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Drell-Yan with e^+e^- at PANDA

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Introduction

- Helmholtz Institute Mainz (HIM) is busy planning for time-like form factor (FF) measurements, $\bar{p}p \rightarrow e^+e^-$, at PANDA

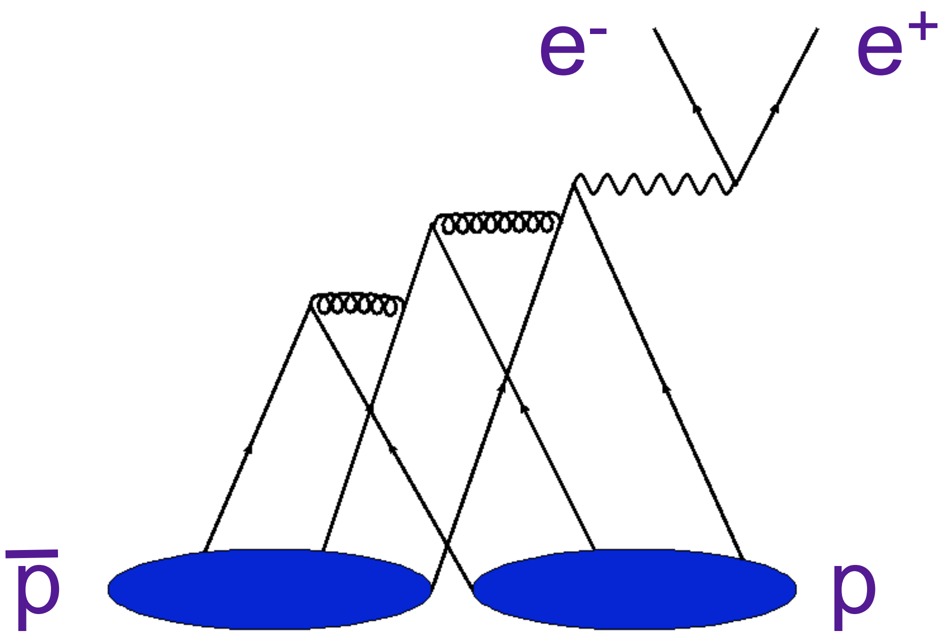
- A complete understanding of these FFs requires a transversely polarized target.

- Drell-Yan (DY) production $pp \rightarrow e^+e^-X$ is the time-like equivalent of deep inelastic scattering (DIS).

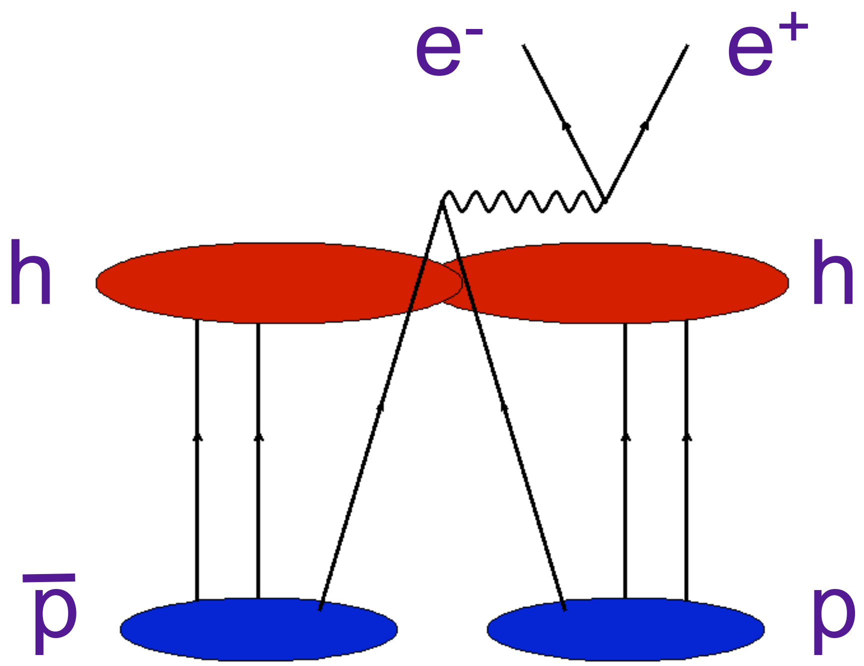
- DY with a polarized target will yield insights into quark orbital angular momentum in the nucleon.

- Planning for a transversely polarized proton target needs to take into account both FF and DY acceptances.

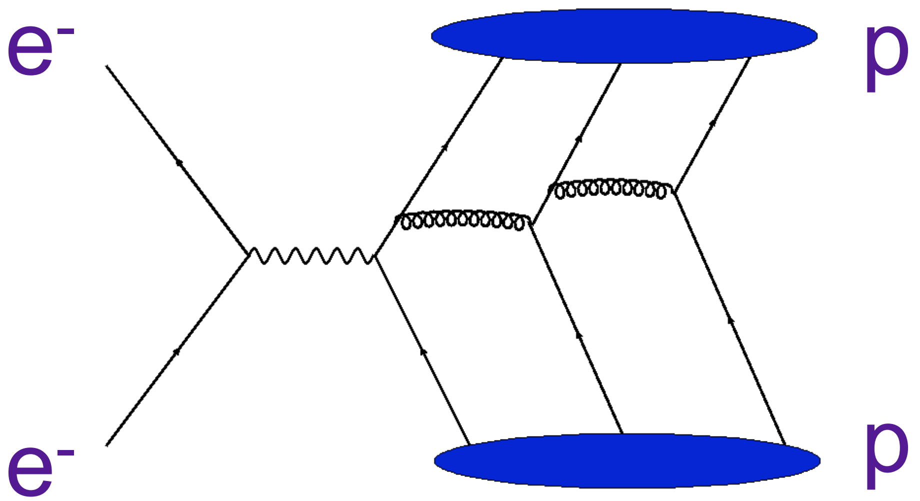
Spacelike/Timelike



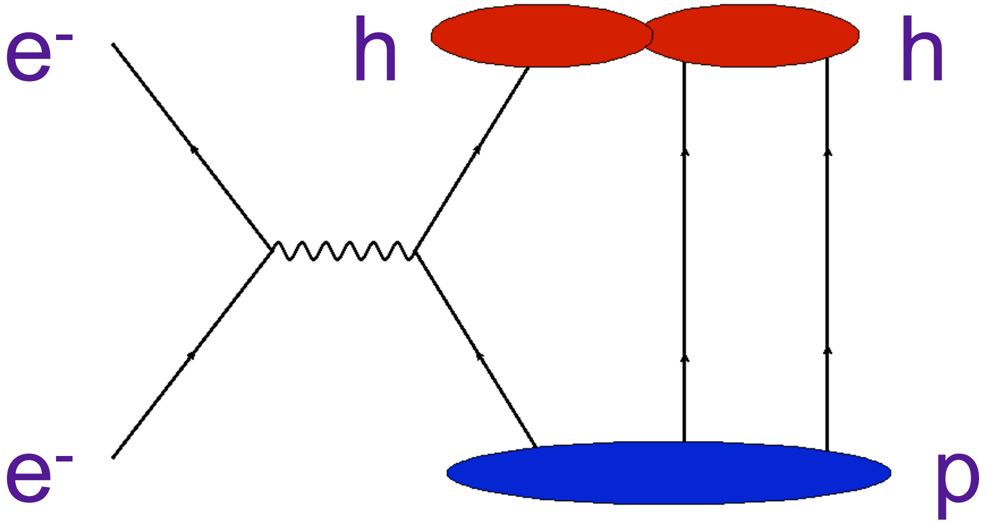
Timelike FF: $\bar{p}p \to e^+e^-$



Drell Yan: $\bar{p}p \to e^+e^-X$



Spacelike FF: (e,e’)



SIDIS: (e,e’h)X

DY Kinematics

P_1, P_2	4-momentum of beam and target hadrons
$q = Q$	magnitude of the virtual photon's 4-momentum
$Q^2 \equiv M^2_{l^+l^-}$	squared 4-momentum of virtual photon
$s = (P_1 + P_2)^2 \simeq 2P_1P_2$	center-of-mass energy squared
$x_1 = \frac{Q^2}{2P_1q}, \quad x_2 = \frac{Q^2}{2P_2q}$	momentum fraction for beam and target quarks
$y = \frac{1}{2}\ln\frac{x_1}{x_2}$	rapidity
$x_F = x_1 - x_2$	Feynman x (= $2q_L/\sqrt{s}$) $q^\mu = (q_0, q_T, 0, q_L)$
$x_{1,2} = \frac{\sqrt{x_F^2 + 4\tau} \pm x_F}{2} = \sqrt{\tau}e^{\pm y}$	$\tau = q^2 / s$

DY and FF Similarities

small at large q^2

FF:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4q^2\sqrt{1-1/\tau}}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta|G_E|^2\right] \qquad \tau = \frac{q^2}{4M^2}$$

small at small x, θ

DY:

$$\frac{d\sigma}{dx_1 dx_2 d\Omega} = \frac{\alpha^2}{4q^2}\left[(1+\cos^2\theta)F_1^{UU} + \sin^2\theta F_2^{UU}\right] \qquad x = \frac{q^2}{2P\cdot q}$$

FF:

$$|G_M| = 22.5\frac{1}{(1+q^2/0.71)^2}\frac{1}{(1+q^2/3.6)} \qquad \sigma(q^2) = \frac{2\pi\alpha^2}{3q^2\sqrt{1-1/\tau}}\left[2|G_M|^2+\frac{1}{\tau}|G_E|^2\right]$$

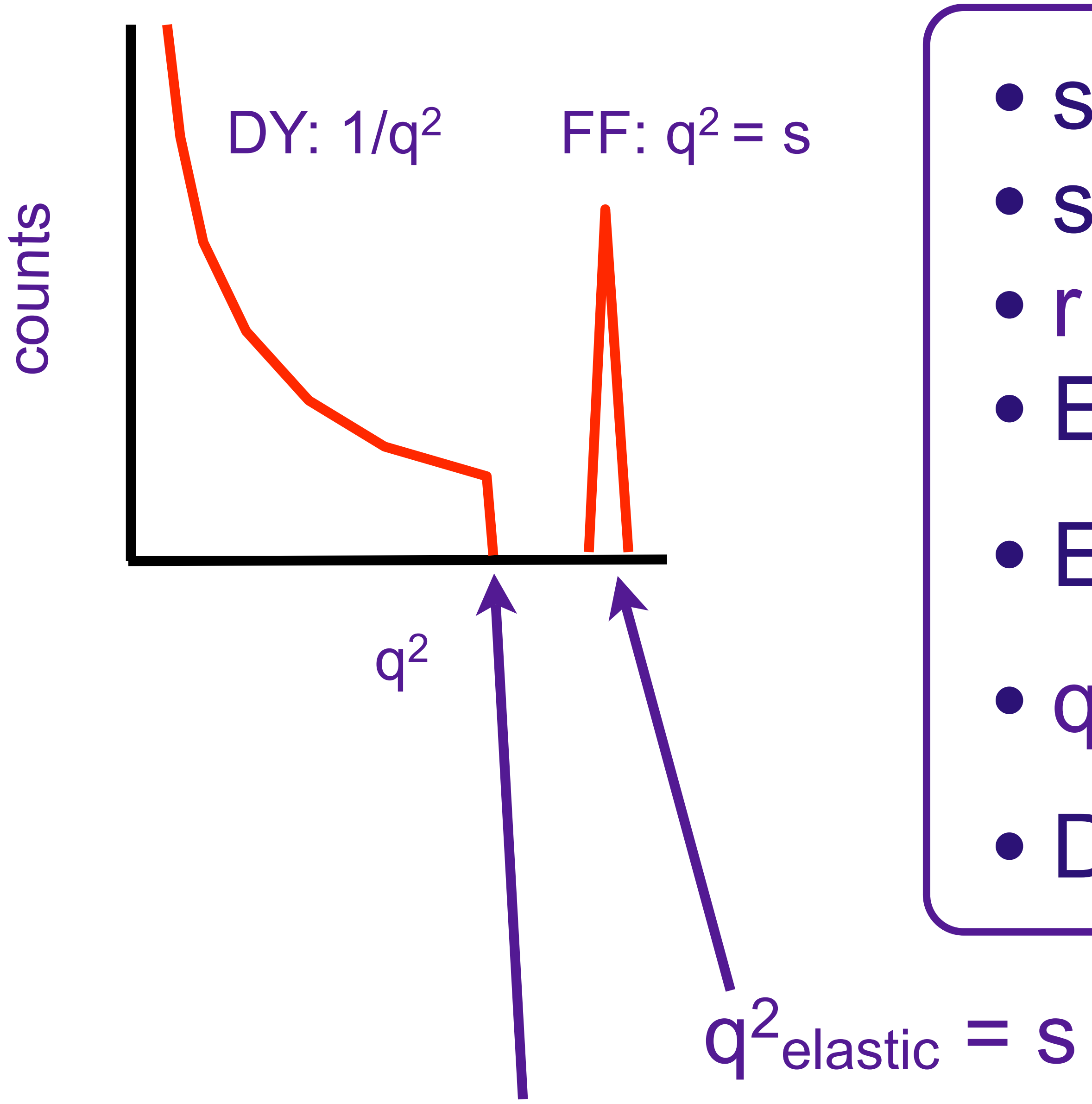
DY:

$$F_1^{UU} = \frac{1}{3}\sum_q e_q^2 f_1^q(x_1) f_1^q(x_2) \qquad \sigma(q^2)_{\text{valence}} = \frac{4\pi\alpha^2}{9q^2}$$

$$\sigma_{e\ell}/\sigma_{DY} \sim \frac{1}{q^6}$$

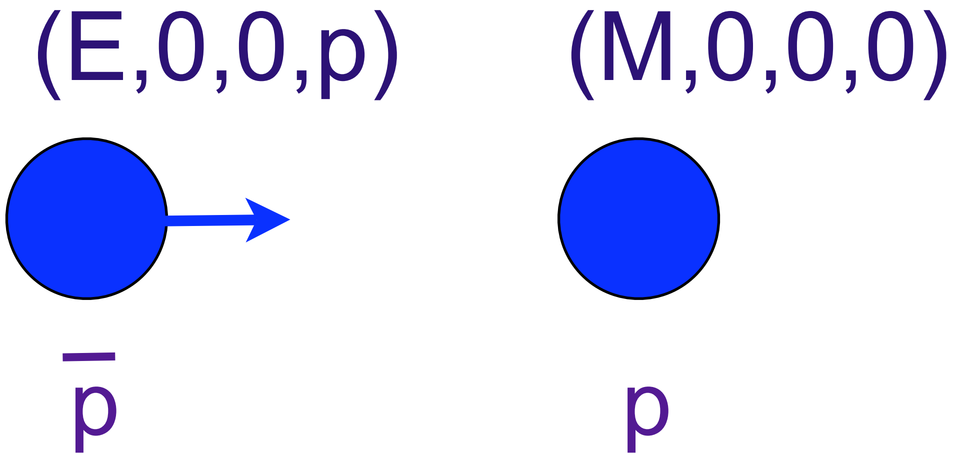
DY and FF e^+e^- pairs have similar distributions at the same q^2, but q^2_{DY} < q^2_{FF} for the same E_{beam}

DY & FF Kinematics

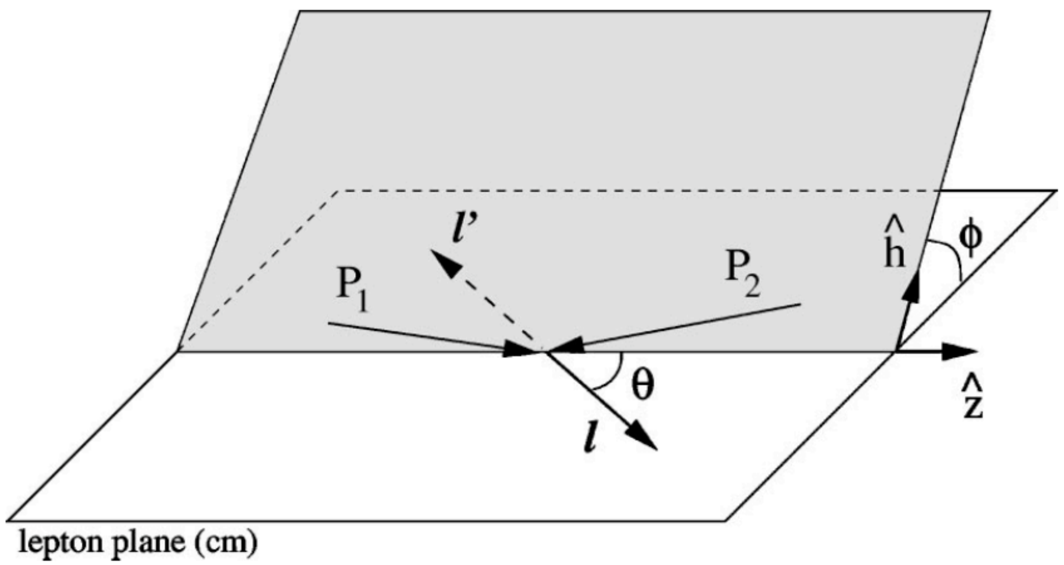


- $s = 2M(M+E)$
- $s_{min} = 4M^2$
- $r = q^2_{DYmax} / q^2_{elastic} = (1-2M/\sqrt{s})^2$
- E=1.5 GeV ⇒ $r = 0.15$
- E=15 GeV ⇒ $r = 0.43$
- $q^2_{DYmax} > 1\ \text{GeV}^2 \Rightarrow s > 8.3\ \text{GeV}^2$
- DY needs E > 3.5 GeV

$q^2_{DYmax} = (\sqrt{s} - 2M)^2$
cutoff assumes only
$\bar{p}pe^+e^-$ in final state



Reference Frames



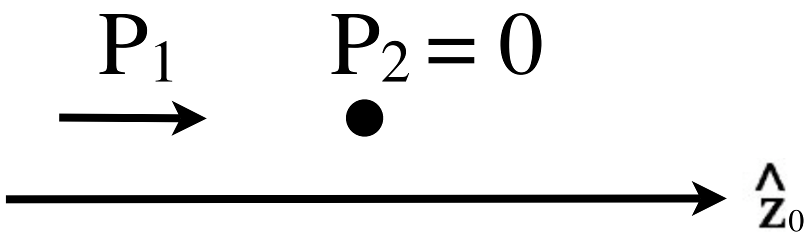
Boer, PRD**60**(99)014012

Lepton Plane (CM) [white]
Collins-Soper (CS) Frame [gray]

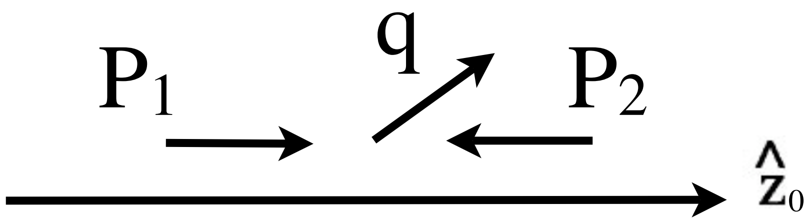
CS:

Boost along z_0 such that $q_L = 0$
Boost along x such that $q_T = 0$
$q_{CS} = (q,0,0,0)$
h is the q_T direction
θ and φ are shown in figure

Lab Frame



CM Frame:
boost along z
$\beta = P_1/(E_1+M)$



$q = (q_0,q_T,0,q_L)$

Drell-Yan Cross Section

Arnold, PR**D79**(09)034005

$$
\begin{aligned}
\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha_{\mathrm{em}}^2}{Fq^2}\{&((1+\cos^2\theta)F_{UU}^1 + (1-\cos^2\theta)F_{UU}^2 + \sin2\theta\cos\phi F_{UU}^{\cos\phi} + \sin^2\theta\cos2\phi F_{UU}^{\cos2\phi})\\
&+ S_{aL}(\sin2\theta\sin\phi F_{LU}^{\sin\phi} + \sin^2\theta\sin2\phi F_{LU}^{\sin2\phi}) + S_{bL}(\sin2\theta\sin\phi F_{UL}^{\sin\phi} + \sin^2\theta\sin2\phi F_{UL}^{\sin2\phi})\\
&+ |\vec{S}_{aT}|[\sin\phi_a((1+\cos^2\theta)F_{TU}^1 + (1-\cos^2\theta)F_{TU}^2 + \sin2\theta\cos\phi F_{TU}^{\cos\phi} + \sin^2\theta\cos2\phi F_{TU}^{\cos2\phi})\\
&+ \cos\phi_a(\sin2\theta\sin\phi F_{TU}^{\sin\phi} + \sin^2\theta\sin2\phi F_{TU}^{\sin2\phi})] + |\vec{S}_{bT}|[\sin\phi_b((1+\cos^2\theta)F_{UT}^1 + (1-\cos^2\theta)F_{UT}^2\\
&+ \sin2\theta\cos\phi F_{UT}^{\cos\phi} + \sin^2\theta\cos2\phi F_{UT}^{\cos2\phi}) + \cos\phi_b(\sin2\theta\sin\phi F_{UT}^{\sin\phi} + \sin^2\theta\sin2\phi F_{UT}^{\sin2\phi})]\\
&+ S_{aL}S_{bL}((1+\cos^2\theta)F_{LL}^1 + (1-\cos^2\theta)F_{LL}^2 + \sin2\theta\cos\phi F_{LL}^{\cos\phi} + \sin^2\theta\cos2\phi F_{LL}^{\cos2\phi})\\
&+ S_{aL}|\vec{S}_{bT}|[\cos\phi_b((1+\cos^2\theta)F_{LT}^1 + (1-\cos^2\theta)F_{LT}^2 + \sin2\theta\cos\phi F_{LT}^{\cos\phi} + \sin^2\theta\cos2\phi F_{LT}^{\cos2\phi})\\
&+ \sin\phi_b(\sin2\theta\sin\phi F_{LT}^{\sin\phi} + \sin^2\theta\sin2\phi F_{LT}^{\sin2\phi})] + |\vec{S}_{aT}|S_{bL}[\cos\phi_a((1+\cos^2\theta)F_{TL}^1 + (1-\cos^2\theta)F_{TL}^2\\
&+ \sin2\theta\cos\phi F_{TL}^{\cos\phi} + \sin^2\theta\cos2\phi F_{TL}^{\cos2\phi}) + \sin\phi_a(\sin2\theta\sin\phi F_{TL}^{\sin\phi} + \sin^2\theta\sin2\phi F_{TL}^{\sin2\phi})]\\
&+ |\vec{S}_{aT}||\vec{S}_{bT}|[\cos(\phi_a+\phi_b)((1+\cos^2\theta)F_{TT}^1 + (1-\cos^2\theta)F_{TT}^2 + \sin2\theta\cos\phi F_{TT}^{\cos\phi} + \sin^2\theta\cos2\phi F_{TT}^{\cos2\phi})\\
&+ \cos(\phi_a-\phi_b)((1+\cos^2\theta)\bar{F}_{TT}^1 + (1-\cos^2\theta)\bar{F}_{TT}^2 + \sin2\theta\cos\phi\bar{F}_{TT}^{\cos\phi} + \sin^2\theta\cos2\phi\bar{F}_{TT}^{\cos2\phi})\\
&+ \sin(\phi_a+\phi_b)(\sin2\theta\sin\phi F_{TT}^{\sin\phi} + \sin^2\theta\sin2\phi F_{TT}^{\sin2\phi})\\
&+ \sin(\phi_a-\phi_b)(\sin2\theta\sin\phi\bar{F}_{TT}^{\sin\phi} + \sin^2\theta\sin2\phi\bar{F}_{TT}^{\sin2\phi})]\}.
\end{aligned}
$$

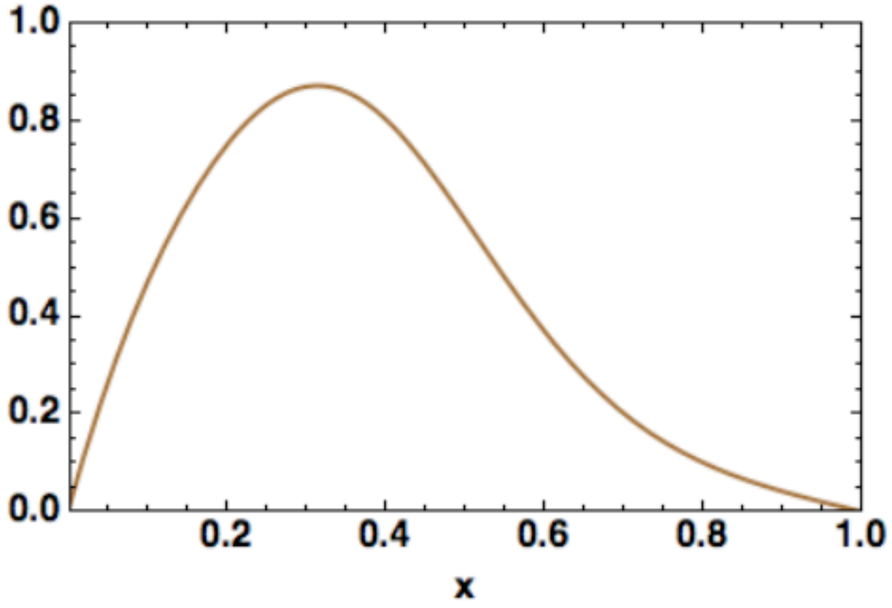
Structure functions F are general

● What PANDA can measure with a transversely polarized proton target

TMDs

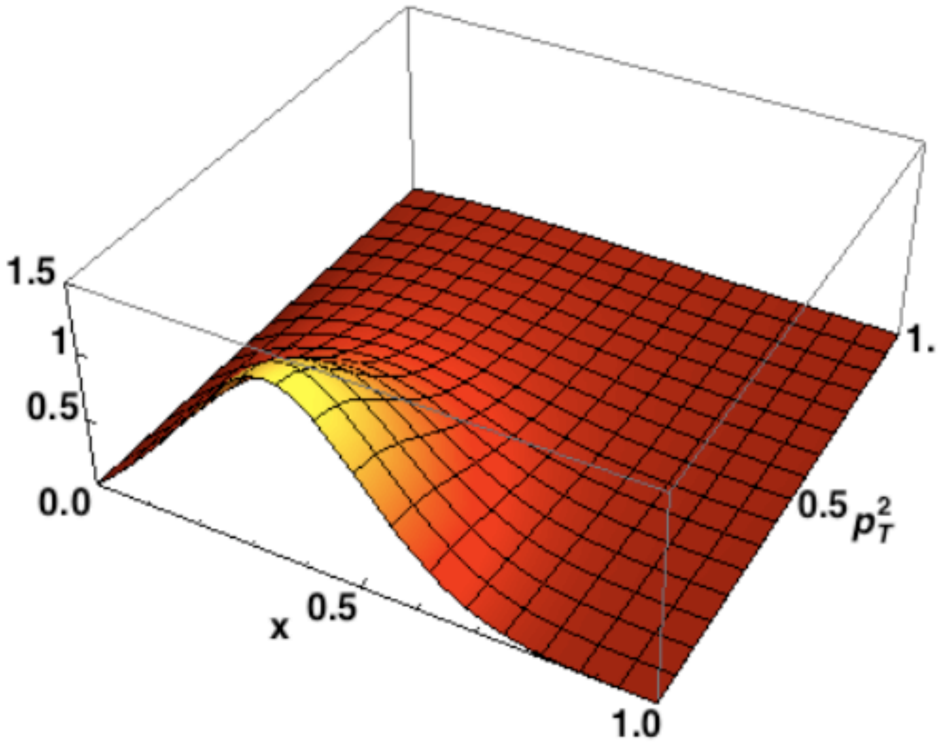
- Any confined quark must have transverse momentum
- Therefore, colinear PDFs cannot give the whole story
- Transverse momentum is related to L_z
- There has been much recent work trying to understand transverse momentum distributions (TMDs)

$xf_1^u(x)$



Standard collinear PDF

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



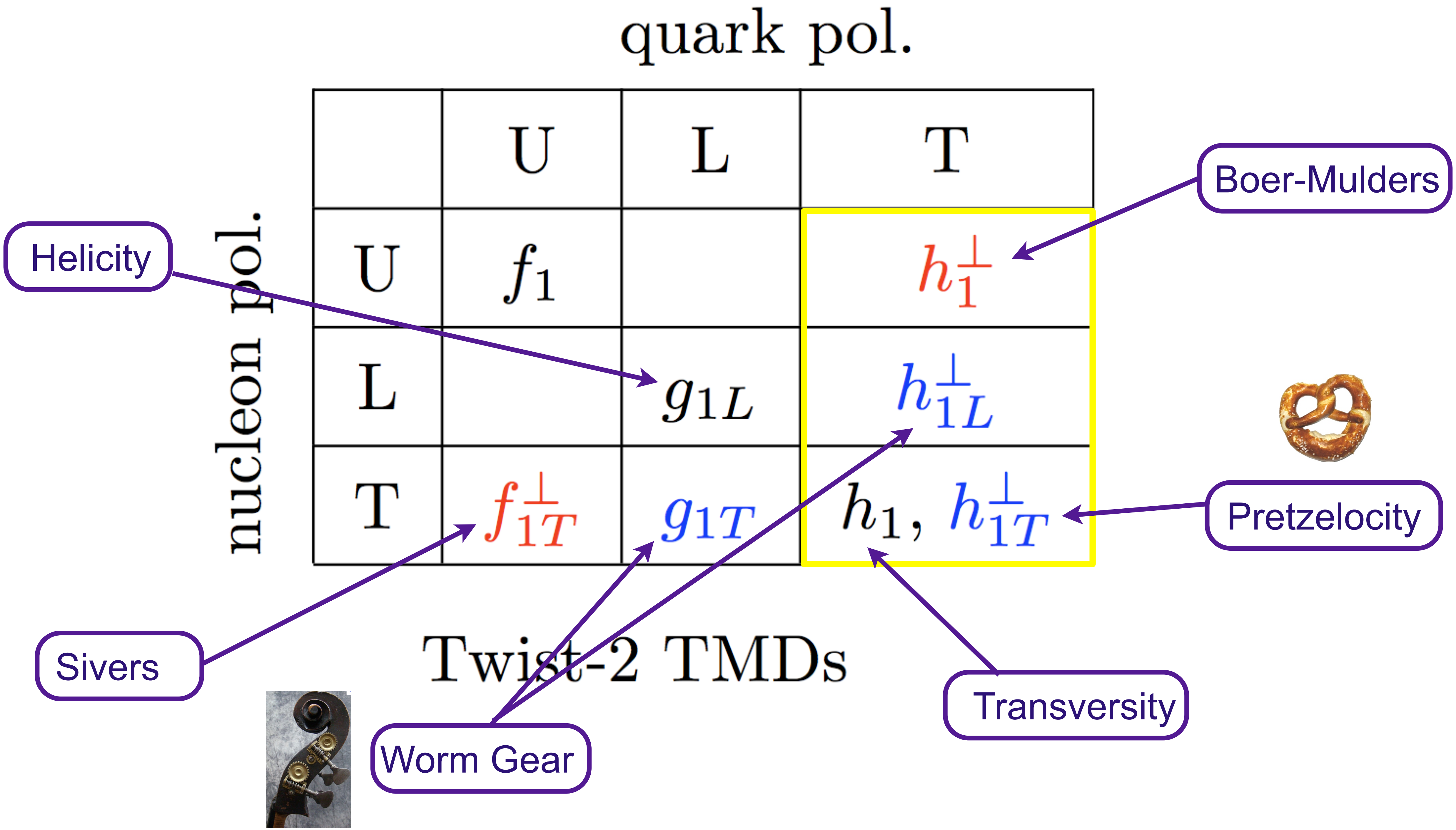
TMD

Primary TMDs

Red: T-odd

Black: survive p_T integration

Yellow box: chiral-odd



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

Leading Order Unpolarized DY

$$\mathcal{C}[w(\vec{k}_{aT},\vec{k}_{bT})f_1\bar{f}_2] \equiv \frac{1}{N_c}\sum_q e_q^2 \int d^2\vec{k}_{aT}d^2\vec{k}_{bT} \times \delta^{(2)}(\vec{q}_T-\vec{k}_{aT}-\vec{k}_{bT})w(\vec{k}_{aT},\vec{k}_{bT}) \times [f_1^q(x_a,\vec{k}_{aT}^2)f_2^{\bar{q}}(x_b,\vec{k}_{bT}^2) + f_1^{\bar{q}}(x_a,\vec{k}_{aT}^2)f_2^q(x_b,\vec{k}_{bT}^2)]. \qquad (89)$$

$$F_{UU}^1 = \mathcal{C}[f_1\bar{f}_1]$$

q_T direction

$$F_{UU}^{\cos 2\phi} = \mathcal{C}\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT})-\vec{k}_{aT}\cdot\vec{k}_{bT}}{M_aM_b}h_1^{\perp}\bar{h}_1^{\perp}\right]$$

Boer-Mulders

- Antiproton $\bar{q}$ = proton q
- $q_T = k_{aT} + k_{bT}$
- Gaussian q_T-dependence often assumed (unrealistic)

$$F^1_{UU}(x_1, x_2, q_T^2) \sim f_1^q(x_1)f^q(x_2)\exp(-q_T^2/\mu^2)$$

Complementarity of pp, ep, ee

Drell-Yan

$$\frac{d\sigma}{dq_T^2} \sim \sum_q e_q^2\, f_1^q(x, p_T^2) \otimes f_1^{\bar{q}}(\bar{x}, \bar{p}_T^2)$$

$q_T=p_T+\bar{p}_T$

SIDIS

$$\frac{d\sigma}{dq_T^2} \sim \sum_q e_q^2\, f_1^q(x, p_T^2) \otimes D_1^q(z, k_T^2)$$

$q_T=zp_T+k_T$

e^+e^- Annihilation

$$\frac{d\sigma}{dq_T^2} \sim \sum_q e_q^2\, D_1^q(z, k_T^2) \otimes D_1^{\bar{q}}(\bar{z}, \bar{k}_T^2)$$

$q_T=k_T+\bar{k}_T$

Leading Order Polarized DY

Sivers

$$F_{UT}^{1} = \mathcal{C}\left[\frac{\vec{h}\cdot\vec{k}_{bT}}{M_b} f_1 \bar{f}_{1T}^{\perp}\right]$$

Transversity

$$F_{UT}^{\sin(2\phi-\phi_b)} = -\mathcal{C}\left[\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} h_1^{\perp} \bar{h}_1\right]$$

$$f_{1T}^{\perp q}(x,k_T)\Big|_{DY} = -f_{1T}^{\perp}(x,k_T)\Big|_{SIDIS}$$

$$h_1^{\perp}(x,k_T)\Big|_{DY} = -h_1^{\perp}(x,k_T)\Big|_{SIDIS}$$

Boer-Mulders

Pretzelocity

$$F_{UT}^{\sin(2\phi+\phi_b)} = -\mathcal{C}\left[\frac{2(\vec{h}\cdot\vec{k}_{bT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}] - \vec{k}_{bT}^{2}(\vec{h}\cdot\vec{k}_{aT})}{2M_a M_b^2} h_1^{\perp} \bar{h}_{1T}^{\perp}\right]$$

$$\boxed{F_{UT}^{\sin(2\phi-\phi_b)} \equiv -\frac{1}{2}\left(F_{UT}^{\cos 2\phi} - F_{UT}^{\sin 2\phi}\right)}$$

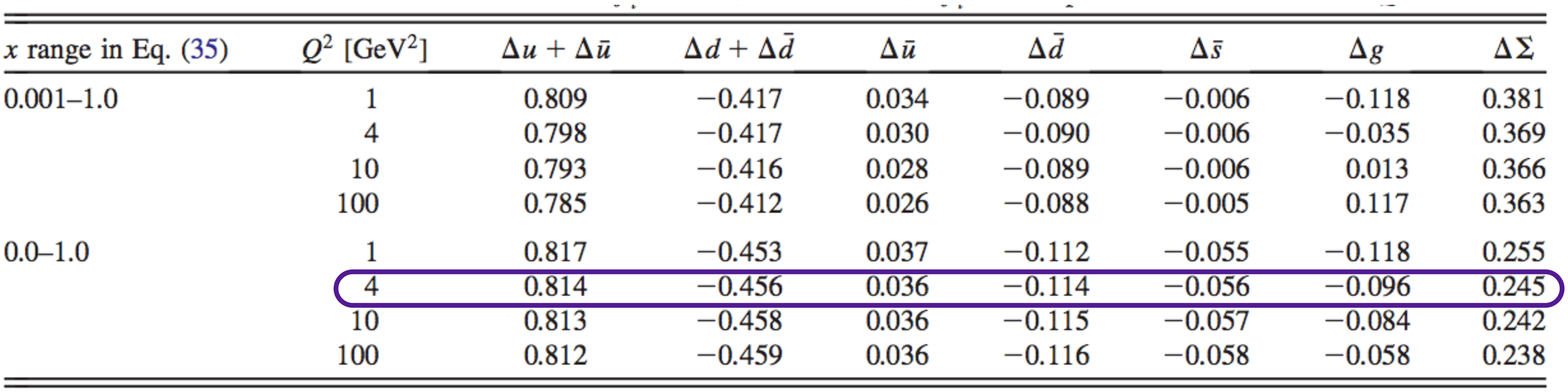
$$\boxed{F_{UT}^{\sin(2\phi+\phi_b)} \equiv \frac{1}{2}\left(F_{UT}^{\cos 2\phi} + F_{UT}^{\sin 2\phi}\right)}$$

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, $h_{1T}^{\perp}$

$$\mathcal{C}[w(\vec{k}_{aT},\vec{k}_{bT}) f_1 \bar{f}_2] \equiv \frac{1}{N_c}\sum_q e_q^2 \int d^2\vec{k}_{aT}\, d^2\vec{k}_{bT} \times \delta^{(2)}(\vec{q}_T - \vec{k}_{aT} - \vec{k}_{bT}) w(\vec{k}_{aT},\vec{k}_{bT}) \times [f_1^q(x_a,\vec{k}_{aT}^2) f_2^{\bar{q}}(x_b,\vec{k}_{bT}^2) + f_1^{\bar{q}}(x_a,\vec{k}_{aT}^2) f_2^q(x_b,\vec{k}_{bT}^2)].$$

DSSV PDFs: Where's L?



x range in Eq. (35)	Q^2 [GeV^2]	$\Delta u + \Delta\bar{u}$	$\Delta d + \Delta\bar{d}$	$\Delta\bar{u}$	$\Delta\bar{d}$	$\Delta\bar{s}$	Δg	$\Delta\Sigma$
0.001–1.0	1	0.809	−0.417	0.034	−0.089	−0.006	−0.118	0.381
	4	0.798	−0.417	0.030	−0.090	−0.006	−0.035	0.369
	10	0.793	−0.416	0.028	−0.089	−0.006	0.013	0.366
	100	0.785	−0.412	0.026	−0.088	−0.005	0.117	0.363
0.0–1.0	1	0.817	−0.453	0.037	−0.112	−0.055	−0.118	0.255
	4	0.814	−0.456	0.036	−0.114	−0.056	−0.096	0.245
	10	0.813	−0.458	0.036	−0.115	−0.057	−0.084	0.242
	100	0.812	−0.459	0.036	−0.116	−0.058	−0.058	0.238

$$\boxed{\frac{1}{2} = \frac{\Delta\Sigma}{2} + \Delta G + L_z}$$

- Significant contributions from x<0.001
- ΔG vanishes with increasing Q^2
- At Q^2=4 GeV^2, L_z = 0.474 (large)
- Errors on ΔG are still very large

Quark Angular Momentum

Bacchetta and Radici
arXiv:1107.5755

$$J^a(Q^2) = \frac{1}{2}\int_0^1 dx\, x \left(H^a(x,0,0;Q^2) + E^a(x,0,0;Q^2)\right)$$

H GPD: colinear f_1^a PDF

$$\sum_q \int_0^1 dx\, E^{q_v}(x,0,0) = \kappa$$

E GPD: does not correspond to a colinear PDF

$$f_{1T}^{\perp(0)a}(x;Q_L^2) = -L(x)\, E^a(x,0,0;Q_L^2)$$

Sivers TMD can be related to E

$$f_{1T}^{\perp(n)a}(x;Q^2) = \int d^2p_T \left(\frac{p_T^2}{2M^2}\right)^n f_{1T}^{\perp a}(x,p_T^2;Q^2)$$

Definition of (n)th moment of p_T^2

Need much better data here

$$L(x) = \frac{K}{(1-x)^\eta}$$

Anzatz for lensing factor

Fit using all Sivers data and nucleon magnetic moments

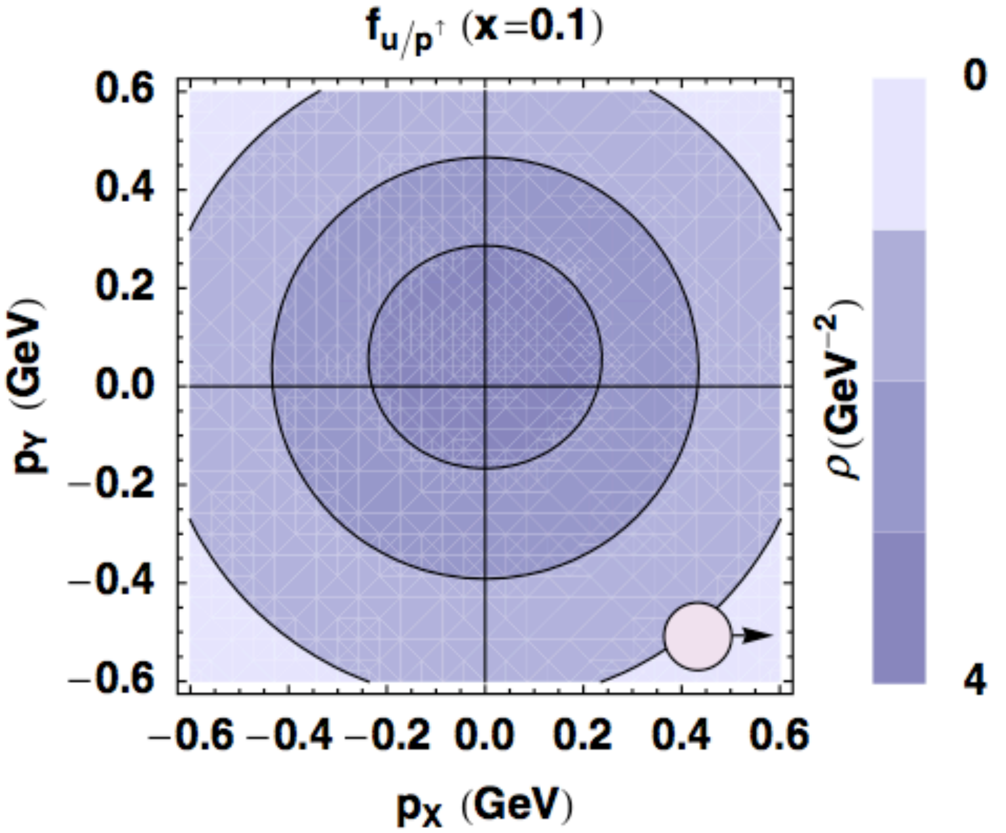
$$\kappa^{u_v} = 1.673 \pm 0.003^{+0.011}_{-0.000}, \quad \kappa^{d_v} = -2.033 \pm 0.002^{+0.011}_{-0.000}$$

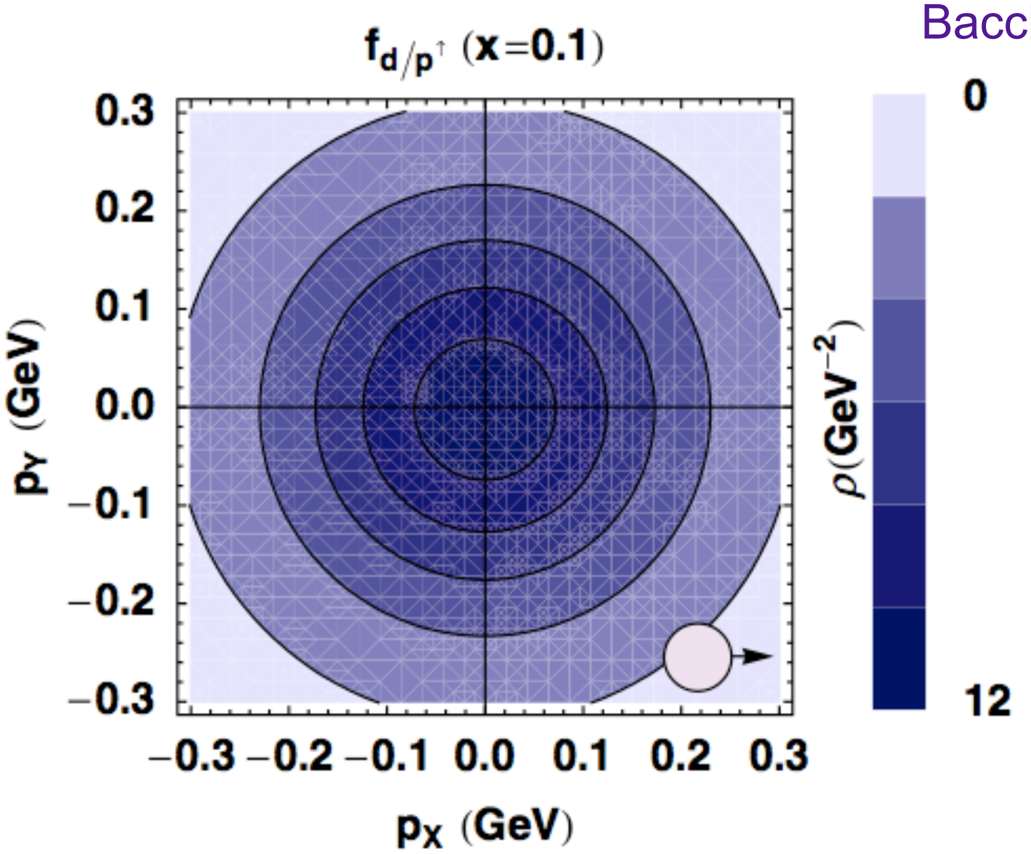
$$\begin{aligned} J^u &= 0.266 \pm 0.002^{+0.009}_{-0.014}, & J^{\bar{u}} &= 0.014 \pm 0.004^{+0.001}_{-0.000}, \\ J^d &= -0.012 \pm 0.003^{+0.024}_{-0.006}, & J^{\bar{d}} &= 0.022 \pm 0.006^{+0.001}_{-0.000}, \\ J^s &= 0.005^{+0.000}_{-0.007}, & J^{\bar{s}} &= 0.004^{+0.000}_{-0.005}. \end{aligned}$$

$$\boxed{\mathbf{J} = 0.299 \pm 0.008^{+0.035}_{-0.032}}$$

Diquark Spectator Model

Bacchetta, PR**D78**(08)074010

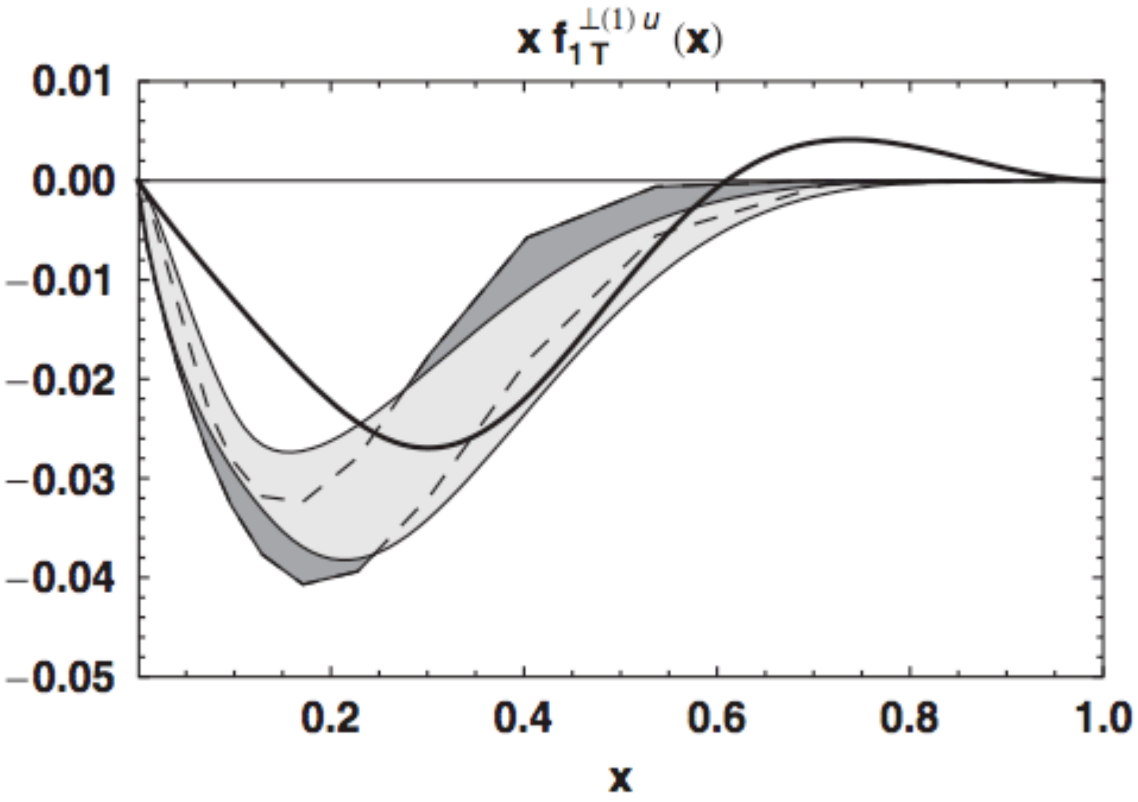


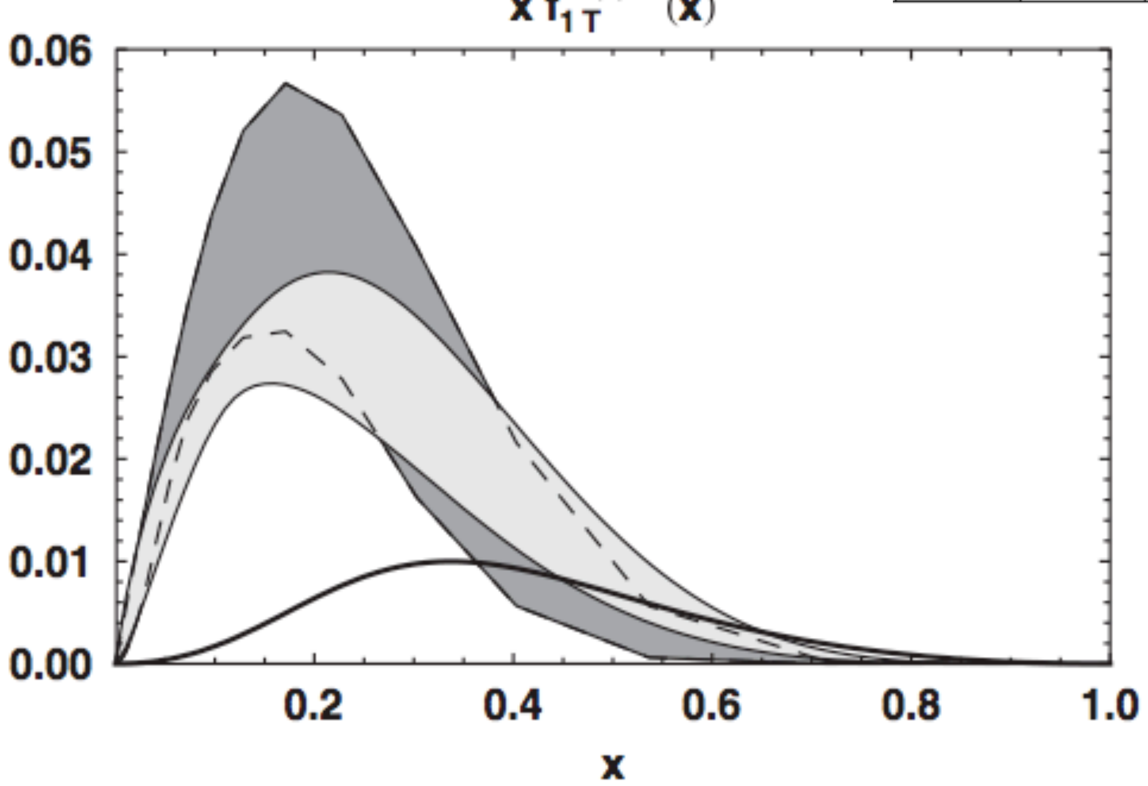


$$f_{1T}^{\perp}$$

Sivers

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





A_NDY at RHIC

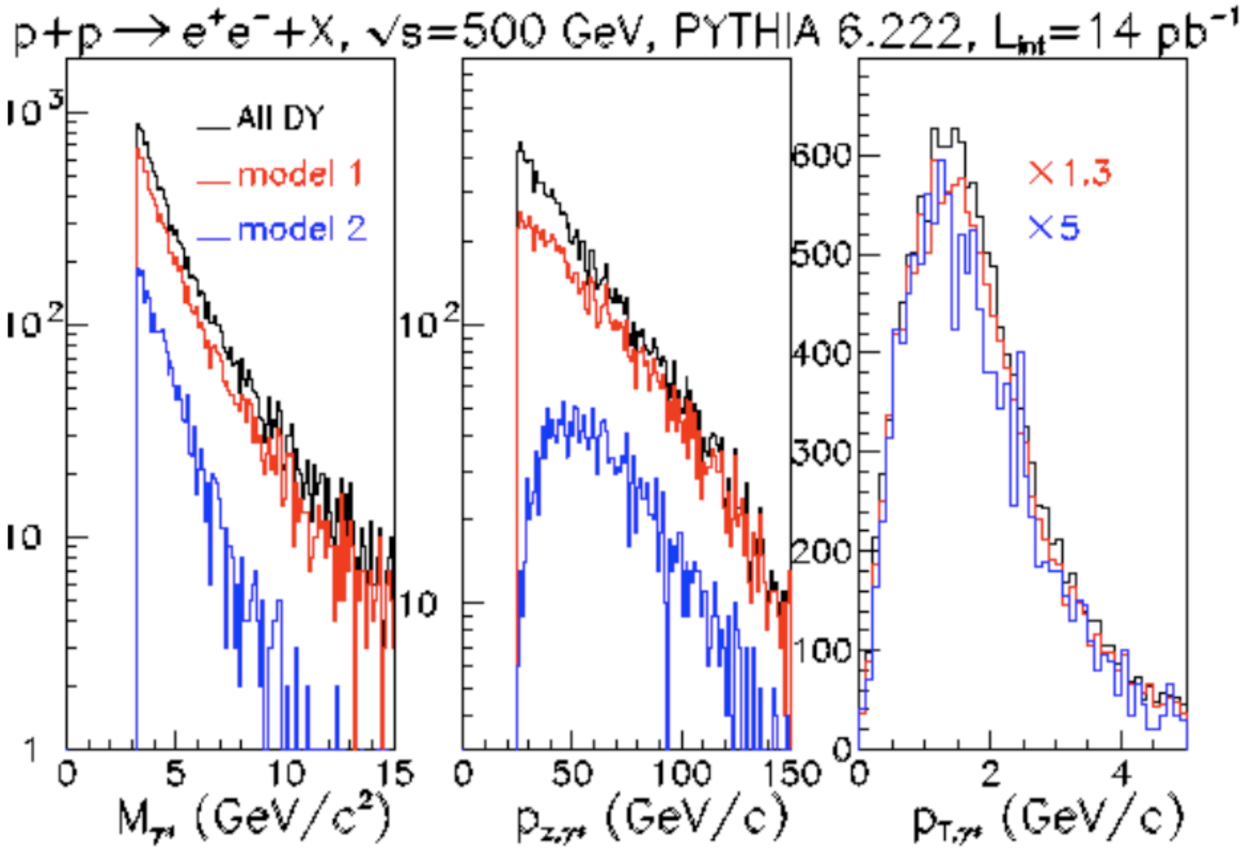
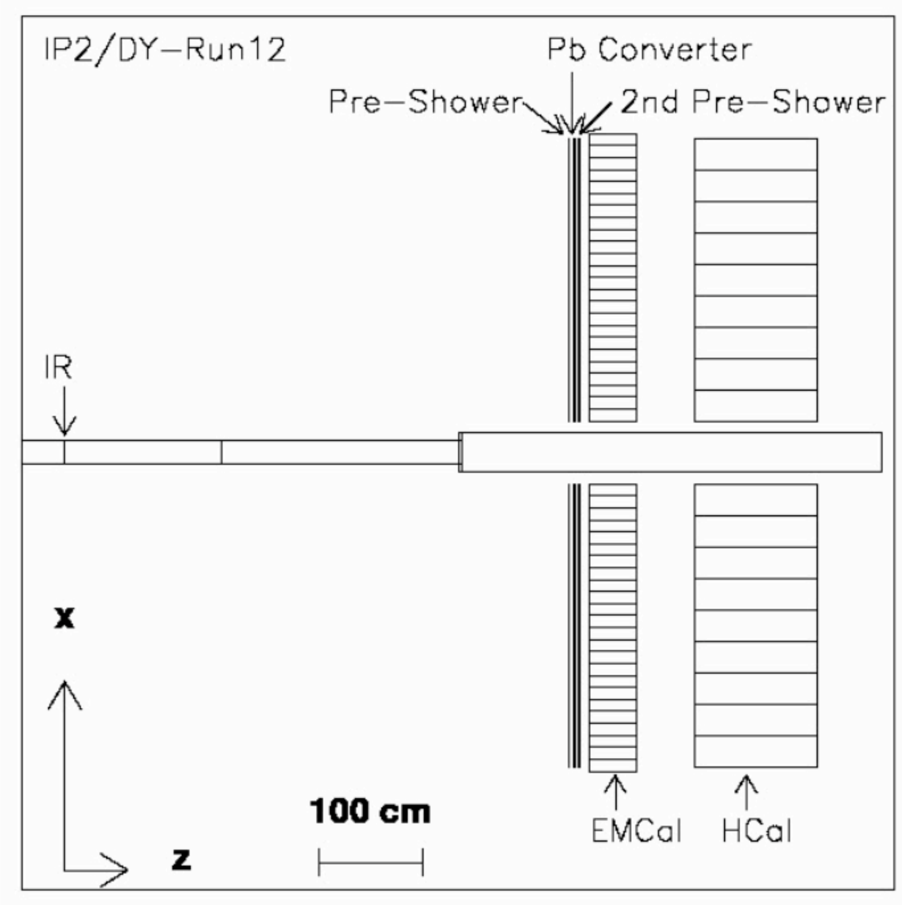


Fig. III-3 Kinematic distributions for the virtual photon. Model 1 would be a final facility and model 2 is the first stage of the proposed feasibility test for studying DY production at RHIC.

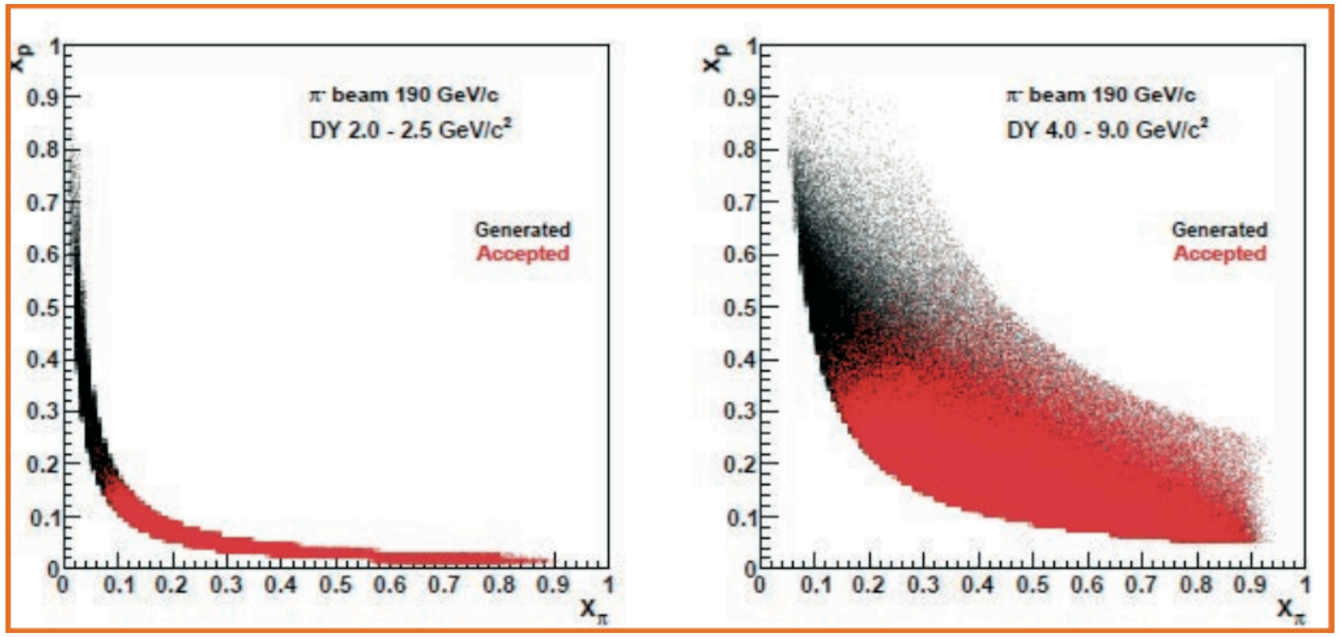
$\sqrt{q^2}$ q_L q_T

$$q = (q_0, q_T, 0, q_L)$$

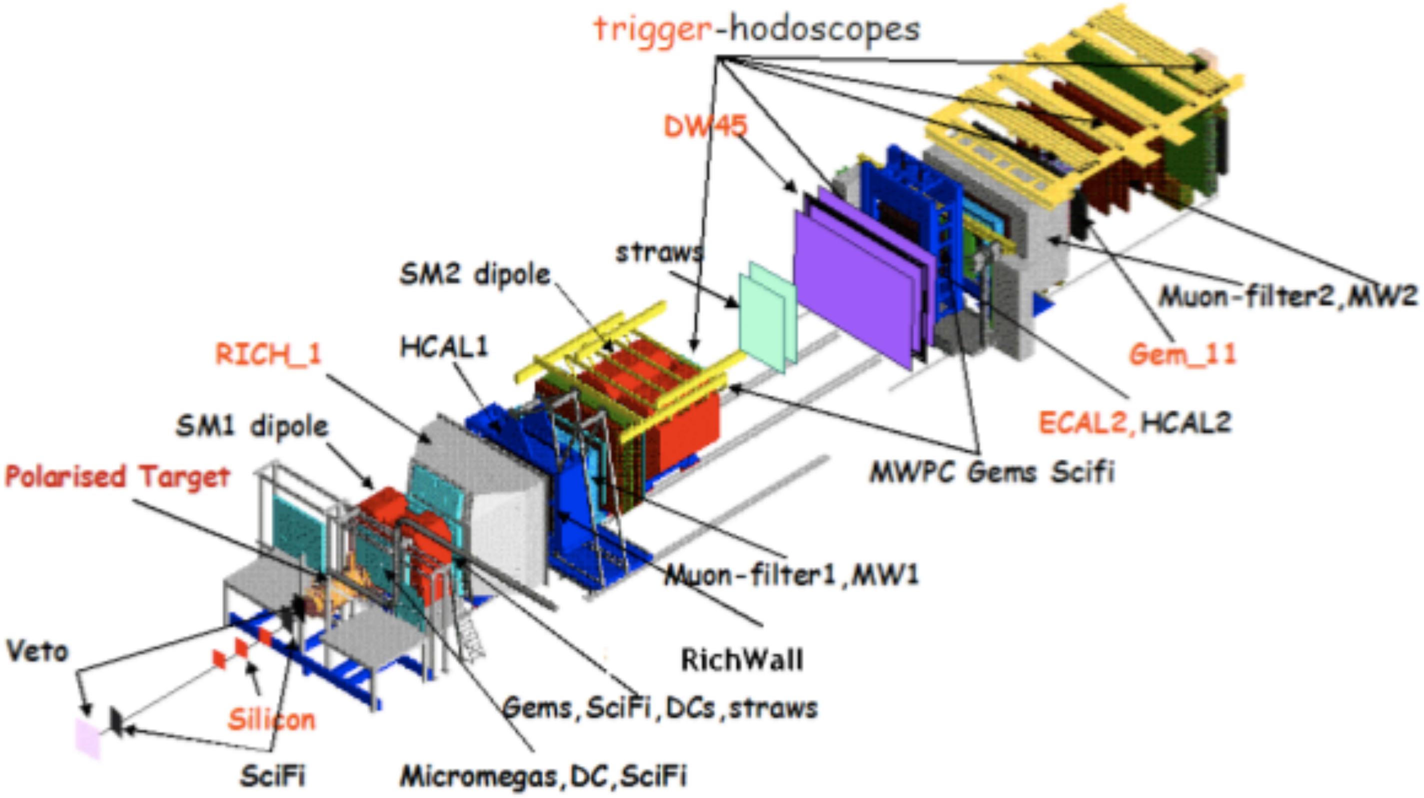
- E. Aschenauer, et al., Large Rapidity Drell-Yan Production at RHIC; Proposal 16 May 2011
- $\sqrt{s} = 500$ GeV, $p^{\uparrow} p \rightarrow e^+ e^- X$ in IP2
- $16 < q^2 < 150$ GeV^2
- $x_F = x_1 - x_2 = 2q_L/\sqrt{s} = 0.1 - 0.6$
- $x_1 \sim 0.1 - 0.6$; $x_2 < 0.01$
- Run 2013 estimate 150 pb^{-1}

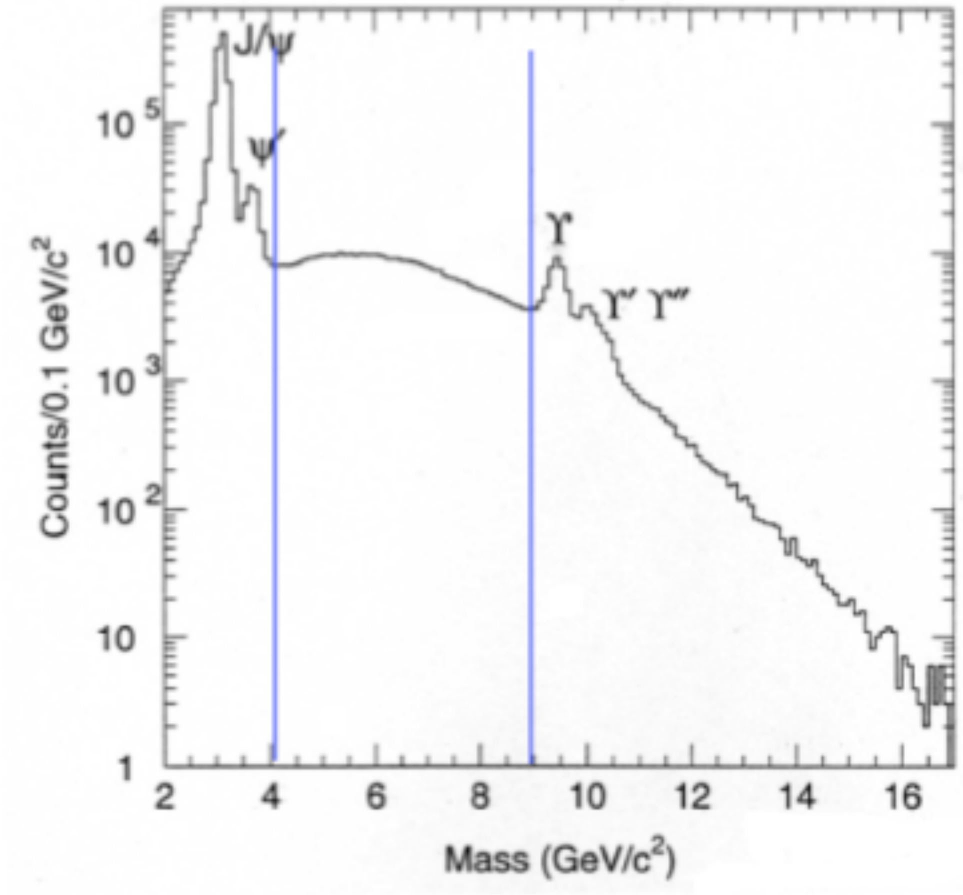


DY at COMPASS



- S. Takekawa, PHOTON2011; M. Chiosso, DY Workshop Santa Fe 2011
- p_{beam} = 190 GeV/c
- $\sqrt{s}$ = 17.4 GeV, $\pi\, p\!\uparrow\, \rightarrow \mu^+ \mu^- X$
- $4 < q^2 < 6$; $16 < q^2 < 81$ GeV^2
- $x_F = x_1 - x_2 = 2q_L/\sqrt{s} = -0.1 - 0.9$
- $0.2 < x_\pi < 0.9$; $0.04 < x_p < 0.4$
- Run for 2 years: 2.9 fb^{-1}





DY at COMPASS

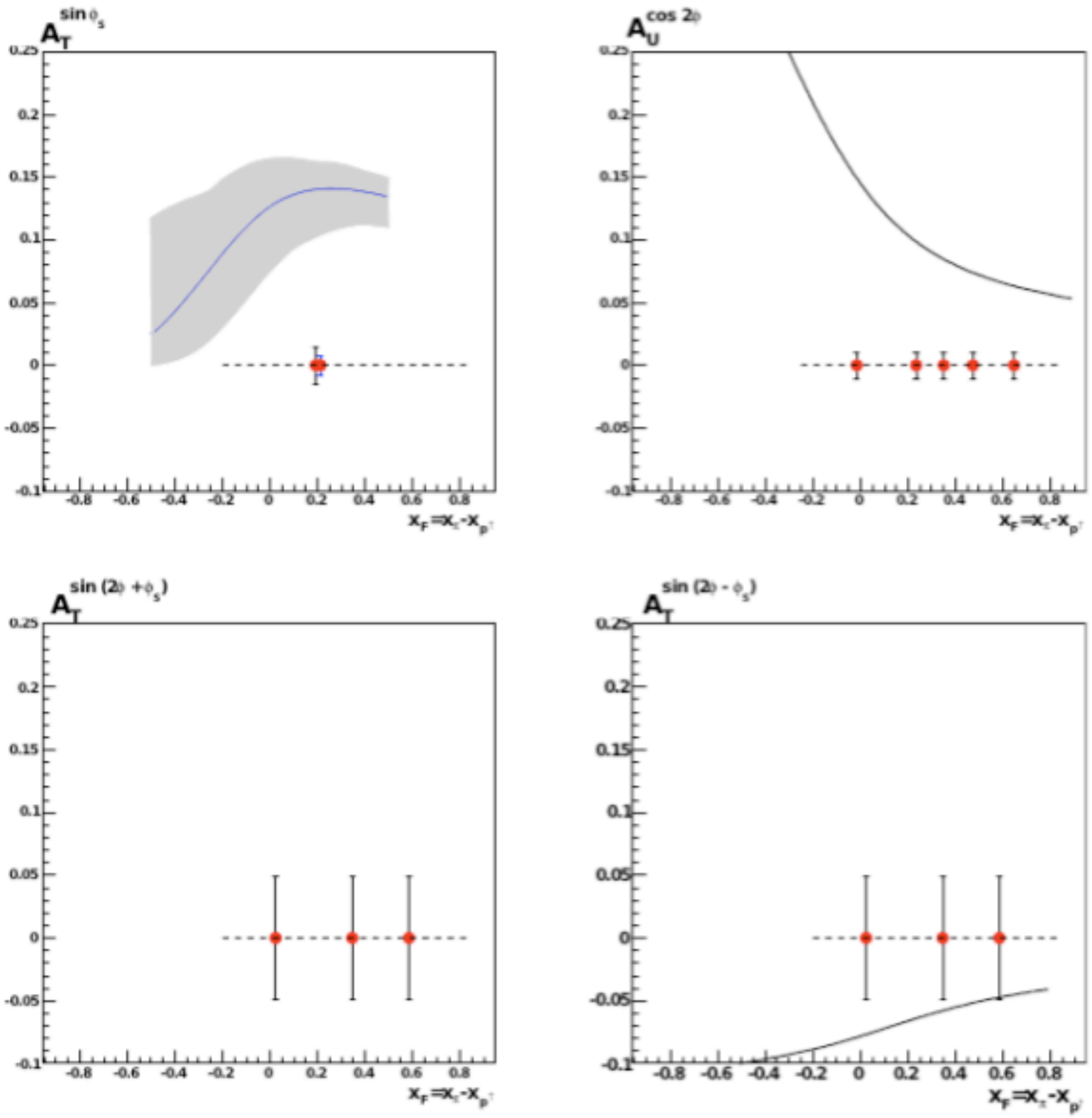
Predictions for asymmetries: 4-9 GeV/c^2 @ COMPASS

Sivers

M. Anselmino et al, Phys. Rev. D 79, 054010 (2009)

Boer-Mulders

B. Zhang et al, Phys. Rev. D 77, 054011 (2008)

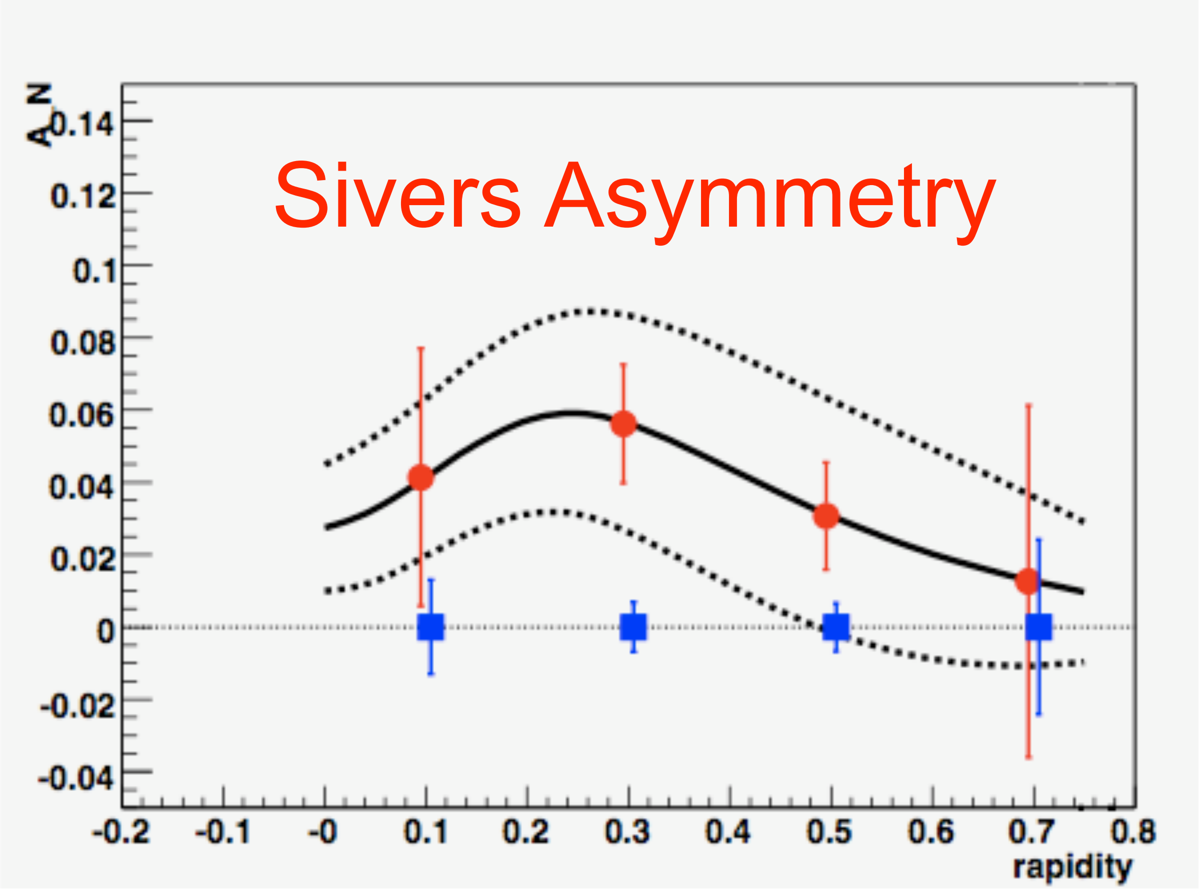


BM ⊗ pretz.

BM ⊗ transv.

A. N. Sissakian, Phys. Part. Nucl. 41, 64-100 (2010)

DY at J-PARC



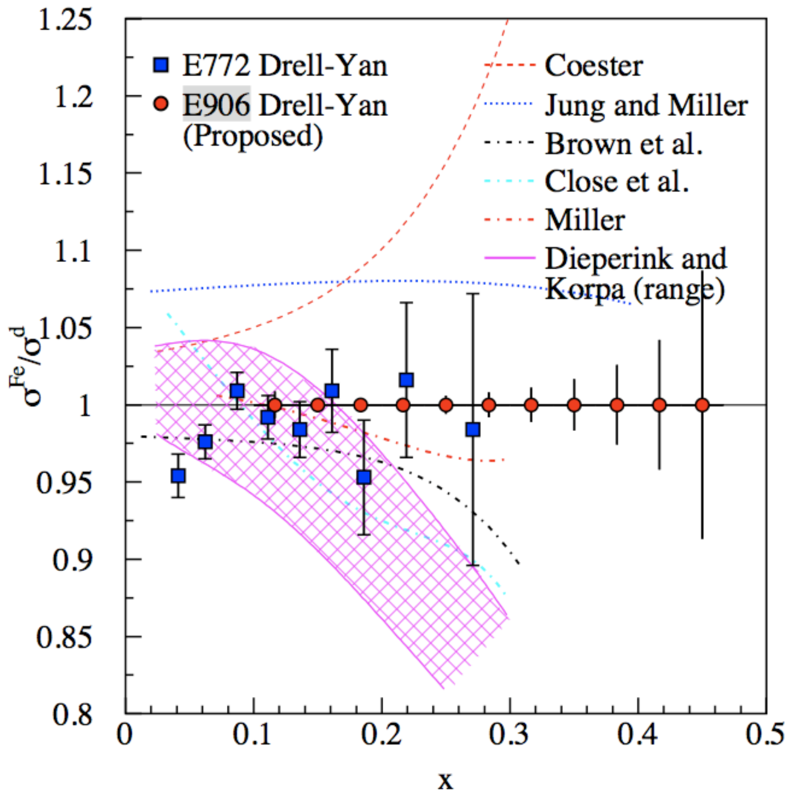
- Y. Goto, PoS(DIS2010)264
- p_{beam} = 30-50 GeV/c
- $\sqrt{s}$ = 8−10 GeV, $p^{\uparrow} p \rightarrow \mu^{+} \mu^{-} X$
- $16 < q^2 < 25$ GeV^2
- $x_1 / x_2 \sim 1.2 - 4$;
- Estimates for 120 days at 50% efficiency and 75% polarization
- Early in the planning stage

Rapidity: $y = \frac{1}{2} \ln \frac{x_1}{x_2}$

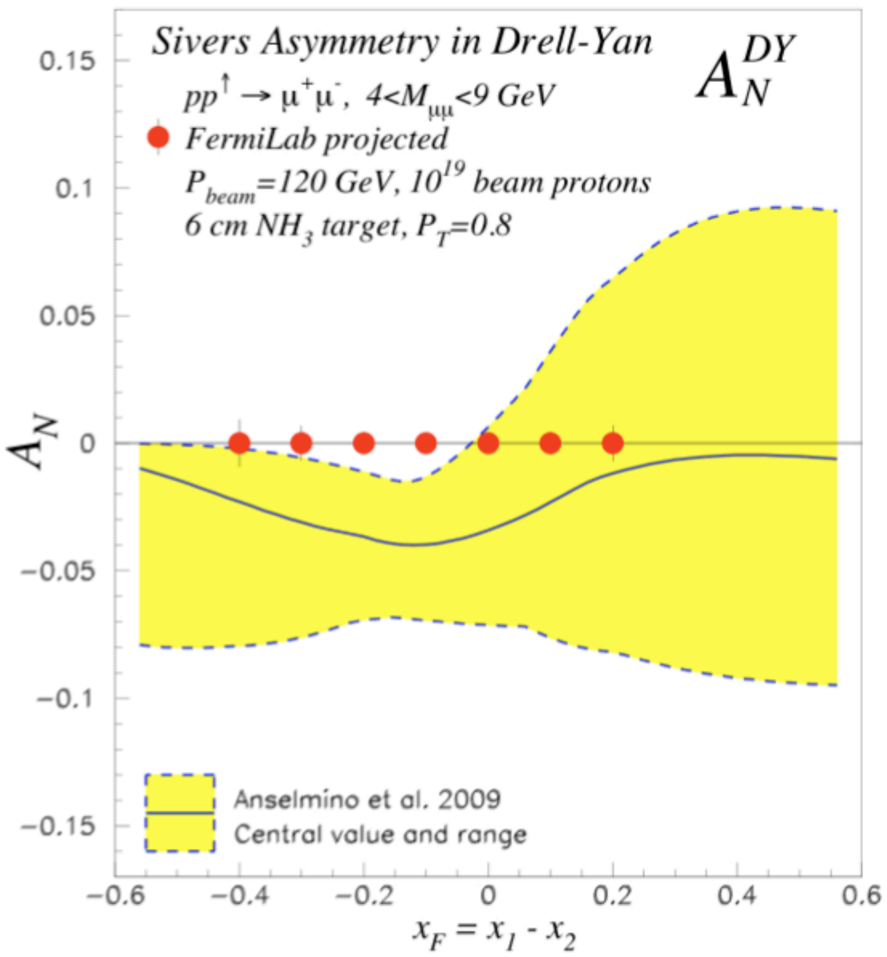
Red: 5% Interaction Length LH_2 target

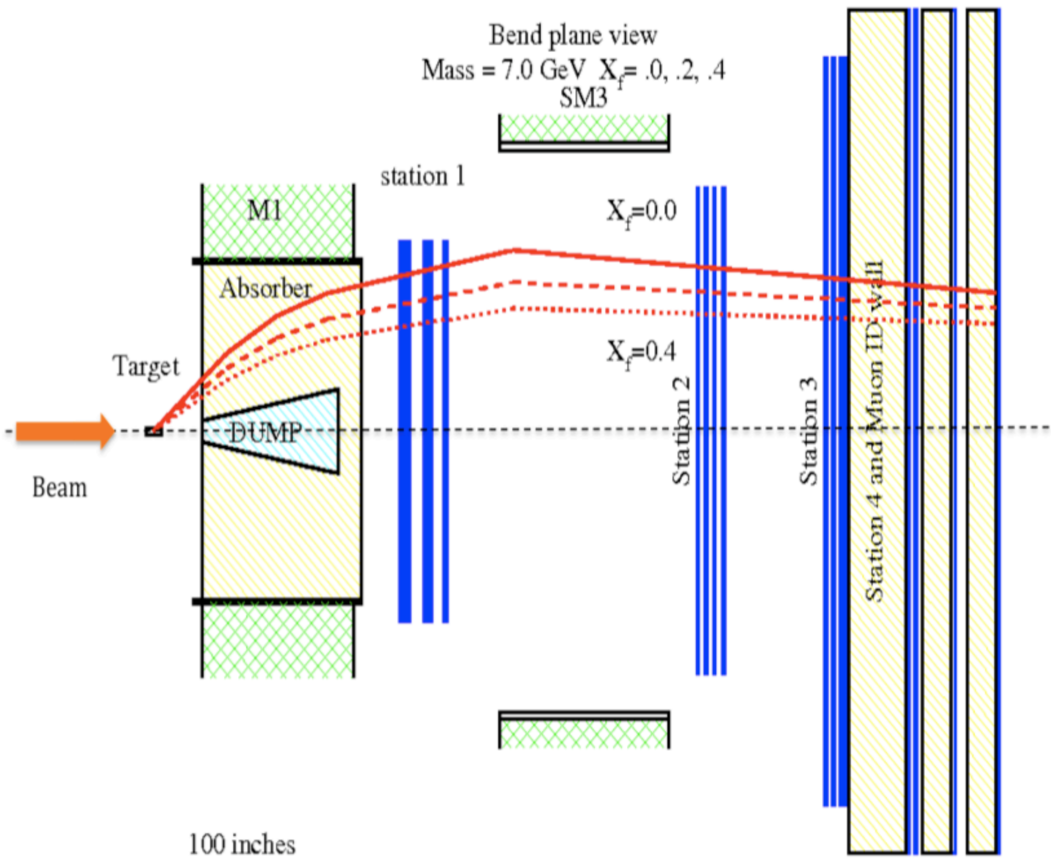
Blue: 20% I.L. solid nuclear target

DY at Fermilab E906



- M.X. Liu, JPCS295(11)012165; SPIN2010; P. Reimer, JPCS295(11)012011
- p_{beam} = 120 GeV/c
- $\sqrt{s}$ = 15 GeV, $p\, p^{\uparrow} \rightarrow \mu^{+} \mu^{-} X$
- $16 < q^2 < 81$ GeV^2
- $x_F = x_1 - x_2 = 2q_L/\sqrt{s} = -0.4 - 0.2$
- $x_1 \sim 0.1 - 0.45$; $x_2 \sim 0.05 - 0.5$
- Estimates for 120 days at 50% efficiency and 75% polarization





DY Comparisons

Experiment	Reaction	√s (GeV)	q^2 (GeV^2)	x_F	x_1, x_2
ANDY @ RHIC	$p^{\uparrow} p \rightarrow e^+ e^- X$	500	16-150	0.1-0.6	0.1-0.6 <0.01
COMPASS @ CERN	$\pi p^{\uparrow} \rightarrow \mu^+ \mu^- X$	17.4	4-6 16-81	-0.1-0.9	0.2-0.9 0.05-0.4
J-PARC	$p p^{\uparrow} \rightarrow \mu^+ \mu^- X$	8-10	16-25	?	?
E906 @ Fermilab	$p p^{\uparrow} \rightarrow \mu^+ \mu^- X$	15	16-81	-0.4-0.2	0.1-0.45 0.05-0.5
Panda @ FAIR	$p^- p^{\uparrow} \rightarrow e^+ e^- X$ $p^- p^{\uparrow} \rightarrow \mu^+ \mu^- X$	2.1-5.5	1-10	depends on target shielding	depends on target shielding

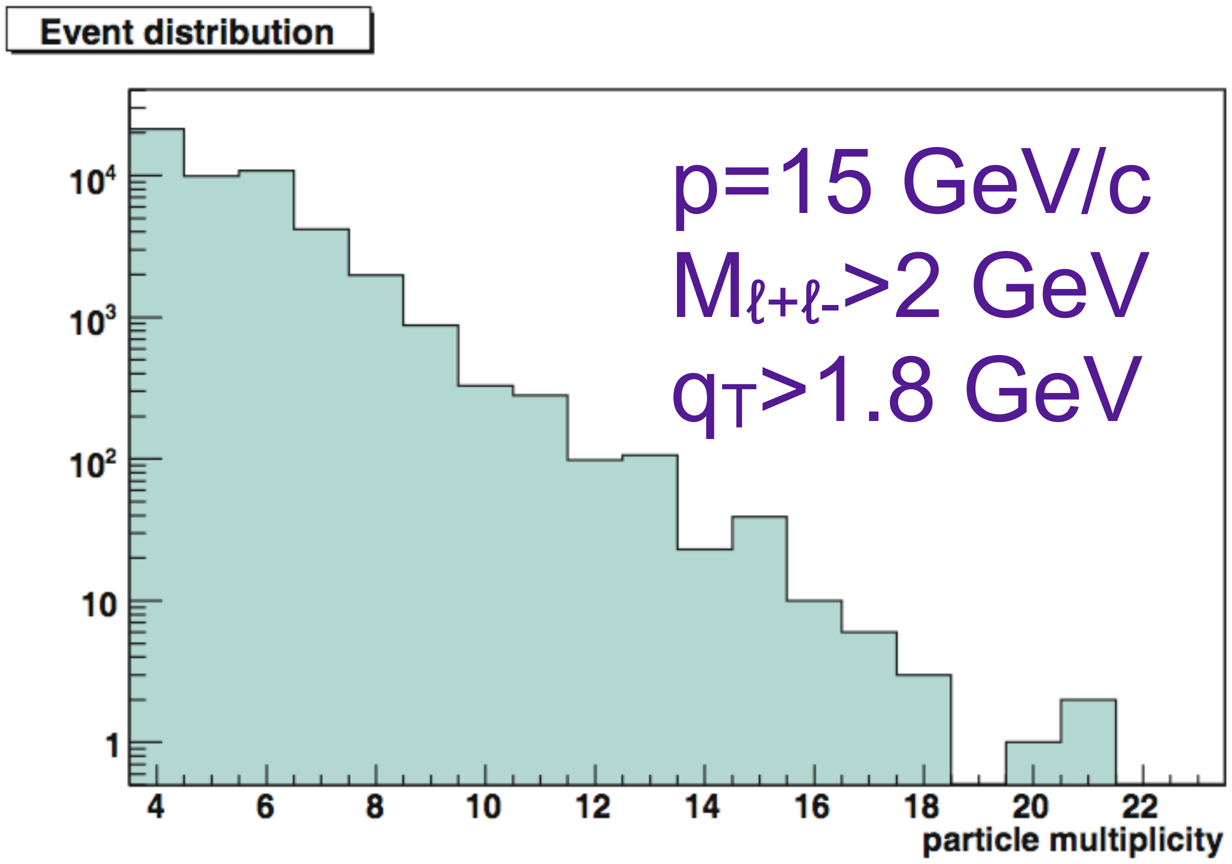
only proton PDFs
$f^q(x_1) f^q(x_2)$

overlap with
JLab kinematics

DY Simulations for PANDA

A. Bianconi, EPJ**A44**(10)313

Generates Drell-Yan events with PYTHIA

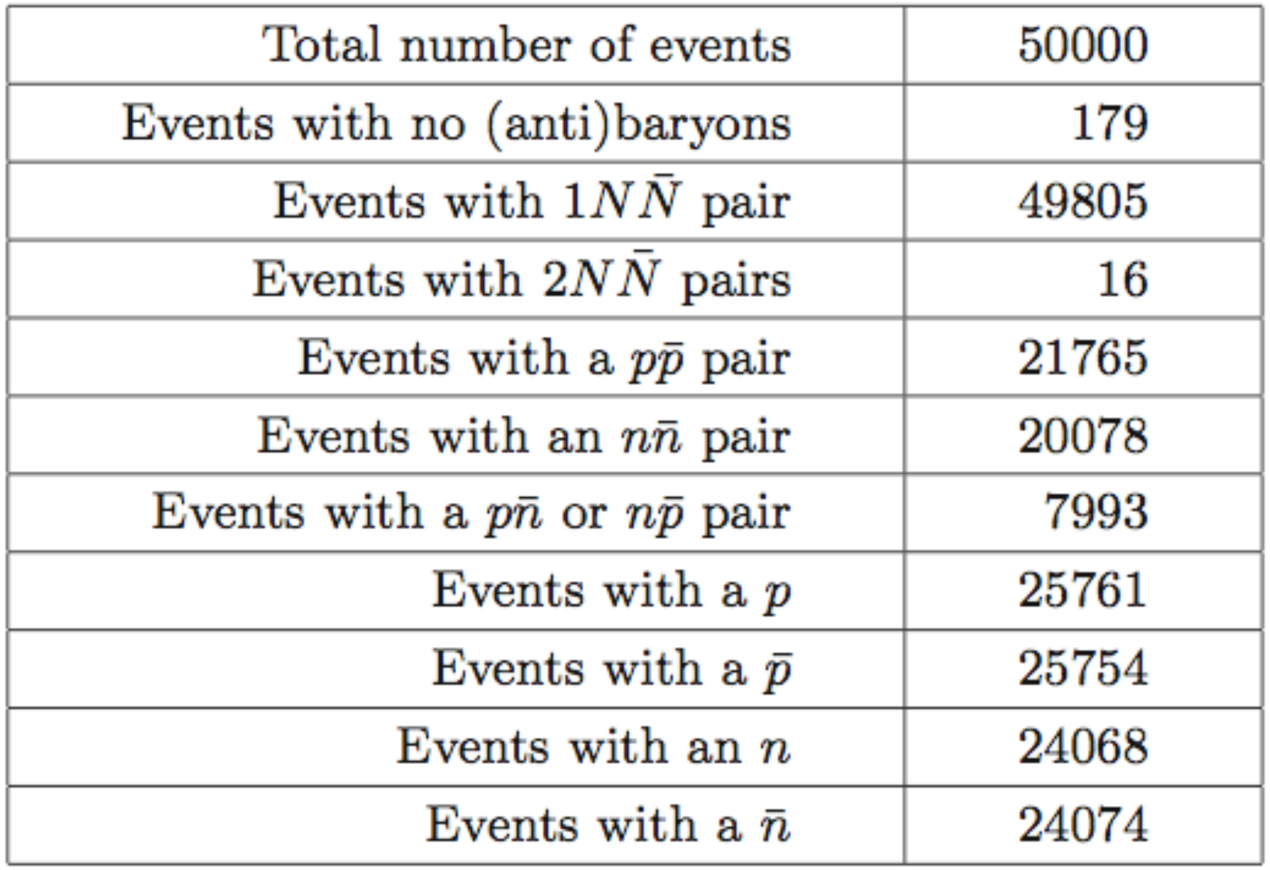


p=15 GeV/c

$M_{\ell+\ell-}$>2 GeV

q_T>1.8 GeV

Fig. 1. Multiplicity of final particles in Drell-Yan dilepton production, including the lepton pair (so, by definition $N > 2$ here). The cutoffs on the dilepton mass and transverse momentum are $M > 2\,\mathrm{GeV}/c^2$, $q_T > 0.8\,\mathrm{GeV}/c$.



Total number of events	50000
Events with no (anti)baryons	179
Events with 1$N\bar{N}$ pair	49805
Events with 2$N\bar{N}$ pairs	16
Events with a $p\bar{p}$ pair	21765
Events with an $n\bar{n}$ pair	20078
Events with a $p\bar{n}$ or $n\bar{p}$ pair	7993
Events with a p	25761
Events with a $\bar{p}$	25754
Events with an n	24068
Events with a $\bar{n}$	24074

Exclusive DY

$$\frac{d^2\sigma_{DY}}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9M^2_{e^+e^-}} \sum_i e_i^2 [q_1^i(x_1)\bar{q}_2^i(x_2) + \bar{q}_1^i(x_1) q_2^i(x_2)]$$

$$\frac{d^2\sigma_{DY}}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9M^2_{e^+e^-}} \frac{1}{9}[4\bar{u}(x_1)\bar{u}(x_2) + 4u(x_1)u(x_2) + \bar{d}(x_1)\bar{d}(x_2) + d(x_1)d(x_2)] \quad \text{for} \quad \bar{p}p$$

$$\begin{array}{lcl}
(uud) + (\bar{u}\bar{u}\bar{d}) & \rightarrow & [u\bar{u} \rightarrow e^+e^- + u\bar{u}] \rightarrow (uud) + (\bar{u}\bar{u}\bar{d}) \equiv p\bar{p} \\
(uud) + (\bar{u}\bar{u}\bar{d}) & \rightarrow & [u\bar{u} \rightarrow e^+e^- + d\bar{d}] \rightarrow (udd) + (\bar{u}\bar{d}\bar{d}) \equiv n\bar{n} \\
(uud) + (\bar{u}\bar{u}\bar{d}) & \rightarrow & [u\bar{u} \rightarrow e^+e^- + s\bar{s}] \rightarrow (uds) + (\bar{u}\bar{d}\bar{s}) \equiv \Lambda\bar{\Lambda} \\
(uud) + (\bar{u}\bar{u}\bar{d}) & \rightarrow & [d\bar{d} \rightarrow e^+e^- + u\bar{u}] \rightarrow (uuu) + (\bar{u}\bar{u}\bar{u}) \equiv \Delta^{++}\overline{\Delta^{++}} \\
(uud) + (\bar{u}\bar{u}\bar{d}) & \rightarrow & [d\bar{d} \rightarrow e^+e^- + d\bar{d}] \rightarrow (uud) + (\bar{u}\bar{u}\bar{d}) \equiv p\bar{p} \\
(uud) + (\bar{u}\bar{u}\bar{d}) & \rightarrow & [d\bar{d} \rightarrow e^+e^- + s\bar{s}] \rightarrow (uus) + (\bar{u}\bar{u}\bar{s}) \equiv \Sigma^+\overline{\Sigma^+}
\end{array}$$

$$\bar{p}(p, e^+e^- p)\bar{p}$$

$$\bar{p}(p, e^+e^-[p\pi^-]_\Lambda)\bar{\Lambda}$$

$$\bar{p}(p, e^+e^-[p\pi^+]_{\Delta^{++}})\bar{\Delta}$$

$\boxed{4u + d}$

$\boxed{4u}$

$\boxed{d}$

$\Lambda \rightarrow p\pi^-$	64%
$\Lambda \rightarrow n\pi^+$	36%
$\Sigma^+ \rightarrow p\pi^0$	52%
$\Sigma^+ \rightarrow n\pi^+$	48%

DY Simulations for PANDA

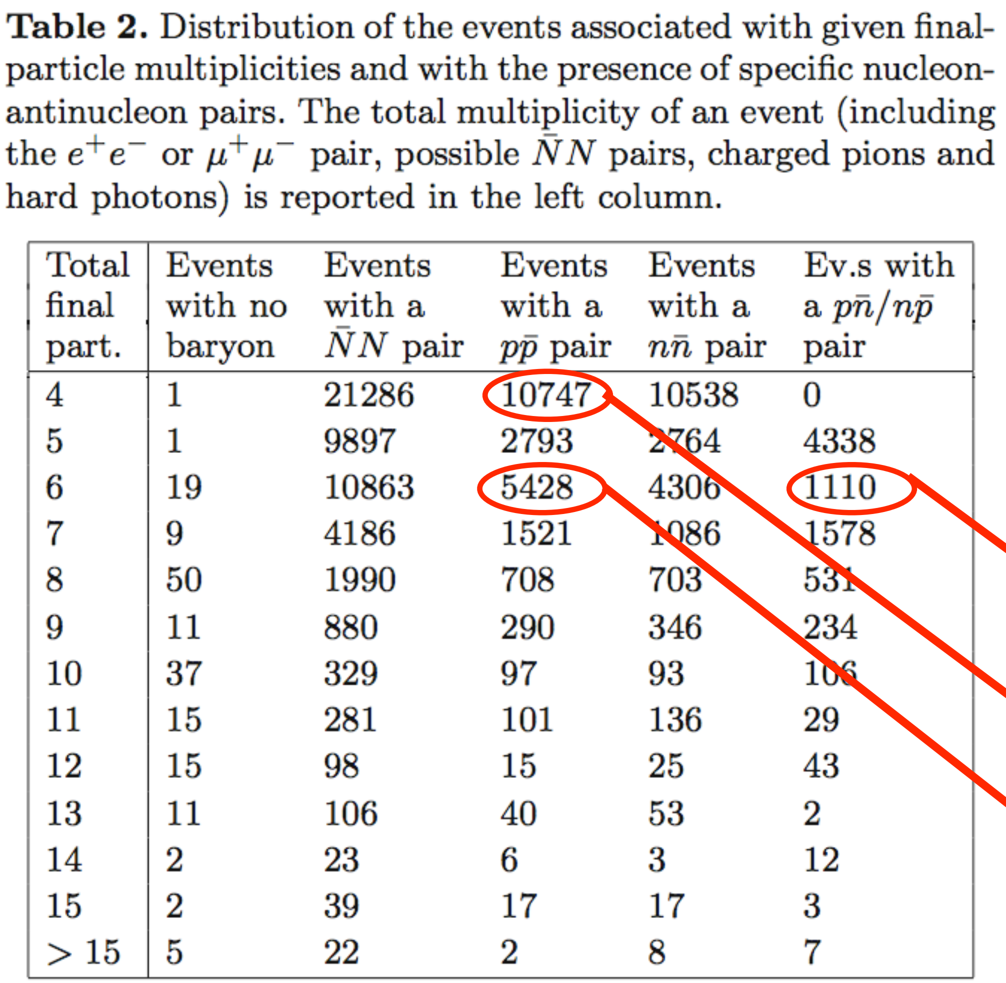


Table 2. Distribution of the events associated with given final-particle multiplicities and with the presence of specific nucleon-antinucleon pairs. The total multiplicity of an event (including the e^+e^- or $\mu^+\mu^-$ pair, possible $\bar{N}N$ pairs, charged pions and hard photons) is reported in the left column.

Total final part.	Events with no baryon	Events with a $\bar{N}N$ pair	Events with a $p\bar{p}$ pair	Events with a $n\bar{n}$ pair	Ev.s with a $p\bar{n}/n\bar{p}$ pair
4	1	21286	10747	10538	0
5	1	9897	2793	2764	4338
6	19	10863	5428	4306	1110
7	9	4186	1521	1086	1578
8	50	1990	708	703	531
9	11	880	290	346	234
10	37	329	97	93	106
11	15	281	101	136	29
12	15	98	15	25	43
13	11	106	40	53	2
14	2	23	6	3	12
15	2	39	17	17	3
> 15	5	22	2	8	7

A. Bianconi, EPJ**A44**(10)313

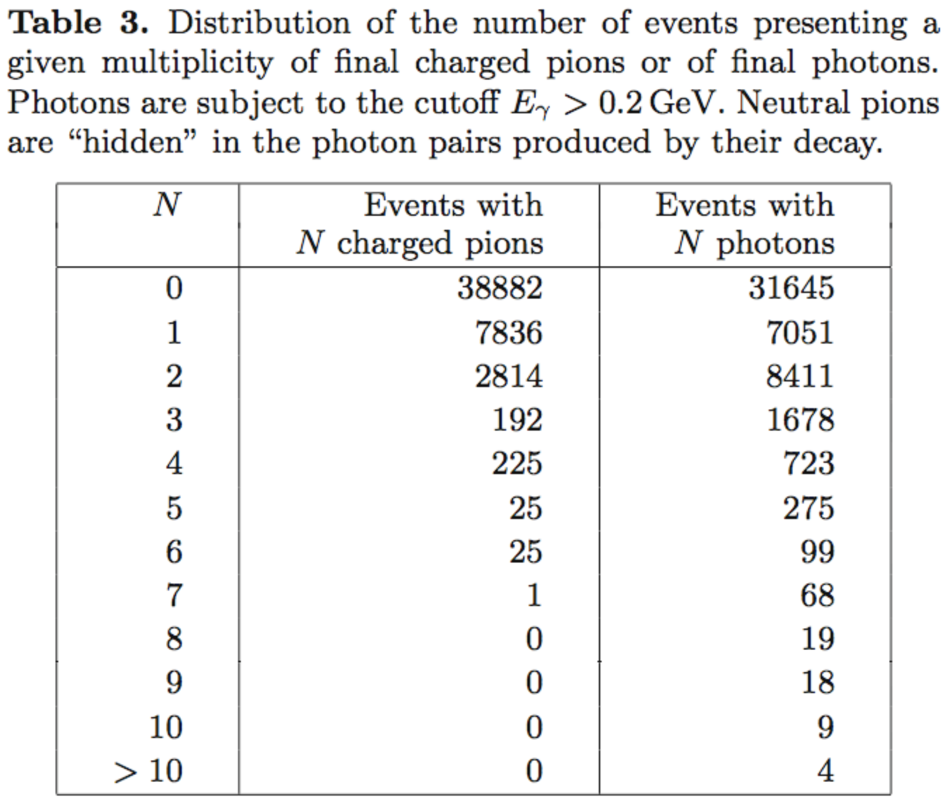


Table 3. Distribution of the number of events presenting a given multiplicity of final charged pions or of final photons. Photons are subject to the cutoff $E_\gamma > 0.2$ GeV. Neutral pions are "hidden" in the photon pairs produced by their decay.

N	Events with N charged pions	Events with N photons
0	38882	31645
1	7836	7051
2	2814	8411
3	192	1678
4	225	723
5	25	275
6	25	99
7	1	68
8	0	19
9	0	18
10	0	9
> 10	0	4

These can be measured in events with one proton, 0 or 2 charged pions and a missing mass of the unobserved anti-nucleon, which is likely at small angles.

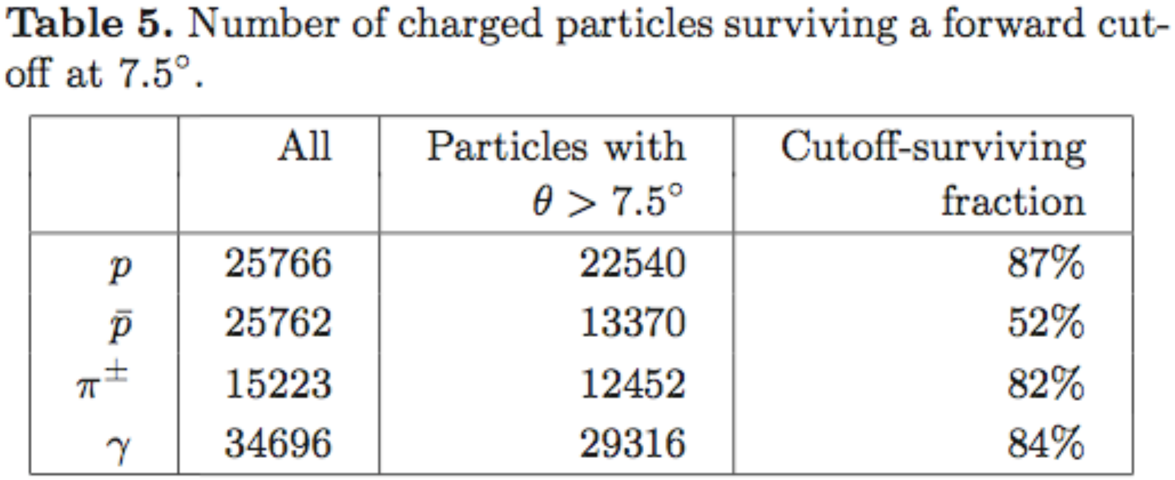
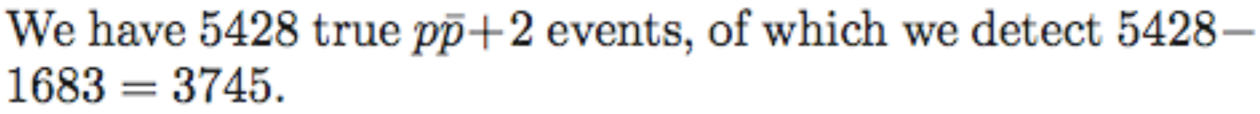


Table 5. Number of charged particles surviving a forward cut-off at 7.5°.

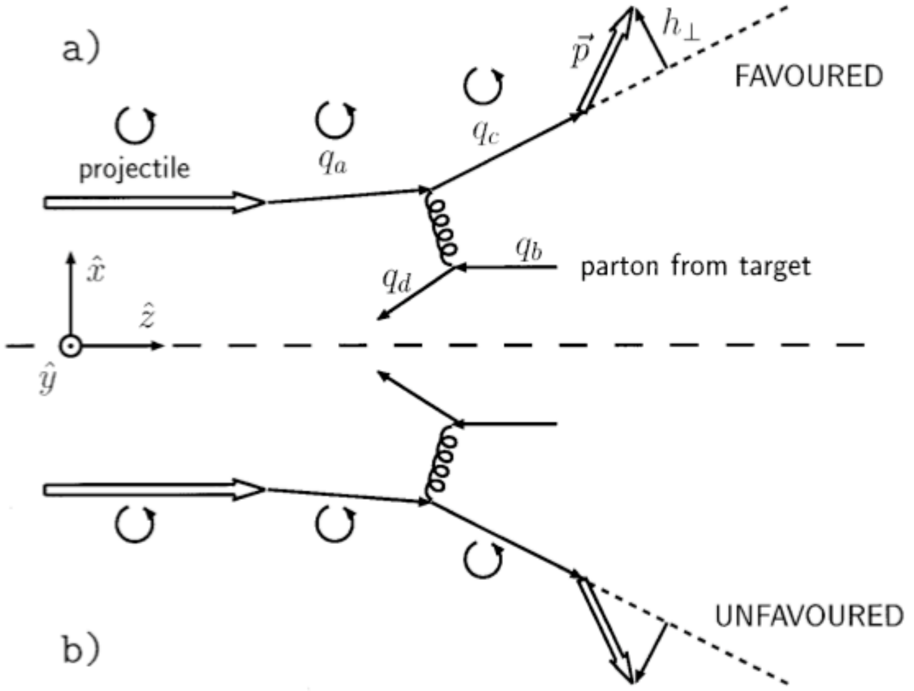
	All	Particles with $\theta > 7.5°$	Cutoff-surviving fraction
p	25766	22540	87%
$\bar{p}$	25762	13370	52%
$\pi^\pm$	15223	12452	82%
γ	34696	29316	84%



We have 5428 true $p\bar{p}$+2 events, of which we detect $5428 - 1683 = 3745$.

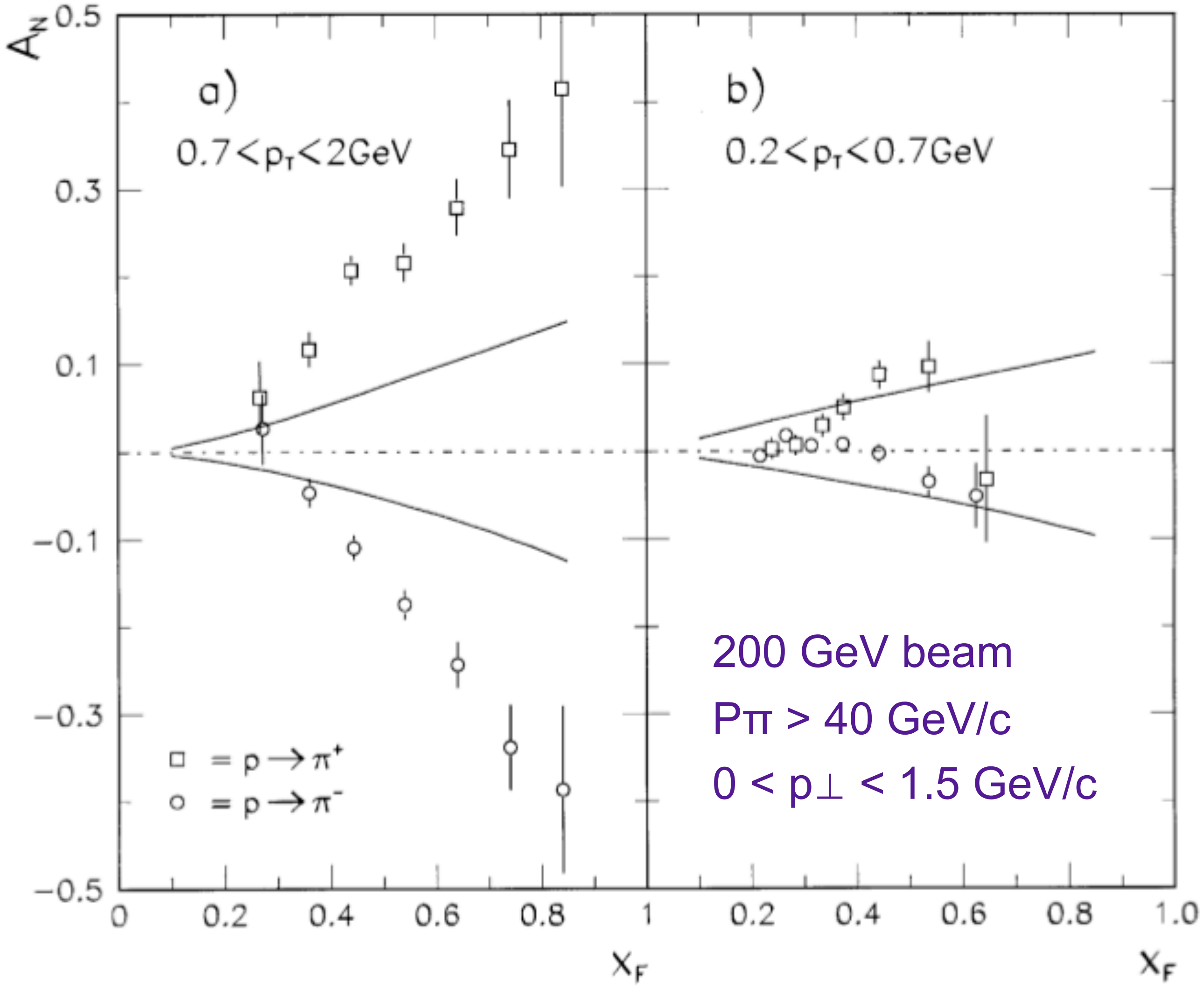
Large Background from Pions

Artru, ZP**C73**(1997)527



$$\boxed{H_1^\perp}$$

Fig. 1. Inclusive pion production. Two events (**a**) and (**b**), symmetric with respect to the $\hat{y}\hat{z}$ plane, are represented. Without polarization, they would have the same probability. In the polarized case, the Collins effect favours the case (**a**). The arrows labelled q_i represent the momenta of the quarks in the subprocess. The spins are denoted by the arch-like arrows. The Collins effect acts at the last stage, where the quark q_c fragments into the pion carrying momentum **p**. $h_\perp$ is the pion's transverse momentum with respect to the quark q_c



200 GeV beam

Pπ > 40 GeV/c

0 < p⊥ < 1.5 GeV/c

Fig. 5. Single spin asymmetry measured by E704 collaboration for charged pions at $0.2 < p_\perp < 2.0$ GeV [6]. The curves are our model results calculated with quark transverse polarizations $\Delta_\perp u/u = -\Delta_\perp d/d = x^2$ and $\beta = 1$

Bravar, PRL**77**(1996)2626 FNAL E704

$$\bar{p}\uparrow + p \rightarrow \pi^-(\pi^+) + X$$

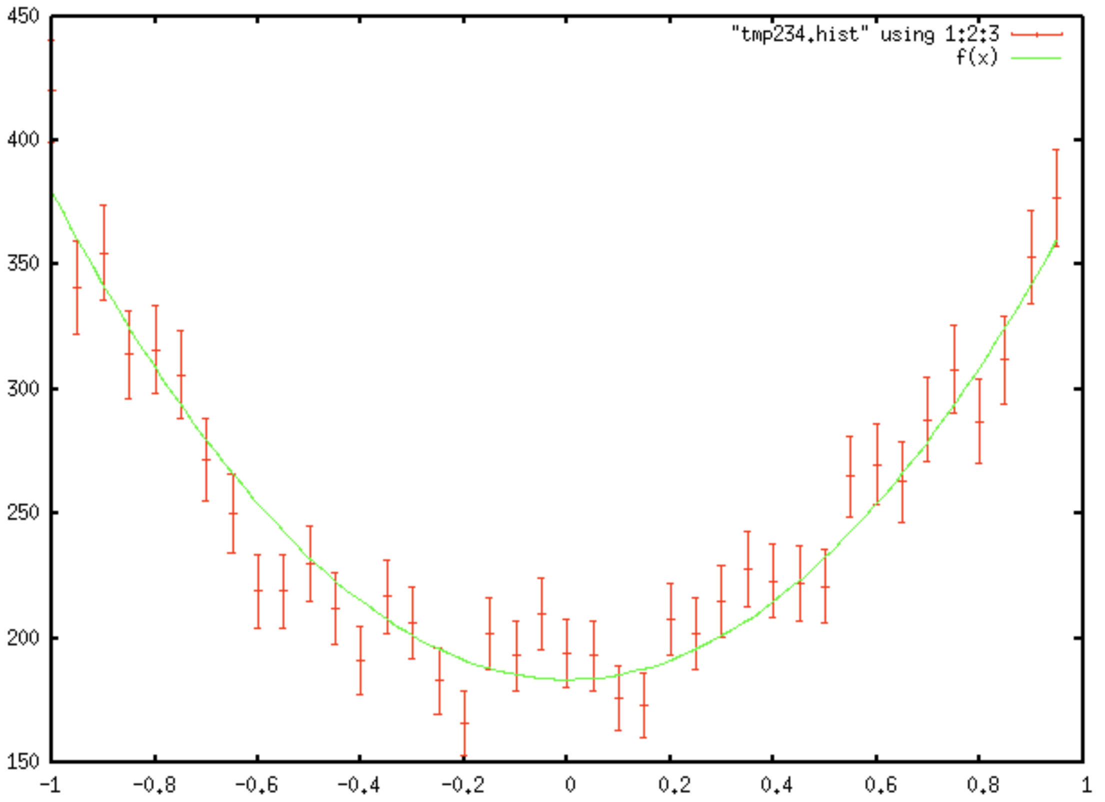
$$A_N = \frac{1}{P_B\langle\cos\phi\rangle}\frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}$$

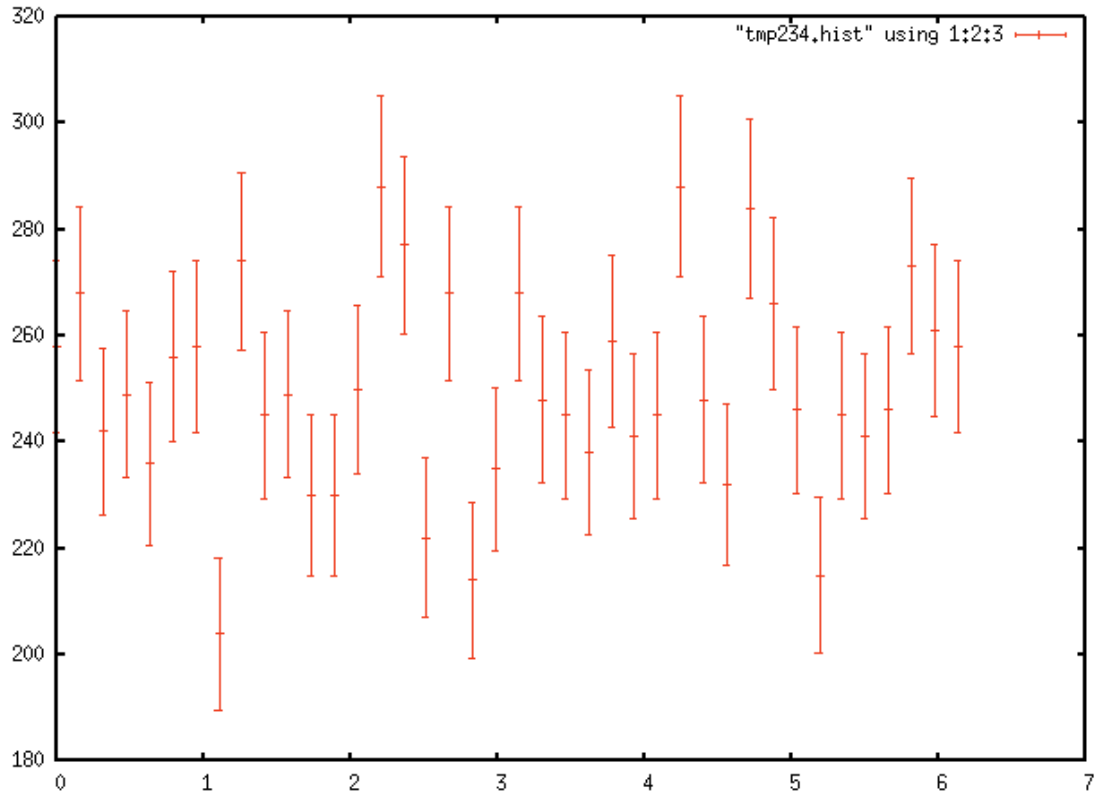
ϕ is angle between beam polarization axis and the normal to the production plane

Collins effect gives the right trend to explain the large asymmetries seen

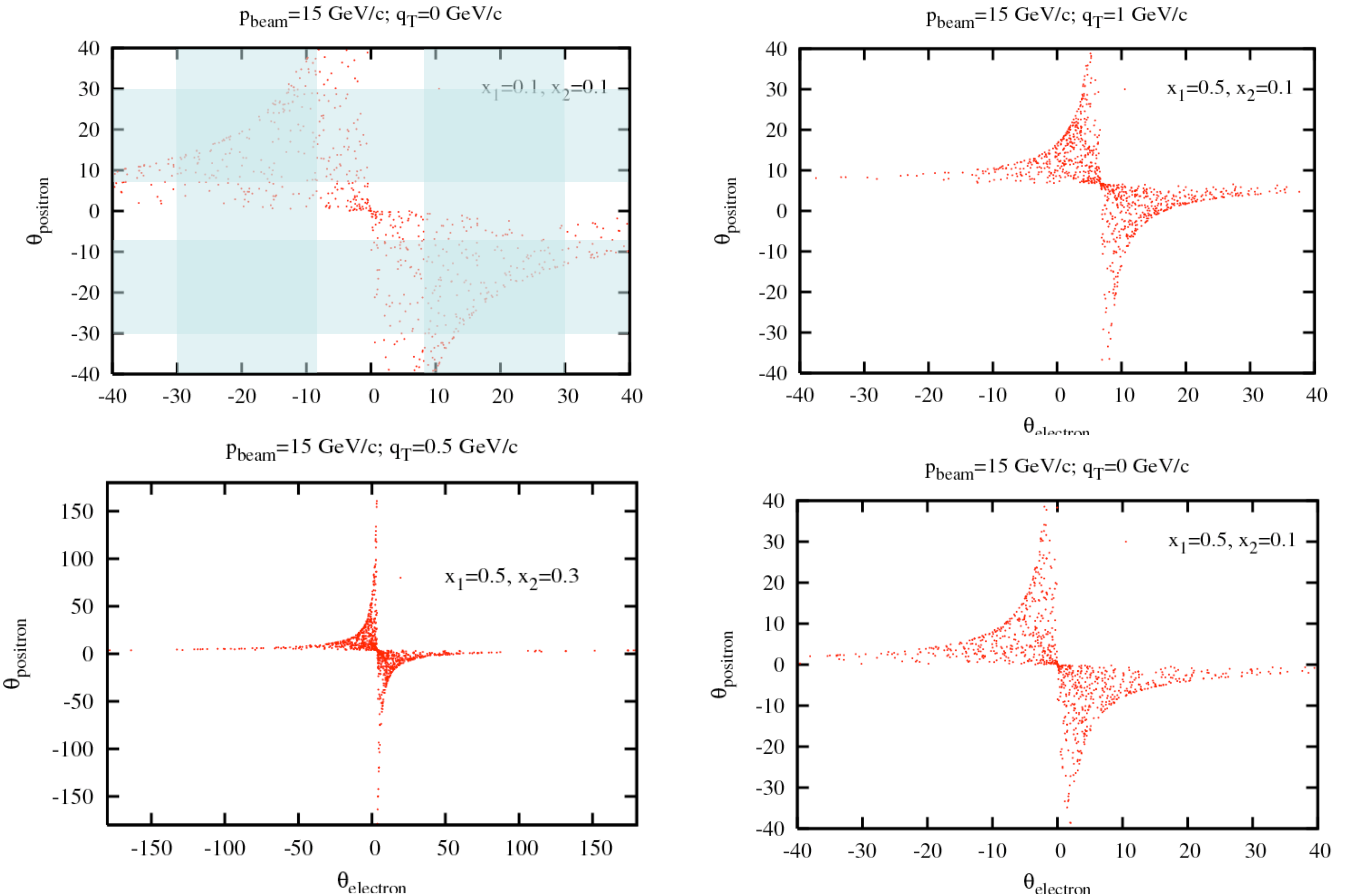
Monte Carlo DY Kinematics

- Structure functions generally depend on x_1, x_2, q_T, (and q^2)
- Let's look at where electron pair events show up for fixed x_1, x_2, q_T and P_{beam}
- $s = 2M(M+E_{beam})$ $q_L = (x_1 - x_2)\sqrt{s}/2$ $q^2 = x_1 x_2 s$
- This gives $q^{\mu}{}_{CM} = (q_0, q_T, 0, q_L)$
- Electron angles in CS frame are picked from a $(1+\cos^2\theta)\sin\theta$ distribution with φ random over 2π.
- Electrons are Lorentz tranformed from CS to CM frame.
- Electrons are Lorentz transformed from CM to Lab frame.
- 1000 events were generated for (θ, φ) with all other kinematic variables fixed.



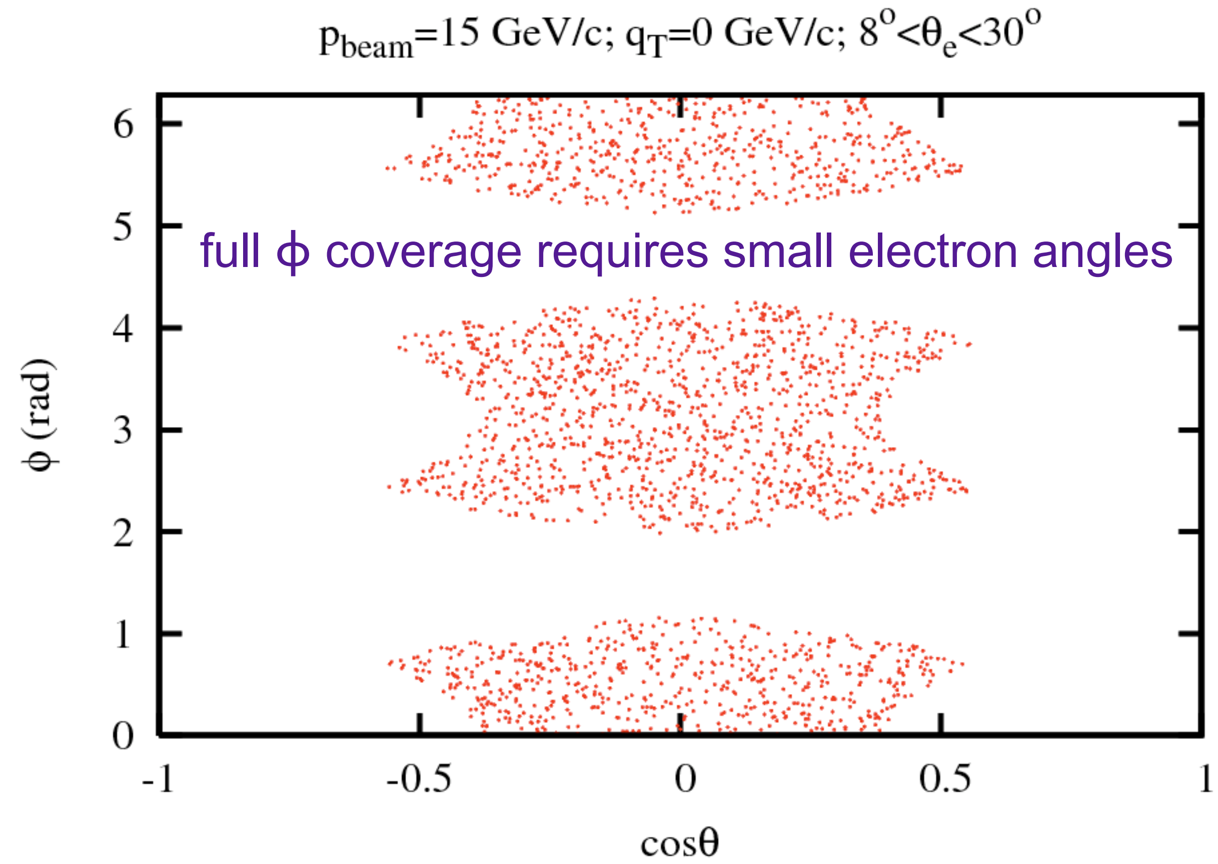


e^+ vs e^- Angles

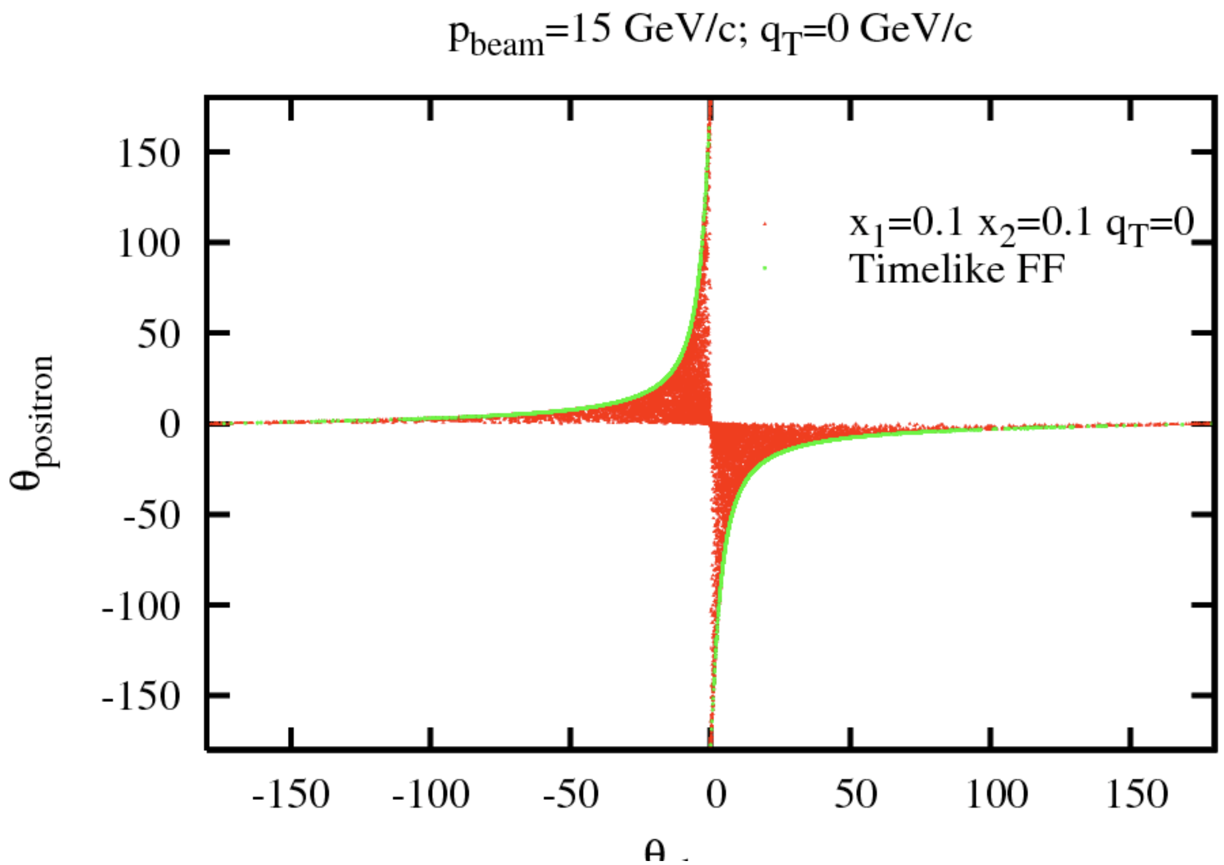


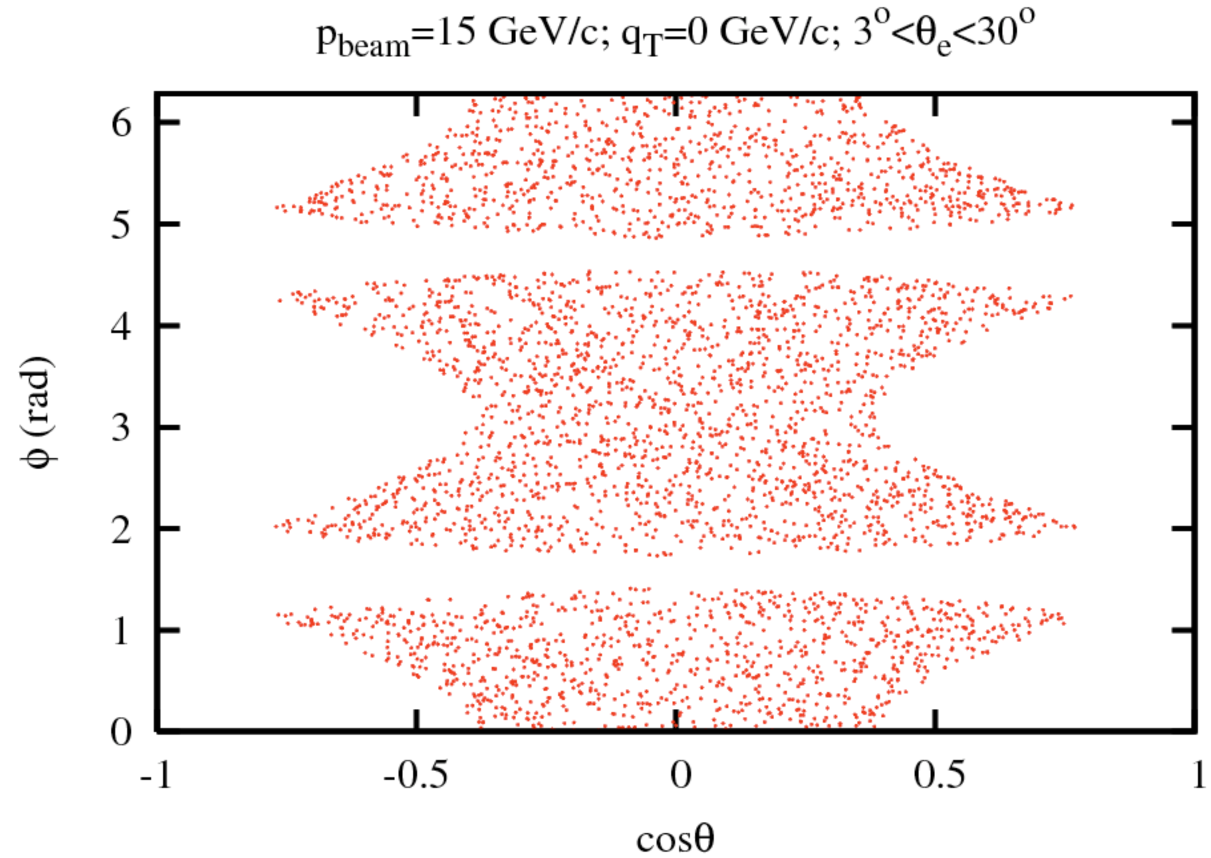
p_{beam}=15 GeV/c; q_T=0 GeV/c
x_1=0.1, x_2=0.1
$\theta_{positron}$
40
30
20
10
0
-10
-20
-30
-40
-40
-30
-20
-10
0
10
20
30
40
p_{beam}=15 GeV/c; q_T=1 GeV/c
x_1=0.5, x_2=0.1
$\theta_{positron}$
$\theta_{electron}$
p_{beam}=15 GeV/c; q_T=0.5 GeV/c
x_1=0.5, x_2=0.3
$\theta_{positron}$
150
100
50
0
-50
-100
-150
$\theta_{electron}$
p_{beam}=15 GeV/c; q_T=0 GeV/c
x_1=0.5, x_2=0.1
$\theta_{positron}$
$\theta_{electron}$

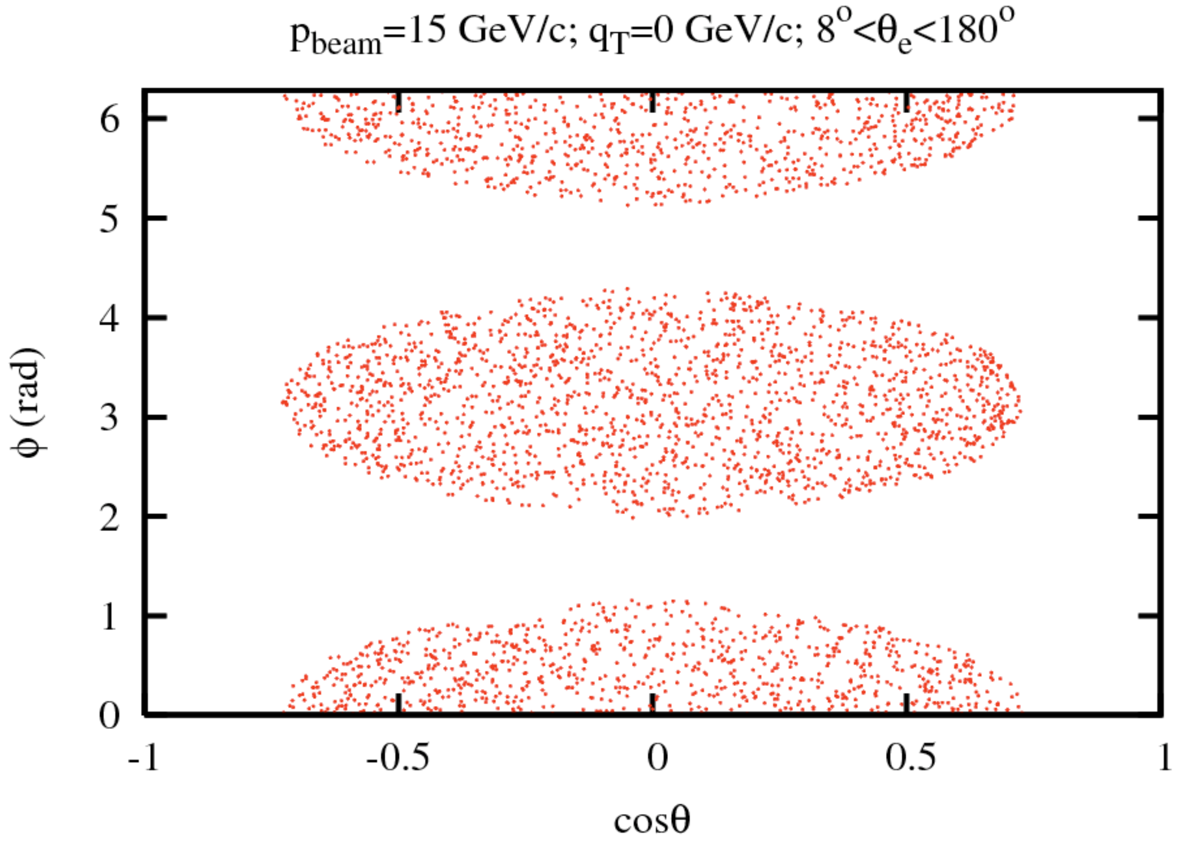
Acceptance


p_{beam}=15 GeV/c; q_T=0 GeV/c; $8^o<\theta_e<30^o$

full ϕ coverage requires small electron angles


p_{beam}=15 GeV/c; q_T=0 GeV/c


p_{beam}=15 GeV/c; q_T=0 GeV/c; $3^o<\theta_e<30^o$


p_{beam}=15 GeV/c; q_T=0 GeV/c; $8^o<\theta_e<180^o$

Next Steps

- Pick x_1, x_2 and q_T given various models of the structure functions F.
- Explore the kinematic sensitivity to measuring the TMDs expected to be convoluted in the structure functions F. We need good (θ,ϕ) coverage to extract various Fs.
- Build in hadronization products to make an exclusive Drell-Yan event generator.
- Analyze with realistic backgrounds in PANDA ROOT.
- Similar constraints on backgrounds as in time-like form factors.

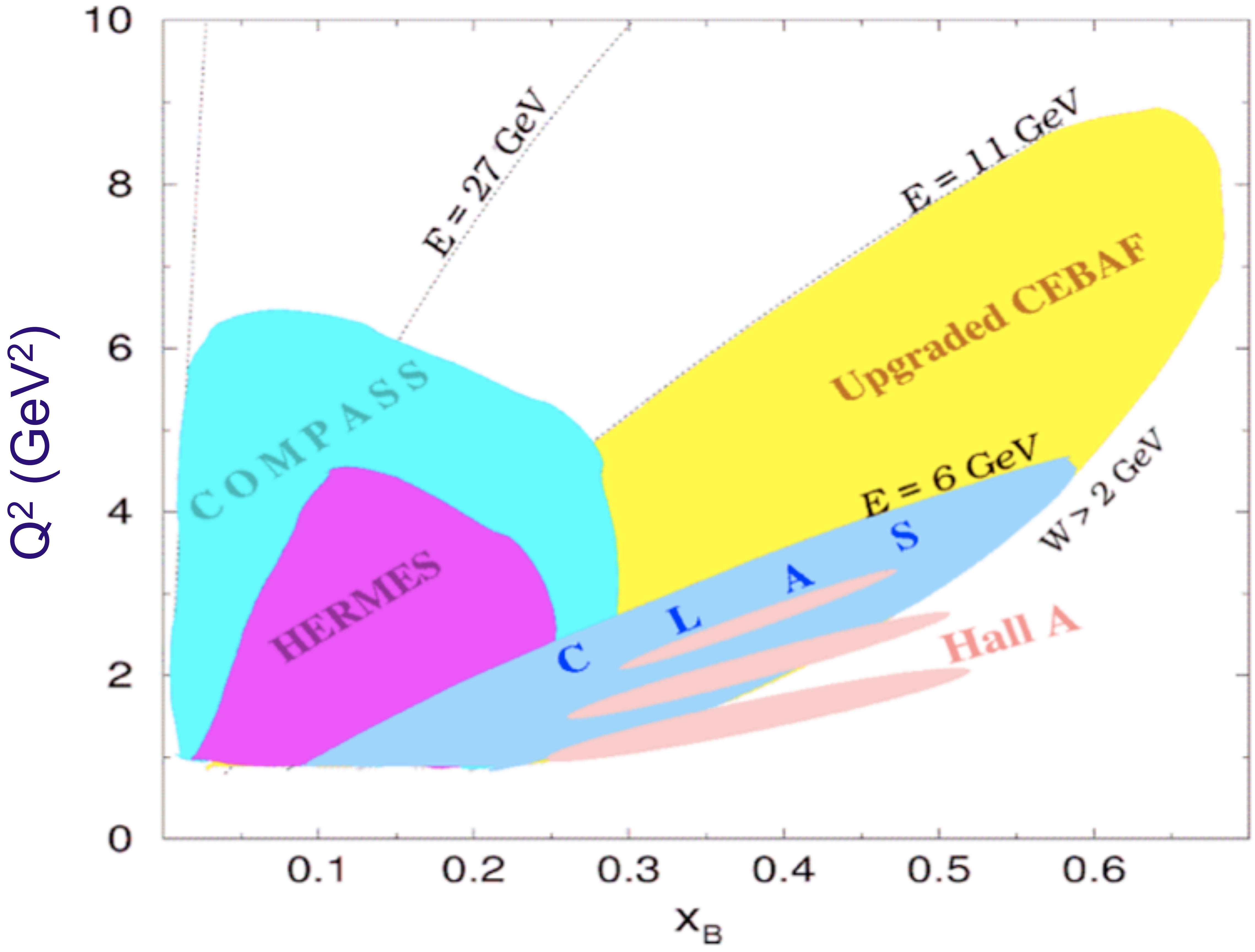
&

Conclusions

- In order to truly understand the nucleon, we will need to explore transverse momentum distributions (TMDs).
- Drell-Yan structure functions are convolutions of two TMDs, and as such are free of hadronization processes (i.e. fragmentation functions).
- TMDs like the Sivers function are sensitive to quark orbital angular momenta.
- Drell-Yan is essential to prove the universality of TMDs.
- A transversely polarized target allows access to 4 different TMDs.
- Exclusive Drell-Yan production can lead to separation of flavor-dependence of the TMDs.
- PANDA has a unique niche among Drell-Yan experiments in that it overlaps with JLab12 kinematics, and the anti-proton simplifies the TMD convolutions.

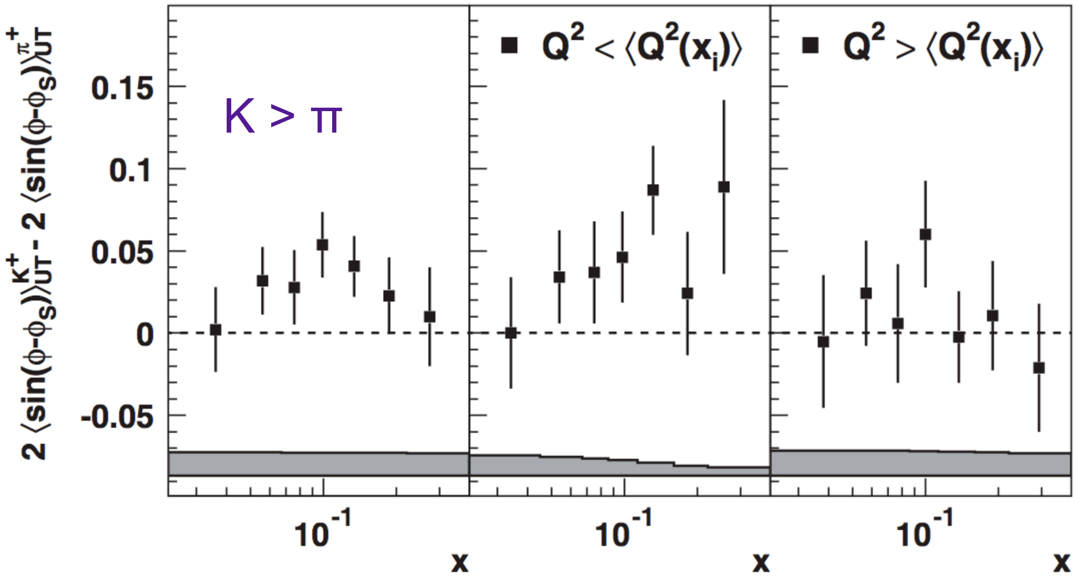
&

Kinematic Coverage



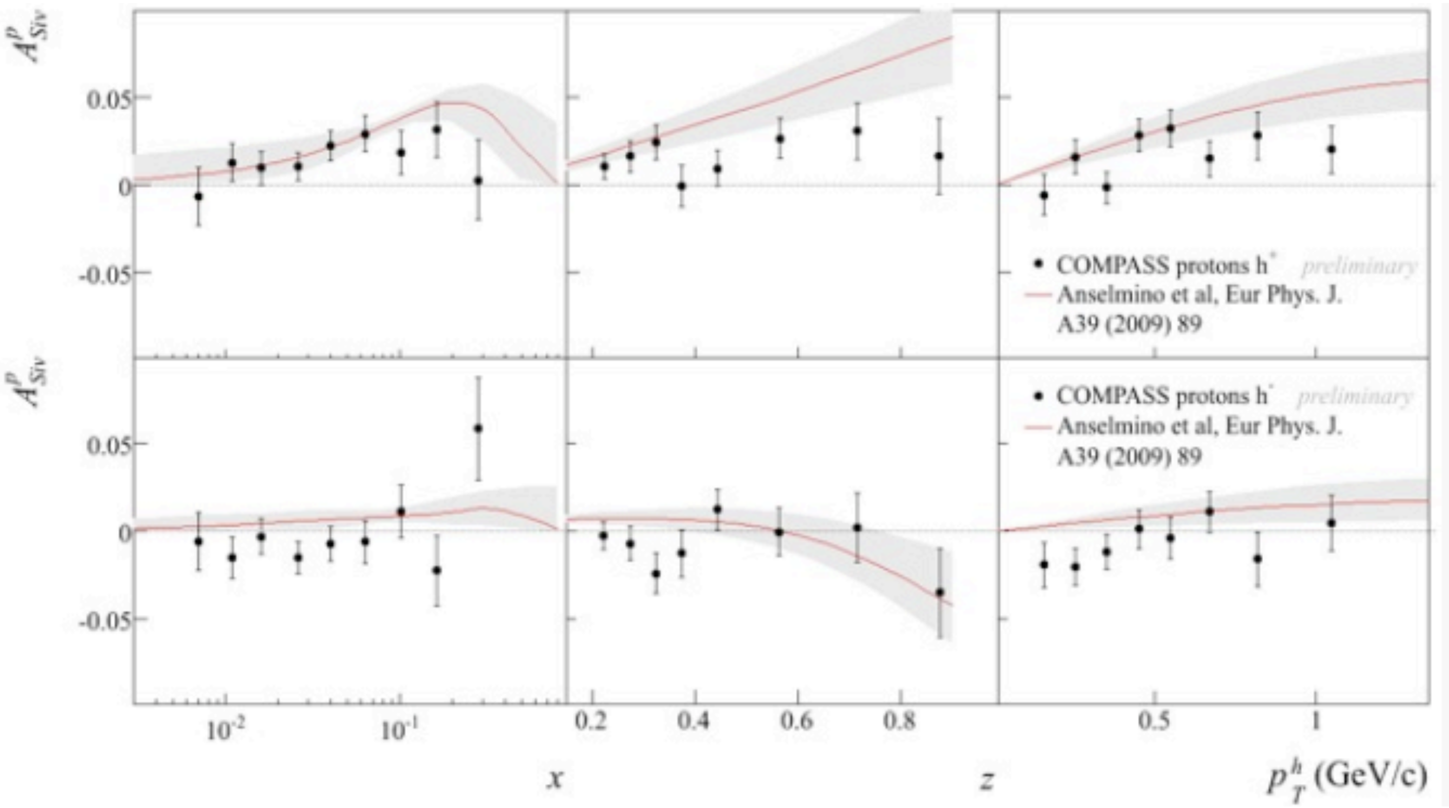
Sivers

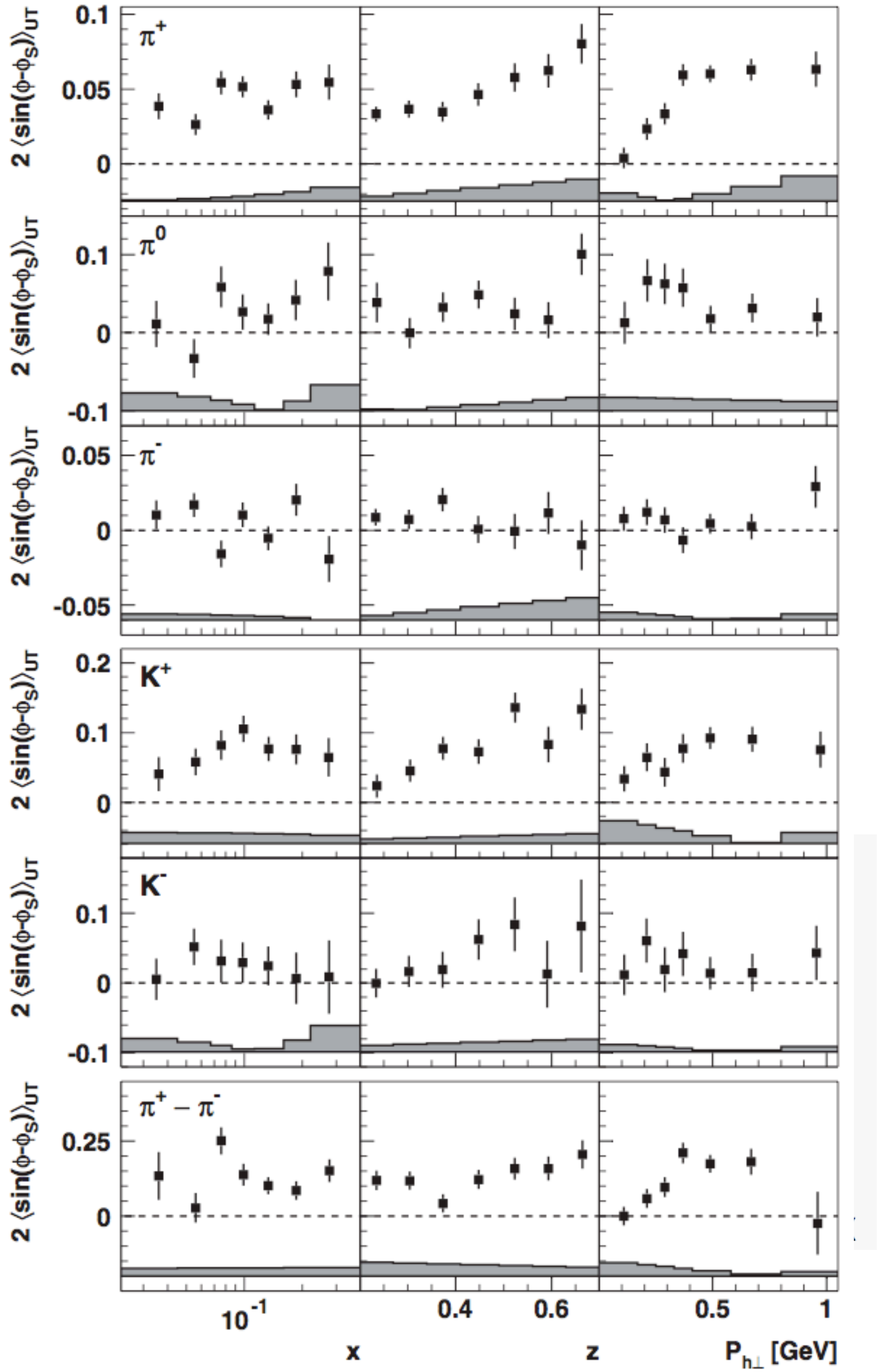
Airapetian, PRL103(09)152002



$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} f_{1T}^{\perp} D_1\right]$$

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





Where We Stand

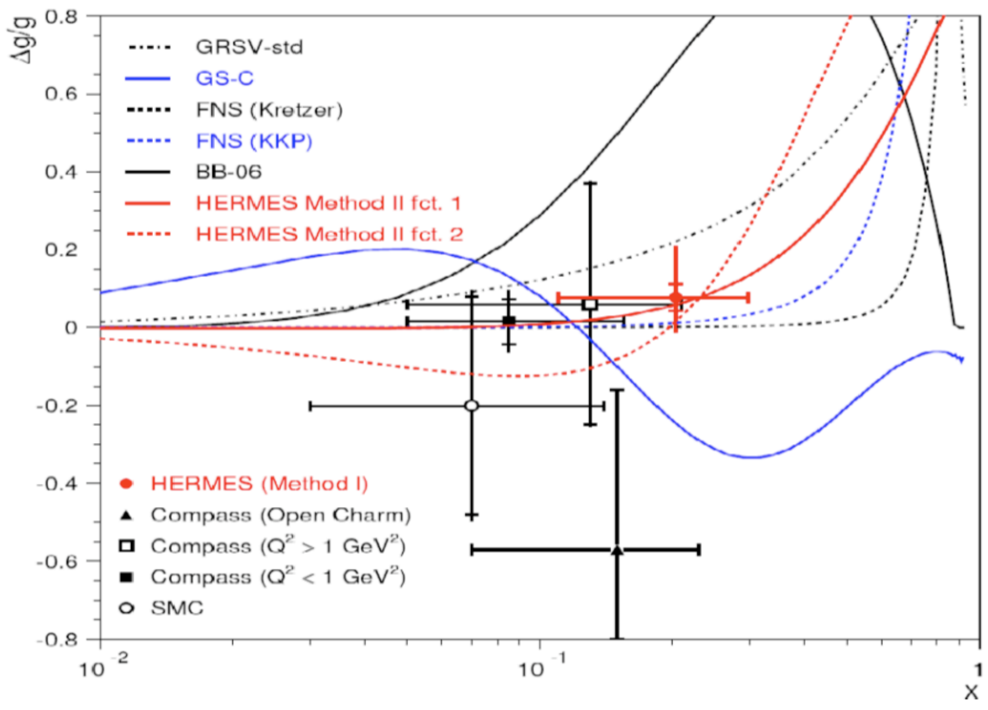
$$\frac{1}{2} = \frac{\Delta\Sigma}{2} + \Delta G + L_z$$

known quite well: 0.13

poorly known but likely small: -0.1

completely unmeasured but likely large: 0.47

NLO QCD fits to $g_1(x,Q^2)$



Transverse Momentum Dependent Parton Distributions (TMDs)?

SIDIS Cross Section

Bacchetta, et al., JHEP 2(2007)093

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = {} & \\
\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{ & F_{UU,T} + \varepsilon\, F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{UU}^{\cos\phi_h} \\
& + \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\, F_{LU}^{\sin\phi_h} \\
& + S_\parallel \left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h}\right] \\
& + S_\parallel \lambda_e \left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\, F_{LL}^{\cos\phi_h}\right] \\
& + |\boldsymbol{S}_\perp| \Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
& \quad + \varepsilon\,\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& \quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
& + |\boldsymbol{S}_\perp|\lambda_e \Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\, F_{LT}^{\cos\phi_S} \\
& \quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},
\end{aligned}
$$

🔴 Leading Twist

🔵 Sub-Leading Twist (extra factor of 1/Q)

🟢 0 (i.e. R=σ_L/σ_T=0)

A_{UL} = {UL terms} / {UU terms}

A_{LL} = {LL terms} / {UU terms}

etc.

TMD Structure Functions

$$\mathcal{C}\big[w\,f\,D\big] = x\sum_a e_a^2 \int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, \delta^{(2)}\big(\boldsymbol{p}_T - \boldsymbol{k}_T - \boldsymbol{P}_{h\perp}/z\big)\, w(\boldsymbol{p}_T,\boldsymbol{k}_T)\, f^a(x,p_T^2)\, D^a(z,k_T^2)$$

$$F_{UU,T} = \mathcal{C}\big[f_1 D_1\big]$$

Unpolarized fragmentation function; integrates to $D_1(z,Q^2)$

Unpolarized structure function; integrates to $F_1(x,Q^2)$

$$F_{LL} = \mathcal{C}\big[g_{1L} D_1\big]$$

Polarized structure function; integrates to $g_1(x,Q^2)$

$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\, h_1 H_1^\perp\right]$$

The Collins fragmentation function

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\, f_{1T}^\perp D_1\right]$$

The Sivers structure function

And there are more...

Function Zoo

Leading Twist TMDs

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

Sub-Leading Twist TMDs

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

Leading Twist FFs

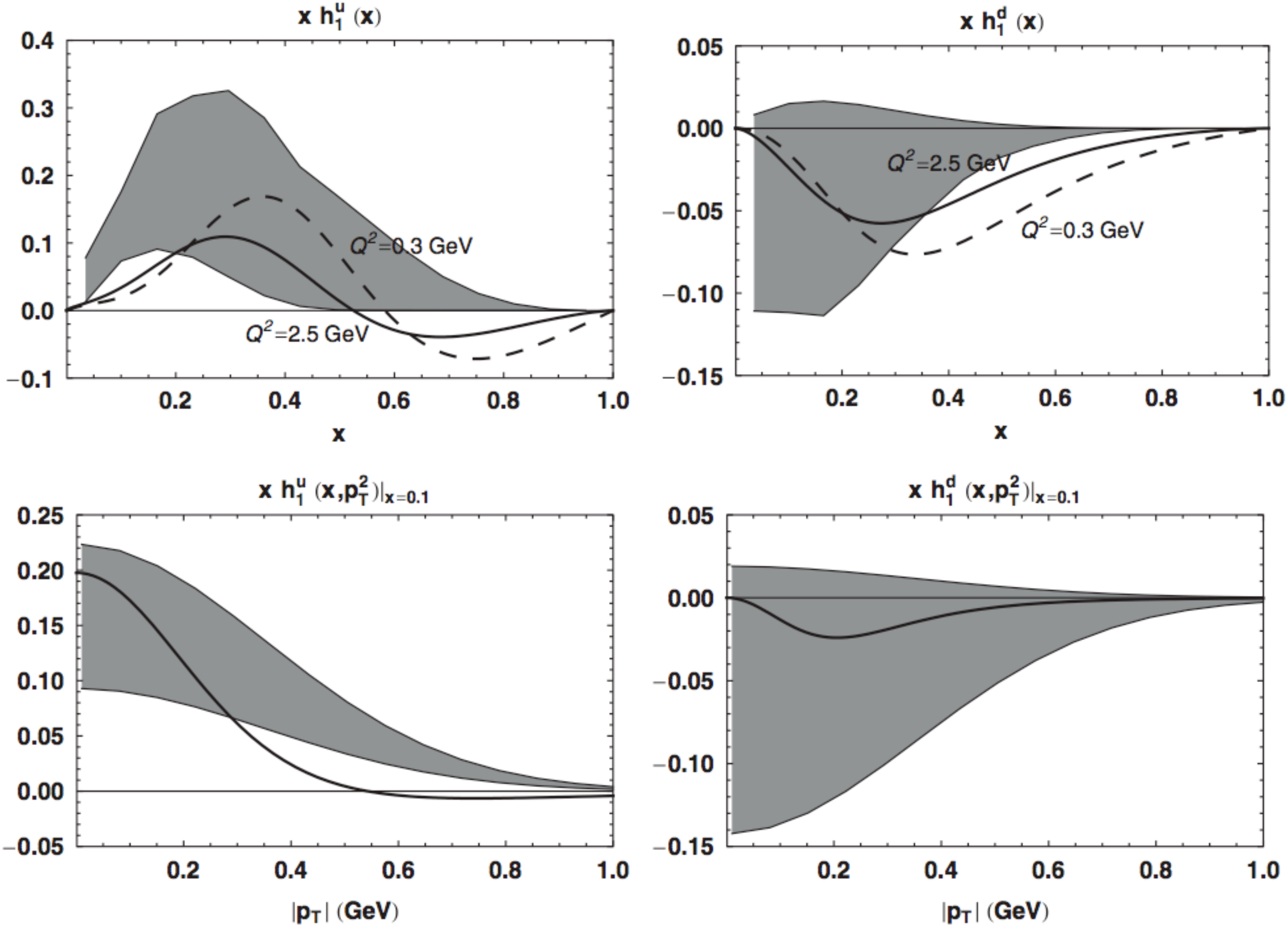
q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

Sub-Leading Twist FFs

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

Diquark Spectator Model

Bacchetta, PR**D78**(08)074010



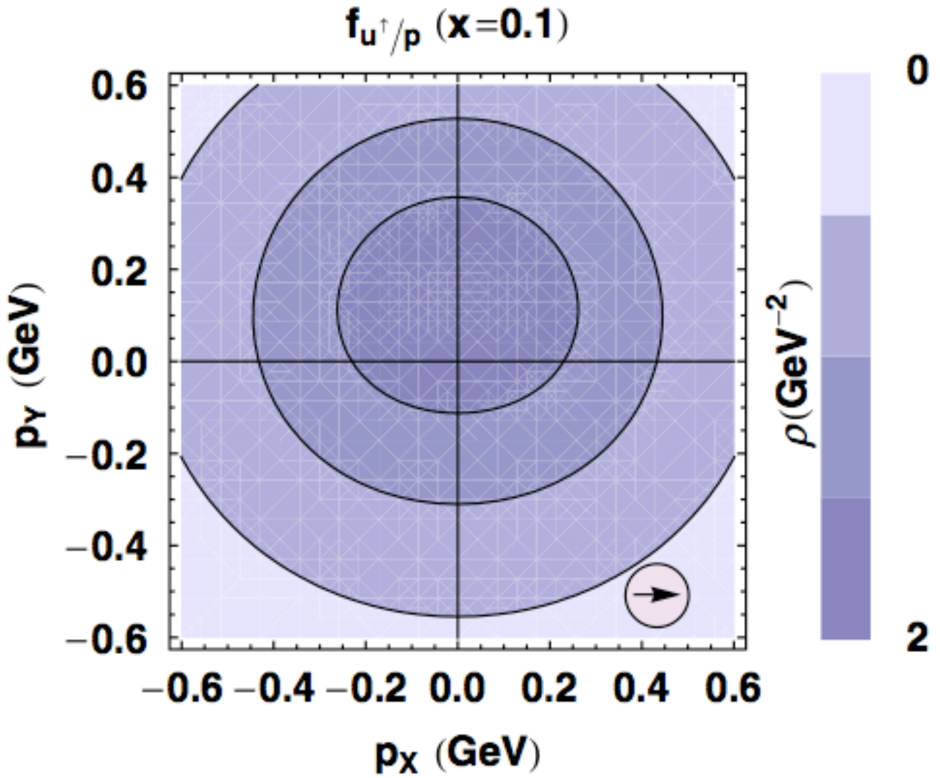
h_1

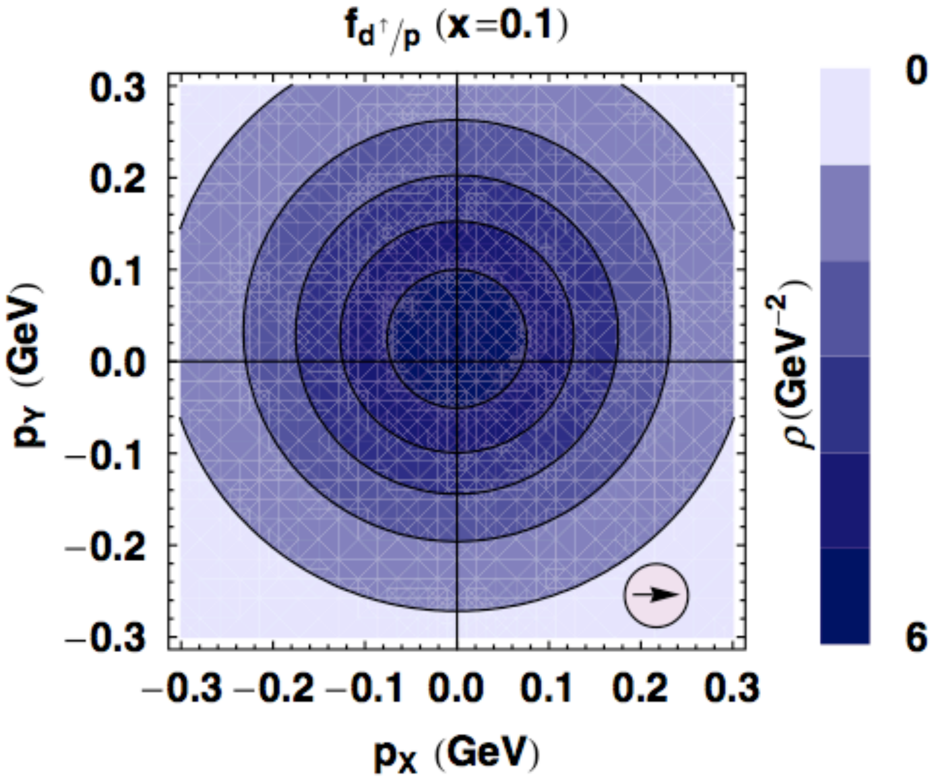
Transversity

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

Diquark Spectator Model

Bacchetta, PR**D78**(08)074010

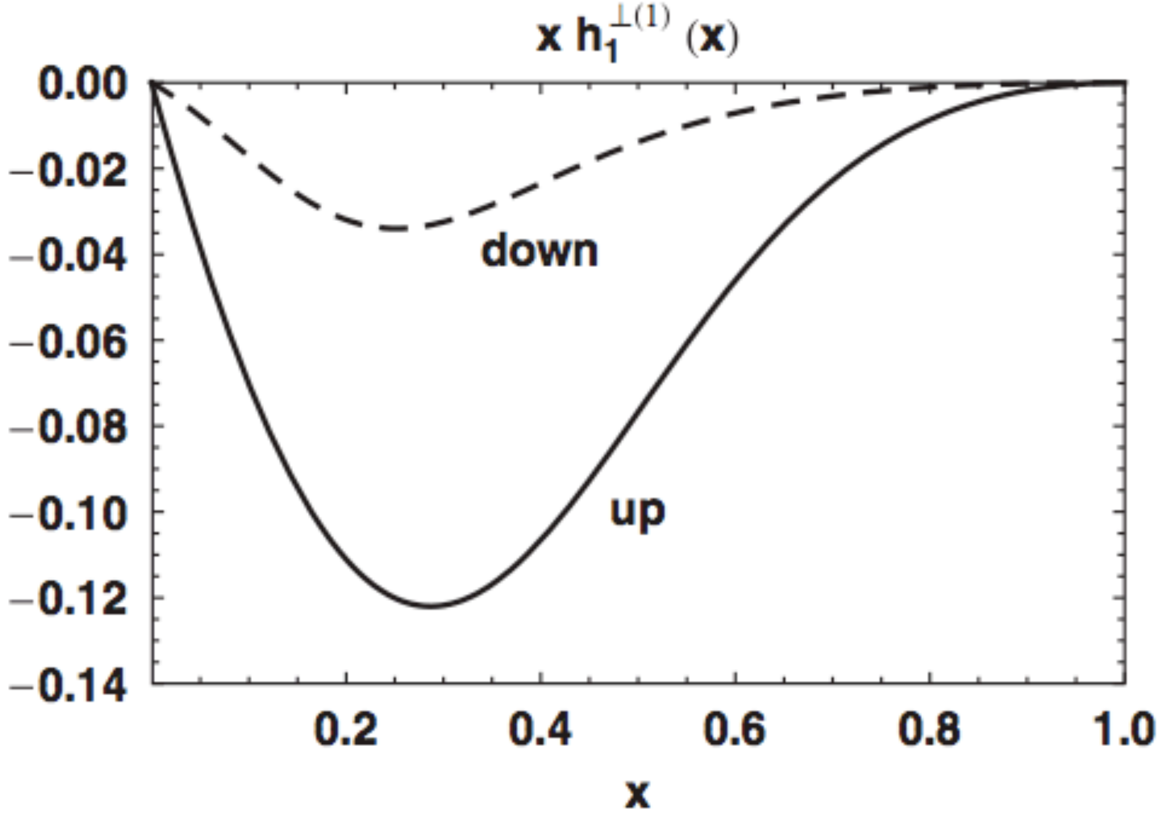


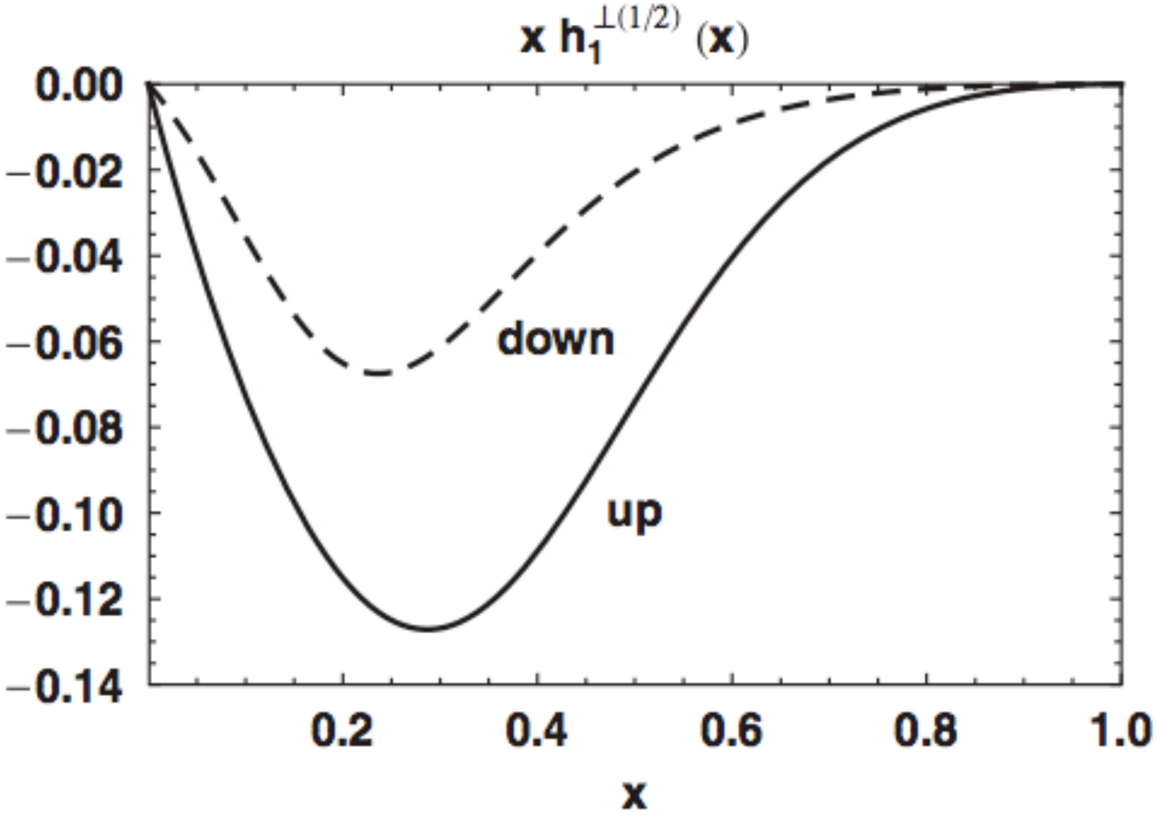


$h_1^\perp$

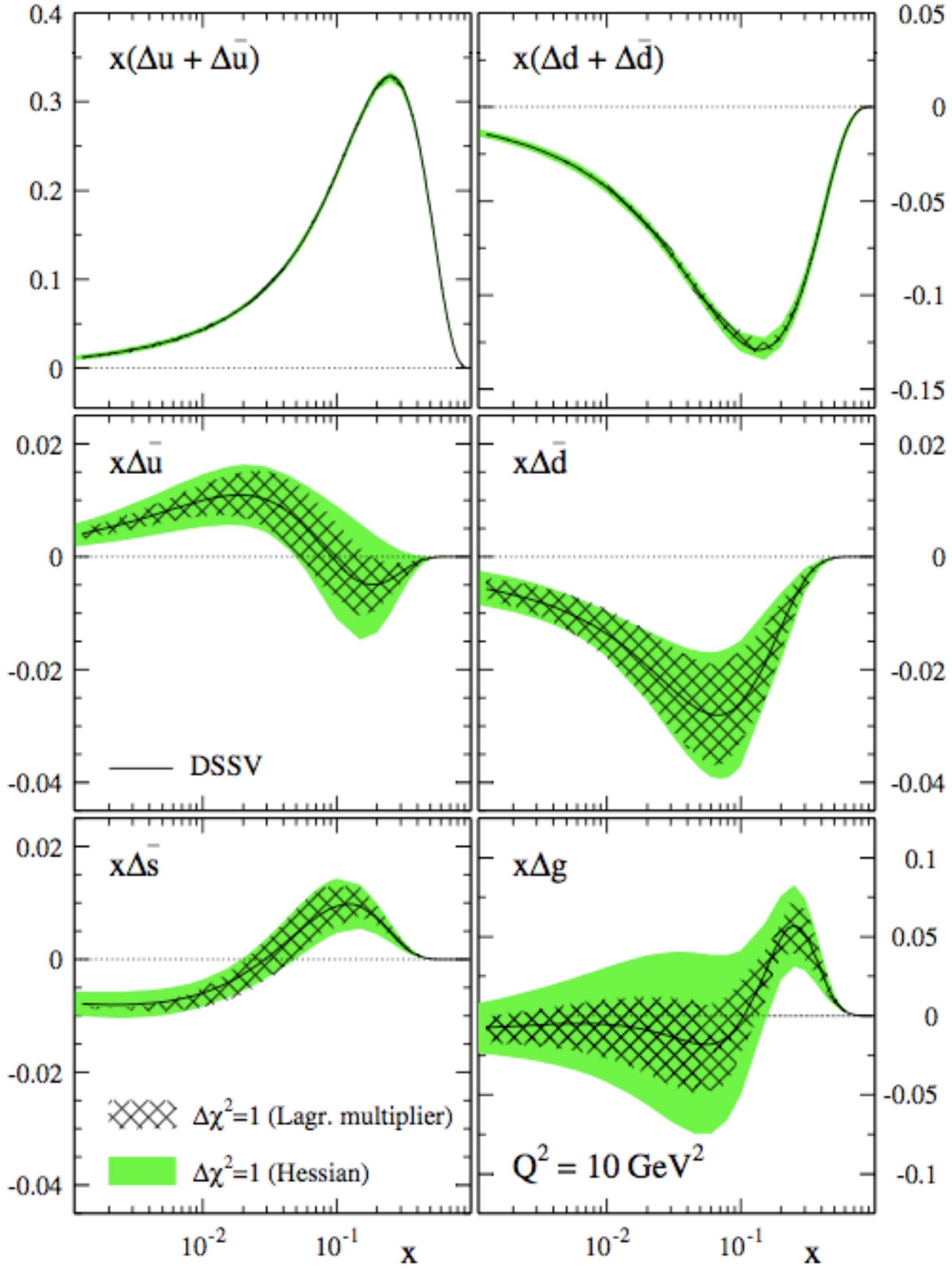
Boer-Mulders

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





Polarized PDFs



DSSV fits

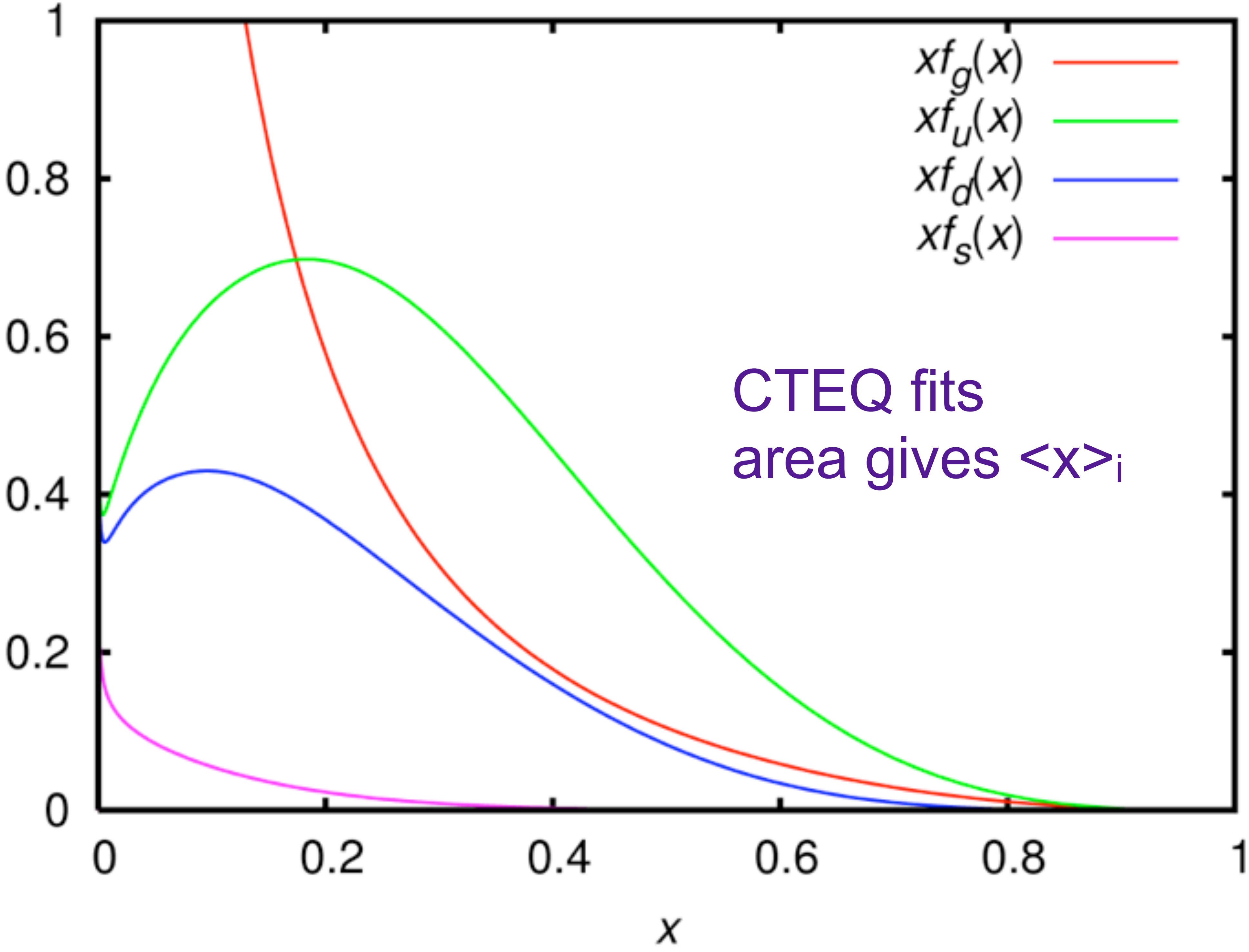
Q^2 evolution is used to determine Δg

Large uncertainties remain

deFlorian, Sassot, Stratmann, Vogelzang

Parton Distribution Functions

Fits to all the world's data yield the probability distributions for finding a quark or a gluon with momentum fraction x at scale Q^2.



CTEQ fits
area gives $\langle x \rangle_i$

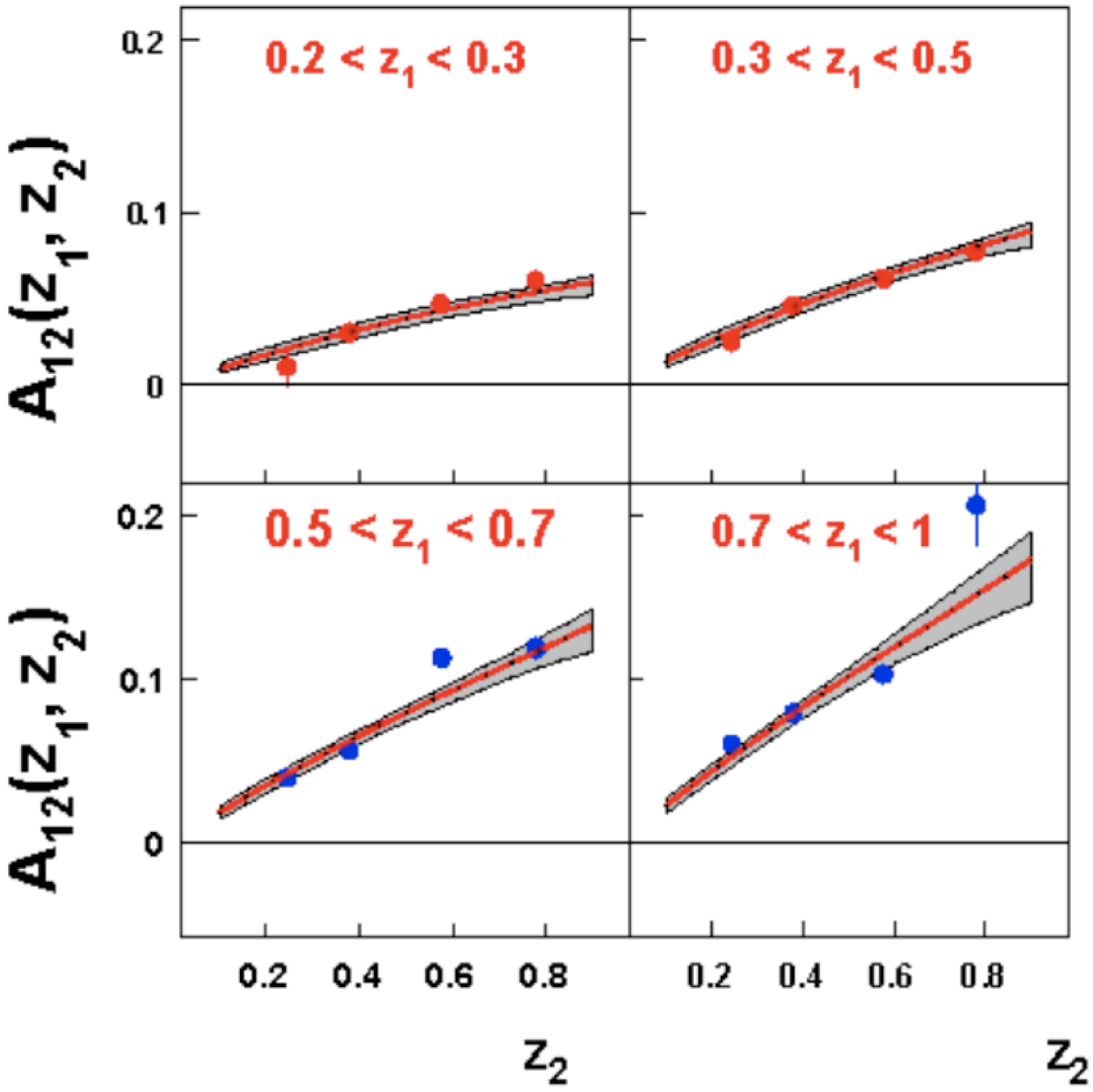
Collins Fragmentation

Seidl, PR**D78**(08)032011 (Belle)

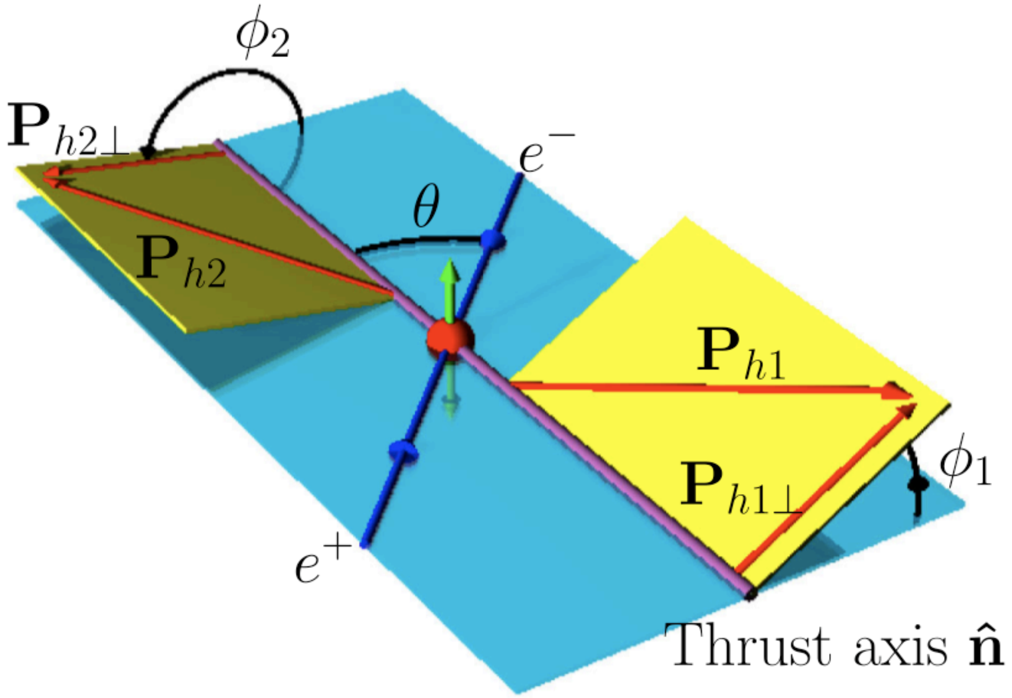
$$N(\phi_1 + \phi_2) \sim a_{12}cos(\phi_1 + \phi_2),\ \ a_{12} \sim H_1^{\perp}(z_1)H_1^{\perp}(z_2)$$

$$A_{12} = a_{12}^{\pi^+,\pi^-} / a_{12}^{(\pi^+,\pi^+),(\pi^-,\pi^-),(\pi^+,\pi^-)}$$

Anselmino, AIPCP**1149**(09)465 [Fits]

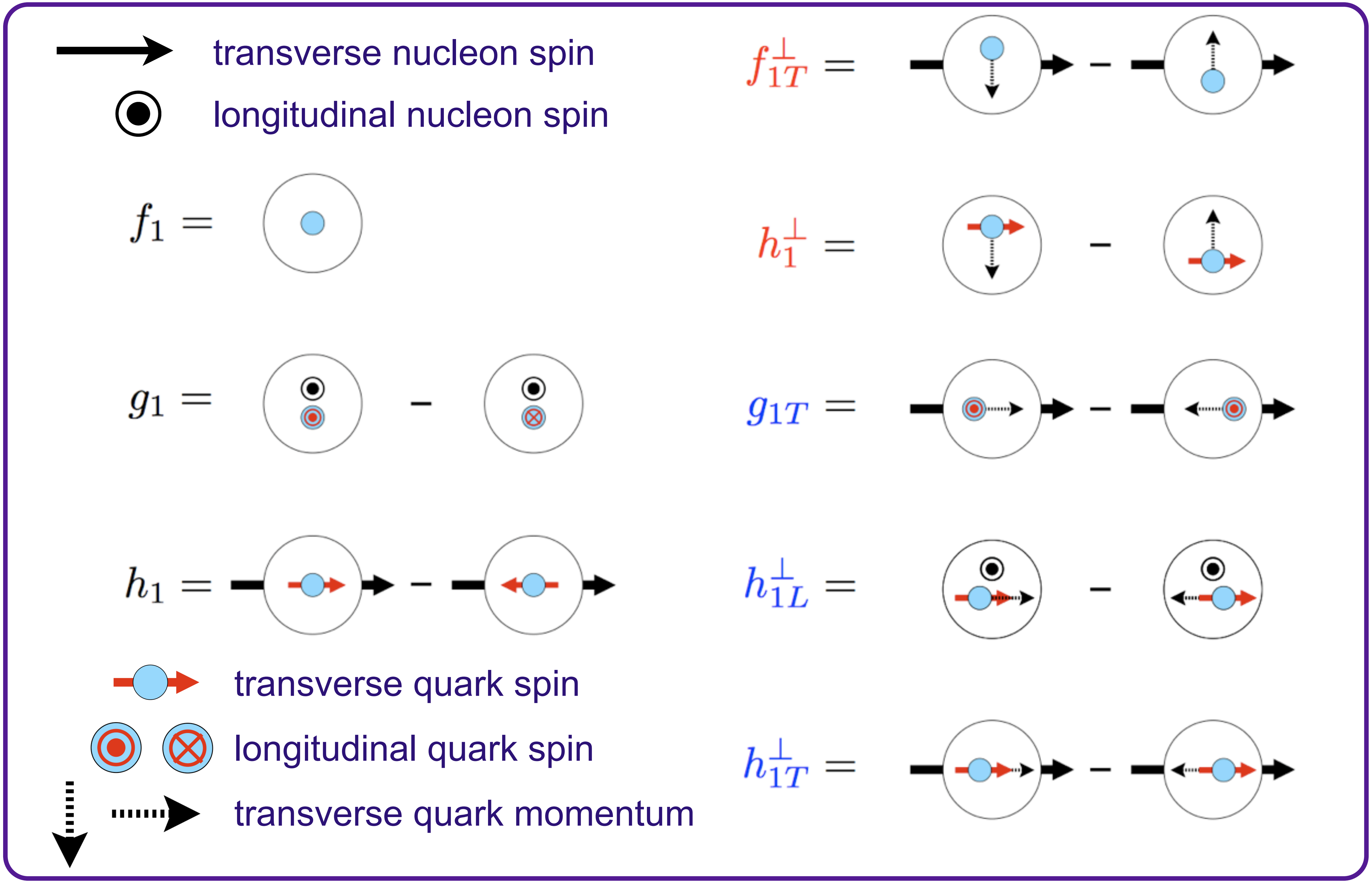


- $e^+e^- \to \pi\pi$
- A_{12}: Ratio cancels QCD radiative and acceptance effects
- CM energy ~10.5 GeV; L=550 fb^{-1}



Intuitive TMDs

from Bacchetta



→ transverse nucleon spin

⊙ longitudinal nucleon spin

transverse quark spin

⊙ ⊗ longitudinal quark spin

transverse quark momentum