NCTS Annual Theory Meeting 2017:
Particles, Cosmology and Strings

NCTS

December 5th-8th, Hsinchu

Recent Results of Drell-Yan Experiments in Exploring the Nucleon Partonic Structure

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The Drell-Yan Process

S.D. Drell and T.M. Yan, PRL 25 (1970) 316

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s\rightarrow\infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s\rightarrow 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.

PRL 25 (1970) 1523

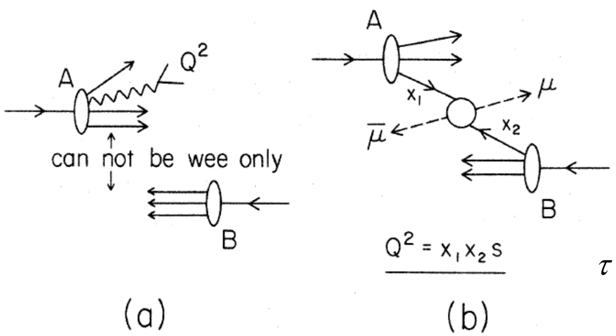


FIG. 1. (a) Production of a massive pair Q^2 from one of the hadrons in a high-energy collision. In this case it is kinematically impossible to exchange "wee" partons only. (b) Production of a massive pair by parton-antiparton annihilation.

$$\tau = \frac{Q^2}{s} = x_1 x_2$$

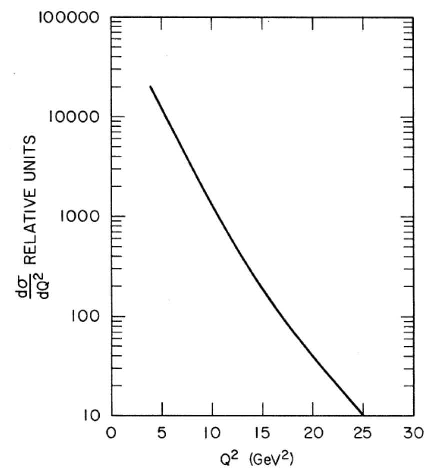
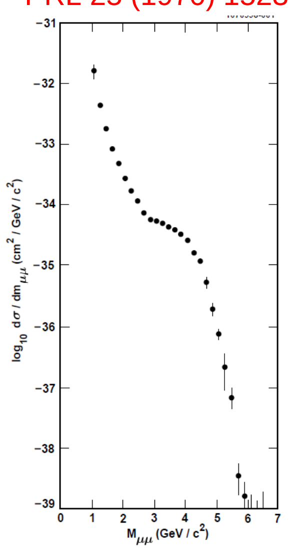


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.



$$\frac{d\sigma}{dQ^2}=\left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\mathfrak{F}(\tau)=\left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\int_0^1 dx_1\int_0^1 dx_2\,\delta(x_1x_2-\tau)\sum_a\lambda_a{}^{-2}F_{2a}(x_1)F_{2\bar{a}}{}'(x_2),$$

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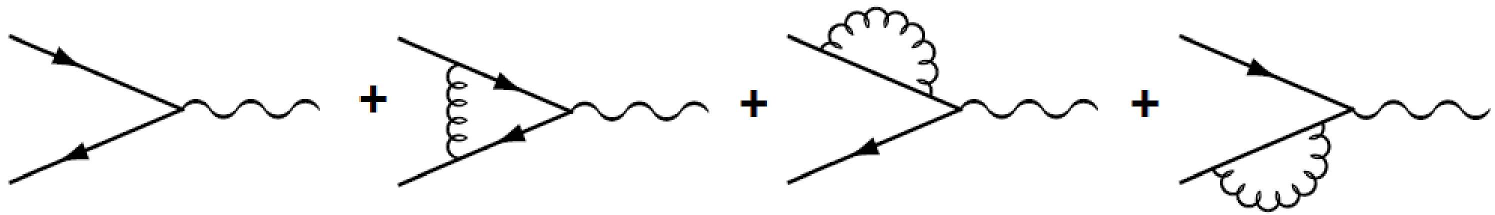
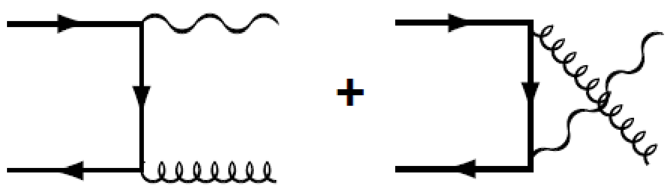
BS, 1960, National Taiwan University. Ph.D., 1968, Harvard University. Research Associate, Stanford Linear Accelerator Center, 1968-70. Assistant Professor, Physics, Cornell University, 1970-76. Associate Professor, Physics, Cornell University, 1976-81. Professor, Physics, Cornell University, 1981-present. Visiting appointments at: Stanford Linear Accelerator Center, 1973-74. Theory Division, CERN, 1977-78. Physics Department, National Taiwan University, 1986. Institue of Physics, Academia Sinica, Taipei, Taiwan, 1991-92. National Center of Theoretical Sciences, Hsinchu, Taiwan, 1997. Alfred Sloan Fellow, 1974-78. Fellow, American Physics Society.

Drell-Yan Process with QCD Effect



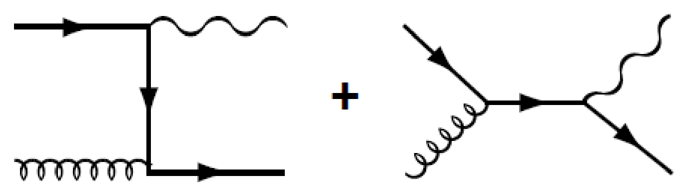
(a)

Quark-antiquark annihilation



(b)

Quark-antiquark annihilation

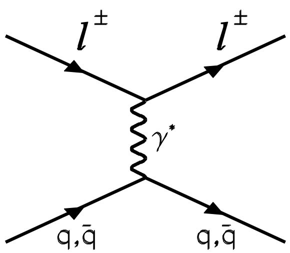


(c)

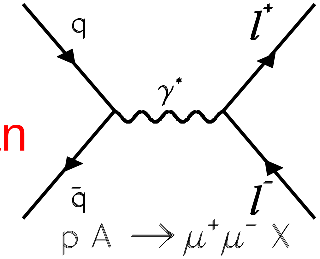
Quark-gluon Compton scattering

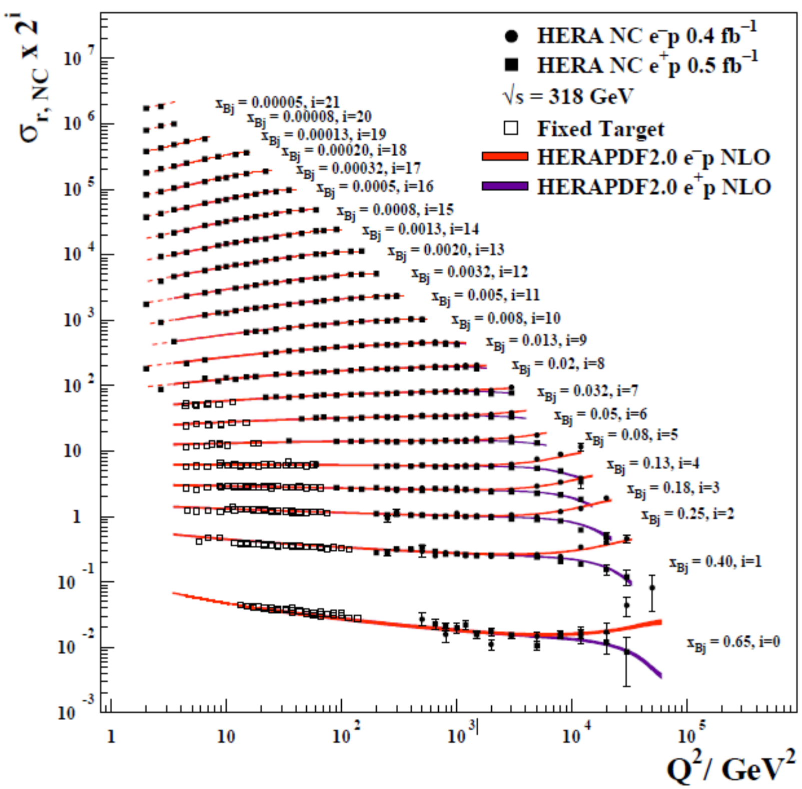
Factorization of Hard Processes

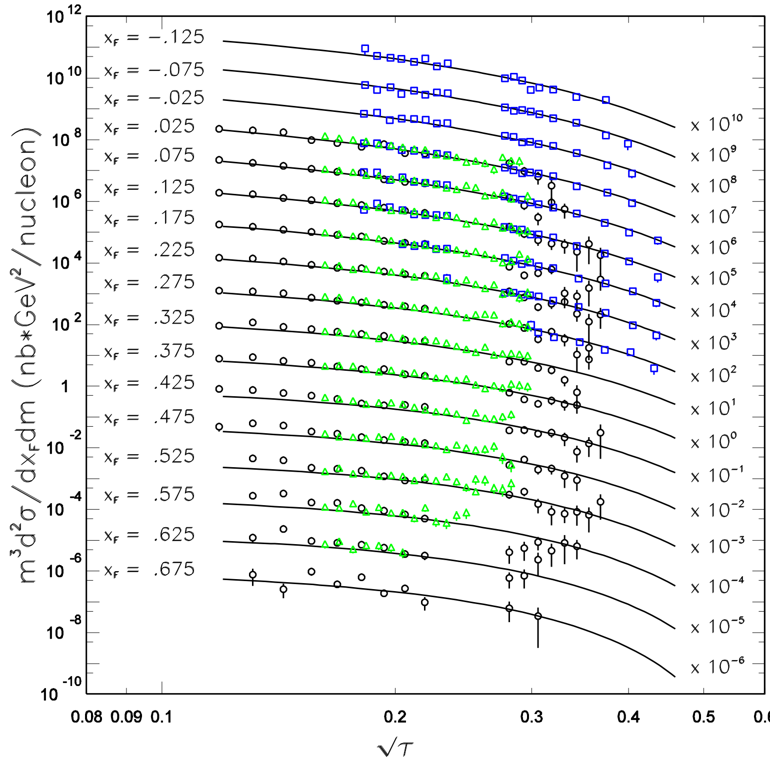
DIS



Drell-Yan

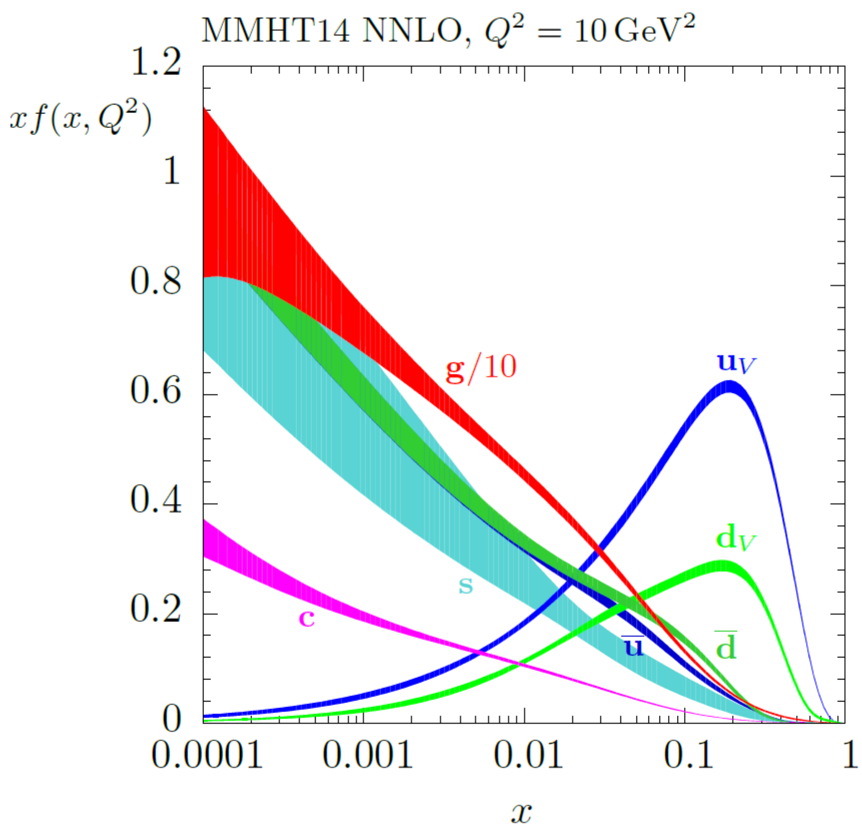




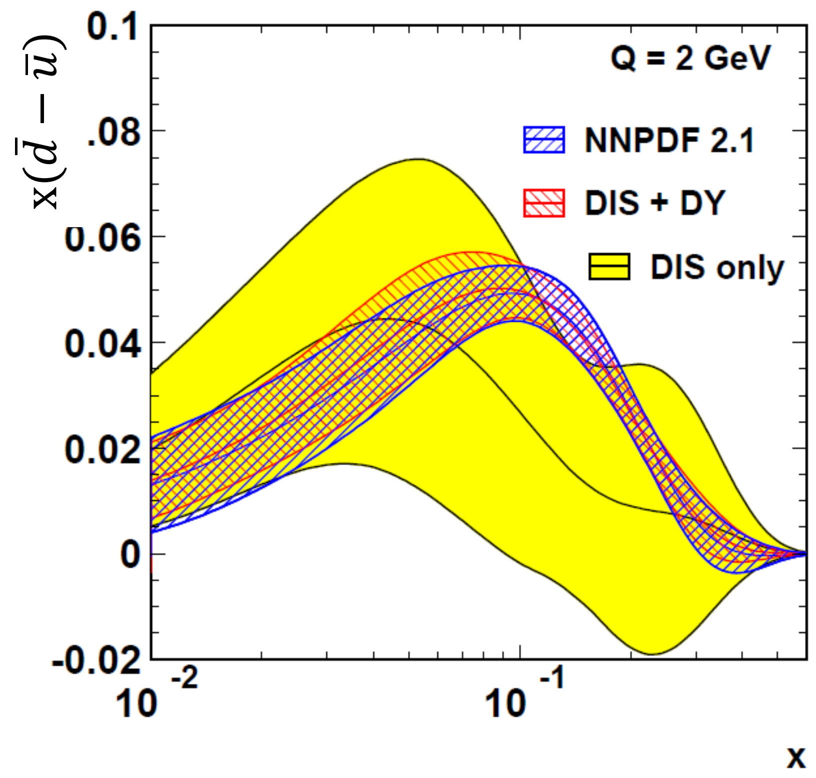


$$\sigma_{proton}(x, Q^2) \sim f_{nucleon}(x, Q^2) \otimes \hat{\sigma}_{hard}(Q^2)$$

Parton distributions of Protons From Global Analysis



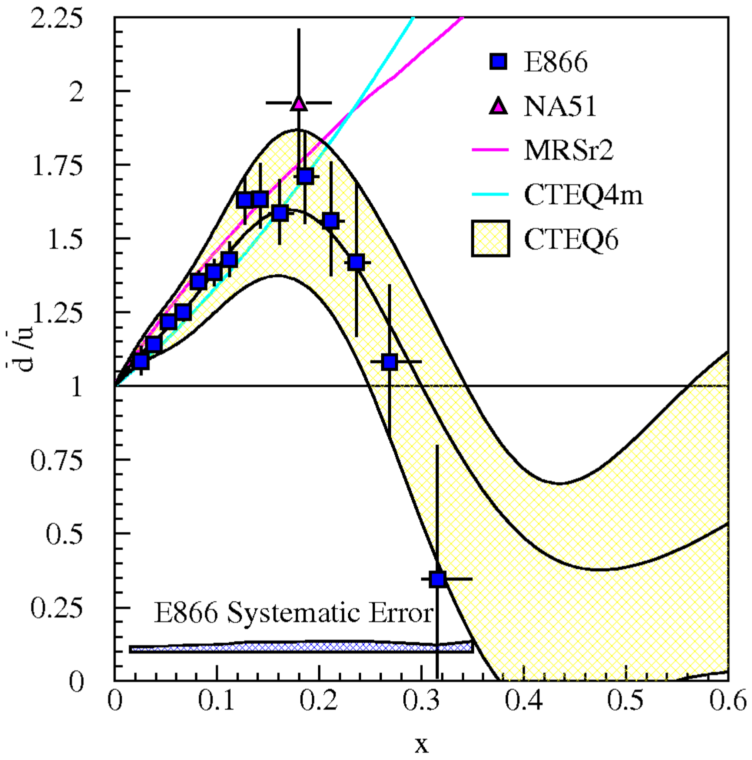
arXiv:1412.3989

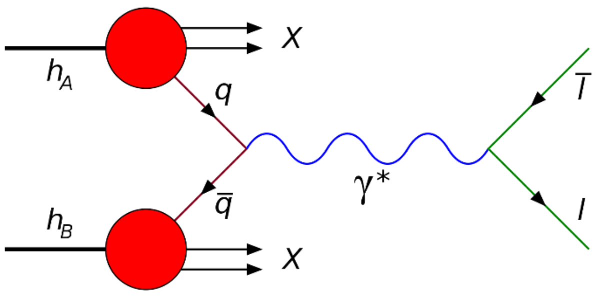


arXiv:1208.1178

Light Antiquark Flavor Asymmetry: Drell-Yan Experiments

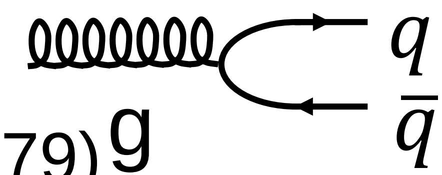
- Naïve Assumption: $\bar{d}(x) = \bar{u}(x)$
- NMC (Gottfried Sum Rule): $\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$
- NA51 (Drell-Yan, 1994):
  $\bar{d} > \bar{u}$ at $x = 0.18$
- E866/NuSea (Drell-Yan, 1998):
  $\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



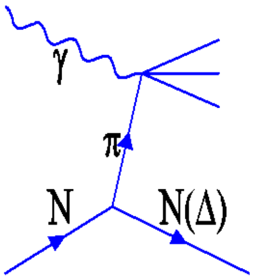


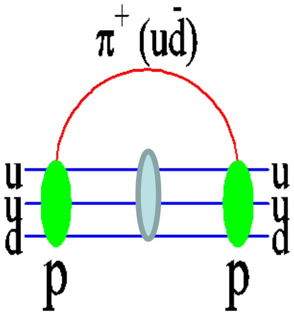
Origin of $\bar{u}(x) \neq \bar{d}(x)$: pQCD or non-pQCD effect?

- Pauli blocking
  - $g \to u\bar{u}$ is more suppressed than $g \to d\bar{d}$ in the proton since |p>=|uud> (Field and Feynman 1977)
  - pQCD calculation (Ross, Sachrajda 1979)



- Meson cloud in the nucleons
(Thomas 1983, Kumano 1991): Sullivan process in DIS.

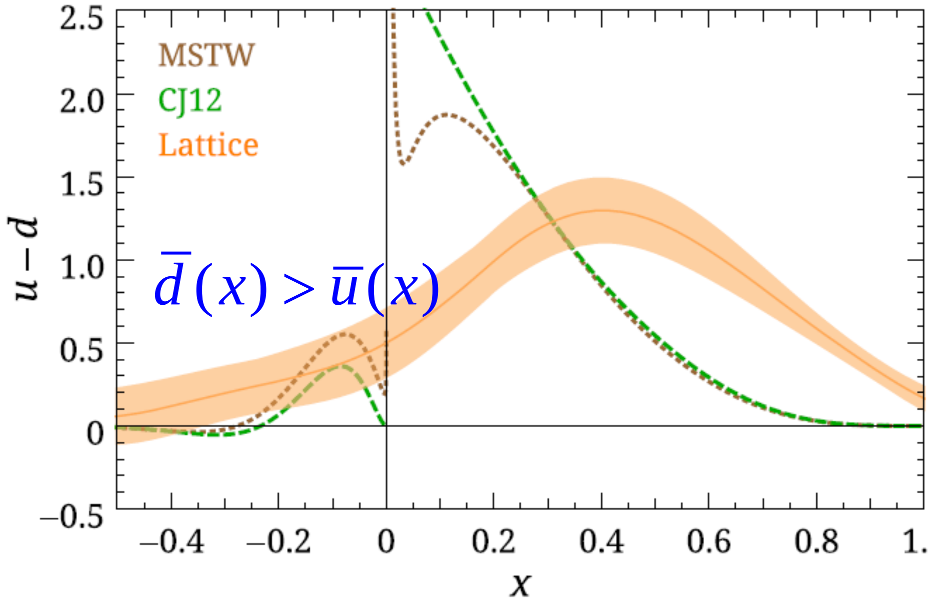




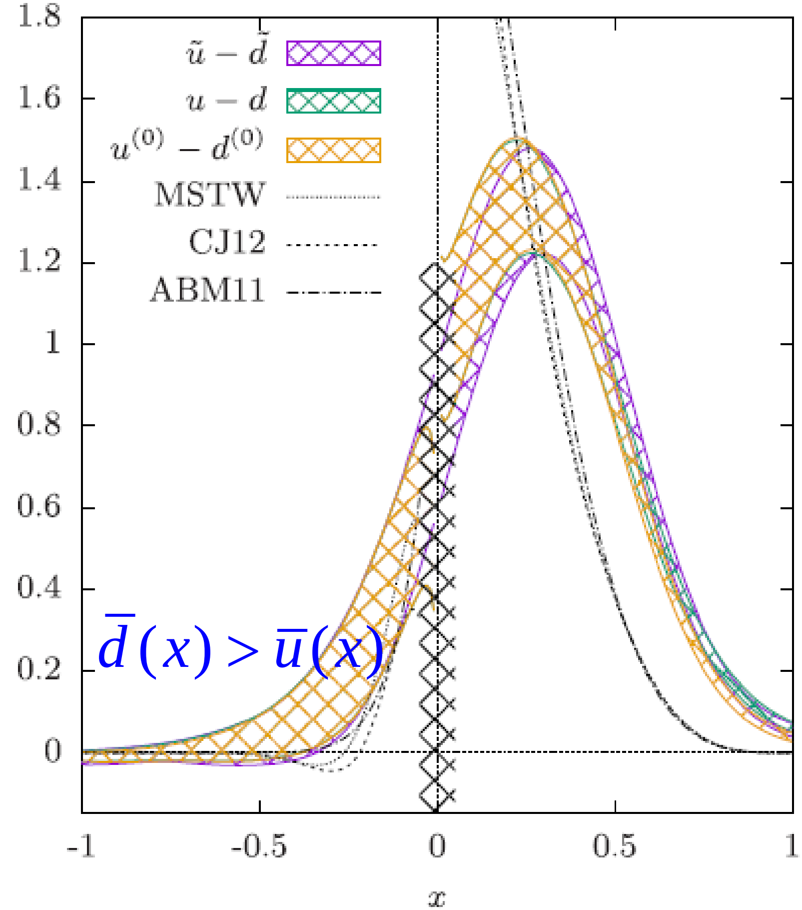
$$p \to N\pi;\ \pi^+ : \pi^0 : \pi^- = 2:1:0$$

Results of $\bar{\mathrm{d}}(x) - \bar{\mathrm{u}}(x)$ from Lattice QCD

H.W. Lin et al., PRD 91, 054510 (2015)

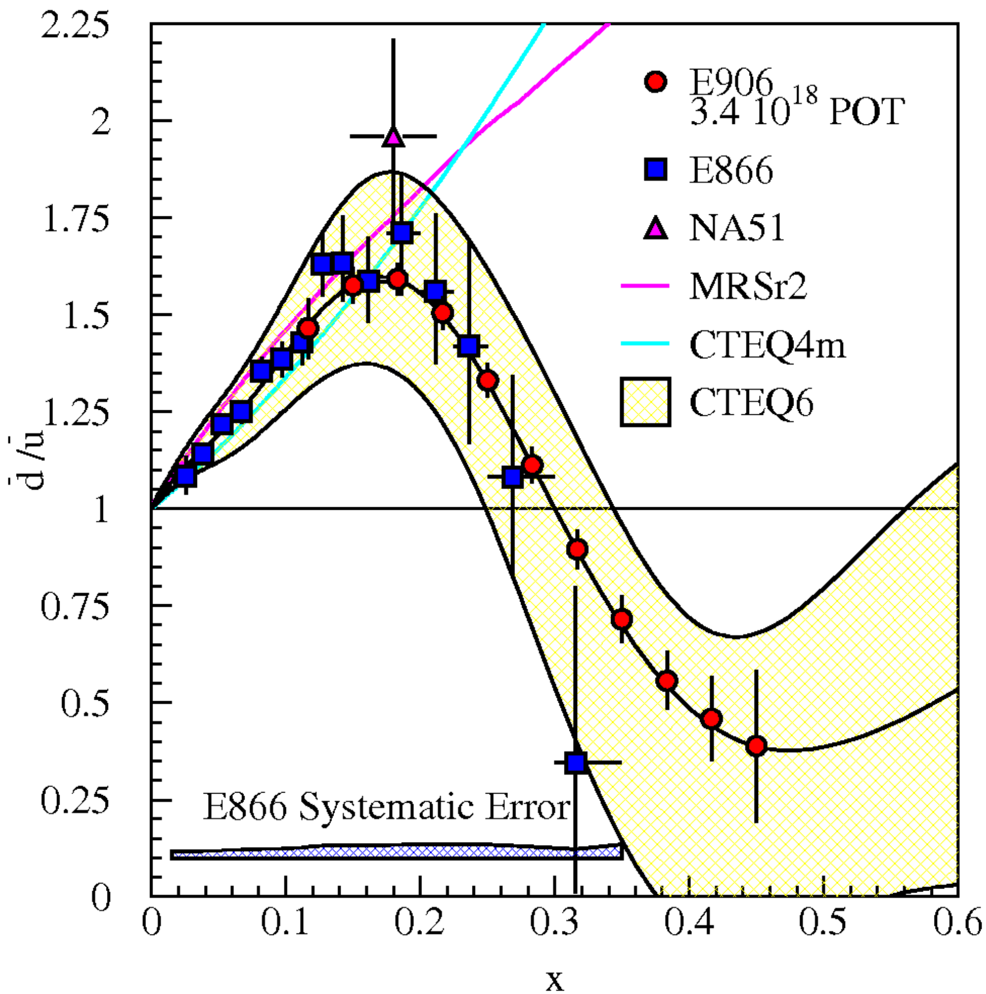


$$\bar{q}(x) = -q(-x)$$



C. Alexandrou et al., PRD 96, 014513 (2017)

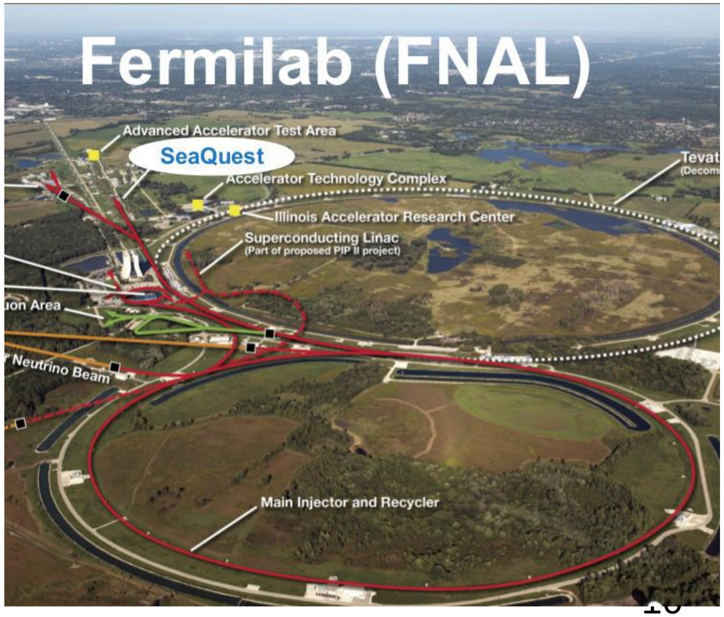
$\bar{d}(x)/\bar{u}(x)$ Measured by FNAL E906/SeaQuest Experiment



$(\bar{d}(x)/\bar{u}(x))$ up to $x_T \sim 0.45$

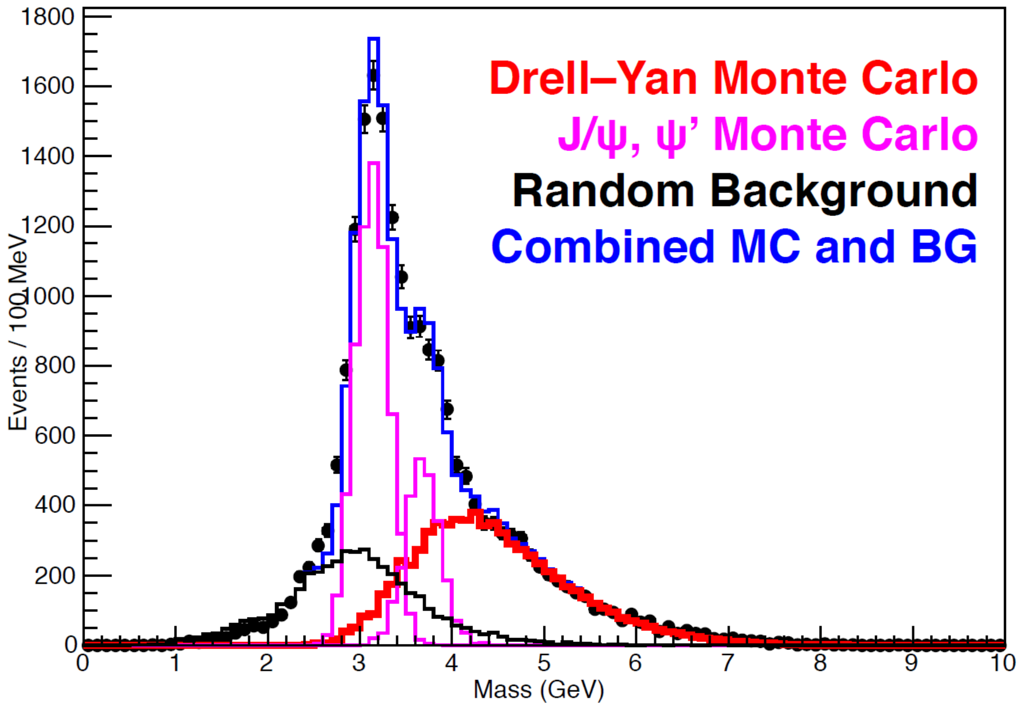
Fermilab E906

- $x_B x_T = \frac{M}{s}$; smaller s, larger x_T
- Unpolarized Drell-Yan using 120 GeV proton beam from Main Injector
- ^1H, ^2H, and nuclear targets

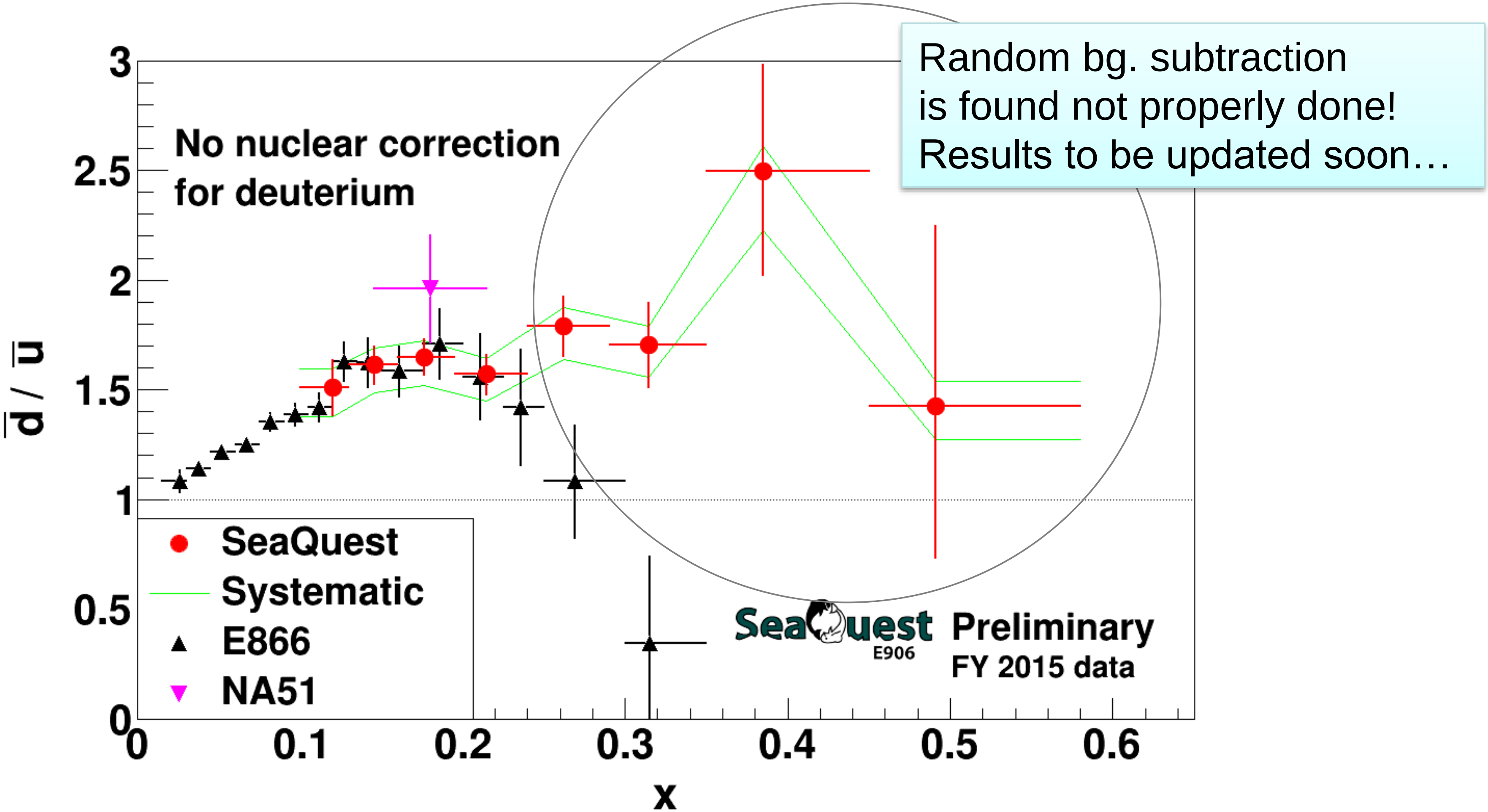


E906/SeaQuest

- Schedules:
  - Run 1 (Mar. 2012 – Apr., 2012): commissioning run.
  - Run 2 (Nov. 2013 – Sep. 2014) : 1st physics run.
  - Run 3 (Nov. 2014 – Jul. 2015): 2nd physics run.
  - Run 4 (Oct. 2015 – Aug., 2016): 3rd physics run.
  - Run 5 (Nov. 2016 – Jul., 2017): 4th physics run.

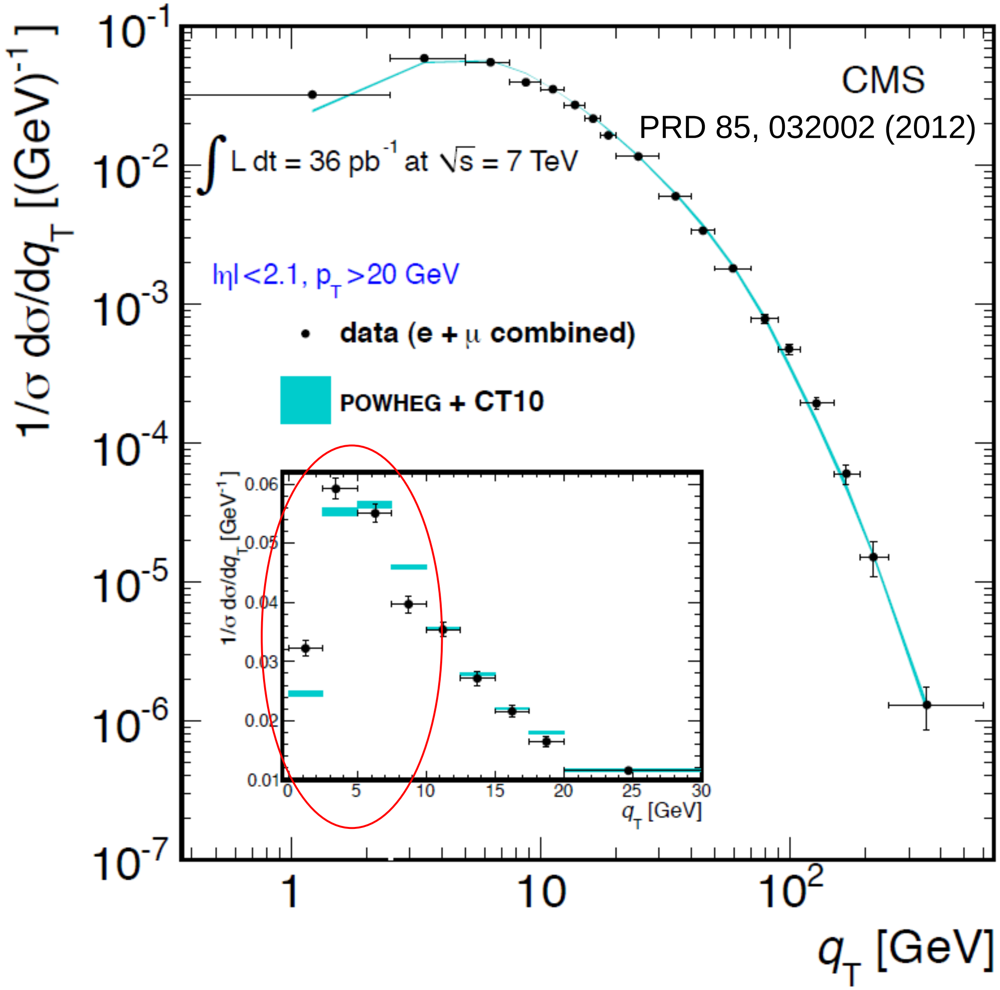


Preliminary Results of $\bar{d}/\bar{u}(x)$from SeaQuest



Why TMDs?

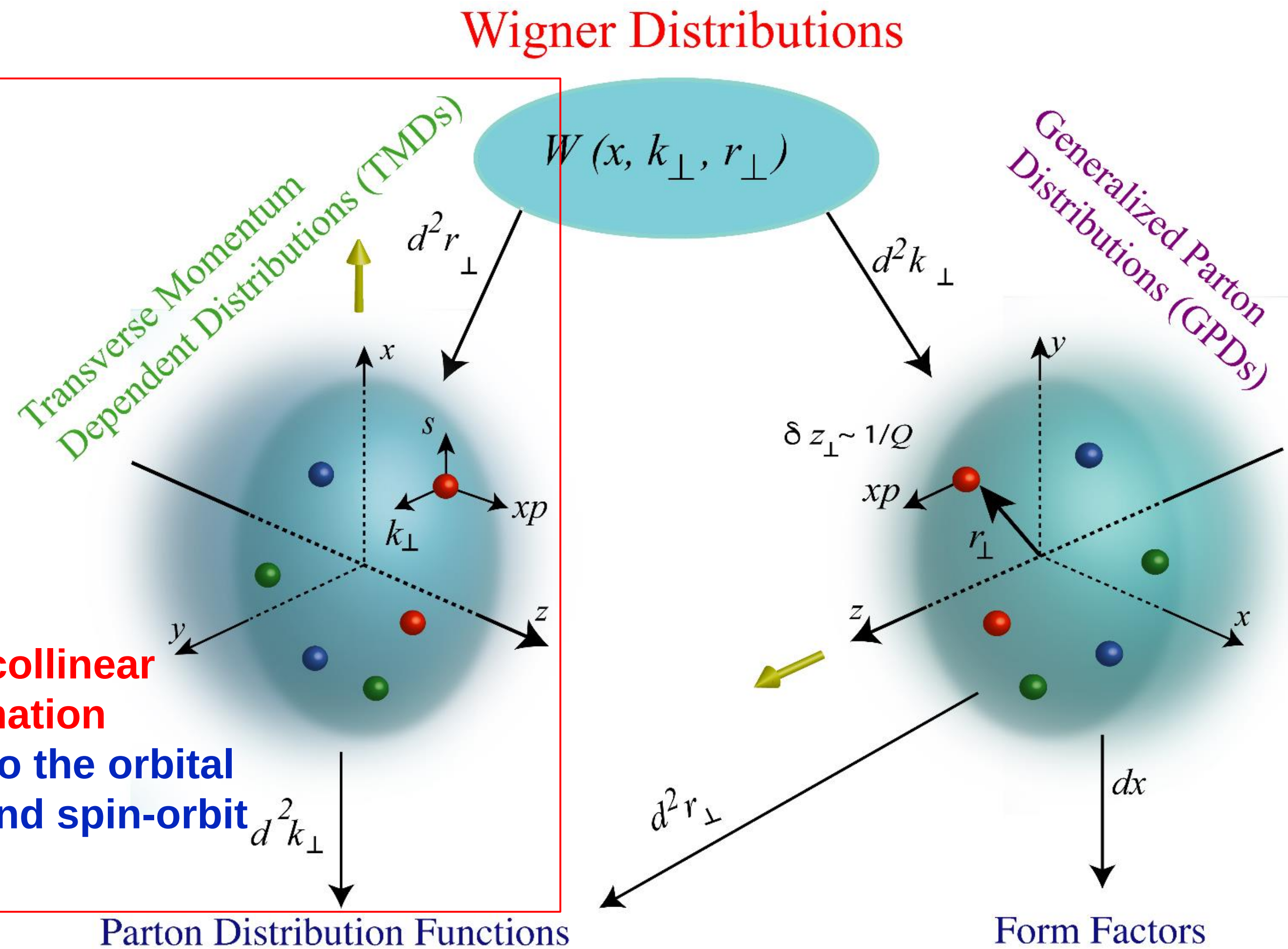
The Z-boson transverse momentum q_T spectrum in pp collisions at the LHC



- At large qT, the NNLO pQCD describes the data better than 10%.
- For qT<10 GeV, pQCD calculation fails: multi-parton QCD radiation.

Angeles-Martinez et al., arXiv: 1507.05267

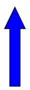
Multi-dimensional Partonic Structures



- **Beyond collinear approximation**
- **Related to the orbital motion and spin-orbit effects.**

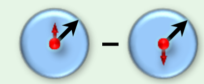
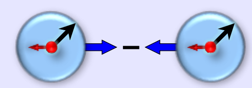
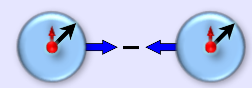
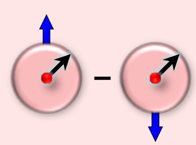
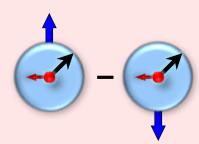
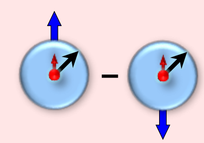
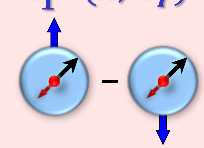
http://www.int.washington.edu/PROGRAMS/17-3/

Leading-Twist Transverse-momentum Dependent **Parton Density Function** (TMDs)

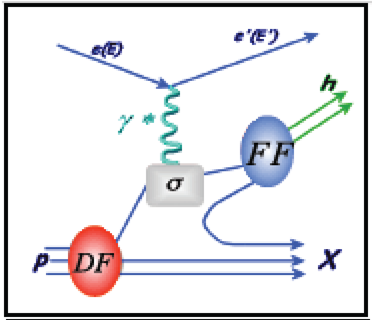
 **spin of the nucleon**

 **spin of the parton**

 **k_T of the parton**

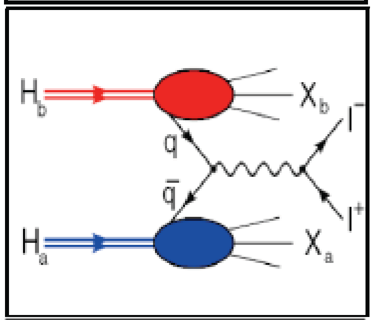
Quark / Nucleon	U	L	T
U	 **number density** $f_1^{q,g}(x,k_T^2)$		 **Boer-Mulders** $h_1^{\perp q,g}(x,k_T^2)$
L		 **Helicity** $g_{1L}^{q,g}(x,k_T^2)$	 **worm-gear L** $h_{1L}^{\perp q,g}(x,k_T^2)$
T	 **Sivers** $f_{1T}^{\perp q,g}(x,k_T^2)$	 **Kotzinian-Mulders worm-gear T** $g_{1T}^{\perp q,g}(x,k_T^2)$	 **Transversity** $h_1^{q,g}(x,k_T^2)$  **Pretzelosity** $h_{1T}^{\perp q,g}(x,k_T^2)$

Accessing TMDs



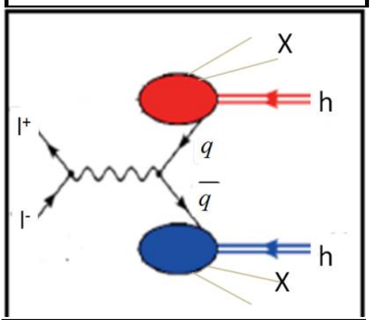
SIDIS: ep → ehX

$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$



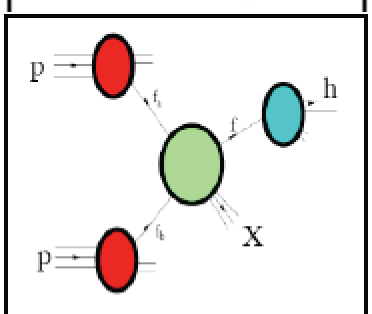
Drell-Yan: pp → e⁺e⁻X

$$\sigma^{pp\to eeX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to ee}$$



Dihadron in e+e-: $e^+e^- \to h_1\ h_2$ X

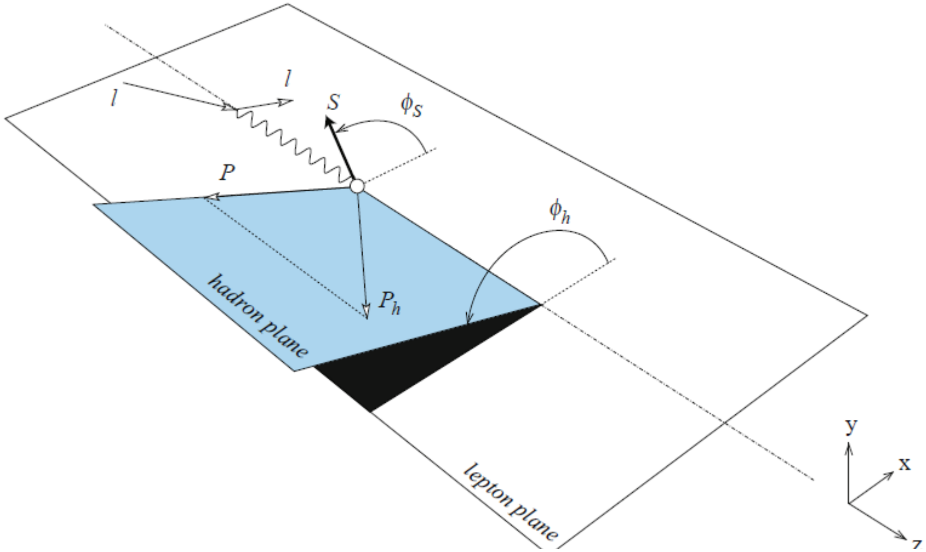
$$\sigma^{ee\to hhX} = \sum_q \sigma^{qq\to ee} \otimes FF \otimes FF$$



Hadron production in pp: pp → hX

$$\sigma^{pp\to hX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to qq} \otimes FF$$

SIDIS cross-sections



$F_{UU}^{\cos(2\phi)}$, $F_{UT}^{\sin(\phi-\phi_S)}$, $F_{UT}^{\sin(\phi+\phi_S)}$:
Structure Functions

$$
\begin{aligned}
&\sigma(\phi,\phi_S) \equiv \frac{\mathrm{d}^6\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\phi\,\mathrm{d}\phi_S\,\mathrm{d}P_{hT}^2} = \\
&\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\, F_{UU}^{\cos\phi} + \epsilon\cos(2\phi)\boxed{F_{UU}^{\cos(2\phi)}} + \lambda_e\left[\sqrt{2\epsilon(1-\epsilon)}\sin\phi\, F_{LU}^{\sin\phi}\right] \\
&+ S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi\, F_{UL}^{\sin\phi} + \epsilon\sin(2\phi)\, F_{UL}^{\sin(2\phi)}\right] + S_L\lambda_e\left[\sqrt{1-\epsilon^2}\, F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi\, F_{LL}^{\cos\phi}\right] \\
&+ |S_T|\Big[\sin(\phi-\phi_S)\left(\boxed{F_{UT,T}^{\sin(\phi-\phi_S)}} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)\boxed{F_{UT}^{\sin(\phi+\phi_S)}} + \epsilon\sin(3\phi-\phi_S)\, F_{UT}^{\sin(3\phi-\phi_S)} \\
&+ \sqrt{2\epsilon(1+\epsilon)}\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)\, F_{UT}^{\sin(2\phi-\phi_S)}\Big] \\
&+ |S_T|\lambda_e\left[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)\, F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)\, F_{LT}^{\cos(2\phi-\phi_S)}\right]\Big\},
\end{aligned}
$$

Avakian et al., Eur. Phys.J. A52 (2016) 150

Polarization-dependent Terms:
Transverse Spin Asymmetry (TSA) A_{UT}

$$\boxed{A_{UT} = \frac{F_{UT}}{F_{UU}} = \frac{1}{fS_T}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}}$$

f: dilution factor due to non-polarizable content of the target

S_T: polarization degree of nucleon transverse spin

- **Advantage**: most of the systematics due to instrumental artifacts cancel.
- **Disadvantage**: unpolarized structure function F_{UU} has to be well known.

SIDIS and single-polarized DY x-sections at twist-2 (LO)

SIDIS

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$

$$\times \left\{ \begin{array}{l} 1 + \boxed{\varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h} \\ + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2}\, A_{LL} \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \end{array} \right] \\ + S_T \lambda \left[\sqrt{\left(1-\varepsilon^2\right)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) \right] \end{array} \right\}$$

DY

$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right)$$

$$\times \left\{ \begin{array}{l} 1 + \boxed{D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

SIDIS-DY bridge

SIDIS		DY
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots$	Boer-Mulders	$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	Sivers	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$	Transversity	$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$
$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretzelosity	$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$
$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$	Worm-gear L	$A_L^{\sin 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1L,p}^{\perp q}$
$A_{LL} \propto g_{1L}^{q} \otimes D_{1q}^{h}$, $A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$		Double polarized DY only

: FFs, further constrained by the e+e- process.

Key Issues of TMDs to be Answered/Tested by Experiments

- **Signals**
- **Factorization and universality**: different processes
- **QCD evolution**: different energies
- **Flavor dependence** $(u,\ d,\ \bar{u},\ \bar{d},\ s,\ \bar{s},\ g)$: different targets and tagged hadrons

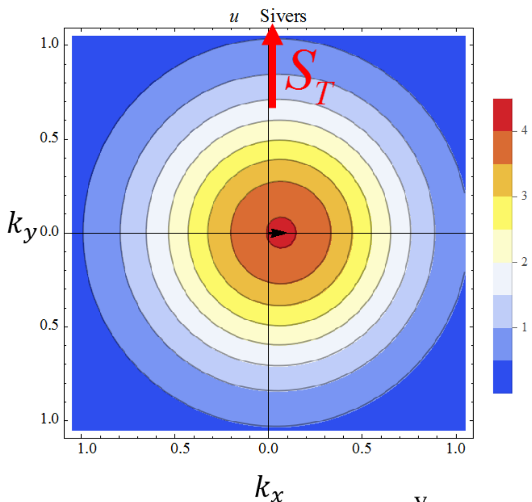
Leading-Twist Transverse-momentum Dependent **Parton Density Function** (TMDs)

- spin of the nucleon
- spin of the parton
- k_T of the parton

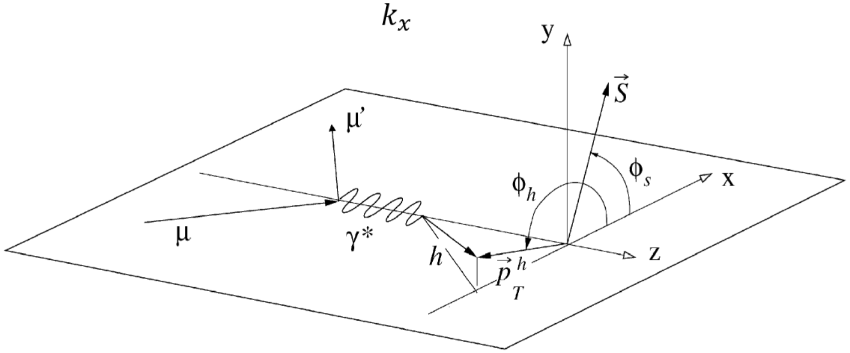
Quark / Nucleon	U	L	T
U	number density $f_1^{q,g}(x,k_T^2)$		Boer-Mulders $h_1^{\perp q,g}(x,k_T^2)$
L		Helicity $g_{1L}^{q,g}(x,k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x,k_T^2)$
T	Sivers $f_{1T}^{\perp q,g}(x,k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x,k_T^2)$	Transversity $h_1^{q,g}(x,k_T^2)$ Pretzelosity $h_{1T}^{\perp q,g}(x,k_T^2)$

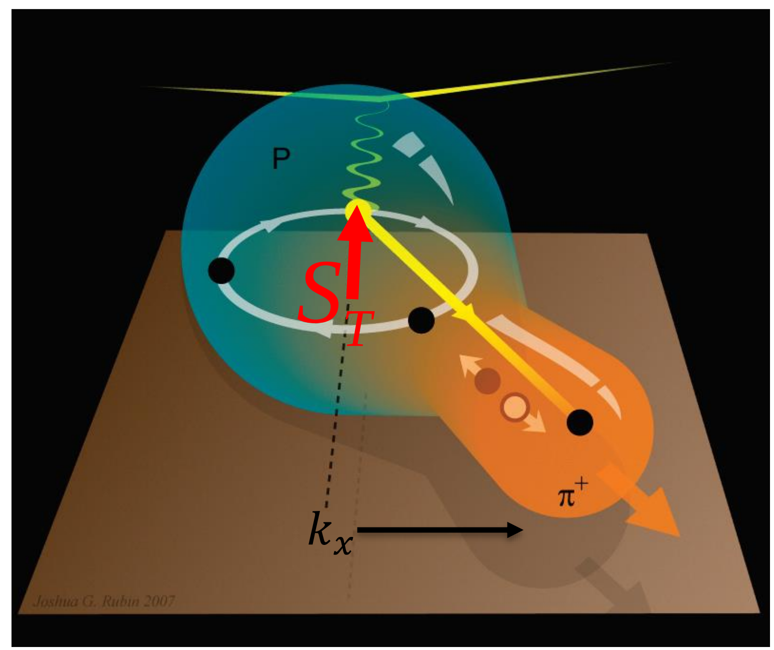
Sivers Asymmetry A_{Siv} in SIDIS (Left-Right Asymmetry w.r.t. S_T)

$$f_{q/p\uparrow}(x,\overrightarrow{k_T},\overrightarrow{S_T}) = f_{q/p}(x,k_T^2) - \frac{1}{M_N} f_{1T}^{\perp q}(x,k_T^2)\overrightarrow{S_T}\cdot(\hat{p}_N \times \overrightarrow{k_T})$$



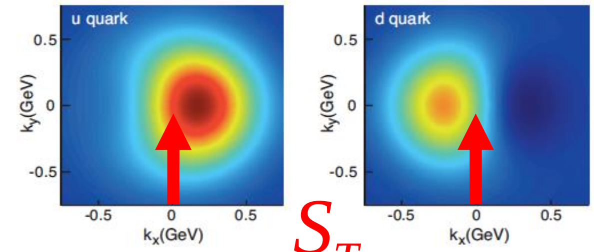
The orbital motion of an u quark inside a proton causes positive-charged pions ($u\bar{d}$) to fly off predominantly to beam-left.





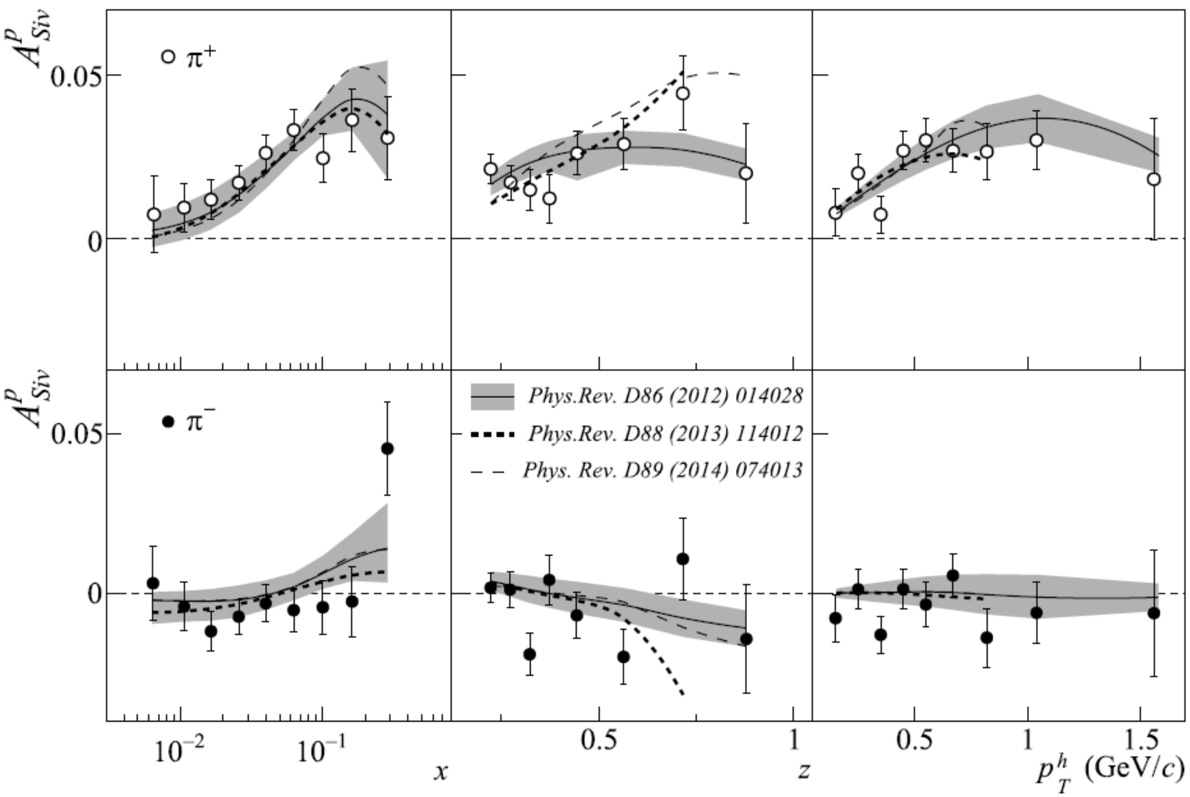
$$A_T^h \equiv \frac{d\sigma(\vec{S}_T) - d\sigma(-\vec{S}_T)}{d\sigma(\vec{S}_T) + d\sigma(-\vec{S}_T)} = \left|\vec{S}_T\right| \cdot \left[D_{NN} \cdot A_{Coll} \cdot \sin(\phi_h + \phi_S - \pi) + A_{Siv} \cdot \sin(\phi_h - \phi_S)\right]$$

Nonzero Sivers Asymmetries from SIDIS

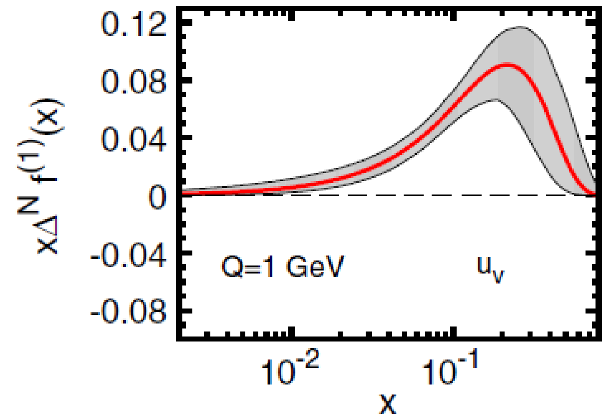


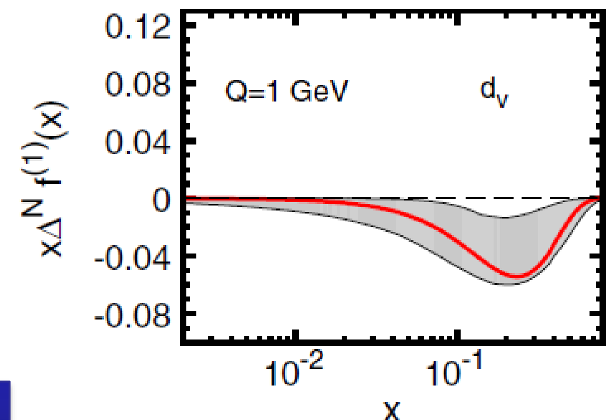
S_T

COMPASS, PLB 744 (2015) 250



Sivers Functions





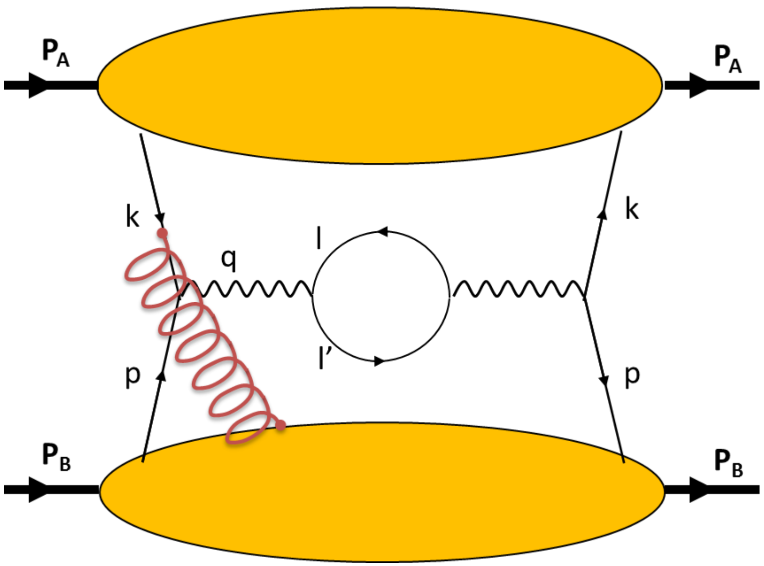
Signals of Sivers functions in SIDIS.
Flavor dependence.

PRD 86, 014028 (2012)
[arXiv:1204.1239]

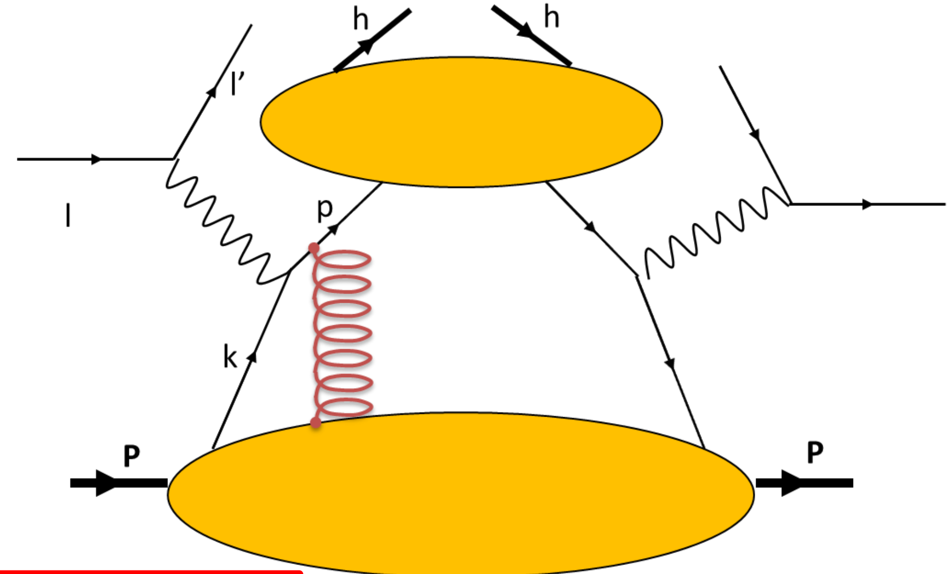
Non-Universality of Sivers Functions

J.C. Collins, Phys. Lett. B 536 (2002) 43
A.V. Belitsky, X. Ji, F. Yuan, Nucl. Phys. B 656 (2003) 165
D. Boer, P.J. Mulders, F. Pijlman, Nucl. Phys. B 667 (2003) 201
Z.B. Kang, J.W. Qiu, Phys. Rev. Lett. 103 (2009) 172001

Drell-Yan



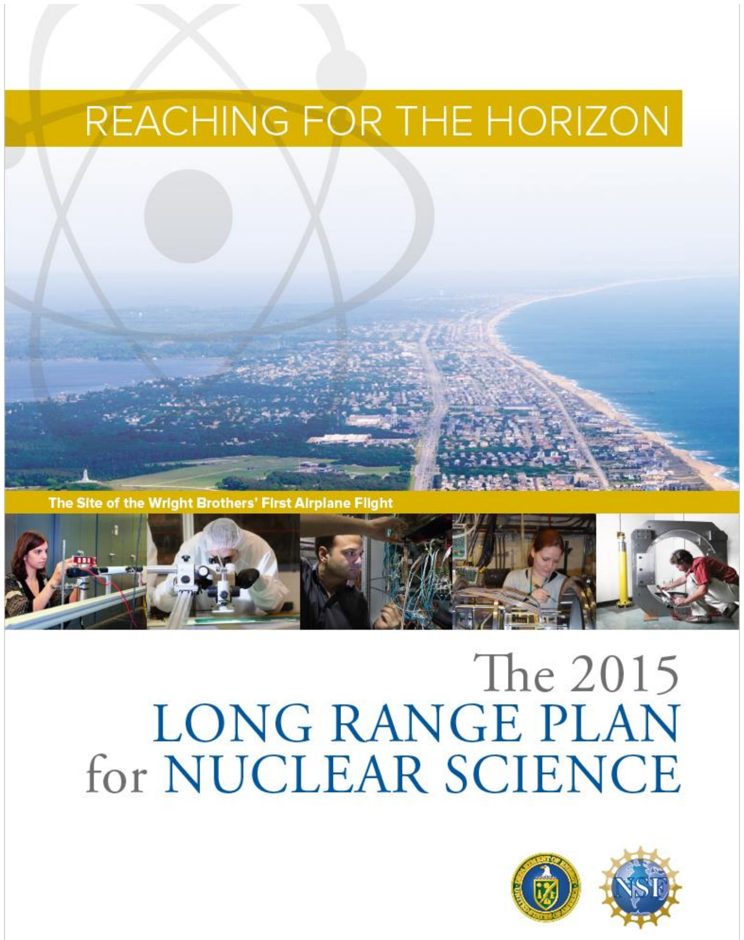
SIDIS



$$\boxed{\text{Sivers}\,|_{DY} = -\text{Sivers}\,|_{SIDIS}}$$

- QCD gluon gauge link (Wilson line) in the initial state (DY) vs. final state interactions (SIDIS).
- ***Fundamental predictions from TMD physics will be tested.***

2015 U.S. Long Range Plan

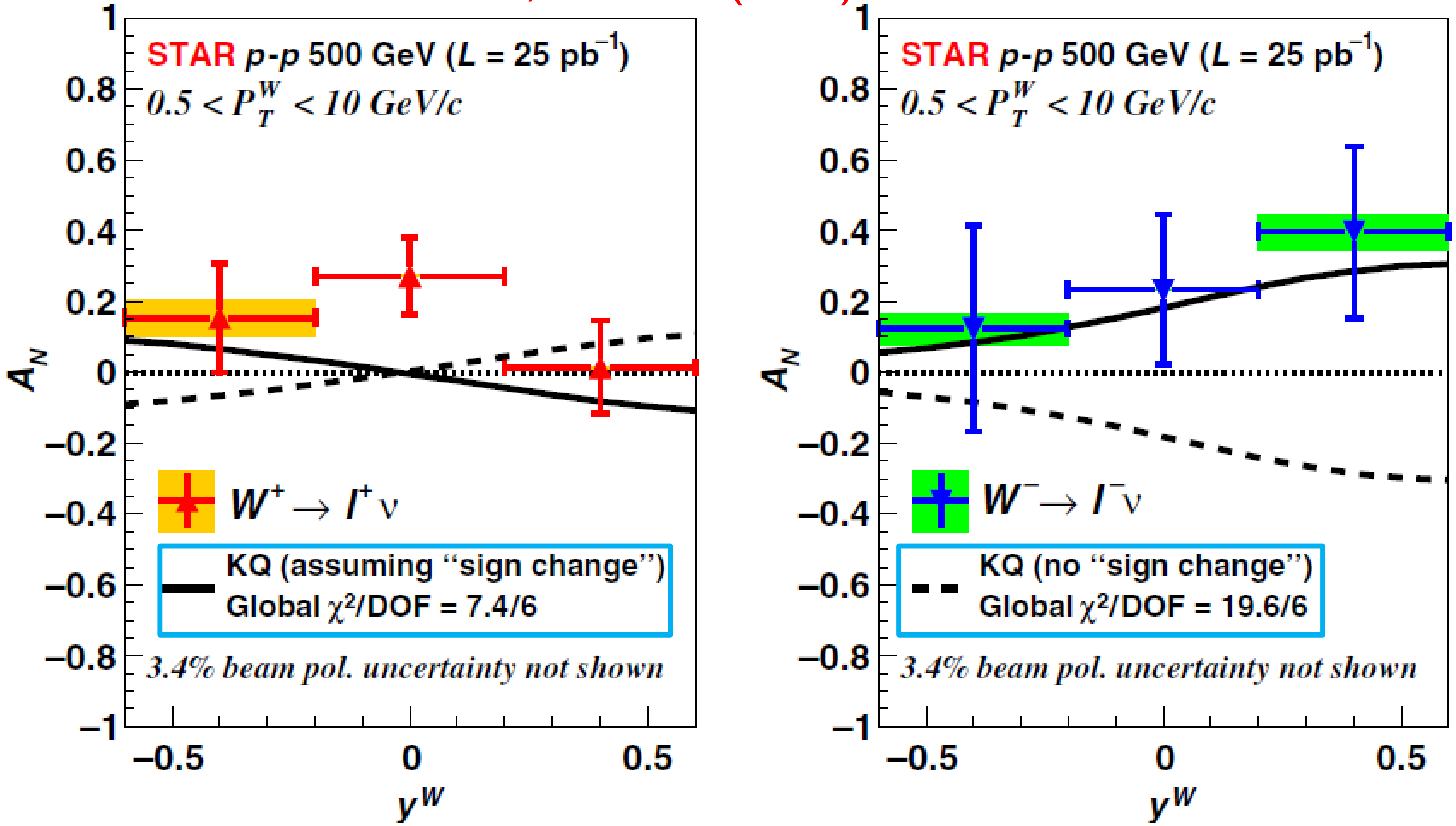


A nonzero Sivers function is considered to be strong evidence for the presence of quark orbital angular momentum. Indeed, it has been measured to be nonzero in the HERMES and JLab experiments. Figure 2.5 shows the unique potential of the JLab 12-GeV program to map the Sivers function for the up quark. The Sivers function has a quite intriguing property predicted by QCD. When measured in SIDIS, it will have one sign, yet when measured in a collision with a proton or pion beam, it should have the opposite sign. This sign change is due to the nature of QCD color interactions and provides an important test of our understanding. It is imperative that the quark Sivers functions that will be measured in SIDIS are also accurately measured with hadron beams, such as the proton beams available at RHIC or Fermilab and the pion beams used by the COMPASS-II experiment at CERN.

https://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

Transverse SSA of W production in polarized pp collisions at RHIC

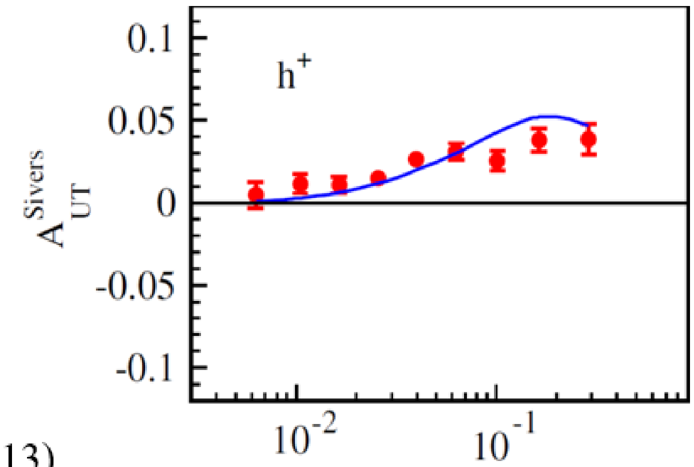
STAR, PRL 116 (2016) 132301



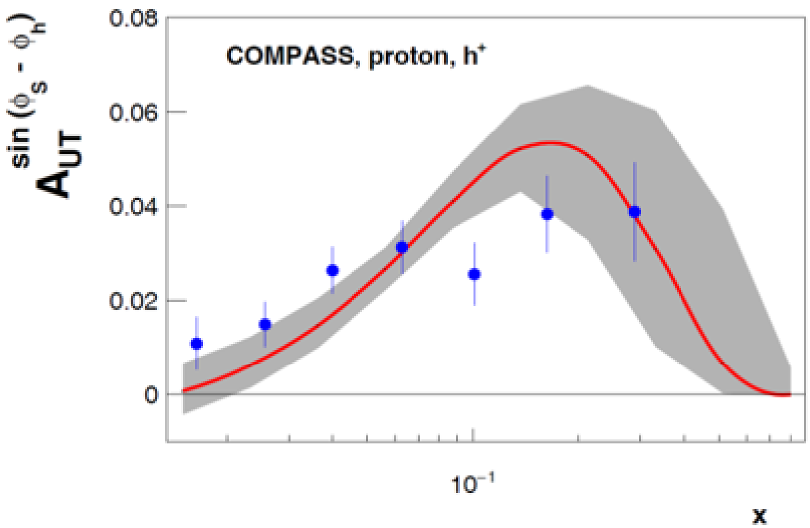
$$A_N = \frac{1}{\langle P \rangle} \frac{\sqrt{N_\uparrow(\phi)N_\downarrow(\phi+\pi)} - \sqrt{N_\uparrow(\phi+\pi)N_\downarrow(\phi)}}{\sqrt{N_\uparrow(\phi)N_\downarrow(\phi+\pi)} + \sqrt{N_\uparrow(\phi+\pi)N_\downarrow(\phi)}},$$

QCD evolution of Sivers function

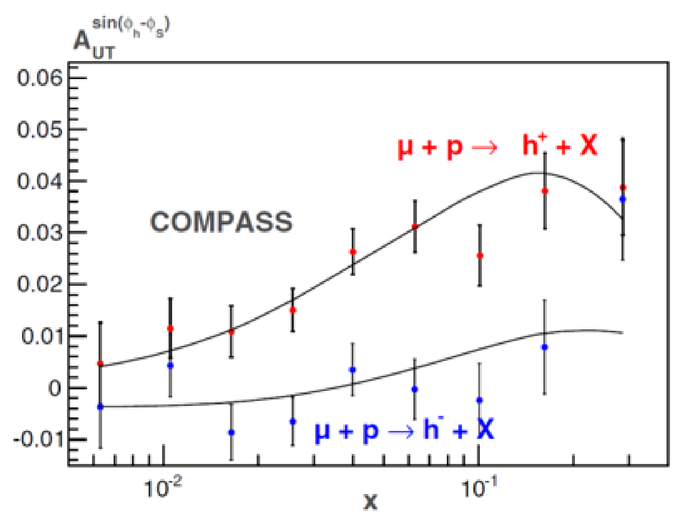
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



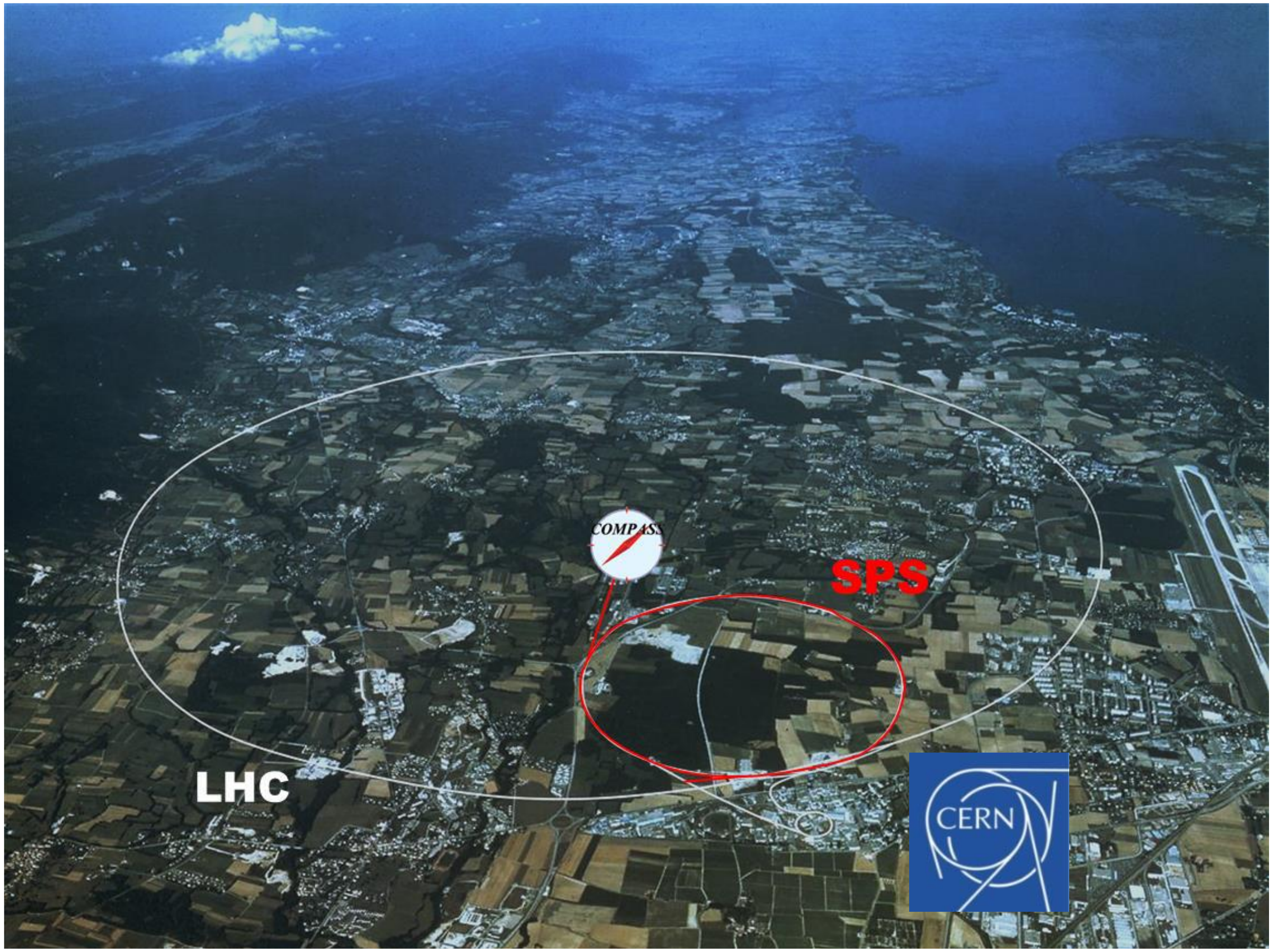
TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



COMPASS Collaboration

(Common Muon and Proton Apparatus for Structure and Spectroscopy)

- 24 institutions from 13 countries – nearly 250 physicists
- Fixed-target experiment at SPS north area
- Physics programs:
  - Nucleon spin and partonic structures
  - Hadron spectroscopy

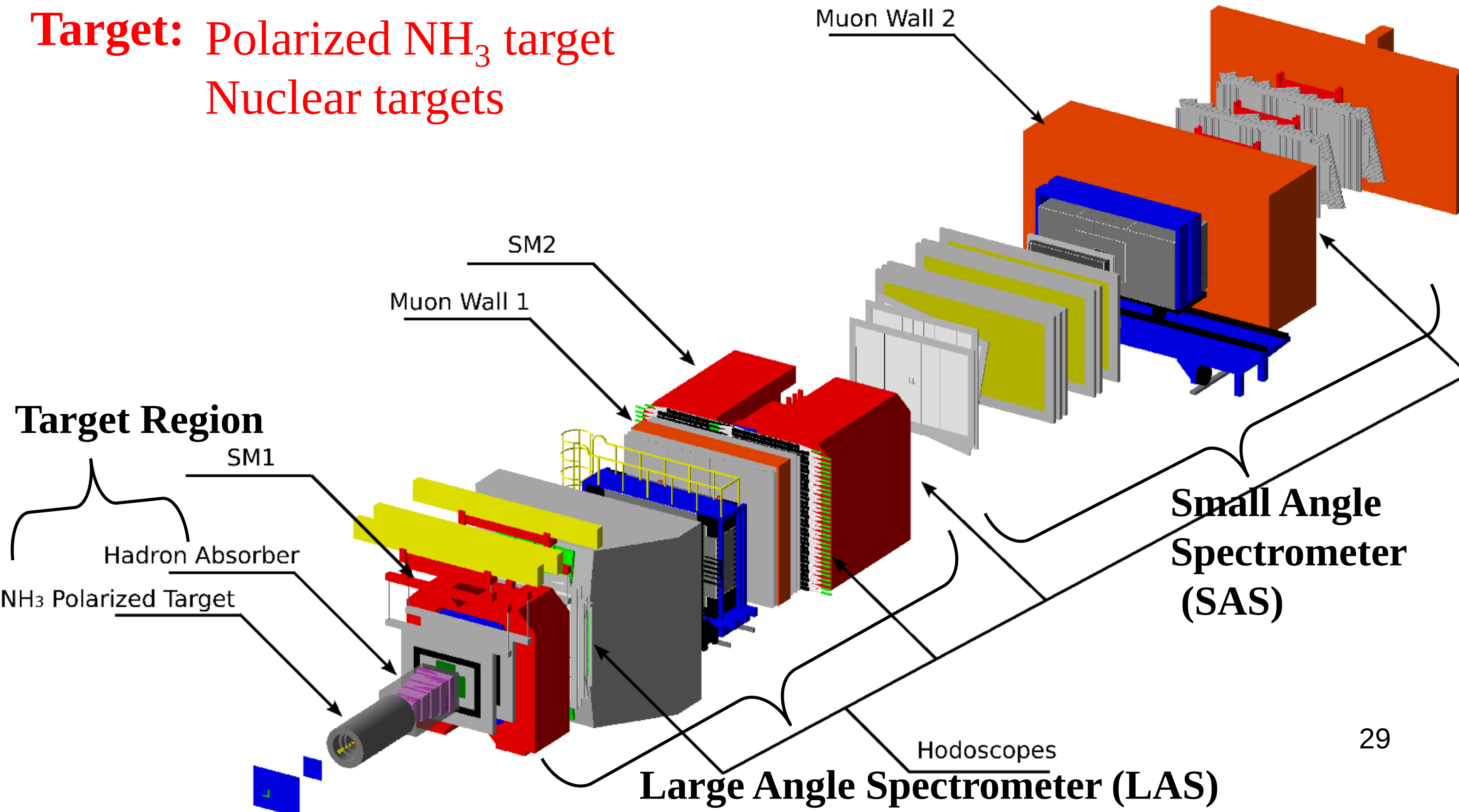


COMPASS Setup (Drell-Yan Runs)

Beam: π^- 190 GeV/c

Target: Polarized NH_3 target

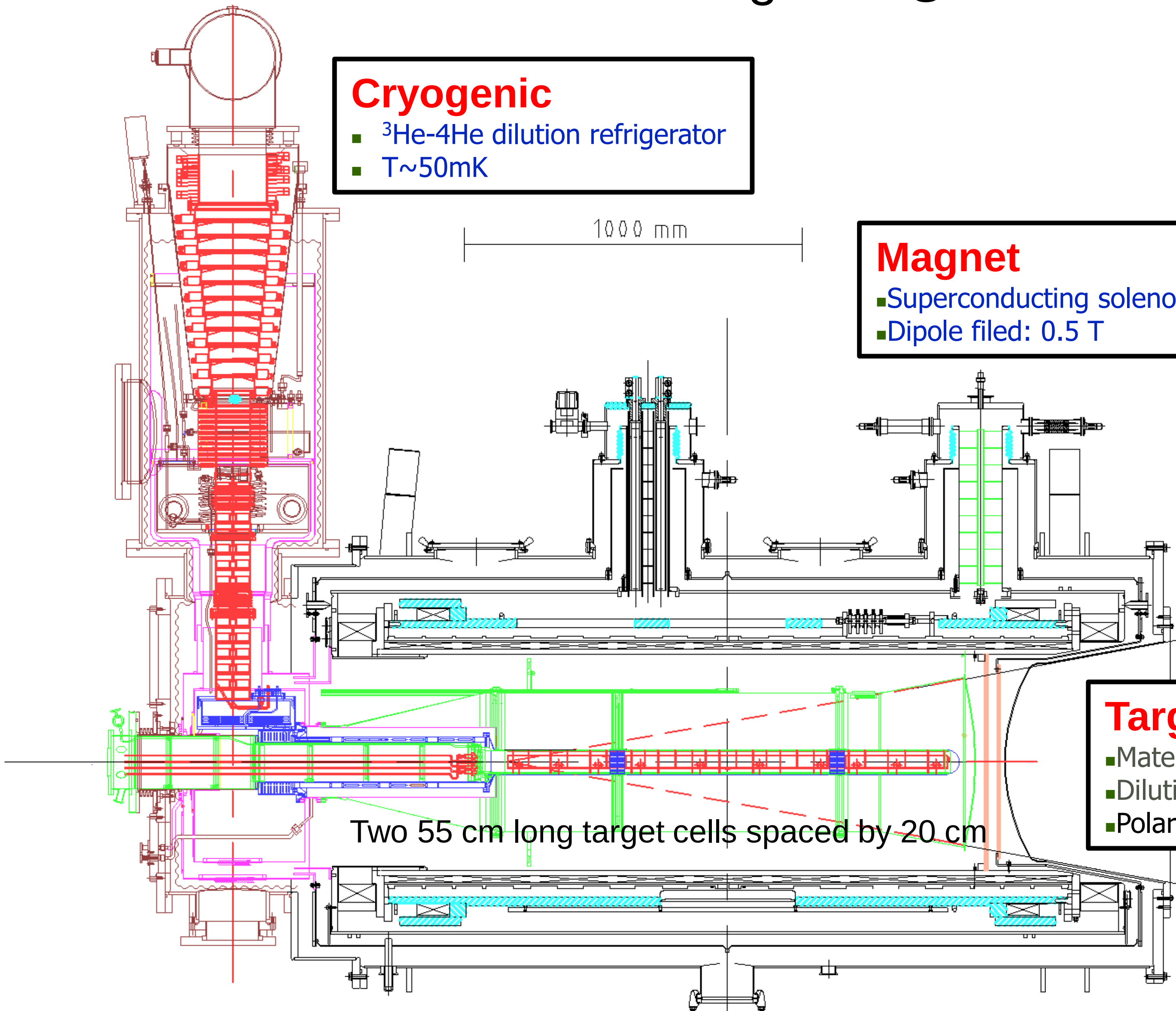
Nuclear targets



Polarized NH_3 Target

Cryogenic
- ^{3}He-4He dilution refrigerator
- T~50mK

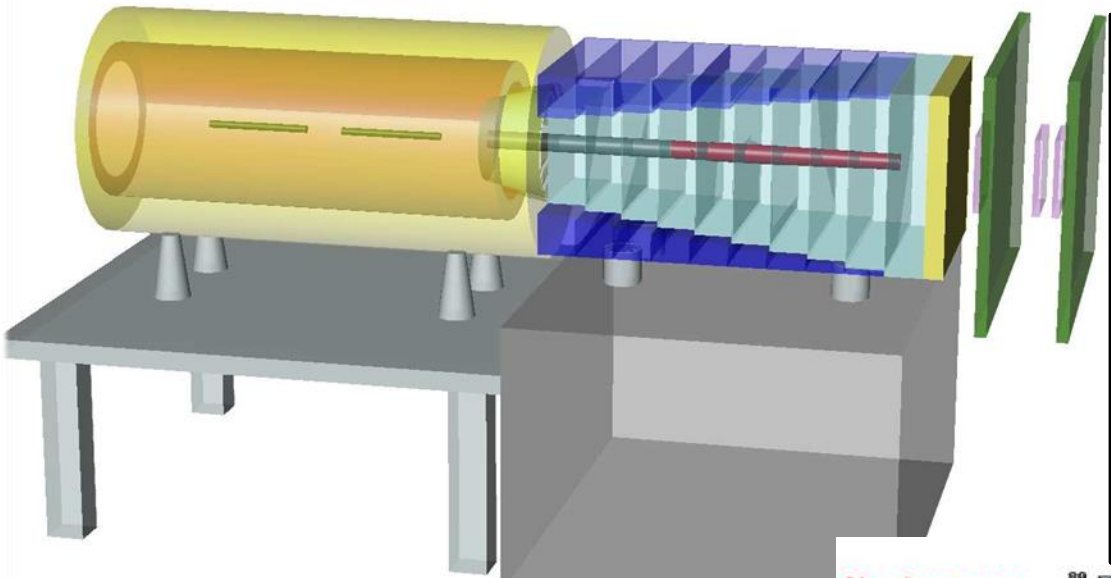
Magnet
- Superconducting solenoid : 2.5 T
- Dipole filed: 0.5 T



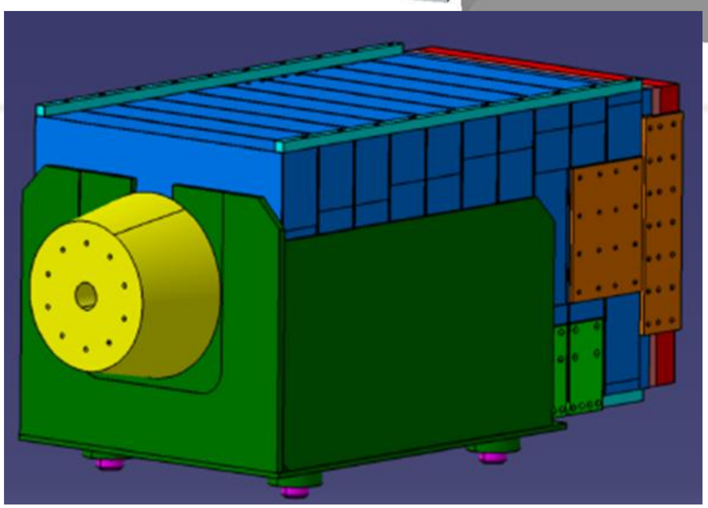
Two 55 cm long target cells spaced by 20 cm

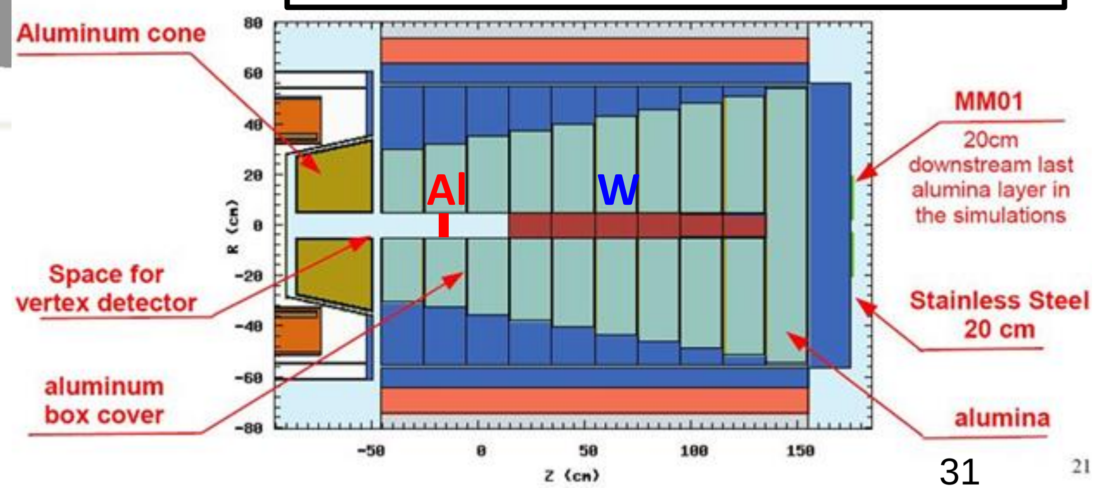
Target
- Materials: p(NH_3)
- Dilution factor: ~0.15
- Polarization: >90%

Hadron Absorber & Nuclear Targets

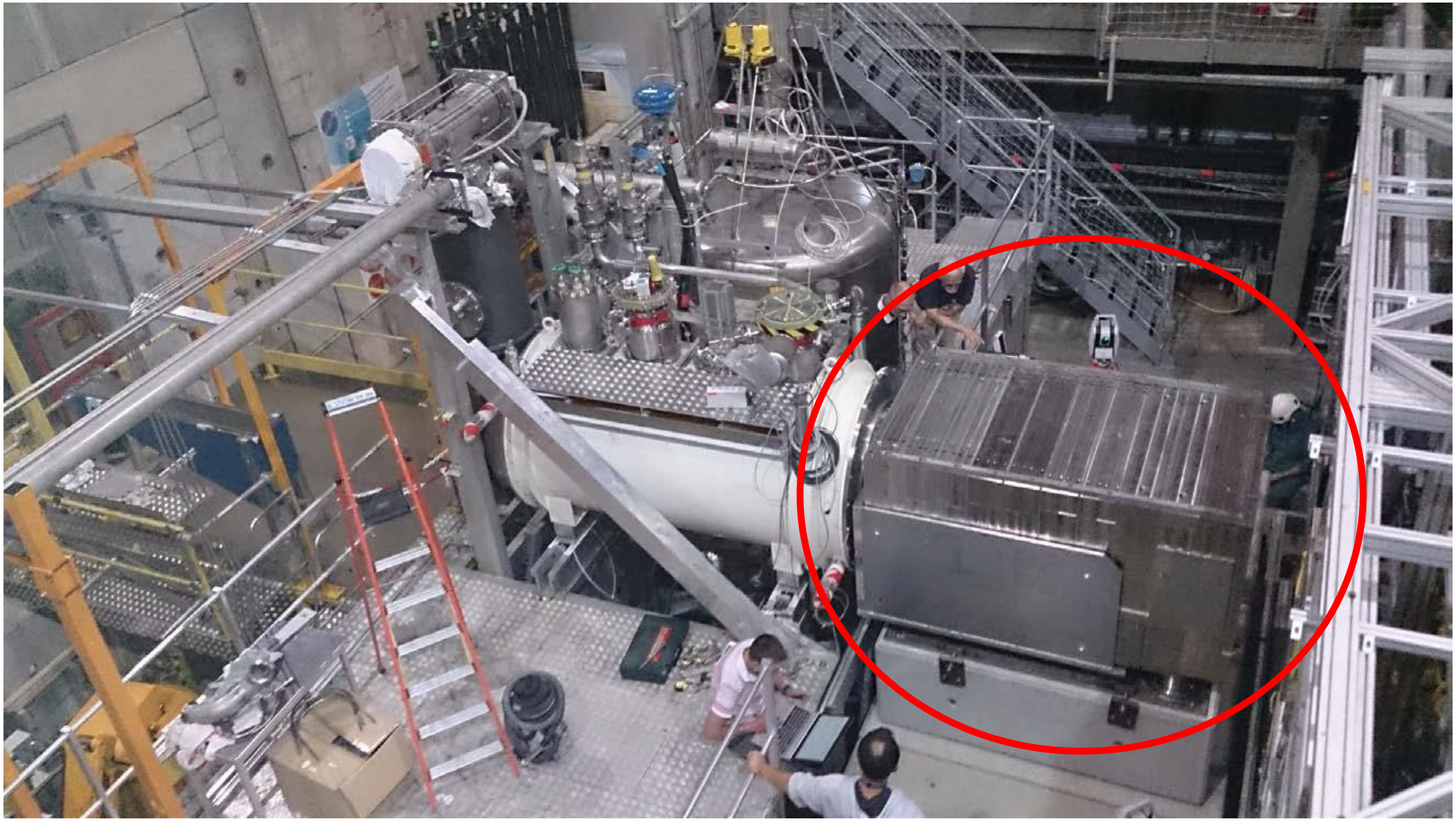


- Absorber: 236 cm long, made of Al_2O_3.
- Radiation lengths (multiple scattering for μ): $x/X_0 = 33.53$
- Hadronic interaction lengths (stopping power for π): $x/\lambda_{int} = 7.25$
- 7 cm Al target
- 120 cm W beam dump

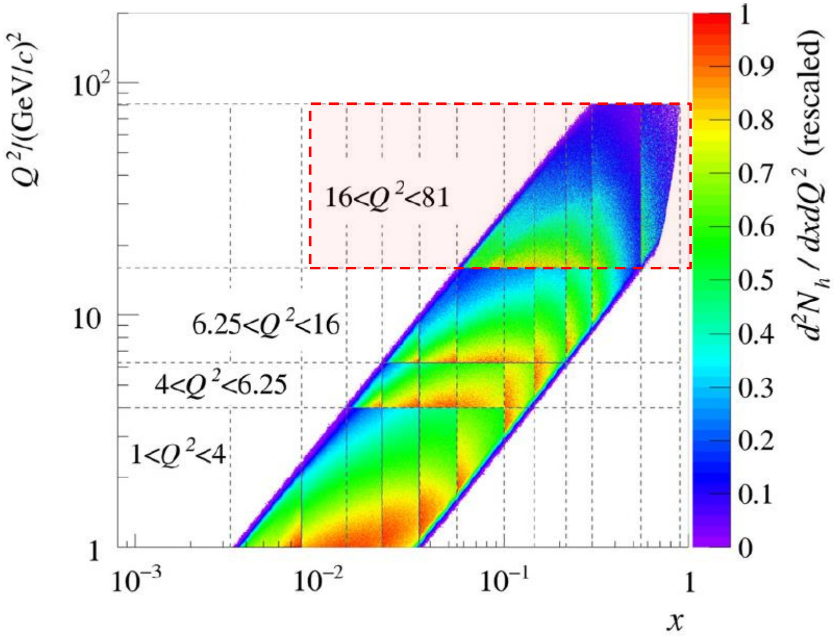


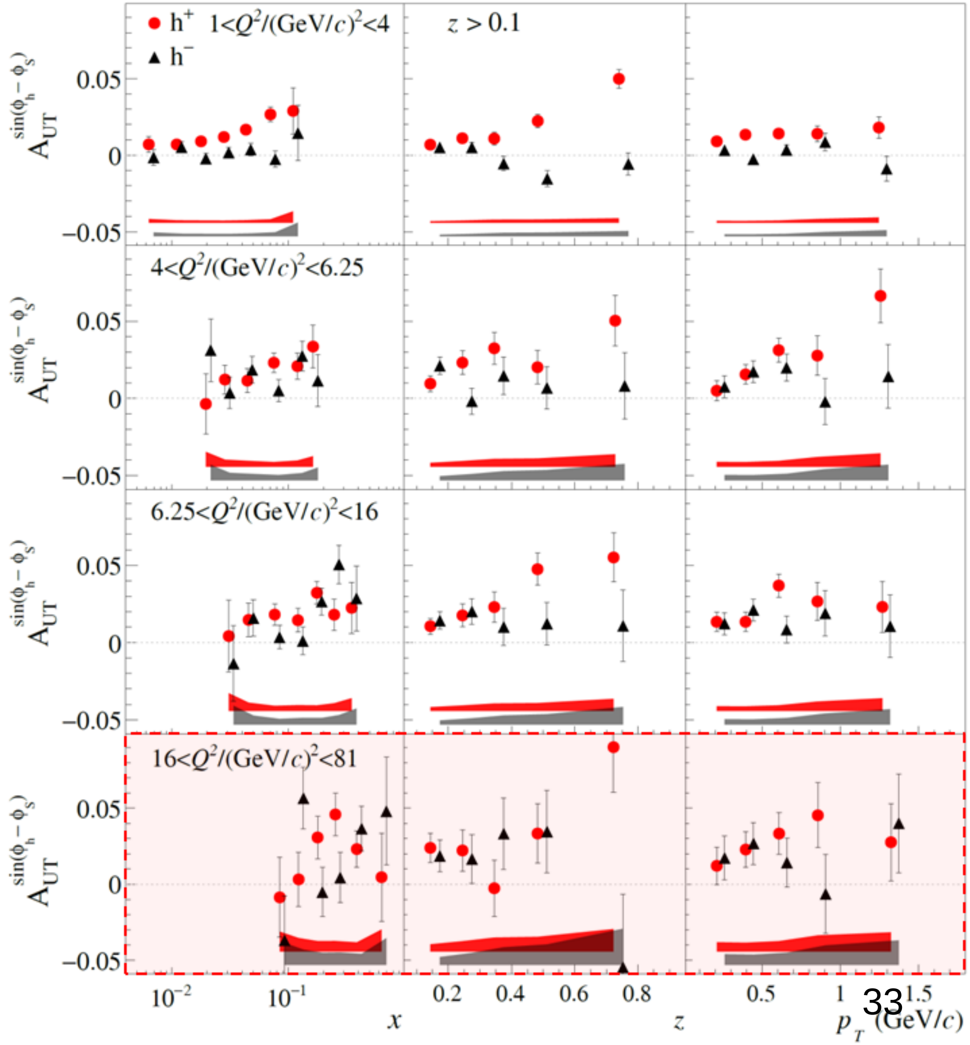


Hadron Absorber & Nuclear Targets



Sivers Asymmetries (x, z, p_T^h, Q^2) in SIDIS





Sivers asymmetry extracted in SIDIS at the hard scales of the Drell–Yan process at COMPASS

COMPASS, PLB 770 (2017) 138

COMPASS-II Transversely Polarized Drell-Yan Program

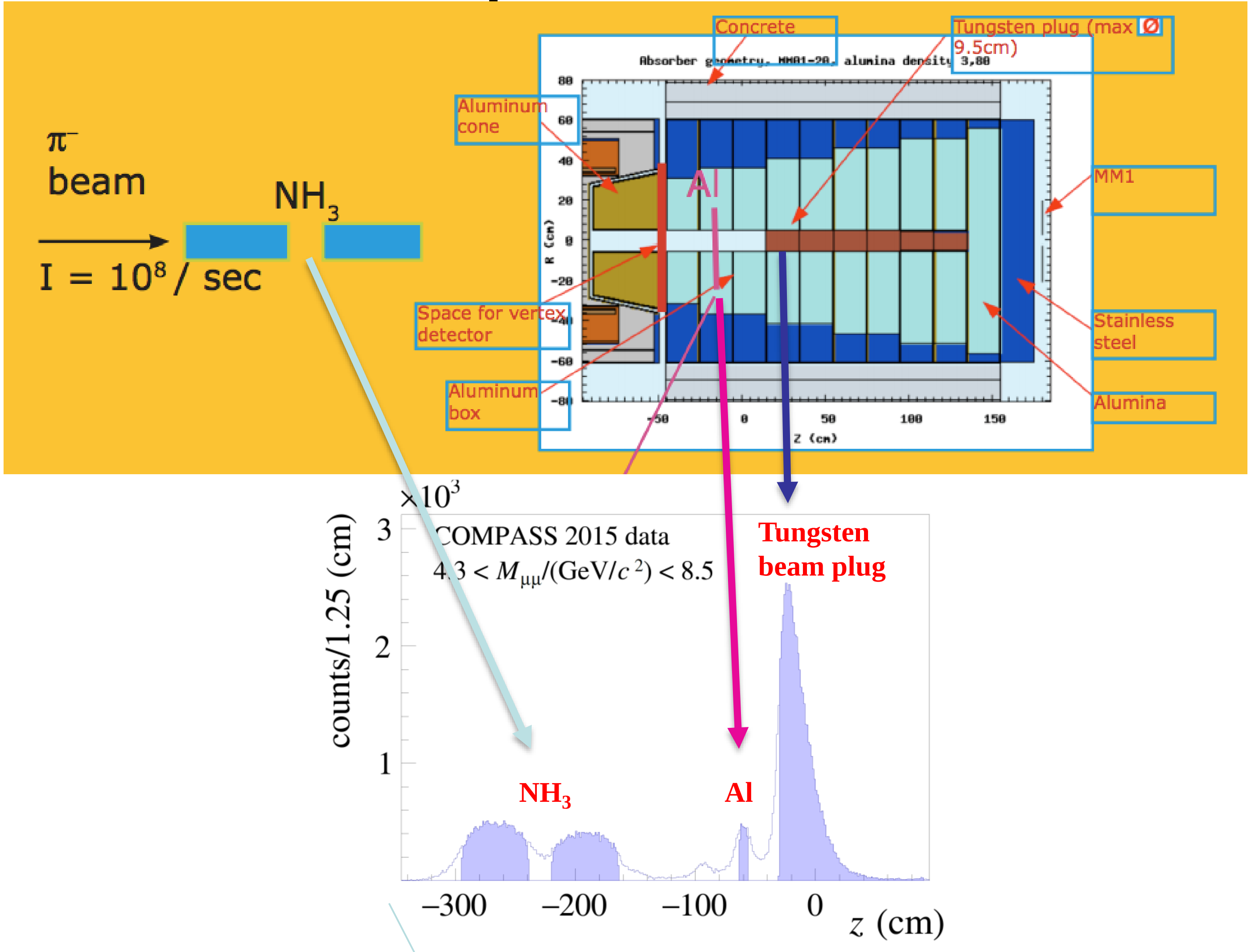
- Schedules:
  - 2014 Oct – Dec: commission Drell-Yan runs
  - 2015: first year of transversely polarized Drell-Yan runs with 190 GeV π^- beam

PRL **119,** 112002 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

First Measurement of Transverse-Spin-Dependent Azimuthal Asymmetries in the Drell-Yan Process

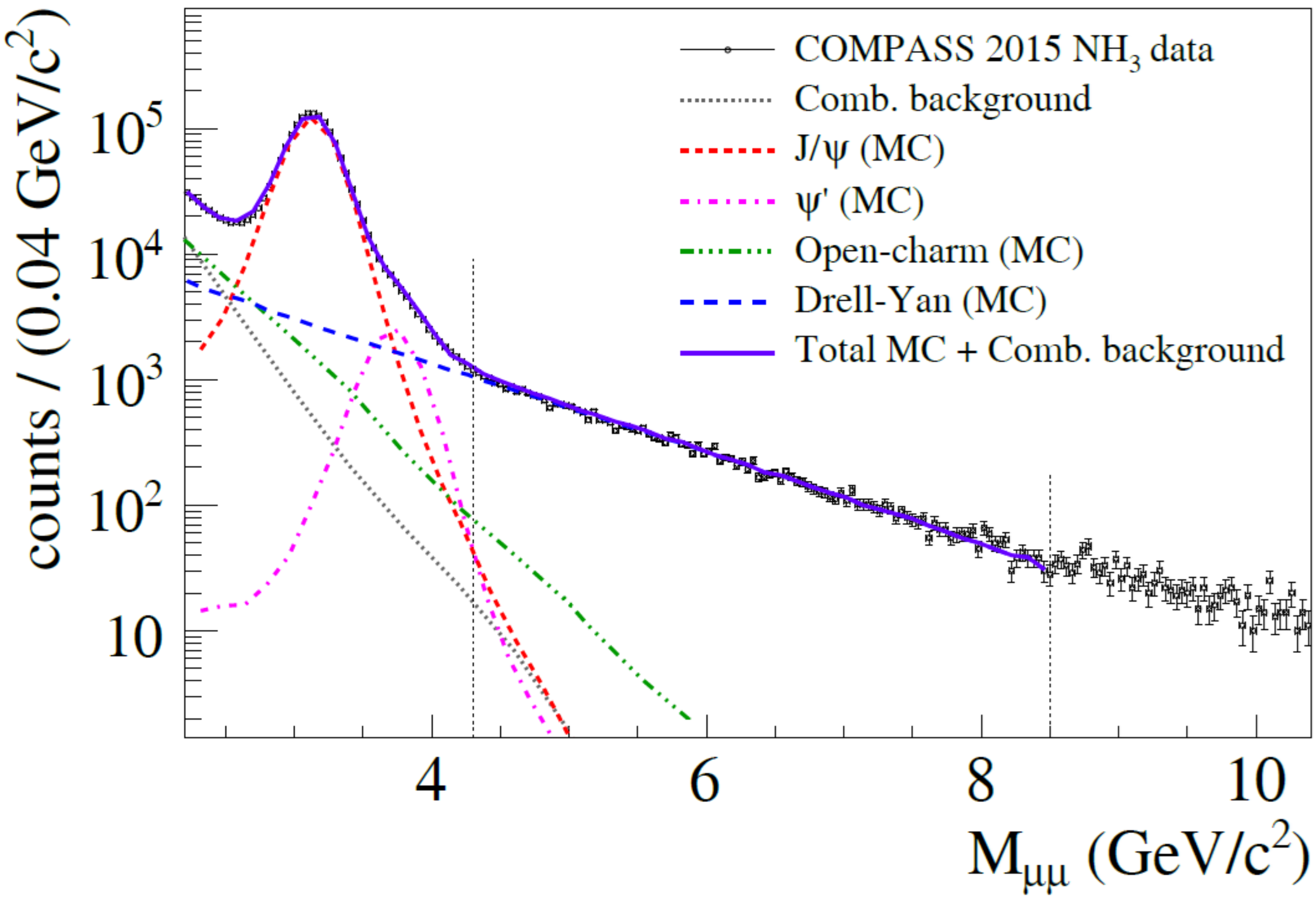
M. Aghasyan,[24] R. Akhunzyanov,[7] G. D. Alexeev,[7] M. G. Alexeev,[25] A. Amoroso,[25,26] V. Andrieux,[27,20] N. V. Anfimov,[7] V. Anosov,[7] A. Antoshkin,[7] K. Augsten,[7,18] W. Augustyniak,[28] A. Austregesilo,[15] C. D. R. Azevedo,[1] B. Badełek,[29] F. Balestra,[25,26] M. Ball,[3] J. Barth,[4] R. Beck,[3] Y. Bedfer,[20] J. Bernhard,[12,9] K. Bicker,[15,9] E. R. Bielert,[9] R. Birsa,[24] M. Bodlak,[17] P. Bordalo,[11,b] F. Bradamante,[23,24] A. Bressan,[23,24] M. Büchele,[8] W.-C. Chang,[21] C. Chatterjee,[6] M. Chiosso,[25,26] I. Choi,[27] S.-U. Chung,[15,c] A. Cicuttin,[24,d] M. L. Crespo,[24,d] S. Dalla Torre,[24] S. S. Dasgupta,[6]

Dimuon Vertex Distributions (2015 Trans.-pol. Drell-Yan Runs)



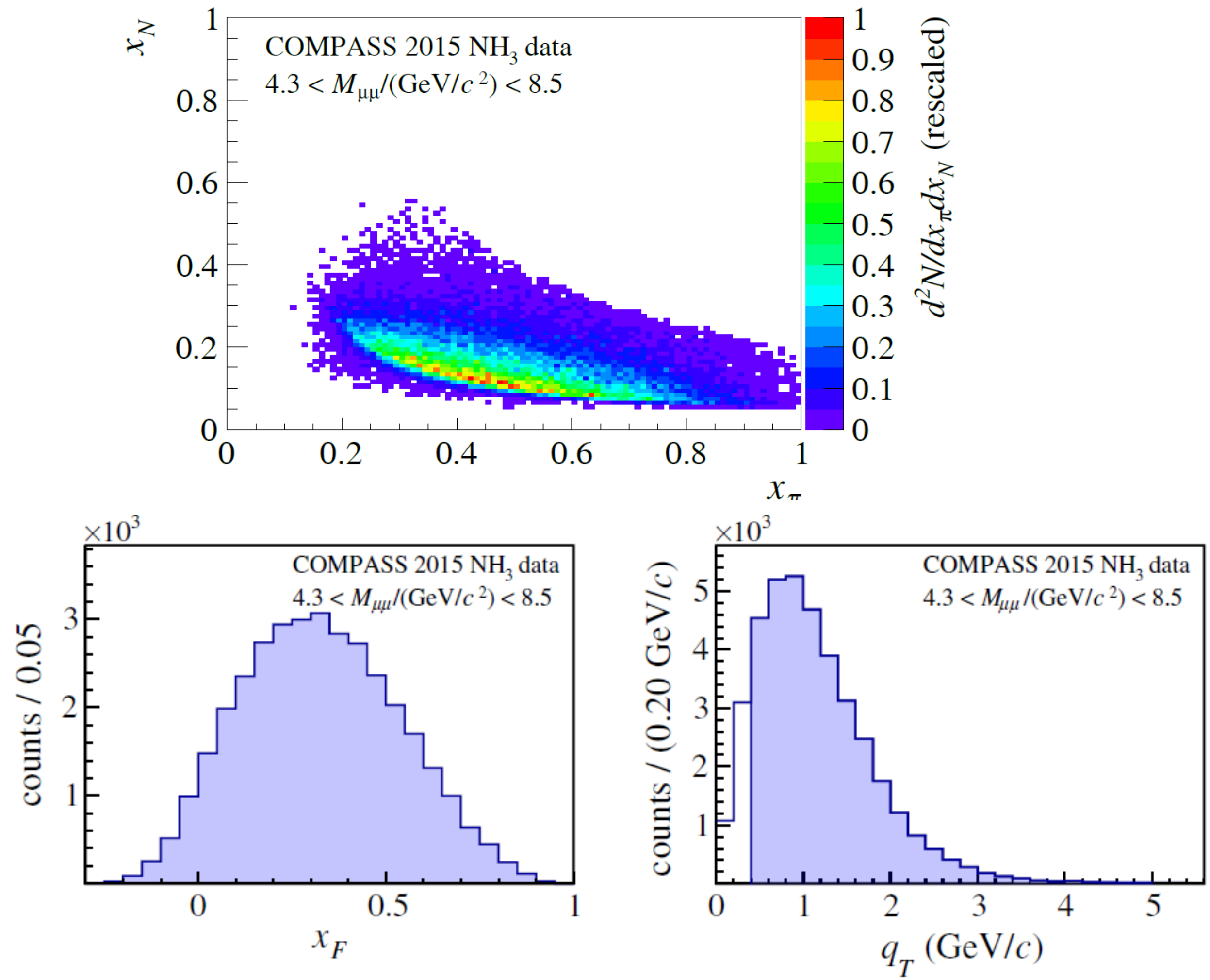
COMPASS, PRL 119 (2017) 112002

Dimuon Invariant-mass Distributions (2015 Trans.-pol. Drell-Yan Runs)



COMPASS, PRL 119 (2017) 112002

Kinematic Acceptance
(2015 Trans.-pol. Drell-Yan Runs)



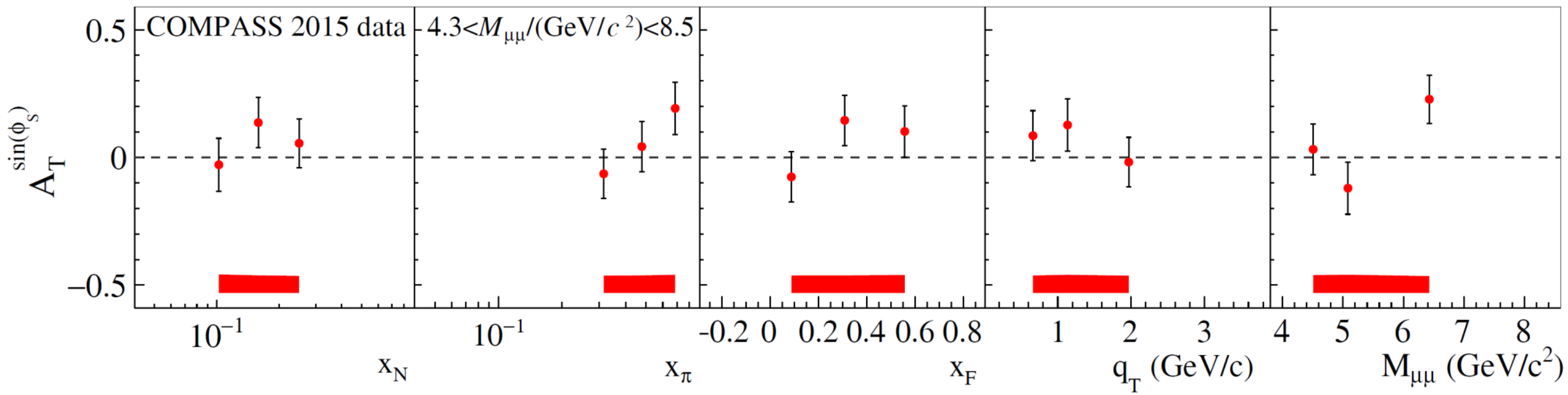
COMPASS, PRL 119 (2017) 112002

Transverse Spin Asymmetries in Trans.-pol. Drell-Yan: Sivers

$$\frac{d\sigma^{LO}}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U^{LO}$$

$$A_T^{\sin\phi_s} \propto \text{Density } f_1|_\pi \otimes \text{Sivers } f_{1T}^\perp|_p$$

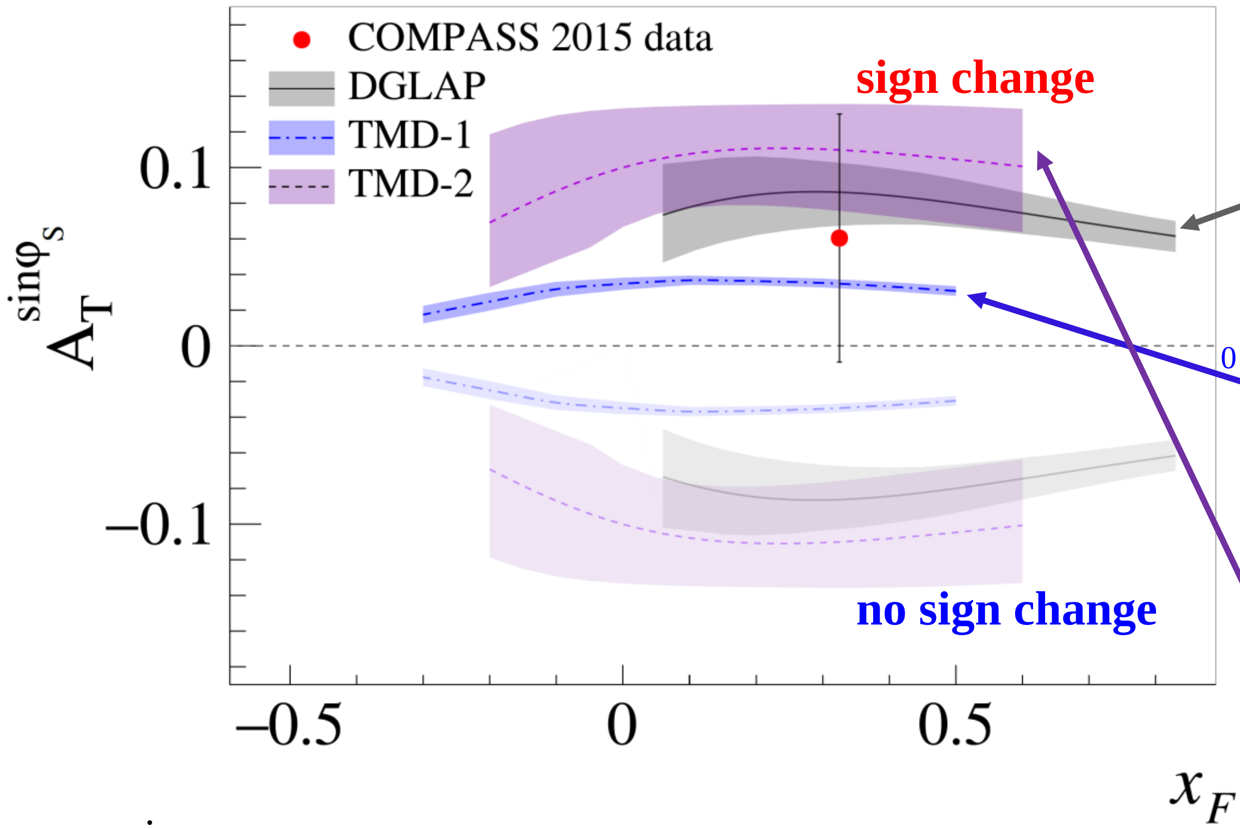
$$\left\{ \left(1 + D_{[\sin^2\theta]}^{LO} A_U^{\cos 2\varphi} \cos 2\varphi\right) + \left|\vec{S}_T\right| \left[\boxed{A_T^{\sin\varphi_S}} \sin\varphi_S + D_{[\sin^2\theta]}^{LO} \left(A_T^{\sin(2\varphi-\varphi_S)} \sin(2\varphi-\varphi_S) + A_T^{\sin(2\varphi+\varphi_S)} \sin(2\varphi+\varphi_S) \right) \right] \right\}$$



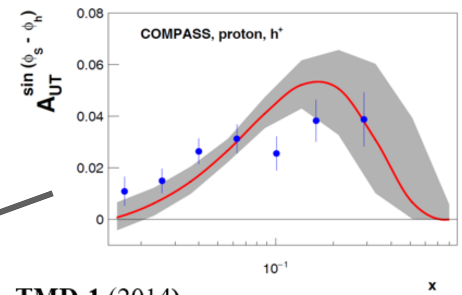
COMPASS, PRL 119 (2017) 112002

Sivers Asymmetry in Drell-Yan: Hint of Sign Change!

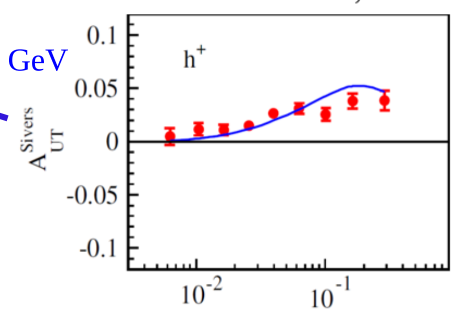
COMPASS, PRL 119 (2017) 112002



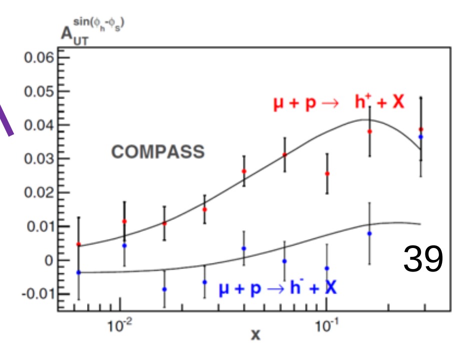
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



$$A_T^{\sin\varphi_s} = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$$

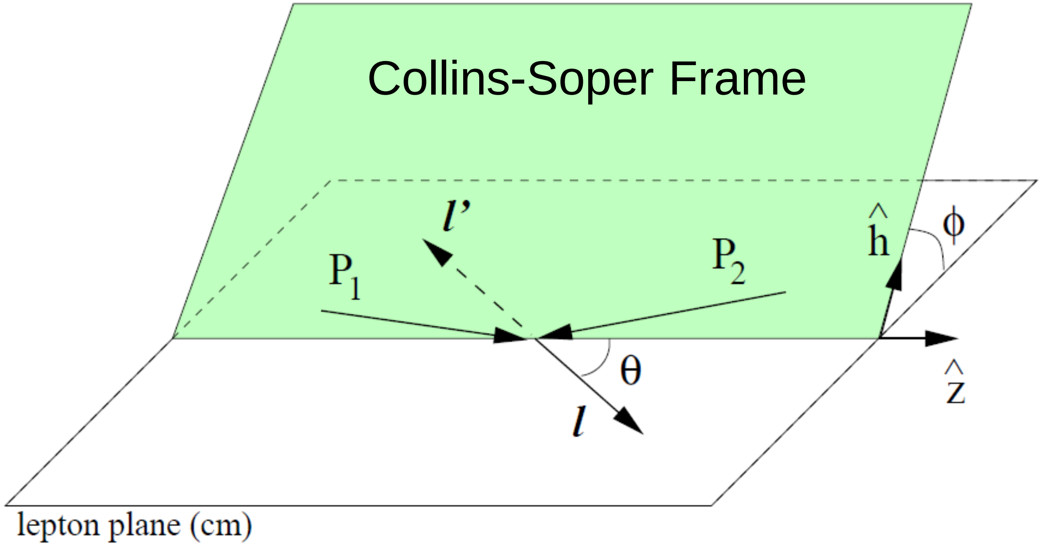
2018: Polarized Drell-Yan program (improved statistics errors of Sivers asymmetries are expected).

Angular Distribution in the "Naïve" Drell-Yan

VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

(3) The virtual photon will be predominantly transversely polarized if it is formed by annihilation of spin-$\frac{1}{2}$ parton-antiparton pairs. This means a distribution in the di-muon rest system varying $\boxed{\text{as } (1+\cos^2\theta) \text{ rather than } \sin^2\theta}$ as found in Sakurai's[10] vector-dominance model, where θ is the angle of the muon with respect to the time-like photon momentum. The model used in Fig.

Angular Distributions of Lepton Pairs



$$\lambda = \frac{2-3A_0}{2+A_0}$$

$$\mu = \frac{2A_1}{2+A_0}$$

$$\nu = \frac{2A_2}{2+A_0}$$

$$\frac{d\sigma}{d\Omega} \propto (1+\lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi)$$

$$\propto [(1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi]$$

$q\bar{q}$ annilation parton model: O(α_s^0) λ=1, μ=ν=0; $A_0 = A_2 = 0$

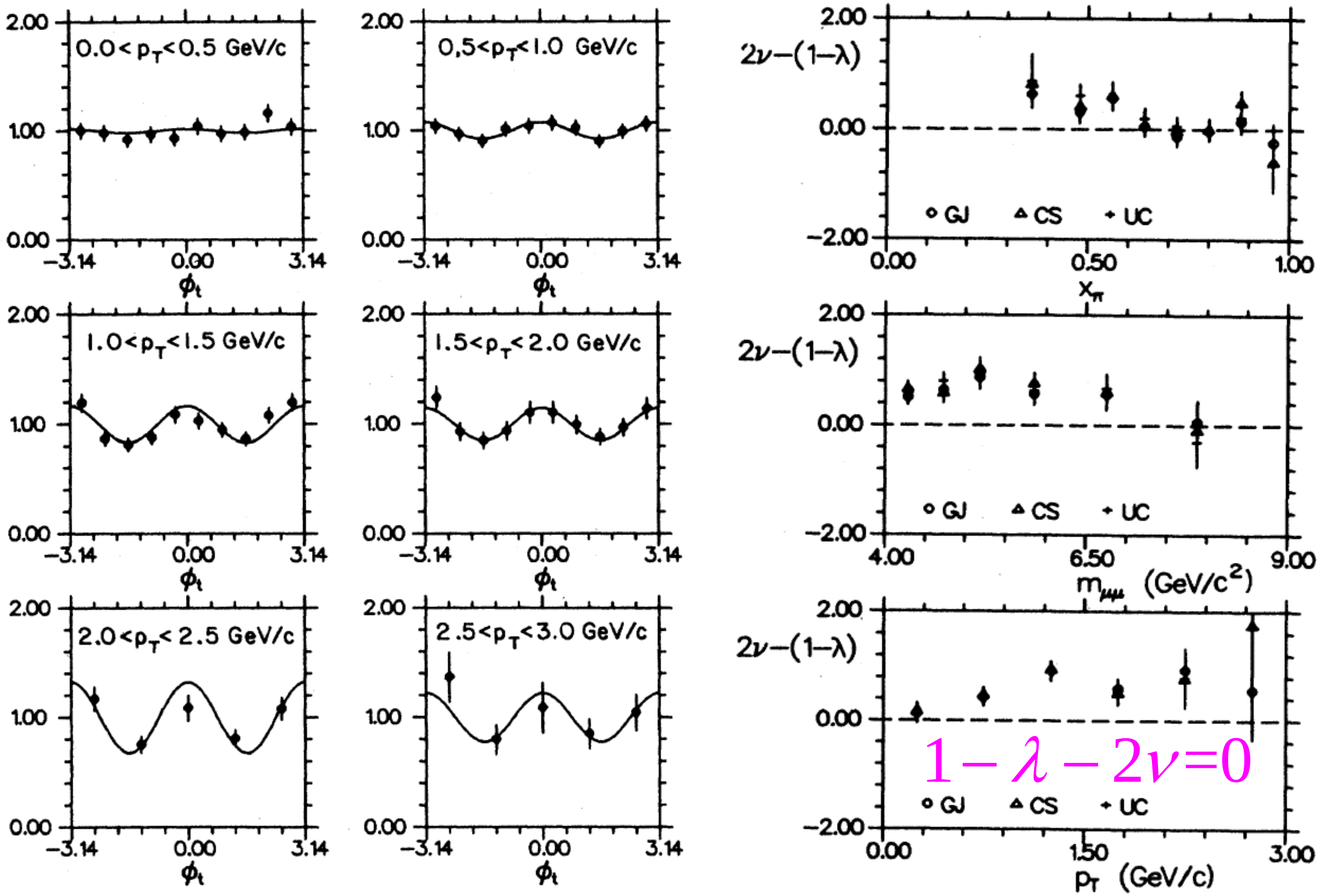
pQCD: O(α_s^1), ; $1-\lambda-2\nu = \frac{4(A_2-A_0)}{2+A_0} = 0$; $A_0 = A_2$

Lam-Tung Relation [PRD 18 (1978) 2447]

E615 @ FNAL: Violation of LT Relation

PRD 39, 92 (1989)

252-GeV π^-+W



$\cos 2\phi$ modulation at large p_T

Leading-Twist Transverse-momentum Dependent **Parton Density Function** (TMDs)

spin of the nucleon

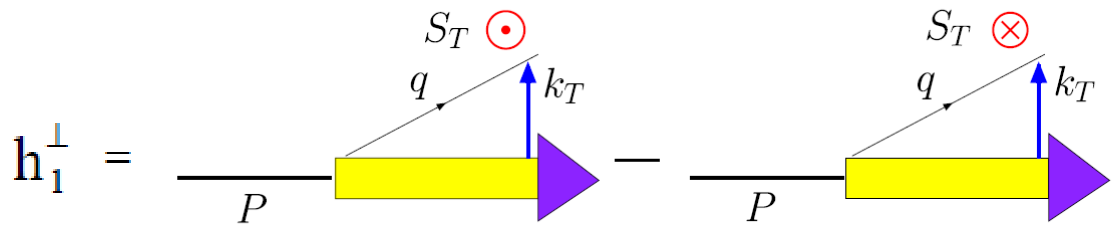
spin of the parton

k_T of the parton

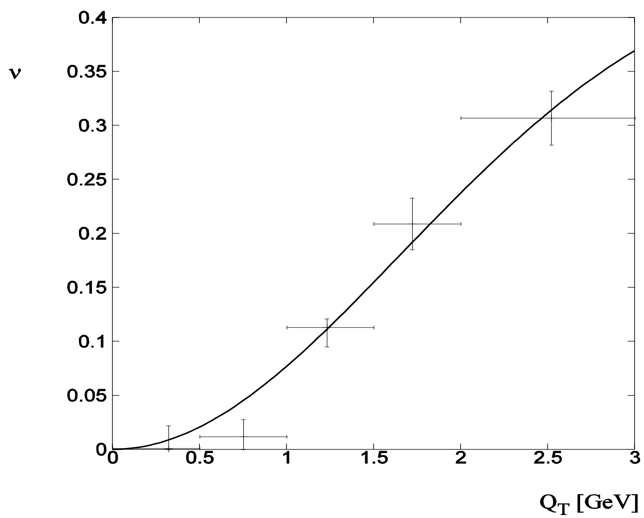
Nucleon \ Quark	U	L	T
U	number density $f_1^{q,g}(x,k_T^2)$		Boer-Mulders $h_1^{\perp q,g}(x,k_T^2)$
L		Helicity $g_{1L}^{q,g}(x,k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x,k_T^2)$
T	Sivers $f_{1T}^{\perp q,g}(x,k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x,k_T^2)$	Transversity $h_1^{q,g}(x,k_T^2)$ Pretzelosity $h_{1T}^{\perp q,g}(x,k_T^2)$

Boer [PRD 60, 014012 (1999)]: Hadronic Effect, Boer-Mulders Functions

Spin-orbit correlation of transversely polarized *noncollinear partons* inside an unpolarized hadron



- Boer-Mulders Function $h_1^{\perp}$: a correlation between quark's k_T and transverse spin S_T in an unpolarized hadron
- $\sigma_{UU} \propto f_1^{(A,\bar{q})} f_1^{(B,q)} + h_1^{\perp(A,\bar{q})} h_1^{\perp(B,q)} \cos 2\phi;\quad \frac{\nu}{2} \propto h_1^{\perp}(N)\overline{h}_1^{\perp}(\pi)$



$$h_1^{\perp}(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x),$$

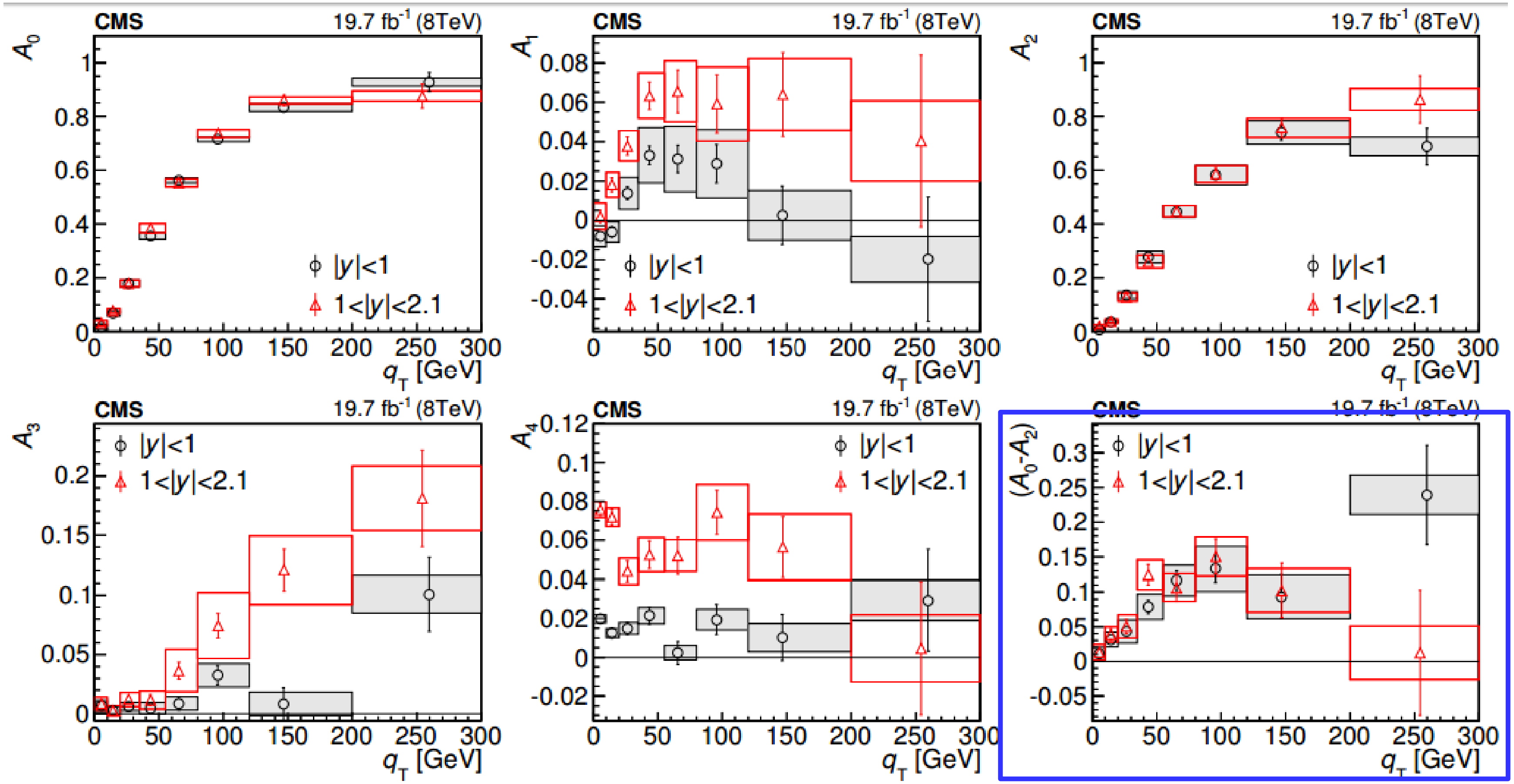
$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2}, \qquad \kappa_1 = C_{H_1} C_{H_2}/2$$

$$\kappa = \frac{\nu}{2} \to 0 \text{ for large } |k_T|$$

Consistency of factorization in term of TMDs

Angular Distributions of Z Production

CMS, PLB750, 154 (2015)



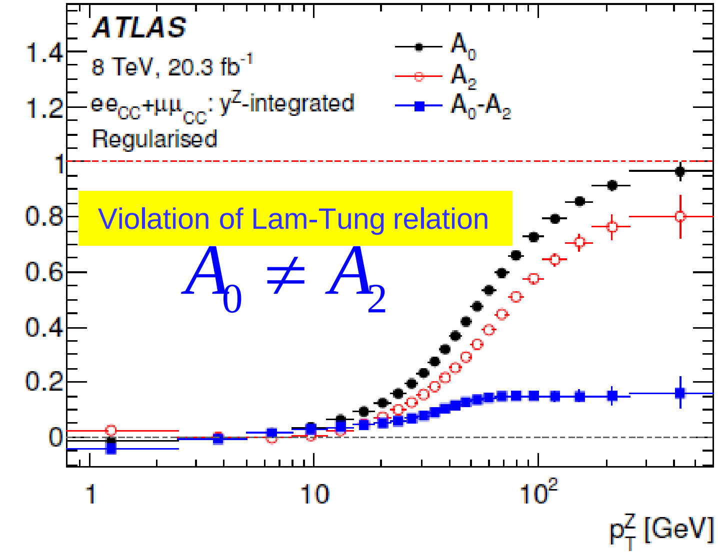
$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \Big[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)$$
$$+A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\Big].$$

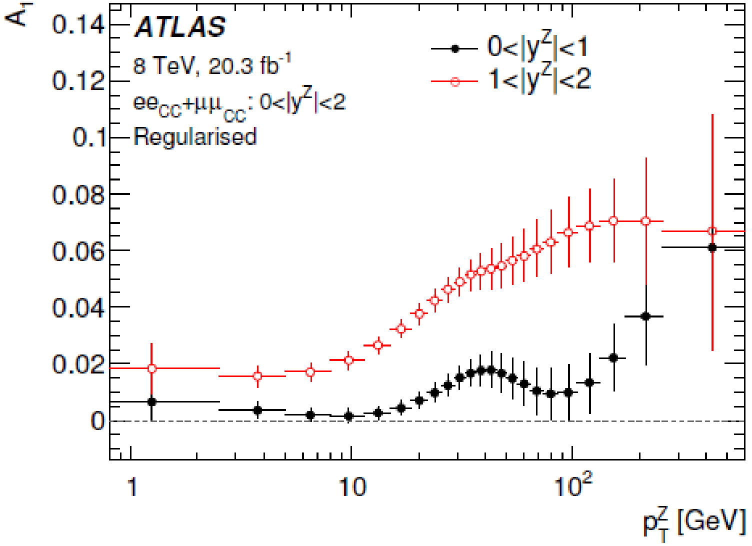
Violation of Lam-Tung relation

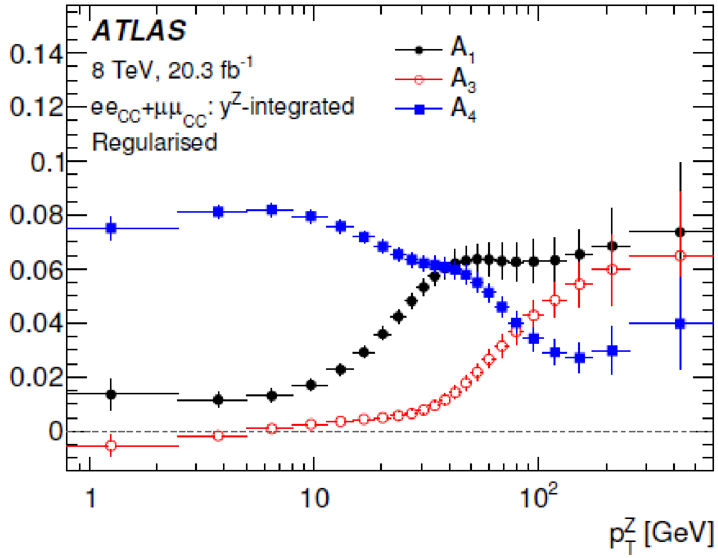
$A_0 \neq A_2$

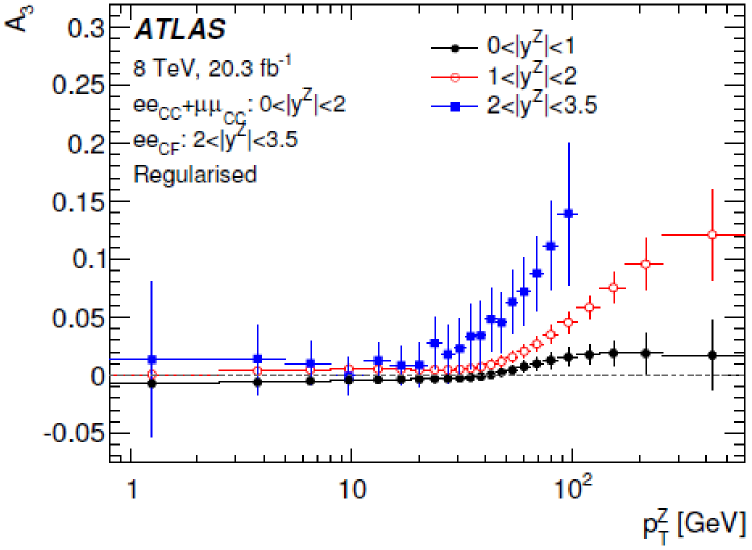
Angular Distributions of Z Production

ATLAS, JHEP08, 159 (2016)





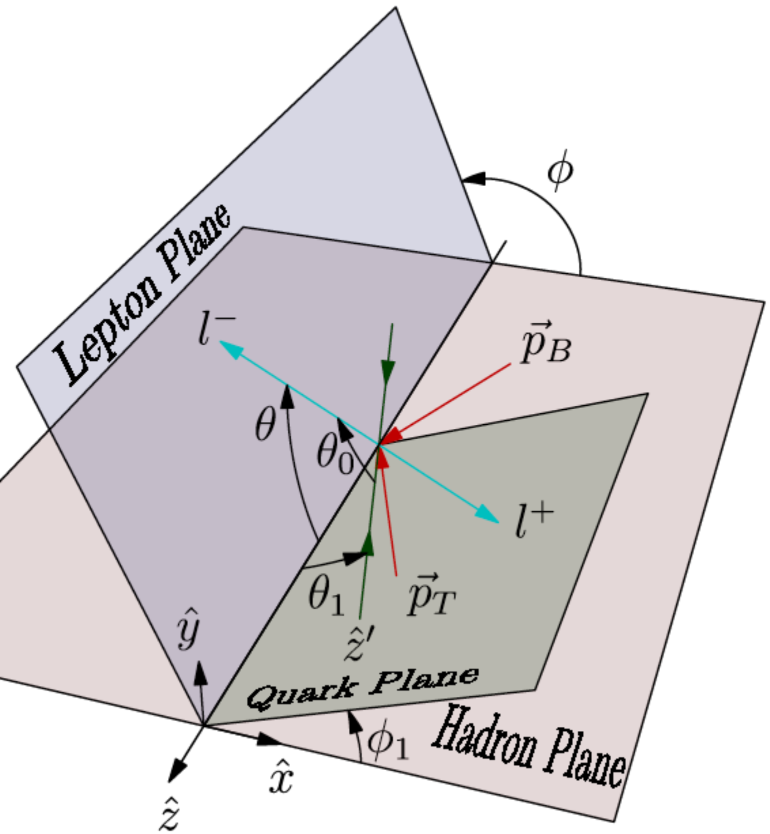




Observations and Interpretations of DY Angular Distributions

- Strong q_T dependence and certain rapidity dependence of A_i (λ, μ, ν).
- Lam-Tung Violation: ($A_0 \neq A_2$)
  - Small q_T:
    - Intrinsic partonic transverse momentum k_T
    - Boer-Mulders functions (Boer 1999)
  - Large q_T:
    - Hard multi-gluon radiation ($O(\alpha_s^2)$ or higher)
- A simple and intuitive interpretation: the geometric picture
  - J.C. Peng, W.C. Chang, R.E. McClellan, O. Teryaev Phys. Lett. B 758, 394 (2016).
  - W.C. Chang, R.E. McClellan, J.C. Peng, O. Teryaev Phys. Rev. D 96, 054020 (2017).

How is the angular distribution expression derived?



Collins-Soper (γ^*/Z rest) Frame

<u>Define three planes in the Collins-Soper frame</u>

1) Hadron Plane ($\vec{P}_B \times \vec{P}_T$)

- Contains the beam $\vec{P}_B$ and target $\vec{P}_T$ momenta
- Angle β satisfies the relation $\tan\beta = q_T / Q$

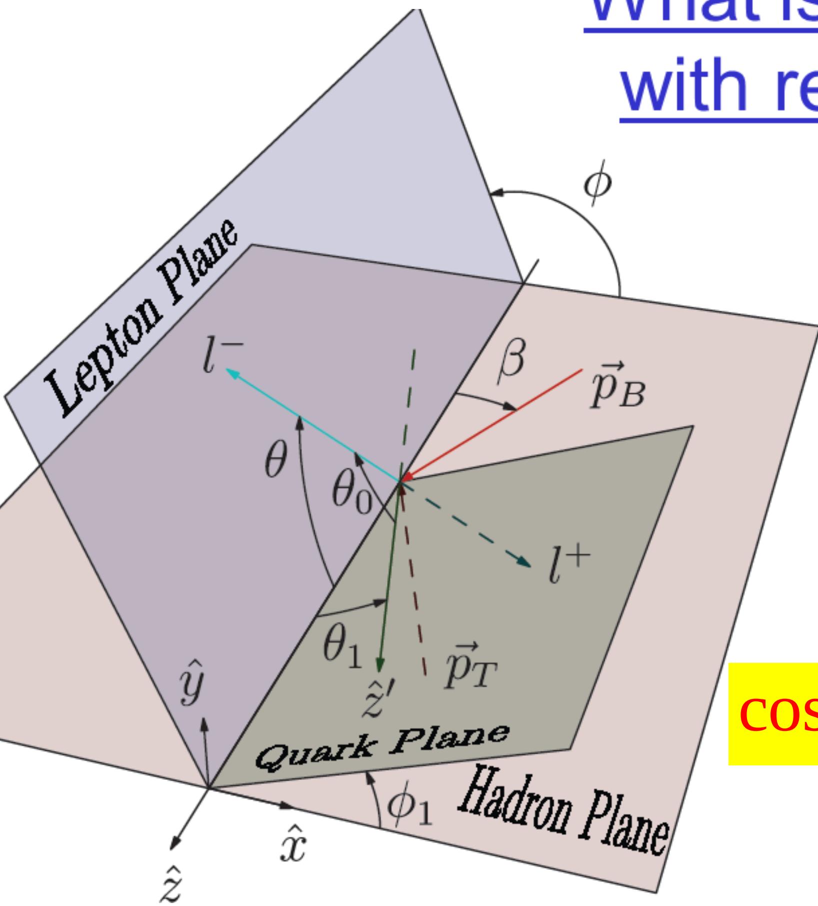
2) Quark Plane ($\hat{z}' \times \hat{z}$)

- q and $\overline{q}$ have head-on collision along the $\hat{z}'$ axis
- $\hat{z}'$ axis has angles θ_1 and φ_1 in the C-S frame

3) Lepton Plane ($\overrightarrow{l^-} \times \hat{z}$)

- l^- and l^+ are emitted back-to-back with equal $|\vec{P}|$
- l^- is emitted at angle θ and φ in the C-S frame

How is the angular distribution expression derived?



What is the lepton angular distribution with respect to the $\hat{z}'$ (natural) axis?

$$\frac{d\sigma}{d\Omega} \propto 1 + a\cos\theta_0 + \cos^2\theta_0$$

a: forward-backward asymmetry coefficient

How to express the angular distribution in terms of θ and Φ?

$$\cos\theta_0 = \cos\theta\cos\theta_1 + \sin\theta\sin\theta_1\cos(\phi - \phi_1)$$

How is the angular distribution expression derived?

$$
\begin{aligned}
\frac{d\sigma}{d\Omega} \propto\ & (1+\cos^2\theta) + \frac{\sin^2\theta_1}{2}(1-3\cos^2\theta) \\
&+ (\frac{1}{2}\sin 2\theta_1 \cos\phi_1)\sin 2\theta\cos\phi \\
&+ (\frac{1}{2}\sin^2\theta_1 \cos 2\phi_1)\sin^2\theta\cos 2\phi \\
&+ (a\sin\theta_1\cos\phi_1)\sin\theta\cos\phi + (a\cos\theta_1)\cos\theta \\
&+ (\frac{1}{2}\sin^2\theta_1 \sin 2\phi_1)\sin^2\theta\sin 2\phi \\
&+ (\frac{1}{2}\sin 2\theta_1 \sin\phi_1)\sin 2\theta\sin\phi \\
&+ (a\sin\theta_1\sin\phi_1)\sin\theta\sin\phi.
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\sigma}{d\Omega} \propto\ & (1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) \\
&+ A_1 \sin 2\theta\cos\phi \\
&+ \frac{A_2}{2}\sin^2\theta\cos 2\phi \\
&+ A_3\sin\theta\cos\phi + A_4\cos\theta \\
&+ A_5\sin^2\theta\sin 2\phi \\
&+ A_6\sin 2\theta\sin\phi \\
&+ A_7\sin\theta\sin\phi.
\end{aligned}
$$

$A_0 - A_7$ are entirely described by θ_1, φ_1 and a.

Some implications of the angular distribution coefficients $A_0 - A_7$

$$A_0 = \langle \sin^2\theta_1 \rangle$$

$$A_1 = \frac{1}{2}\langle \sin 2\theta_1 \cos\phi_1 \rangle$$

$$A_2 = \langle \sin^2\theta_1 \cos 2\phi_1 \rangle$$

$$A_3 = a\langle \sin\theta_1 \cos\phi_1 \rangle$$

$$A_4 = a\langle \cos\theta_1 \rangle$$

$$A_5 = \frac{1}{2}\langle \sin^2\theta_1 \sin 2\phi_1 \rangle$$

$$A_6 = \frac{1}{2}\langle \sin 2\theta_1 \sin\phi_1 \rangle$$

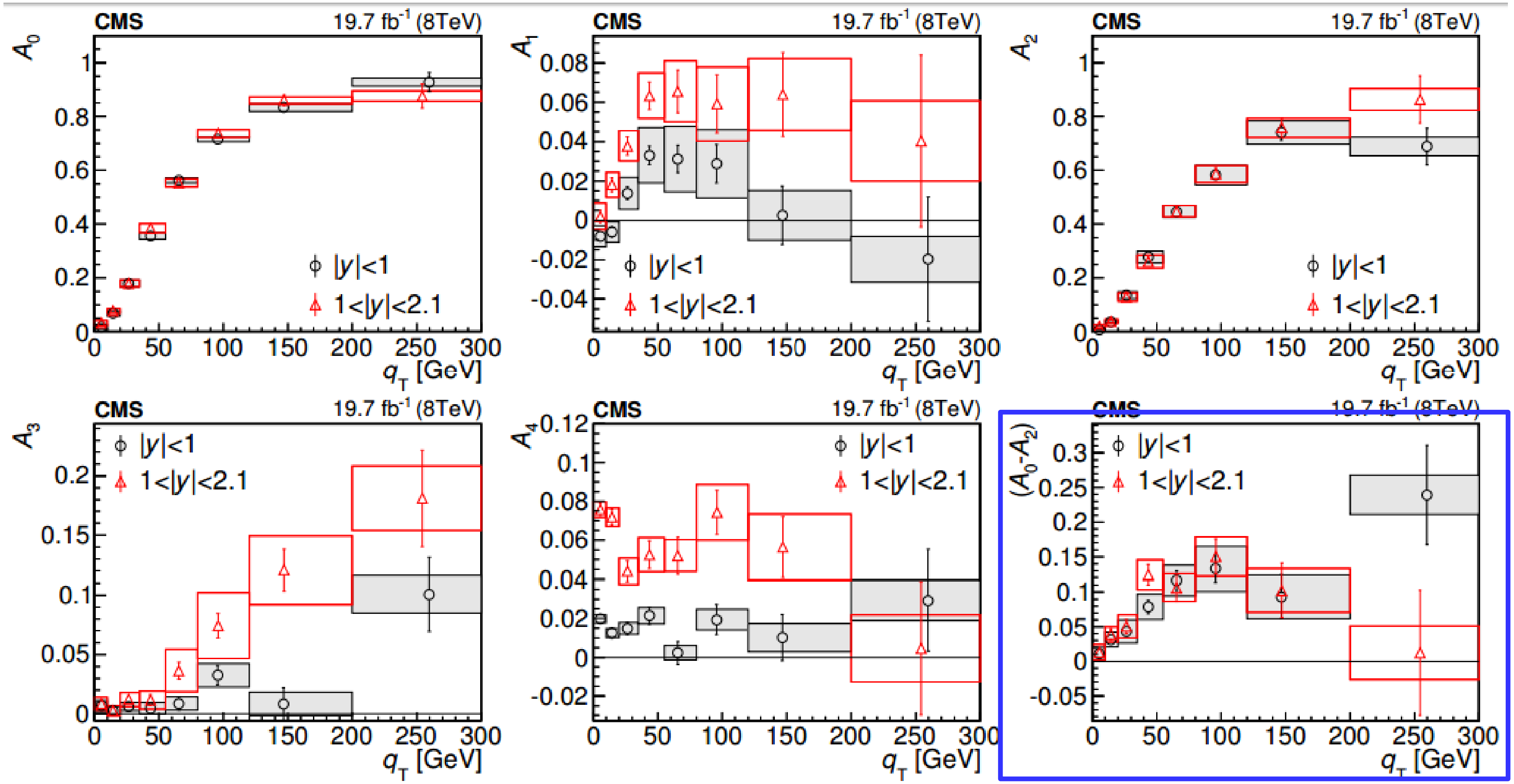
$$A_7 = a\langle \sin\theta_1 \sin\phi_1 \rangle$$

$$\boxed{\tan\theta_1 = q_T / Q}$$

- $A_0 \geq A_2$ (or $1 - \lambda - 2\nu \geq 0$)
- Lam-Tung relation ($A_0 = A_2$) is satisfied when $\phi_1 = 0$.
- Forward-backward asymmetry, a, is reduced by a factor of $\langle \cos\theta_1 \rangle$ for A_4.
- A_5, A_6, A_7 are odd functions of ϕ_1 and must vanish from symmetry consideration.
- A_0, A_2 and A_3 increase with q_T monotonically while A_4 decreases with q_T monotonically.
- A_1 ($\propto \langle \sin 2\theta \rangle$) first increases with q_T, reaching a maximum, and then decrease.
- Some equality and inequality relations among $A_0 - A_7$ can be obatined.

Angular Distributions of Z Production

CMS, PLB750, 154 (2015)



$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \Big[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)$$

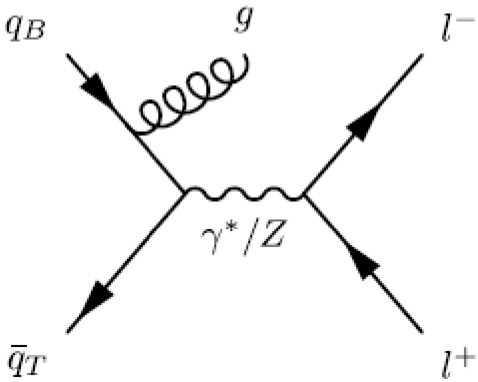
$$+A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\Big].$$

Violation of Lam-Tung relation

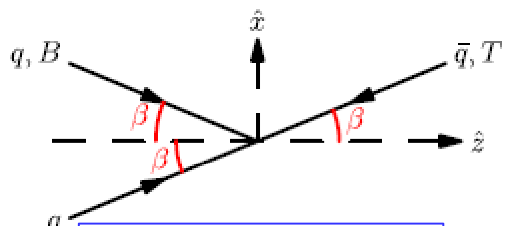
$$A_0 \neq A_2$$

θ_1 and ϕ_1 at $O(\alpha_s^1)$: $q\bar{q} \to \gamma^*/Zg$

Collins-Soper (γ^*/Z rest) Frame

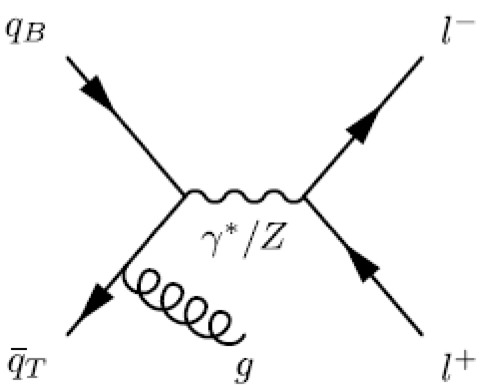


(a)

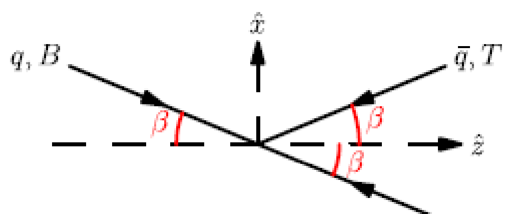


$$\boxed{\theta_1 = \beta;\ \phi_1 = 0}$$

(b)



(c)



$$\boxed{\theta_1 = \beta;\ \phi_1 = \pi}$$

(d)

$$A_0^{q\bar{q}} = \frac{q_T^2}{Q^2 + q_T^2} \text{ (Collins 1979)}$$

$$A_0 = A_2 = \left\langle \sin^2\theta_1 \right\rangle = \frac{q_T^2}{Q^2 + q_T^2} > 0$$

$$\lambda = \frac{2 - 3A_0}{2 + A_0} = \frac{2Q^2 - q_T^2}{2Q^2 + 3q_T^2}$$

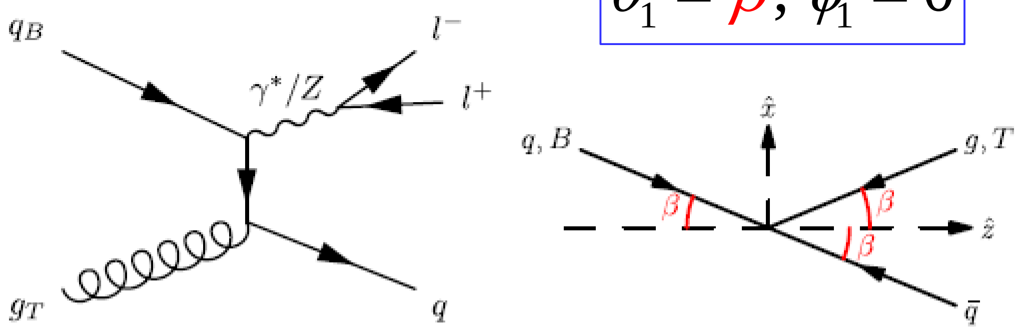
$$\nu = \frac{2A_2}{2 + A_0} = \frac{2q_T^2}{2Q^2 + 3q_T^2}$$

θ_1 and ϕ_1 at $O(\alpha_s^1)$: $qg \to \gamma^*/Zq$

Collins-Soper (γ^*/Z rest) Frame

$$A_0^{qg} = \frac{5q_T^2}{Q^2 + 5q_T^2} \text{ (Thews 1979)}$$

$$\boxed{\theta_1 = \beta;\ \phi_1 = 0}$$

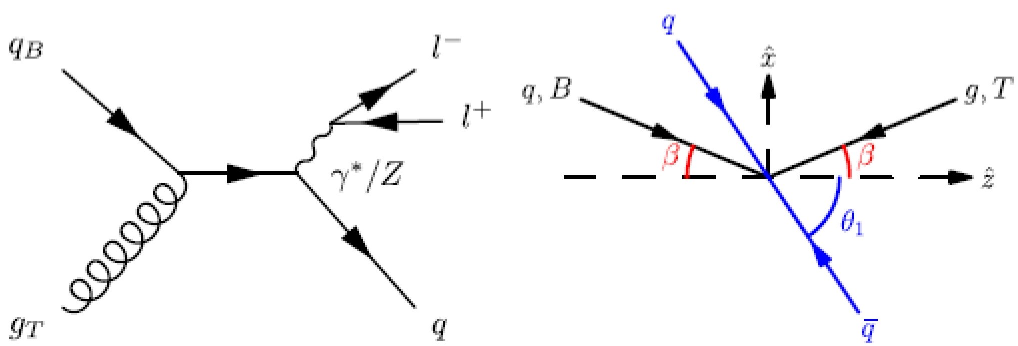


(a) (b)

$$A_0 = A_2 = \langle \sin^2\theta_1 \rangle \approx \frac{5q_T^2}{Q^2 + 5q_T^2} > 0$$

$$\lambda = \frac{2 - 3A_0}{2 + A_0} = \frac{2Q^2 - 5q_T^2}{2Q^2 + 15q_T^2}$$

$$\nu = \frac{2A_2}{2 + A_0} = \frac{10q_T^2}{2Q^2 + 15q_T^2}$$

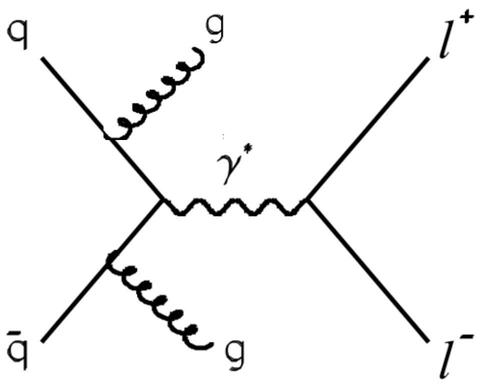


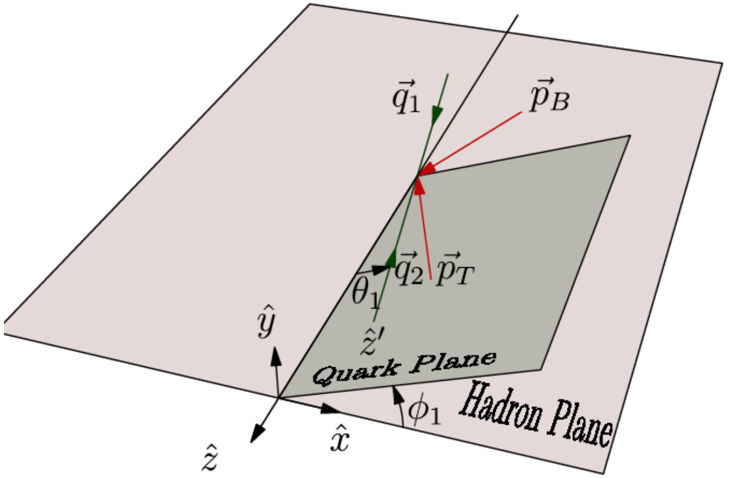
(c) (d)

$$\boxed{\theta_1 > \beta;\ \phi_1 = 0}$$

Origins of the non-coplanarity

1) Processes at order α_s^2 or higher



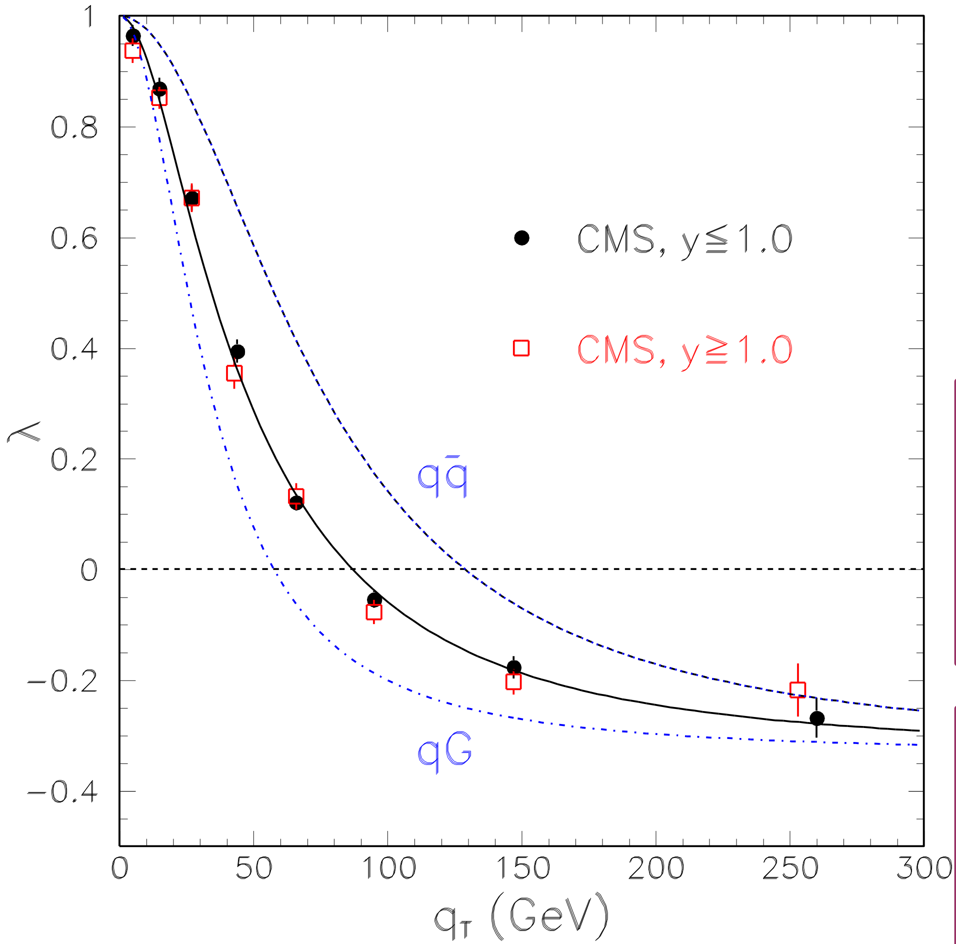


$q-\bar{q}$ axis is non-coplanar relative to the hadron plane

2) Intrinsic k_T from interacting partons

Compare with CMS data on λ

(Z production in p+p collision at 8 TeV)



$$\lambda = \frac{2Q^2 - q_T^2}{2Q^2 + 3q_T^2} \quad \text{for} \quad q\bar{q} \to ZG$$

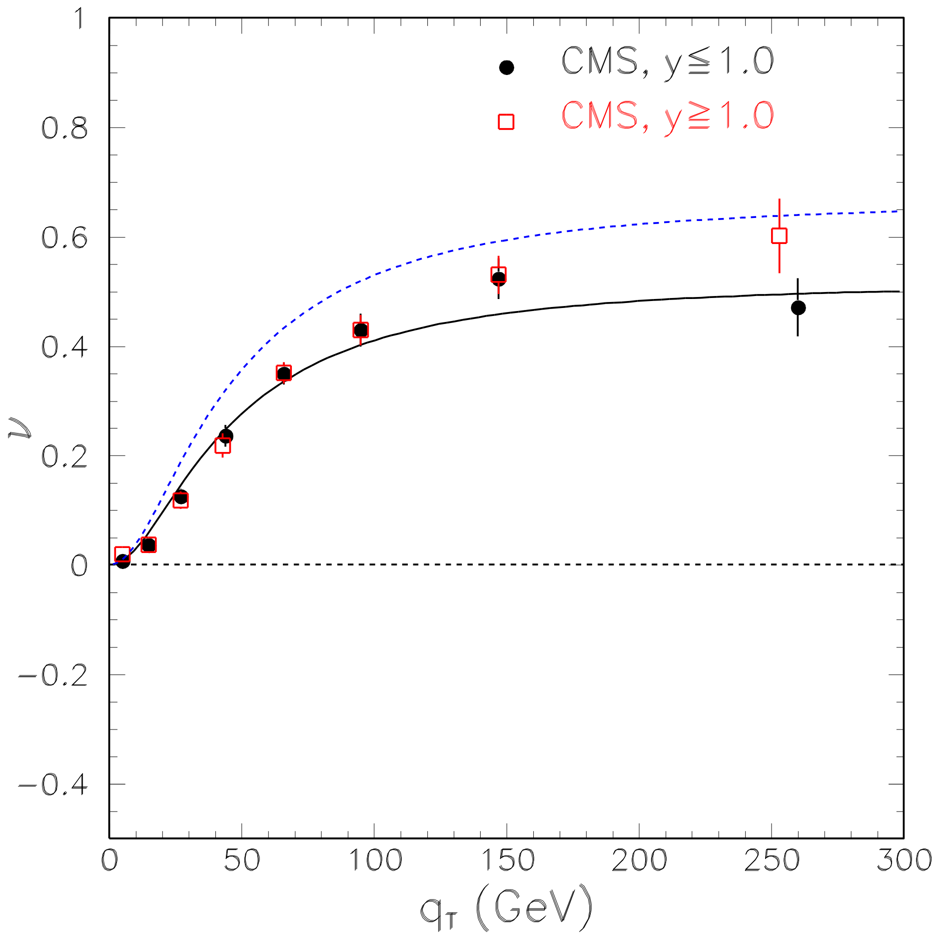
$$\lambda = \frac{2Q^2 - 5q_T^2}{2Q^2 + 15q_T^2} \quad \text{for} \quad qG \to Zq$$

For both processes
λ = 1 at q_T = 0 (θ_1=0°)
λ = -1/3 at q_T = ∞ (θ_1=90°)

Data can be well described with a mixture of 58.5% qG and 41.5% $q\bar{q}$ processes

Compare with CMS data on ν

(*Z* production in *p*+*p* collision at 8 TeV)



$$\nu = \frac{2q_T^2}{2Q^2 + 3q_T^2} \quad \text{for} \quad q\bar{q} \to ZG$$

$$\nu = \frac{10q_T^2}{2Q^2 + 15q_T^2} \quad \text{for} \quad qG \to Zq$$

Dashed curve corresponds to a mixture of 58.5% qG and 41.5% $q\bar{q}$ processes

Solid curve corresponds to

$$\left\langle \sin^2\theta_1 \cos 2\phi_1 \right\rangle / \left\langle \sin^2\theta_1 \right\rangle = 0.77$$

$q - \bar{q}$ axis is non-coplanar relative to the hadron plane

Summary

- Unique information of the x-dependence of sea quark flavor structure has been obtained with Drell-Yan experiments. SeaQuest experiment will extend the measurement of $\bar{d}(x)/\bar{u}(x)$ to the large-x regions.
- COMPASS experiment has found that DY Sivers asymmetry is consistent with the predicted sign change. It provides a further good understanding of transverse orbital motion of valence quarks.
- Violation of the Lam-Tung relation is observed at large-q_T regions of Z production. It could be interpreted by the non-coplanarity effects induced by the higher-order QCD processes.