TRANSVERSE PHYSICS WITH SIDIS, e^+e^- & pp

Alessandro Bacchetta
University of Pavia and INFN

Istituto Nazionale di Fisica Nucleare

"Focus should always be kept on things that are exciting"

Les Bland

1 TMD opportunities in Drell-Yan

1 TMD opportunities in Drell-Yan

2 The dihadron way to transversity

1.1 The sign change

Generalized universality

$$f_{1T}^{\perp}\big|_{\mathrm{SIDIS}} = -f_{1T}^{\perp}\big|_{\mathrm{DY}}$$

$$h_{1}^{\perp}\big|_{\mathrm{SIDIS}} = -h_{1}^{\perp}\big|_{\mathrm{DY}}$$

Generalized universality

$$f_{1T}^{\perp}\big|_{\mathrm{SIDIS}} = -f_{1T}^{\perp}\big|_{\mathrm{DY}}$$

$$h_{1}^{\perp}\big|_{\mathrm{SIDIS}} = -h_{1}^{\perp}\big|_{\mathrm{DY}}$$

J. Collins, PLB 536 (02)

“[The experimental check of the change of sign] would crucially test the factorization approach to the description of processes sensitive to transverse parton momenta.”

“[The experimental check of the change of sign] would crucially test the factorization approach to the description of processes sensitive to transverse parton momenta.”

Efremov, Goeke, Menzel, Metz, Schweitzer, PLB 612 (05)

"It is a remarkable and fundamental QCD prediction that really tests all concepts we know of for analyzing hard-scattering reactions in strong interactions, and it awaits experimental verification."

"It is a remarkable and fundamental QCD prediction that really tests all concepts we know of for analyzing hard-scattering reactions in strong interactions, and it awaits experimental verification."

Bomhof, Mulders, Vogelsang, Yuan, PRD 75 (07)

“Its experimental verification would be crucial to confirm the validity of our present conceptual framework for analyzing hard hadronic reactions.”

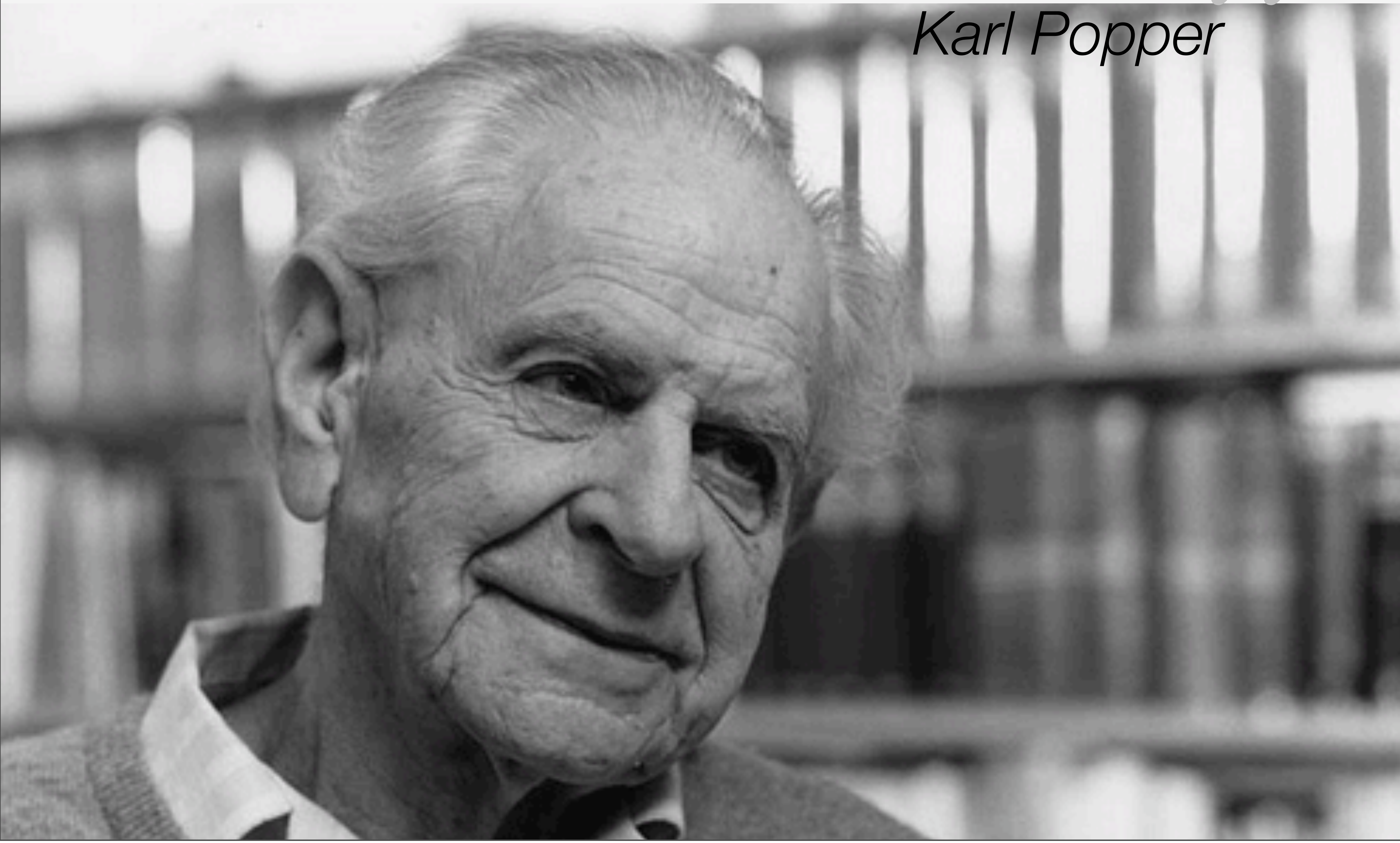
“Its experimental verification would be crucial to confirm the validity of our present conceptual framework for analyzing hard hadronic reactions.”

A.B., Bomhof, D’Alesio, Mulders, Murgia, PRL 99 (07)

What happens if we don't find the sign change?

“Good tests kill flawed theories. We remain alive to guess again.”

Karl Popper

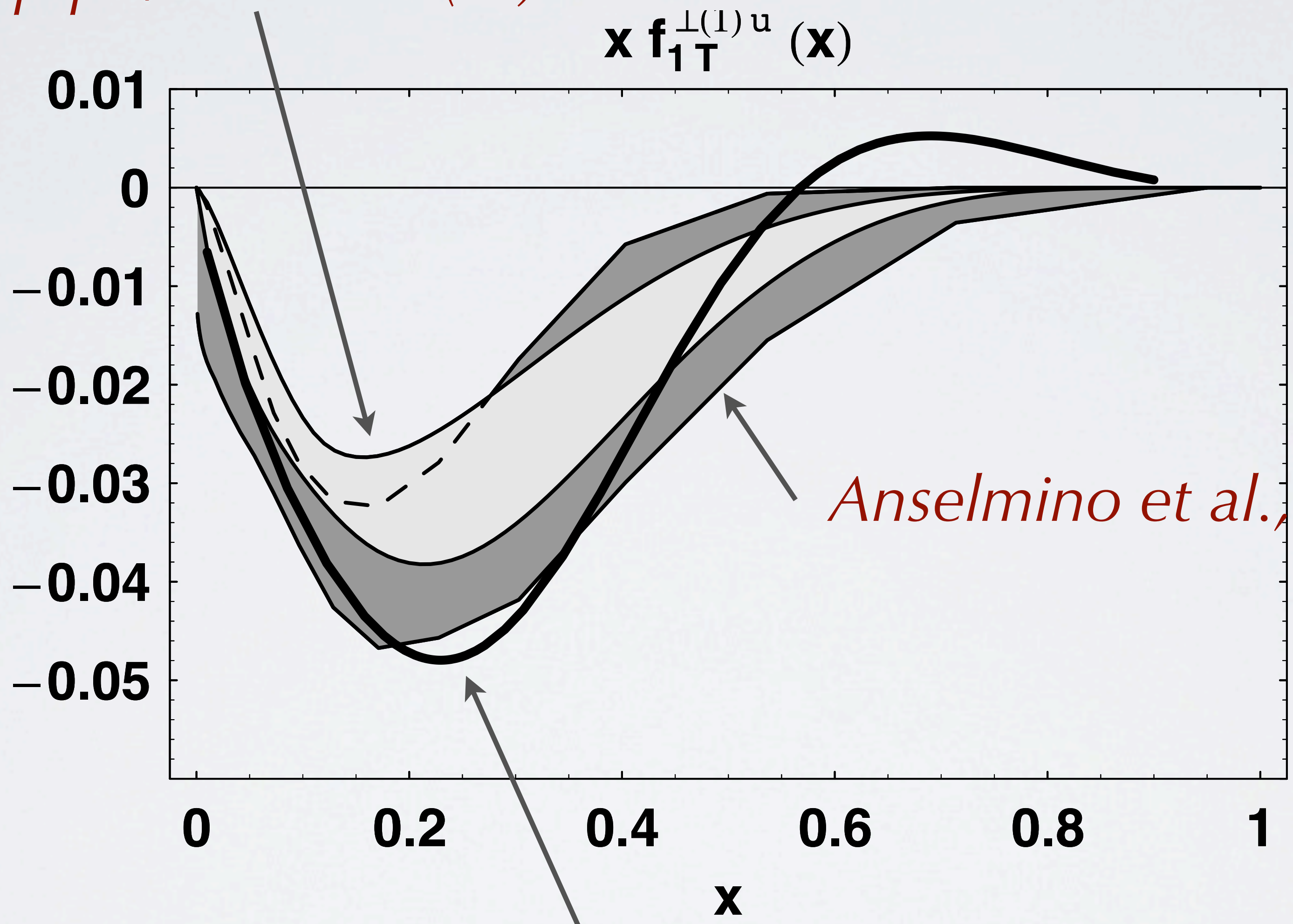


- TMD factorization **cannot be used** (bad and far-reaching conclusion). Problems also with CSS formalism.

- TMD factorization cannot be used (bad and far-reaching conclusion). Problems also with CSS formalism.
- We are oversimplifying the phenomenological analysis.

Nodes in the Sivers function

Collins et al., hep-ph/0510342 (fit)

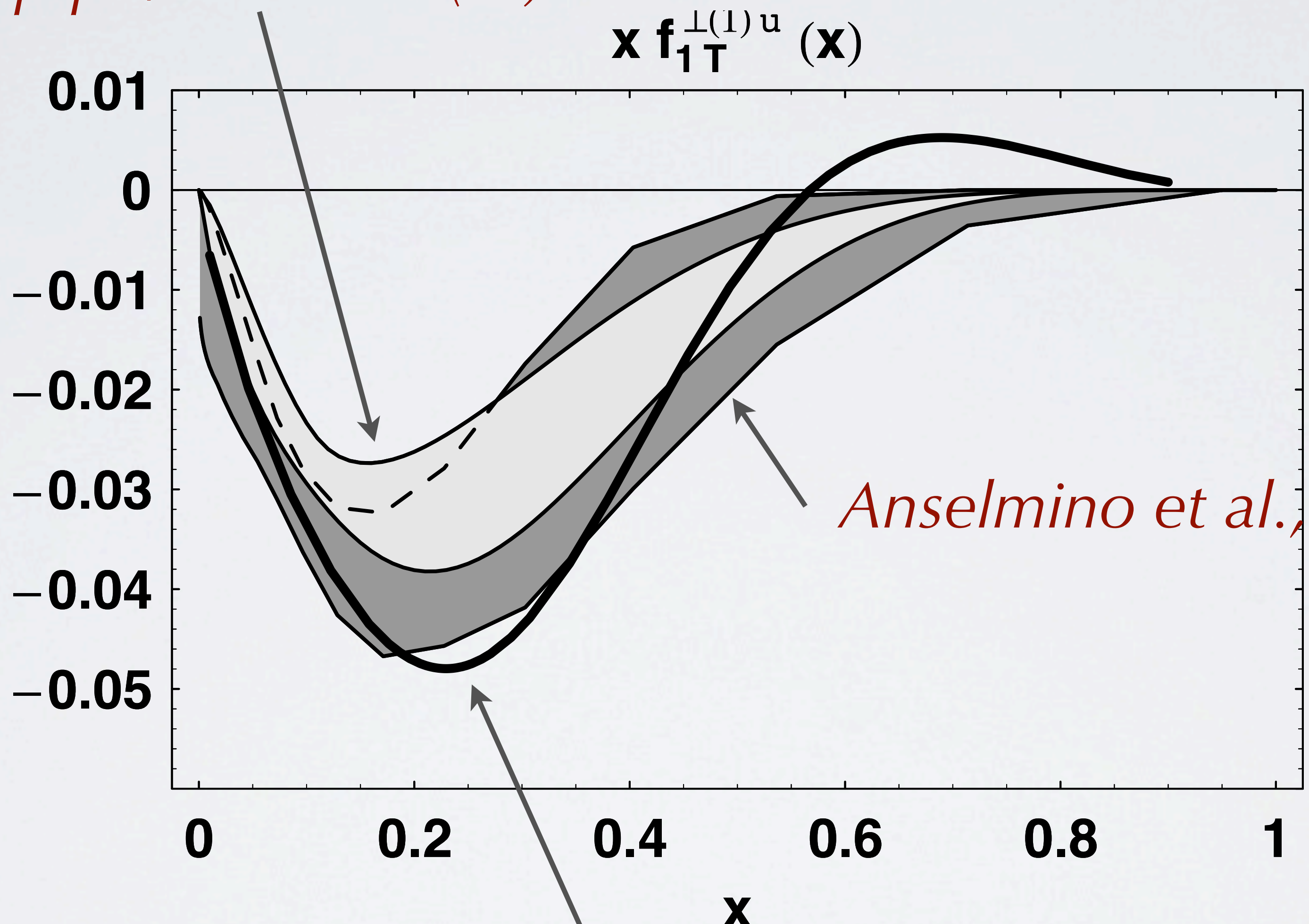


Anselmino et al., EPJA39(09) (fit)

A.B., Conti, Guagnelli, Radici, arXiv:1003.1328 (model)

Nodes in the Sivers function

Collins et al., hep-ph/0510342 (fit)

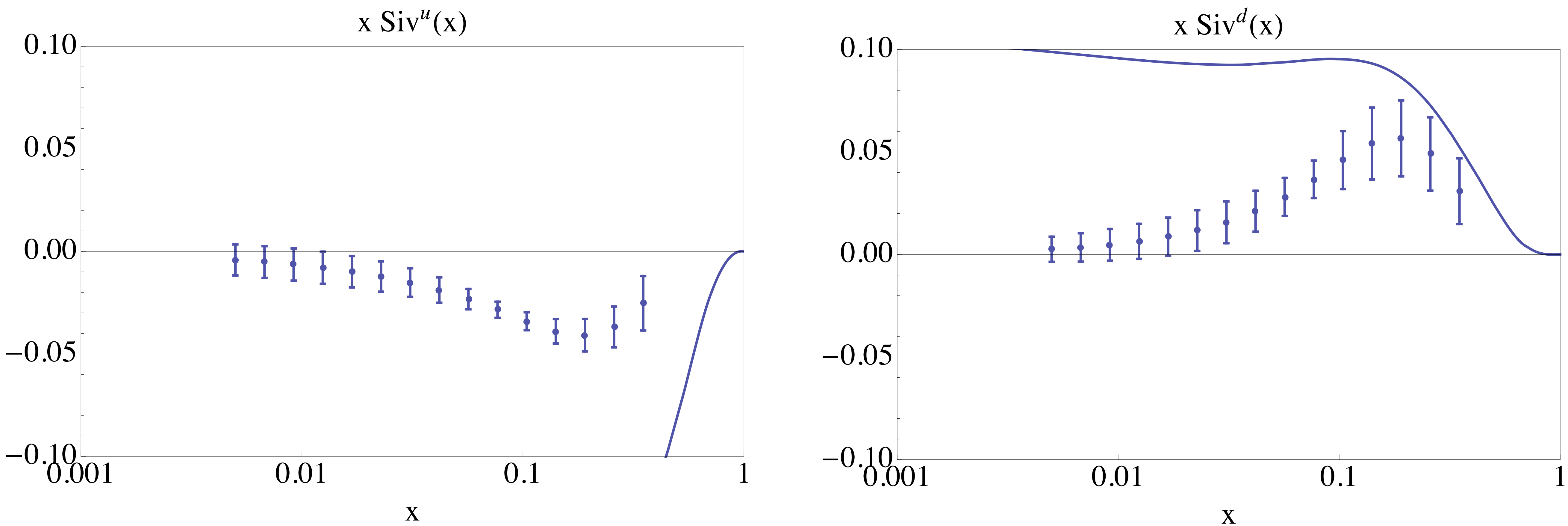


Anselmino et al., EPJA39(09) (fit)

A.B., Conti, Guagnelli, Radici, arXiv:1003.1328 (model)

See discussion in D. Boer arXiv:1105.2543 (yesterday!), talks by Z. Kang and A. Prokudin

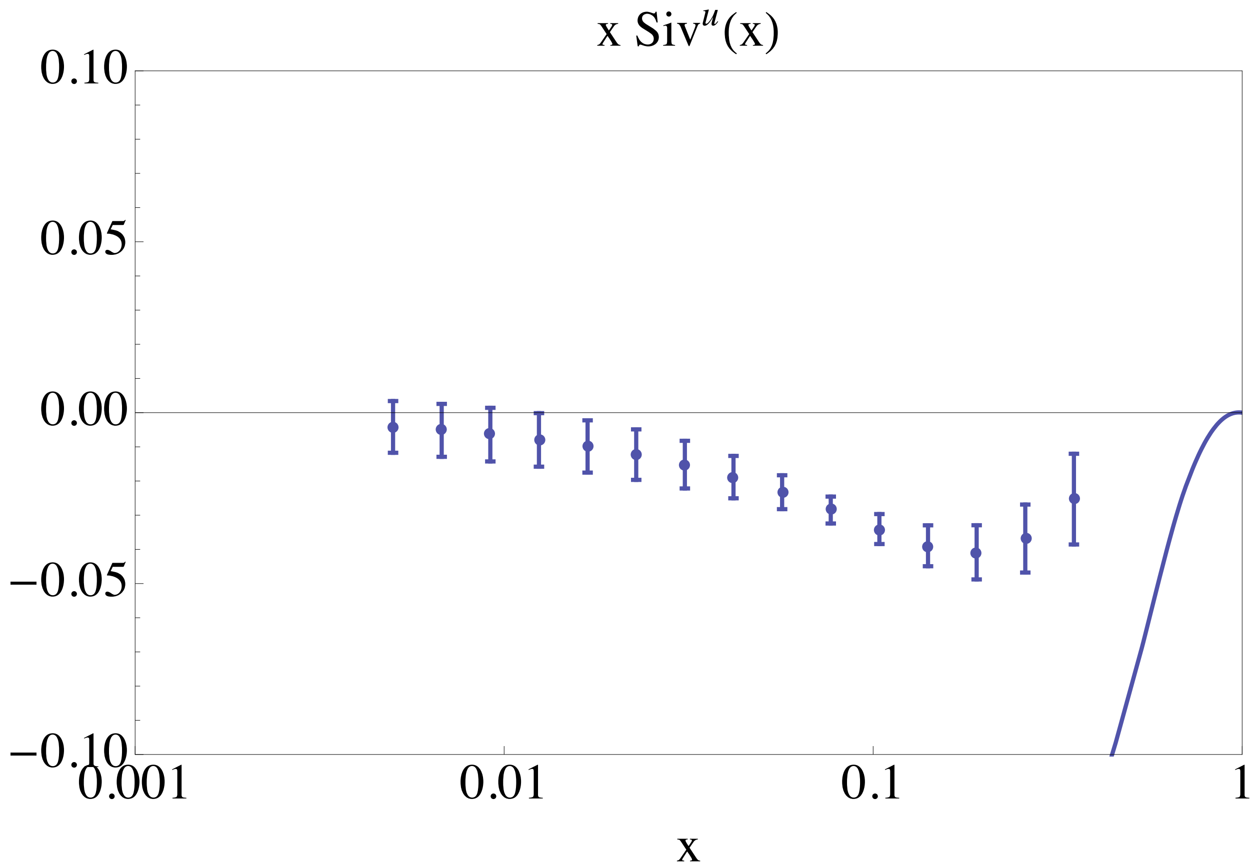
“Toy” neural-network fit

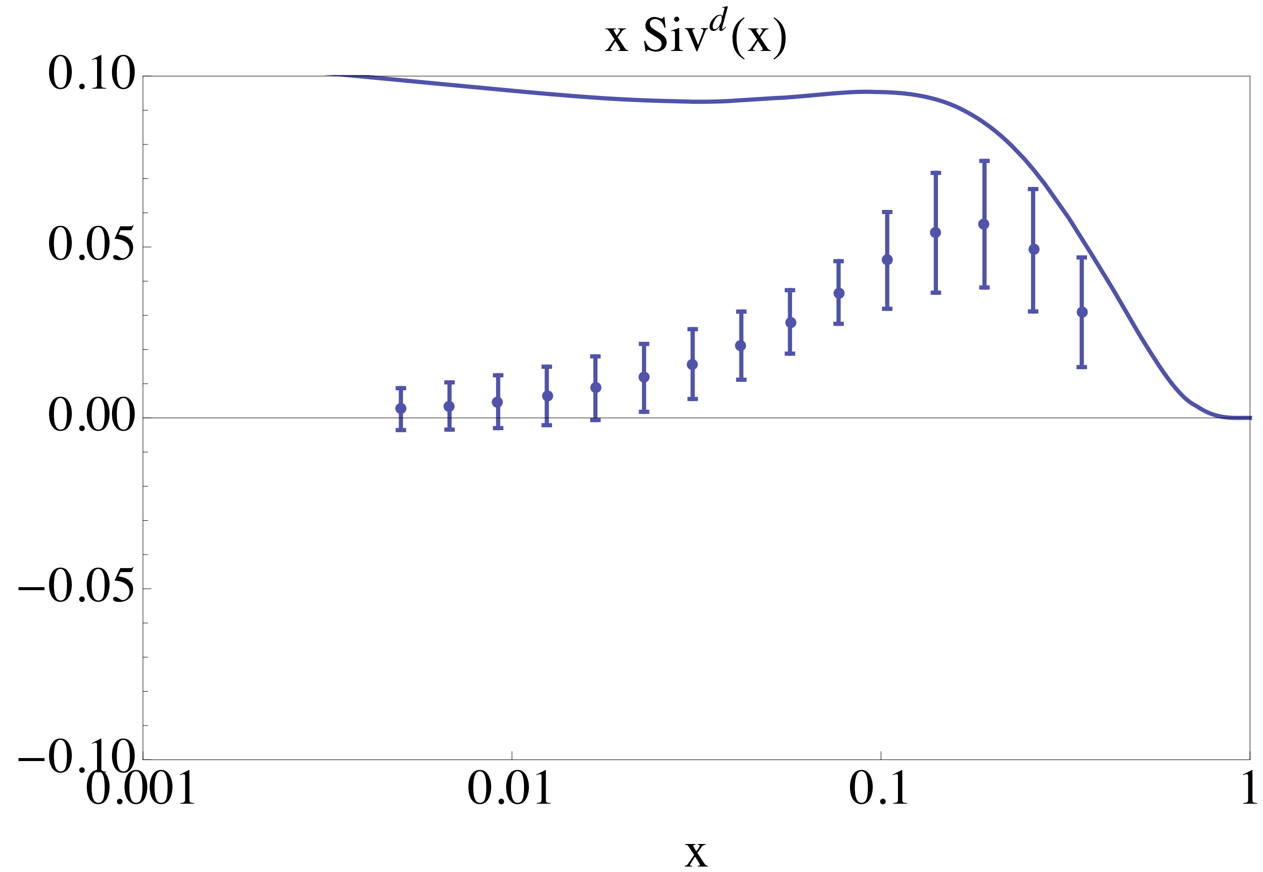


Use “fake data” obtained from parametrization of Anselmino et al., EPJA39(09)

“Toy” neural-network fit

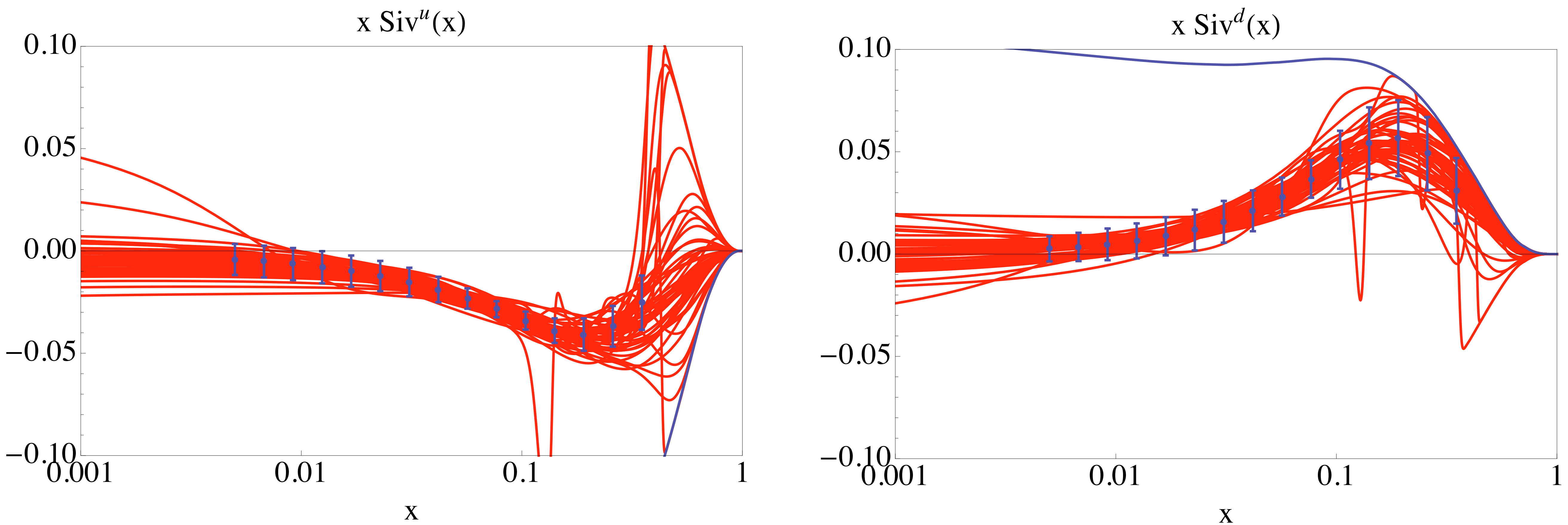
ideas inspired by NNPDF Coll., NPB838 (10)





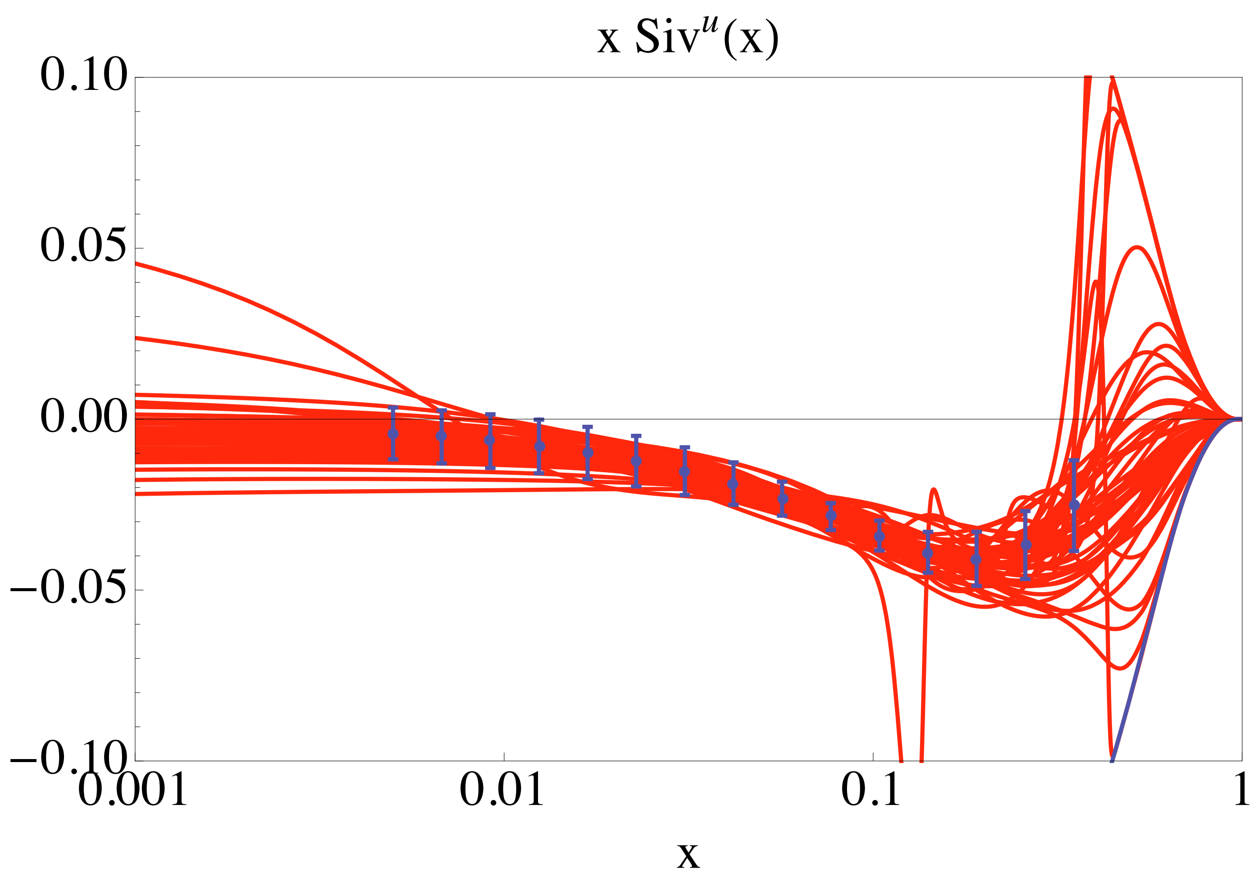
Use “fake data” obtained from parametrization of Anselmino et al., EPJA39(09)

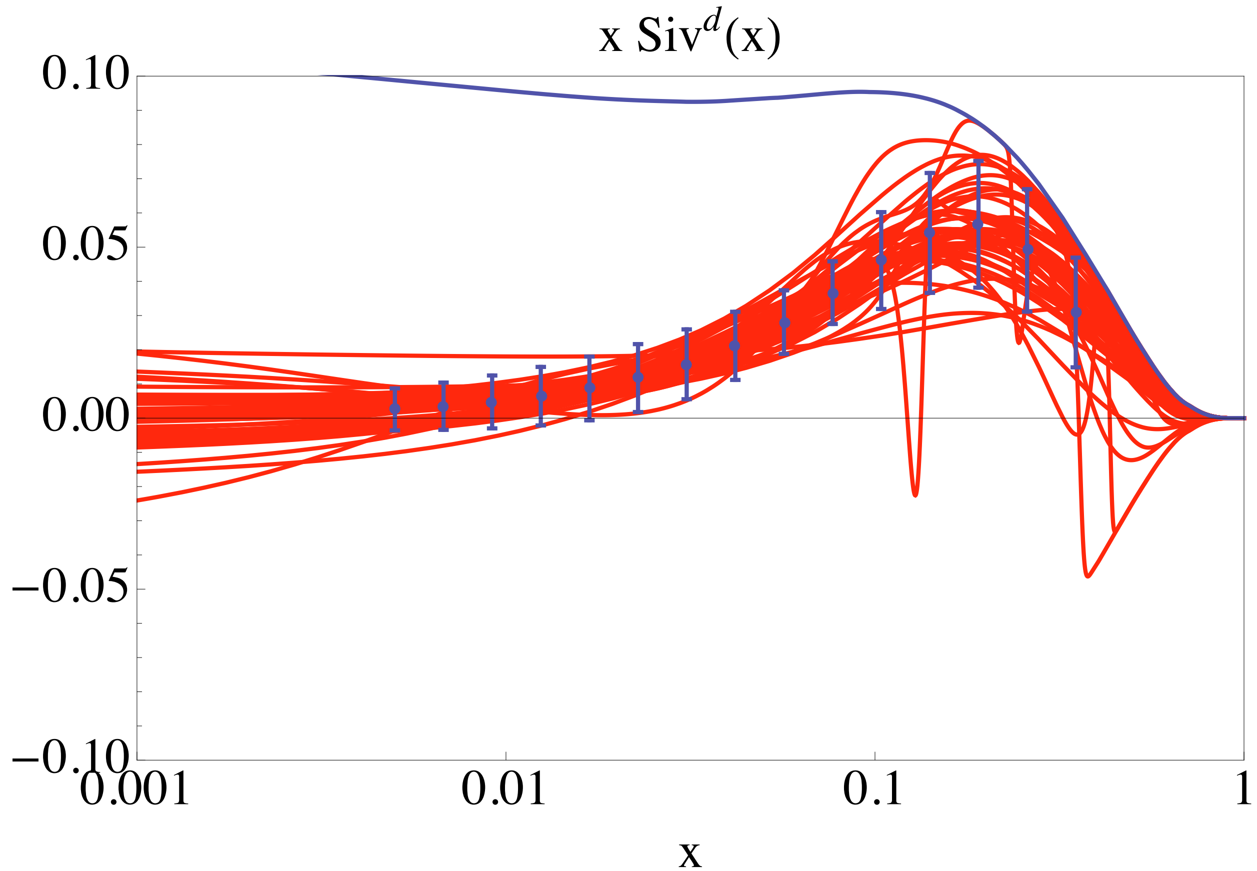
“Toy” neural-network fit



All curves have χ^2<1.6

"Toy" neural-network fit





All curves have χ^2<1.6

Neural-network fits are the best tools to avoid biased functional forms

1.2 Other TMD features

Unpol. TMD “state of the art”

$$f_1(x, k_T; Q) = \frac{1}{2\pi} \int d^2 b_T e^{-ik_T \cdot b_T} [C \otimes f_1](x, b_T)\, e^{-S'(b_T,Q)}\, e^{-S'_{\mathrm{NP}}(x,b_T,Q,\alpha_i)}$$

T. Rogers, M. Aybat, arXiv:1101.5057
talk by G. Sterman and by T. Rogers

Unpol. TMD "state of the art"

$$f_1(x, k_T; Q) = \frac{1}{2\pi} \int d^2 b_T e^{-ik_T \cdot b_T} [C \otimes f_1](x, b_T)\, e^{-S'(b_T, Q)}\, e^{-S'_{\mathrm{NP}}(x, b_T, Q, \alpha_i)}$$

collinear PDF

T. Rogers, M. Aybat, arXiv:1101.5057
talk by G. Sterman and by T. Rogers

Unpol. TMD "state of the art"

$$f_1(x, k_T; Q) = \frac{1}{2\pi} \int d^2 b_T e^{-i k_T \cdot b_T} [C \otimes f_1](x, b_T)\, e^{-S'(b_T, Q)}\, e^{-S'_{\mathrm{NP}}(x, b_T, Q, \alpha_i)}$$

collinear PDF

pQCD

T. Rogers, M. Aybat, arXiv:1101.5057
talk by G. Sterman and by T. Rogers

Unpol. TMD "state of the art"

$$f_1(x, k_T; Q) = \frac{1}{2\pi}\int d^2b_T e^{-ik_T\cdot b_T}[C\otimes f_1](x, b_T)\, e^{-S'(b_T,Q)}\, e^{-S'_{\rm NP}(x,b_T,Q,\alpha_i)}$$

collinear PDF

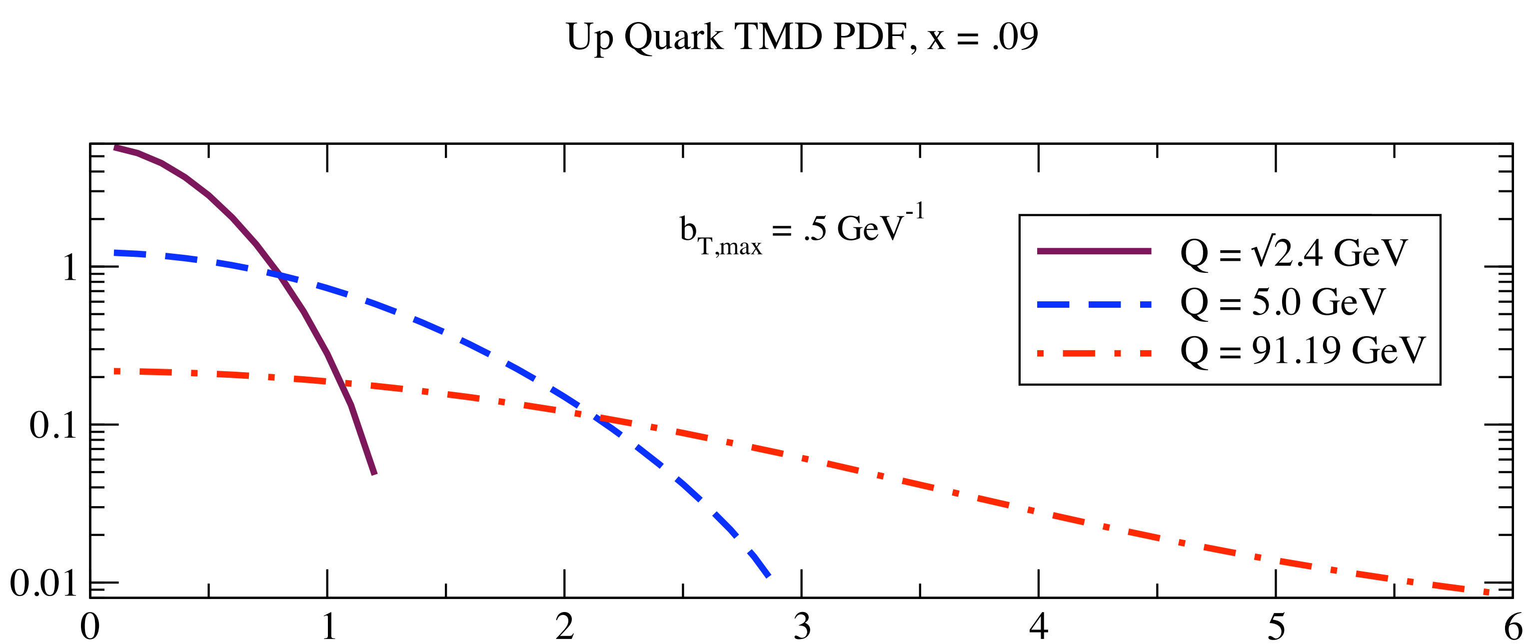
pQCD

nonperturbative part of TMD

T. Rogers, M. Aybat, arXiv:1101.5057
talk by G. Sterman and by T. Rogers

Unpol. TMD "state of the art"

$$f_1(x, k_T; Q) = \frac{1}{2\pi} \int d^2 b_T e^{-ik_T \cdot b_T} [C \otimes f_1](x, b_T)\, e^{-S'(b_T,Q)}\, e^{-S'_{\rm NP}(x,b_T,Q,\alpha_i)}$$



T. Rogers, M. Aybat, arXiv:1101.5057
Landry, Brock, Nadolsky, Yuan, PRD67 (03)
P. Schweitzer, T. Teckentrup, A. Metz, PRD81(10)

BLNY fit

Landry, Brock, Nadolsky, Yuan, PRD67 (03)

Experiment	Reference	Reaction	$\sqrt{S}$ (GeV)	δN_{exp}
R209	[14]	$p + p \to \mu^+\mu^- + X$	62	10%
E605	[15]	$p + Cu \to \mu^+\mu^- + X$	38.8	15%
E288	[16]	$p + Cu \to \mu^+\mu^- + X$	27.4	25%
CDF-Z (Run-0)	[17]	$p + \bar{p} \to Z + X$	1800	–
DØ -Z (Run-1)	[18]	$p + \bar{p} \to Z + X$	1800	4.3%
CDF-Z (Run-1)	[19]	$p + \bar{p} \to Z + X$	1800	3.9%

BLNY fit

Landry, Brock, Nadolsky, Yuan, PRD67 (03)

Experiment	Reference	Reaction	$\sqrt{S}$ (GeV)	δN_{exp}
R209	[14]	$p + p \to \mu^+\mu^- + X$	62	10%
E605	[15]	$p + Cu \to \mu^+\mu^- + X$	38.8	15%
E288	[16]	$p + Cu \to \mu^+\mu^- + X$	27.4	25%
CDF-Z (Run-0)	[17]	$p + \bar{p} \to Z + X$	1800	–
DØ -Z (Run-1)	[18]	$p + \bar{p} \to Z + X$	1800	4.3%
CDF-Z (Run-1)	[19]	$p + \bar{p} \to Z + X$	1800	3.9%

D-Y (including Z production) is the most important source of information for unpolarized TMDs

BLNY fit

Landry, Brock, Nadolsky, Yuan, PRD67 (03)

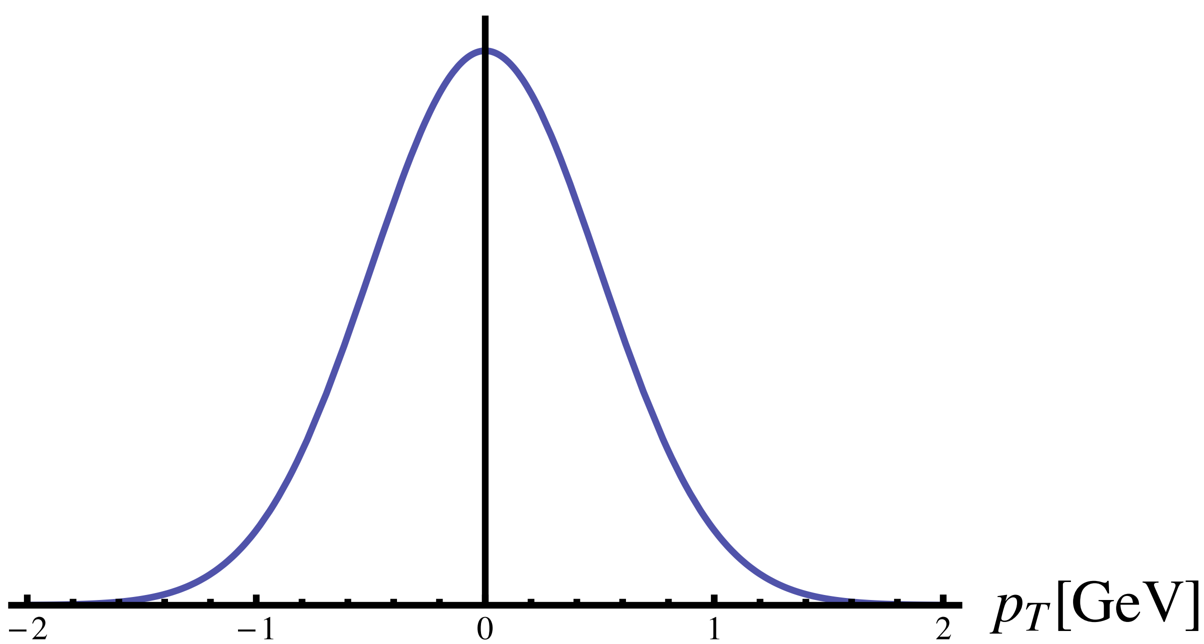
Experiment	Reference	Reaction	$\sqrt{S}$ (GeV)	δN_{exp}
R209	[14]	$p + p \to \mu^+\mu^- + X$	62	10%
E605	[15]	$p + Cu \to \mu^+\mu^- + X$	38.8	15%
E288	[16]	$p + Cu \to \mu^+\mu^- + X$	27.4	2[illegible]
CDF-Z (Run-0)	[17]	$p + \bar{p} \to Z + X$	1800	[illegible]
DØ -Z (Run-1)	[18]	$p + \bar{p} \to Z + X$	1800	4.3%
CDF-Z (Run-1)	[19]	$p + \bar{p} \to Z + X$	1800	3.9%

AnDY

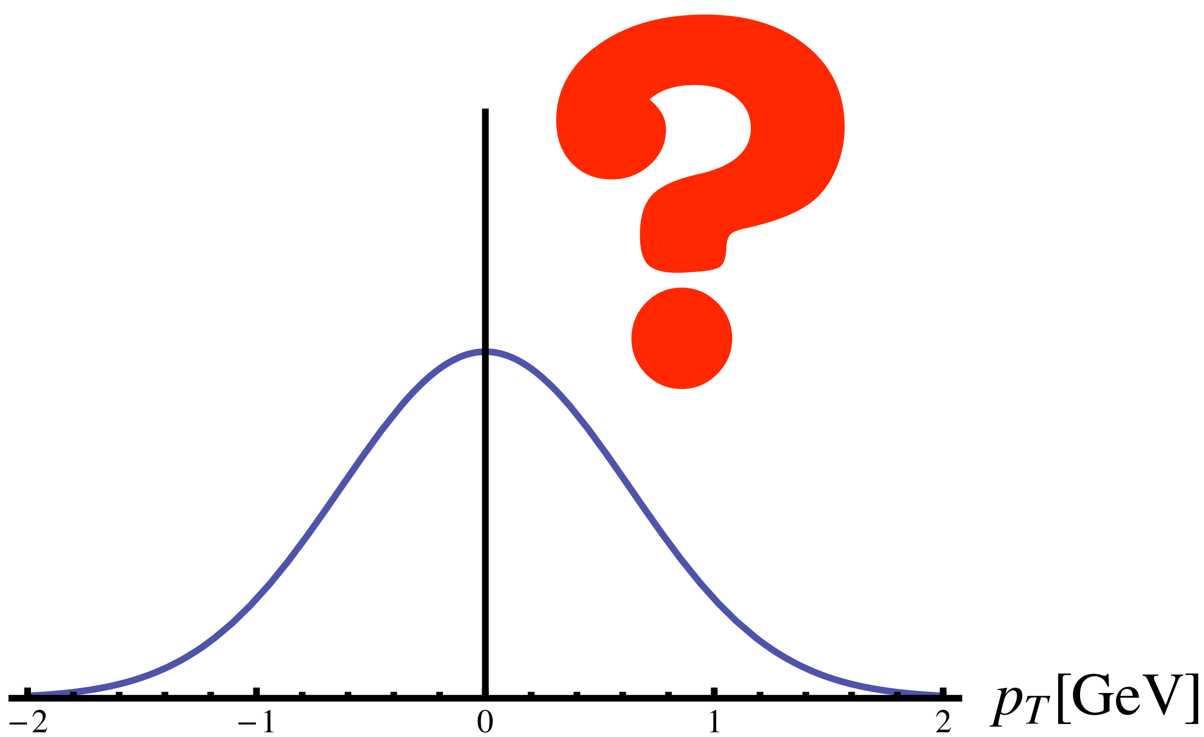
D-Y (including Z production) is the most important source of information for unpolarized TMDs

x dependence of TMDs

x=0.1

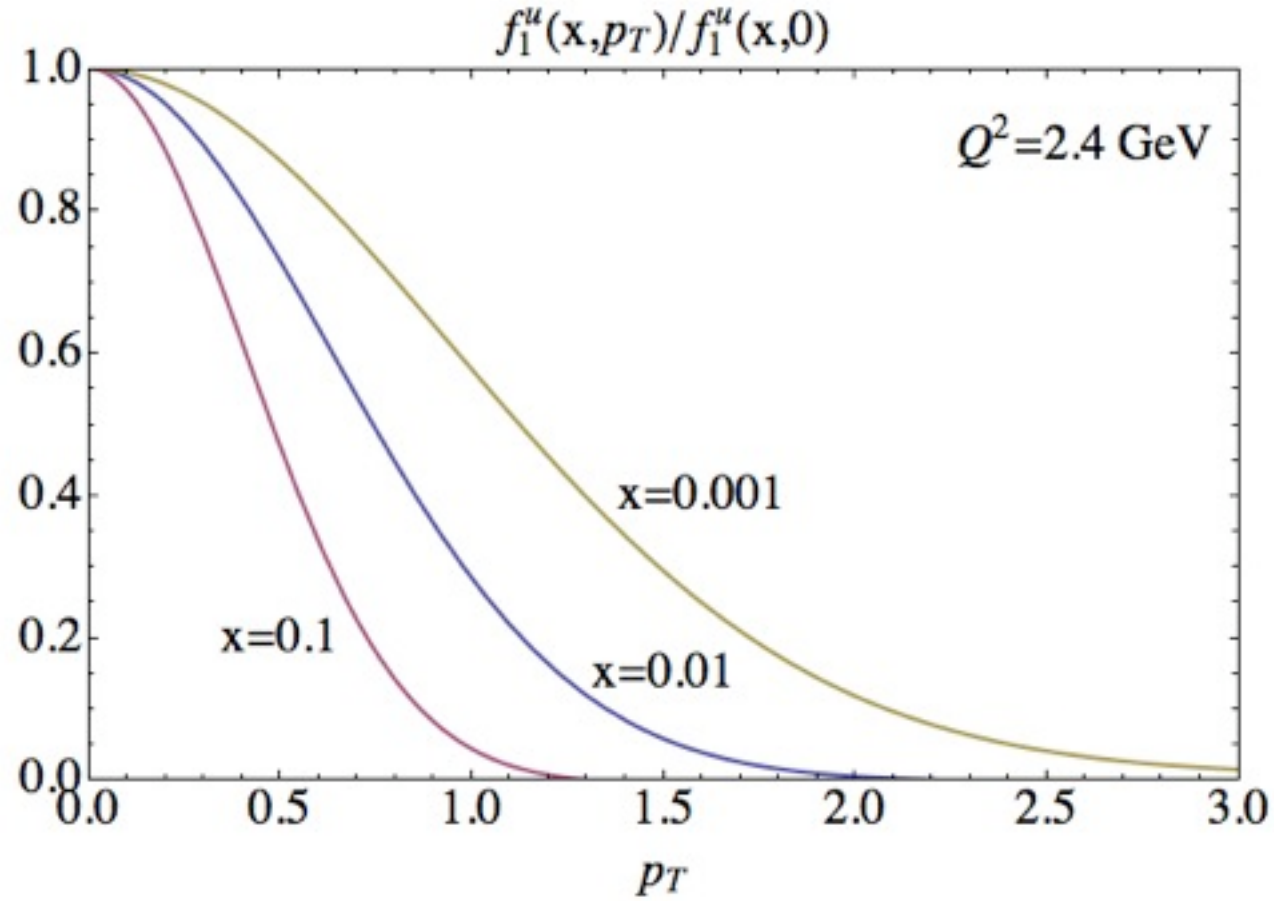


x=0.001



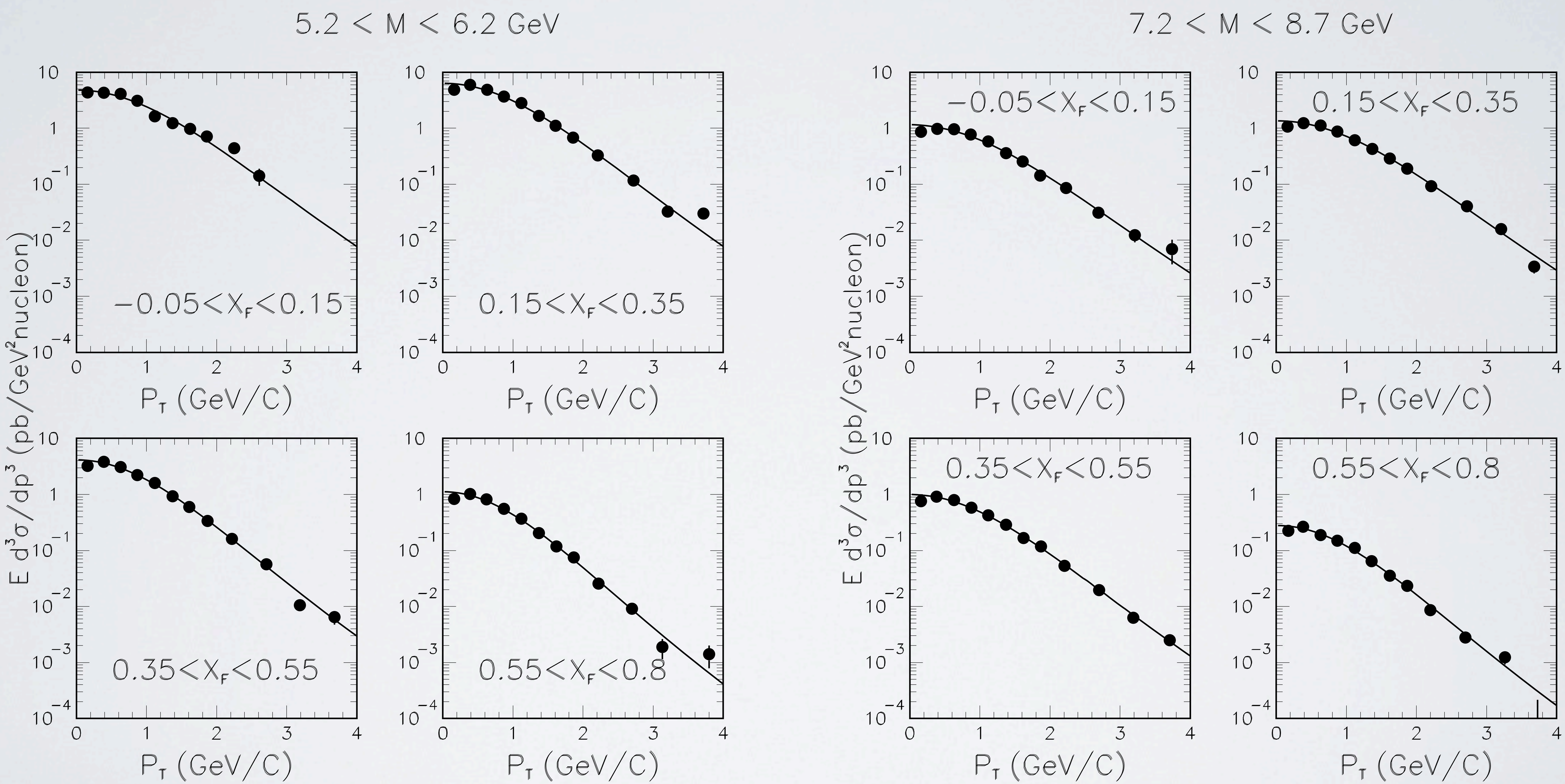
x dependence of TMDs

T. Rogers, M. Aybat, arXiv:1101.5057
Landry, Brock, Nadolsky, Yuan, PRD67 (03)
P. Schweitzer, T. Teckentrup, A. Metz, PRD81(10)



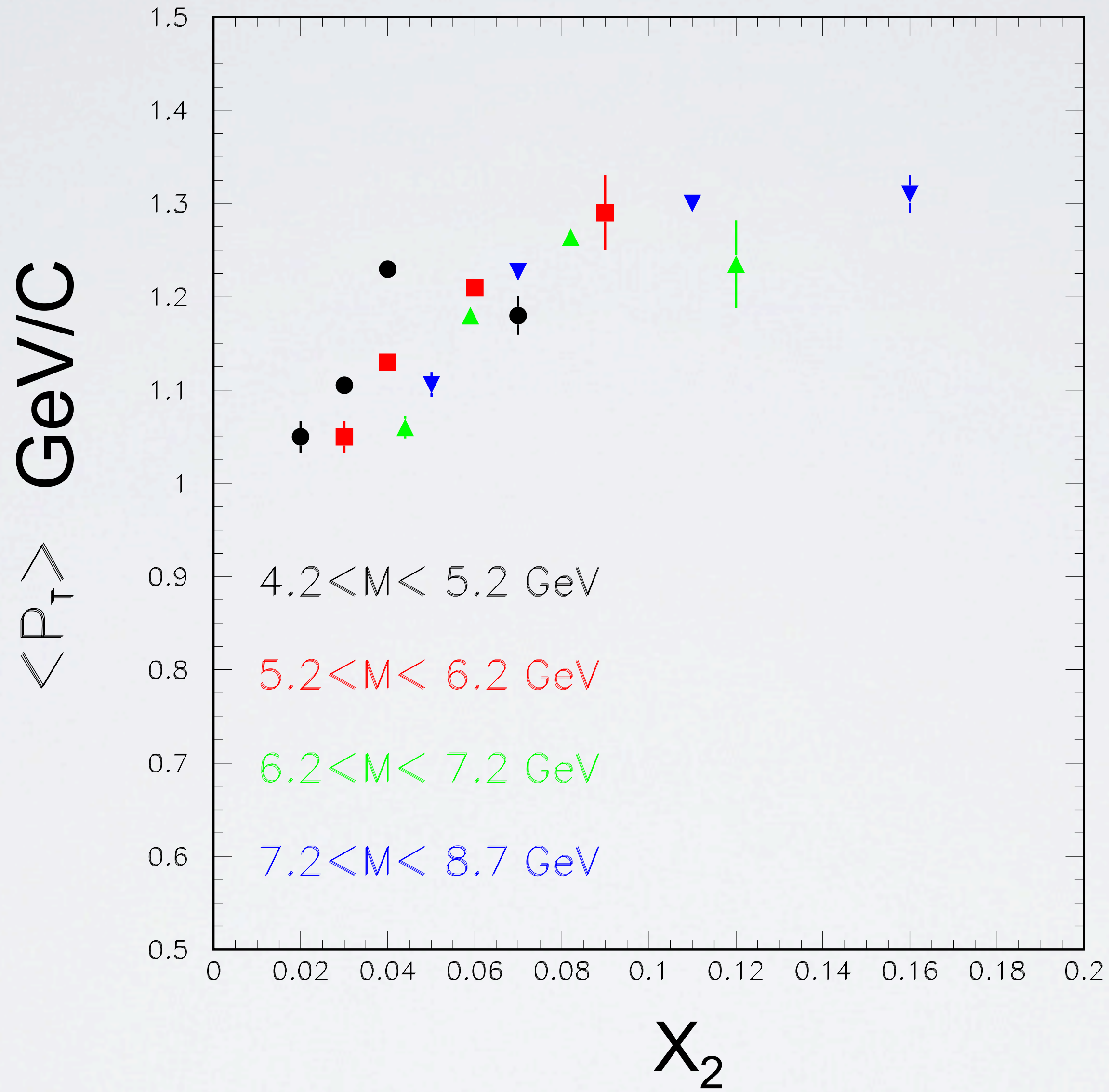
Widening driven by Tevatron data

Multidim. studies are needed



talk by J.-C. Peng

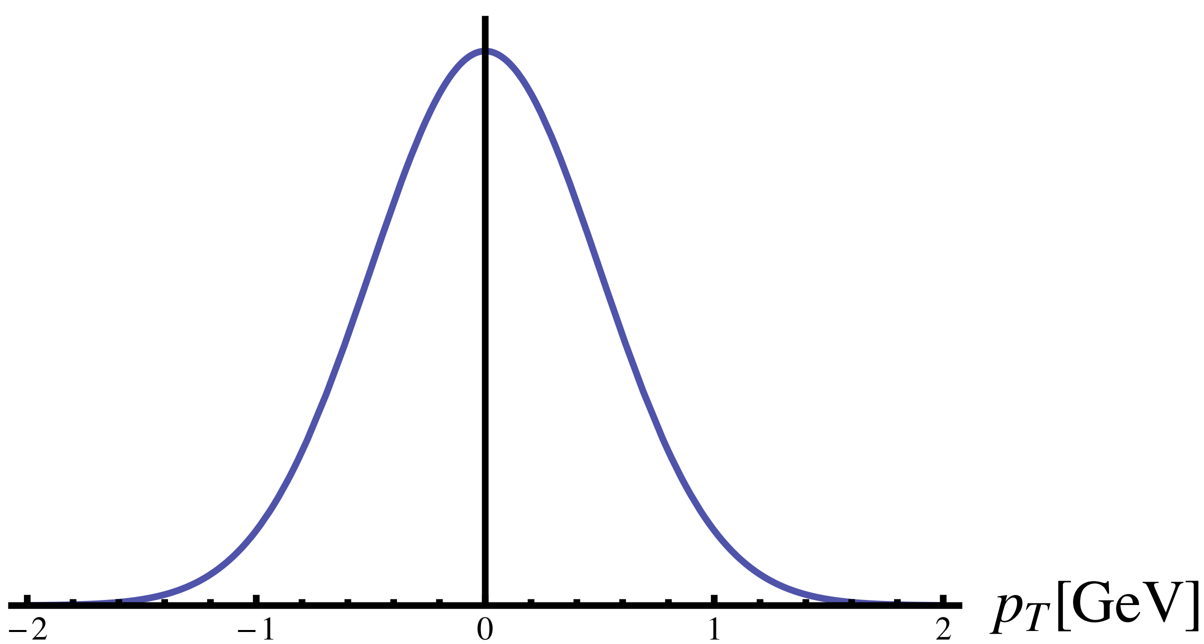
New E866 data

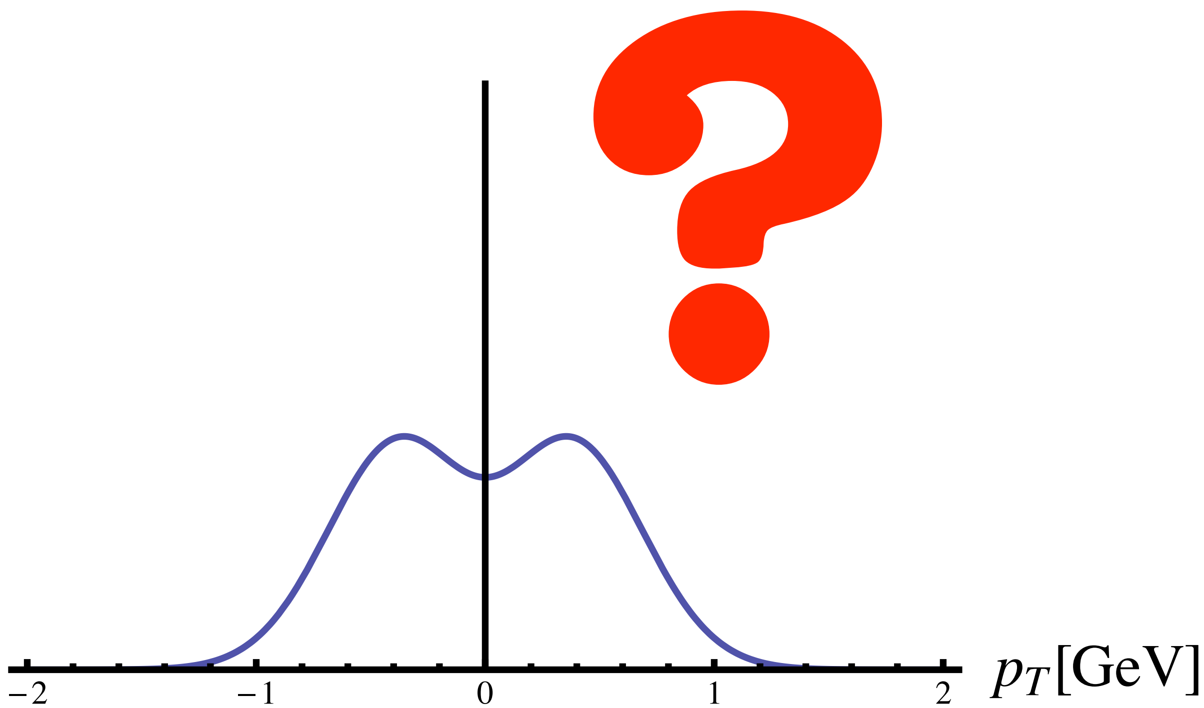


Behavior opposite to BLNY fit

talk by J.-C. Peng

Non-Gaussian TMDs

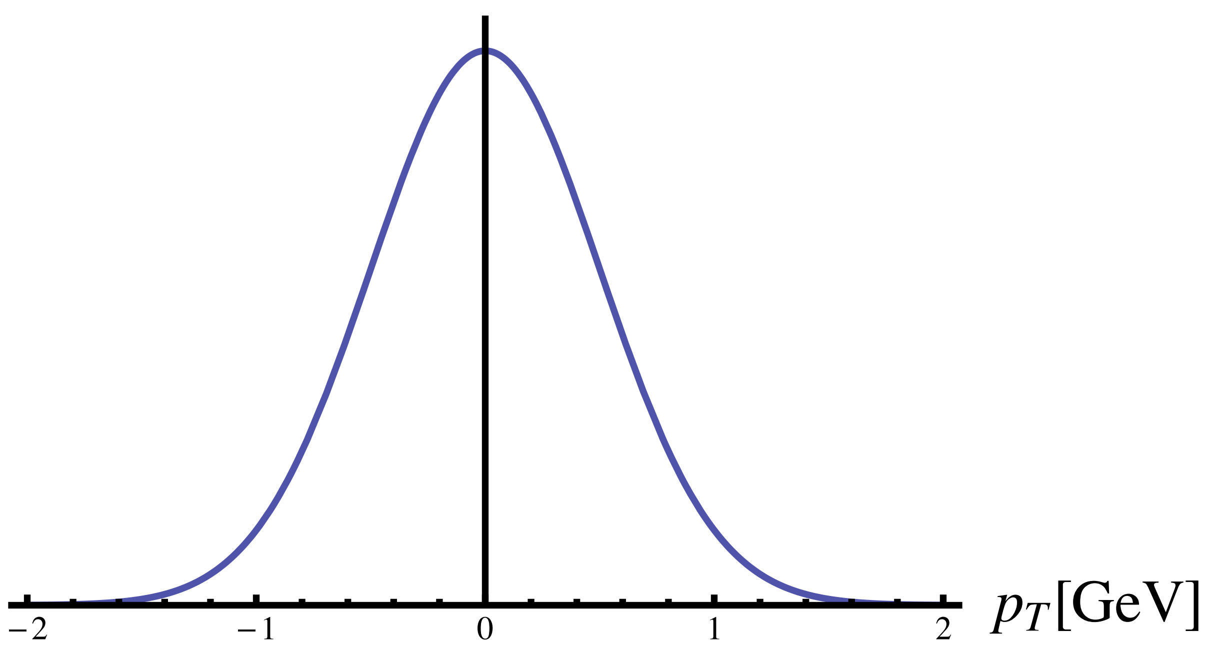




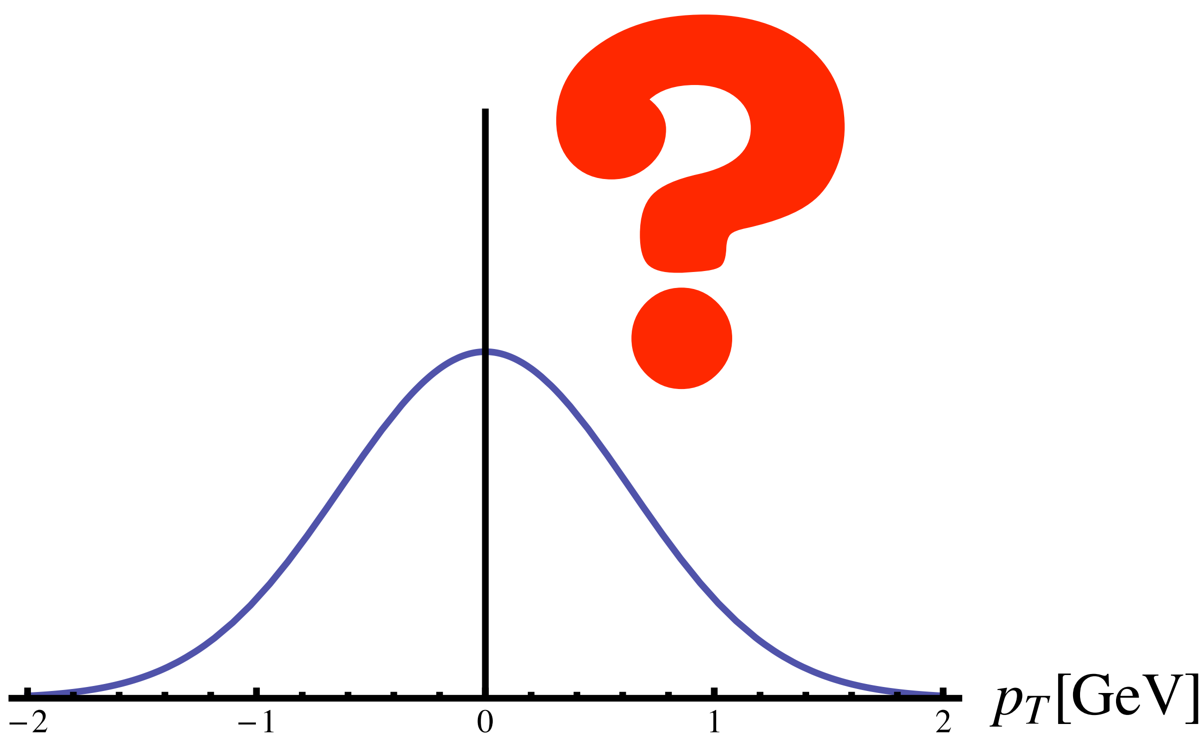
With orbital angular momentum, TMDs cannot be Gaussians!

Flavor-dependent TMDs

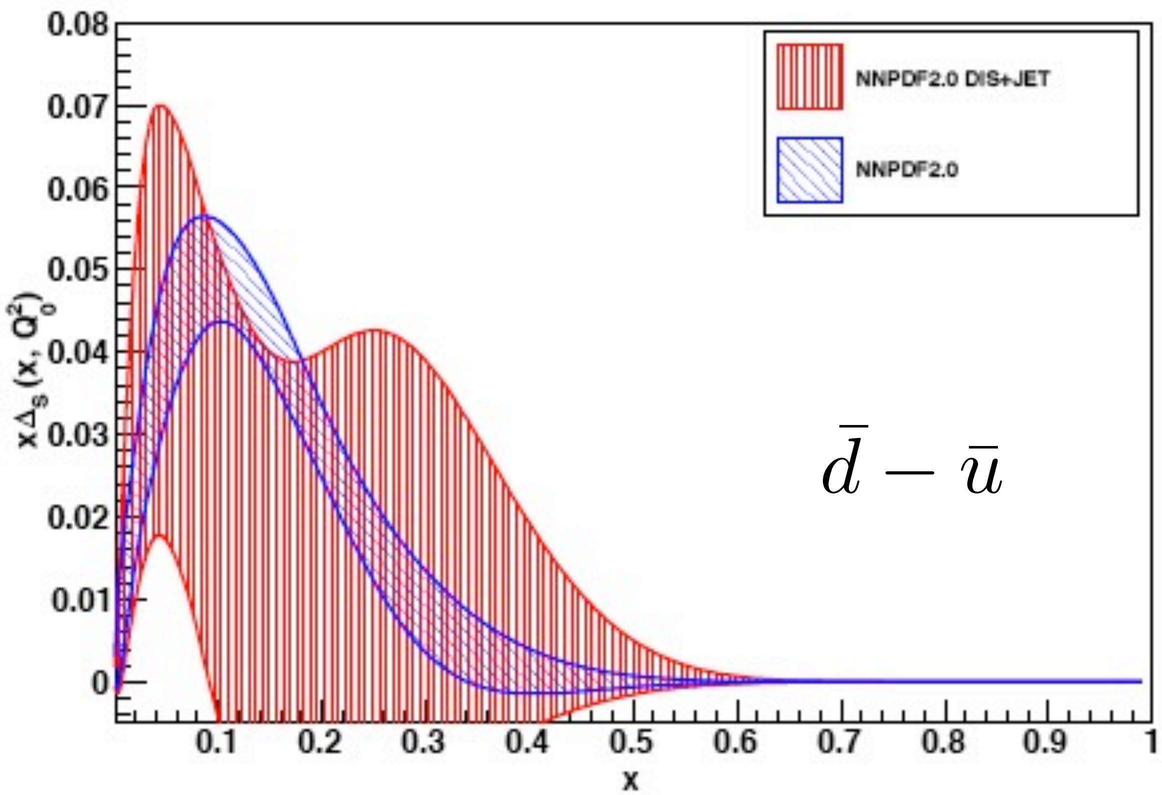
valence

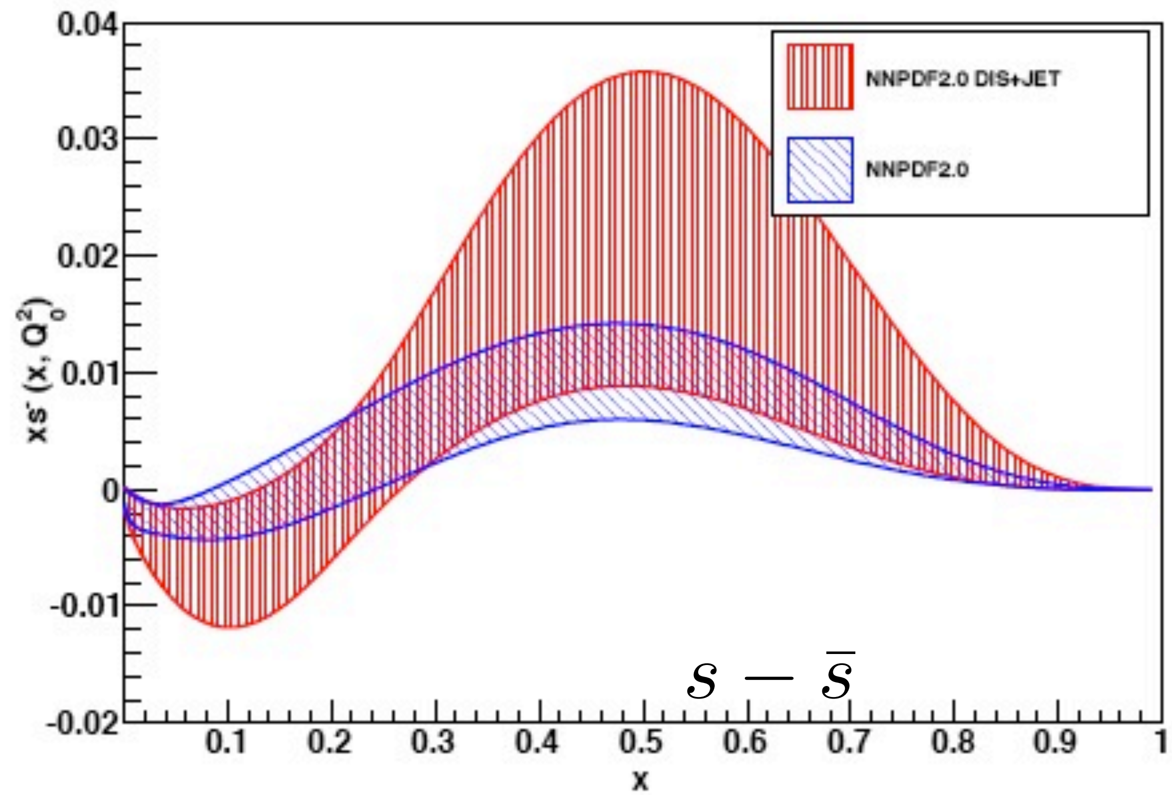


sea



D-Y: impact on PDFs

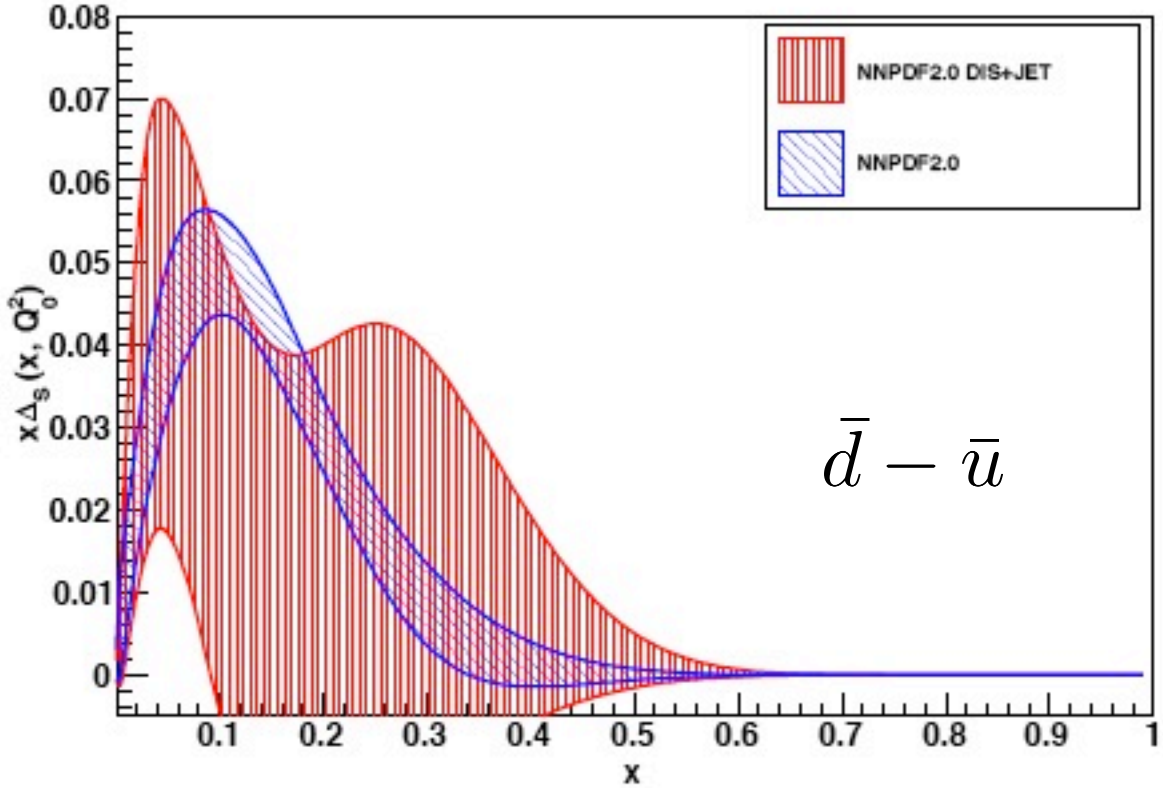


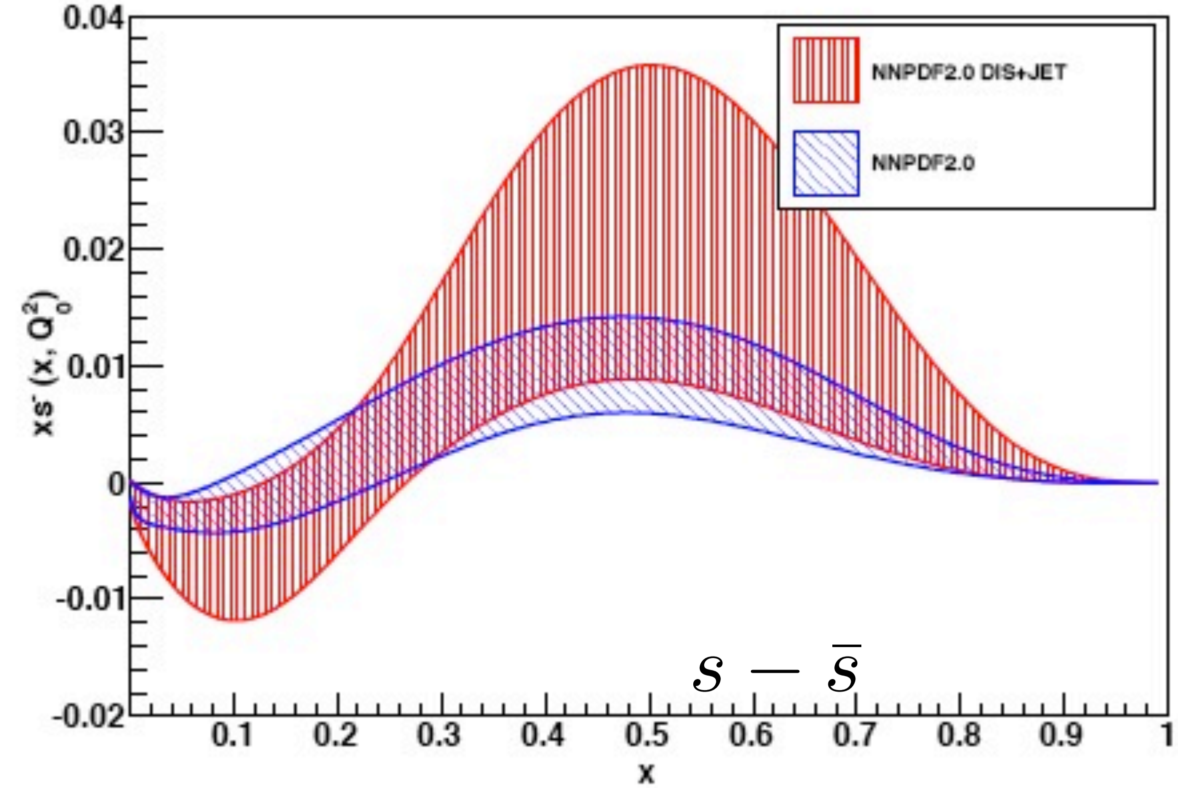


Blue: adding E605 and E866 data

We can expect similar impact on TMDs

D-Y: impact on PDFs





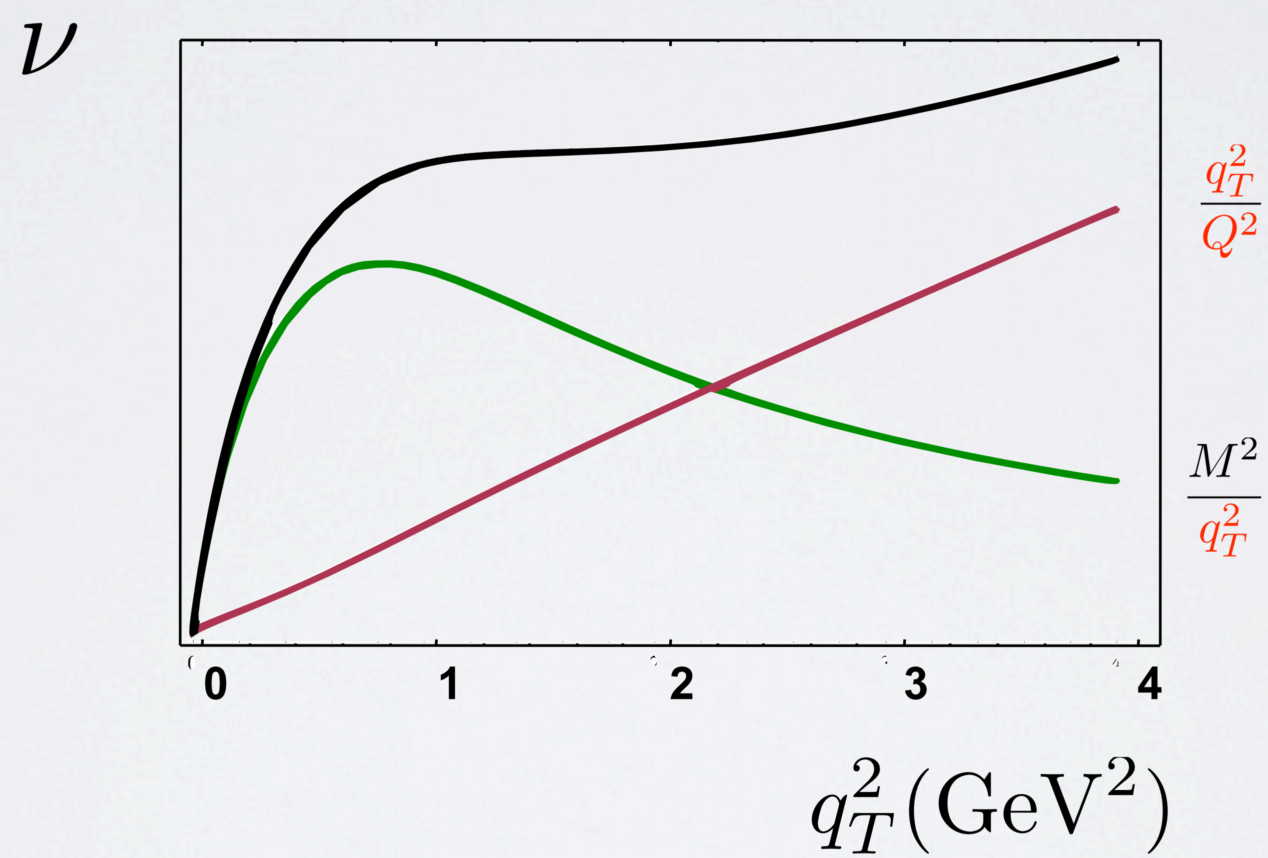
Blue: adding E605 and E866 data

We can expect similar impact on TMDs

NNPDF Coll., NPB838 (10)

On the cos2ϕ modulation

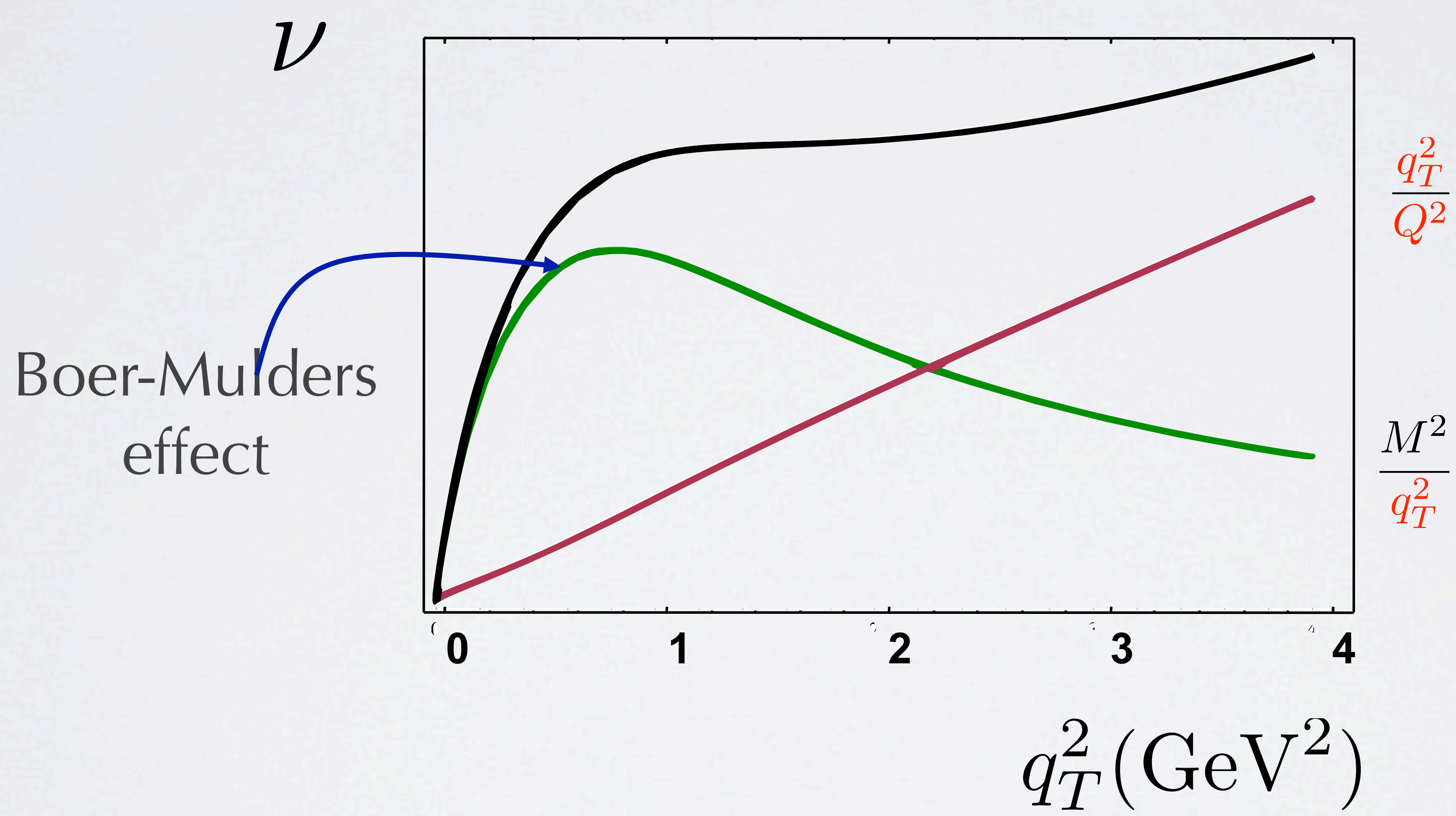
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$



Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

On the cos2ϕ modulation

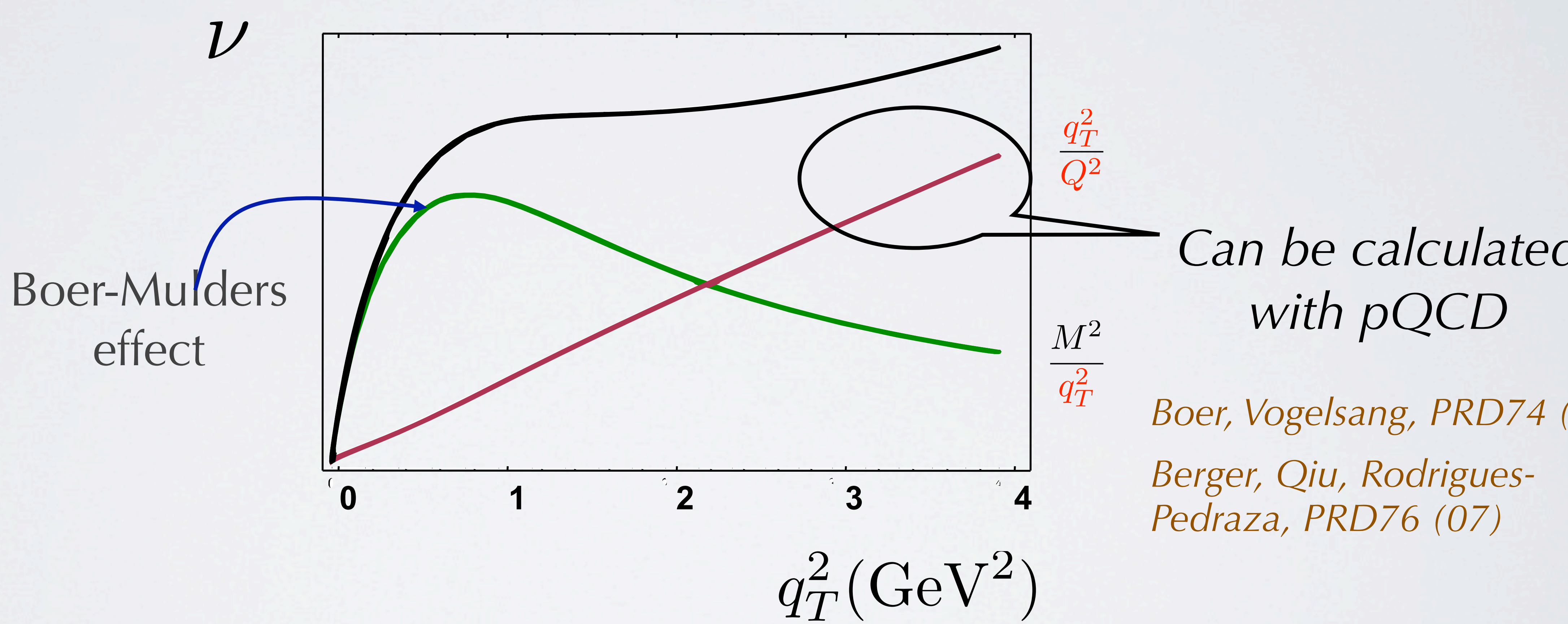
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$



Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

On the cos2 ϕ modulation

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



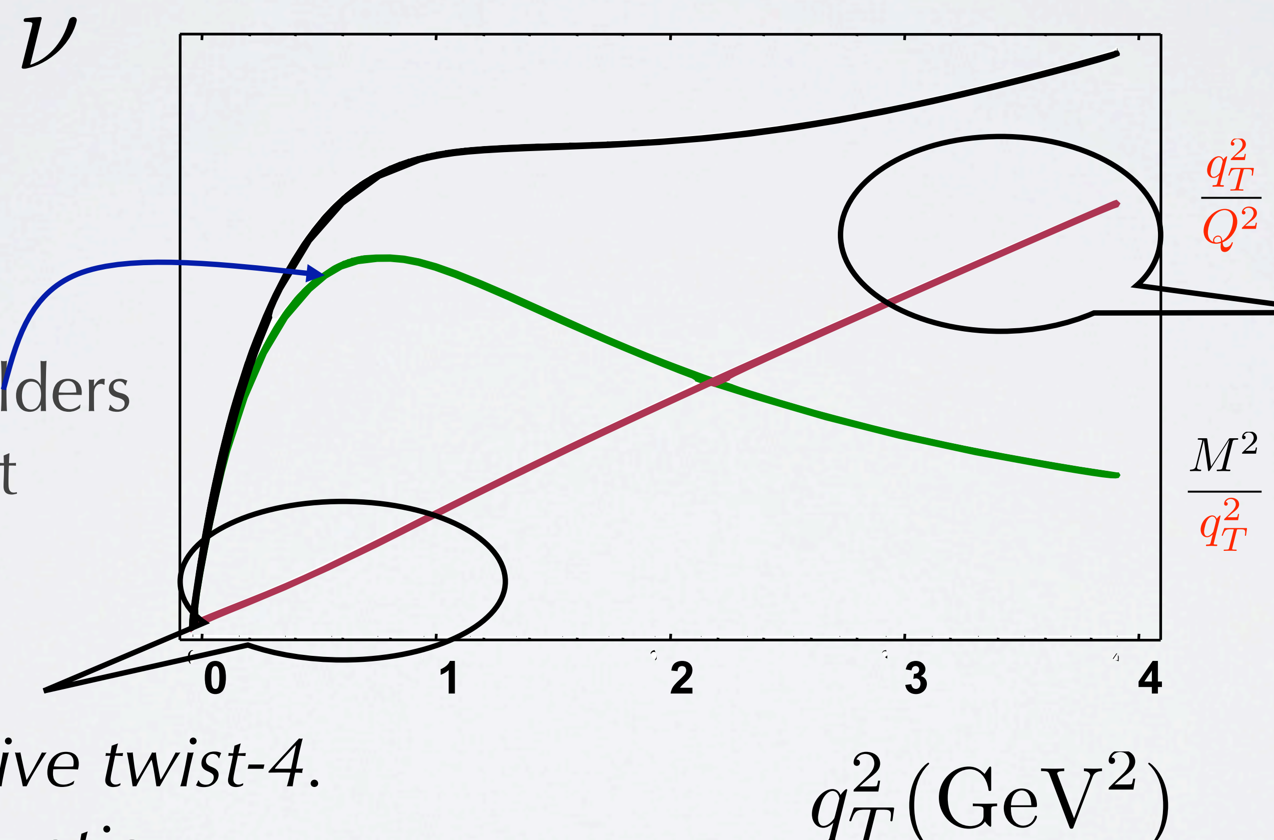
Boer, Vogelsang, PRD74 (06)

Berger, Qiu, Rodrigues-Pedraza, PRD76 (07)

Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

On the $\cos 2\phi$ modulation

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



Boer-Mulders effect

Can be calculated with pQCD

Nonperturbative twist-4.
No factorization.
(Cahn twist-4 can be a model?)

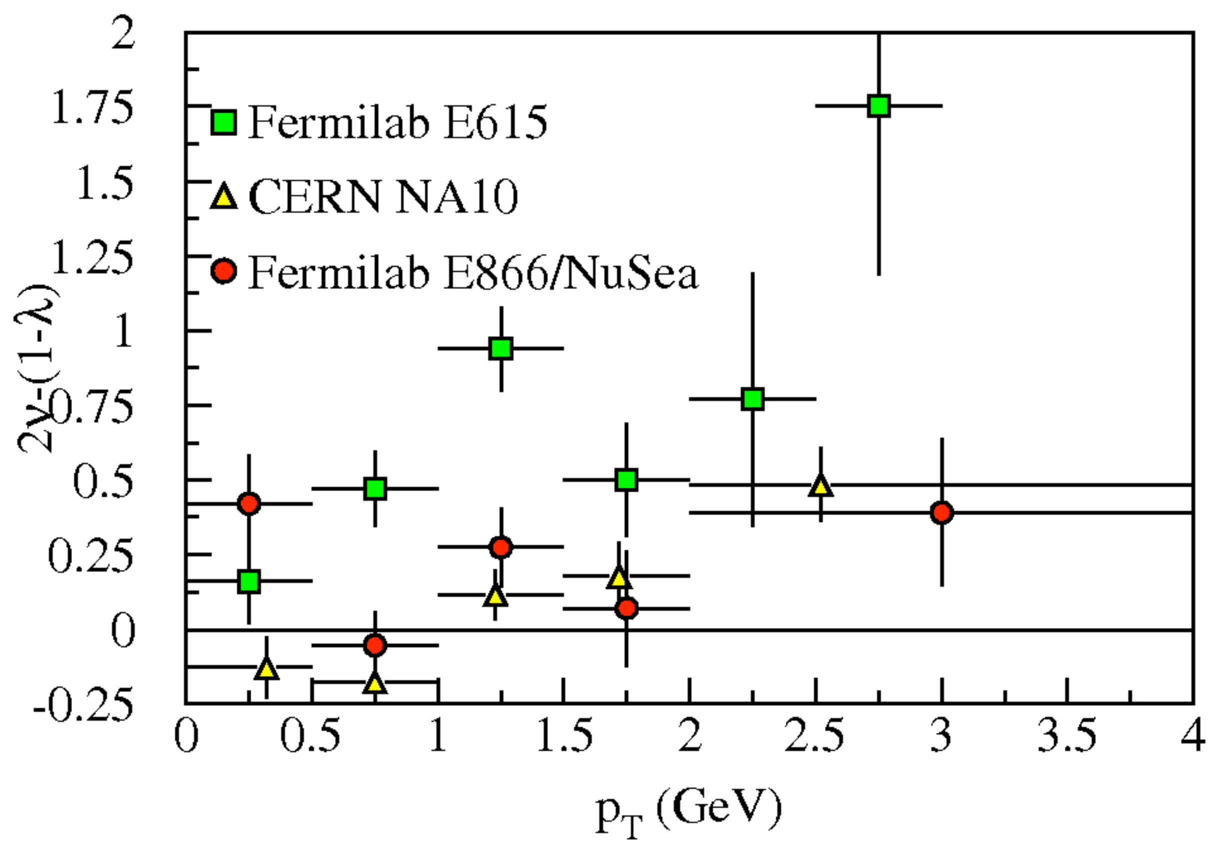
Boer, Vogelsang, PRD74 (06)

Berger, Qiu, Rodrigues-Pedraza, PRD76 (07)

Bacchetta, Boer, Diehl, Mulders, JHEP08 (08)

Violation of Lam-Tung relation

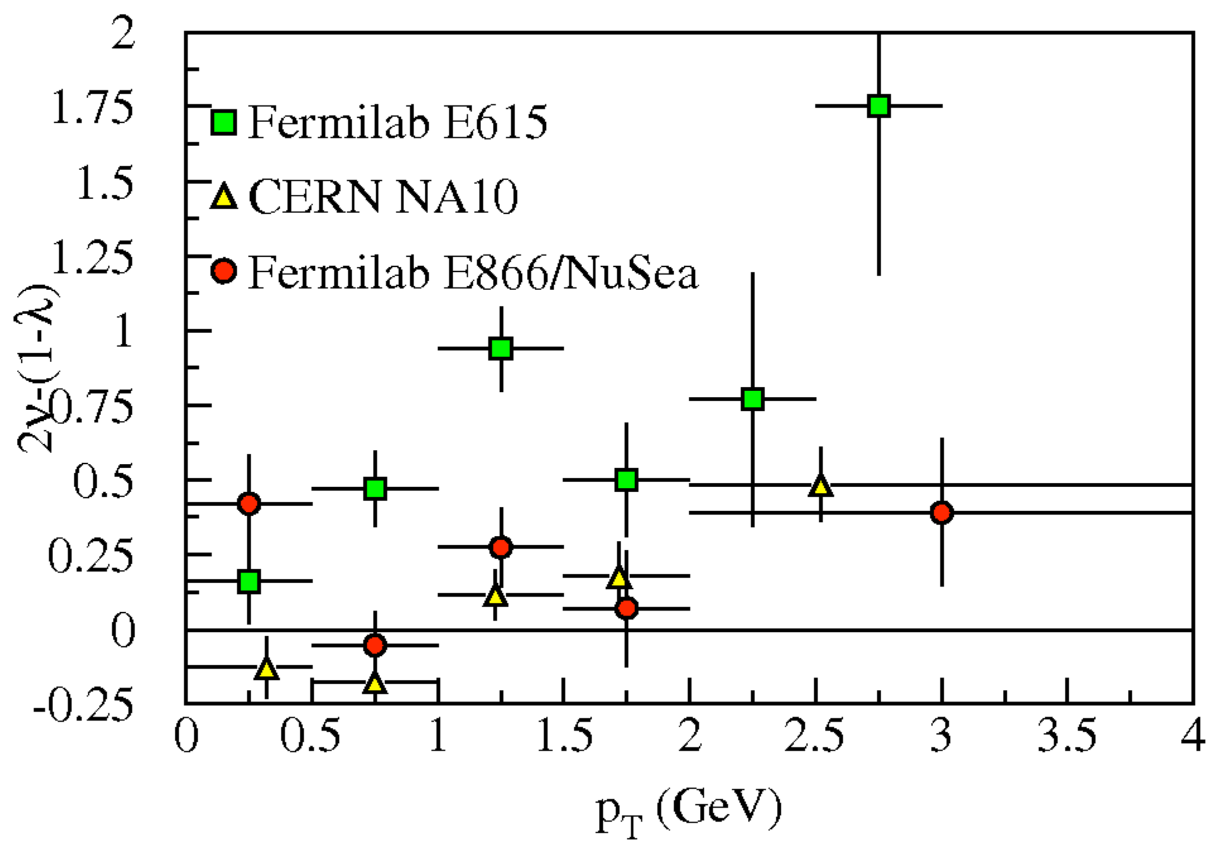
$$1 - \lambda = 2\nu$$



May be a better way to study Boer-Mulders function, since pQCD contributions should cancel

Violation of Lam-Tung relation

$$1 - \lambda = 2\nu$$

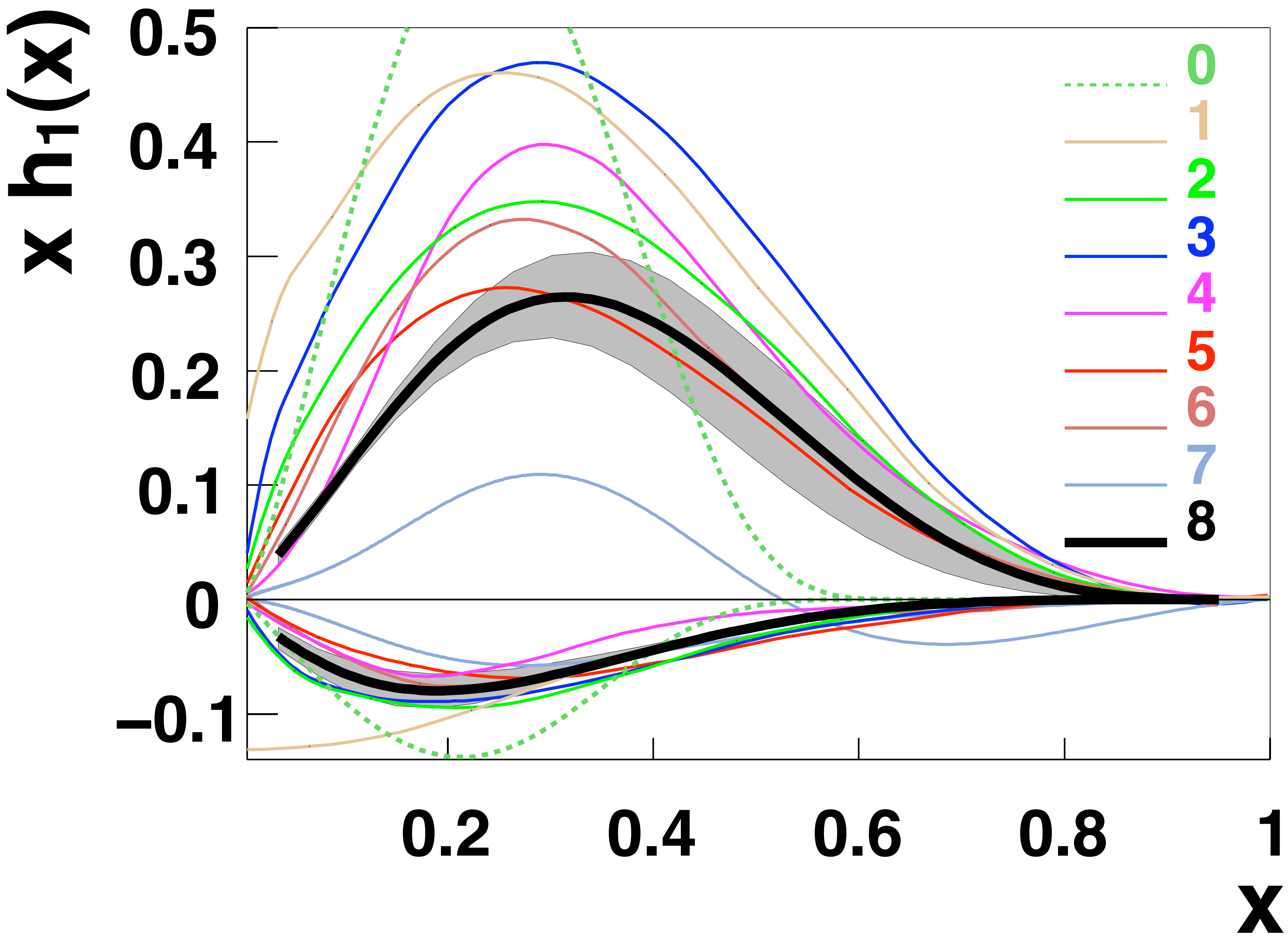


talk by P. Reimer

May be a better way to study Boer-Mulders function, since pQCD contributions should cancel

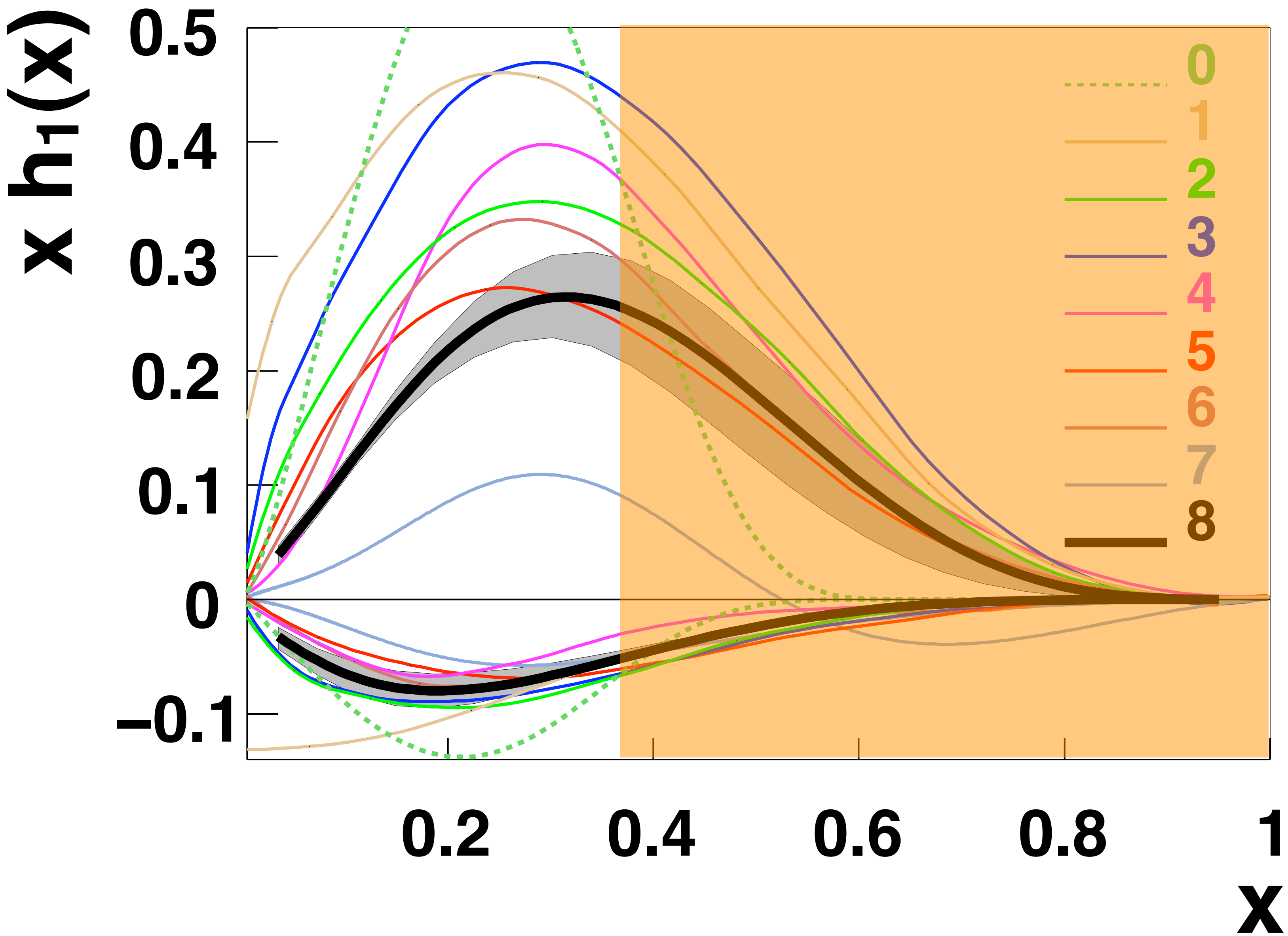

2 The
dihadron way
to transversity

Transversity state of the art



[1-7] models, [8] Anselmino et al., arXiv:0807.0173

Transversity state of the art



[1-7] models, [8] Anselmino et al., arXiv:0807.0173

Single hadron

SIDIS

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

Single hadron

SIDIS

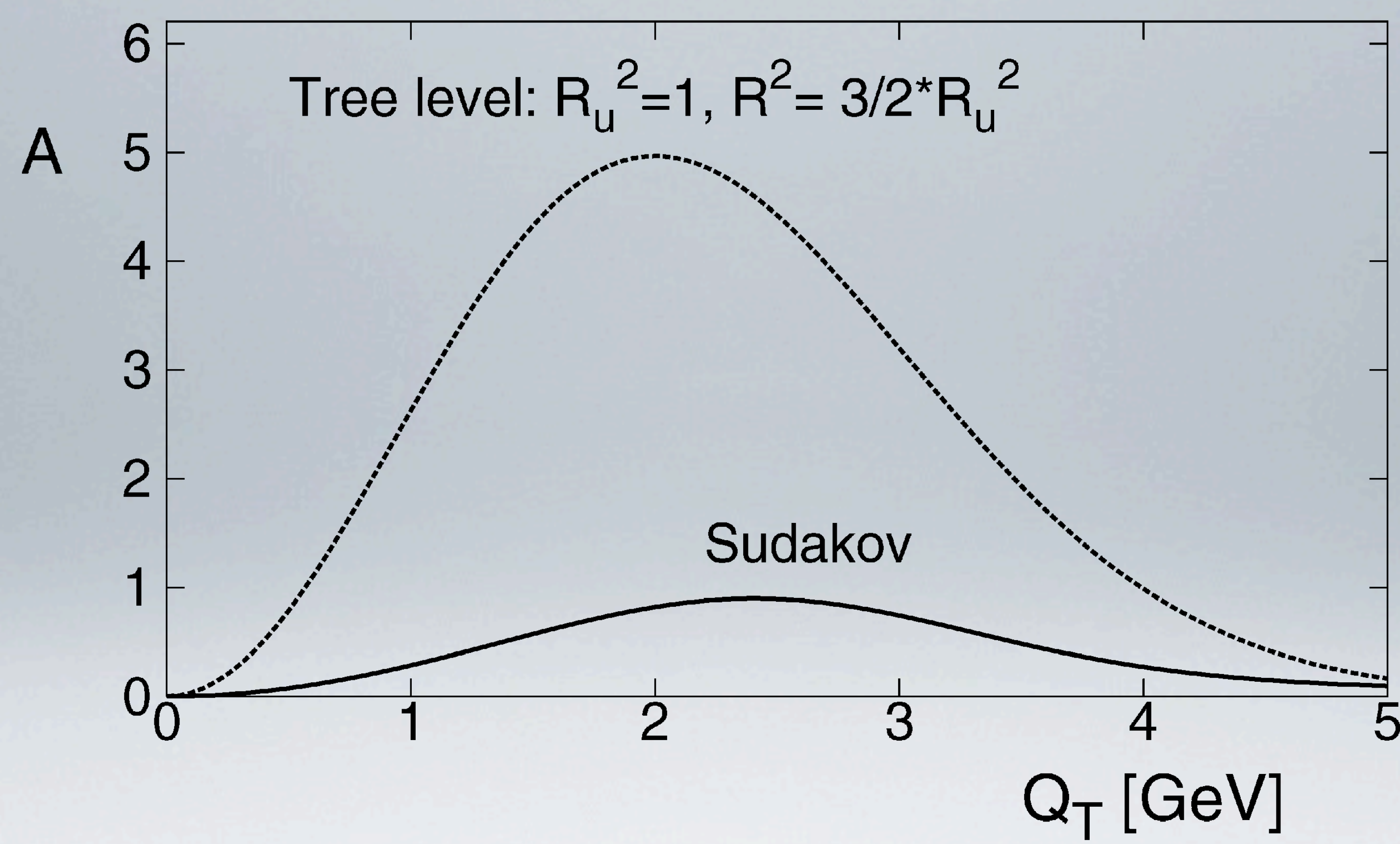
$$A_{DIS}(x,z,P_{h\perp}^2) = -\langle C_y\rangle \, \frac{\sum_q e_q^2 \, h_1^q(x,p_T^2) \otimes_C H_{1,q}^{\perp}(z,k_T^2)}{\sum_q e_q^2 \, f_1^q(x,p_T^2) \otimes D_{1,q}(z,k_T^2)}$$

e^+e^-

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

Effect of TMD evolution?

D. Boer, NPB806 (09)

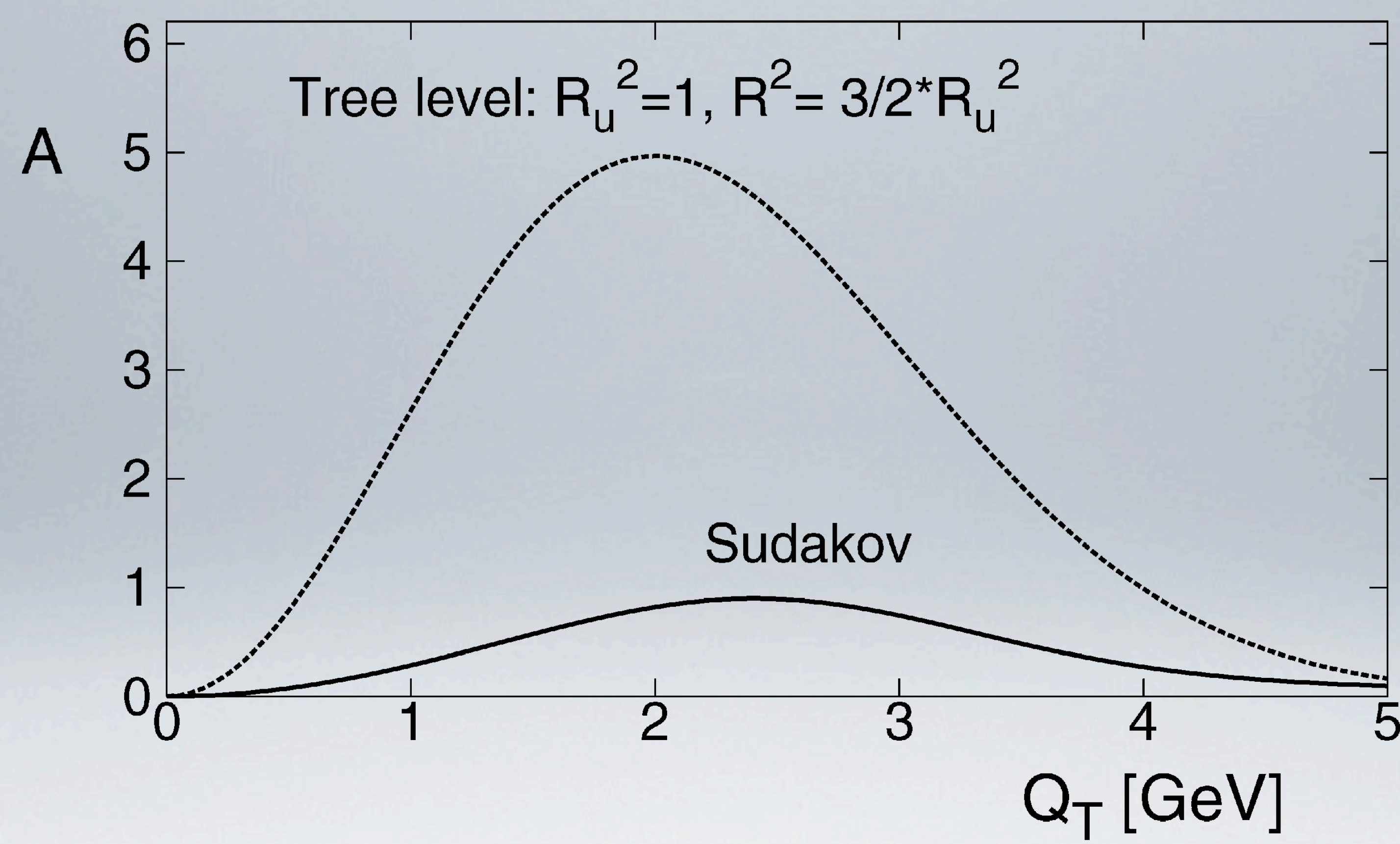


“

”

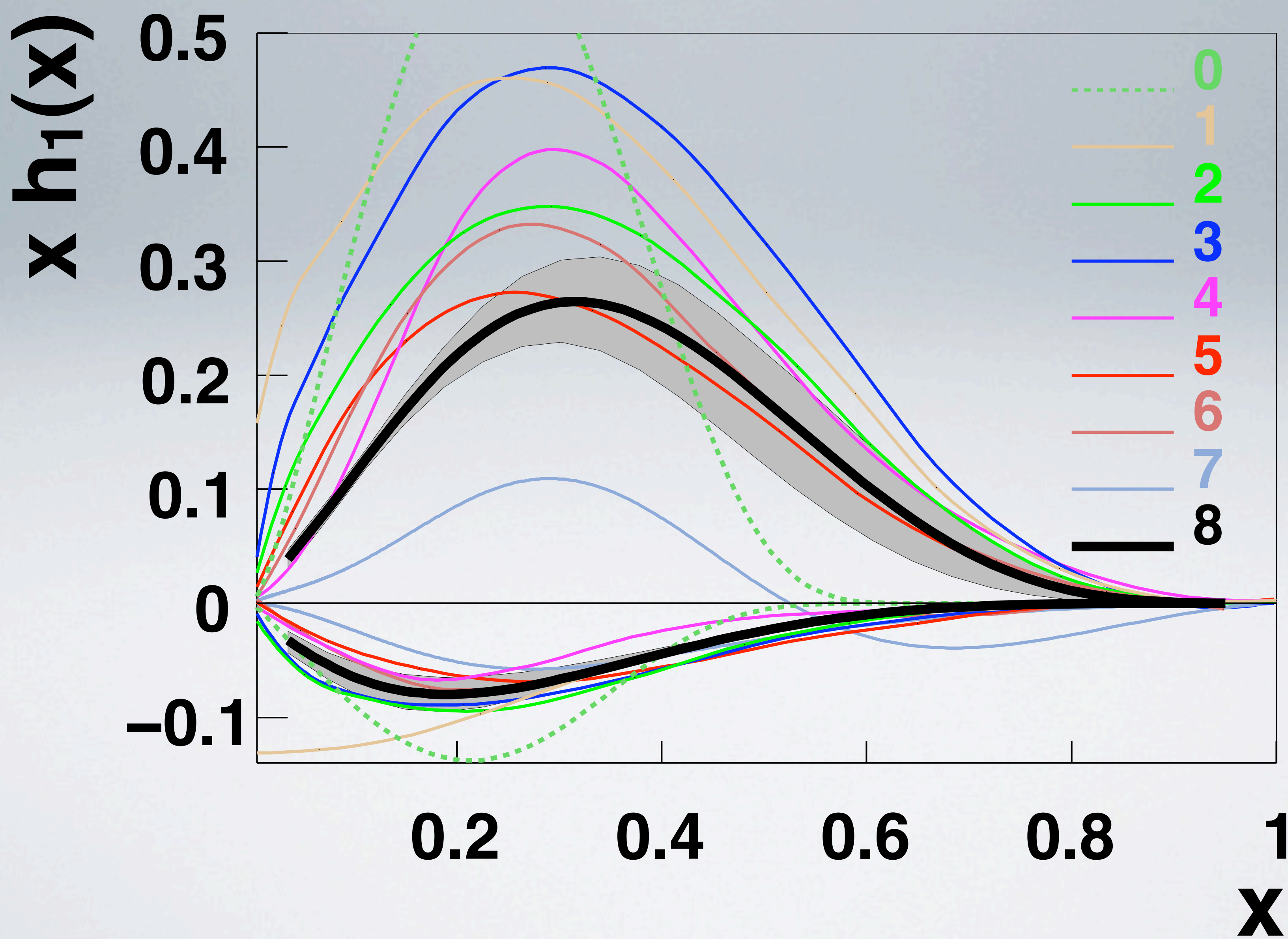
Effect of TMD evolution?

D. Boer, NPB806 (09)



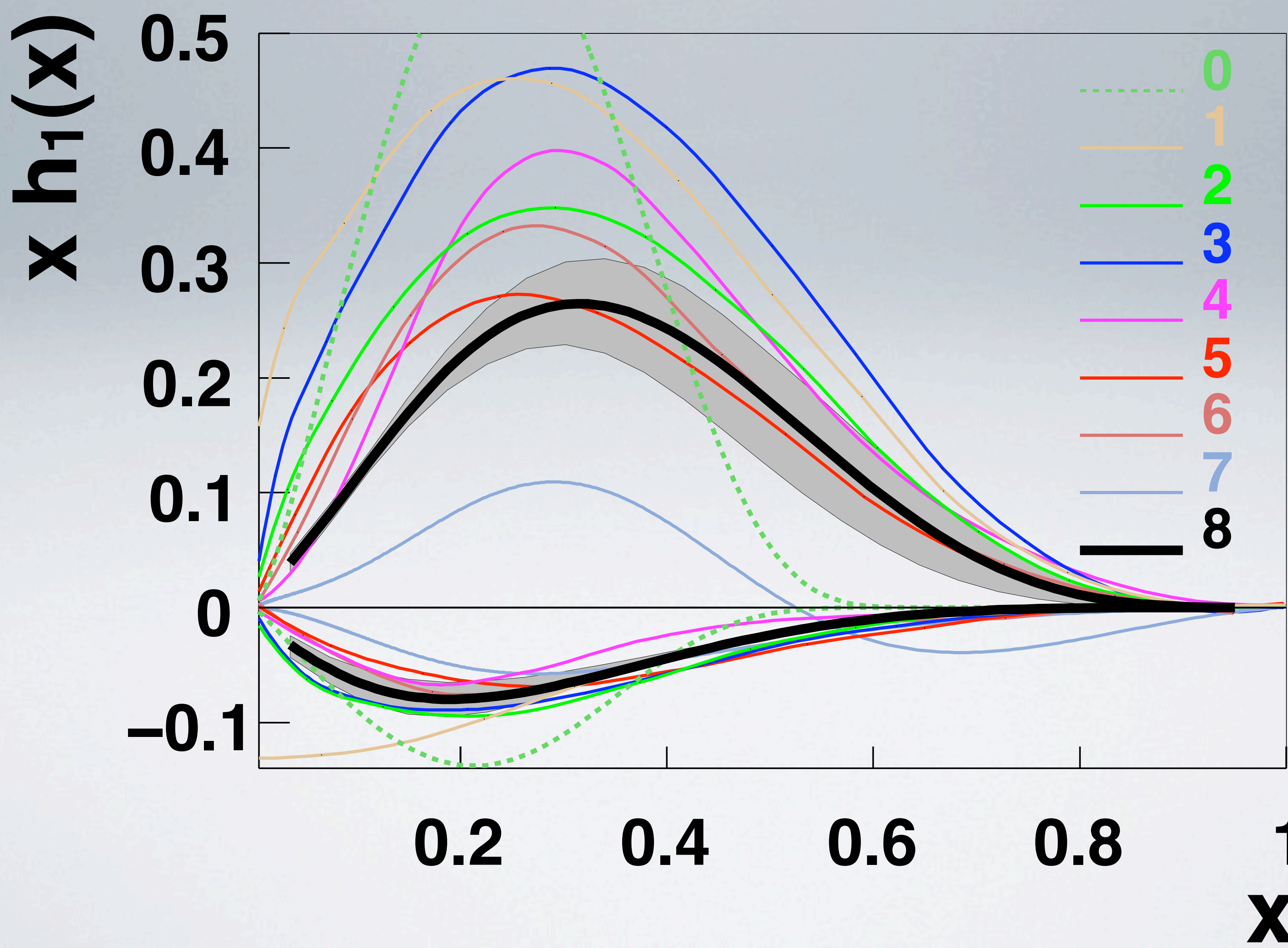
"Tree level extractions of the Collins function at large Q^2 therefore can significantly underestimate its actual magnitude"

Effect on transversity



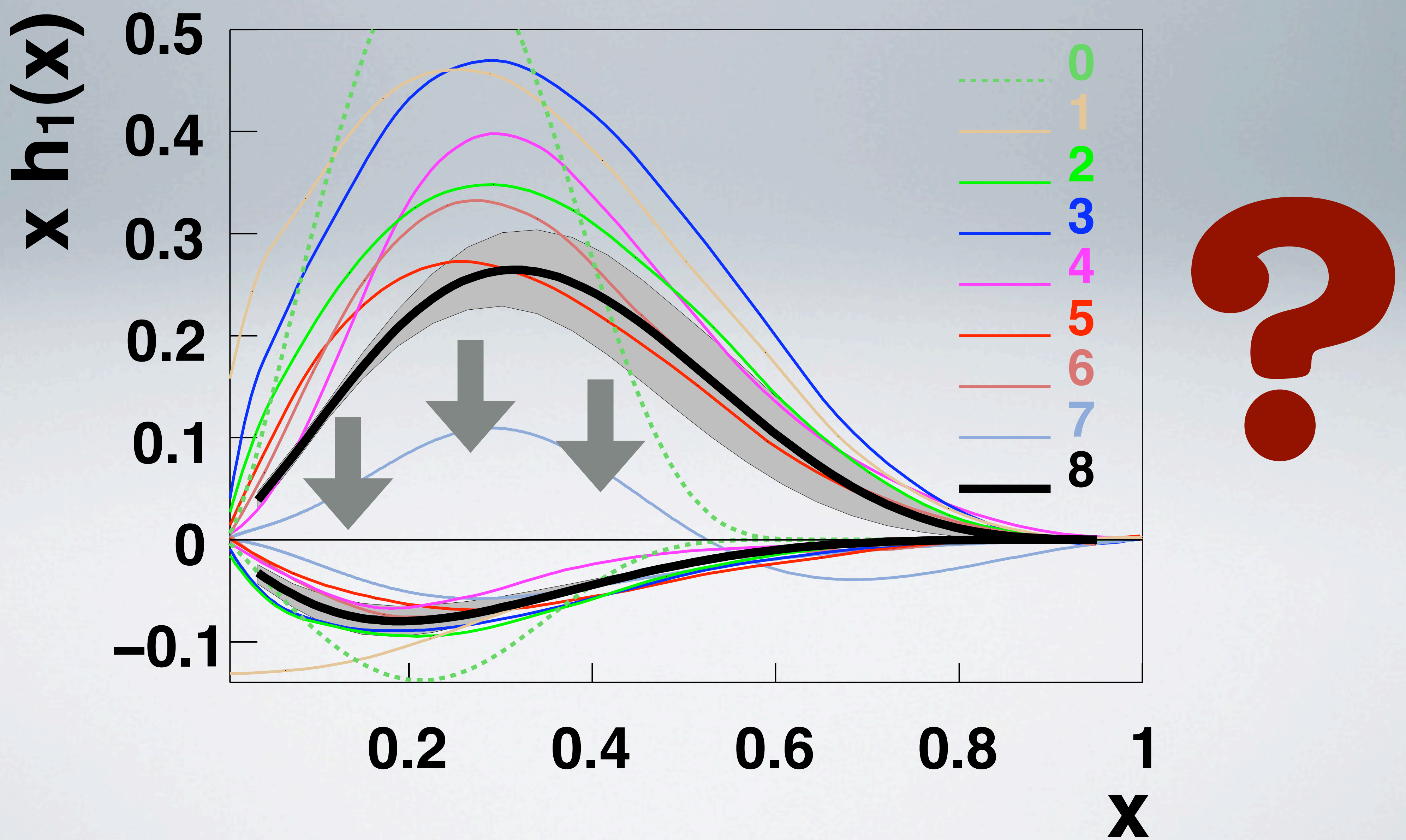
Effect on transversity

Collins function underestimated ⇒ transversity overestimated



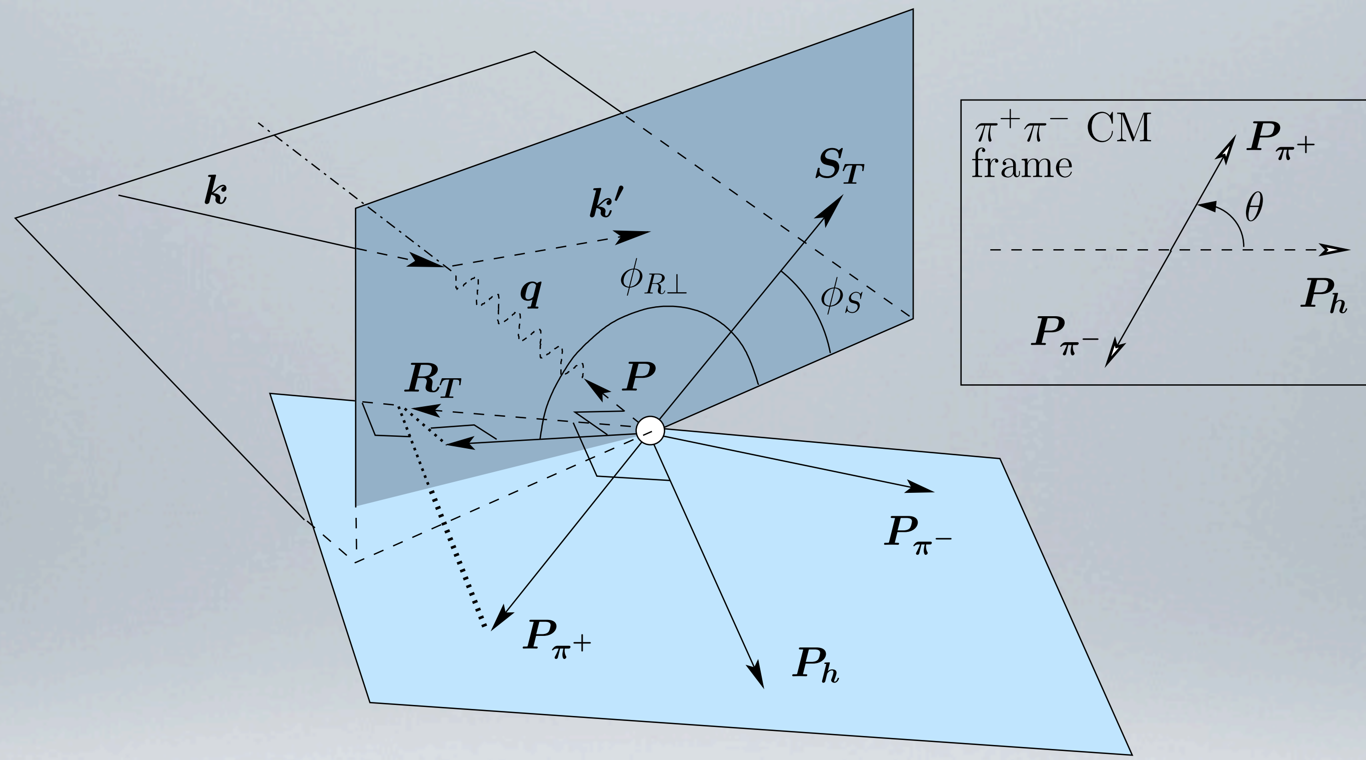
Effect on transversity

Collins function underestimated ⇒
transversity overestimated



An independent extraction of transversity is needed...

Two hadrons in SIDIS



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

talk by G. Schnell

Note: most of the theory work done in Pavia

Two hadrons

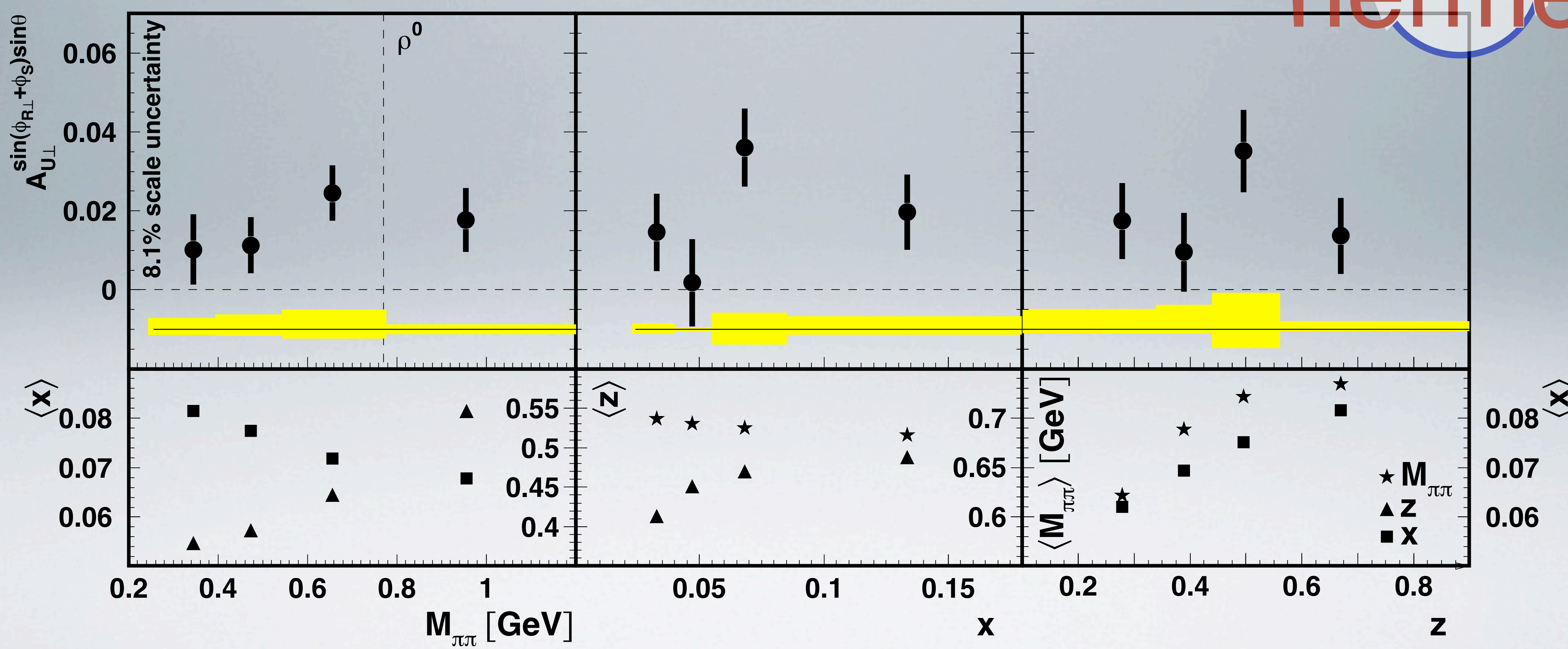
SIDIS

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

e^+e^-

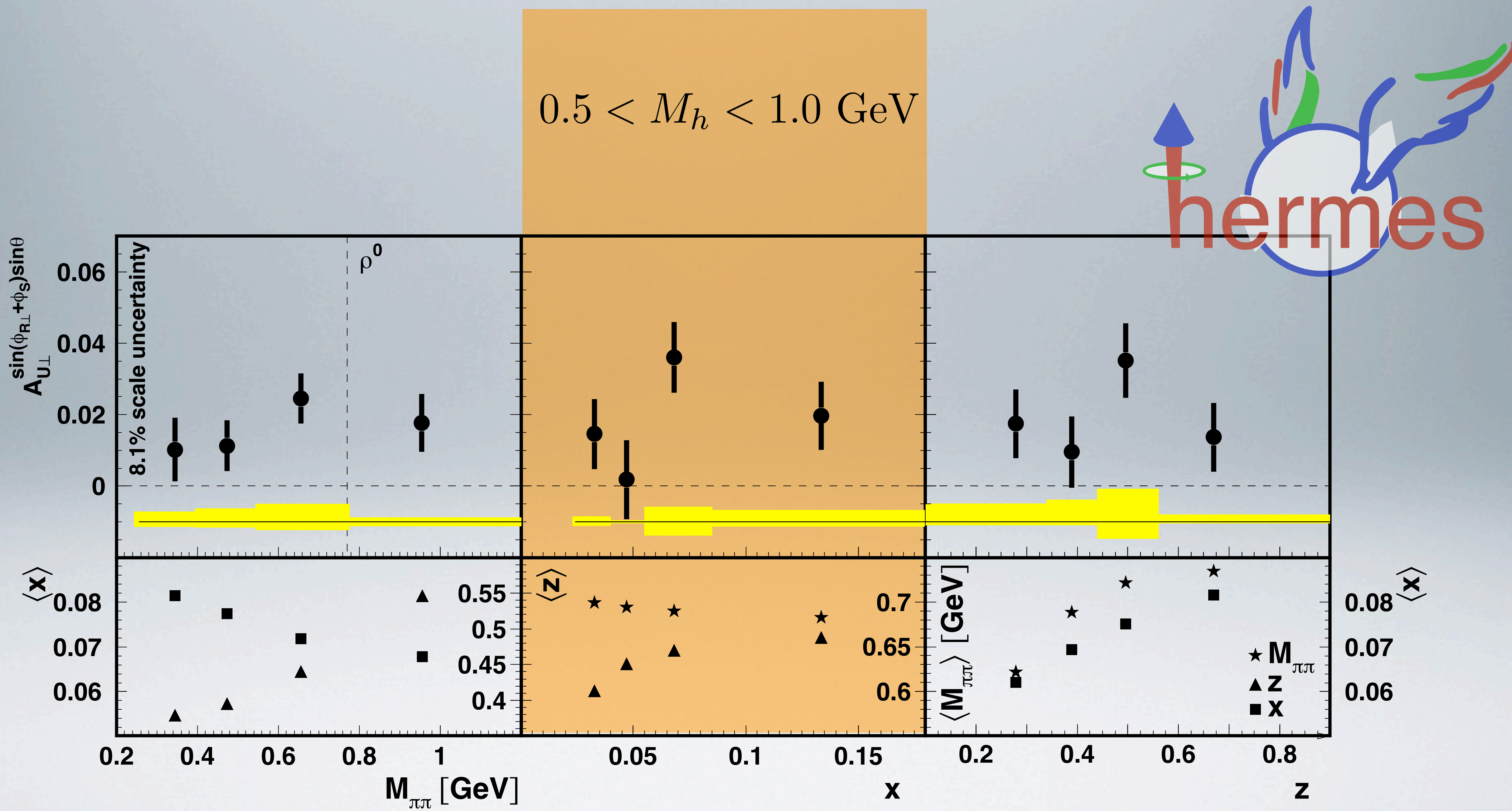
$$A_{e+e-}(z,M_h^2,\bar{z},\bar{M}_h^2) = -\frac{\langle\sin^2\theta_2\rangle\langle\sin\theta\rangle\,\langle\sin\bar{\theta}\rangle}{\langle 1+\cos^2\theta_2\rangle}\ \frac{\sum_q e_q^2\,\frac{|\boldsymbol{R}|}{M_h}\,H_{1,q}^{\sphericalangle}(z,M_h^2)\,\frac{|\bar{\boldsymbol{R}}|}{\bar{M}_h}\,H_{1,\bar{q}}^{\sphericalangle}(\bar{z},\bar{M}_h^2)}{\sum_q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

HERMES data



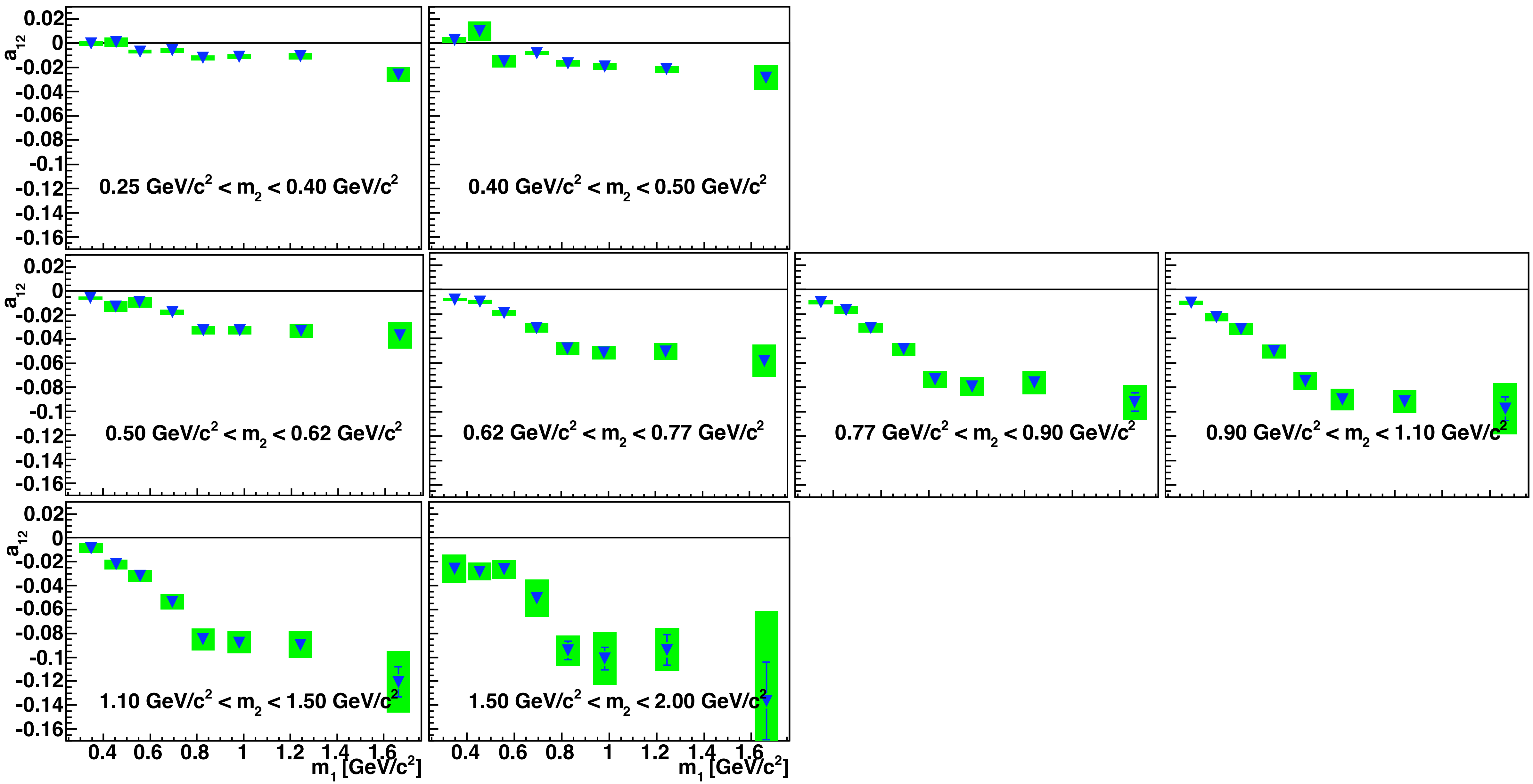
$A_{U\perp}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$
8.1% scale uncertainty
ρ^0
$\langle x \rangle$
$\langle z \rangle$
$\langle M_{\pi\pi} \rangle$ [GeV]
$M_{\pi\pi}$ [GeV]
x
z
★ $M_{\pi\pi}$
▲ z
■ x

HERMES data



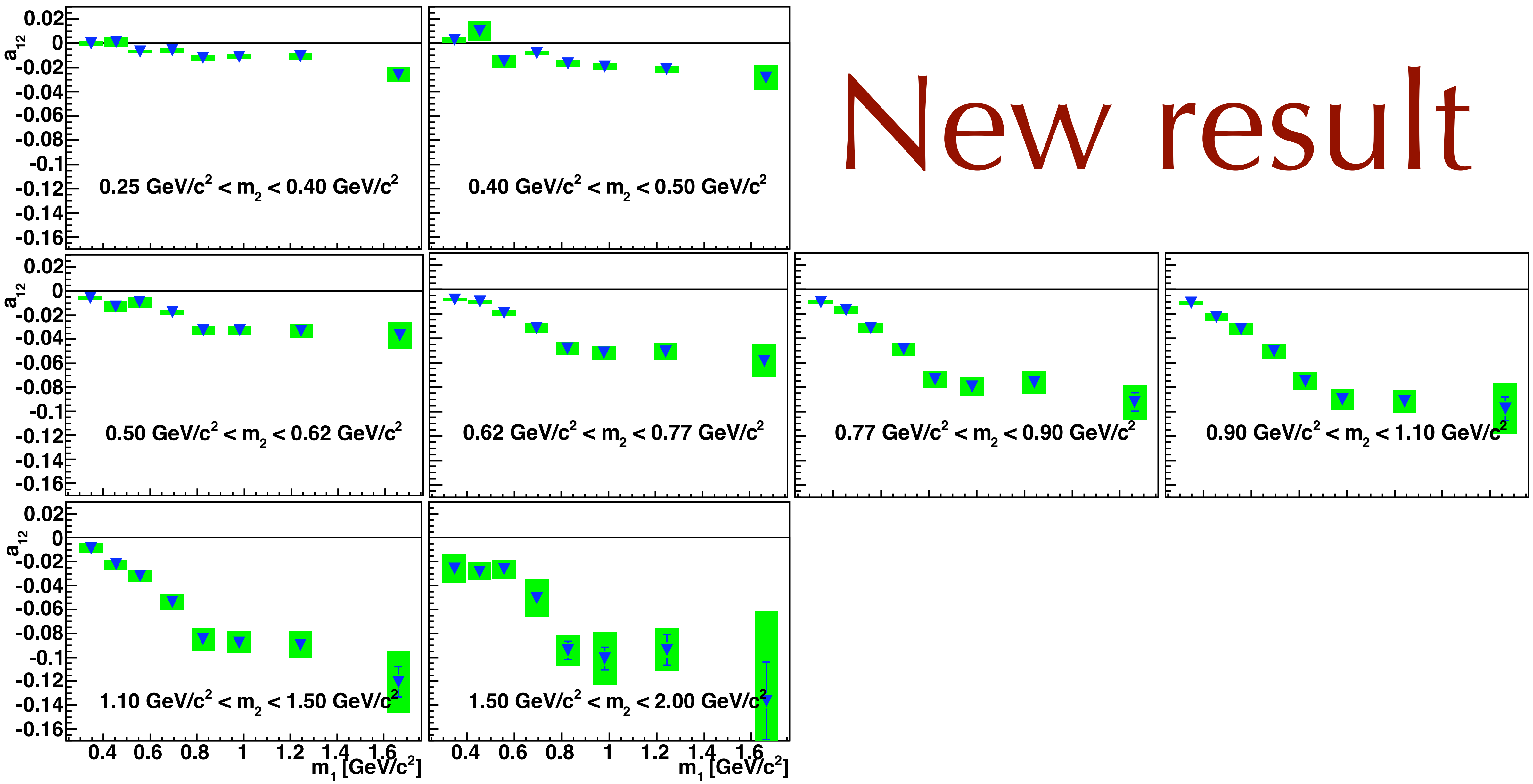
$0.5 < M_h < 1.0$ GeV
hermes
$A_{U\perp}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$
8.1% scale uncertainty
ρ^0
0.06
0.04
0.02
0
⟨x⟩
0.08
0.07
0.06
0.55
0.5
0.45
0.4
⟨z⟩
0.7
0.65
0.6
⟨$M_{\pi\pi}$⟩ [GeV]
★ $M_{\pi\pi}$
▲ z
■ x
0.2 0.4 0.6 0.8 1
$M_{\pi\pi}$ [GeV]
0.05 0.1 0.15
x
0.2 0.4 0.6 0.8
z

BELLE data



Vossen, Seidl et al. (Belle), arXiv:1104.2425 [hep-ex]

BELLE data

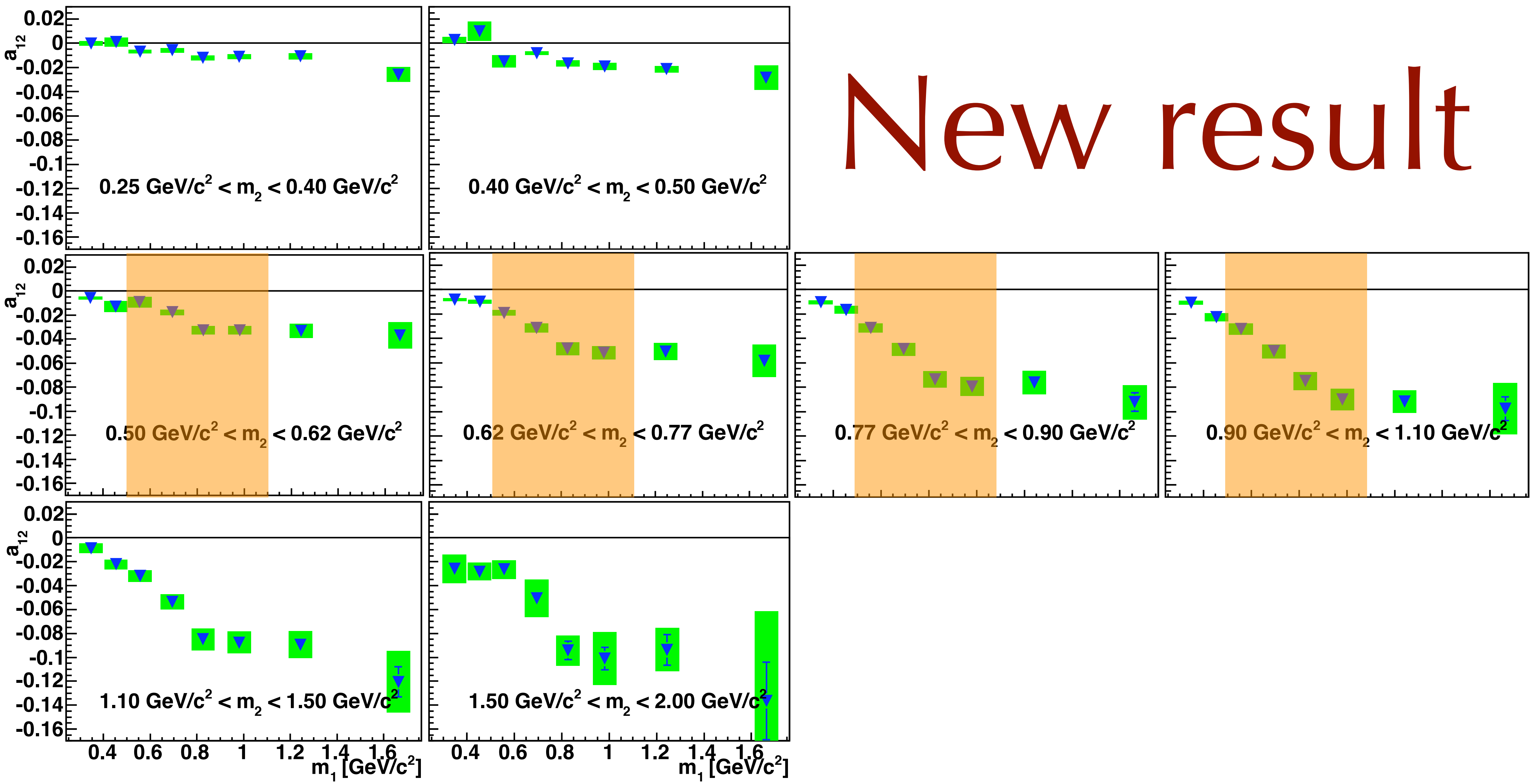


New result

Vossen, Seidl et al. (Belle), arXiv:1104.2425 [hep-ex]

BELLE data

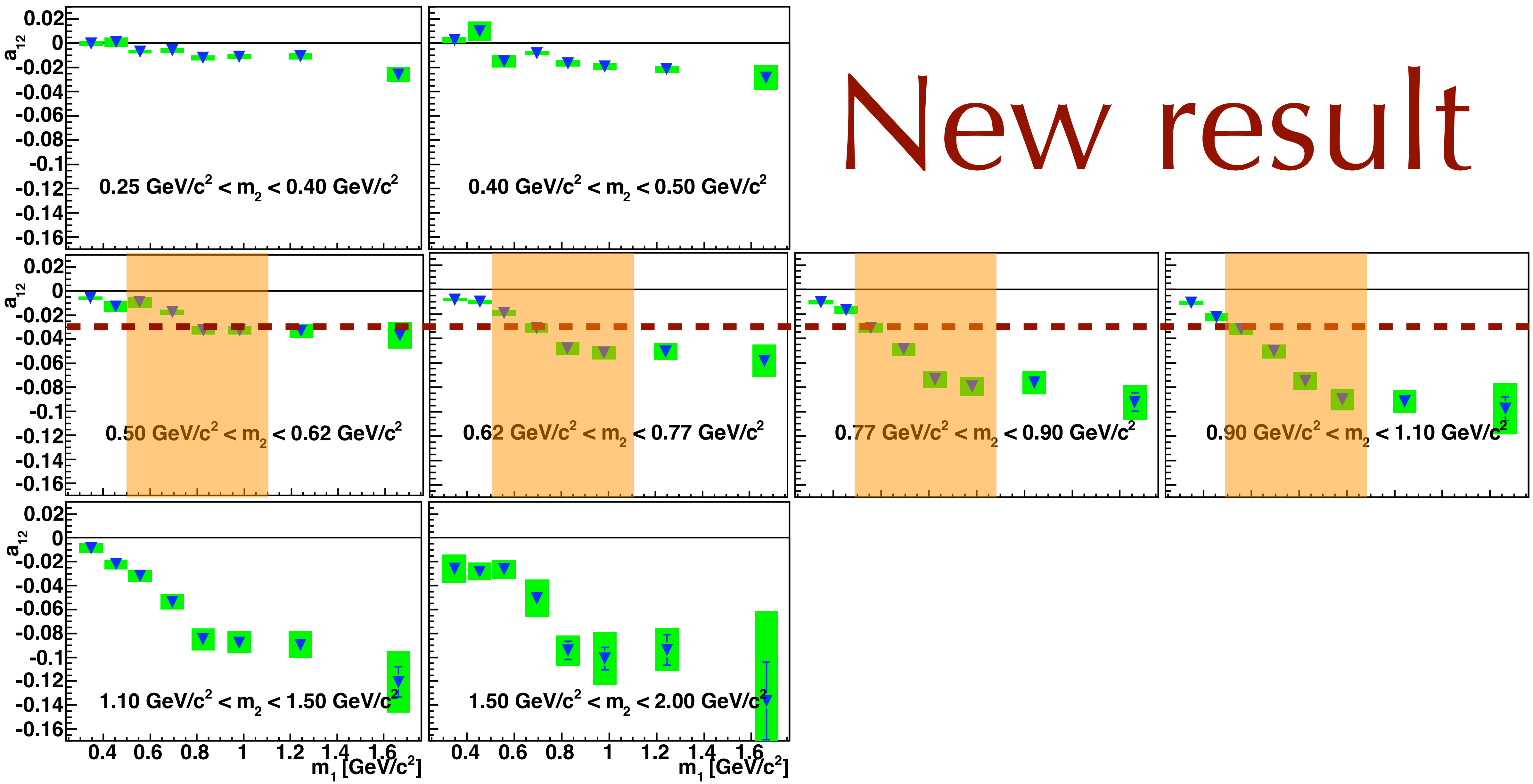
New result



Vossen, Seidl et al. (Belle), arXiv:1104.2425 [hep-ex]

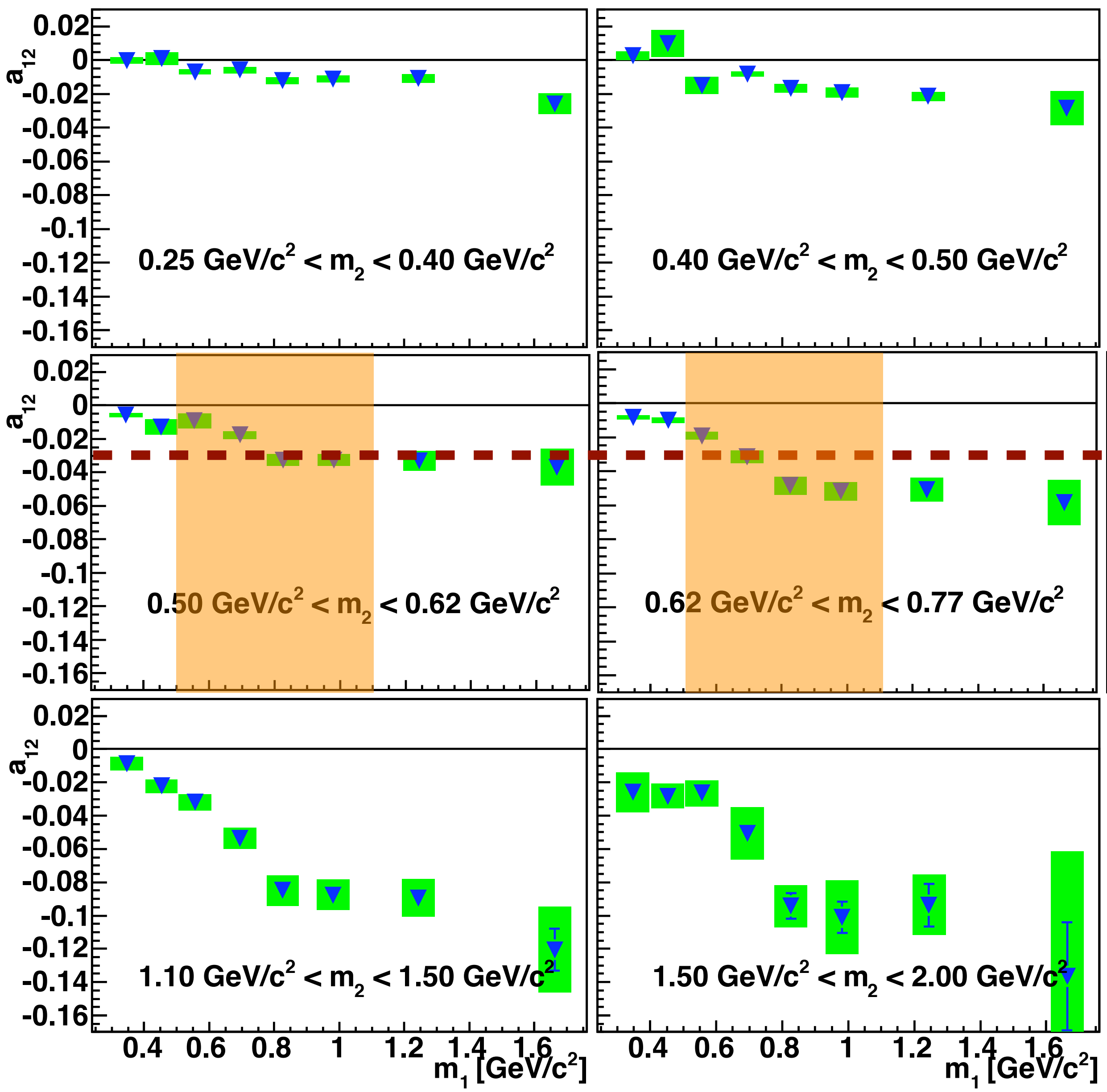
BELLE data

New result



Vossen, Seidl et al. (Belle), arXiv:1104.2425 [hep-ex]

BELLE data



New result

3% asymmetry

(weighted average in the region of interest)

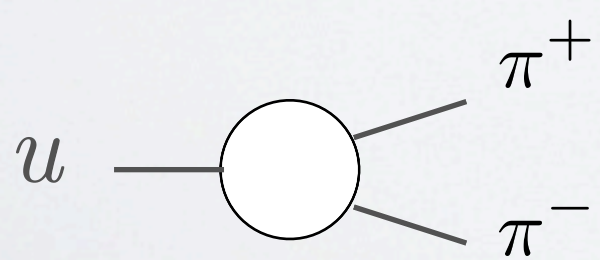
Vossen, Seidl et al. (Belle), arXiv:1104.2425 [hep-ex]

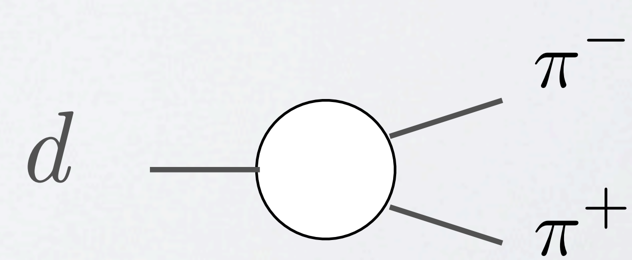
Assumptions

$$D_1^u = D_1^d = D_1^{\bar{u}} = D_1^{\bar{d}}$$
$$D_1^s = D_1^{\bar{s}}$$
$$D_1^c = D_1^{\bar{c}}$$

$$H_1^{\triangleleft u} = -H_1^{\triangleleft d} = -H_1^{\triangleleft \bar{u}} = H_1^{\triangleleft \bar{d}}$$
$$H_1^{\triangleleft s} = -H_1^{\triangleleft \bar{s}} = H_1^{\triangleleft c} = -H_1^{\triangleleft \bar{c}} = 0$$

Based on charge conjugation and isospin symmetry





Simplified expressions

SIDIS

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

e^+e^-

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

Simplified expressions

SIDIS

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

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

e^+e^-

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

Simplified expressions

SIDIS

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

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

e^+e^-

From BELLE: $\frac{n_u^{\uparrow}}{n_u} = 25\%$

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

Simplified expressions

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

SIDIS

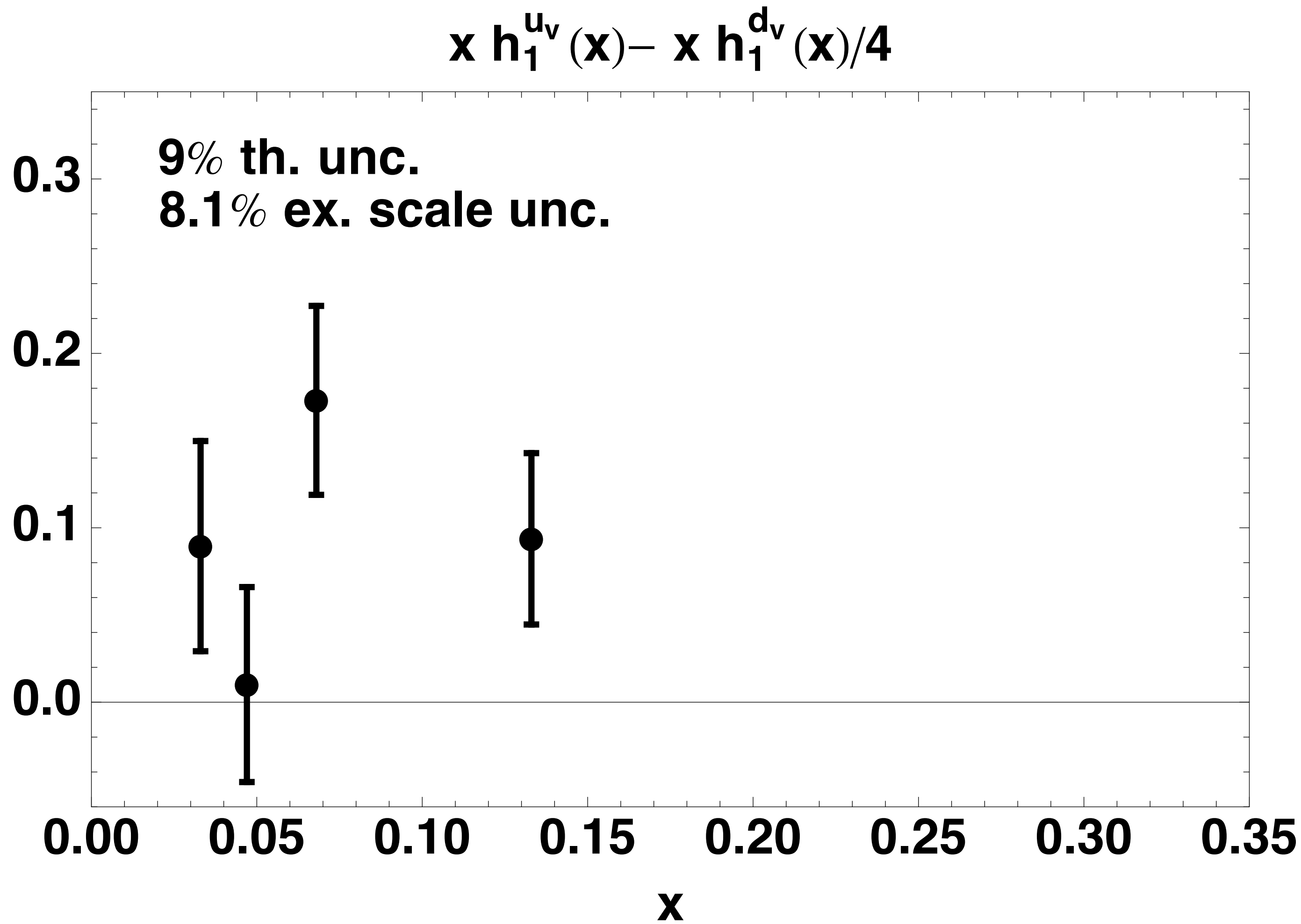
$$A_{DIS}(x) \approx -\langle C_y \rangle \, \frac{(h_1^{u_v}(x) - h_1^{d_v}(x)/4)}{(f_1^{u+\bar{u}}(x) + f_1^{d+\bar{d}}(x)/4)} \, \frac{n_u^\uparrow}{n_u}$$

From BELLE: $\frac{n_u^\uparrow}{n_u} = 25\%$

e+e−

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

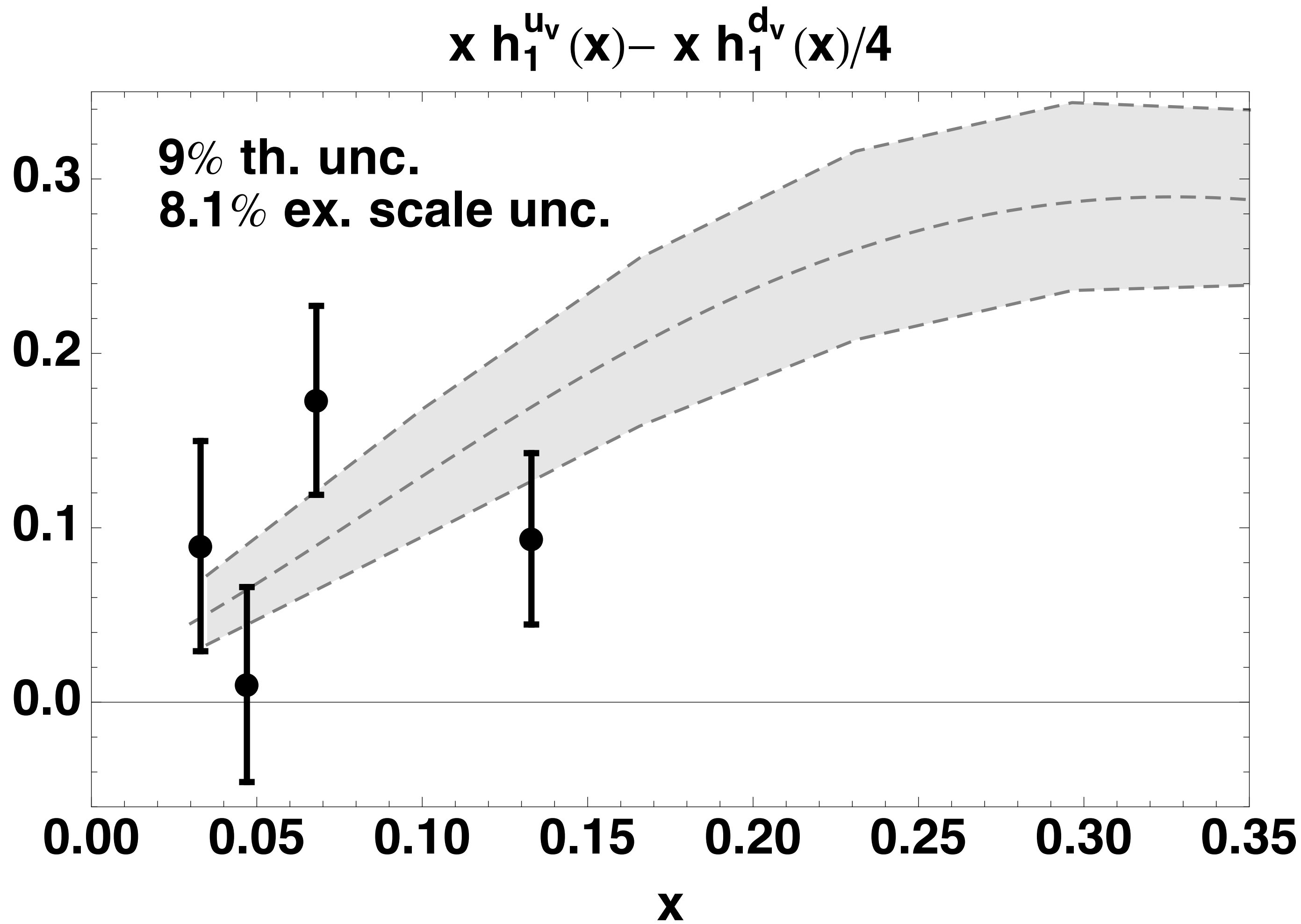
First glimpses at transversity



New result

Bacchetta, Radici, Courtoy, arXiv:1104.3855

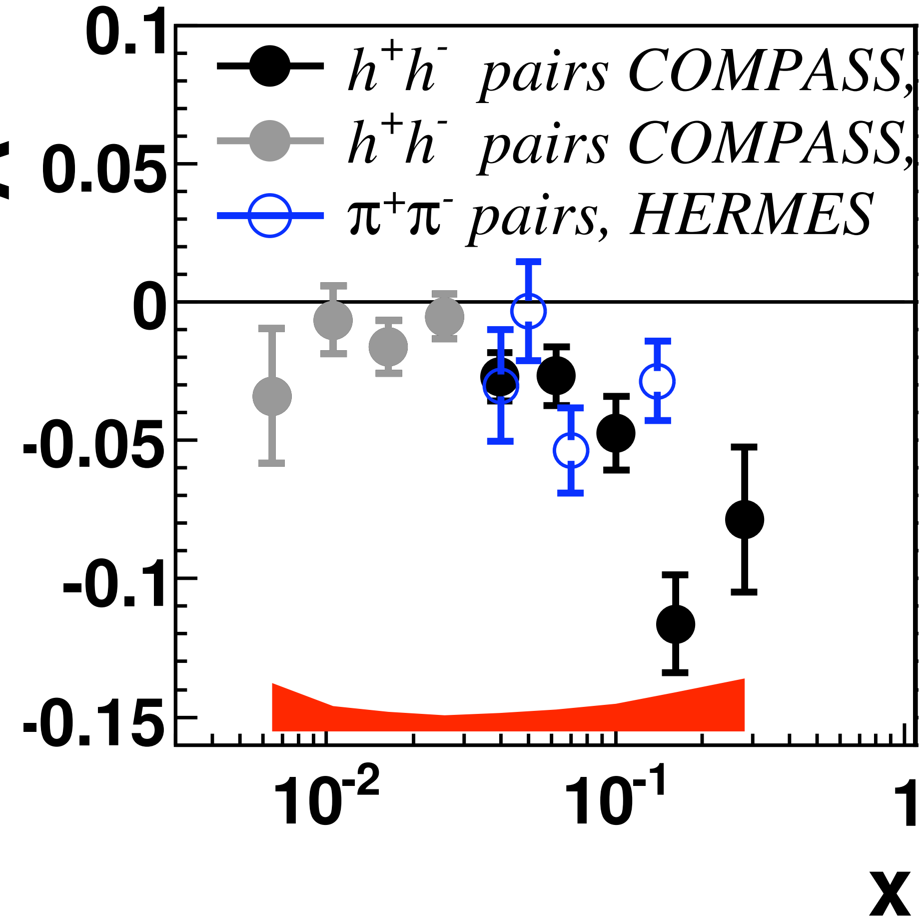
First glimpses at transversity



Not in disagreement with Anselmino et al.

More data are needed

More data are needed

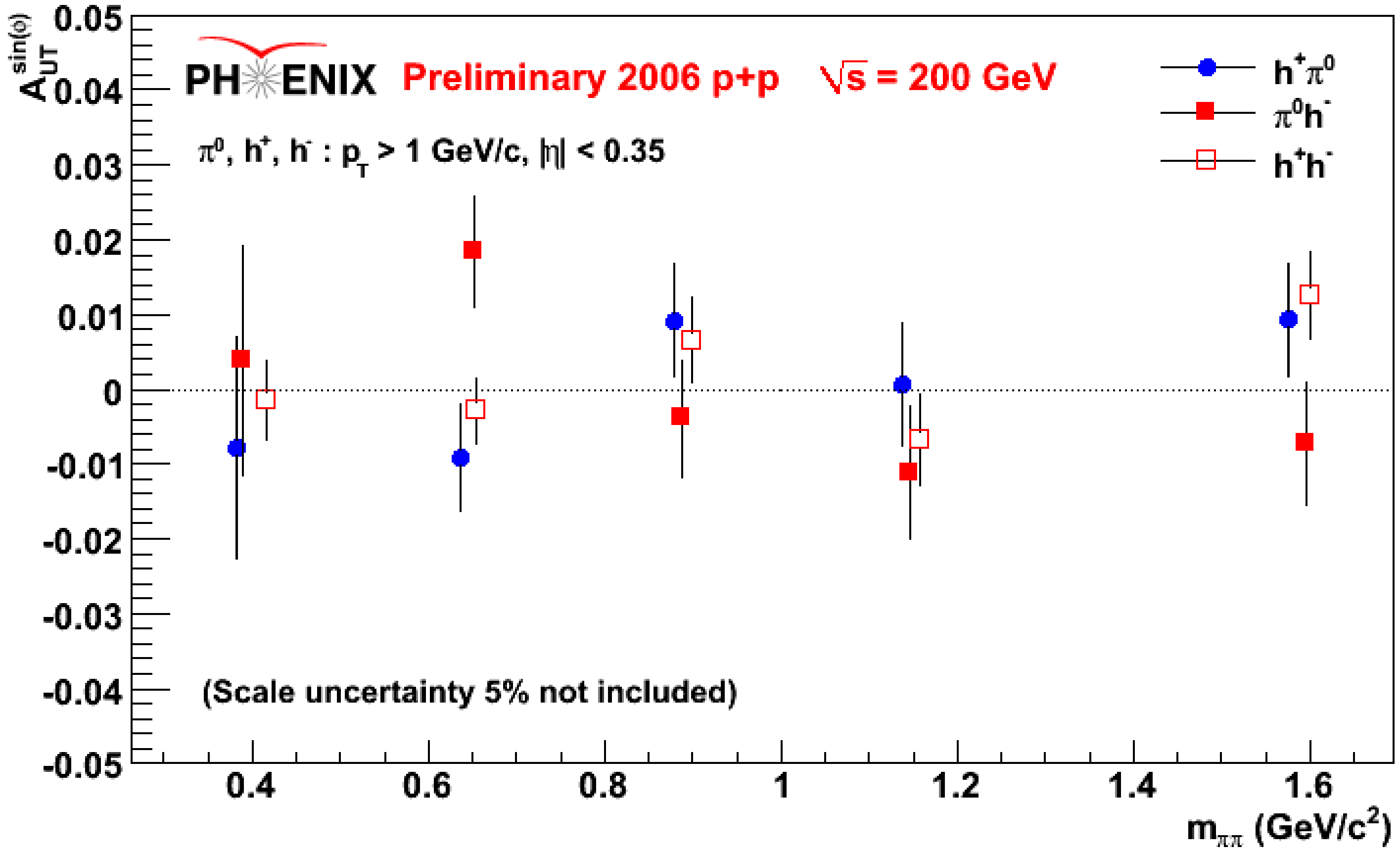


Preliminary

H. Wollny, CERN-THESIS-2010-108

What about *pp* collisions?

R. Yang, Beijing Transversity Workshop, 2008



$$d\sigma_{UT} = 2\,|\mathbf{P}_{C\perp}|\sum_{a,b,c,d}\frac{|\mathbf{R}_C|}{M_C}\,|\mathbf{S}_{BT}|\,\sin\left(\phi_{S_B}-\phi_{R_C}\right)\int\frac{dx_a dx_b}{16\pi z_c}\,f_1^a(x_a)\,h_1^b(x_b)\,\frac{d\Delta\hat{\sigma}_{ab^\uparrow\to c^\uparrow d}}{d\hat{t}}\,H_{1,ot}^{\sphericalangle c}(z_c,M_C^2)$$

Bigger at forward rapidities

Advertisement

Aurore Courtoy
has been working on this analysis
and is looking for a post-doc position...