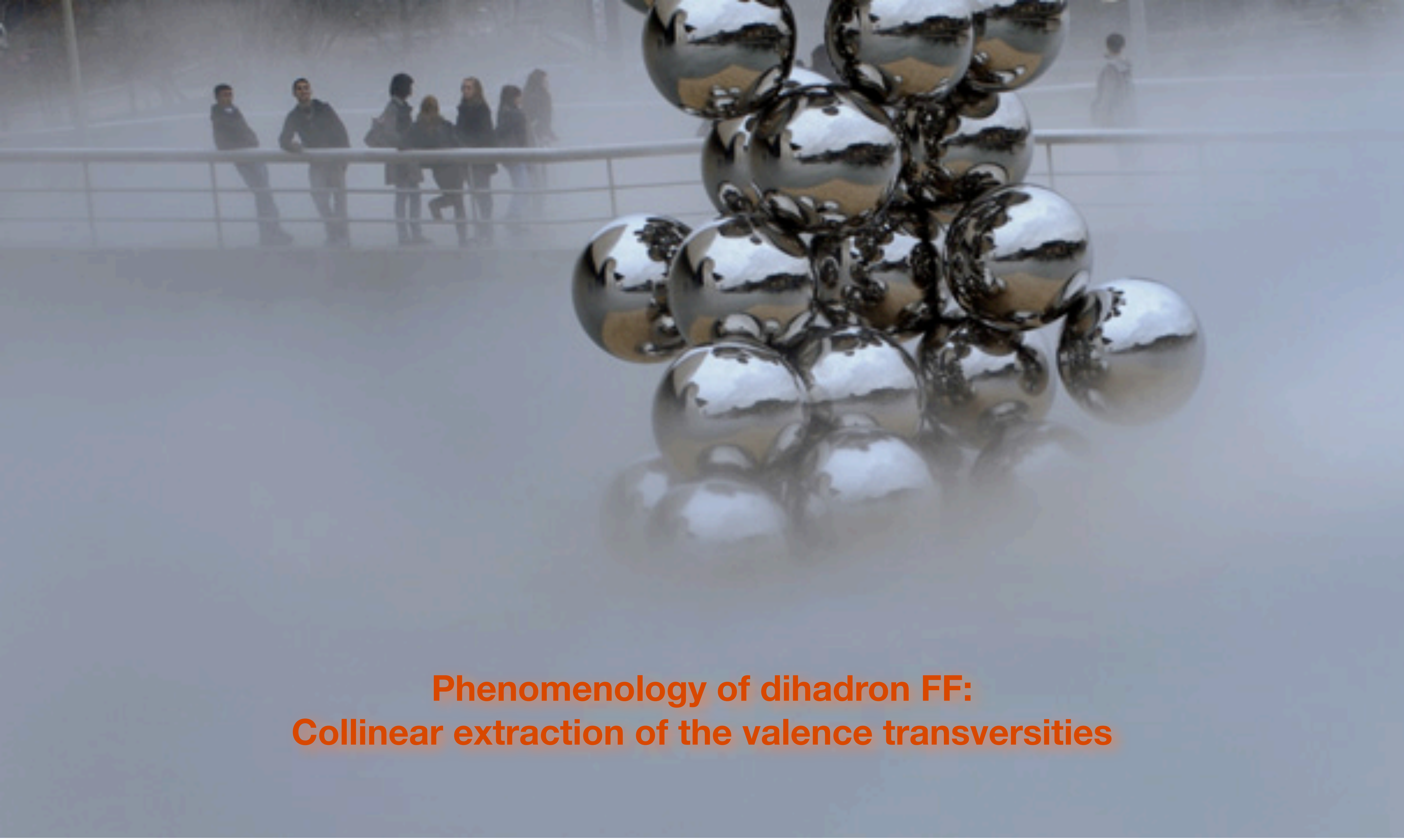
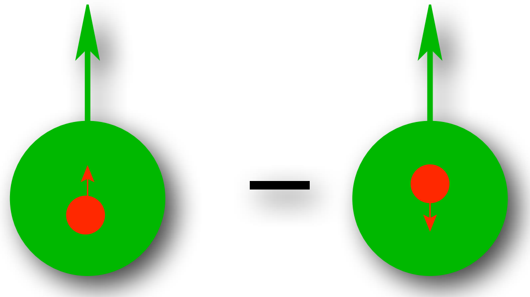


Phenomenology of dihadron FF: Collinear extraction of the valence transversities

QCD'N 2012

Aurore Courtoy
IFPA-Université de Liège (Belgium)

Outline



Extraction of valence transversities from collinear framework

- State-of-the-art
- Dihadron Fragmentation Functions in a nutshell
- Collinear extraction of transversities
- Statistical analysis: fit and error propagation.
- Outlook

in collaboration with Alessandro Bacchetta and Marco Radici in Pavia

State-of-the-art:
Extractions of transversity

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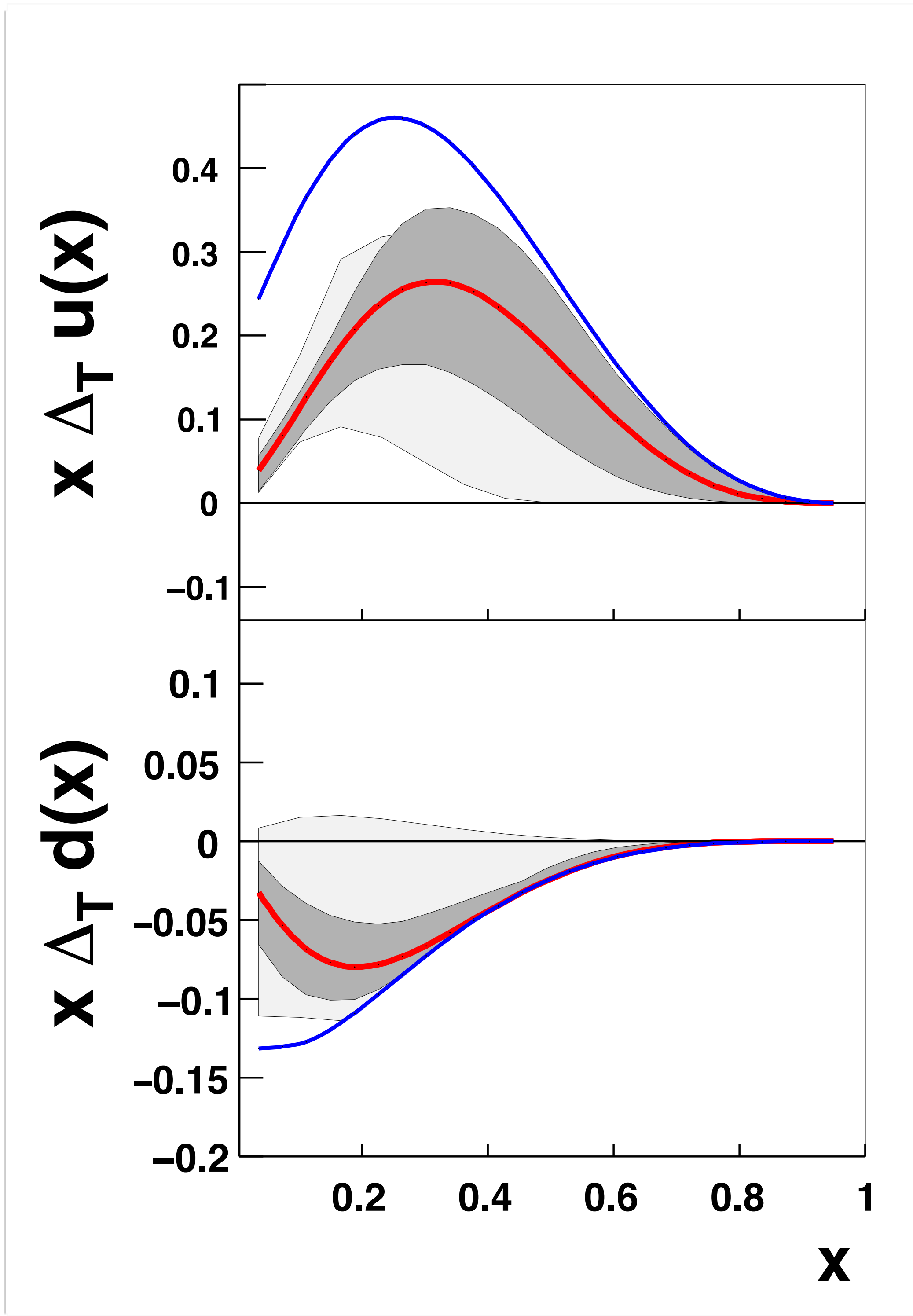
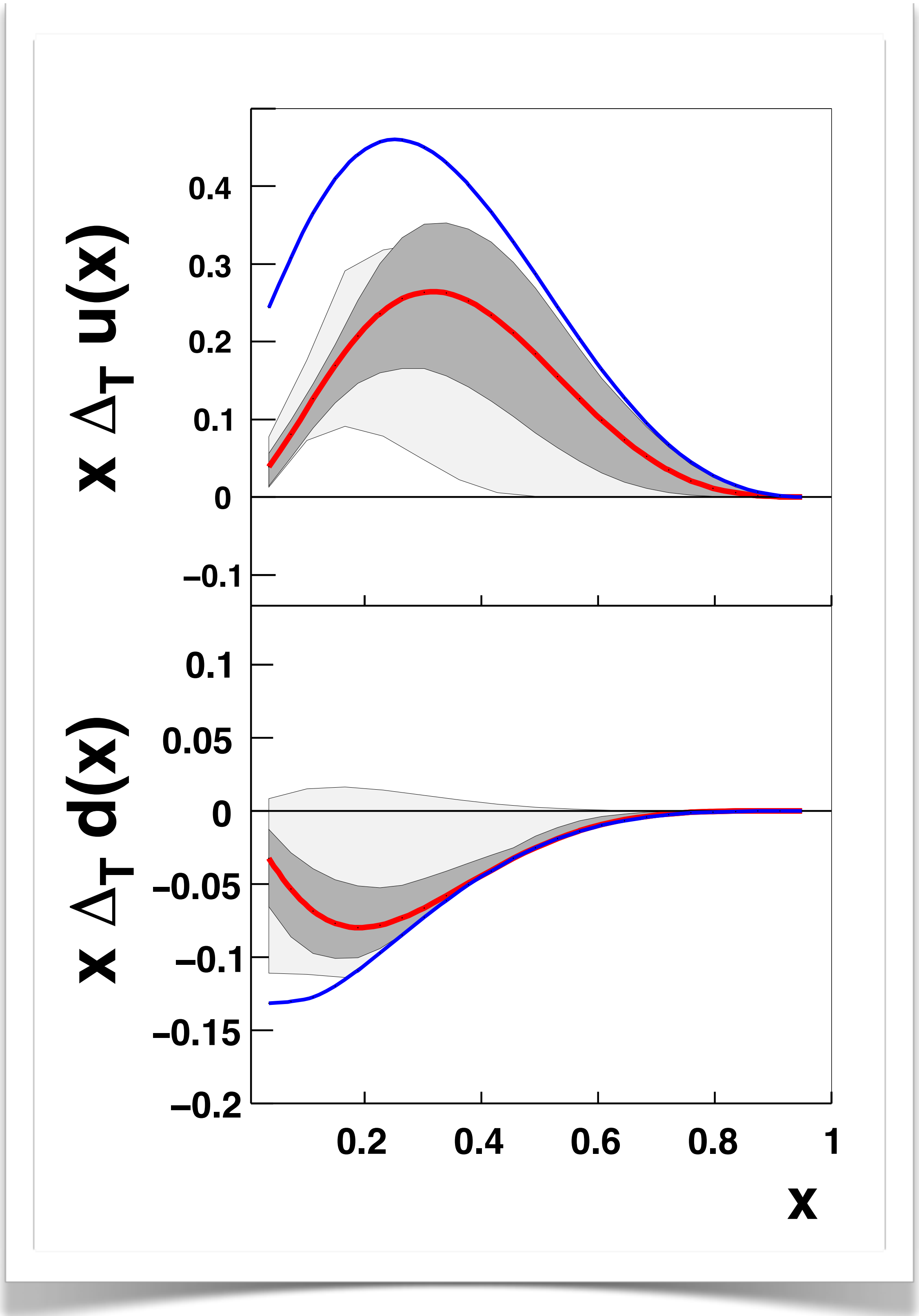
Extractions of transversity



"TMD extraction"
Torino 09

State-of-the-art:
Extractions of transversity



"TMD extraction"
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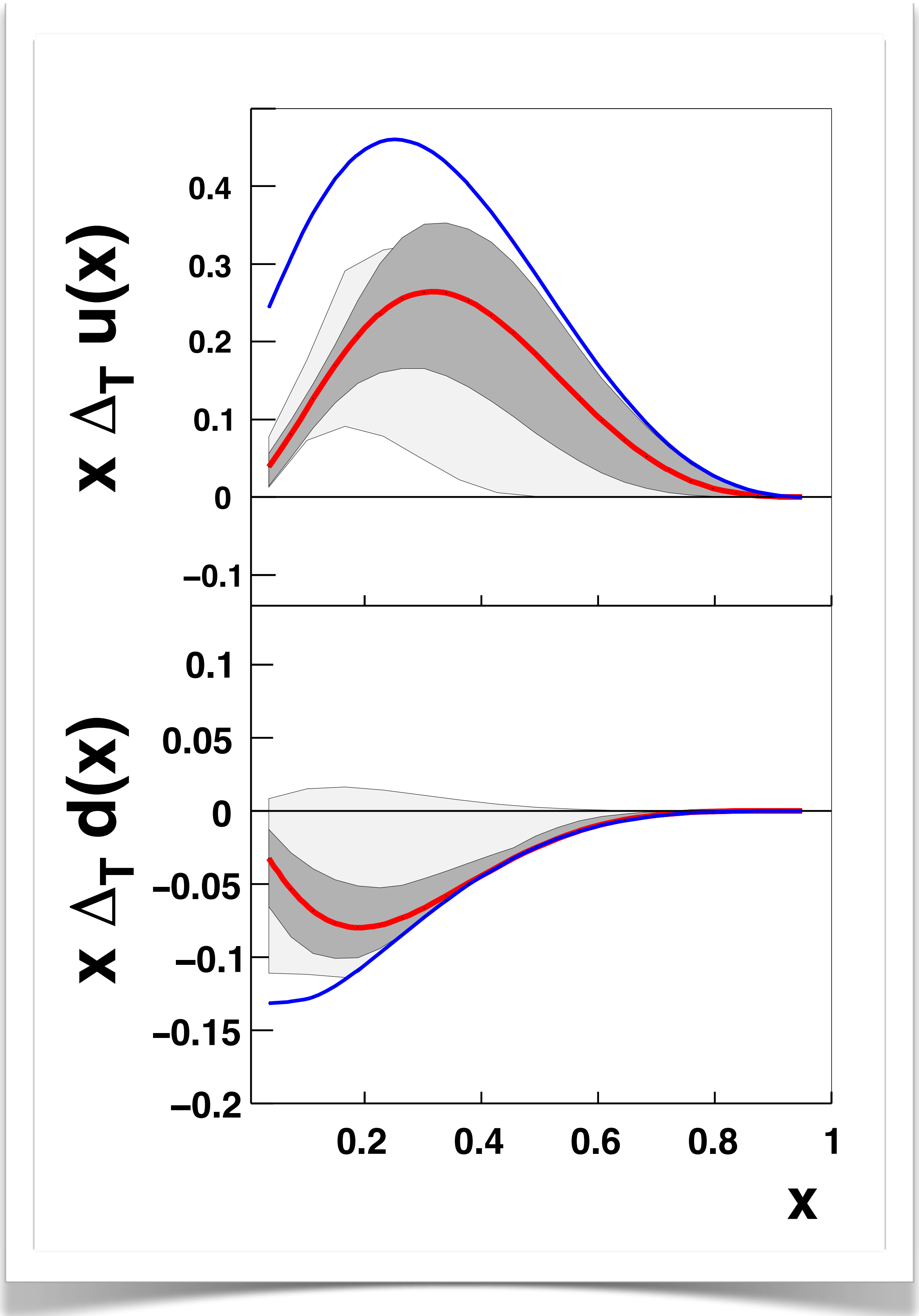
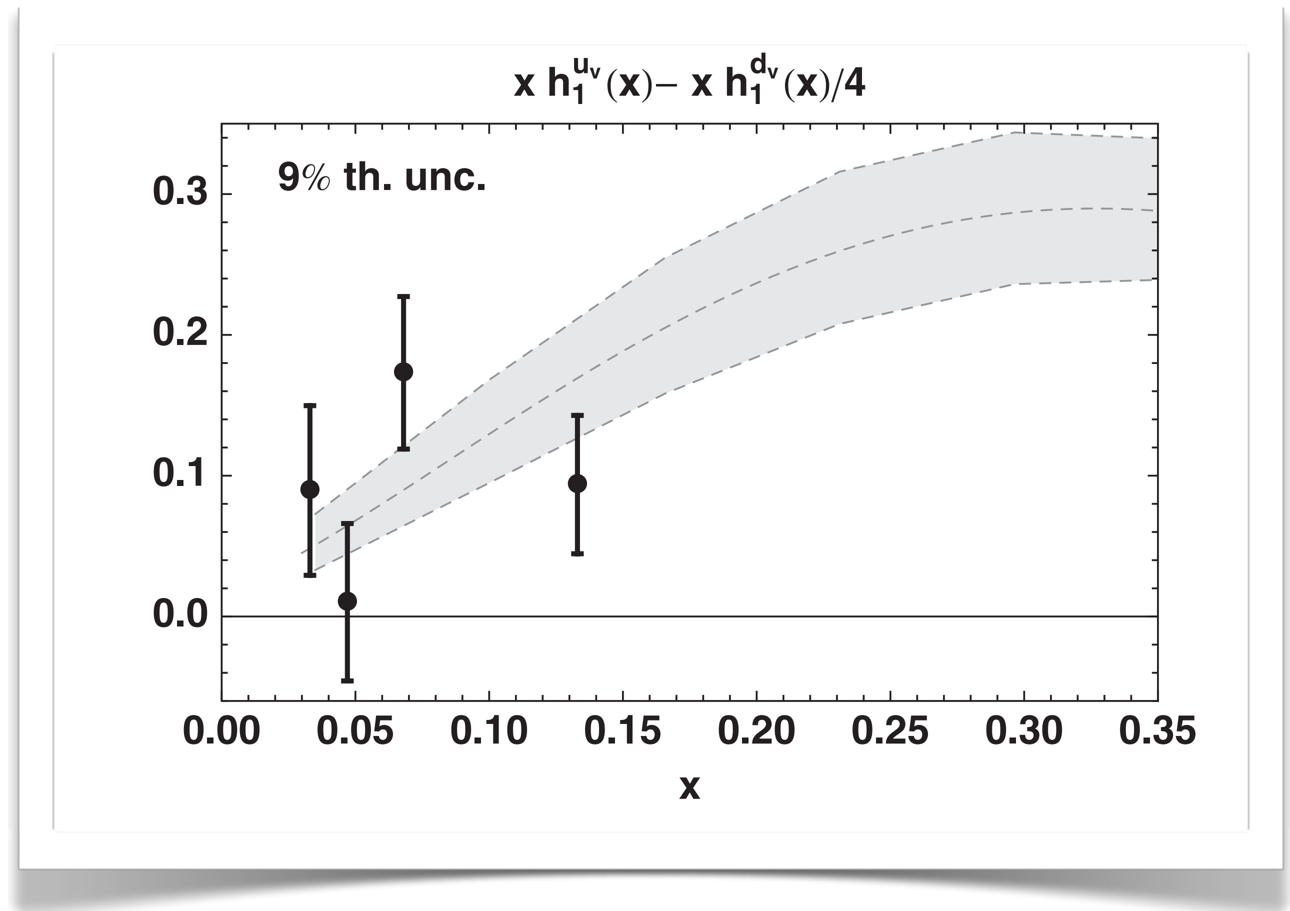
State-of-the-art: Extractions of transversity

"Collinear extraction"
Pavia 11





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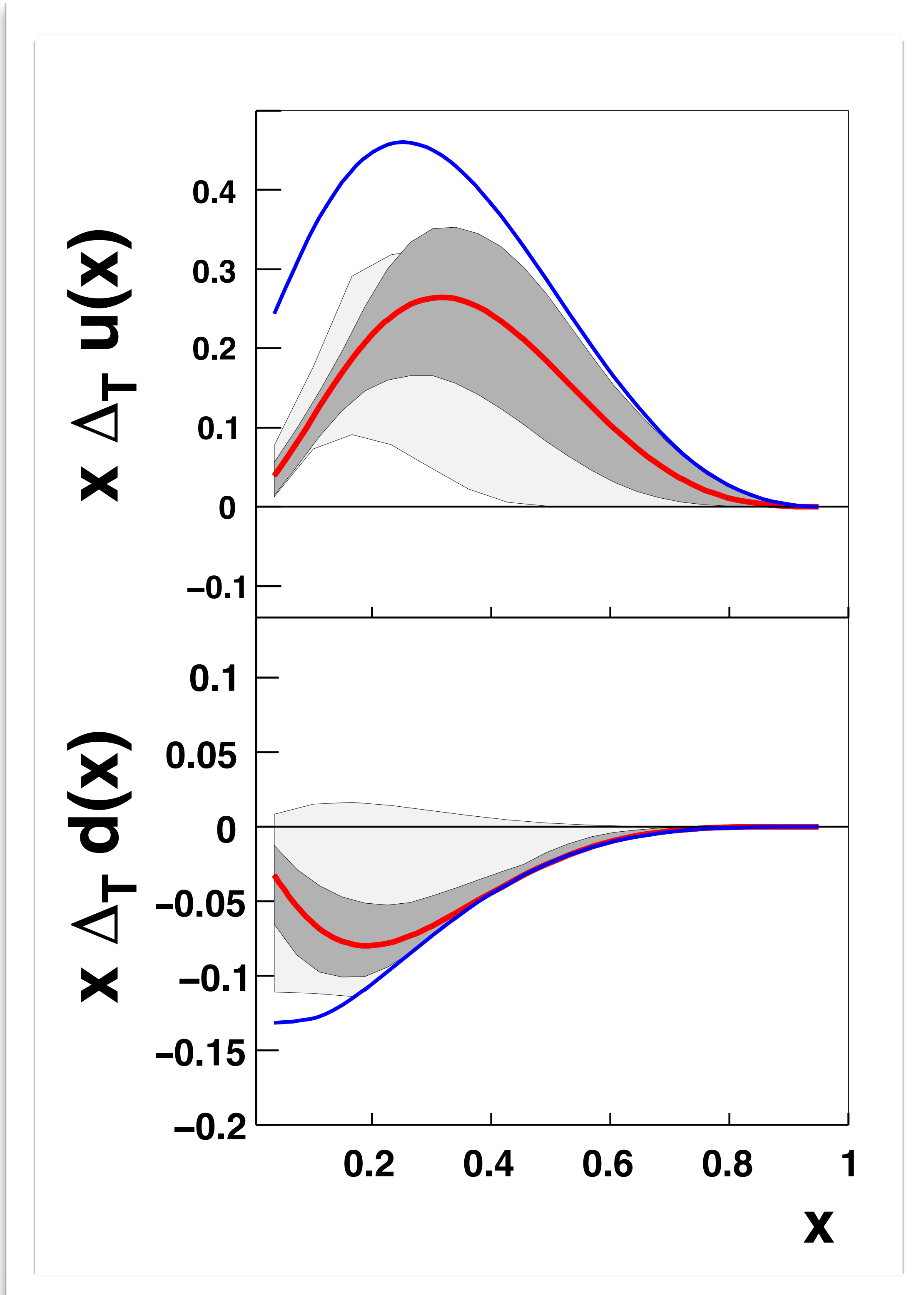
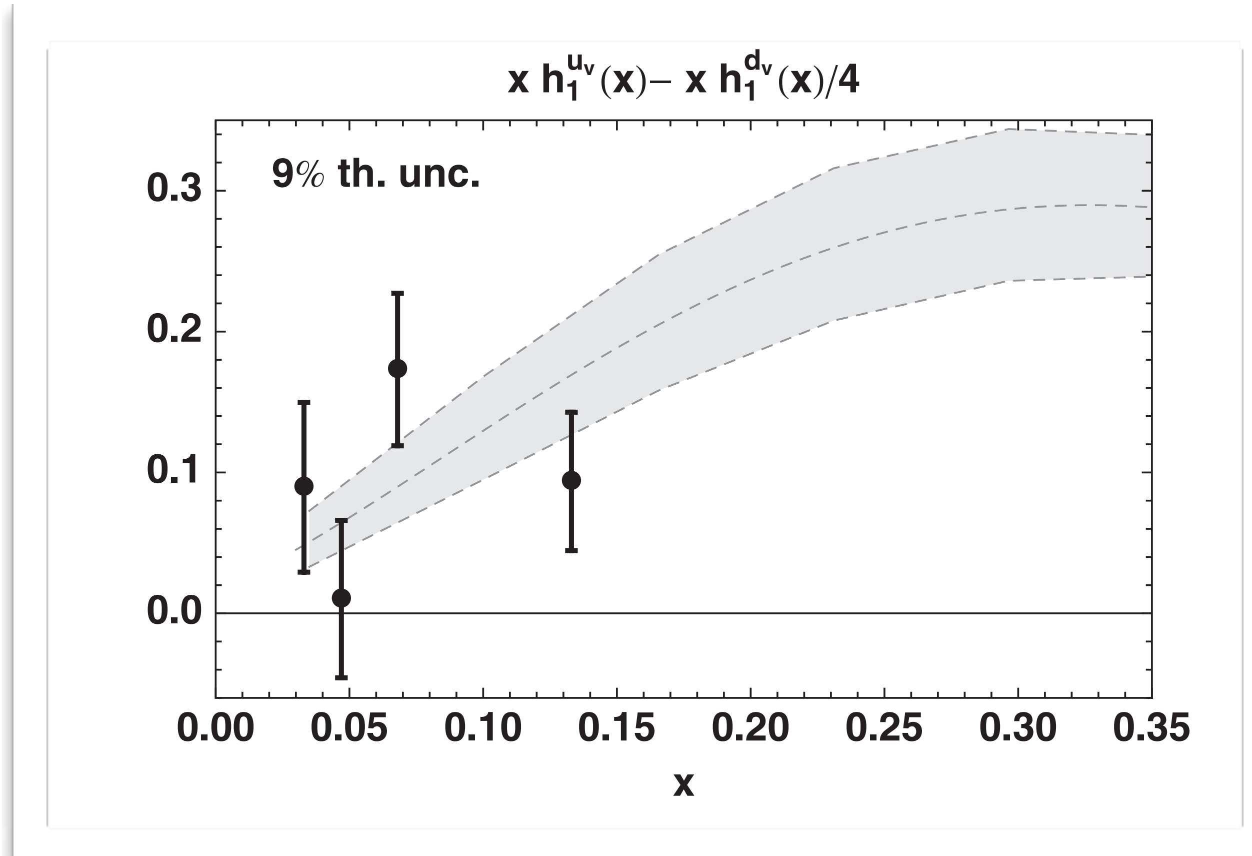


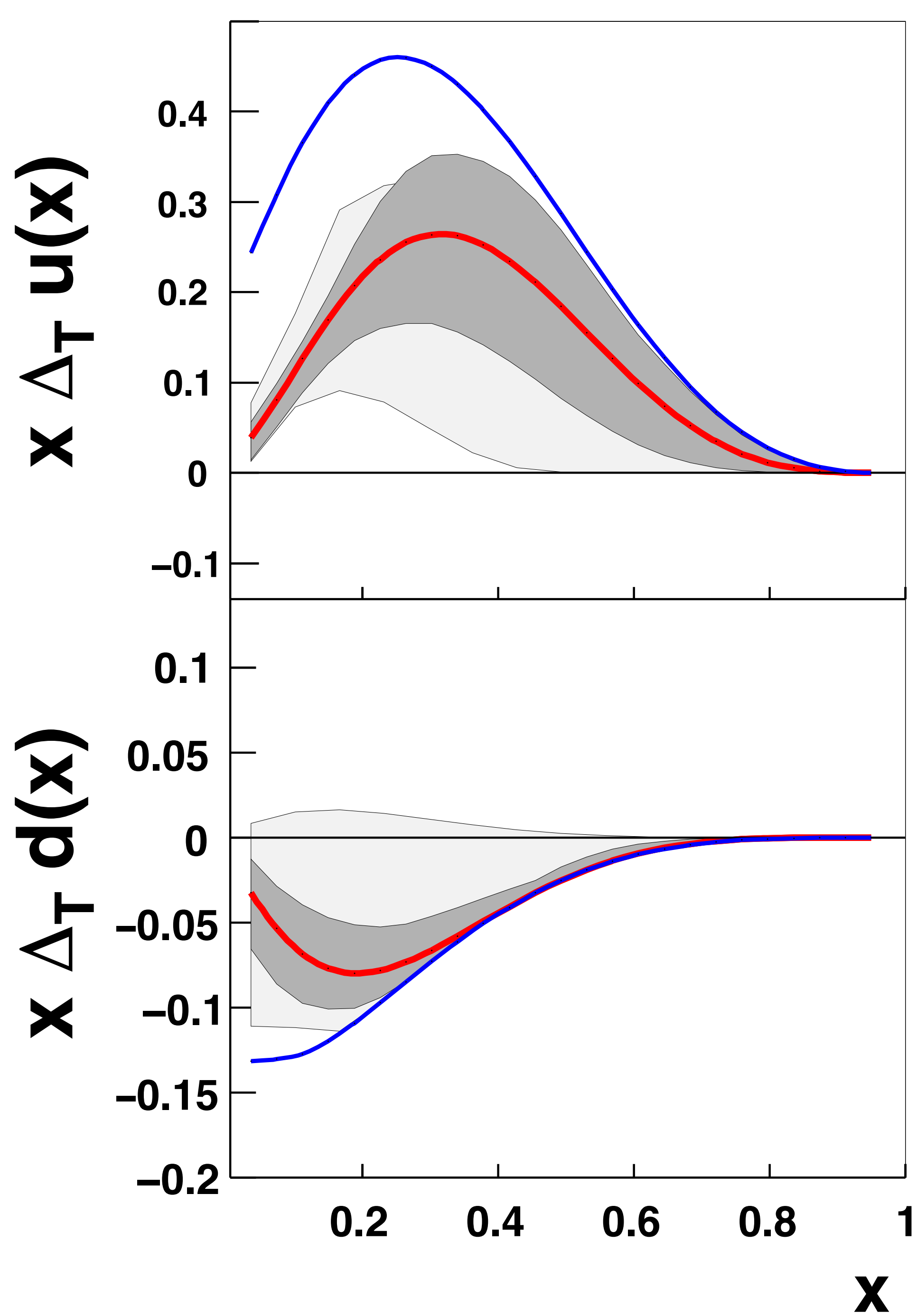


Talk by U. d'Alesio

State-of-the-art: Extractions of transversity

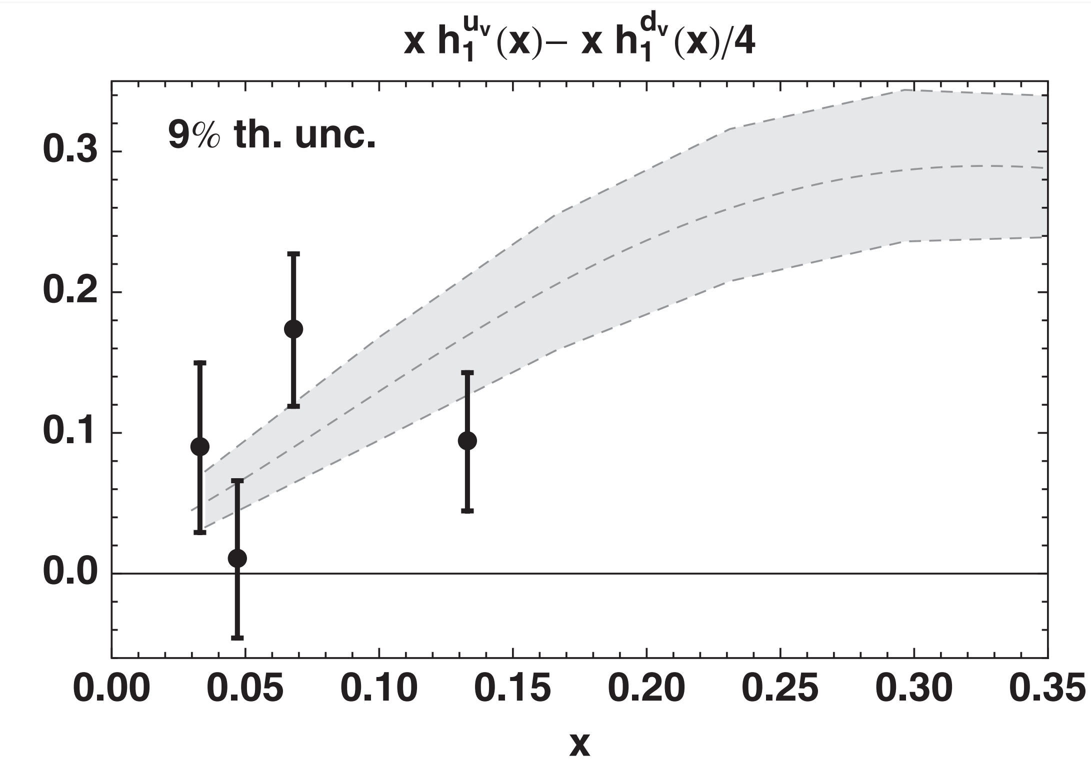
"TMD extraction"
Torino 09

"Collinear extraction"
Pavia 11



Talk by U. d'Alesio

“TMD extraction”
Torino 09



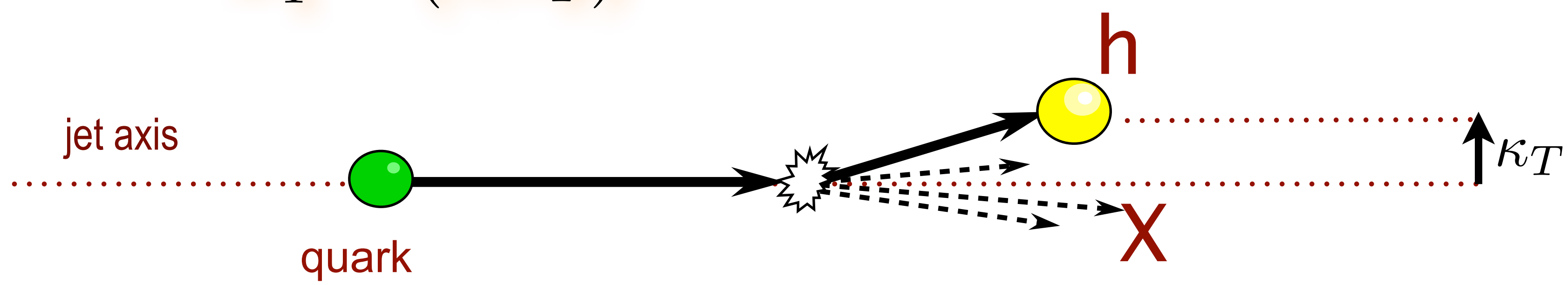
This talk

State-of-the-art: Extractions of transversity

“Collinear extraction”
Pavia 11

Dihadron Fragmentation Functions in a nutshell

✦ **TMD FF** $D_1^{q\to h}\left(z,\kappa_T^2\right)$



TMD factorization

Dihadron Fragmentation Functions in a nutshell

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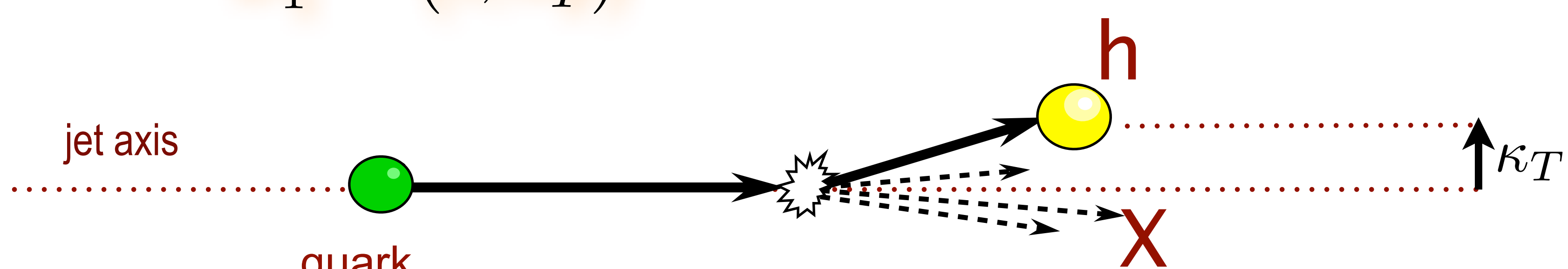
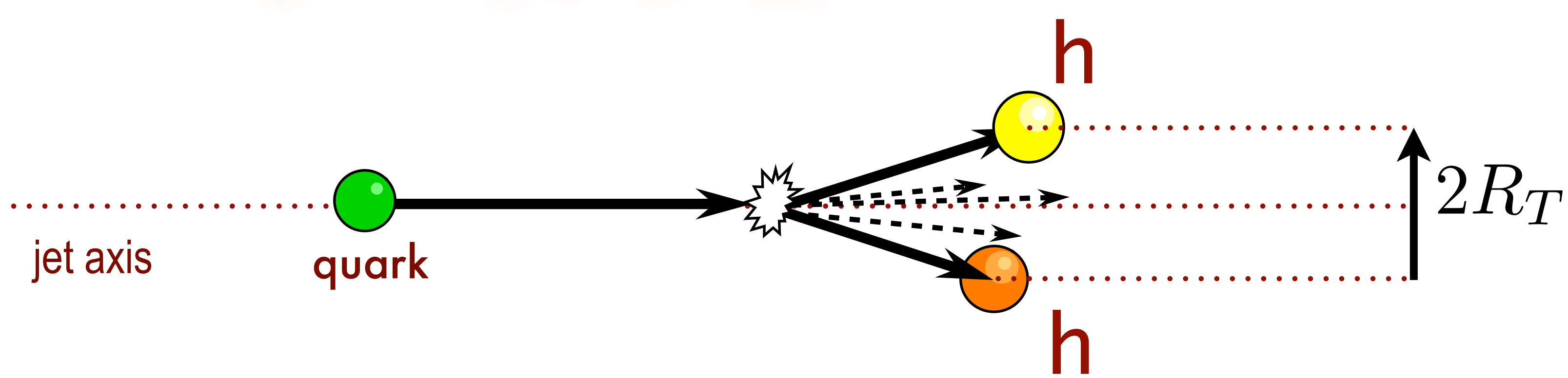


TMD factorization

✦ **DiFF** $D_1^{q\to h_1h_2}\left(z_1,z_2,R_T^2\right)$

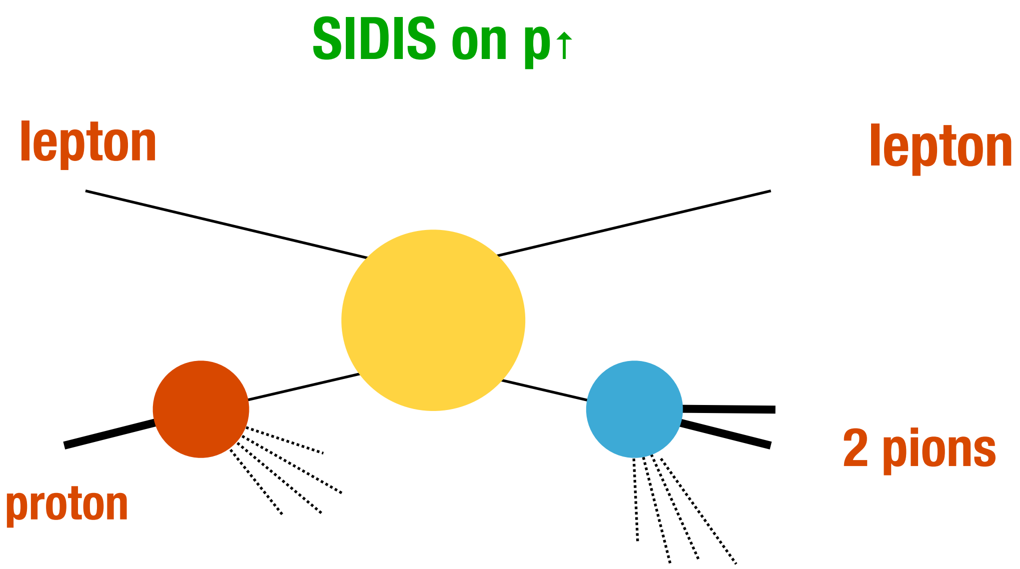


Collinear factorization

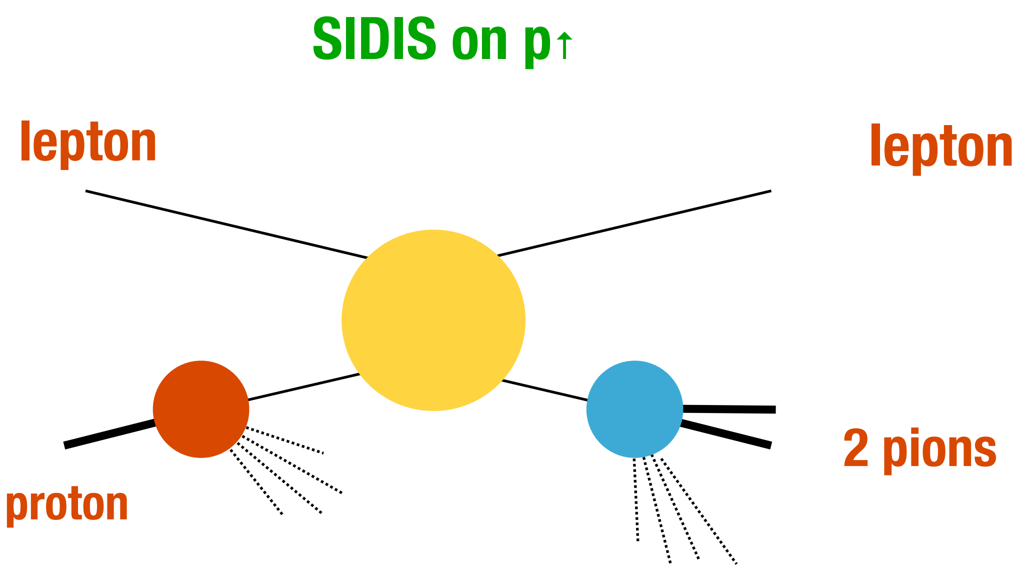
Here: $D_1^{q\to\pi^+\pi^-}(z,M_h)$ $z=z_1+z_2$ $2\,|\mathbf{R}|=\sqrt{M_h^2-4m_\pi^2}$

Frameworks for DiFFs

Frameworks for DiFFs

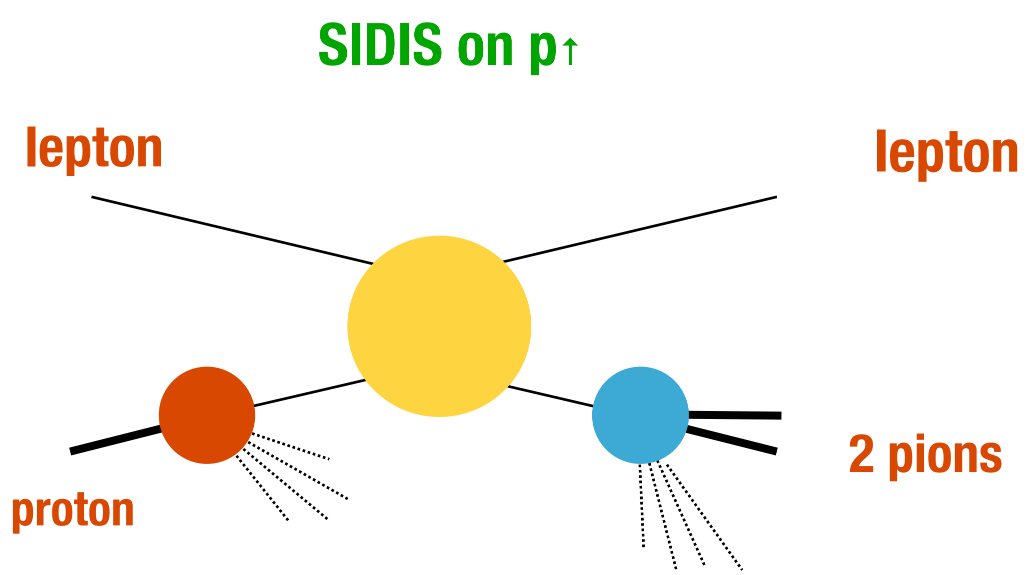


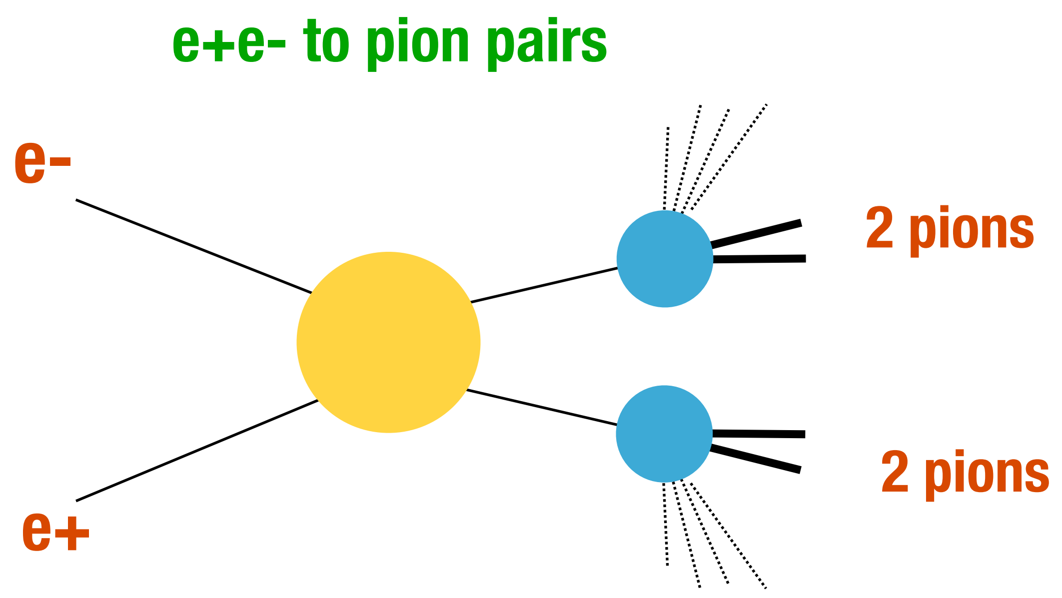
Frameworks for DiFFs



Talks by
M. Diefenthaler
C. Braun
H. Avakian

Frameworks for DiFFs





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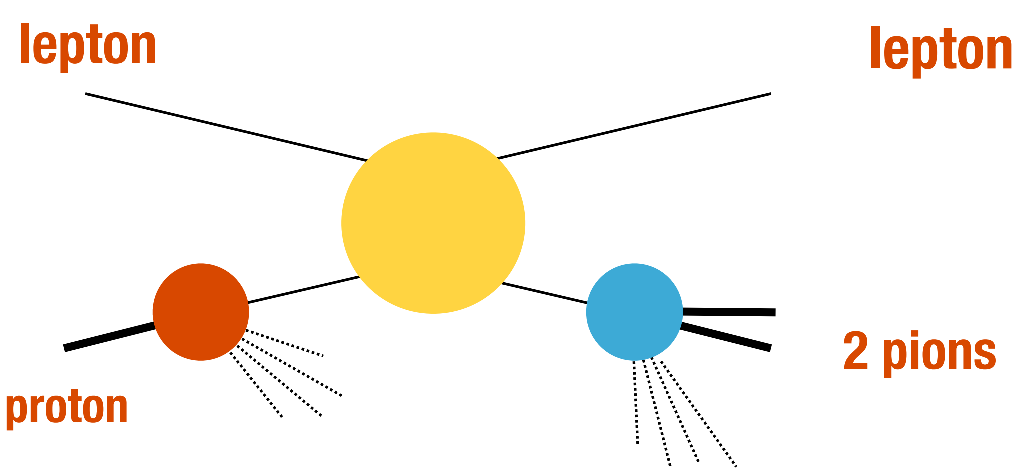
Frameworks for DiFFs

SIDIS on p↑



Talks by
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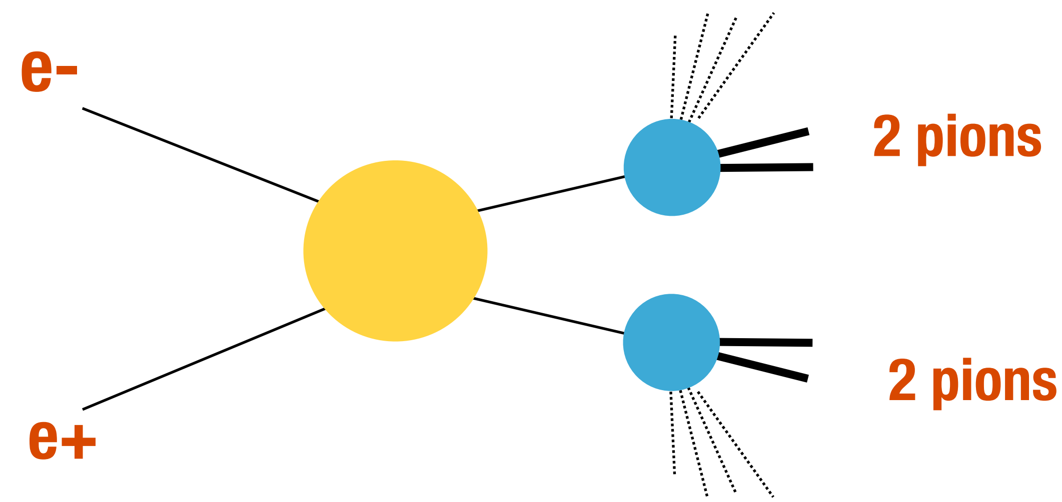
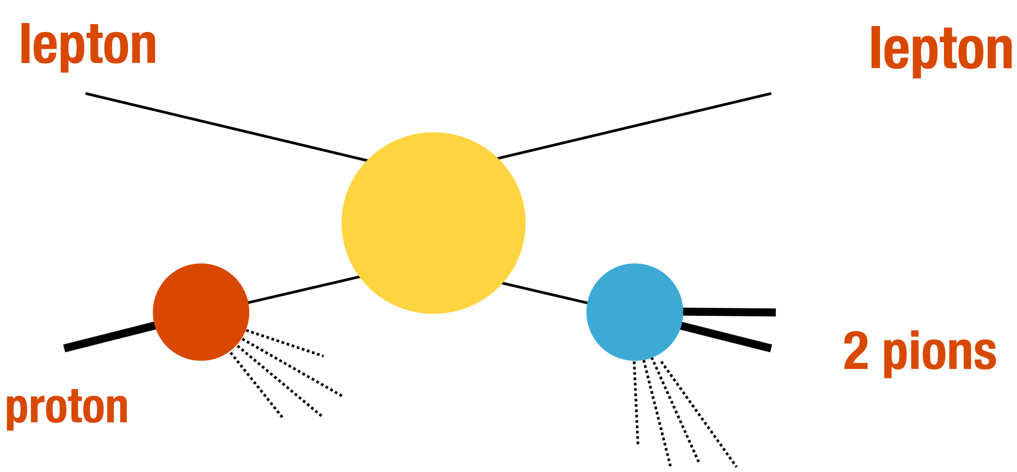
e+e- to pion pairs



Talks by
R. Seidl
I. Garzia

Frameworks for DiFFs

SIDIS on p↑



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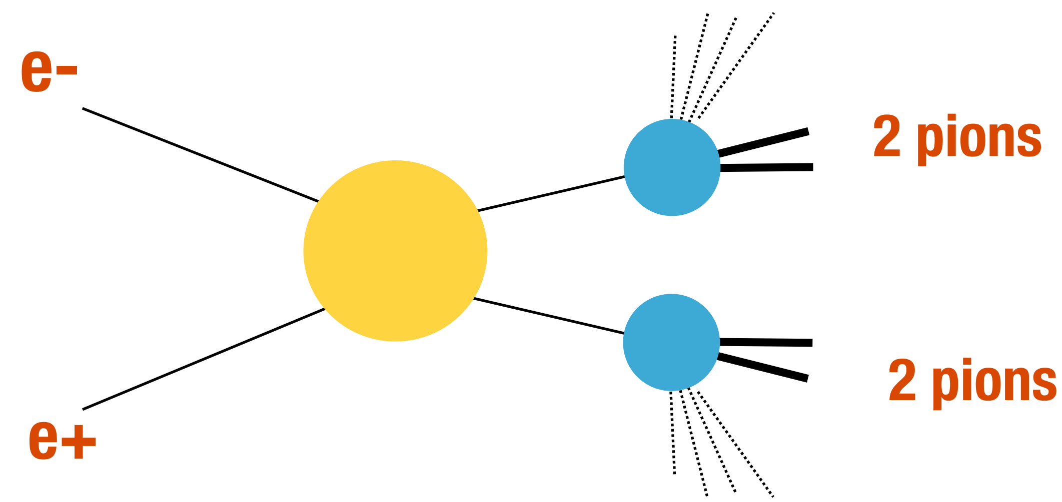

Talks by
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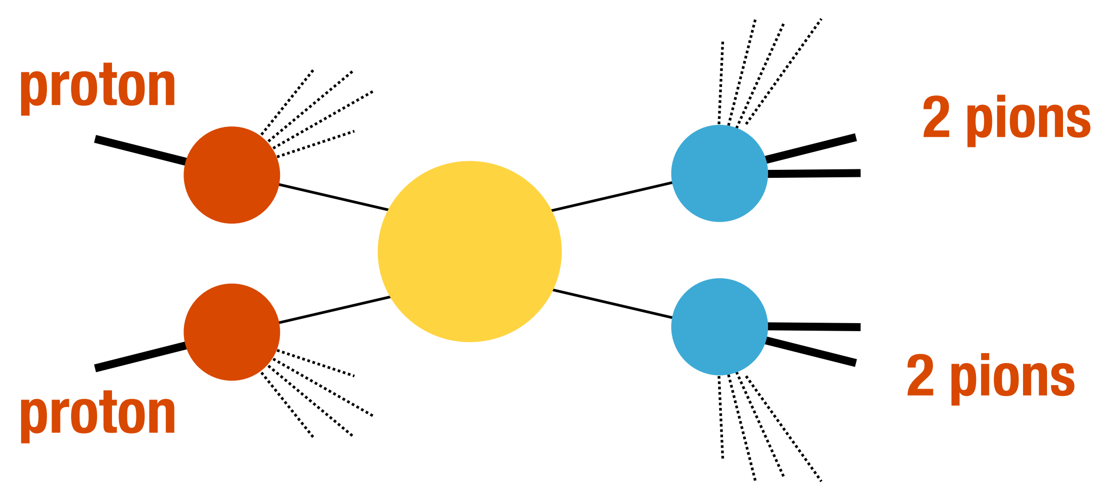
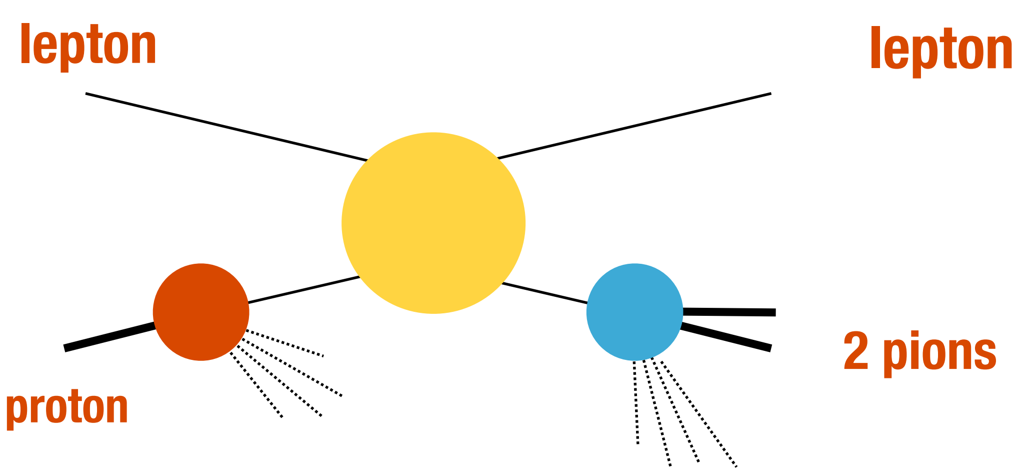
pp↑ to pion pairs



Frameworks for DiFFs

SIDIS on $p^{\uparrow}$



Talks by
M. Diefenthaler
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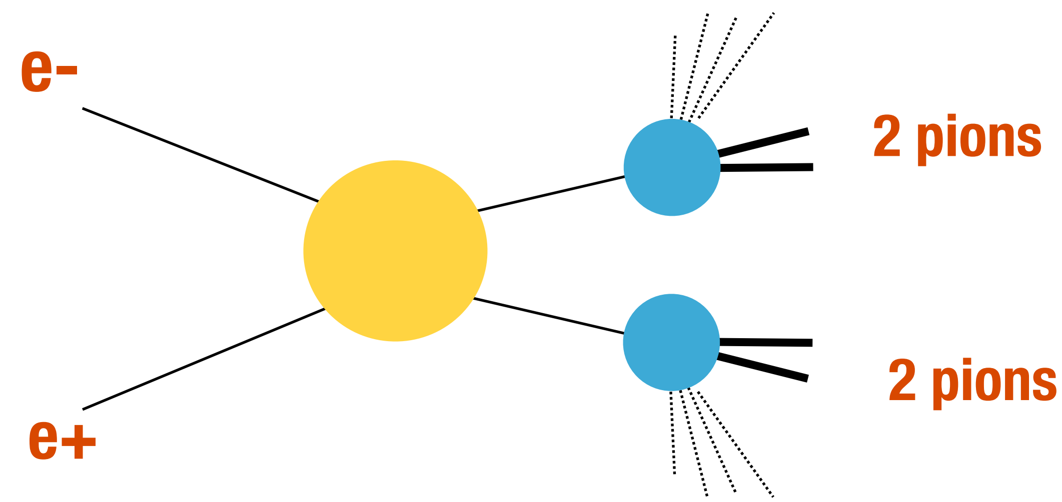
H. Avakian

e+e- to pion pairs



Talks by
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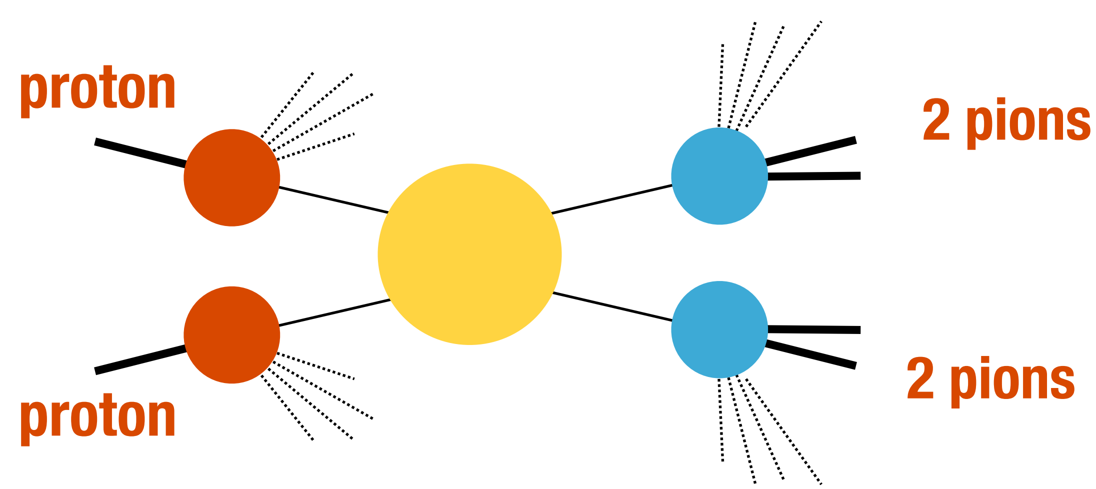
I. Garzia

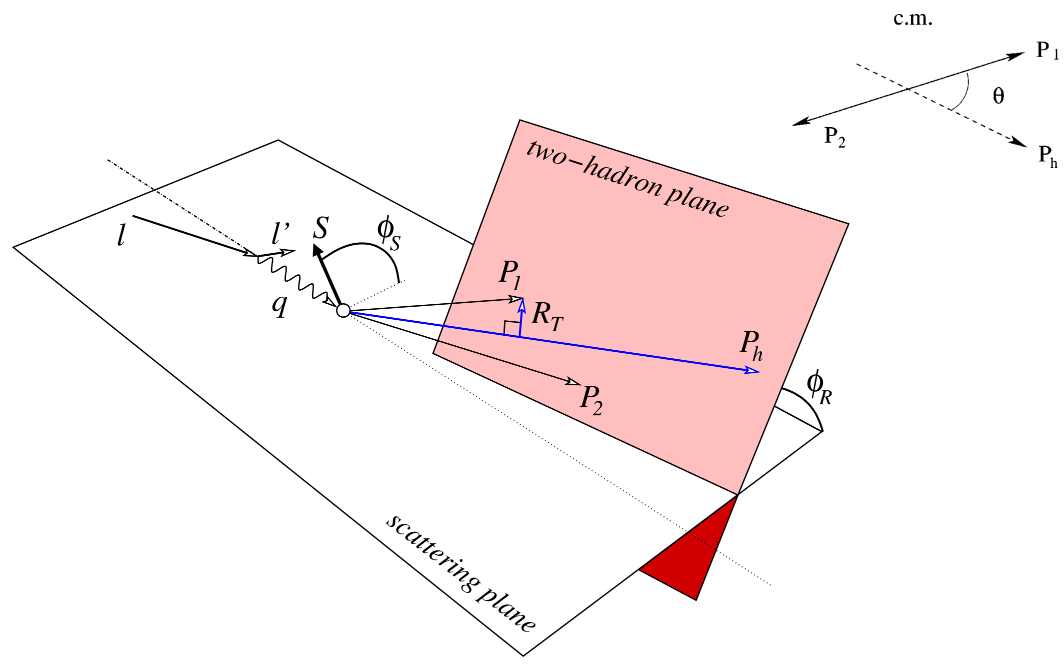
$pp^{\uparrow}$ to pion pairs



- Collinear factorization
- Universality
- No convolution
- Evolution understood

SIDIS production of pion pairs

@ COMPASS & HERMES



Chiral-odd DiFF:

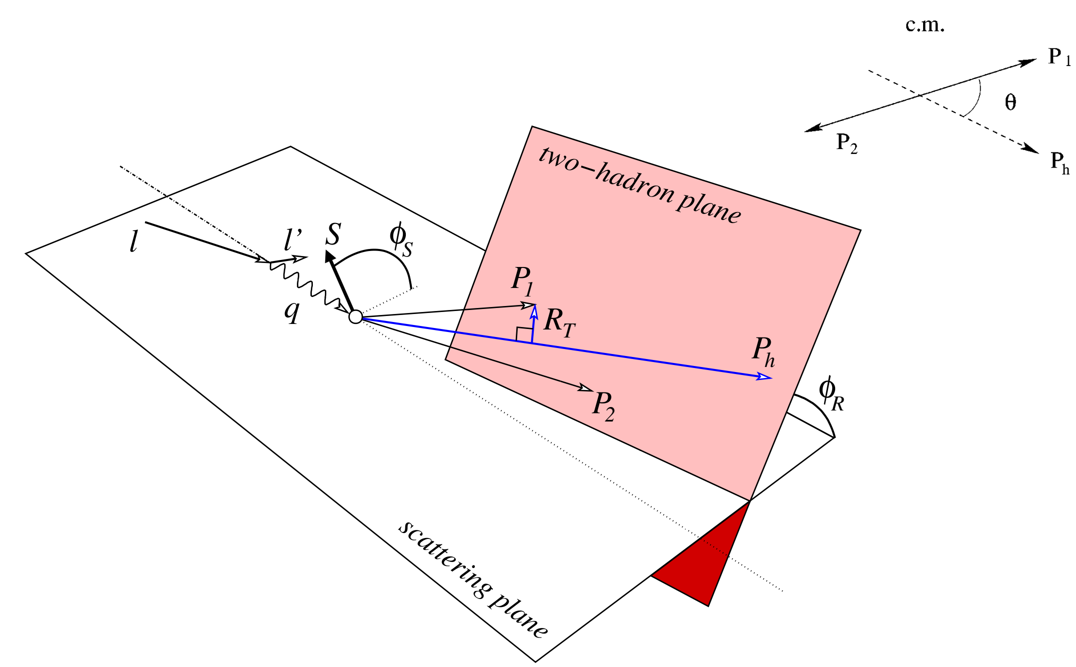
Distribution of hadrons inside the jet
is related to the

Direction of the transverse polarization of the fragmenting quarks

$$A_{\text{DIS}}(x,z,M_h^2,Q^2) = -C_y \frac{\sum_q e_q^2\, h_1^q(x,Q^2)\, \frac{|\bar{R}|}{M_h}\, H_{1,sp}^{q\to\pi^+\pi^-}(z,M_h^2,Q^2)}{\sum_q e_q^2\, f_1^q(x,Q^2) \quad D_1^{q\to\pi^+\pi^-}(z,M_h^2,Q^2)}$$

SIDIS production of pion pairs

@ COMPASS & HERMES



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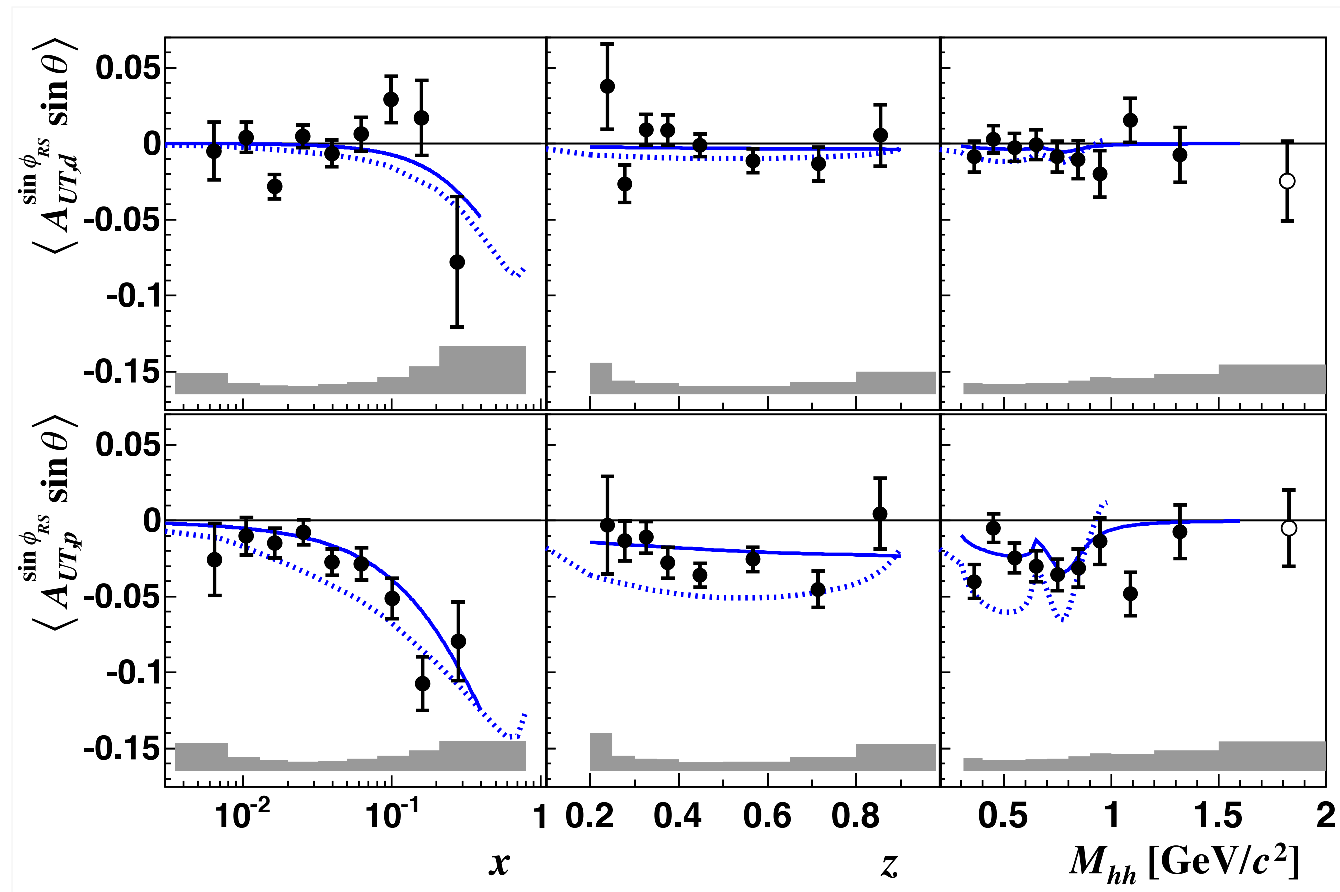
Knowledge on DiFFs leads to $h_1(x, Q^2)$

SIDIS production of pion pairs

@ COMPASS & HERMES

2002-4 Deuteron Data

2007 Proton Data



SIDIS production of pion pairs

@ COMPASS & HERMES

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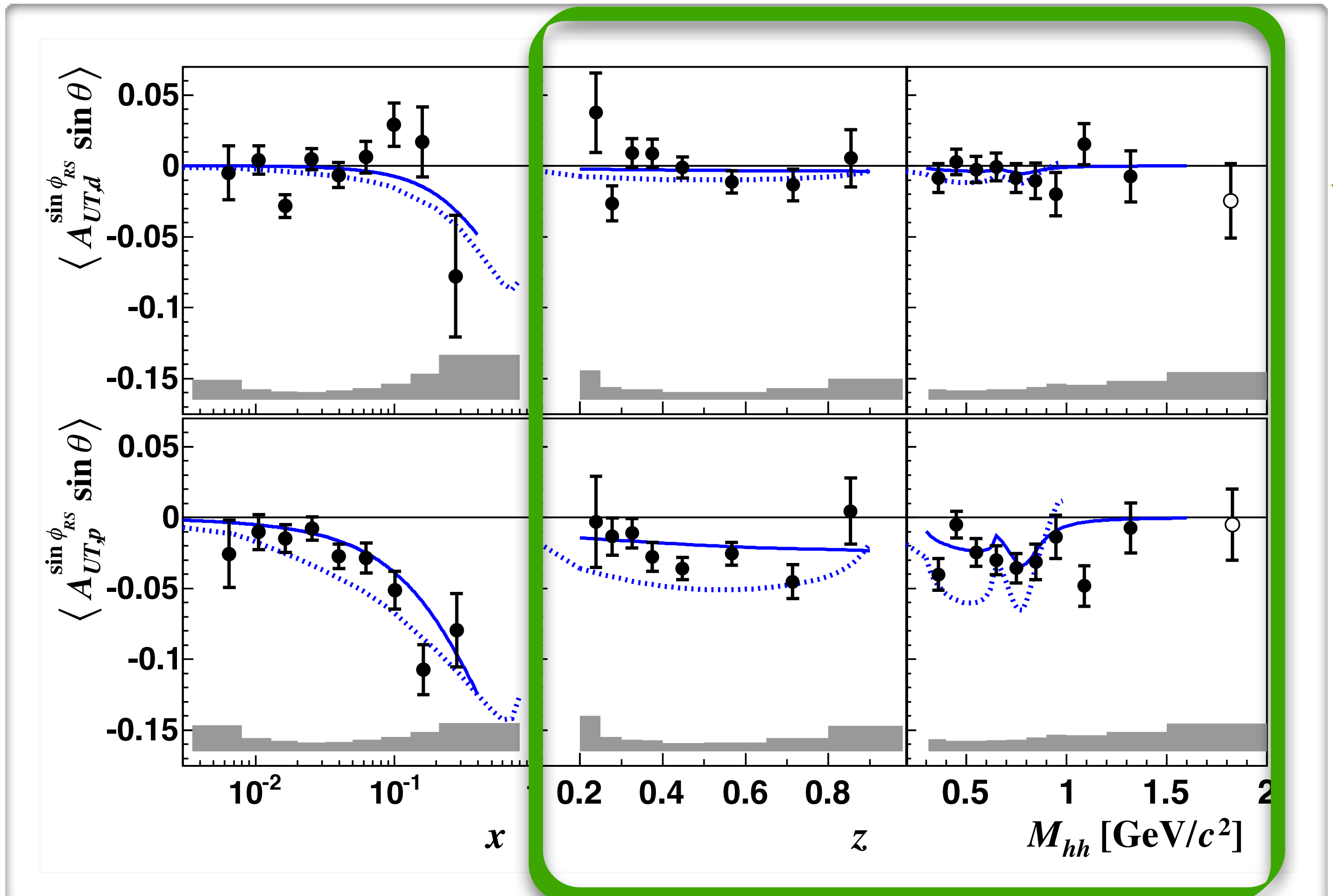

(z, M_h)-dpdence determined by DiFF from Belle

[A.C., Bacchetta, Radici, Bianconi, Phys.Rev. D85]

SIDIS production of pion pairs

@ COMPASS & HERMES

2002-4 Deuteron Data

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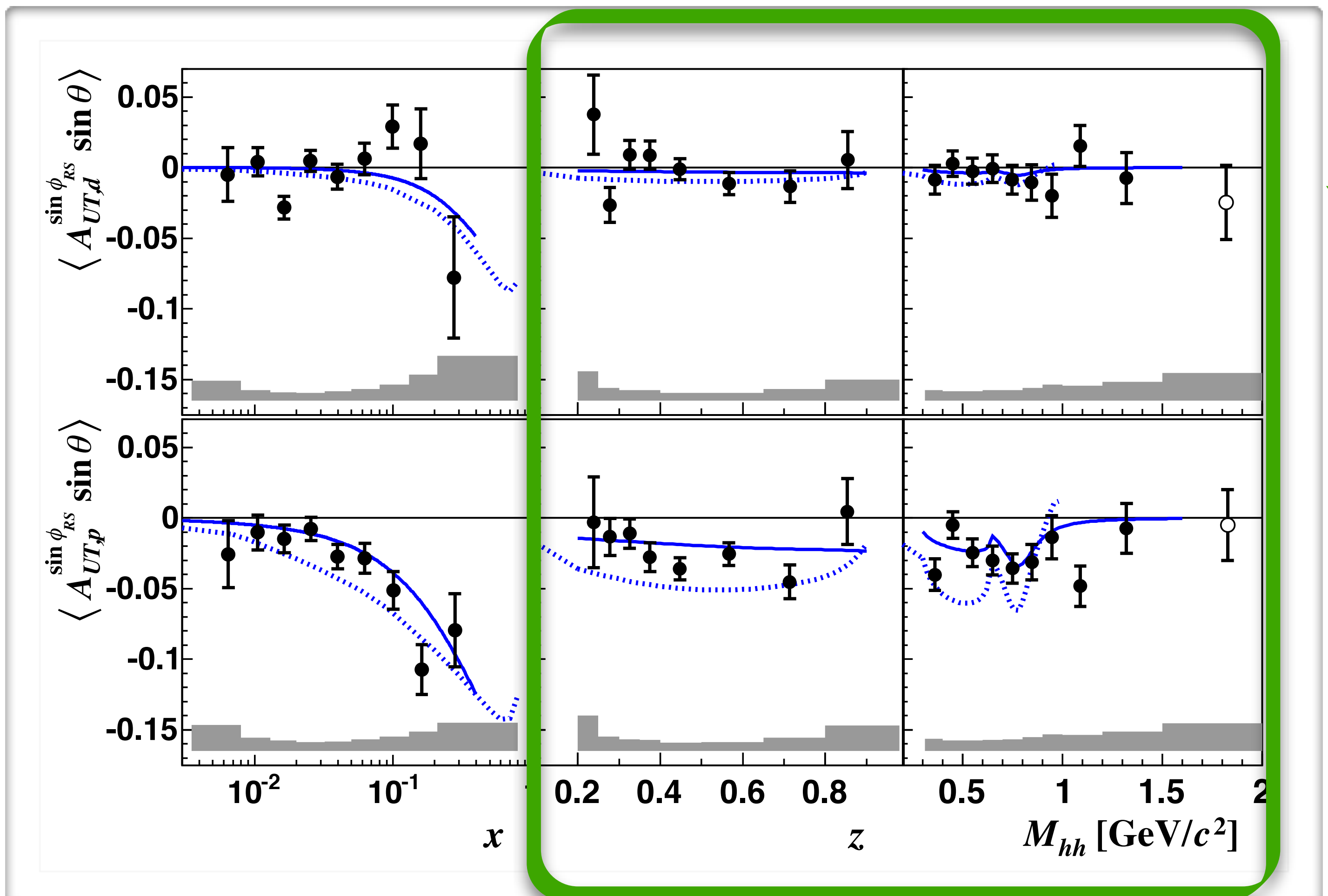


(z, M_h)-dpdence determined by DiFF from Belle

[A.C., Bacchetta, Radici, Bianconi, Phys.Rev. D85]

COMPASS range: $0.2<z<1$ & $0.29<M_h<1.29$ GeV

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

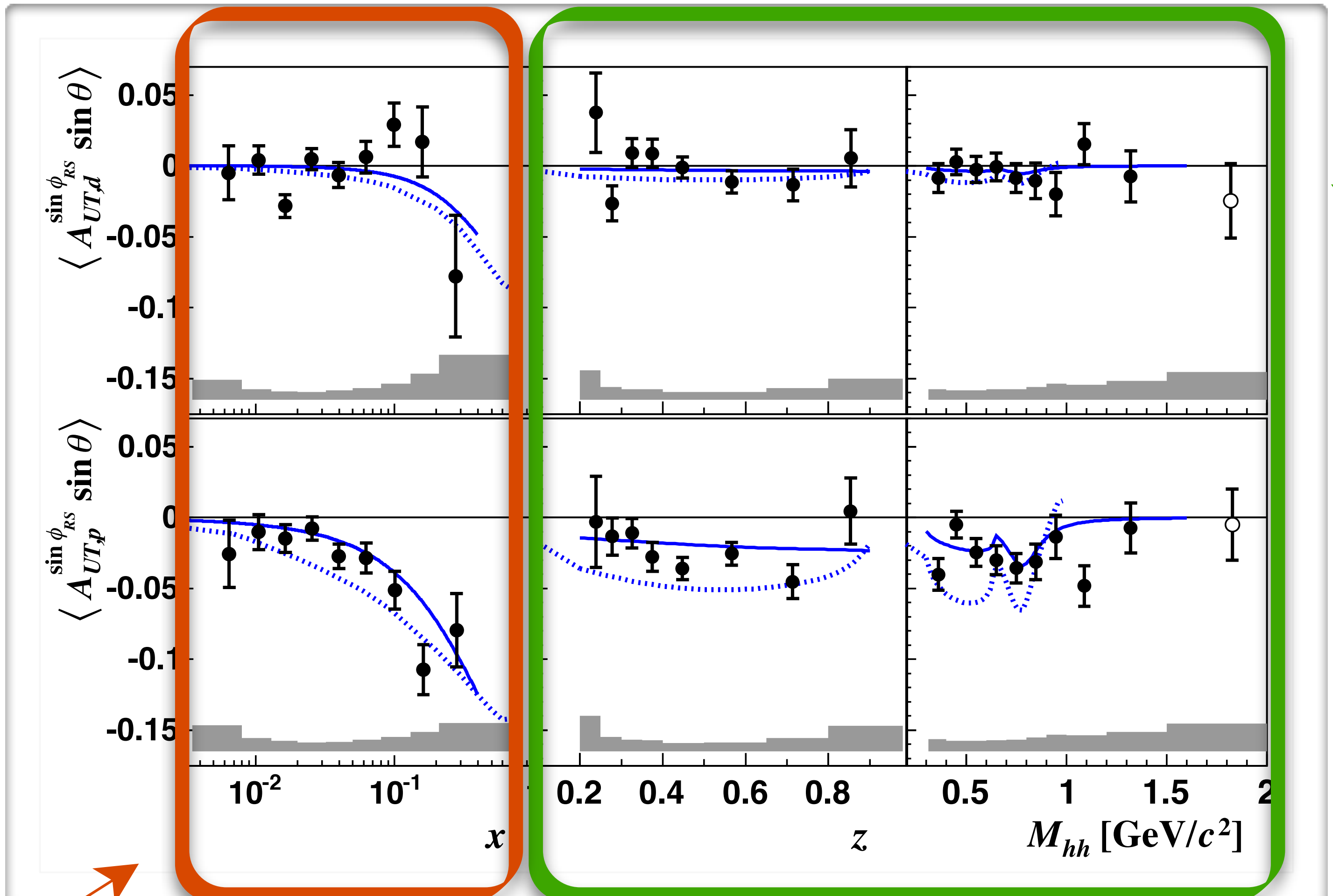
$$n_q^{\uparrow}(Q^2) = \int dz dM_h \, \frac{|\mathbf{R}|}{M_h} \, H_{1,sp}^{\sphericalangle q}(z, M_h; Q^2)$$

SIDIS production of pion pairs

@ COMPASS & HERMES

2002-4 Deuteron Data

2007 Proton Data



(z, M_h)-dpdence determined by DiFF from Belle

[A.C., Bacchetta, Radici, Bianconi, Phys.Rev. D85]

x-dependence only from Transversity

COMPASS range: $0.2<z<1$ & $0.29<M_h<1.29$ GeV

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Transversity from $A_{UT}^{\sin(\Phi_R+\Phi_S)\sin\theta}$

$$A_{\mathrm{DIS}}(x,Q^2) = -C_y \frac{\sum_q e_q^2\, h_1^q(x,Q^2)\, n_q^{\uparrow}(Q^2)}{\sum_q e_q^2\, f_1^q(x,Q^2)\, n_q(Q^2)}$$

Using symmetries for DiFFs:

$$H_1^{\sphericalangle,\,u} = -H_1^{\sphericalangle,\,d} = -\overline{H}_1^{\sphericalangle,\,u} = \overline{H}_1^{\sphericalangle,\,d}$$

$$D_1^u = D_1^d = \overline{D}_1^u = \overline{D}_1^d\,;$$
$$D_1^s = \overline{D}_1^s\,, \quad D_1^c = \overline{D}_1^c$$

Proton

$$x h_1^{u_v}(x,Q^2) - \tfrac{1}{4}\, x h_1^{d_v}(x,Q^2) \propto -A_{\mathrm{DIS}}(x,Q^2)\, \frac{n_u(Q^2)}{n_u^{\uparrow}(Q^2)} \sum_{q=u,d,s} \frac{e_q^2}{e_u^2}\, x f_1^{q+\bar{q}}(x,Q^2)$$

Deuteron

$$x h_1^{u_v}(x,Q^2) + x h_1^{d_v}(x,Q^2) \propto \frac{5}{3} A_{\mathrm{DIS}}(x,Q^2)\, \frac{n_u(Q^2)}{n_u^{\uparrow}(Q^2)}\, x \left(f_1^{u+\bar{u}} + f_1^{d+\bar{d}} + \frac{2}{5} f_1^{s+\bar{s}} \right)$$

and combinations of both ...

Transversity from $A_{UT}^{\sin(\Phi_R+\Phi_S)\sin\theta}$

$$A_{\mathrm{DIS}}(x,Q^2) = -C_y \frac{\sum_q e_q^2\, h_1^q(x,Q^2)\, n_q^{\uparrow}(Q^2)}{\sum_q e_q^2\, f_1^q(x,Q^2)\, n_q(Q^2)}$$

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$$D_1^u = D_1^d = \overline{D}_1^u = \overline{D}_1^d\,;\quad D_1^s = \overline{D}_1^s\,,\quad D_1^c = \overline{D}_1^c$$

Proton

$$xh_1^{u_v}(x,Q^2) - \frac{1}{4}\, xh_1^{d_v}(x,Q^2) \propto -A_{\mathrm{DIS}}(x,Q^2)\frac{n_u(Q^2)}{n_u^{\uparrow}(Q^2)} \sum_{q=u,d,s} \frac{e_q^2}{e_u^2}\, x f_1^{q+\bar{q}}(x,Q^2)$$

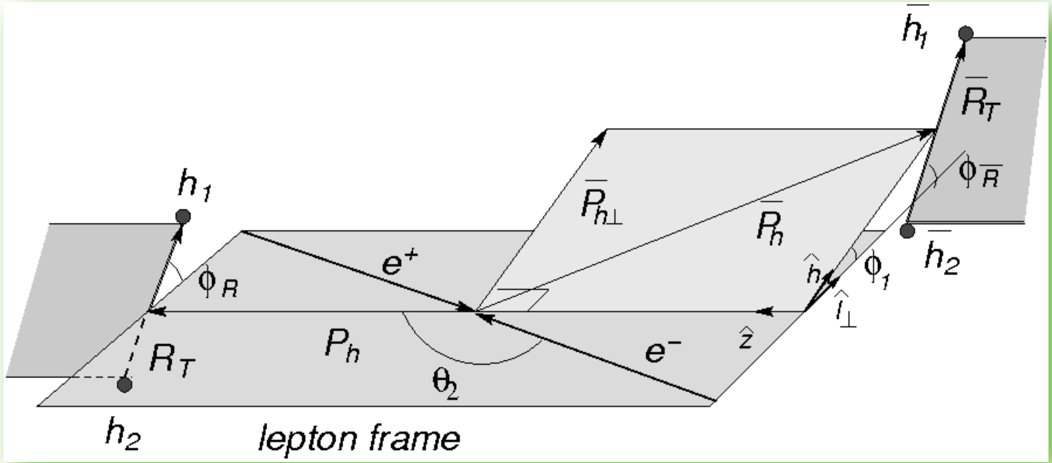
Deuteron

$$xh_1^{u_v}(x,Q^2) + xh_1^{d_v}(x,Q^2) \propto \frac{5}{3} A_{\mathrm{DIS}}(x,Q^2)\frac{n_u(Q^2)}{n_u^{\uparrow}(Q^2)}\, x\left(f_1^{u+\bar{u}} + f_1^{d+\bar{d}} + \frac{2}{5} f_1^{s+\bar{s}}\right)$$

and combinations of both ...

Semi-Inclusive production of pion pair in e+e-annihilation @Belle

[Belle, Phys.Rev.Lett.107.072004]

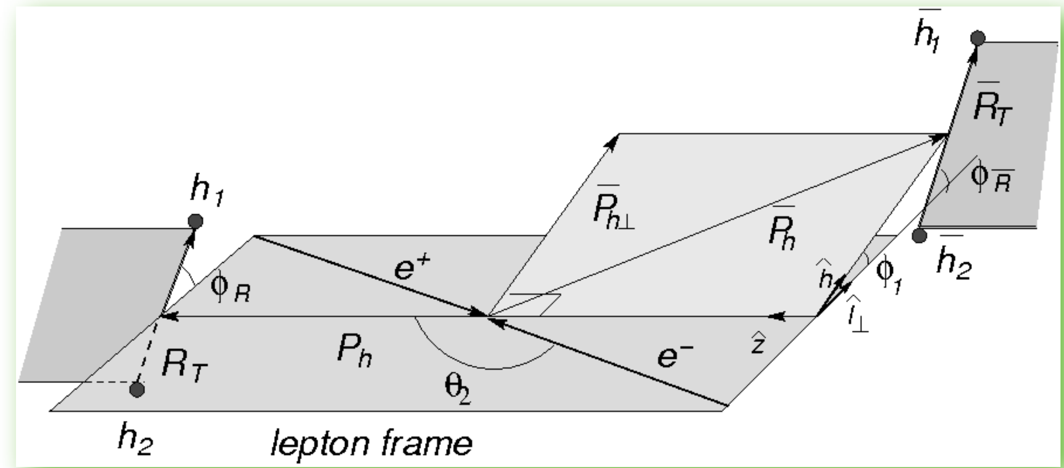


- ✦ 2 hemispheres
- ✦ azimuthal modulation between the 2 hemispheres

$$A_{e+e-}(z, M_h^2, \bar{z}, \bar{M}_h^2) \propto -f\,(\theta_2)\; g\,(\theta)\, g\,(\bar{\theta}) \;\; \frac{\sum_q \, e_q^2 \, H_1^{\sphericalangle\, q}(z, M_h^2) \;\; H_1^{\sphericalangle\, q}(\bar{z}, \bar{M}_h^2)}{\sum_q \, e_q^2 D_1^q(z, M_h^2)\, D_1^q(\bar{z}, \bar{M}_h^2)}$$

Semi-Inclusive production of pion pair in e+e-annihilation @Belle

[Belle, Phys.Rev.Lett.107.072004]



- 2 hemispheres
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$$A_{e+e-}(z, M_h^2, \bar{z}, \bar{M}_h^2) \propto -f(\theta_2)\ g(\theta)\, g(\bar{\theta})\ \frac{\sum_q e_q^2\, H_1^{\sphericalangle\, q}(z, M_h^2)\ H_1^{\sphericalangle\, q}(\bar{z}, \bar{M}_h^2)}{\sum_q e_q^2 D_1^q(z, M_h^2)\, D_1^q(\bar{z}, \bar{M}_h^2)}$$

Two ways of analyzing the DiFFs

- **1st analysis:** direct analysis from experimental data [Bacchetta, A.C., Radici, PRL 107 (2011)]
- **2nd analysis:** analysis from fit of the data [A.C., Bacchetta, Radici, Bianconi, Phys.Rev. D85]

Transversity from e $p^{\uparrow} \rightarrow$ e' ($\pi^+\pi^-$) X @ HERMES

$$x h_1^{u_v}(x,Q^2) - \frac{1}{4}\, x h_1^{d_v}(x,Q^2) = -C_y^{-1}\, A_{\mathrm{DIS}}(x,Q^2)\, \frac{n_u(Q^2)}{n_u^{\uparrow}(Q^2)} \sum_{q=u,d,s} \frac{e_q^2}{e_u^2}\, x f_1^{q+\bar{q}}(x,Q^2)$$

with 1-to-100 GeV^2 evolution correction: small corrections

HERMES range: -0.259^{-1} (± 25% theo. err.) from fit

integrated in mean values

Transversity from e $p^{\uparrow} \to e'$ ($\pi^+\pi^-$) X @ HERMES

$$x h_1^{u_v}(x,Q^2) - \frac{1}{4}\, x h_1^{d_v}(x,Q^2) = -C_y^{-1}\, A_{\rm DIS}(x,Q^2)\, \frac{n_u(Q^2)}{n_u^{\uparrow}(Q^2)} \sum_{q=u,d,s} \frac{e_q^2}{e_u^2}\, x f_1^{q+\bar{q}}(x,Q^2)$$

with 1-to-100 GeV^2 evolution correction: small corrections

HERMES range: -0.259^{-1} (± 25% theo. err.) from fit

integrated in mean values

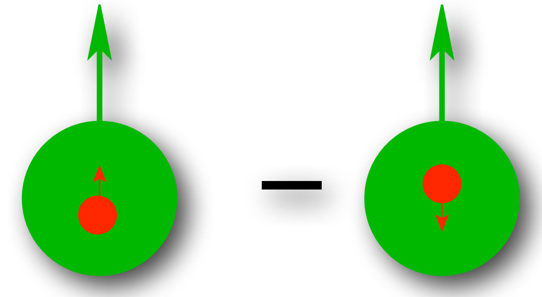
Transversity from e $p^{\uparrow} \to e'$ ($\pi^+\pi^-$) X @ COMPASS 2007

$$x h_1^{u_v}(x,Q^2) - \frac{1}{4}\, x h_1^{d_v}(x,Q^2) = -C_y^{-1}\, A_{\rm DIS}(x,Q^2)\, \frac{n_u(Q^2)}{n_u^{\uparrow}(Q^2)} \sum_{q=u,d,s} \frac{e_q^2}{e_u^2}\, x f_1^{q+\bar{q}}(x,Q^2)$$

with 1-to-100 GeV^2 evolution correction: negligible corrections

COMPASS range: -0.208^{-1} (± 19% theo. err.) from fit

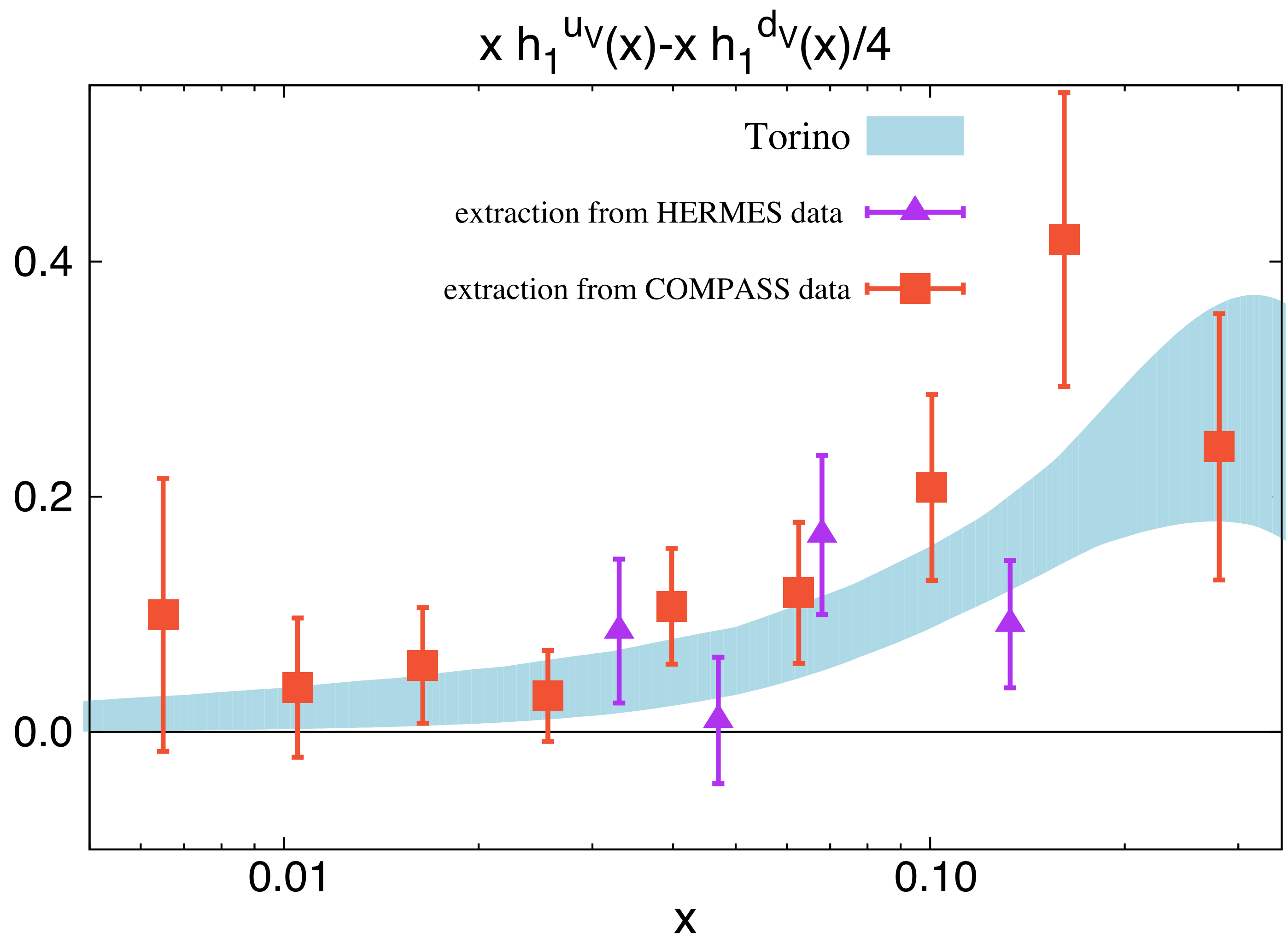
Transversity from Proton data



Transversity from pion pair production SIDIS off transversely polarized target

- from HERMES data
- DiFF analysis
  point by point from fit
- PRL107

- from COMPASS data
- DiFF analysis
  point by point from fit
- new analysis

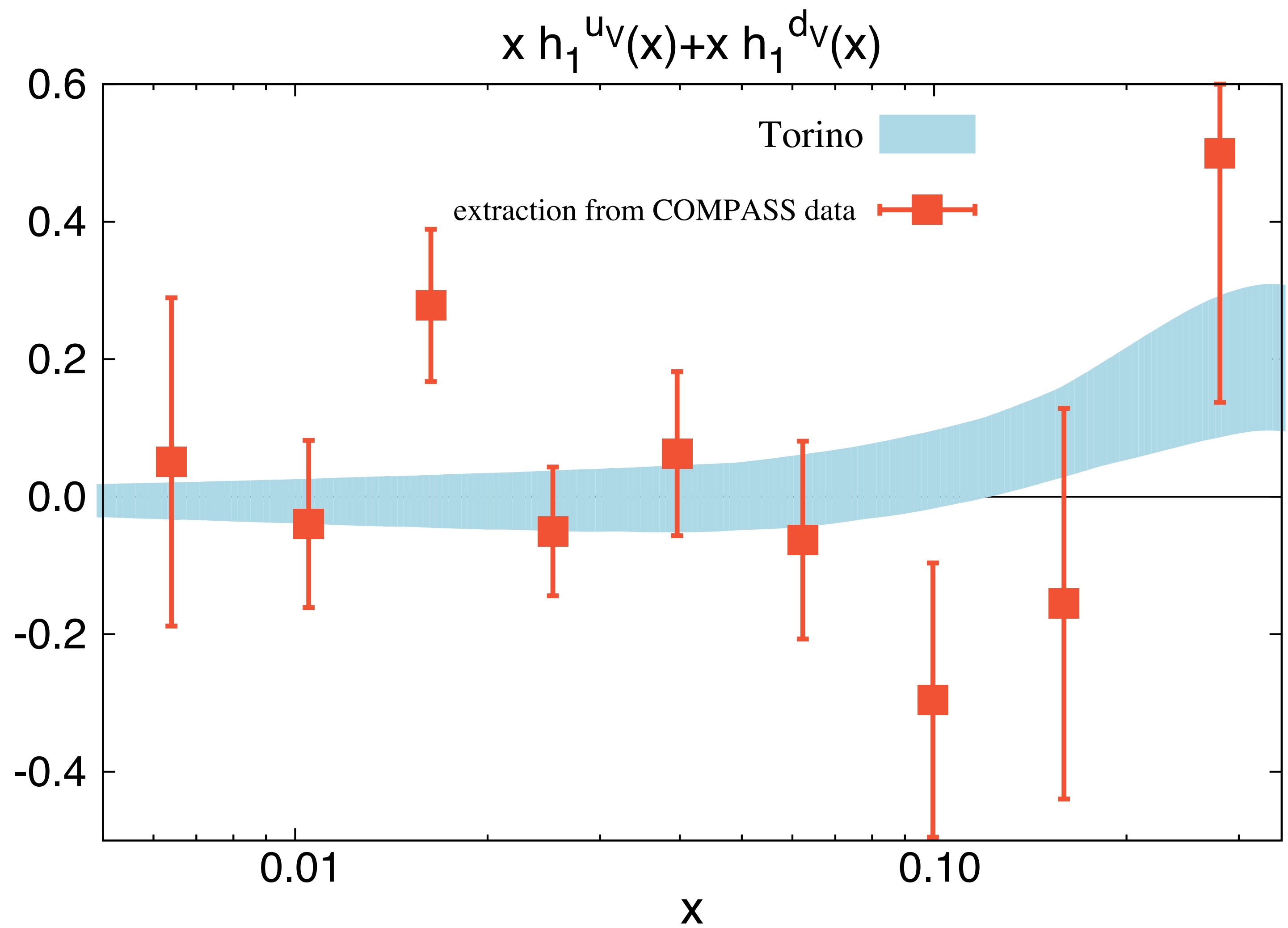


Band:
Torino 2009 transversity

$f_1(x)$ from MSTW08

Transvertsity from Deuteron data

COMPASS 2002-2004



- from COMPASS data
- DiFF analysis

  point by point from fit
- new analysis

Band:
Torino 2009 transversity

$f_1(x)$ from MSTW08

Fitting the Valence Transversities

Fitting the Valence Transversities

Constraints from first principles

✦ Soffer bound

$$2|h_1^q(x,Q^2)| \le |f_1^q(x,Q^2) + g_1^q(x,Q^2)| \equiv 2\,\mathrm{SB}^q(x,Q^2)$$

✦ $h_1(x=1)=0$; the parton model predicts $h_1(x=0)=0$ but too restrictive in QCD

Fitting the Valence Transversities

Constraints from first principles

- ✦ **Soffer bound**

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

- ✦ **$h_1(x=1)=0$** ; the parton model predicts $h_1(x=0)=0$ but too restrictive in QCD

QCD evolution with HOPPET code

- ✦ **of the Soffer bound:** LO evolution of $f_1(x)$ from MSTW08 & $g_1(x)$ from DSS

- ✦ **of the DiFF & h_1:** LO as in previous papers

Fitting the Valence Transversities

Constraints from first principles

- ✦ Soffer bound

$$2|h_1^q(x,Q^2)| \le |f_1^q(x,Q^2) + g_1^q(x,Q^2)| \equiv 2\,\mathrm{SB}^q(x,Q^2)$$

- ✦ $h_1(x=1)=0$; the parton model predicts $h_1(x=0)=0$ but too restrictive in QCD

QCD evolution with HOPPET code

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$$x\, h_1^{q_V}(x,Q_0^2) = FF(\mathrm{param}, x, Q_0^2)\,\left(x\,\mathrm{SB}^q(x,Q_0^2) + x\,\mathrm{SB}^{\bar{q}}(x,Q_0^2)\right)$$

with FF defined [-1,1]

Fitting the Valence Transversities

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The Functional Form

$$x\, h_1^{q_V}(x) = \tanh\left(x^{1/2}\,(A_q + B_q\, x + C_q\, x^2)\right)\,\left(x\,\mathrm{SB}^q(x) + x\,\mathrm{SB}^{\bar{q}}(x)\right)/2$$

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judicious choice for integrability of the transversities

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2nd order polynomial

$$A_u + B_u\, x + C_u\, x^2 \qquad A_d + B_d\, x + C_d\, x^2$$

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Hybrid up 2nd -down 1st order polynomial

$$A_u + B_u\,x + C_u\,x^2 \qquad A_d + B_d\,x$$

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1st order polynomial

$$A_u + B_u\, x \qquad A_d + B_d\, x$$

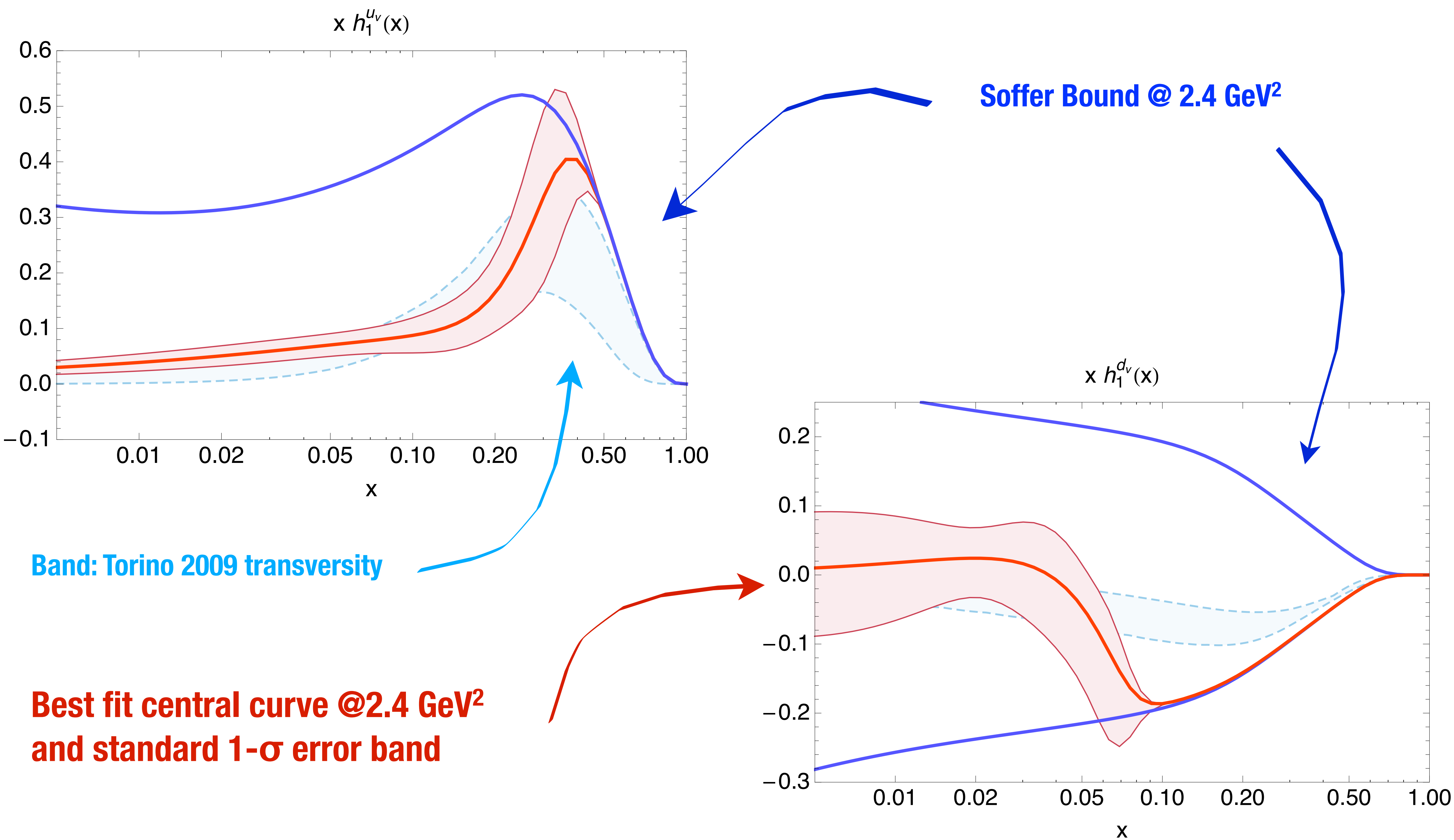
$$\chi^2/d.o.f. \simeq 1.1$$

Hybrid up 2nd -down 1st order polynomial

no significant change in the χ^2/dof in the 3 versions

$$A_u + B_u\, x + C_u\, x^2 \qquad A_d + B_d\, x$$

Our Flexible Functional Form *2nd order polynomial*



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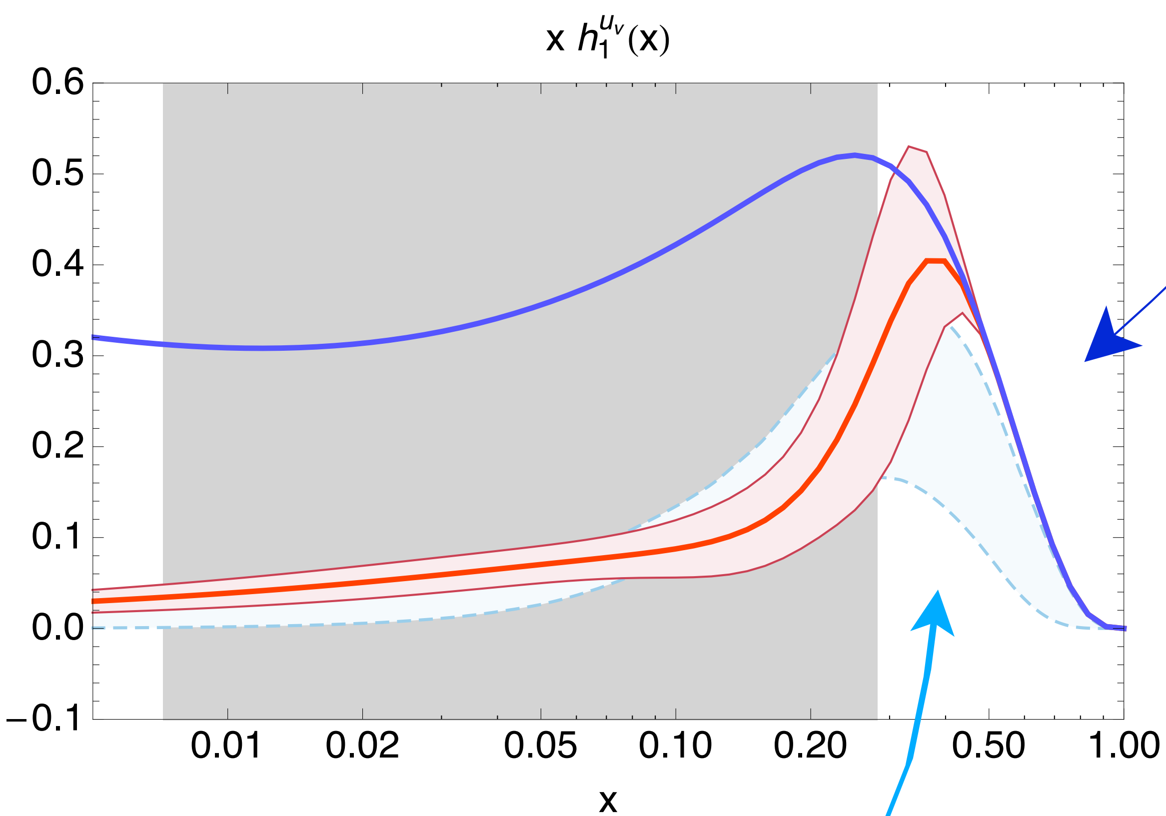
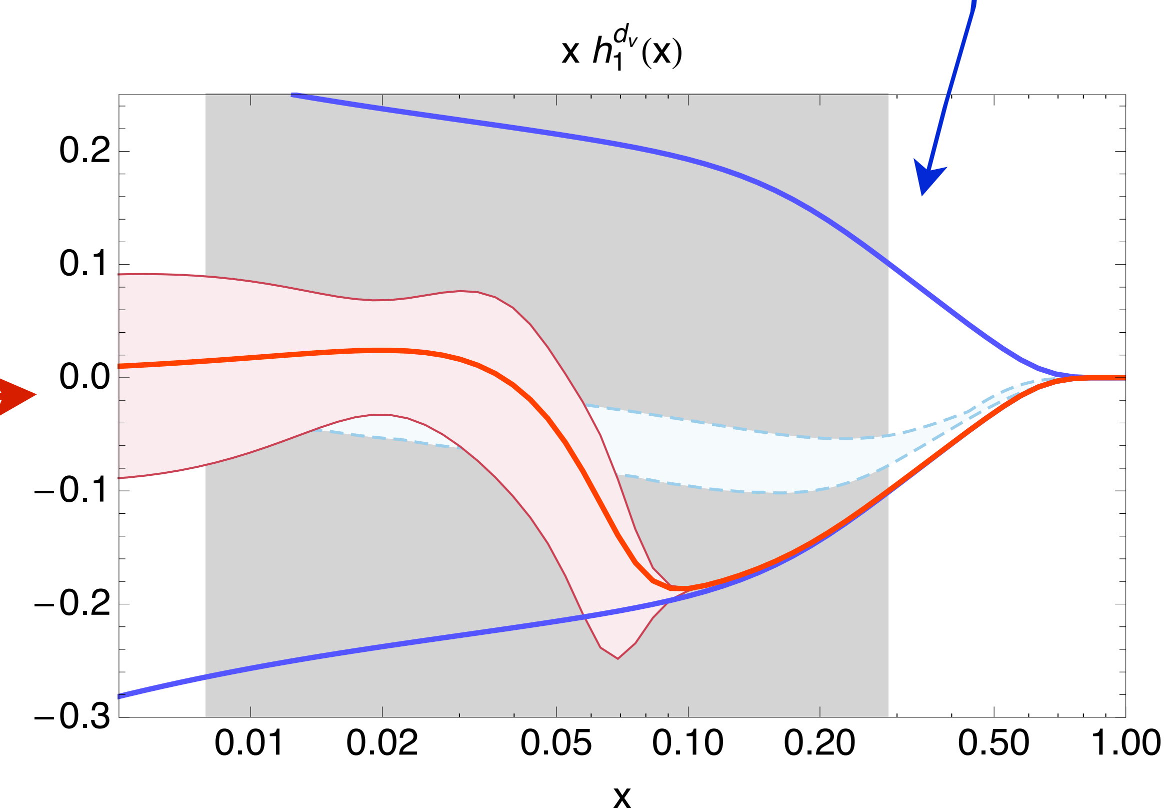


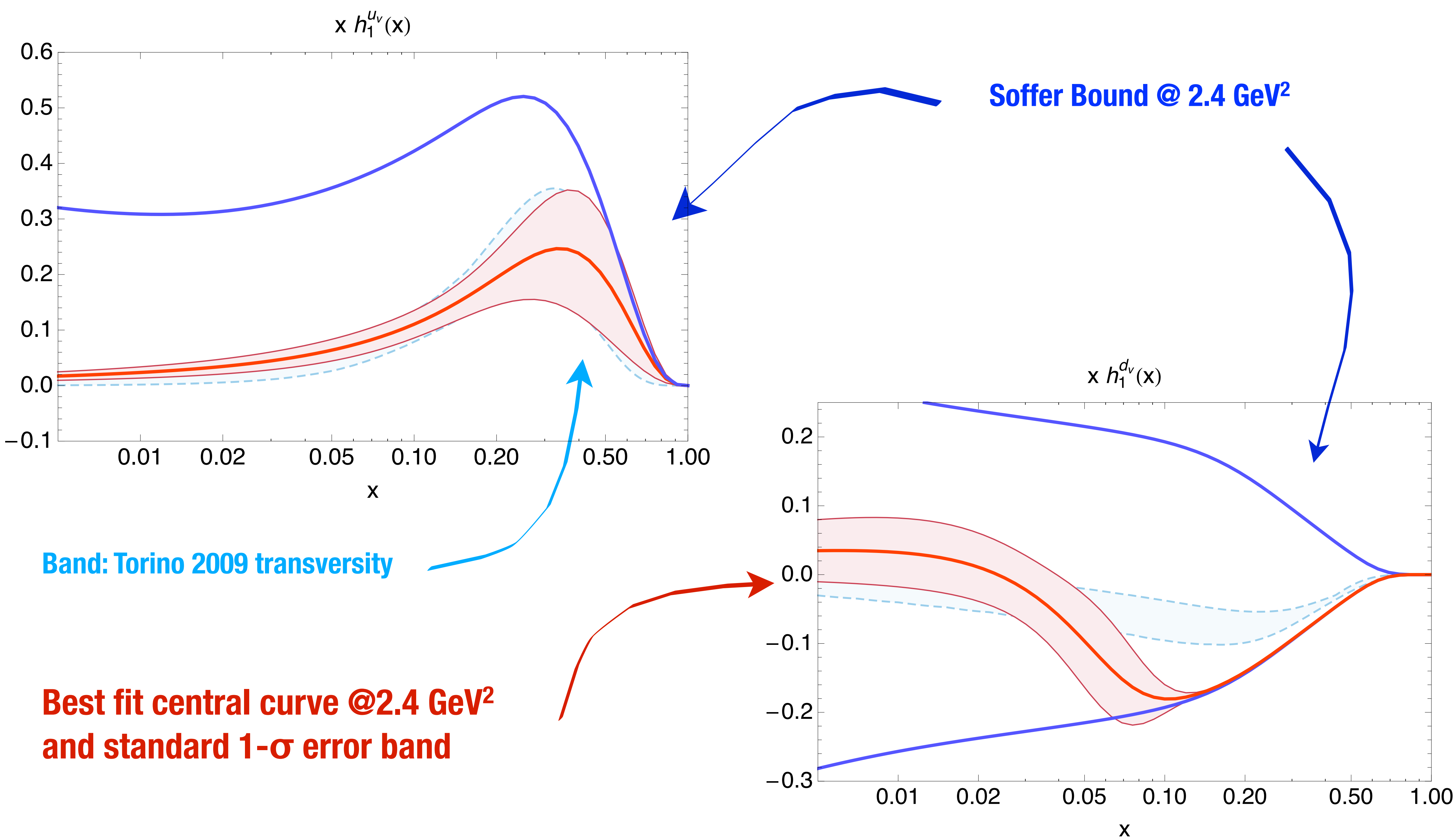
Soffer Bound @ 2.4 GeV^2

Band: Torino 2009 transversity

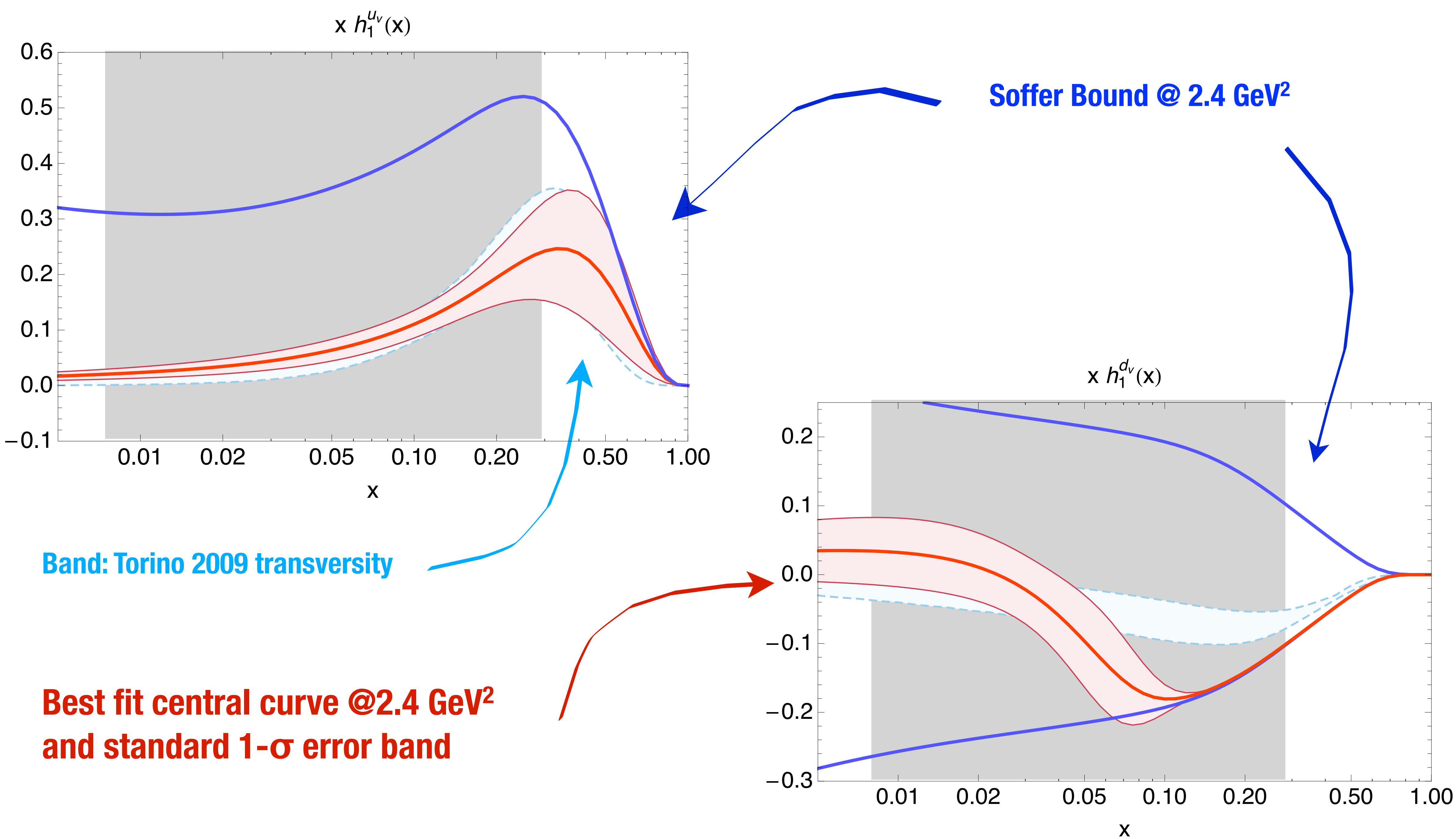
Best fit central curve @2.4 GeV^2
and standard 1-σ error band



Our Rigid Functional Form *1st order polynomial*

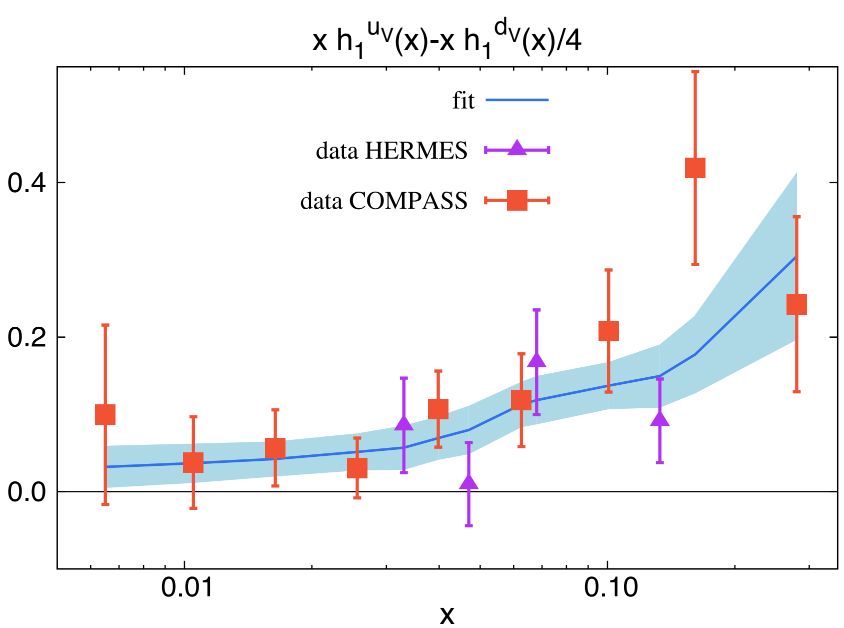


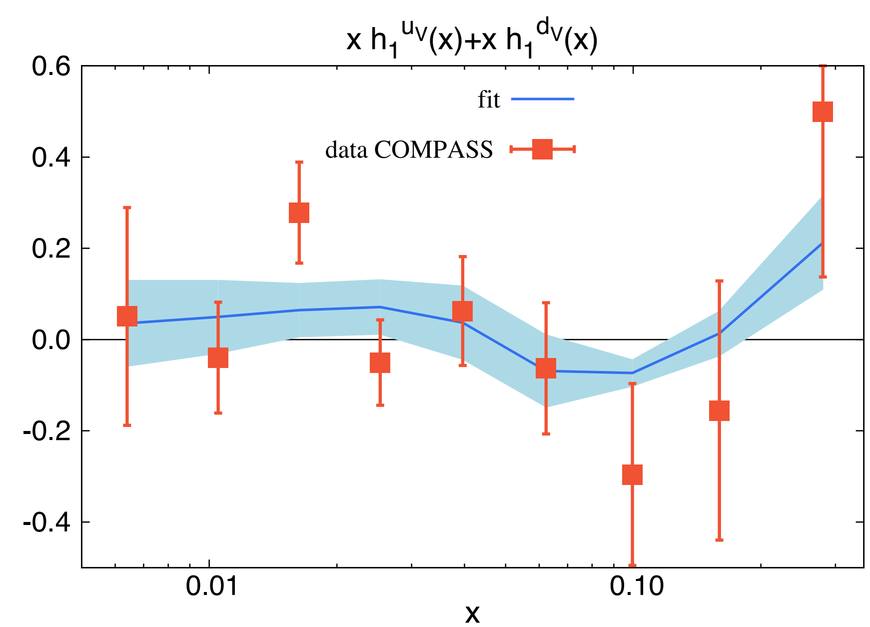
Our Rigid Functional Form *1st order polynomial*



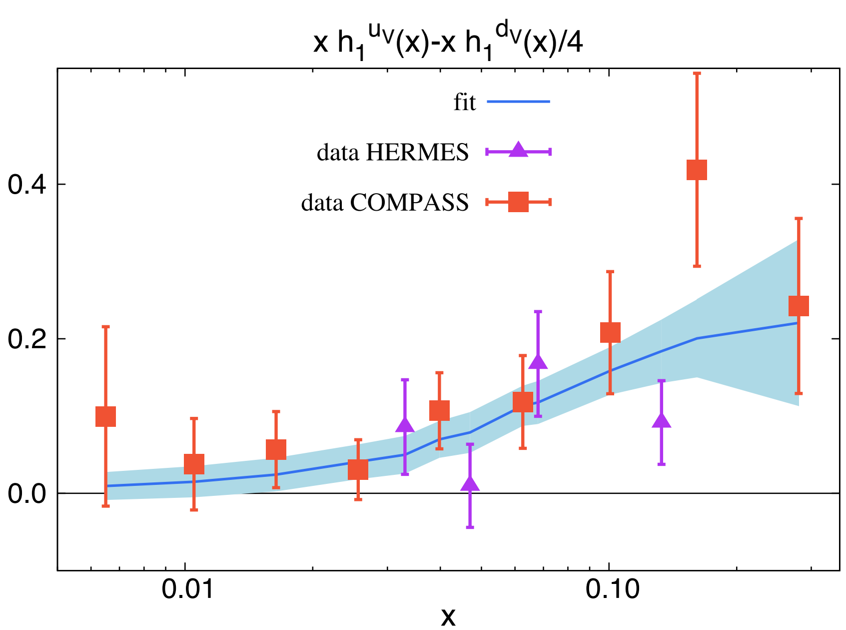
Comparison with extraction

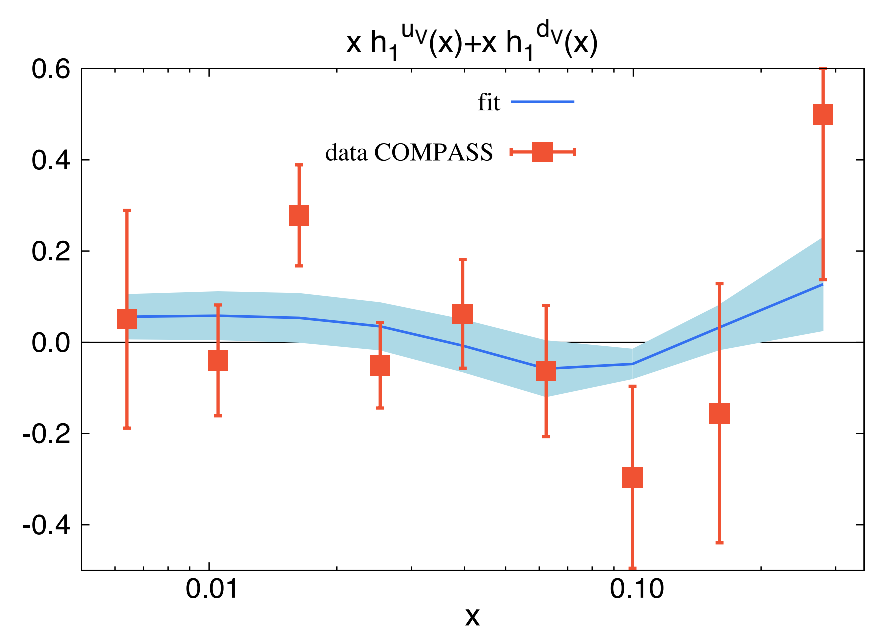
PROTON **DEUTERON**





flexible functional form





rigid functional form

The Error Analysis: *the Monte Carlo approach*

Too small errors w.r.t. ABSENCE of data

- ✦ the error is smaller where there are NO data → low and large-x !!!
- ✦ standard error propagation dictated by error on parameters

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- ✦ the error band is now made by 68% of the *n* replica point by point

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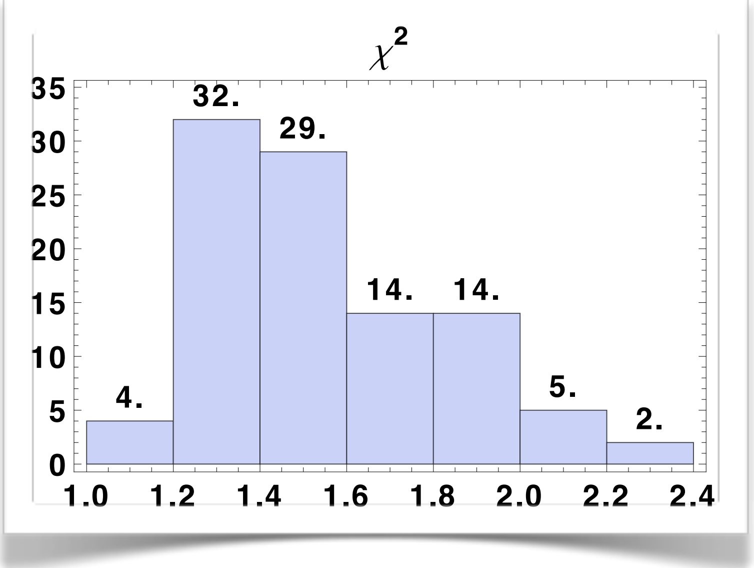
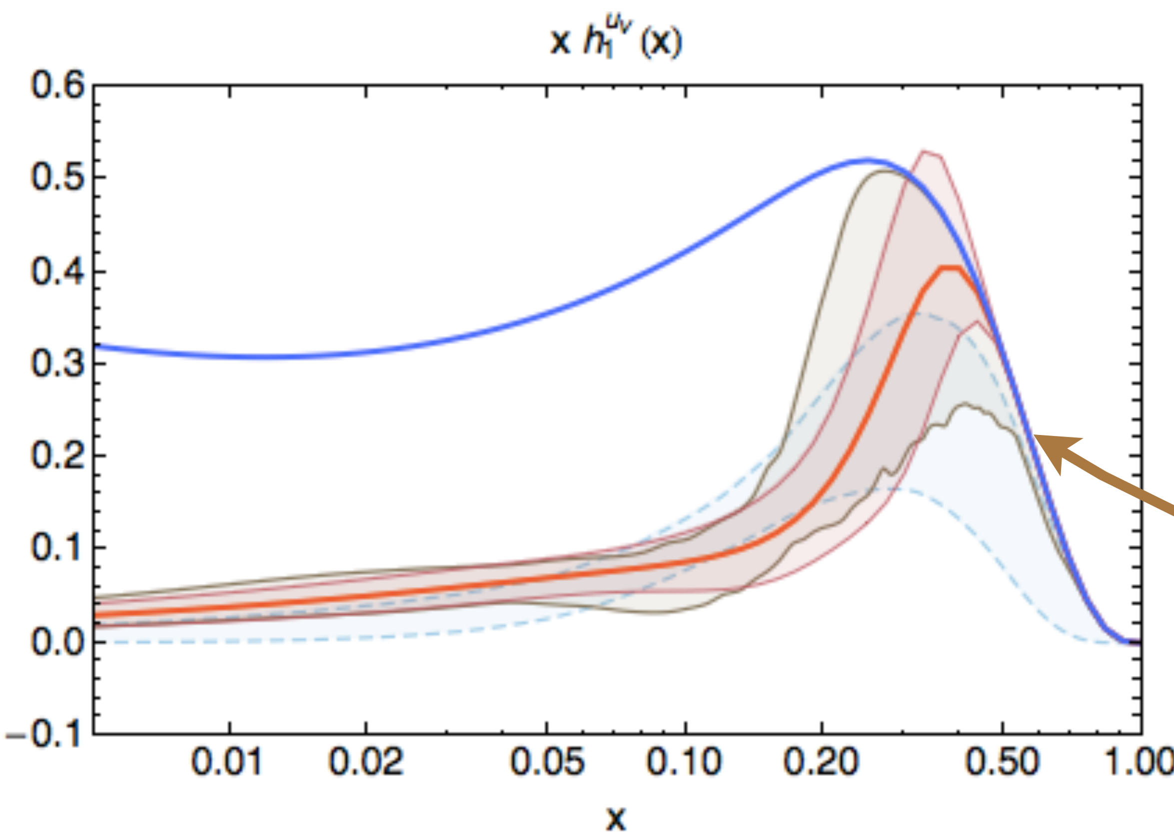
Distribution of the χ^2 for

- ➡ *n=100 replica*
- ➡ *our flexible functional form*

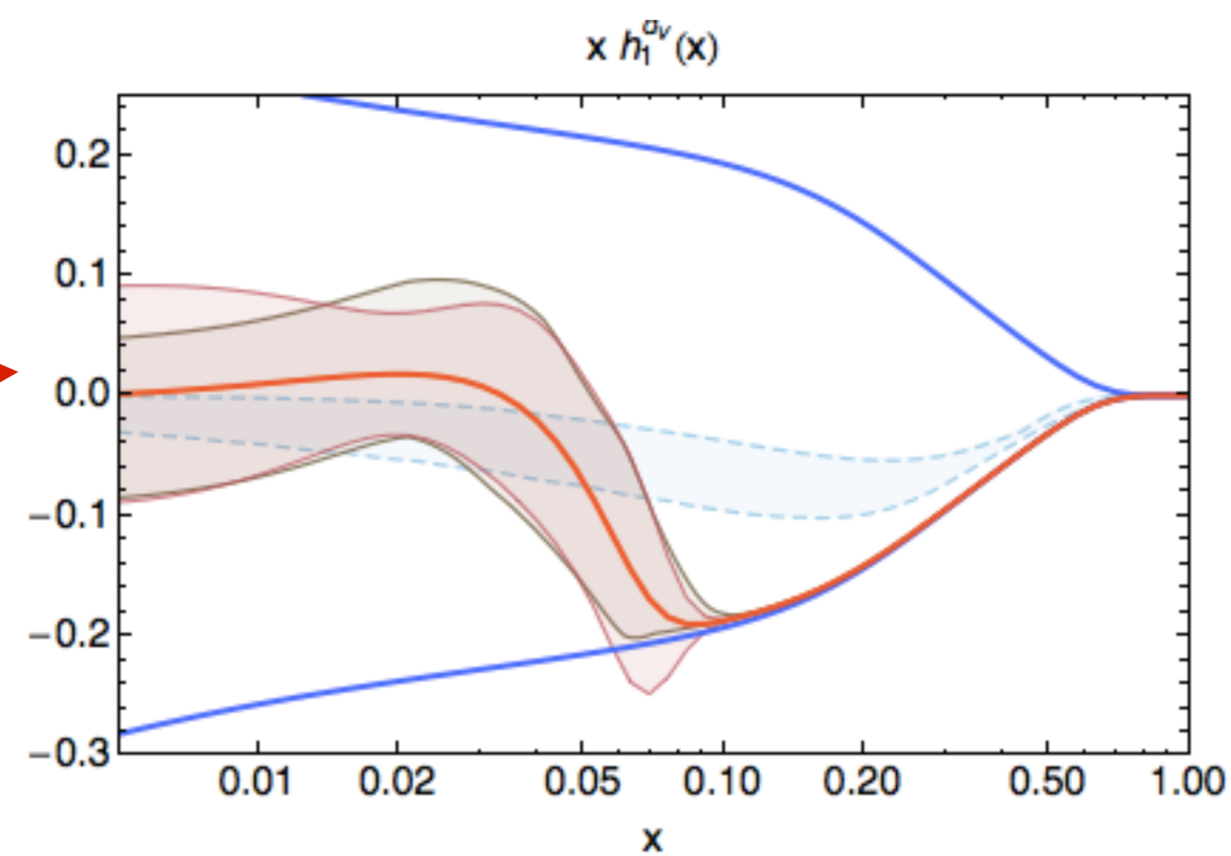


The Error Analysis: *the Monte Carlo approach*

2nd order polynomial



1σ error band from replicas @2.4 GeV^2



Best fit central curve @2.4 GeV^2
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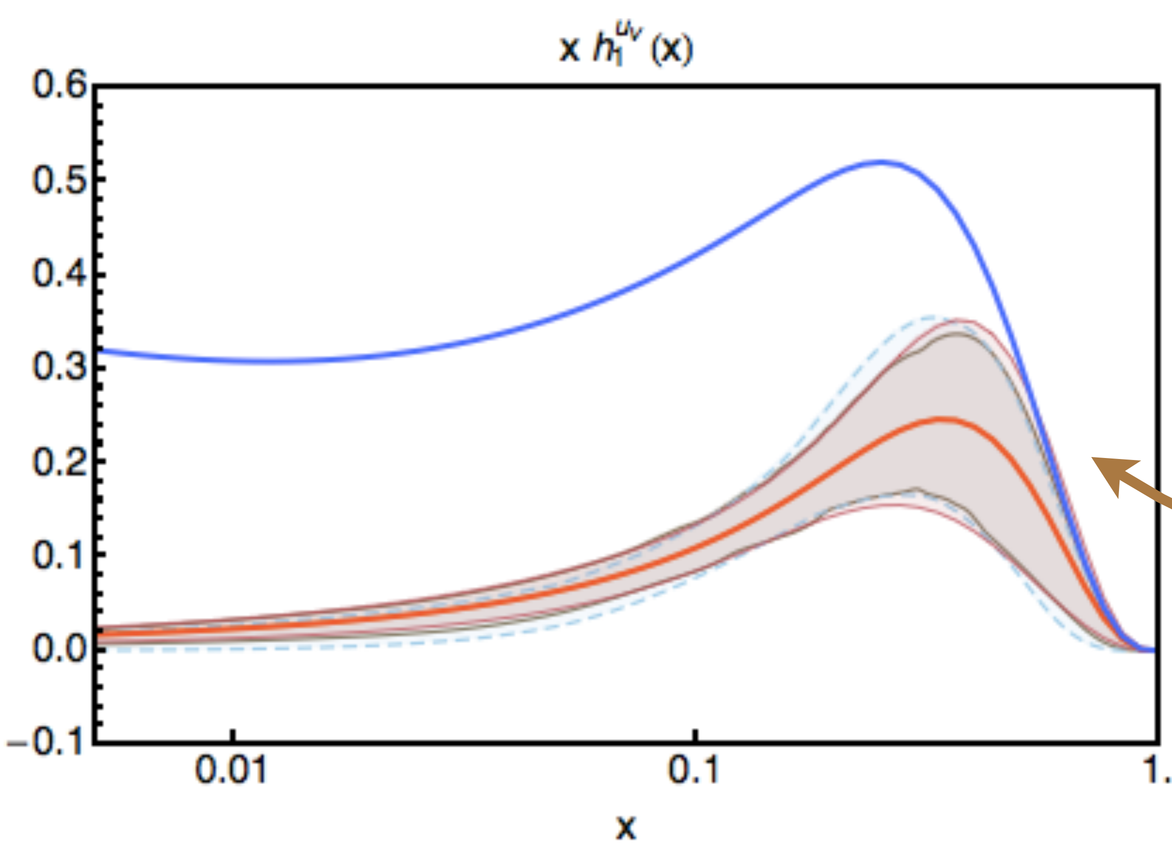
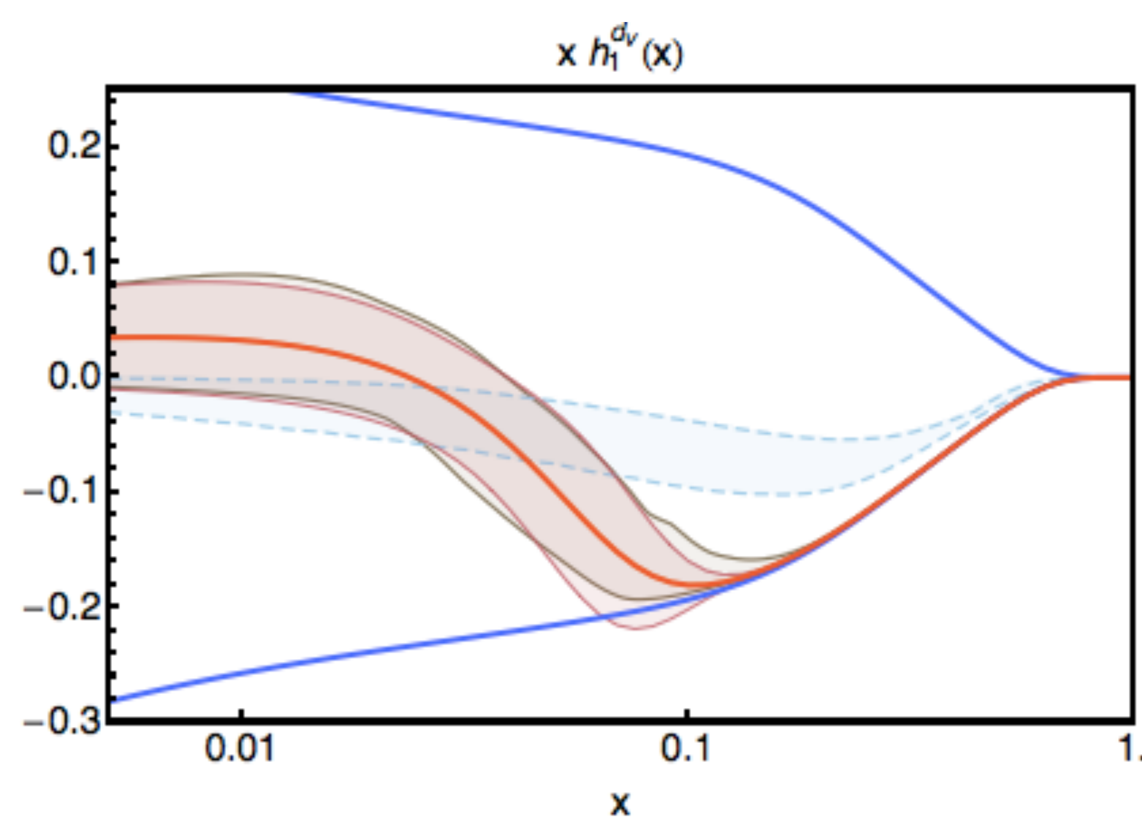
The Error Analysis: *the Monte Carlo approach*

1st order polynomial



1σ error band from replicas @2.4 GeV²



Best fit central curve @2.4 GeV²
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Monte Carlo Approach:

some illustrations

Can we find “unforeseen” replica?

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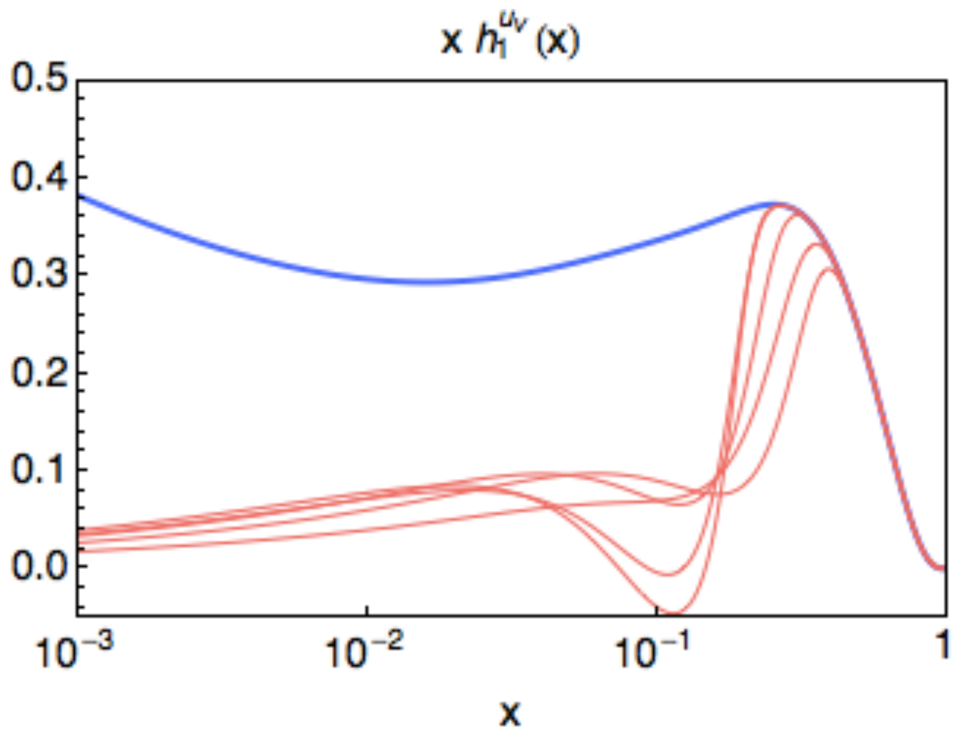
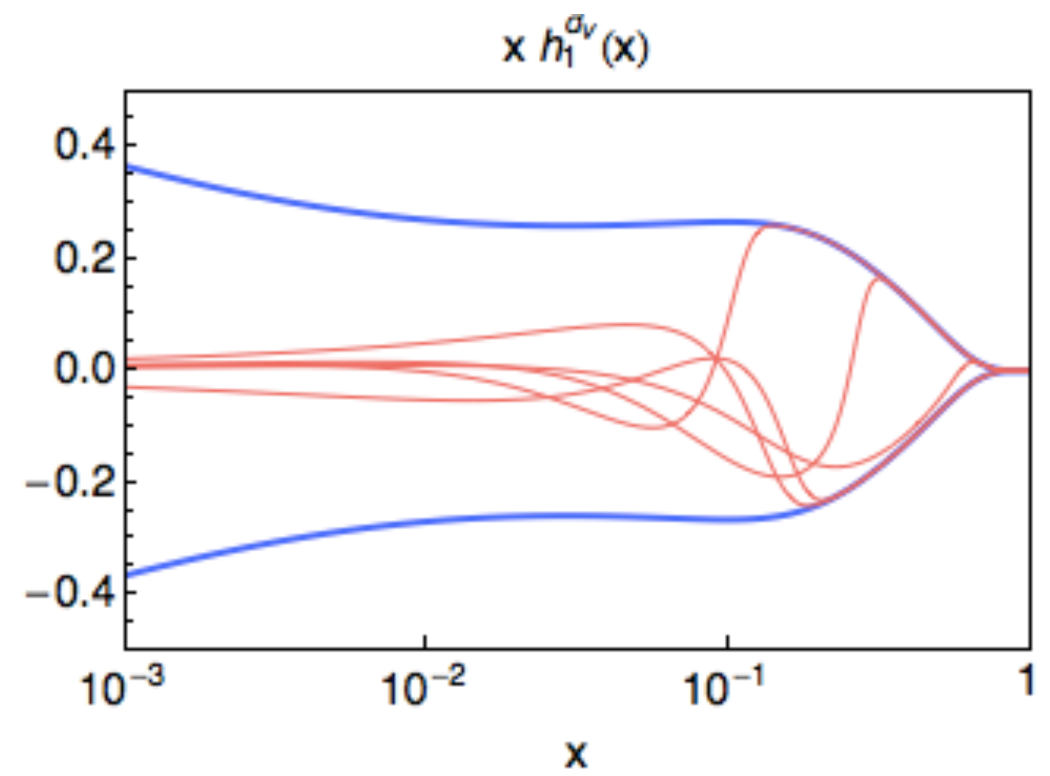
some illustrations

Can we find "unforeseen" replica?

Yes, here at 1GeV^2

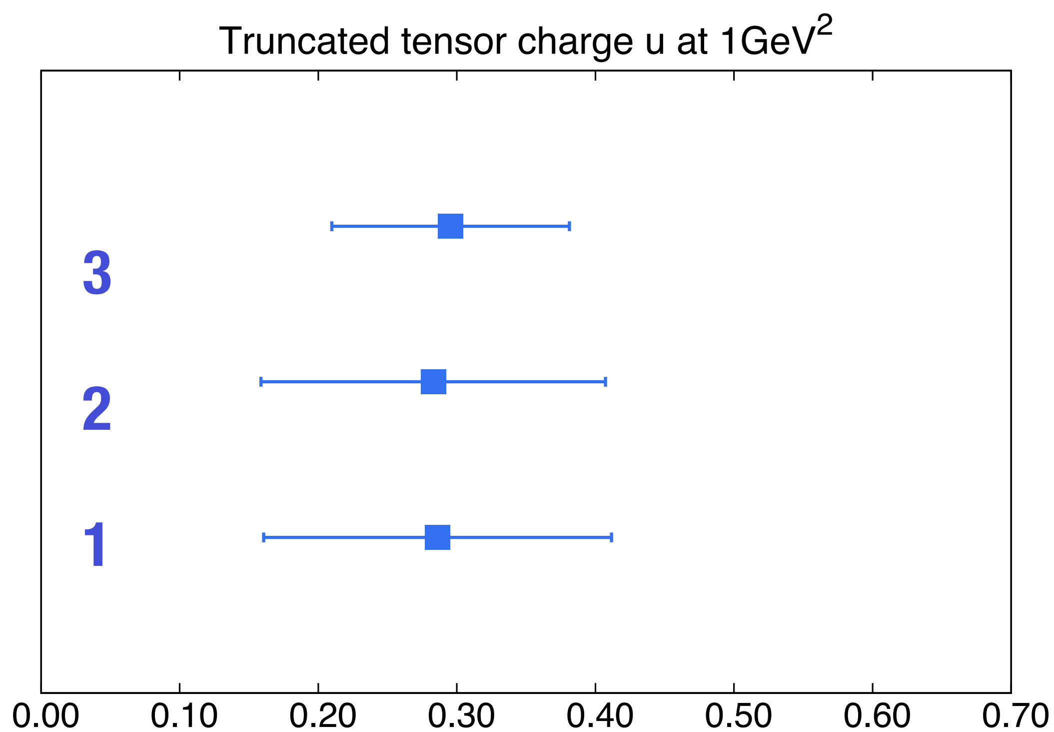




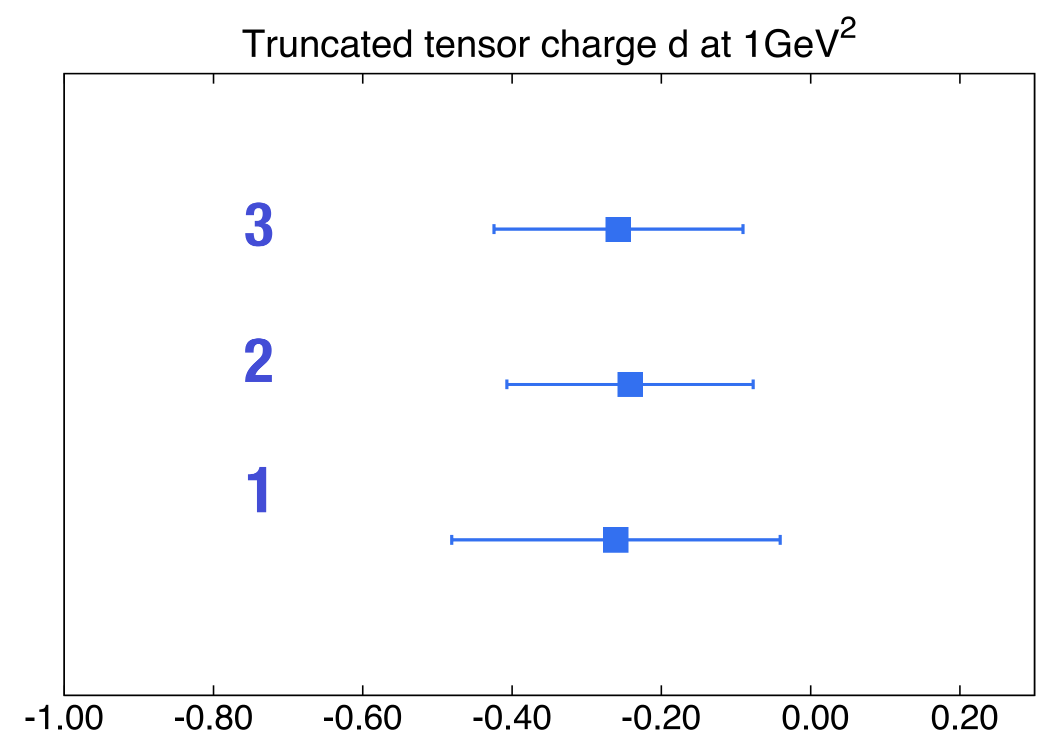
X^2/dof

1.56557
1.42199
1.79911
2.07397
1.75523

Tensor Charge *where we have data*



$$\delta q = \int_{6.4\times 10^{-3}}^{0.28} dx\, h_1^q(x)$$



1-flexible
2-hybrid
3-rigid

Tensor Charge

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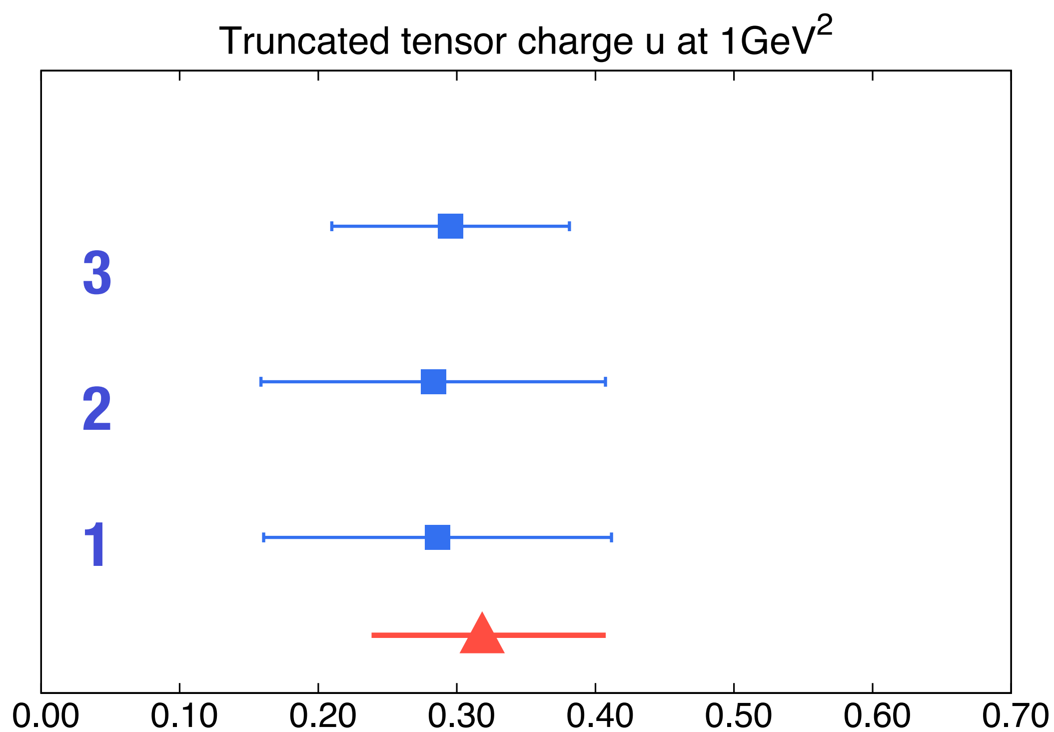

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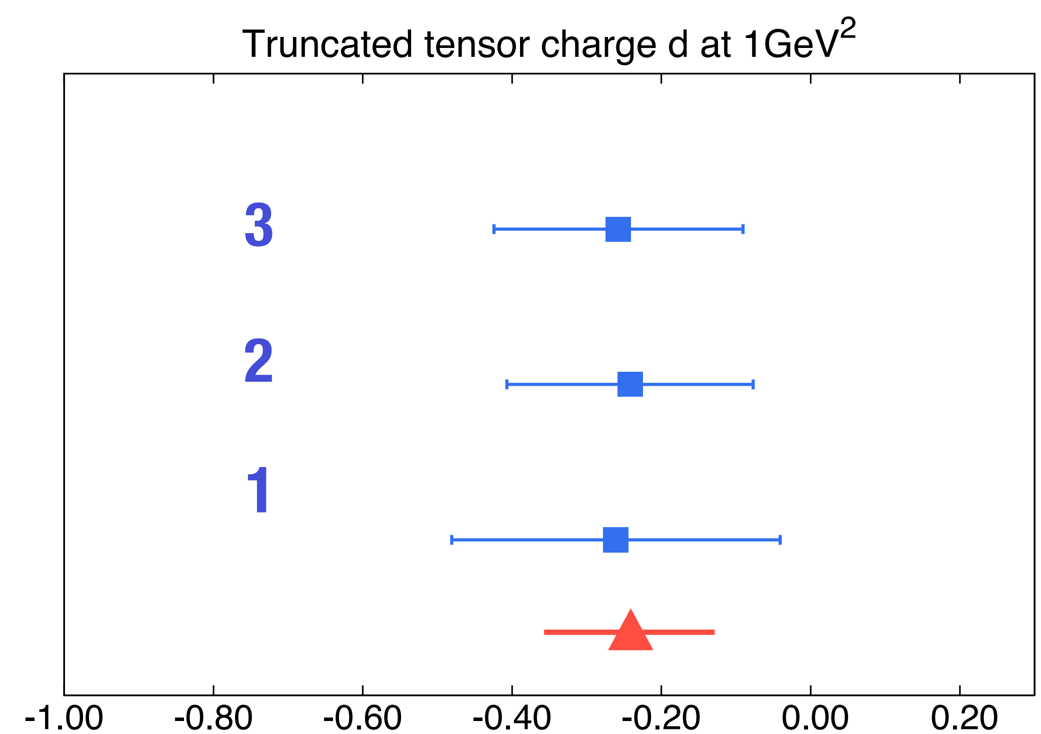

1-flexible
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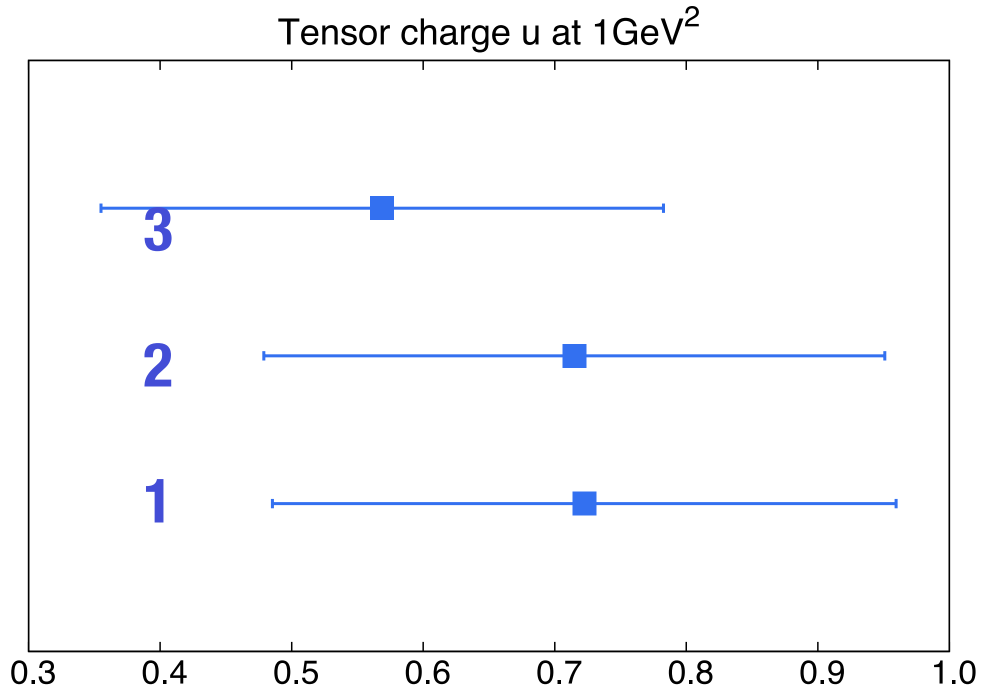
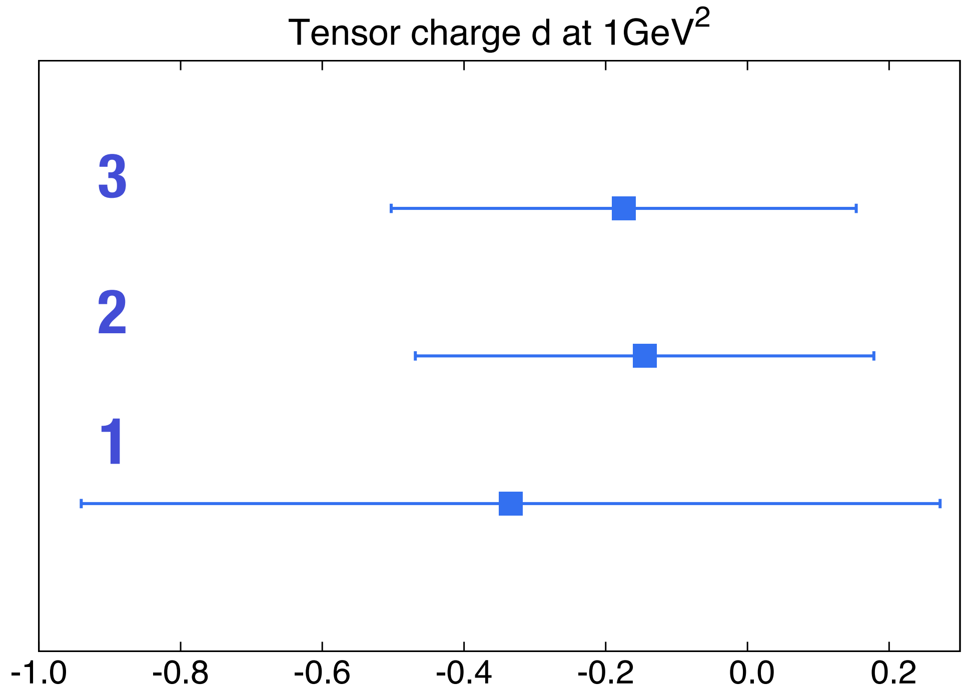
MC flexible

Tensor Charge

full range 10^{-10}- 1





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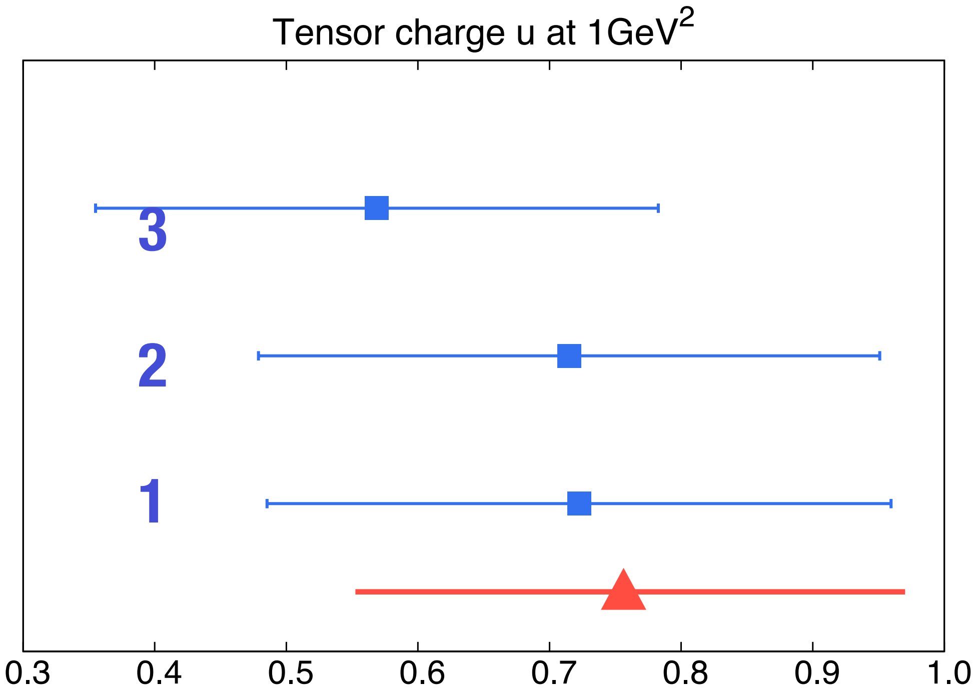

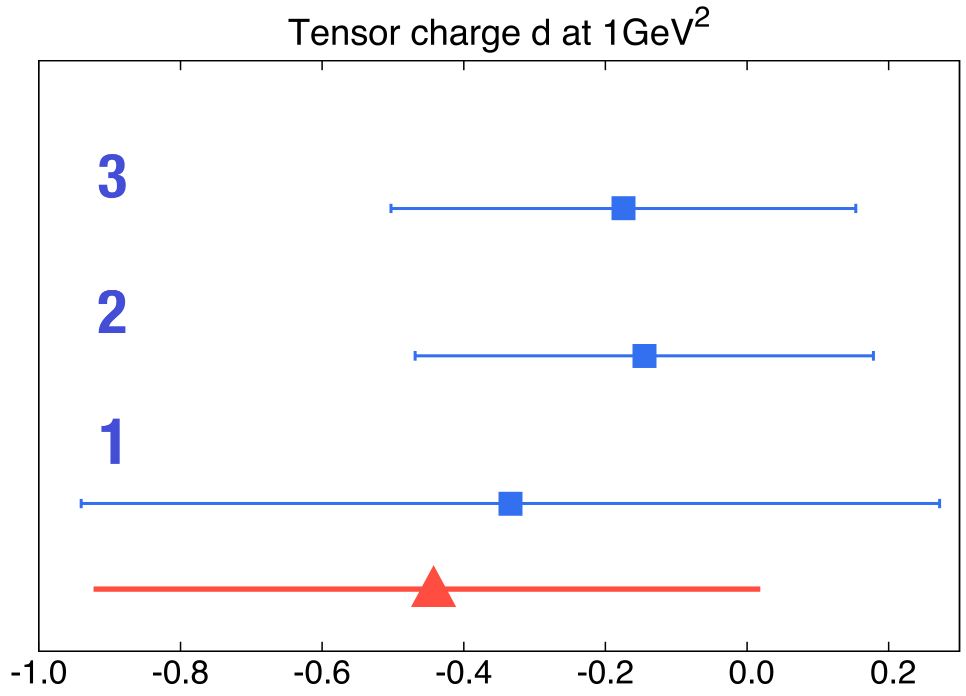

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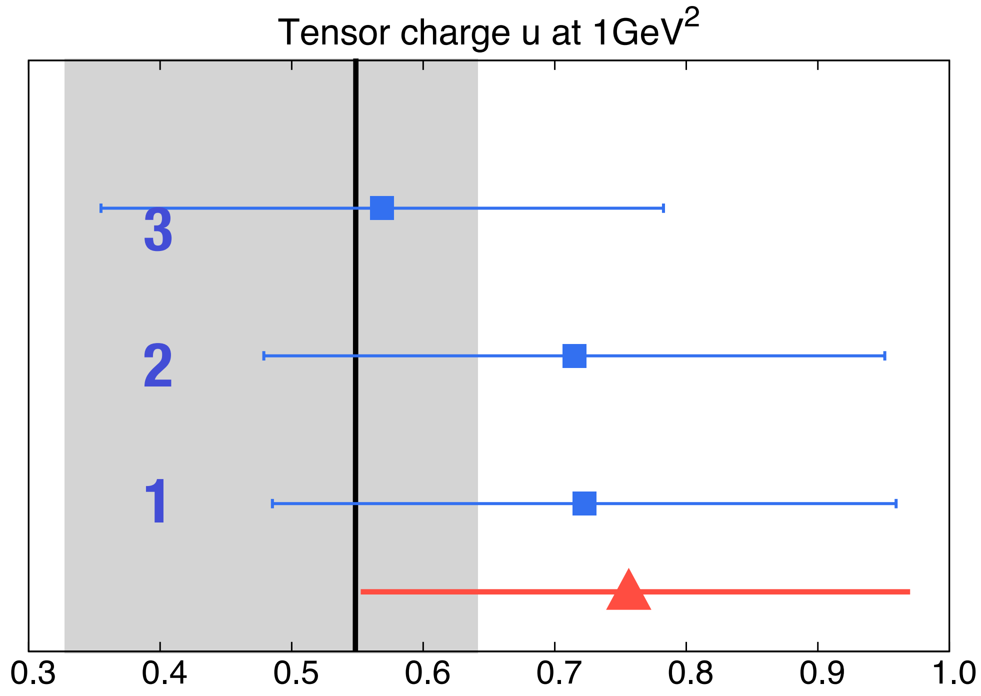
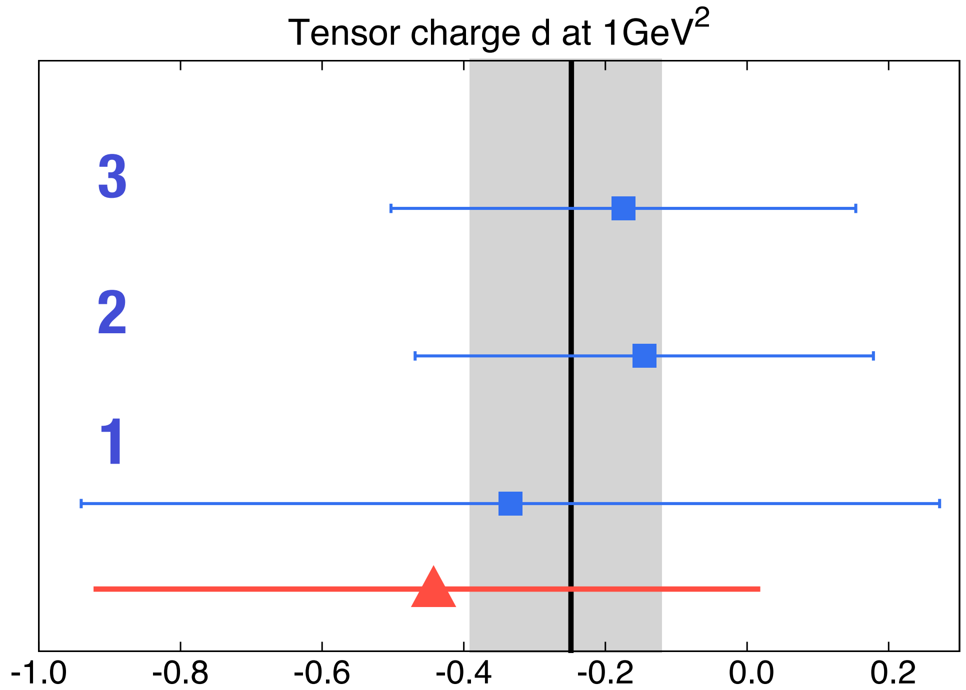


Torino result @ different scale (0.8 GeV^2)



1-flexible

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MC flexible

Conclusion

Extraction of valence transversities from collinear framework

- Transversity via DiFF
  - Flavor decomposition thanks to the available proton and deuteron data
  - Fits for h_1^u & h_1^d drafting... [Bacchetta, Courtoy, Radici]
  - *Functional Form* crucial to standard fitting procedure
    - ➡ Highly unconstrained outside data range
    - ➡ *Important!* e.g., for tensor charge
    - ➡ We NEED more data at higher x-values → JLab@12GeV
  - Monte Carlo-like error analysis
    - ➡ Compatible with standard analysis
    - ➡ Bigger errorbands

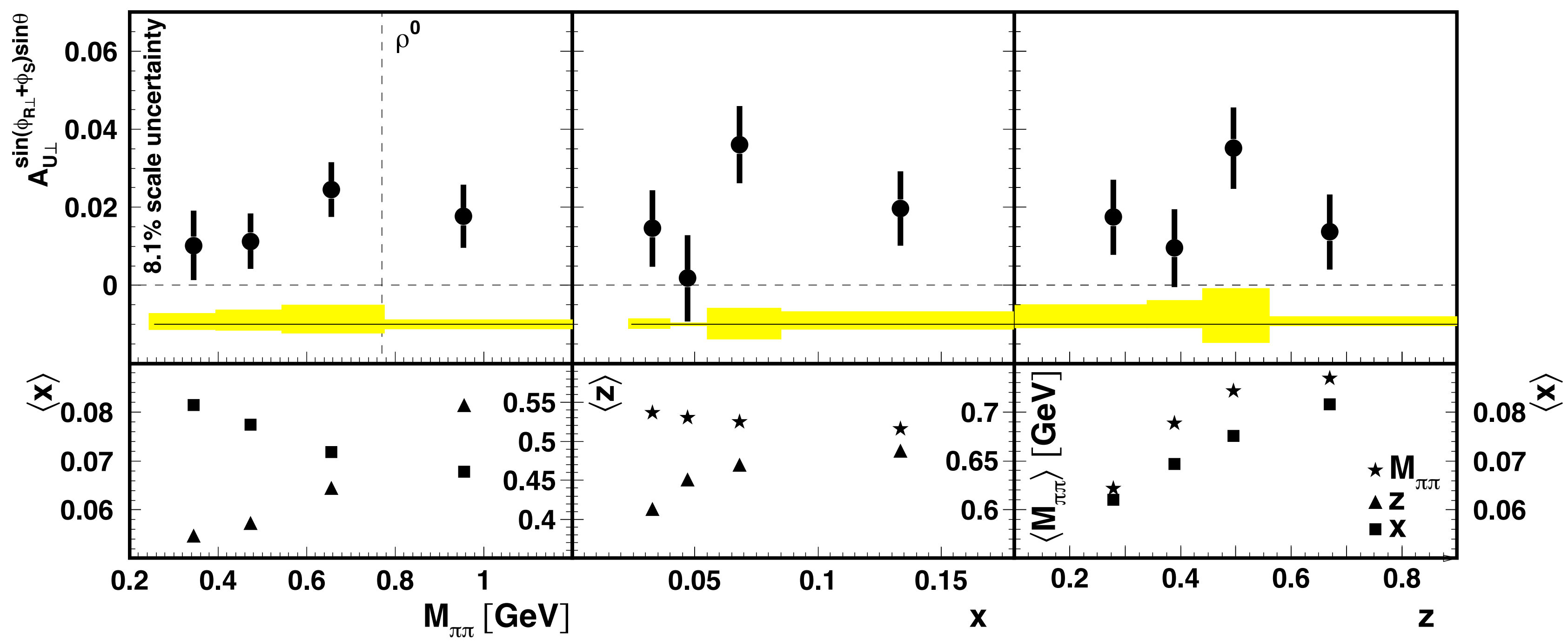
Outlook

- **Dihadron Fragmentation Functions**
  - **Fits** in (z, M_h, Q^2) with more accurate Q^2 evolution [Bacchetta, Bianconi, Courtoy, Radici]
  - **Data for Unpolarized DiFF** *Talk by N. Makke*
- **Transversity via DiFF**
  - **Flavor decomposition** we need Kaon data from Belle as well
  - **Fits for h_1^u & h_1^d** we need data for x>0.3 !

Back-up slides

$A_{UT}^{\sin(\Phi_R+\Phi_S)\sin\theta}$ @ HERMES

[JHEP 06, 017 (2008)]



- ✦ integrated over 0.5<Mh<1GeV
- ✦ integrated over 0.2<z<1

$$n_q(Q^2) \quad = \int dz\, dM_h^2\, D_1^{q\to\pi^+\pi^-}(z, M_h^2, Q^2)$$

$$A_{\rm DIS}(x,Q^2) = -C_y\, \frac{\sum_q e_q^2\, h_1^q(x,Q^2)\, n_q^\uparrow(Q^2)}{\sum_q e_q^2\, f_1^q(x,Q^2)\, n_q(Q^2)}$$

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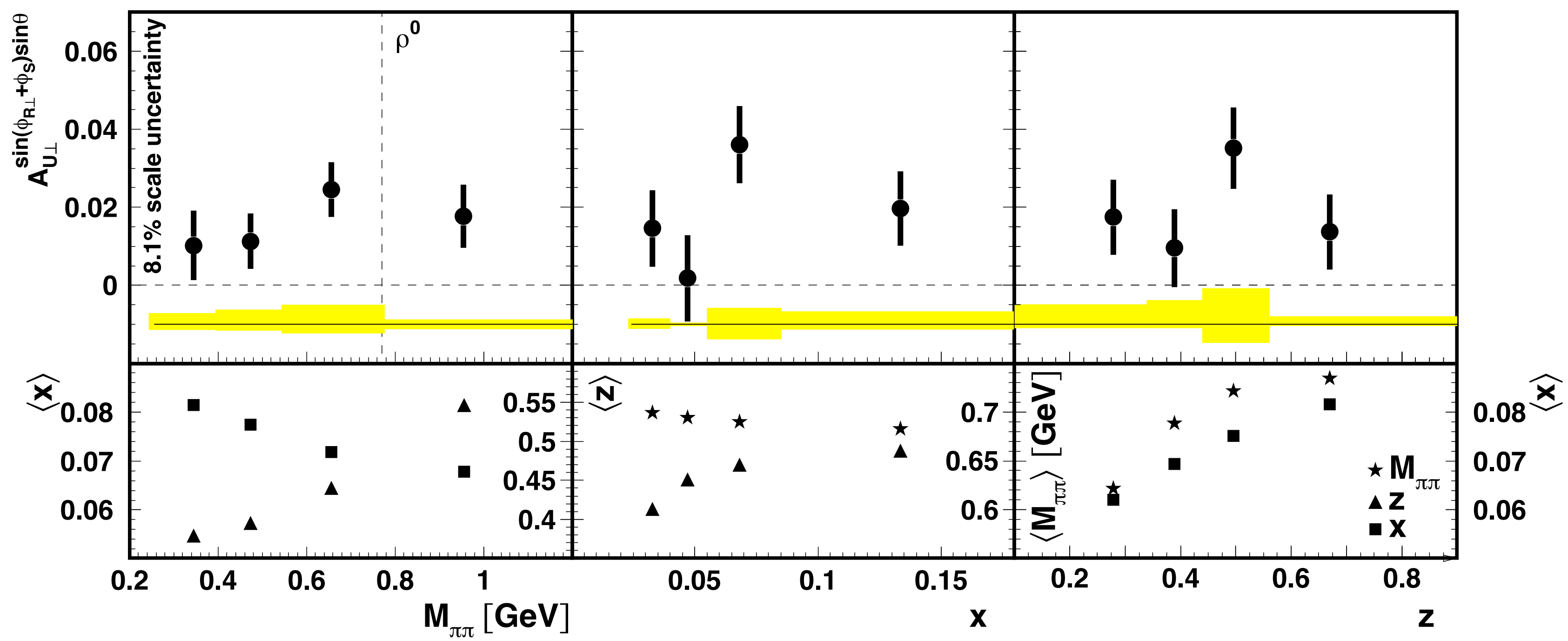

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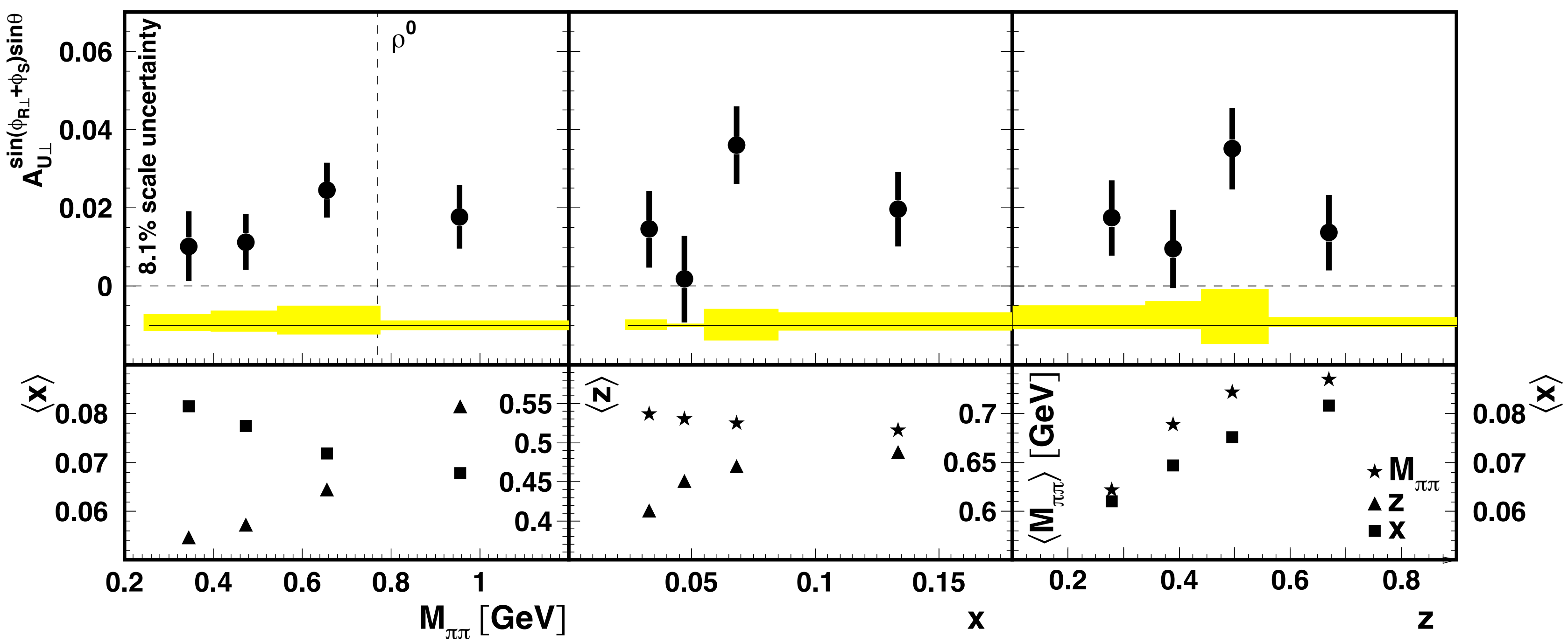

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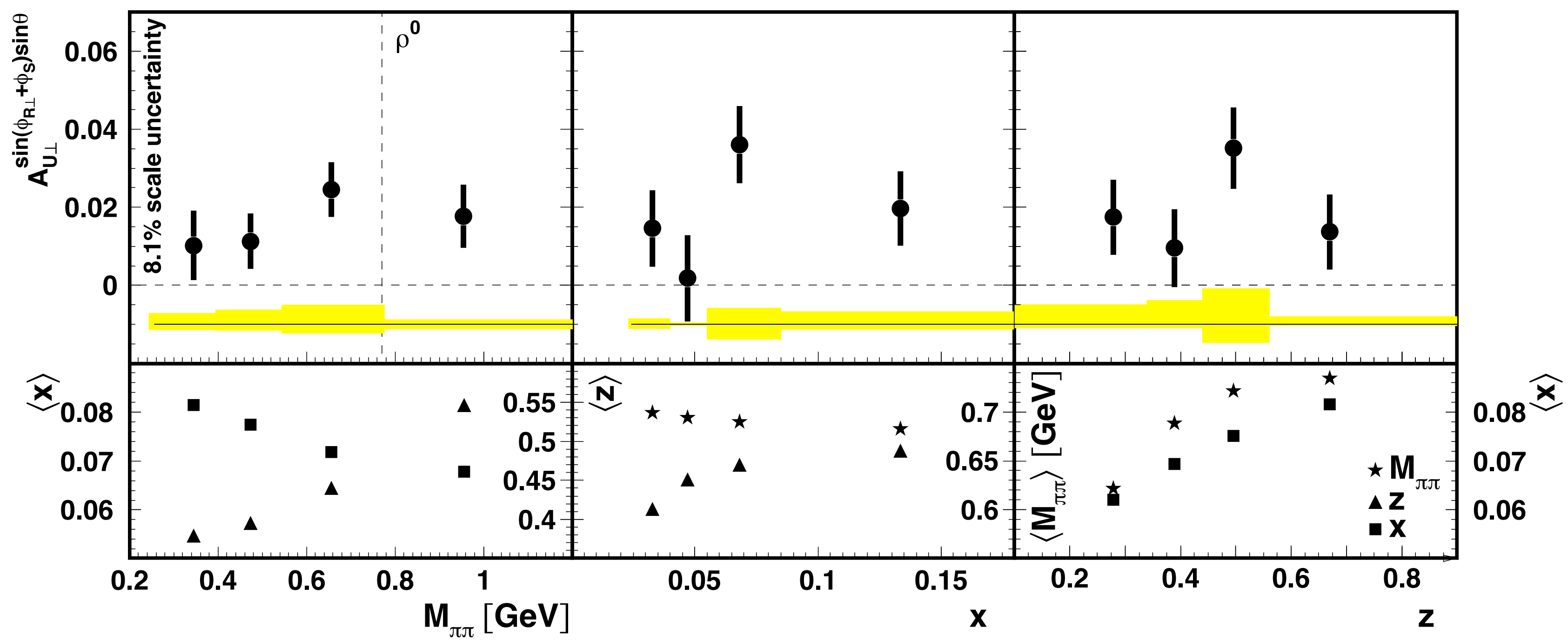
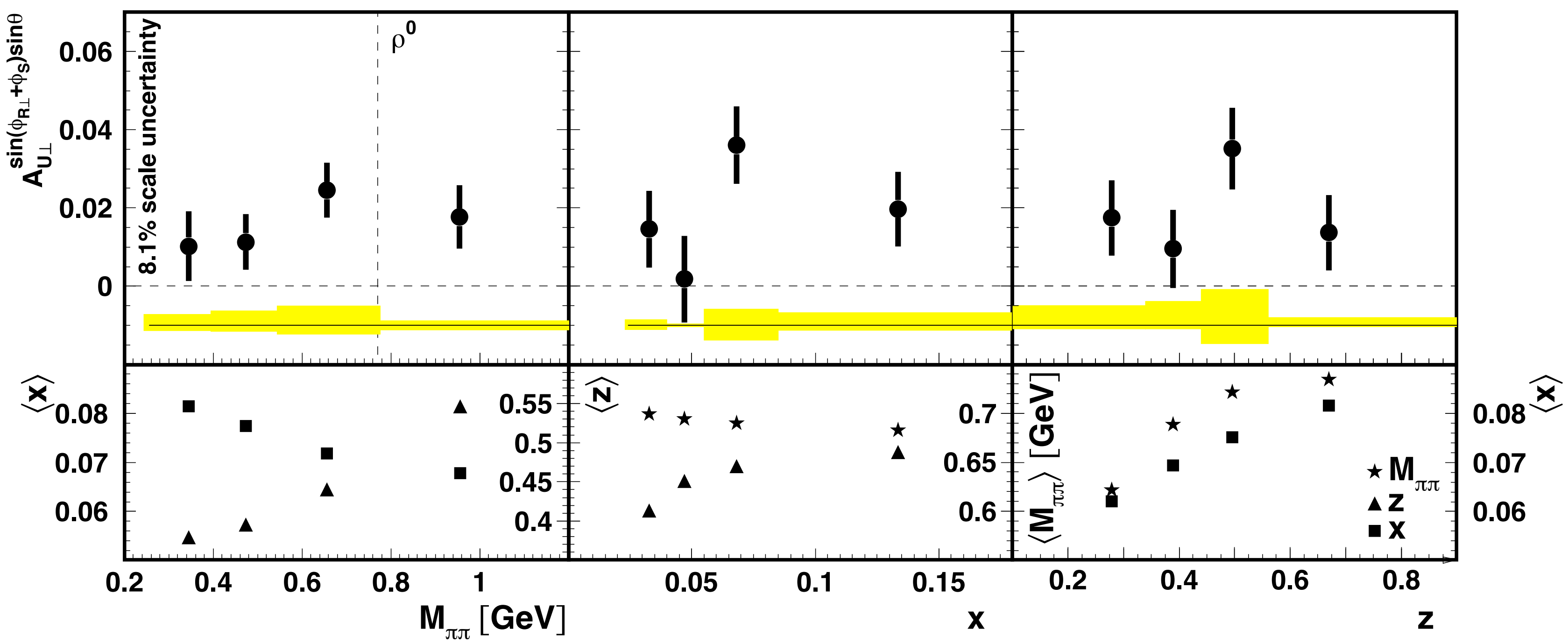


$$A_{\mathrm{DIS}}(x,Q^2) = -C_y \frac{\sum_q e_q^2\, h_1^q(x,Q^2)\, n_q^{\uparrow}(Q^2)}{\sum_q e_q^2\, f_1^q(x,Q^2)\, n_q(Q^2)}$$

$$xh_1^{u_v}(x,Q^2) - \tfrac{1}{4}\, xh_1^{d_v}(x,Q^2) = -C_y^{-1}\, A_{\mathrm{DIS}}(x,Q^2)\, \frac{n_u(Q^2)}{n_u^{\uparrow}(Q^2)} \sum_{q=u,d,s} \frac{e_q^2}{e_u^2}\, x f_1^{q+\bar{q}}(x,Q^2)$$

$A_{UT}^{\sin(\Phi_R+\Phi_S)\sin\theta}$ @ HERMES

[JHEP 06, 017 (2008)]



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$A^{\cos(\Phi_R+\Phi_{\bar{R}})}$

$e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}\ (\pi^+\pi^-)_{jet2}\ X$ @ Belle

From Belle data & for HERMES range (in particular M_{h1}-M_{h2} asymmetries):

0.871

-0.0307±0.0011

$$(A_{e+e-})_H = -\frac{\langle \sin^2\theta_2 \rangle}{\langle 1+\cos^2\theta_2 \rangle}\,\frac{\langle \sin\theta \rangle\,\langle \sin\bar{\theta} \rangle\,5\,(n_u^{\uparrow})^2}{6\,(n_u)^2+4\,(n_c)^2}$$

$4\ n_c^2/6\ n_u^2=0.415$

0.753

$A^{\cos(\Phi_R+\Phi_{\bar{R}})}$

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-0.0307±0.0011

0.871

0.753

$4\ n_c^2/6\ n_u^2$=0.415

Evolution effects : From Belle's scale to HERMES and COMPASS'scale

→ needs analytical expression and gluon DiFF → fits → [arXiv:1202.0323]

$A^{\cos(\Phi_R+\Phi_{\bar{R}})}$

$e^+e^- \to (\pi^+\pi^-)_{jet1}\ (\pi^+\pi^-)_{jet2}$ X @ Belle

From Belle data & for HERMES range (in particular M_{h1}-M_{h2} asymmetries):

$$(A_{e+e-})_H = -\frac{\langle \sin^2\theta_2\rangle}{\langle 1+\cos^2\theta_2\rangle}\ \frac{\langle \sin\theta\rangle\, \langle \sin\bar{\theta}\rangle\, 5\,(n_u^{\uparrow})^2}{6\,(n_u)^2+4\,(n_c)^2}$$

-0.0307±0.0011

0.871

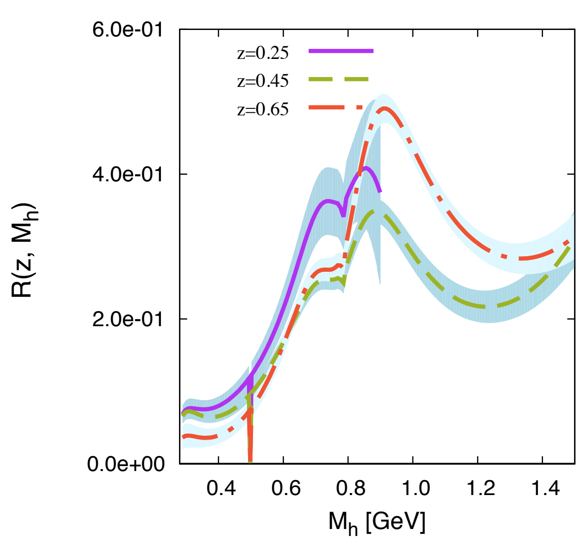
$4\, n_c^2/6\, n_u^2$=0.415

0.753

Evolution effects : From Belle's scale to HERMES and COMPASS'scale

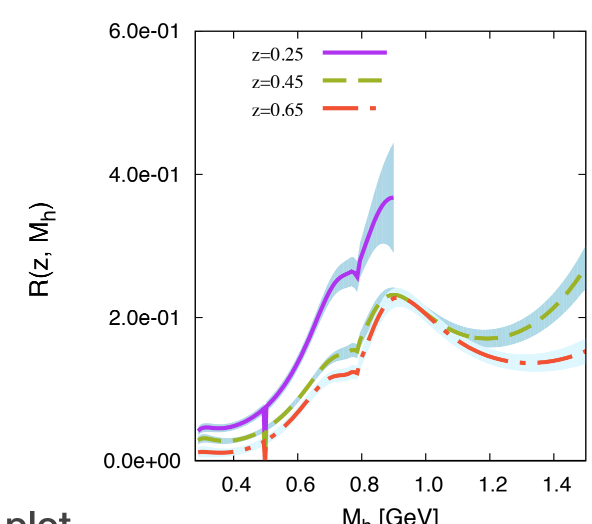
→ needs analytical expression and gluon DiFF → fits → [arXiv:1202.0323]

Q^2=1GeV^2



→

Q^2=100GeV^2



only $H_1^{<}$ evolution on plot

Can Transversity Be Measured?

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R.L. Jaffe, Xue-min Jin, Jian Tang (MIT, LNS).
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Invited paper, presented at the 2nd Topical Workshop,
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- Semi-Inclusive DIS :
  - Single-Particle Fragmentation → $h_1 \otimes H_1^{\perp}$
  - Two-Particle Fragmentation → h_1 $H_1^{<}$

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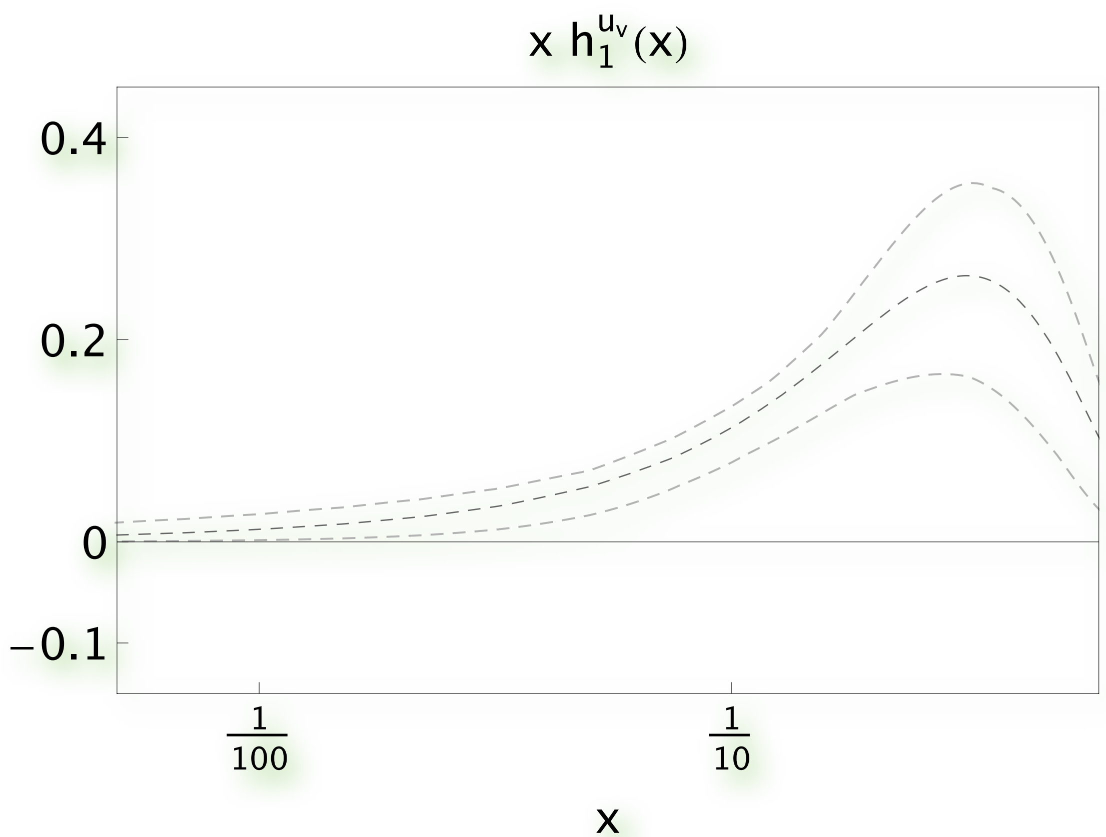
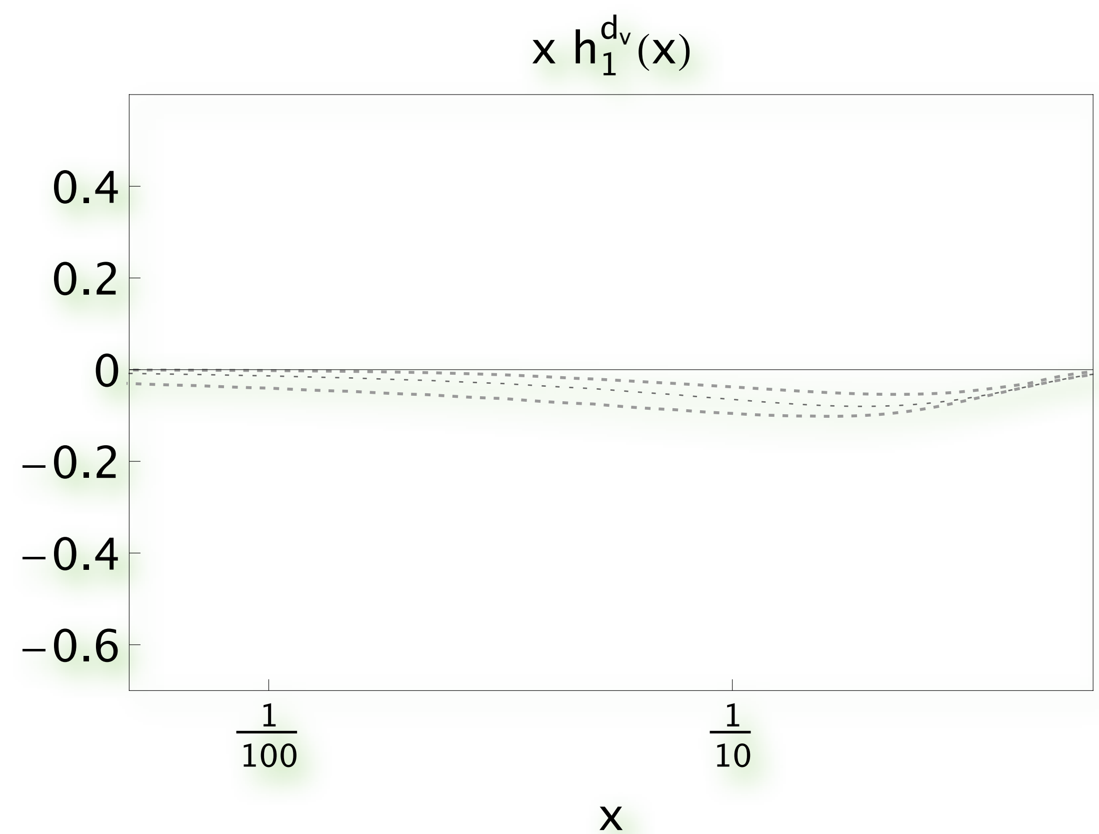
This talk

Transversity : flavor decomposition

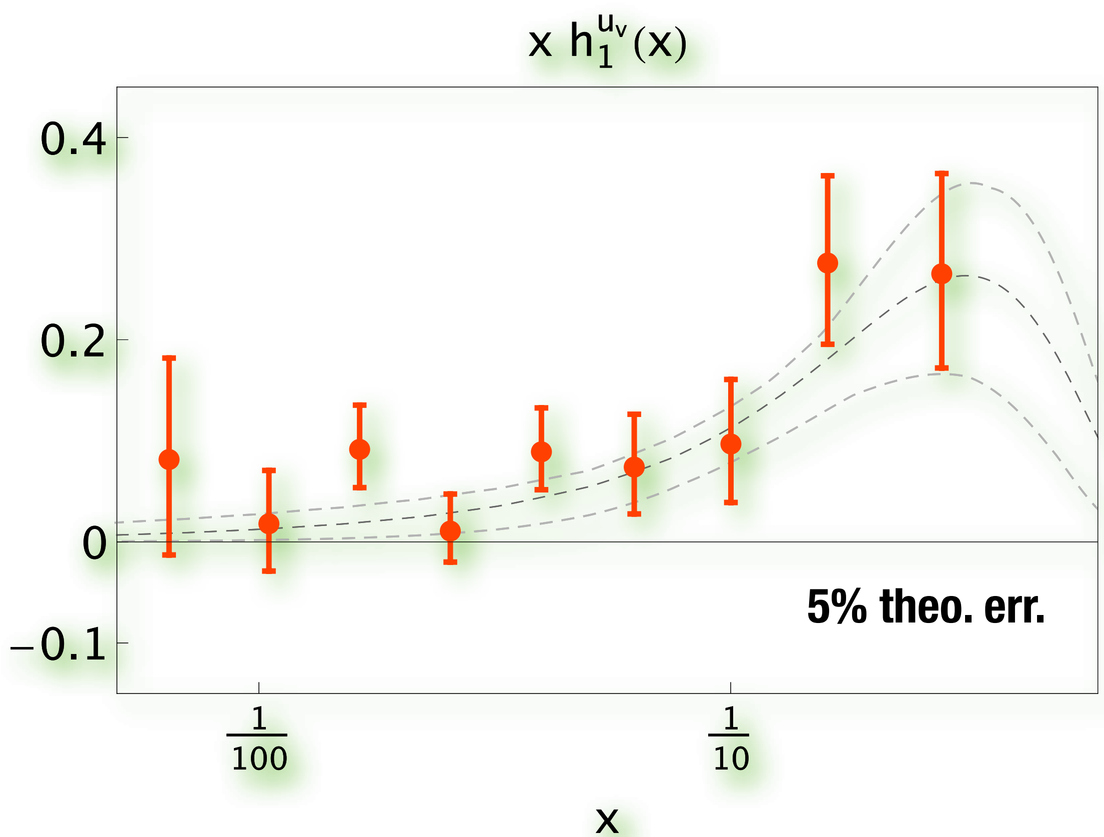


COMPASS
Deuteron 2002-2004
Proton 2007

Band: Torino 2009 transversity



Transversity : flavor decomposition



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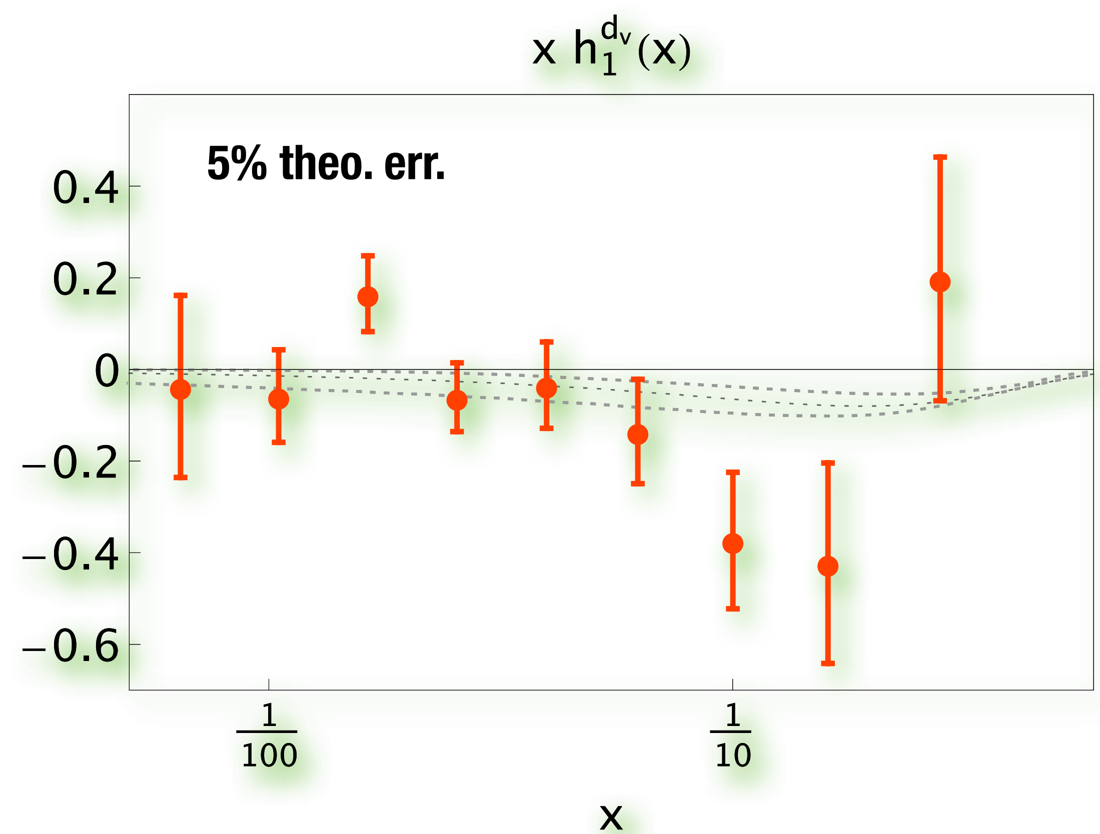
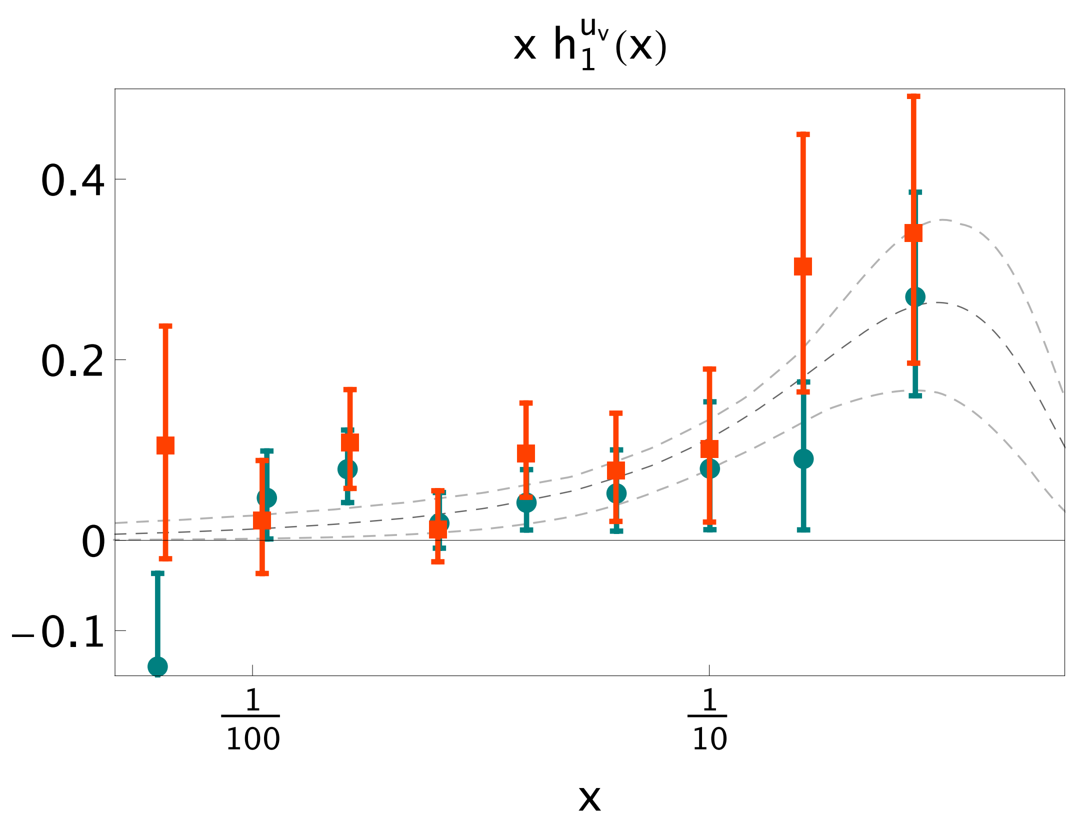
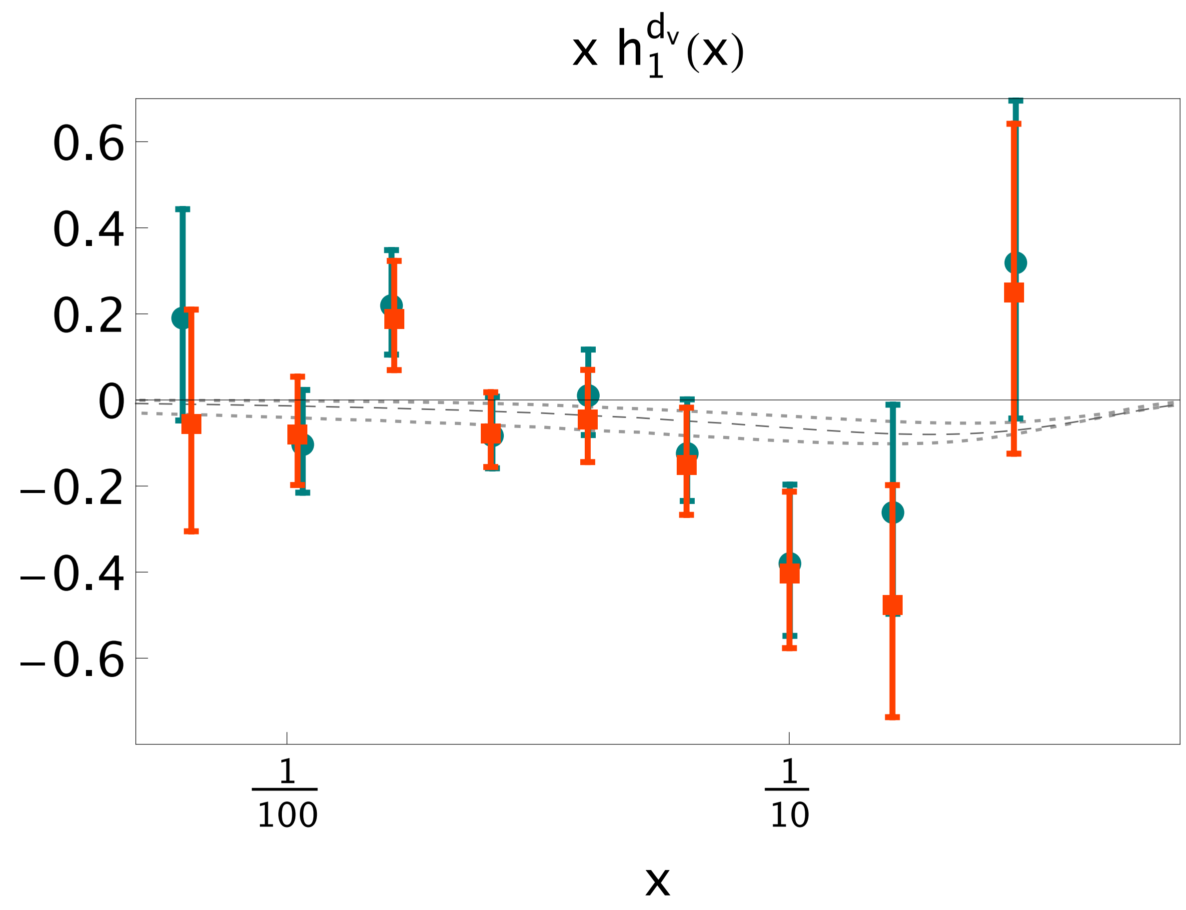


PRELIMINARY

Off the record: COMPASS data on Proton 2010

2nd order polynomial





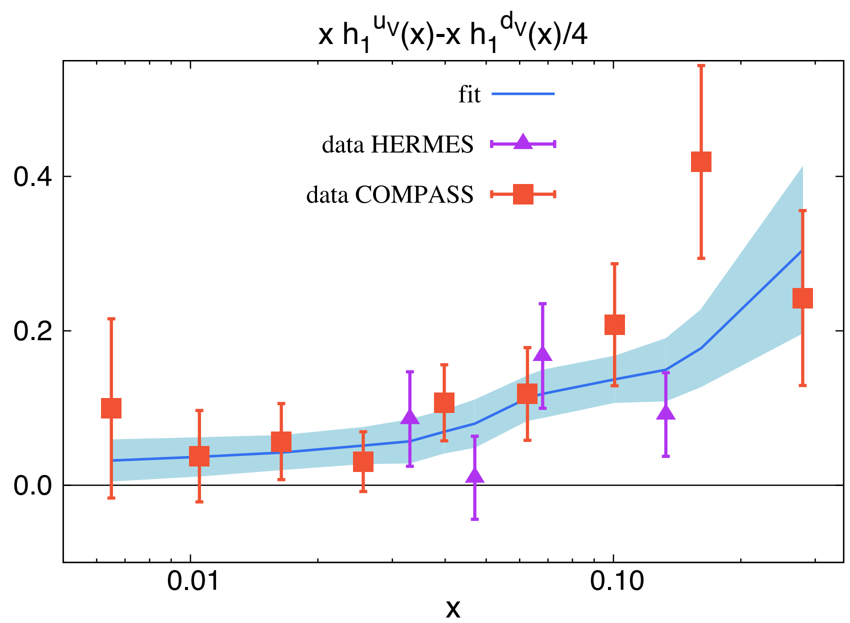
COMPASS 2004 (P) & 2007 (D)

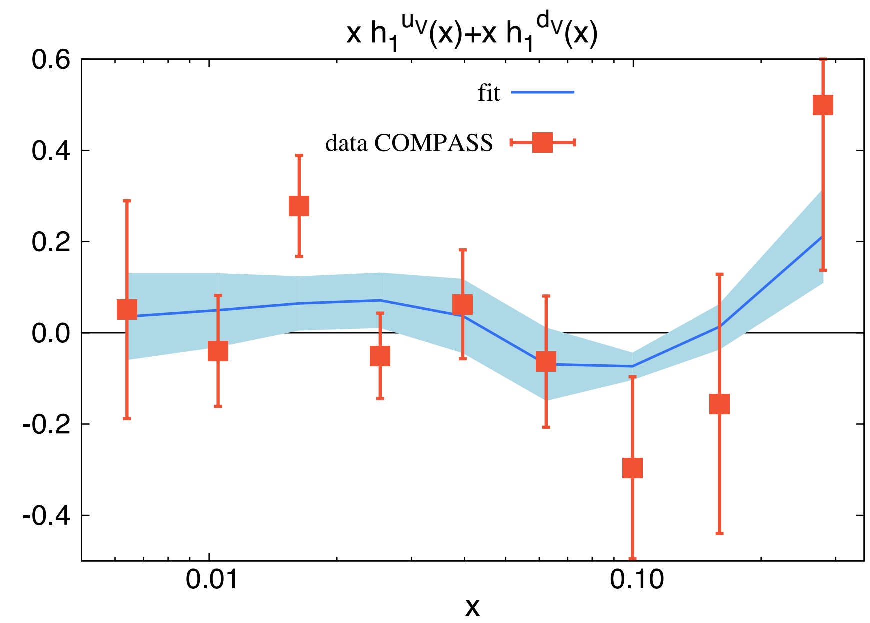
COMPASS 2010 (P) & 2007 (D)

Comparison with extraction

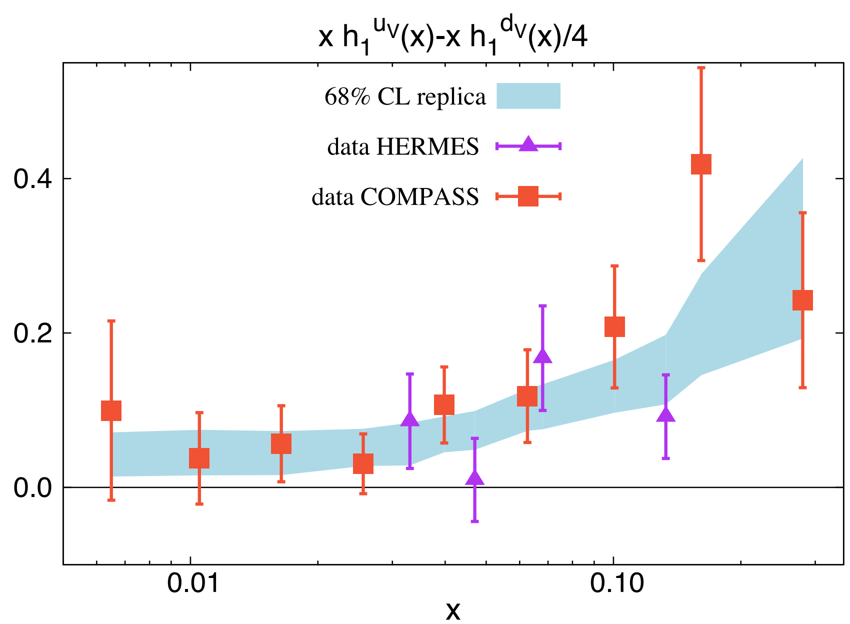
PROTON

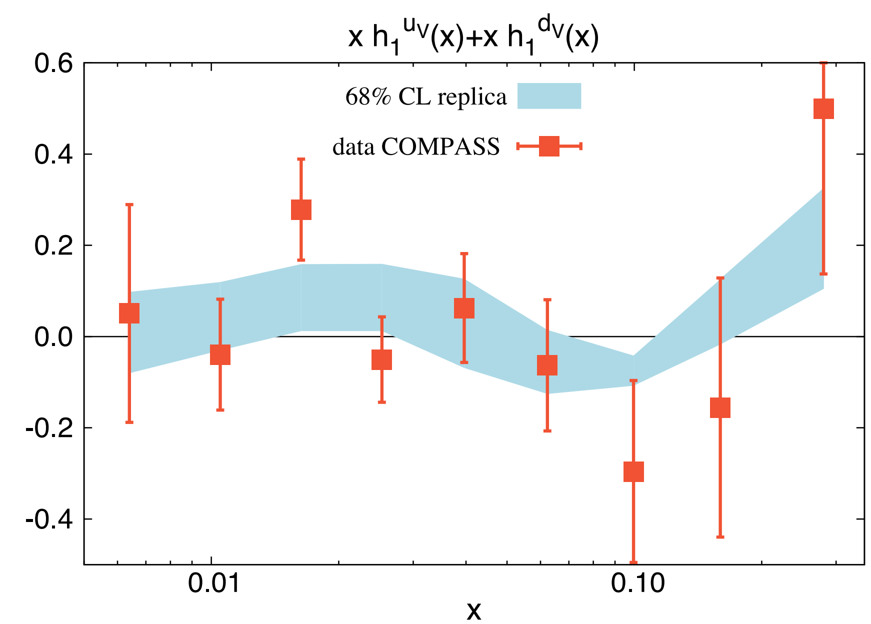
DEUTERON





flexible functional form





replica with flexible ff