TMD EXTRACTION WITH GLOBAL FITS & ANN

Ishara Fernando, Devin Seay, Nicholas Newton & Dustin Keller

University of Virginia (UVA) Spin Physics Group

@ APS-DNP 2021

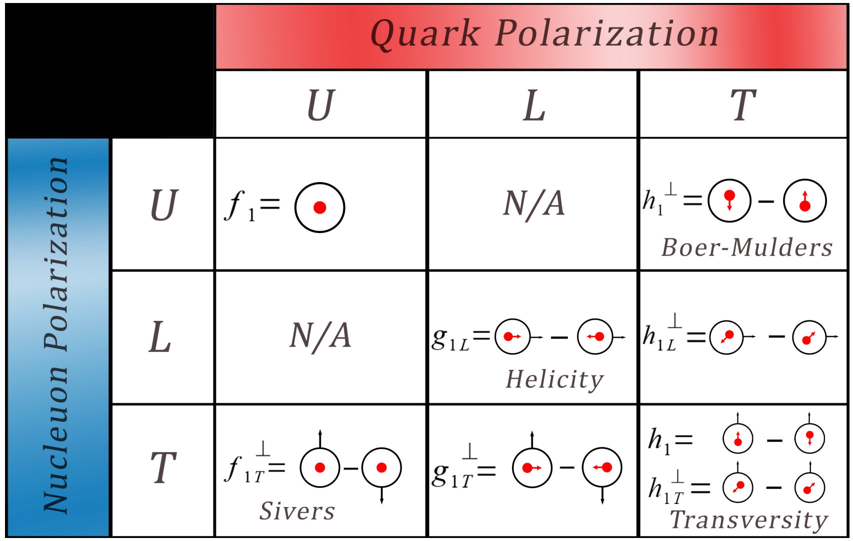
October 13, 2021

This work is supported by DOE contract DE-FG02-96ER40950

OUTLINE

- A brief Introduction to TMD PDFs
- Sivers Function
- Sivers asymmetry from SIDIS
- Sivers asymmetry from DY
- Global analyses of Sivers function
- Fitting methodology
- Neural Network approach with SIDIS
- Fit results to SIDIS
- Fit results to SIDIS & DY
- Discussion & Future work

TMD PDFS



$$\Phi(x,k_T;S) = \int \frac{d\xi^- d\xi_T}{(2\pi)^3} e^{ik.\xi} \langle P,S|\bar{\psi}(0)\, \mathcal{U}_{[0,\xi]}\, \psi(\xi)|P,S\rangle|_{\xi^+=0}$$

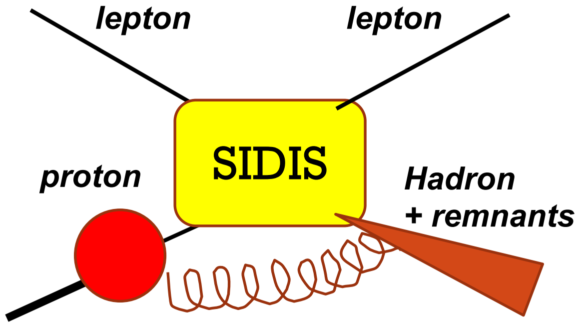
Quark correlator can be decomposed into 8 components
(6 T -even and 2 T -odd terms) at leading-twist

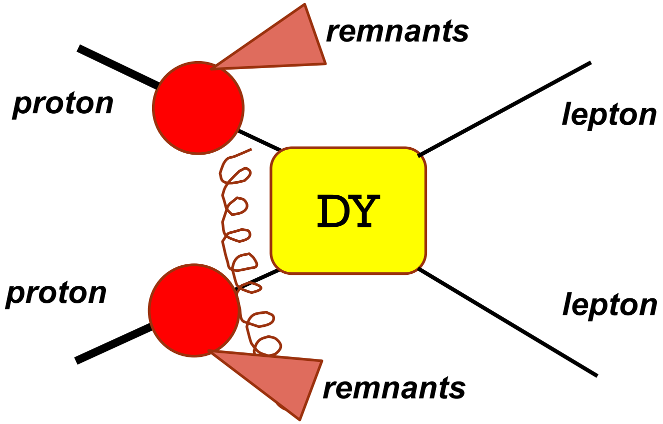
$$\Phi(x,k_T,P,S) = f_1(x,k_T^2)\frac{\not{P}}{2} + \frac{h_{1T}(x,k_T^2)}{4}\gamma_5[\not{S}_T,\not{P}] + \frac{S_L}{2} g_{1L}(x,k_T^2)\gamma_5\not{P} + \frac{k_T.S_T}{2M} g_{1T}(x,k_T^2)\gamma_5\not{P}$$
$$+ S_L h_{1L}^\perp(x,k_T^2)\gamma_5\frac{[\not{k}_T,\not{P}]}{4M} + \frac{k_T.S_T}{2M} h_{1T}^\perp(x,k_T^2)\gamma_5\frac{[\not{k}_T,\not{P}]}{4M}$$

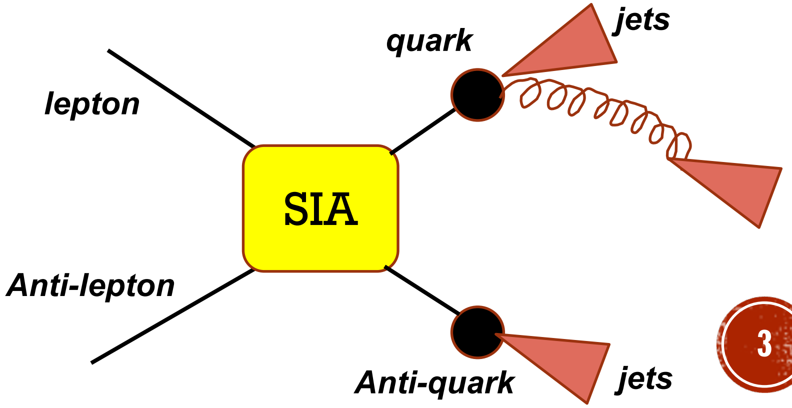
T-even

$$+ ih_1^\perp(x,k_T^2)\frac{[\not{k}_T,\not{P}]}{4M} - \frac{\epsilon_T^{k_T S_T}}{4M} f_{1T}^\perp(x,k_T^2)\not{P}$$

T-odd



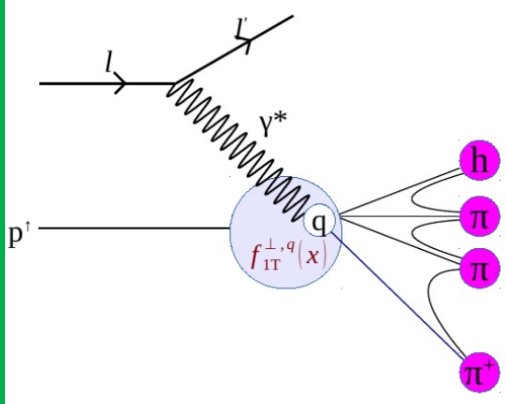




TMD PDFs

SIDIS

Polarized Semi-Inclusive DIS



$$\frac{d\sigma^{LO}_{SIDIS}}{dx\,dy\,dz\,dp_T^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]$$

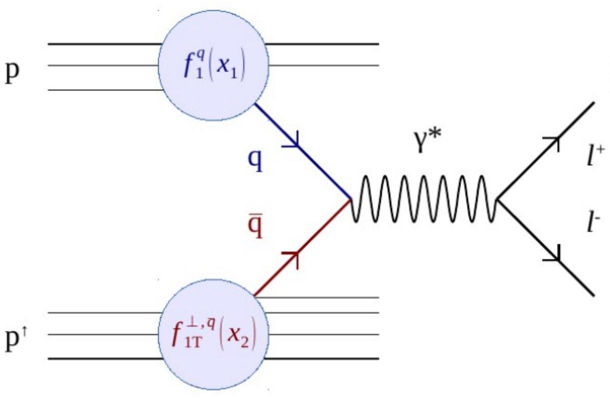
$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right) + S_T\left[\begin{array}{l}\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\ +\sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\ +\sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{array}\right]\right.$$

PDF ⊗ FF

$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$	BM	⊗ CF
$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	Sivers	⊗ FF
$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$	Transv	⊗ CF
$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretz	⊗ CF

DY

Polarized Drell-Yan



$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\left\{1+\cos^2\theta+\sin^2\theta\cos 2\varphi_{CS}A_U^{\cos 2\varphi_{CS}} + S_T\left[\begin{array}{l}\left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S}\\ +\sin^2\theta\left(\begin{array}{l}\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}\\ +\sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)}\end{array}\right)\end{array}\right]\right\}$$

beam target

PDF ⊗ PDF

BM ⊗	BM	$A_T^{\cos 2\varphi_{CS}} \propto h_1^{\perp q} \otimes h_1^{\perp q}$
f_1 ⊗	Sivers	$A_T^{\sin\varphi_S} \propto f_1^{q} \otimes f_{1T}^{\perp q}$
BM ⊗	Transv	$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_1^{\perp q} \otimes h_{1T}^{\perp q}$
BM ⊗	Pretz	$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_1^{\perp q} \otimes h_1^{q}$

$$h_1^{\perp q}\Big|_{SIDIS} = -h_1^{\perp q}\Big|_{DY}$$

$$f_{1T}^{\perp q}\Big|_{SIDIS} = -f_{1T}^{\perp q}\Big|_{DY}$$

$$h_1^{q}\Big|_{SIDIS} = h_1^{q}\Big|_{DY}$$

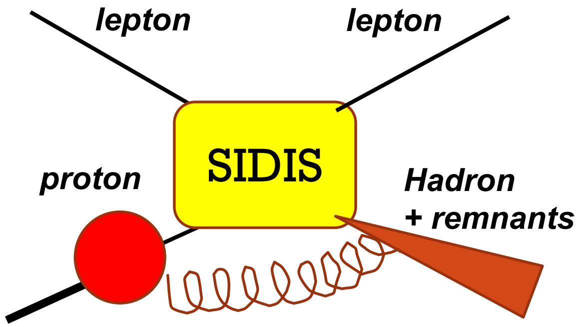
$$h_{1T}^{\perp q}\Big|_{SIDIS} = h_{1T}^{\perp q}\Big|_{DY}$$

* For these two processes TMD factorization is proven

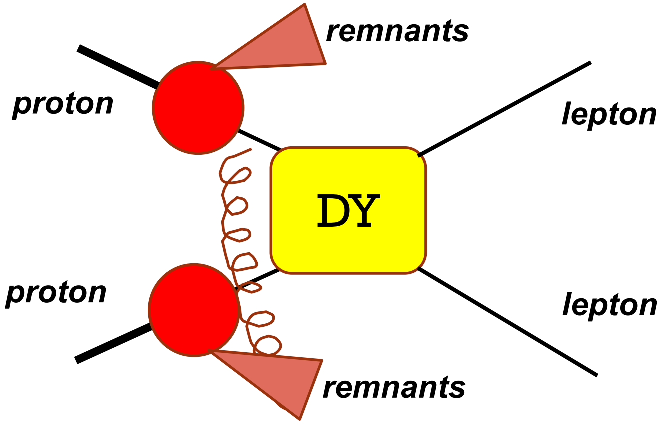
SIVERS FUNCTION

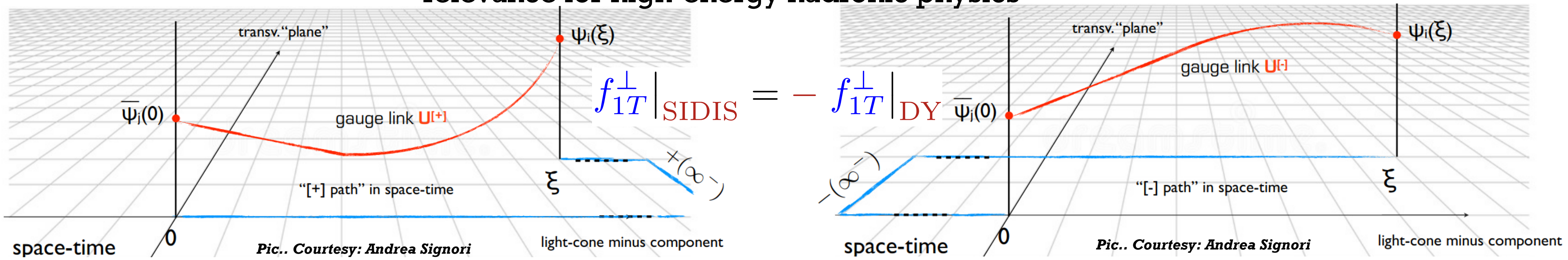
$$f_{q/p^{\uparrow}}(x,\mathbf{k_T}) = f_{q/p}(x,\mathbf{k_T}) + f_{1T}^{\perp}(x,\mathbf{k_T})\mathbf{S}.(\hat{\mathbf{P}} \times \hat{\mathbf{k_T}})$$

The Sivers function describes the correlation between the momentum direction of the struck quark and the spin of its parent nucleon.



- The gauge-invariant definition of the Sivers function predicts the opposite sign for the Sivers function in SIDIS compared to processes with color charges in the initial state and a colorless final state in Drell-Yan, $J/\psi, W^{\pm}, Z$
- This inclusion of the gauge link has profound consequences on factorization proofs and on the concept of universality, which are of fundamental relevance for high-energy hadronic physics



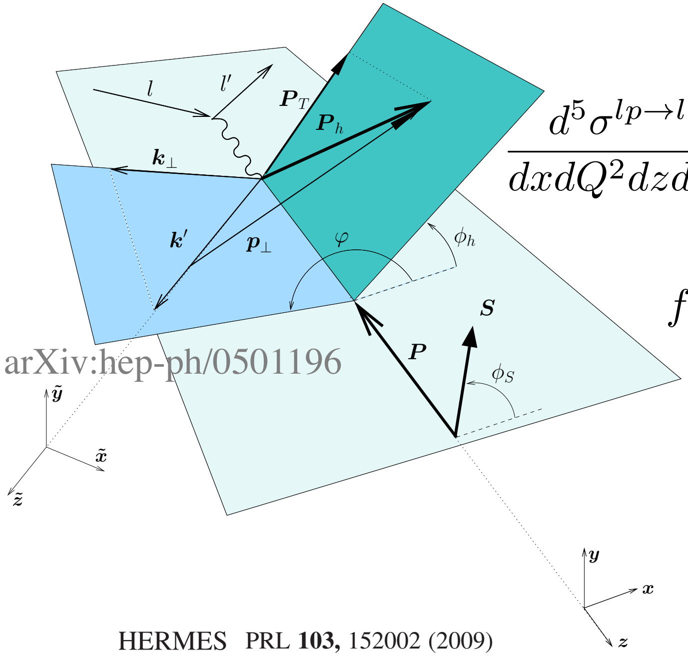


$$f_{1T}^{\perp}\big|_{\mathrm{SIDIS}} = - f_{1T}^{\perp}\big|_{\mathrm{DY}}$$

Pic.. Courtesy: Andrea Signori

Pic.. Courtesy: Andrea Signori

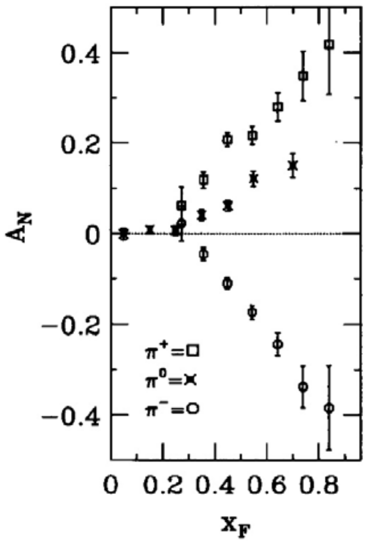
SIVERS ASYMMETRY FROM SIDIS



arXiv:hep-ph/0501196

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

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

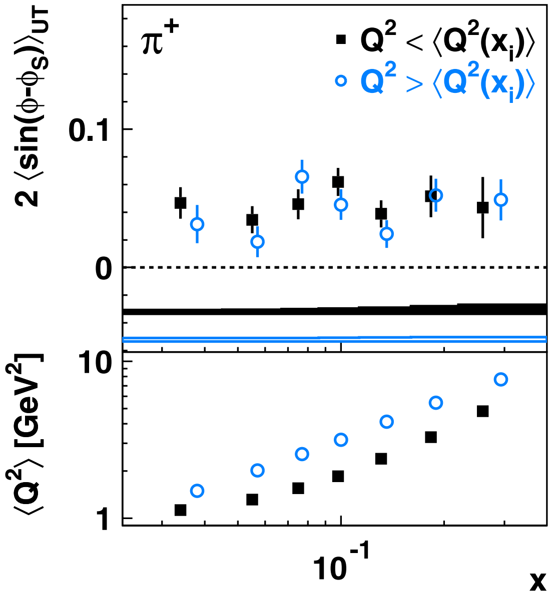


Asymmetry in $pp^\uparrow \to \pi X$ pion production from E704

Single Spin Asymmetry (Sivers Asymmetry)

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

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



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

$$\langle p_\perp^2\rangle = 0.12 \pm 0.01 \text{ GeV}^2$$
$$\langle k_\perp^2\rangle = 0.57 \pm 0.08 \text{ GeV}^2$$

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

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

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

SIVERS ASYMMETRY FROM DRELL-YAN

$$f_{q/p}(x,k_\perp) = f_q(x)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle} \qquad \langle k_\perp^2\rangle = 0.25\ \mathrm{GeV}^2$$

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

$$\begin{aligned}\Delta^N f_{q/p^\uparrow}(x,k_\perp) &= 2\,\mathcal{N}_q(x)\,h(k_\perp)\,f_{q/p}(x,k_\perp)\\ &\equiv \Delta^N f_{q/p^\uparrow}(x)\,h(k_\perp)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle}\end{aligned}$$

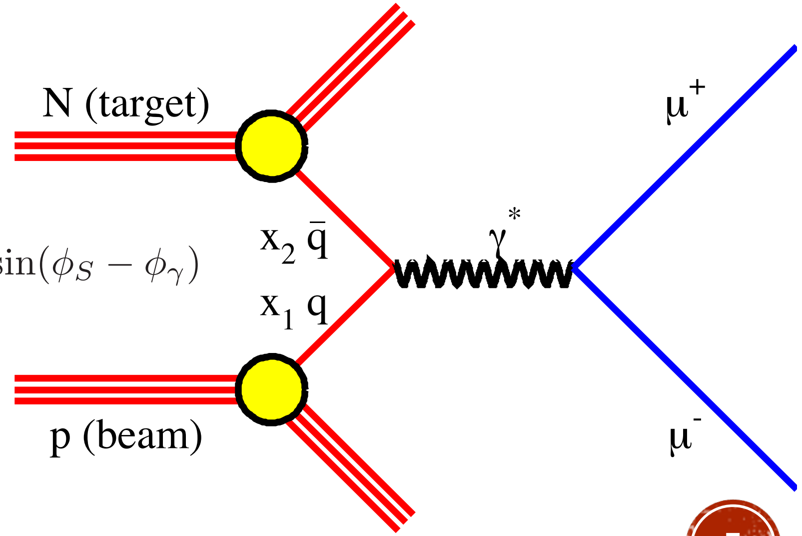
$$h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M_1}\,e^{-k_\perp^2/M_1^2}\,.$$

$$\frac{1}{\langle k_S^2\rangle} = \frac{1}{M_1^2} + \frac{1}{\langle k_{\perp 1}^2\rangle}$$

$$A_N^{\sin(\phi_\gamma-\phi_S)}(x_F,M,q_T) = \frac{\int d\phi_\gamma\,[N(x_F,M,q_T,\phi_\gamma)]\,\sin(\phi_\gamma-\phi_S)}{\int d\phi_\gamma\,[D(x_F,M,q_T)]}$$

$$\begin{aligned}N(x_F,M,q_T,\phi_\gamma) &\equiv \frac{d^4\sigma^\uparrow}{dx_F\,dM^2\,d^2\boldsymbol{q}_T} - \frac{d^4\sigma^\downarrow}{dx_F\,dM^2\,d^2\boldsymbol{q}_T}\\ &= \frac{4\,\pi\,\alpha^2}{9\,M^2\,s}\sum_q\frac{e_q^2}{x_1+x_2}\,\Delta^N f_{q/A^\uparrow}(x_1)\,f_{\bar q/B}(x_2)\,\sqrt{2e}\,\frac{q_T}{M_1}\,\frac{\langle k_S^2\rangle^2\,\exp\left[-q_T^2/\left(\langle k_S^2\rangle+\langle k_{\perp 2}^2\rangle\right)\right]}{\pi\left[\langle k_S^2\rangle+\langle k_{\perp 2}^2\rangle\right]^2\langle k_{\perp 2}^2\rangle}\,\sin(\phi_S-\phi_\gamma)\end{aligned}$$

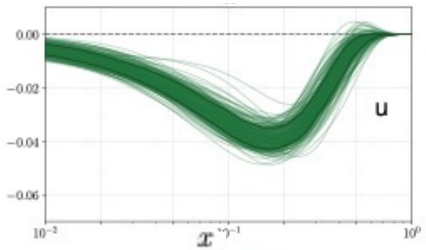
$$\begin{aligned}D(x_F,M,q_T) &\equiv \frac{1}{2}\left[\frac{d^4\sigma^\uparrow}{dx_F\,dM^2\,d^2\boldsymbol{q}_T} + \frac{d^4\sigma^\downarrow}{dx_F\,dM^2\,d^2\boldsymbol{q}_T}\right] = \frac{d^4\sigma^{unp}}{dx_F\,dM^2\,d^2\boldsymbol{q}_T}\\ &= \frac{4\,\pi\,\alpha^2}{9\,M^2\,s}\sum_q\frac{e_q^2}{x_1+x_2}f_{q/A}(x_1)\,f_{\bar q/B}(x_2)\,\frac{\exp\left[-q_T^2/\left(\langle k_{\perp 1}^2\rangle+\langle k_{\perp 2}^2\rangle\right)\right]}{\pi\left[\langle k_{\perp 1}^2\rangle+\langle k_{\perp 2}^2\rangle\right]}\end{aligned}$$

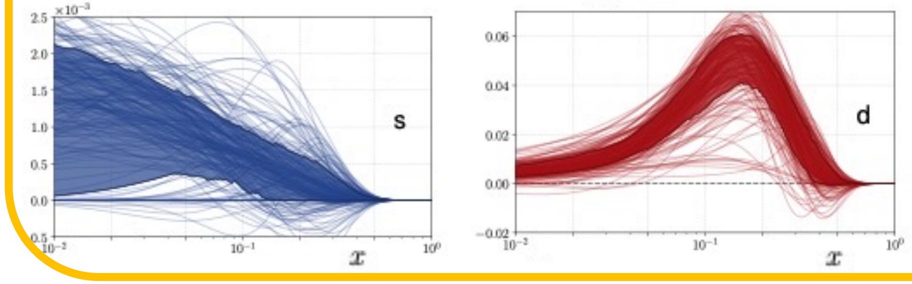


M. Anselmino et. al.arXiv: 0901.3078 (2009)

GLOBAL ANALYSES OF SIVERS FUNCTION

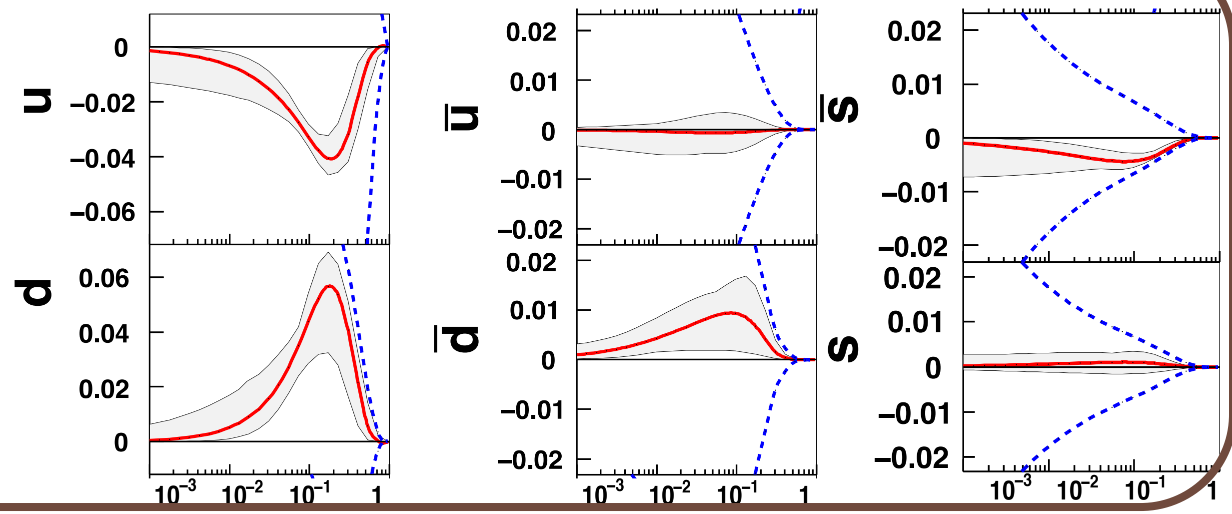
A. Bacchetta, F. Delcarro,
C. Pasiano, M. Radici
arXiv 2004.14278
(2020)



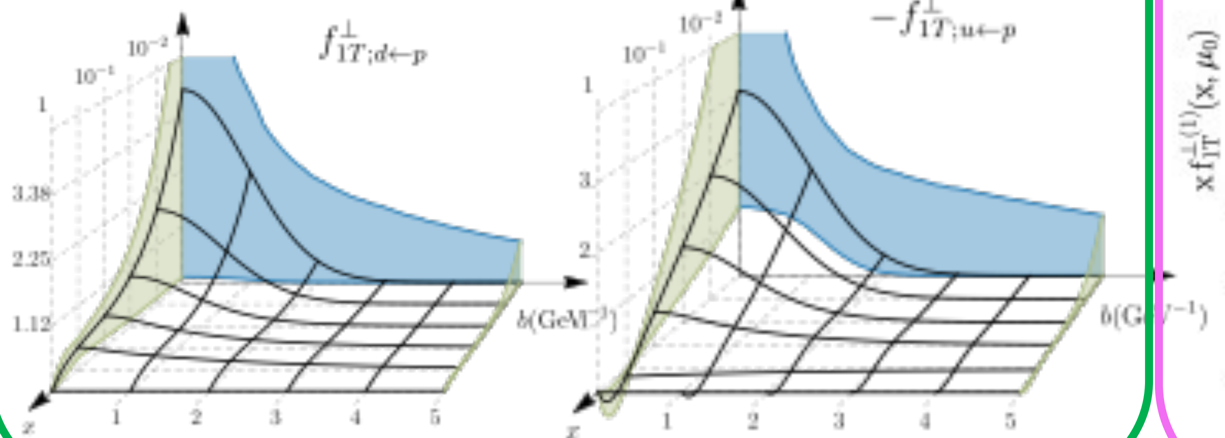


HERMES (2020)
COMPASS (2009)
COMPASS (2015)
JLab (2011)

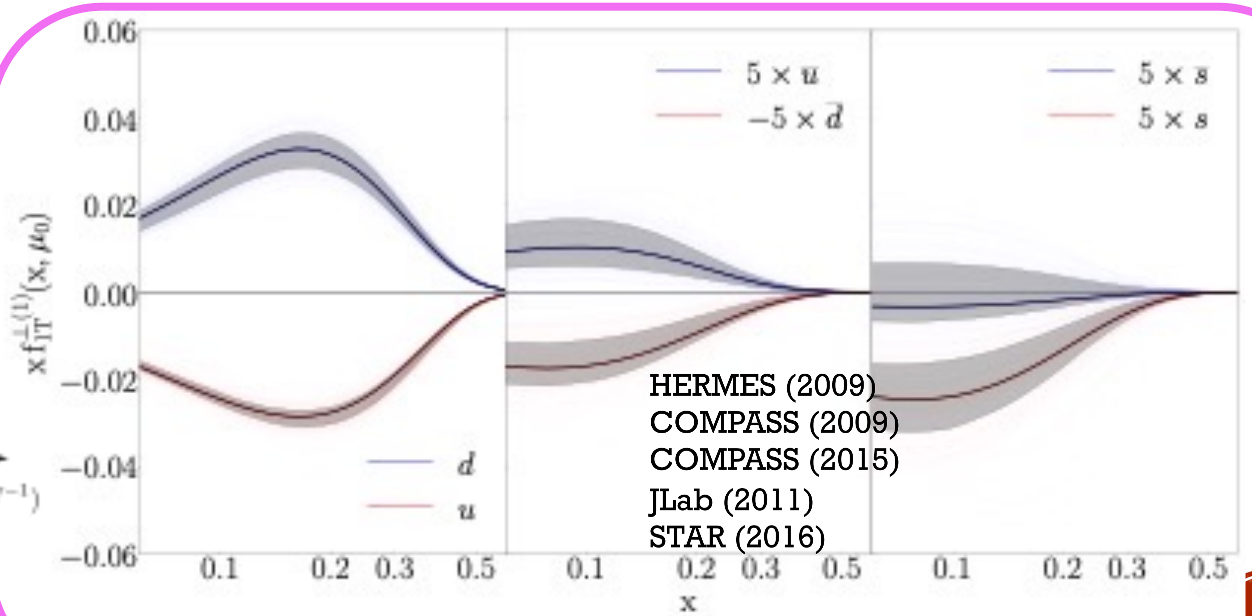
M. Anselmino, M. Boglion, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin_PRD_79_54010_(2009)



HERMES (2020), COMPASS (2009),COMPASS (2015)
JLab (2011), STAR (2016),COMPASS DY (2017)



M. Bury, A. Prokudin , A. Vladimirov,, JHEP_05_151 (2021)



HERMES (2009)
COMPASS (2009)
COMPASS (2015)
JLab (2011)
STAR (2016)

M. Echevarria, Z. Kang, J. Terry_JHEP_01_126_(2021)

FITTING METHODOLOGY

Inputs:

- 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

Fit parameters (13):

$$M_1$$

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

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

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

Data Sets (on consideration):

<u>SIDIS</u>

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

<u>DY</u>

- COMPASS_2017 (from Bakur Parsamyan)

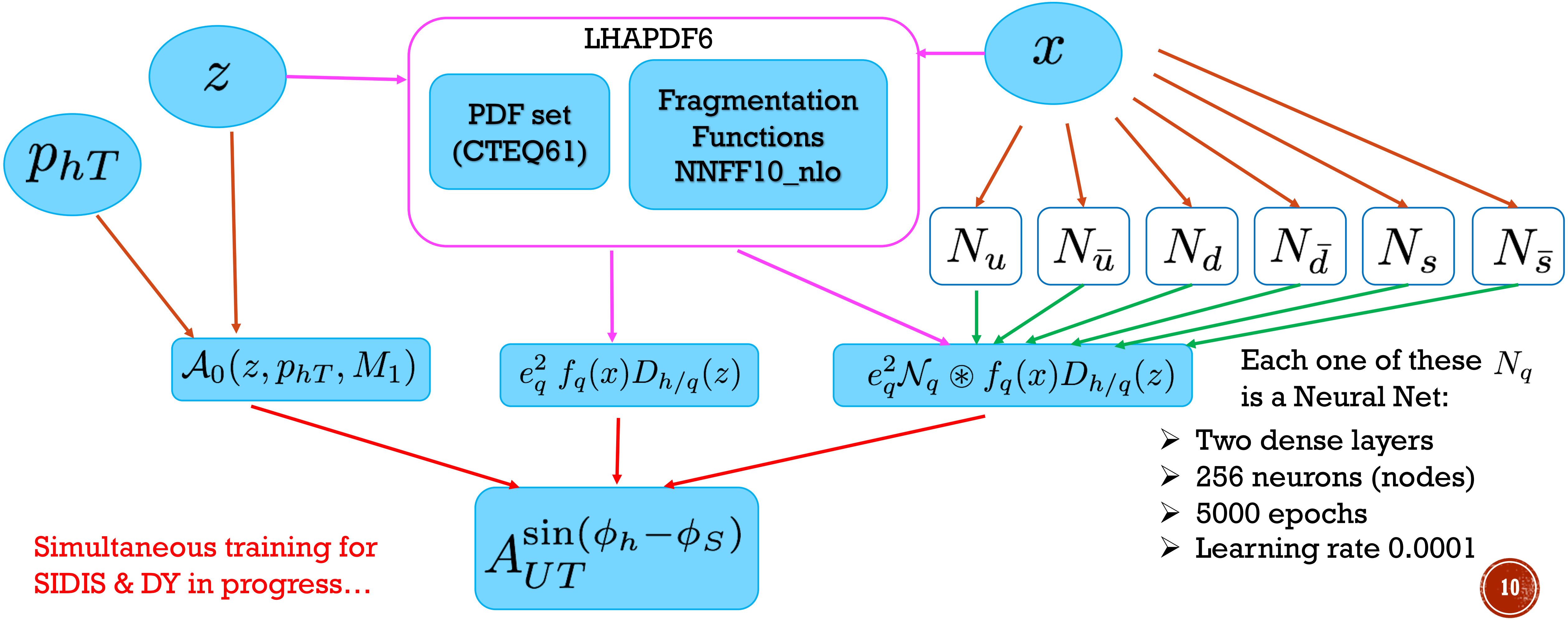
Fitting routines:

- "iminuit" (python supported version of MINUIT)
- Using a Neural Network approach

NEURAL NETWORK APPROACH WITH SIDIS DATA

Motivation for ANN

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



Each one of these N_q is a Neural Net:

- Two dense layers
- 256 neurons (nodes)
- 5000 epochs
- Learning rate 0.0001

Simultaneous training for SIDIS & DY in progress…

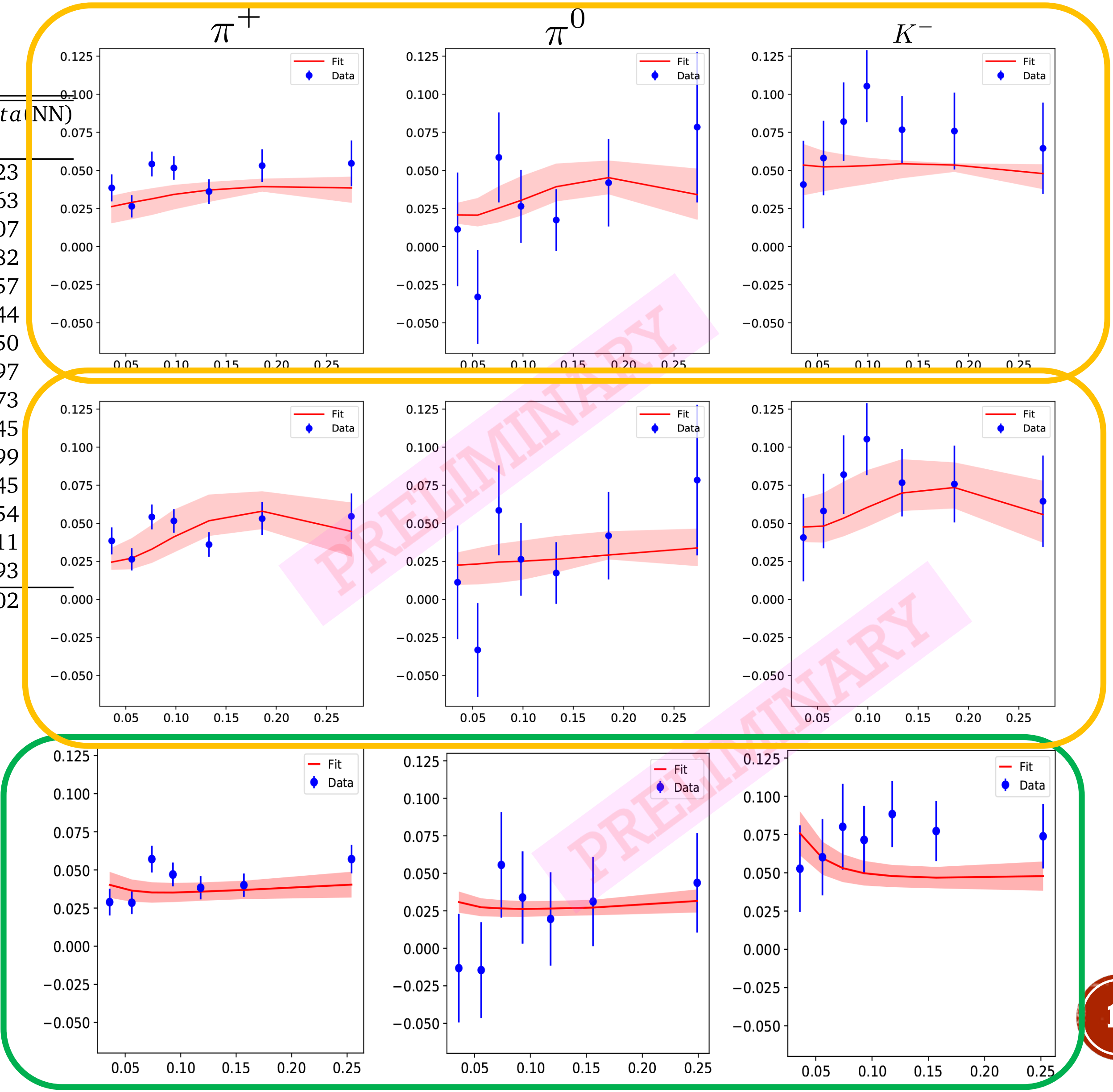
FITS TO SIDIS DATA : INITIAL ATTEMPTS

Individual fits

Hadron	Dependence	ndata (HERMES2009)	$\chi^2/ndata$ (HERMES2009)	$\chi^2/ndata$(NN) (HERMES2009)	ndata (HERMES2020)	$\chi^2/ndata$ (HERMES2020)	$\chi^2/ndata$(NN) (HERMES2020)
π^+	x	7	2.53	2.29	8	2.12	2.23
π^+	z	7	1.02	1.01	11	1.49	1.63
π^+	p_{hT}	7	5.23	3.40	8	1.14	2.07
π^-	x	7	1.94	3.13	8	1.81	2.82
π^-	z	7	2.45	0.52	11	1.16	0.57
π^-	p_{hT}	7	1.61	1.96	8	1.20	1.44
π^0	x	7	0.85	0.90	8	0.40	0.50
π^0	z	7	1.11	1.13	11	0.95	0.97
π^0	p_{hT}	7	2.00	1.61	8	0.50	0.73
K^+	x	7	1.22	1.78	8	0.48	1.45
K^+	z	7	2.97	3.69	11	6.31	7.99
K^+	p_{hT}	7	2.65	1.29	8	1.26	2.45
K^-	x	7	0.49	0.52	8	0.26	0.54
K^-	z	7	0.52	0.57	10	0.93	1.11
K^-	p_{hT}	7	0.96	0.73	8	0.79	2.93
Total		105	1.84	1.64	134	1.477	2.02

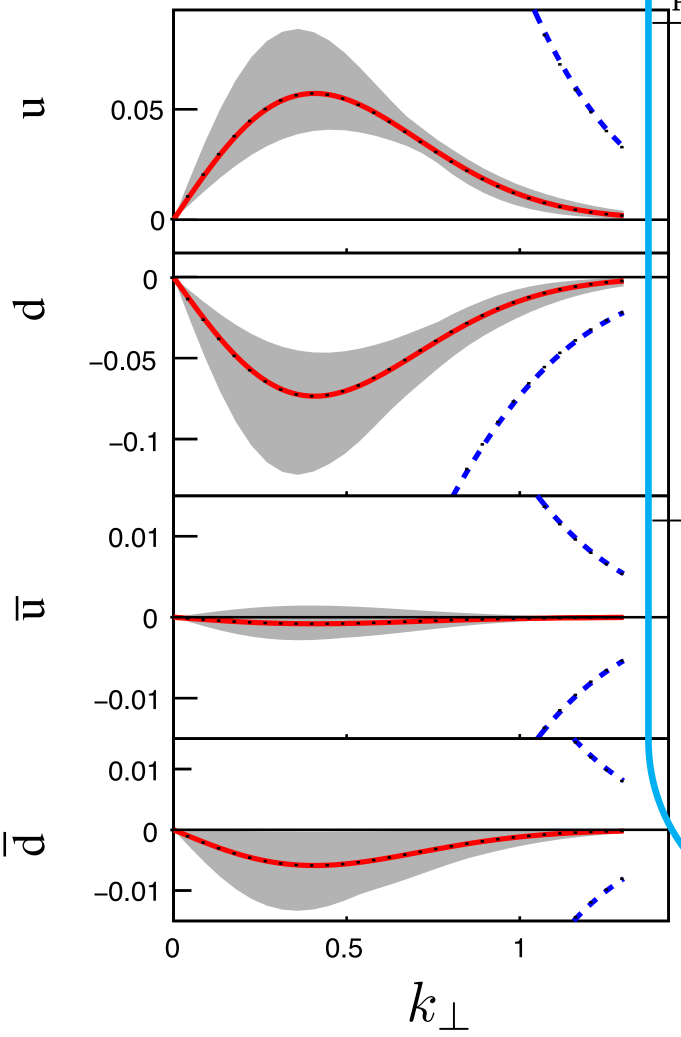
Parameter	HERMES 2009	HERMES2020
M_1	1.303 ± 0.010	7.590 ± 0.008
N_u	0.169 ± 0.002	0.960 ± 0.084
α_u	0.645 ± 0.125	2.291 ± 0.200
β_u	3.122 ± 2.661	9.826 ± 1.556
$N_{\bar{u}}$	0.007 ± 0.003	0.205 ± 0.02
N_d	- 0.434 ± 0.005	- 4.713 ± 0.004
. α_d	1.777 ± 0.909	0.482 ± 0.866
β_d	7.788 ± 2.144	(5.675 ± 6.45) $\times 10^{-6}$
$N_{\bar{d}}$	- 0.142 ± 0.048	1.490 ± 0.05
N_s	0.563 ± 0.073	4.528 ± 0.073
α_s	(6.84 ± 10.00) $\times 10^{-5}$	(1.745 ± 9.20) $\times 10^{-5}$
β_s	(5.987 ± 8.77) $\times 10^{-10}$	(6.082 ± 9.55) $\times 10^{-10}$
$N_{\bar{s}}$	- 0.122 ± 0.504	8.692 ± 0.46

Projected Asymmetries For HERMES 2020 Trained based on HERMES 2009



GLOBAL FIT TO SIDIS DATA

HERMES2009, COMPASS2009, COMPASS2015

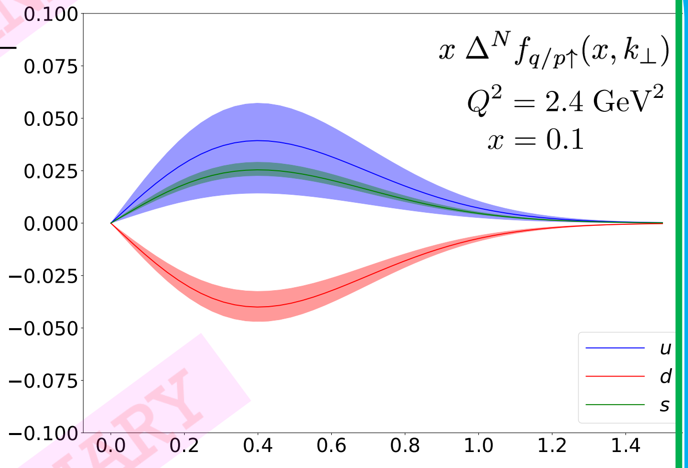


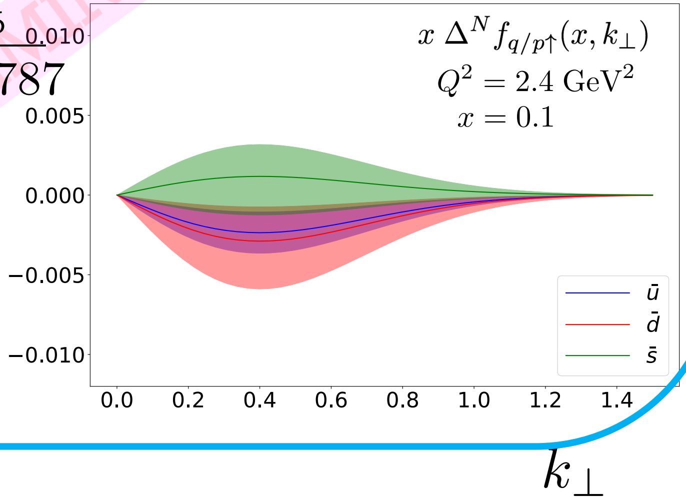
M. Anselmino et. al. arXiv: 1612.06413(2016)

HERMES2009, HERMES2020
COMPASS2009, COMPASS2015

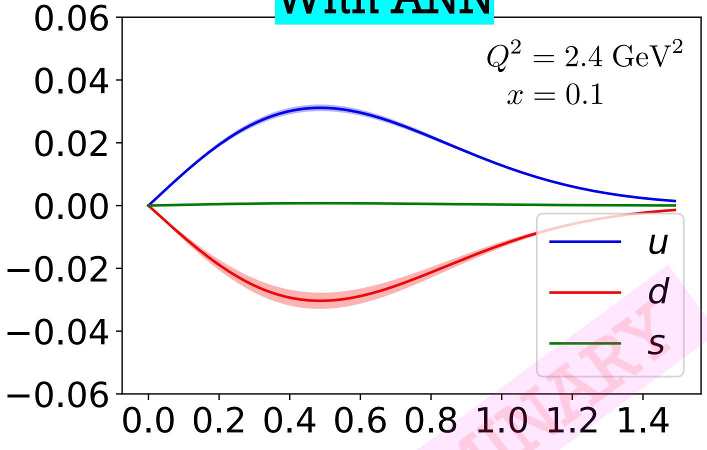
Parameter	Value
M_1	5.35 ± 0.16
N_u	0.62 ± 0.12
α_u	2.537 ± 0.018
β_u	13.82 ± 0.14
$N_{\bar{u}}$	-0.189 ± 0.035
N_d	-1.15 ± 0.05
. α_d	2.2 ± 0.05
β_d	9.12 ± 0.33
$N_{\bar{d}}$	-0.16 ± 0.06
N_s	10.09 ± 0.18
α_s	0.497 ± 0.019
β_s	0.066 ± 0.004
$N_{\bar{s}}$	0.18 ± 0.16

$\chi^2/\mathrm{NDF} = 1.787$

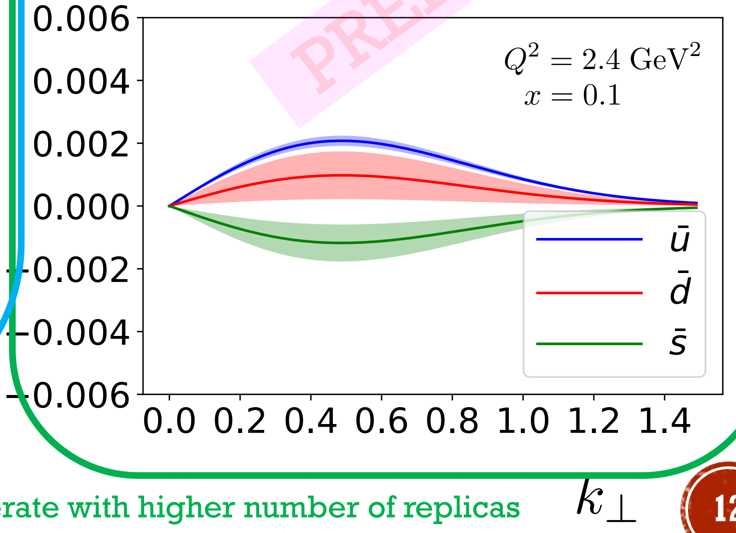




HERMES2009, HERMES2020
COMPASS2009, COMPASS2015
With ANN



NN Trained 90% of SIDIS Loss ~1.82



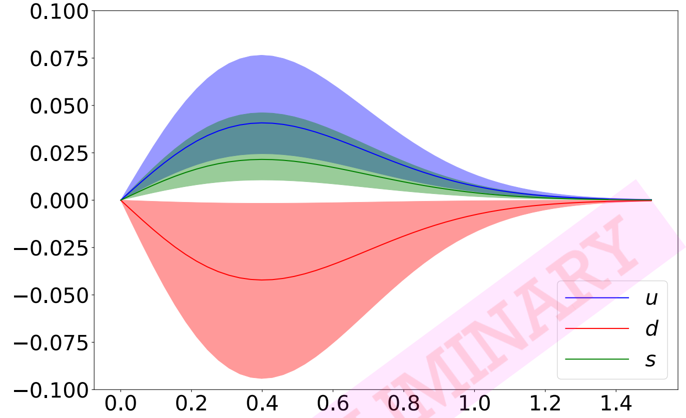
ANN: with few replicas→ need to generate with higher number of replicas

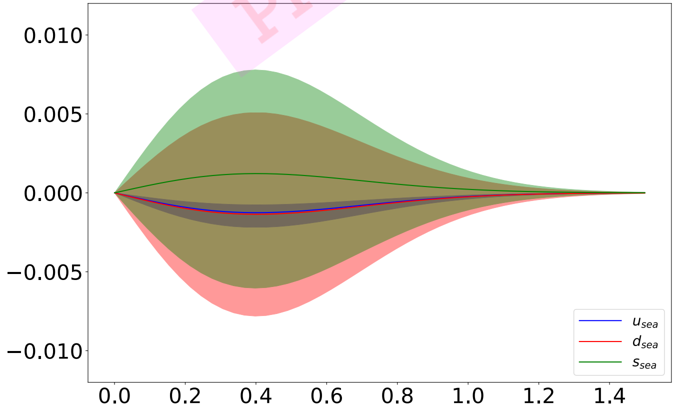
PRELIMINARY

GLOBAL FIT TO SIDIS & DY DATA

PRELIMINARY

With sign change



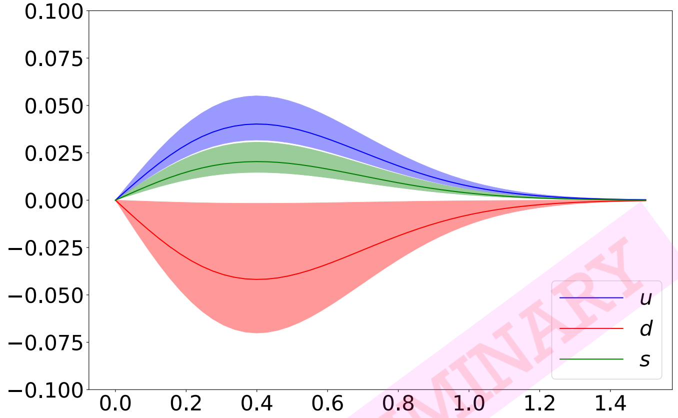


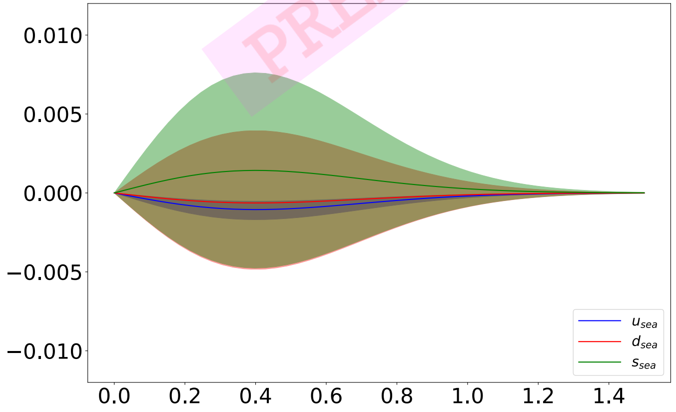
Parameter	sign-flip	no-sign-flip
M_1	5.7 ± 0.8	6.1 ± 0.5
N_u	0.69 ± 0.08	0.72 ± 0.05
α_u	2.74 ± 0.09	2.71 ± 0.05
β_u	15.1 ± 0.6	15.05 ± 0.30
$N_{\bar{u}}$	-0.107 ± 0.017	-0.096 ± 0.018
N_d	-1.34 ± 0.15	-1.30 ± 0.11
. α_d	1.6 ± 0.4	1.36 ± 0.31
β_d	5.4 ± 2.5	4.7 ± 1.8
$N_{\bar{d}}$	-0.08 ± 0.13	-0.04 ± 0.12
N_s	11.2 ± 1.4	12.0 ± 0.9
α_s	0.85 ± 0.09	0.91 ± 0.05
β_s	0.46 ± 0.12	0.52 ± 0.07
$N_{\bar{s}}$	0.2 ± 0.4	0.25 ± 0.32
χ^2/N	1.871	1.870

Ongoing work:

- Analyzing the fit results & optimizing the fitting framework
- DY extension to the SIDIS NN model

Without sign change





$k_\perp$

DISCUSSION & FUTURE WORK

- Performing simultaneous fits to SIDIS and DY data with higher statistics of replicas (on-going).
- Improving the Neural Network to train simultaneously on both SIDIS & DY data with optimizing hyperparameters with higher statistics of replicas.
- Investigating towards Sivers Asymmetry extraction from Drell –Yan with/without considering the "sign-flip" of the Sivers Function.
- Simultaneous fits to Sivers function and Boer-Mulders function (on-going).

SPINQUEST (E1039) EXPERIMENT AT FERMILAB

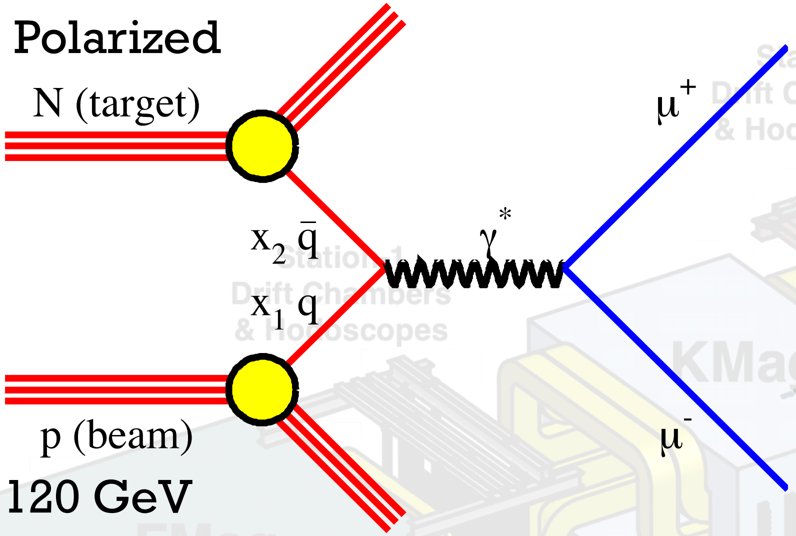
- Measurement of 'sea' quark Sivers function

Stay Tuned!

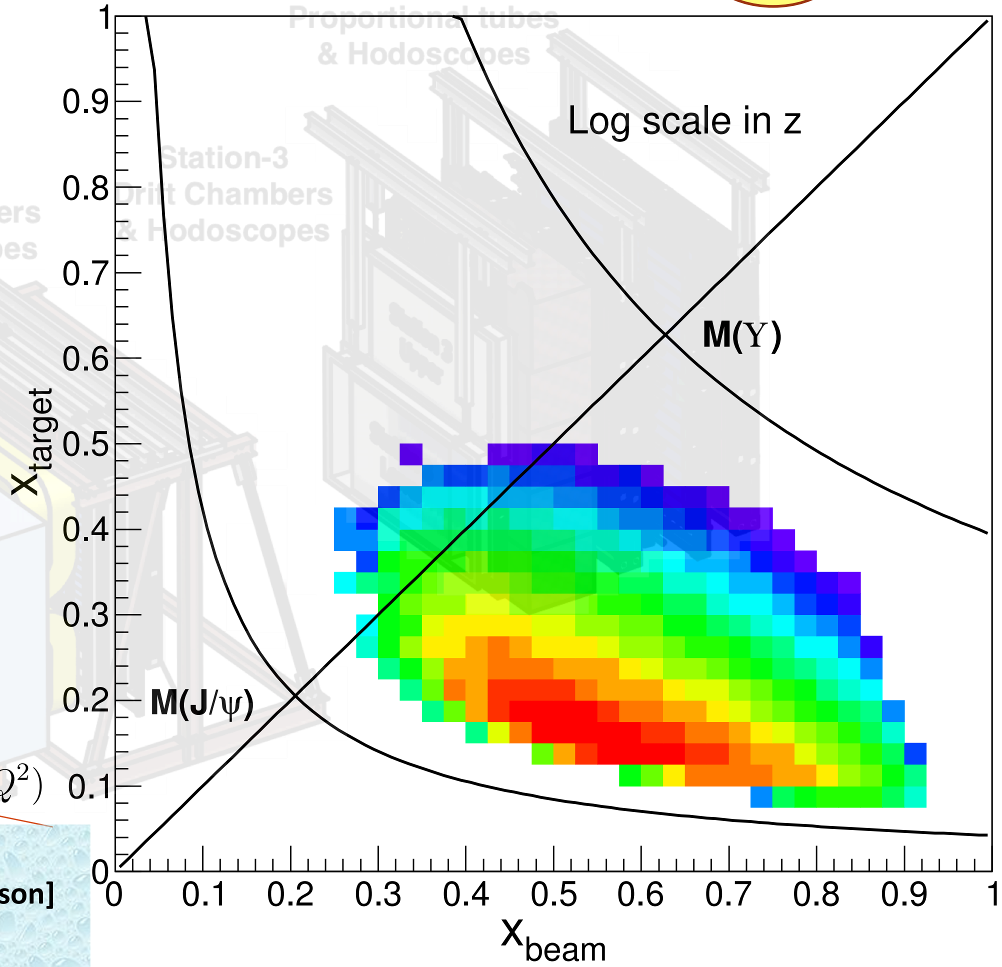
SPIN QUEST

Fermilab

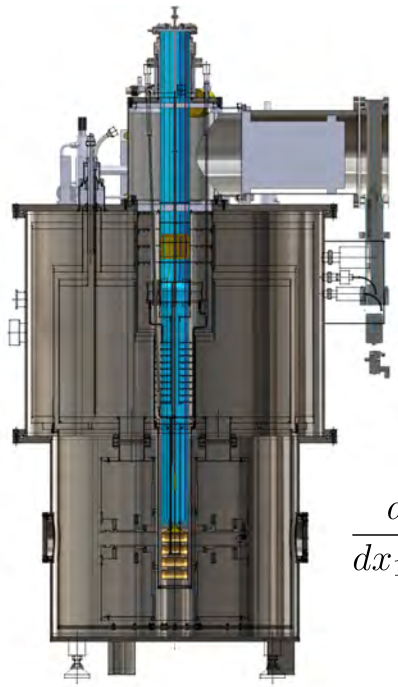
$$pp^{\uparrow}(d^{\uparrow}) \rightarrow \mu^{+}\mu^{-}X,\ 4 < M_{\mu\mu} < 9\ GeV$$



120 GeV proton beam



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



LANL-UVA Polarized Target

Please Join The Effort
Dustin Keller (dustin@virginia.edu)[Spokesperson]
Kun Liu ([Spokesperson])

https://spinquest.fnal.gov/

http://twist.phys.virginia.edu/E1039/

Thank you

UNIVERSITY of VIRGINIA

UVA - Spin
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This work is supported by DOE contract DE-FG02-96ER40950