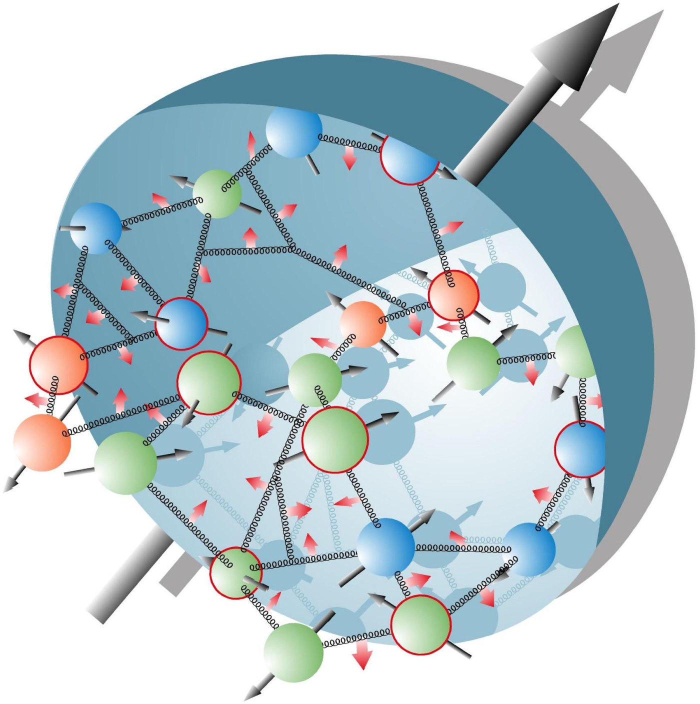
SIVERS EXTRACTION WITH NEURAL NETWORK



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University of Virginia (UVA) Spin Physics Group

@ DIS-2021

April 13, 2021

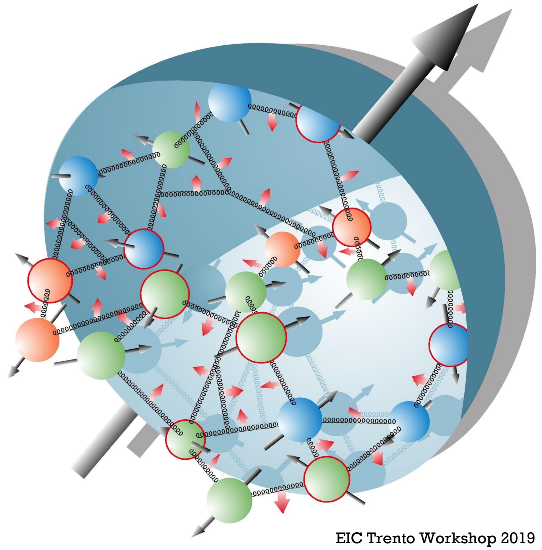
UNIVERSITY of VIRGINIA

SPIN QUEST

Fermilab

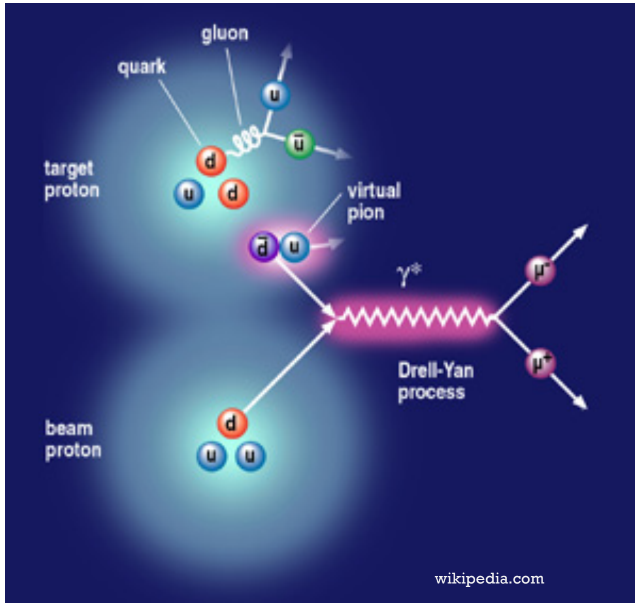
PROBING TMDs

Transverse
Momentum
Dependent
Parton Distribution
Functions
(TMD-PDFs)

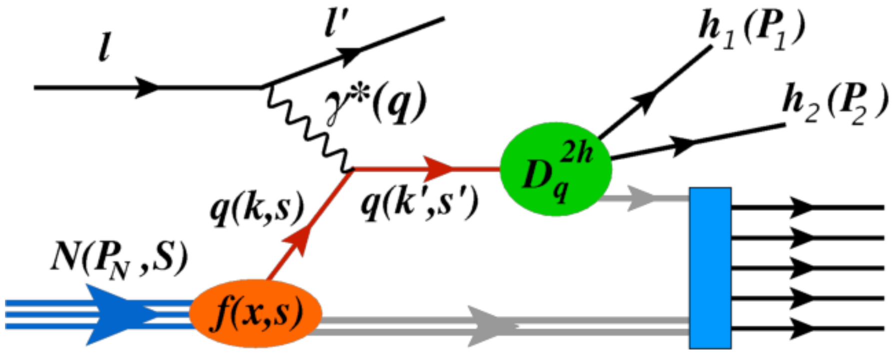


EIC Trento Workshop 2019

Drell-Yan (DY)

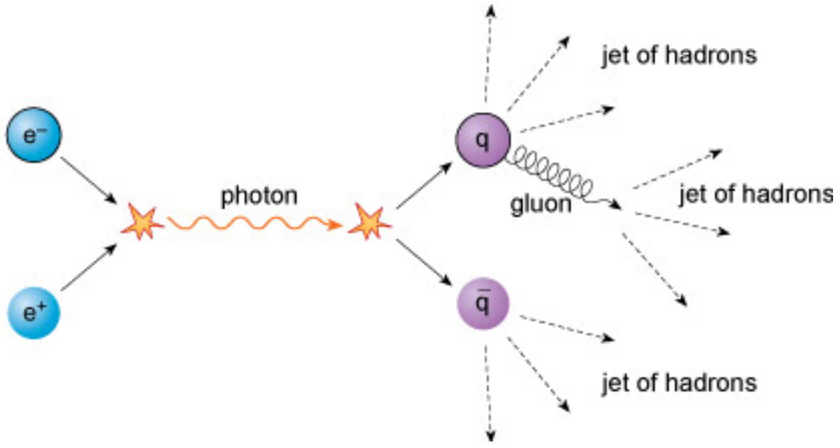


Semi Inclusive Deep Inelastic Scattering (SIDIS)

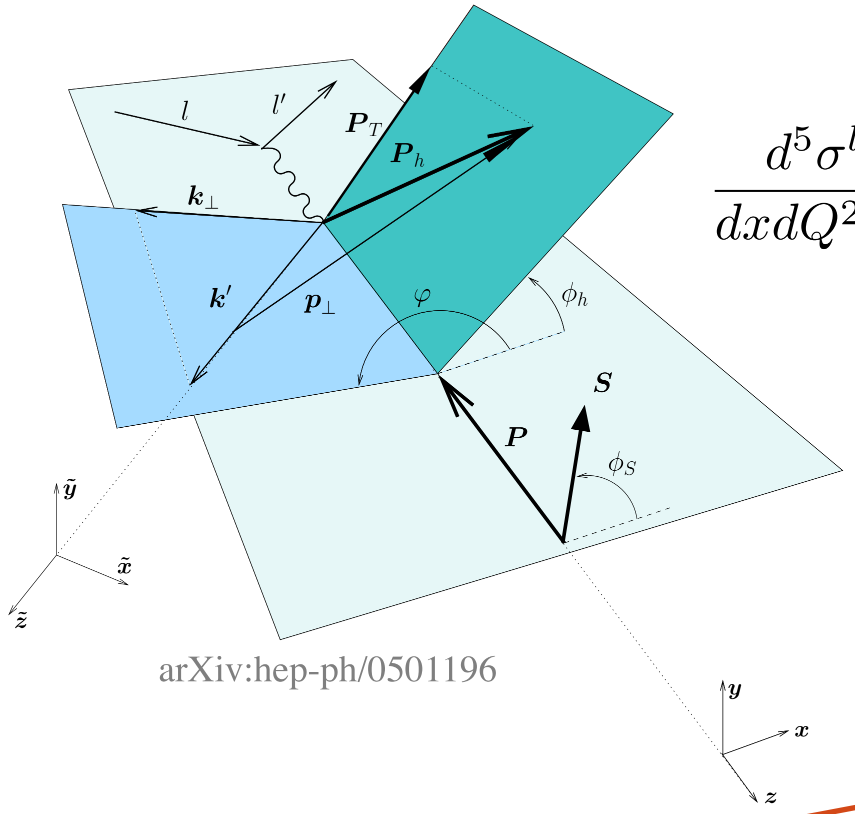


https://api.semanticscholar.org/CorpusID:119277556

Electron-positron annihilation



Semi Inclusive Deep Inelastic Scattering (SIDIS) Process



arXiv:hep-ph/0501196

$$\frac{d^5\sigma^{lp\to lhX}}{dx dQ^2 dz d^2 p_{hT}} \propto \sum_q e_q^2 \int d^2\mathbf{k}_\perp \, \mathcal{K}(x, p_{hT}, Q^2) f_q(x, \mathbf{k}_\perp) D_{h/q}(z, p_\perp) + \mathcal{O}\left(\mathbf{k}_\perp / Q\right)$$

Fragmentation Functions

Leading Twist TMDs

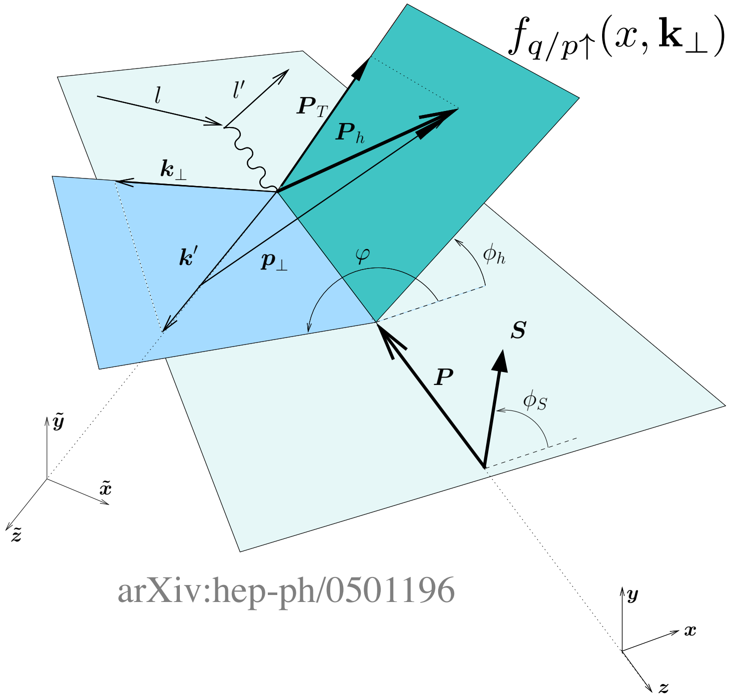
Nucleon Spin — Quark Spin

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	f_1 =		$h_1^\perp$ = — Boer-Mulders
L		g_{1L} = — Helicity	$h_{1L}^\perp$ = —
T	$f_{1T}^\perp$ = — Sivers	$g_{1T}^\perp$ = —	h_1 = — Transversity; $h_{1T}^\perp$ = —

$$f_{q/p\uparrow}(x, \mathbf{k}_\perp) = f_{q/p}(x, k_\perp) + \frac{1}{2}\Delta^N f_{q/p\uparrow}(x, k_\perp)\mathbf{S}.(\hat{\mathbf{p}} \times \hat{\mathbf{k}}_\perp)$$

$$= f_{q/p}(x, k_\perp) - \frac{k_\perp}{m_p} f_{1T}^{\perp q}(x, k_\perp)\mathbf{S}.(\hat{\mathbf{p}} \times \hat{\mathbf{k}}_\perp)$$

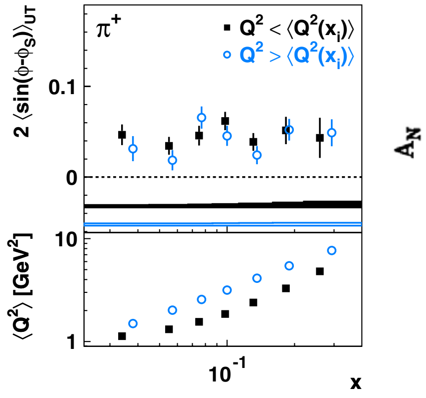
SIVERS ASYMMETRY FROM SIDIS

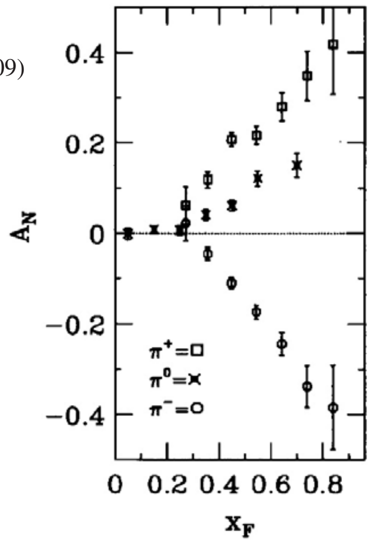


arXiv:hep-ph/0501196

$$f_{q/p\uparrow}(x,\mathbf{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p\uparrow}(x,k_\perp)\mathbf{S}.(\hat{\mathbf{p}}\times\hat{\mathbf{k}}_\perp)$$
$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{m_p} f_{1T}^{\perp q}(x,k_\perp)\mathbf{S}.(\hat{\mathbf{p}}\times\hat{\mathbf{k}}_\perp)$$

HERMES PRL **103**, 152002 (2009)





Asymmetry in $pp^\uparrow \to \pi X$ pion production from E704

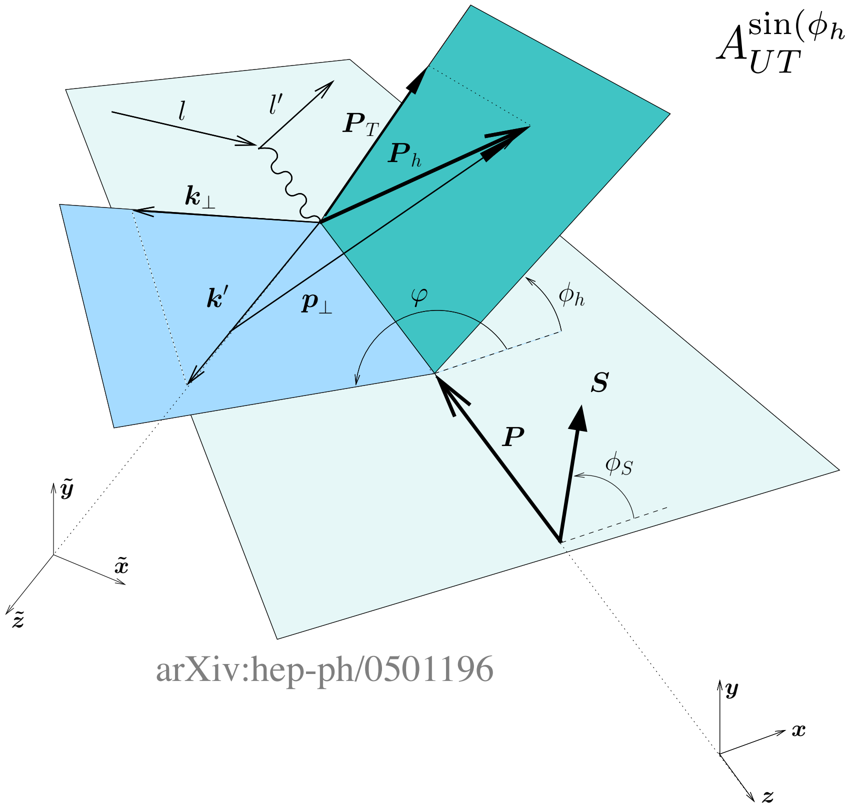
Single Spin Asymmetry (Sivers Asymmetry)

$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,y,z,p_{hT}) = \frac{d\sigma^{l\uparrow p\to hlX} - d\sigma^{l\downarrow p\to lhX}}{d\sigma^{l\uparrow p\to hlX} + d\sigma^{l\downarrow p\to hlX}} \equiv \frac{d\sigma\uparrow - d\sigma\downarrow}{d\sigma\uparrow + d\sigma\downarrow}$$

$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,y,z,p_{hT}) = \frac{[z^2\langle k_\perp^2\rangle + \langle p_\perp^2\rangle]\langle k_S^2\rangle^2}{[z^2\langle k_S^2\rangle + \langle p_\perp^2\rangle]\langle k_\perp^2\rangle^2} \exp\left[-\frac{p_{hT}^2\, z^2\left(\langle k_S^2\rangle - \langle k_\perp^2\rangle\right)}{\left(z^2\langle k_S^2\rangle + \langle p_\perp^2\rangle\right)\left(z^2\langle k_\perp^2\rangle + \langle p_\perp^2\rangle\right)}\right]$$
$$\times \frac{\sqrt{2e}\; z\; p_{hT}}{M_1} \frac{\sum_q \mathcal{N}_q e_q^2 f_q(x) D_{h/q}(z)}{\sum_q e_q^2 f_q(x) D_{h/q}(z)}$$

M. Anselmino et. al. arXiv: 1612.06413(2016)

SIVERS ASYMMETRY FROM SIDIS



arXiv:hep-ph/0501196

$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,y,z,p_{hT}) = \frac{[z^2\langle k_\perp^2\rangle + \langle p_\perp^2\rangle]\langle k_S^2\rangle^2}{[z^2\langle k_S^2\rangle + \langle p_\perp^2\rangle]\langle k_\perp^2\rangle^2} \exp\left[-\frac{p_{hT}^2\, z^2\left(\langle k_S^2\rangle - \langle k_\perp^2\rangle\right)}{\left(z^2\langle k_S^2\rangle + \langle p_\perp^2\rangle\right)\left(z^2\langle k_\perp^2\rangle + \langle p_\perp^2\rangle\right)}\right]$$

$$\times \frac{\sqrt{2e}\; z\; p_{hT}}{M_1} \frac{\sum_q \mathcal{N}_q e_q^2 f_q(x) D_{h/q}(z)}{\sum_q e_q^2 f_q(x) D_{h/q}(z)}$$

$$\langle k_S^2\rangle = \frac{M_1^2\langle k_\perp^2\rangle}{M_1^2 + \langle k_\perp^2\rangle} \qquad \langle k_\perp^2\rangle = 0.57 \pm 0.08\ \text{GeV}^2 \qquad \langle p_\perp^2\rangle = 0.12 \pm 0.01\ \text{GeV}^2$$

$D_{h/q}(z)$ is the fragmentation function for a quark with flavor q in a hadron h

$$D_{h/q}(z, p_\perp) = D_{h/q}(z)\frac{1}{\pi\langle p_\perp^2\rangle} e^{-p_\perp^2/\langle p_\perp^2\rangle}$$

$\langle p_\perp^2\rangle$ is the width of the unpolarized TMD-PDFs

$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,y,z,p_{hT}) = \mathcal{A}_0(z, p_{hT}, M_1)\left(\frac{\sum_q \mathcal{N}_q e_q^2 f_q(x) D_{h/q}(z)}{\sum_q e_q^2 f_q(x) D_{h/q}(z)}\right)$$

$$\mathcal{N}_q(x) = N_q x^{\alpha_q}(1-x)^{\beta_q}\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\beta_q^{\beta_q}} \qquad \mathcal{N}_{\bar{q}}(x) = N_{\bar{q}}$$

M. Anselmino et. al.arXiv: 1612.06413(2016)

FITTING METHODOLOGY

Inputs:

$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,y,z,p_{hT}) = \frac{[z^2\langle k_\perp^2\rangle + \langle p_\perp^2\rangle]\langle k_S^2\rangle^2}{[z^2\langle k_S^2\rangle + \langle p_\perp^2\rangle]\langle k_\perp^2\rangle^2} \exp\left[-\frac{p_{hT}^2\, z^2\left(\langle k_S^2\rangle - \langle k_\perp^2\rangle\right)}{\left(z^2\langle k_S^2\rangle + \langle p_\perp^2\rangle\right)\left(z^2\langle k_\perp^2\rangle + \langle p_\perp^2\rangle\right)}\right]$$

$$\times \frac{\sqrt{2e}\, z\, p_{hT}}{M_1} \frac{\sum_q \mathcal{N}_q e_q^2 f_q(x) D_{h/q}(z)}{\sum_q e_q^2 f_q(x) D_{h/q}(z)}$$

- Unpolarized PDFs : LHAPDF6 (CTEQ61)
- Fragmentation Functions:
  - Pi+: NNFF10_Pip_nlo
  - Pi- : NNFF10_Pim_nlo
  - Pi0: NNFF10_Pisum_nlo
  - K+: NNFF10_Kap_nlo
  - K- : NNFF10_Kam_nlo

V. Bertone et. al arXiv:1706.07049

Data Sets (on consideration):

- HERMES_p_2009 (from Luciano Pappalardo)
- COMPASS_d_2009 (from Bakur Parsamyan)
- COMPASS_p_2015 (from Bakur Parsamyan)
- HERMES_p_2020 (from Luciano Pappalardo)

Fit parameters (13):

$$M_1$$

$$N_u, \alpha_u, \beta_u, N_{\bar{u}}$$

$$N_d, \alpha_d, \beta_d, N_{\bar{d}}$$

$$N_s, \alpha_s, \beta_s, N_{\bar{s}}$$

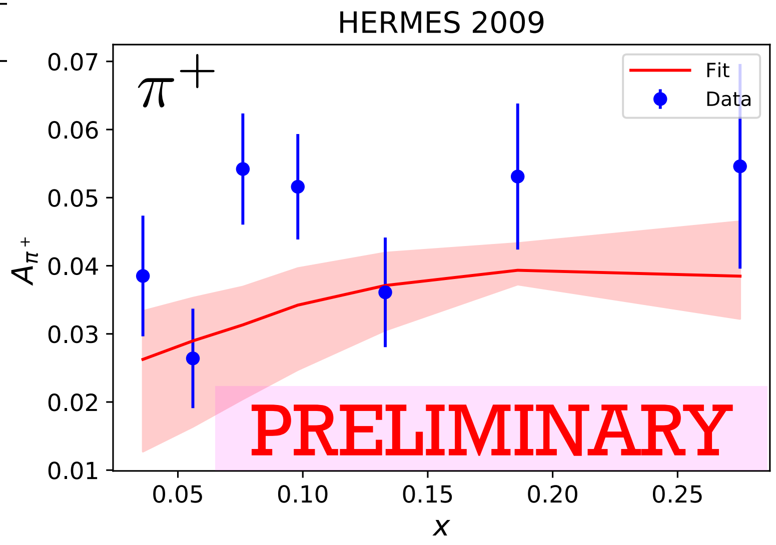
Fitting routines:

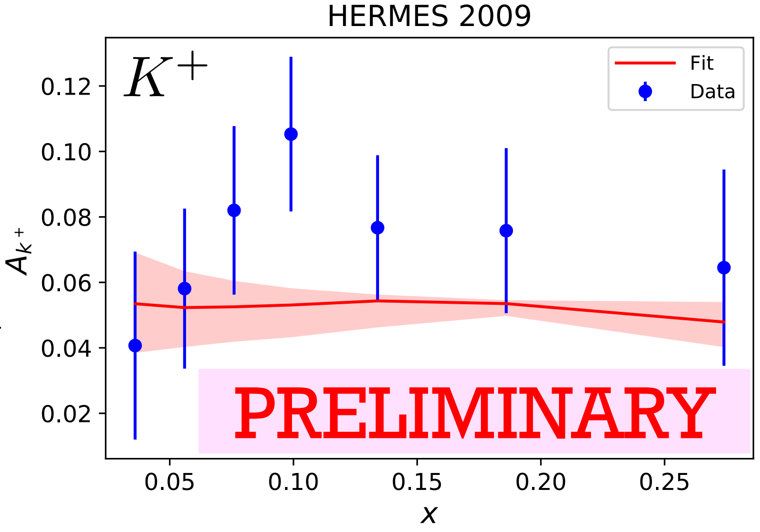
- "iminuit" (python supported version of MINUIT)
- Python scipy.oprimize.curve_fit
- Using a Neural Network approach

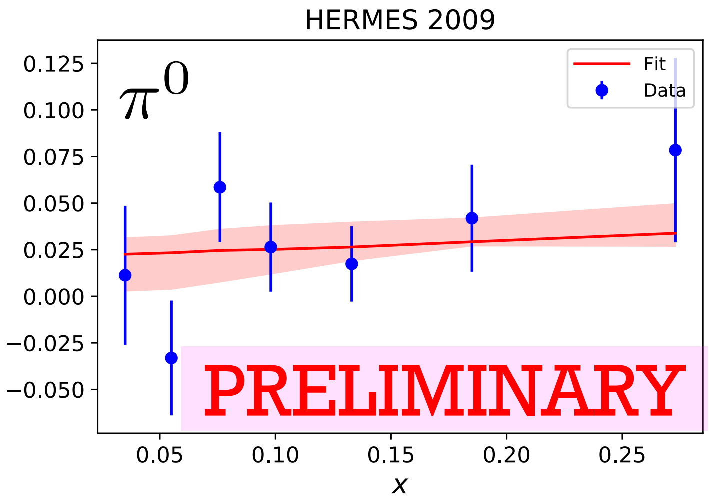
FITS TO HERMES(2009) [PRELIMINARY]

Hadron	Dependence	ndata	$\chi^2/ndata$
π^+	x	7	2.53
π^+	z	7	1.02
π^+	p_{hT}	7	5.23
π^-	x	7	1.94
π^-	z	7	2.45
π^-	p_{hT}	7	1.61
π^0	x	7	0.85
π^0	z	7	1.11
π^0	p_{hT}	7	2.00
K^+	x	7	1.22
K^+	z	7	2.97
K^+	p_{hT}	7	2.65
K^-	x	7	0.49
K^-	z	7	0.52
K^-	p_{hT}	7	0.96
Total		105	1.84

Parameter	Value
M_1	1.303 ± 0.010
N_u	0.169 ± 0.002
α_u	0.645 ± 0.125
β_u	3.122 ± 2.661
$N_{\bar{u}}$	0.007 ± 0.003
N_d	$- 0.434 \pm 0.005$
α_d	1.777 ± 0.909
β_d	7.788 ± 2.144
$N_{\bar{d}}$	$- 0.142 \pm 0.048$
N_s	0.563 ± 0.073
α_s	$(6.84 \pm 10.00) \times 10^{-5}$
β_s	$(5.987 \pm 8.77) \times 10^{-10}$
$N_{\bar{s}}$	$- 0.122 \pm 0.504$

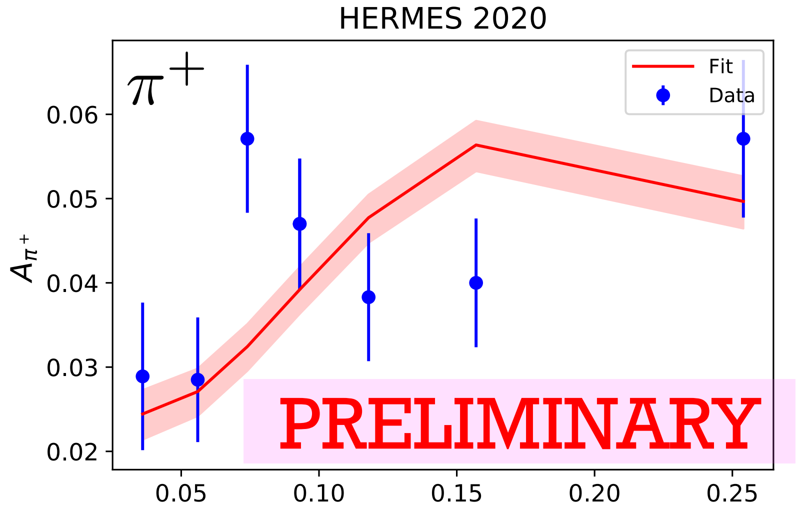


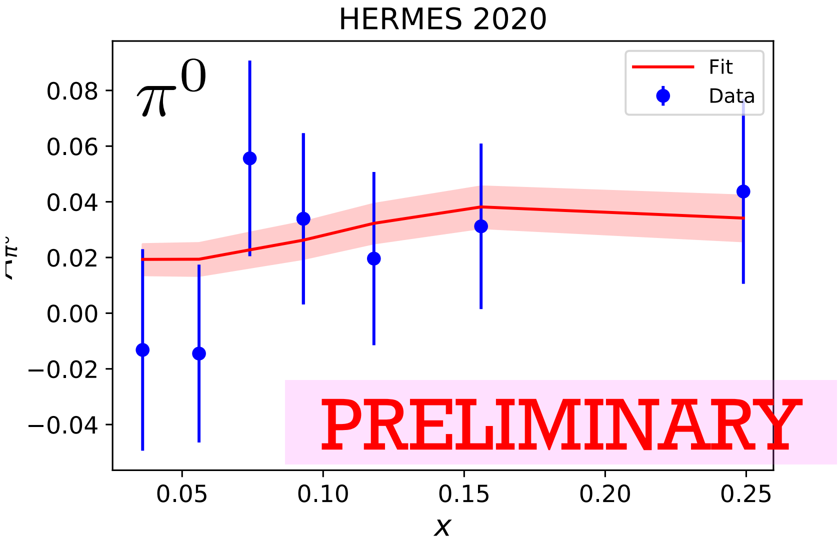




FITS TO HERMES(2020) [PRELIMINARY]

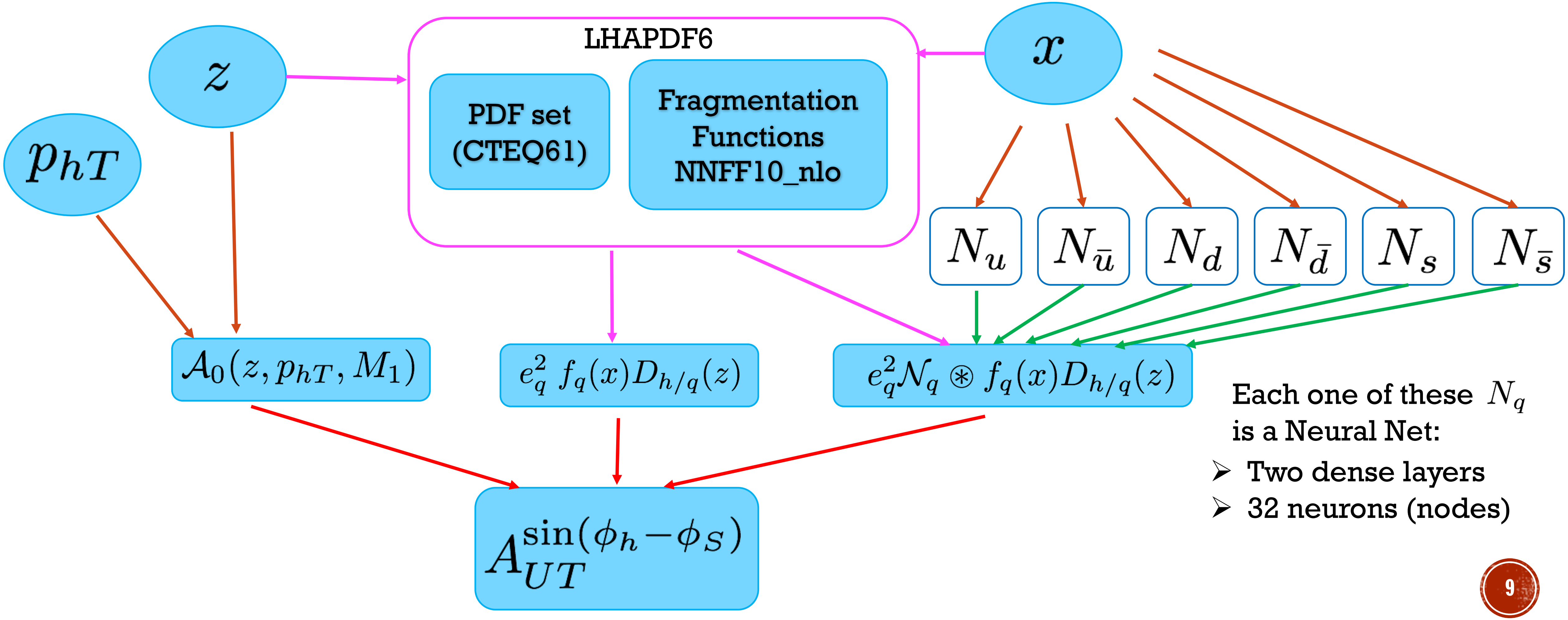
Hadron	Dependence	ndata	$\chi^2/ndata$
π^+	x	8	2.12
π^+	z	11	1.49
π^+	p_{hT}	8	1.14
π^-	x	8	1.81
π^-	z	11	1.16
π^-	p_{hT}	8	1.20
π^0	x	8	0.40
π^0	z	11	0.95
π^0	p_{hT}	8	0.50
K^+	x	8	0.48
K^+	z	11	6.31
K^+	p_{hT}	8	1.26
K^-	x	8	0.26
K^-	z	10	0.93
K^-	p_{hT}	8	0.79
Total		134	1.477





NEURAL NETWORK APPROACH

$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,y,z,p_{hT}) = \mathcal{A}_0(z,p_{hT},M_1)\left(\frac{\sum_q \mathcal{N}_q e_q^2 f_q(x) D_{h/q}(z)}{\sum_q e_q^2 f_q(x) D_{h/q}(z)}\right)$$

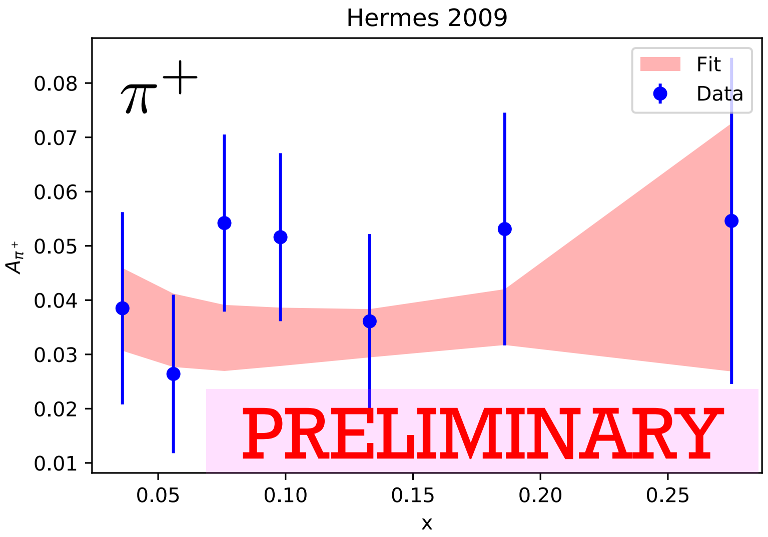


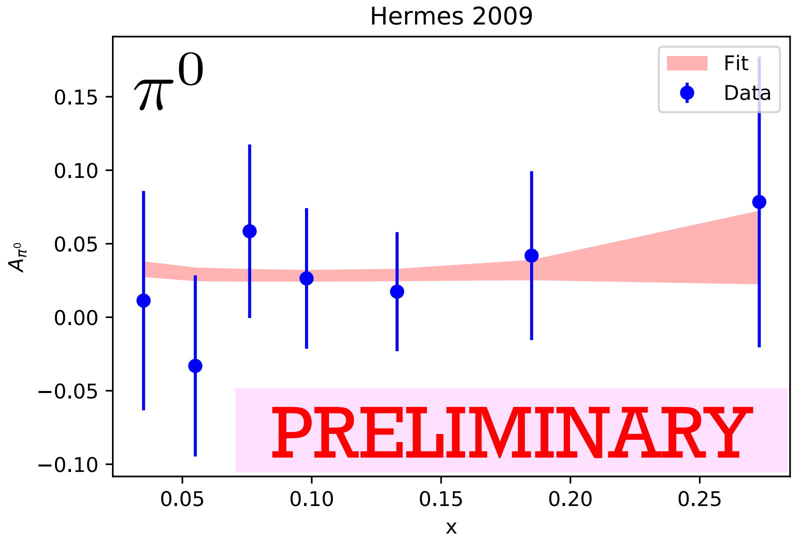
Each one of these N_q is a Neural Net:

- Two dense layers
- 32 neurons (nodes)

NN FITS TO HERMES(2009) [PRELIMINARY]

Hadron	Dependence	ndata	$\chi^2/ndata$
π^+	x	7	2.29
π^+	z	7	1.01
π^+	p_{hT}	7	3.40
π^-	x	7	3.13
π^-	z	7	0.52
π^-	p_{hT}	7	1.96
π^0	x	7	0.90
π^0	z	7	1.13
π^0	p_{hT}	7	1.61
K^+	x	7	1.78
K^+	z	7	3.69
K^+	p_{hT}	7	1.29
K^-	x	7	0.52
K^-	z	7	0.57
K^-	p_{hT}	7	0.73
Total		105	1.64

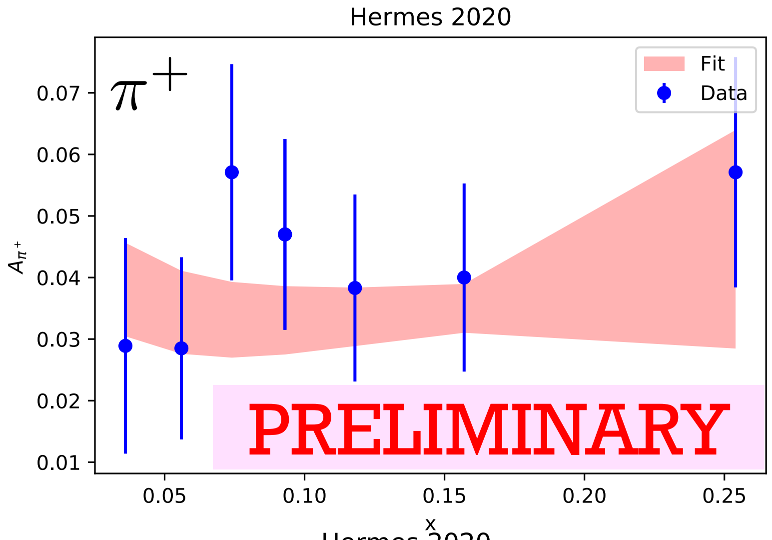


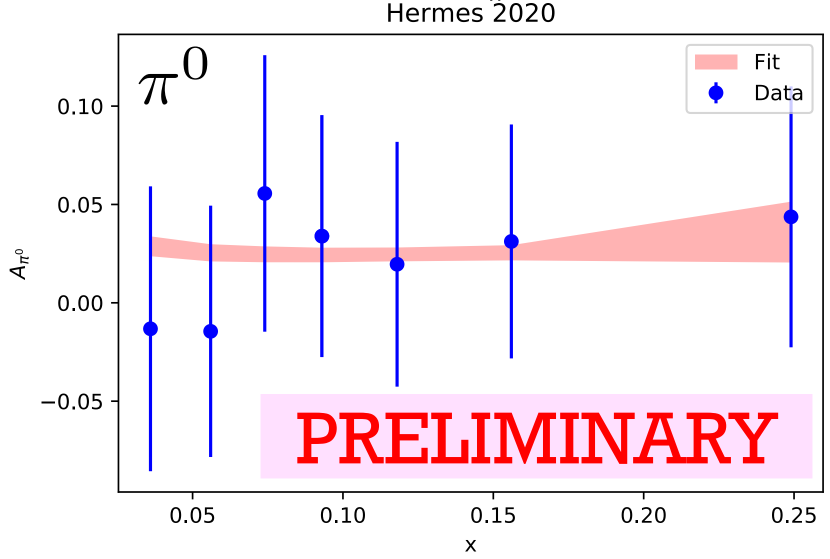


NN PREDICTIONS FOR HERMES(2020) [PRELIMINARY]

Trained using HERMES 2009 data set

Hadron	Dependence	ndata	$\chi^2/ndata$
π^+	x	8	2.23
π^+	z	11	1.63
π^+	p_{hT}	8	2.07
π^-	x	8	2.82
π^-	z	11	0.57
π^-	p_{hT}	8	1.44
π^0	x	8	0.50
π^0	z	11	0.97
π^0	p_{hT}	8	0.73
K^+	x	8	1.45
K^+	z	11	7.99
K^+	p_{hT}	8	2.45
K^-	x	8	0.54
K^-	z	10	1.11
K^-	p_{hT}	8	2.93
Total		134	2.02





SIVERS FUNCTION

From regular fit results

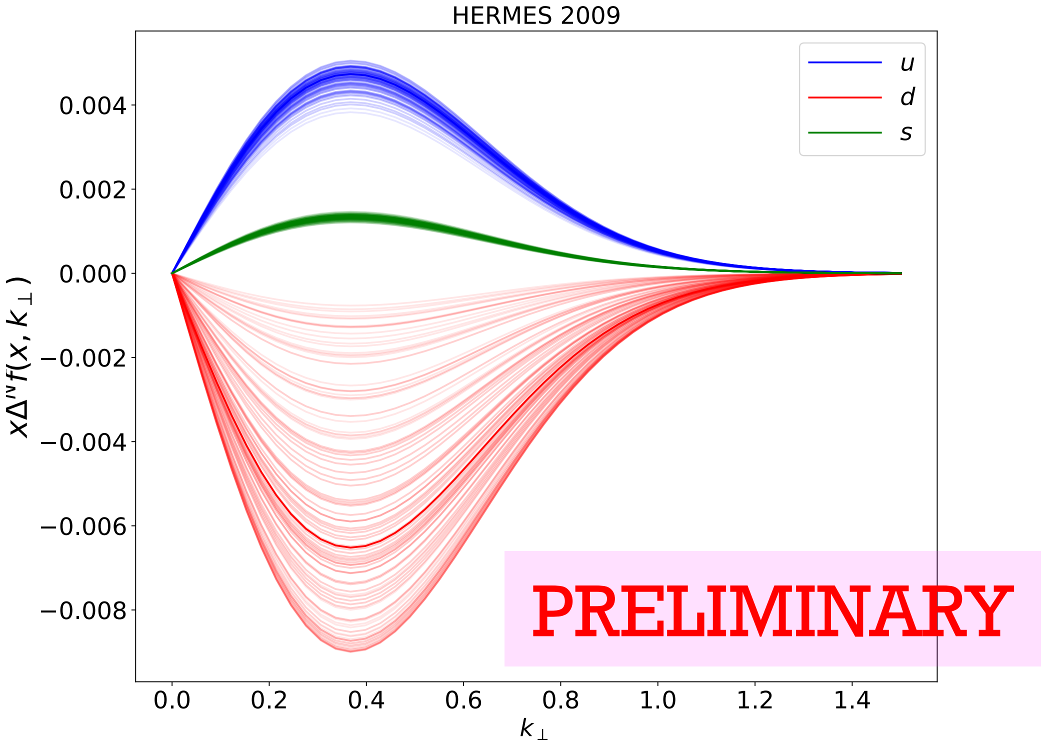
$$f_{q/p}(x,k_\perp) = f_q(x)\frac{1}{\pi\langle k_\perp^2\rangle}e^{-k_\perp^2/\langle k_\perp^2\rangle},$$

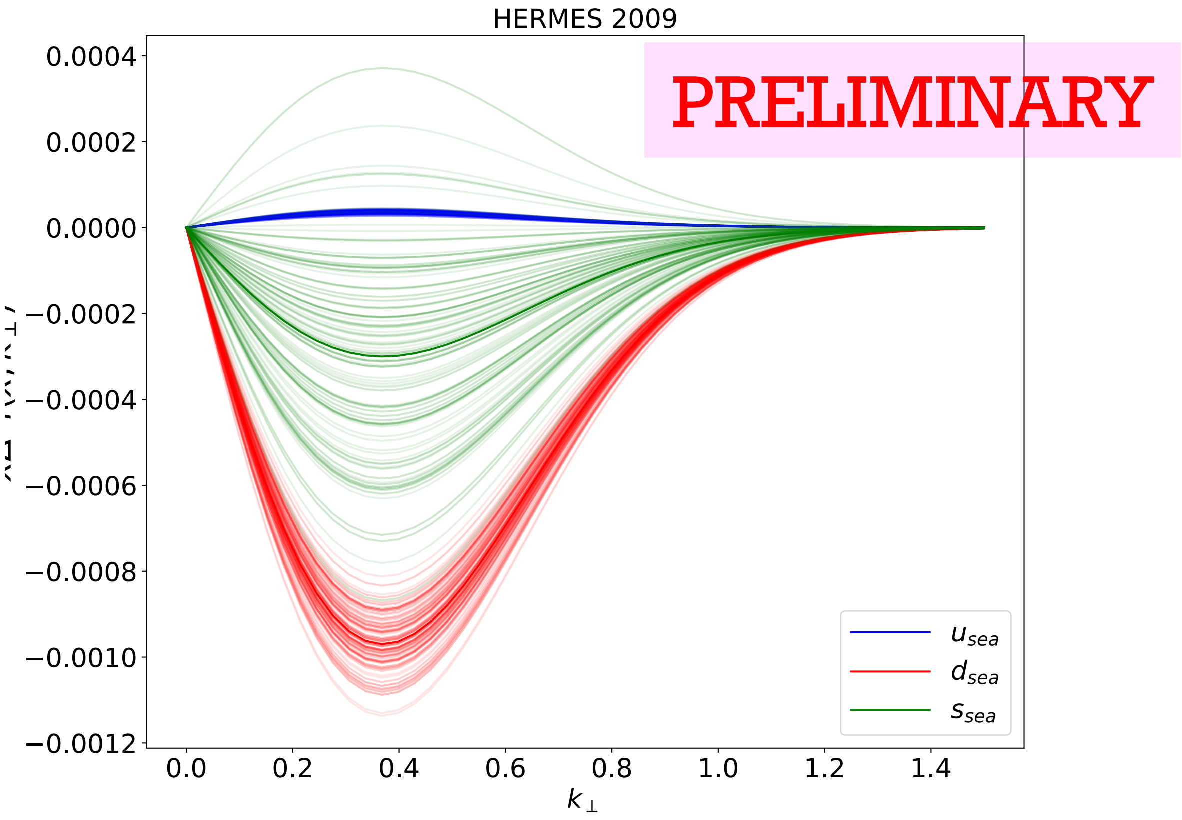
$$\Delta^N f_{q/p^\uparrow}(x,k_\perp) = 2\mathcal{N}_q(x)h(k_\perp)f_{q/p}(x,k_\perp),$$

$$\mathcal{N}_q(x) = N_q x^{\alpha_q}(1-x)^{\beta_q}\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\beta_q^{\beta_q}},$$

$$h(k_\perp) = \sqrt{2e}\frac{k_\perp}{M_1}e^{-k_\perp^2/M_1^2}$$

$$x\,\Delta^N f_{q/p^\uparrow}(x,k_\perp)$$



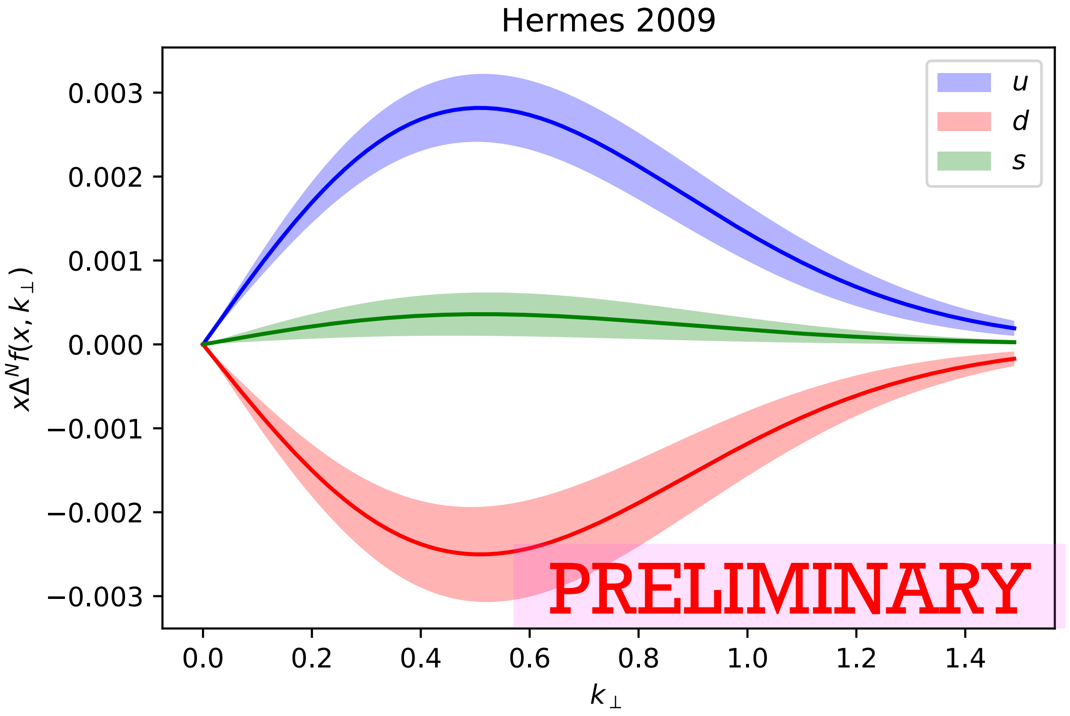


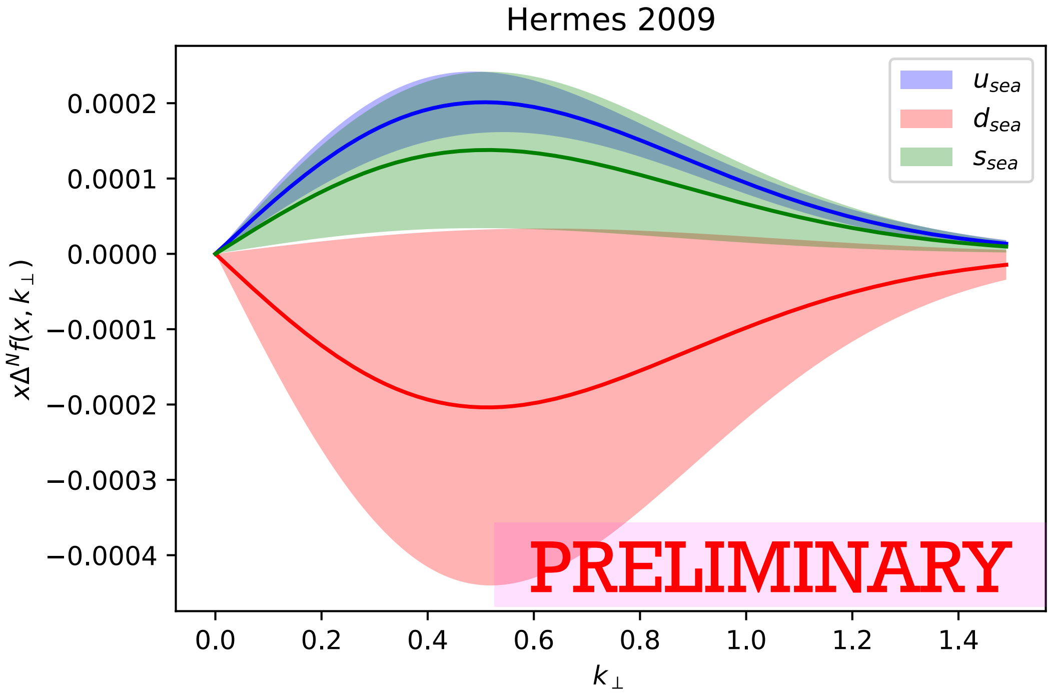
$x = 0.1$ $\quad$ $\langle p_\perp^2\rangle = 0.12 \pm 0.01\ \mathrm{GeV}^2$

$Q^2 = 2.4\ GeV^2/c^2$ $\quad$ $\langle k_\perp^2\rangle = 0.57 \pm 0.08\ \mathrm{GeV}^2$

SIVERS FUNCTION FROM THE NEURAL NETWORK

$$x\,\Delta^N f_{q/p\uparrow}(x, k_\perp)$$





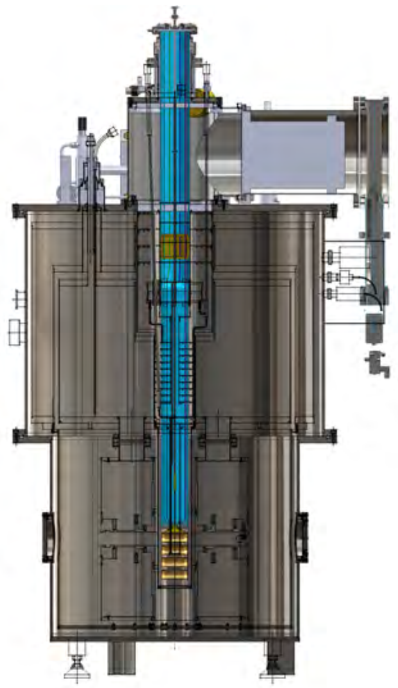
SPIN-QUEST (E1039) EXPERIMENT AT FERMILAB

SPIN QUEST

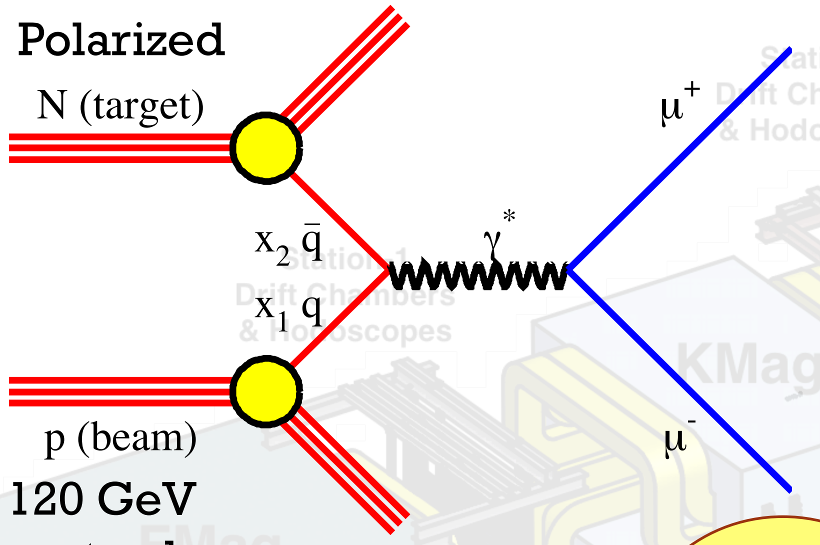
Fermilab

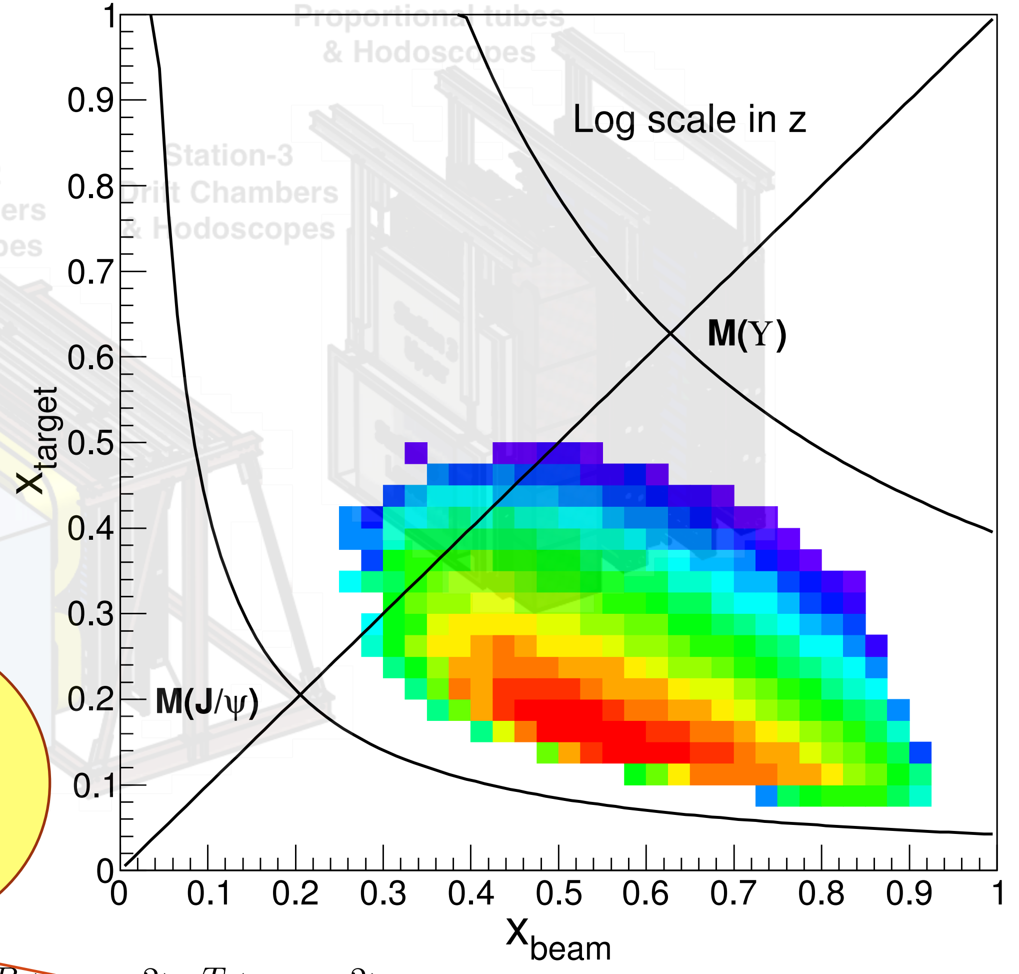
- First measurement of 'sea' quark Sivers function

$pp^{\uparrow}(d^{\uparrow}) \rightarrow \mu^{+}\mu^{-}X,\ 4 < M_{\mu\mu} < 9\ GeV$



LANL-UVA Polarized Target





Stay Tuned!

$$\frac{d\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_i e_i^2\left(q_i^B(x_1,Q^2)\bar{q}_i^T(x_2,Q^2) + \bar{q}_i^B(x_1,Q^2)q_i^T(x_2,Q^2)\right)$$

DISCUSSION & FUTURE WORK

- Fits to individual data sets can be implemented with the inclusion of s-quarks
- Performing global fits (on-going work)
- Hyperparameter search to optimize the Neural Network (NN)
- Exploring different NN architectures to handle different quark flavors
- Training with more LHAPDF sets
- Investigating towards Sivers Asymmetry extraction from Drell –Yan with/without considering the "sign-flip" of the Sivers Function.

THANK YOU!