MC-generators and flavor decomposition in SIDIS

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Introduction
MC studies of Bessel weighting
Extraction of k_T-dependent TMDs
- Kinematic dependences of A_1
- Study effect of spin-orbit correlations on x-dependence
- Extraction of b_T-dependence of TMDs

Summary

Flavor Decomposition for PDF (LO)

lepton helicity → λ_e, **proton helicity** → λ

$$\frac{d\sigma_{\lambda,\lambda_e}}{dx\,dQ^2\,dz} = \frac{\lambda_e\,\lambda\,y\,(1-\frac{1}{2}\,y)\sum_{a,\bar{a}} e_a^2\,x_B\,g_1^a(x_B)D_1^a(z_h)}{\left(1-y+\frac{1}{2}\,y^2\right)\sum_{a,\bar{a}} e_a^2\,x_B\,f_1^a(x_B)D_1^a(z_h)}$$

$$d\sigma^{\pi^+} \propto e_u^2 u(x) D_u^{\pi^+}(z) + e_d^2 d(x) D_d^{\pi^+}(z)$$
$$d\sigma^{\pi^-} \propto e_d^2 d(x) D_d^{\pi^-}(z) + e_u^2 u(x) D_u^{\pi^-}(z)$$

$D_u^{\pi^+}=D_d^{\pi^-}$, favored;
$D_u^{\pi^-}=D_d^{\pi^+}$, unfavored

$$A_p^{\pi^+-\pi^-}(x) = \frac{4\Delta u_V(x) - \Delta d_V(x)}{4u_V(x) - d_V(x)} \qquad A_d^{\pi^+-\pi^-}(x) = \frac{\Delta u_V(x) + \Delta d_V(x)}{u_V(x) + d_V(x)}$$

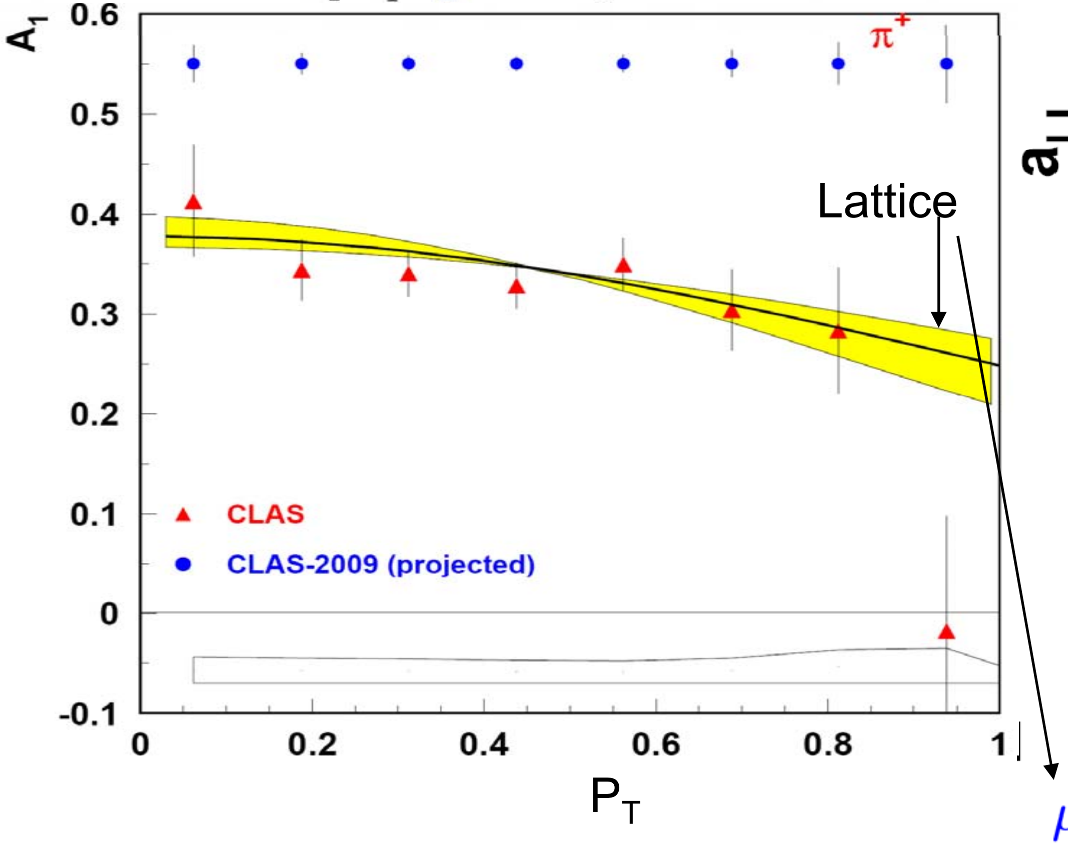
$$\Delta u = \frac{4}{15}[A_{1,p}^{\pi}(4u+d) - A_{1,n}^{\pi}(d+u/4)] \qquad \Delta d = \frac{4}{15}[A_{1,n}^{\pi}(4d+u) - A_{1,p}^{\pi}(u+d/4)]$$

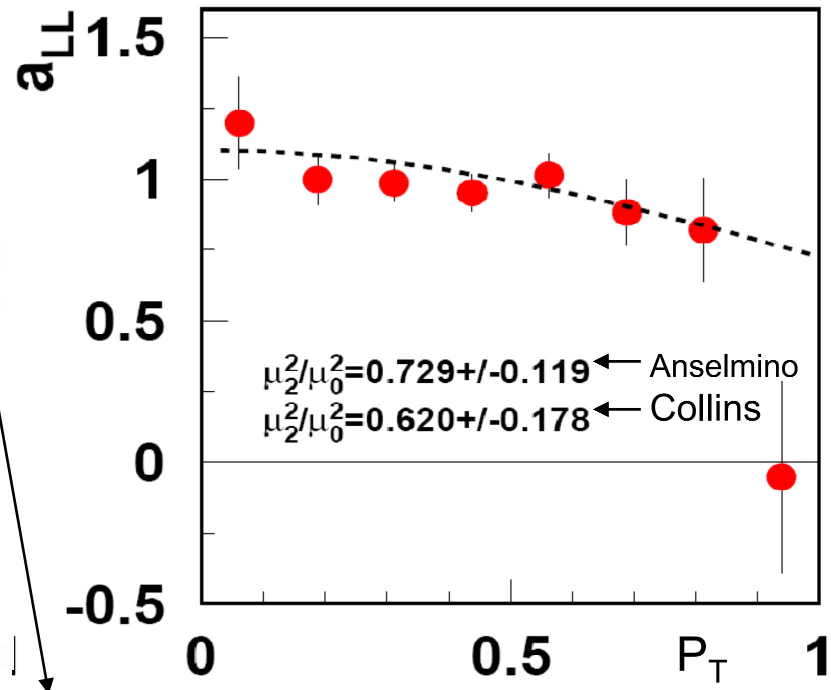
A_1 P_T-dependence

arXiv:1003.4549

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}$$

$$A_1(x,z,P_T) = A_1(x,z)\underbrace{\frac{\langle P_T^{2,unp}\rangle}{\langle P_T^{2,pol}\rangle} \exp(-P_T^2/\langle P_T^{2,pol}\rangle - P_T^2/\langle P_T^{2,unp}\rangle)}_{a_{LL}}$$

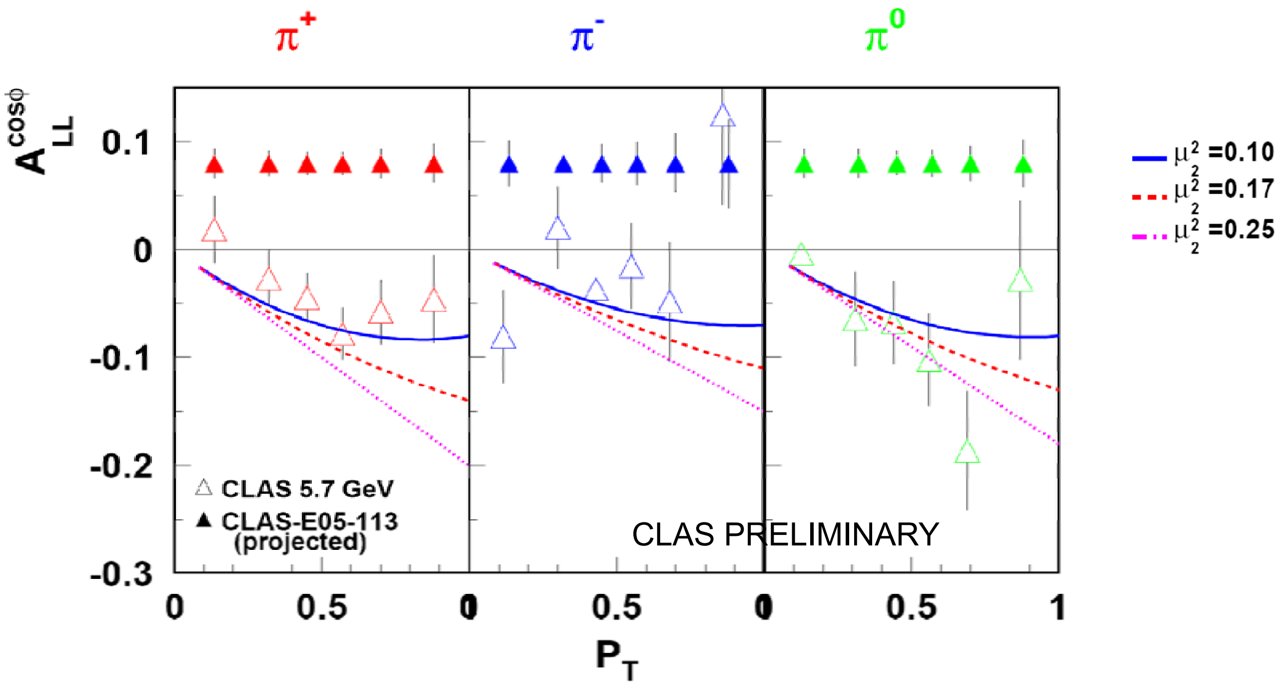




$$\mu_2^2/\mu_0^2 = 0.692 \pm 0.039 \pm 0.045$$

CLAS data suggests that width of g_1 is less than the width of f_1

cosϕ moment in A_{LL}-P_T-dependence



hep-ph/0608048
μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

$$\sigma_0 = \frac{1+(1-y)^2}{xy^2}\frac{1}{\mu_D^2+z^2\mu_0^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_0^2}\right)\sum_q e_q^2 f_1^q(x) D_q^h(z)$$

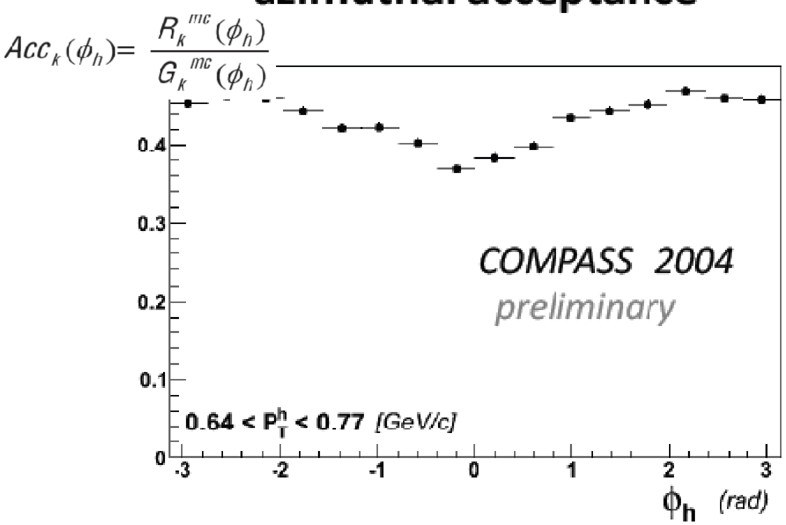
$$A_{LL}^{\cos\phi} \sim e_L H_1^\perp$$

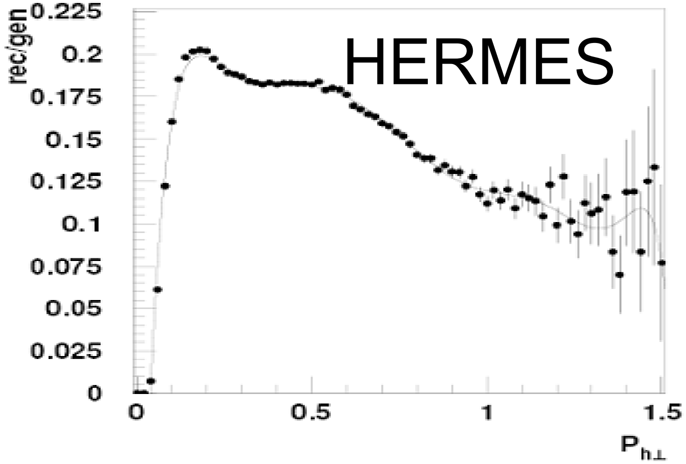
$$A_{LL}^{\cos\phi} \sim g_L^\perp D_1$$

P_T-dependence of cosϕ moment of double spin asymmetry is most sensitive to k_T-distributions of quarks with spin orientations along and opposite to the proton spin.

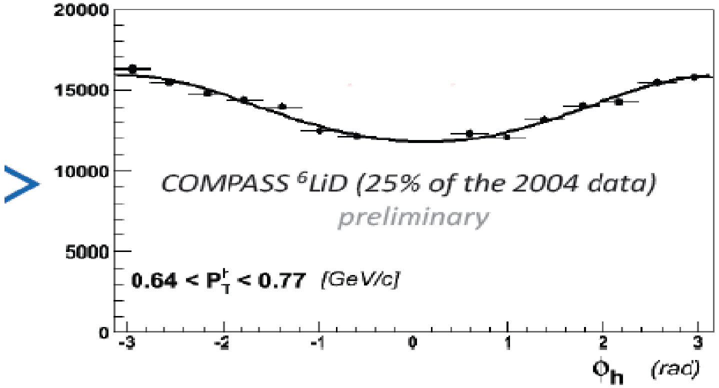
Acceptances and efficiencies

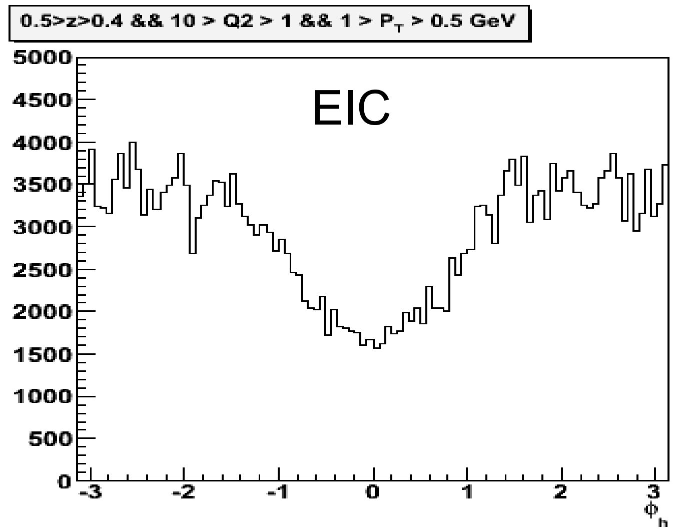
azimuthal acceptance





measured azimuthal distributions corrected by the acceptance



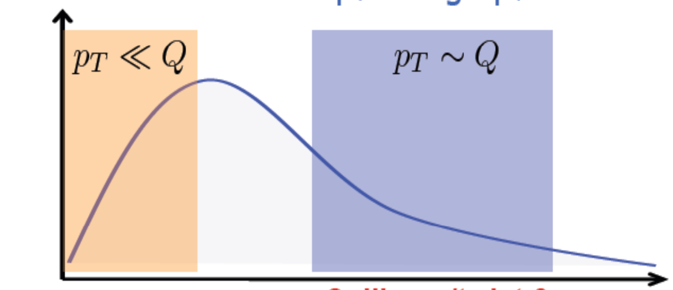


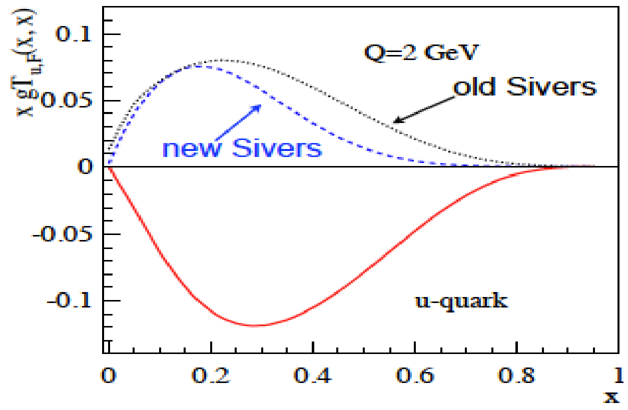
How acceptance in ϕ and P_T affect the A_1 and Δs extractions in SIDIS?

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

k_T-dependence of TMDs

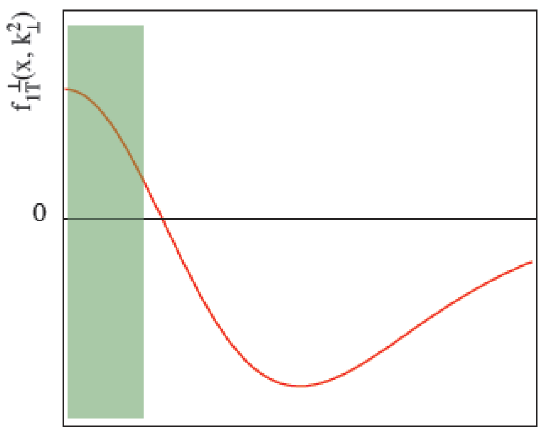
- Transition from low p_T to high p_T

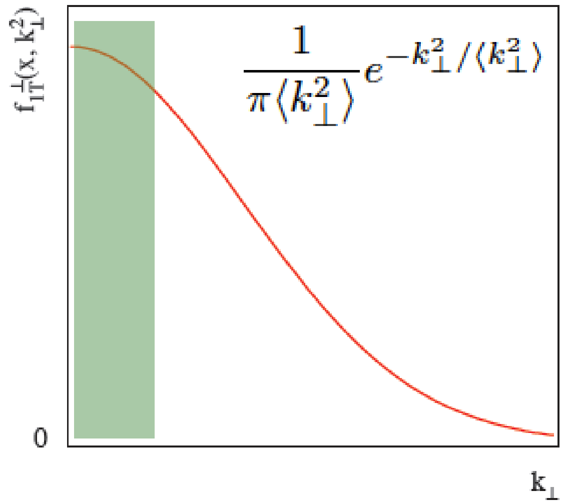




Directly obtained ETQS functions are opposite in sign to those from k_T moments "sign mismatch"

Sivers function extracted assuming k_T distribution is gaussian

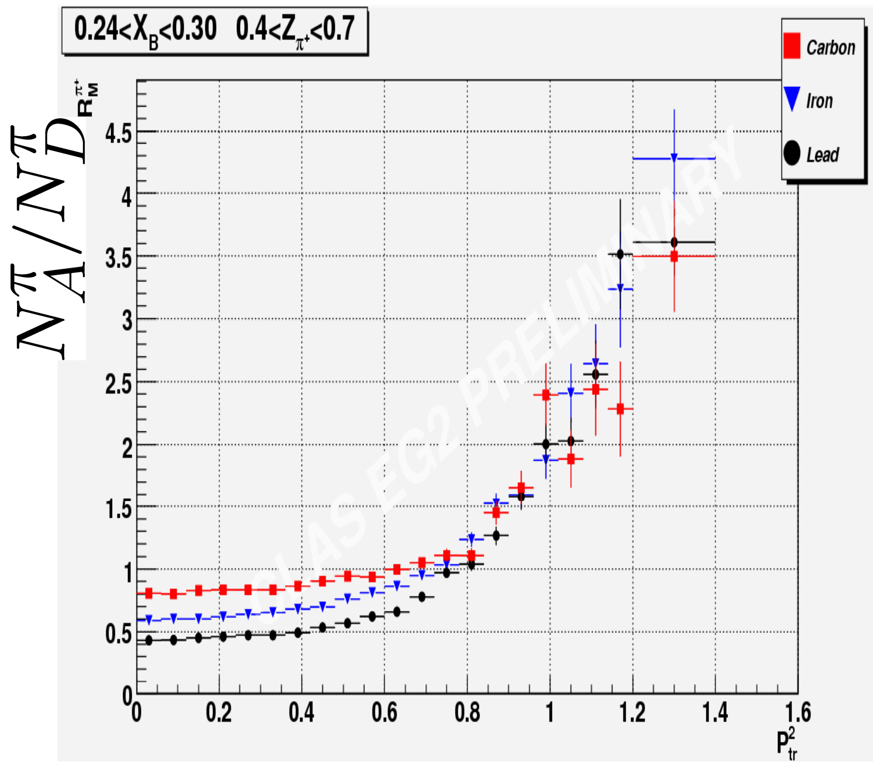




- With orbital angular momentum TMD can't be gaussian
- How to measure k_T-dependences of TMDs

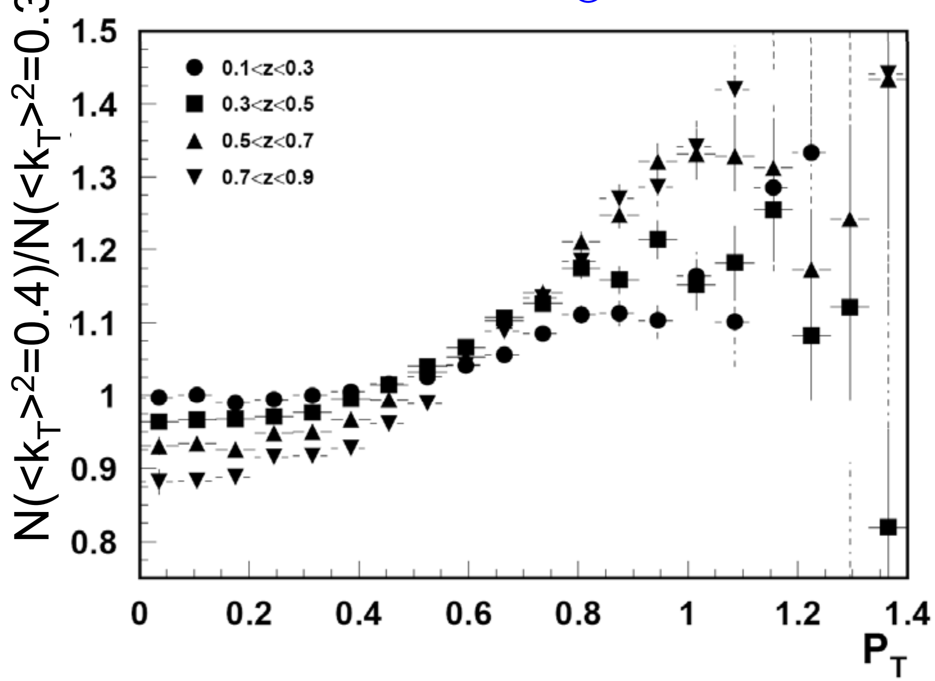
(Z. Kang et al, 2011)

k_T-distributions & dilution factor



bigger effect at large z

$P_T = p_\perp + z\, k_T$



Higher probability to find a hadron at large P_T in nuclei

→

k_T-distributions may be wider in nuclei?

Understanding of nuclear modifications of hadronic distributions is crucial for polarized target data analysis

SIDIS x-section

SIDIS $\ell(l) + N(P,S) \to \ell(l) + h(P_h) + X$

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$

$$+S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h) F_{UL}^{\sin 2\phi_h}\right]$$

$$+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right]$$

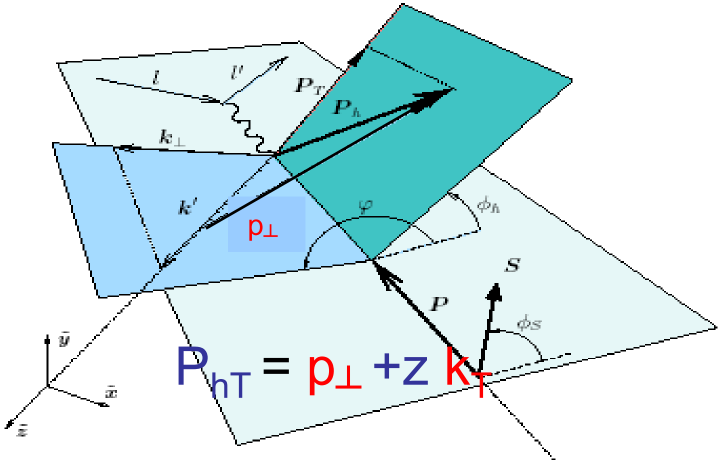
$$+|S_\perp|\left[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\right.$$

$$+\varepsilon\sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin(3\phi_h-\phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$\left.+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)}\right]$$

$$+|S_\perp|\lambda_e\left[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}\right.$$

$$\left.\left.+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\right\}, \qquad ($$



$P_{hT} = p_\perp + z\,k_T$

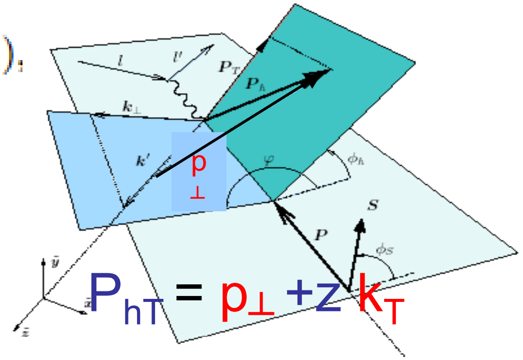
$$F_{UU,T} = x\sum_a e_a^2\, f_1^a(x)\, D_1^a(z)$$

$$F_{UU,T} = x\sum_a e_a^2\int d^2p_T\, d^2k_T\,\delta^{(2)}(p_T - k_T - P_{h\perp}/z)\, w(p_T,k_T)\, f^a(x,p_T^2)\, D^a(z,k_T^2).$$

SIDIS with Bessel weighting

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

$$\delta^{(2)}(z\boldsymbol{p}_T + \boldsymbol{K}_T - \boldsymbol{P}_{h\perp}) = \int \frac{d^2 \boldsymbol{b}_T}{(2\pi)^2} e^{i\boldsymbol{b}_T(z\boldsymbol{p}_T + \boldsymbol{K}_T - \boldsymbol{P}_{h\perp})}$$

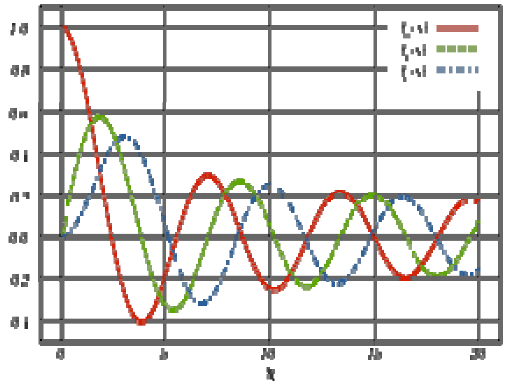


$$F_{UU,T} = x_B \sum_a e_a^2 \int \frac{d|\boldsymbol{b}_T|}{(2\pi)} |\boldsymbol{b}_T| \, J_0(|\boldsymbol{b}_T| \, |\boldsymbol{P}_{h\perp}|) \; \tilde{f}_1(x, z^2 \boldsymbol{b}_T^2) \; \tilde{D}_1(z, \boldsymbol{b}_T^2)$$

$$\int_0^\infty d|\boldsymbol{P}_{h\perp}| \, |\boldsymbol{P}_{h\perp}| \, J_n(|\boldsymbol{P}_{h\perp}| \, |\boldsymbol{b}_T|) \, J_n(|\boldsymbol{P}_{h\perp}| \, \mathcal{B}_T) = \frac{1}{\mathcal{B}_T} \delta(|\boldsymbol{b}_T| - \mathcal{B}_T)$$

$$\tilde{f}_1^q(x, z^2 b_T^2) \, \tilde{D}_1^{q \to \pi}(z, b_T^2)$$

$$\tilde{f}(x, \boldsymbol{b}_T^2) \equiv \int d^2 \boldsymbol{p}_T \, e^{i\boldsymbol{b}_T \cdot \boldsymbol{p}_T} \; f(x, \boldsymbol{p}_T^2) = 2\pi \int d|\boldsymbol{p}_T| |\boldsymbol{p}_T| \; J_0(|\boldsymbol{b}_T| |\boldsymbol{p}_T|) \; f(x, \boldsymbol{p}_T^2)$$



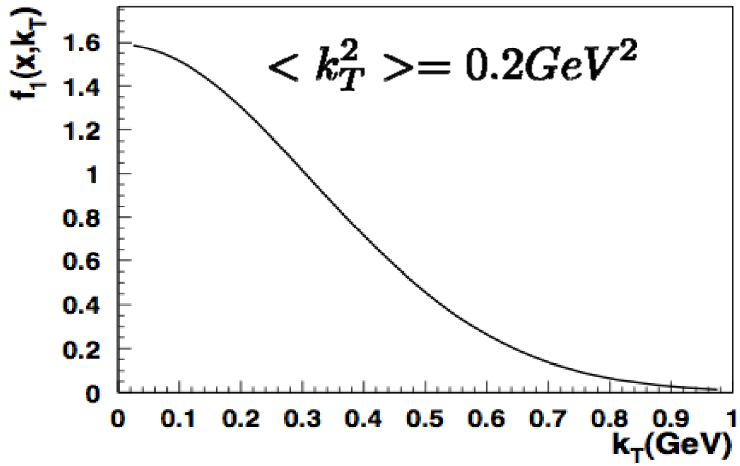
$$F_{LL} = x_B \sum_a e_a^2 \int \frac{d|\boldsymbol{b}_T|}{(2\pi)} |\boldsymbol{b}_T| \, J_0(|\boldsymbol{b}_T| \, |\boldsymbol{P}_{h\perp}|) \; \tilde{g}_{1L}(x, z^2 \boldsymbol{b}_T^2) \; \tilde{D}_1(z, \boldsymbol{b}_T^2)$$

- the formalism in **b_T-space** avoids convolutions
- provides a model independent way to study kinematical dependences of TMD

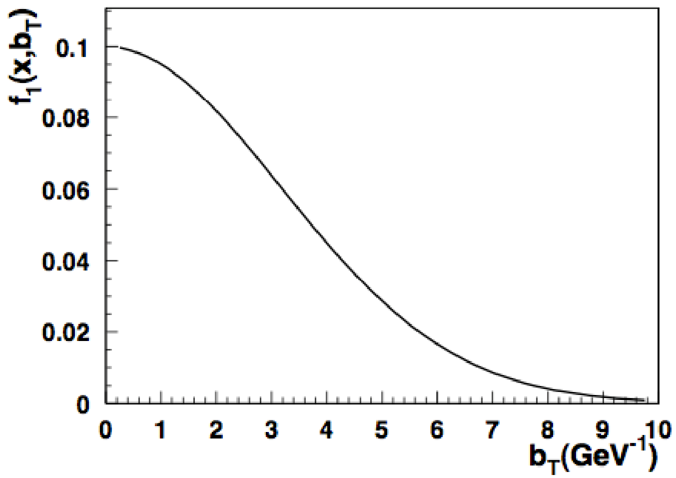
SIDIS with Bessel weighting

$$\tilde{f}(x, b_T^2) \equiv \int d^2 p_T \, e^{i b_T \cdot p_T} \, f(x, p_T^2) = 2\pi \int d|p_T||p_T| \; J_0(|b_T||p_T|) \; f(x, p_T^2)$$

$$f_1(x, k_T) = \frac{N}{\pi < k_T^2 >} e^{-\frac{k_T^2}{<k_T^2>}}$$



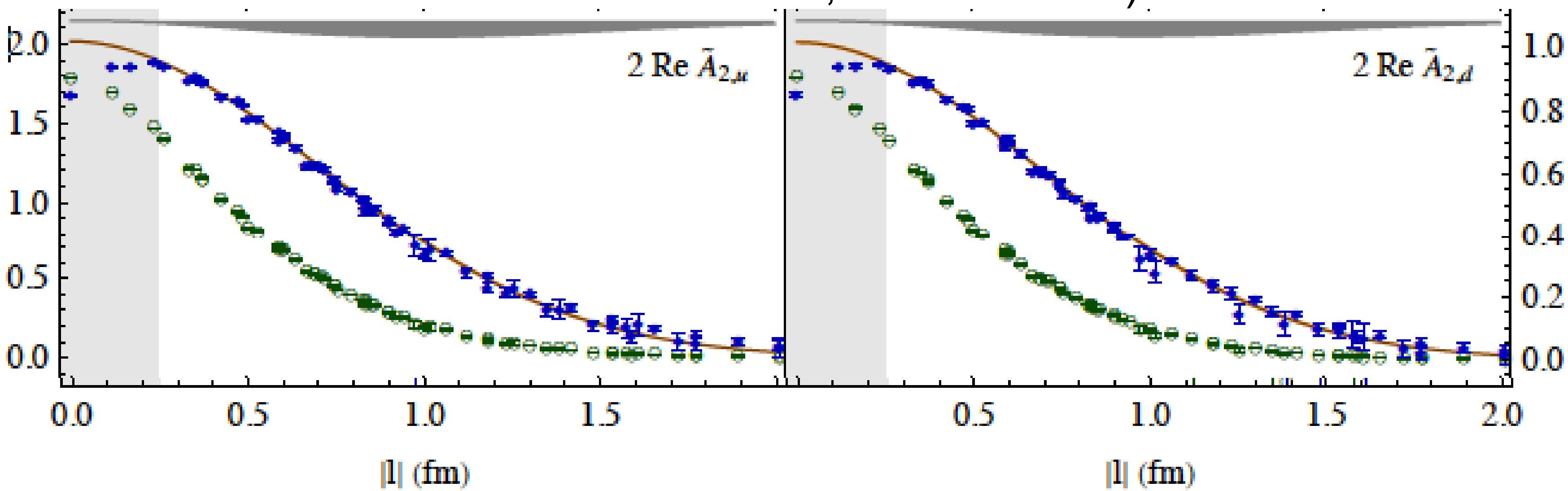
$$\tilde{f}_1(x, b_T^2) = \frac{1}{2} < k_T^2 > N e^{-\frac{<k_T^2> b_T^2}{4}}$$



•the data analysis can be performed in the **b_T-space**.

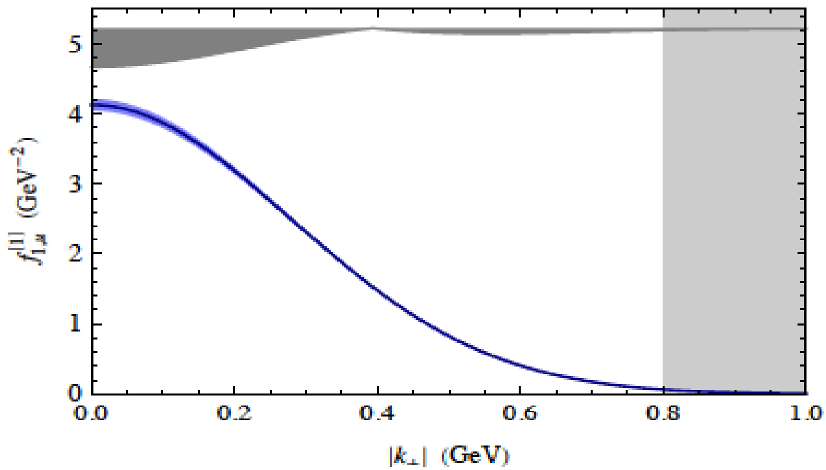
Lattice calculations and b_T-space

(PDFs in terms of Lorenz invariant amplitudes $\tilde{A}_i$
Musch et al, arXiv:1011.1213)

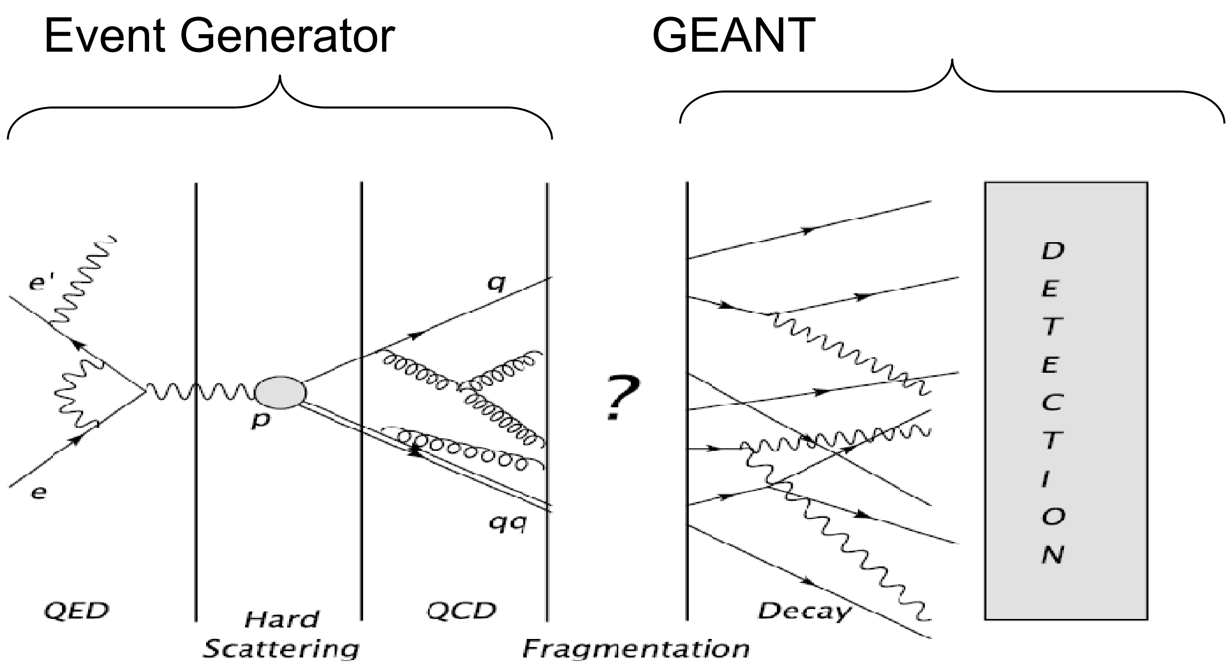


	c_2	σ_2
$\tilde{A}_{2,u}$	$2.0186 \pm 0.0063 \pm 0.0008$	$1.001 \pm 0.010 \pm 0.068$
$\tilde{A}_{2,d}$	$1.0171 \pm 0.0064 \pm 0.0005$	$0.975 \pm 0.012 \pm 0.063$

$$f_1^{[1]}(\boldsymbol{k}_\perp^2) = \frac{c_2\,\sigma_2^2}{4\pi} e^{-\frac{\boldsymbol{k}_\perp^2}{(2/\sigma_2)^2}}$$

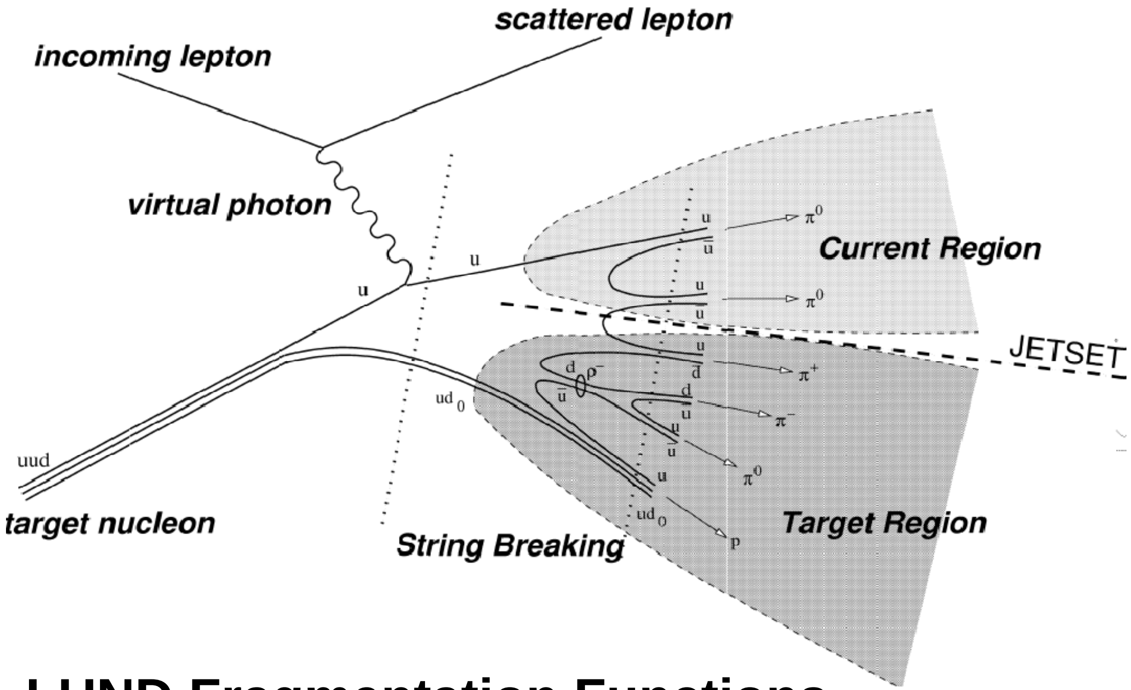


Hadron production in hard scattering



LUND MC (LEPTO/PEPSI/JETSET)
Model based (NJL,…)
SIDIS x-section based dedicated MC

JETSET:Single particle production in hard scattering

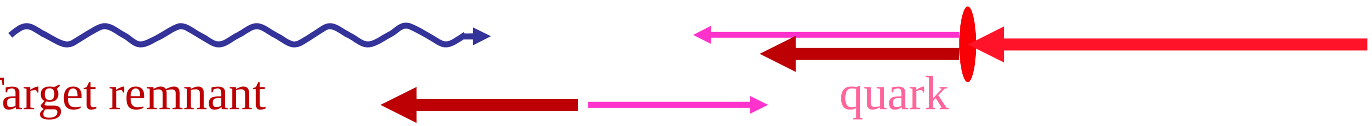


High probability to detect leading hadron in the forward detector

DIS:
Q^2>1GeV^2
W^2>4 GeV^2 (10)
y<0.85

LUND Fragmentation Functions

- Before
- After



The primary hadrons produced in string fragmentation come from the string as a whole, rather than from an individual parton.

LUND Fragmentation Functions

parameter	JETSET	default	HERMES	CLAS
$q^s{}_{supp}$	PARJ(2)	0.3	0.28	0.1
$q^s q^s{}_{sup}$	PARJ(3)	0.4	0.4	0.2
S1	PARJ(12)	0.6	0.6	0.4
μ_D	PARJ(21)	0.36	0.38	0.3
η	PARJ(23)	0.01	0.01	0.1
ΔE	PARJ(33)	0.8	0.8	0.3
a	PARJ(41)	0.3	1.13	1.1
a_{qq}	PARJ(45)	0.5	1.05	1.0

Relative suppression of di-quark pairs compared to quark pairs (qq_{supp}), strange quarks to u quarks (q_{supp}), and extra suppresion of strange diquarks($q^s q^s_{supp}$)

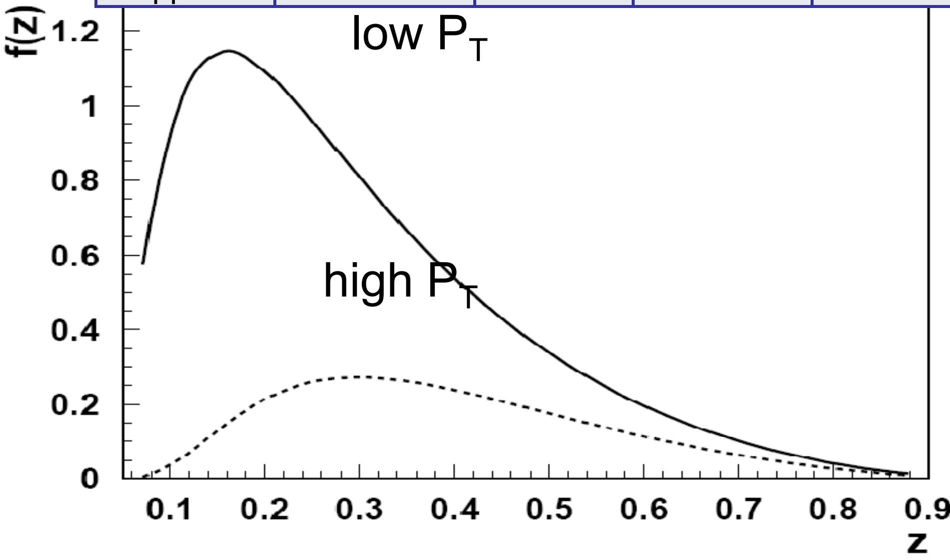
$$f(P_T) \sim e^{\frac{-P_T^2}{\mu_D^2}}$$

Distributions in P_T given by a gaussian with width μ_D with additional exponential $e^{-P_T/\mu_{D'}}$ from fraction η

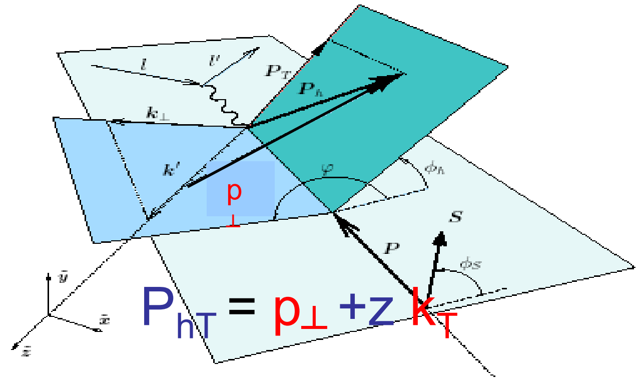
$$f(z) \sim z^{-1}(1-z)^{a+a_{q\bar{q}}} e^{\frac{-b(m_h^2+P_T^2)}{z}}$$

Suppression for diquarks at large z $\rightarrow a_{q\bar{q}}$

PDF side: gaussian $\langle k_T^2 \rangle$



FAST-MC for CLAS12



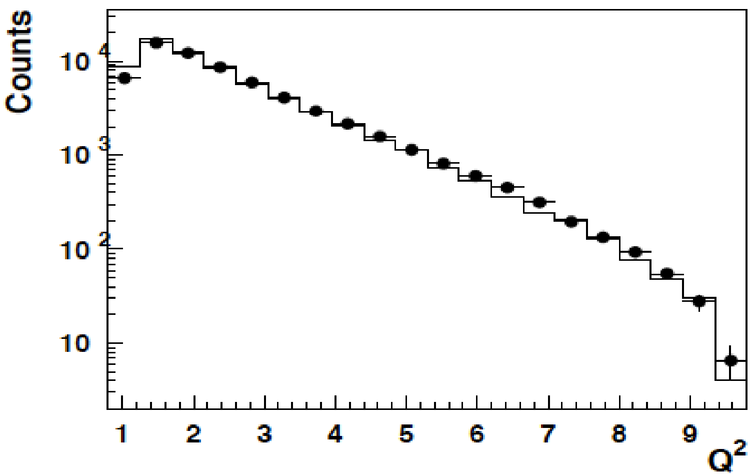
SIDIS MC in 7D ($x,y,z,\phi,\phi_S,p_T,\lambda,\pi$)

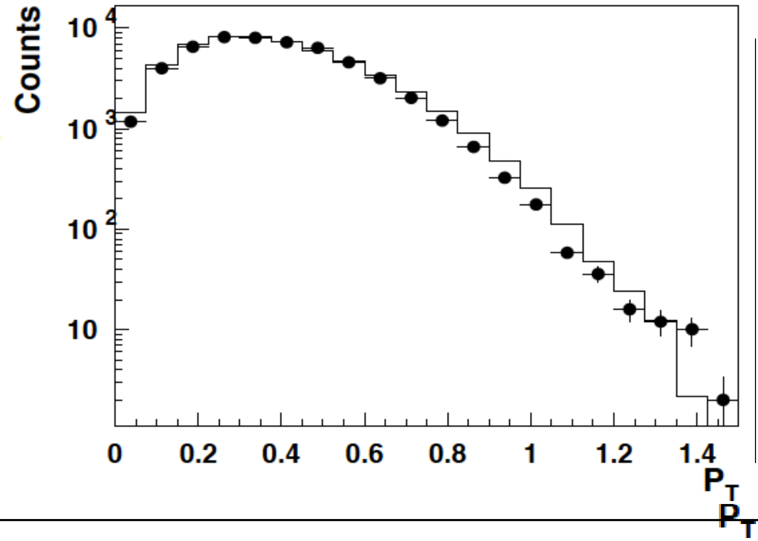
Simple model with 10% difference between f_1 (0.2GeV^2) and g_1 widths with a fixed width for D_1 (0.14GeV^2)

$$f_q(x,k_\perp) = f_q(x)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle}$$

CLAS12 acceptance & resolutions

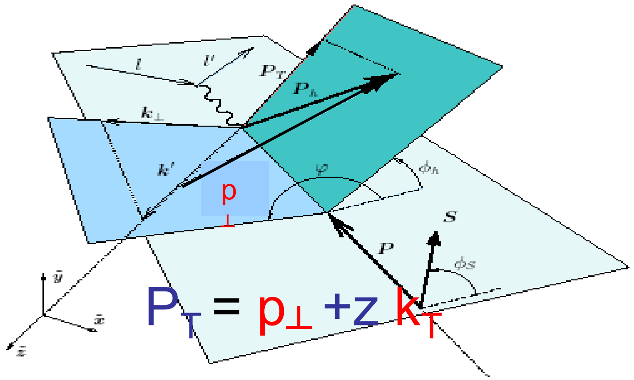
Events in CLAS12





Reasonable agreement of kinematic distributions with realistic LUND simulation

FAST-MC for CLAS12



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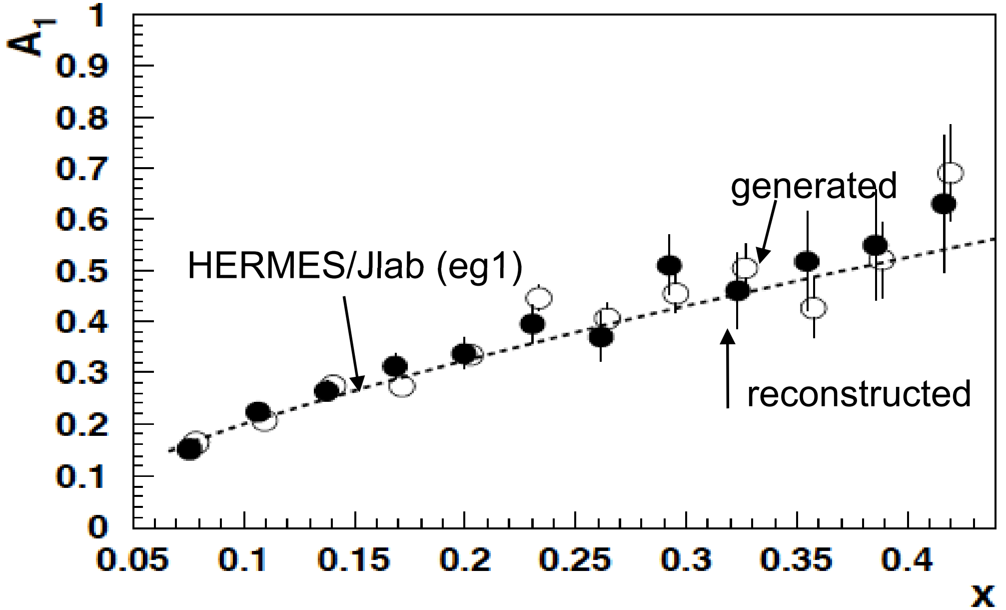
CLAS12 acceptance & resolutions



Reasonable agreement of kinematic distributions with SIDIS data

BGMP: extraction of k_T-dependent PDFs

Need: project x-section onto Fourier mods in b_T-space to avoid convolution

Boer, Gamberg, Musch &Prokudin arXiv:1107.5294

$$\int_0^\infty d|P_{h\perp}|\,|P_{h\perp}|\,J_0(|P_{h\perp}||b_T|)\left[\frac{d\sigma}{dx_B\,dy\,d\phi_S\,dz_h\,d\phi_h\,|P_{h\perp}|d|P_{h\perp}|}\right]$$

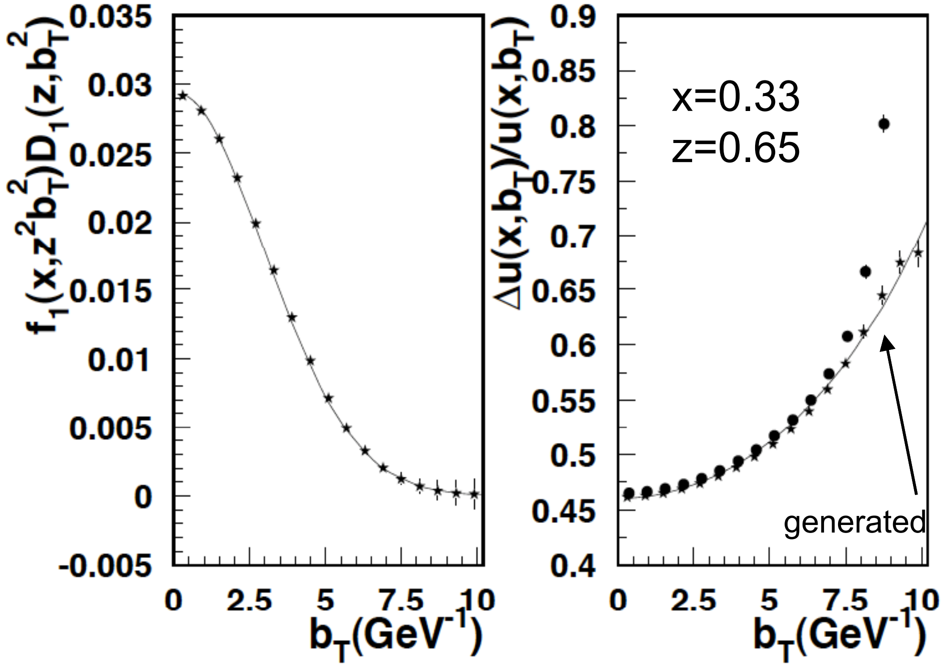
$$S_\pi^{unp\pm}(x_i, z_i, b_{Tj}) = \sum_{i=1}^{N_\pi^+/N_\pi^-} J_0(b_{Tj}P_{Ti})/\eta_i/A(x_i, y_i)$$

acceptance

$$A(x,y) = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)$$

$$\tilde{f}_1^q(x, z^2 b_T^2)\,\tilde{D}_1^{q\to\pi}(z, b_T^2)$$

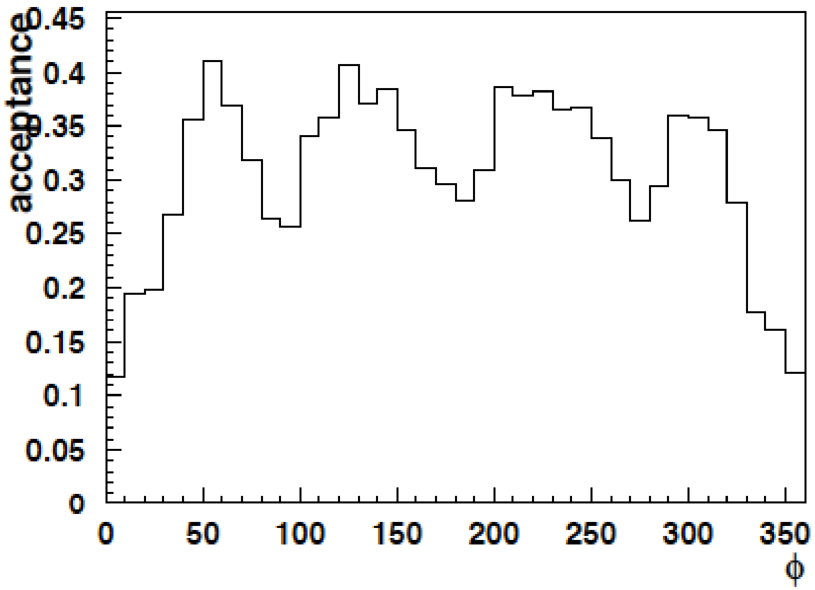
$$\Delta u(x,b_T)/u(x,b_T) = \frac{S_\pi^{pol+} - S_\pi^{pol-}}{S_\pi^{unp+} + S_\pi^{unp-}}$$

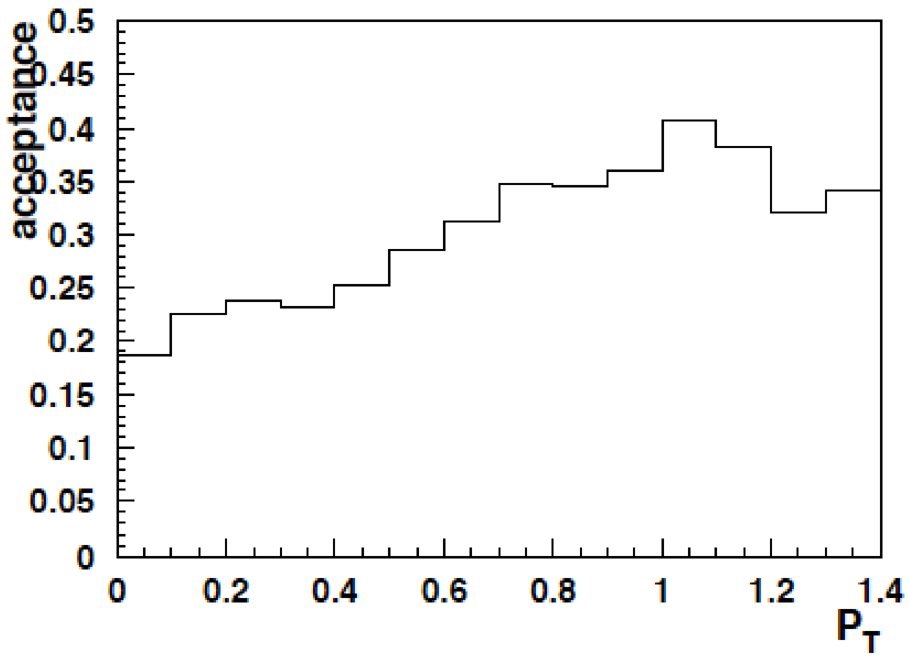


- BGMP provides a model independent way to extract k_T-dependences of helicity distributions
- requires wide range in hadron P_T

Acceptance effects

Acceptance for CLAS12 using CLAS-DIS generator using FAST-MC
(0.4<z<0.5,0.1<x<0.2)





Acceptance corrections are important even for full kinematical coverage

BGMP: extraction of k_T-dependent TMDs

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

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = -x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)} |b_T|^2 J_1(|b_T|\,|P_{h\perp}|)\; Mz\; \tilde{f}_{1T}^{\perp(1)}(x, z^2 b_T^2)\; \tilde{D}_1(z, b_T^2)$$

$$F_{LL} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)} |b_T|\, J_0(|b_T|\,|P_{h\perp}|)\; \tilde{g}_{1L}(x, z^2 b_T^2)\; \tilde{D}_1(z, b_T^2)\ ,$$

$$F_{LT}^{\cos(\phi_h-\phi_s)} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)} |b_T|^2 J_1(|b_T|\,|P_{h\perp}|)\; Mz\;\; \tilde{g}_{1T}^{\perp(1)}(x, z^2 b_T^2)\; \tilde{D}_1(z, b_T^2)\ ,$$

$$F_{UT}^{\sin(\phi_h+\phi_S)} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)} |b_T|^2 J_1(|b_T|\,|P_{h\perp}|)\; M_h z\; \tilde{h}_1(x, z^2 b_T^2)\; \tilde{H}_1^{\perp(1)}(z, b_T^2)\ ,$$

$$F_{UU}^{\cos(2\phi_h)} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)} |b_T|^3 J_2(|b_T|\,|P_{h\perp}|) M M_h z^2\; \tilde{h}_1^{\perp(1)}(x, z^2 b_T^2)\; \tilde{H}_1^{\perp(1)}(z, b_T^2)\ ,$$

$$F_{UL}^{\sin(2\phi_h)} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)} |b_T|^3 J_2(|b_T|\,|P_{h\perp}|) M M_h z^2\; \tilde{h}_{1L}^{\perp(1)}(x, z^2 b_T^2)\; \tilde{H}_1^{\perp(1)}(z, b_T^2)\ ,$$

$$F_{UT}^{\sin(3\phi_h-\phi_S)} = x_B \sum_a e_a^2 \int \frac{d|b_T|}{(2\pi)} |b_T|^4 J_3(|b_T|\,|P_{h\perp}|) \frac{M^2 M_h z^3}{4} \tilde{h}_{1T}^{\perp(2)}(x, z^2 b_T^2)\; \tilde{H}_1^{\perp(1)}(z, b_T^2)\ .$$

- BGMP provides a model independent way to extract k_T-dependences of TMD
- requires wide range in hadron P_T

Summary

•Understanding of k_T-dependence is crucial for SIDIS data analysis

•New SIDIS MC developed allowing simulation in 8D ($x,y,z,\phi,\phi_S,p_T,h,\lambda$) to test the k_T-dependent TMD flavor decomposition

•Bessel weighting procedure tested with a simple model

•Ratio of TMDs recovered with good precision within CLAS12 accessible kinematics

Plans

•Implement all structure functions
•Develop the procedure for k_T-dependent flavor decomposition for all TMDs (including f_1 and g_1)
•Extract f_1, g_1 and h_{1L} k_T-dependences from CLAS6 data
•Study models for nuclear PDFs and NH_3 dilutions
•………..