Workshop on partonic transverse momentum distributions

Alessandro Bacchetta (U. Pavia)
Gunar Schnell (DESY)

THE TALKS

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- 17 talks

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- Experiment: BELLE, COMPASS, HERMES, H1, JLAB

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- Theory: factorization, evolution, lattice QCD

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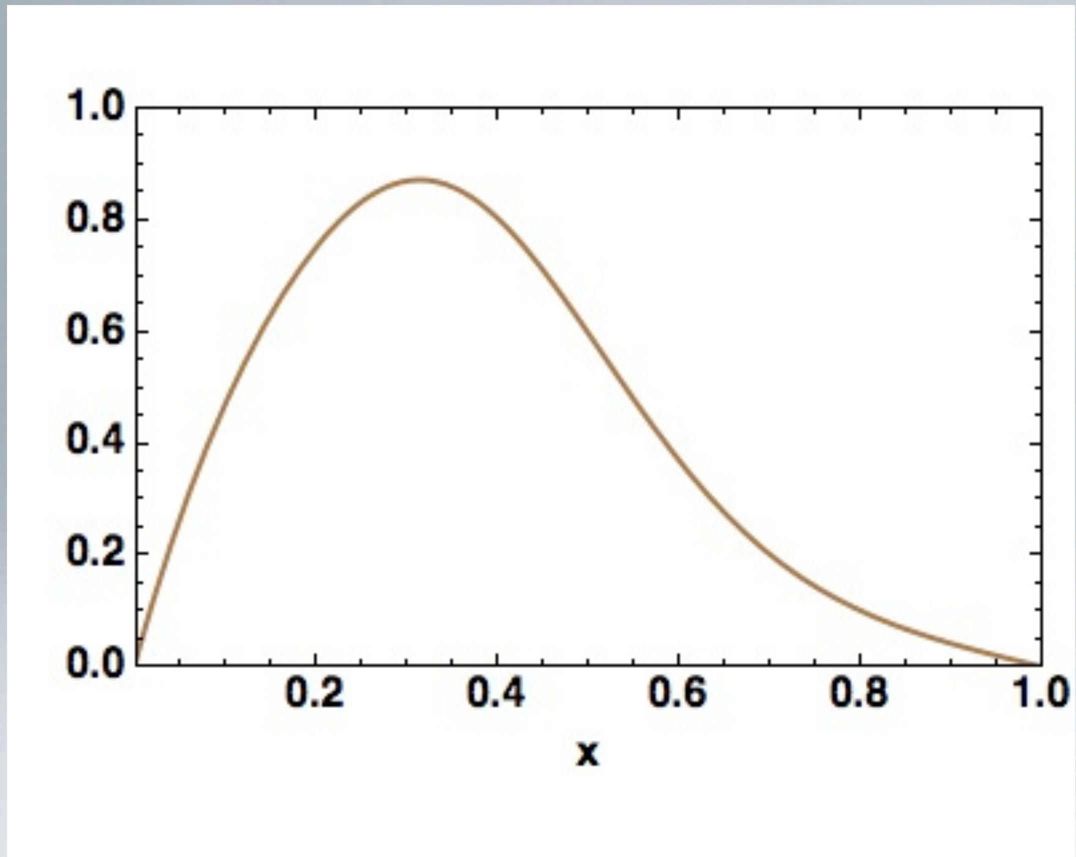
- Experiment: BELLE, COMPASS, HERMES, H1, JLAB
- Theory: factorization, evolution, lattice QCD
- Phenomenology: fits, models

THE TMDs

$xf_1^u(x)$



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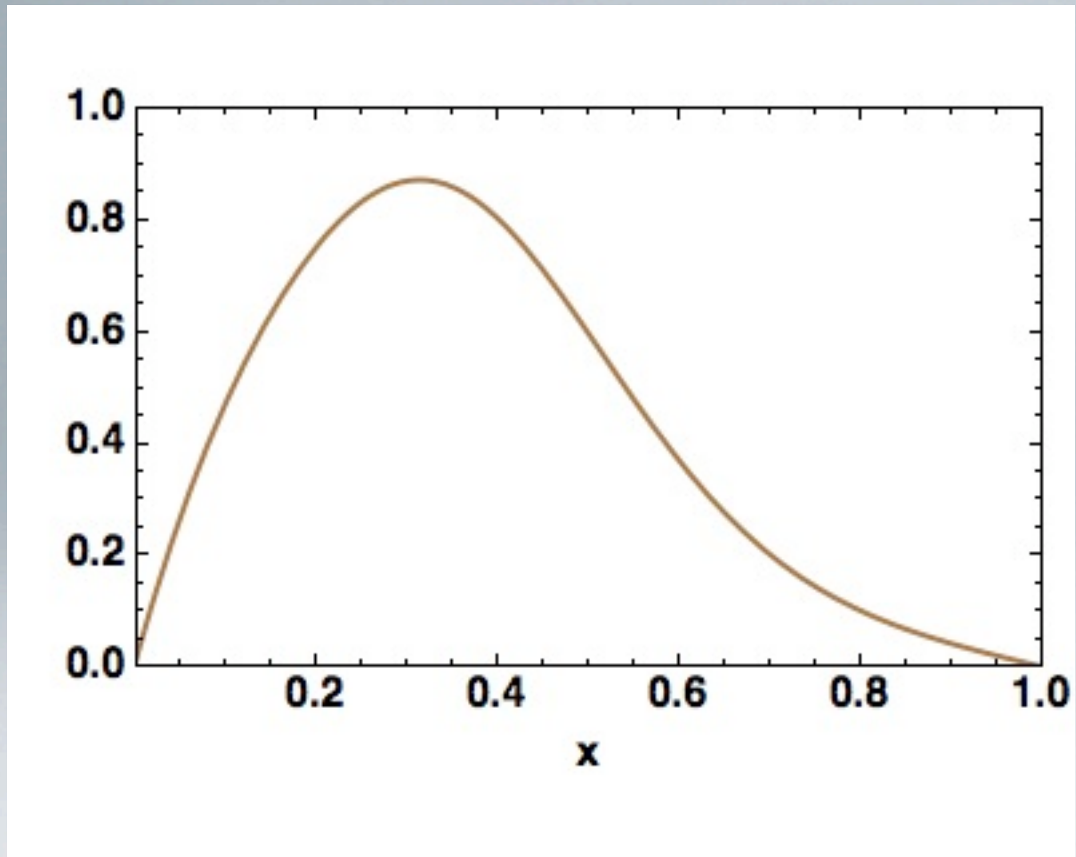
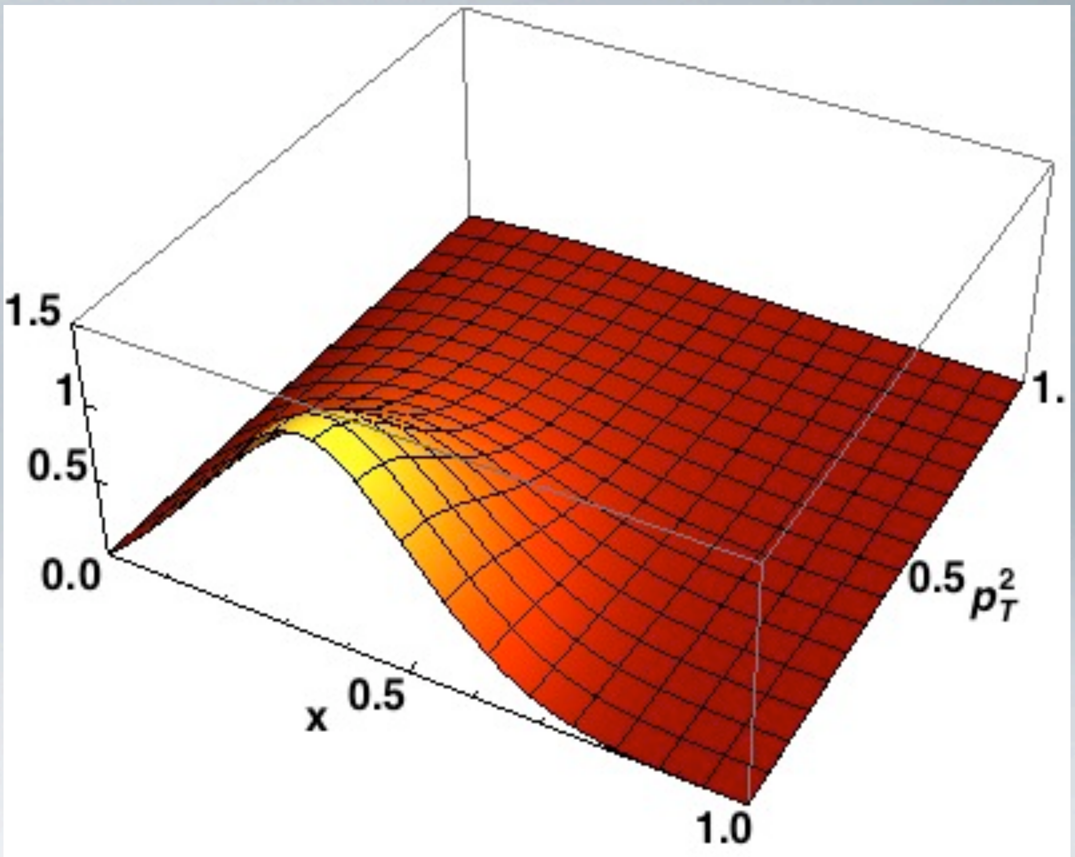


$xf_1^u(x, p_T^2)$



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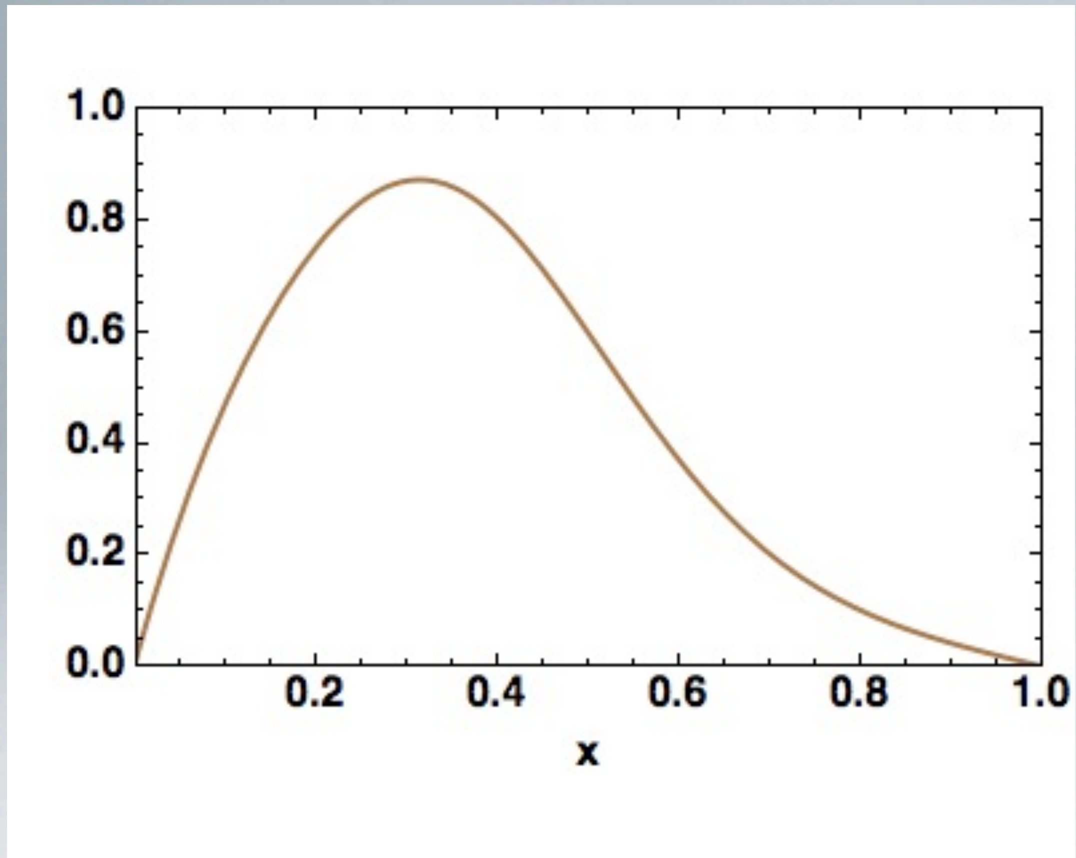

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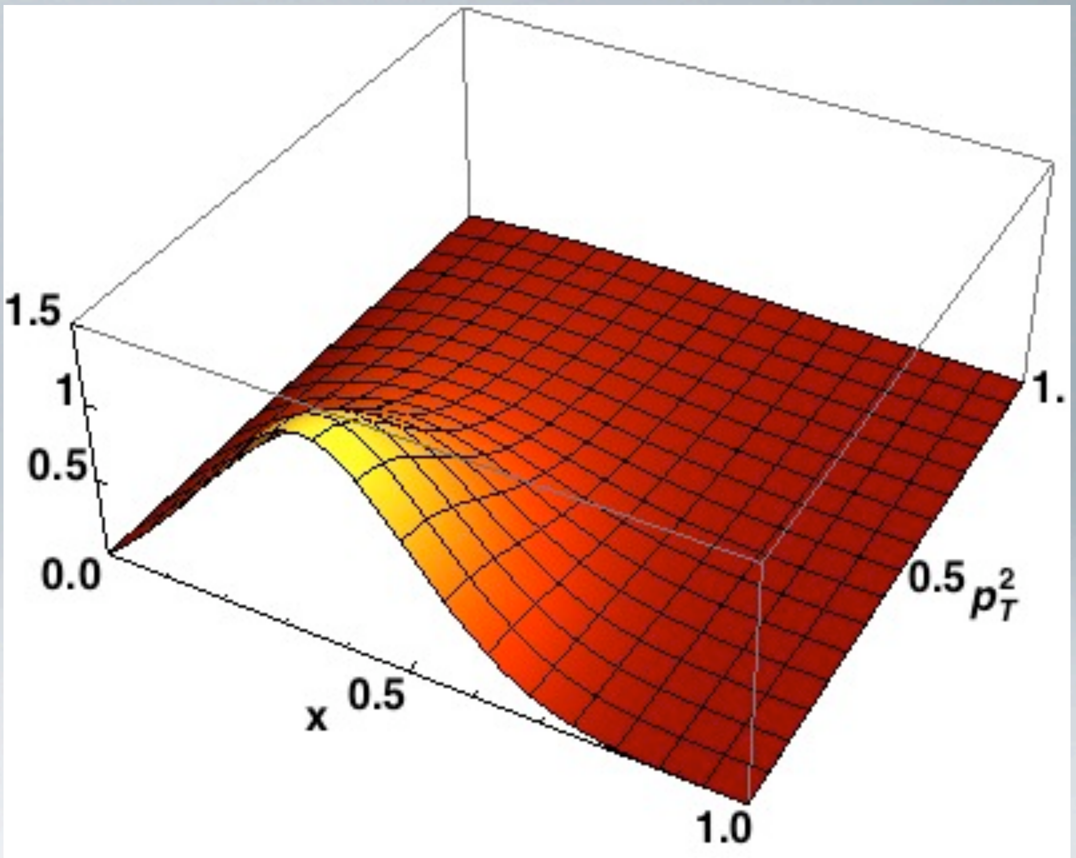

Why?

Exploring new dimensions, 3D momentum structure, tomography in momentum space, impact on high energy physics...

THE TMDs

talk by E. Boglione

THE TMDs

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quark pol.

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

Twist-2 TMDs

TMDs in black survive transverse-momentum integration
TMDs in red are T-odd

THE TMDs

talk by E. Boglione

helicity

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Boer-Mulders

Sivers

Twist-2 TMDs

transversity

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THE TMDs

talk by E. Boglione

quark pol. (columns) / nucleon pol. (rows)

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

Twist-2 TMDs

helicity

Boer-Mulders

Sivers

worm-gear

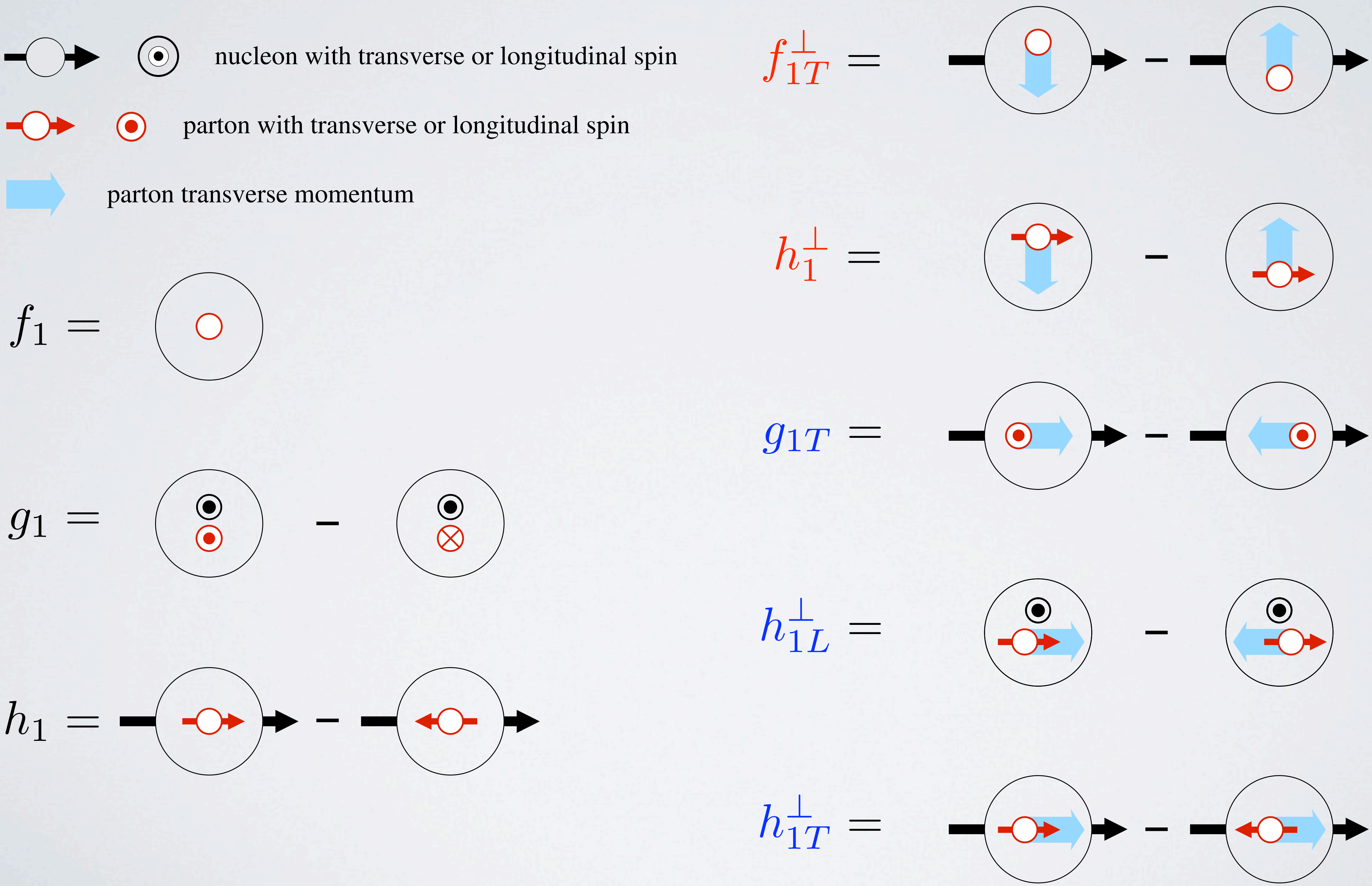
transversity

pretzelosity

TMDs in black survive transverse-momentum integration
TMDs in red are T-odd

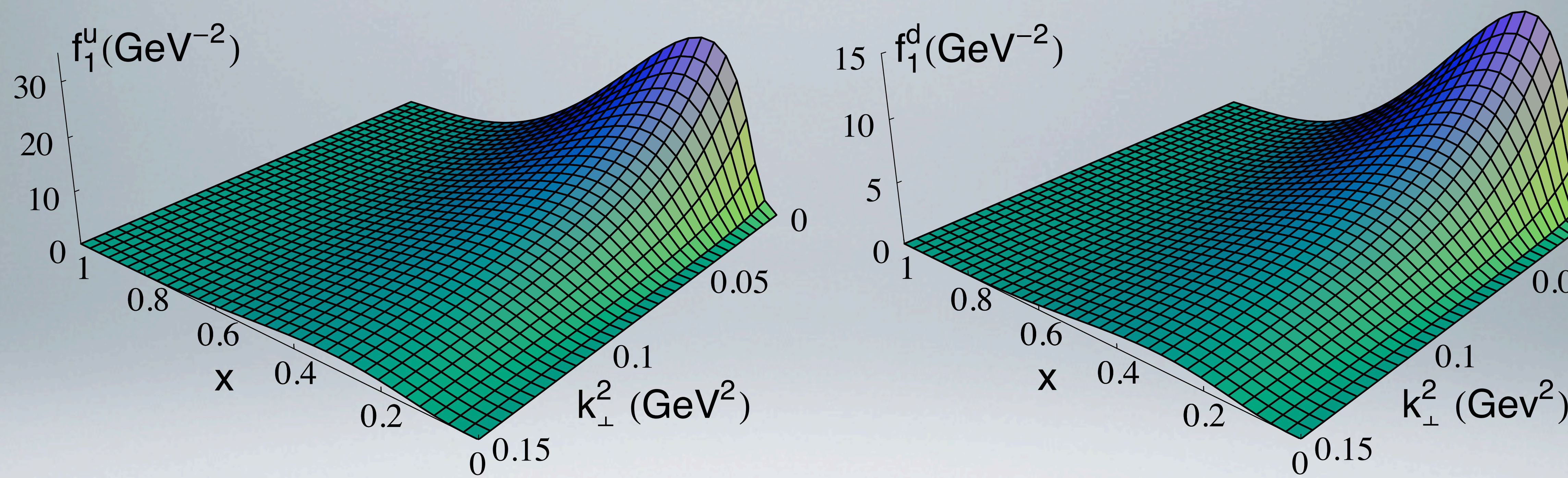
PROBABILISTIC INTERPRETATION

Proton goes out of the screen/ photon goes into the screen



MODELS

talk by S. Boffi



Light-cone quark model

SIVERS FUNCTION IN MODELS

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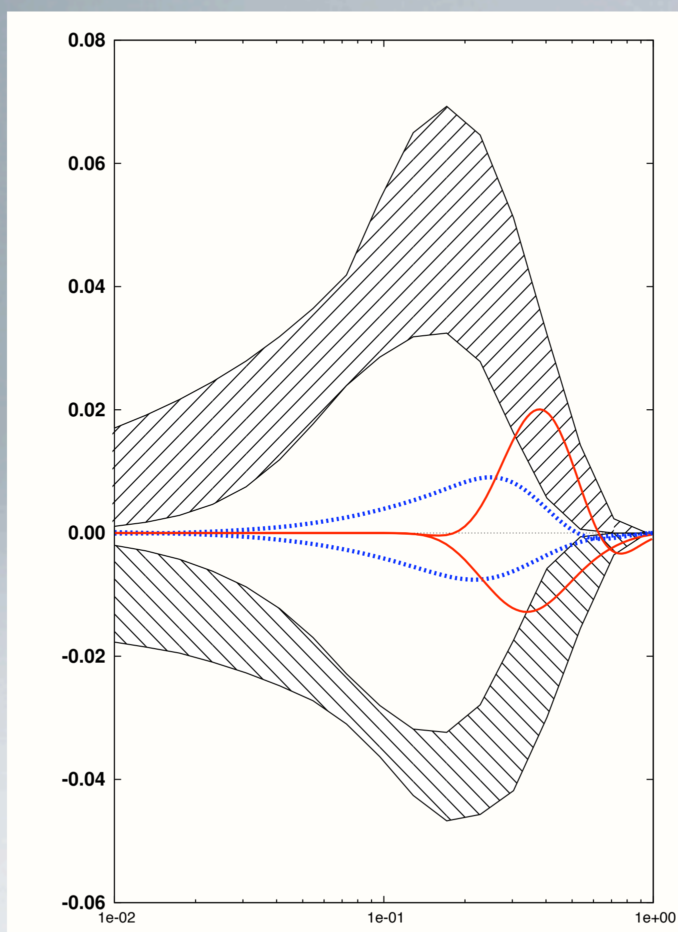
A. Courtoy's talk



MIT bag

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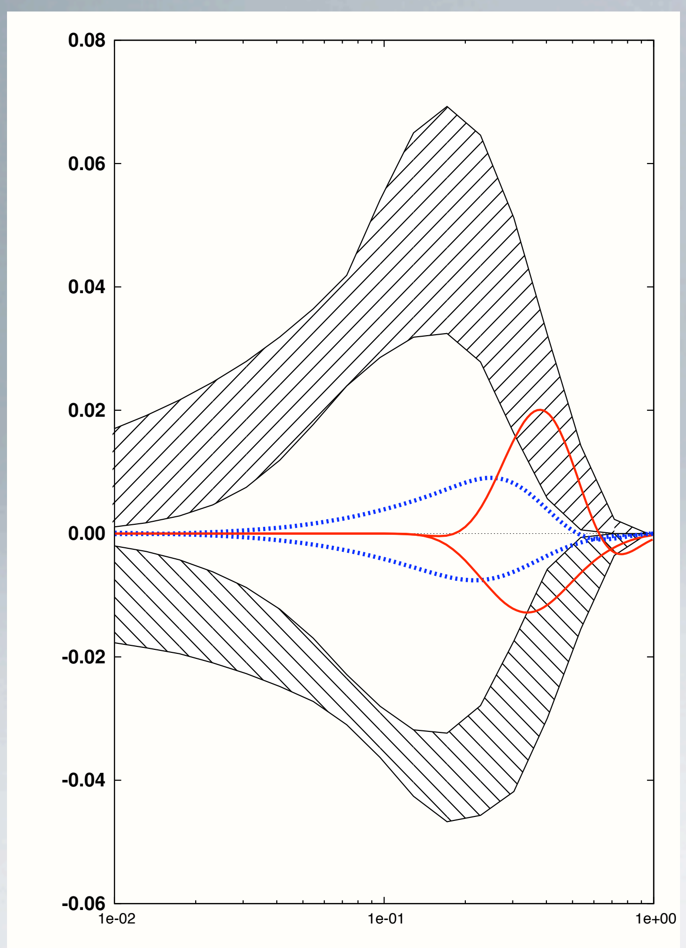
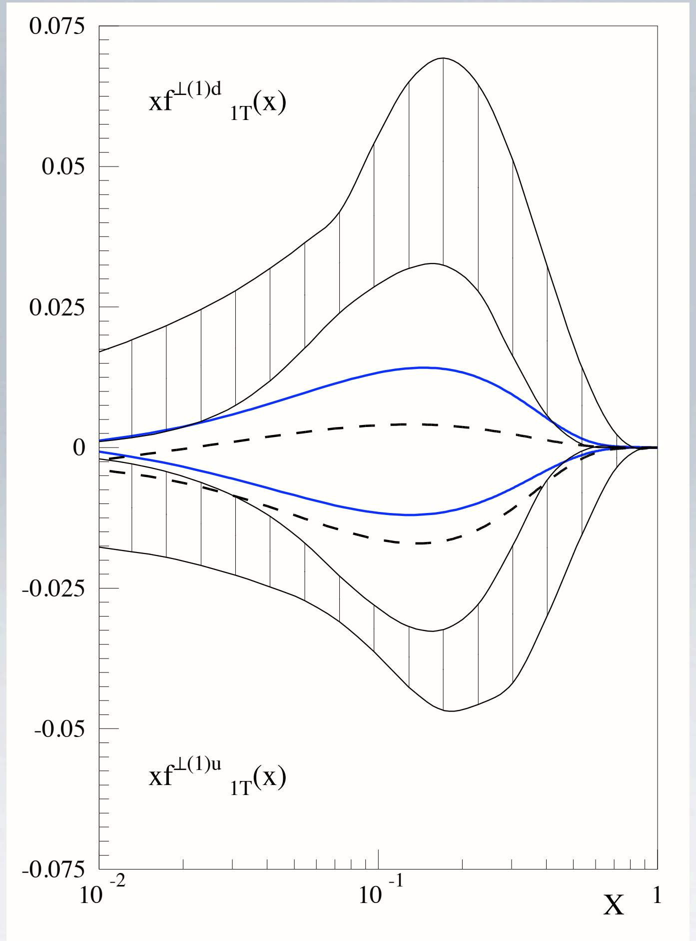


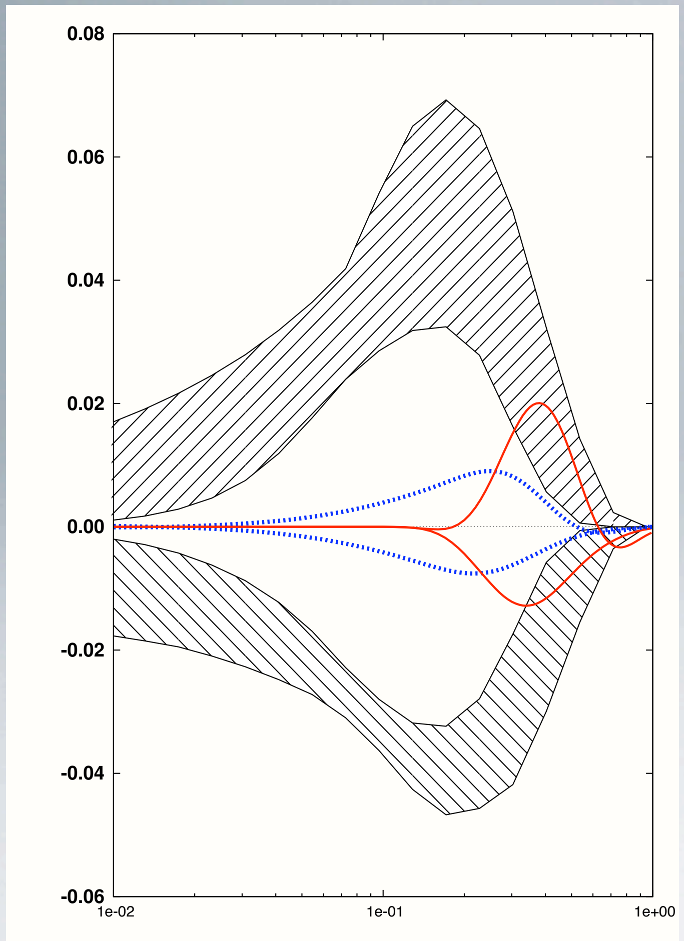


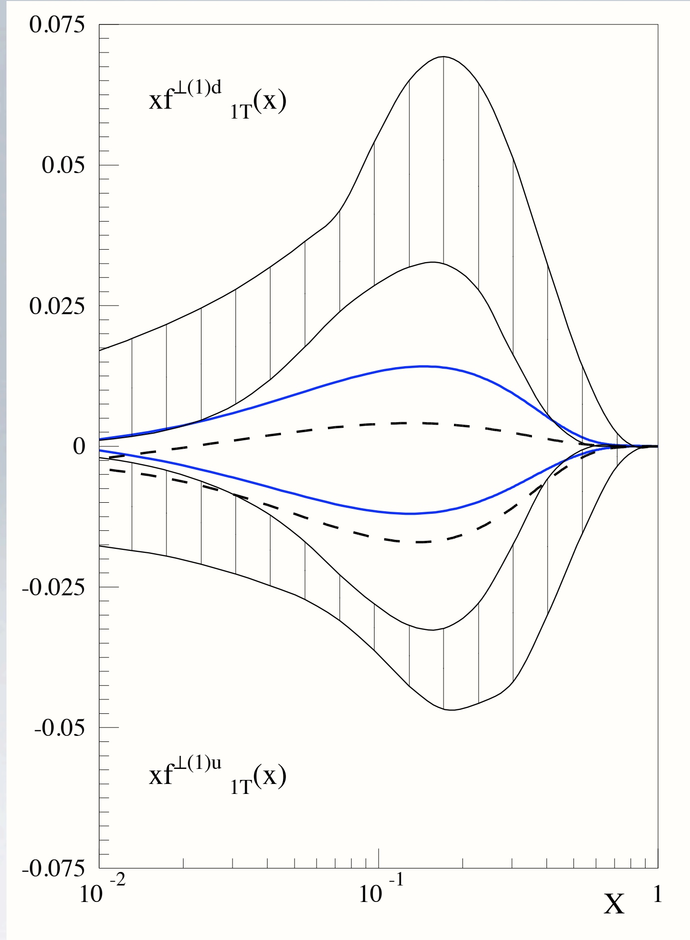
MIT bag Constituent quark

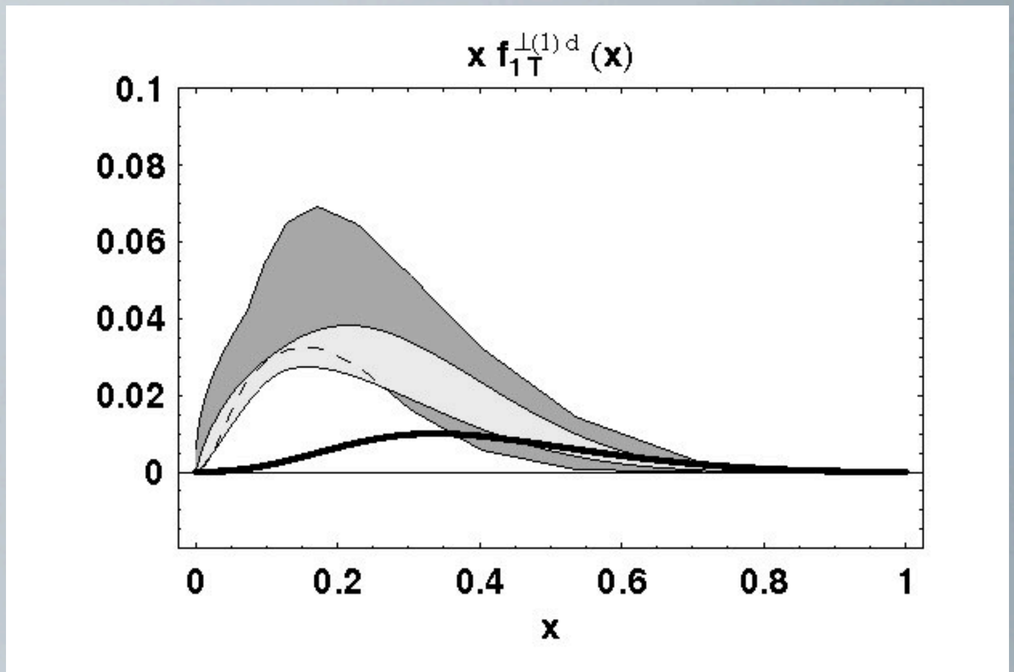
SIVERS FUNCTION IN MODELS

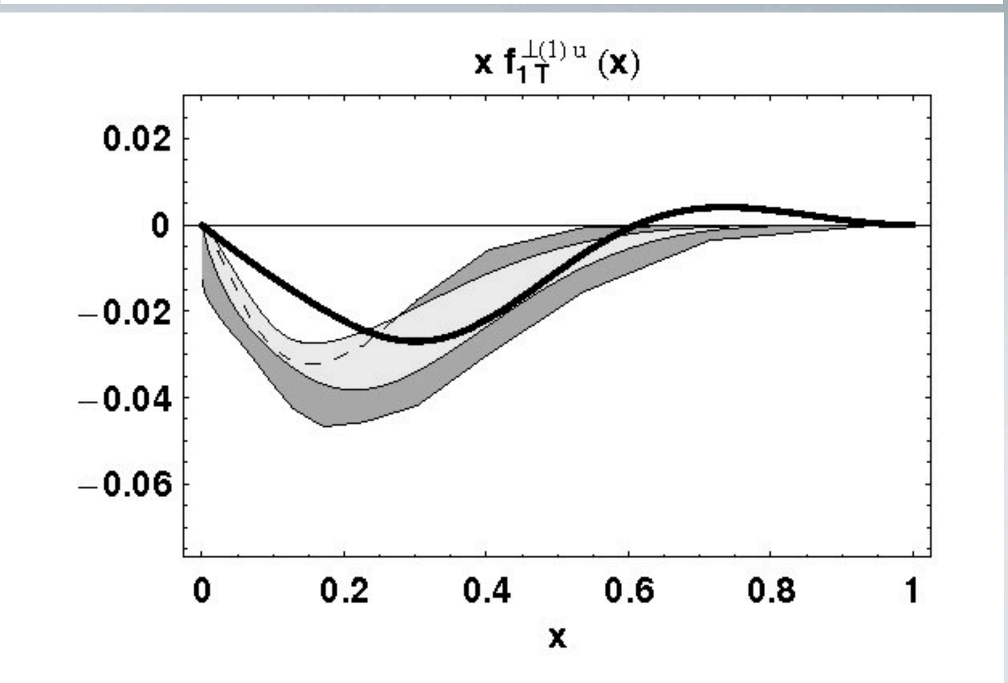
M. Radici's talk

A. Courtoy's talk









MIT bag

Constituent quark

Diquark spectator

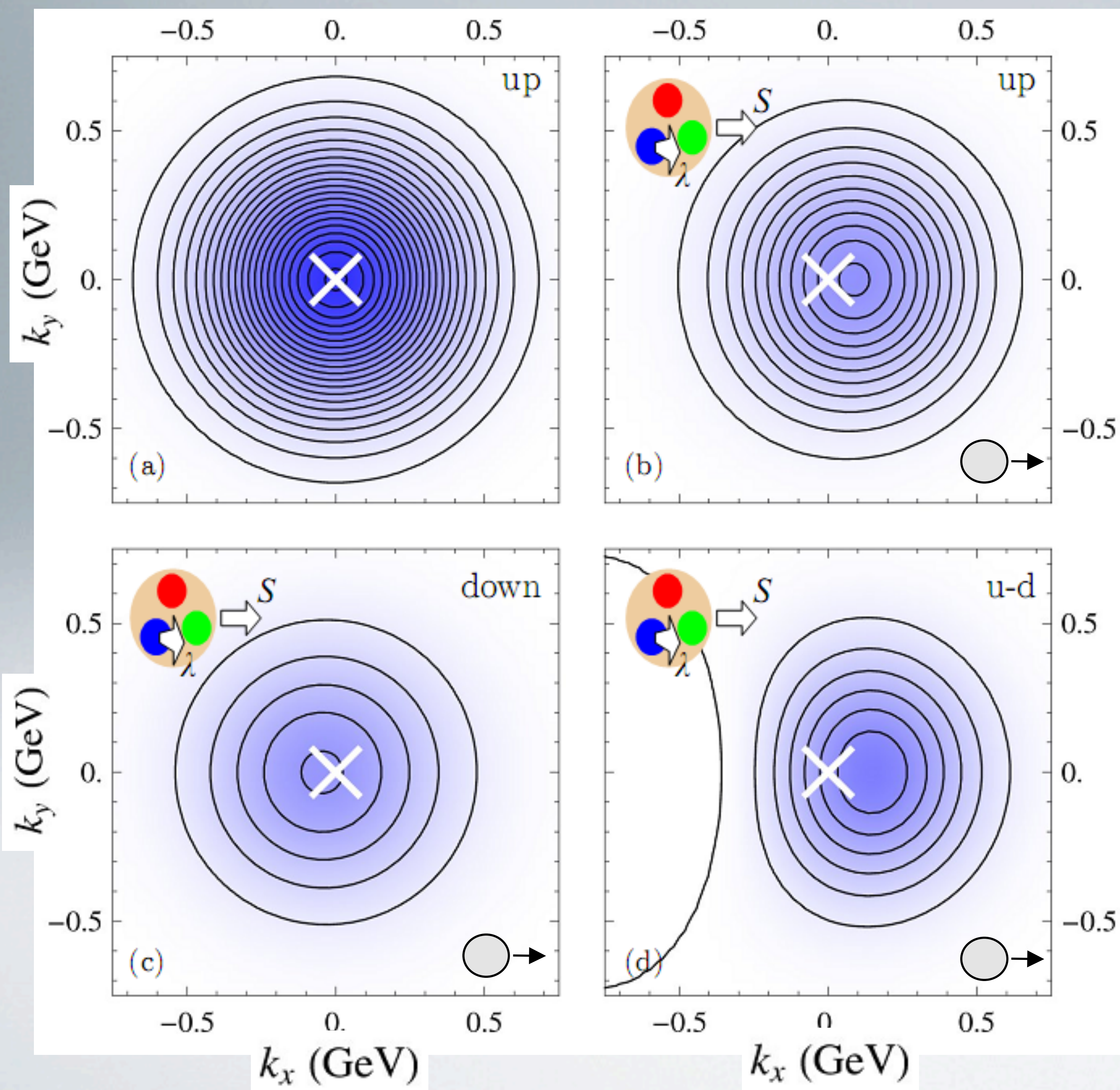
A. Courtoy's talk

"Do not quench your inspiration and imagination; do not become the slave of your model"

Vincent Van Gogh

EXPLORATORY LATTICE CALCULATIONS

P. Hägler's talk



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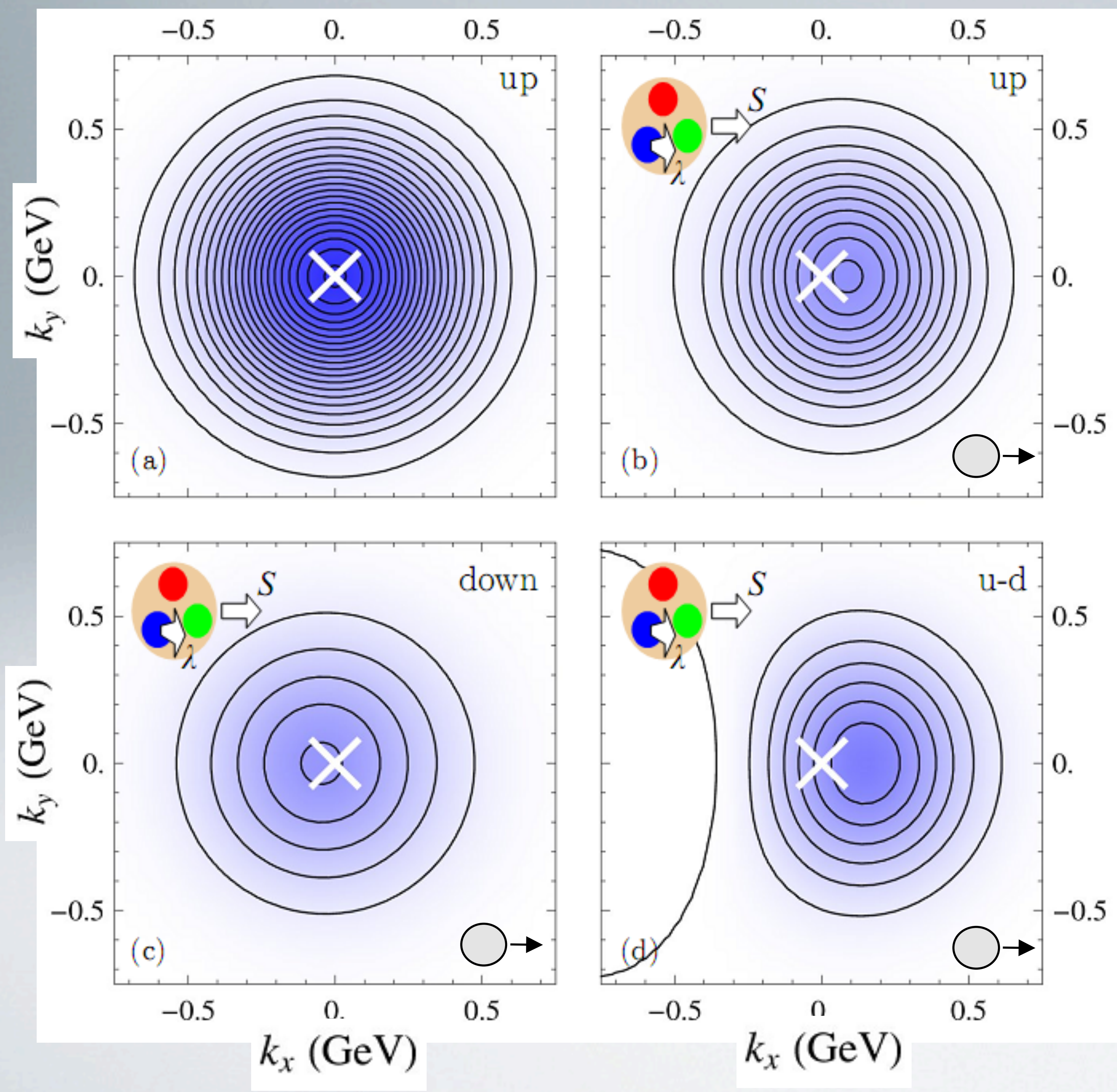

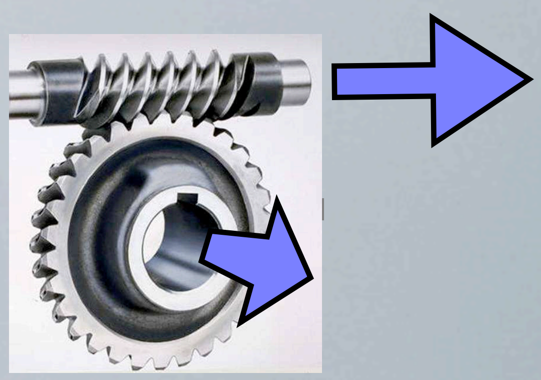

A worm gear

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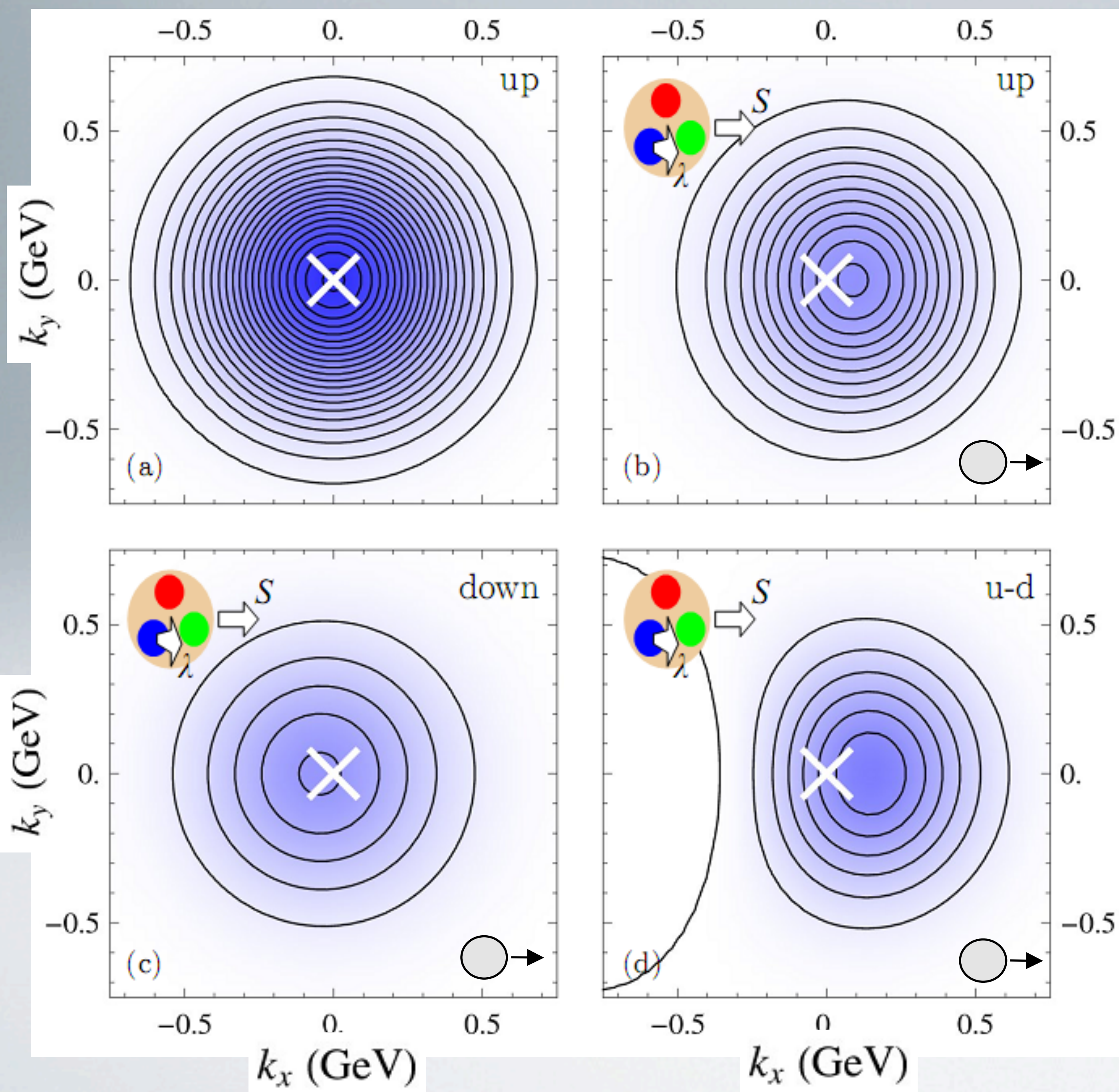

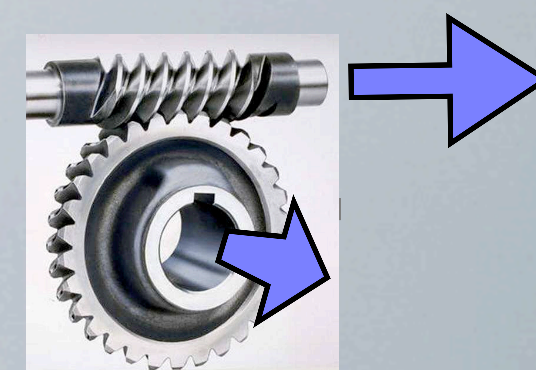

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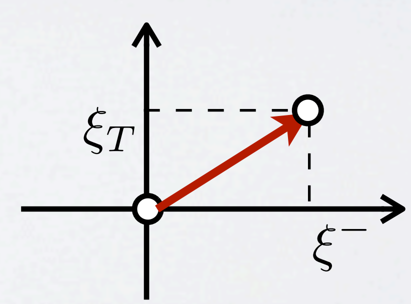
Caveat: gauge link!



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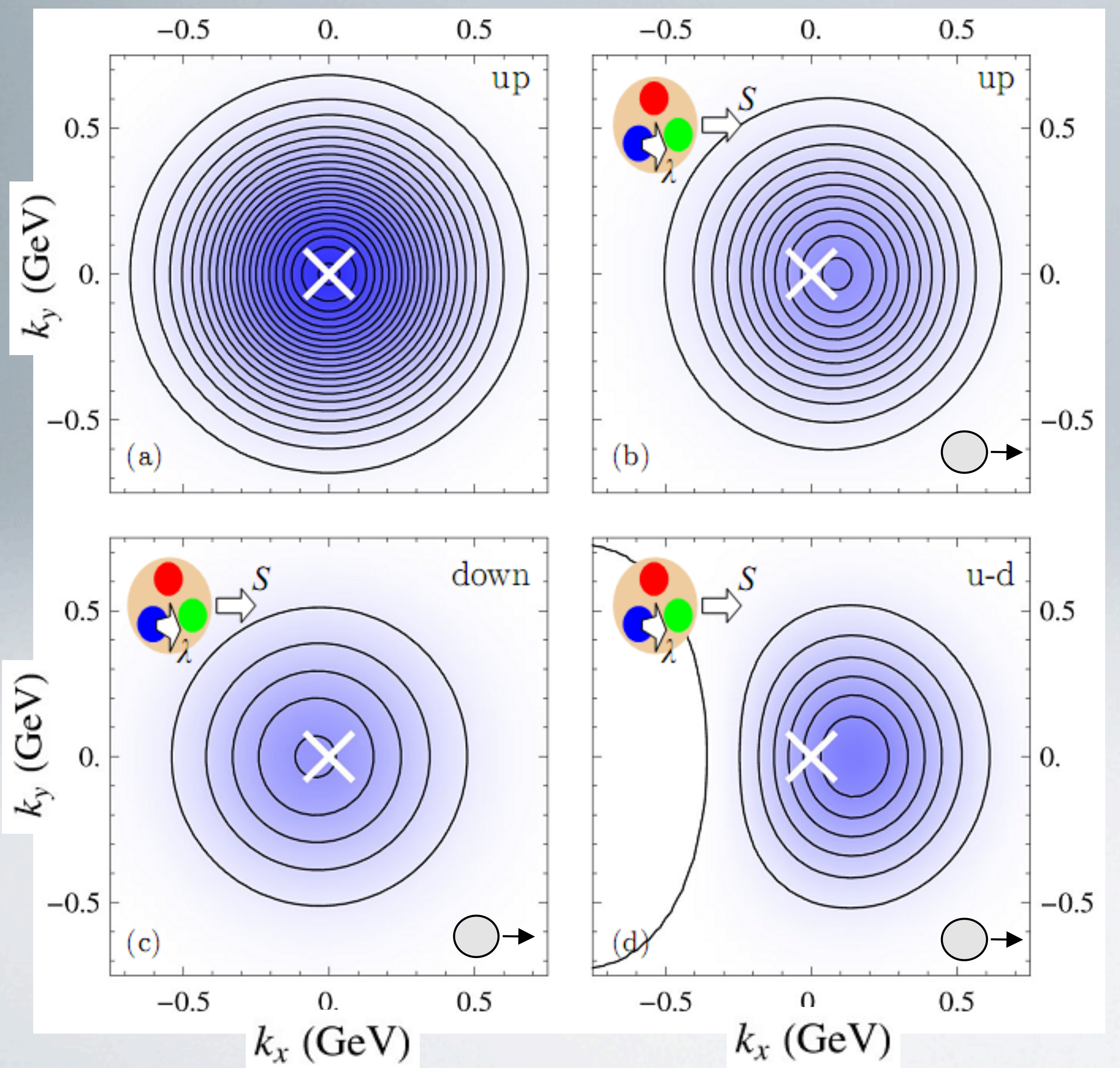

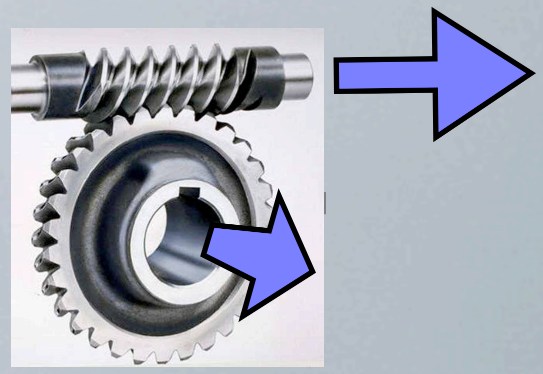

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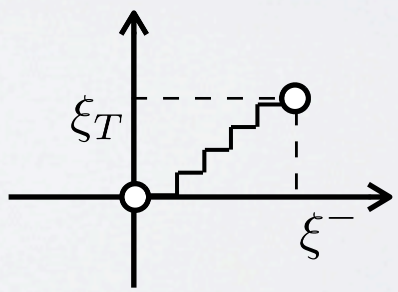


Isolating TMD contribution

Parton distribution (i.e. Sivers effect):

Drell-Yan: $p^{\uparrow} p \rightarrow e^{+} e^{-} X$

Jet (integrated) physics: $p^{\uparrow} p \rightarrow jet\ X,\quad p^{\uparrow} p \rightarrow jet\ jet\ X,$

Prompt gamma: $p^{\uparrow} p \rightarrow \gamma\, X,\ p^{\uparrow} p \rightarrow \gamma\, jet\ X$

Multidimensional analyses: $e\ p^{\uparrow} \rightarrow e^{'}\ h\ X$

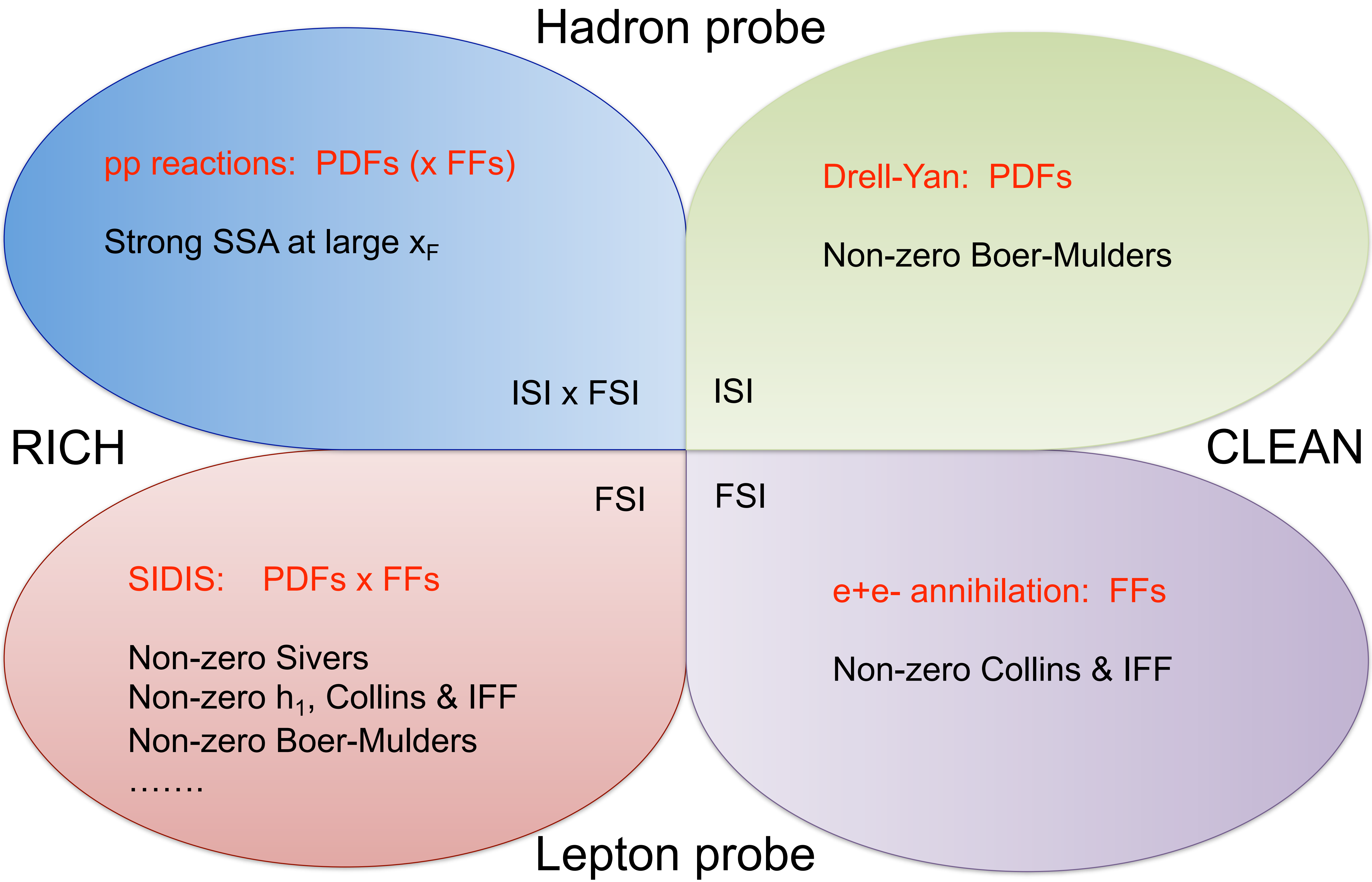
Fragmentation (i.e. Collins effect):

Electron-positron reaction: $e^{+} e^{-} \rightarrow h\ h\ X$

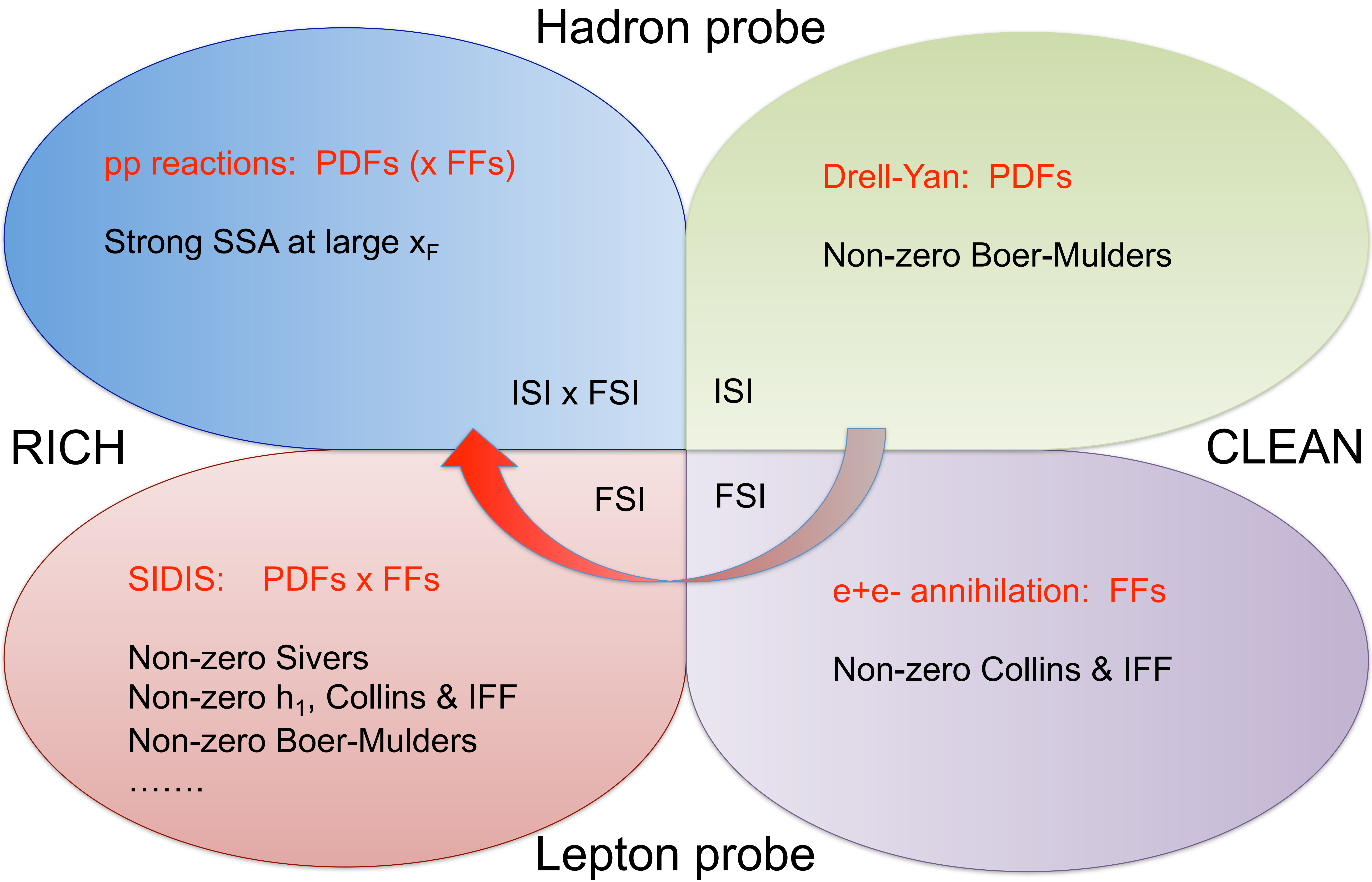
Hadron production with different spin and mass: $p^{\uparrow} p,\ ep^{\uparrow} \rightarrow \pi\ X,\ \omega\ X,\ K^{*} X$

Measurement that depend on the azimuth about the trust axis: $\bar{p}\ p \rightarrow (\Lambda^{\uparrow} jet)\ jet\ X$

TMD palette


Hadron probe
pp reactions: PDFs (x FFs)
Strong SSA at large x_F
Drell-Yan: PDFs
Non-zero Boer-Mulders
ISI x FSI
ISI
RICH
CLEAN
FSI
FSI
SIDIS: PDFs x FFs
Non-zero Sivers
Non-zero h_1, Collins & IFF
Non-zero Boer-Mulders
....
e+e- annihilation: FFs
Non-zero Collins & IFF
Lepton probe

TMD palette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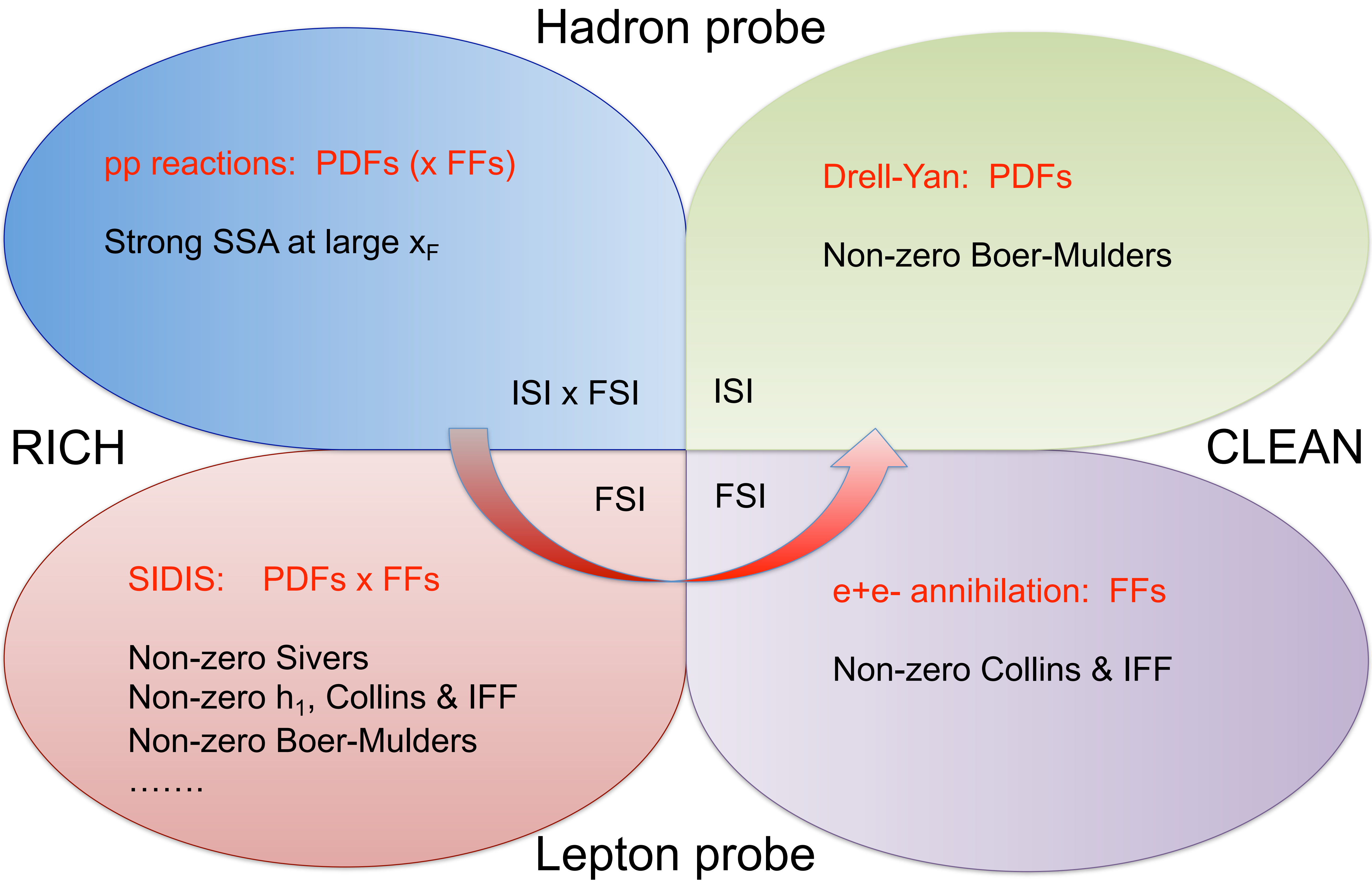
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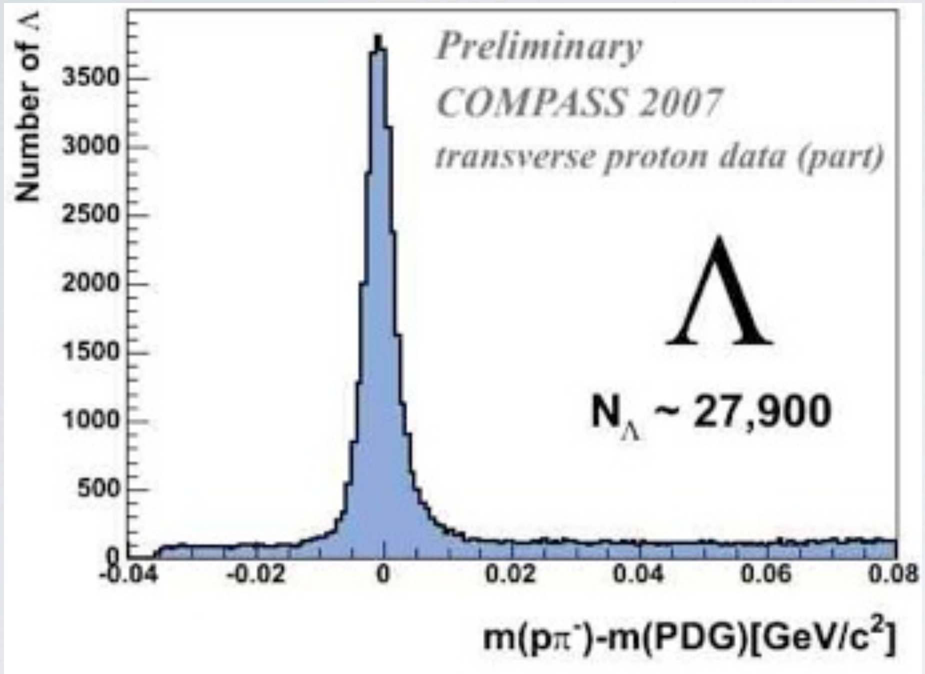
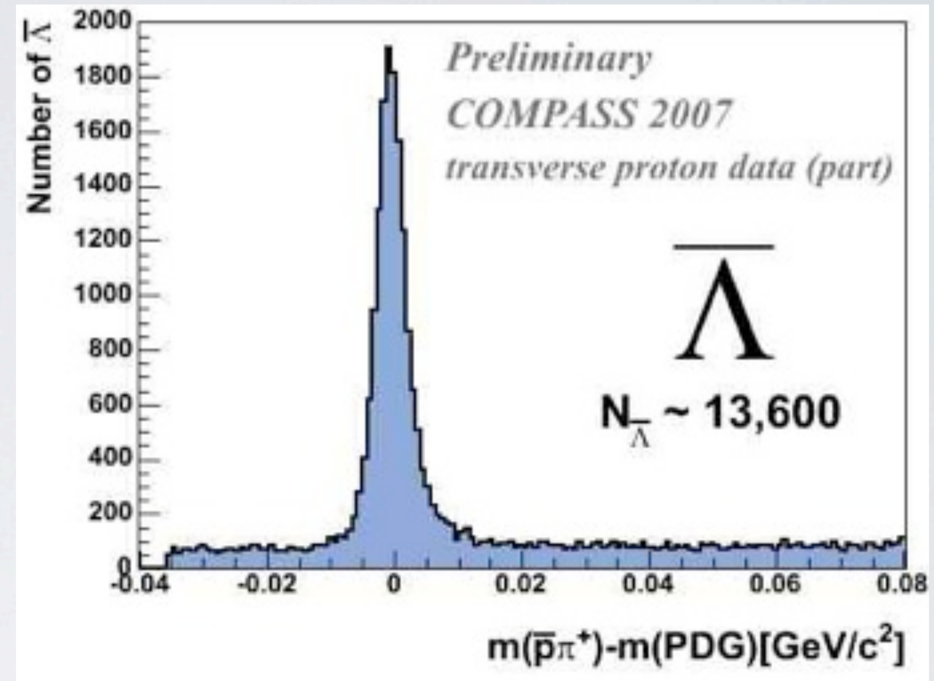
MISSION 1: TRANSVERSITY

THE COLLINEAR APPROACH

talk by R. Joosten





$$\mathcal{P}_\Lambda(x,y,z) = \mathcal{P}_T D_{NN}(y) \frac{\sum_q e_q^2 h_1^q(x) H_1^{q\to\Lambda}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\Lambda}(z)}$$

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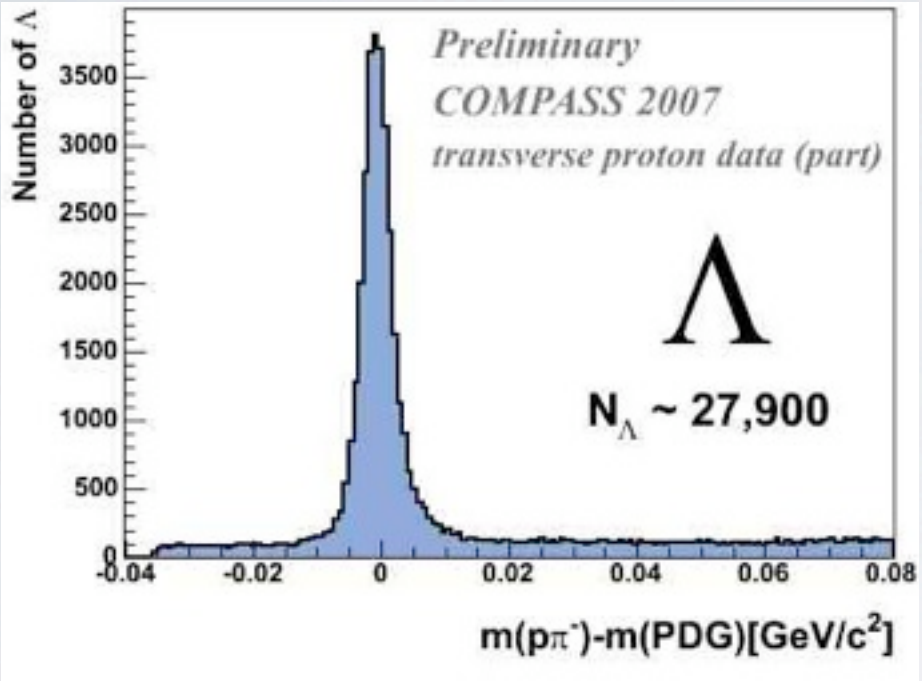

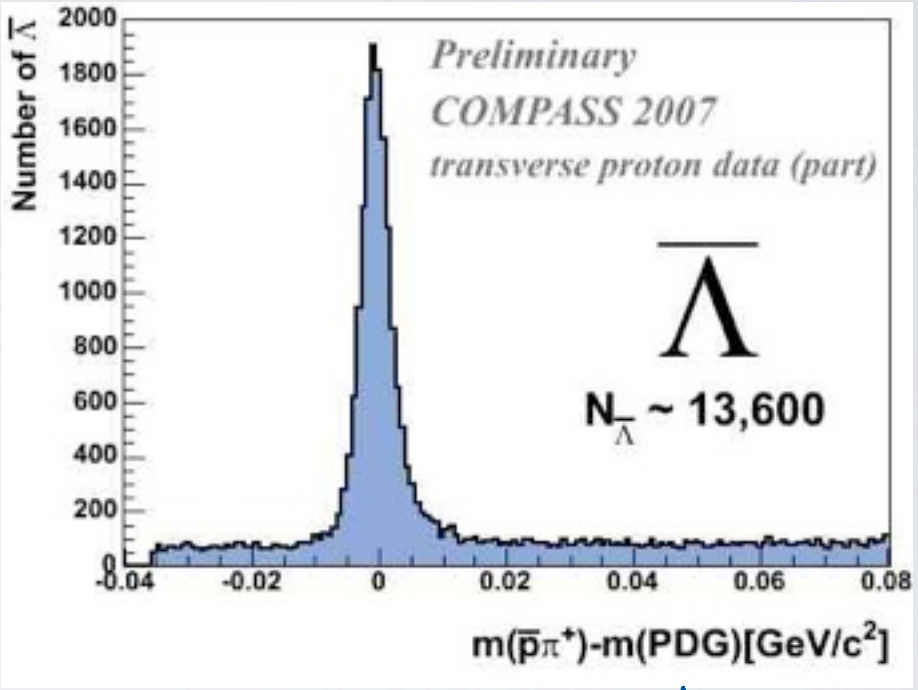

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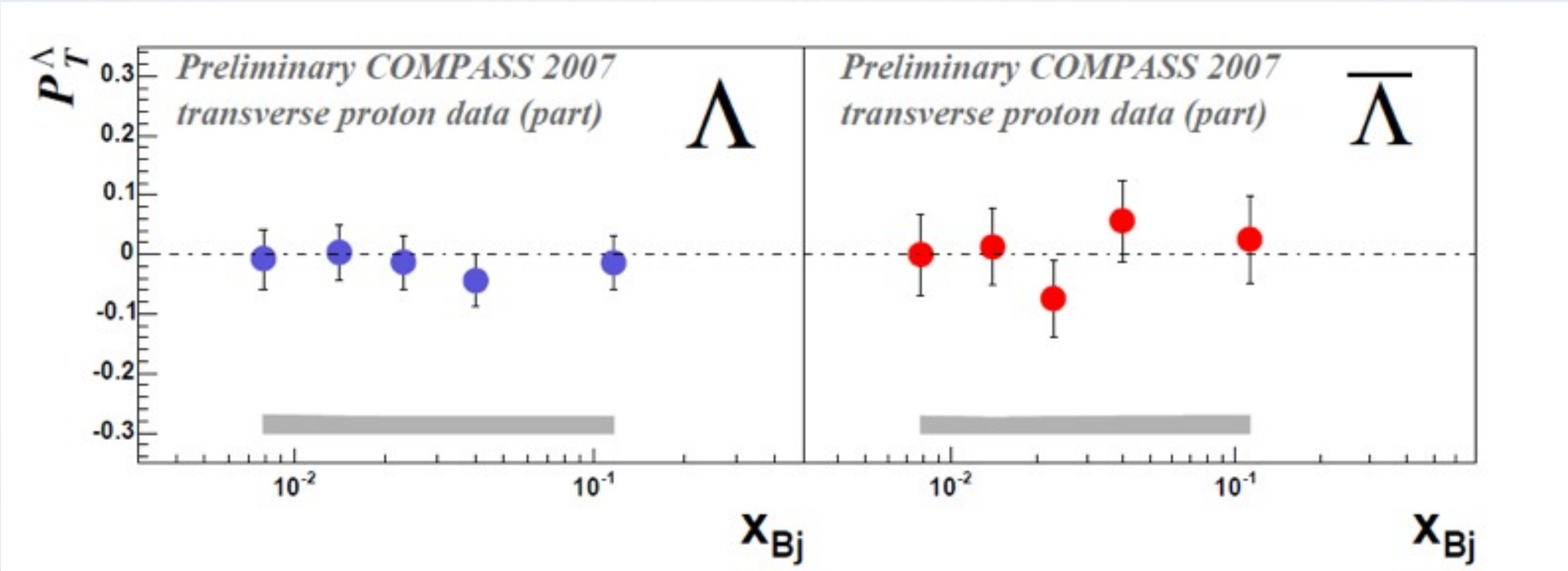

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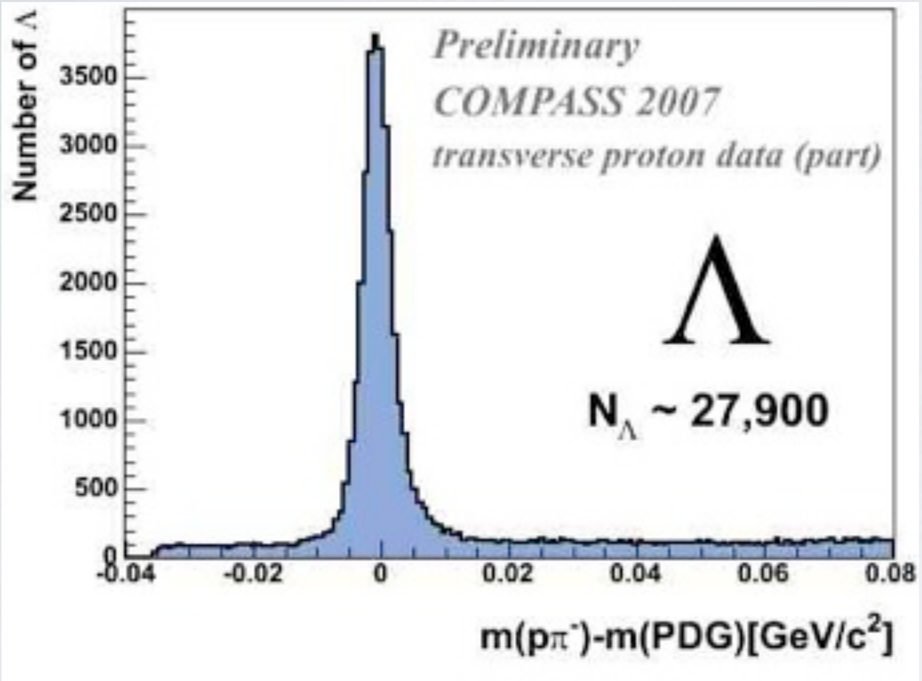

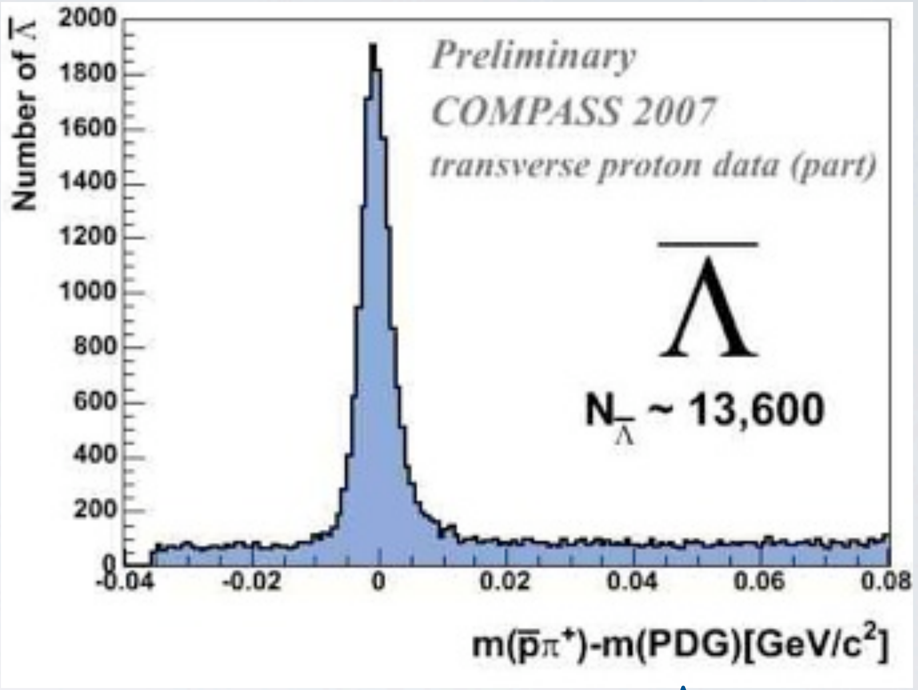

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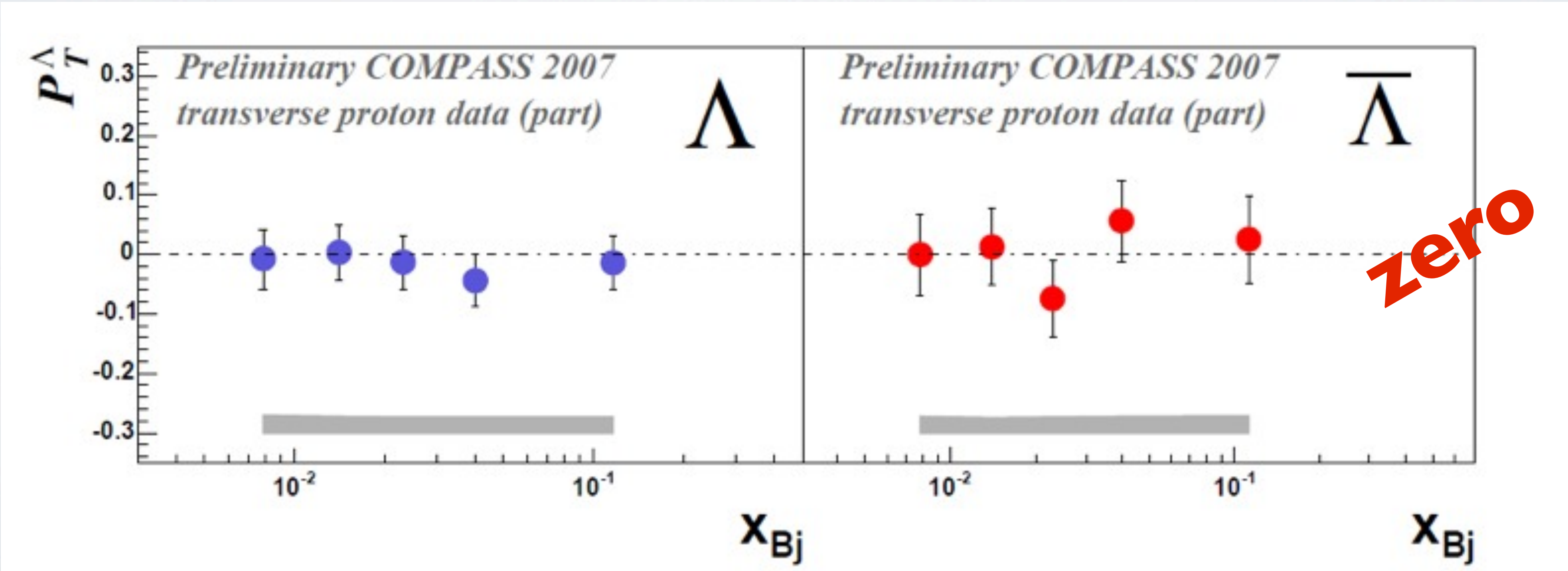


THE COLLINEAR APPROACH II

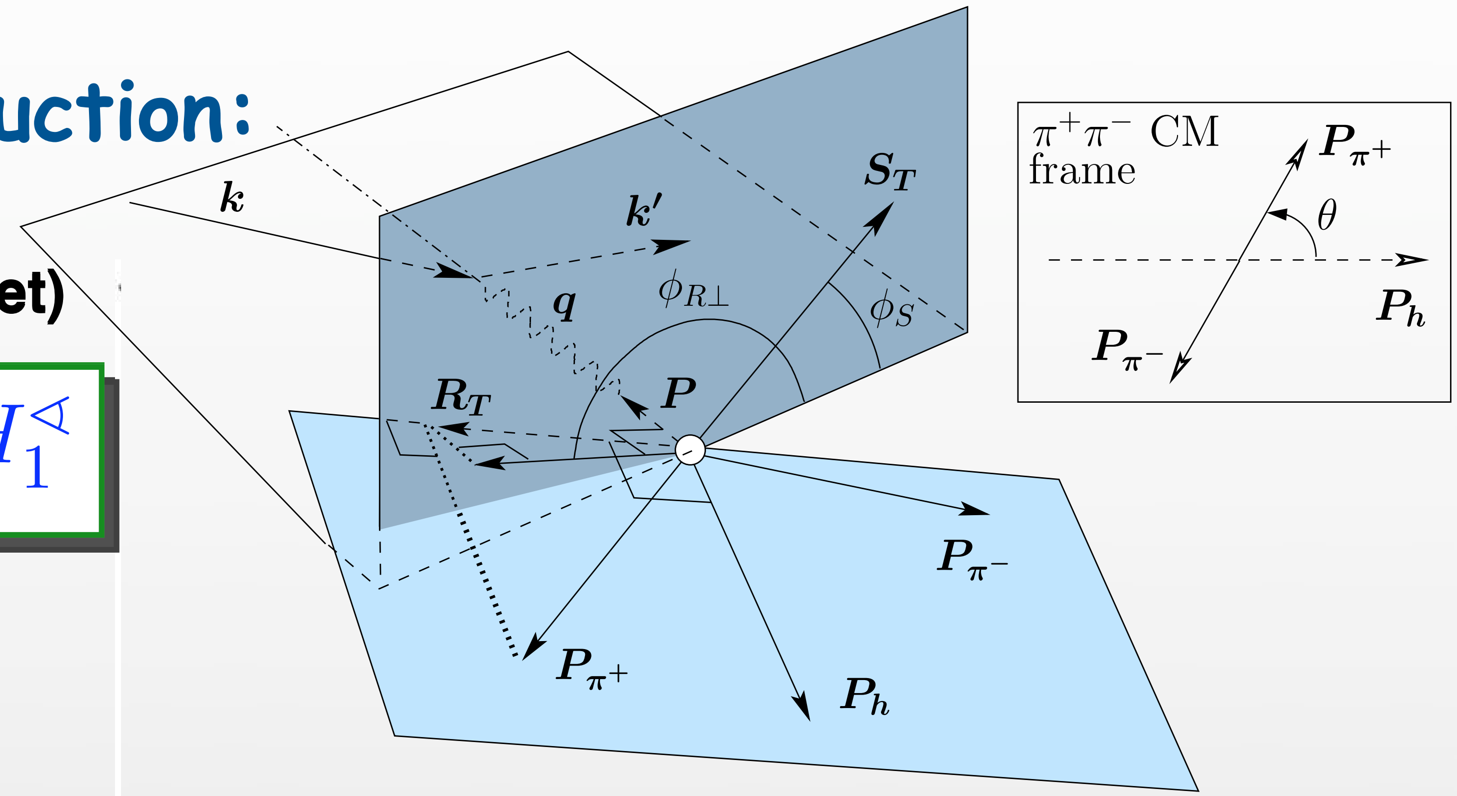
spin-dependent 2-hadron production:

(Unpolarized beam, Transversely pol. target)

$$\sigma_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sum e_q^2 \, h_1^q \, H_1^{\sphericalangle}$$

$$H_1^{\sphericalangle} = H_1^{\sphericalangle}(z, \zeta, M_{\pi\pi}^2)$$

$$(\zeta \sim z_1/(z_1 + z_2))$$



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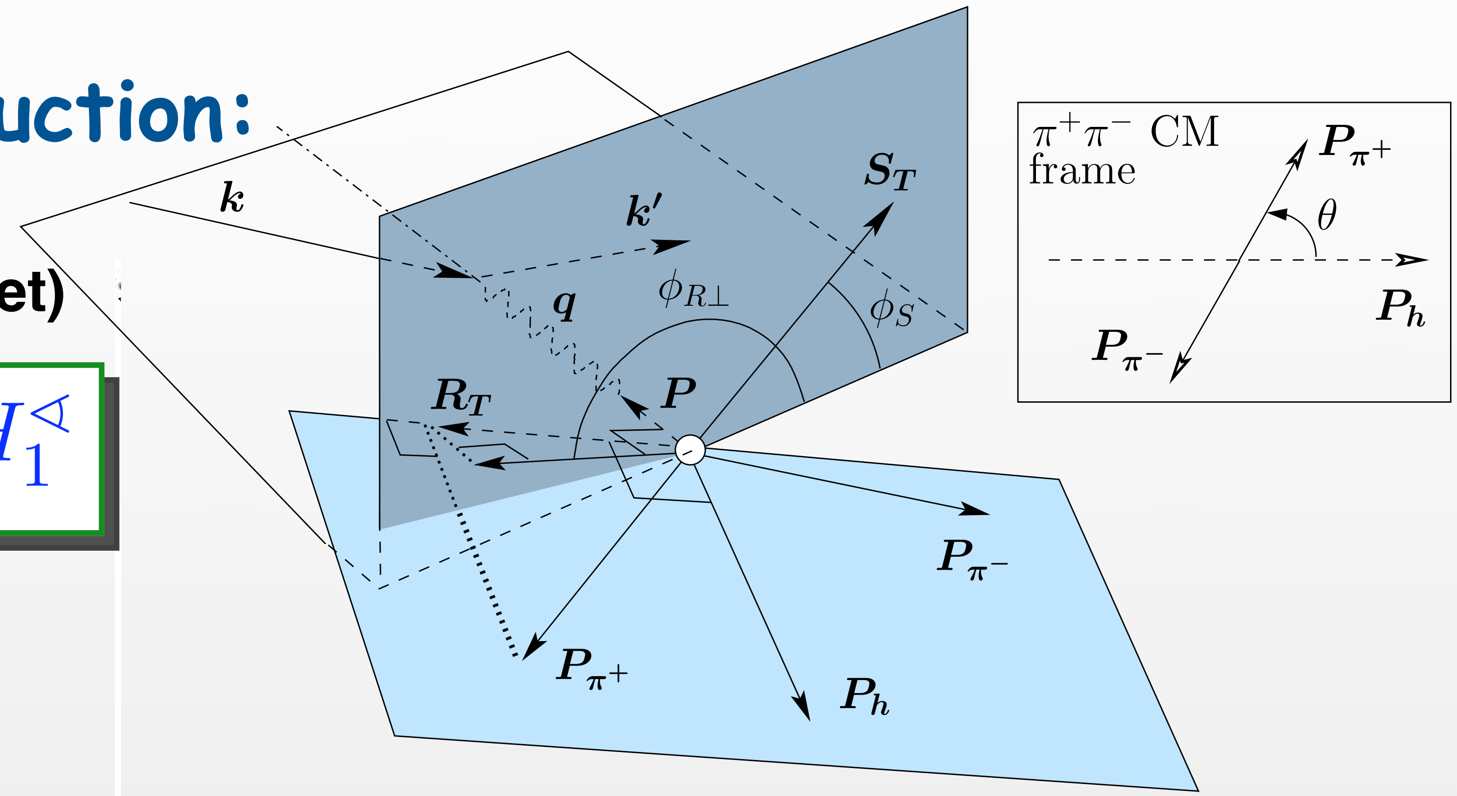

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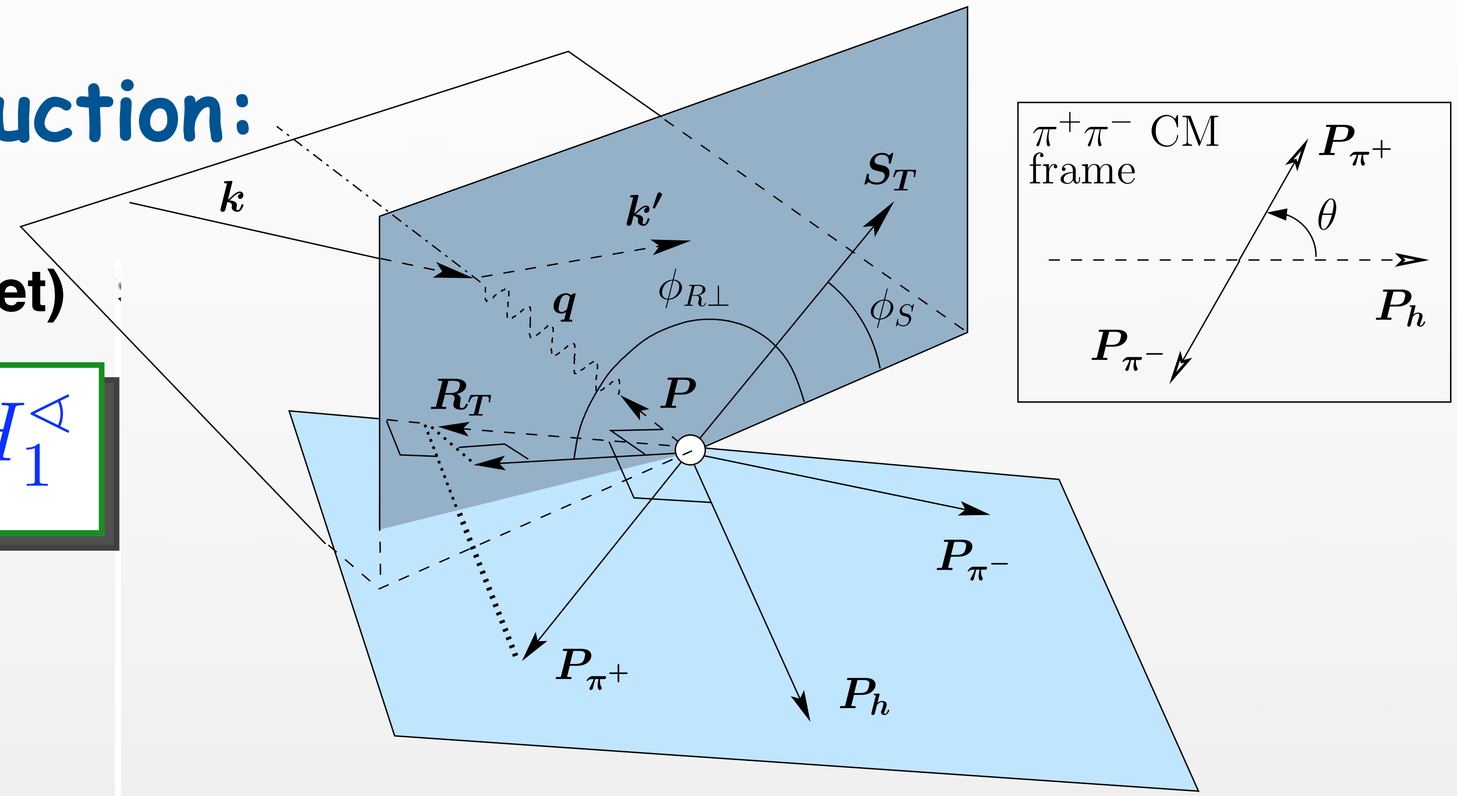

only relative momentum of hadron pair relevant

$\Rightarrow$ integration over transverse momentum of hadron pair simplifies factorization and Q^2 evolution

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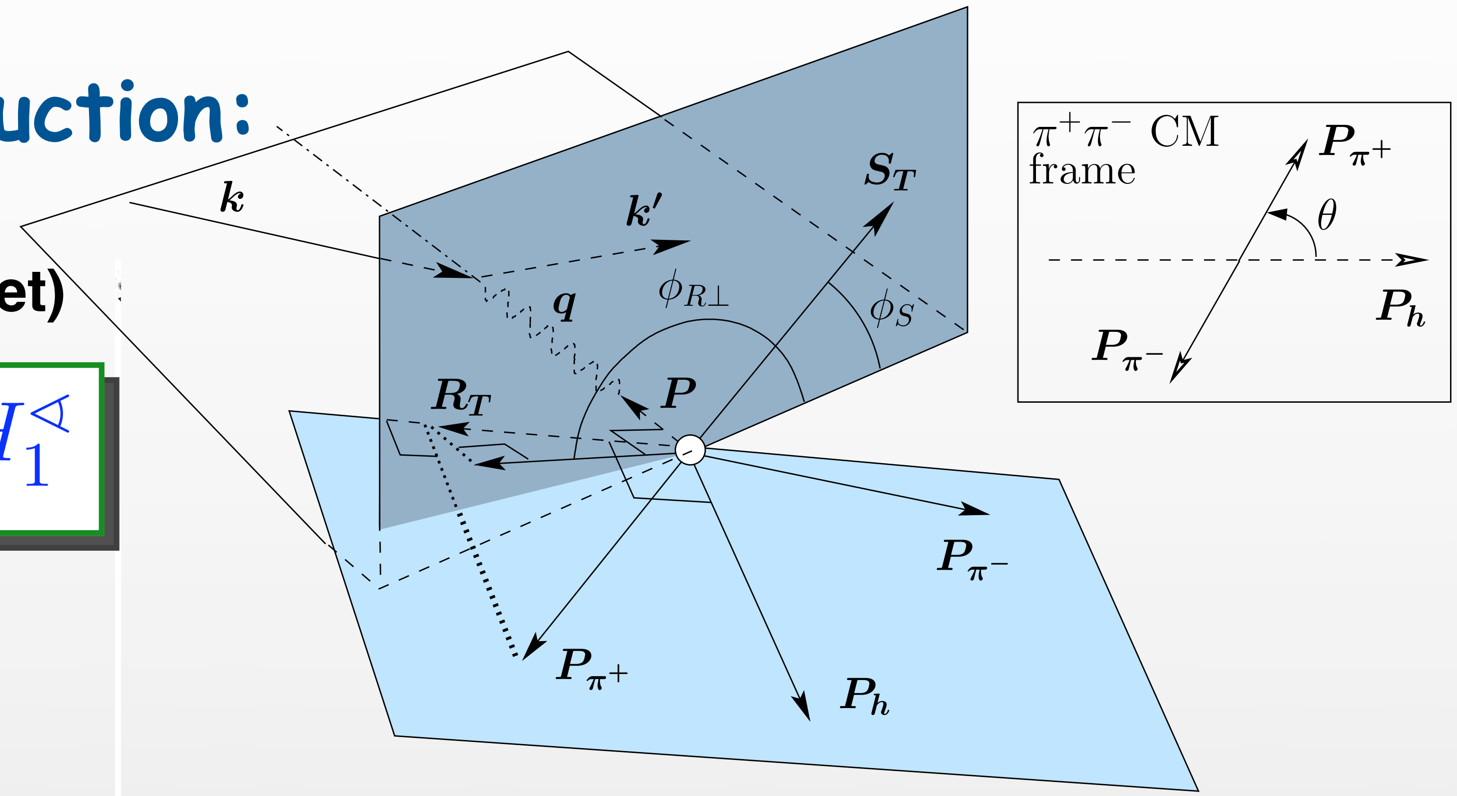


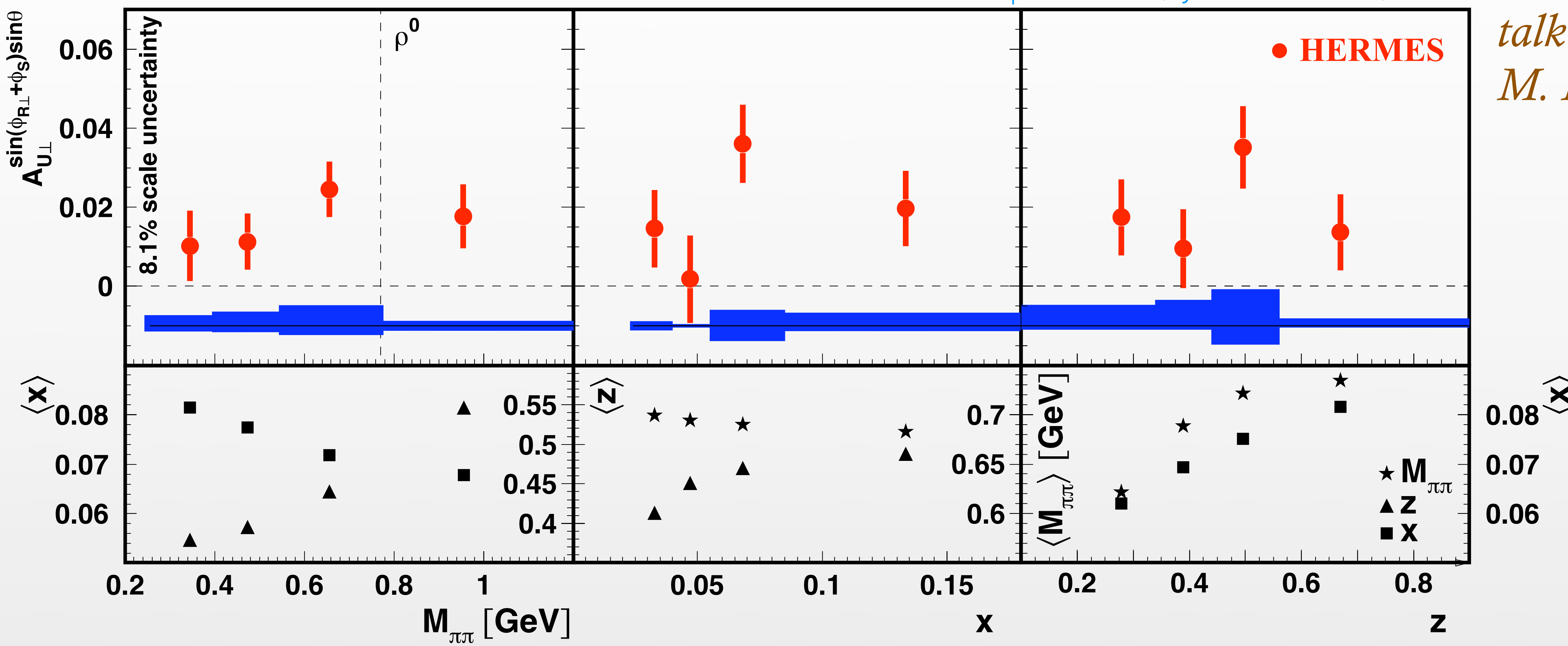
- only relative momentum of hadron pair relevant

  $\Rightarrow$ integration over transverse momentum of hadron pair simplifies factorization and Q^2 evolution

- however, cross section becomes quite complex (differential in 9 variables)

IFF IN SEMI-INCLUSIVE DIS

A. Airapetian et al., JHEP 0806:017,2008



talk by M. Diefenthaler

- ☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!
- ☑ invariant-mass dependence rules out Jaffe model

IFF IN SEMI-INCLUSIVE DIS

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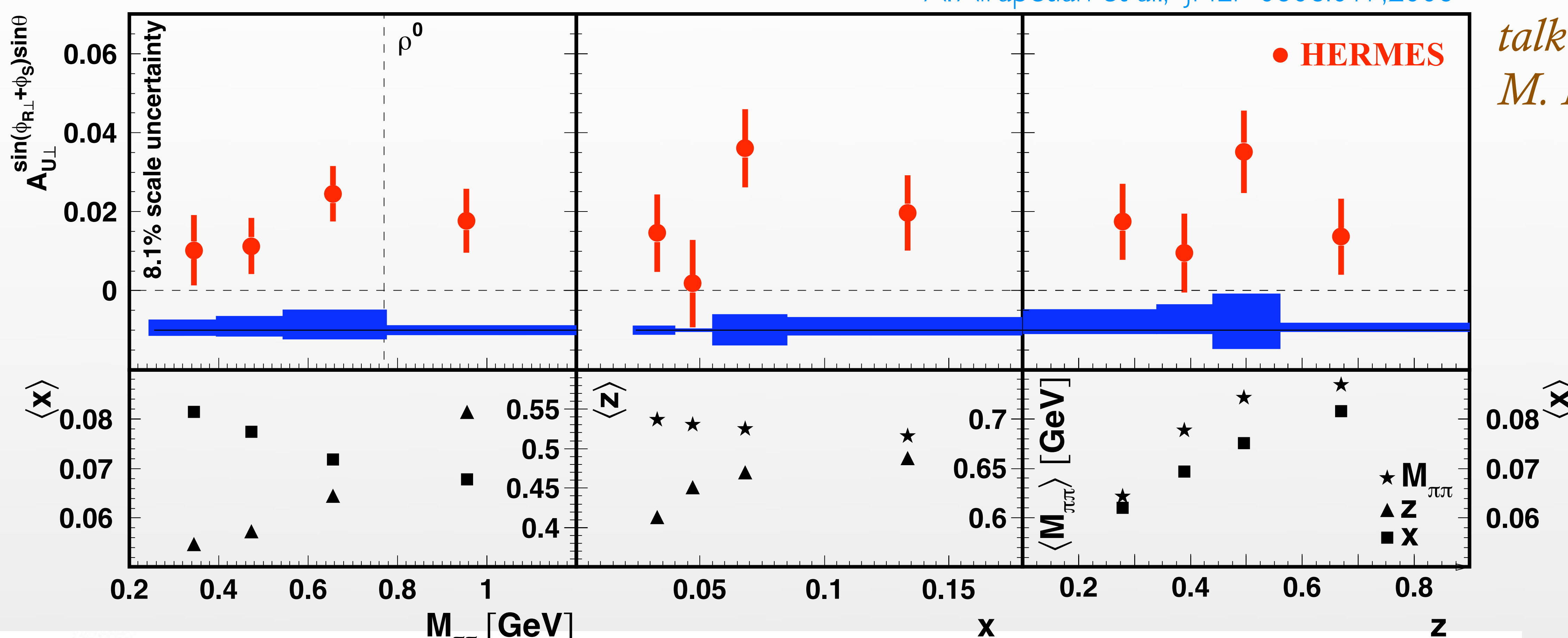

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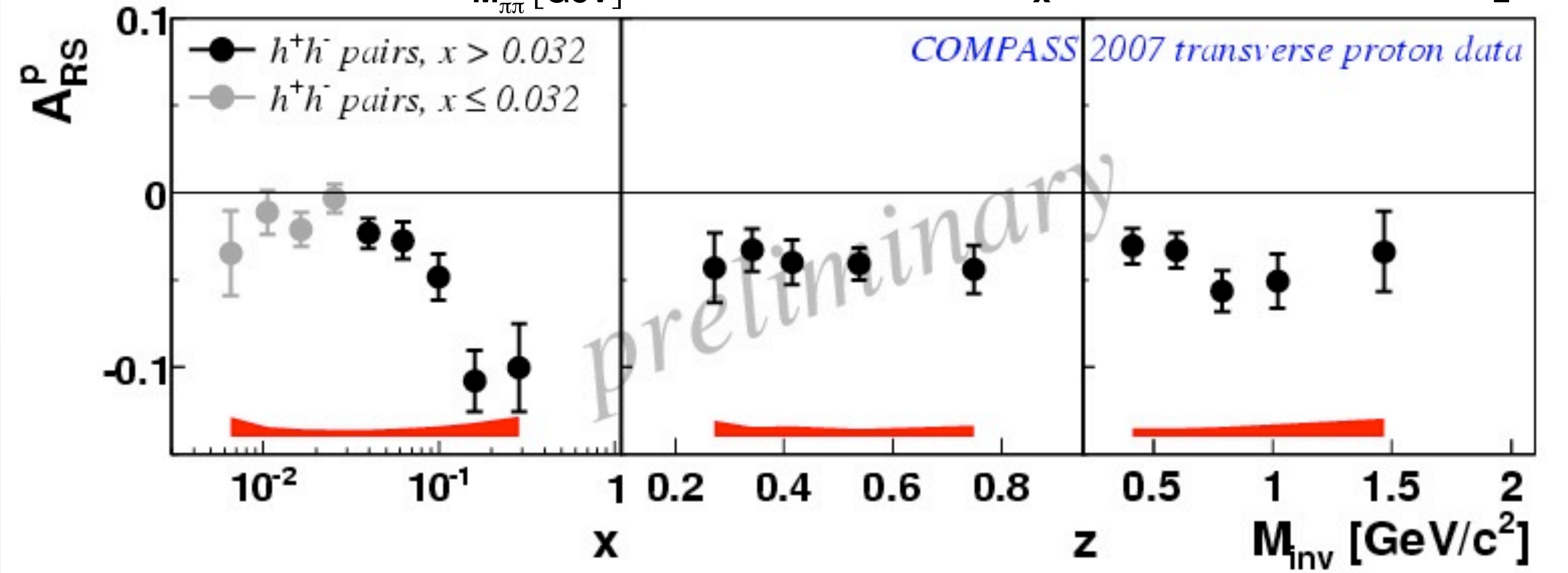
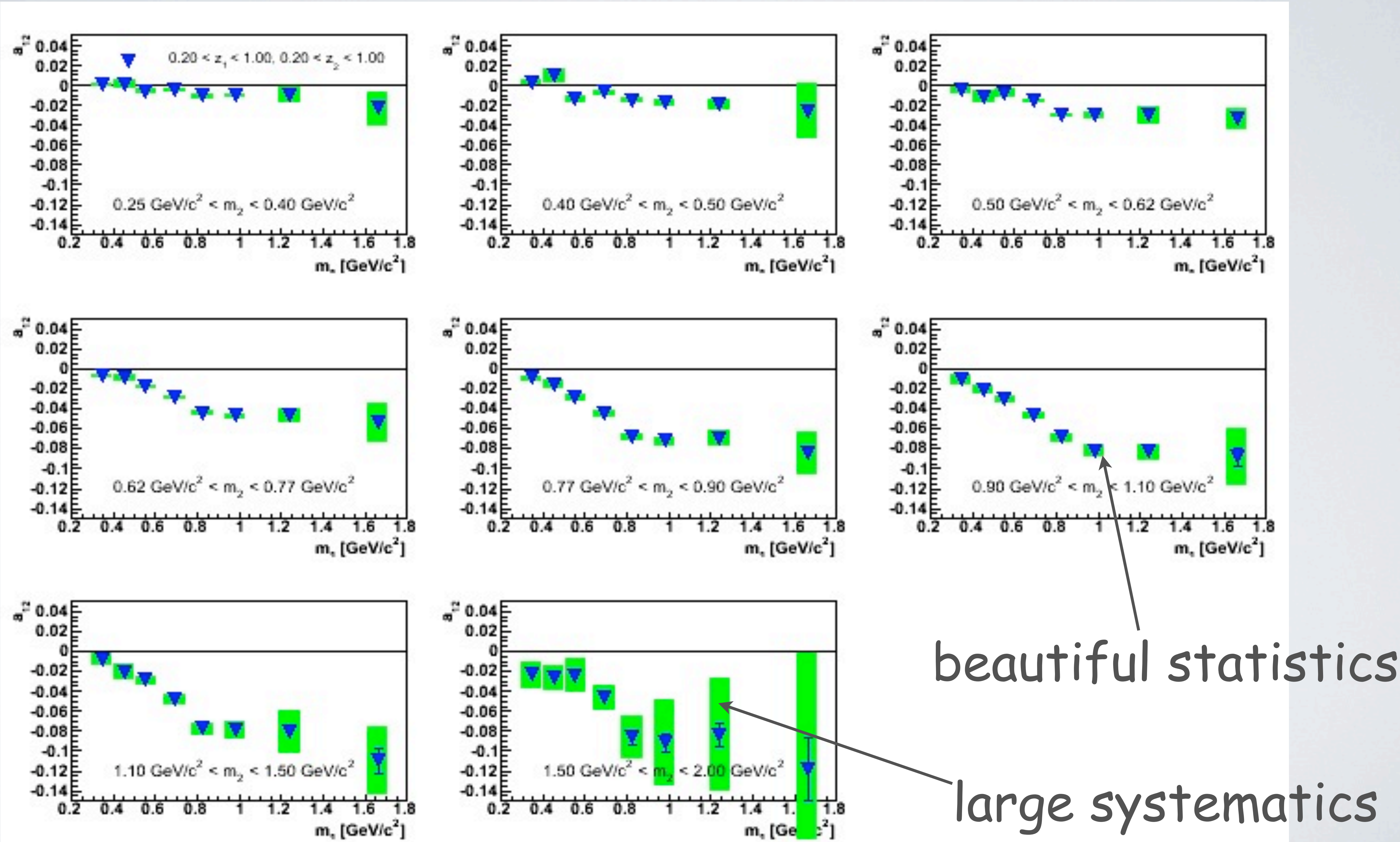


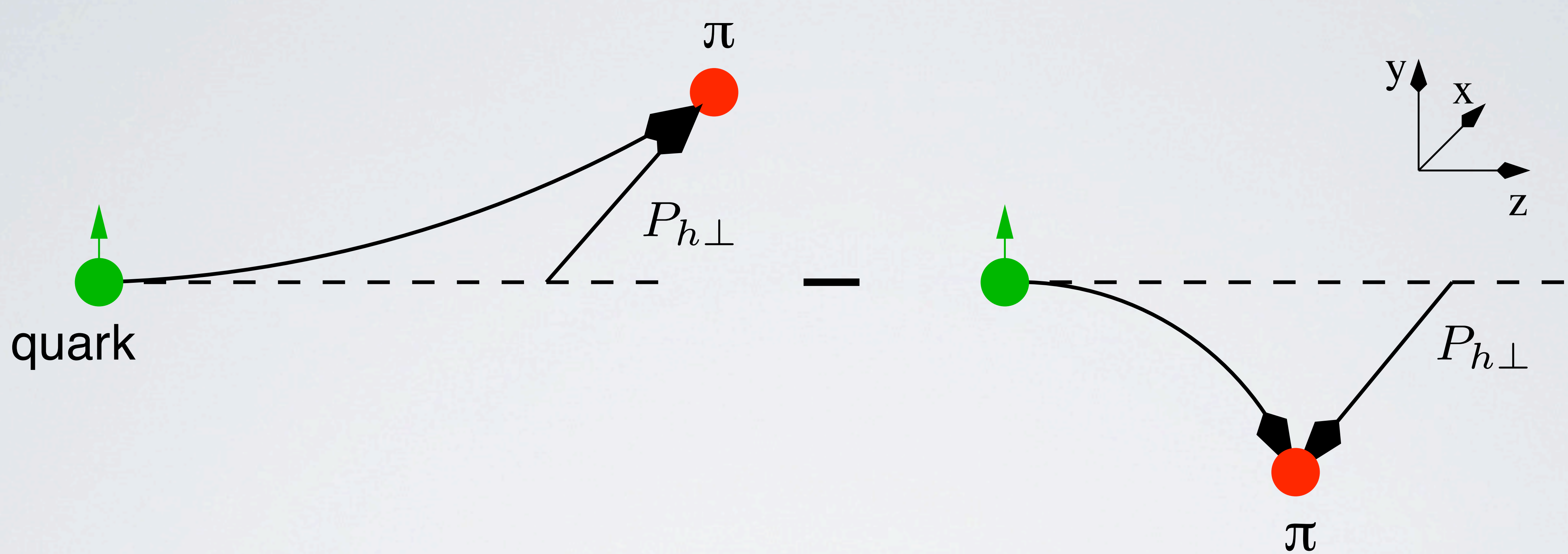
talk by
R. Joosten

IFF IN E+E- AT BELLE

talk by M. Grosse-Perdekamp



THE TMD APPROACH



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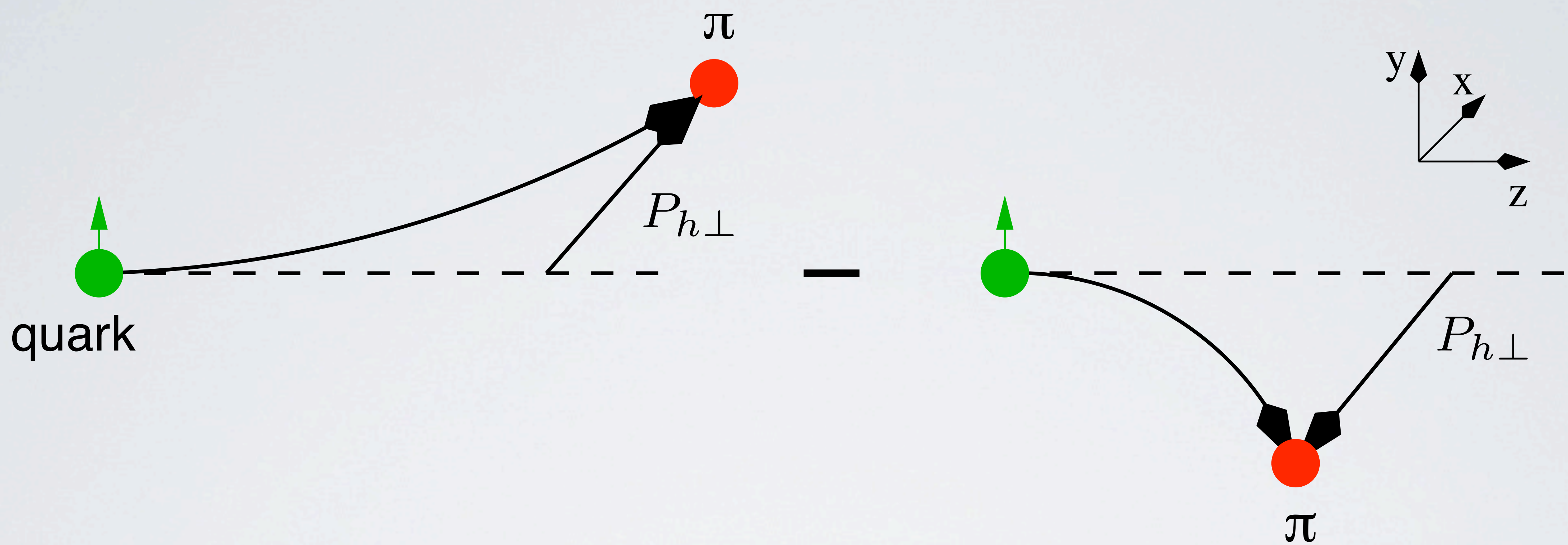
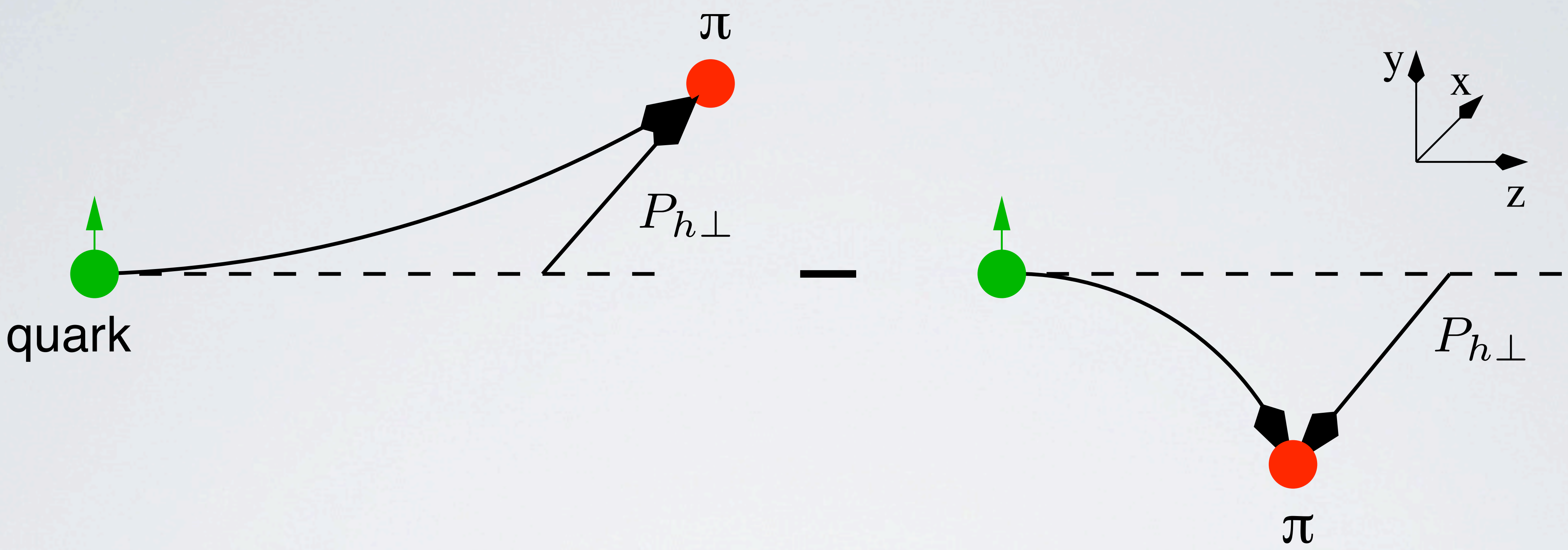


Collins function provides a correlation between spin of quark and transverse momentum of hadron produced

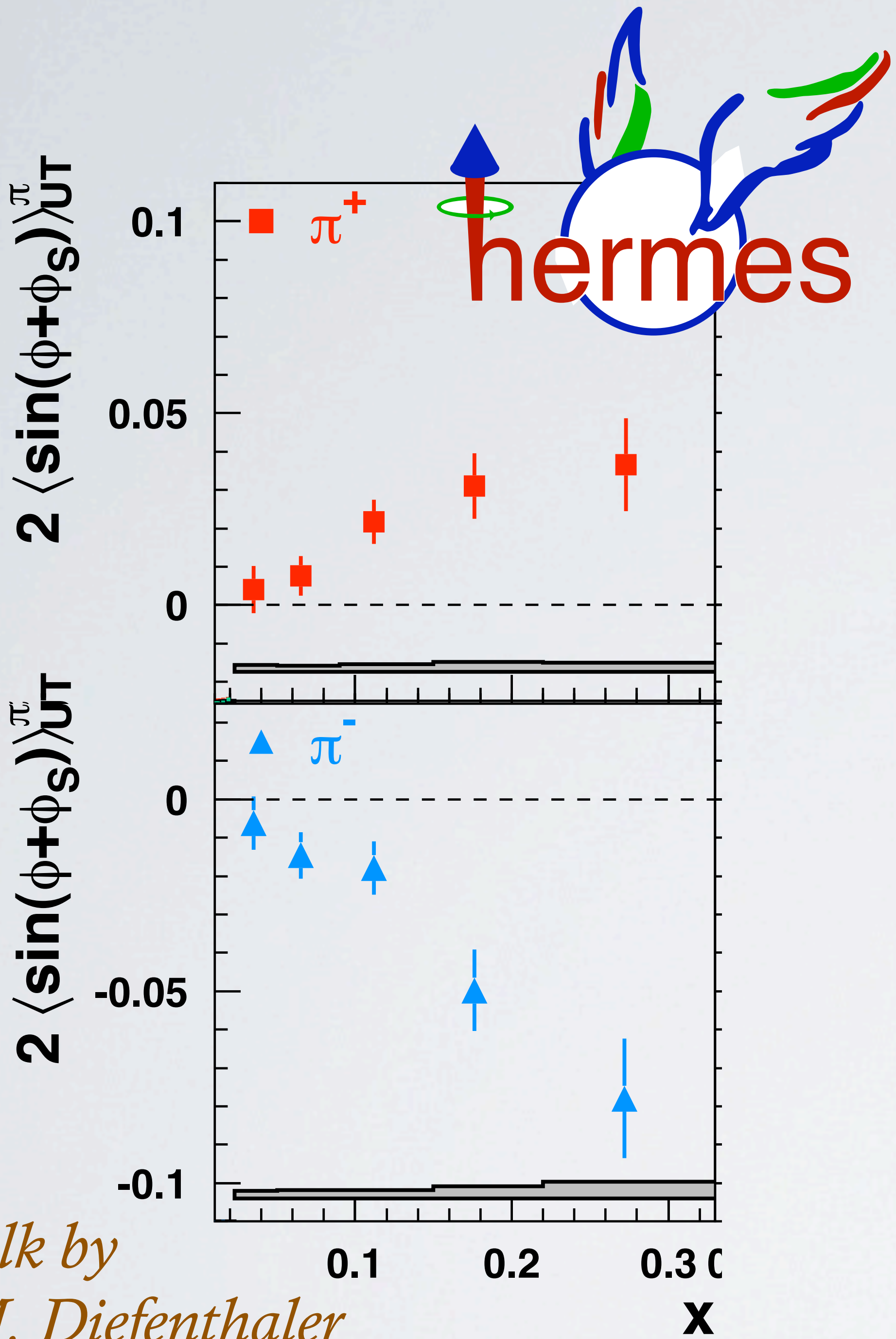
THE TMD APPROACH



- Collins function provides a correlation between spin of quark and transverse momentum of hadron produced

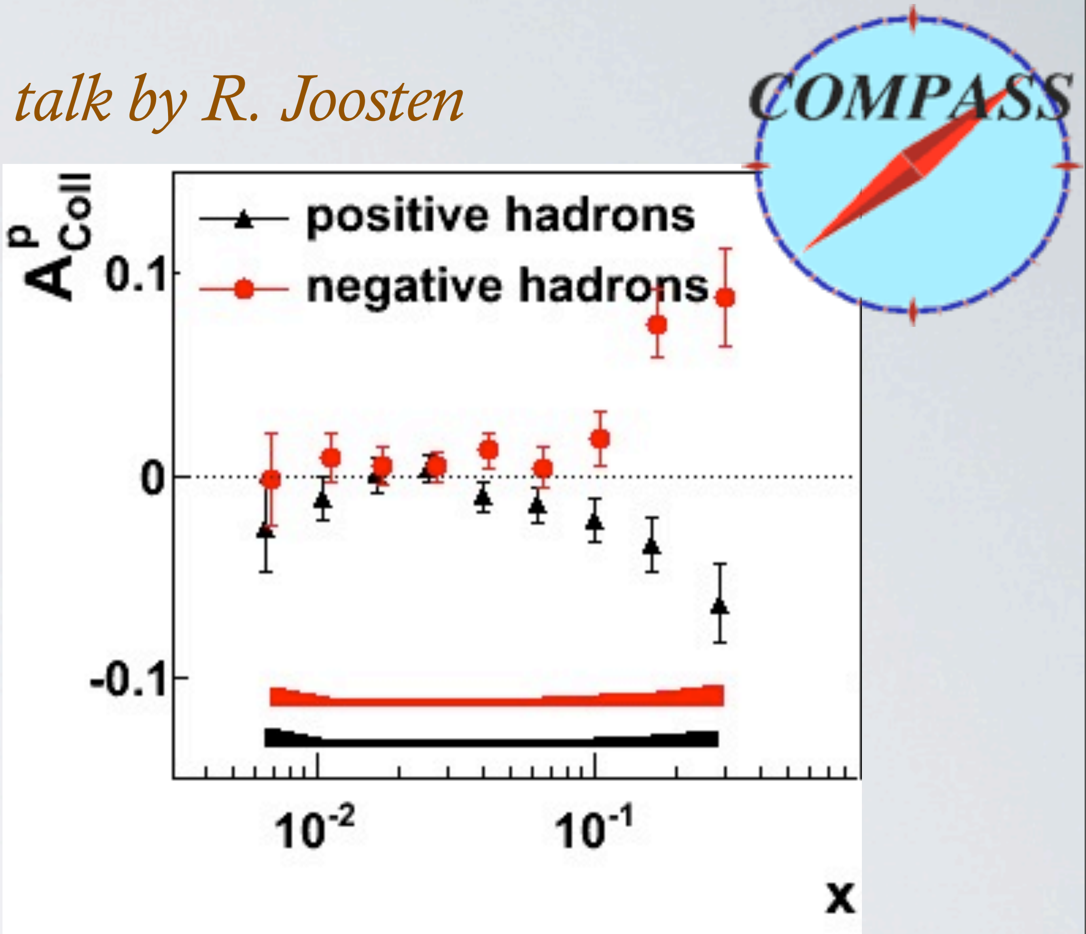
- requires TMD formalism - factorization, universality and evolution more complex

COLLINS EFFECT IN SIDIS



talk by M. Diefenthaler

talk by R. Joosten



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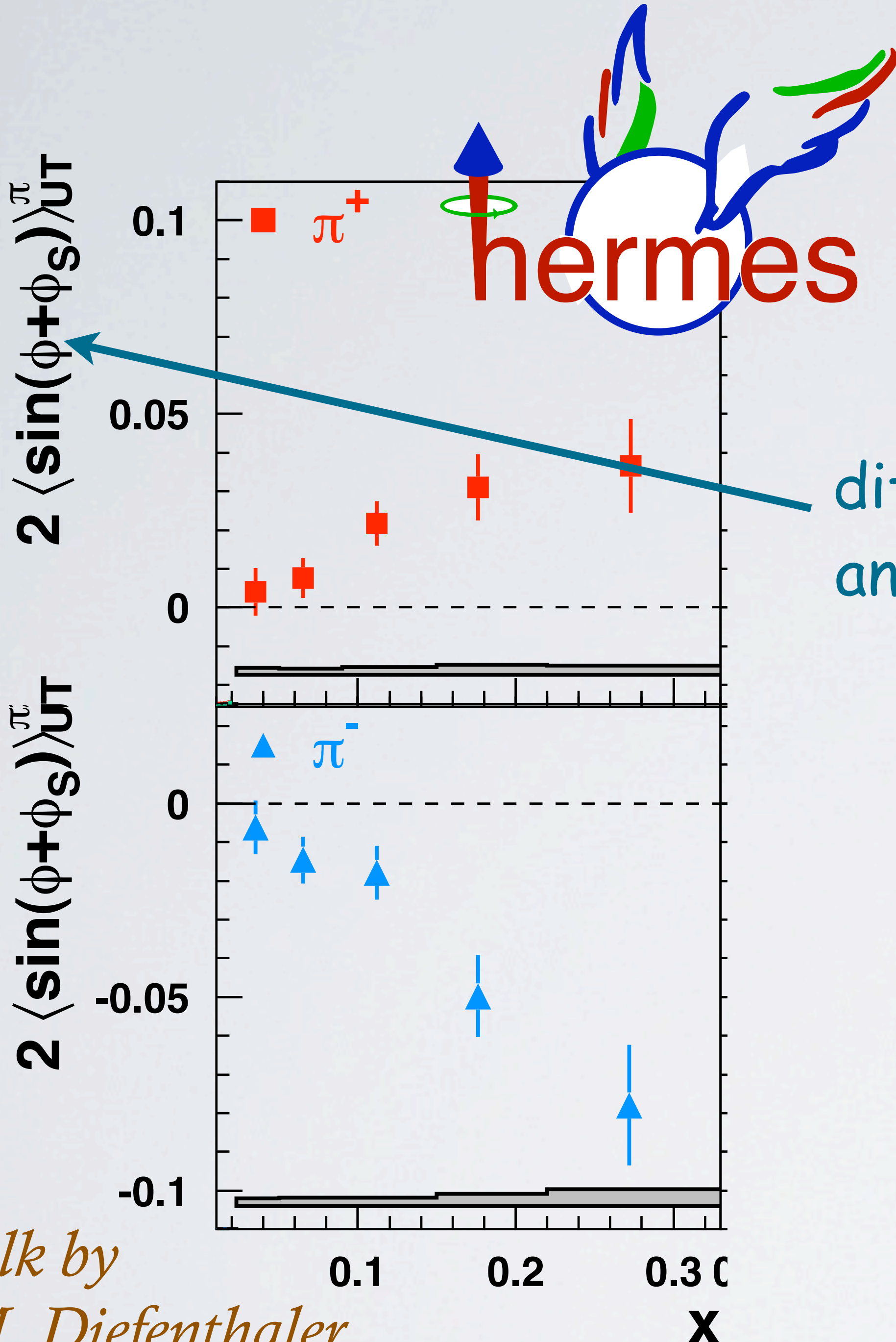
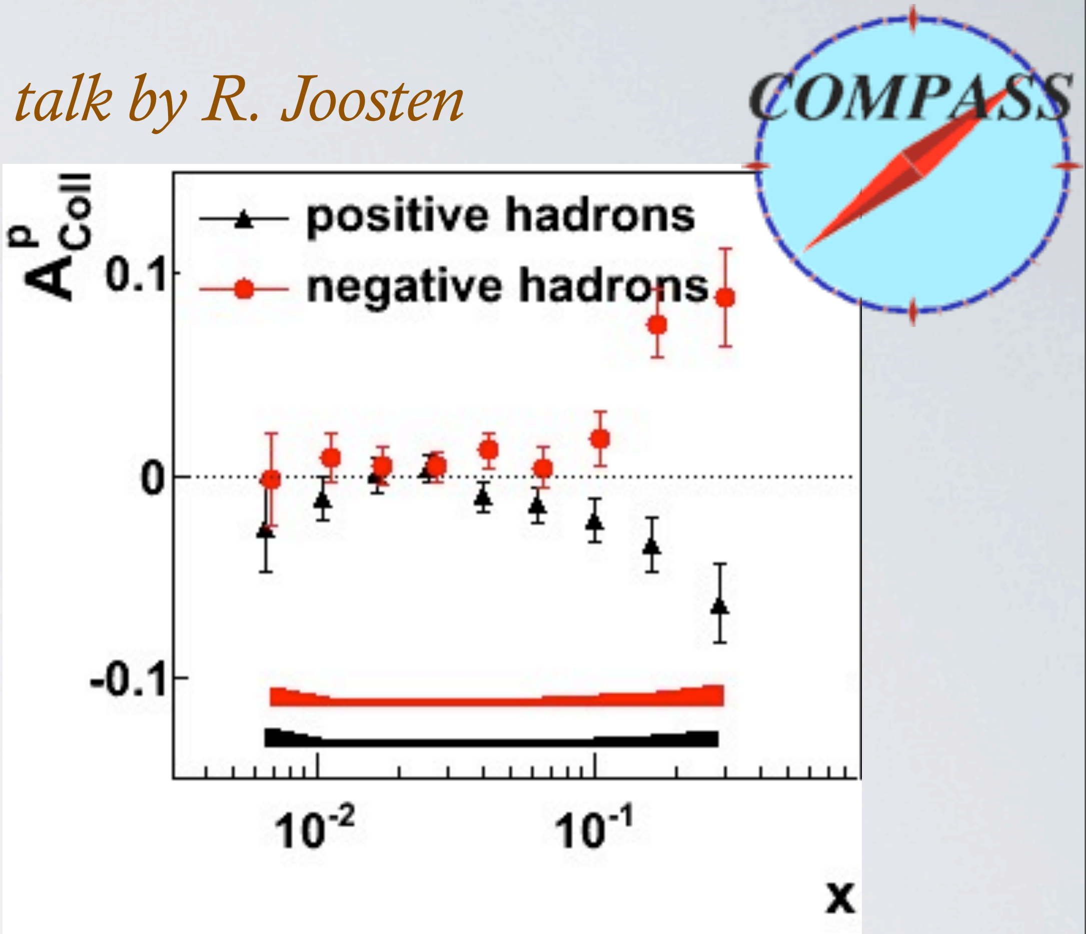


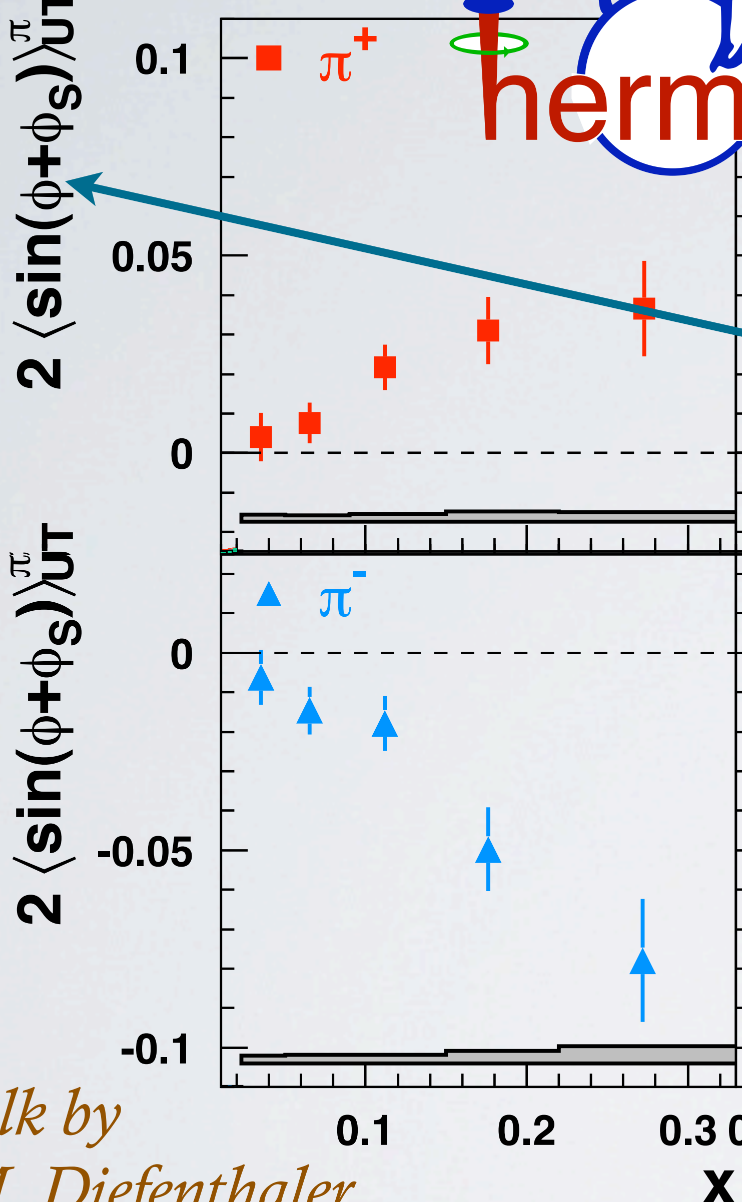
talk by M. Diefenthaler

different definitions of angular dependence and of asymmetry

talk by R. Joosten

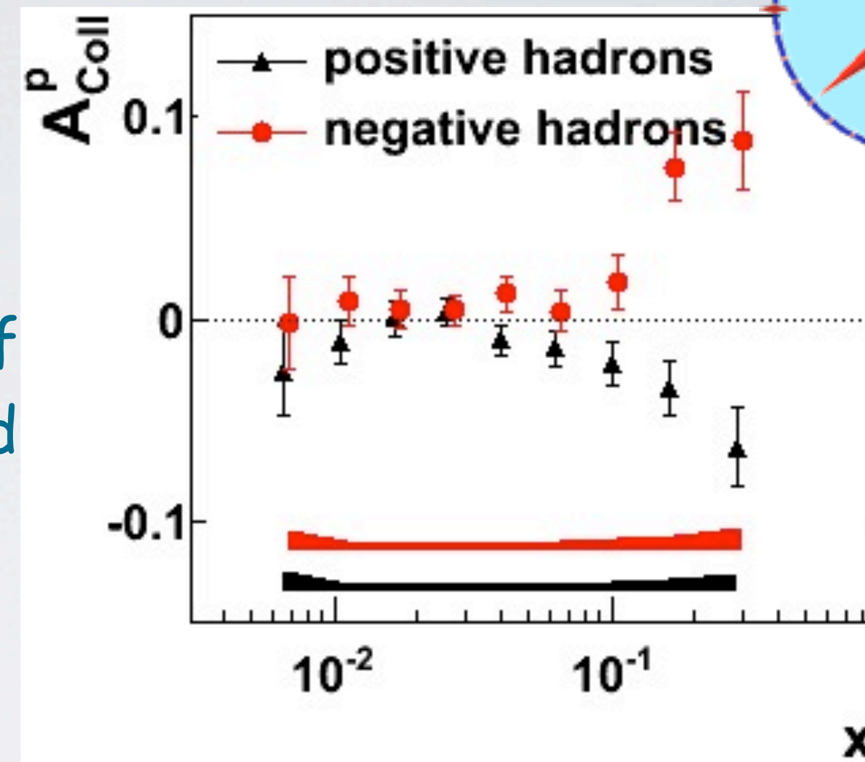


COLLINS EFFECT IN SIDIS

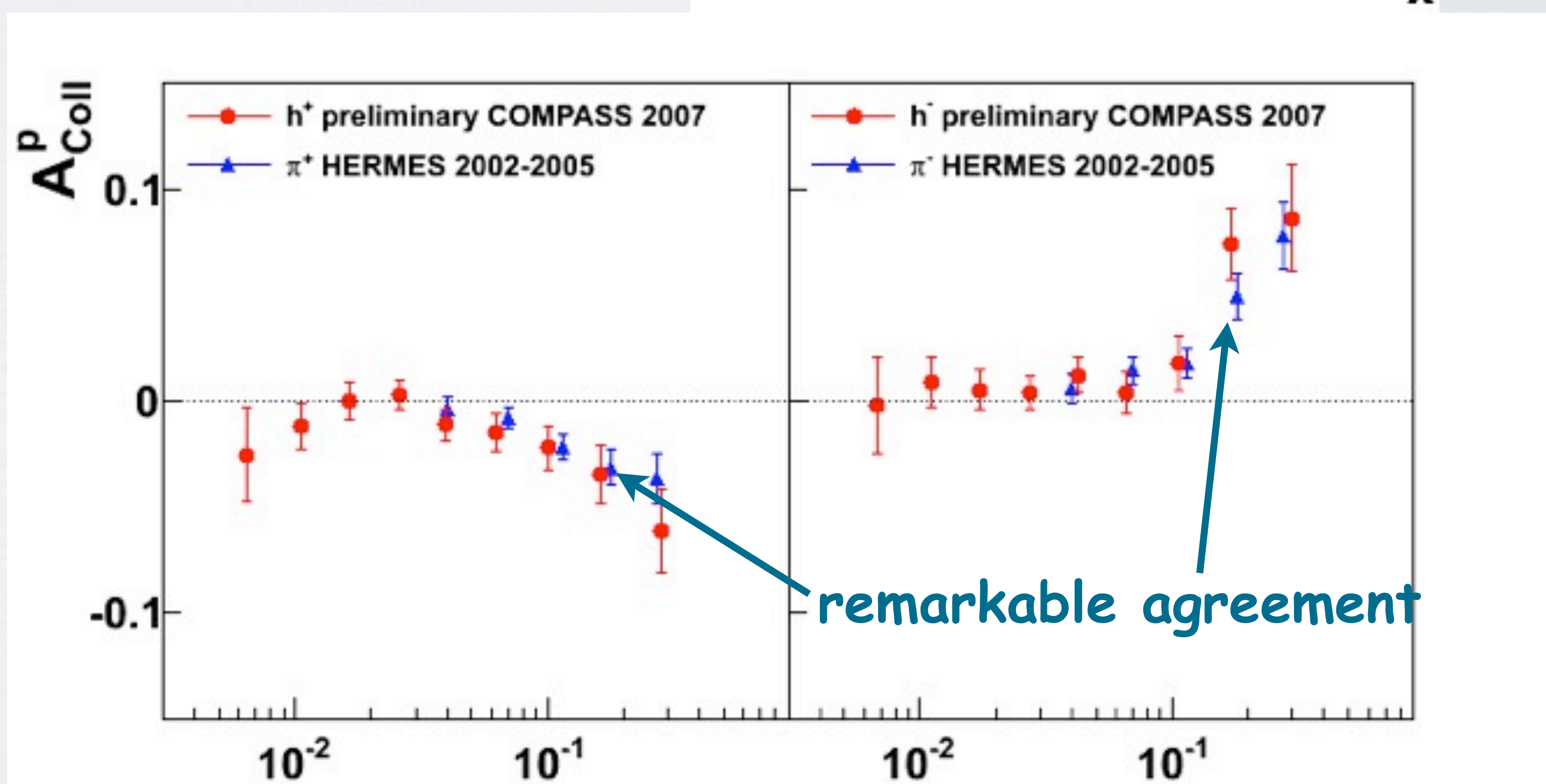


talk by M. Diefenthaler

talk by R. Joosten



different definitions of angular dependence and of asymmetry

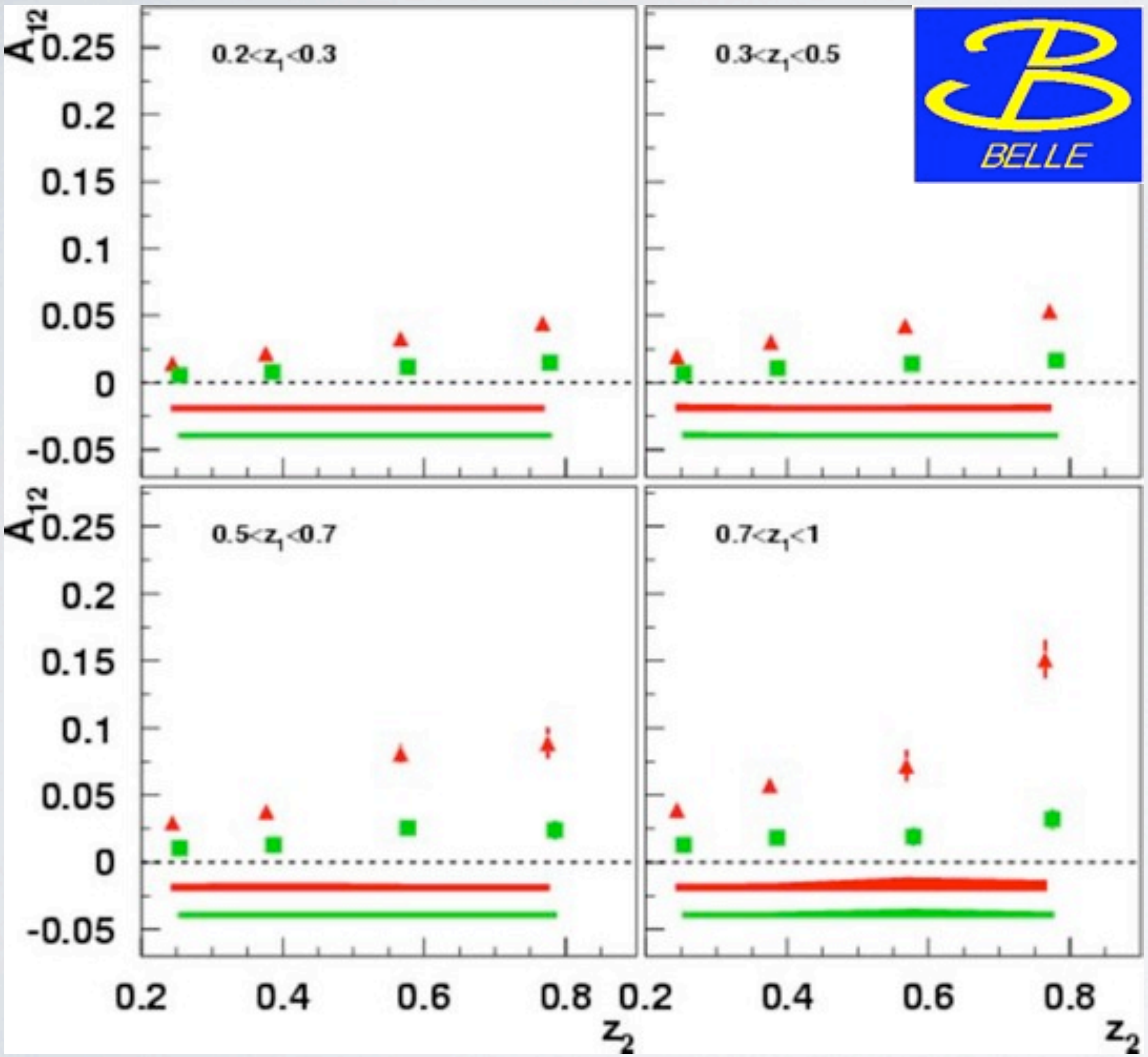


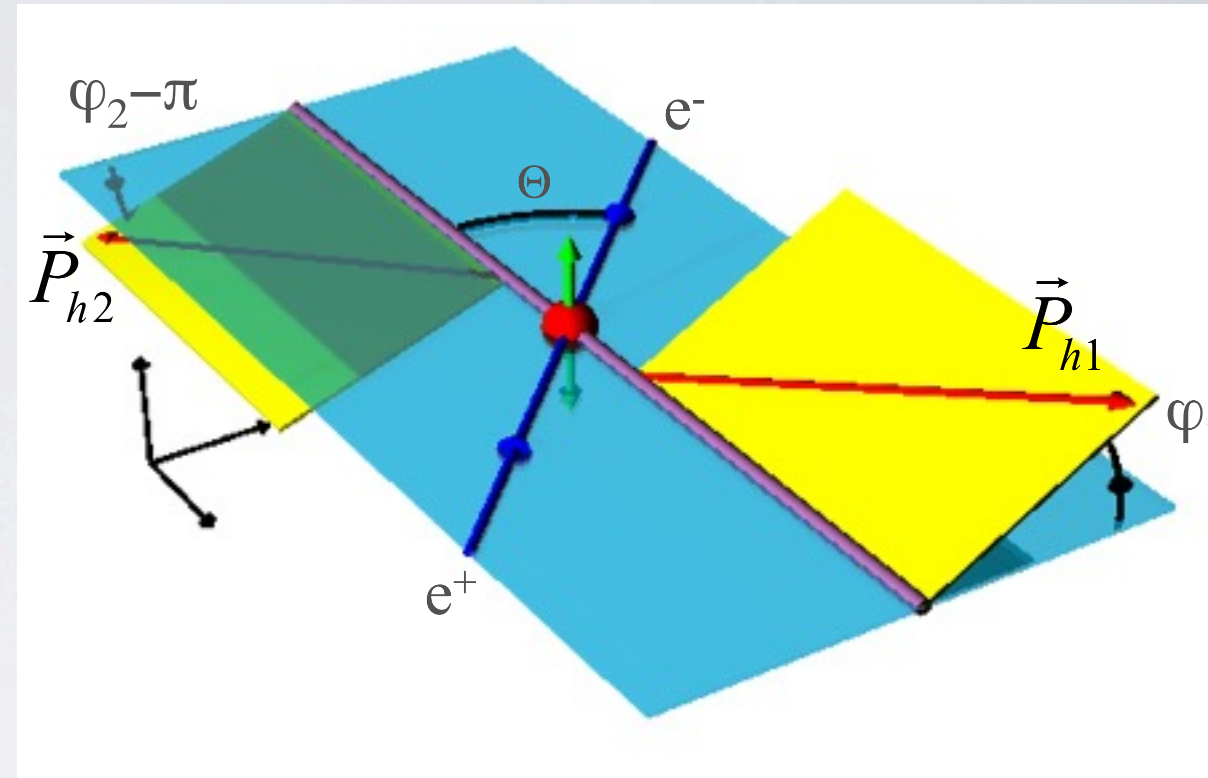
remarkable agreement

COLLINS EFFECT IN E^{+}E^{-}

talk by M. Grosse-Perdekamp

A_{12} (cos($\phi_1 + \phi_2$) moments) ~ (CFF)^2

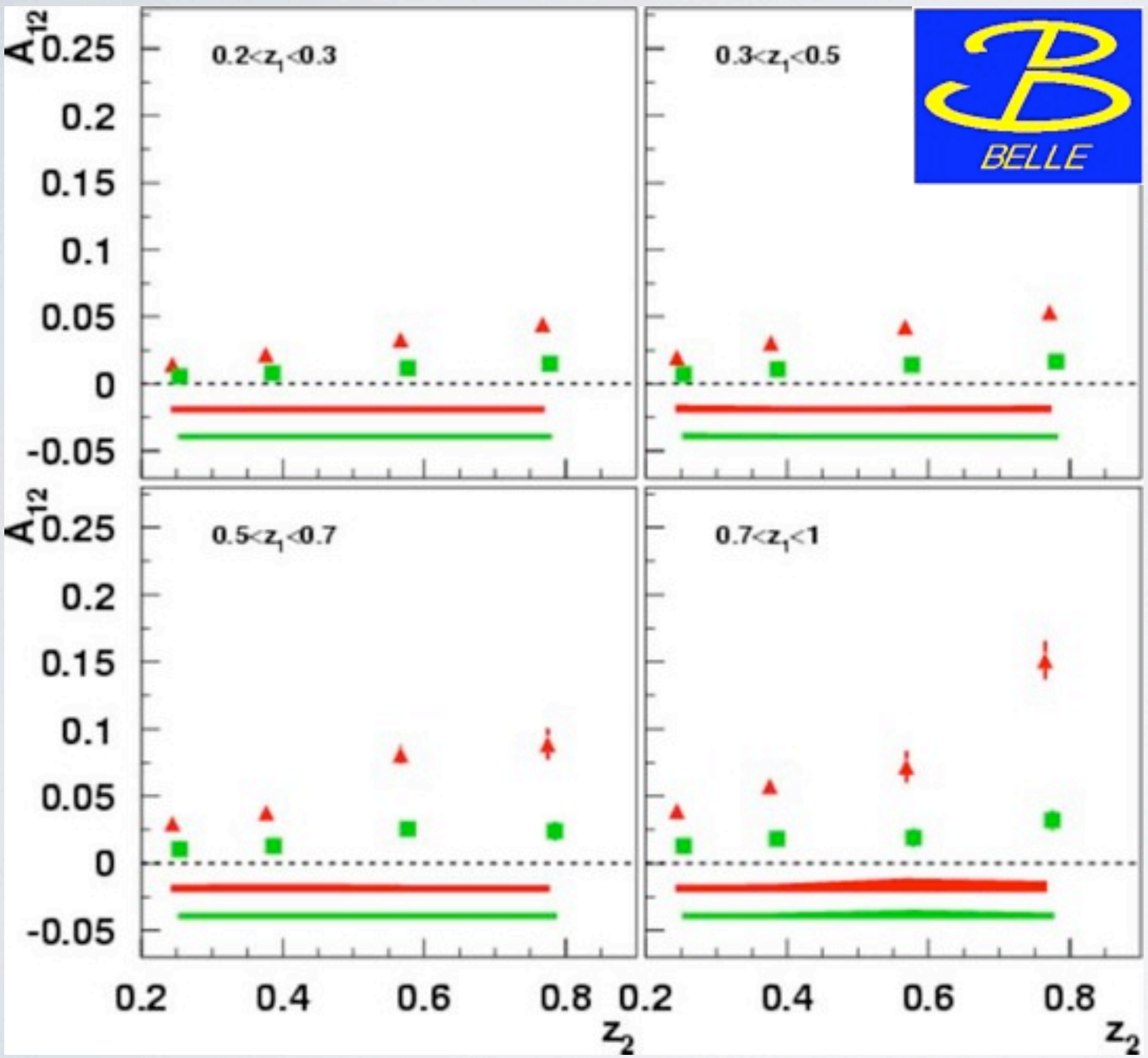


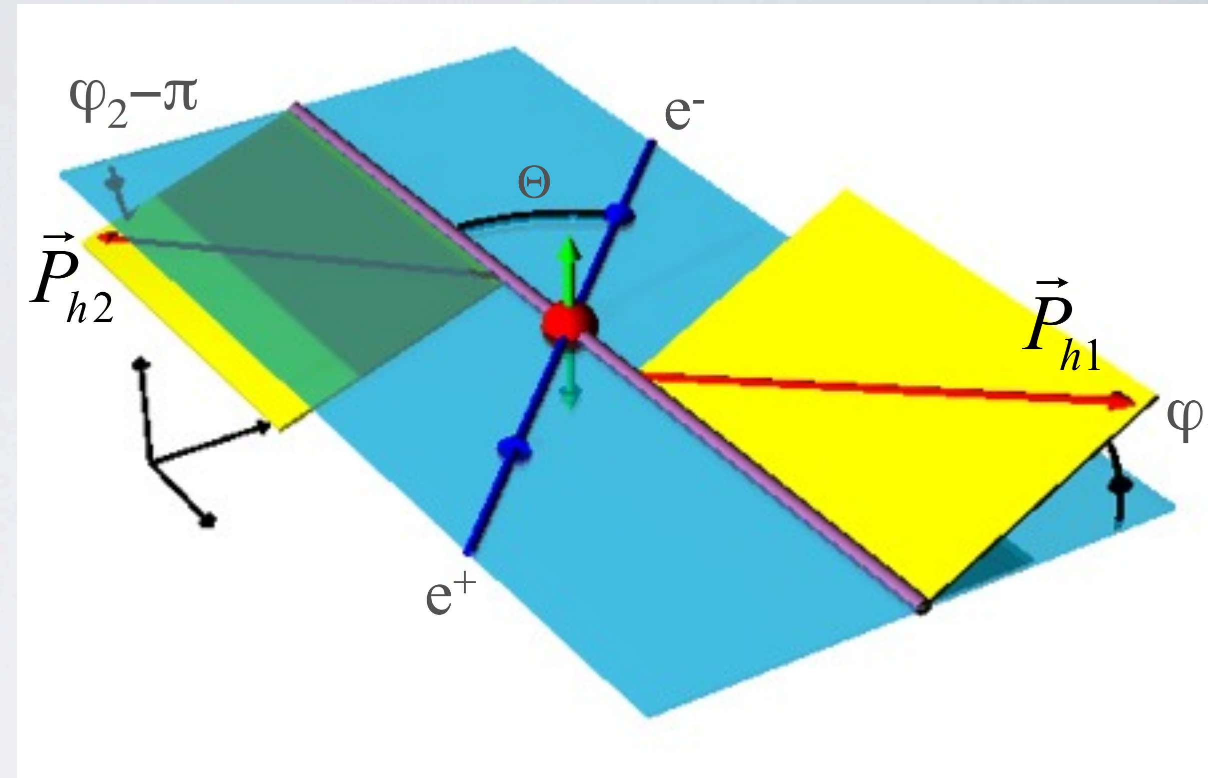


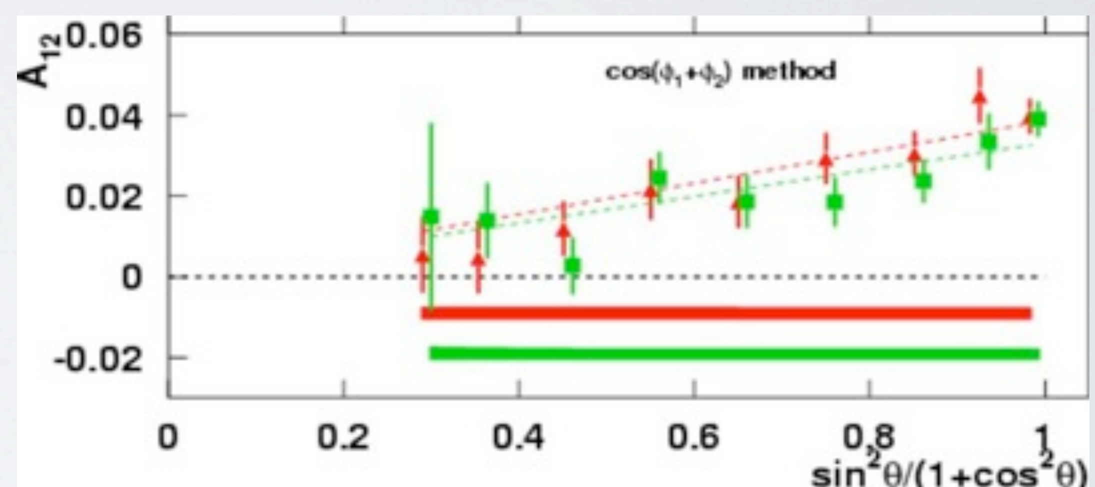
COLLINS EFFECT IN E^+E^-

talk by M. Grosse-Perdekamp

A_{12} ($\cos(\phi_1 + \phi_2)$ moments) ~ $(CFF)^2$

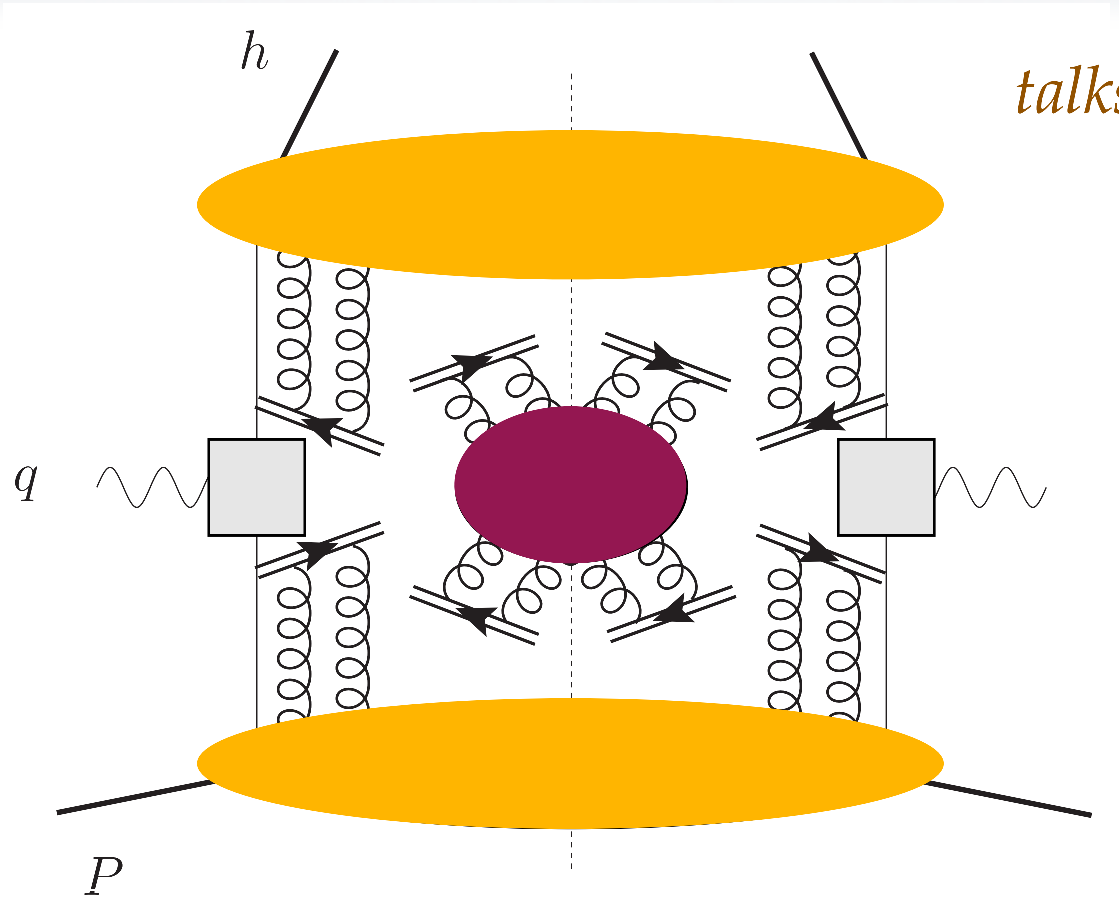






should depend linearly on $\sin^2\theta/(1+\cos^2\theta)$

FACTORIZATION

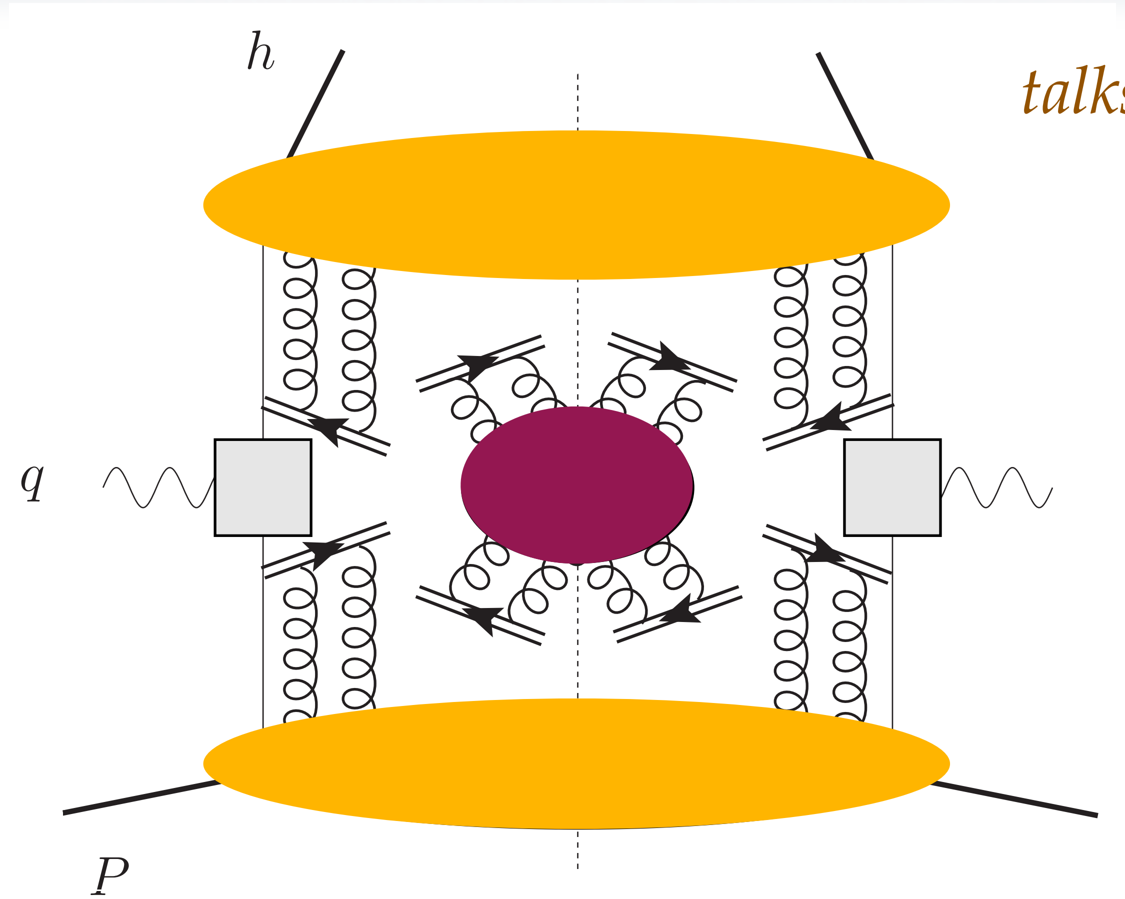


talks by I. Cherednikov and J. Qiu

$$F_{UU,T}(x,z,P_{h\perp}^2,Q^2) = \mathcal{C}'\left[f_1 D_1\right]$$
$$= H(Q^2,\mu^2,\zeta,\zeta_h)\int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, d^2\boldsymbol{l}_T\, \delta^{(2)}\big(\boldsymbol{p}_T - \boldsymbol{k}_T + \boldsymbol{l}_T - \boldsymbol{P}_{h\perp}/z\big)$$
$$x\sum_a e_a^2\, f_1^a(x,p_T^2,\mu^2,\zeta)\, D_1^a(z,k_T^2,\mu^2,\zeta_h)\, U(l_T^2,\mu^2,\zeta\zeta_h)$$

FACTORIZATION

talks by I. Cherednikov and J. Qiu



$$F_{UU,T}(x, z, P_{h\perp}^2, Q^2) = \mathcal{C}'\left[f_1 D_1\right]$$

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$$x \sum_a e_a^2\, f_1^a(x, p_T^2, \mu^2, \zeta)\, D_1^a(z, k_T^2, \mu^2, \zeta_h)\, U(l_T^2, \mu^2, \zeta\zeta_h)$$

Hard part

TMD PDF

TMD FF

Soft factor

x EVOLUTION OF MOMENTS

talk by J. Qiu

x EVOLUTION OF MOMENTS

talk by J. Qiu

$$\frac{\partial f_1^{\mathrm{NS}}(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \frac{d\xi}{\xi} f_1^{\mathrm{NS}}(\xi,\mu^2) P_{qq}(z) \Big|_{z=x/\xi}$$

x EVOLUTION OF MOMENTS

talk by J. Qiu

$$\frac{\partial f_1^{\rm NS}(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi}\int_x^1 \frac{d\xi}{\xi} f_1^{\rm NS}(\xi,\mu^2) P_{qq}(z)\Big|_{z=x/\xi}$$

$$T_F(x,x) \equiv \int d^2p_T\, p_T^2\, f_{1T}^{\perp}(x,p_T^2)$$

$$\begin{aligned}\frac{\partial \mathcal{T}_{q,F}(x,x,\mu_F)}{\partial \ln \mu_F^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\Big\{ & P_{qq}(z)\,\mathcal{T}_{q,F}(\xi,\xi,\mu_F) \\ & + \frac{C_A}{2}\left[\frac{1+z^2}{1-z}\left[\mathcal{T}_{q,F}(\xi,x,\mu_F) - \mathcal{T}_{q,F}(\xi,\xi,\mu_F)\right] + z\,\mathcal{T}_{q,F}(\xi,x,\mu_F)\right] \\ & + \frac{C_A}{2}\left[\mathcal{T}_{\Delta q,F}(x,\xi,\mu_F)\right]\Big\},\end{aligned}$$

x EVOLUTION OF MOMENTS

talk by J. Qiu

$$\frac{\partial f_1^{\rm NS}(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi}\int_x^1 \frac{d\xi}{\xi} f_1^{\rm NS}(\xi,\mu^2) P_{qq}(z)\Big|_{z=x/\xi}$$

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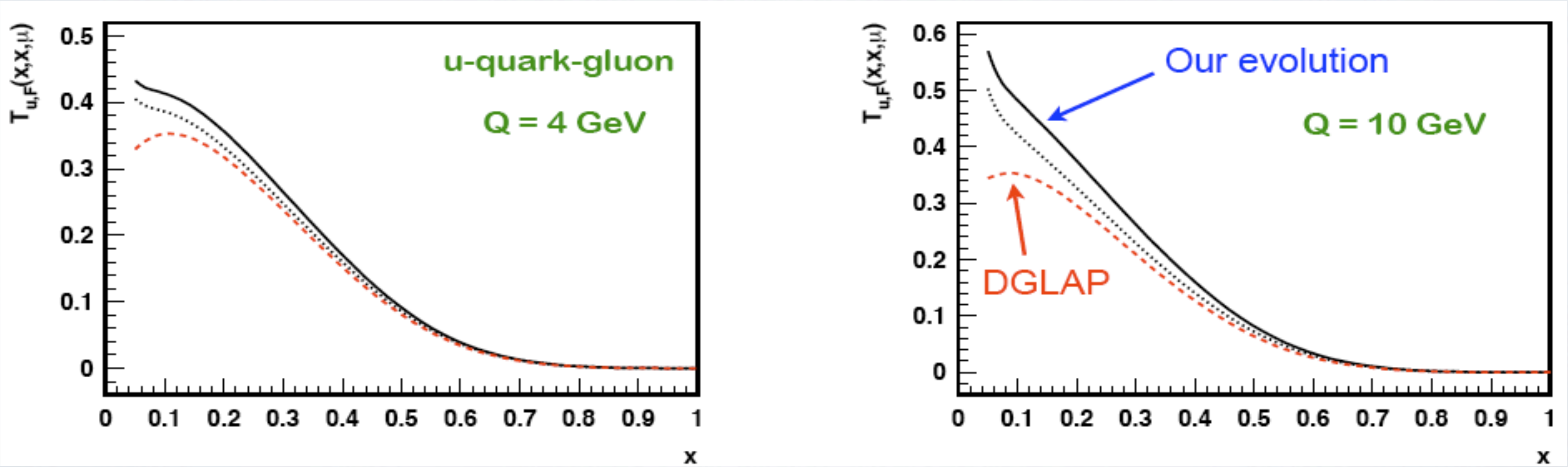

GAUGE LINKS

talk by I. Cherednikov

$$f_1^q(x, p_T^2) = \int \frac{d\xi^- d^2\xi_T}{16\pi^3}\, e^{ip\cdot\xi} \langle P|\bar{\psi}^q(0) U_{[0,\xi]} \gamma^+ \psi^q(\xi)|P\rangle\Big|_{\xi^+=0}$$

GAUGE LINKS

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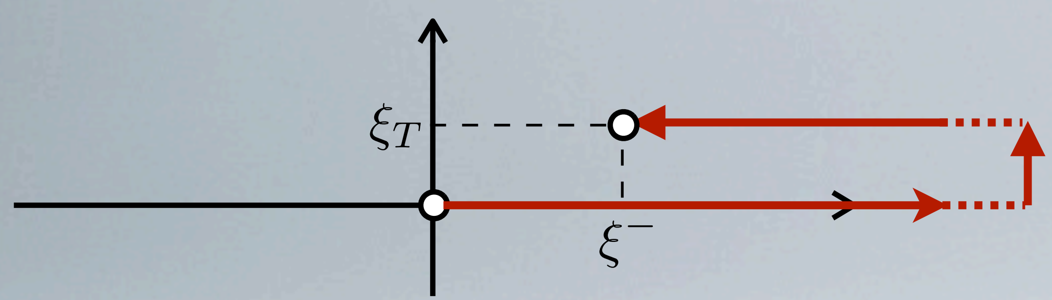
$$f_1^q(x, p_T^2) = \int \frac{d\xi^- d^2\xi_T}{16\pi^3}\, e^{ip\cdot\xi} \langle P|\bar{\psi}^q(0) U_{[0,\xi]} \gamma^+ \psi^q(\xi)|P\rangle \Big|_{\xi^+=0}$$



GAUGE LINKS

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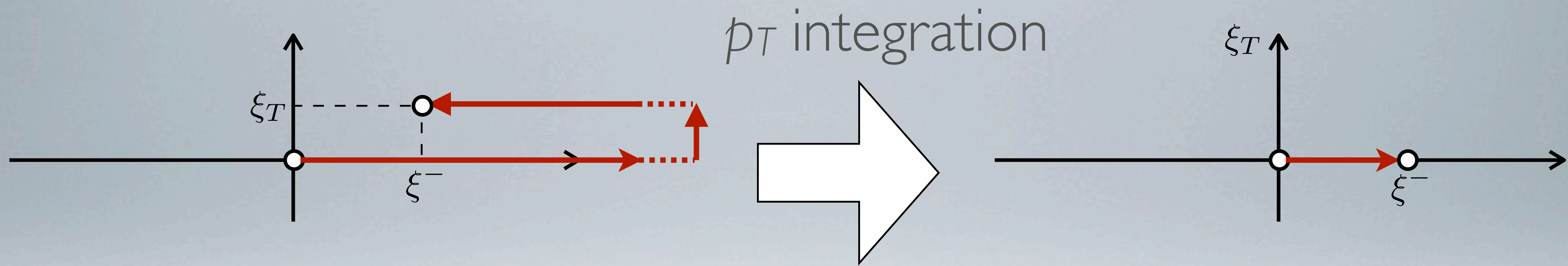

GAUGE LINKS

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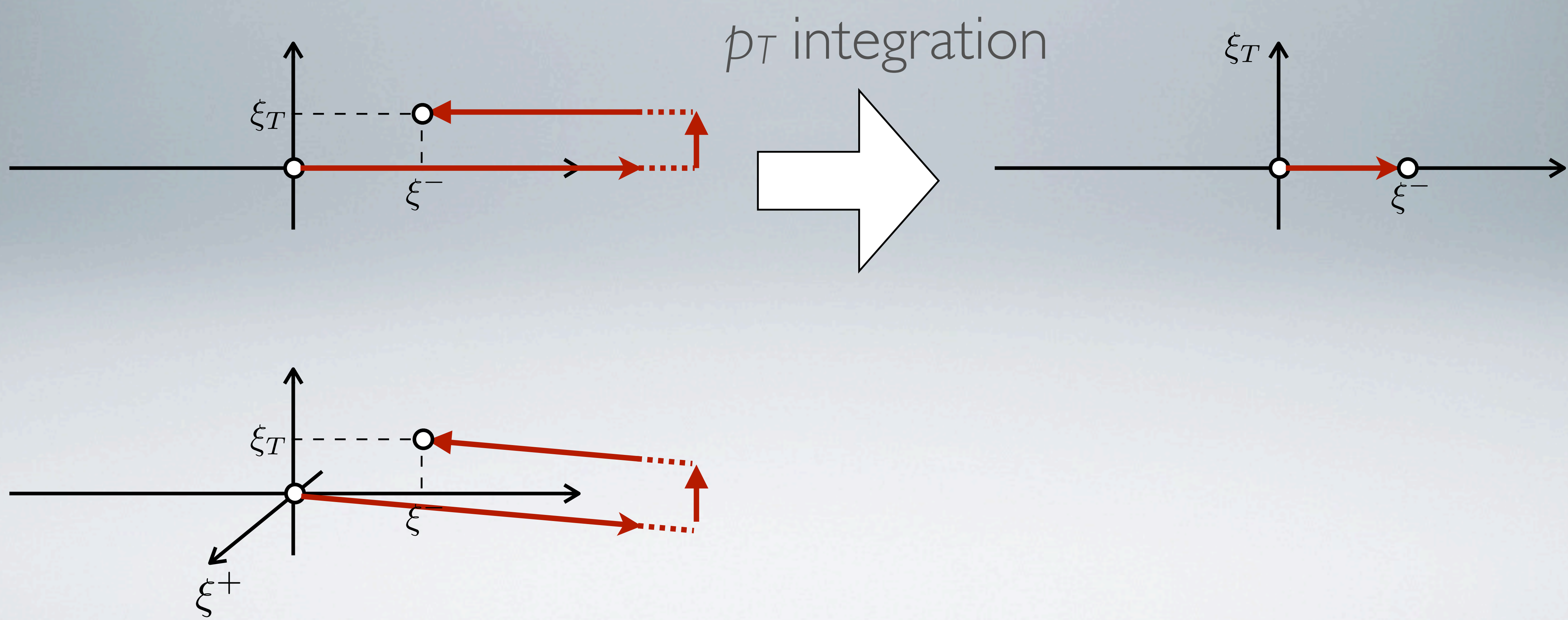

GAUGE LINKS

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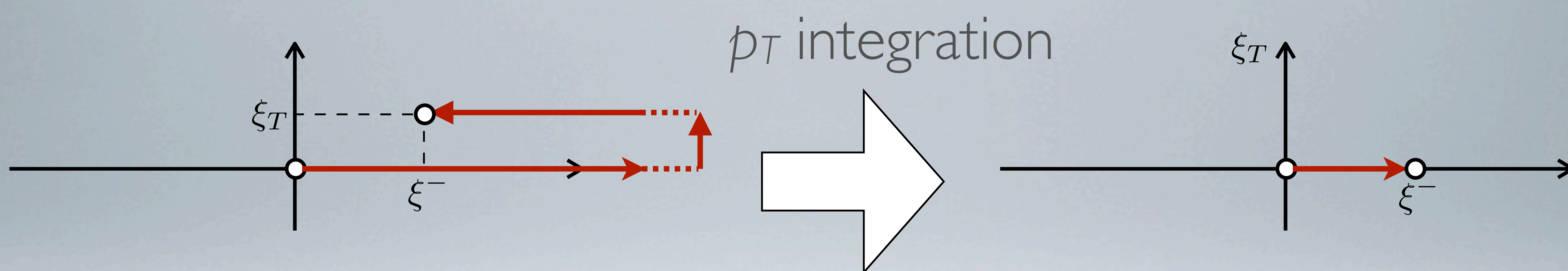
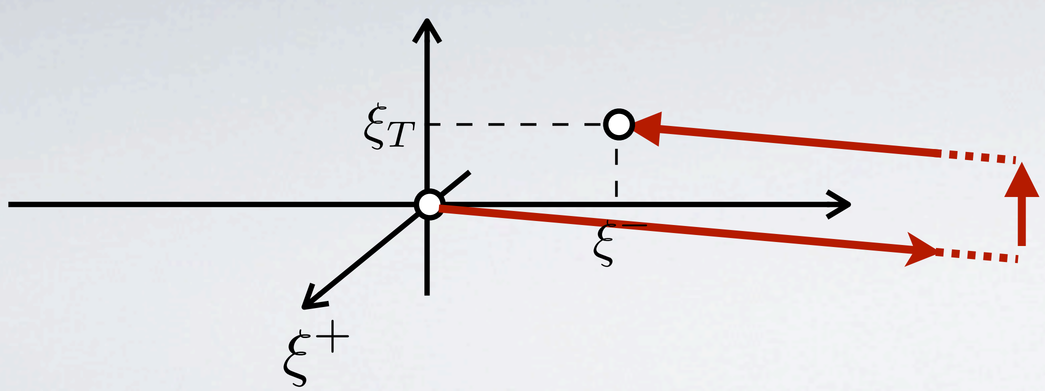
$$f_1^q(x, p_T^2) = \int \frac{d\xi^- d^2\xi_T}{16\pi^3}\, e^{ip\cdot\xi} \langle P|\bar{\psi}^q(0) U_{[0,\xi]} \gamma^+ \psi^q(\xi)|P\rangle \Big|_{\xi^+=0}$$



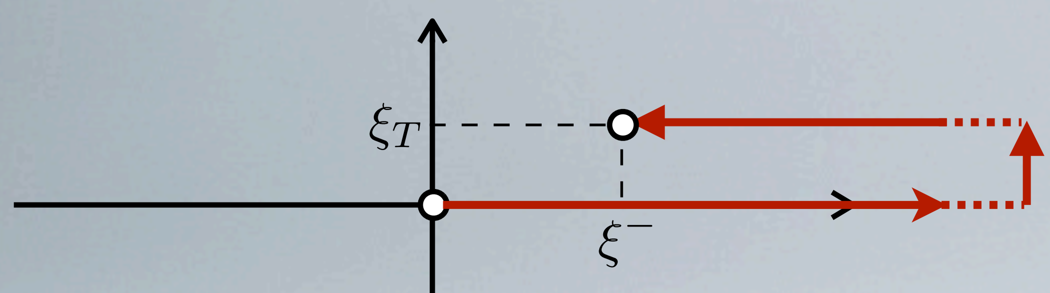


$$f_1^q(x, p_T^2, \zeta) = \int \frac{d\xi^- d^2\xi_T}{16\pi^3}\, e^{ip\cdot\xi} \langle P|\bar{\psi}^q(0) U^{\zeta}_{[0,\xi]} \gamma^+ \psi^q(\xi)|P\rangle \Big|_{\xi^+=0}$$

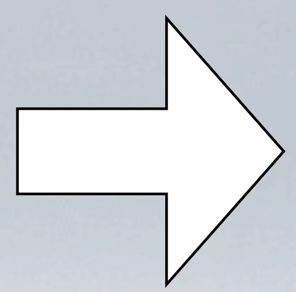
GAUGE LINKS

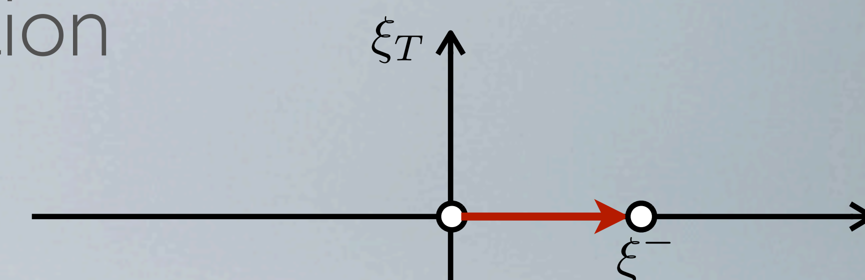
talk by I. Cherednikov

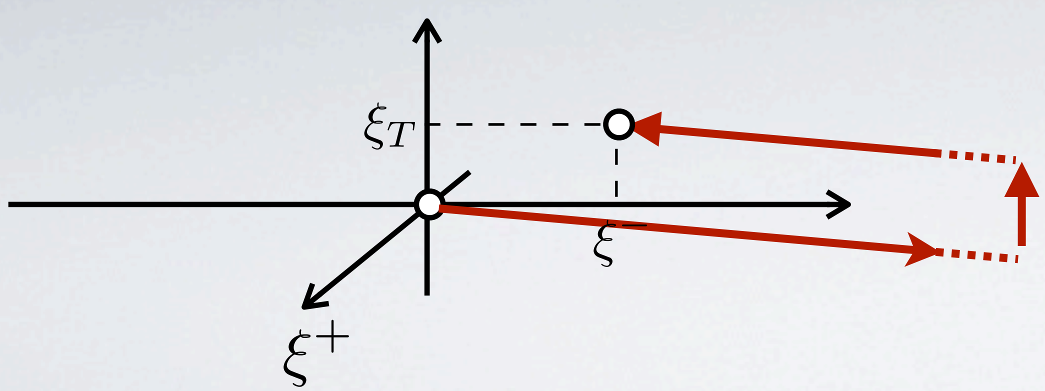
$$f_1^q(x, p_T^2) = \int \frac{d\xi^- d^2\xi_T}{16\pi^3}\, e^{ip\cdot\xi} \langle P|\bar{\psi}^q(0) U_{[0,\xi]} \gamma^+ \psi^q(\xi)|P\rangle\Big|_{\xi^+=0}$$



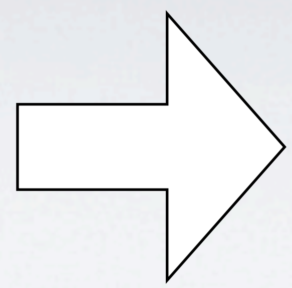
p_T integration







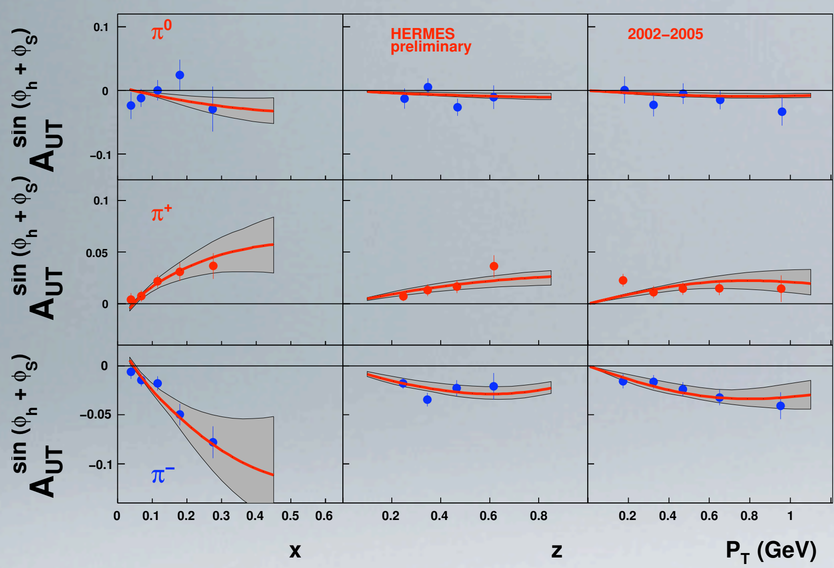
p_T integration

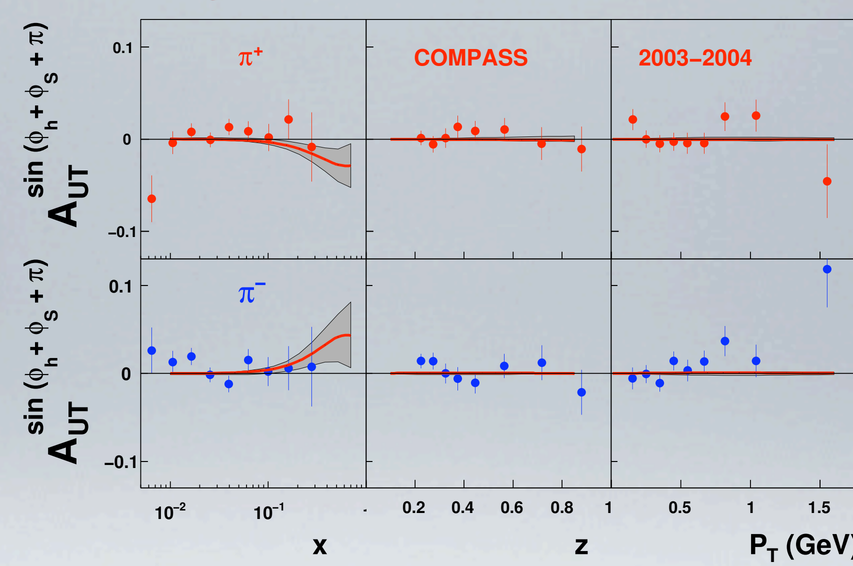


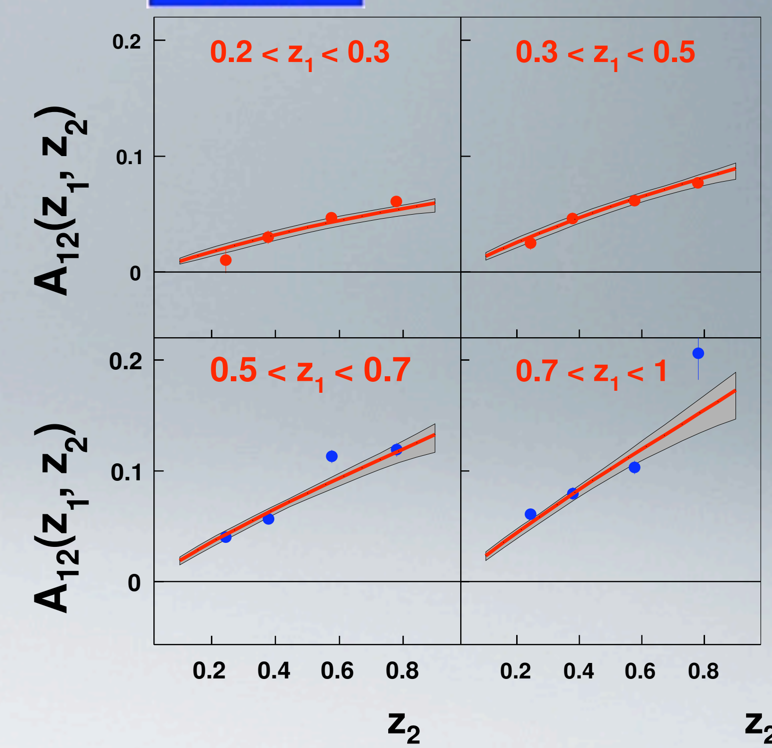
$$f_1^q(x, p_T^2, \zeta) = \int \frac{d\xi^- d^2\xi_T}{16\pi^3}\, e^{ip\cdot\xi} \langle P|\bar{\psi}^q(0) U^{\zeta}_{[0,\xi]} \gamma^+ \psi^q(\xi)|P\rangle\Big|_{\xi^+=0}$$

FIT OF COLLINS EFFECT

talk by U. D'Alesio



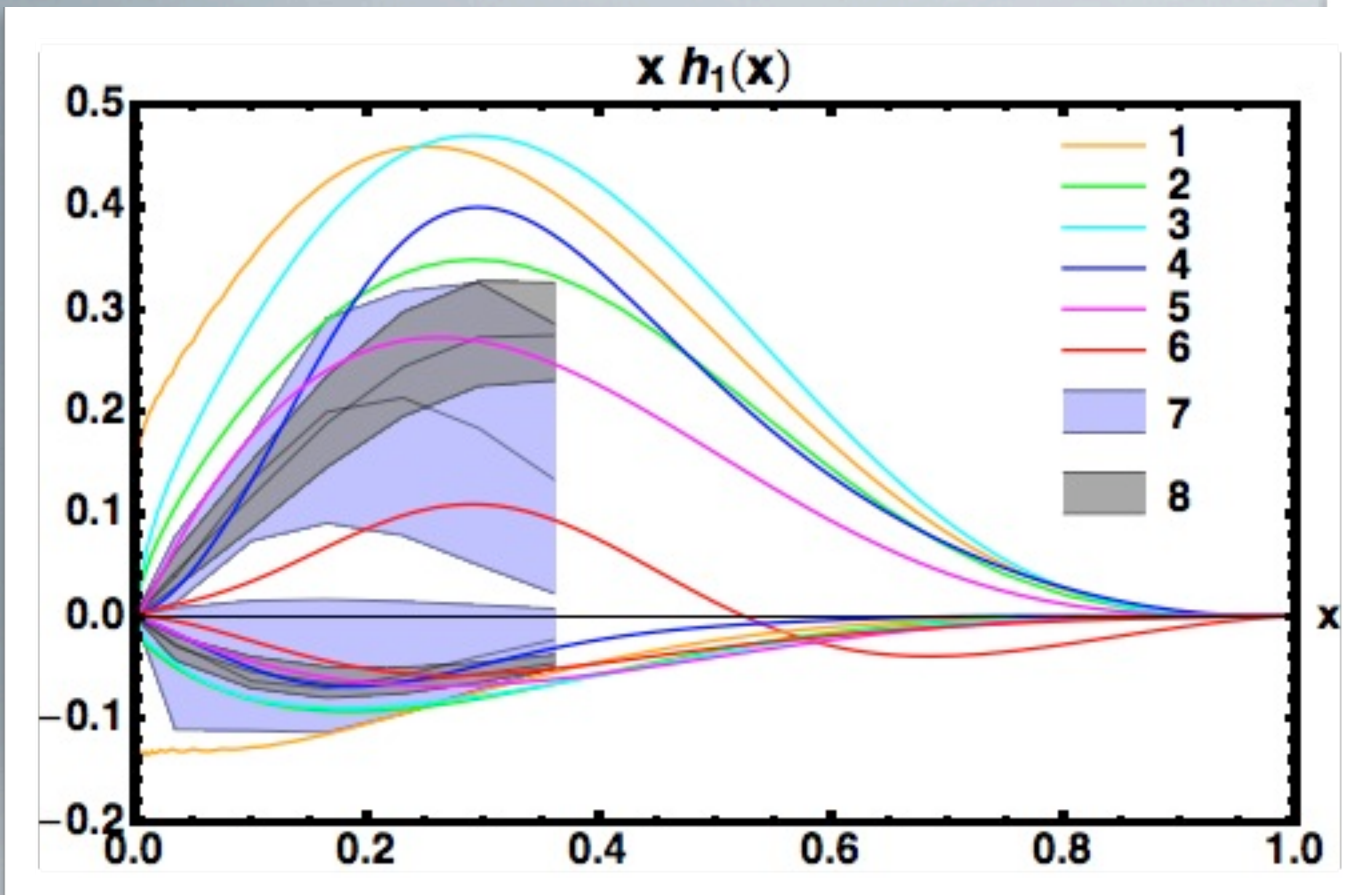


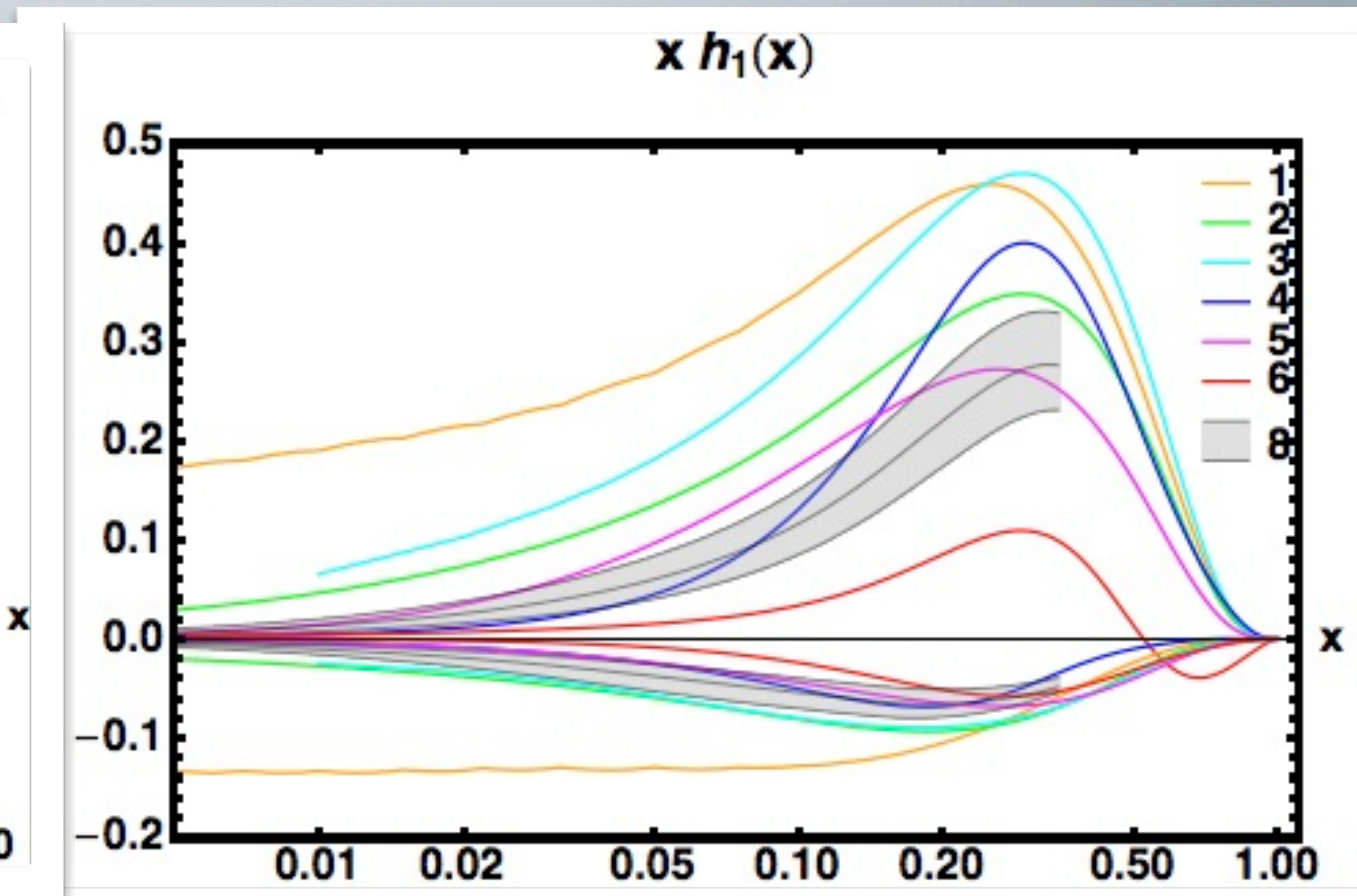


[left] HERMES data [*Diefenthaler et al. 2007*] (hydrogen target)

[right] COMPASS data [*Alekseev et al. 2008*]. (deuteron target)

TRANSVERSITY

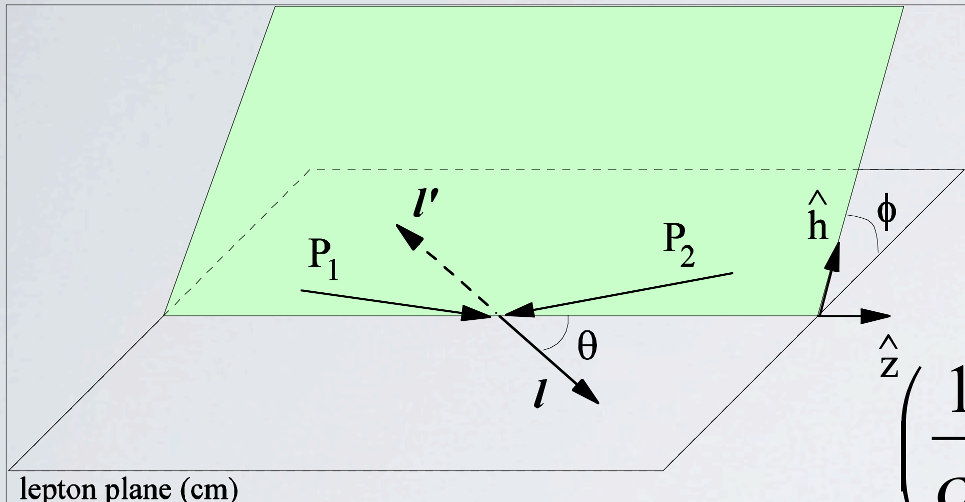




[1] Soffer et al. PRD 65 (02)
[2] Korotkov et al. EPJC 18 (01)
[3] Schweitzer et al., PRD 64 (01)
[4] Wakamatsu, PLB 509 (01)
[5] Pasquini et al., PRD 72 (05)
[6] Bacchetta, Conti, Radici, PRD 78 (08)
[7] Anselmino et al., PRD 75 (07)
[8] Anselmino et al., arXiv:0807.0173

MISSION 2: T-ODD FUNCTIONS

BOER-MULDERS EFFECT IN DRELL-YAN

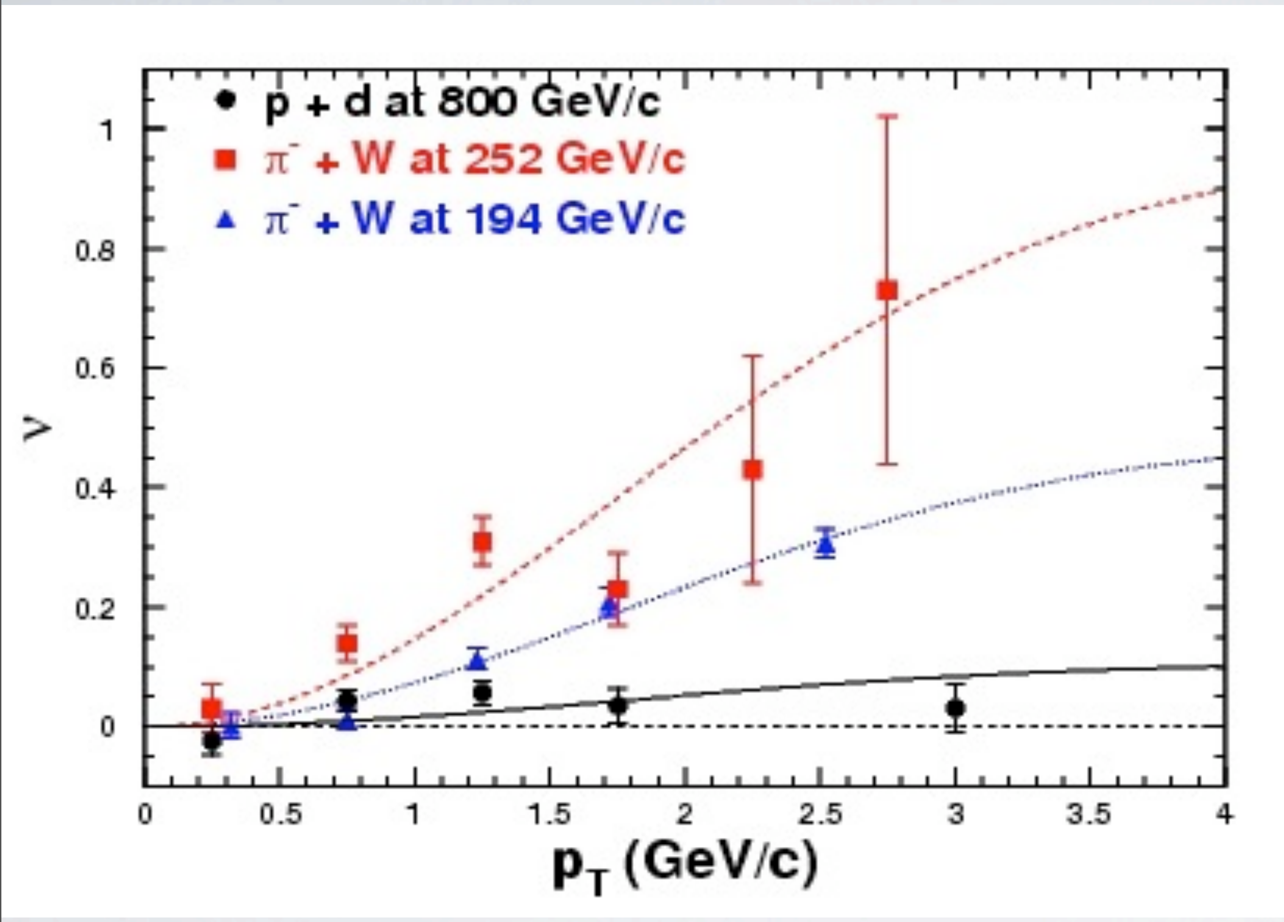


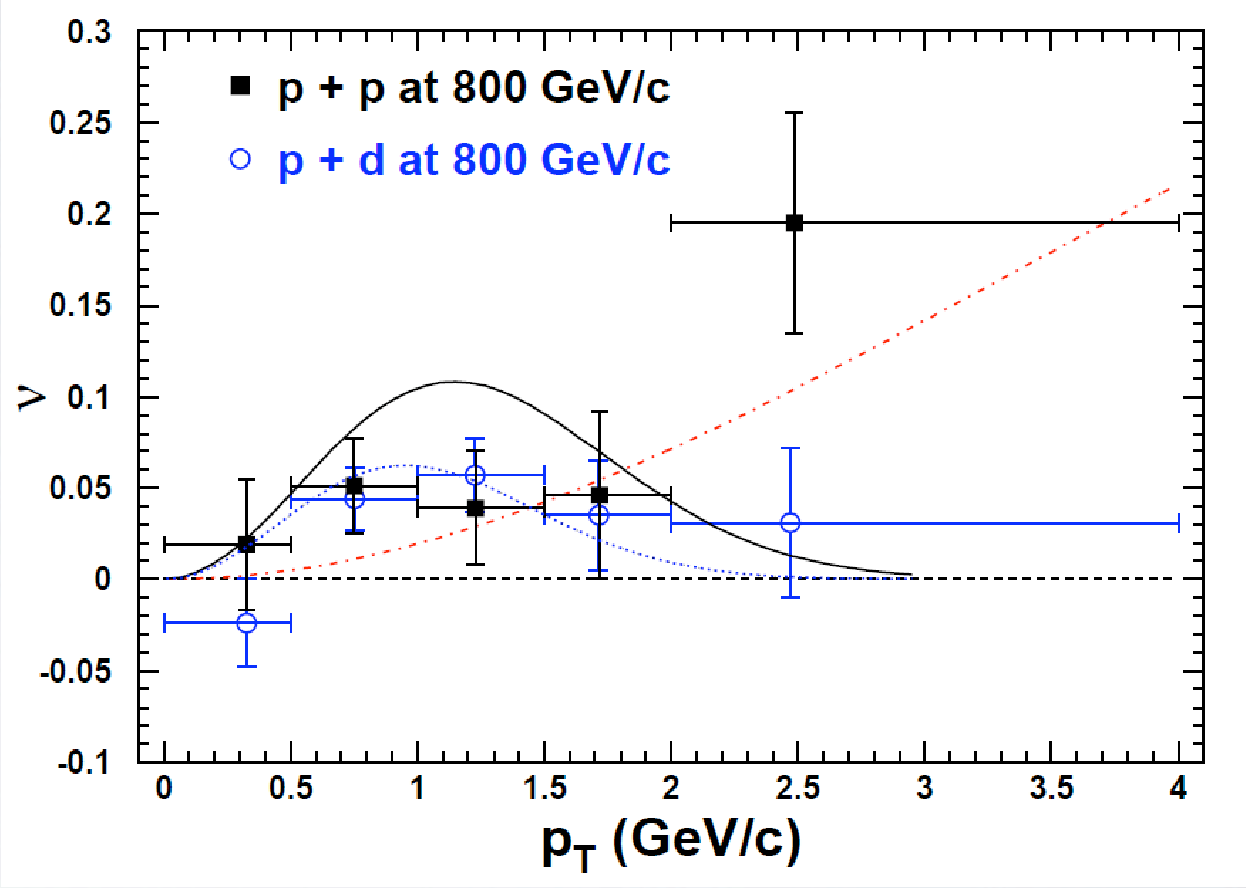
talk by J.C. Peng

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right) = \left[\frac{3}{4\pi}\right]\left[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

- Lam-Tung relation: $1-\lambda = 2\,\nu$
  - insensitive to QCD corrections
  - clear sign for Boer-Mulders effect ($\sim \nu$)
  - violated in pion-induced Drell-Yan

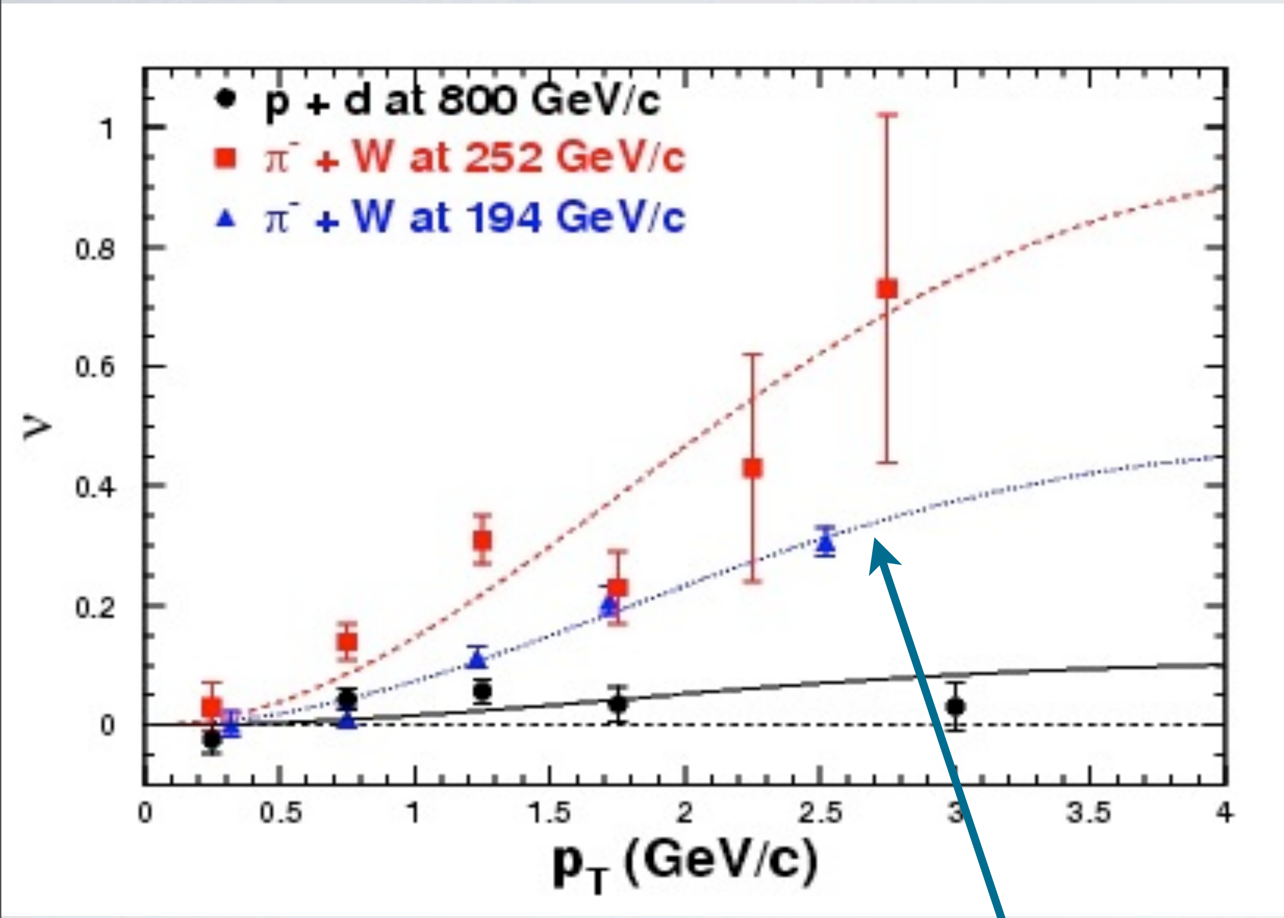
SIGNS OF BOER-MULDERS

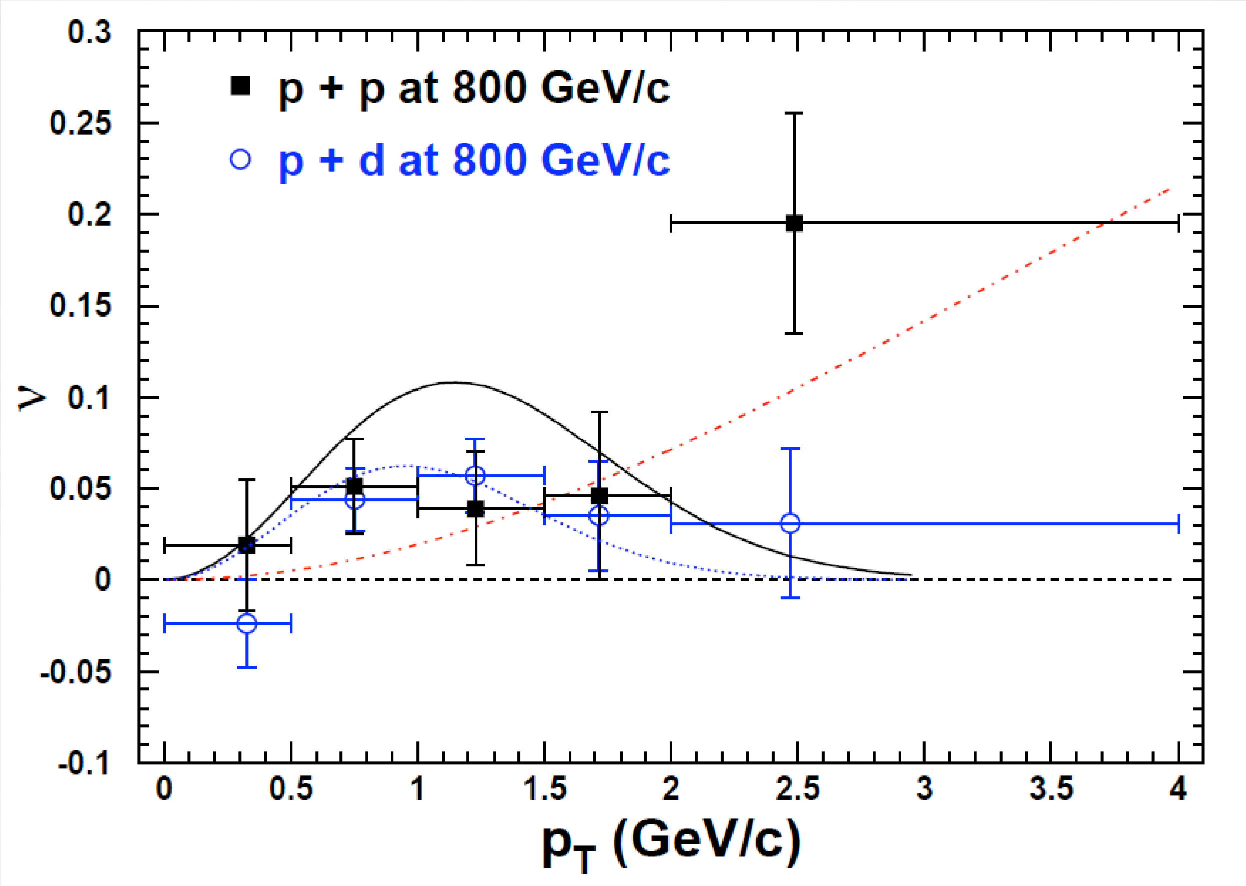




talk by J.C. Peng

SIGNS OF BOER-MULDERS

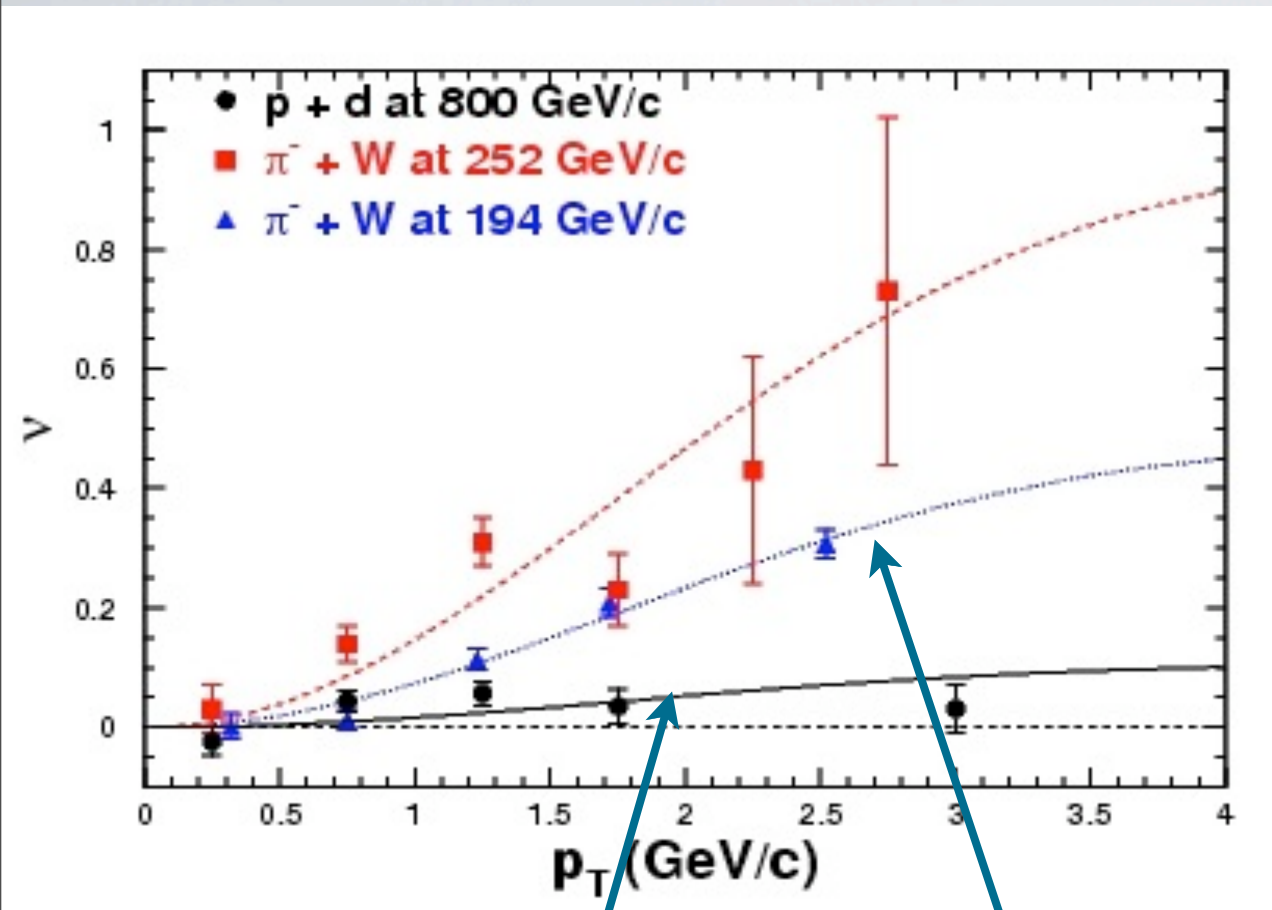


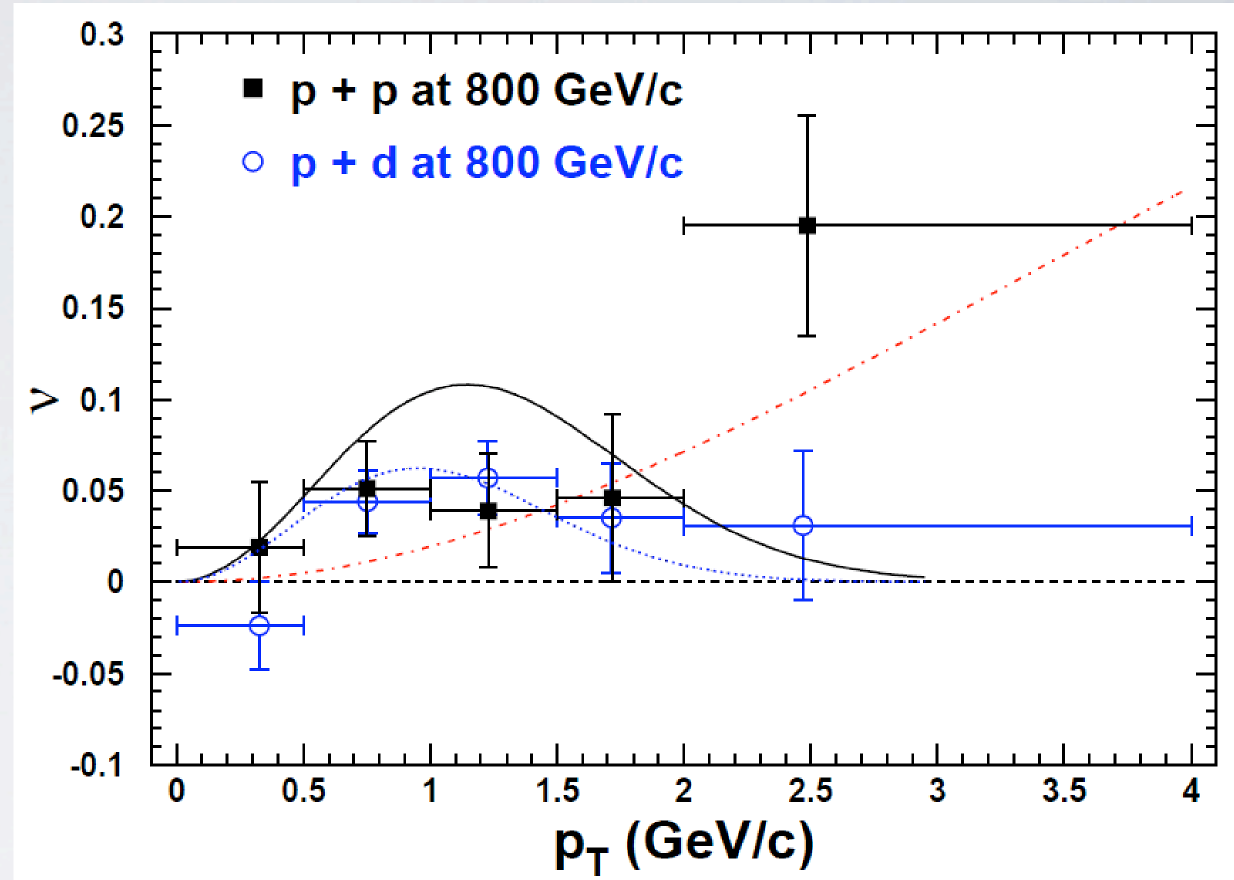


talk by J.C. Peng

valence BM fctn

SIGNS OF BOER-MULDERS



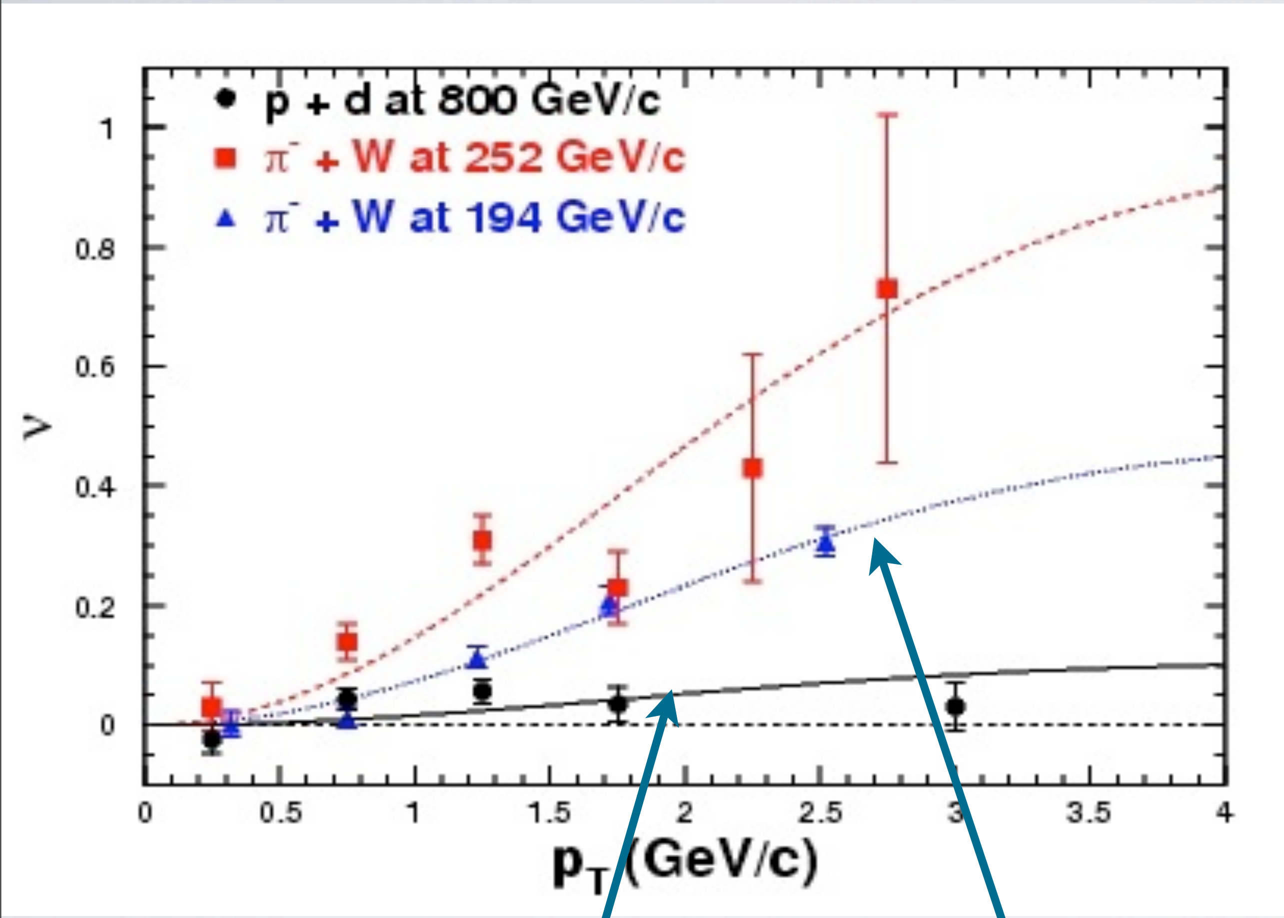


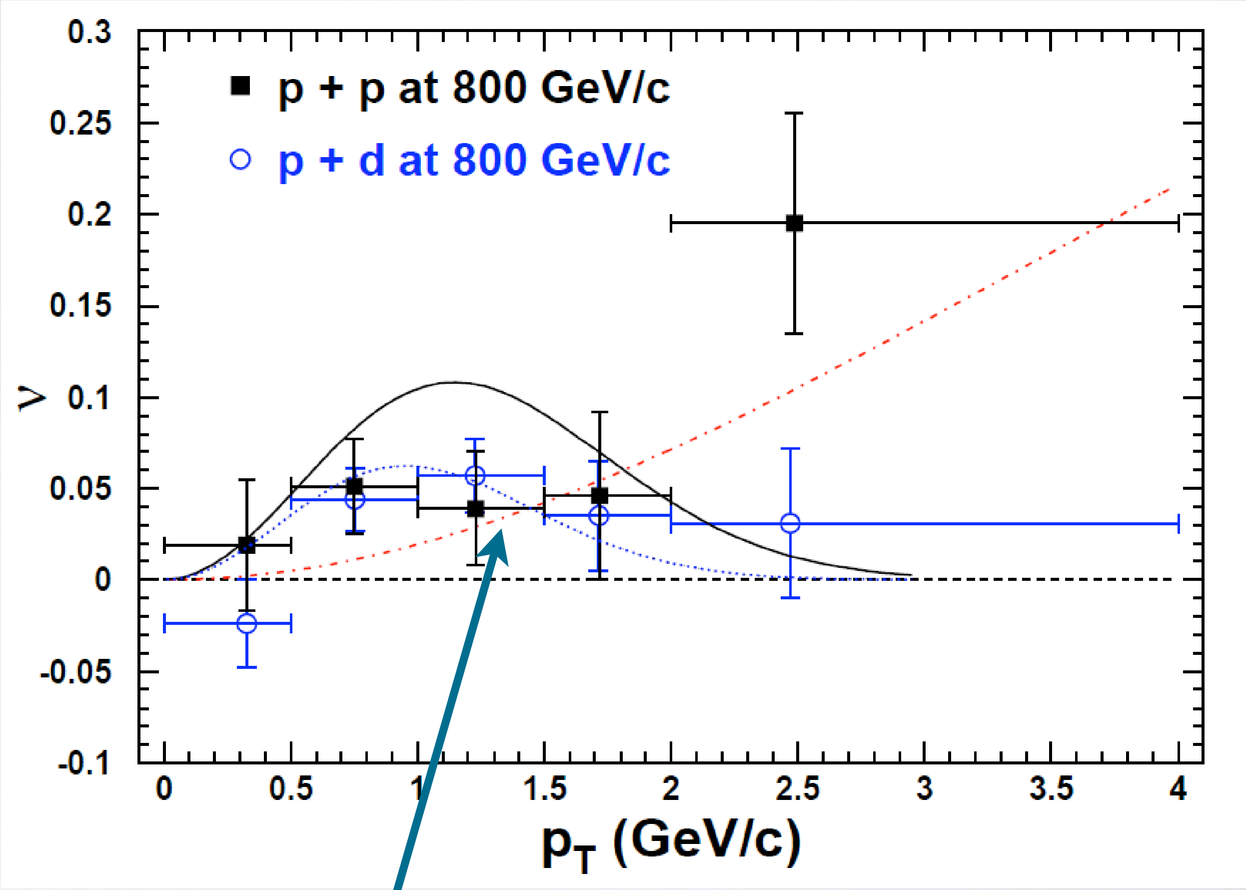
talk by J.C. Peng

valence and sea BM fctn

valence BM fctn

SIGNS OF BOER-MULDERS





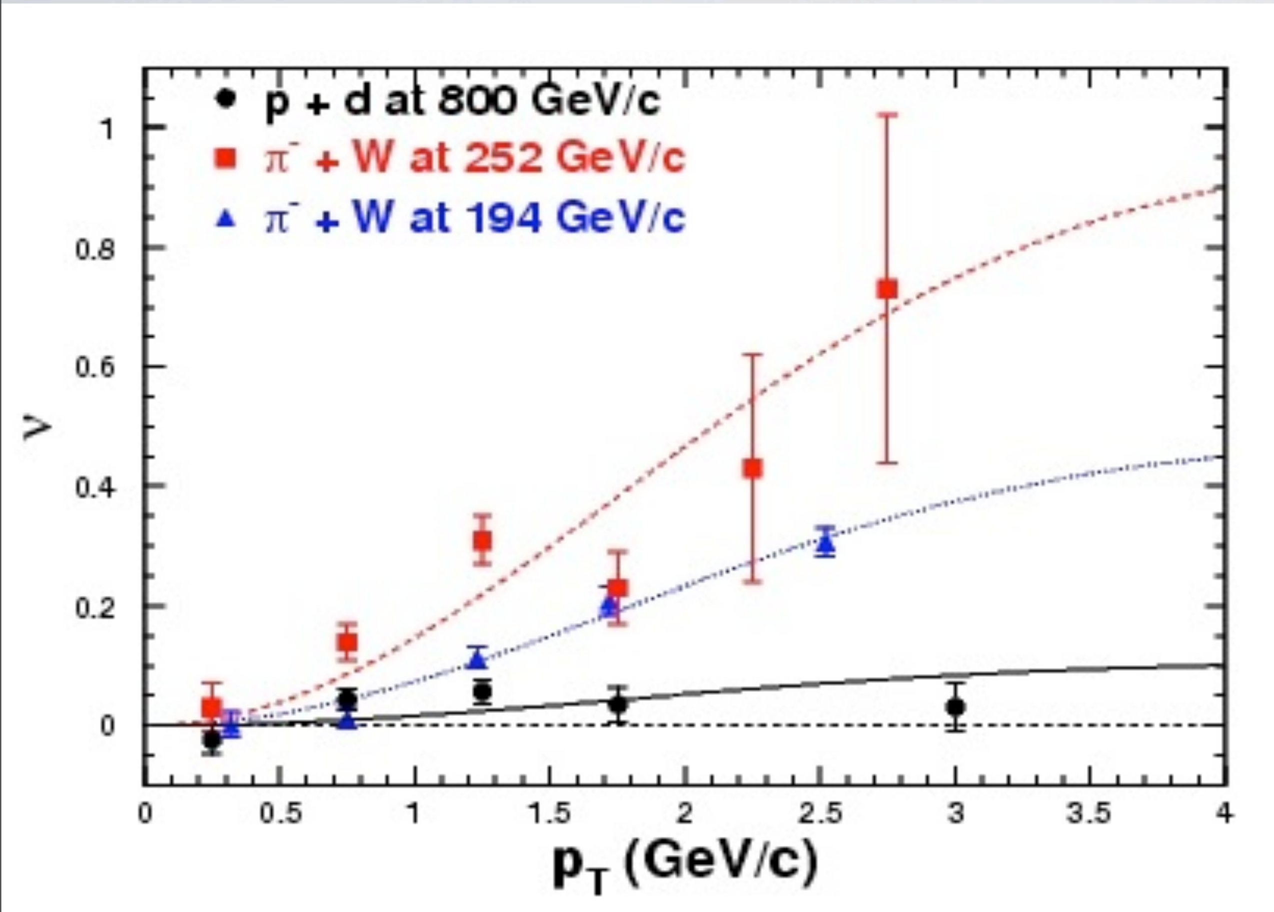
talk by J.C. Peng

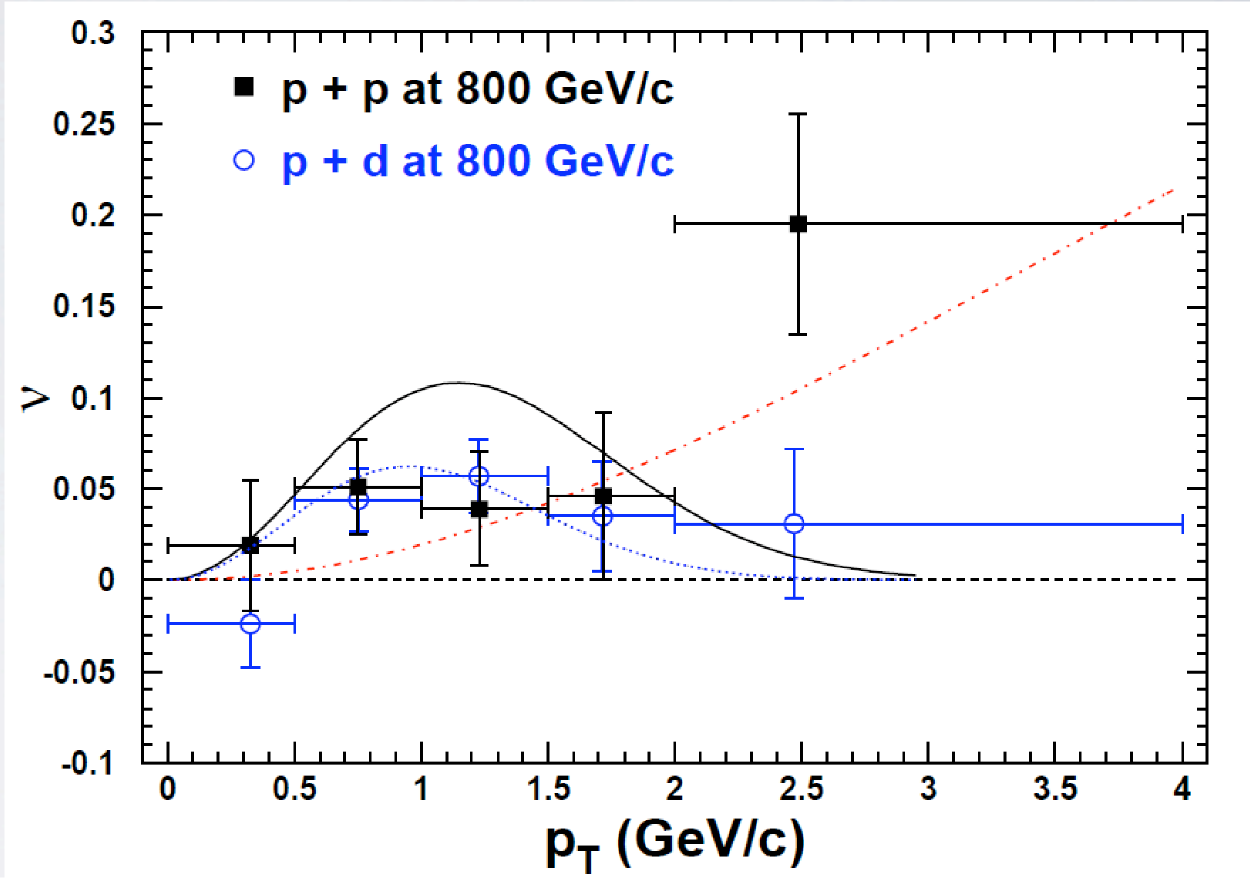
similar BM fctn for up and down quarks?

valence and sea BM fctn

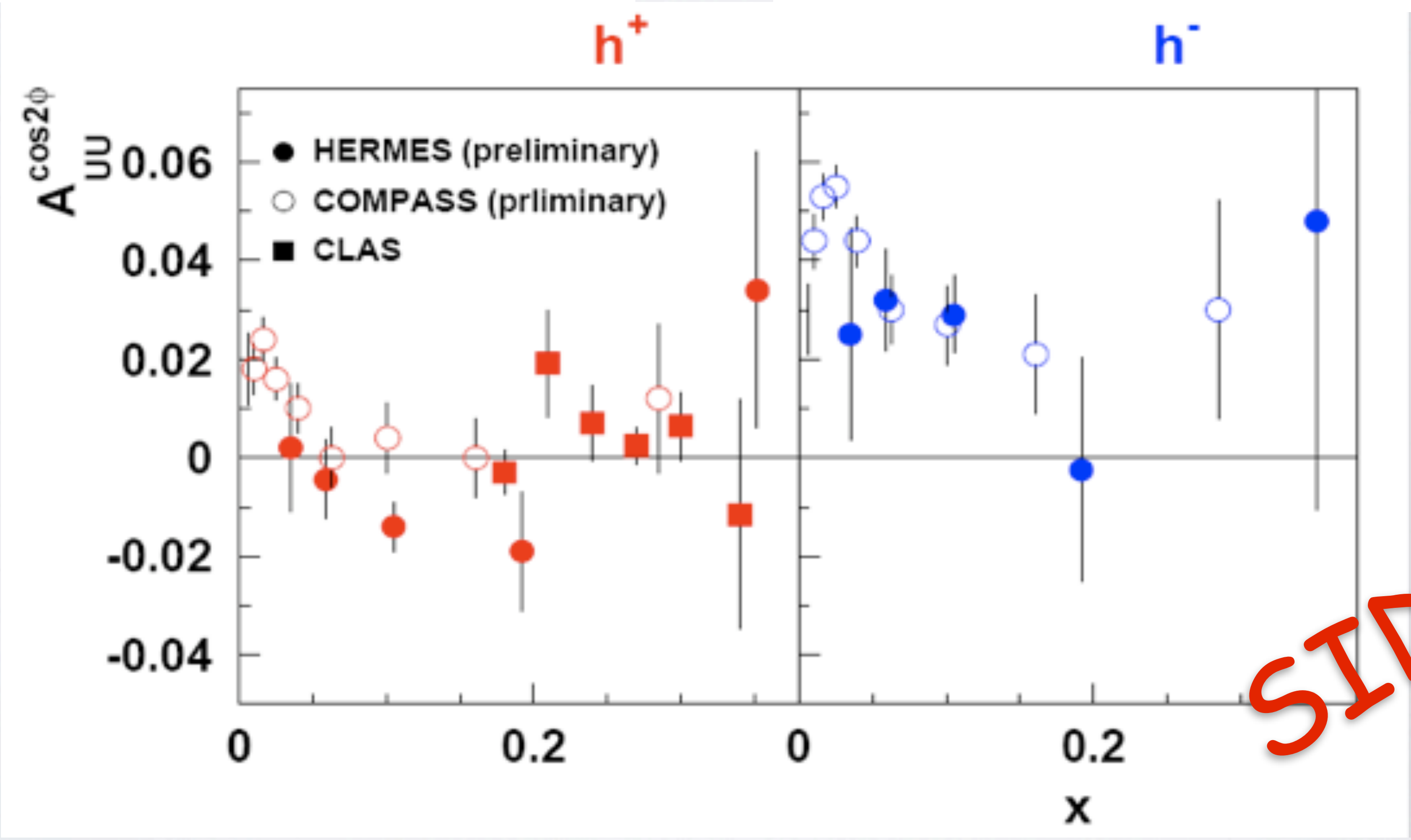
valence BM fctn

SIGNS OF BOER-MULDERS





talk by J.C. Peng

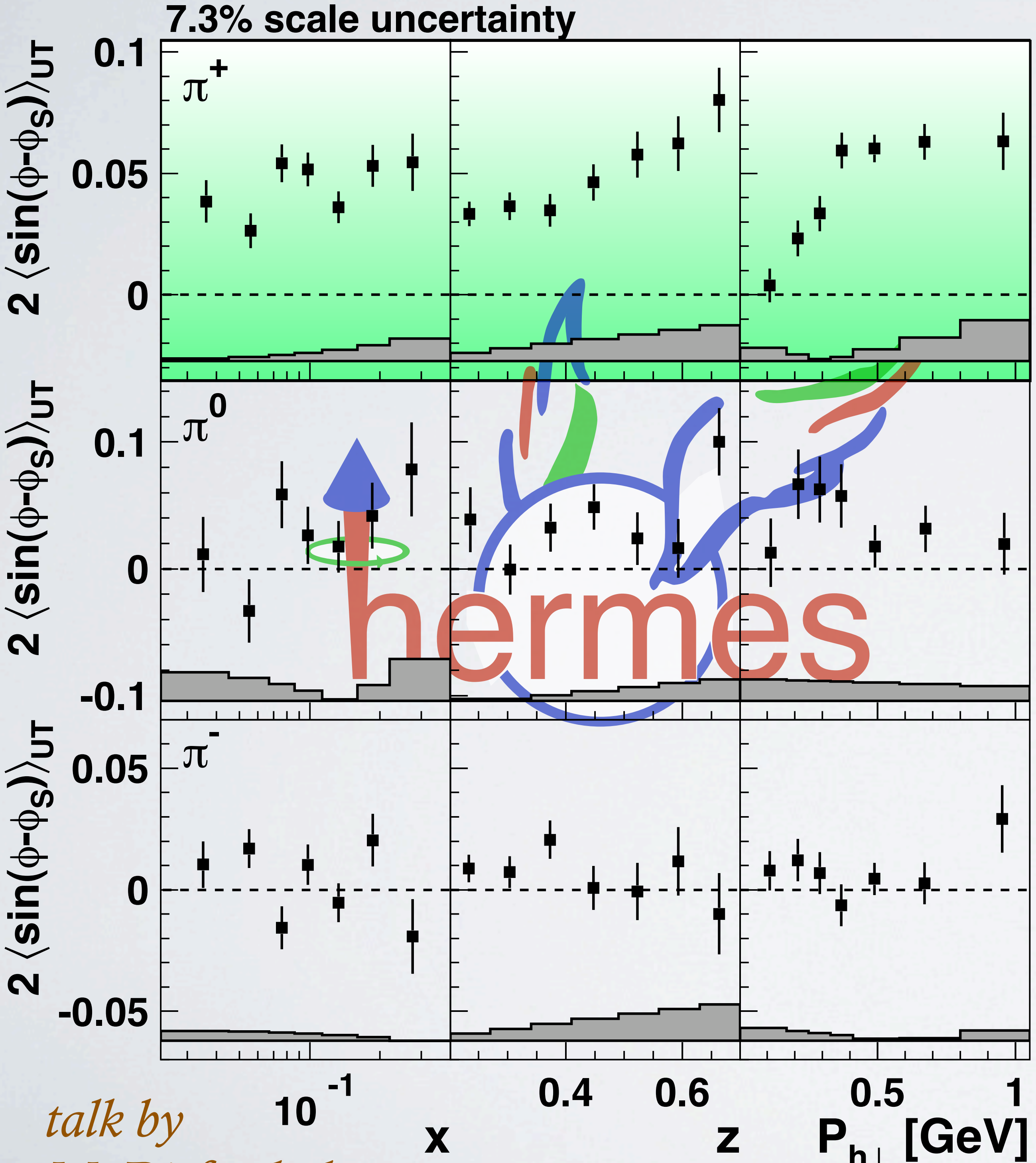


SIDIS

talk by H. Avakian

SIVERS EFFECT IN SIDIS

$$2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}} = -\frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2)\otimes D_1^q(z,K_T^2)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}$$

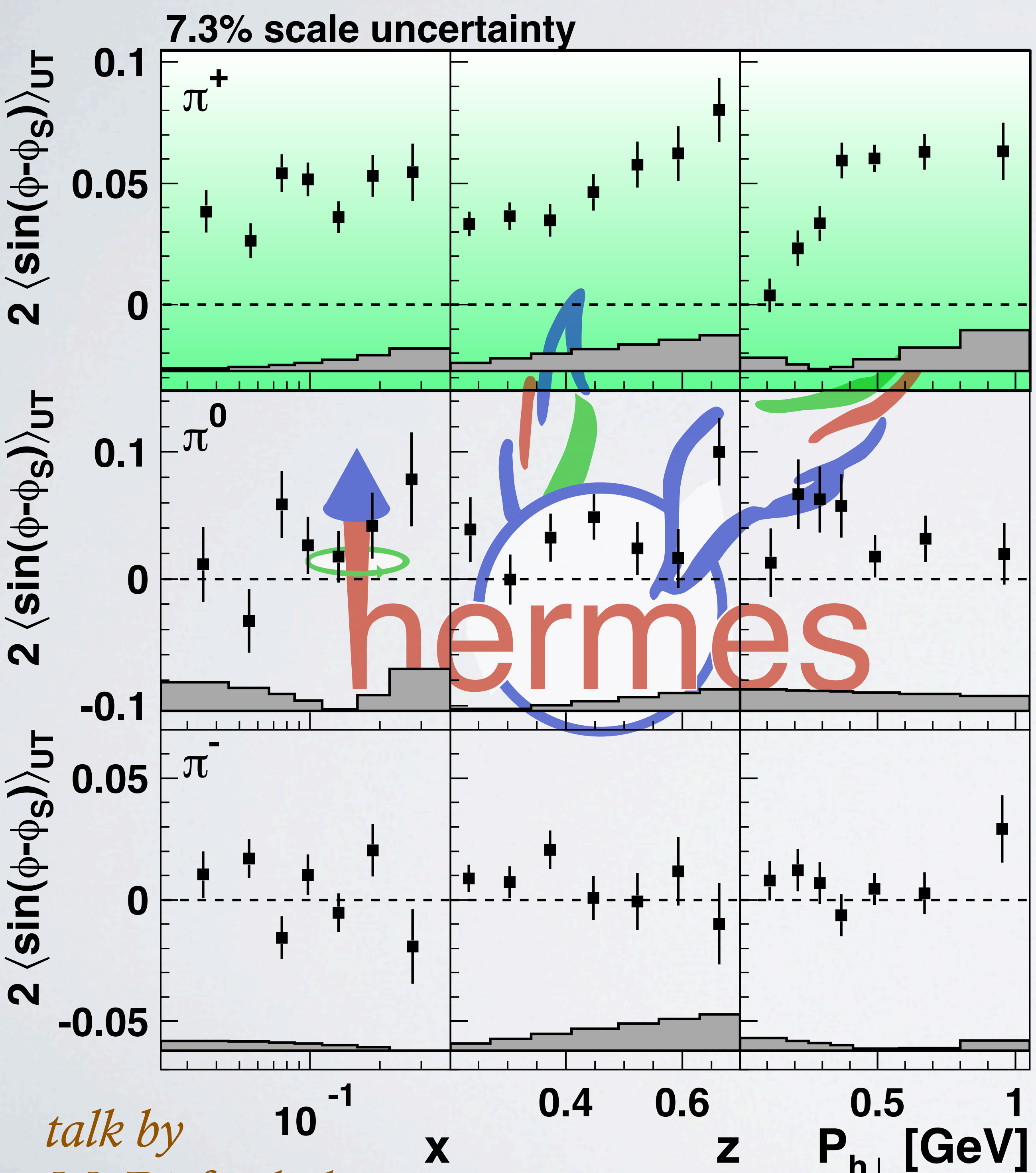


$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,K_T^2)}{f_1^u(x)\;D_1^{u\to\pi^+}(z)}$$

talk by
M. Diefenthaler

SIVERS EFFECT IN SIDIS

$$2\langle\sin(\phi-\phi_S)\rangle_{\rm UT} = -\frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2)\otimes D_1^q(z,K_T^2)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}$$



π^+ dominated by u-quark scattering:

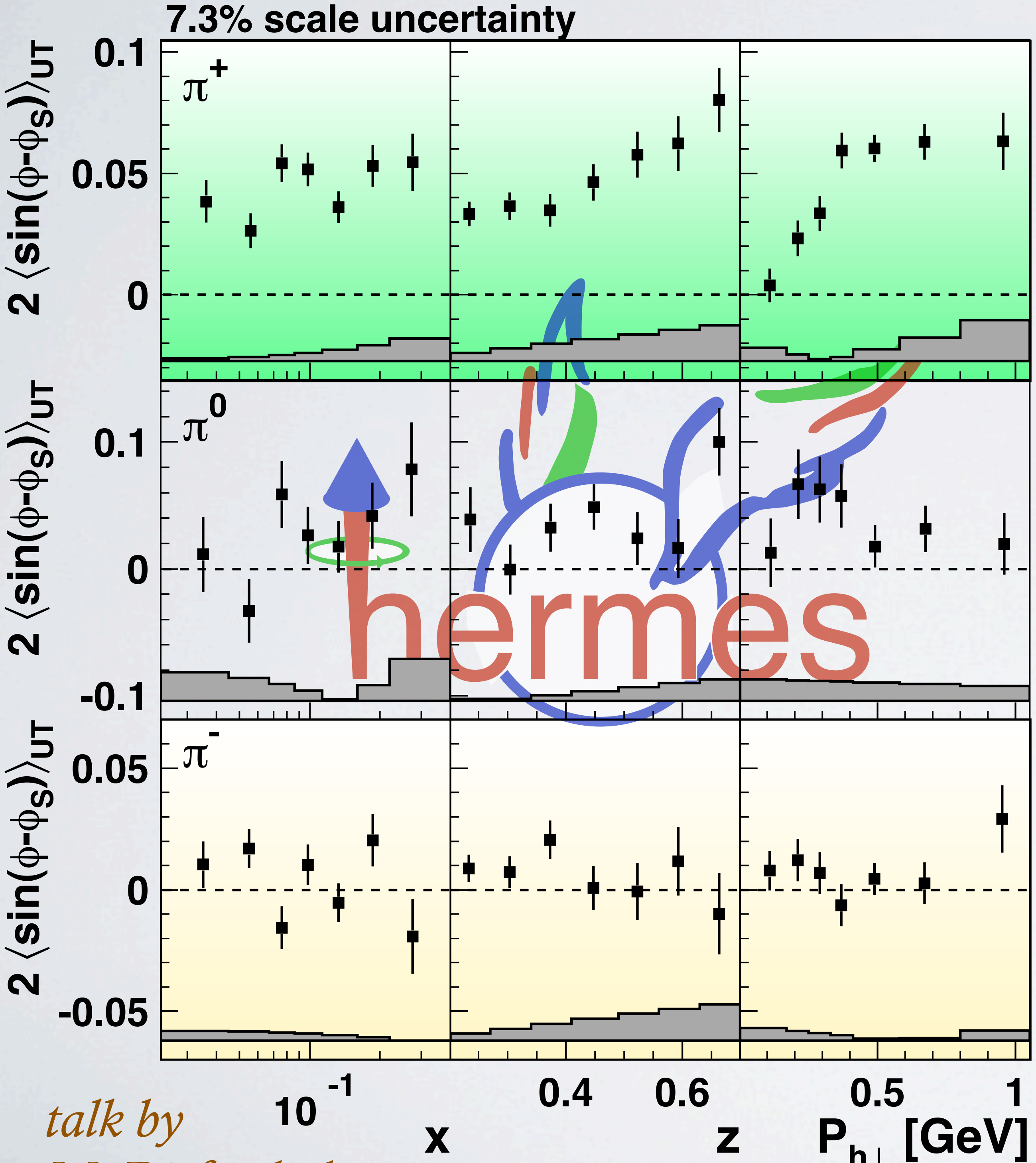
$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,K_T^2)}{f_1^u(x)\ D_1^{u\to\pi^+}(z)}$$

☛ **u-quark Sivers DF < 0**

talk by M. Diefenthaler

SIVERS EFFECT IN SIDIS

$$2\langle\sin(\phi-\phi_S)\rangle_{\rm UT} = -\frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2)\otimes D_1^q(z,K_T^2)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}$$



π^+ dominated by u-quark scattering:

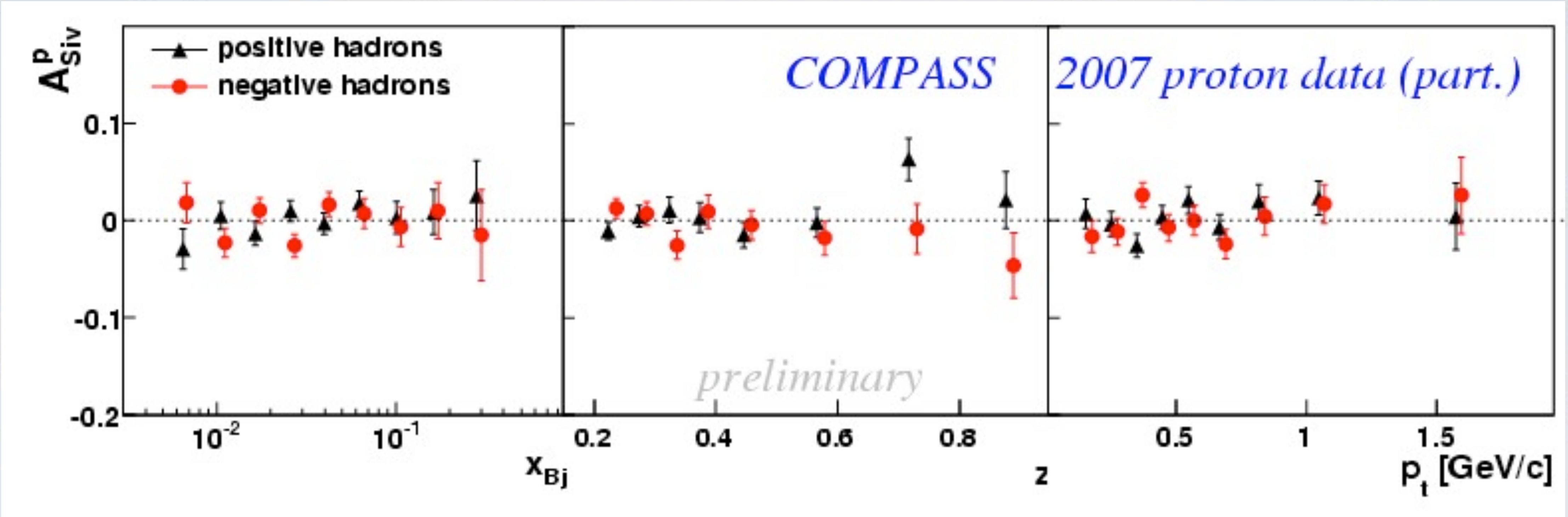
$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,K_T^2)}{f_1^u(x)\; D_1^{u\to\pi^+}(z)}$$

☛ **u-quark Sivers DF < 0**

☛ **d-quark Sivers DF > 0 (cancelation for π^-)**

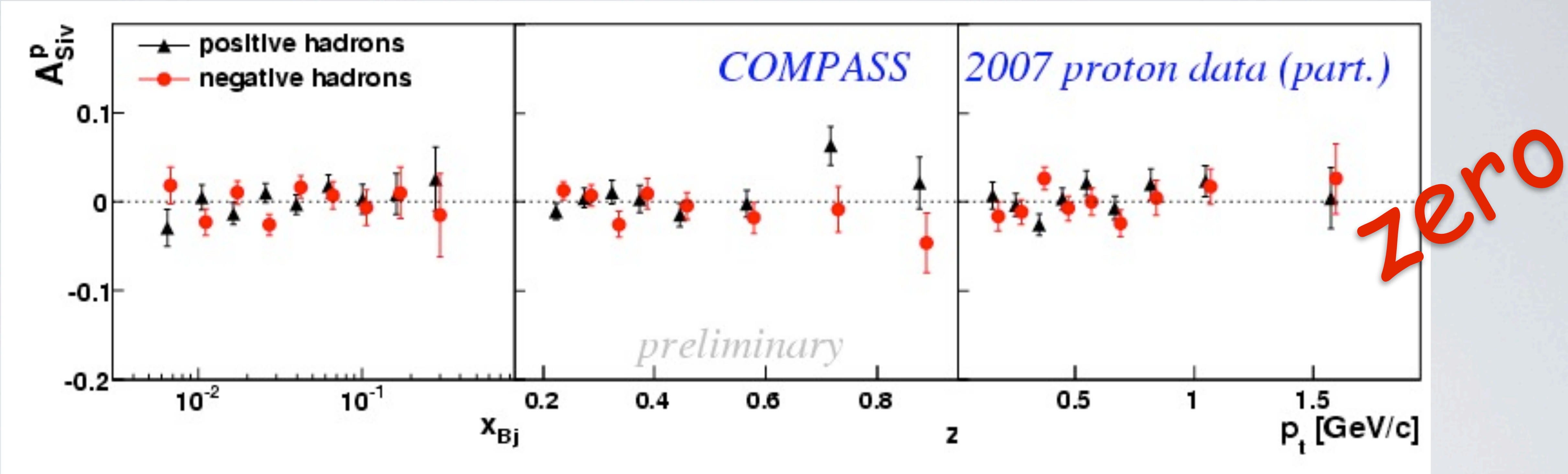
talk by M. Diefenthaler

THE "SIVERS RIDDLE"



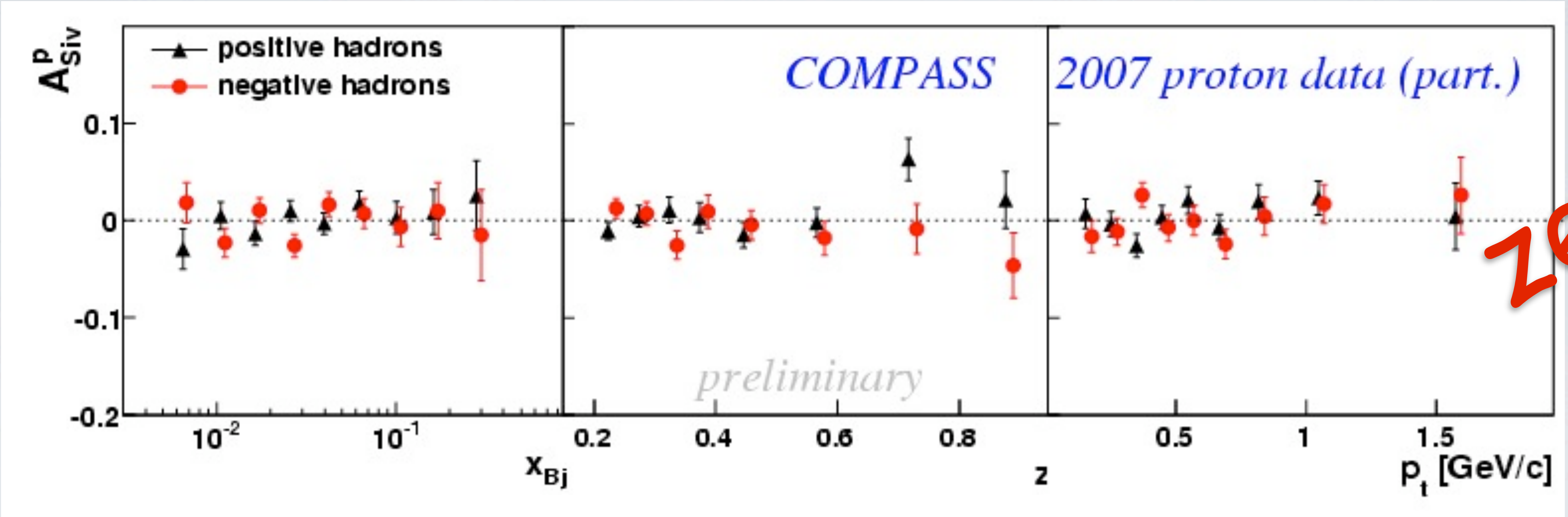
talk by R. Joosten

THE "SIVERS RIDDLE"

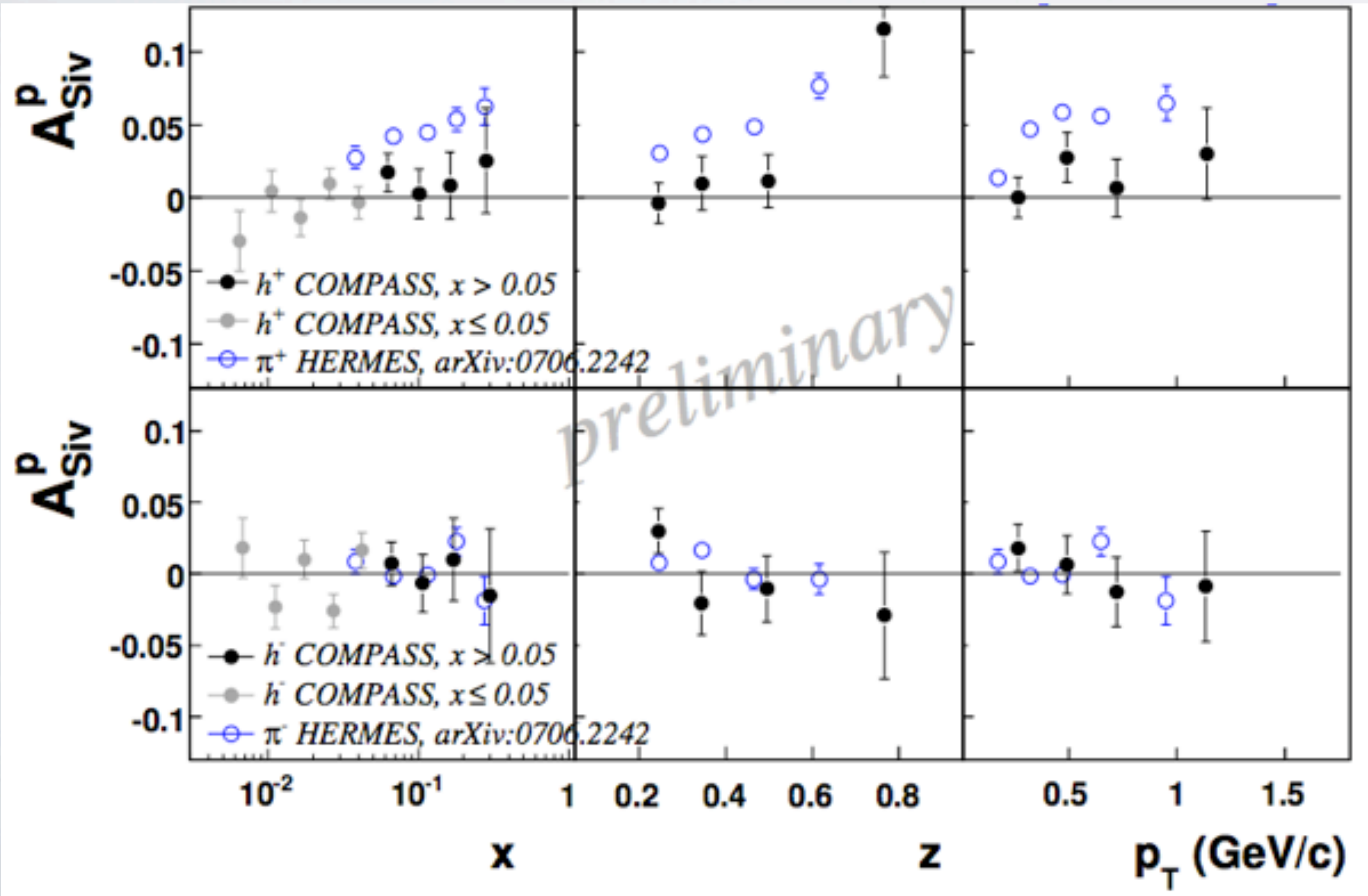


talk by R. Joosten

THE "SIVERS RIDDLE"

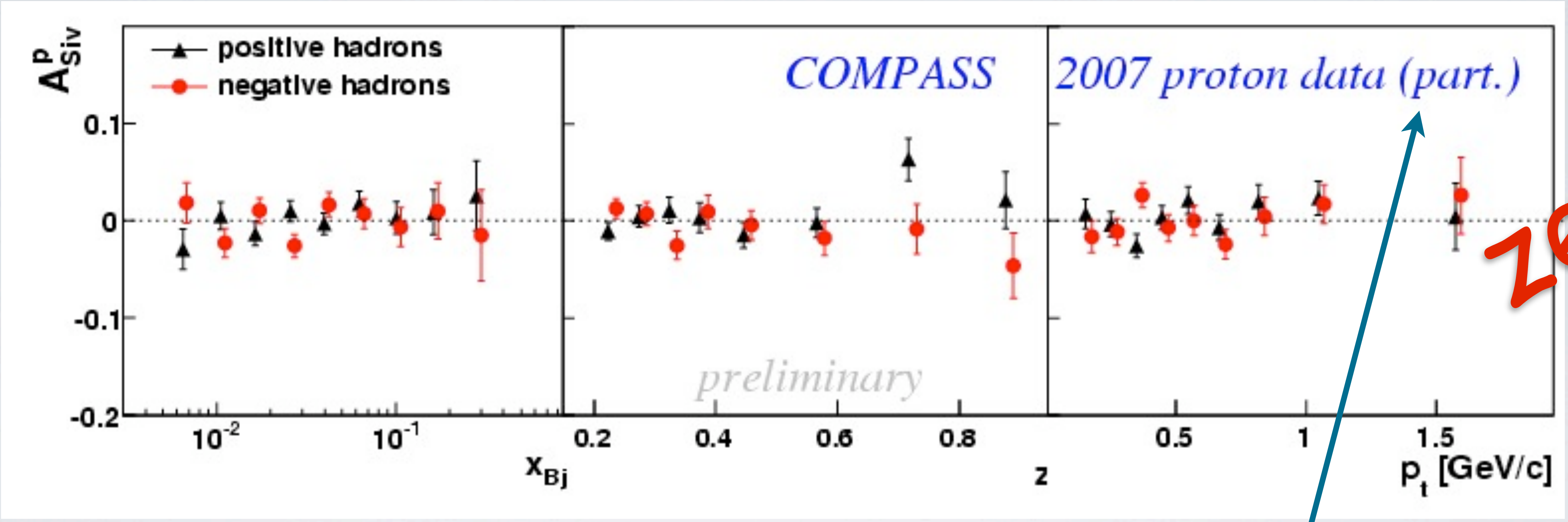


zero

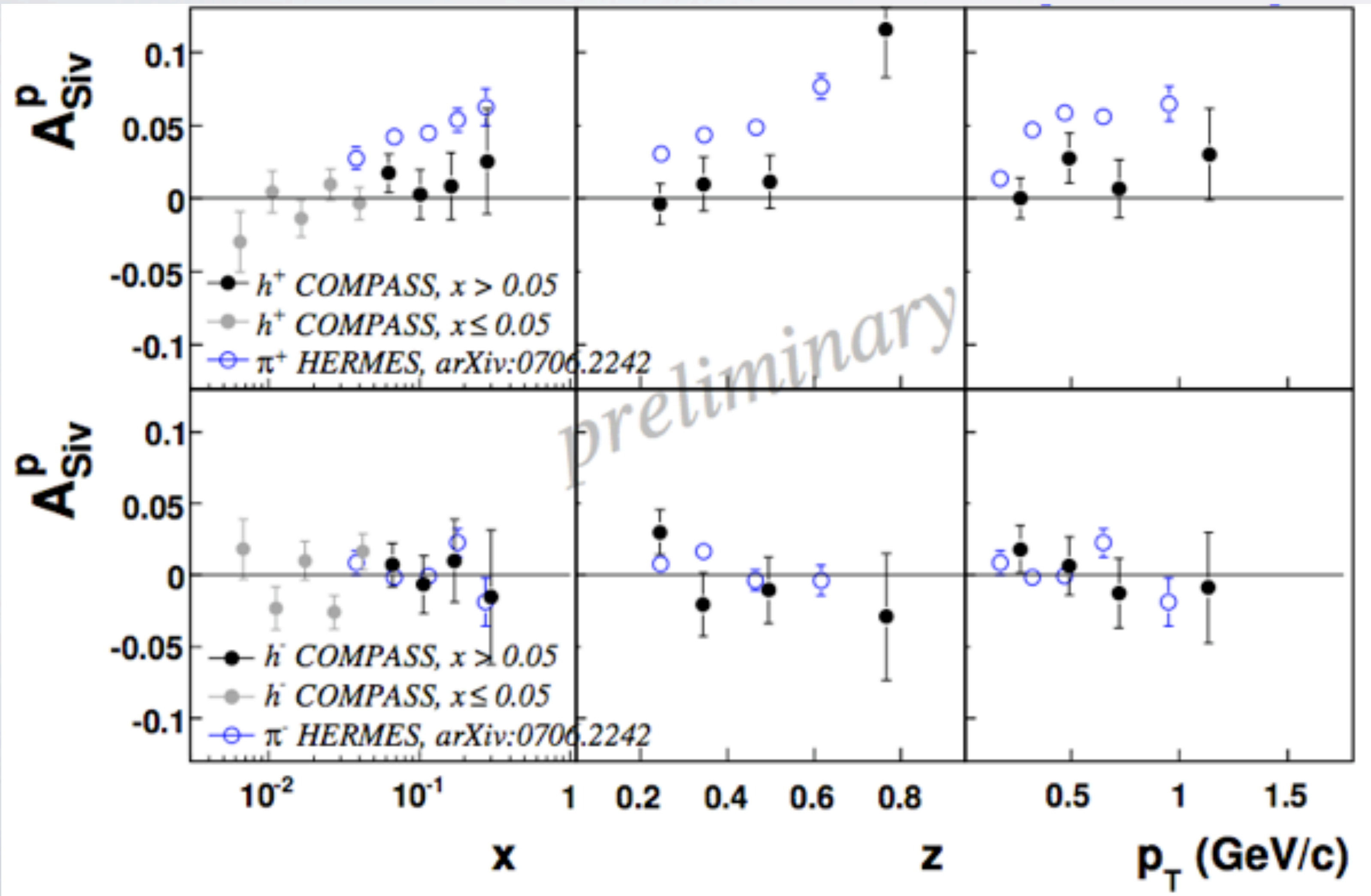


talk by R. Joosten

THE "SIVERS RIDDLE"



zero



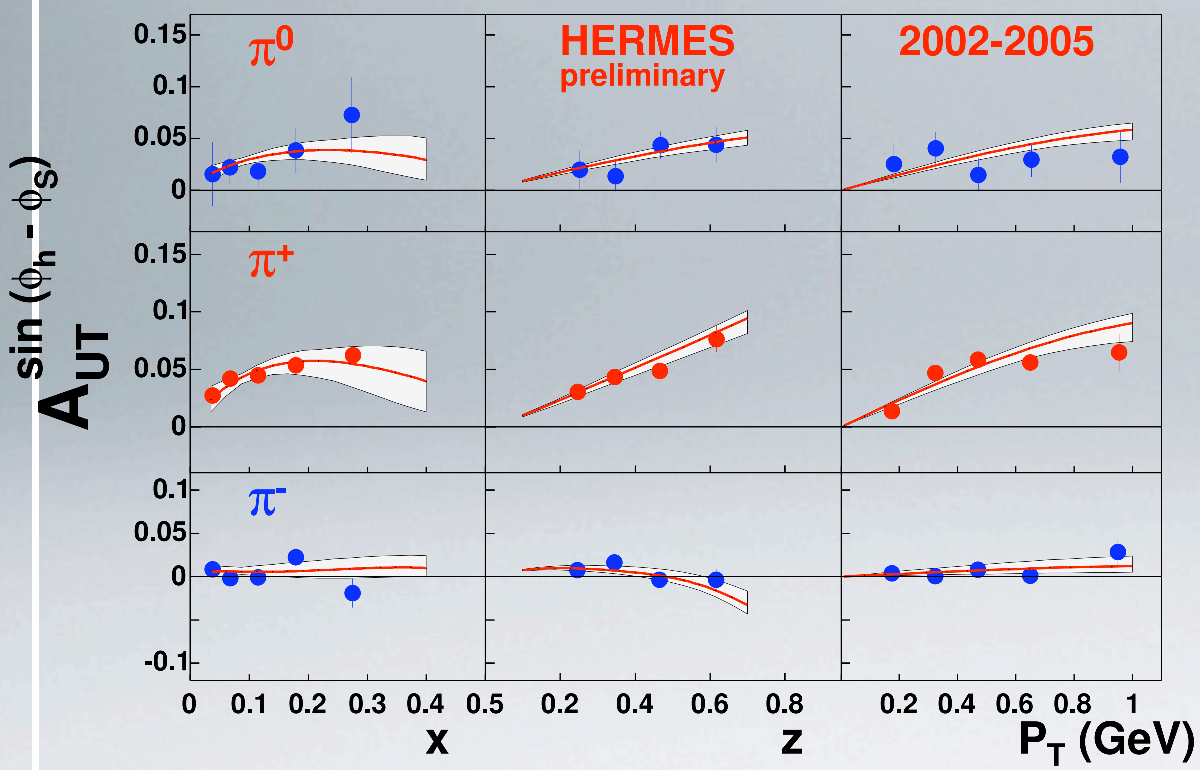
only a fraction of proton data analyzed

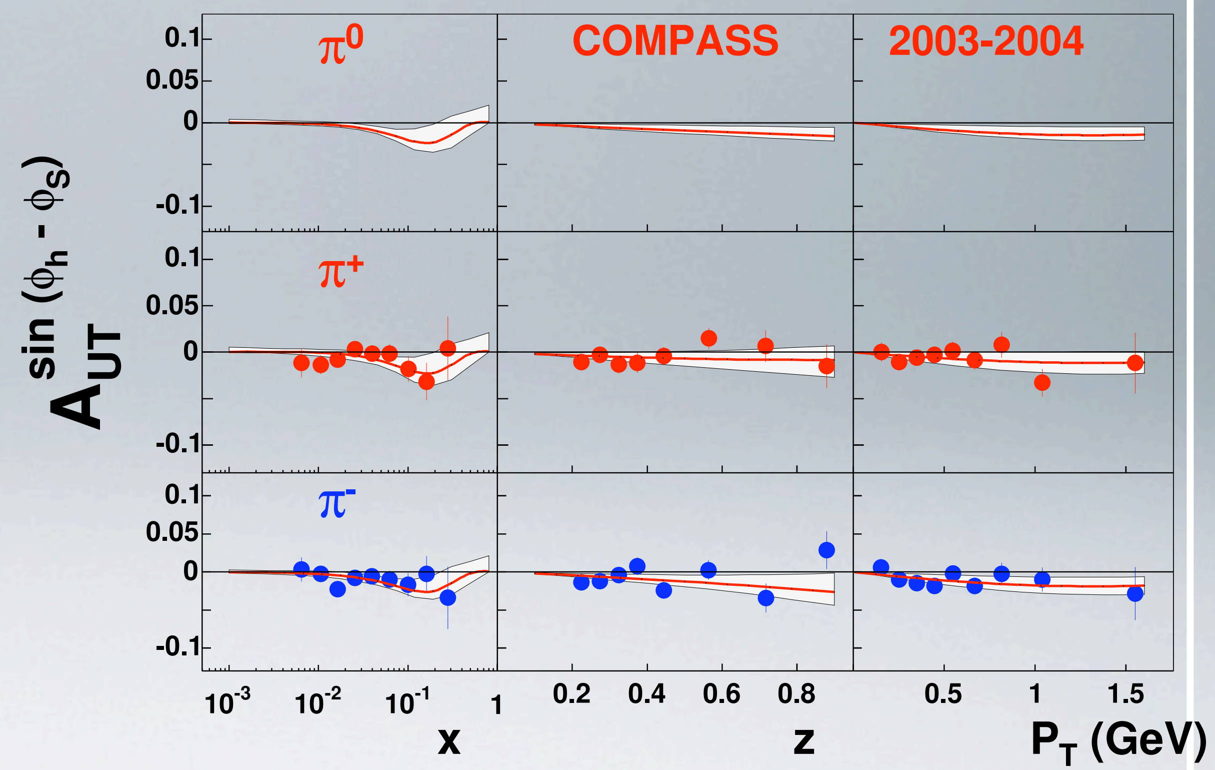
"please wait for better data from COMPASS" [R. Joosten]

talk by R. Joosten

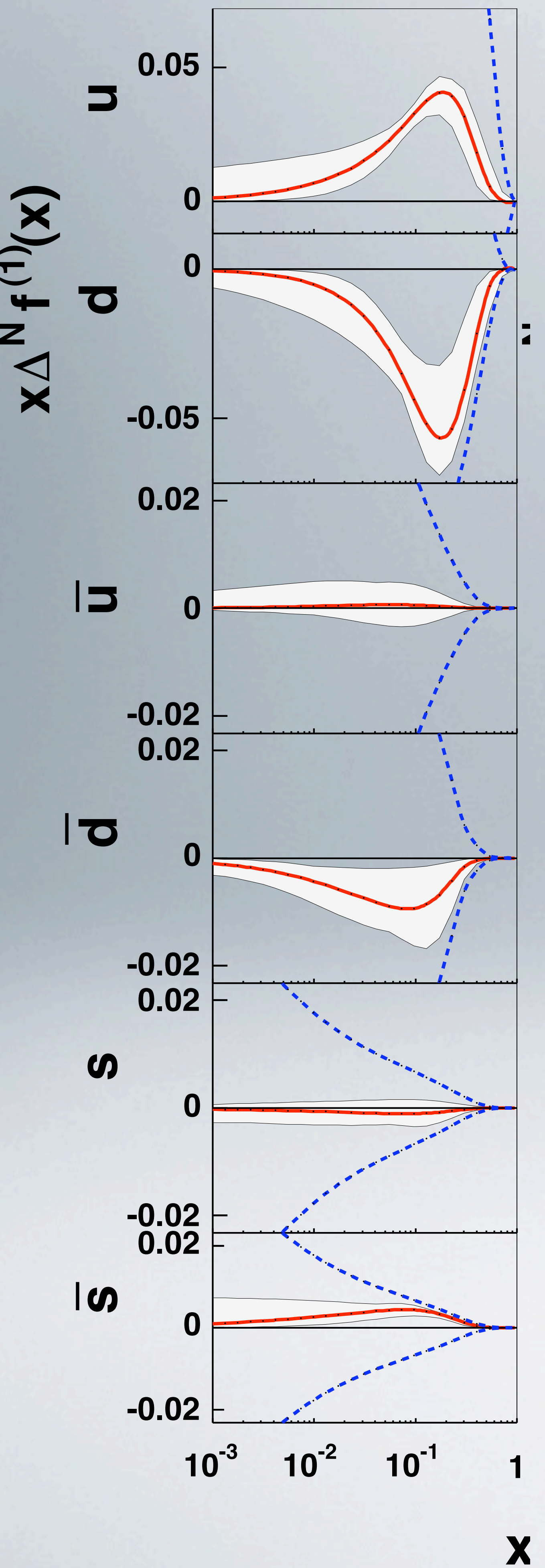
FIT OF THE SIVERS EFFECT

talk by U. D'Alesio



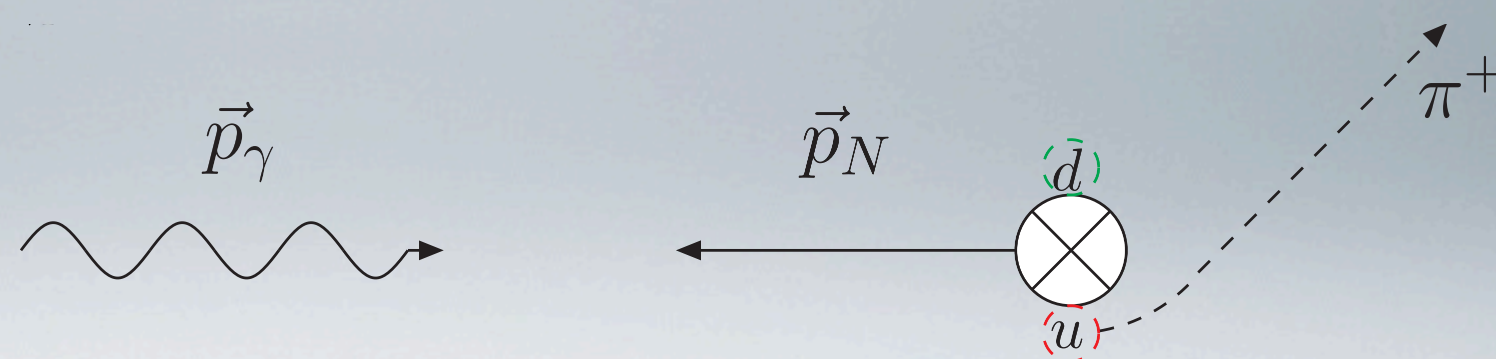


Fit of HERMES data [*Diefenthaler et al. 2006, Pappalardo et al. 2008*] and COMPASS data [*Martin et al. 2006*] (deuteron target)



SIVERS FUNCTION FROM FIT

talk by U. D'Alesio



$$-f_{1T}^{\perp q} \sim \kappa^q$$

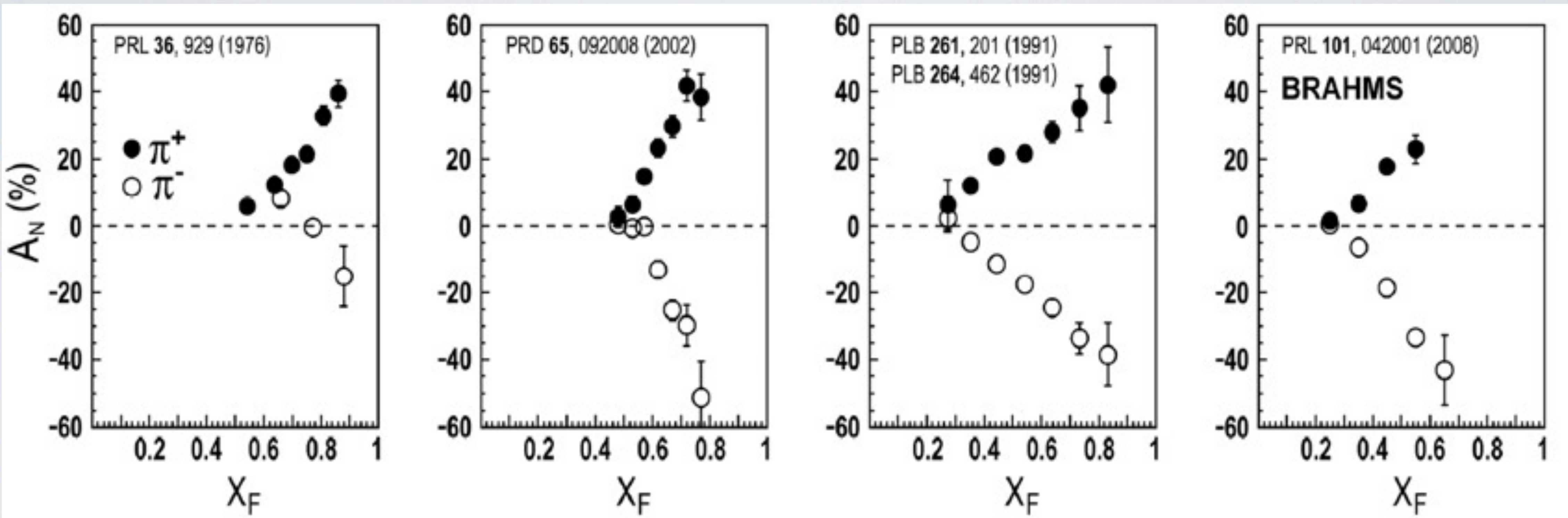
$$\kappa^u = 1.67$$

$$\kappa^d = -2.03$$

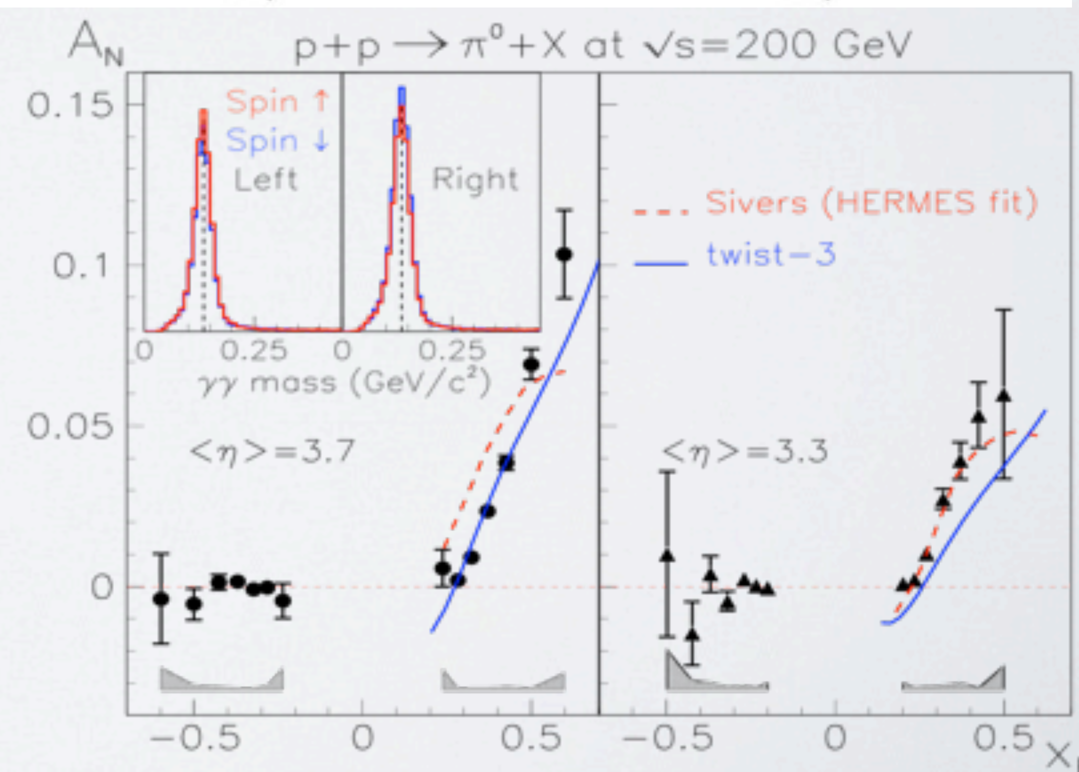
talk by M. Burkardt

SSA IN PP COLLISIONS

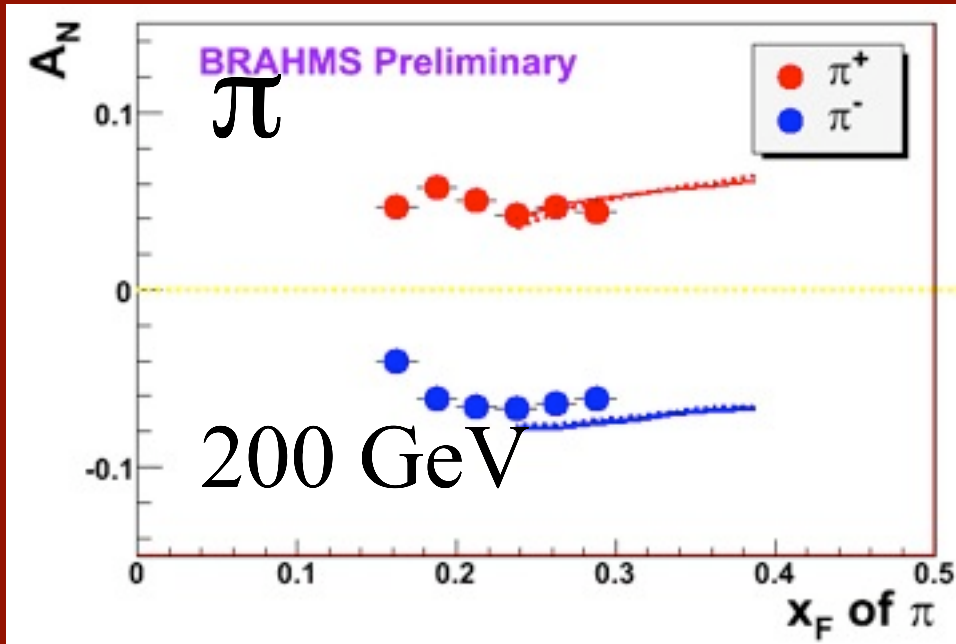
ANL	BNL	FNAL	RHIC
√s=4.9 GeV	√s=6.6 GeV	√s=19.4 GeV	√s=62.4 GeV

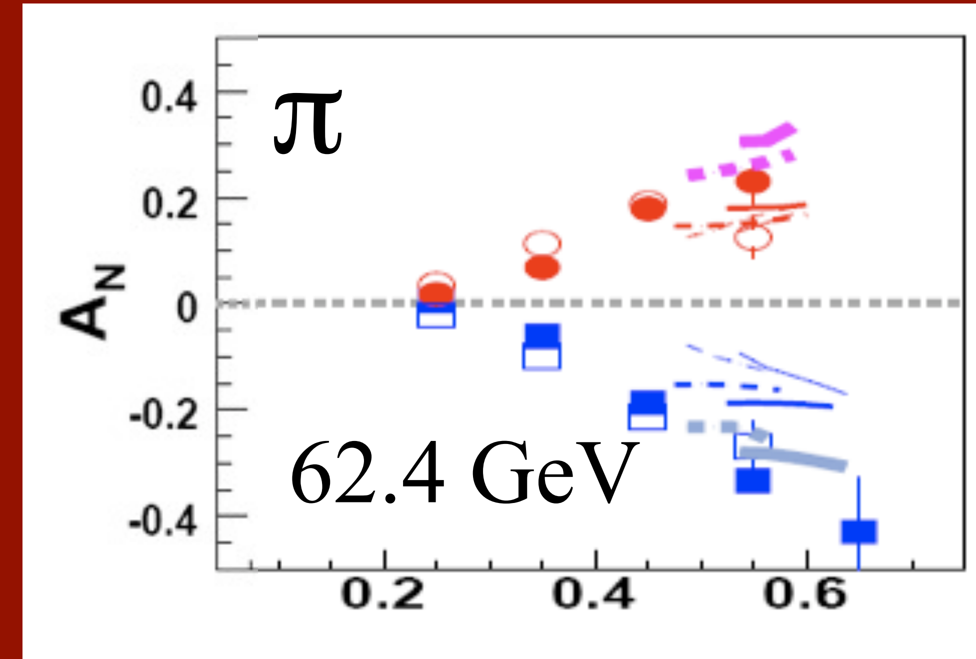


- is it Sivers?
- is it Collins?
- or is it twist-3?



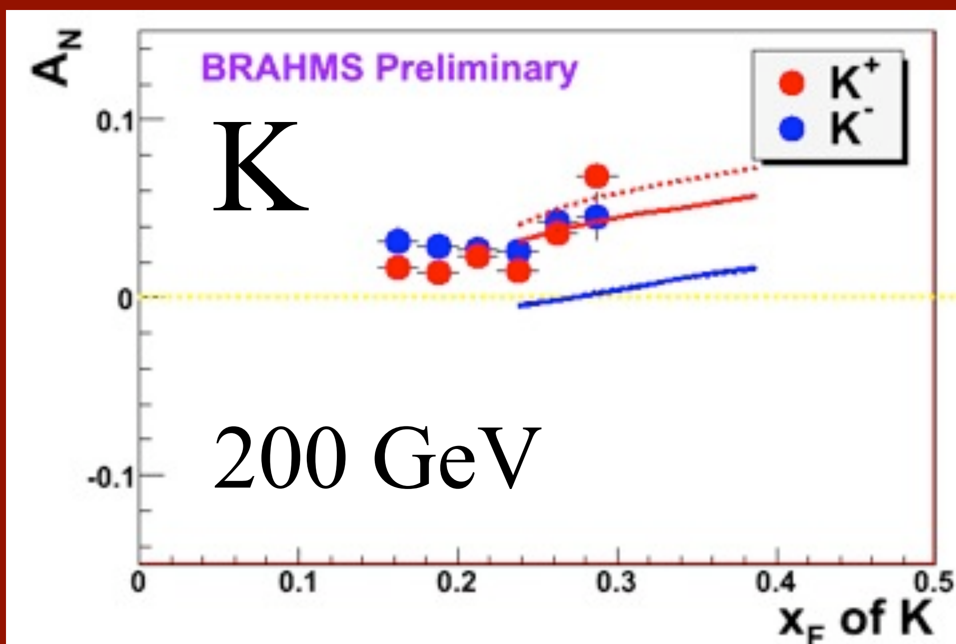
talk by C. Aidala

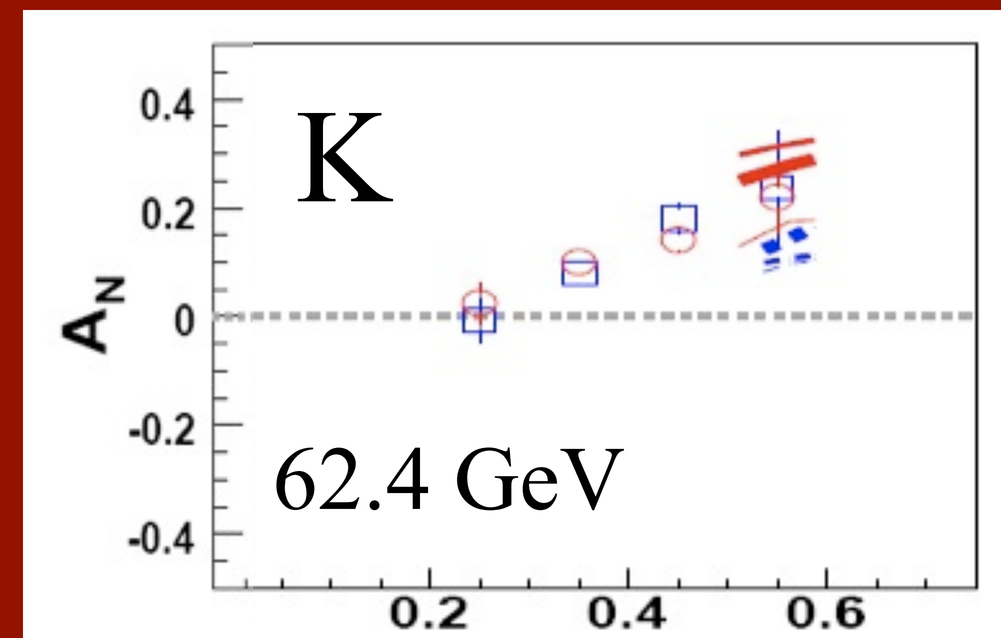




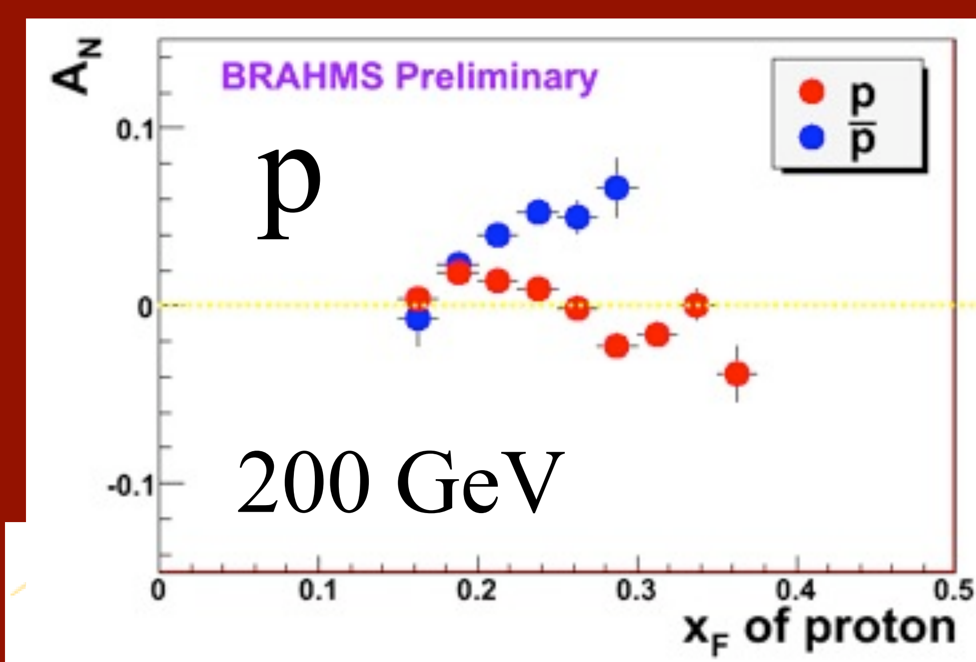
SSAs observed at RHIC: 200 and 62.4 GeV

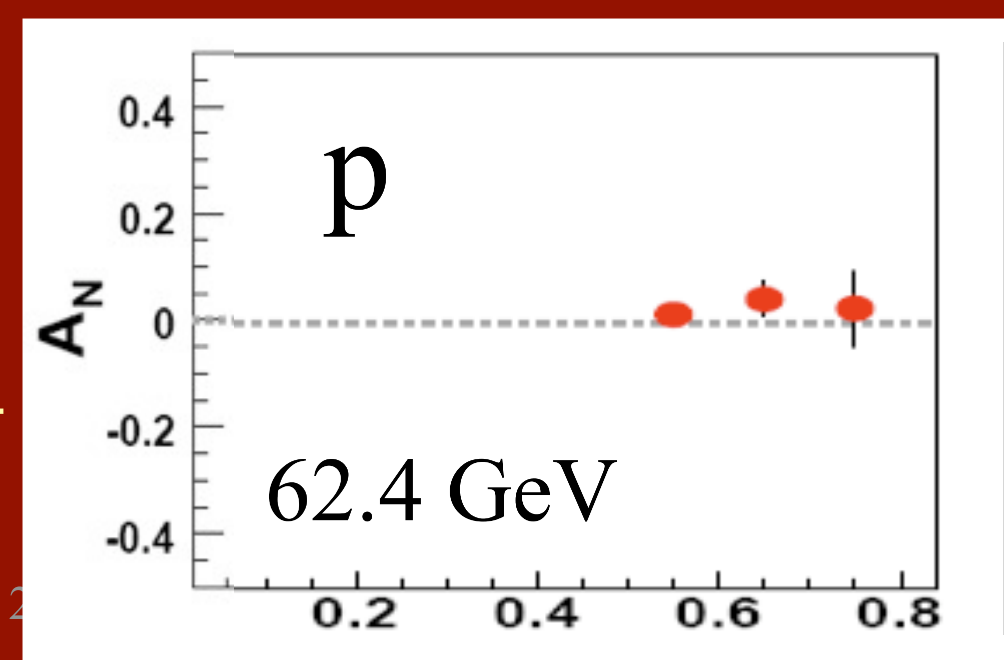
Note different scales





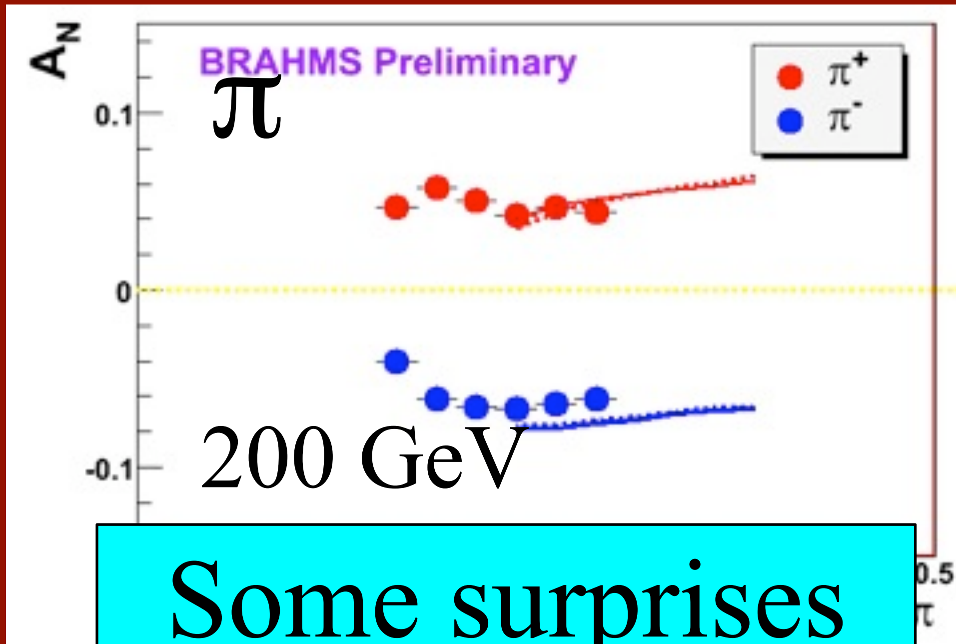
K- asymmetries underpredicted



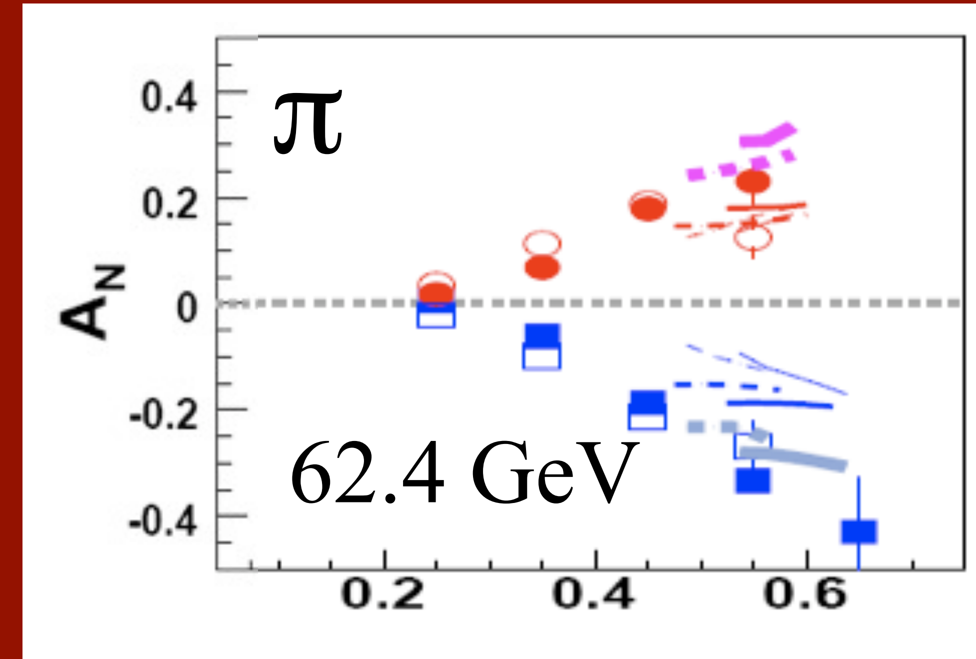


Large antiproton asymmetry?? Unfortunately no 62.4 GeV measurement

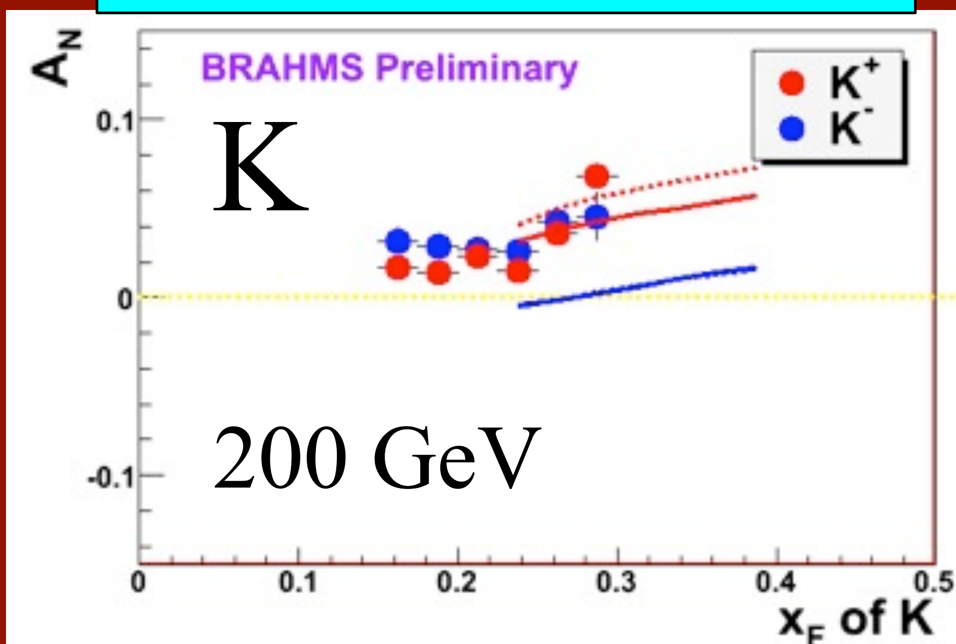
SSAs observed at RHIC: 200 and 62.4 GeV



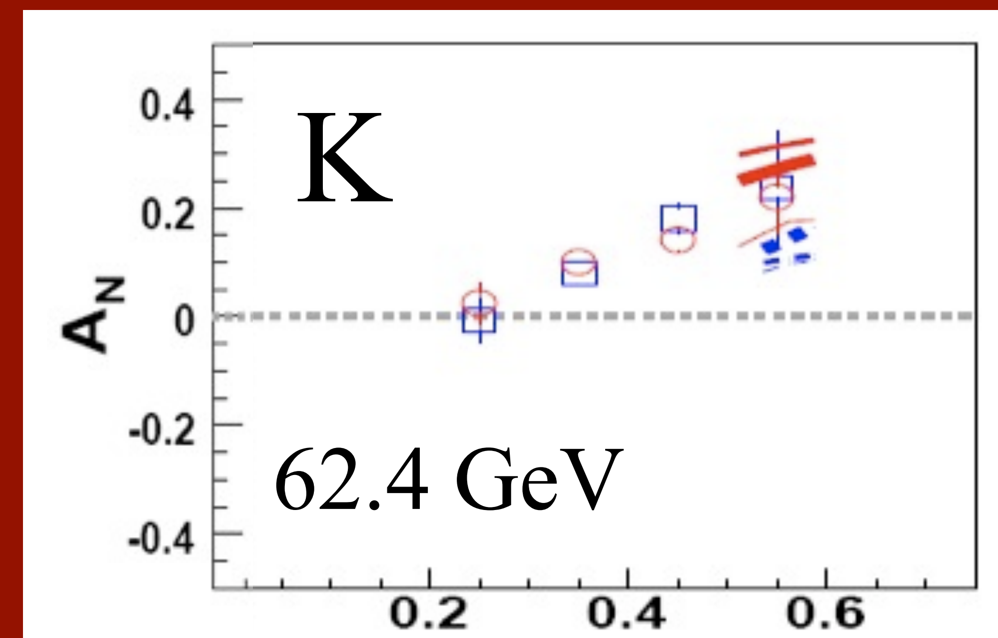
Some surprises

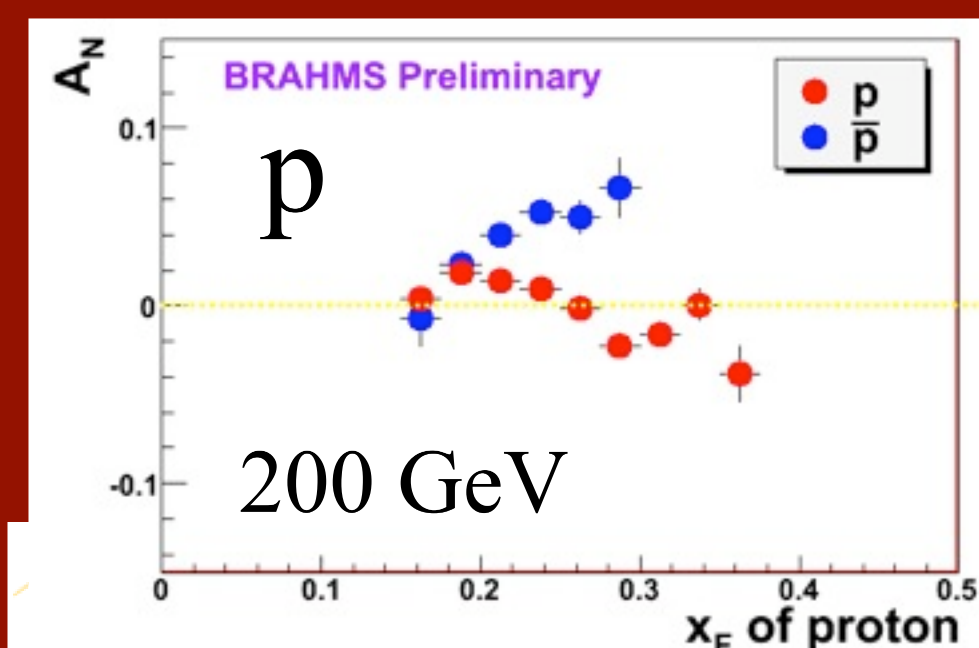


Note different scales

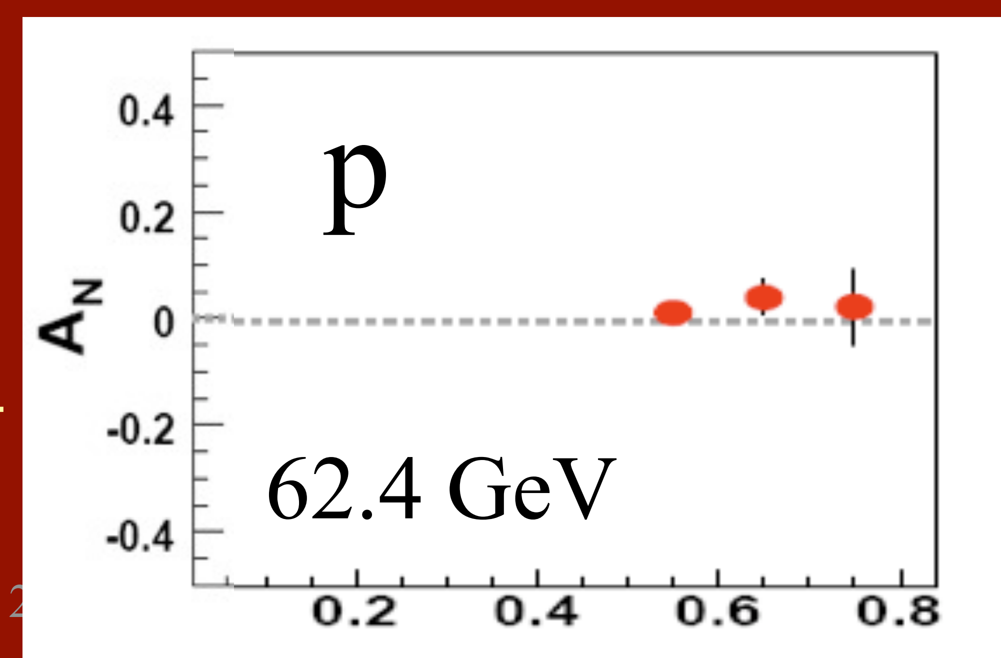


K- asymmetries underpredicted





Large antiproton asymmetry?? Unfortunately no 62.4 GeV measurement

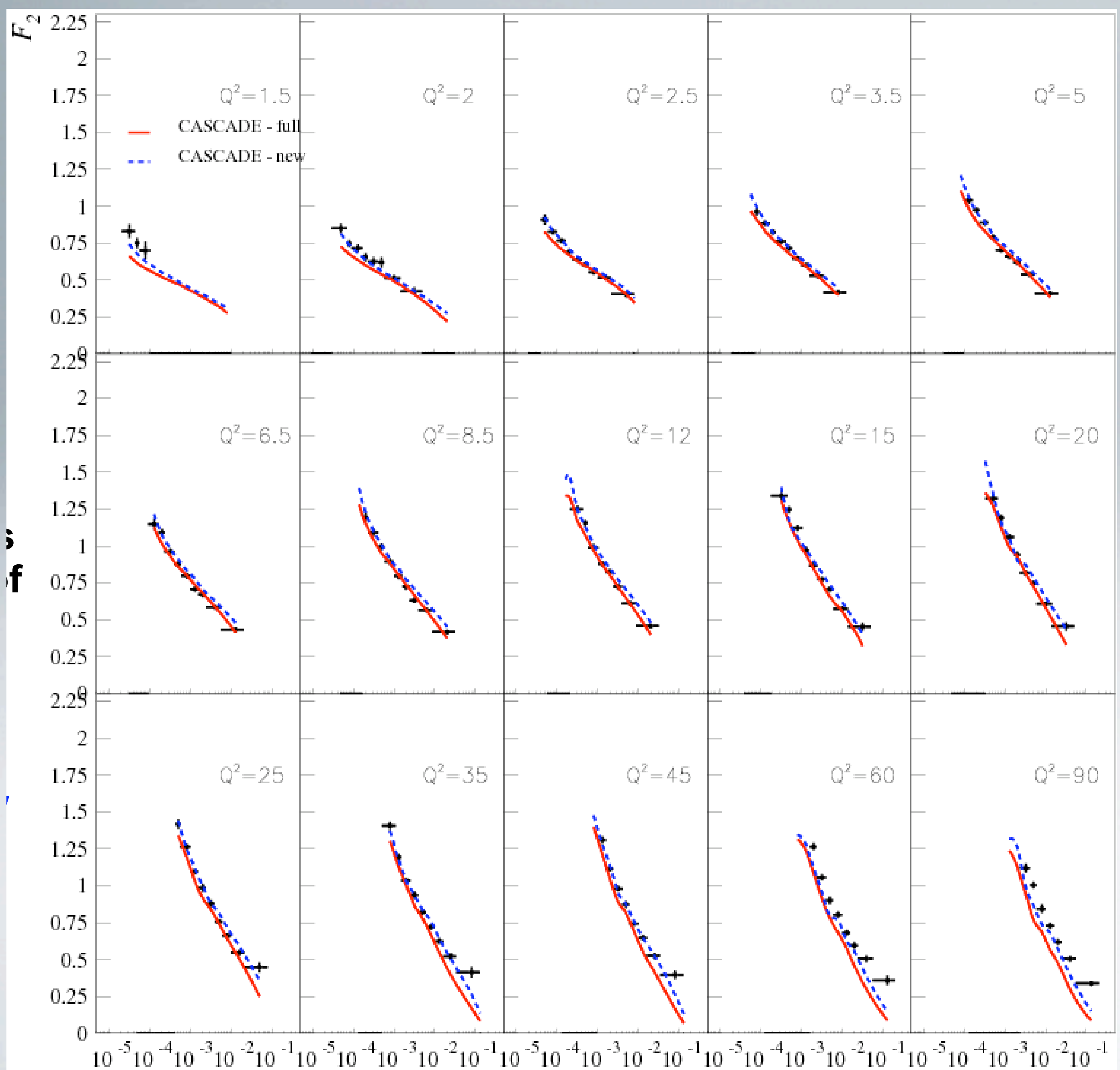


OTHER MISSIONS...

GLUON TMD AT H1

$$xf^g(x, k_T^2, Q_0) = Nx^{-B}(1-x)^C(1-Dx)\exp\left(\frac{(k_t-\mu)^2}{\sigma^2}\right)$$

talk by A. Knutsson



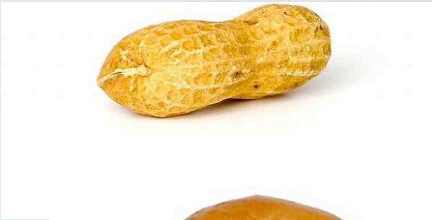
Minimum
N = 0.487 +/- 0.007
B = 0.097 +/- 0.003
D = -5.10 +/- 0.35
Chi2/ndf = 2.8

Note: dijet data seem to require a large shift

PRETZELOSITY & OTHERS

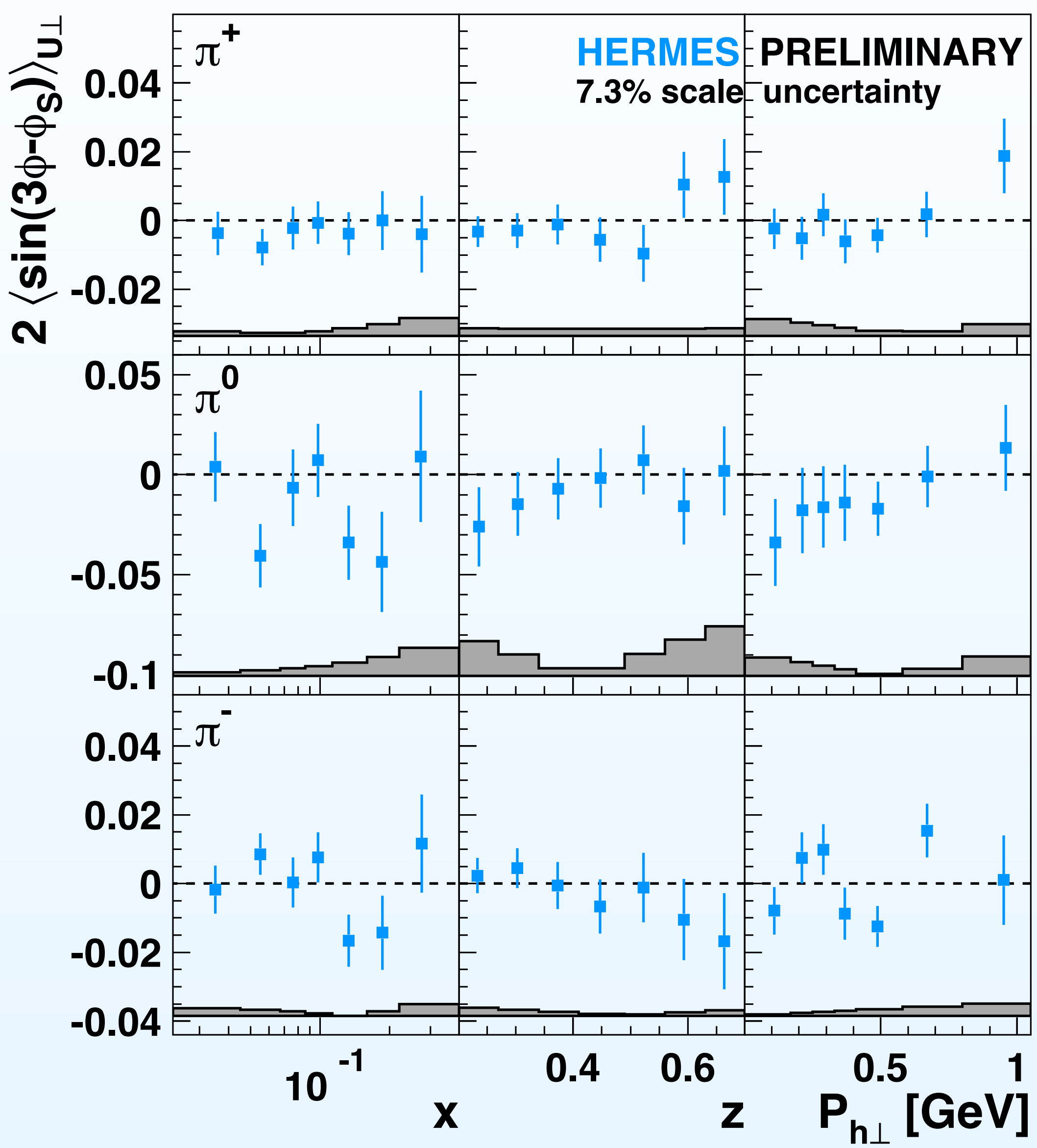
talk by M. Burkardt

- for example, $h_{1T}^{\perp} > 0$ implies nucleon prolate when quark transversity parallel nucleon spin
- and more oblate when quark transversity anti-parallel nucleon spin
- and for some spin configurations may even resemble a pretzel ... (G.A. Miller, 2003)

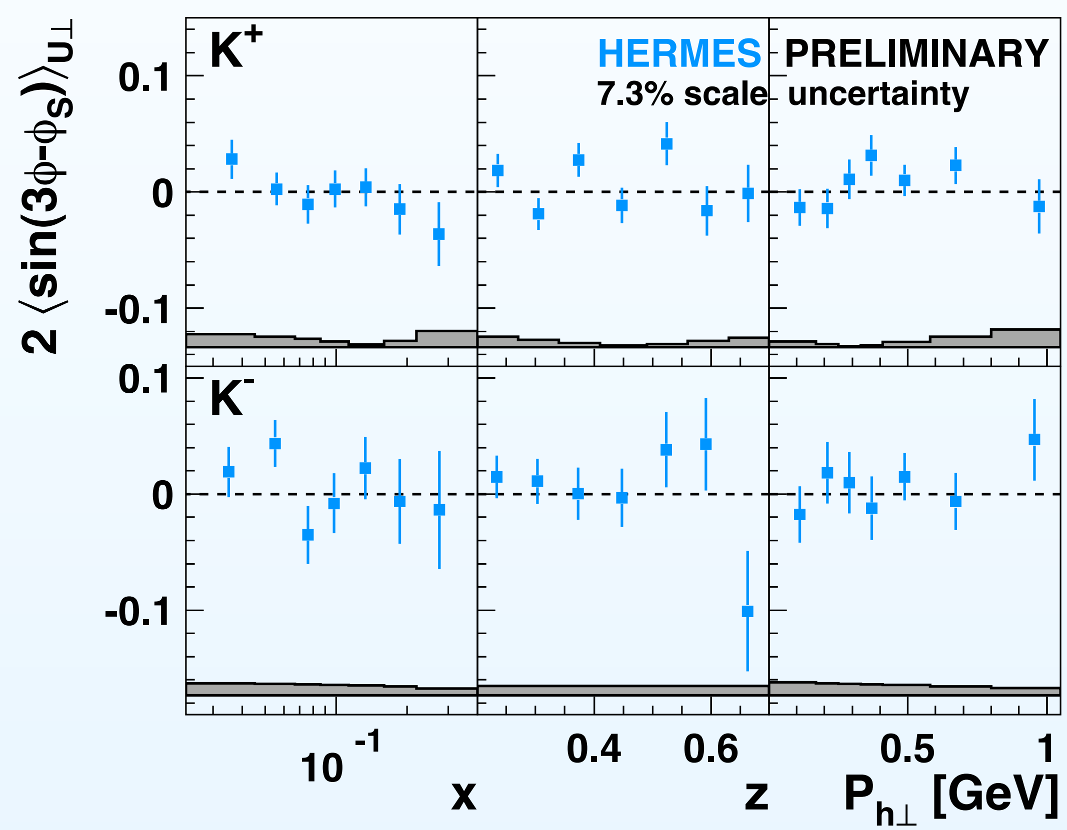


PRETZELOSITY AT hermes

The $\langle \sin(3\phi - \phi_S) \rangle_{U\perp}$ Fourier component:



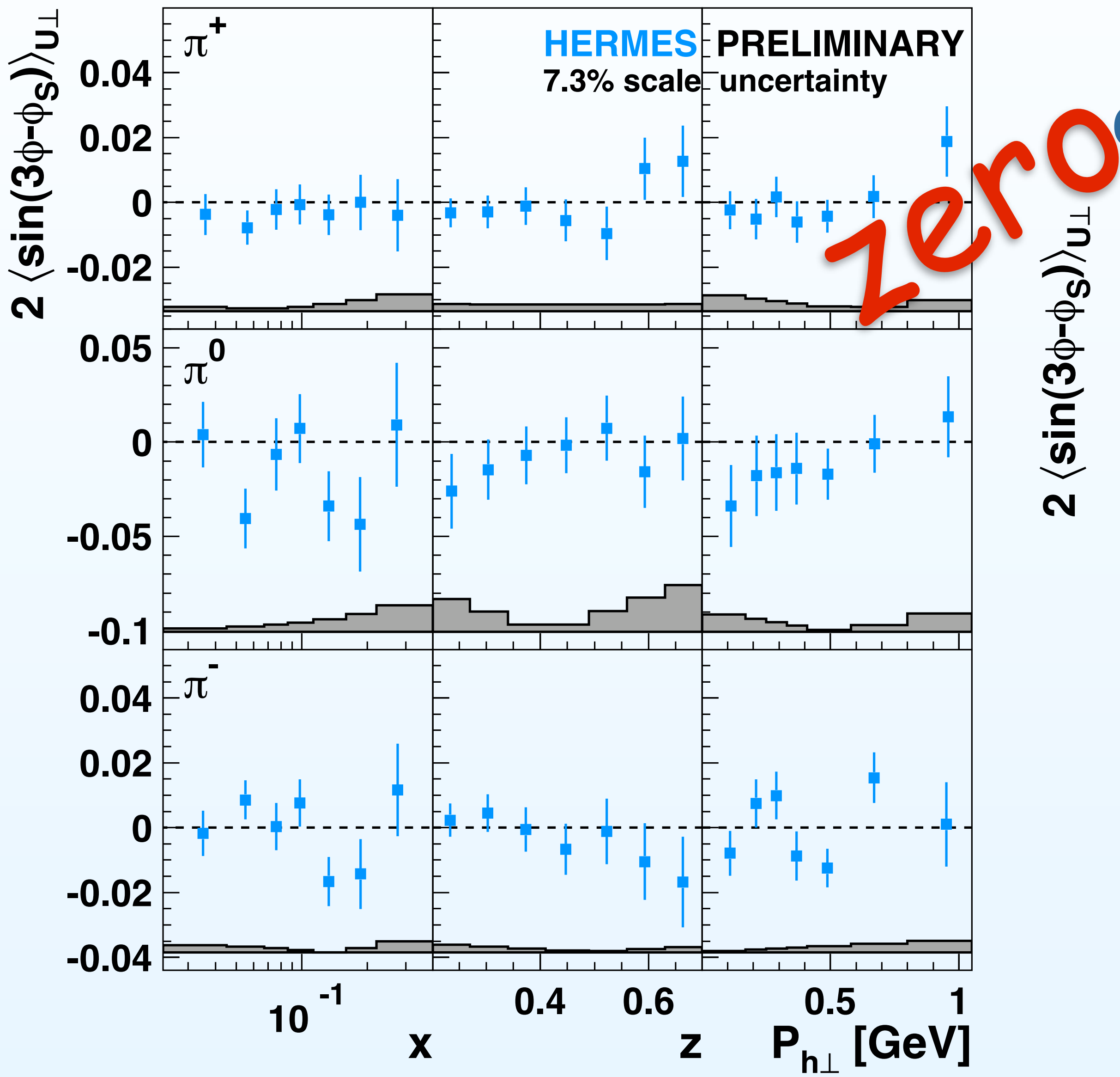
suppressed w.r.t.
Collins and Sivers amplitudes



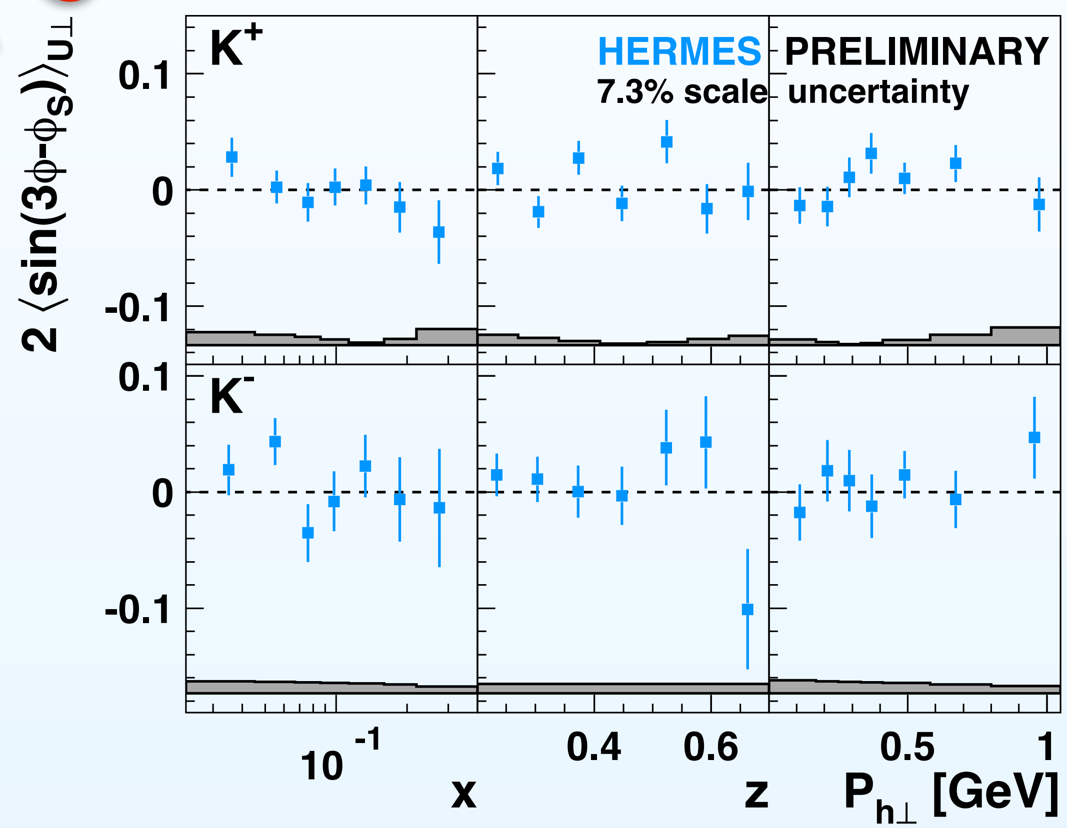
talk by M. Diefenthaler

PRETZELOSITY AT hermes

The $\langle \sin(3\phi - \phi_S) \rangle_{U\perp}$ Fourier component:



suppressed w.r.t. Collins and Sivers amplitudes



talk by M. Diefenthaler

workshop *"Partonic transverse momentum distributions"* at EINN 2009, September 28th 2009 – p.31/32

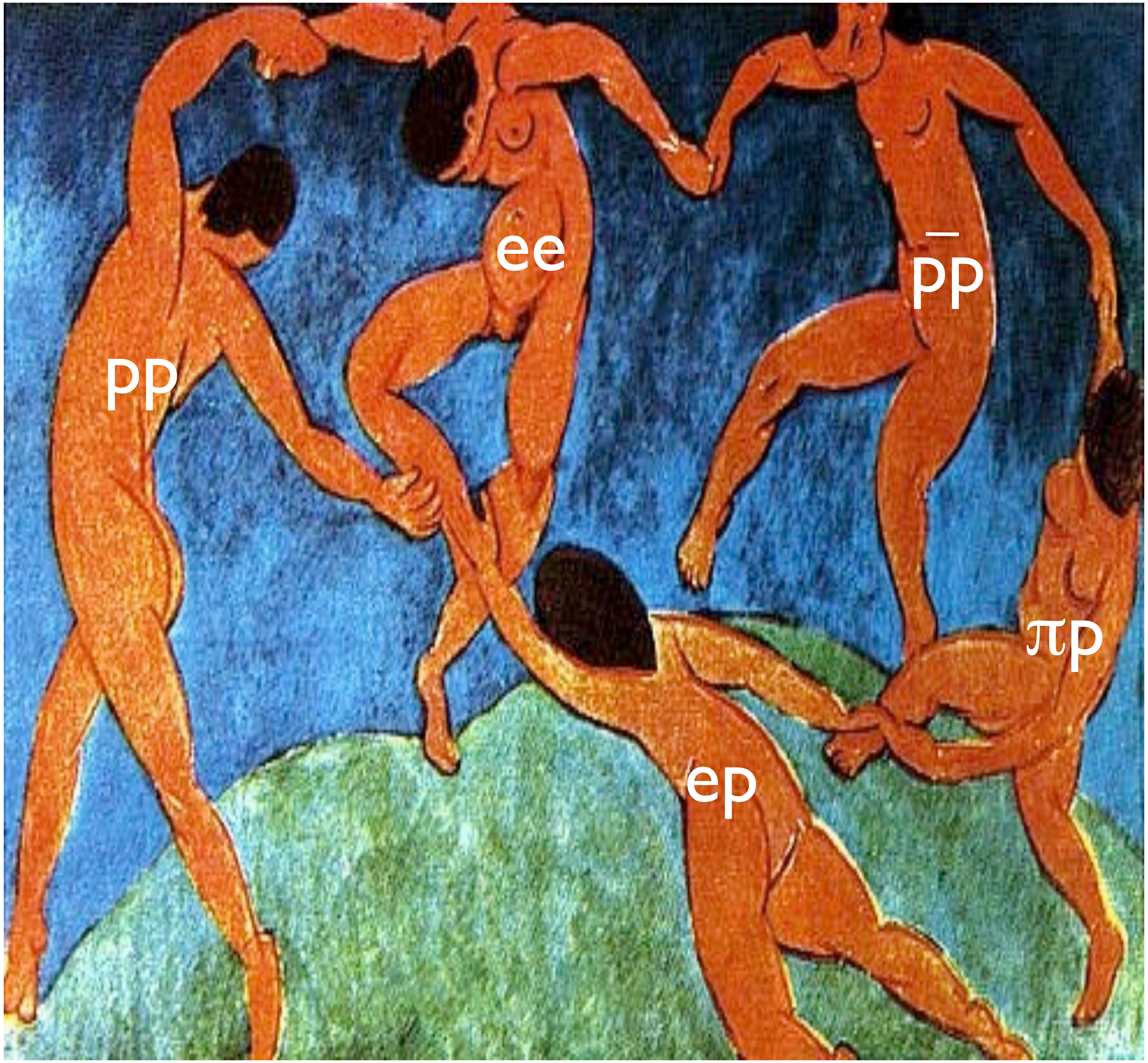
PRESENT AND FUTURE

The TMD treasure map *(from M. Contalbrigo's talk)*

PRESENT AND FUTURE

The TMD treasure map *(from M. Contalbrigo's talk)*

A 10 years party



We opened a window to a new world....

Jump in and see you at the beach....