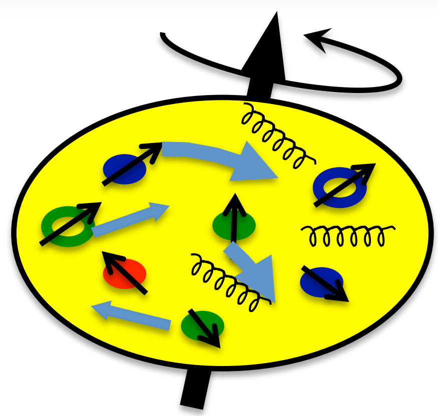
Spin Physics Highlights: WG6



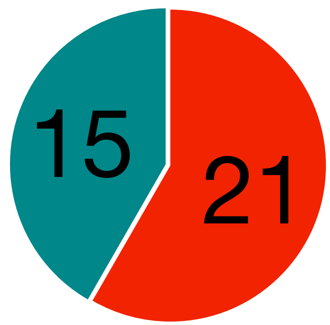
Francesca Giordano, Ted Rogers, Patricia Solvignon

DIS 2015: spin session

Proton Helicity

Hari Guragain
Xuan Li
Devika S Gunarathne
Mike Beaumier
Nilanga Liyanage

Experiment
Theory



Future Experiments

Zhihong Ye
Markus Diefenthaler
Elke C Aschenauer

GPDs

Philipp K Gorg
Carlos M Camacho
Maxime Defurne
Pawel Sznajder

Simonetta Liuti
Carlos Granados

And more...

Peter Lowdon (Boundary terms)
Aurore Courtoy (DiHadrons)
Nobuo Sato (proton/nuclear pdf)
Tomas Kasemets (double parton scattering)

TMDs

Isabella Garzia
Anselm Vossen
Erin Seder
Giulio Sbrizzai
Salvatore Fazio
Kalyan Allada
Kenneth Barish
James L Drachenberg

John Collins
Wenjuan Mao
Lingyun Dai
Osvaldo Gonzales
Cristian Pisano
Matthias Burkardt

Twist 3

Yuji Koike
Daniel Pytoniak
(Andreas Metz)

Spin Physics and Transverse Structure

TMD structures for quark and gluon PDFs

Piet Mulders

QUARKS	$\not p$	$\not p \gamma_5$	$\not p \gamma^\alpha \gamma_5$
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_{1T}, $h_{1T}^\perp$

GLUONS	$-g_T^{\alpha\beta}$	$\varepsilon_T^{\alpha\beta}$	$p_T^{\alpha\beta}$
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_{1T}^g, $h_{1T}^{\perp g}$

Plenary Session

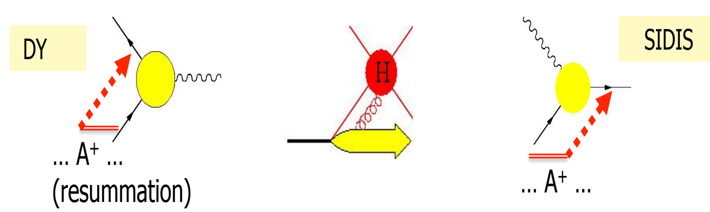
Non-universality because of process dependent gauge links

$$\Phi_{ij}^{q[C]}(x, p_T; n) = \int \frac{d(\xi.P)\, d^2\xi_T}{(2\pi)^3} e^{i p.\xi} \langle P | \overline{\psi}_j(0) U_{[0,\xi]}^{[C]} \psi_i(\xi) | P \rangle_{\xi.n=0}$$

TMD

path dependent gauge link

- Gauge links associated with dimension zero (not suppressed!) collinear $A^n = A^+$ gluons, leading for TMD correlators to process-dependence:



TMD factorization, Non-Perturbative Evolution

John Collins

$$\frac{\mathrm{d}\ln \tilde{f}_{f/H}(x, b_\mathsf{T}; Q^2; Q)}{\mathrm{d}\ln Q} = \gamma(\alpha_s(Q)) - \int_{\mu_b}^{Q} \frac{\mathrm{d}\mu}{\mu} \gamma_K(\alpha_s(\mu)) + \tilde{K}(b_\mathsf{T}; \mu_b)$$
$$= \gamma(\alpha_s(Q)) - \int_{\mu_{b_*}}^{Q} \frac{\mathrm{d}\mu}{\mu} \gamma_K(\alpha_s(\mu)) + \tilde{K}(b_*; \mu_{b_*}) - g_K(b_\mathsf{T}; b_{\max})$$

$$g_K(b_\mathsf{T}; b_{\max}) = g_0(b_{\max}) \left(1 - \exp\left[- \frac{C_F \alpha_s(\mu_{b_*}) b_\mathsf{T}^2}{\pi g_0(b_{\max})\, b_{\max}^2} \right] \right)$$
$$g_0(b_{\max}) = g_0(b_{\max,0}) + \frac{2C_F}{\pi} \int_{C_1/b_{\max,0}}^{C_1/b_{\max}} \frac{d\mu'}{\mu'} \alpha_s(\mu')$$

(JCC & Rogers, PRD 91, 074020 (2015), arXiv:1412.3820)

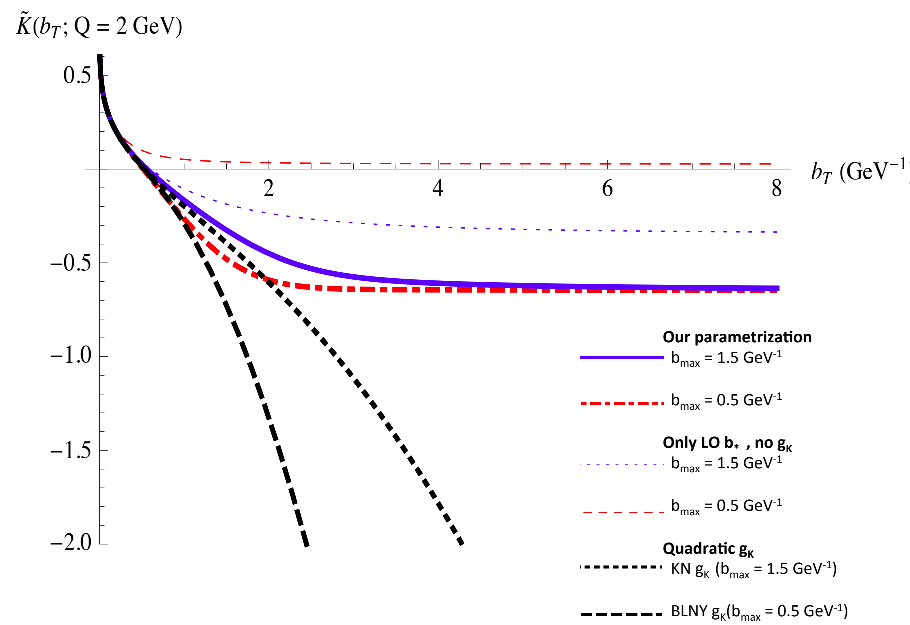
TMD factorization, Non-Perturbative Evolution

John Collins

$$\frac{\mathrm{d}\ln \tilde{f}_{f/H}(x, b_\mathrm{T}; Q^2; Q)}{\mathrm{d}\ln Q} = \gamma(c$$

$$= \gamma(c$$

Results with new parameterization for $\tilde{K}$



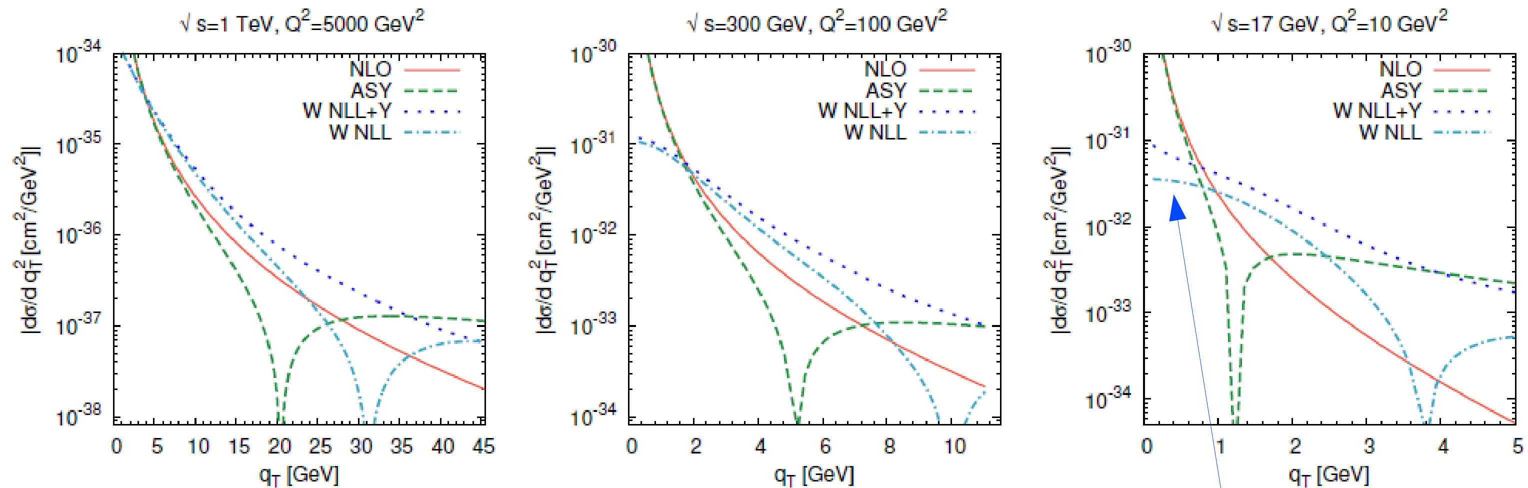
$$g_K(b_\mathrm{T}; b_\mathrm{max}) = g_0(b_\mathrm{max}) \left(1 - \exp\right.$$

$$g_0(b_\mathrm{max}) = g_0(b_{\mathrm{max},0}) + \frac{2C_F}{\pi} \int$$

(JCC & Rogers, PRD 91, 074020 (2015), arXiv:1412.3820)

J Osvaldo González Hernández

Large and small q_T Matching



$$\frac{d\sigma^{\rm NLO}}{dx\,dy\,dz\,dq_T^2} = \frac{d\sigma^{\rm ASY}}{dx\,dy\,dz\,dq_T^2} + Y$$

sizable contribution from Y term

M. Boglione, J Osvaldo González Hernández, S. Melis, A. Prokudin, JHEP 1502 (2015) 095

- Message: Large-small q_T matching is important and delicate

Overview of Twist-3 Factorization

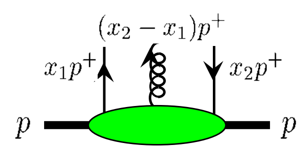
by Yuji Koike

- Twist-3 approaches has been extensively developed for both pole and non-pole contributions.

⋆ Quark-gluon correlation functions in the ⊥ polarized nucleon.

"*F*-type"

$$\int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle PS|\bar{\psi}_j(0) g F^{\alpha\beta}(\mu n) n_\beta \psi_i(\lambda n)|PS\rangle$$
$$= \frac{M_N}{4} (\not{p})_{ij}\, \epsilon^{\alpha p n S_\perp} G_F(x_1,x_2) + i \frac{M_N}{4} (\gamma_5 \not{p})_{ij}\, S_\perp^\alpha \widetilde{G}_F(x_1,x_2) + \cdots$$



"*D*-type"

$$\int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle PS|\bar{\psi}_j(0) D_\perp^\alpha(\mu n) \psi_i(\lambda n)|PS\rangle$$
$$= \frac{M_N}{4} (\not{p})_{ij}\, \epsilon^{\alpha p n S_\perp} G_D(x_1,x_2) + i \frac{M_N}{4} (\gamma_5 \not{p})_{ij}\, S_\perp^\alpha \widetilde{G}_D(x_1,x_2) + \cdots$$

M_N: Nucleon mass.

$p^2 = n^2 = 0,\ p \cdot n = 1$

Overview of Twist-3 Factorization

by Yuji Koike

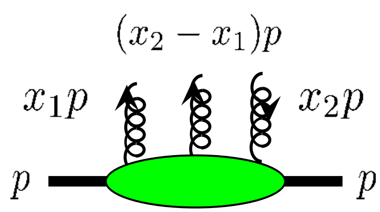
- Twist-3 approaches has been extensively developed for both pole and non-pole contributions.

⋆ Quark-gluon correlation functions in the ⊥ polarized nucleon.

"*F*-type"

$(x_2 - x_1)p^+$

⋆ Twist-3 "three-gluon" correlation functions



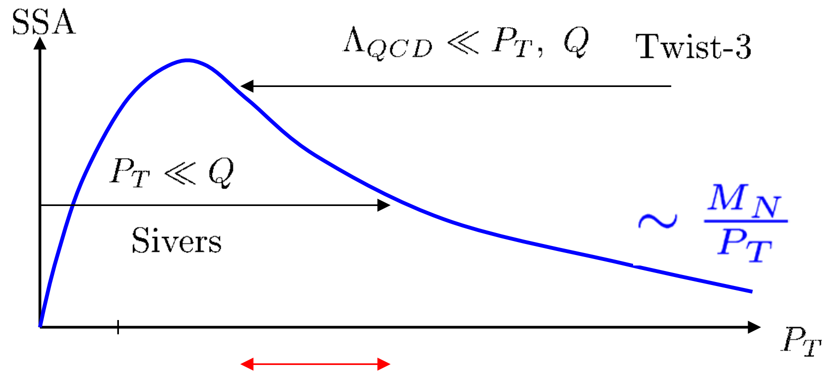
Beppu-Koike-Tanaka-Yoshida (PRD 82('10)054005)

See also, Belitsky-Ji-Lu-Osborne, PRD63,094012(2001)
Braun-Manashov-Pirnay, PRD80,114002(2009).

Overview of Twist-3 Factorization

by Yuji Koike

⋆ Relation between TMD and Twist-3 at intermediate P_T ($\Lambda_{\rm QCD} \ll P_T \ll Q$)



$\Lambda_{\rm QCD} \ll P_T \ll Q$

Twist-τ =
Suppressed by $\left(\frac{\Lambda_{\rm QCD}}{Q}\right)^{\tau-2}$

Equivalent for Sivers asymmetry $F^{\sin(\phi_h-\phi_S)}$ and for DY, consistently with $f_{1T}^{\perp}|_{\rm DIS} = -f_{1T}^{\perp}|_{\rm DY}$.

· Ji-Qiu-Vogelsang-Yuan (PRL 97('06)082002, PLB638('06)178).
· Koike-Vogelsang-Yuan (PLB'07) ($\leftarrow \widetilde{G}_F$-contribution)

· 3-gluon contribution to $F^{\sin(\phi_h-\phi_S)}$ is also shown to be consistent between the two frameworks. (Dai,Kang,Prokdin,Vitev,arXiv:1409.5851[hep-ph])

· Similar equivalence also shown for Collins asymmetry $F^{\sin(\phi_h+\phi_S)}$.

Lingyun Dai

Kang, Prokudin, Vitev arXiv:1409.5851

NLO weighted Sivers asymmetry in SIDIS: three-gluon correlator

Three gluon contribution to:

- evolution of Qiu-Sterman function

$$\frac{\partial}{\partial \ln \mu_f^2} T_{q,F}(x_B, x_B, \mu_f^2) = \frac{\alpha_s}{2\pi} \int_{x_B}^{1} \frac{dx}{x^2} P_{q\leftarrow g}(\hat{x}) \left(\frac{1}{2}\right) \left[O(x,x,\mu_f^2) + O(x,0,\mu_f^2) + N(x,x,\mu_f^2) - N(x,0,\mu_f^2)\right]$$

- coefficient function

$$C_{q\leftarrow g,1}(\hat{x}) = \frac{\alpha_s}{4\pi}\left[P_{q\leftarrow g}(\hat{x}) \ln\left(\frac{c^2}{b^2\mu^2}\right) + \hat{x}(1-\hat{x})\right],$$

$$C_{q\leftarrow g,2}(\hat{x}) = \frac{\alpha_s}{4\pi}\left[P_{q\leftarrow g}(\hat{x}) \ln\left(\frac{c^2}{b^2\mu^2}\right) - \frac{1}{2}\left(1 - 6\hat{x} + 6\hat{x}^2\right)\right].$$

- TMD and collinear twist-3 formalisms are consistent in $\Lambda_{QCD} \ll p_{h\perp} \ll Q$ region

Lingyun Dai

Kang, Prokudin, Vitev arXiv:1409.5851

NLO weighted Sivers asymmetry in SIDIS: three-gluon correlator

- three-gluon correlation functions contribution:

$$\frac{\partial}{\partial \ln \mu_f^2} T_{q,F}$$

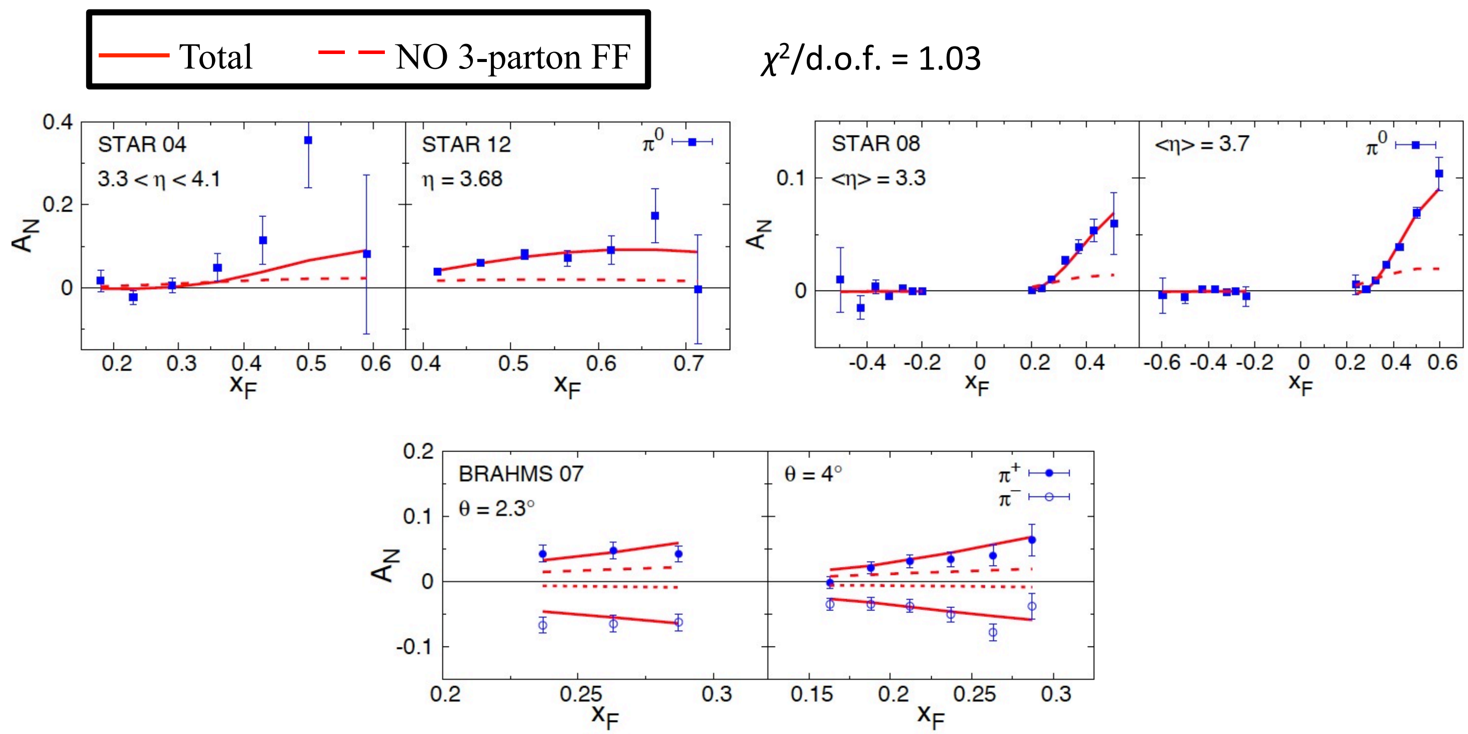
$$\frac{d\langle p_{h\perp}\Delta\sigma\rangle}{dx_B dy dz_h} = -\frac{z_h\sigma_0}{2}\frac{\alpha_s}{2\pi}\sum_q e_q^2 \int_{x_B}^1 \frac{dx}{x^2}\int_{z_h}^1 \frac{dz}{z} D_{h/q}(z)\Bigg\{\delta(1-\hat{z})\ln\left(\frac{Q^2}{\mu_f^2}\right)P_{q\leftarrow g}(\hat{x})$$
$$\times\left(\frac{1}{2}\right)\left[O(x,x,\mu_f^2)+O(x,0,\mu_f^2)+N(x,x,\mu_f^2)-N(x,0,\mu_f^2)\right]$$
$$+\left(\frac{1}{4}\right)\left[\left(\frac{dO(x,x,\mu_f^2)}{dx}-\frac{2O(x,x,\mu_f^2)}{x}\right)\hat{H}_1+\left(\frac{dO(x,0,\mu_f^2)}{dx}-\frac{2O(x,0,\mu_f^2)}{x}\right)\hat{H}_2\right.$$
$$\left.+\frac{O(x,x,\mu_f^2)}{x}\hat{H}_3+\frac{O(x,0,\mu_f^2)}{x}\hat{H}_4\right]+\left(\frac{1}{4}\right)\left[\left(\frac{dN(x,x,\mu_f^2)}{dx}-\frac{2N(x,x,\mu_f^2)}{x}\right)\hat{H}_1\right.$$
$$\left.-\left(\frac{dN(x,0,\mu_f^2)}{dx}-\frac{2N(x,0,\mu_f^2)}{x}\right)\hat{H}_2+\frac{N(x,x,\mu_f^2)}{x}\hat{H}_3-\frac{N(x,0,\mu_f^2)}{x}\hat{H}_4\right]\Bigg\},$$

- TMD and collinear twist-3 formalisms are consistent in $\Lambda_{QCD} \ll p_{h\perp} \ll Q$ region

Transverse single-spin asymmetries in pion and photon production from proton-proton collisions

Kanazawa, Koike, Metz, DP - PRD 89(RC) (2014)

Daniel Pitonyak

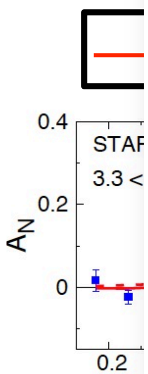


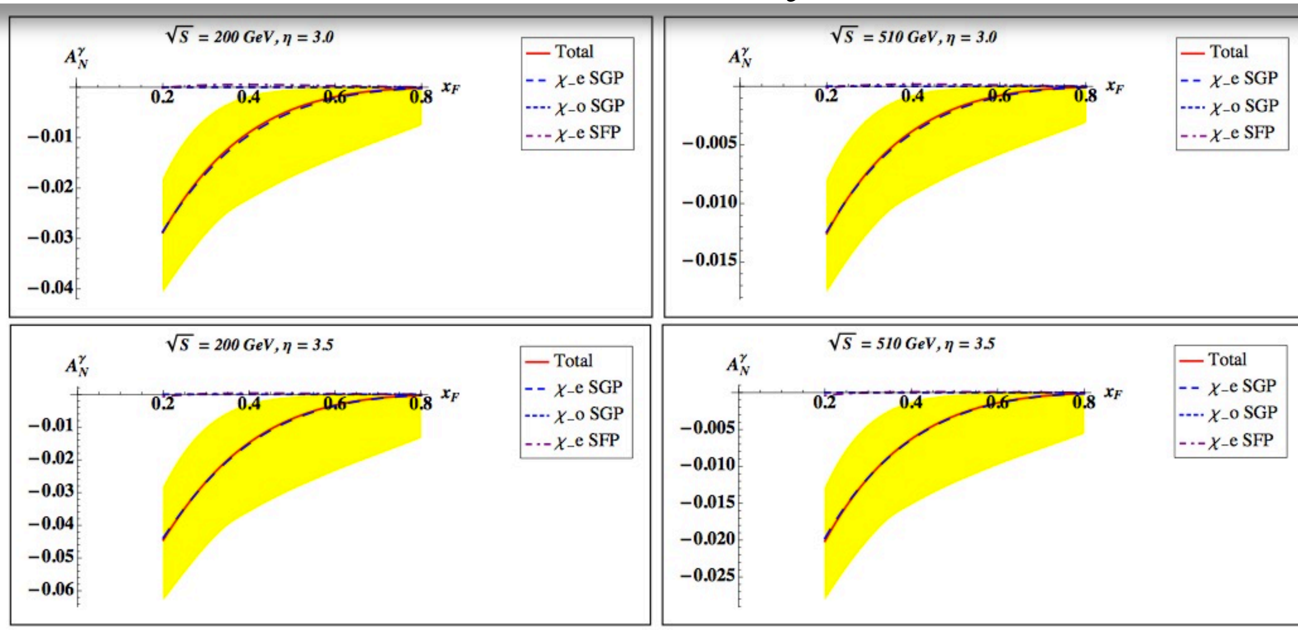
- Including the (total) fragmentation term leads to very good agreement with the RHIC data, especially with its characteristic rise towards large x_F
- Without the 3-parton FF, one has difficulty describing the RHIC data
- *H* term dominates the asymmetry

Transverse single-spin asymmetries in pion and photon production from proton-proton collisions

Kanazawa, Koike, Metz, DP - PRD 89(RC) (2014)

Daniel Pitonyak





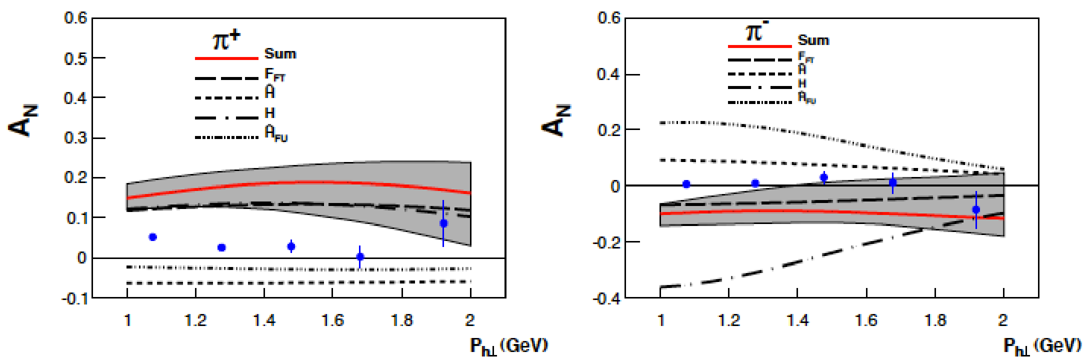
- Measurements planned by PHENIX and STAR at RHIC
- Sivers-type contribution is dominant, others are negligible
  - ➡ Can "cleanly" extract QS function to help resolve "sign mismatch" issue
  - ➡ Clear measurement of a negative A_N would be a strong indication on the process dependence of the Sivers function (see also TSSA in inclusive DIS – Metz, et al. (2012), and in jet production from A_NDY – Gamberg, Kang, Prokudin (2013))

Twist-3 Spin Observables for Single-Hadron Production in DIS

(A. Metz, Temple University, Philadelphia)

talk mainly based on
arXiv:1407.5078, Gamberg, Kang, A.M., Pitonyak, Prokudin
arXiv:1411.6459, Kanazawa, A.M., Pitonyak, Schlegel
arXiv:1503.02003, Kanazawa, A.M., Pitonyak, Schlegel

- Numerical results and discussion
  - comparison with HERMES data (JLab data are at very low $P_{h\perp}$)



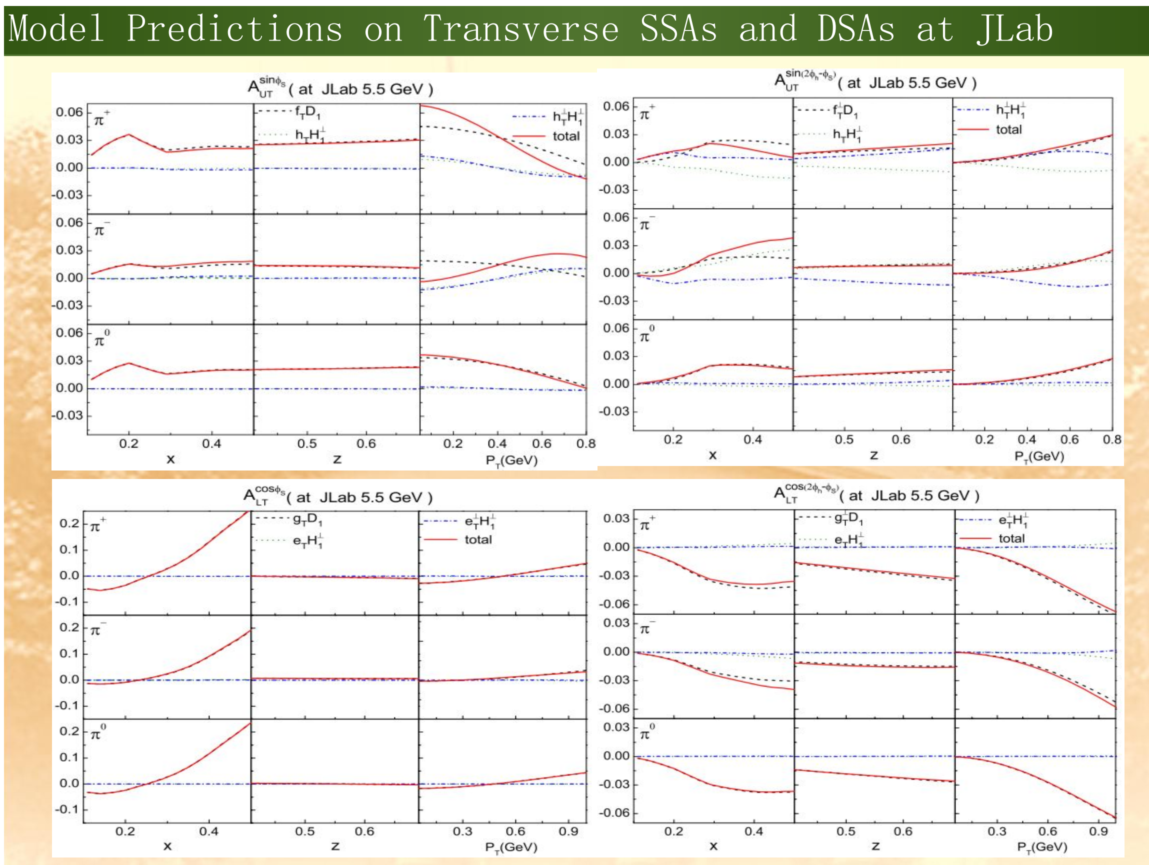
* error band based on uncertainties of $f_{1T}^{\perp}$, h_1, $H_1^{\perp}$ only
* relatively poor comparison with data, especially for π^+ production
* potential reasons for discrepancy:

(1) no error band for twist-3 FF $\hat{H}_{FU}^{\Im}$ and hence for FF H

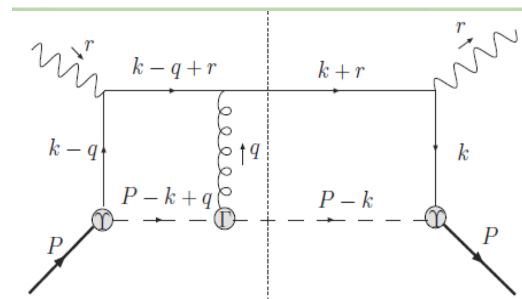
(2) (significant) other source(s) for A_N in $p\,p^{\uparrow} \to h\,X$

(3) leading order formalism not appropriate for rather low $P_{h\perp}$ of available data; HERMES: even data at highest $P_{h\perp}$ dominated by quasi-real photo-production $\longrightarrow$ calculation of NLO correction needed

Transverse single-spin asymmetries $A_{UT}^{\sin\phi_S}$ and $A_{UT}^{\sin(2\phi_h-\phi_S)}$ in SIDIS



Wenjuan Mao



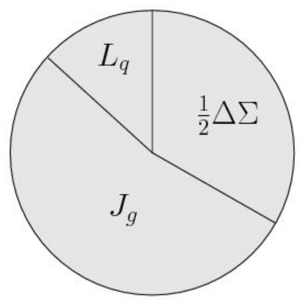
Phys.Rev. D90 (2014) 1, 014048

Transverse Force on Quarks in DIS

Matthias Burkardt

The Nucleon Spin Pizzas 12

Ji decomposition



'pizza tre stagioni'

$$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + L_q + J_g$$

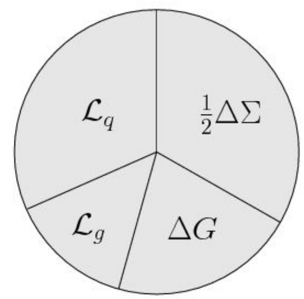
$$\frac{1}{2}\Delta q = \frac{1}{2}\int d^3x \,\langle P,S|\, q^\dagger(\vec{x})\Sigma^3 q(\vec{x})\,|P,S\rangle$$

$$L_q = \int d^3x \langle P,S| q^\dagger(\vec{x})\left(\vec{x}\times i\vec{D}\right)^3 q(\vec{x})|P,S\rangle$$

$$J_g = \int d^3x \,\langle P,S|\, \left[\vec{x}\times\left(\vec{E}\times\vec{B}\right)\right]^3 |P,S\rangle$$

- $i\vec{D} = i\vec{\partial} - g\vec{A}$

Jaffe-Manohar decomposition



'pizza quattro stagioni'

light-cone framework & gauge $A^+ = 0$

$$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

$$\mathcal{L}_q = \int d^3r \langle P,S|\, \bar{q}(\vec{r})\gamma^+\left(\vec{r}\times i\vec{\partial}\right)^z q(\vec{r})|P,S\rangle$$

$$\Delta G = \varepsilon^{+-ij}\int d^3r \,\langle P,S|\, \mathrm{Tr} F^{+i}A^j\,|P,S\rangle$$

$$\mathcal{L}_g = 2\int d^3r \langle P,S|\mathrm{Tr} F^{+j}\left(\vec{x}\times i\vec{\partial}\right)^z A^j|P,S\rangle$$

manifestly gauge invariant definition for each term exists ($\rightarrow$ Hatta)

Transverse Force on Quarks in DIS

Matthias Burkardt

straight line ($\rightarrow$Ji)

$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + L_q + J_g$

$L_q = \int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left(\vec{x} \times i\vec{D}\right)^z q(\vec{x})|P,S\rangle$

- $i\vec{D} = i\vec{\partial} - g\vec{A}$

light-cone staple ($\rightarrow$ Jaffe-Manohar)

$\frac{1}{2} = \sum_q \frac{1}{2}\Delta q + \mathcal{L}_q + \Delta G + \mathcal{L}_g$

$\mathcal{L}^q = \int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left(\vec{x} \times i\vec{\mathcal{D}}\right)^z q(\vec{x})|P,S\rangle$

$i\mathcal{D}^j = i\partial^j - gA^j(x^-, \mathbf{x}_\perp) - g\int_{x^-}^{\infty} dr^- F^{+j}$

difference $\mathcal{L}^q - L^q$

$\mathcal{L}^q - L^q = -g\int d^3x \langle P,S|\bar{q}(\vec{x})\gamma^+\left[\vec{x} \times \int_{x^-}^{\infty} dr^- F^{+\perp}(r^-, \mathbf{x}_\perp)\right]^z q(\vec{x})|P,S\rangle$

Towards a Direct Measurement of the Quark Orbital Angular Momentum Distribution

Simonetta Liuti
University of Virginia

$$\underbrace{x\tilde{G}_2(x) + xG_2(x)}_{t=3} = \underbrace{\int d^2k_T \frac{k_T \cdot \Delta_T}{\Delta_T^2} G_{14}\left(x, 0, \vec{k}_T\right) + \int d^2k_T \frac{k_T^2}{M^2} F_{14}\left(x, 0, \vec{k}_T\right)}_{\tau=2} + \underbrace{\bar{G}_2^{tw3}}_{\tau=3}$$

$$x\tilde{G}_2(x) + xG_2(x) = G_{14}^{(1')} + F_{14}^{(1)} + \bar{G}_2^{tw3}$$

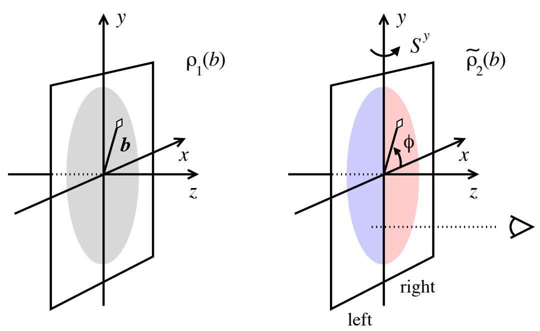
A sum rule relating Ji and JM OAM

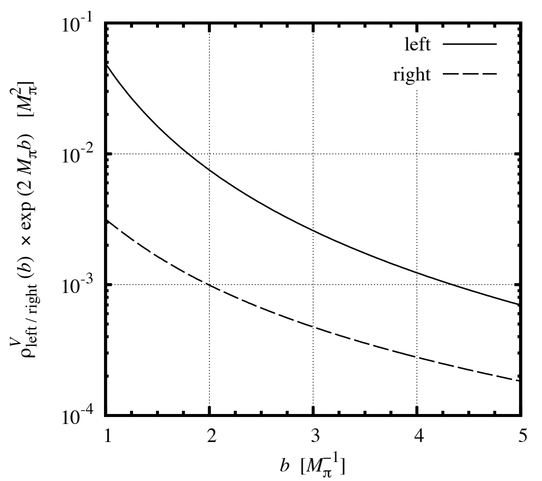
Left-right asymmetry of transverse densities from chiral dynamics

Carlos Granados

Transverse polarization and asymmetry

CG, C. Weiss, arXiv:1503.04839 [hep-ph]





LFWF components of a transversely polarized nucleon,

$$\begin{aligned}
\Phi_{\rm tr}(+,+) &= \sin\alpha\, U_1, \\
\Phi_{\rm tr}(-,-) &= -\sin\alpha\, U_1, \\
\Phi_{\rm tr}(+,-) &= U_0 + \cos\alpha\, U_1, \\
\Phi_{\rm tr}(-,+) &= -U_0 + \cos\alpha\, U_1,
\end{aligned}$$

Define Left and Right transverse densities from LFWF at $\alpha = 0$,

$$\left.\begin{array}{l} \rho^V_{\rm left}(b) \\ \rho^V_{\rm right}(b) \end{array}\right\} = \int_0^1 dy\, \frac{|\Phi_{\rm tr}(y, \mp r_T \boldsymbol{e}_x; -, +)|^2}{2\pi y \bar{y}^3}$$

$$[r_T = b/\bar{y}]$$

to find for the charge and magnetization densities that

$$\left.\begin{array}{l} \rho^V_1(b) \\ \widetilde{\rho}^V_2(b) \end{array}\right\} = \frac{1}{2}[\pm\rho^V_{\rm left}(b) + \rho^V_{\rm right}(b)].$$

-$\widetilde{\rho}_2$ measures Left-Right asymmetry of LF currents in the nucleon.
Strikingly large in the chiral periphery, generates the near equality $\rho_1 \approx -\widetilde{\rho}_2$.

Spatial Boundary Terms, Angular Momentum and QFT

Peter Lowdon

- It turns out that by using this more rigorous QFT approach one can determine a necessary and sufficient condition for these terms to vanish [Lowdon (2014)]:

$$\int d^3x \, \partial_i B^i \;\; vanishes\ in\ \mathcal{H} \quad \Longleftrightarrow \quad \int d^3x \, \partial_i B^i |0\rangle = 0$$

An interesting feature of this condition is that it only depends on the action of the operator on the vacuum state

…and from this one has the following condition:

$$\text{If } \exists |p\rangle \in \mathcal{H} \text{ s.t: } \langle p| \int d^3x \, \partial_i B^i |0\rangle \neq 0 \implies \int d^3x \, \partial_i B^i \neq 0$$

→ which can then be applied to the superpotentials $\mathcal{S}_1^i$ and $\mathcal{S}_2^i$

[P. Lowdon, *Nucl. Phys. B* **889**, 801 (2014).]

Spatial Boundary Terms, Angular Momentum and QFT

Peter Lowdon

- It turns ou
can determ
to vanish [

$\int$

An interesting
depends on the a

…*and fron*

If $\exists|p\rangle$

→ which car

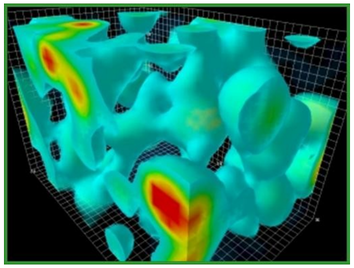
- So in this case if $\exists|p\rangle \in \mathcal{H} \;\; s.t. \;\; \langle p|\mathcal{S}_1^i|0\rangle \neq 0$ or: $\langle p|\mathcal{S}_2^i|0\rangle \neq 0$ then $\mathcal{S}_1^i$ or $\mathcal{S}_2^i$ are non-vanishing as operators
- Choosing $|p\rangle = |0\rangle$ one has: $\langle 0|\mathcal{S}_1^i|0\rangle \sim \epsilon^{ijk}\epsilon^{0jkl}\langle 0|\overline{\psi}\gamma^l\gamma^5\psi|0\rangle$

Evidence [Pasupathy, Singh (2006)] *to suggest this is non-vanishing*

→ which suggests: $J^i_{QCD} \neq S^i_q + L^i_q + S^i_g + L^i_g$

- This condition therefore casts doubt on the validity of the Jaffe-Manohar angular momentum operator decomposition

→ *what's interesting about the apparent failure of this decomposition is that it follows from the non-trivial structure of the QCD vacuum*



[The University of Adelaide (2015)]

[J. Pasupathy and R. K. Singh, *Int. J. Mod. Phys. A* **21**, 5099 (2006).]

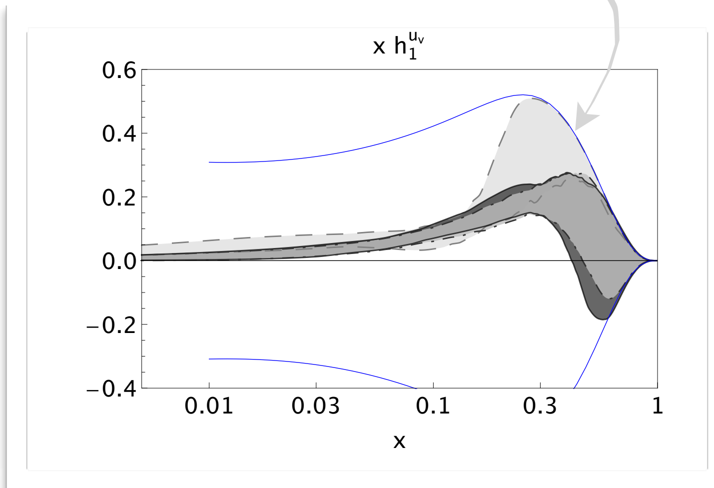
Update on the phenomenology of collinear Dihadron FFs

Aurore Courtoy

- **Collinear extraction** [Pavia]
- **TMD extraction** [Anselmino et al, Kang et al]
- **GPD extraction** [Goldstein et al]

State-of-the-art: Extractions of transversity

OLD 1σ error band from replicas @2.4 GeV^2



NEW 1σ error band from replicas @2.4 GeV^2

$\alpha_S(M_Z^2)$=0.125 $\alpha_S(M_Z^2)$=0.139

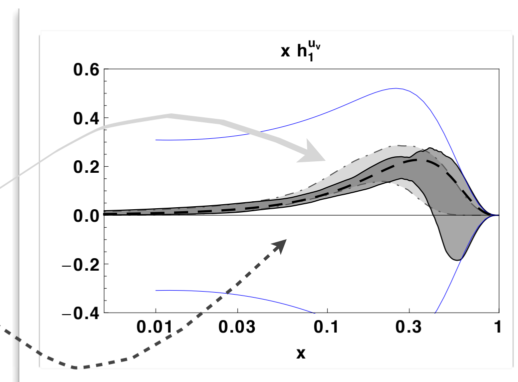
NEW FOR DIFF EXTRACTION

➡COMPASS data for identified pions

➡Two Values for $\alpha_S(M_Z^2)$

➡Replica methods for both pol. DiFF & transversity

Torino 2013 @2.4 GeV^2



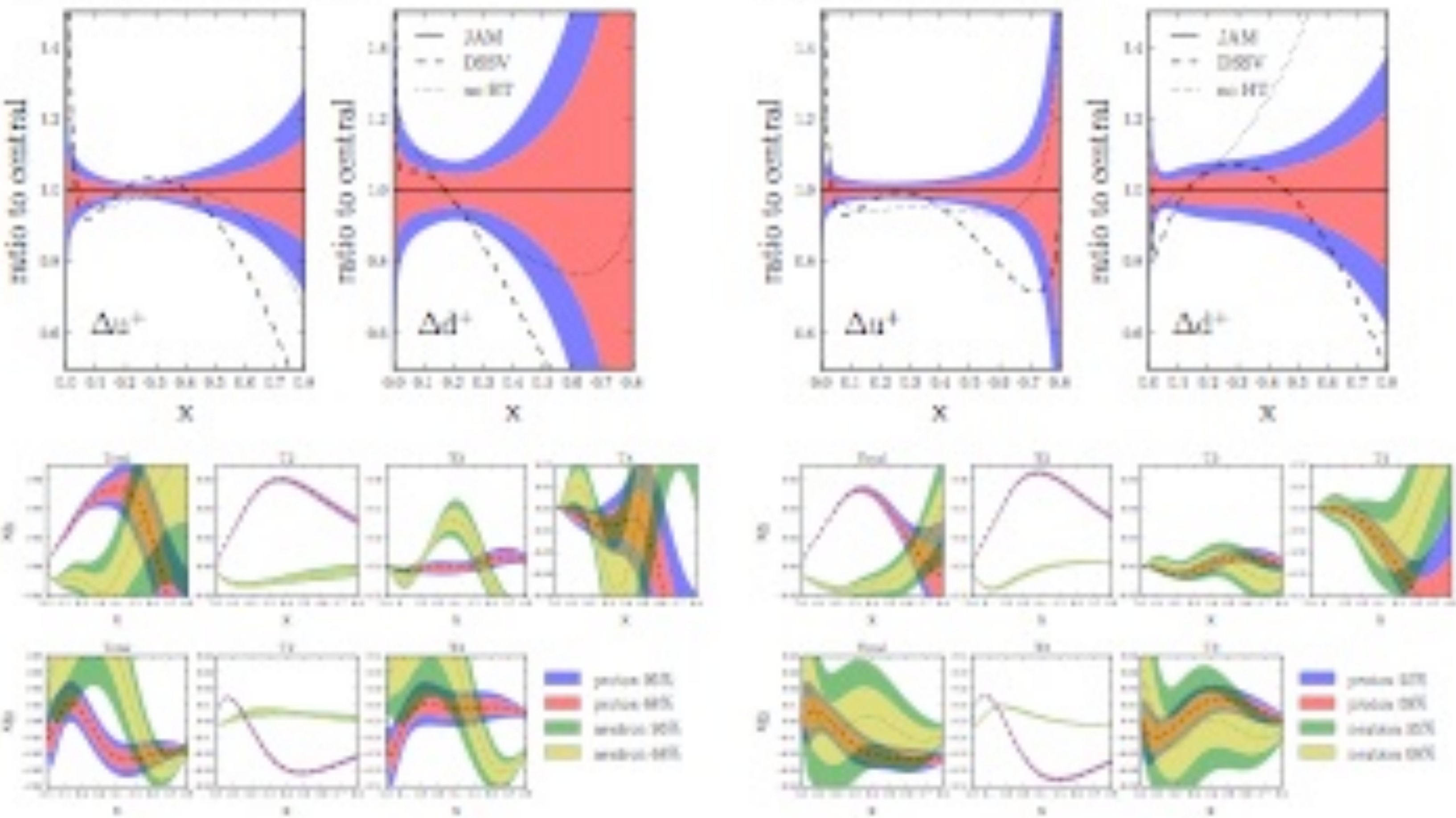
Kang et al central value

Pavia 15
1503.03495

Nobuo Sato

The JAM analysis (summary)

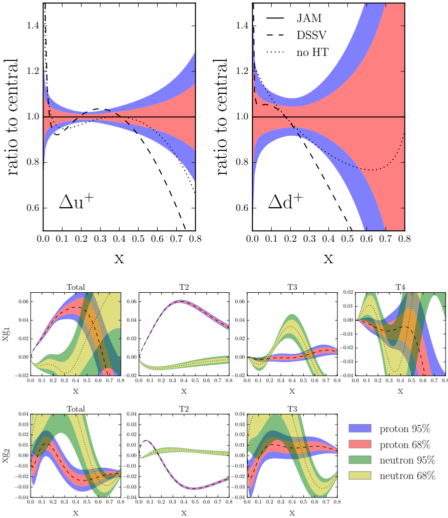
without JLab data | with JLab data



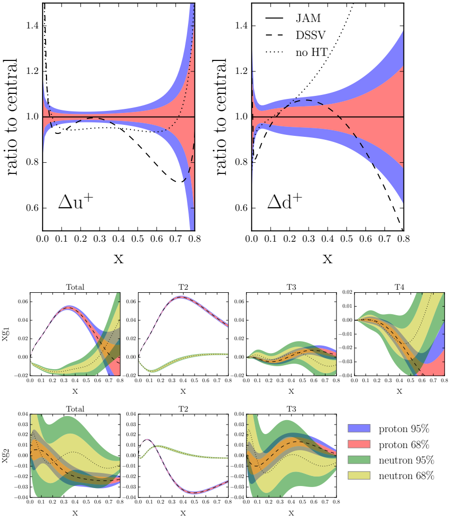
- The new JLab data conclusively favors the extraction of g_1 and g_2 with HT contributions.

The JAM analysis (summary)

without JLab data



with JLab data



- The new JLab data conclusively favors the extraction of g_1 and g_2 with HT contributions.

Polarization in Double Parton Scattering

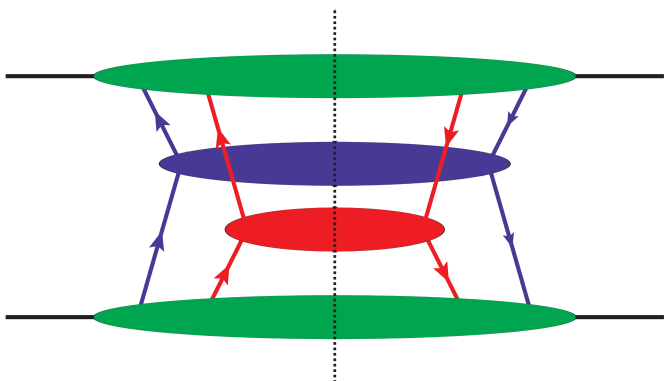
Tomas Kasemets

Polarization in DPS

- Longitudinal polarization:
  - Changes rate as well as rapidity and $|p_T|$ distributions
- Transverse quark/linear gluon polarization
- Leads to azimuthal asymmetries
- Double Drell-Yan

$$d\sigma_{DPS}(pp \to ZZ \to l_1\bar{l}_1 l_2 \bar{l}_2) \subset A\cos(2\Delta\phi) f_{\delta q \delta q} f_{\delta \bar{q} \delta \bar{q}}$$

TK, M. Diehl, 2012



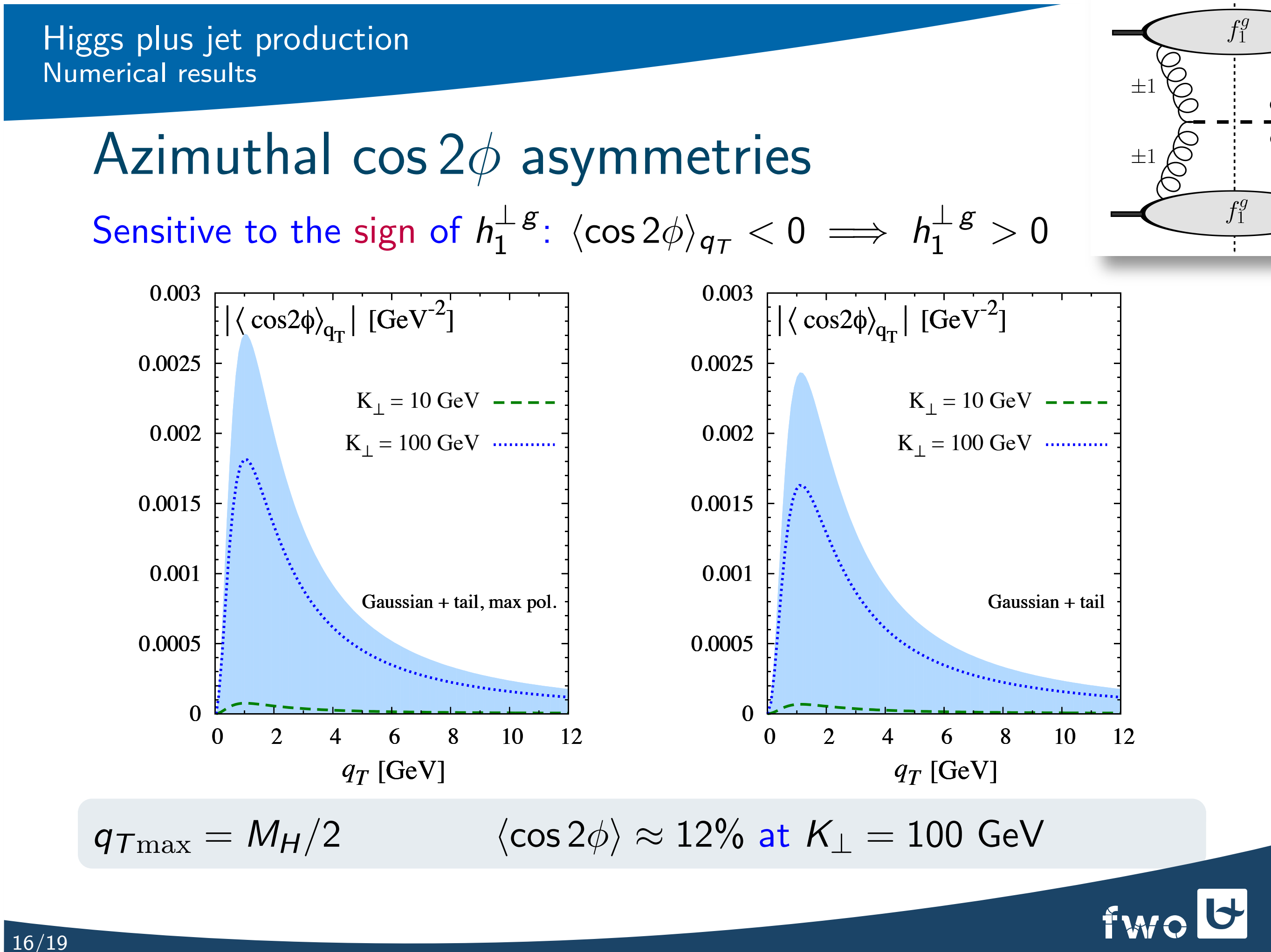
$$d\sigma_{DPS}(pp \to c_1\bar{c}_1 c_2 \bar{c}_2) \subset B\cos(2\Delta\phi) f_{\delta g g} f_{g \delta g} + C\cos(4\Delta\phi) f_{\delta g \delta g} f_{\delta g \delta g}$$

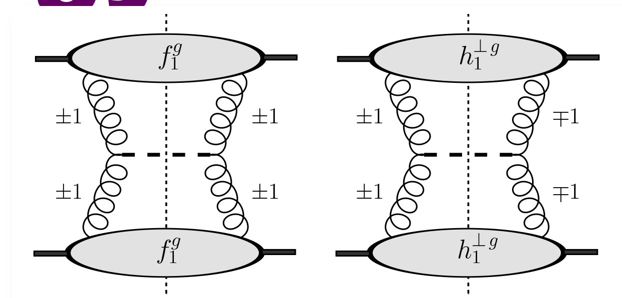
for linearly polarized gluons

Echevarria, TK, Mulders, Pisano, 2015

Gluon TMDs and Higgs Phenomenology

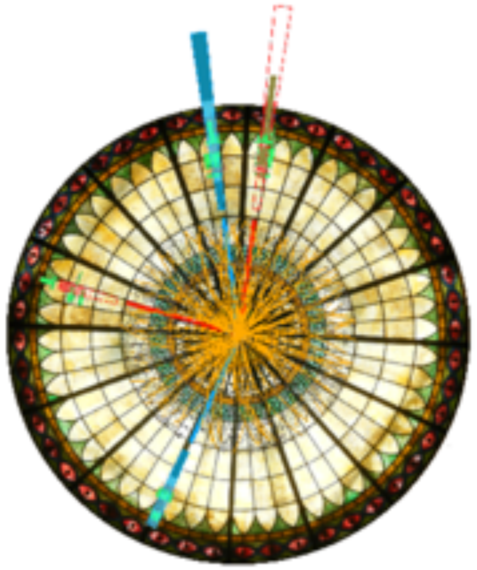
Cristian Pisano





News from the Experiments

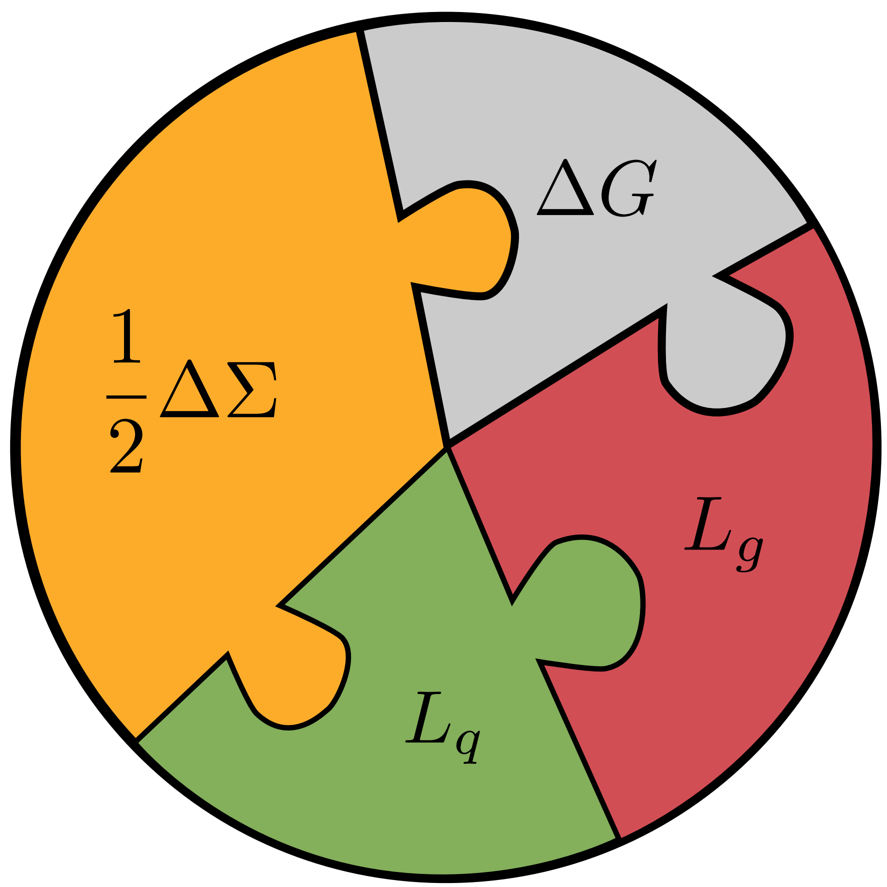
Francesca Giordano, Ted Rogers



Spin Puzzle

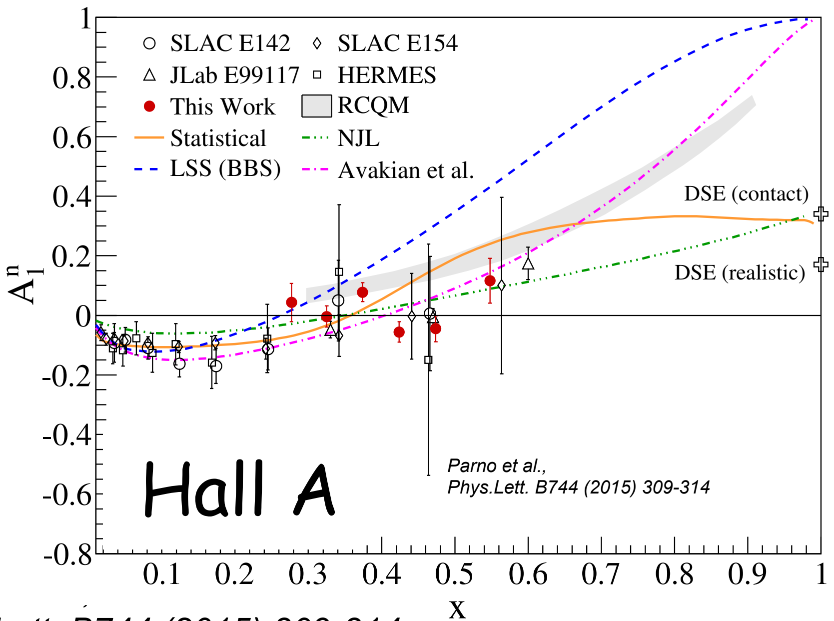
Parton contribution to the proton spin

$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark spins}} + \underbrace{\Delta G}_{\text{gluon spins}} + \underbrace{L_z}_{\text{quark\&gluon orbital motion}}$$

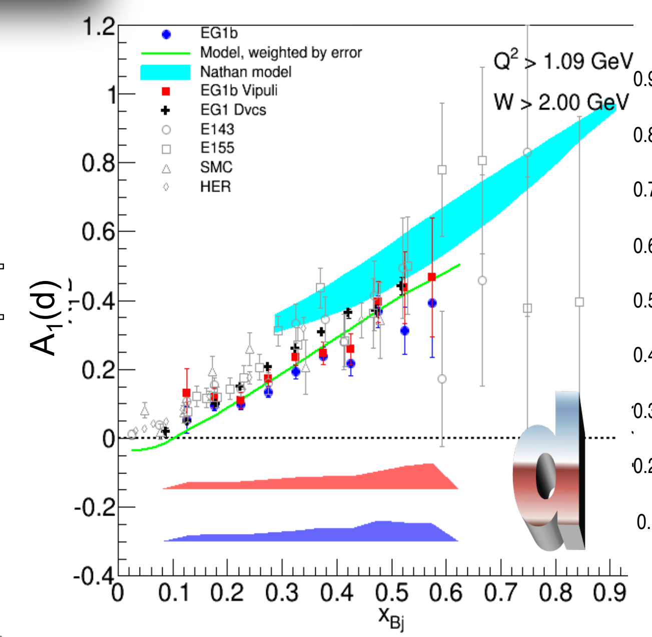


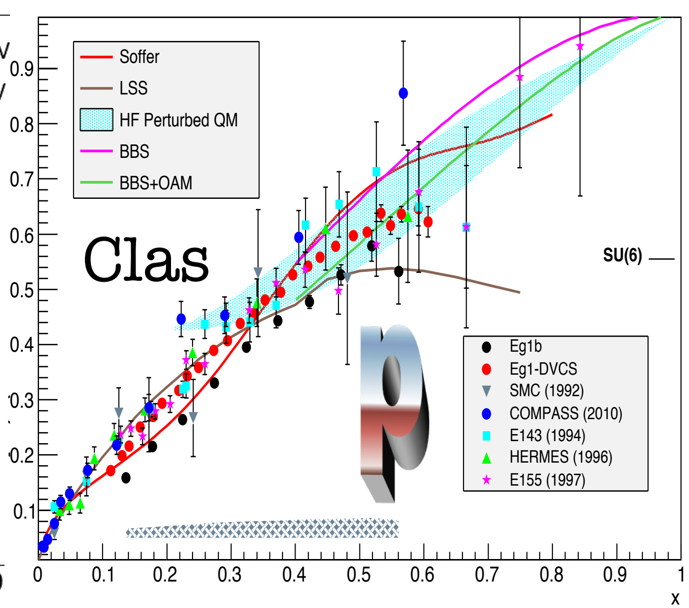
Proton helicity from Quarks:Valence

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{g_1}{F_1}$$



Phys.Lett. B744 (2015) 309-314

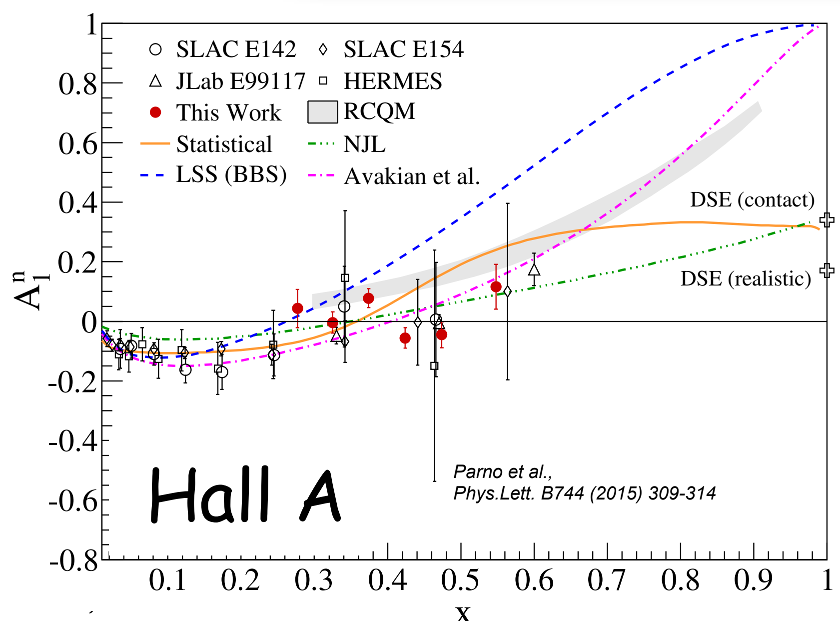




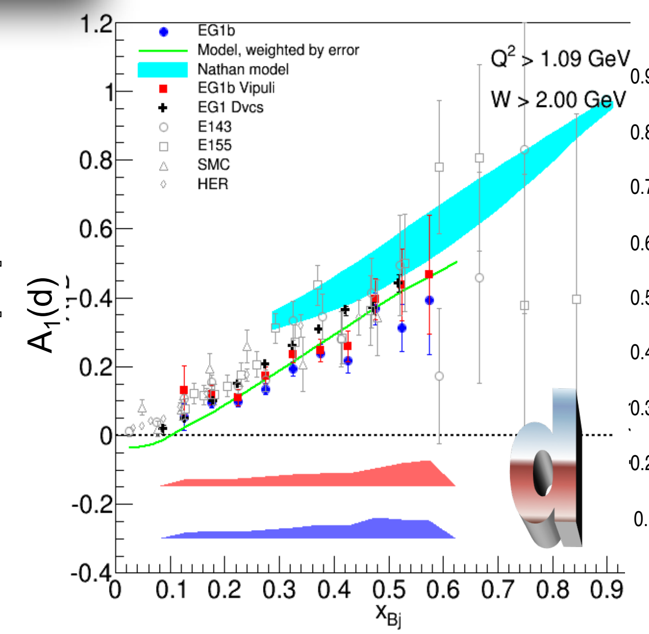
Proton helicity from Quarks:Valence

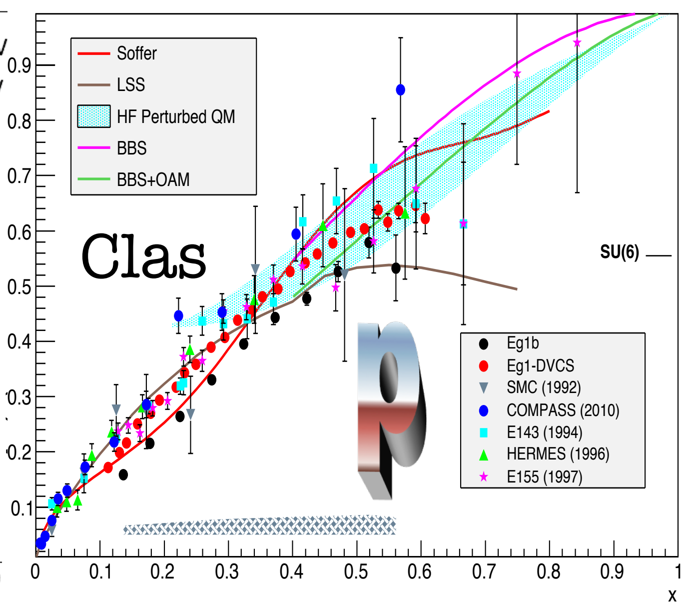
$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{g_1}{F_1}$$

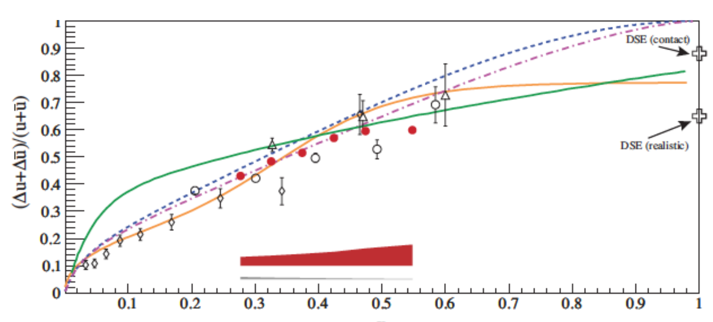
Jefferson Lab
Thomas Jefferson National Accelerator Facility

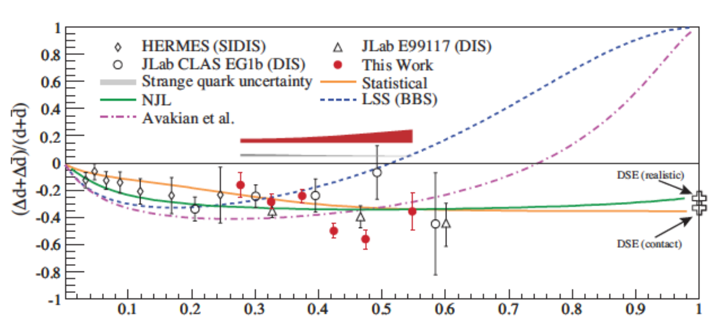


Phys.Lett. B744 (2015) 309-314





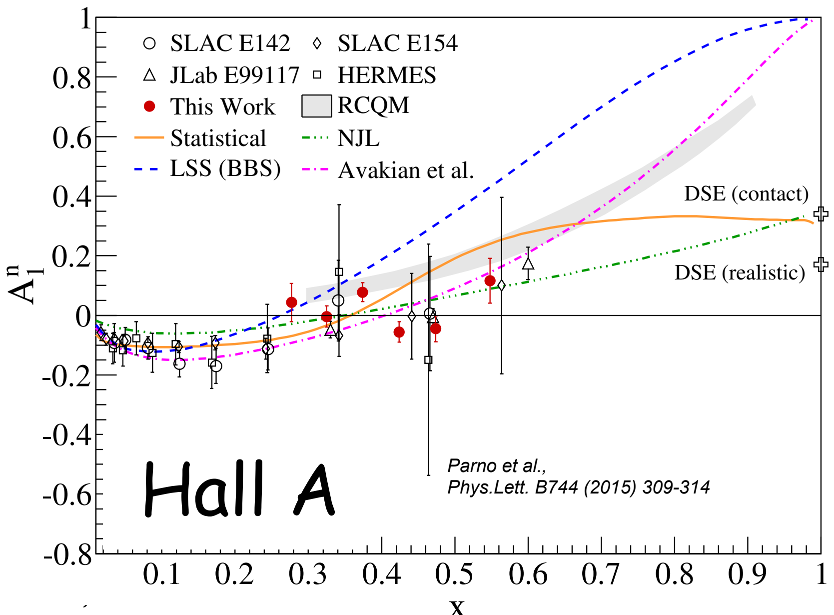




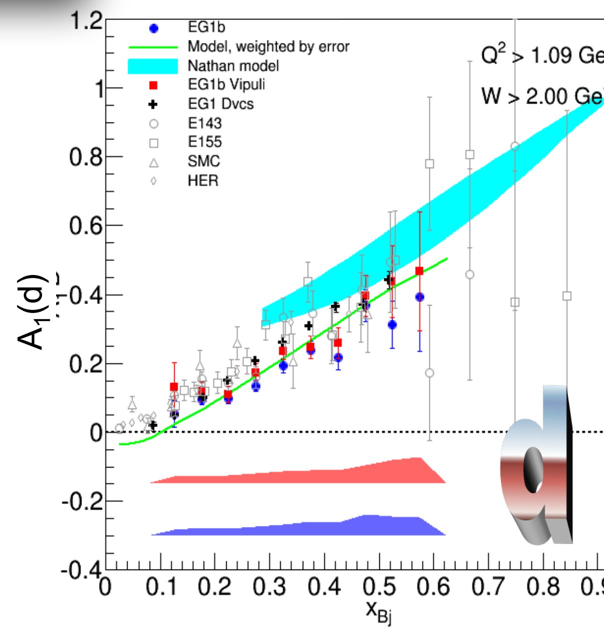
Proton helicity from Quarks:Valence

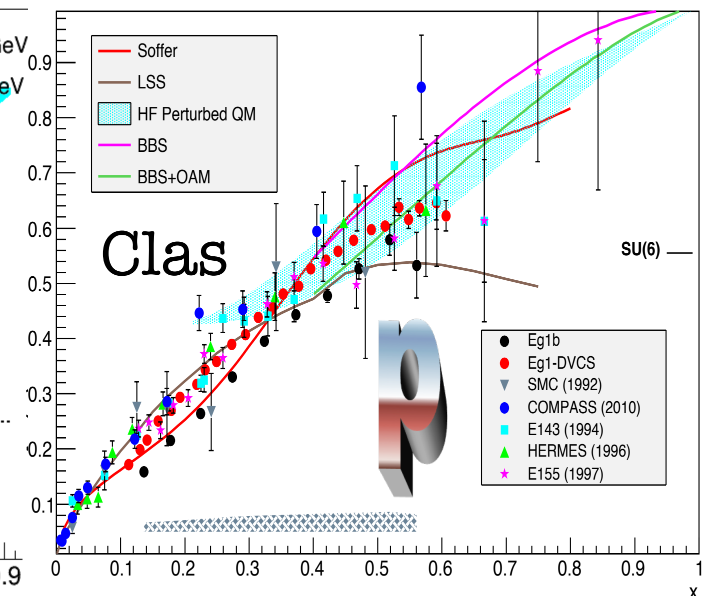
$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{g_1}{F_1}$$

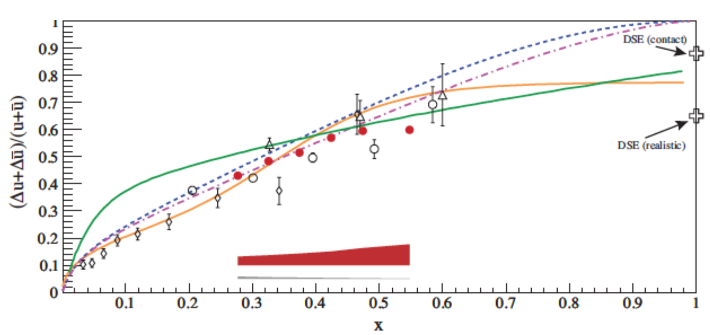
Jefferson Lab
Thomas Jefferson National Accelerator Facility

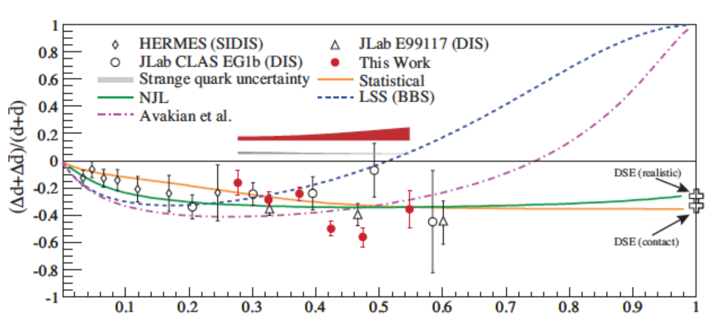


Phys.Lett. B744 (2015) 309-314



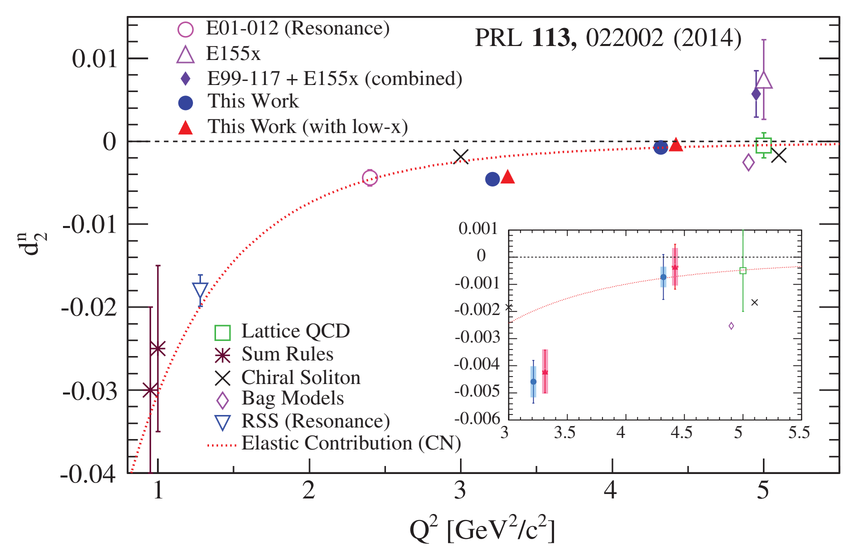




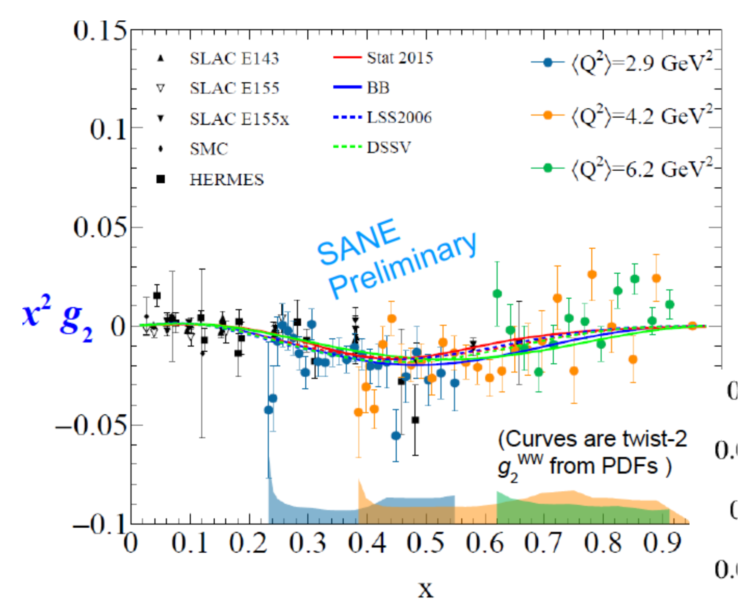


Moments of g_2 SF

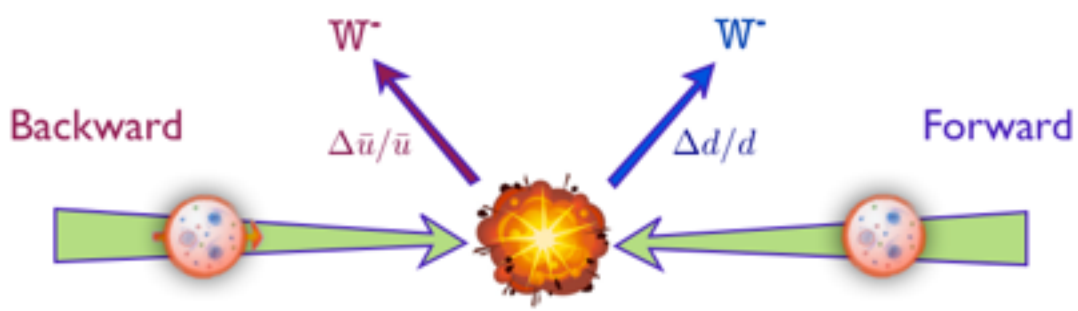
Hall A

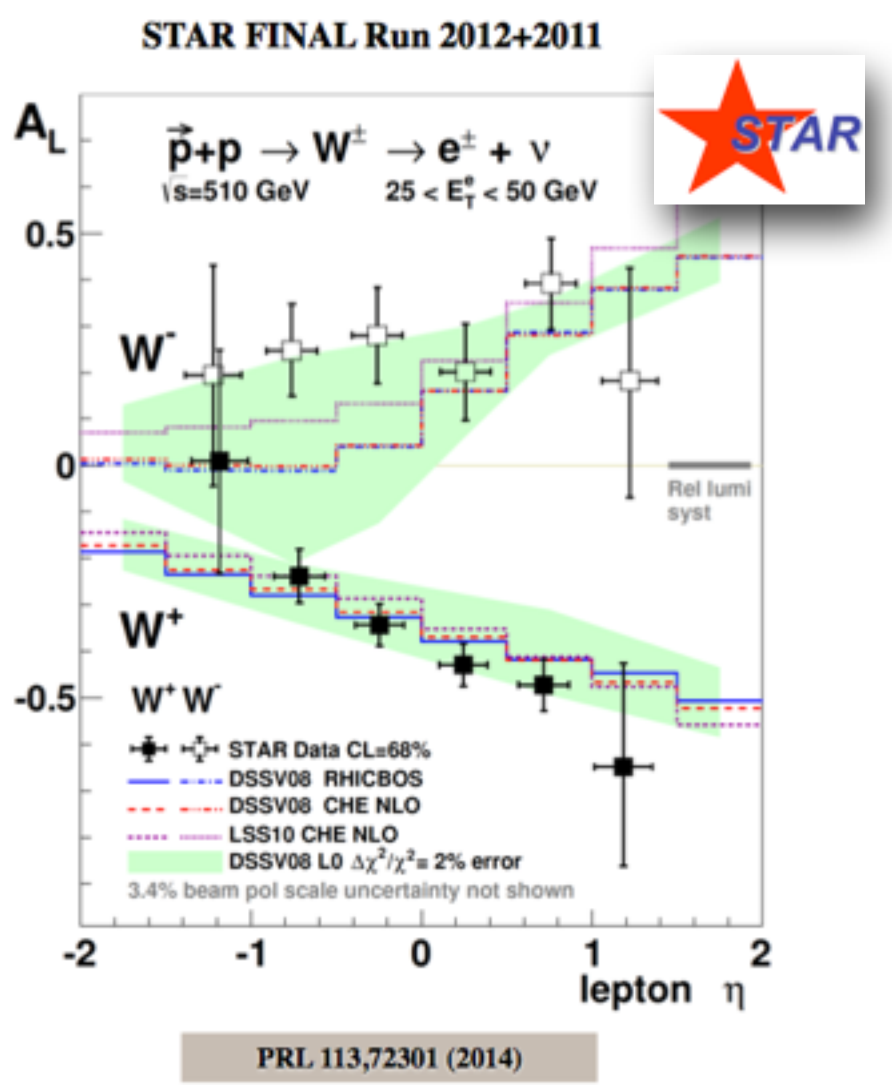


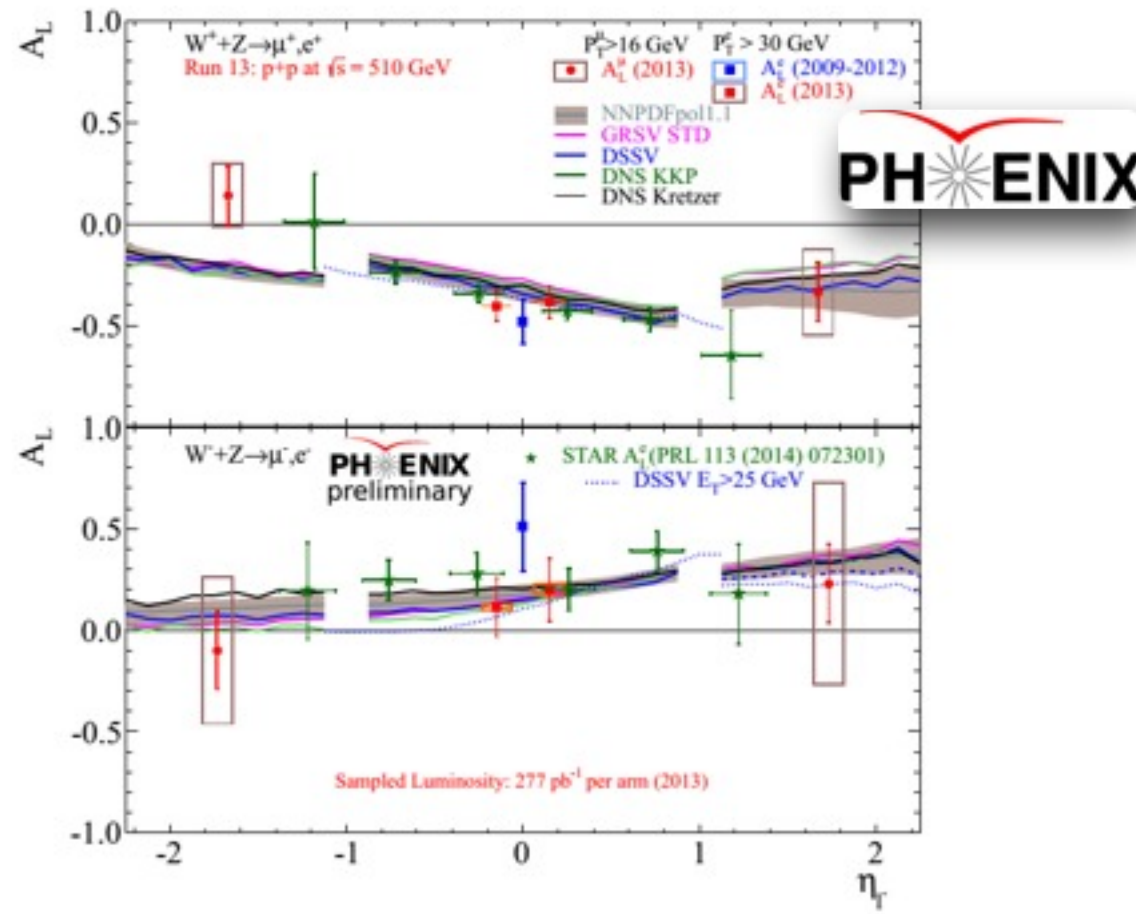
Hall C



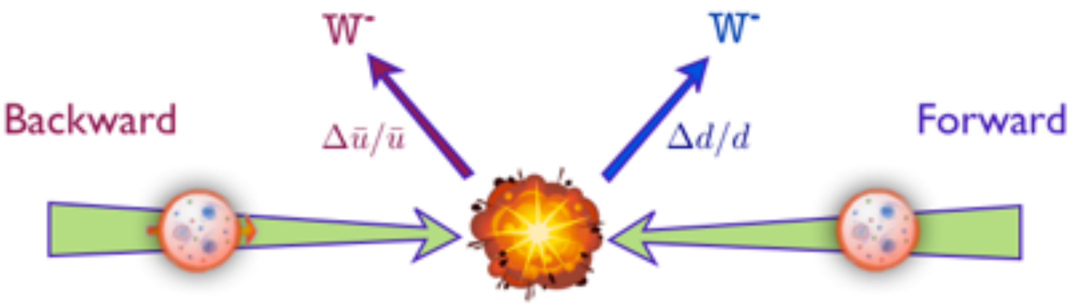
Proton helicity from Quarks: Sea

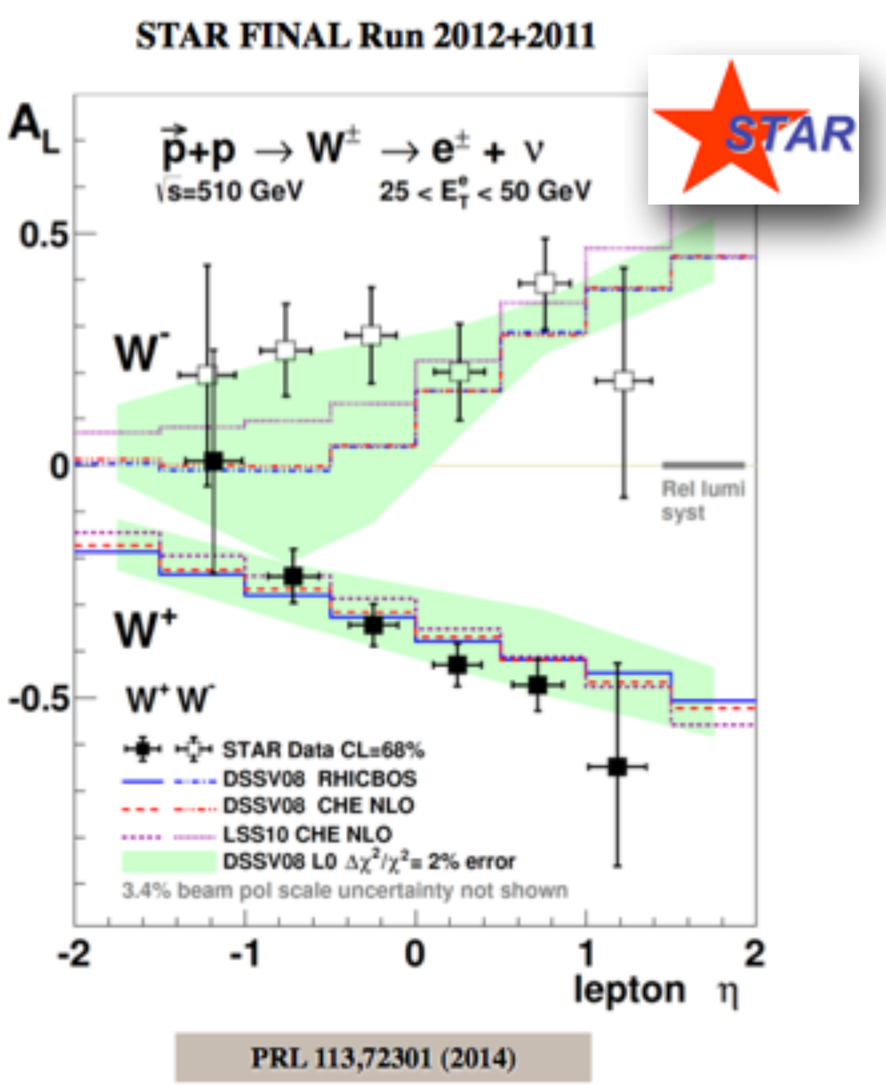


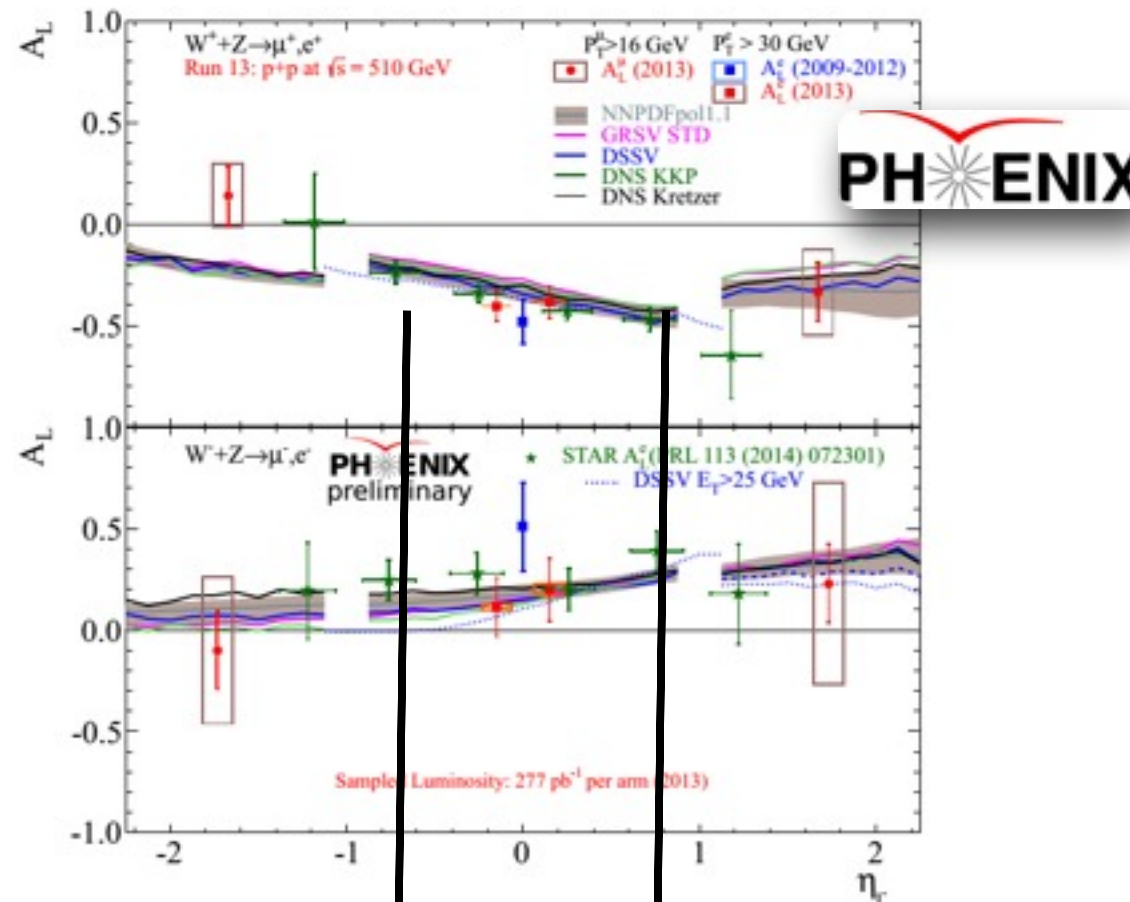


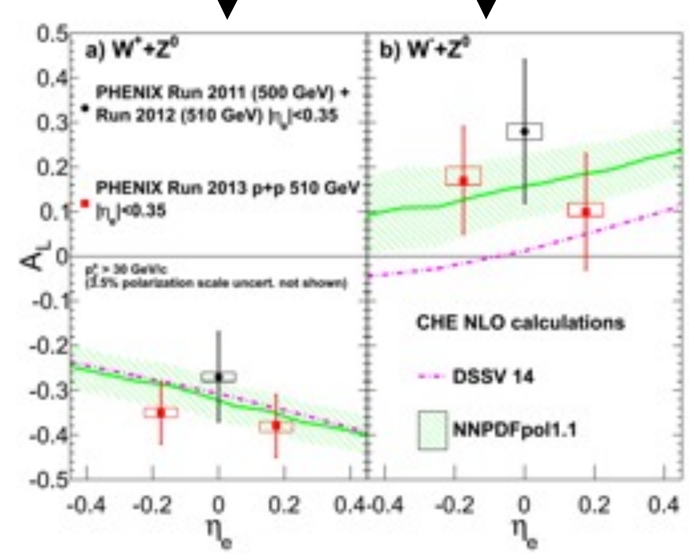


Proton helicity from Quarks: Sea



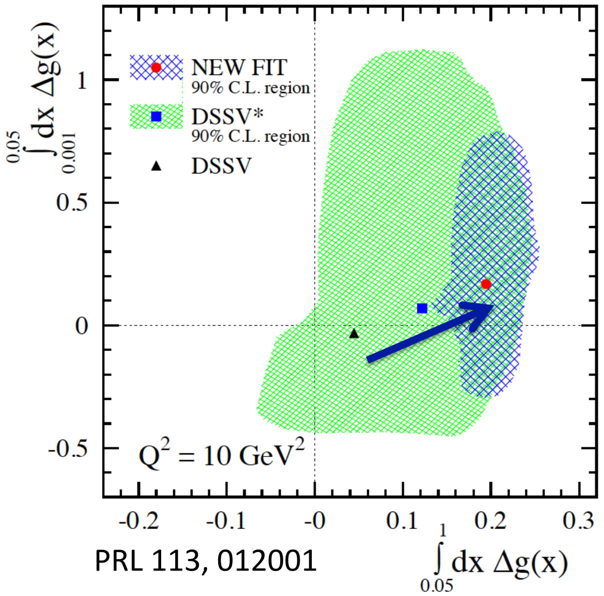




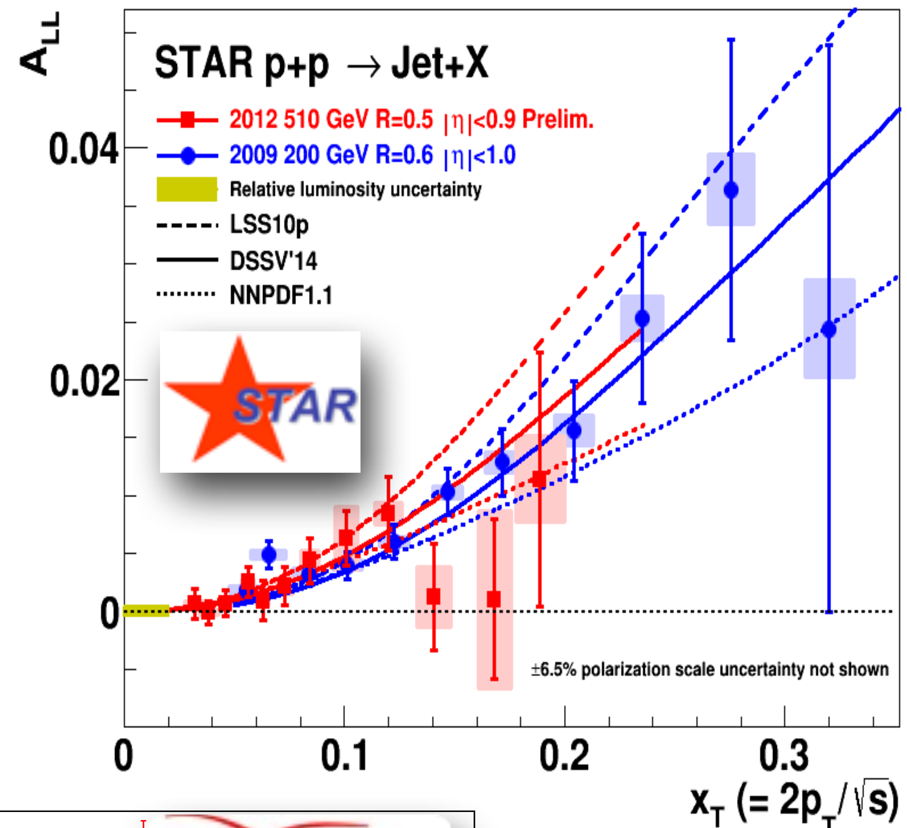


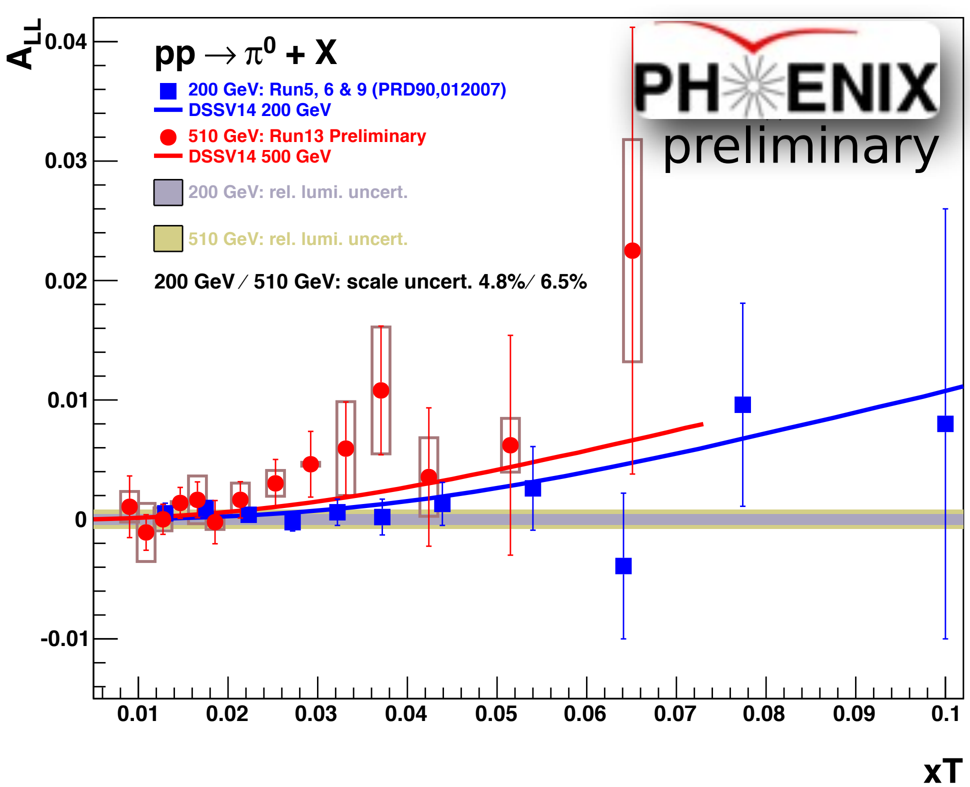
http://arXiv.org/pdf/1504.07451v1.pdf

Proton helicity from Gluons

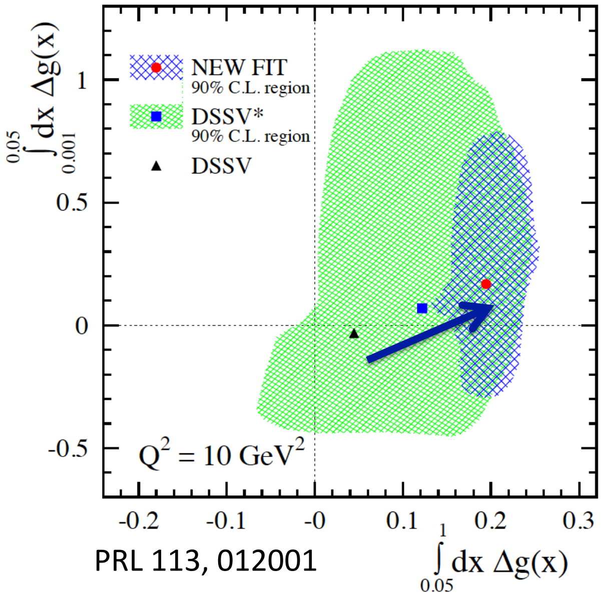


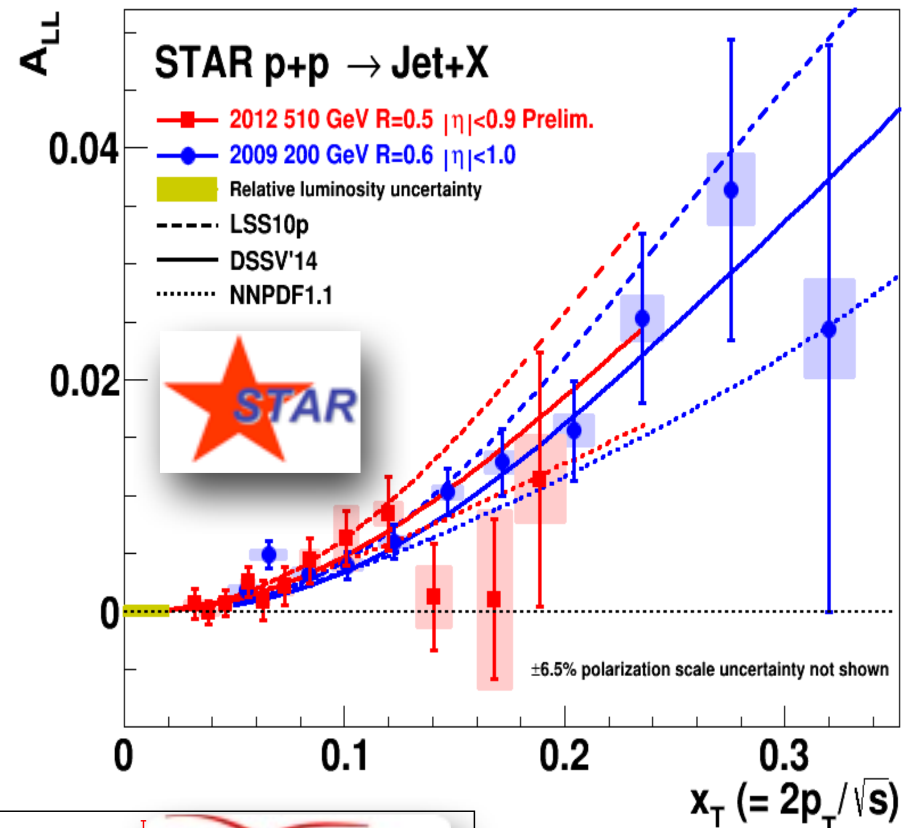
PRL 113, 012001

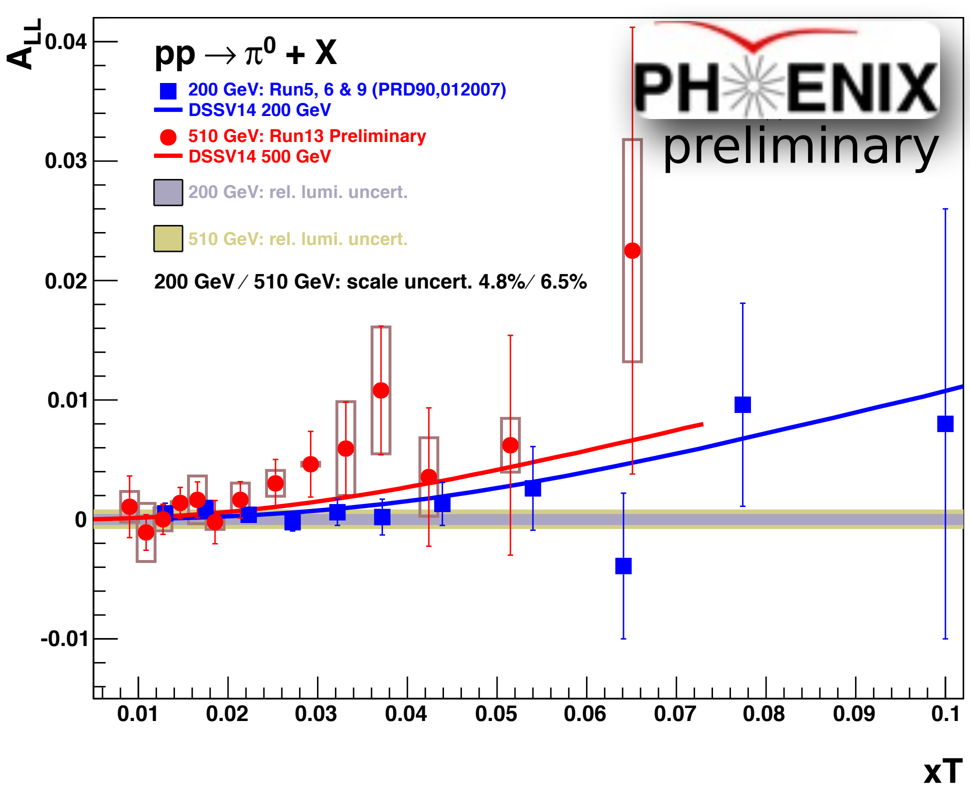




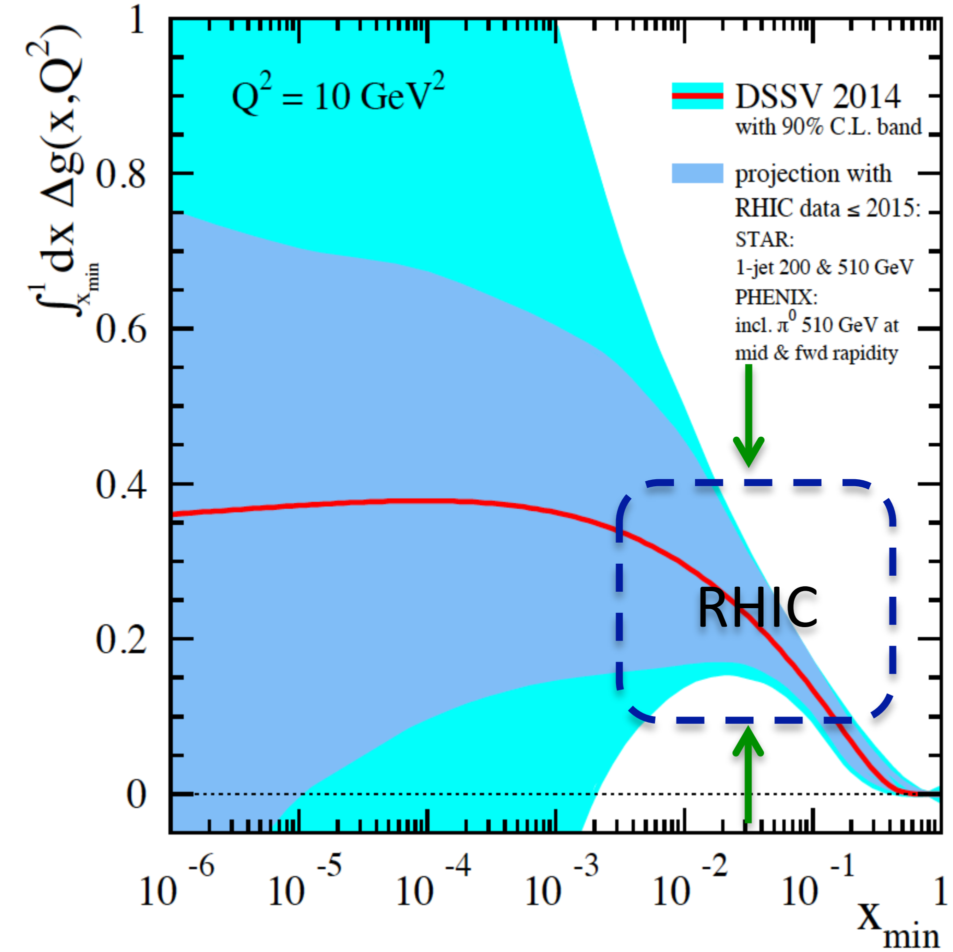
Proton helicity from Gluons







More data from 2013 and 2015

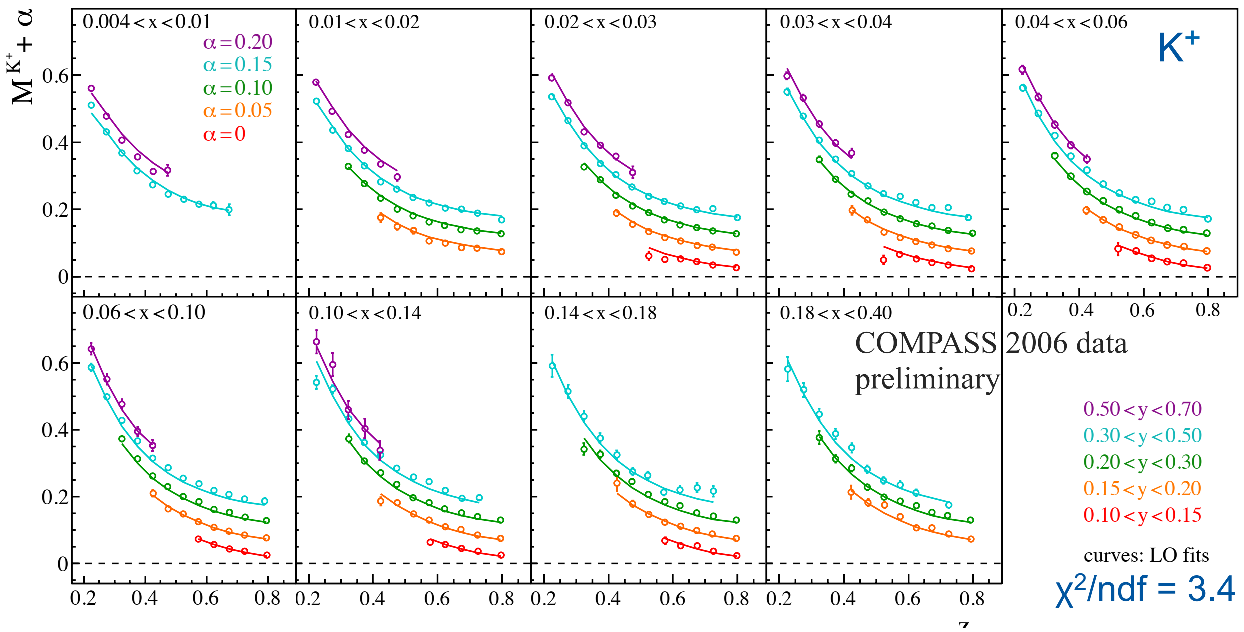


PDF & Fragmentation

Multi-D Kaon multiplicities

317 kinematic bins

Example of fit



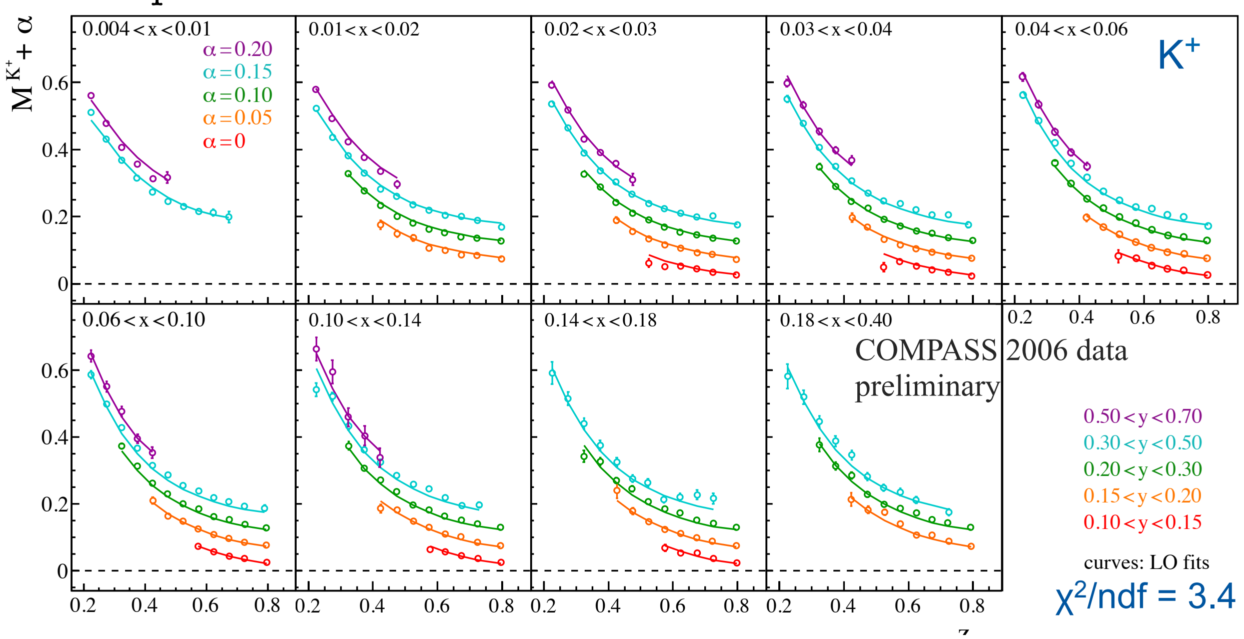
χ^2/ndf = 3.4

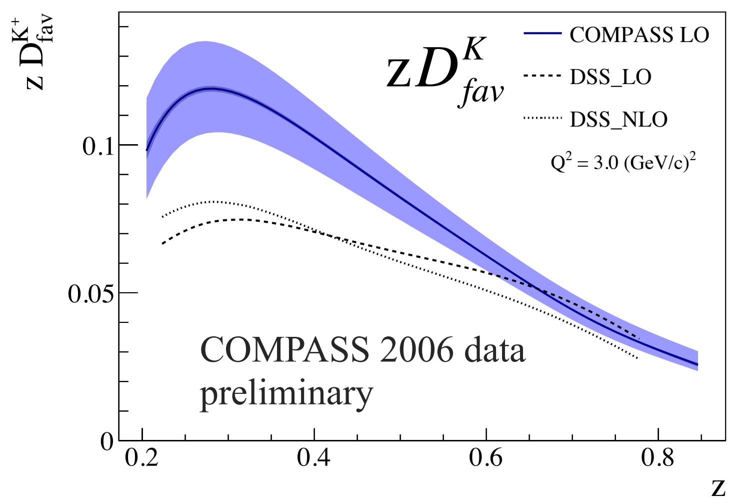
PDF & Fragmentation

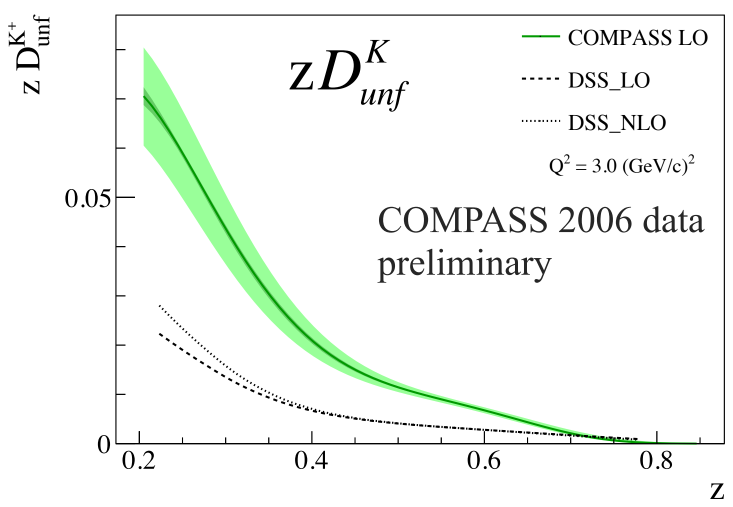
Multi-D Kaon multiplicities

317 kinematic bins

Example of fit





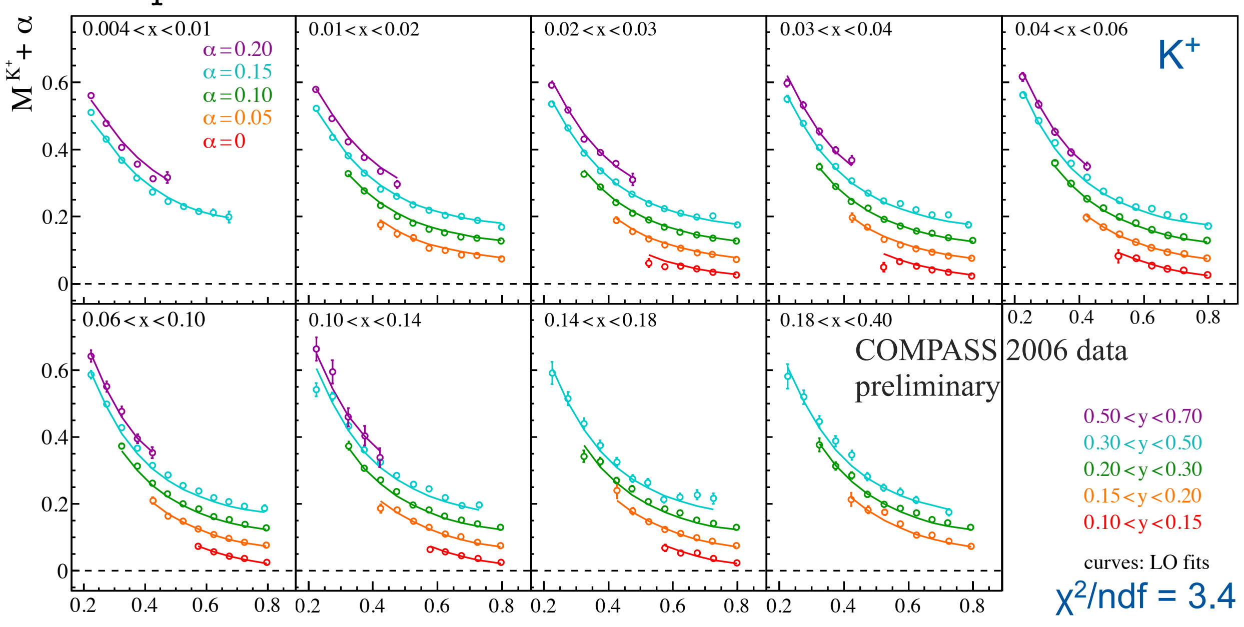


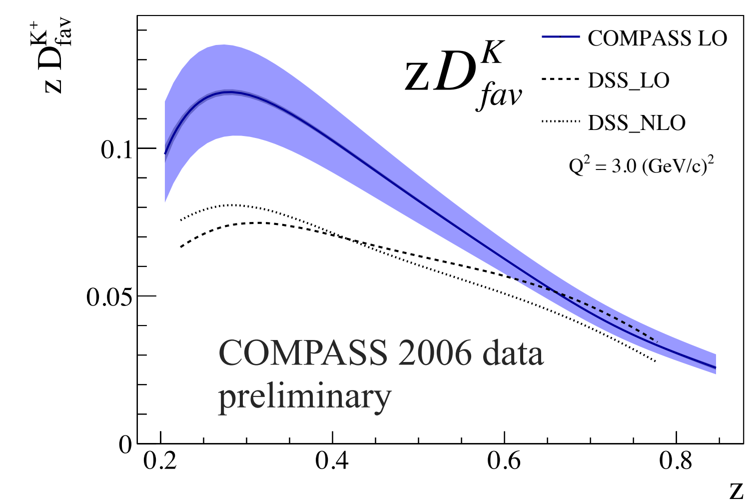
PDF & Fragmentation

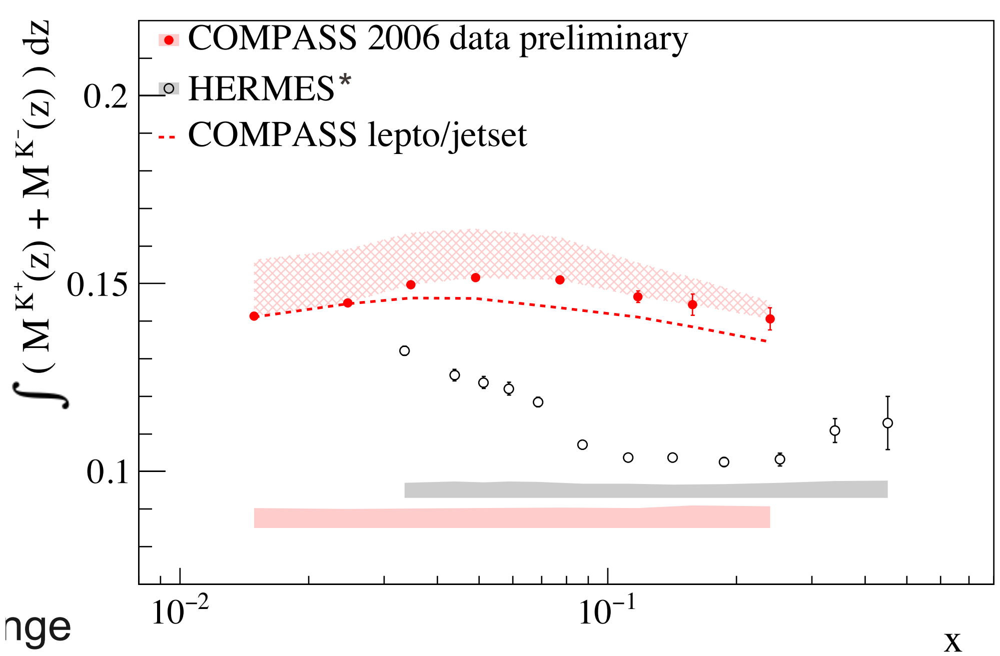
Multi-D Kaon multiplicities

317 kinematic bins

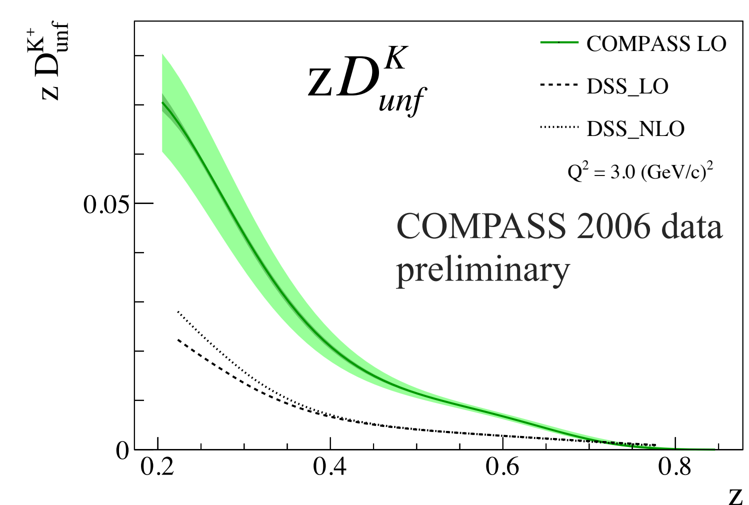
Example of fit







nge



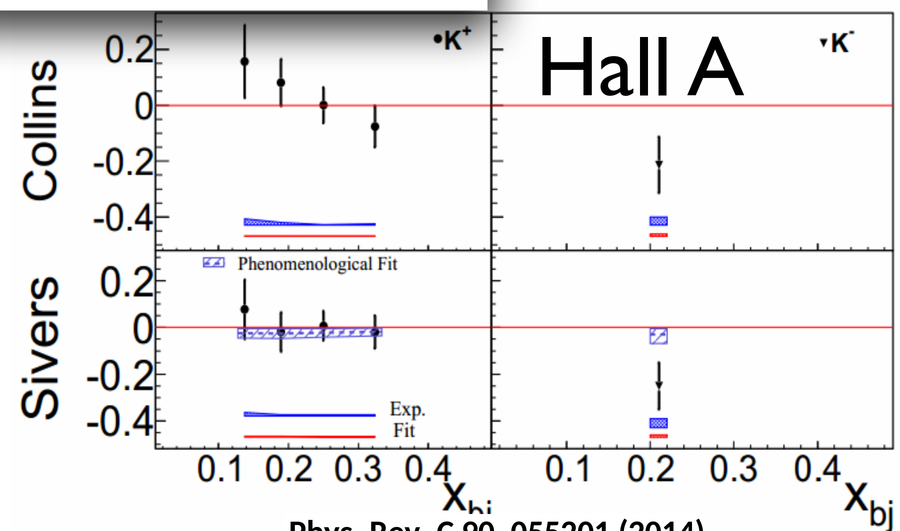
TMDs

Proton distribution in momentum space

TMD Transversity

Jefferson Lab
Thomas Jefferson National Accelerator Facility

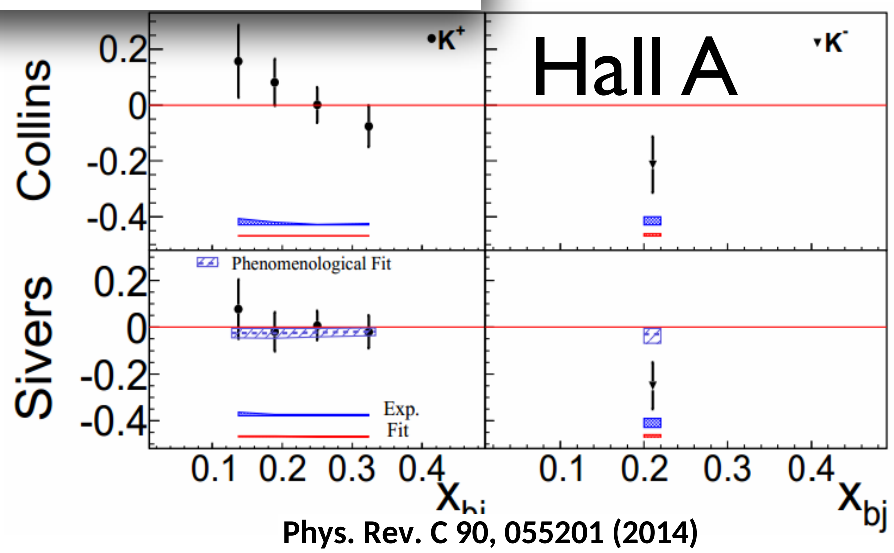
$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$



Phys. Rev. C 90, 055201 (2014)

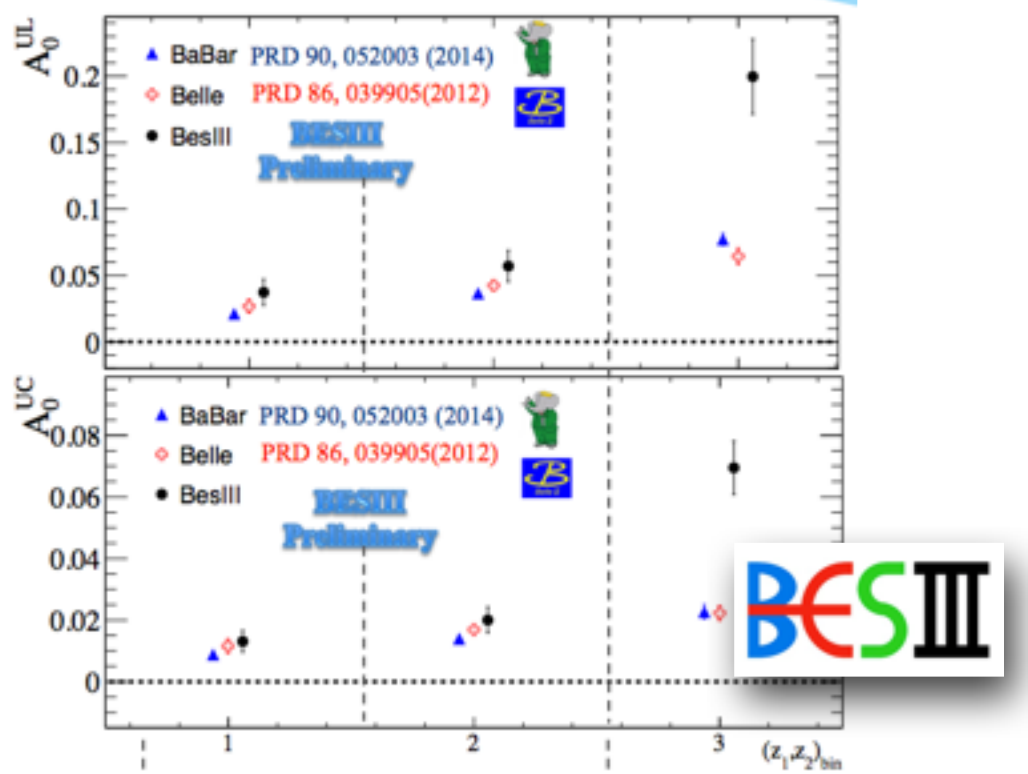
TMD Transversity

$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$



Phys. Rev. C 90, 055201 (2014)

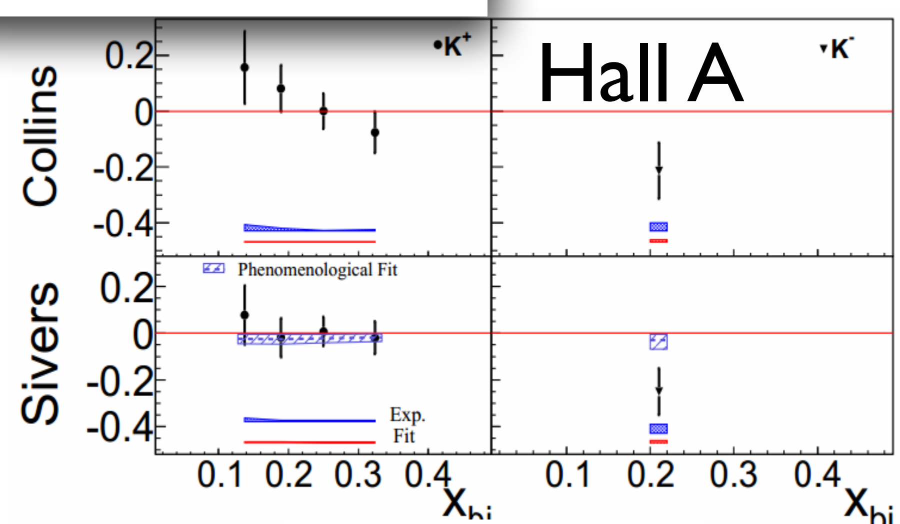
Pion Collins at low energy (Q^2 =13 GeV^2)



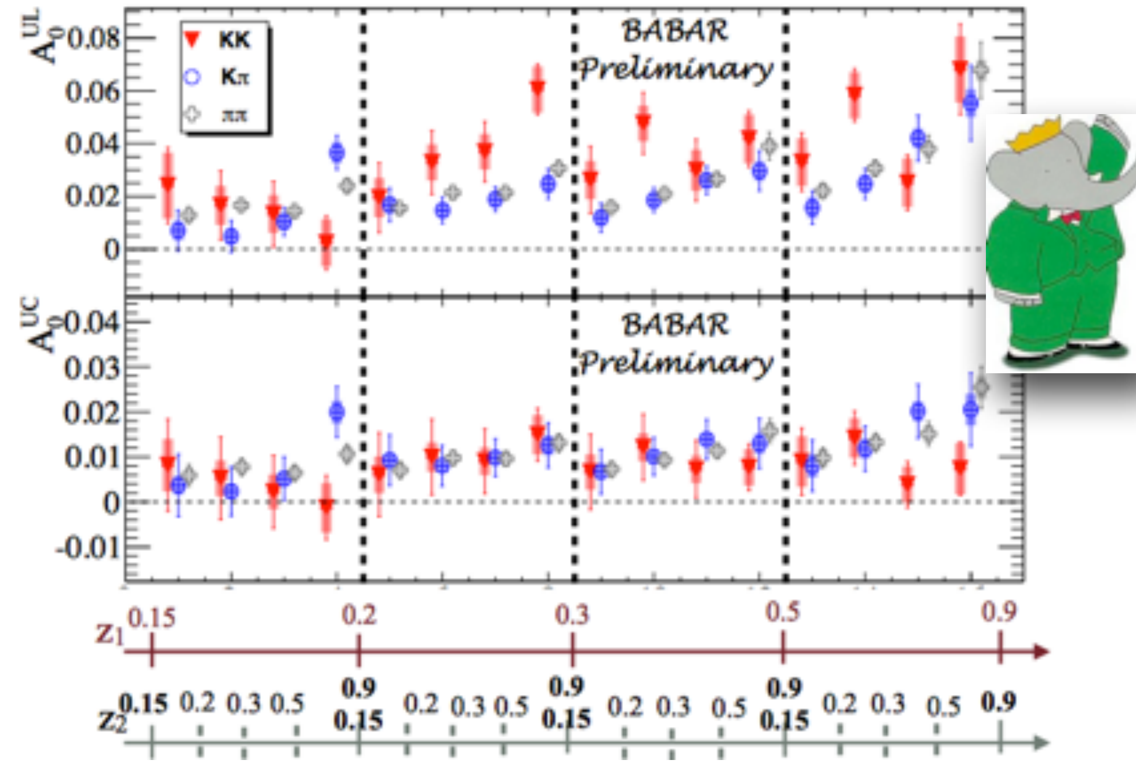
TMD Transversity

Jefferson Lab
Thomas Jefferson National Accelerator Facility

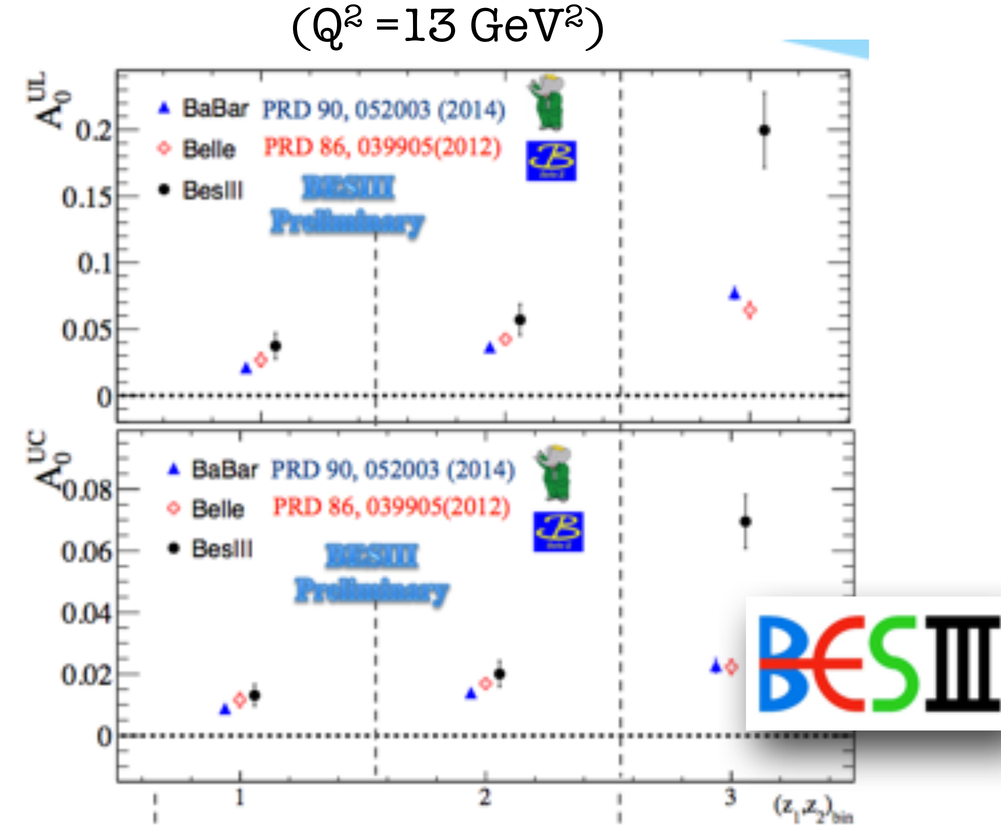
$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$



Phys. Rev. C 90, 055201 (2014)



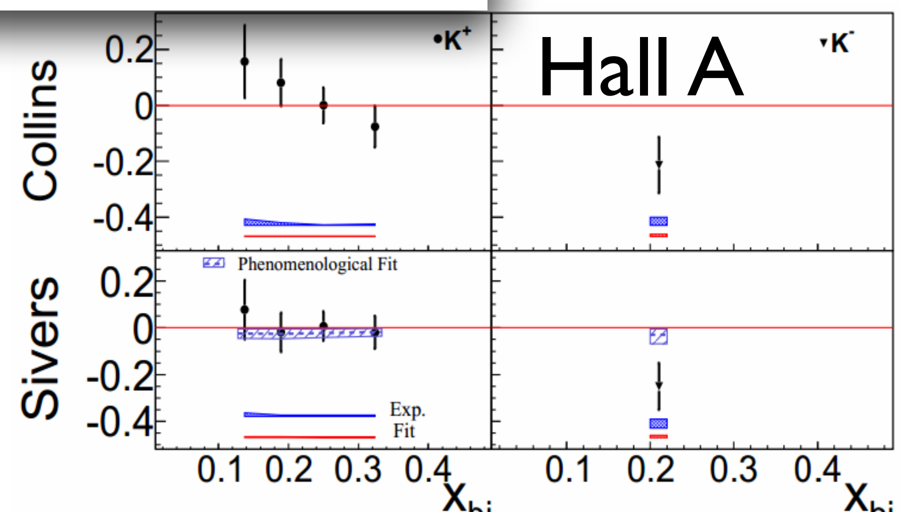
Pion Collins at low energy
(Q^2 =13 GeV^2)



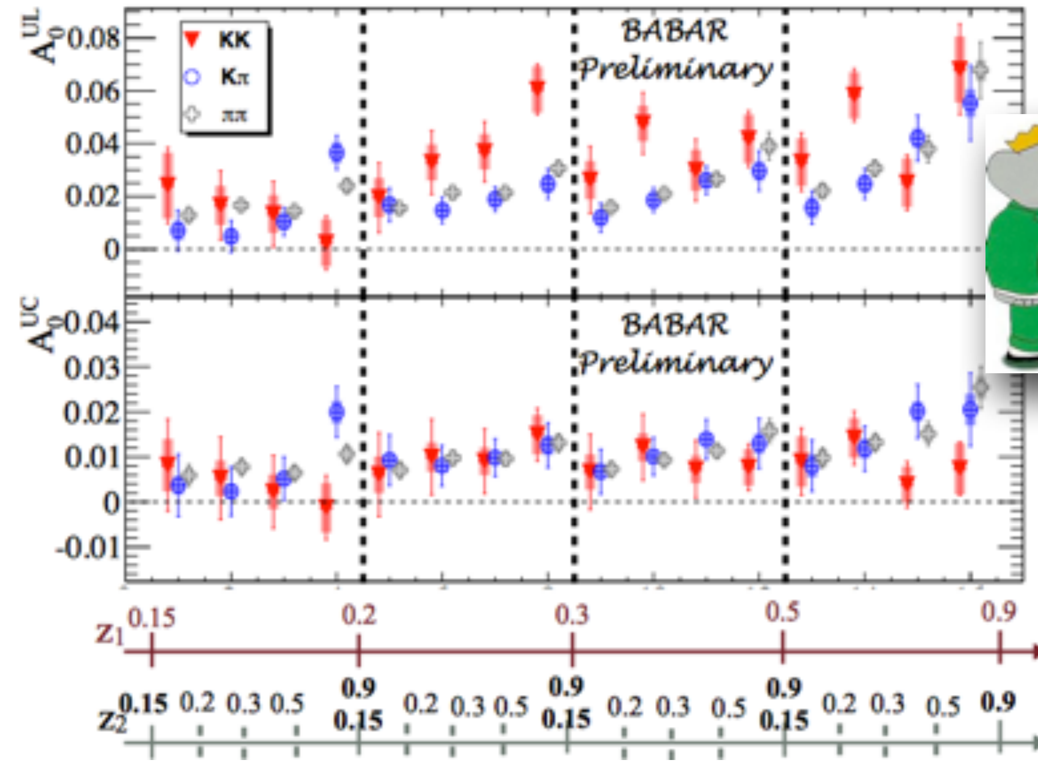
TMD Transversity

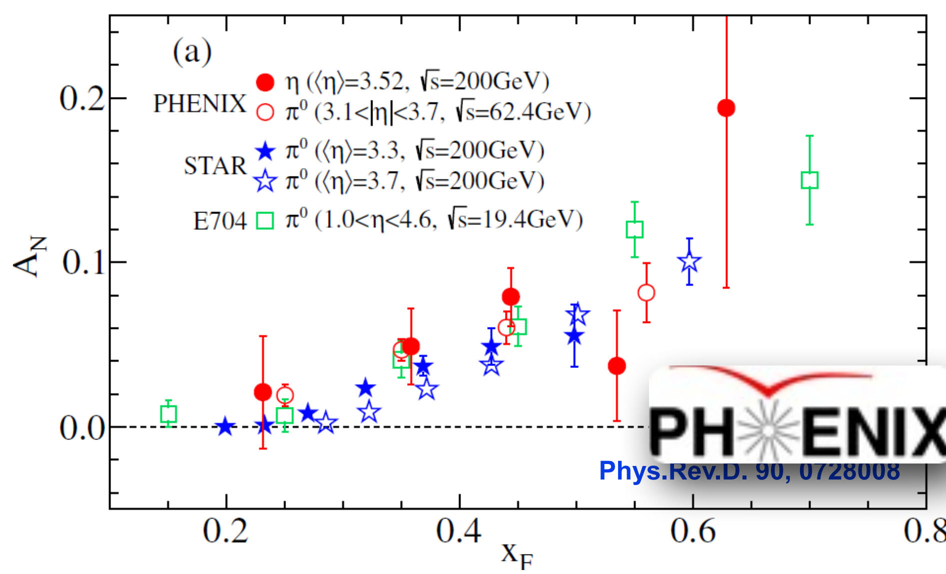
Jefferson Lab

$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$

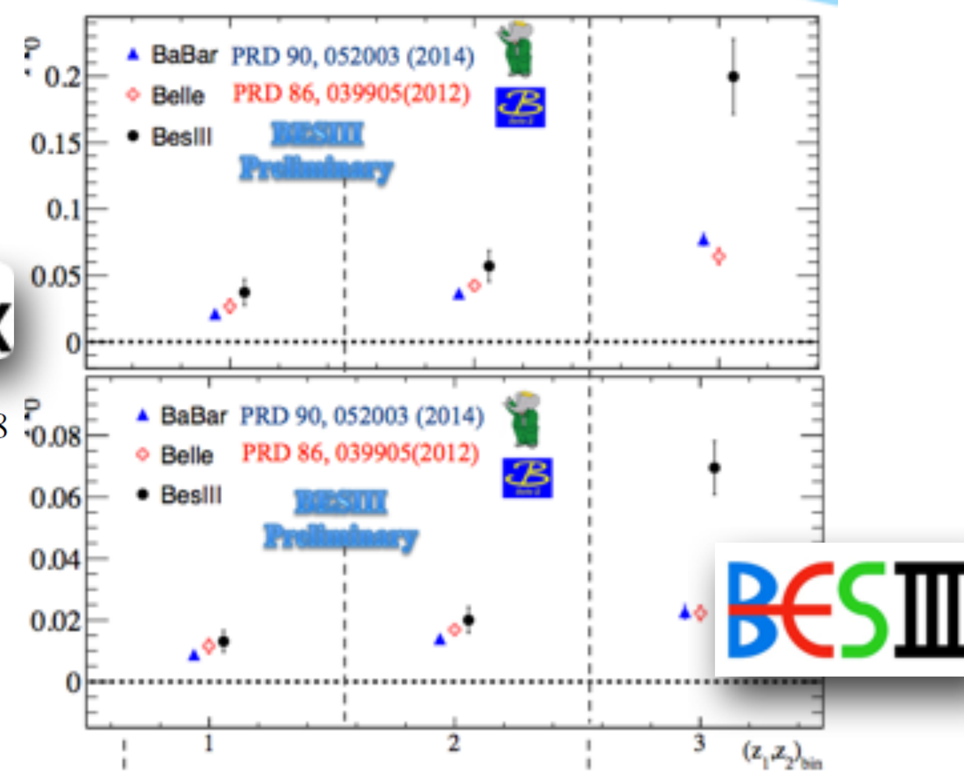


Phys. Rev. C 90, 055201 (2014)



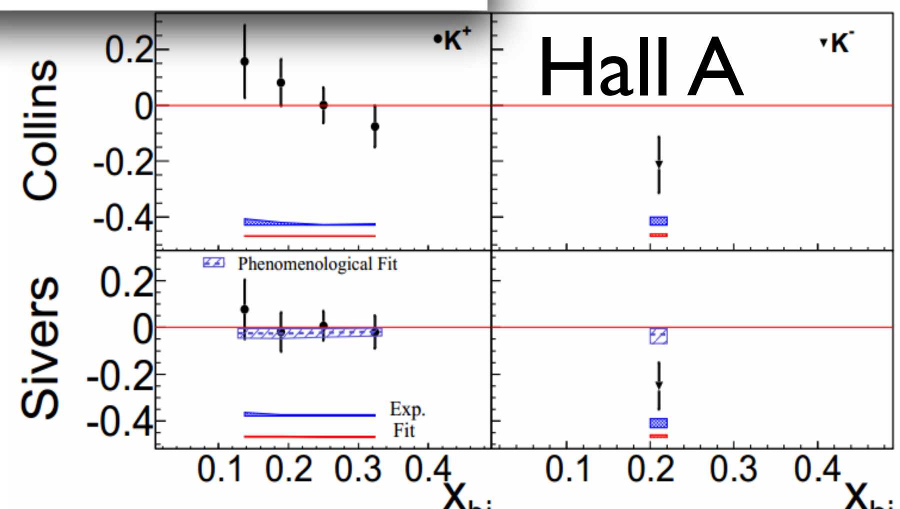


Pion Collins at low energy (Q^2 =13 GeV^2)

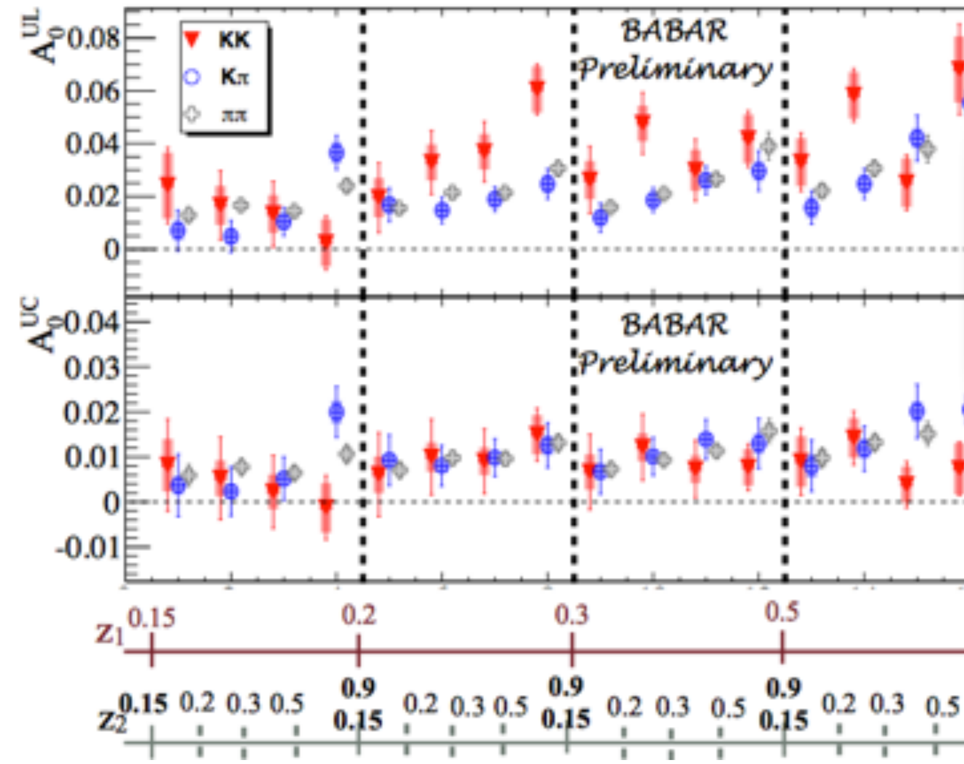


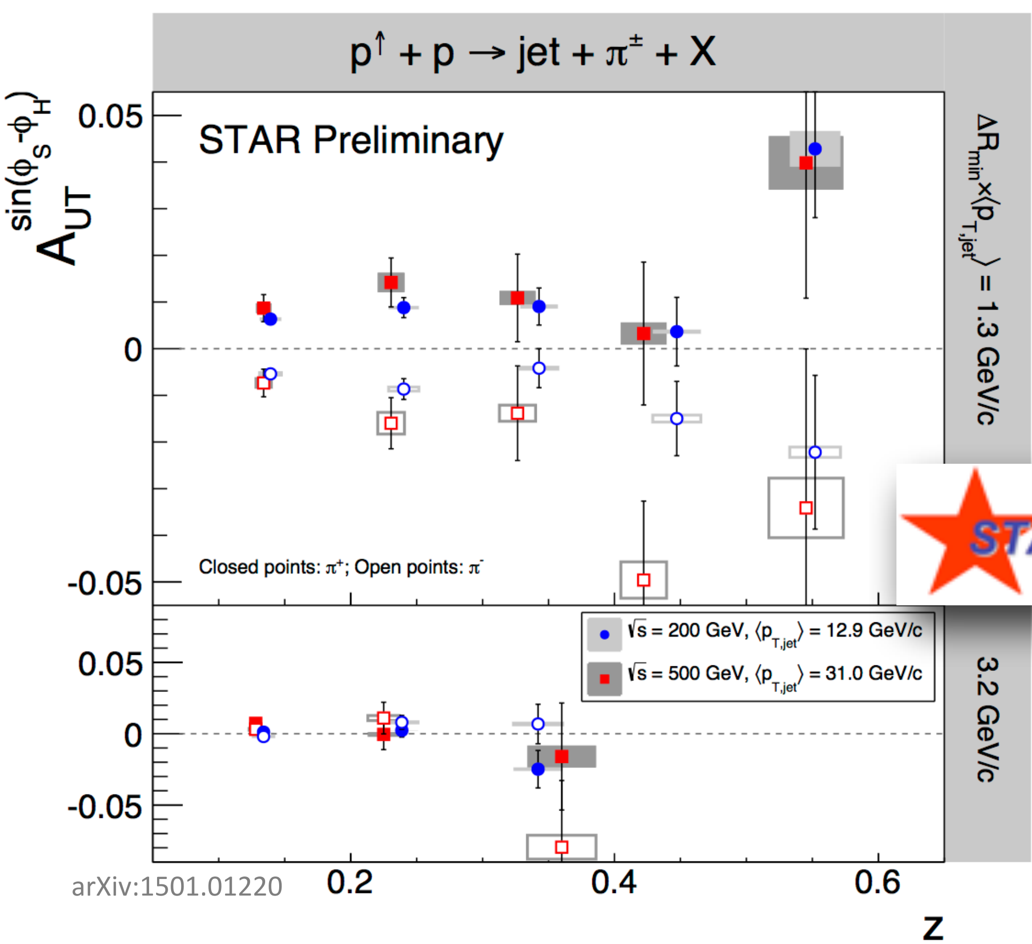
TMD Transversity

$$A_{UT} \propto h_1 \otimes H_1^\perp$$

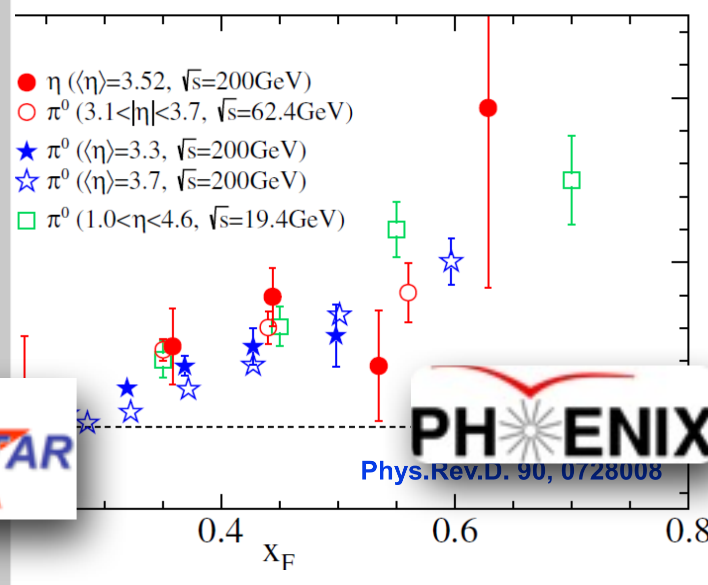


Phys. Rev. C 90, 055201 (2014)





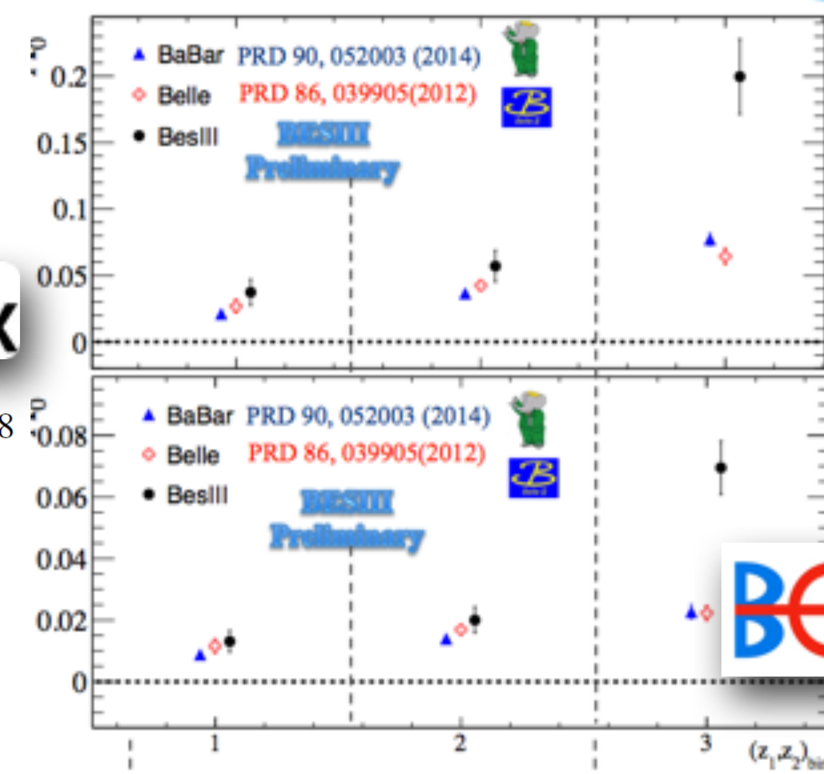
arXiv:1501.01220



Phys.Rev.D. 90, 072008

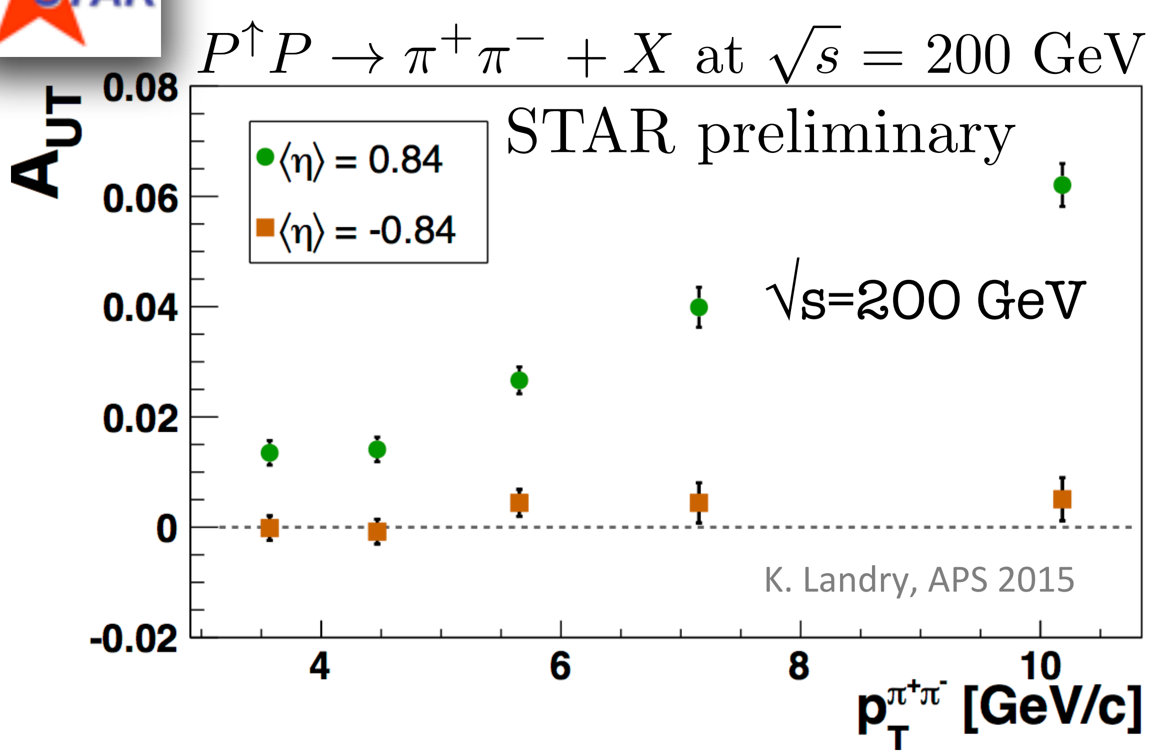
Pion Collins at low energy

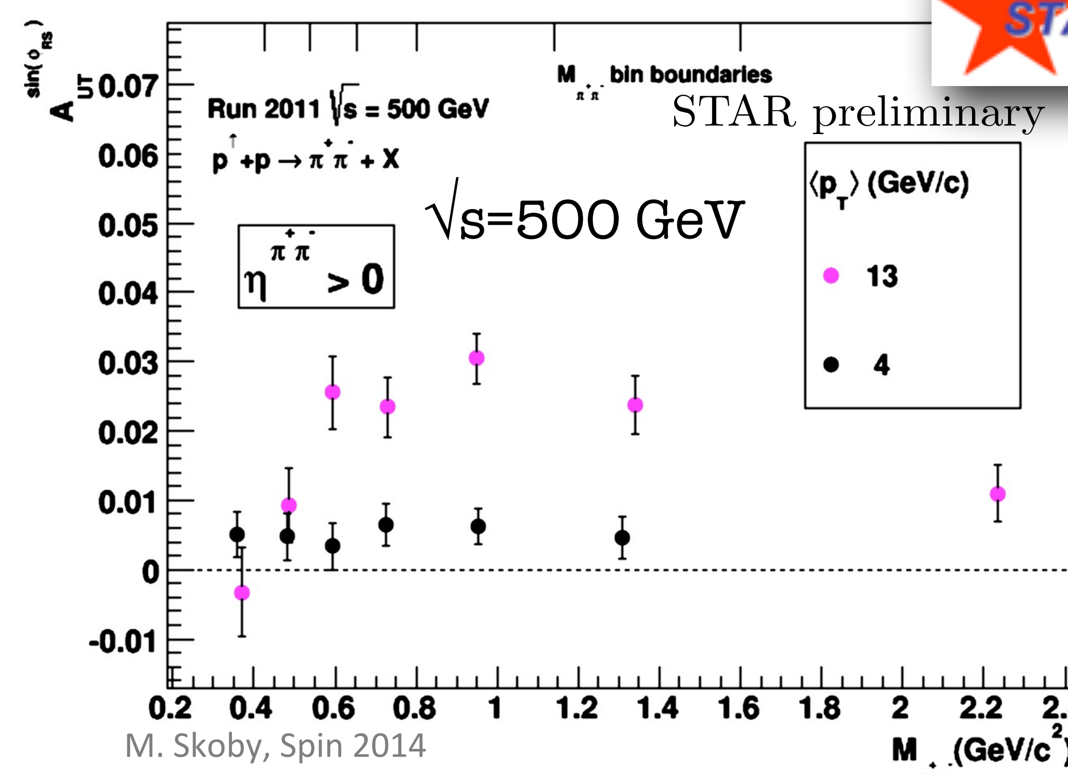
(Q^2 =13 GeV^2)



Collinear Transversity

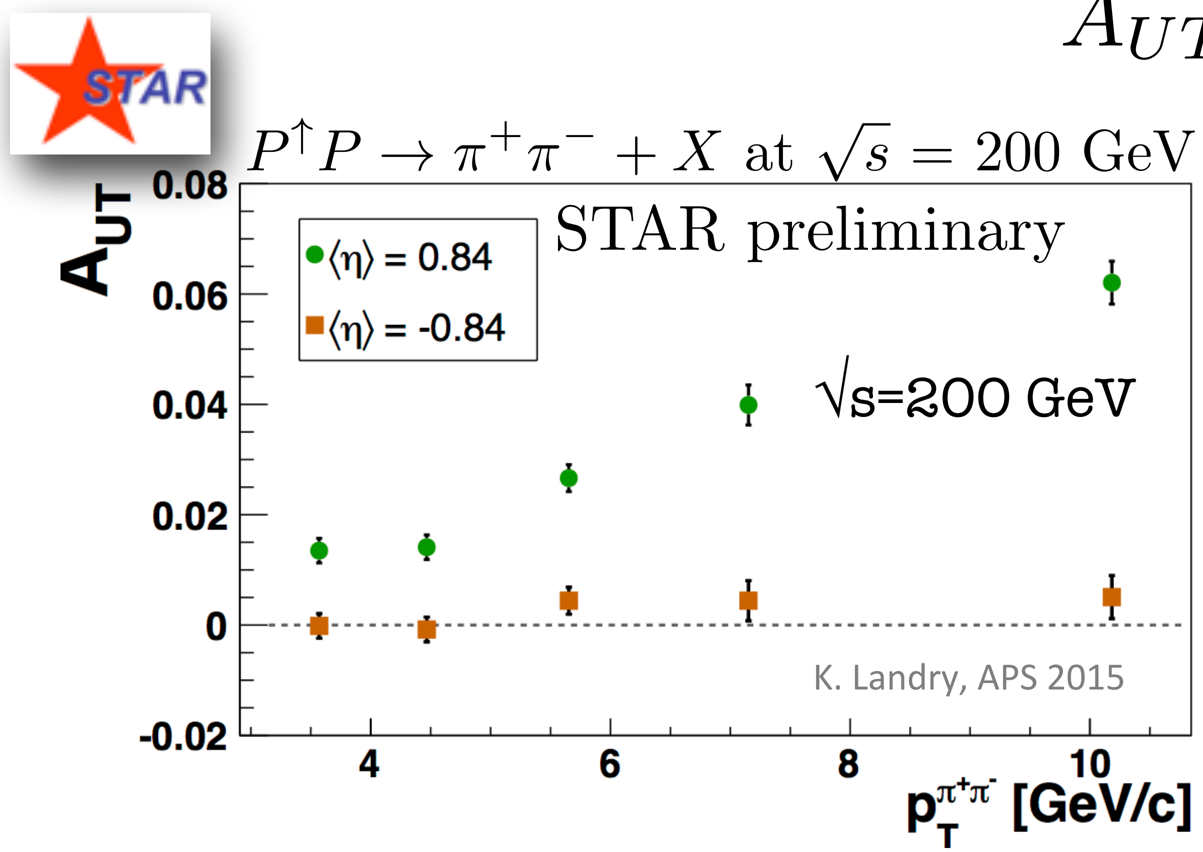
$$A_{UT} \propto h_1 \times H_1^{\sphericalangle}$$

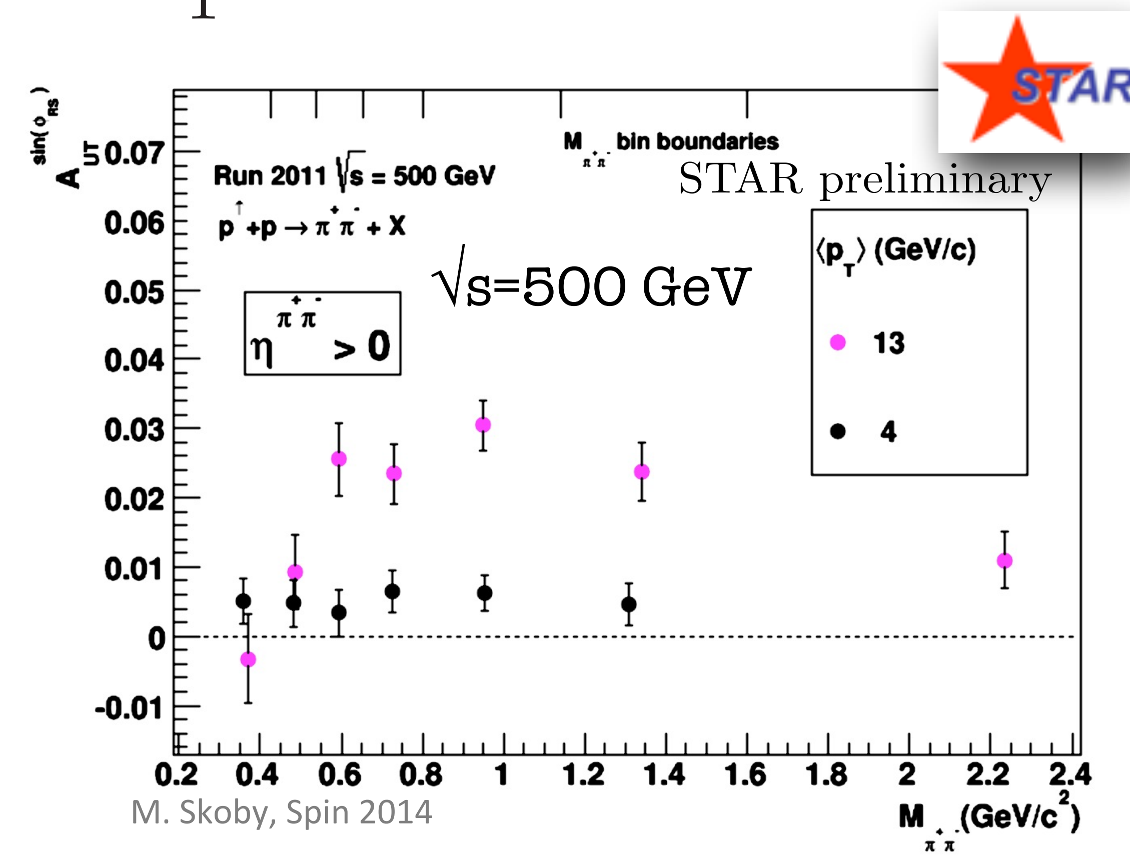


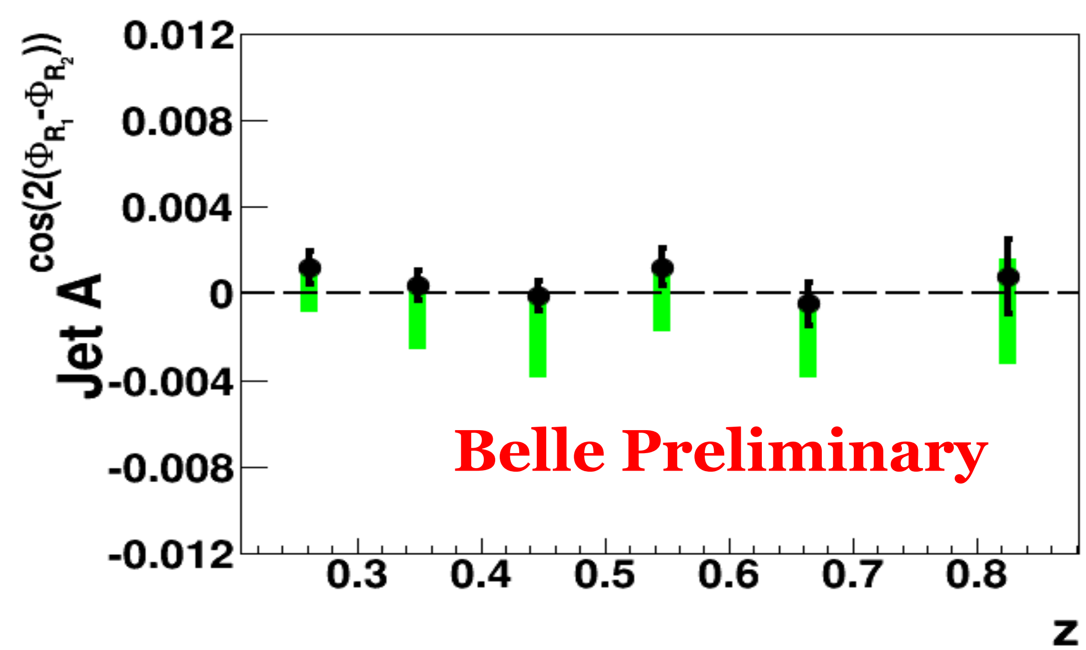


Collinear Transversity

$$A_{UT} \propto h_1 \times H_1^{\sphericalangle}$$

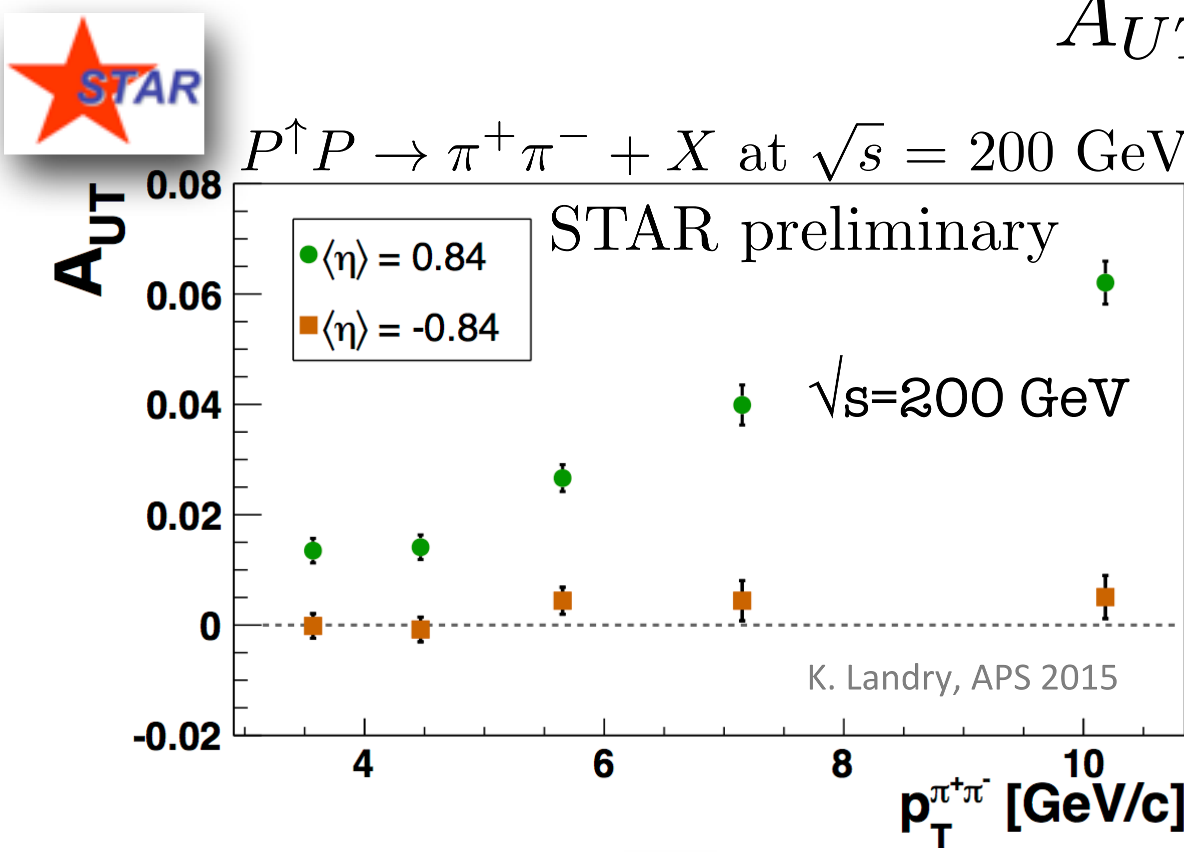


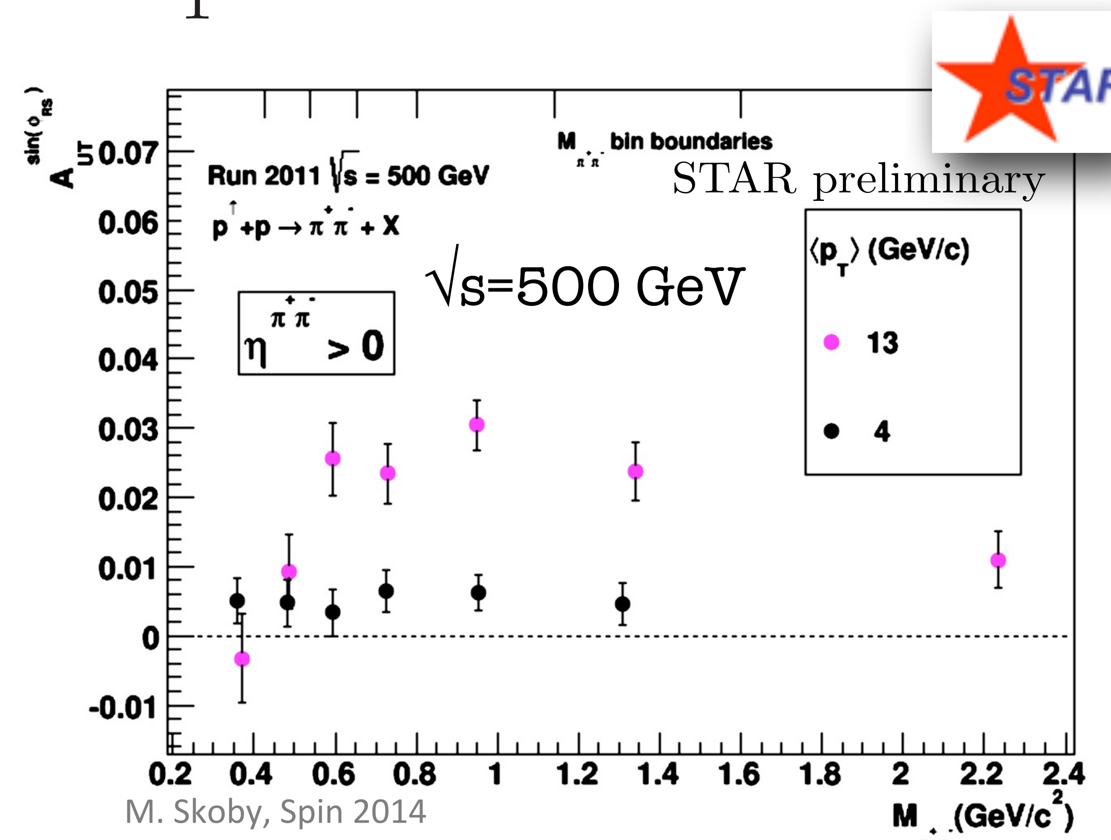


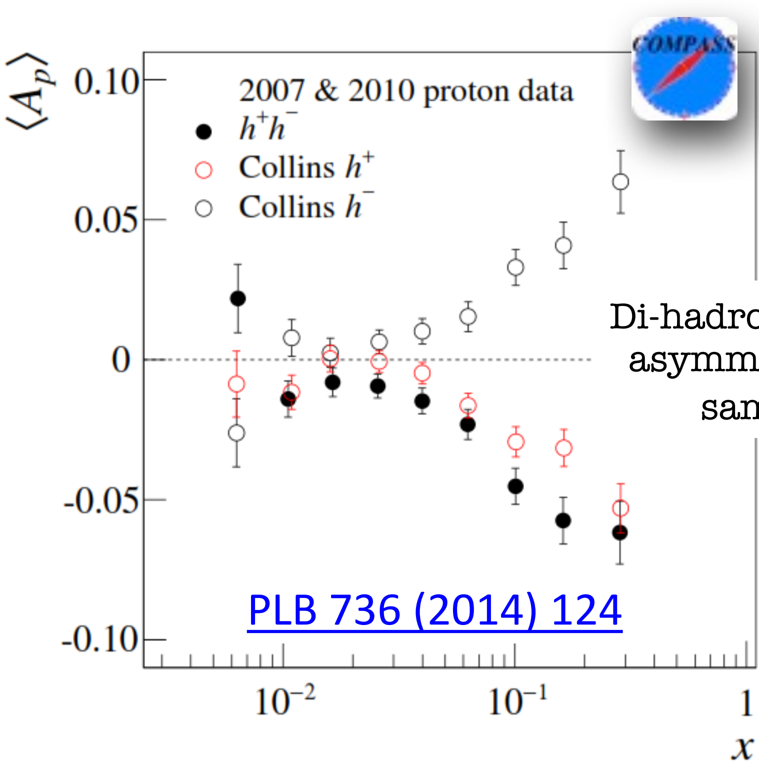


Collinear Transversity

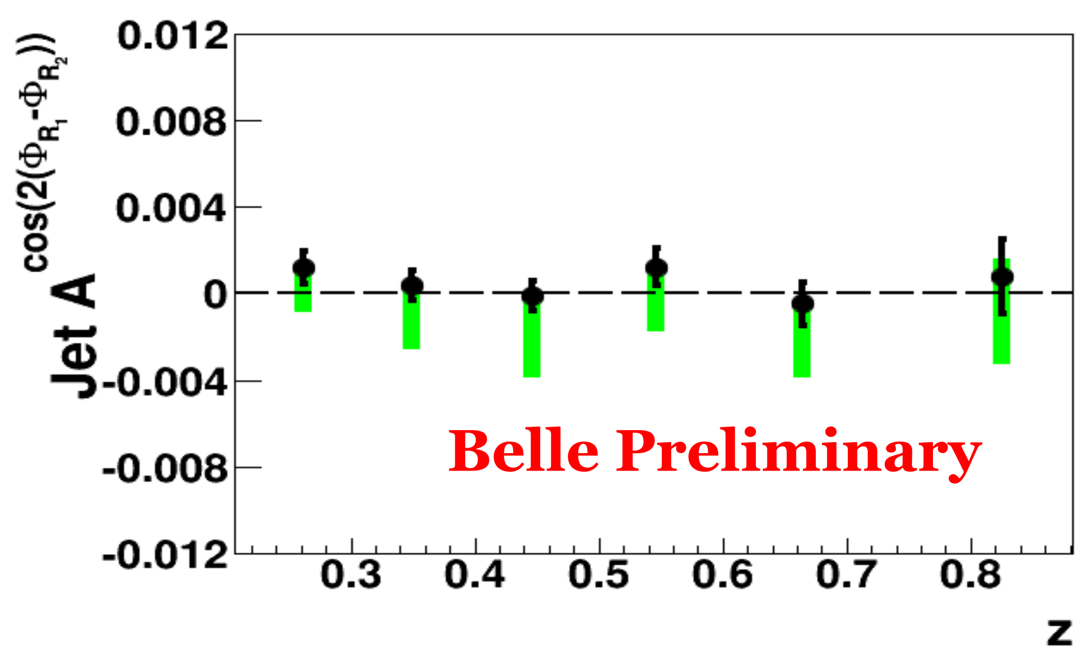
$$A_{UT} \propto h_1 \times H_1^{\sphericalangle}$$



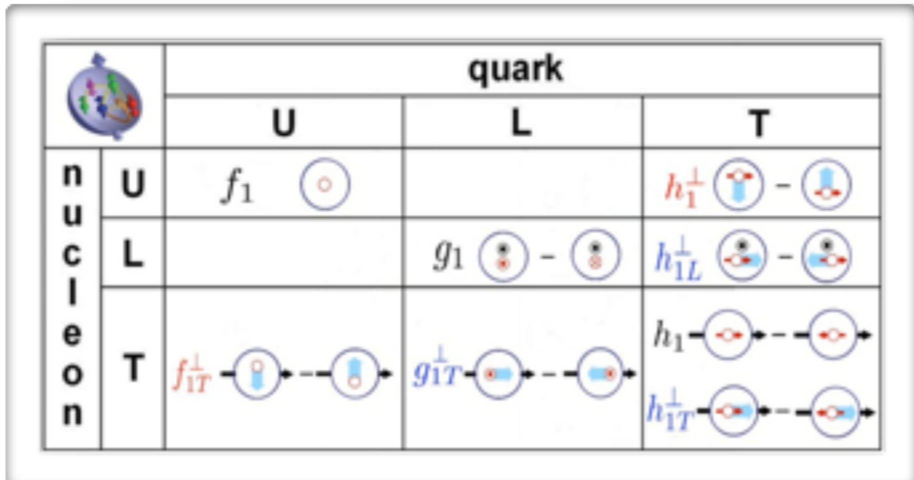




Di-hadron and single-hadron asymmetries generated by same mechanism?

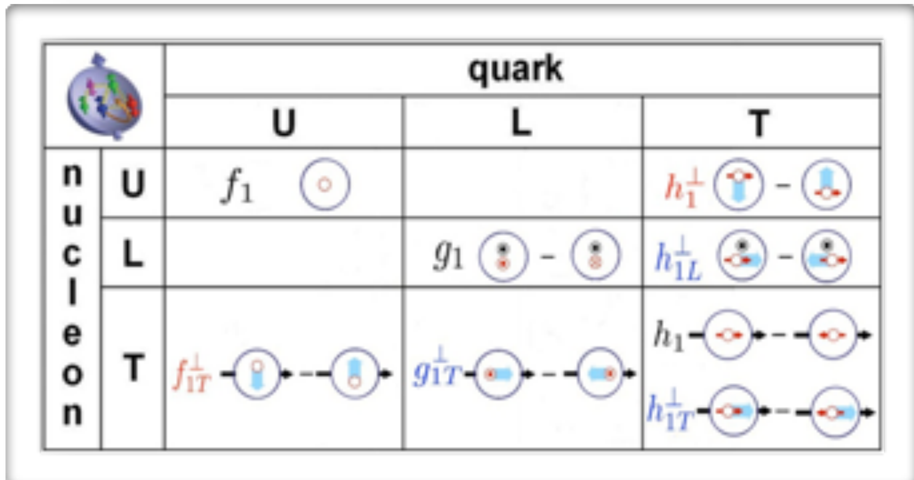


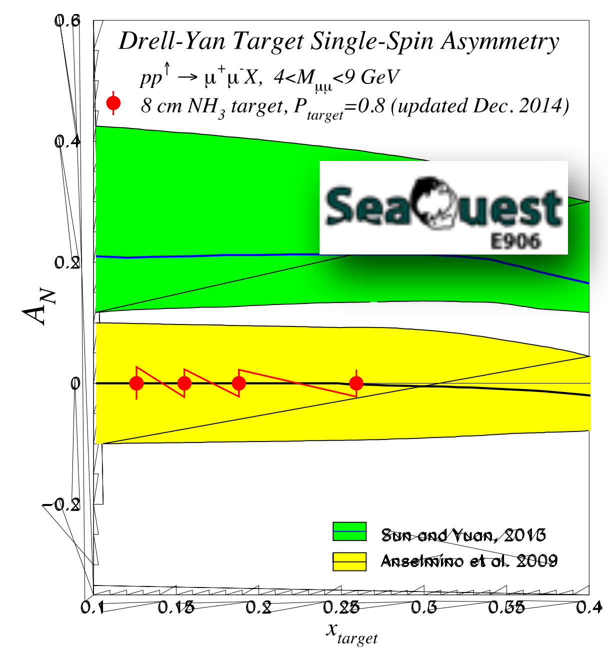
TMDs



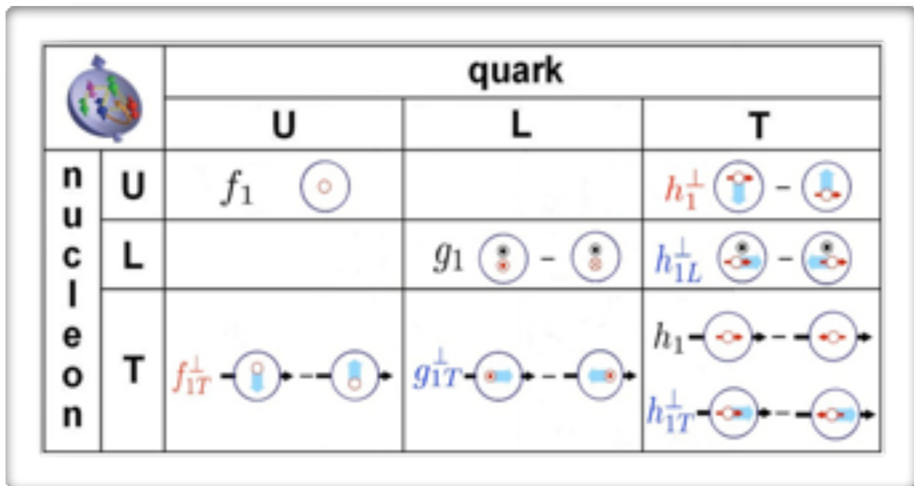
quark
U
L
T
nucleon
U
L
T
f_1
g_1
$h_1^\perp$
$h_{1L}^\perp$
h_1
$f_{1T}^\perp$
$g_{1T}^\perp$
$h_{1T}^\perp$

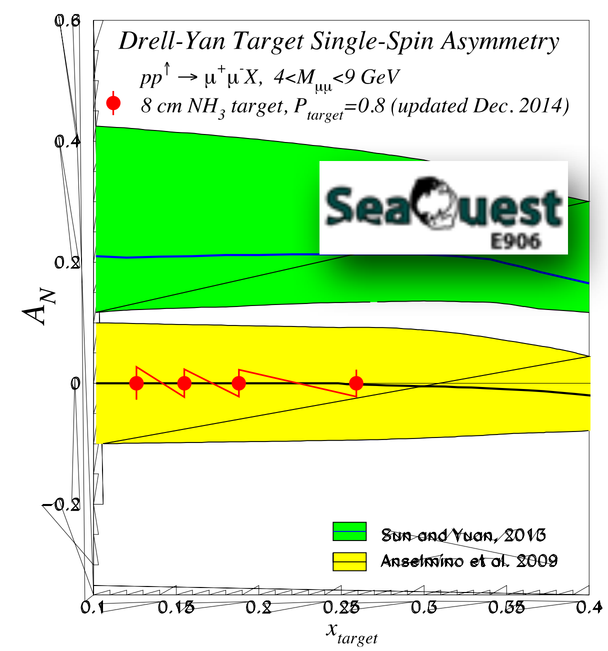
TMDs


quark
U
L
T
nucleon
U
L
T
f_1
$h_1^\perp$
g_1
$h_{1L}^\perp$
$f_{1T}^\perp$
$g_{1T}^\perp$
h_1
$h_{1T}^\perp$

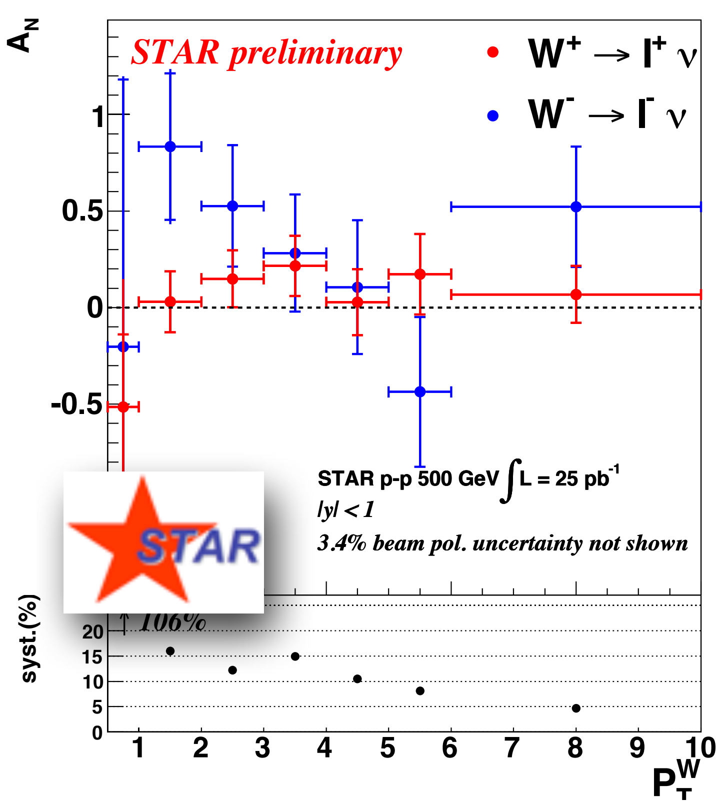

Drell-Yan Target Single-Spin Asymmetry
$pp^\uparrow \rightarrow \mu^+\mu^- X$, $4<M_{\mu\mu}<9$ GeV
8 cm NH_3 target, P_{target}=0.8 (updated Dec. 2014)
SeaQuest
E906
A_N
x_{target}
Sun and Yuan, 2013
Anselmino et al. 2009
0.6
0.4
0.2
0
−0.2
0.1
0.15
0.2
0.25
0.3
0.35
0.4

TMDs

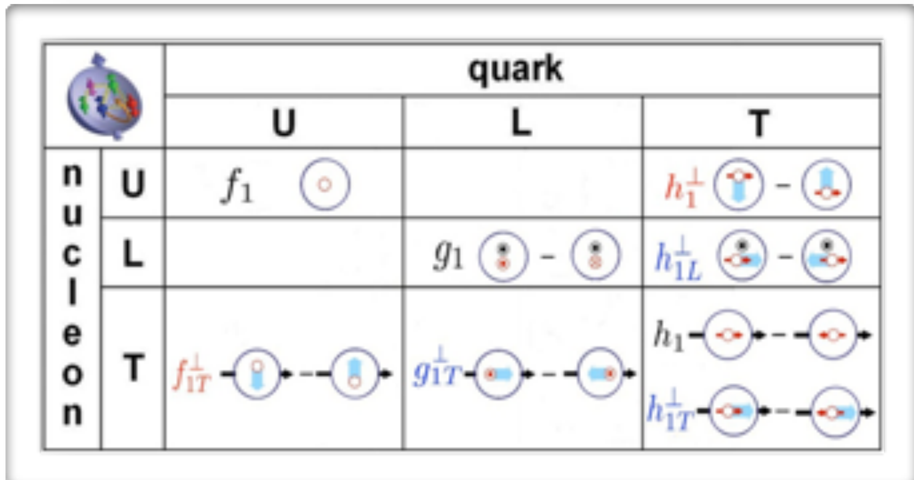


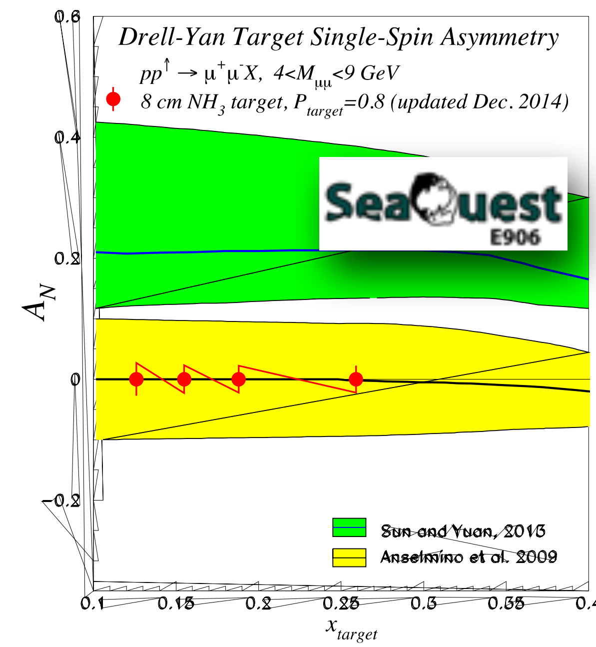


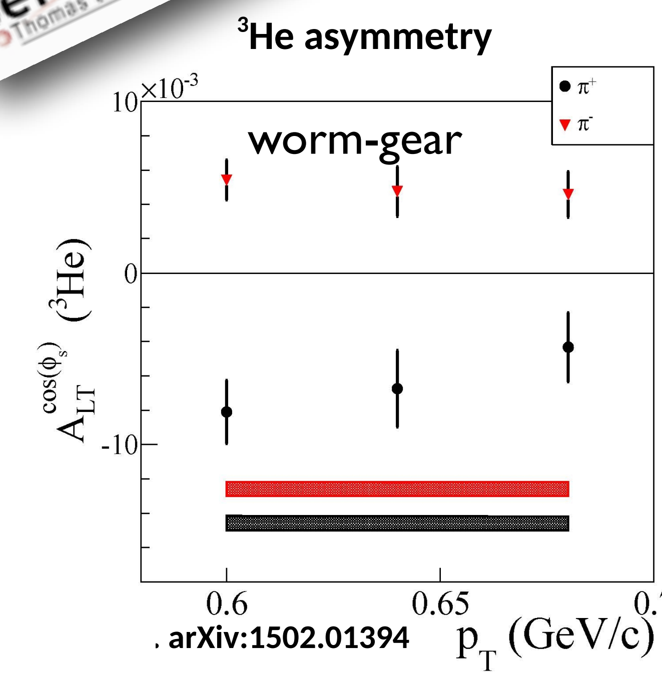
Hint of Sivers sign-change in pp?
More data on the way!



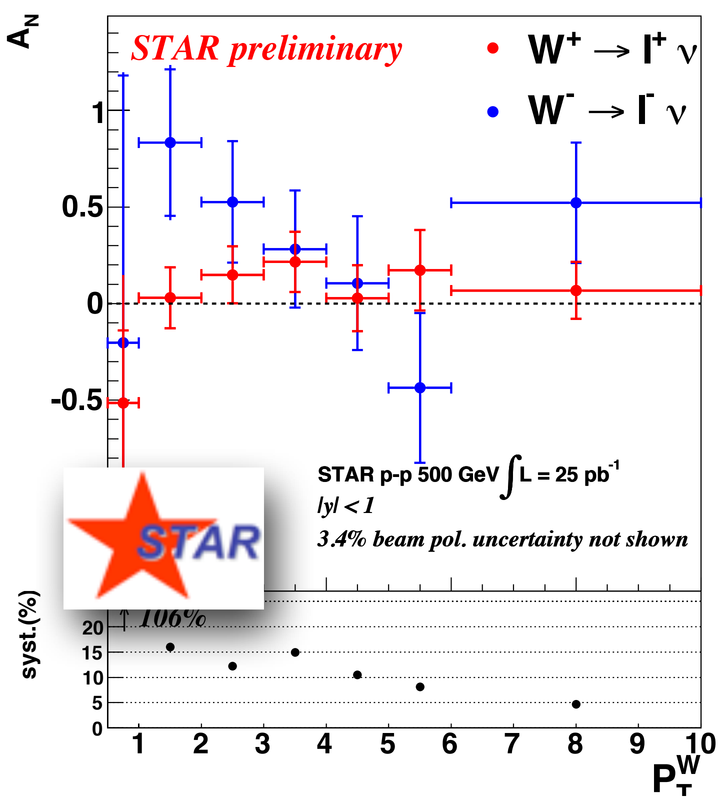
TMDs



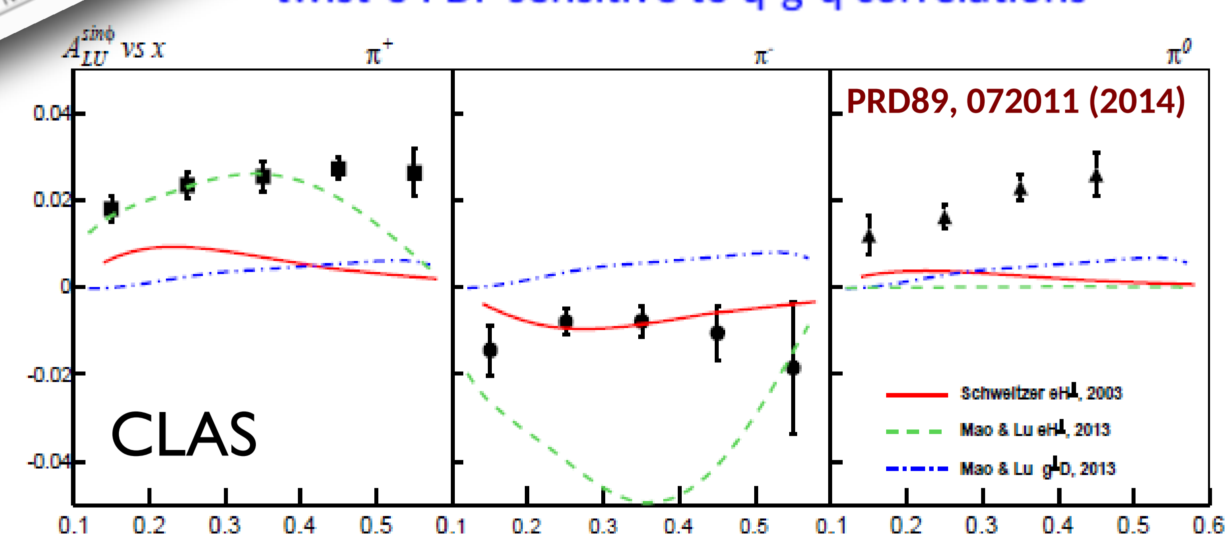




Hint of Sivers sign-change in pp?
More data on the way!

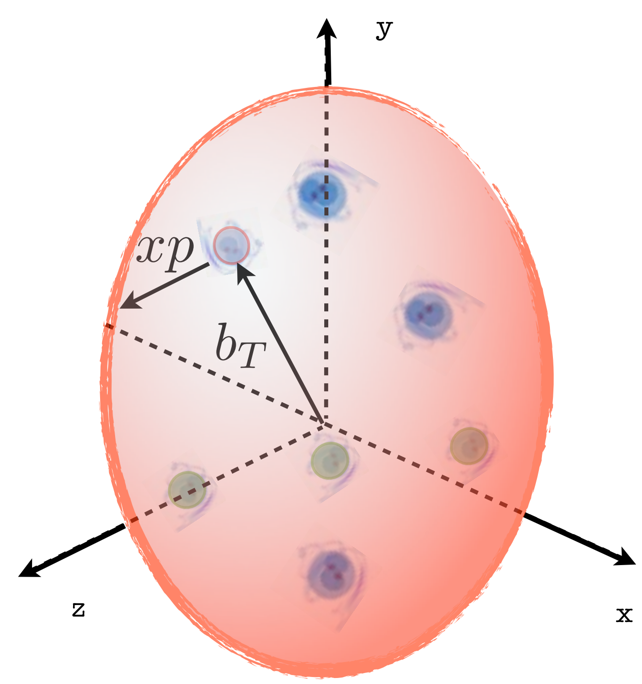


twist-3 PDF sensitive to q-g-q correlations



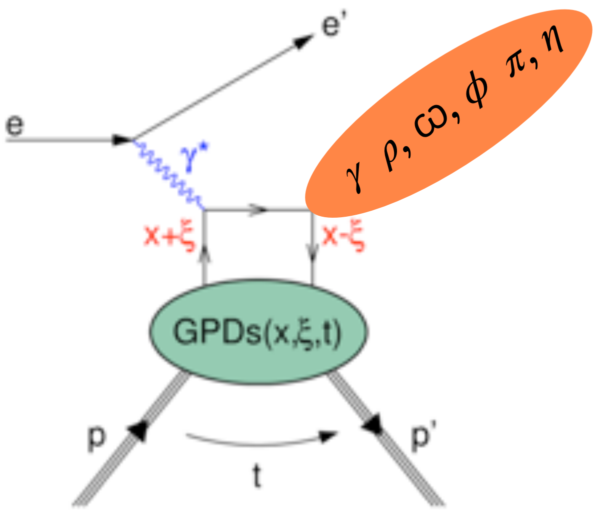
GPDs

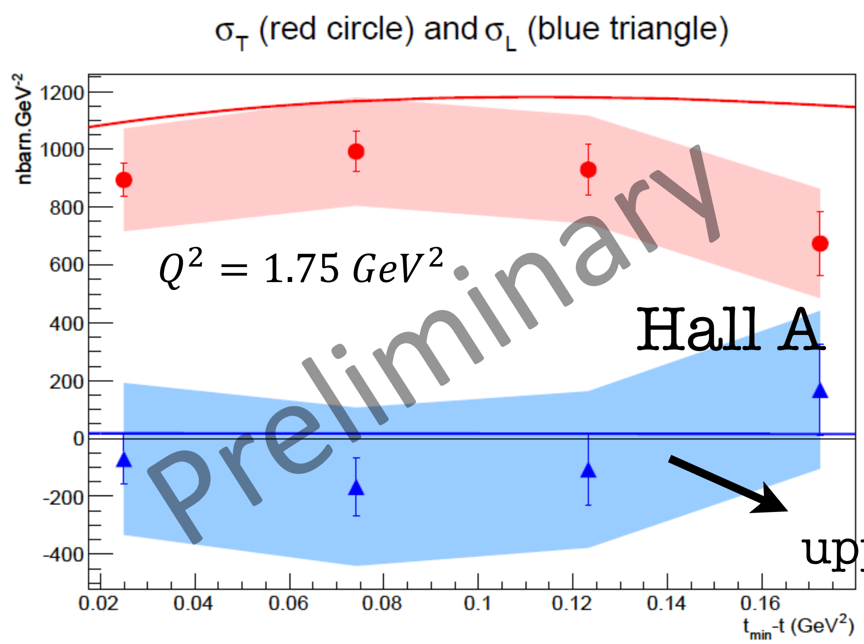
Proton distribution in impact parameter space

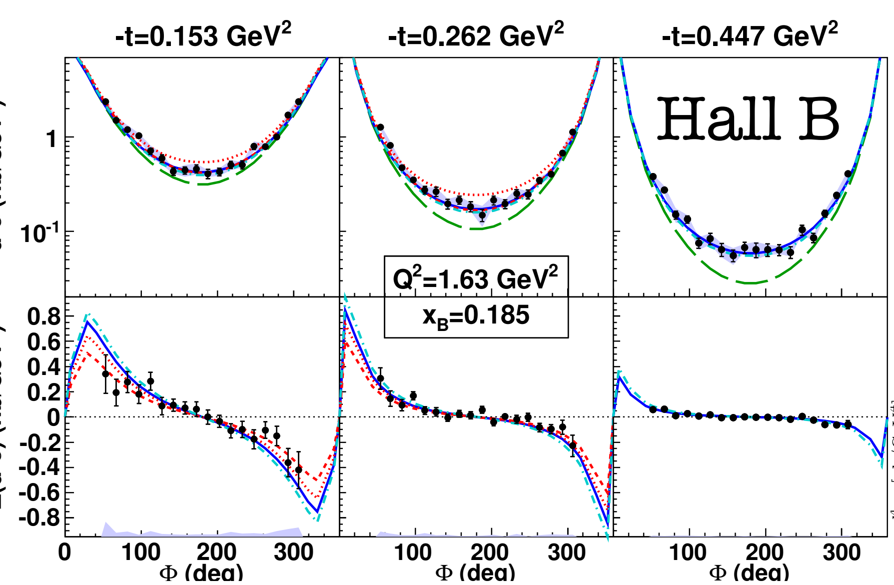


Constraining GPDs

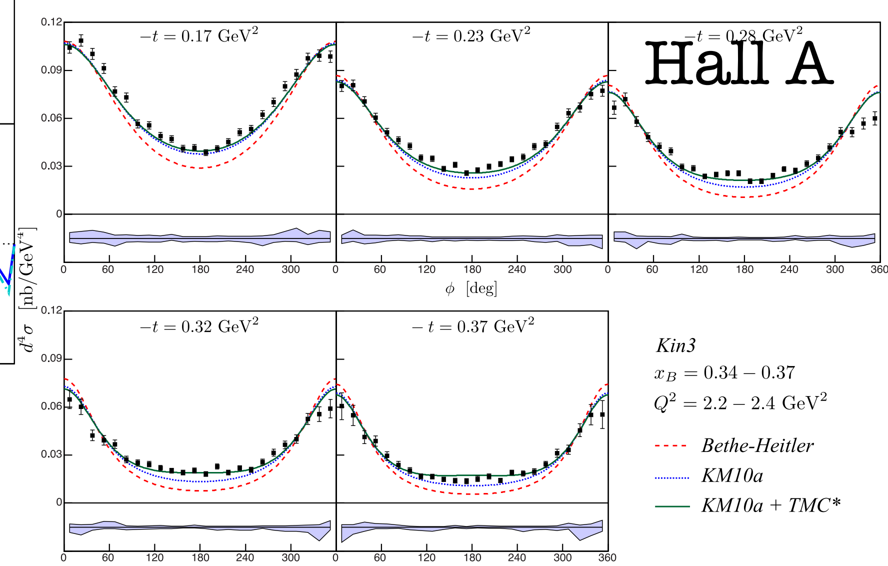
- DVCS $(\gamma) \rightarrow H,\ E,\ \tilde{H},\ \tilde{E}$
- Vector mesons $(\rho, \omega, \phi) \rightarrow H,\ E$
- Pseudoscalar mesons $(\pi, \eta) \rightarrow \tilde{H},\ \tilde{E}$



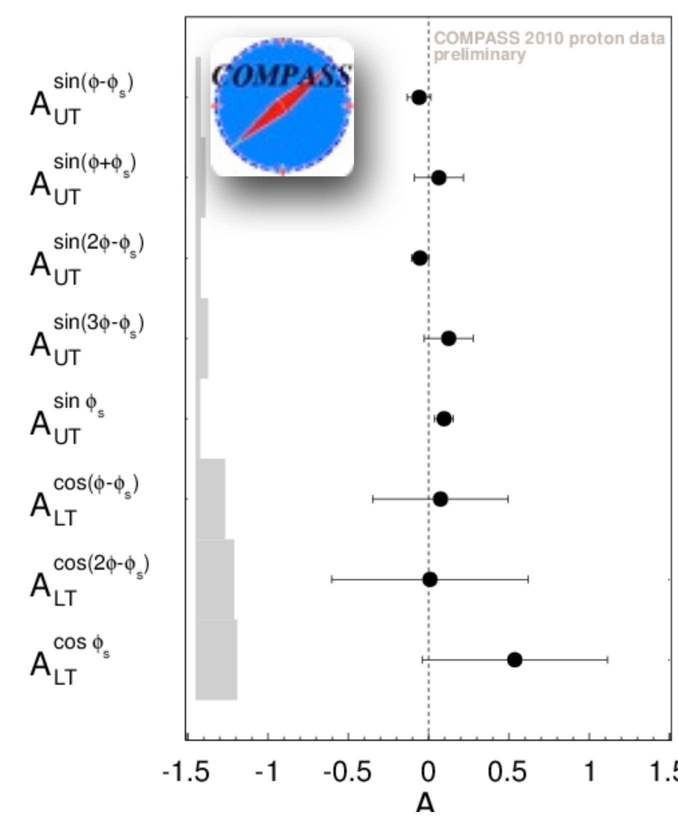




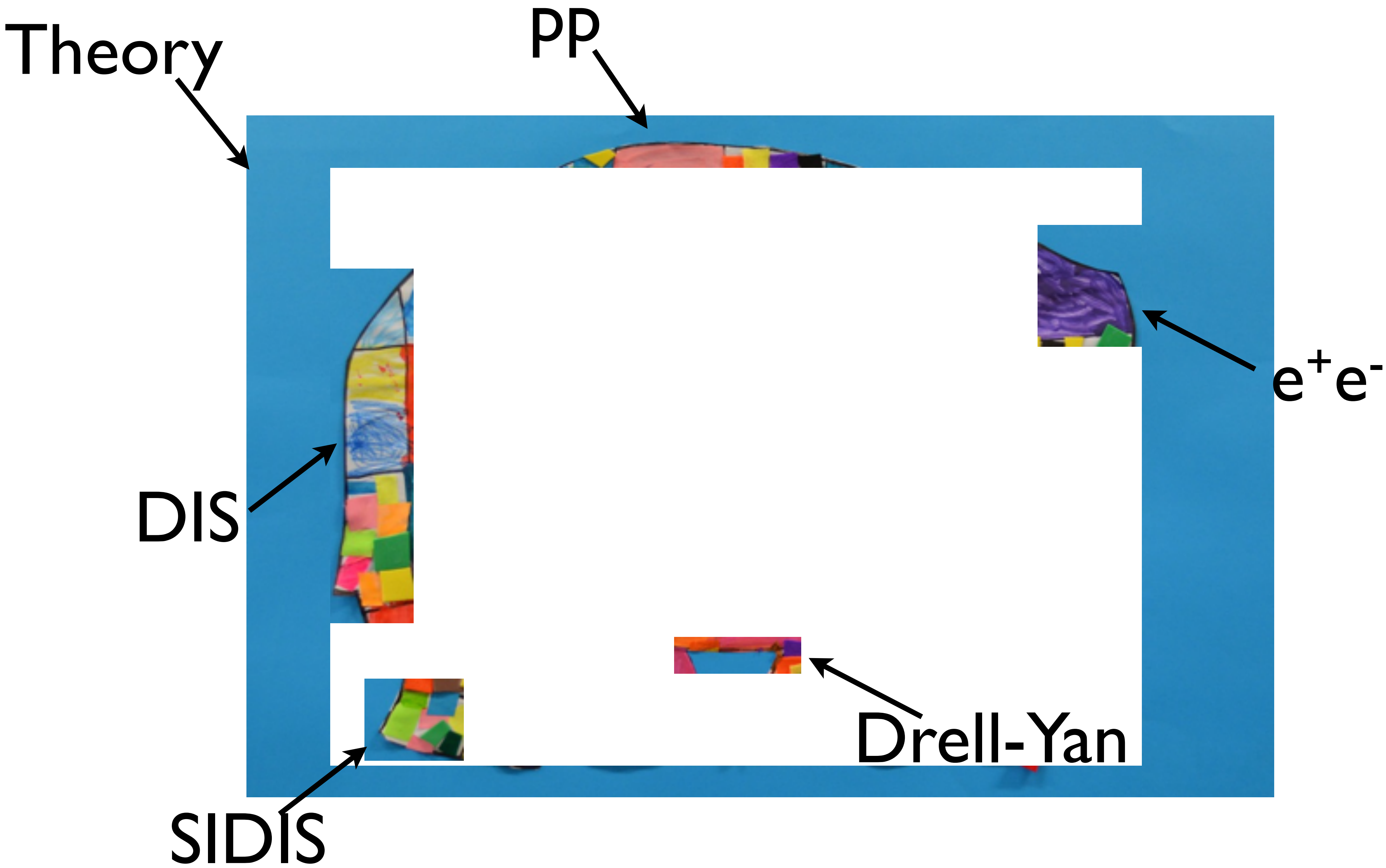
DVCS cross section modulation



ω production



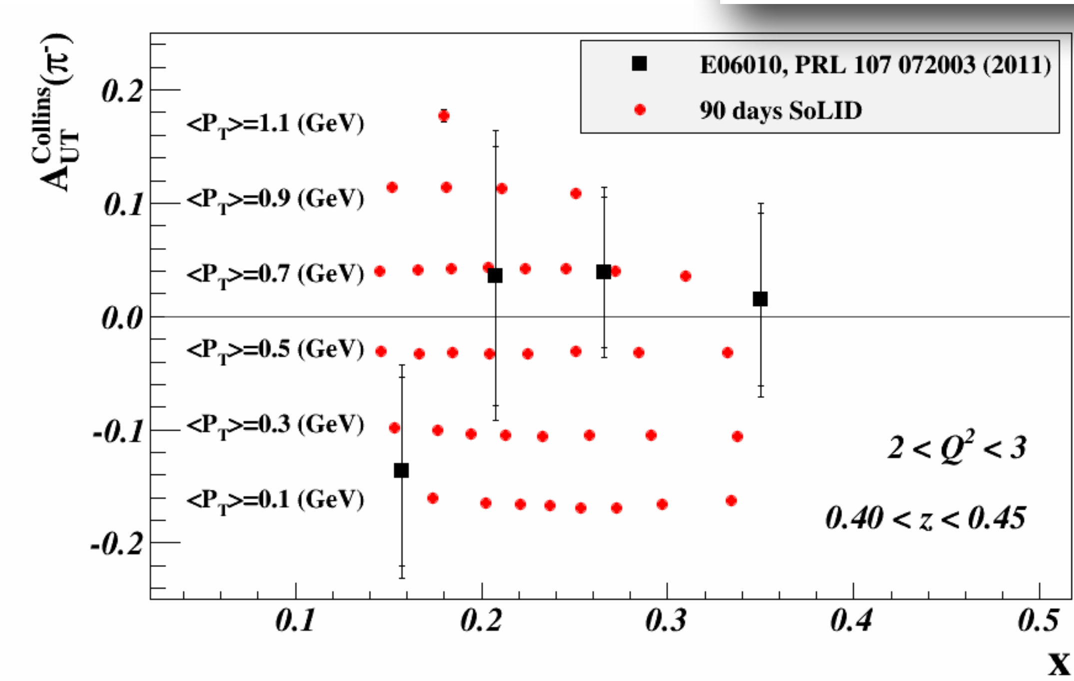
The complete picture

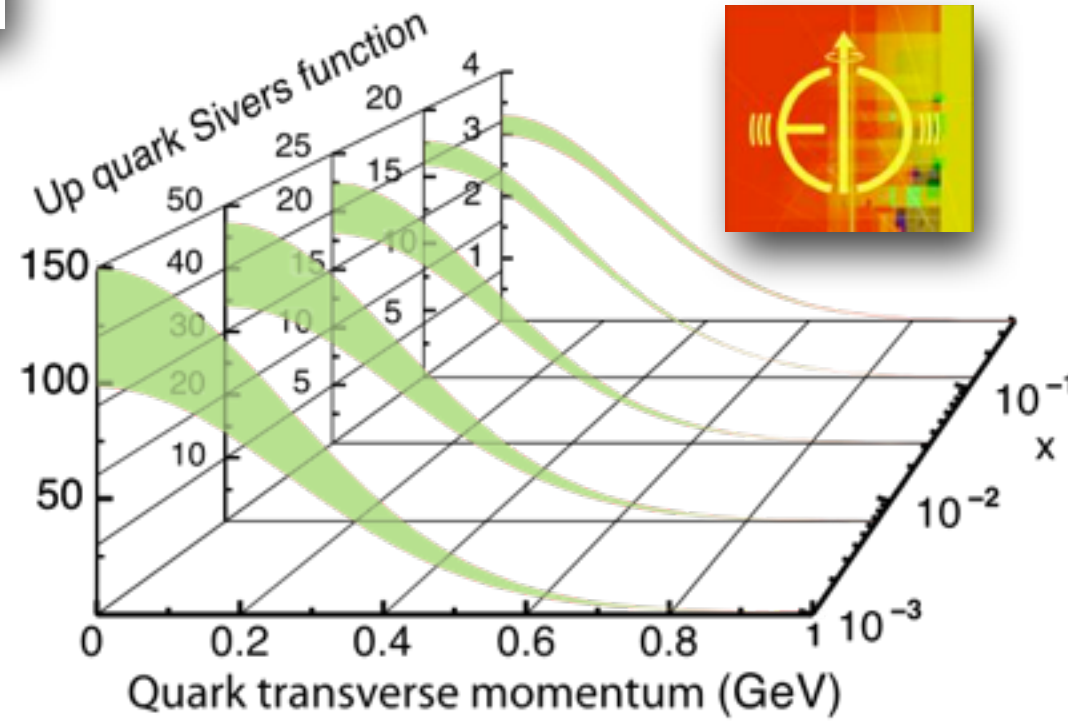


*The elephant and the blind men

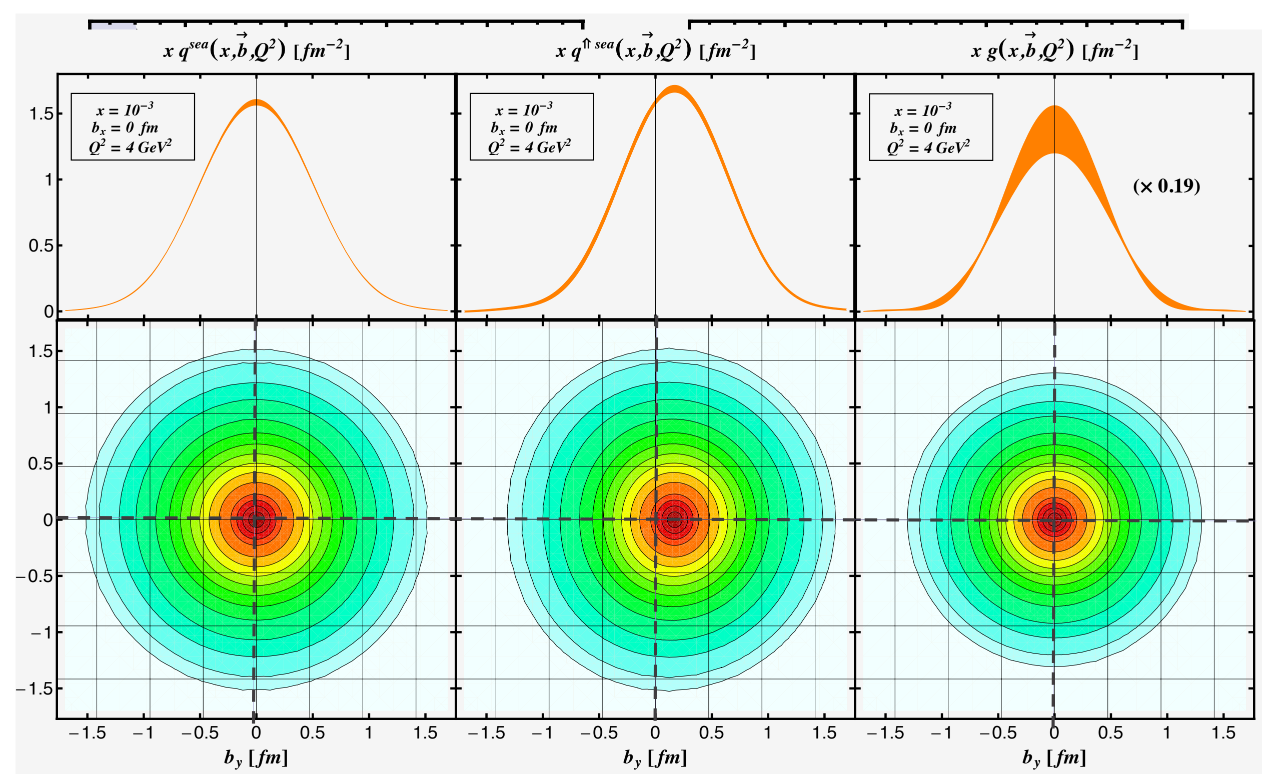
What's next?

(see WG7 summary talk)

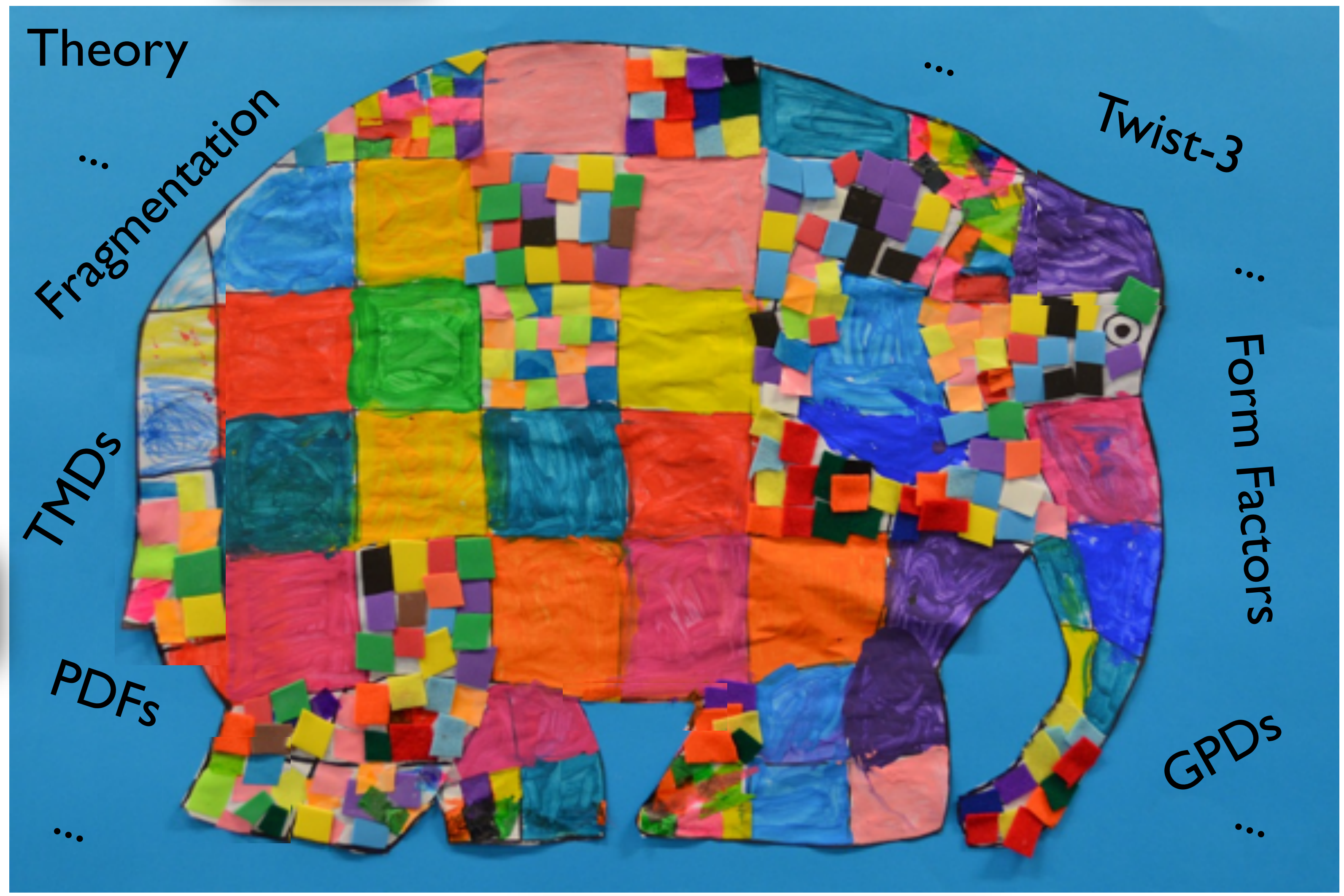




and much more ...!



The complete picture



*The elephant and the blind men

The complete picture

THANKS
to all the speakers!

*The elephant and the blind men