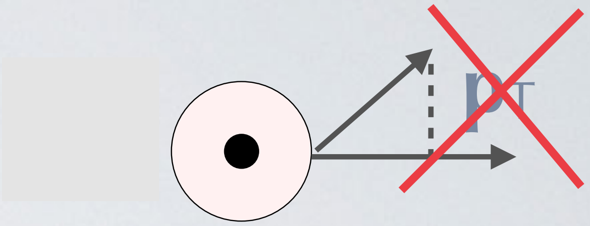

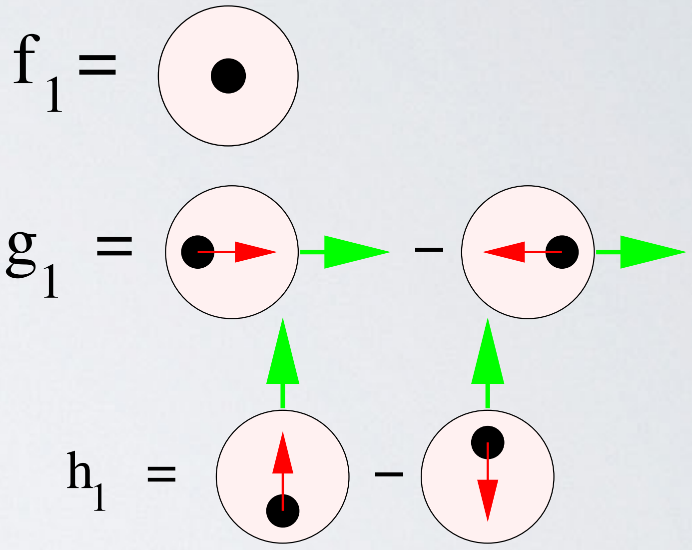

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nucleon polarization	U	L	T
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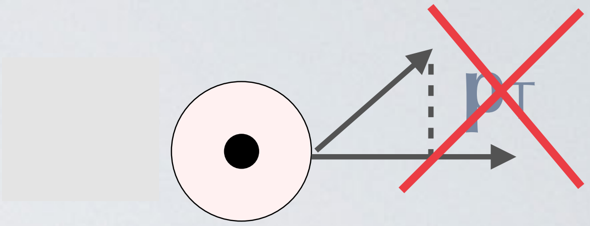
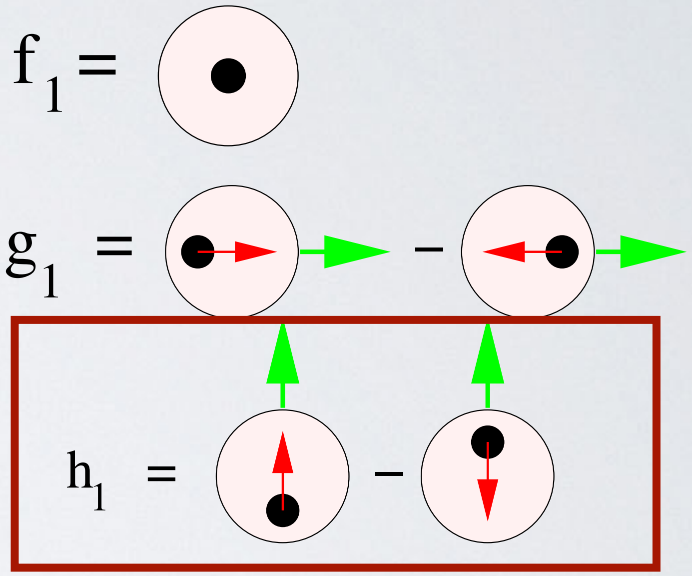




f_1 from fits of **thousands** data

g_1 from fits of **hundreds** data

h_1 from fits of **tens** data

poorly known

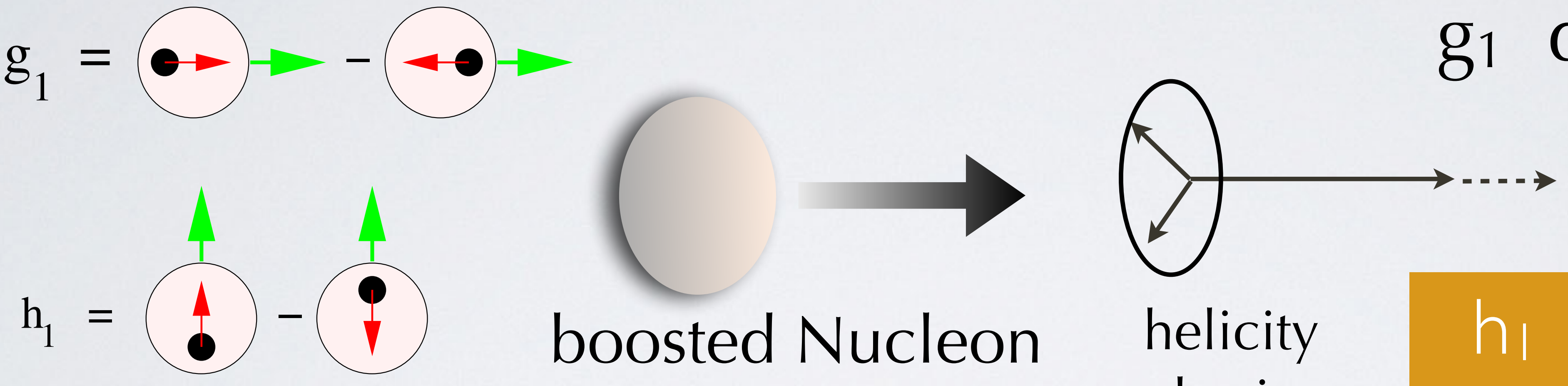
~ 3000 **CT14**, *arXiv:1506.07443*
~ 4000 **CJ12**, *P.R. D**84** (11) 014008*
~ 4300 **NNPDF3.0**, *JHEP **1504** (15) 040*
....

~ 500 **NNPDFpol1.1**, *N.P. **B887** (14) 276*
(~ 2500 (?) ***JAM*** *arXiv:1601.07782*)

268 **"Collins"** *Anselmino et al., P.R. D**92** (15) 114023*
68 **"DiFF"** *Radici et al., JHEP **1505** (15) 123*

Transversity : Why

- transversity is very different from helicity



boosted Nucleon

helicity
basis

g_1 diagonal

h_1 non diagonal
(“chiral-odd”)

- no h_1 for gluons
  (in Nucleon) → pure non-singlet evolution

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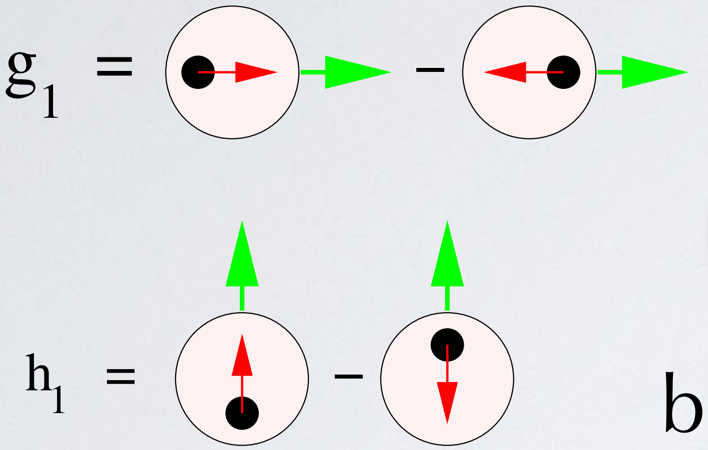

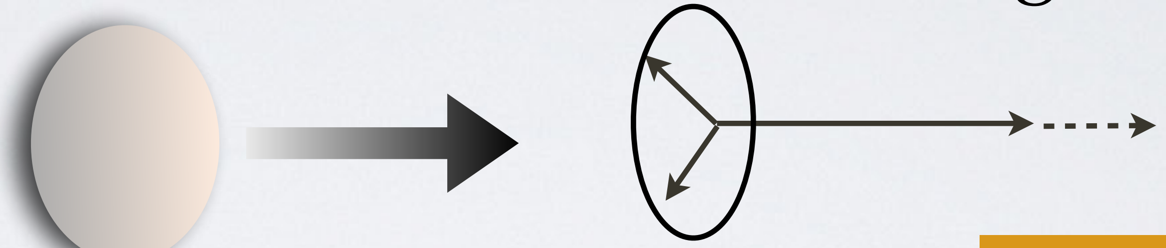

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playground for tests of perturbative and nonperturbative QCD

Tensor Charge

- 1st Mellin moment of transversity ⇒ tensor “charge”

$$\delta q \equiv g_T^q = \int_0^1 dx \ \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$$

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no associated conserved current in $\mathcal{L}_{\mathrm{QCD}}$

↓

tensor “charge” g_T	scales with Q^2	C-odd
axial charge g_A	conserved	C-even

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tensor charge not directly accessible in $\mathcal{L}_{\mathrm{SM}}$

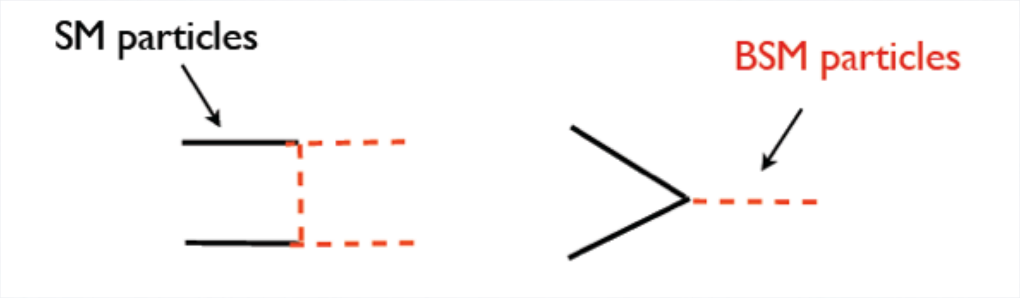
low-energy footprint of new physics at higher scales ?

potential for BSM discovery ?

search for new physics **B**eyond **S**tandard **M**odel

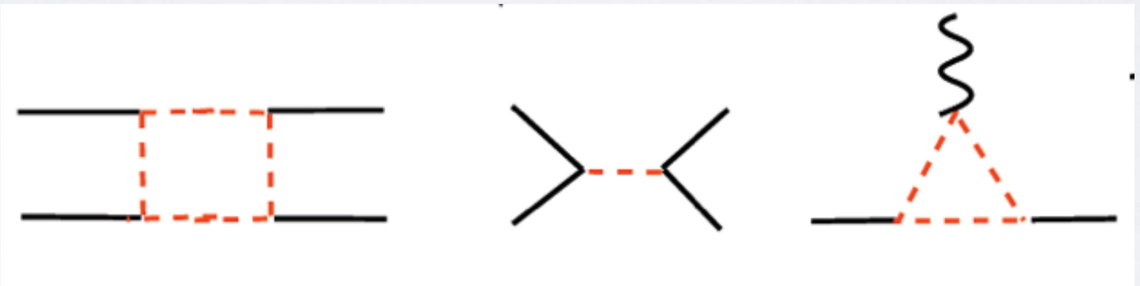
E

M_{BSM}
high energy



direct access

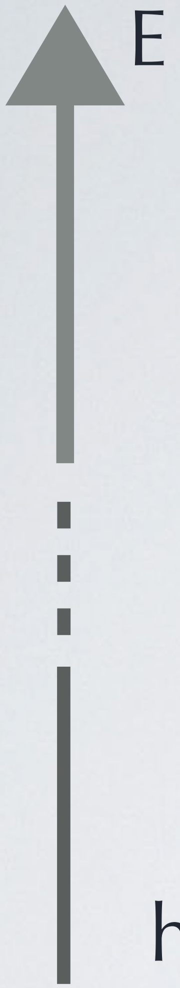
$E_{exp} \ll M_{BSM}$
low energy
high precision



indirect access
virtual effects

potential for BSM discovery ?

search for new physics **B**eyond **S**tandard **M**odel



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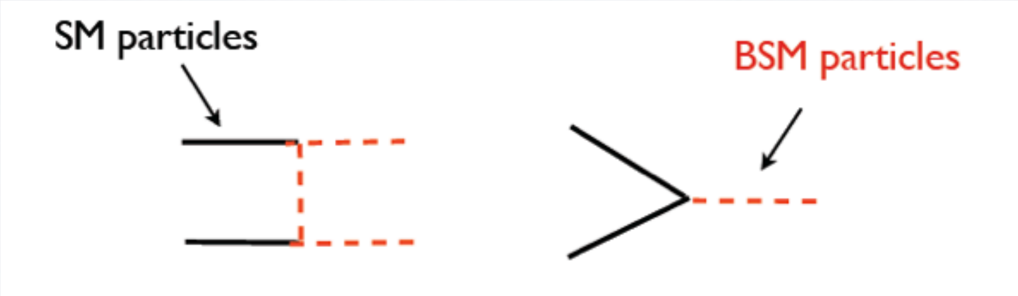

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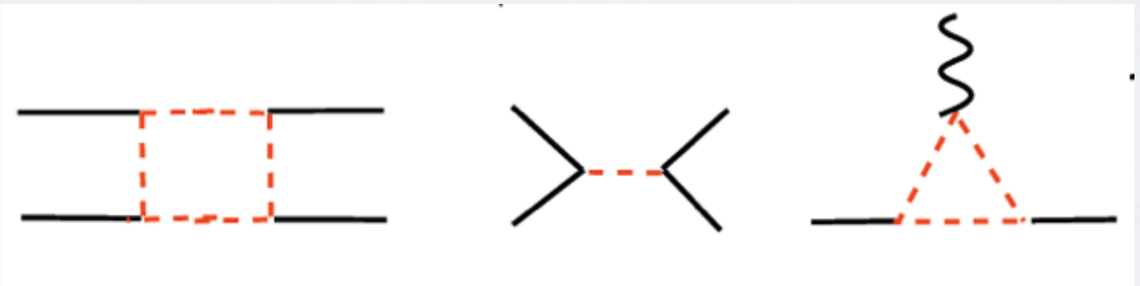
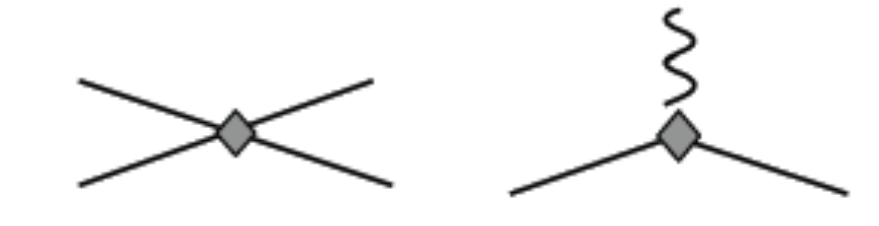
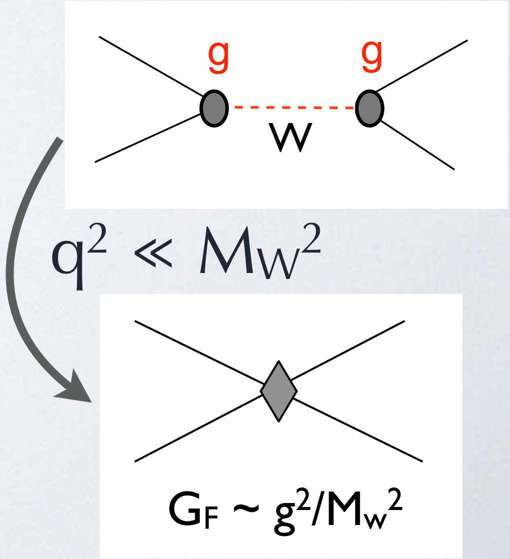


indirect access
virtual effects

footprint:
new local operators

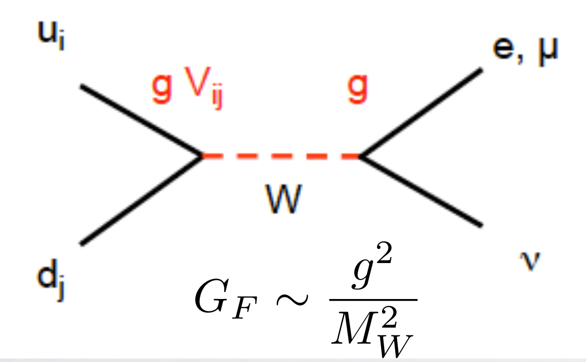


Example:
weak CC
interaction



potential for BSM discovery ?

Example: neutron β−decay n → p e^- $\bar{\nu}_e$



tree-level SM, V-A universality (+ radiative corr.'s…)

$$\mathcal{L}_{\text{SM}} \sim G_F\, V_{ud}\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e\ \langle p|\bar{u}\gamma^\mu(1-\gamma_5)d|n\rangle$$

$q^2 \sim (M_p - M_n)^2 \approx 0$

g_V g_A

potential for BSM discovery ?

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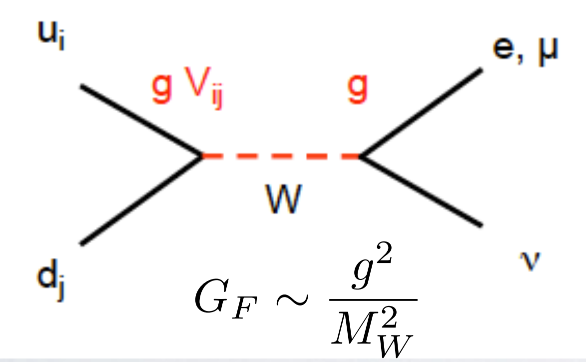

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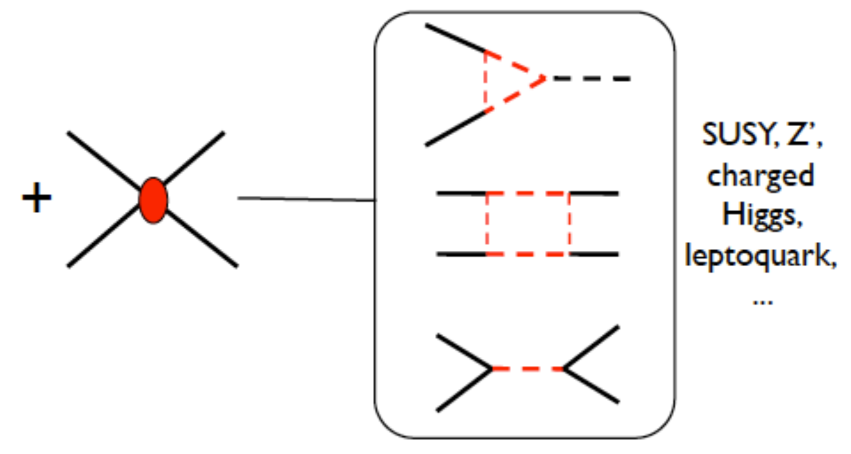


$$+\mathcal{L}_{\rm eff} \sim G_F V_{ud} \sum_{\Gamma} \Big[\, \epsilon_\Gamma\; \bar{e}\,\Gamma\,\nu_{eL}\, \langle p|\bar{u}\Gamma d|n\rangle \;+ \ldots \Big]$$

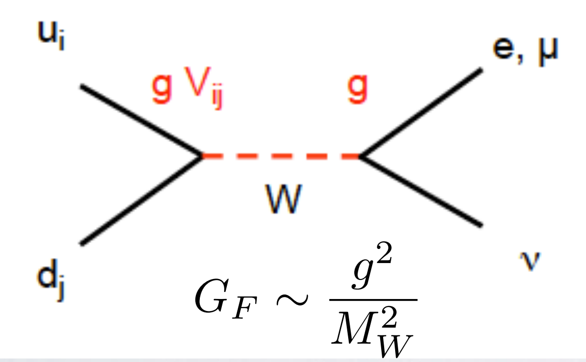
g_S , g_P , g_T

effective couplings

Γ = V-A, V+A, 1, γ_5, $\sigma^{\mu\nu}$

potential for BSM discovery ?

Example: neutron β−decay $n \to p\, e^- \bar{\nu}_e$



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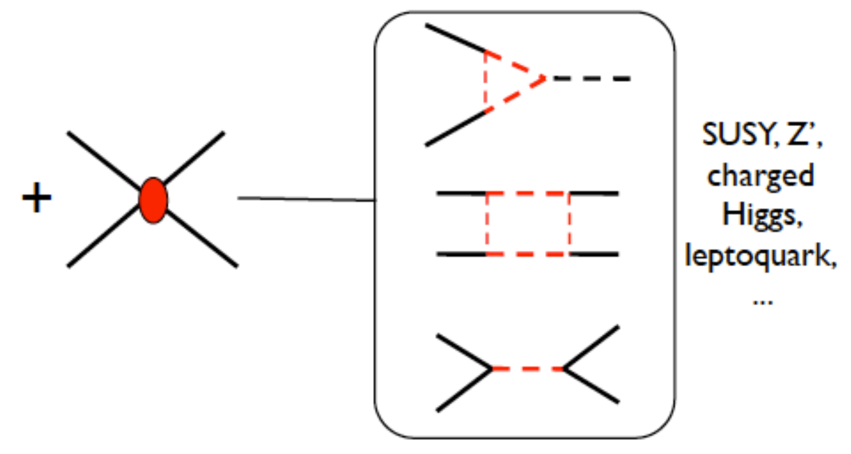

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effective couplings

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Γ = V-A, V+A, 1, γ_5, $\sigma^{\mu\nu}$

precision of measurement → $\epsilon_\Gamma\, g_\Gamma \approx \frac{M_W^2}{M_{\rm BSM}^2}$ ← bound on BSM scale

precision of 0.1% ⇒ [3-5] TeV for BSM scale

neutron β–decay and tensor charge

tensor contribution to neutron β-decay

$$\mathcal{L}_{\mathrm{eff,\,T}} \;\sim\; G_F\, V_{ud}\; \epsilon_T\; \bar{e}\,\sigma_{\mu\nu}\,\nu_{e\mathrm{L}}\; \langle p|\bar{u}\,\sigma^{\mu\nu}\,d|n\rangle$$

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isospin symmetry

$$\langle p, S_p |\, \bar{u}\, \sigma^{\mu\nu} u \;-\; \bar{d}\, \sigma^{\mu\nu} d\, | p, S_p \rangle$$

same structure of isovector component of
1st Mellin moment of transversity

$$\begin{aligned}\langle p, S_p |\, \bar{q}\, \sigma^{\mu\nu}\, q\, | p, S_p \rangle &= \left(P^\mu S_p^\nu - P^\nu S_p^\mu \right)\, g_T^q(Q^2) \\ &= \left(P^\mu S_p^\nu - P^\nu S_p^\mu \right) \int dx\; h_1^{q-\bar{q}}(x, Q^2)\end{aligned}$$

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knowledge of isovector tensor charge g_T^{u-d} affects
precision of tensor coupling $G_F V_{ud}\, \boldsymbol{\varepsilon}_T\, g_T$ in **β**-decay

CP violation in BSM

in some BSM theories,
the leading CP-violating (CPV) couplings
are related to fermion Electric Dipole Moments (EDM)

$$\mathcal{L}_{\mathrm{CPV}} \supset \; ie \sum_{f=u,d,s,e} d_f \; \bar{f}\, \sigma_{\mu\nu}\gamma_5\, f \; F^{\mu\nu}$$

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

neutron EDM

$$d_n \; = \; g_T^u\, d_u \, + \, g_T^d\, d_d \, + \, g_T^s\, d_s$$

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exp. bounds

+ improved knowledge on flavor-diagonal tensor charges

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neutron EDM

$$d_n = g_T^u d_u + g_T^d d_d + g_T^s d_s$$

exp. bounds

+ improved knowledge on flavor-diagonal tensor charges

constraints on CP violation encoded in q EDM

Present extractions of transversity

quark polarization

nucleon polarization

	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
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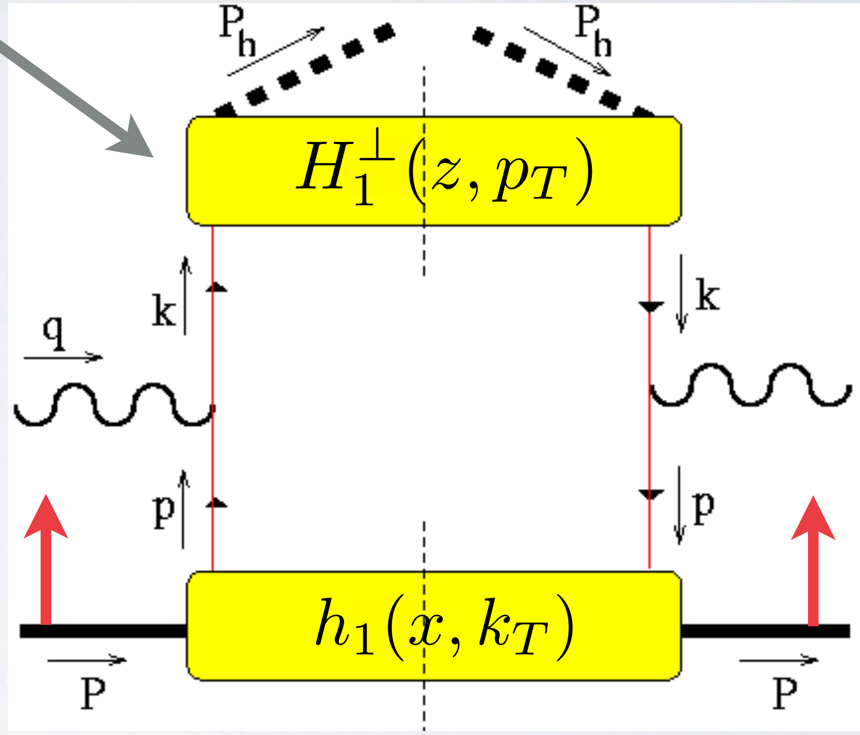
TMD factorization

Collins funct.

h_1 “considered” as a TMD



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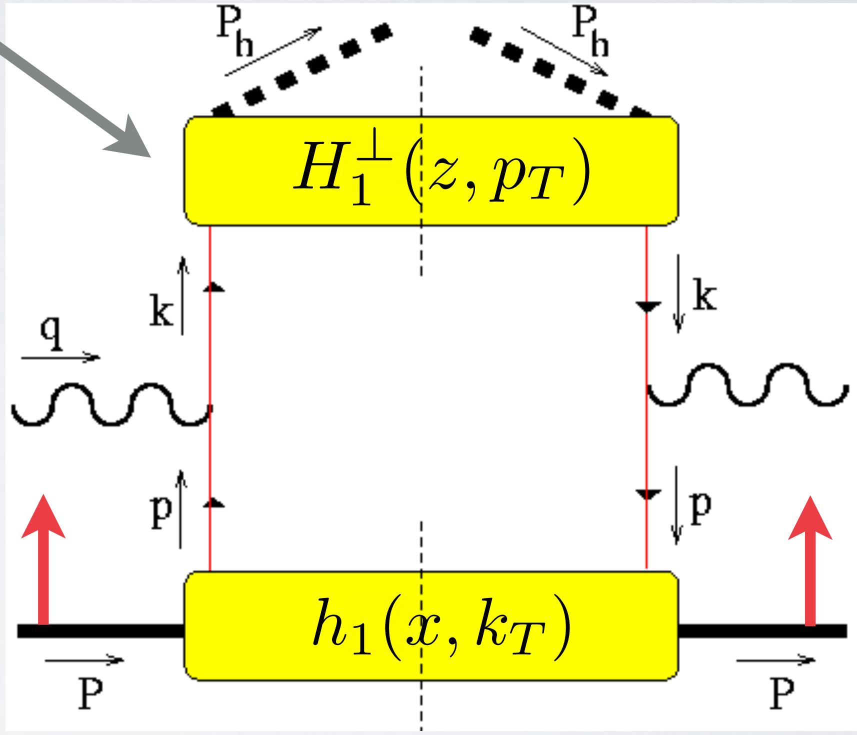
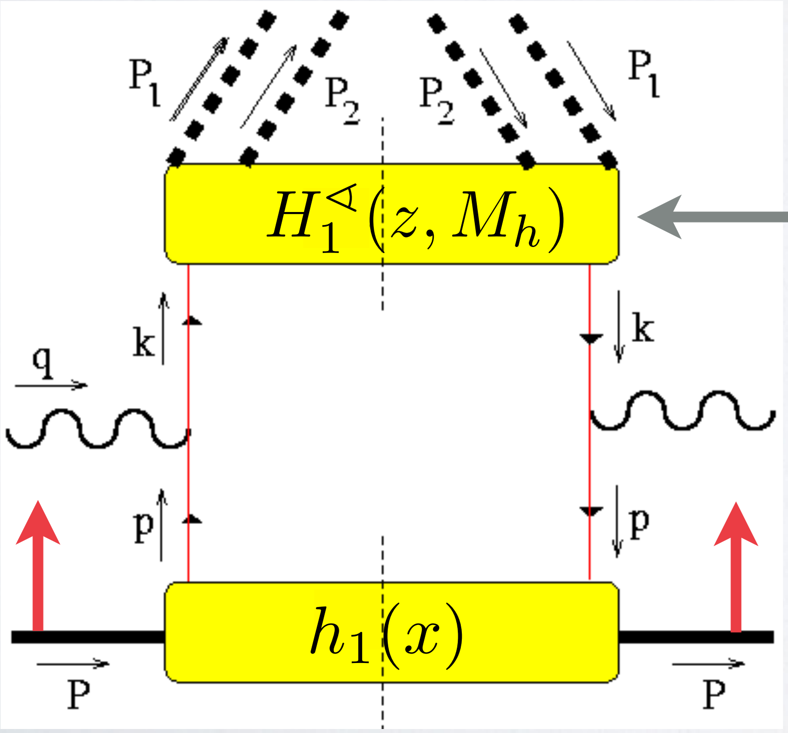


h_1 "considered"
as a PDF



Interference
Fragm. **F**unct. (IFF)

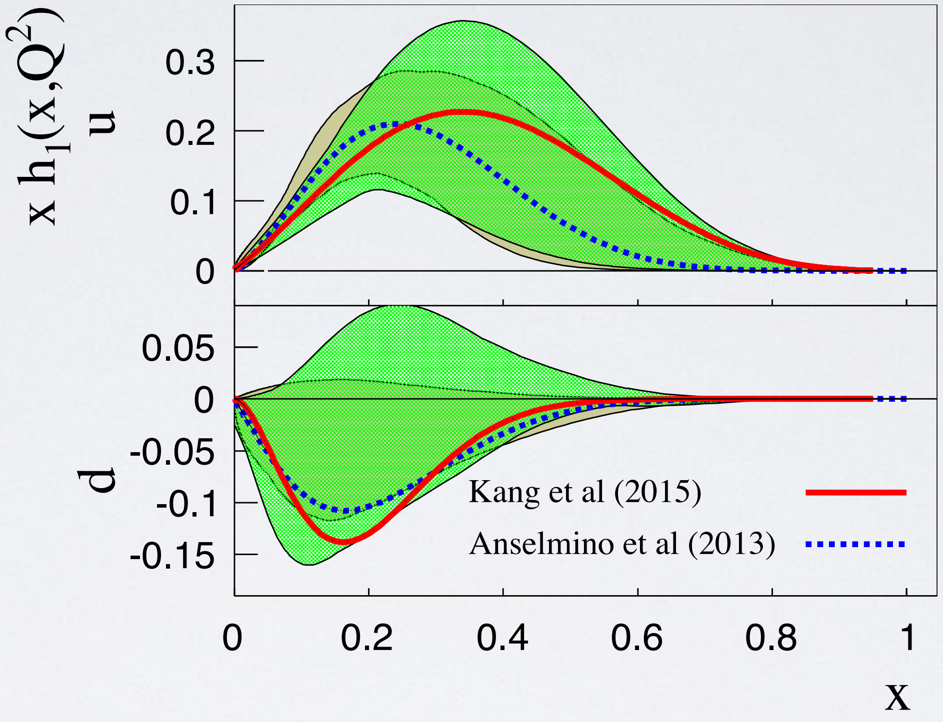
collinear
factorization

The status of the art

🟩 **Kang** et al., *P.R. D**93** (16) 014009*

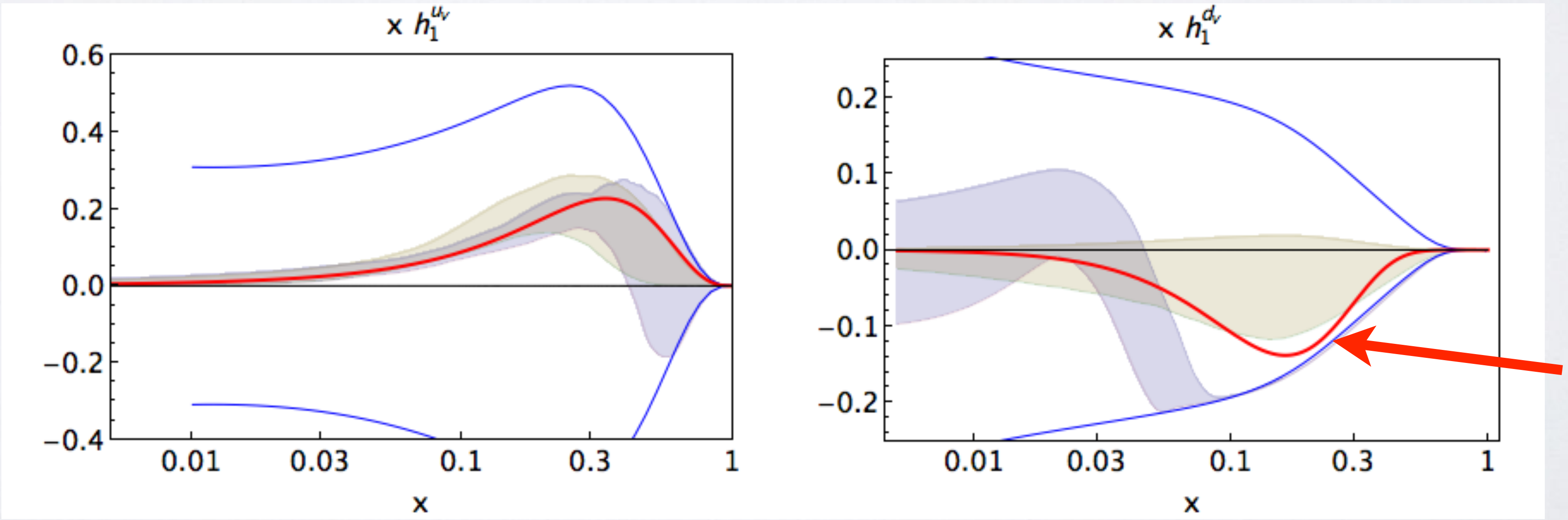
▨ **Anselmino** et al., *P.R. D**87** (13) 094019*

TMD factorization



up

down



Anselmino et al.,
2013 ▨

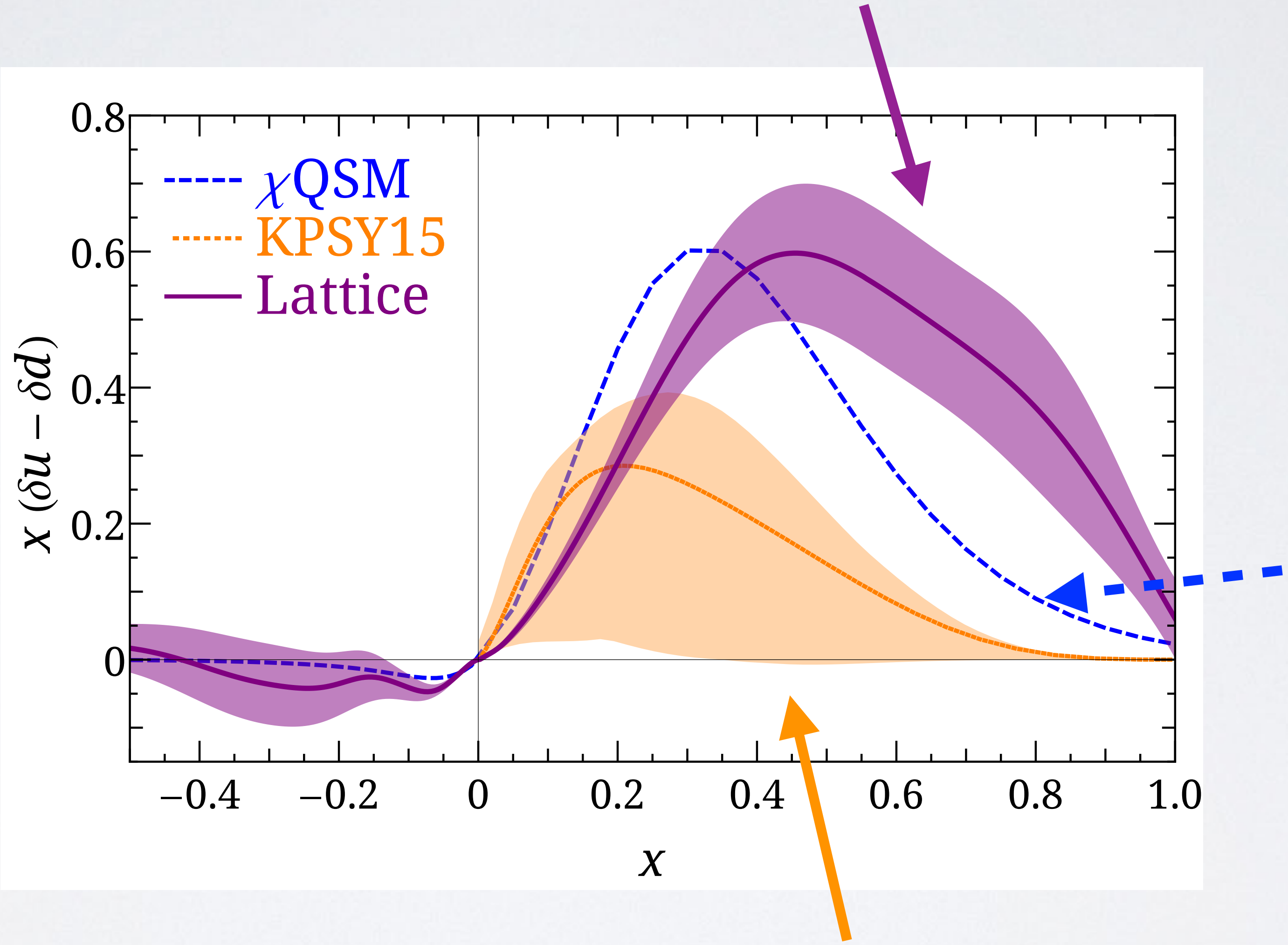
collinear factorization

Radici et al., ▨
*JHEP **1505** (15) 123*

Kang et al.,
2015

The status of the art

very recently, also lattice calculation of “quasi-transversity” using Ji’s LaMET



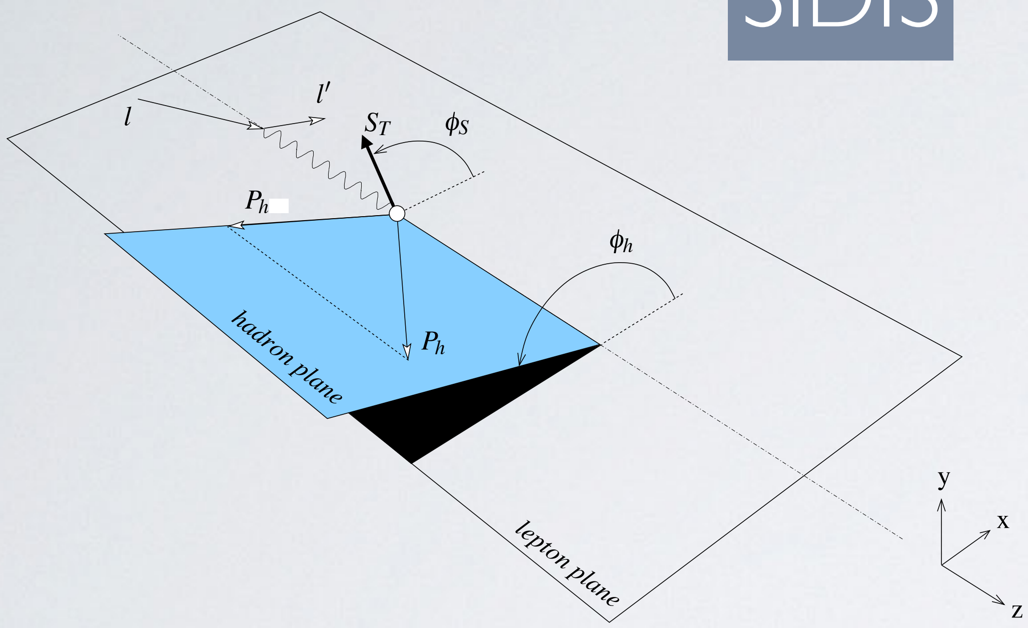
Chen et al.,
arXiv:1603.06664

Schweitzer et al.,
*P.R. D**64** (01) 034013*

Kang et al.,
*P.R. D**93** (16) 014009*

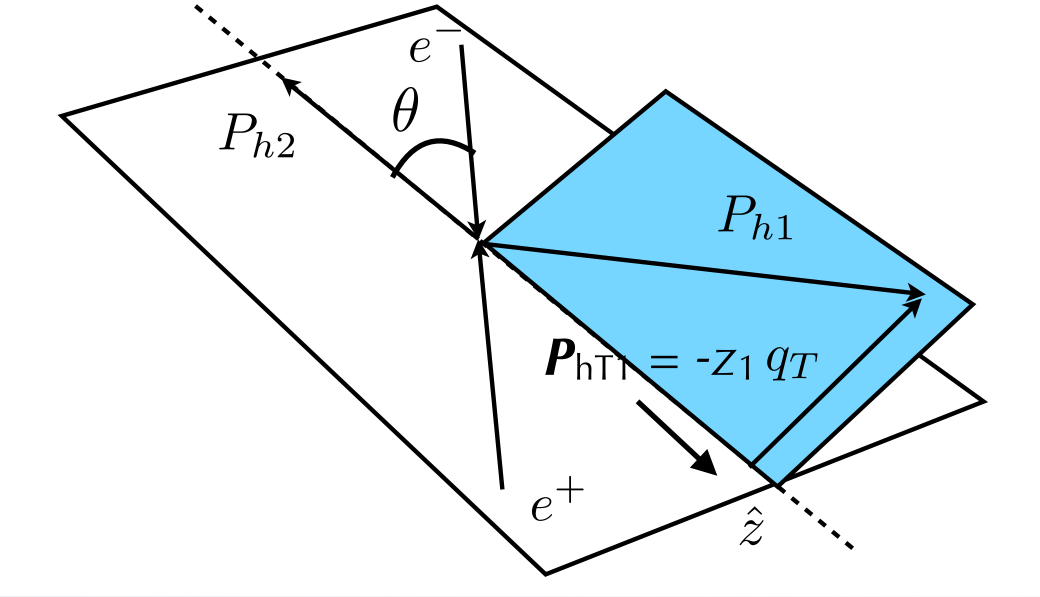
single-hadron fragmentation : the Collins effect

SIDIS



$$A^{\sin(\phi_h+\phi_S)}_{\text{SIDIS}}(x, z, P_T^2) \sim \frac{\sum_q e_q^2\; h_1^q(x, \boldsymbol{k}_\perp^2) \otimes H_{1,q}^\perp(z, \boldsymbol{p}_\perp^2)}{\sum_q e_q^2\; f_1^q(x, \boldsymbol{k}_\perp^2) \otimes D_{1,q}(z, \boldsymbol{p}_\perp^2)}$$

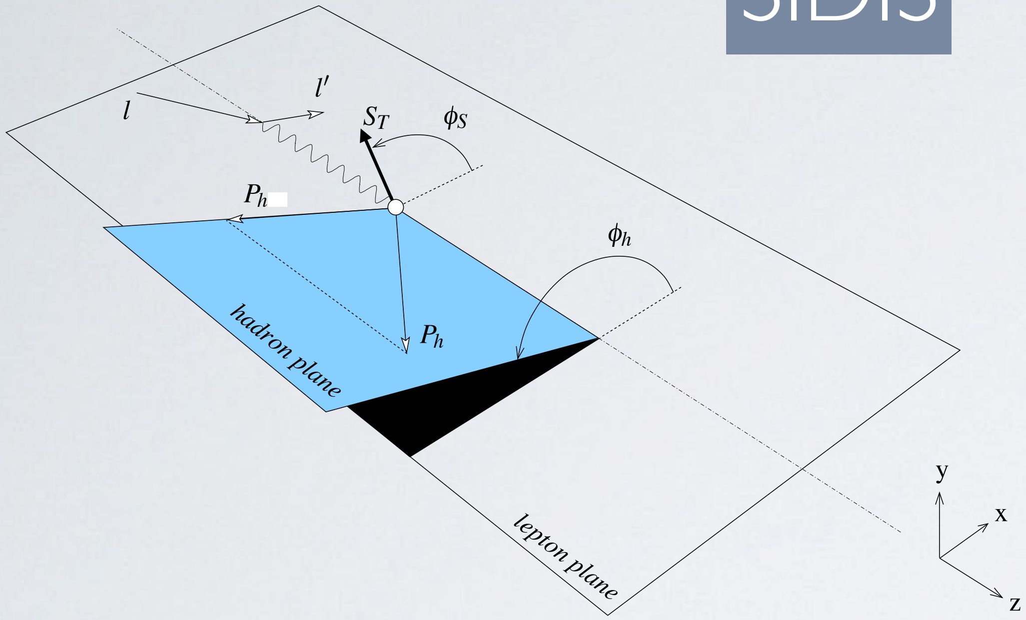
e^+e^-



$$A^{\cos 2\phi_1}_{e^+e^-}(z_1, z_2, P_{1T}^2) \sim \frac{\sin^2\theta}{1+\cos^2\theta} \times \frac{\sum_q e_q^2\; H_{1,q}^\perp(z_1, \boldsymbol{p}_{1\perp}^2) \otimes H_{1,\bar{q}}^\perp(z_2, \boldsymbol{p}_{2\perp}^2)}{\sum_q e_q^2\; D_{1,q}(z_1, \boldsymbol{p}_{1\perp}^2) \otimes D_{1,\bar{q}}(z_2, \boldsymbol{p}_{2\perp}^2)}$$

single-hadron fragmentation : the Collins effect

SIDIS



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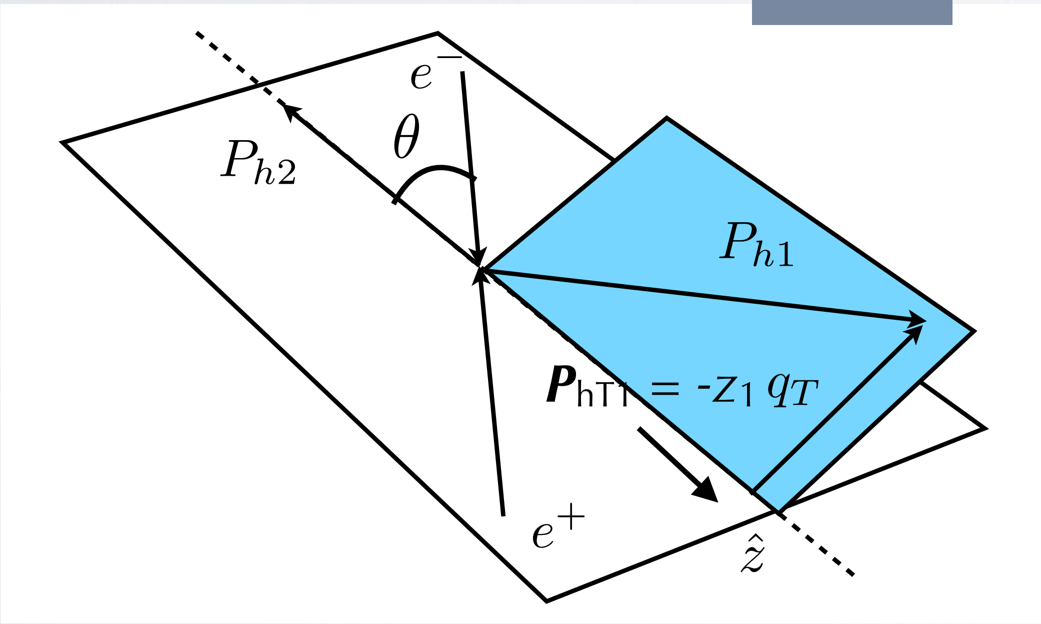
$$\ldots\otimes\ldots \longrightarrow \int d\boldsymbol{k}_\perp\, d\boldsymbol{p}_\perp\ \delta(z\boldsymbol{k}_\perp+\boldsymbol{p}_\perp-\boldsymbol{P}_T)\ldots$$

e^+e^-



$$\ldots\otimes\ldots \longrightarrow \int d\boldsymbol{p}_{1\perp}\, d\boldsymbol{p}_{2\perp}\ \delta(\boldsymbol{p}_{1\perp}+\boldsymbol{p}_{2\perp}+\frac{\boldsymbol{P}_{1T}}{z_1})\ldots$$

$$A_{e^+e^-}^{\cos 2\phi_1}(z_1,z_2,P_{1T}^2) \sim \frac{\sin^2\theta}{1+\cos^2\theta}$$

$$\times\ \frac{\sum_q e_q^2\ H_{1,q}^\perp(z_1,\boldsymbol{p}_{1\perp}^2)\ \otimes\ H_{1,\bar{q}}^\perp(z_2,\boldsymbol{p}_{2\perp}^2)}{\sum_q e_q^2\ D_{1,q}(z_1,\boldsymbol{p}_{1\perp}^2)\ \otimes\ D_{1,\bar{q}}(z_2,\boldsymbol{p}_{2\perp}^2)}$$

Collins effect : the TORINO extraction

Anselmino et al.,
*P.R. D***92** *(15) 114023*

- separate collinear x (z) and $k_\perp$ ($p_\perp$) dependence
- Q^2-independent Gaussian ansatz for $k_\perp$ ($p_\perp$) dependence
- same Gaussian widths for h_1 & f_1; different for $H_1^\perp$ & D_1

$<\boldsymbol{k}^2{}_\perp> = 0.57$ GeV^2
$<\boldsymbol{p}^2{}_\perp> = 0.12$ GeV^2
from analysis of
SIDIS multiplicities

Collins effect : the TORINO extraction

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$\langle \boldsymbol{k}^2_\perp \rangle = 0.57$ GeV^2
$\langle \boldsymbol{p}^2_\perp \rangle = 0.12$ GeV^2
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- different collinear shape for favored & disfavored $H_1^\perp$
- DGLAP evolution of collinear dependence; Soffer bound built in $h_1(x,Q_0)$
- two schemes: chiral-odd evo for h_1 only; or for h_1 and $H_1^\perp$

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- two schemes: chiral-odd evo for h_1 only; or for h_1 and $H_1^\perp$

- 4 parameters for h_1, 5 for $H_1^\perp$ => total 9 fit parameters
- 122 e^+e^- data from BELLE (z_1,z_2) dep. and BABAR ($z_1,z_2,\mathbf{P}_{1T}$) dep.
- 146 SIDIS data from hermes and COMPASS

- global χ^2/dof in [0.84 - 1.2] at 95.45% C.L. (⇔ $\Delta\chi^2 = 17.2$)

Collins effect with TMD evolution

Kang et al.,
*P.R. D***93** *(16) 014009*

- first analysis implementing TMD evolution
- NLO + NLL resummation
- Soffer bound built in "PDF term" $h_1(x,Q_0)$ as in TORINO param.
- different fav. & disfav. "PDF term" $H^{(3)}$ at Q_0 " " "
- chiral-odd evo for both "PDF terms", but only homogen. eq. for $H^{(3)}$

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- first analysis implementing TMD evolution
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- different fav. & disfav. “PDF term” $H^{(3)}$ at Q_0 “ “ “
- chiral-odd evo for both “PDF terms”, but only homogen. eq. for $H^{(3)}$

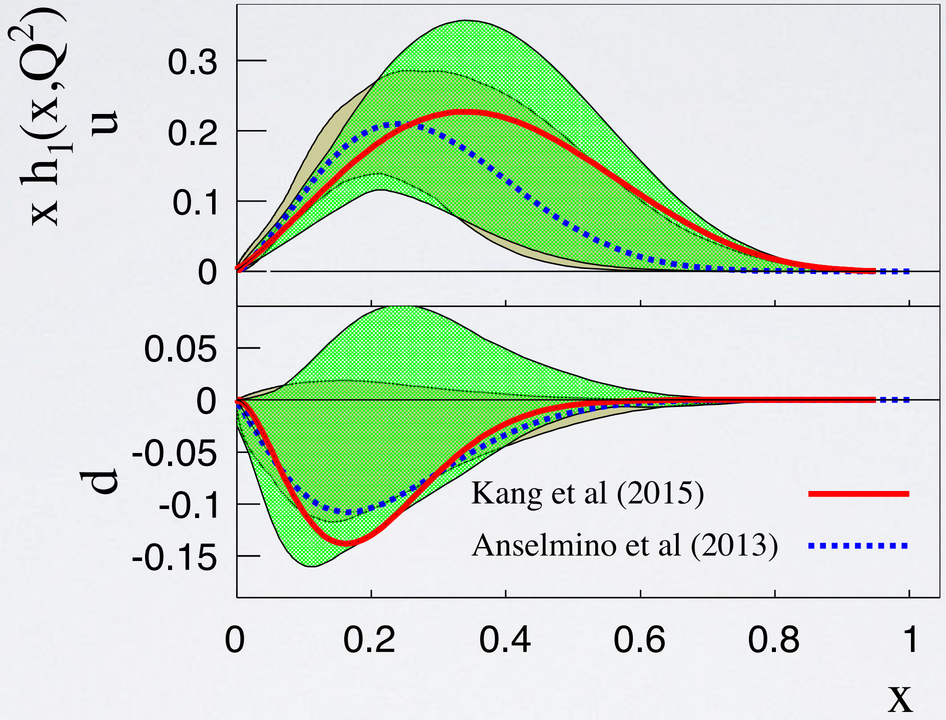
- total 13 fit parameters
- 122 e^+e^- data from BELLE (z_1,z_2) dep. and BABAR $(z_1,z_2,\mathbf{P}_{1T})$ dep.
- 140 SIDIS data from hermes and COMPASS and Jefferson Lab
- global $\chi^2/\mathrm{dof} = 0.88$ with $\Delta\chi^2 = 22.3$

Transversity from Collins effect

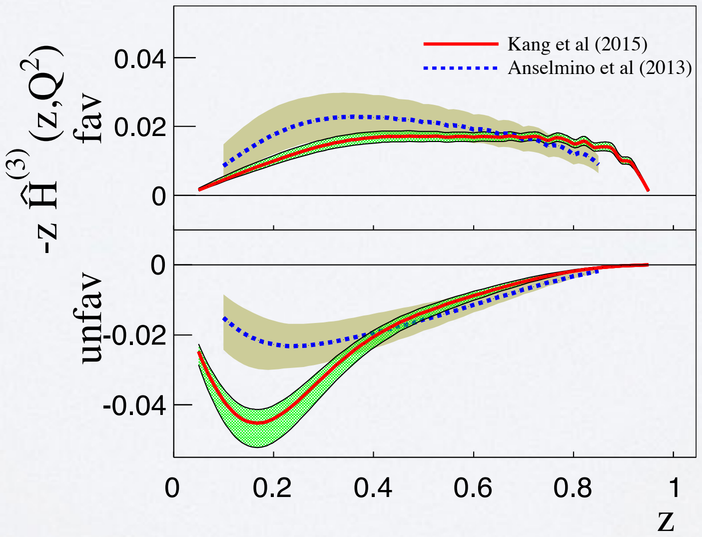
🟩 **Kang** et al., *P.R. D**93** (16) 014009*

▨ **Anselmino** et al., *P.R. D**87** (13) 094019*

very compatible
no sensitivity to evolution



Collins function



$$-z\hat{H}^{(3)}(z) = \frac{1}{2m_h} H_1^{\perp(1)}(z)$$

Transversity from Collins effect

🟩 **Kang** et al.,
*P.R. D**93** (16) 014009*

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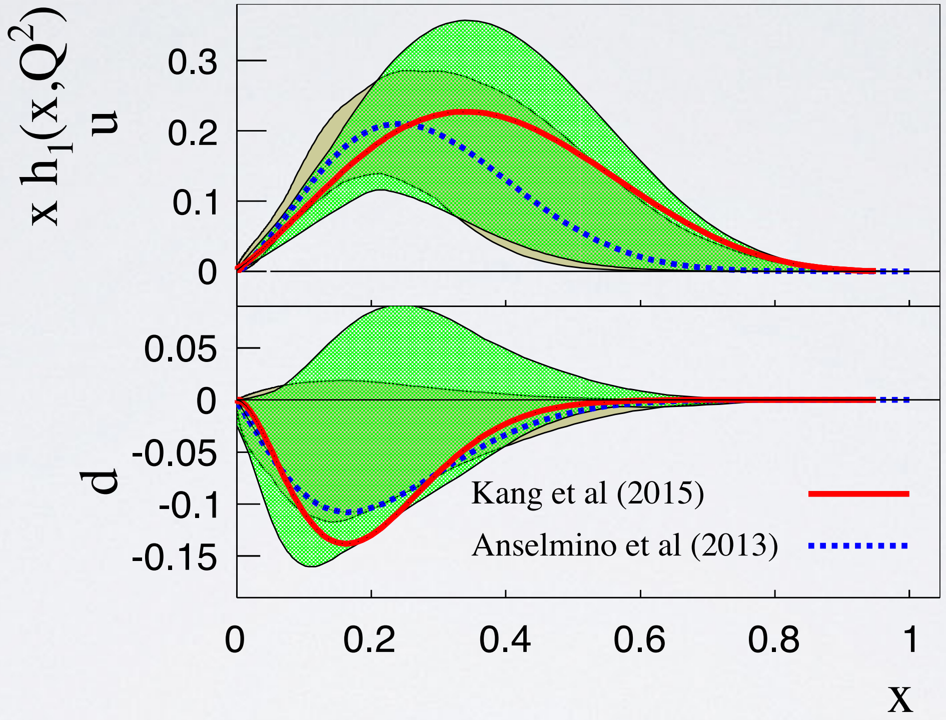
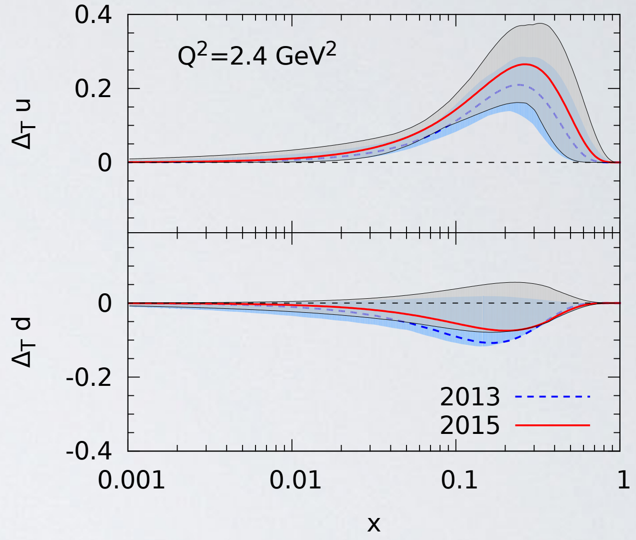


recently updated

Anselmino et al.,
*P.R. D**92** (15) 114023*



Collins function

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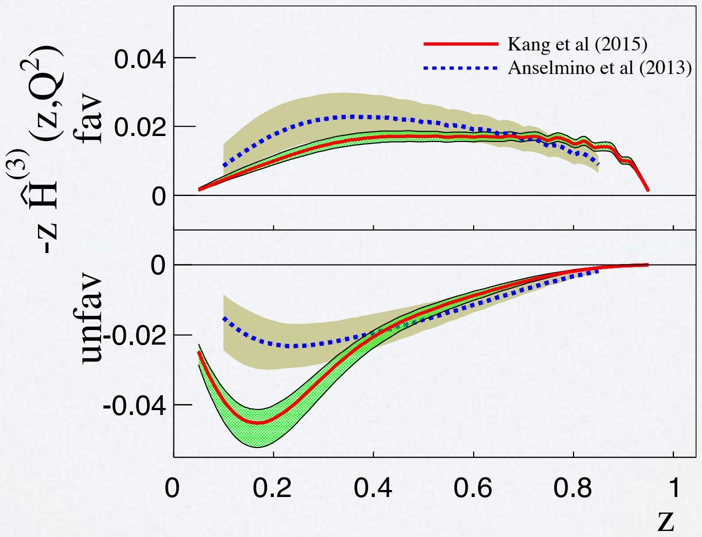

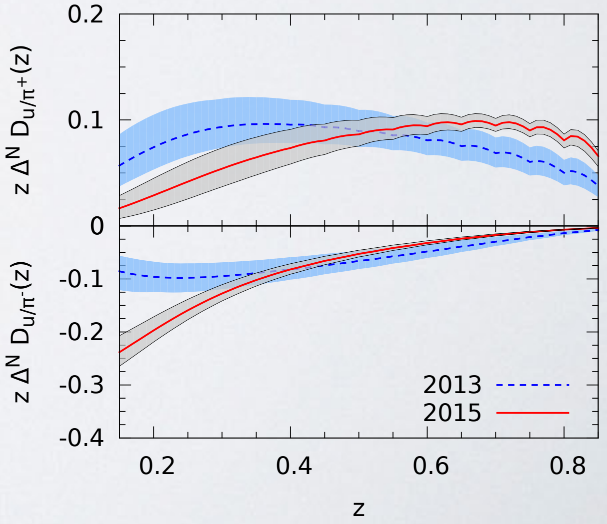

Transversity from Collins effect

🟩 **Kang** et al.,
*P.R. D**93** (16) 014009*

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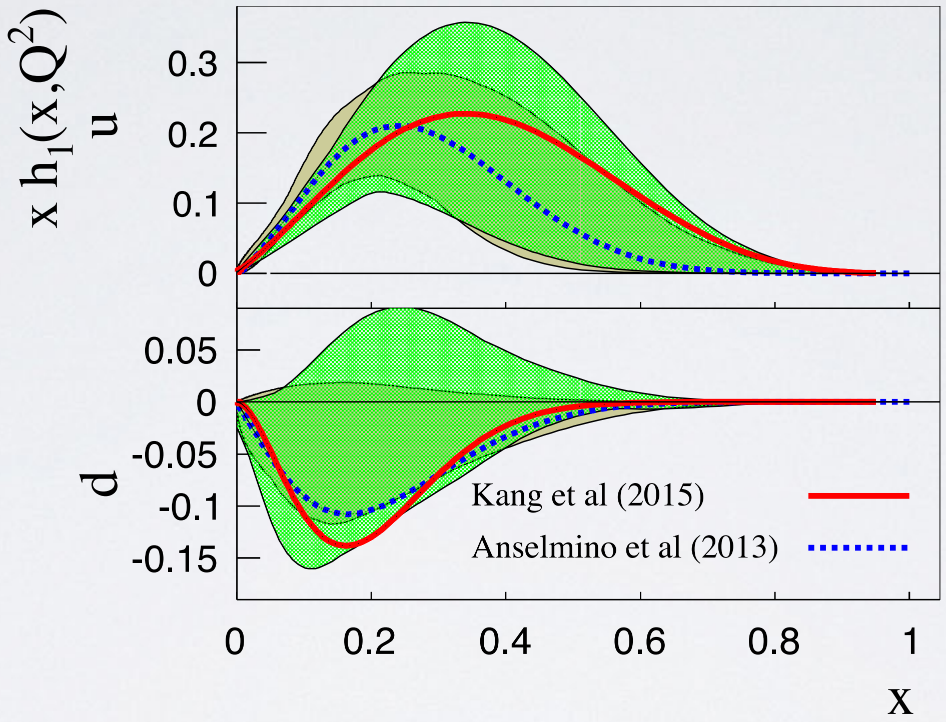
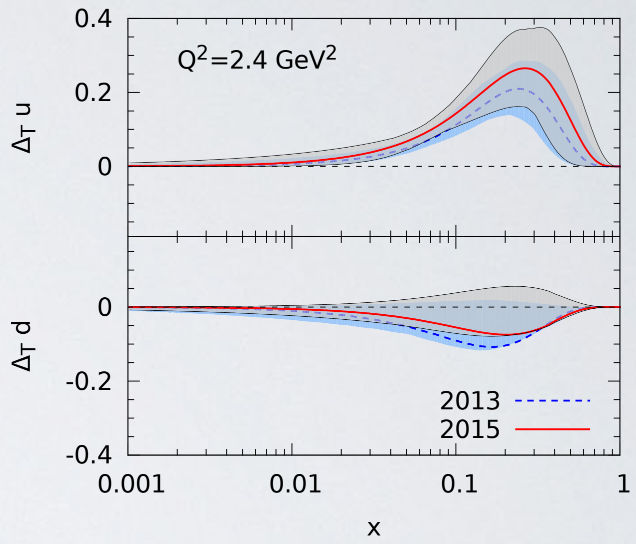
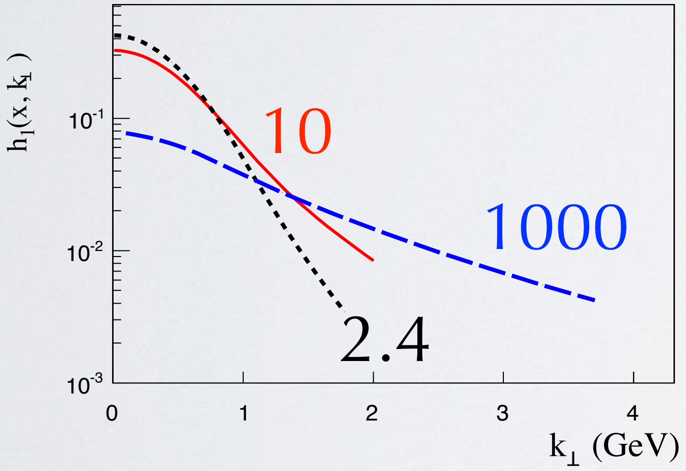


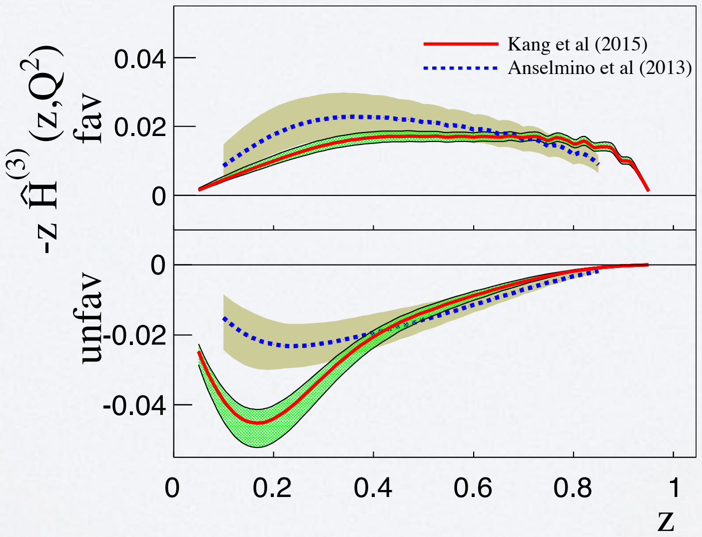


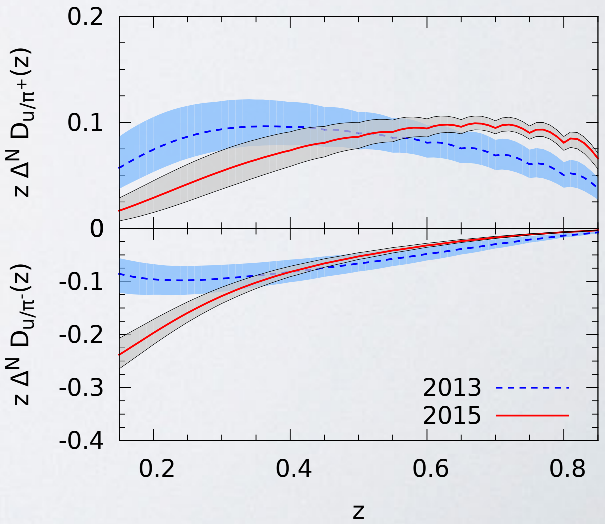
$k_\perp$ spread with Q^2



$$-z\hat{H}^{(3)}(z) = \frac{1}{2m_h} H_1^{\perp(1)}(z)$$

Collins function



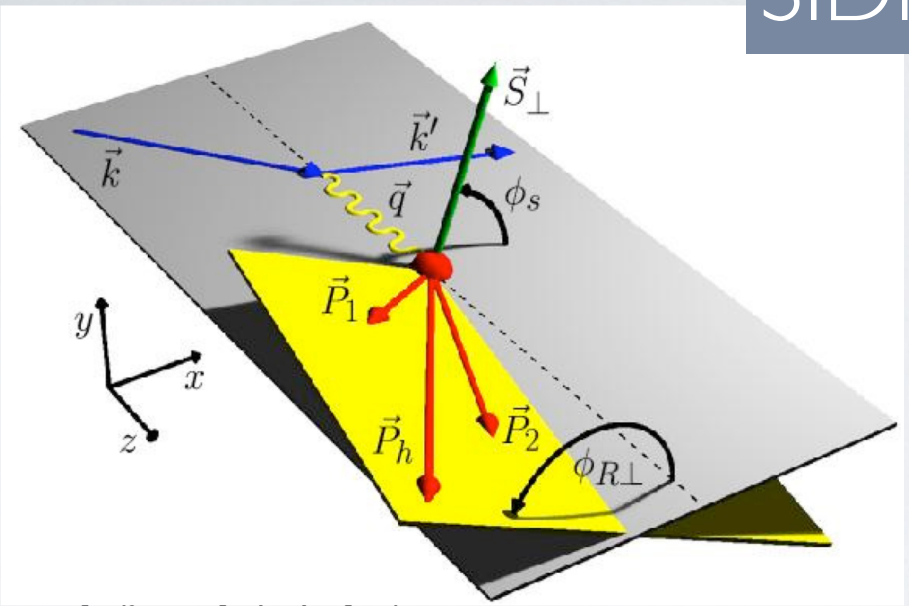


di-hadron fragmentation

*Radici, Jakob, Bianconi, P.R. D**65** (02) 074031*
*Bacchetta & Radici, P.R. D**67** (03) 094002*

SIDIS

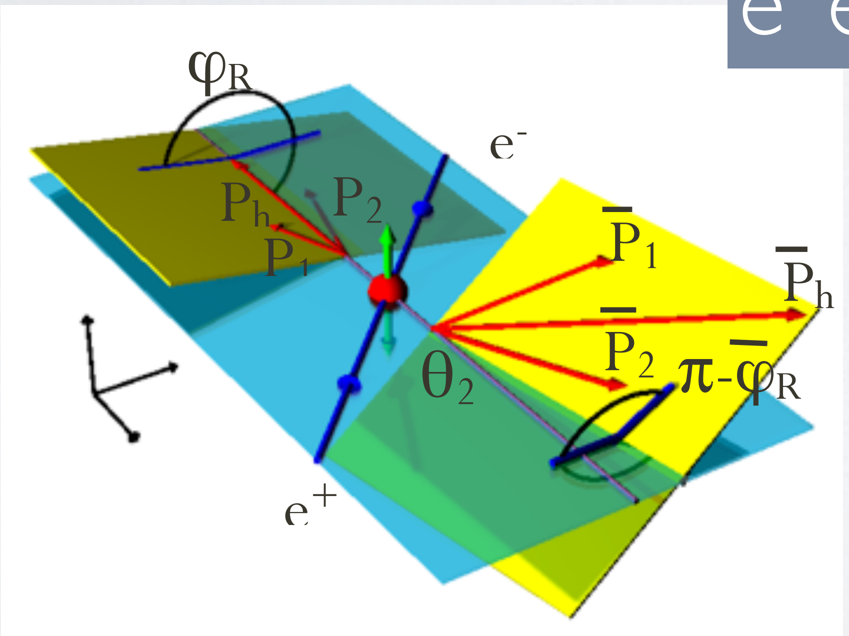
$e\, p^{\uparrow} \to e' \, (\pi,\pi)\, X$



$$A^{\sin(\phi_R+\phi_S)}_{\text{SIDIS}}(x,z,M_h^2) \sim -\frac{\sum_q e_q^2\ h_1^q(x)\ \frac{|\boldsymbol{R}_T|}{M_h}\, H_{1,q}^{\sphericalangle}(z,M_h^2)}{\sum_q e_q^2\ f_1^q(x)\ D_{1,q}(z,M_h^2)}$$

e^+e^-

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



$$A^{\cos(\phi_R+\bar{\phi}_R)}_{e^+e^-}(z,M_h^2,\bar{z},\bar{M}_h^2) = \frac{\sin^2\theta_2}{1+\cos^2\theta_2}$$

$$\times\ \frac{\sum_q e_q^2\ \frac{|\boldsymbol{R}_T|}{M_h}\, H_{1,q}^{\sphericalangle}(z,M_h^2)\ \frac{|\bar{\boldsymbol{R}}_T|}{\bar{M}_h}\, H_{1,\bar{q}}^{\sphericalangle}(\bar{z},\bar{M}_h^2)}{\sum_q e_q^2\ D_{1,q}(z,M_h^2)\ D_{1,\bar{q}}(\bar{z},\bar{M}_h^2)}$$

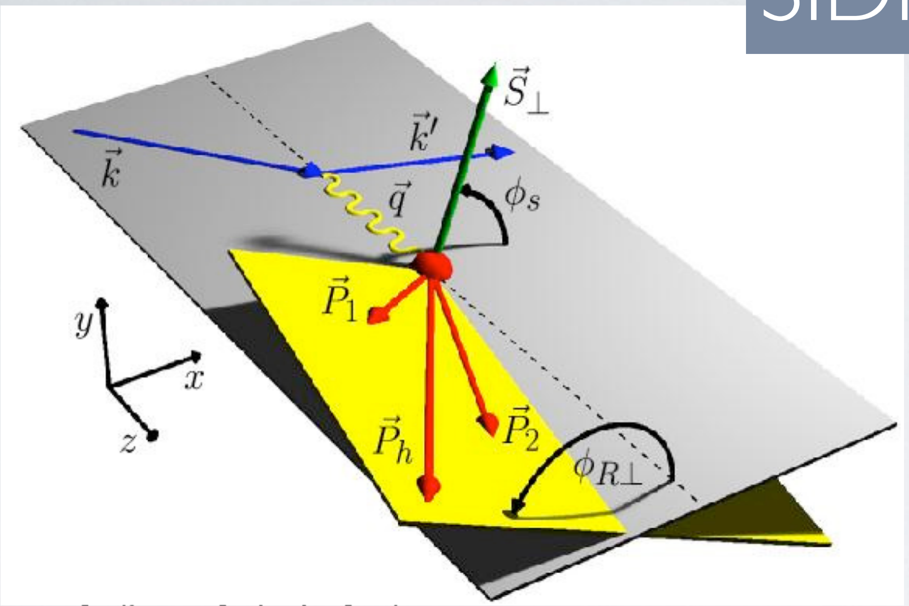
*Artru & Collins, Z.Ph. C**69** (96) 277*
*Boer, Jakob, Radici, P.R. D**67** (03) 094003*

di-hadron fragmentation

*Radici, Jakob, Bianconi, P.R. D**65** (02) 074031*
*Bacchetta & Radici, P.R. D**67** (03) 094002*

SIDIS

$e\, p^{\uparrow} \rightarrow e'\, (\pi,\pi)\, X$



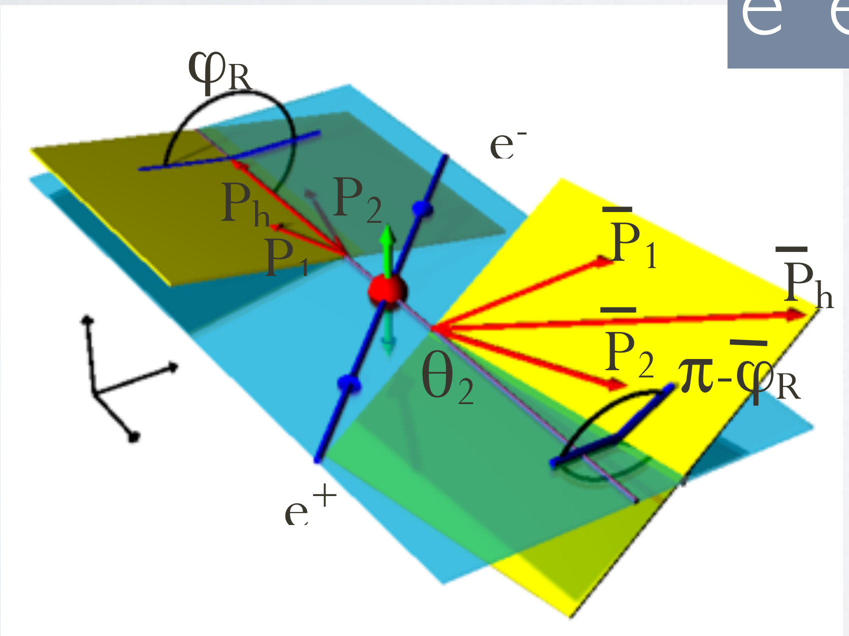
$$A_{\rm SIDIS}^{\sin(\phi_R+\phi_S)}(x,z,M_h^2) \sim -\frac{\sum_q e_q^2\; h_1^q(x)\; \frac{|\boldsymbol{R}_T|}{M_h}\; H_{1,q}^{\triangleleft}(z,M_h^2)}{\sum_q e_q^2\; f_1^q(x)\; D_{1,q}(z,M_h^2)}$$

DGLAP evolution

no convolution simple products

e^+e^-

$e^+\, e^- \rightarrow (\pi^+\pi^-)\, (\pi^+\pi^-)\, X$



$$A_{e^+e^-}^{\cos(\phi_R+\bar{\phi}_R)}(z,M_h^2,\bar{z},\bar{M}_h^2) = \frac{\sin^2\theta_2}{1+\cos^2\theta_2}$$

$$\times\;\frac{\sum_q e_q^2\; \frac{|\boldsymbol{R}_T|}{M_h}\; H_{1,q}^{\triangleleft}(z,M_h^2)\; \frac{|\bar{\boldsymbol{R}}_T|}{\bar{M}_h}\; H_{1,\bar{q}}^{\triangleleft}(\bar{z},\bar{M}_h^2)}{\sum_q e_q^2\; D_{1,q}(z,M_h^2)\; D_{1,\bar{q}}(\bar{z},\bar{M}_h^2)}$$

*Artru & Collins, Z.Ph. C**69** (96) 277*
*Boer, Jakob, Radici, P.R. D**67** (03) 094003*

chiral-odd DiFF as quark spin analyzer

Collins, Heppelman, Ladinsky, N.P. ***B420*** *(94)*

It is ≠ 0 even if we integrate over
the pair total transverse momentum $\int d(\boldsymbol{P}_{h1T} + \boldsymbol{P}_{h2T})$
(equivalent to take $P_{h1}+P_{h2}$ ‖ quark, as in figure)
quark polarization connected to $2\boldsymbol{R}_T = \boldsymbol{P}_{h1T} - \boldsymbol{P}_{h2T}$
(only if $h_1 \neq h_2$)

effect encoded in chiral-odd $H_1^{\sphericalangle}(z, M_h^2)$
with $z=z_1+z_2$ and pair invariant mass M_h (<-> $|\boldsymbol{R}_T|$)

extraction of DiFF

extract DiFF from

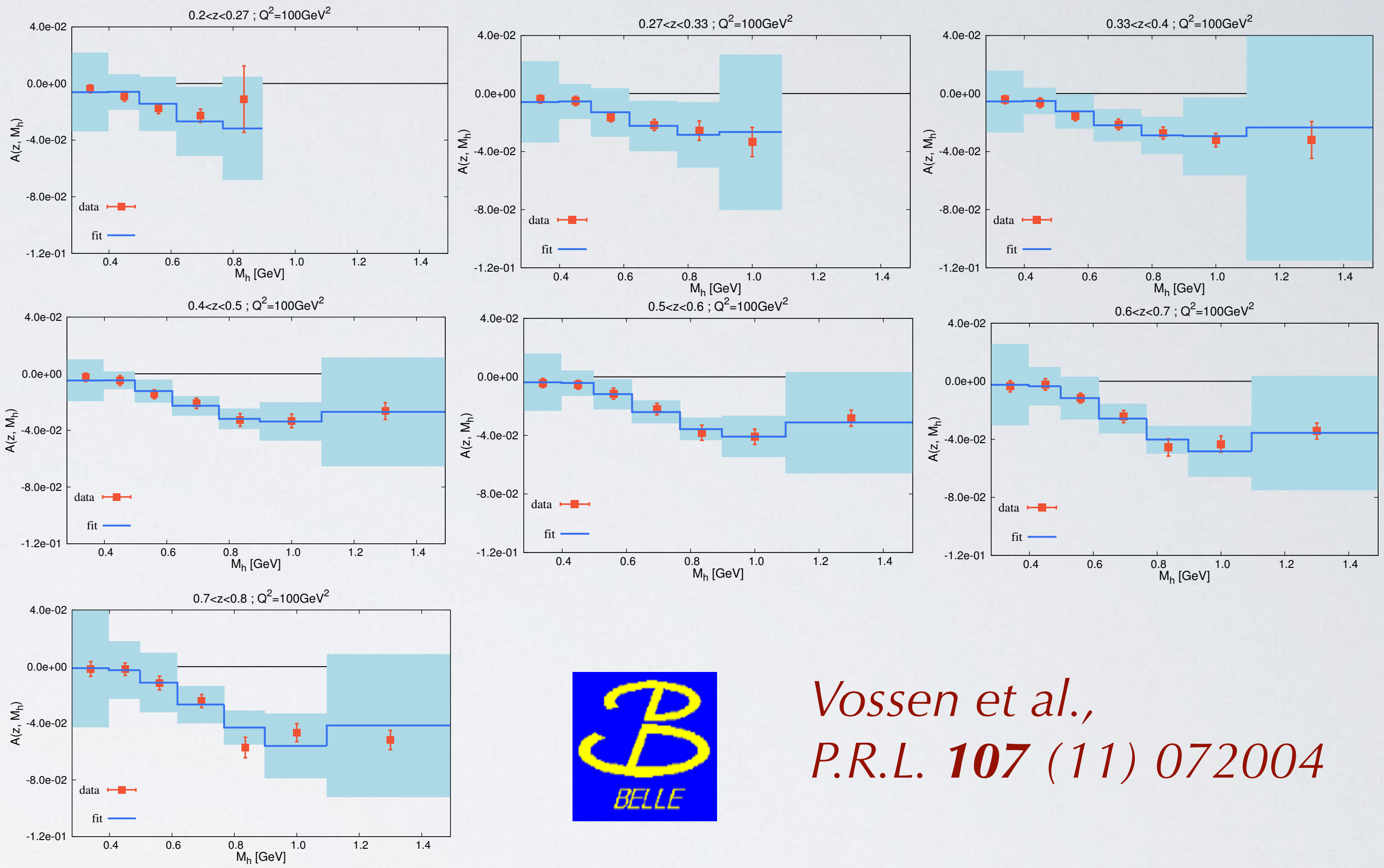
$e^+ e^- \to (\pi^+\pi^-)\ (\pi^+\pi^-)\ X$

46 bins in (z, M_h)

9 parameters

χ^2/d.o.f. = 0.57

*Courtoy et al., P.R. D**85** (12) 114023*



Vossen et al.,
*P.R.L. **107** (11) 072004*

extraction of DiFF

extract DiFF from

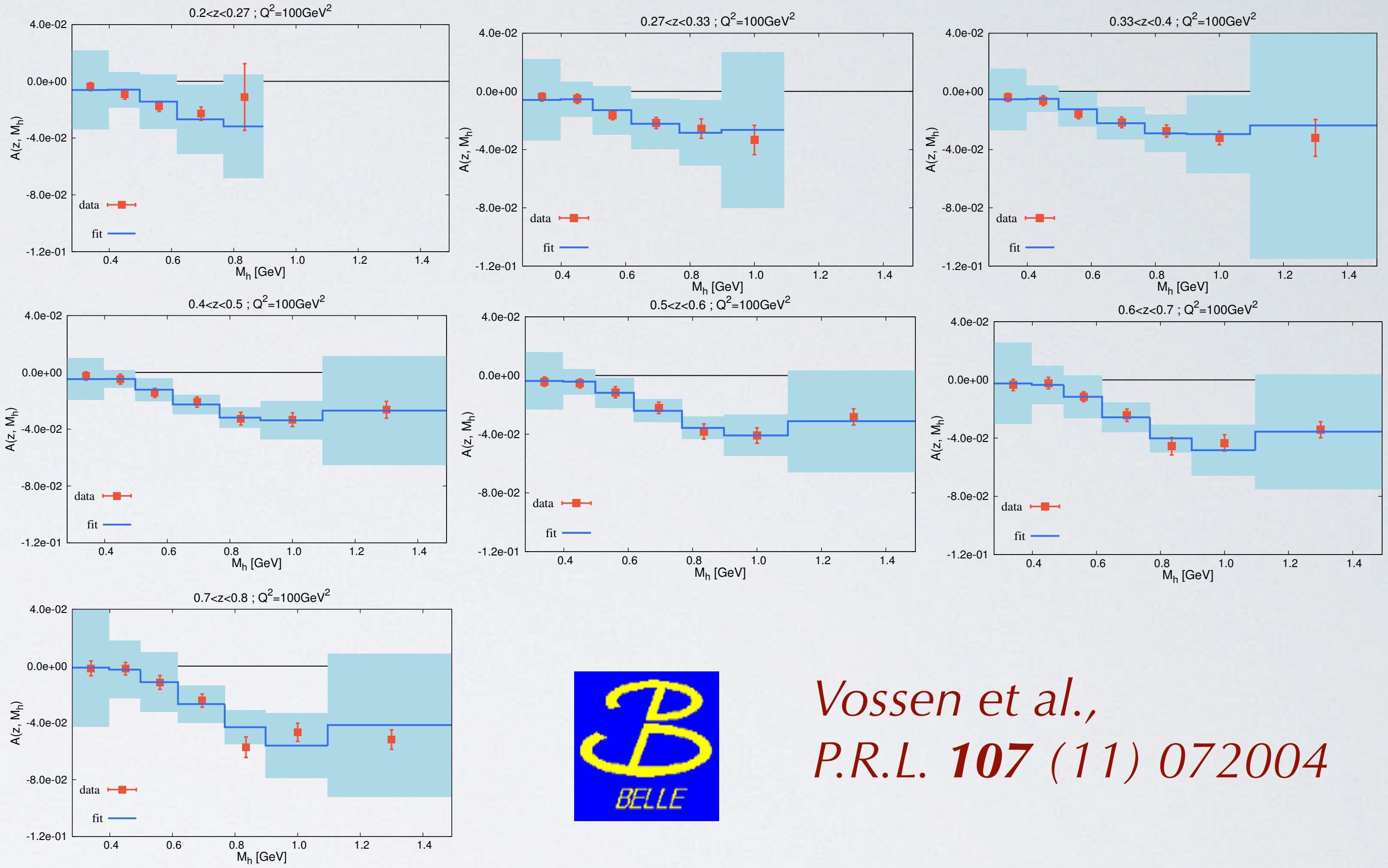
$e^+ e^- \to (\pi^+\pi^-)\ (\pi^+\pi^-)\ X$

46 bins in (z, M_h)

9 parameters

$\chi^2/\mathrm{d.o.f.} = 0.57$

*Courtoy et al., P.R. D**85** (12) 114023*



*Vossen et al., P.R.L. **107** (11) 072004*

Limitations

- no unpolarized data for D_1

  need multiplicities for $e^+e^- \to (\pi^+\pi^-)\ X$

  $e\ p \to e'\ (\pi^+\pi^-)\ X$

- little sensitivity to gluon $D_1{}^g$

- no data for $z < 0.2$

- approach valid for $M_h \ll Q$

DiFF and transversity : the Pavia extraction

$$A_{\mathrm{SIDIS}}^{\sin(\phi_R+\phi_S)}(x,z,M_h^2) \sim -\frac{\sum_q e_q^2\ h_1^q(x)\ \frac{|\boldsymbol{R}_T|}{M_h}\ H_{1,q}^{\sphericalangle}(z,M_h^2)}{\sum_q e_q^2\ f_1^q(x)\ D_{1,q}(z,M_h^2)}$$

x-dep. of SSA given by PDFs only

DiFF and transversity : the Pavia extraction

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x-dep. of SSA given by PDFs only

$$n_q^{\uparrow} = \int dz \int dM_h^2\, \frac{|\mathbf{R}|}{M_h}\, H_{1,sp}^{\sphericalangle\, q}(z,M_h^2)$$

$$n_q = \int dz \int dM_h^2\, D_1^q(z,M_h^2)$$

$$n_q = n_{\bar{q}} \qquad n_q^{\uparrow} = -n_{\bar{q}}^{\uparrow}$$

$$n_u^{\uparrow} = -n_d^{\uparrow}$$

separate valence u and d

proton

$$x h_1^p(x) \equiv x h_1^{u_v}(x) - \frac{1}{4}\, x h_1^{d_v}(x)$$

$$= -\frac{A(y)}{B(y)}\, \frac{[A_{UT}^{\sin(\phi_R+\phi_S)}]_p}{e_u^2\, n_u^{\uparrow}}\, \frac{9}{4} \sum_{q=u,d,s} e_q^2\, x f_1^{q+\bar{q}}(x)\, n_q$$

deuteron

$$x h_1^D(x) \equiv x h_1^{u_v}(x) + x h_1^{d_v}(x)$$

$$= -\frac{A(y)}{B(y)}\, \frac{[A_{UT}^{\sin(\phi_R+\phi_S)}]_D}{e_u^2\, n_u^{\uparrow}}\, 3 \sum_{q=u,d,s} [e_q^2\, n_q + e_{\tilde{q}}^2\, n_{\tilde{q}}]\, x f_1^{q+\bar{q}}(x)$$

$$\tilde{q} = d, u, s$$

DiFF and transversity : the Pavia extraction

- parametrization at $Q_0^2 = 1$ GeV^2

$$xh_1^{q_v}(x) = \tanh\left[\sqrt{x}\,\left(A_q + B_q x + C_q x^2 + D_q x^3\right)\right]\,\left[x\,\mathrm{SB}_q(x) + x\,\overline{\mathrm{SB}}_{\bar{q}}(x)\right]$$

satisfies **S**offer **B**ound at any Q^2

$$2|h_1^q(x,Q^2)| \leq 2\,\mathrm{SB}_q(x) = |f_1^q(x) + g_1^q(x)|$$

DiFF and transversity : the Pavia extraction

- parametrization at $Q_0^2 = 1$ GeV^2

$$xh_1^{q_v}(x) = \tanh\left[\sqrt{x}\,\left(A_q + B_q x + C_q x^2 + D_q x^3\right)\right]\,\left[x\,\mathrm{SB}_q(x) + x\,\overline{\mathrm{SB}}_{\bar{q}}(x)\right]$$

rigid

satisfies **S**offer **B**ound at any Q^2

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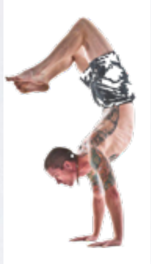
DiFF and transversity : the Pavia extraction

- parametrization at $Q_0^2 = 1$ GeV^2

$$xh_1^{q_v}(x) = \tanh\left[\sqrt{x}\left(A_q + B_q x + C_q x^2 + D_q x^3\right)\right]\left[x\,\mathrm{SB}_q(x) + x\,\overline{\mathrm{SB}}_{\bar{q}}(x)\right]$$

rigid

flexible



satisfies **S**offer **B**ound at any Q^2

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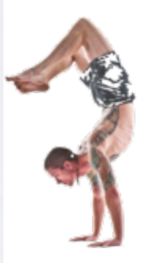
DiFF and transversity : the Pavia extraction

- parametrization at $Q_0^2 = 1\ \mathrm{GeV}^2$

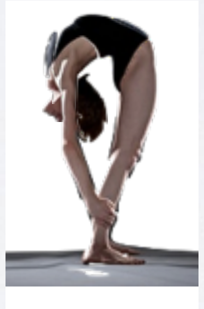
$$xh_1^{q_v}(x) = \tanh\left[\sqrt{x}\left(A_q + B_q x + C_q x^2 + D_q x^3\right)\right]\ \left[x\,\mathrm{SB}_q(x) + x\,\overline{\mathrm{SB}}_{\bar{q}}(x)\right]$$

rigid

flexible



extra-flexible



satisfies **S**offer **B**ound at any Q^2

$$2|h_1^q(x,Q^2)| \leq 2\ \mathrm{SB}_q(x) = |f_1^q(x) + g_1^q(x)|$$

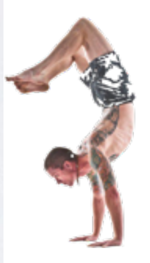
DiFF and transversity : the Pavia extraction

- parametrization at $Q_0^2 = 1\ \mathrm{GeV}^2$

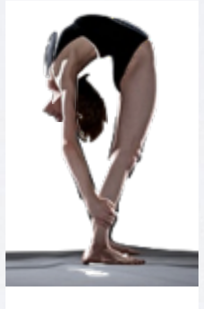
$$xh_1^{q_v}(x) = \tanh\left[\sqrt{x}\left(A_q + B_q x + C_q x^2 + D_q x^3\right)\right]\ \left[x\,\mathrm{SB}_q(x) + x\,\overline{\mathrm{SB}}_{\bar{q}}(x)\right]$$

rigid

flexible



extra-flexible



satisfies **S**offer **B**ound at any Q^2

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- 22 SIDIS data from hermes and COMPASS

Airapetian et al.,
JHEP ***0806*** *(08) 017*

Adolph et al.,
P.L. ***B713*** *(12)*

Braun et al.,
E.P.J. Web Conf. ***85*** *(15) 02018*

history of upgrading fits

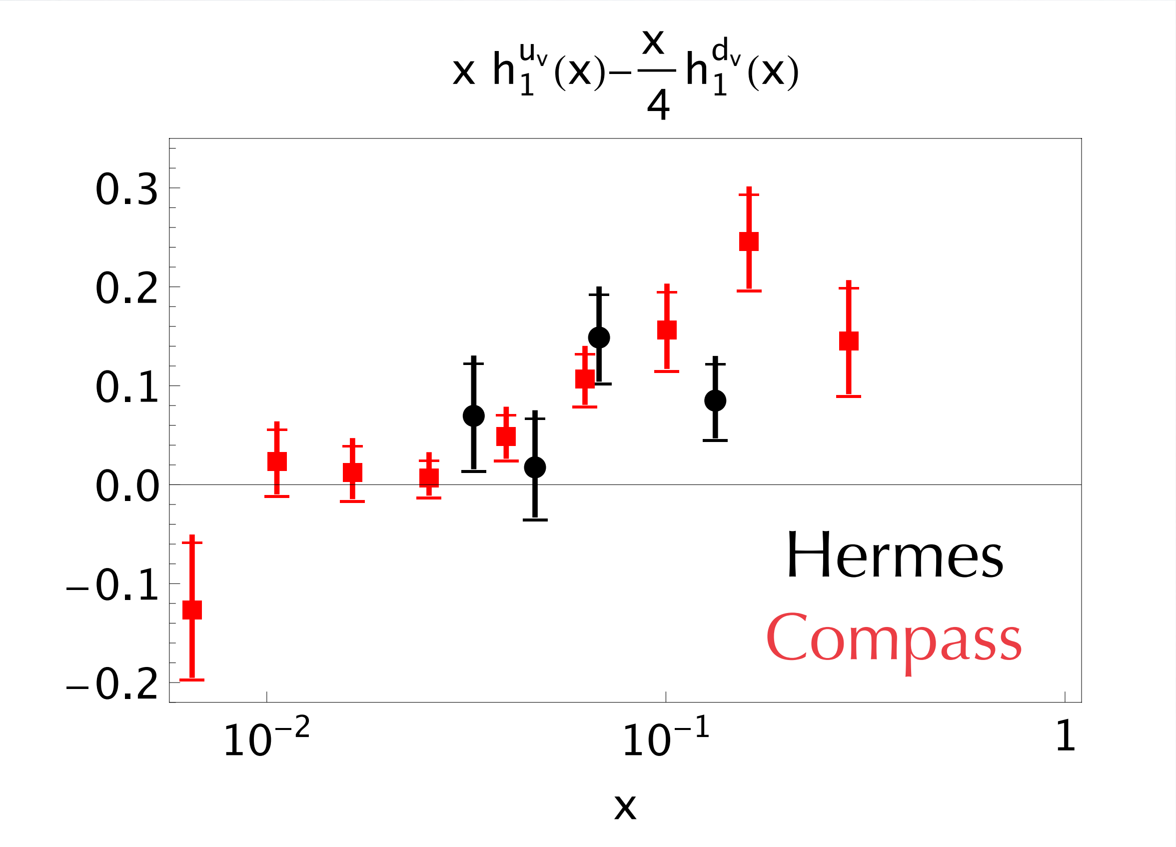
Bacchetta, Courtoy, Radici,
P.R.L. ***107*** *(11) 012001*

Bacchetta, Courtoy, Radici,
JHEP ***1303*** *(13) 119*

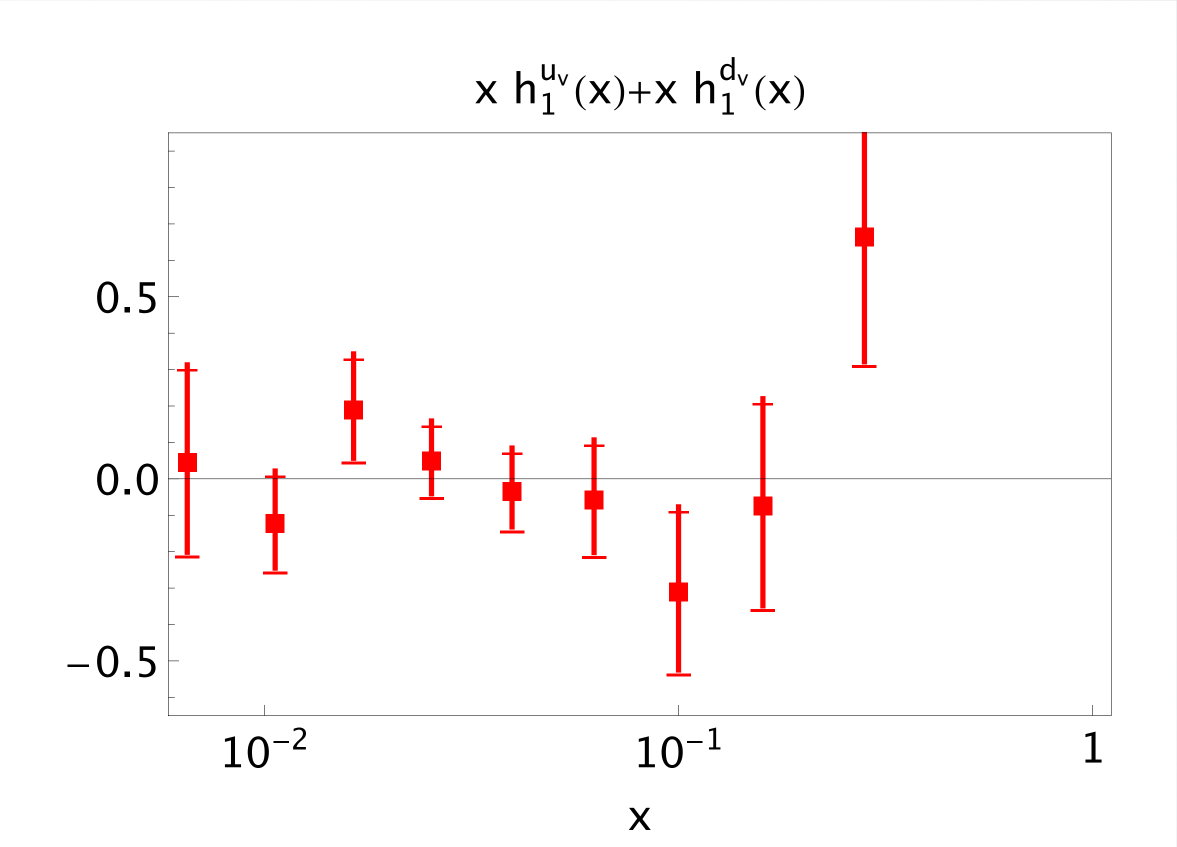
Radici et al.,
JHEP ***1505*** *(15) 123*

error analysis : the replica method

proton



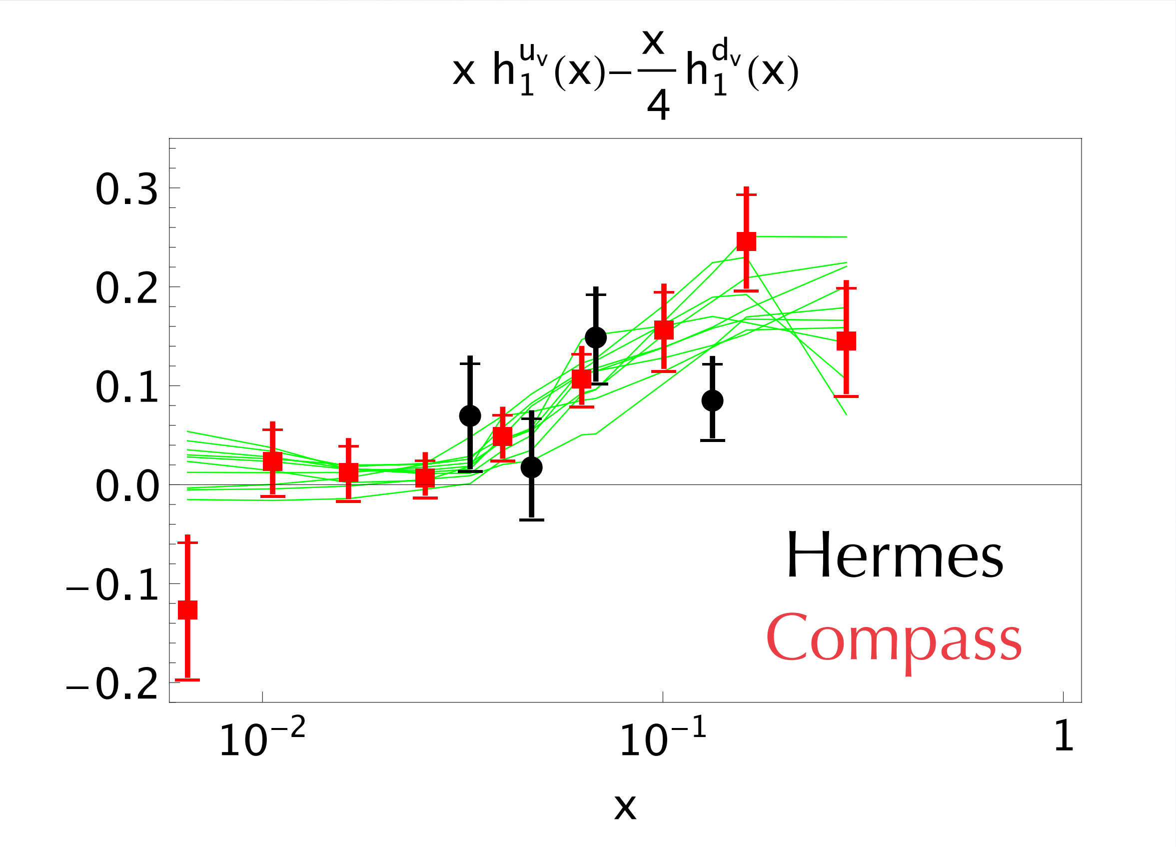
deuteron



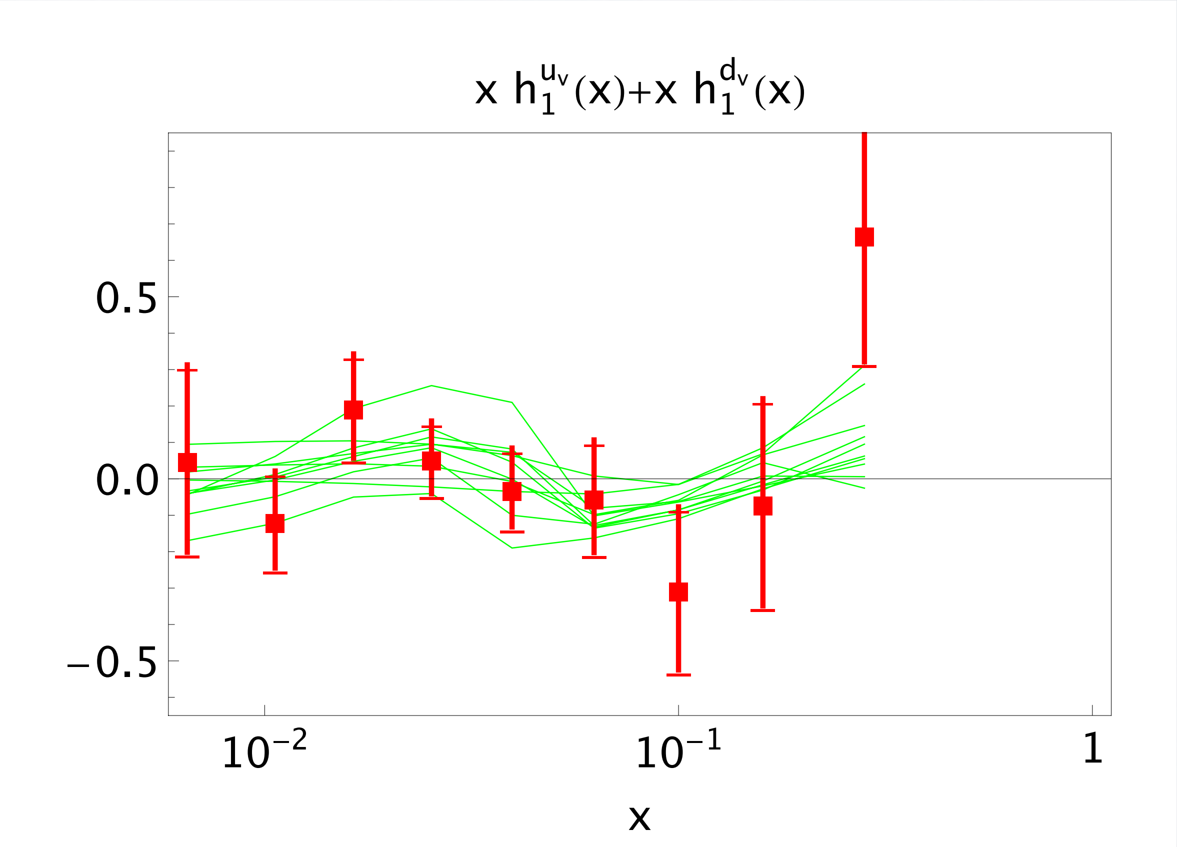
error analysis : the replica method

fit with **10** replica

proton



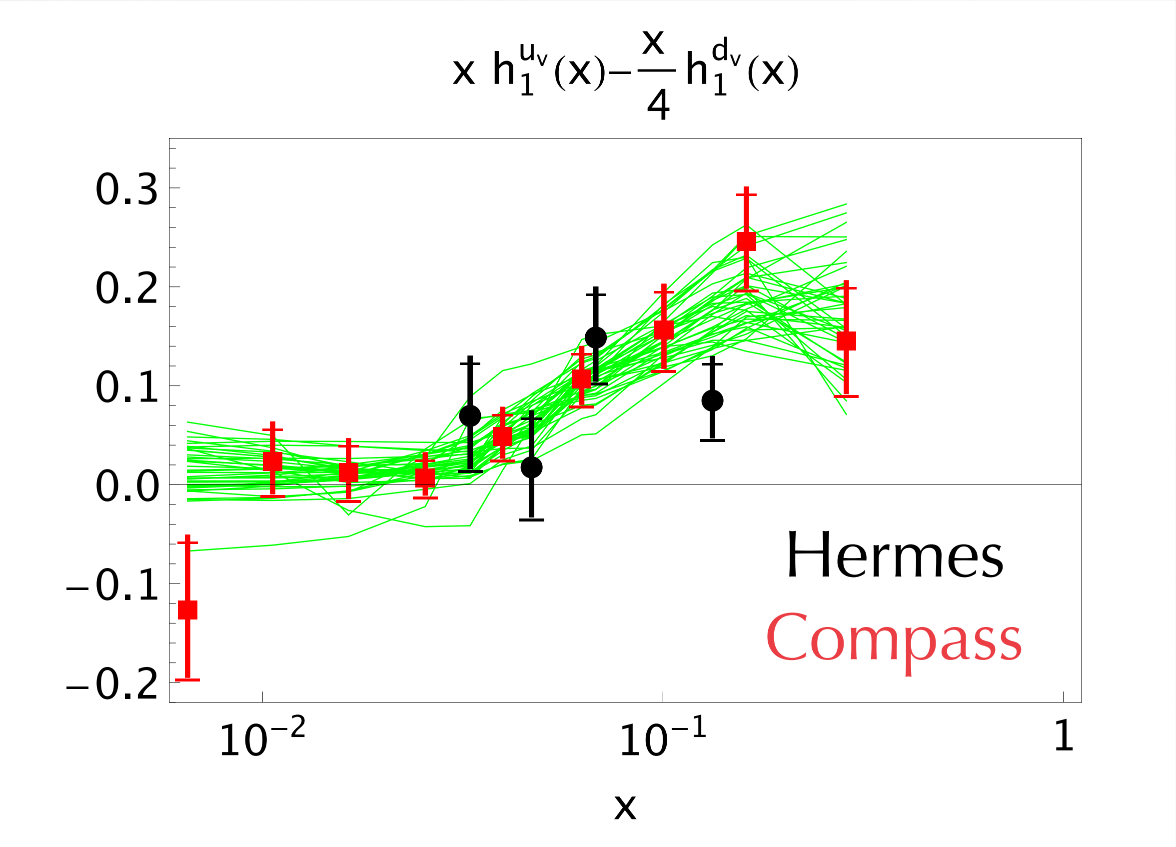
deuteron



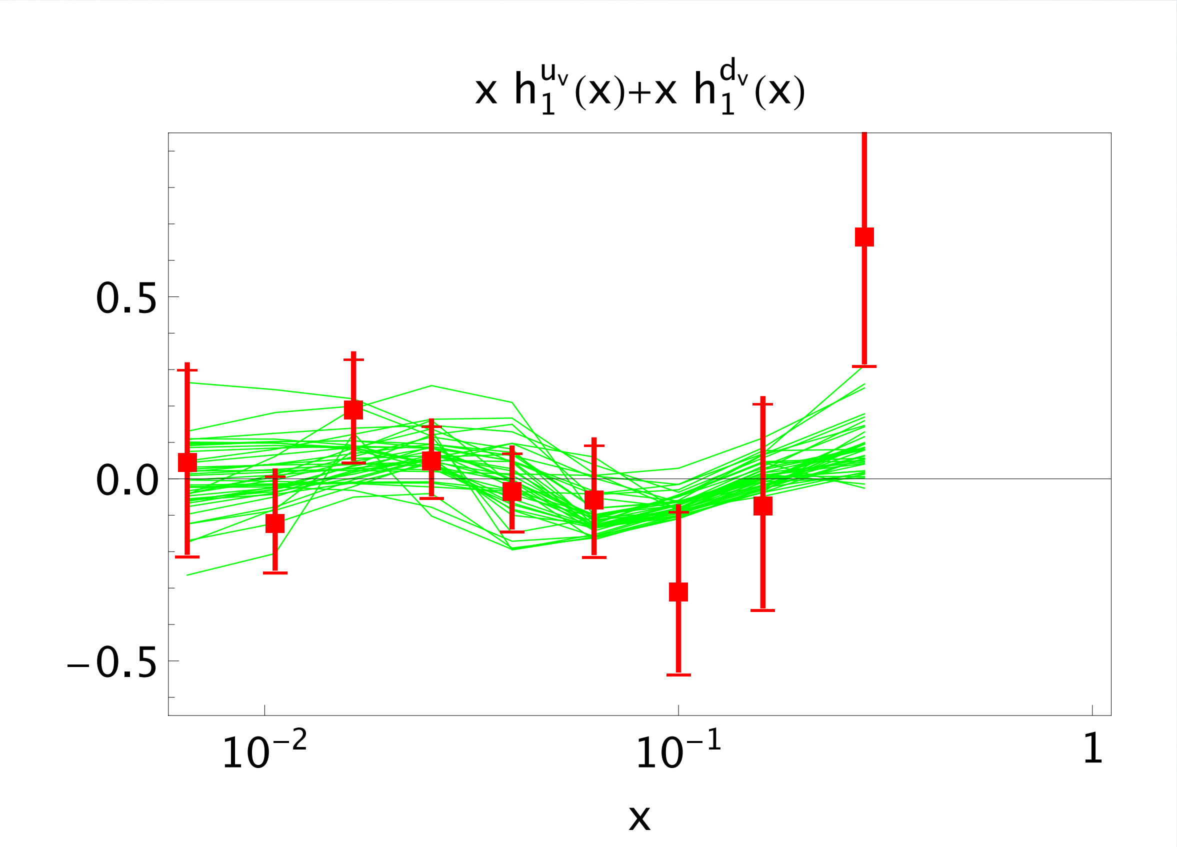
error analysis : the replica method

fit with **40** replica

proton



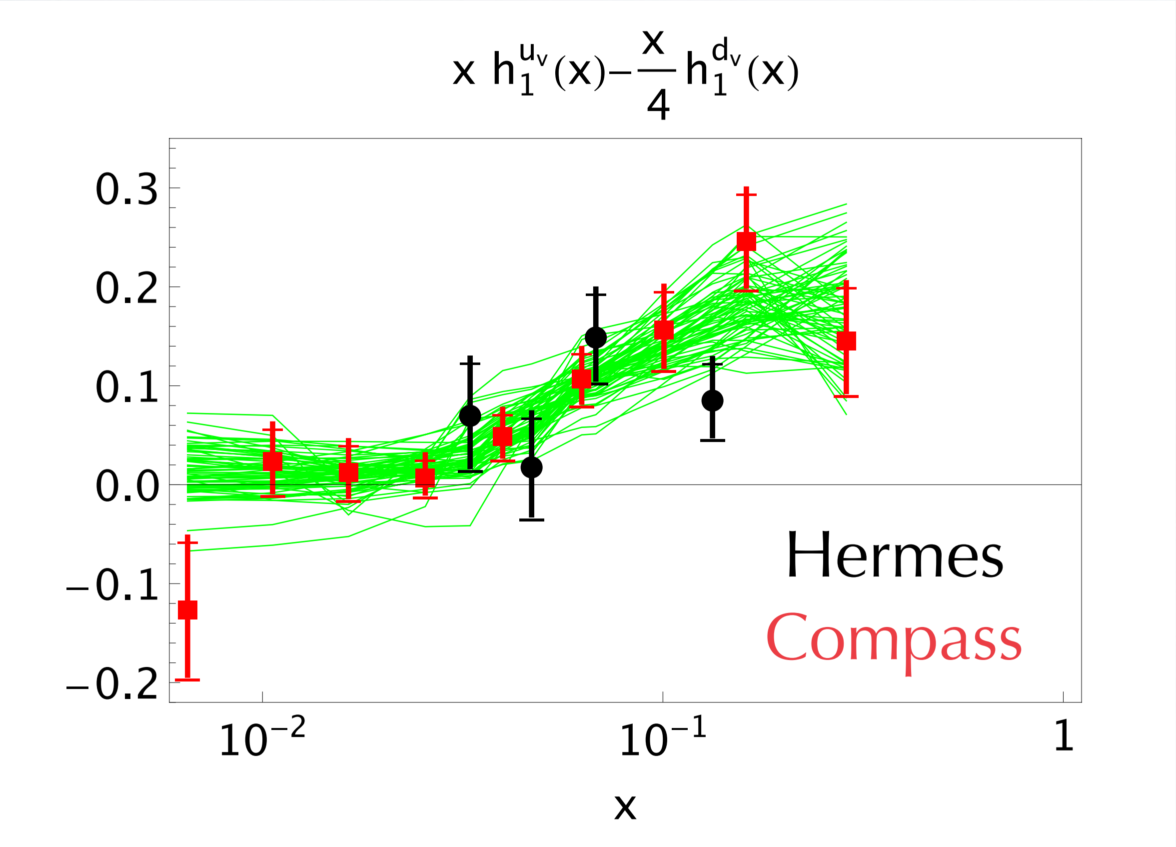
deuteron



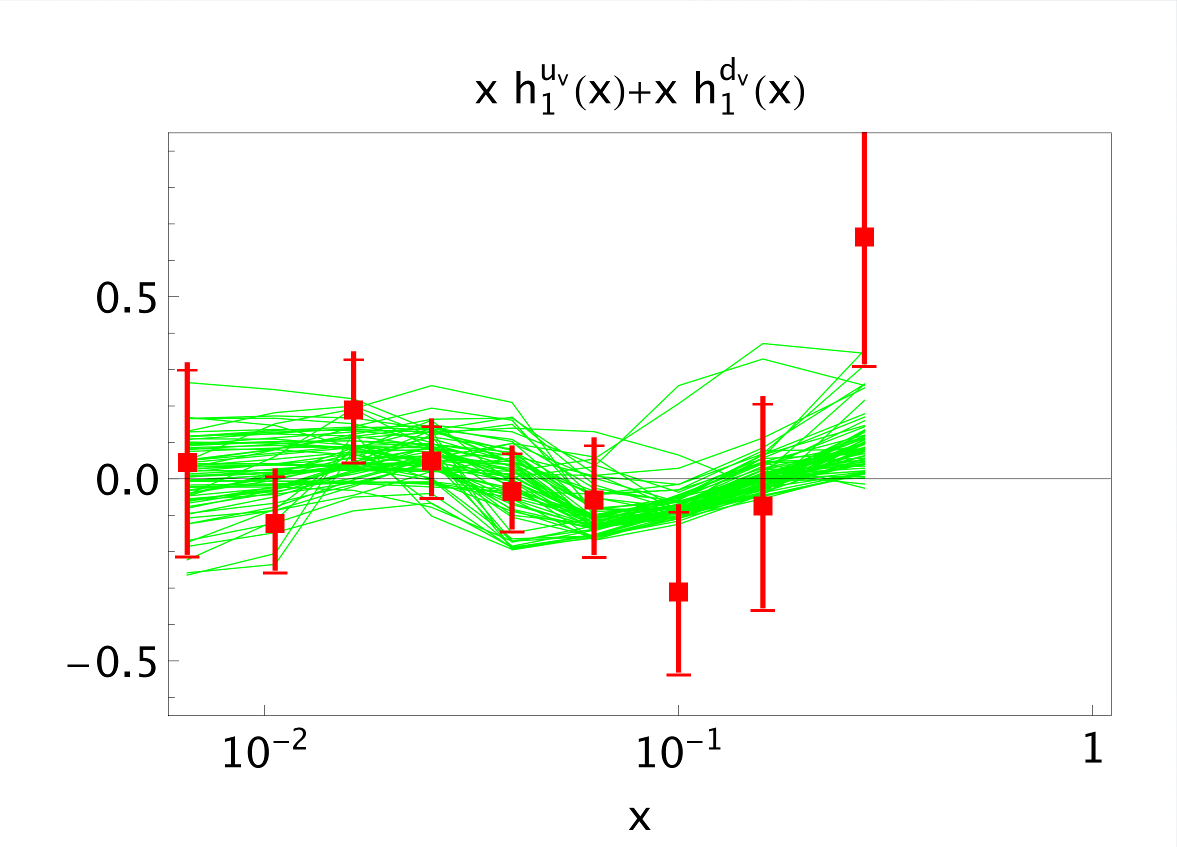
error analysis : the replica method

fit with **70** replica

proton



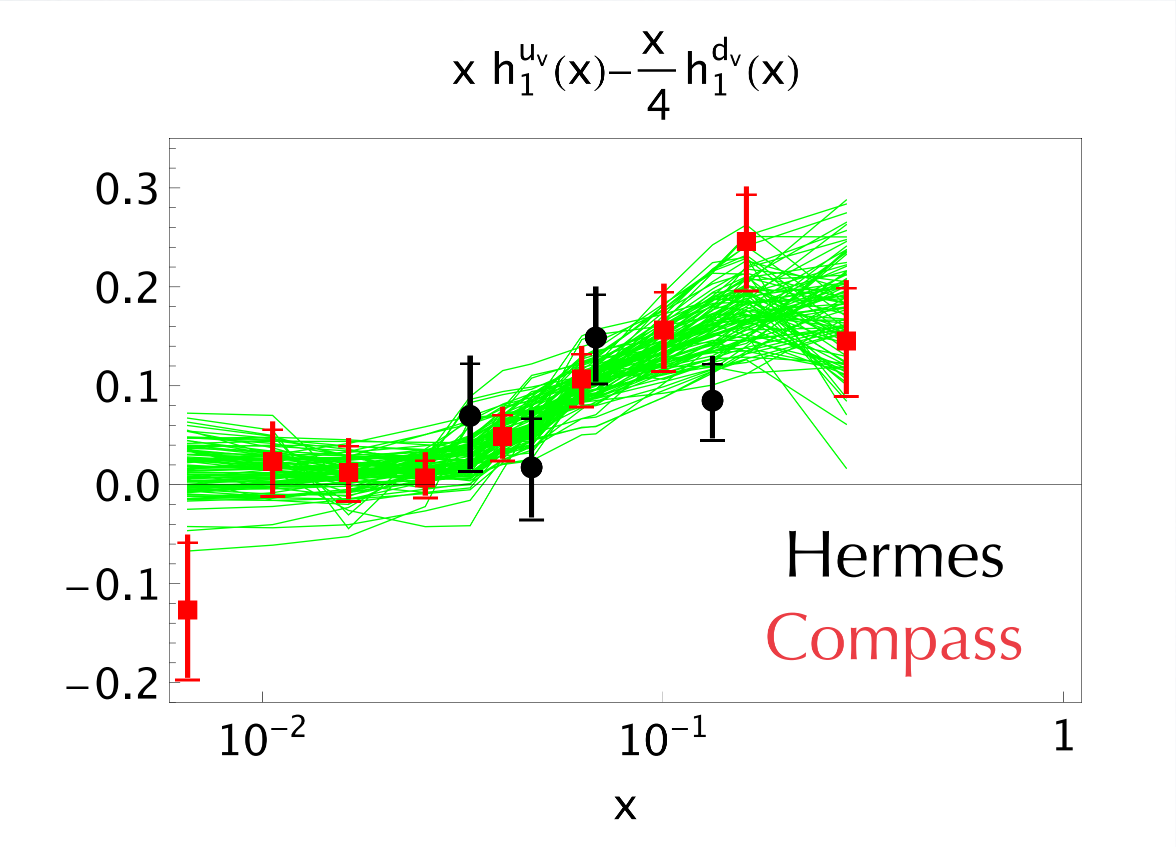
deuteron



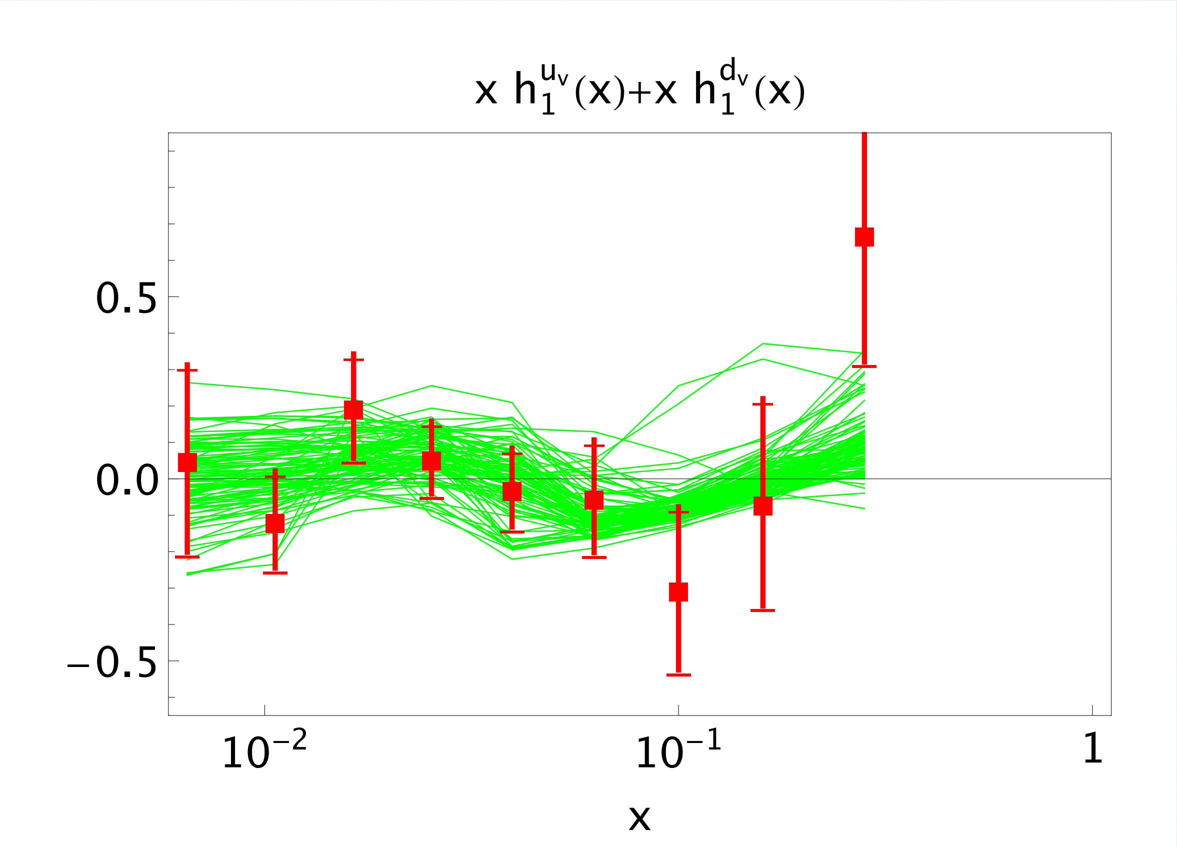
error analysis : the replica method

fit with **100** replica

proton



deuteron

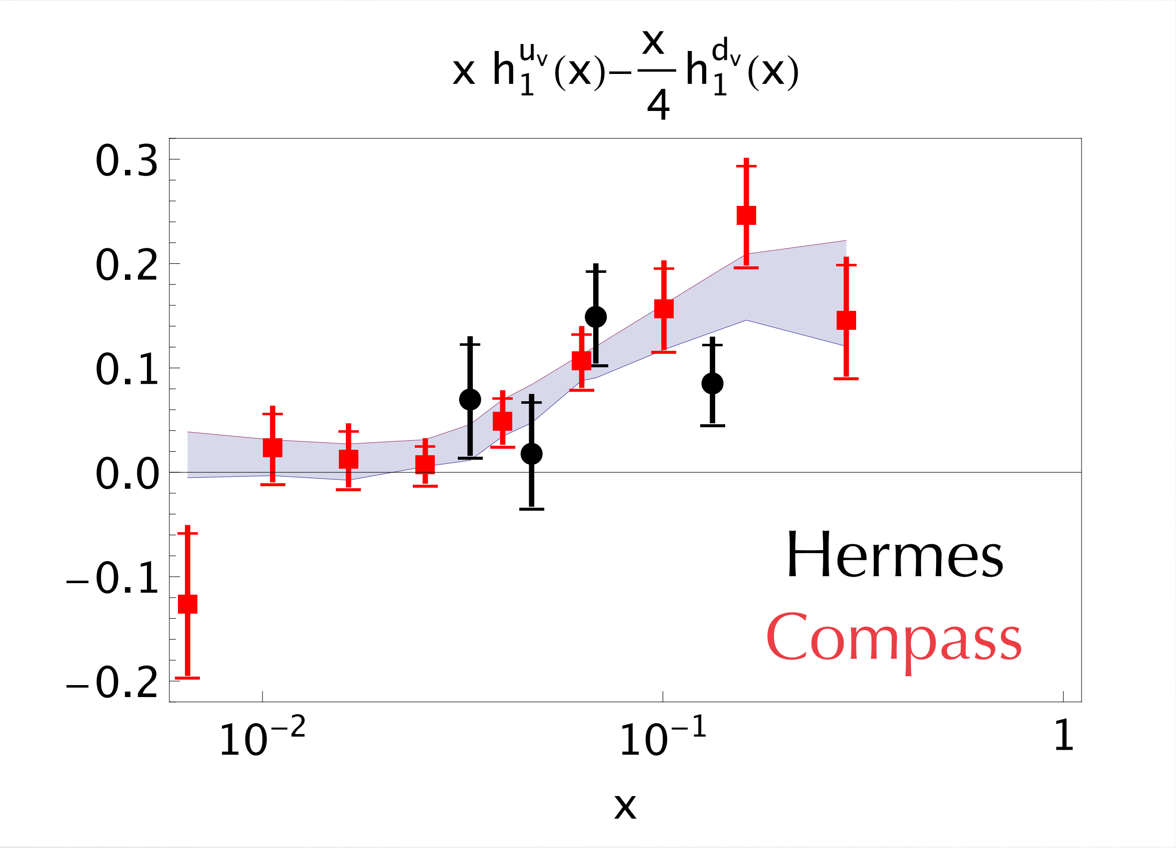


error analysis : the replica method

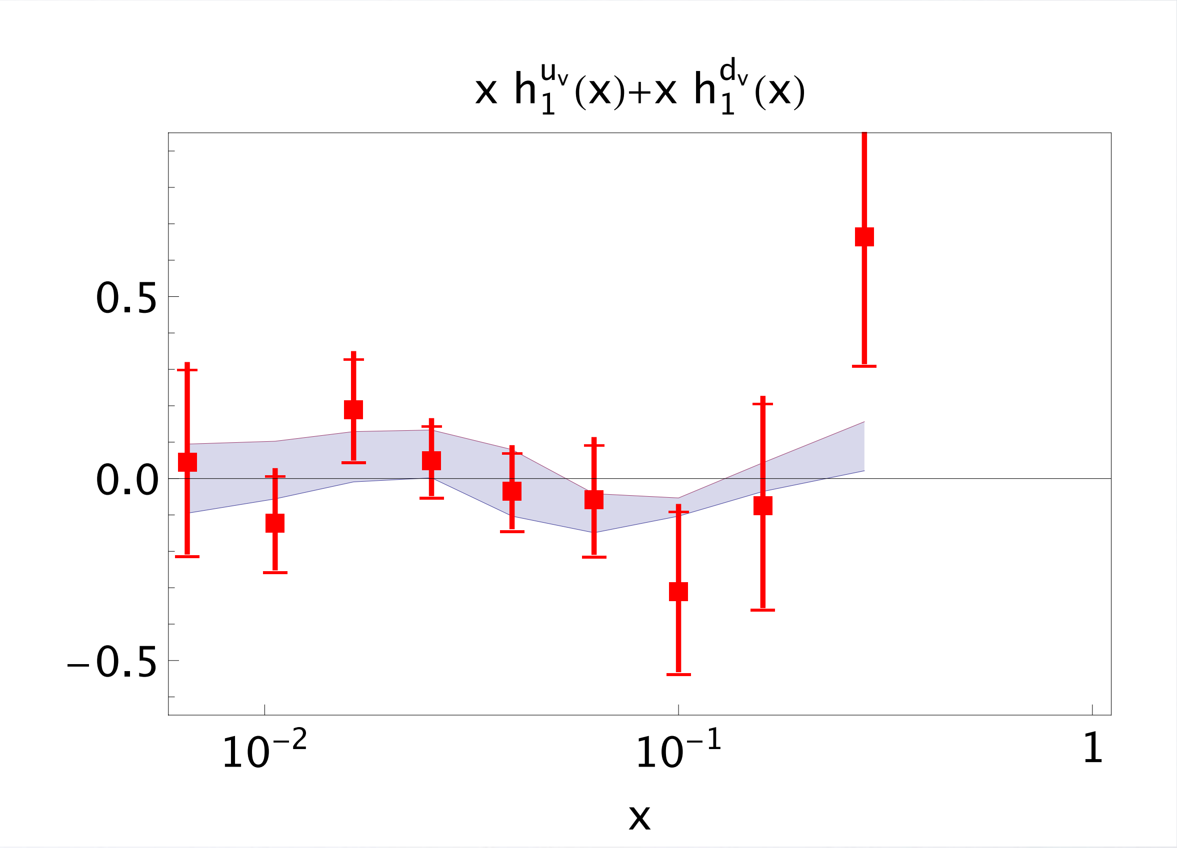
taking the **68%** band

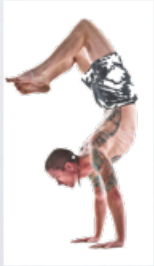
(distribution is not necessarily a Gaussian)

proton



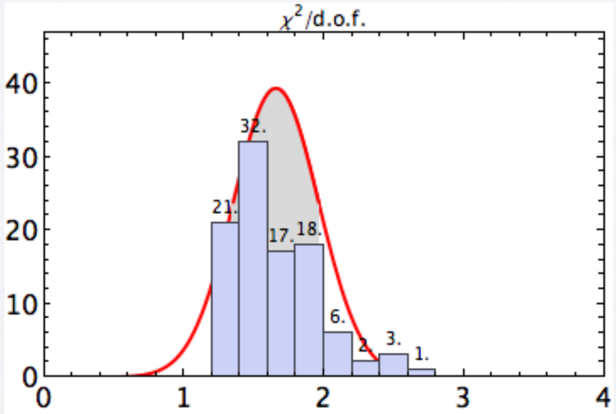
deuteron





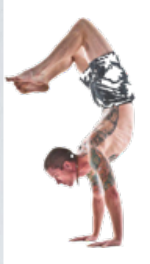
"average"

χ^2/d.o.f. ~ 1.65



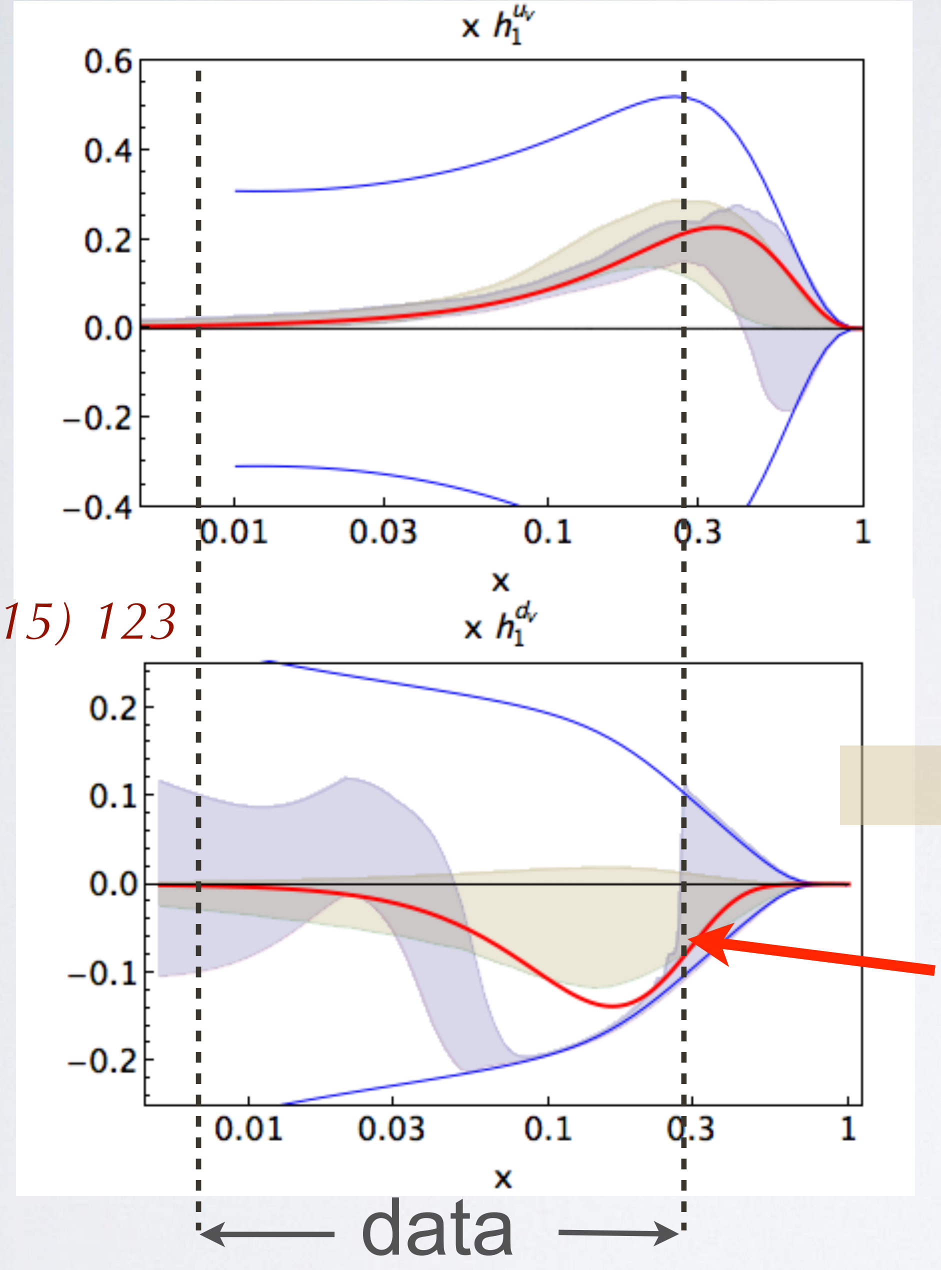
comparison with Collins effect

up

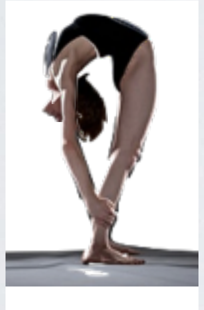


🟦

Radici et al.,
*JHEP **1505** (15) 123*



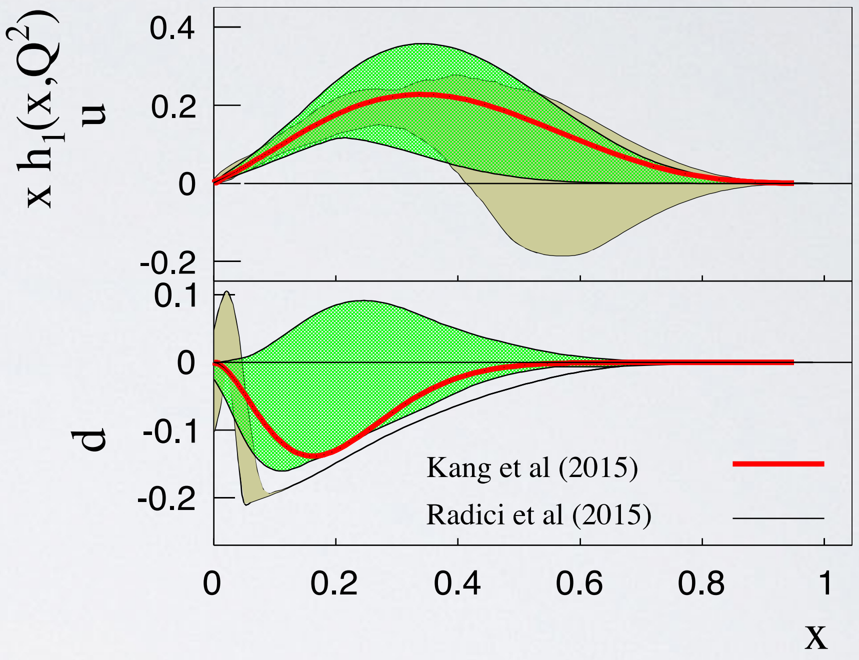
down



🟫 **Anselmino** et al.,
2013

Kang et al.,
2015

Kang et al. 2015 <-> Pavia 2015

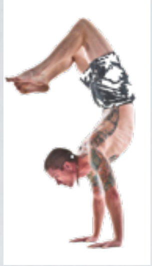


Q^2=2.4 GeV^2

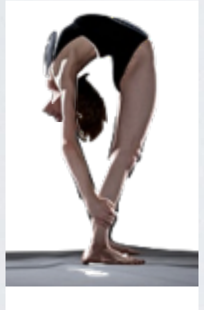
linear
scale

comparison with Collins effect

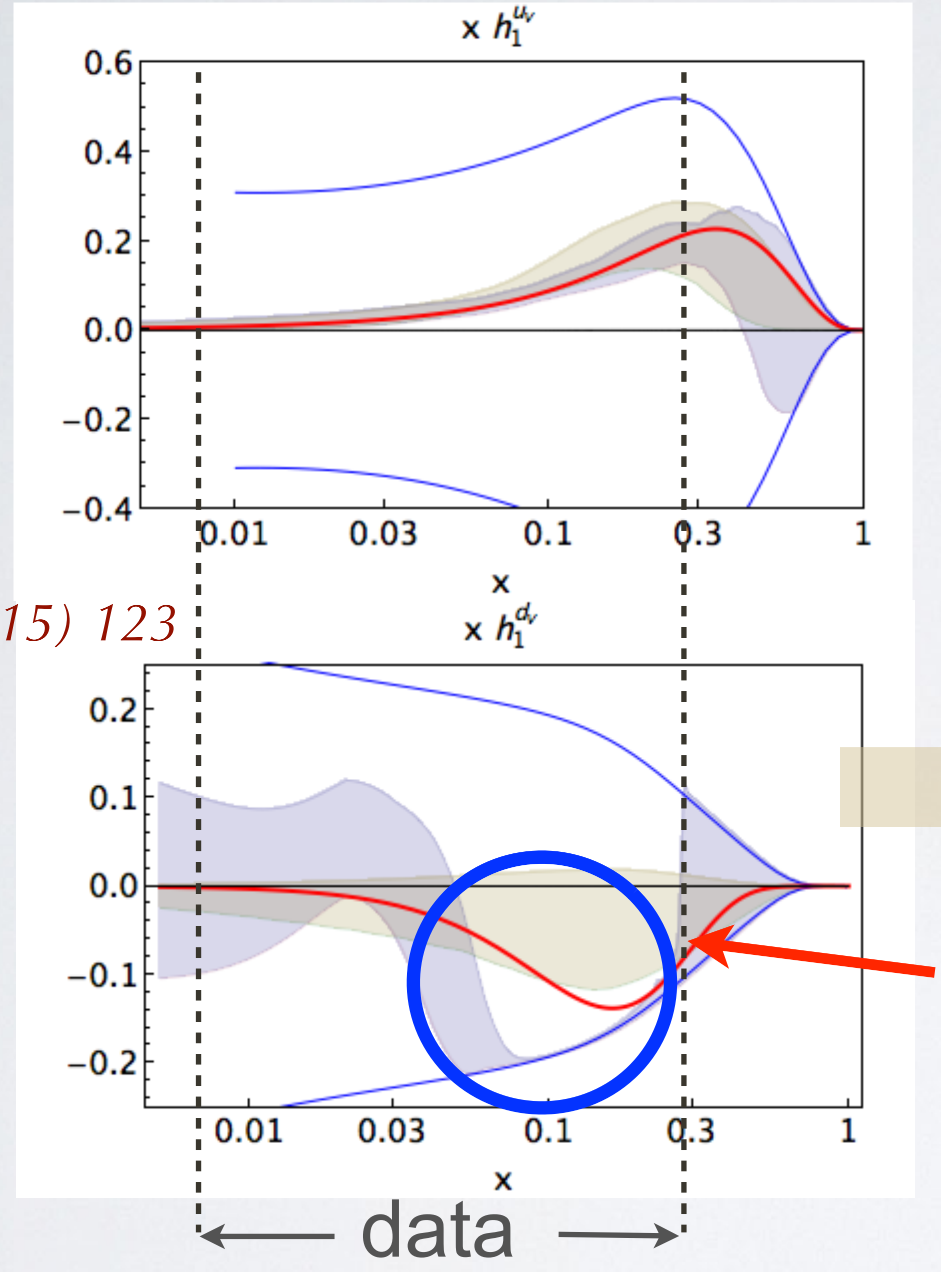
up



down



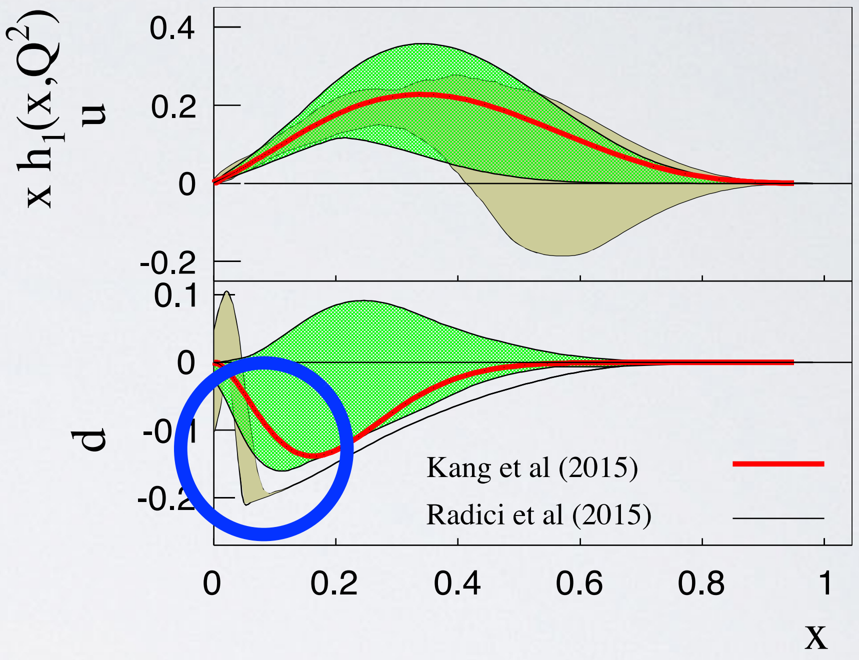
▨ **Radici** et al.,
*JHEP **1505** (15) 123*



▨ **Anselmino** et al.,
2013

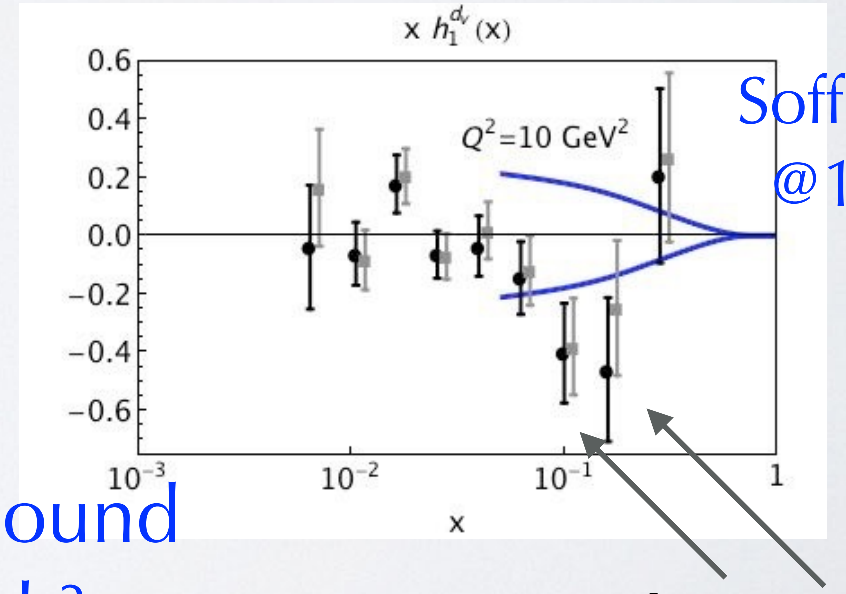
Kang et al.,
2015

Kang et al. 2015 <-> Pavia 2015



Q^2=2.4 GeV^2

linear
scale



Soffer bound
@10 GeV^2

Q^2 ~ 9,15 GeV^2

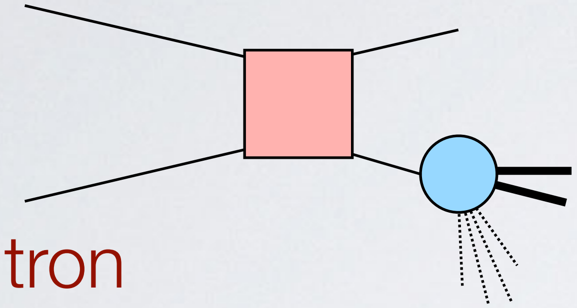
tension driven by
COMPASS deuteron data

is Soffer bound
violated ?

Ralston, arXiv:0810.0871

collinear factorization in hard processes

Artru & Collins, Z.Phys. ***C69*** *(96) 277*
*Boer, Jakob, Radici, P.R.D****67*** *(03) 094003*



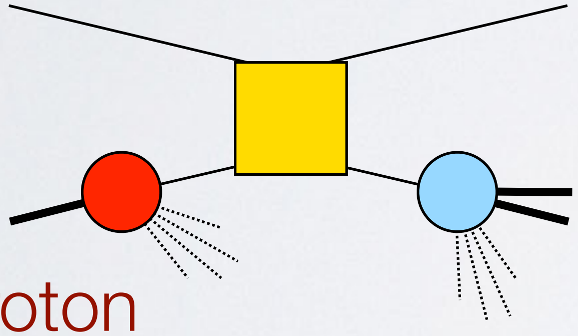
e^+e^-

factorization

electron

2 pions

positron



lepton

lepton

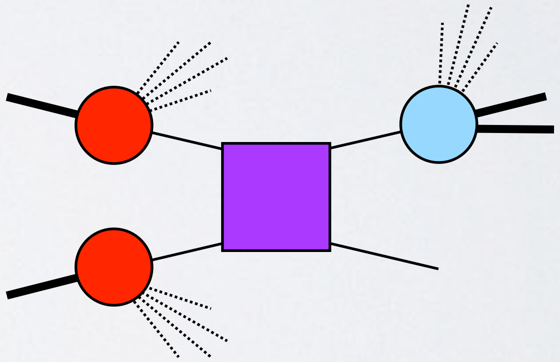
2 pions

proton

SIDIS

factorization

*Jaffe, Jin, Tang, P.R.L.****80*** *(98) 1166*
*Radici, Jakob, Bianconi, P.R.D****65*** *(02) 074031*
*Bacchetta & Radici, P.R. D****67*** *(03) 094002*



proton

2 pions

proton

factorization

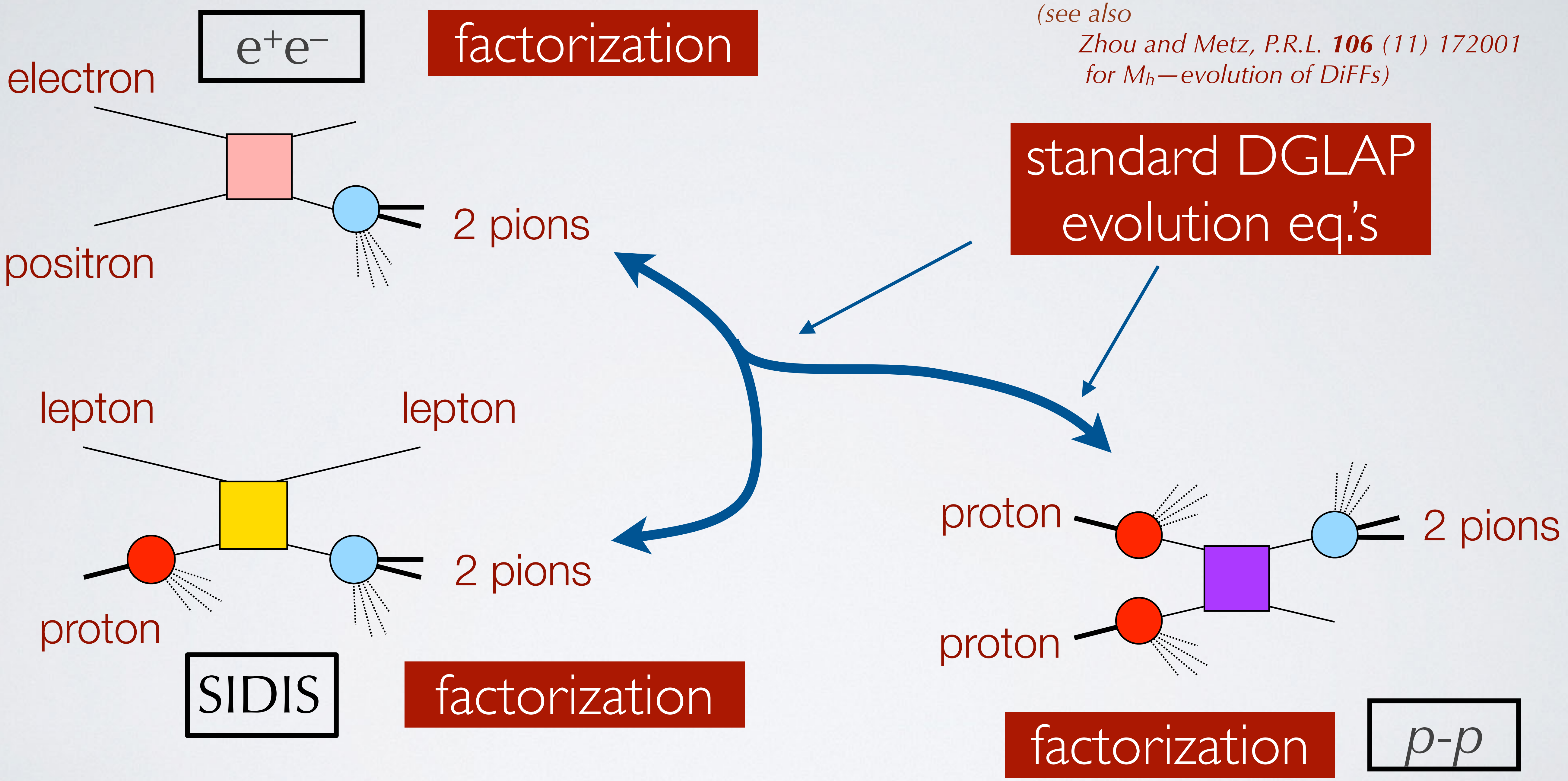
p-p

*Bacchetta & Radici, P.R. D****70*** *(04) 094032*

collinear factorization in hard processes

Artru & Collins, Z.Phys. ***C69*** *(96) 277*
*Boer, Jakob, Radici, P.R.D**67*** *(03) 094003*

*DeFlorian & Vanni, P.L.**B578*** *(04) 139*
*Ceccopieri, Radici, Bacchetta, P.L.**B650*** *(07) 81*
(see also
Zhou and Metz, P.R.L. ***106*** *(11) 172001*
for M_h—evolution of DiFFs)



factorization

standard DGLAP evolution eq.'s

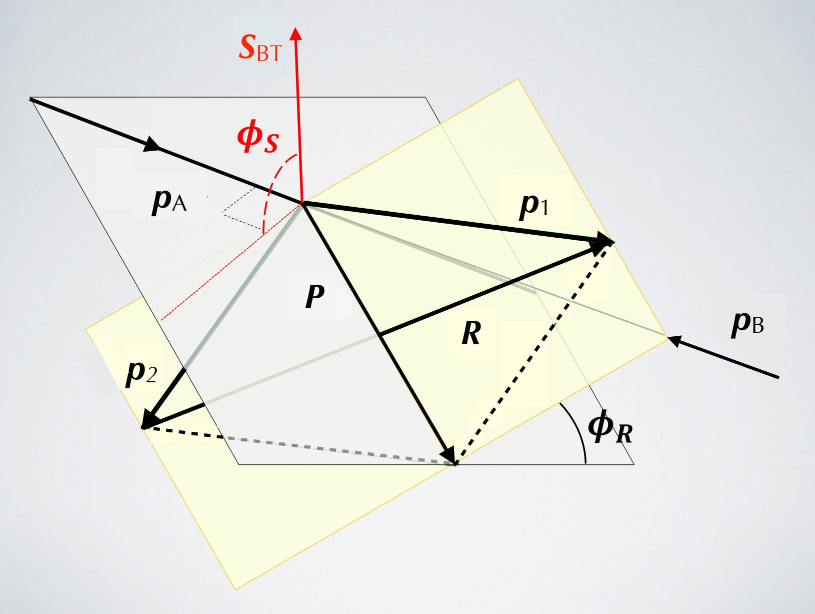
factorization

factorization

*Jaffe, Jin, Tang, P.R.L.**80*** *(98) 1166*
*Radici, Jakob, Bianconi, P.R.D**65*** *(02) 074031*
*Bacchetta & Radici, P.R. D**67*** *(03) 094002*

*Bacchetta & Radici, P.R. D**70*** *(04) 094032*

the process p + p$^{\uparrow}$ → (π π) + X



$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$

B beam polarized

↓

forward
polarized particles
at $\eta < 0$

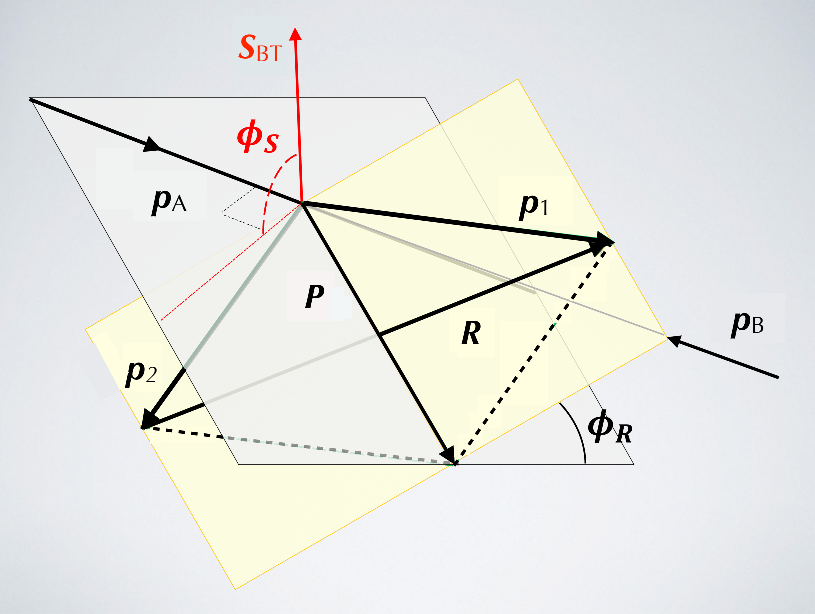
$$\frac{d\sigma^0}{d\eta\, d|\boldsymbol{P}_T|\, dM} = 2\,|\boldsymbol{P}_T| \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, f_1^b(x_b)\, \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}}\, D_1^c(\bar{z}, M)$$

$$\hat{t} = t\, x_a / \bar{z}$$

$$\frac{d\sigma_{UT}}{d\eta\, d|\boldsymbol{P}_T|\, dM} = |\boldsymbol{S}_{BT}|\, 2\,|\boldsymbol{P}_T|\, \frac{|\boldsymbol{R}|}{M}\, \sin\theta \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, h_1^b(x_b)\, \frac{d\Delta\hat{\sigma}_{ab^\uparrow \to c^\uparrow d}}{d\hat{t}}\, H_1^{\sphericalangle c}(\bar{z}, M)$$

*Bacchetta & Radici, P.R. D**70** (04) 094032*

the process p + p$^\uparrow$ → (π π) + X



dσ ~ dσ^0 + sin(Φ$_S$-Φ$_R$) dσ$_{UT}$

B beam polarized

↓

forward
polarized particles
at η < 0

$$\frac{d\sigma^0}{d\eta\, d|\boldsymbol{P}_T|\, dM} = 2\,|\boldsymbol{P}_T| \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, f_1^b(x_b)\, \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}}\, D_1^c(\bar{z}, M)$$

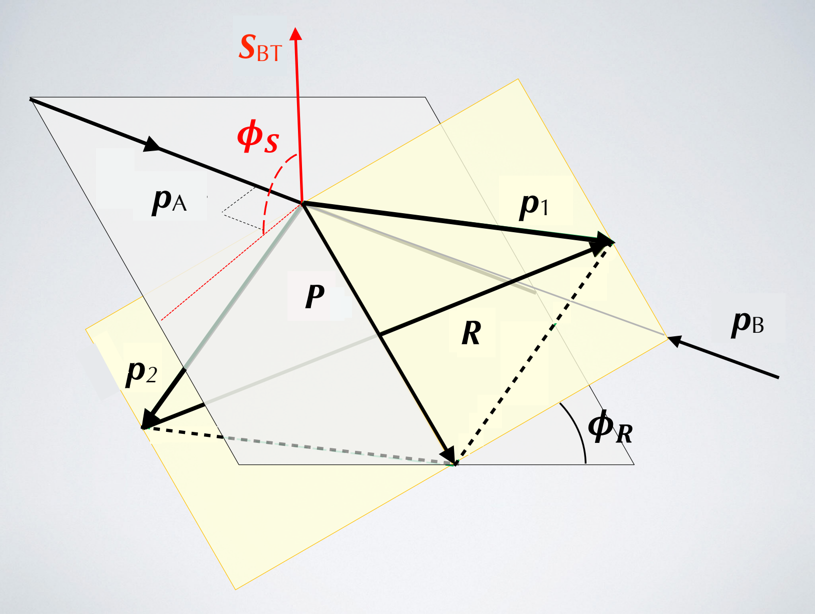
$$\hat{t} = t\, x_a/\bar{z}$$

$$\frac{d\sigma_{UT}}{d\eta\, d|\boldsymbol{P}_T|\, dM} = |\boldsymbol{S}_{BT}|\, 2\,|\boldsymbol{P}_T|\, \frac{|\boldsymbol{R}|}{M}\, \sin\theta \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, h_1^b(x_b)\, \frac{d\Delta\hat{\sigma}_{ab^\uparrow\to c^\uparrow d}}{d\hat{t}}\, H_1^{\sphericalangle c}(\bar{z}, M)$$

specific spin asymmetry due to transversity and chiral-odd DiFF

not possible for single-hadron production (no factorization th.)

the process $p + p^{\uparrow} \to (\pi\ \pi) + X$



$$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$$

B beam polarized

↓

forward
polarized particles
at $\eta < 0$

$$\frac{d\sigma^0}{d\eta\, d|\boldsymbol{P}_T|\, dM} = 2\,|\boldsymbol{P}_T| \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, f_1^b(x_b)\, \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}}\, D_1^c(\bar{z}, M)$$

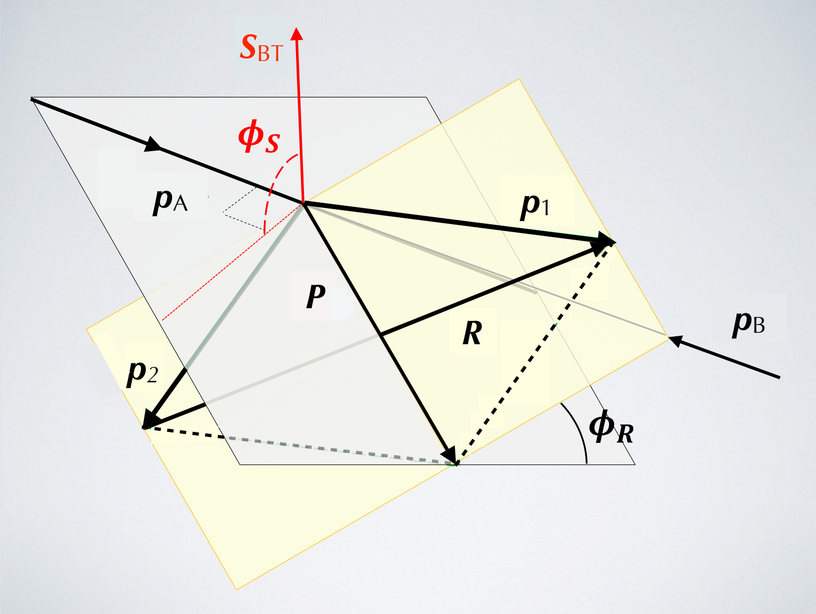
$$\hat{t} = t\, x_a/\bar{z}$$

$$\frac{d\sigma_{UT}}{d\eta\, d|\boldsymbol{P}_T|\, dM} = |\boldsymbol{S}_{BT}|\, 2\,|\boldsymbol{P}_T|\, \frac{|\boldsymbol{R}|}{M} \sin\theta \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, h_1^b(x_b)\, \frac{d\Delta\hat{\sigma}_{ab^{\uparrow}\to c^{\uparrow} d}}{d\hat{t}}\, H_1^{\sphericalangle c}(\bar{z}, M)$$

$$\frac{|\boldsymbol{R}|}{M} = \frac{1}{2}\sqrt{1 - 4\frac{m_\pi^2}{M^2}}$$

M = invariant mass of $(\pi\ \pi)$

the process $p + p^{\uparrow} \rightarrow (\pi\ \pi) + X$



$$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$$

B beam polarized

↓

forward
polarized particles
at $\eta < 0$

$$\frac{d\sigma^0}{d\eta\, d|\boldsymbol{P}_T|\, dM} = 2\,|\boldsymbol{P}_T| \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \boxed{\bar z}}\, f_1^a(x_a)\, f_1^b(x_b)\, \frac{d\hat\sigma_{ab\to cd}}{d\hat t}\, D_1\boxed{(\bar z,} M)$$

$$\hat t = t\, x_a \boxed{/\bar z}$$

$$\frac{d\sigma_{UT}}{d\eta\, d|\boldsymbol{P}_T|\, dM} = |\boldsymbol{S}_{BT}|\, 2\,|\boldsymbol{P}_T|\, \frac{|\boldsymbol{R}|}{M}\, \sin\theta \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \boxed{\bar z}}\, f_1^a(x_a)\, h_1^b(x_b)\, \frac{d\Delta\hat\sigma_{ab^{\uparrow}\to c^{\uparrow}d}}{d\hat t}\, H_1^{\sphericalangle}\boxed{(\bar z,} M)$$

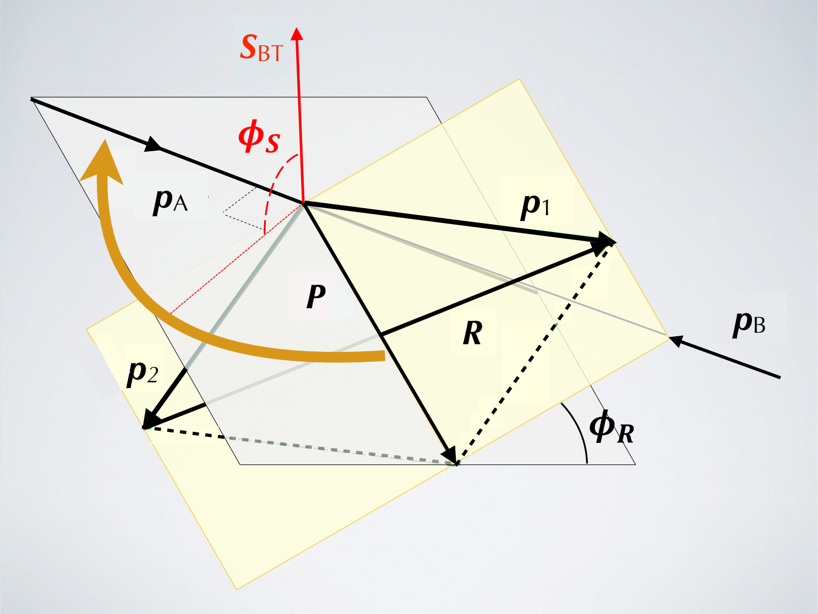
conservation of momenta in *ab*→*cd*

⇒ (ππ) fract. energy fixed to

$$\bar z = \frac{|\boldsymbol{P}_T|}{\sqrt{s}}\, \frac{x_a e^{-\eta} + x_b e^{\eta}}{x_a x_b}$$

η = pseudorapidity

the process $p + p^{\uparrow} \rightarrow (\pi\ \pi) + X$



$d\sigma \sim d\sigma^0 + \sin(\Phi_S - \Phi_R)\, d\sigma_{UT}$

B beam polarized

↓

forward
polarized particles
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$$\frac{d\sigma^0}{d\eta\, d|\boldsymbol{P}_T|\, dM} = 2\,|\boldsymbol{P}_T| \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{8\pi^2 \bar{z}}\, f_1^a(x_a)\, f_1^b(x_b)\, \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}}\, D_1^c(\bar{z}, M)$$

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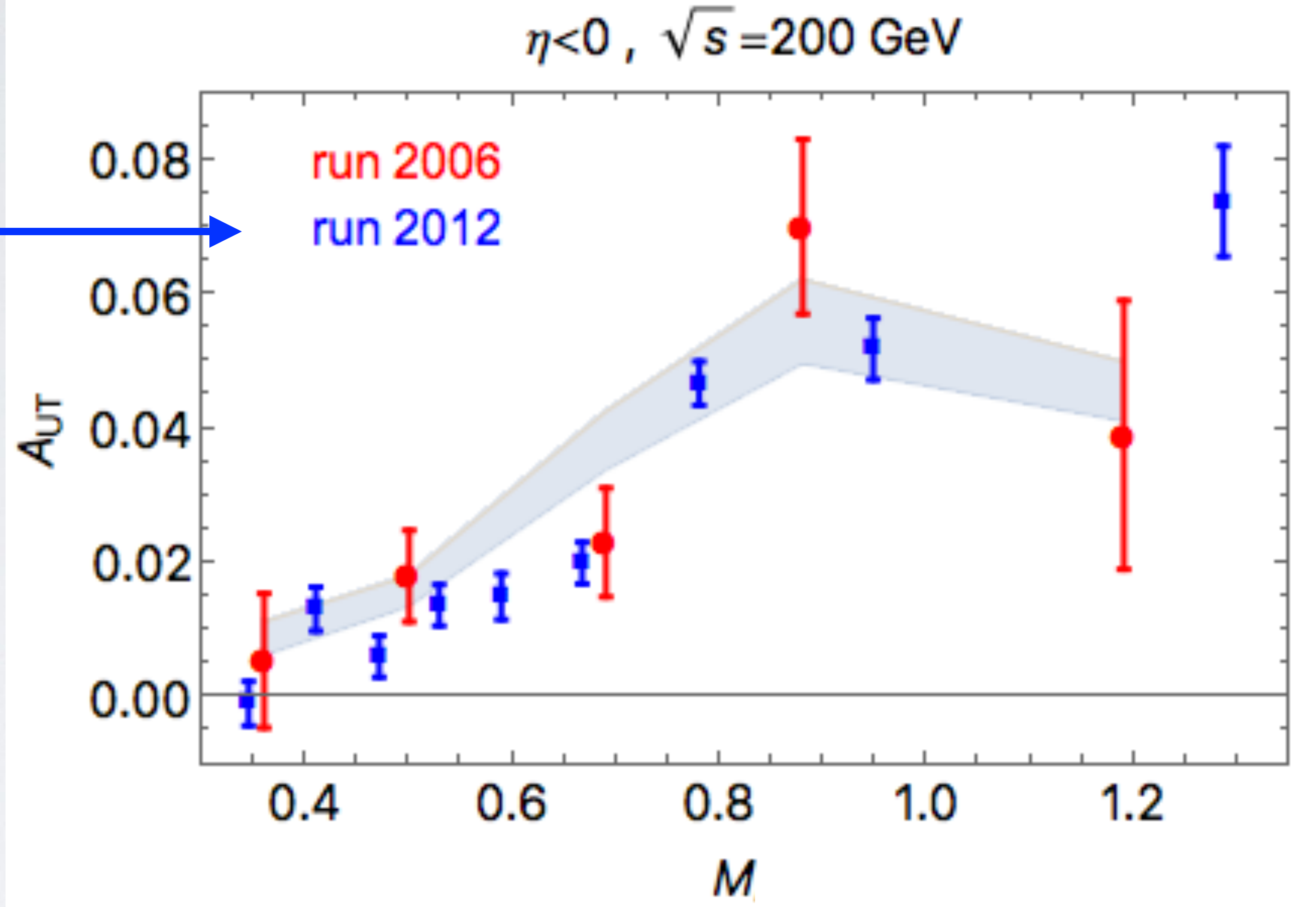
$|\boldsymbol{P}_T|$ = transverse component of
pair total momentum
with respect to *A* beam

hard scale $|\boldsymbol{P}_T| \gg M, M_A, M_B$

forward $A_{UT}(M)$

PRELIMINARY



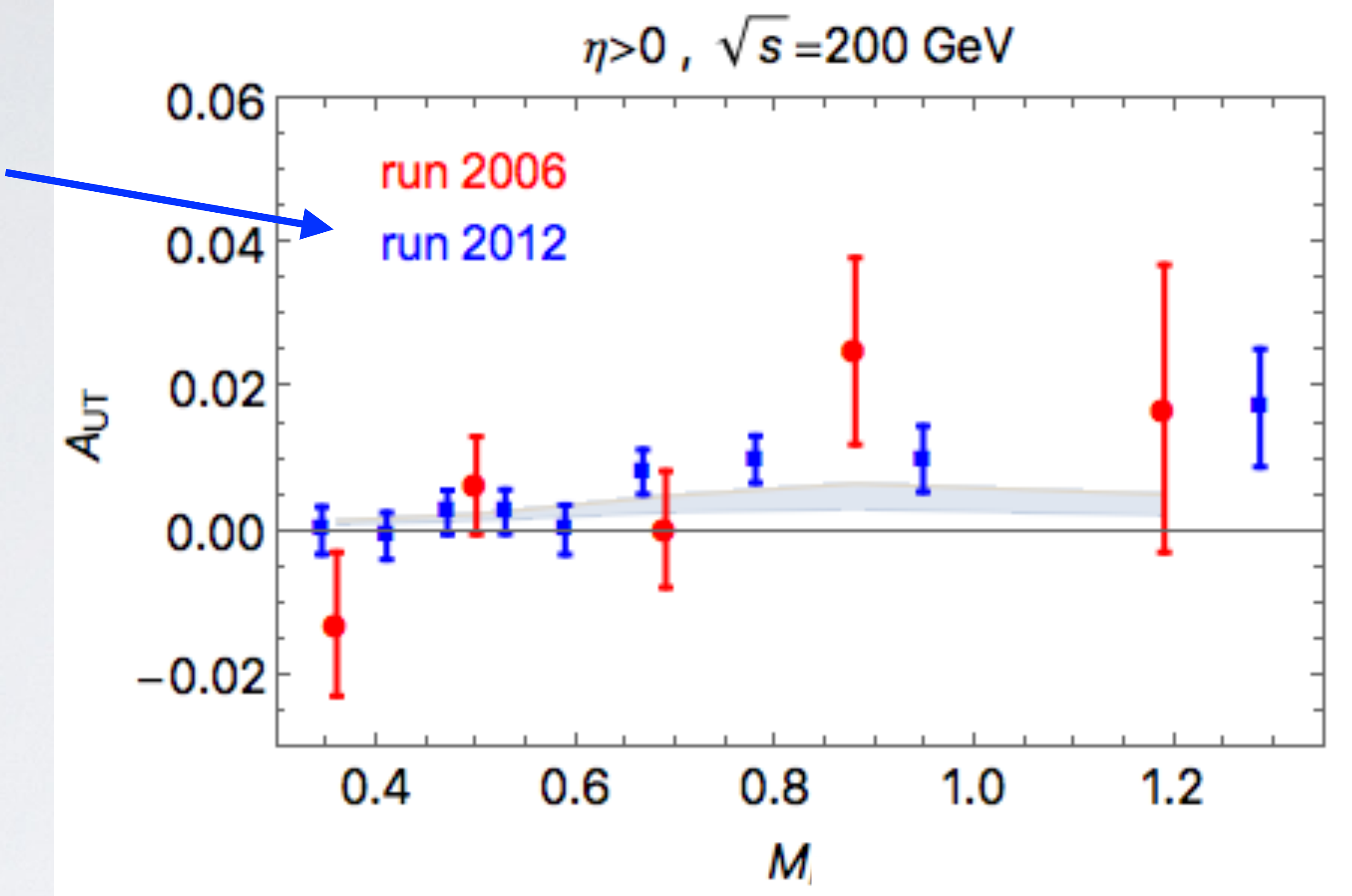
prediction of new STAR data using 68% of replicas forward $A_{UT}(M)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(2015) 242501*

run 2012 *K. Landry, talk at APS 2015*

backward $A_{UT}(M)$

PRELIMINARY



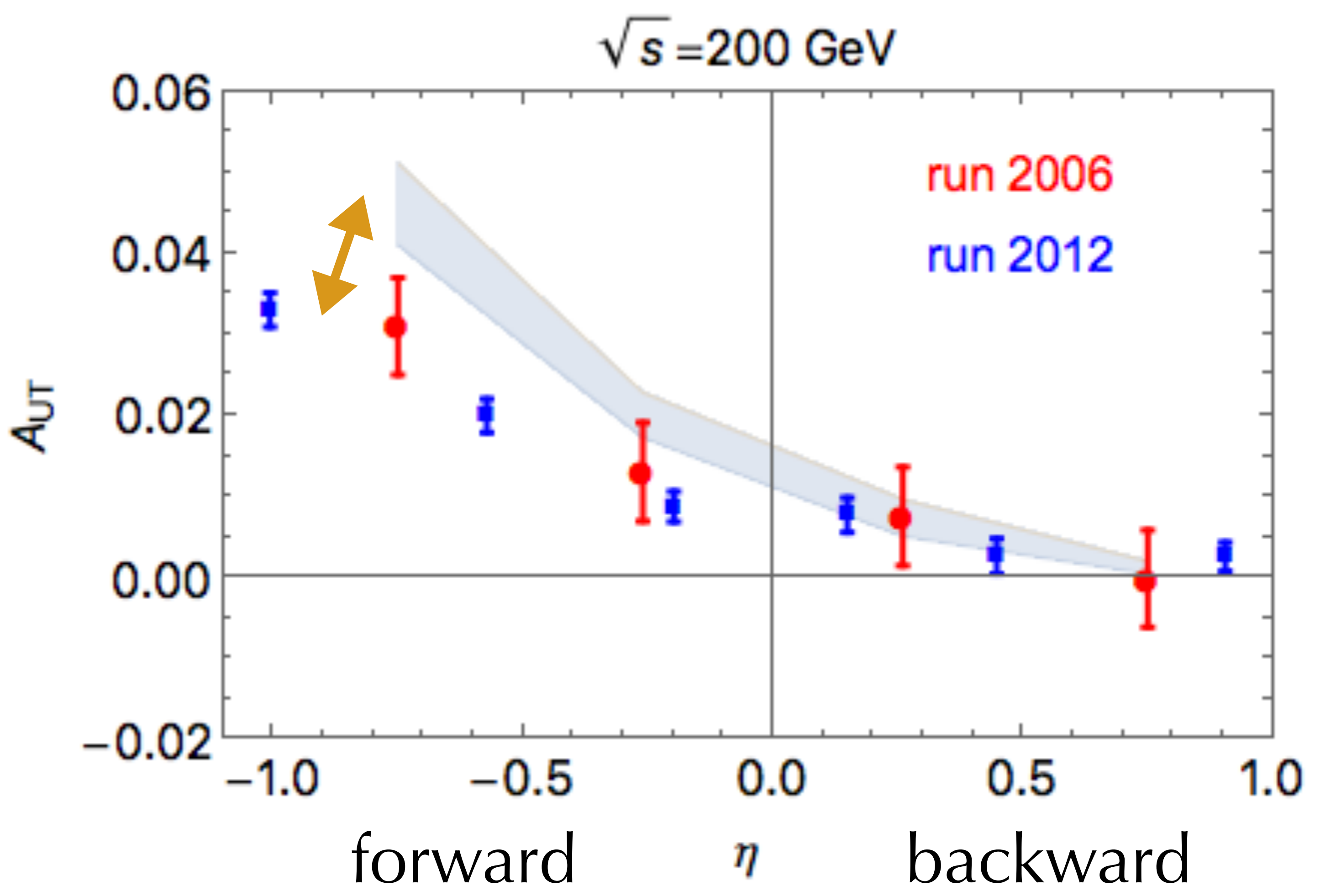
prediction of new STAR data using 68% of replicas backward $A_{UT}(M)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(2015) 242501*

run 2012 *K. Landry, talk at APS 2015*

$A_{UT}(\eta)$

problem ?



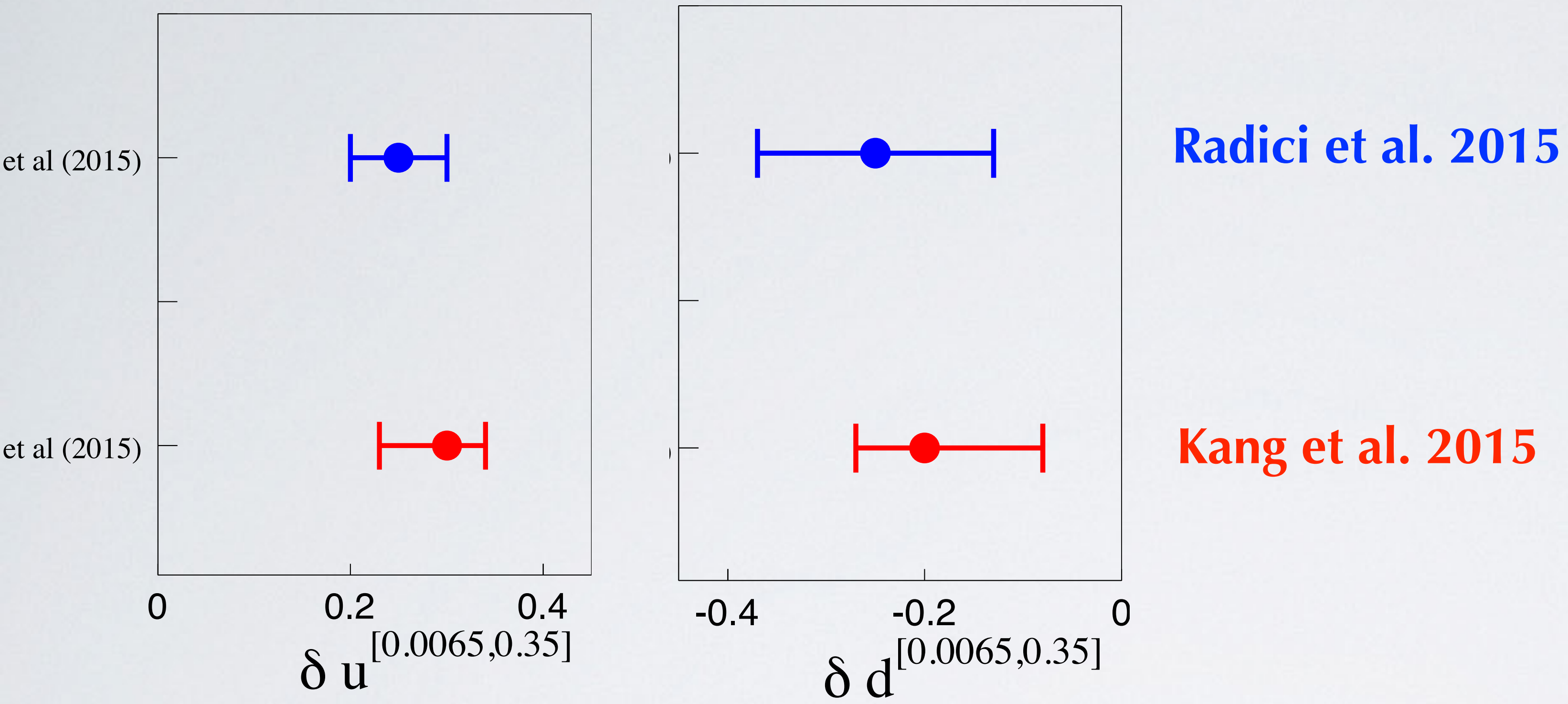
prediction of new STAR data using 68% of replicas $A_{UT}(\eta)$

run 2006 *Adamczyk et al. (STAR), P.R.L.* ***115*** *(2015) 242501*

run 2012 *K. Landry, talk at APS 2015*

back to tensor charge

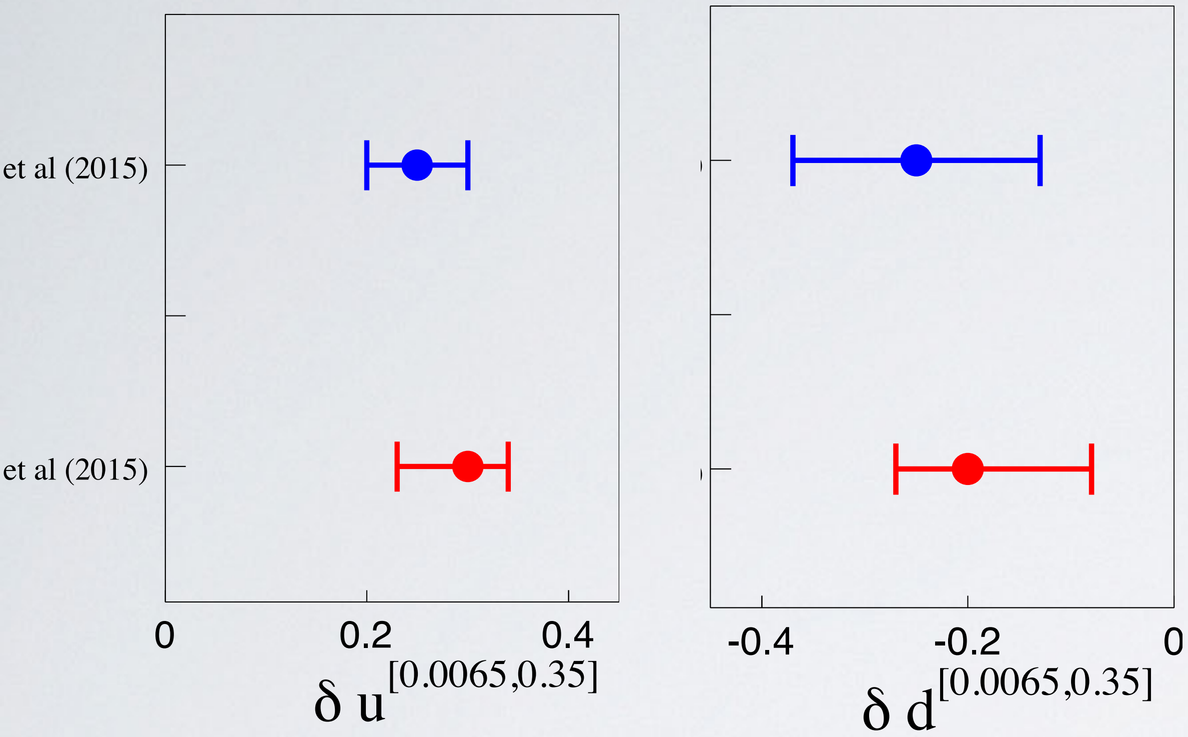
$Q^2 = 10\ \mathrm{GeV}^2$



truncated to data range
$x \in [0.0065, 0.35]$

back to tensor charge

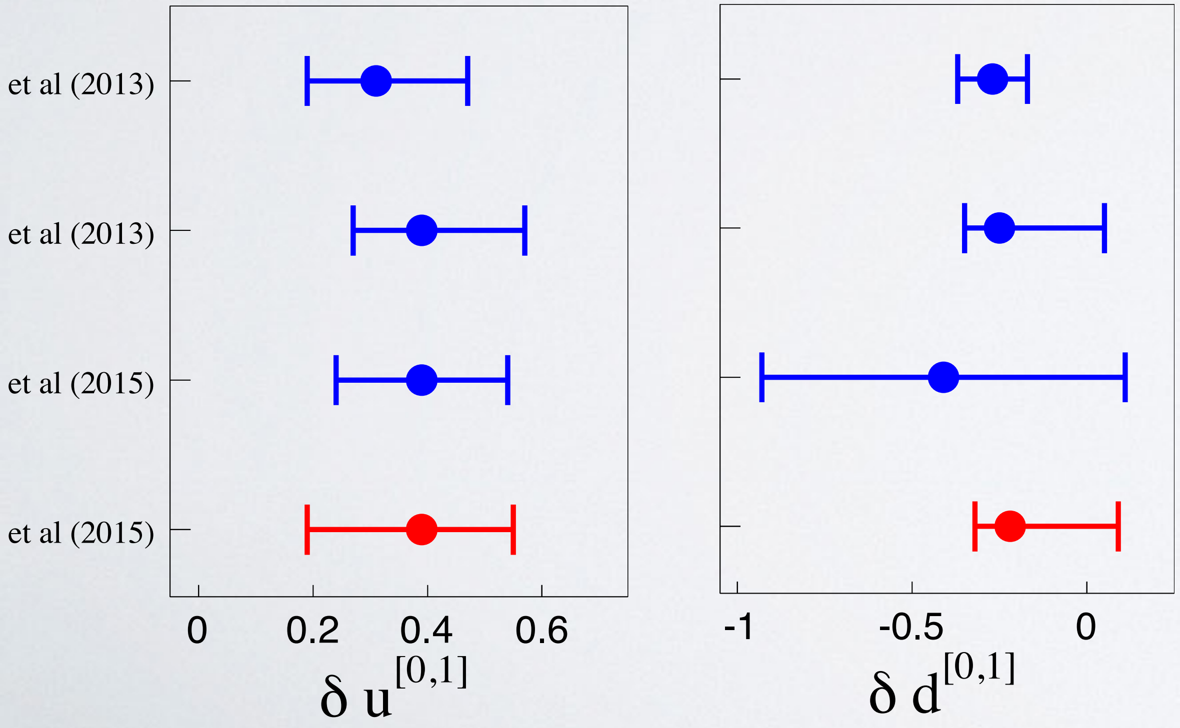
$Q^2 = 10 \text{ GeV}^2$



Radici et al. 2015

Kang et al. 2015

truncated to data range
$x \in [0.0065, 0.35]$



Anselmino et al. 2013

} $Q^2 = 0.8$

Radici et al. 2015
$Q^2 = 1$

Kang et al. 2015
$Q^2 = 10$

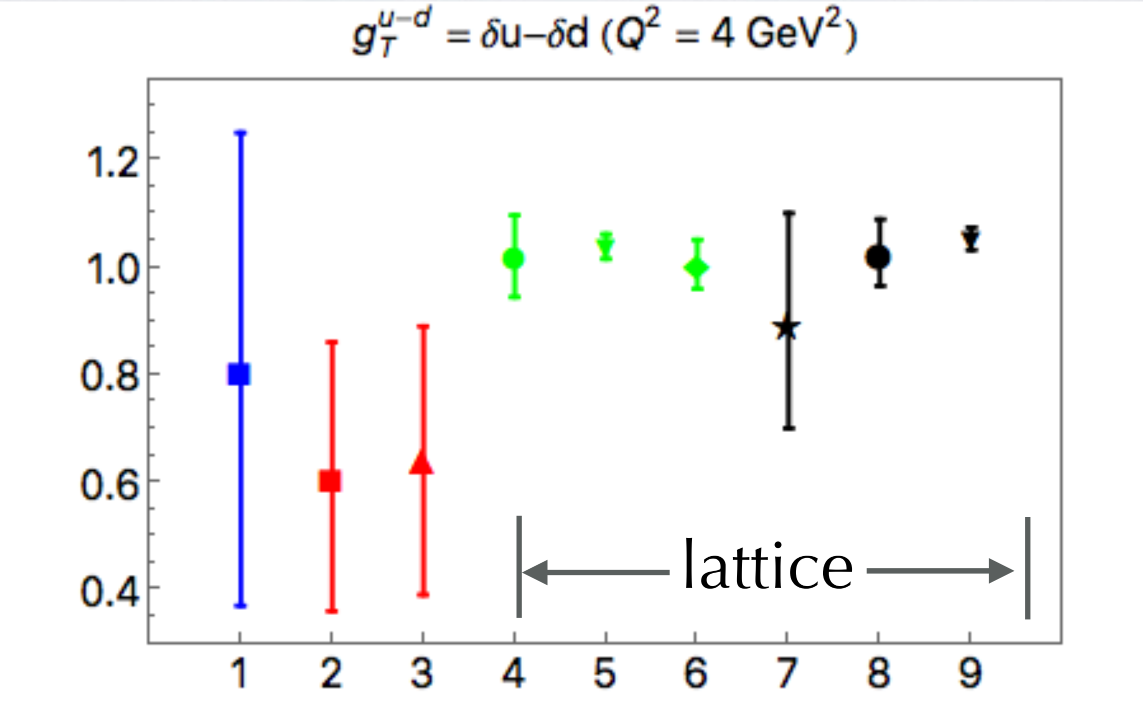
extrapolation to [0,1]

↓

expect larger uncertainties

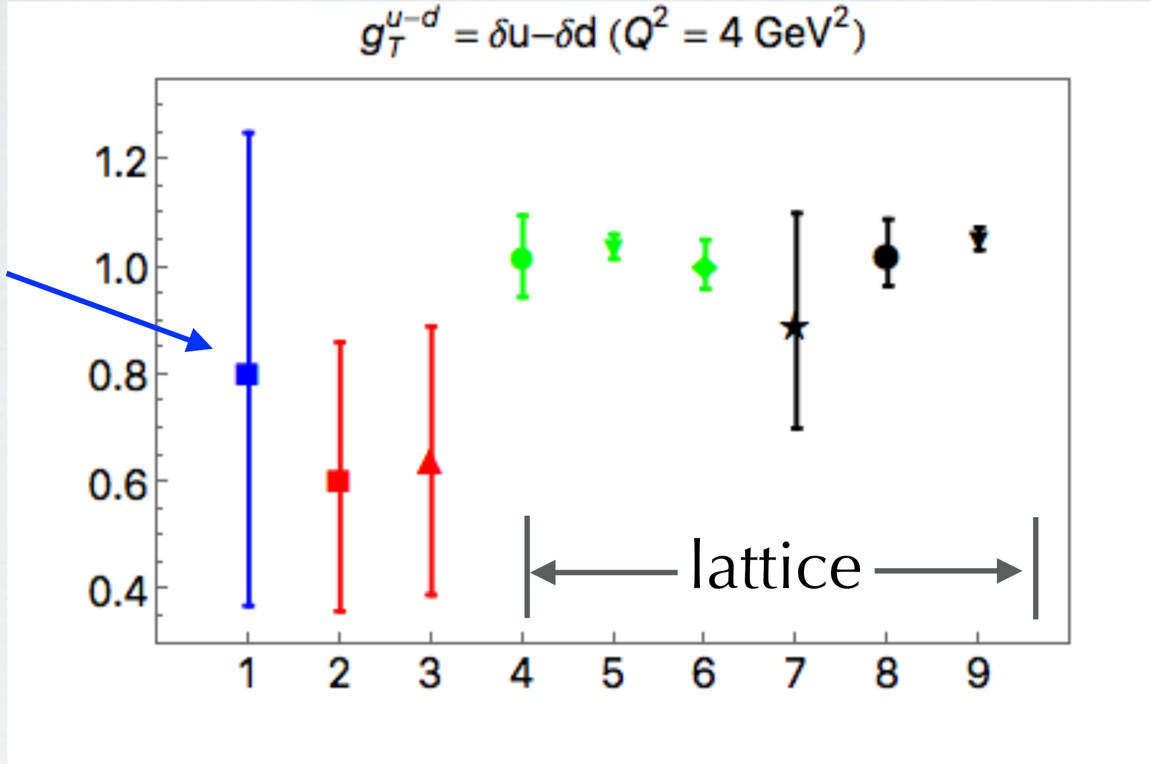
neutron β-decay <—> isovector tensor charge

$g_T^{u\text{-}d}$ affects tensor coupling in **β**-decay

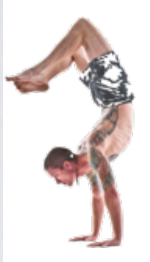


neutron β-decay <—> isovector tensor charge

$g_T^{u\text{-}d}$ affects tensor coupling in β-decay

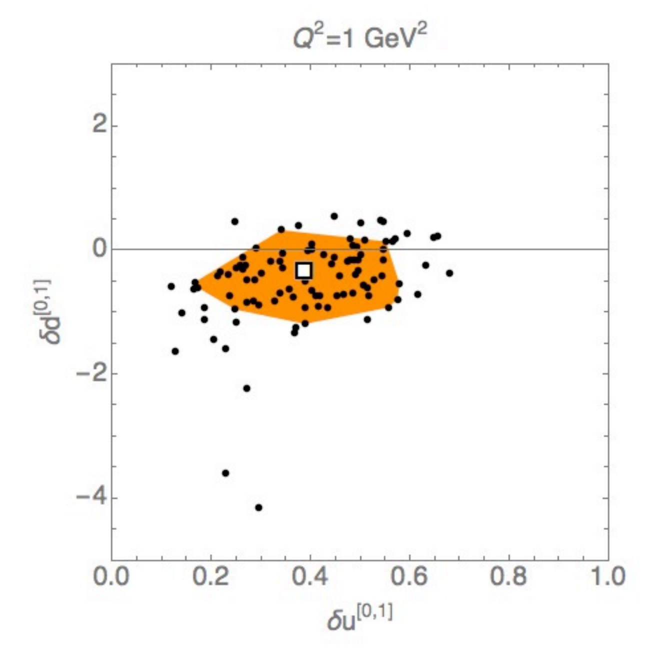


1) Radici et al. 2015



$Q^2 = 4$ GeV^2

$\alpha_S = 0.125$



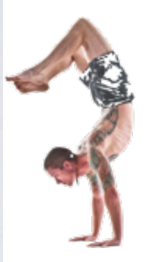
neutron β-decay <—> isovector tensor charge

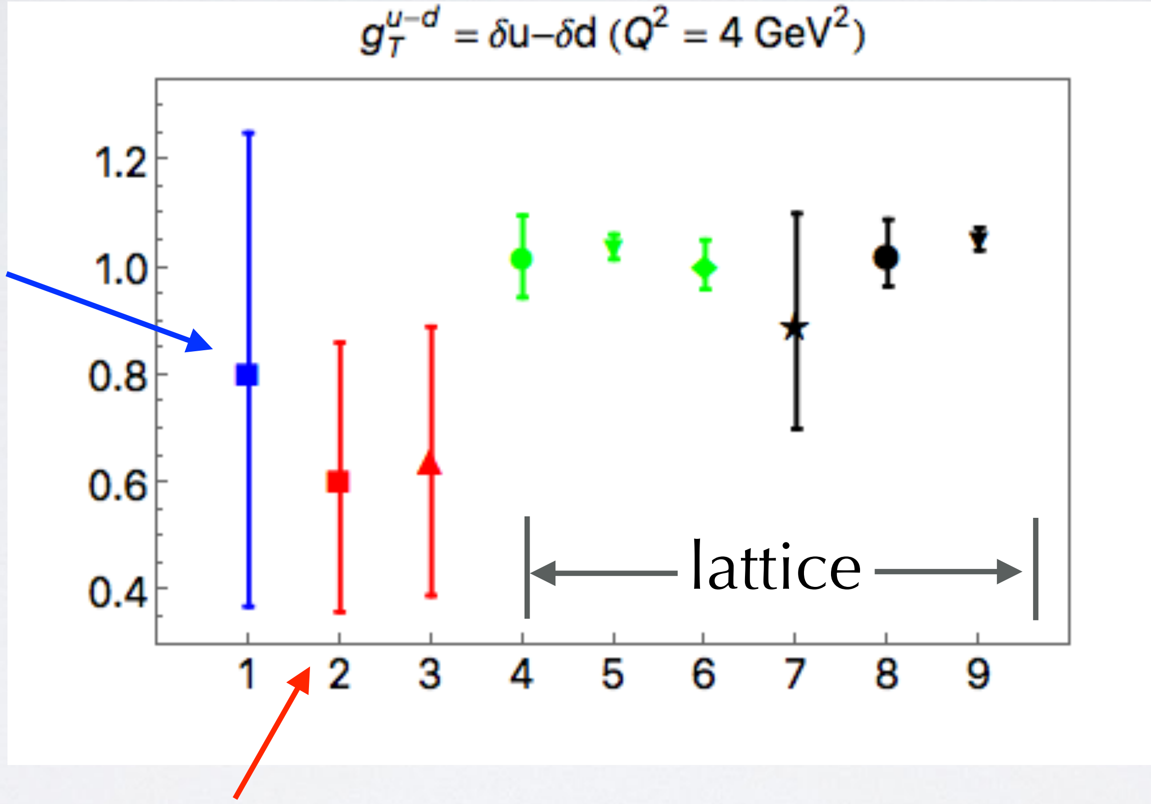
$g_T^{u\text{-}d}$ affects tensor coupling in β-decay

1) Radici et al. 2015

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

$\alpha_S = 0.125$





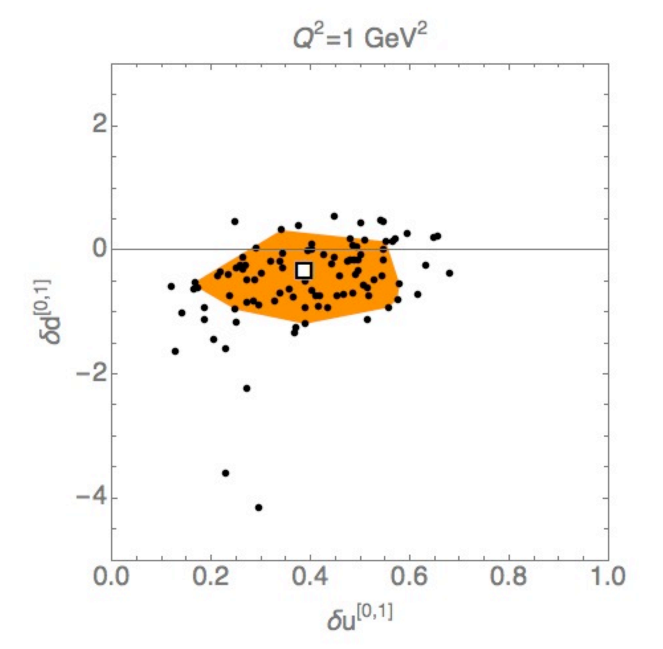
$Q^2 = 4\ \mathrm{GeV}^2$ except

2) Kang et al. 2015

$Q^2 = 10$

3) Anselmino et al. 2013

$Q^2 = 0.8$



2) Kang et al. 2015

3) Anselmino et al. 2013

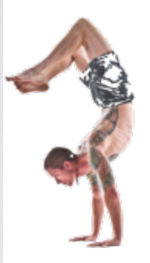
neutron β-decay <—> isovector tensor charge

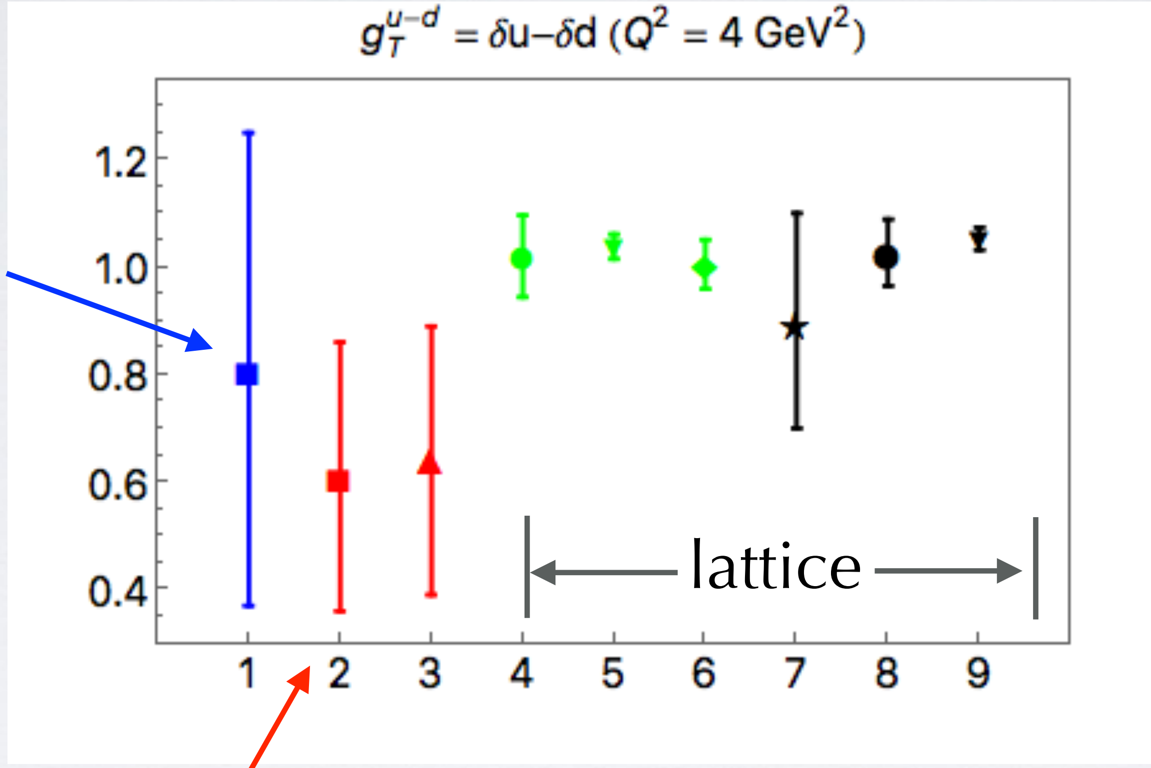
$g_T^{u\text{-}d}$ affects tensor coupling in β-decay

1) Radici et al. 2015

Q^2 = 4 GeV^2

α_S = 0.125





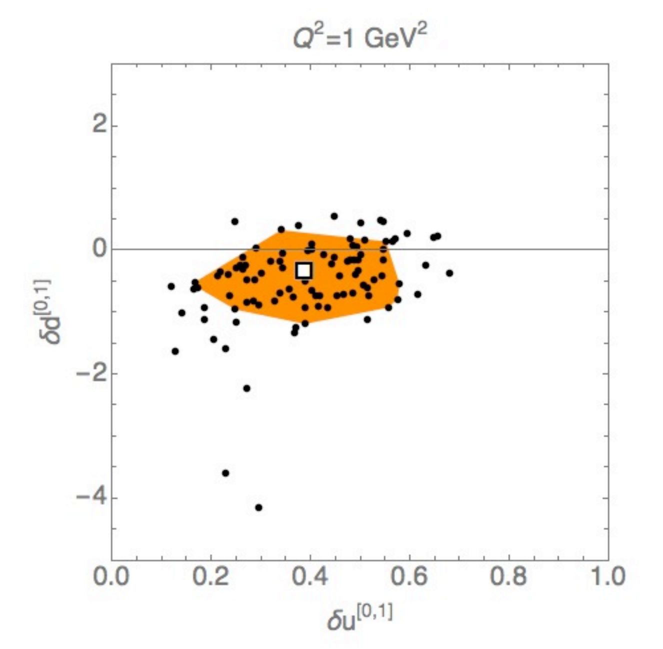
Q^2 = 4 GeV^2 except

2) Kang et al. 2015

Q^2 = 10

3) Anselmino et al. 2013

Q^2 = 0.8



2) Kang et al. 2015

3) Anselmino et al. 2013

4) PNDME ‘15	*Bhattacharya et al., P.R. D92 (15)*
5) LHPC ‘12	*Green et al., P.R. D86 (12)*
6) RQCD ‘14	*Bali et al., P.R. D91 (15)*
7) RBC-UKQCD	*Aoki et al., P.R. D82 (10)*
8) ETMC ‘15	*Abdel-Rehim et al., P.R.D92 (15);*
9) ETMC ‘15	*E P.R.D93 (16)*

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current most stringent constraints on BSM tensor coupling come from

- Dalitz-plot study of radiative pion decay $\pi^+ \rightarrow e^+ \nu_e \gamma$

Bychkov et al. (PIBETA), P.R.L. ***103*** *(09) 051802*

- measurement of correlation parameters in neutron β-decay of various nuclei

Pattie et al., P.R. C88 (13) 048501

$$\boxed{|\,\varepsilon_T\, g_T\,| \lesssim 5 \times 10^{-4}}$$

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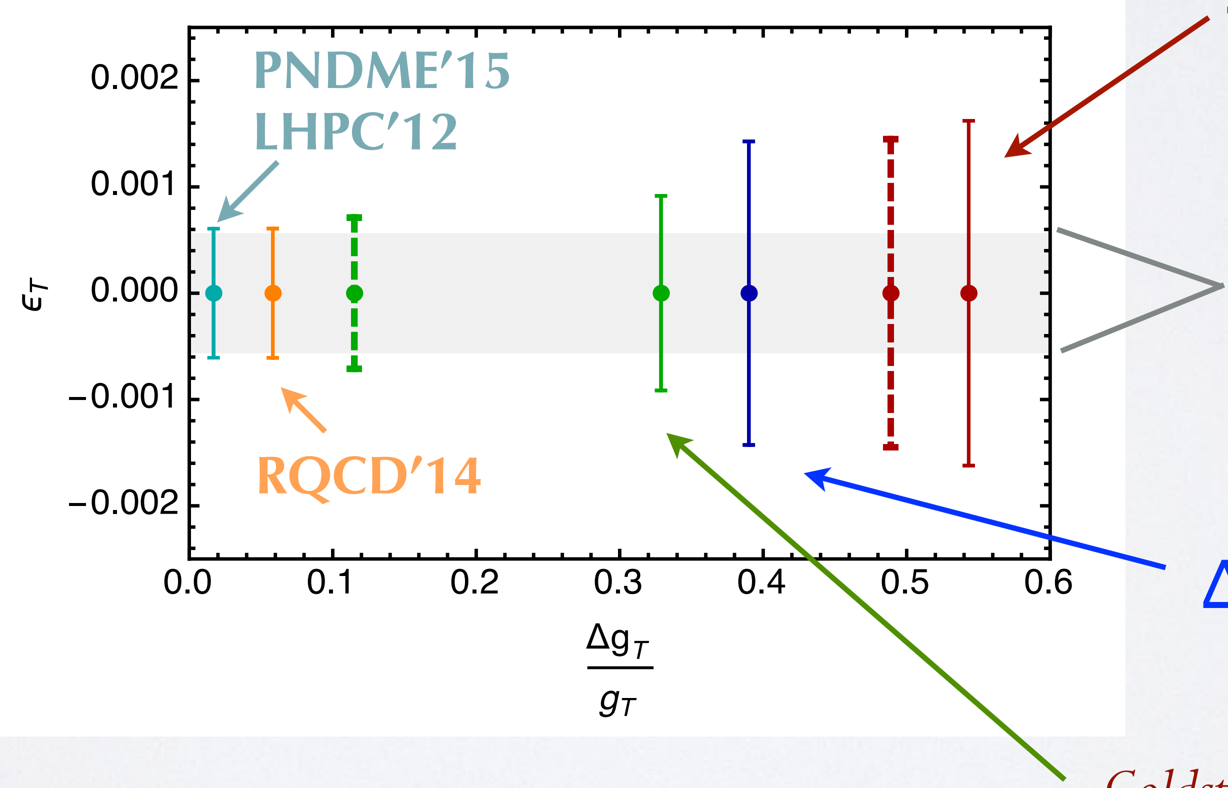

$\Delta\varepsilon_T$ from **Radici et al. 2015**

$\Delta\varepsilon_T$ assuming Δg_T=0

$\Delta\varepsilon_T$ from **Anselmino et al. 2013**

Goldstein et al., arXiv:1401.0438

Courtoy et al., P.R.L. ***115*** *(2015) 162001*

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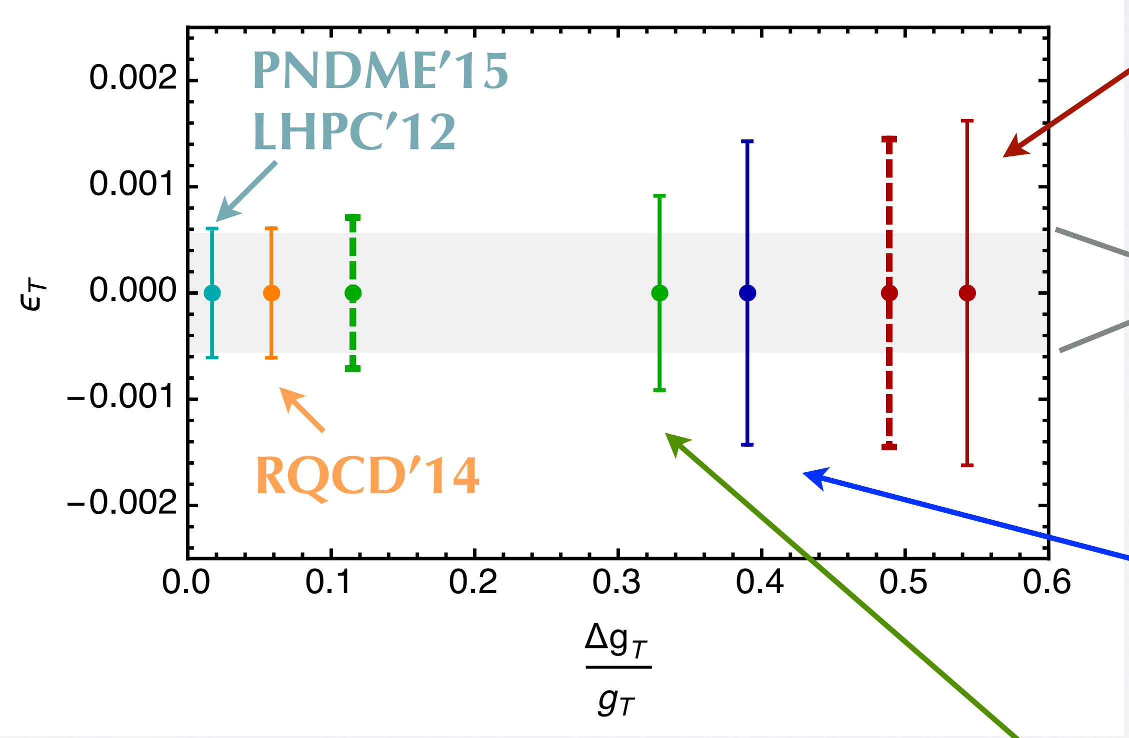
need more data to adapt phenomenology to precision of measurements and lattice



$\Delta\varepsilon_T$ from **Radici et al. 2015**

(to be improved with RHIC data)

$\Delta\varepsilon_T$ assuming Δg_T=0

$\Delta\varepsilon_T$ from **Anselmino et al. 2013**

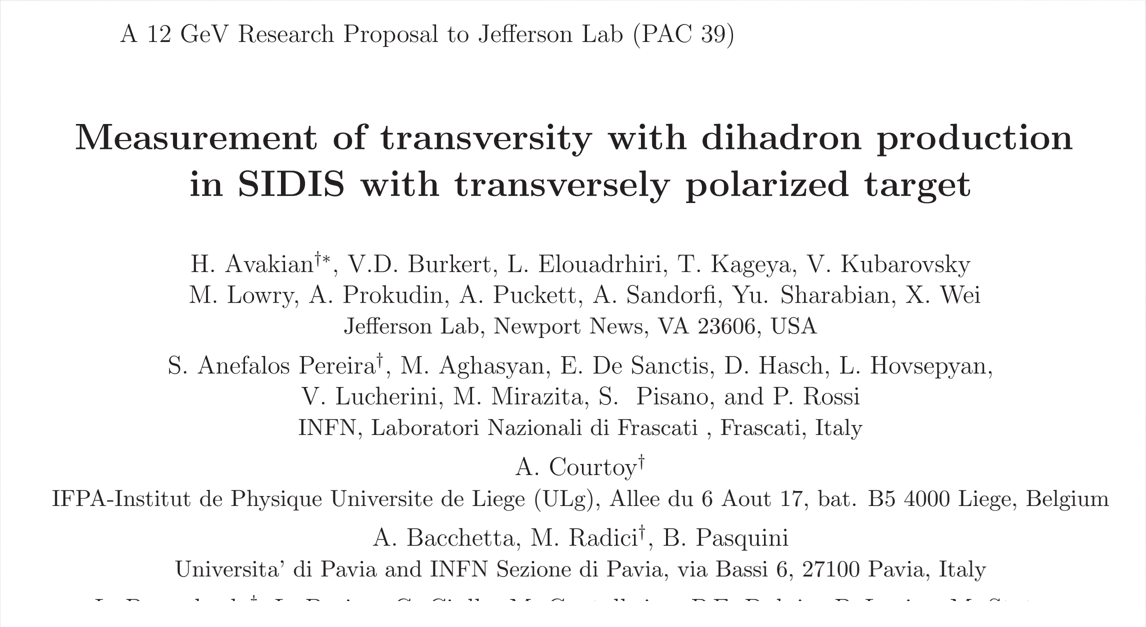
Goldstein et al., arXiv:1401.0438

Courtoy et al., P.R.L. ***115*** *(2015) 162001*

JLab12 Di-hadron proposals

Jefferson Lab

PR12-12-009 **Hall B**, using CLAS12 detector with transversely polarized HD-Ice target



A 12 GeV Research Proposal to Jefferson Lab (PAC 39)

Measurement of transversity with dihadron production in SIDIS with transversely polarized target

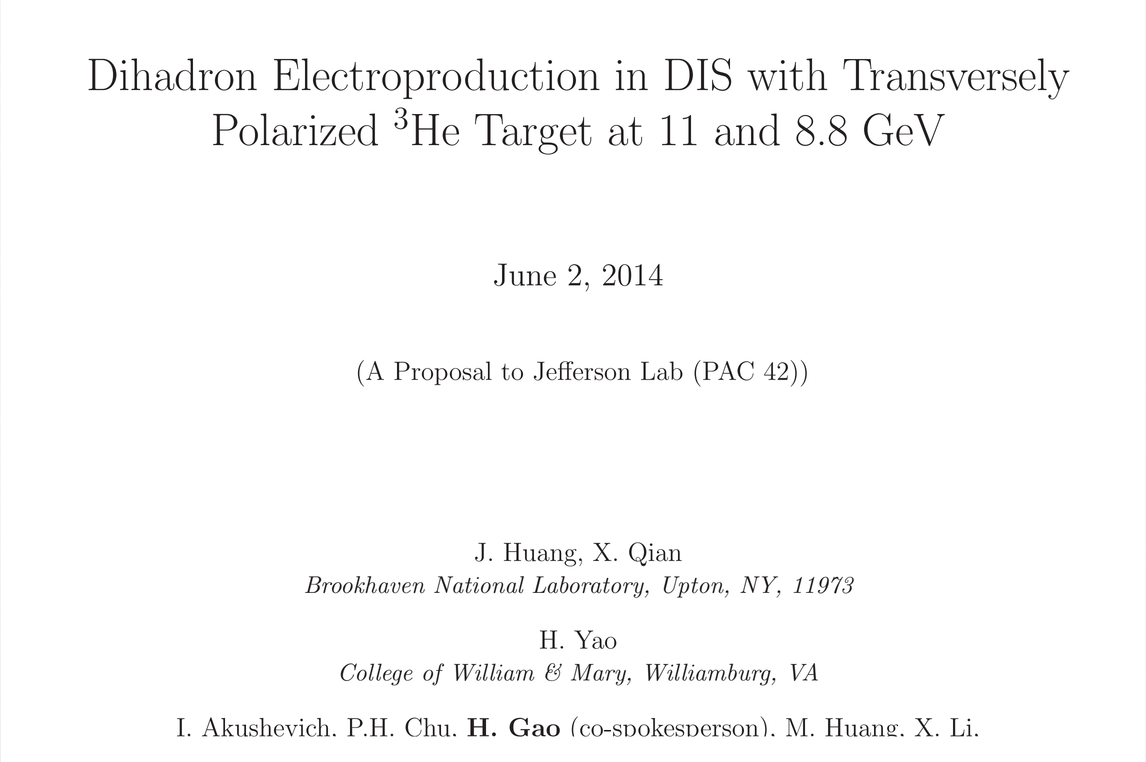
H. Avakian[†*], V.D. Burkert, L. Elouadrhiri, T. Kageya, V. Kubarovsky
M. Lowry, A. Prokudin, A. Puckett, A. Sandorfi, Yu. Sharabian, X. Wei
Jefferson Lab, Newport News, VA 23606, USA

S. Anefalos Pereira[†], M. Aghasyan, E. De Sanctis, D. Hasch, L. Hovsepyan,
V. Lucherini, M. Mirazita, S. Pisano, and P. Rossi
INFN, Laboratori Nazionali di Frascati , Frascati, Italy

A. Courtoy[†]
IFPA-Institut de Physique Universite de Liege (ULg), Allee du 6 Aout 17, bat. B5 4000 Liege, Belgium

A. Bacchetta, M. Radici[†], B. Pasquini
Universita' di Pavia and INFN Sezione di Pavia, via Bassi 6, 27100 Pavia, Italy

PAC39: rating A , approval C1 (subject to further test on HD-Ice target)



Dihadron Electroproduction in DIS with Transversely Polarized ^{3}He Target at 11 and 8.8 GeV

June 2, 2014

(A Proposal to Jefferson Lab (PAC 42))

J. Huang, X. Qian
Brookhaven National Laboratory, Upton, NY, 11973

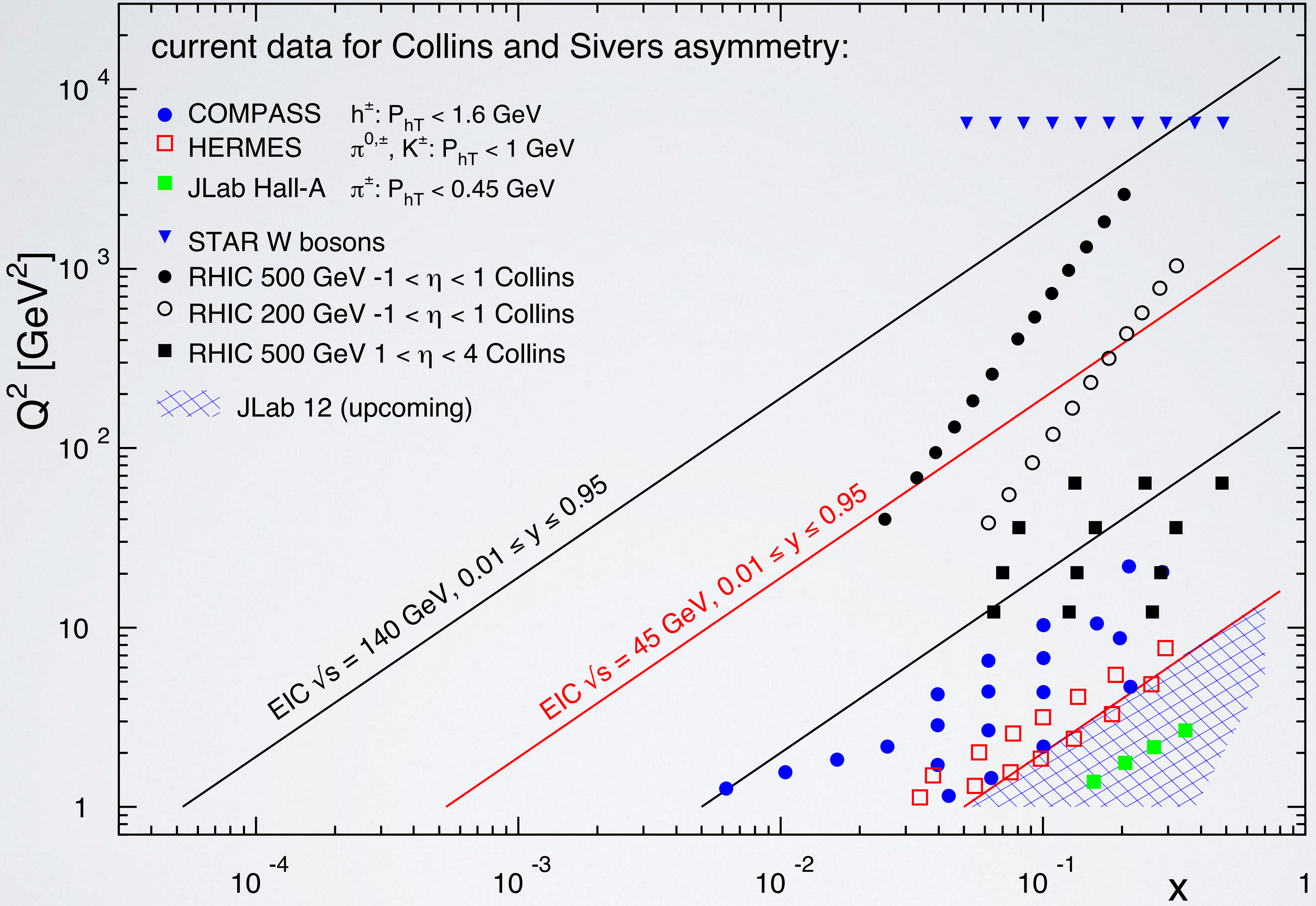
H. Yao
College of William & Mary, Williamburg, VA

I. Akushevich, P.H. Chu, **H. Gao** (co-spokesperson), M. Huang, X. Li.

Hall A, using SoLID detector with transversely polarized ^{3}He target
⇒ separate u and d

PAC42: “valid addition” to approved E12-10-006 (E12-10-006A)

(x, Q^2) (future) data coverage



Aschenauer et al. (RHIC SPIN Coll.), arXiv:1602.03922

Conclusions

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JLab12

EIC