Polarized Drell-Yan at COMPASS-II: Transverse Spin Physics Program

BAKUR PARSAMYAN

University of Turin and INFN section of Turin

on behalf of the COMPASS Collaboration

UNIVERSITÀ DEGLI STUDI DI TORINO

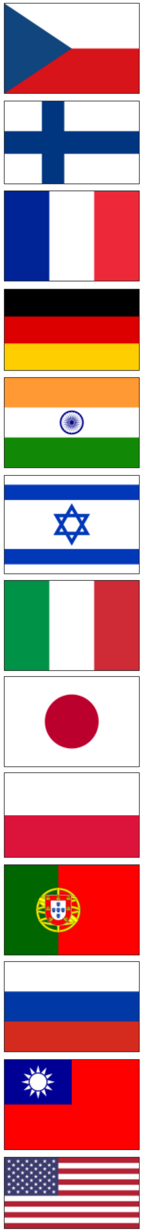
ALMA UNIVERSITAS TAURINENSIS

The 21st International Symposium on Spin Physics (Spin2014)

Beijing, China

October 20 - 24, 2014

COMPASS collaboration



24 institutions from 13 countries – nearly 250 physicists

Common **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

- **CERN SPS north area**
- **Fixed target experiment**
- **Taking data since 2002**

Wide physics program

COMPASS-I

- **Muon and hadron beams**
- **Nucleon spin structure**
- **Spectroscopy**

COMPASS-I talks at SPIN2014:

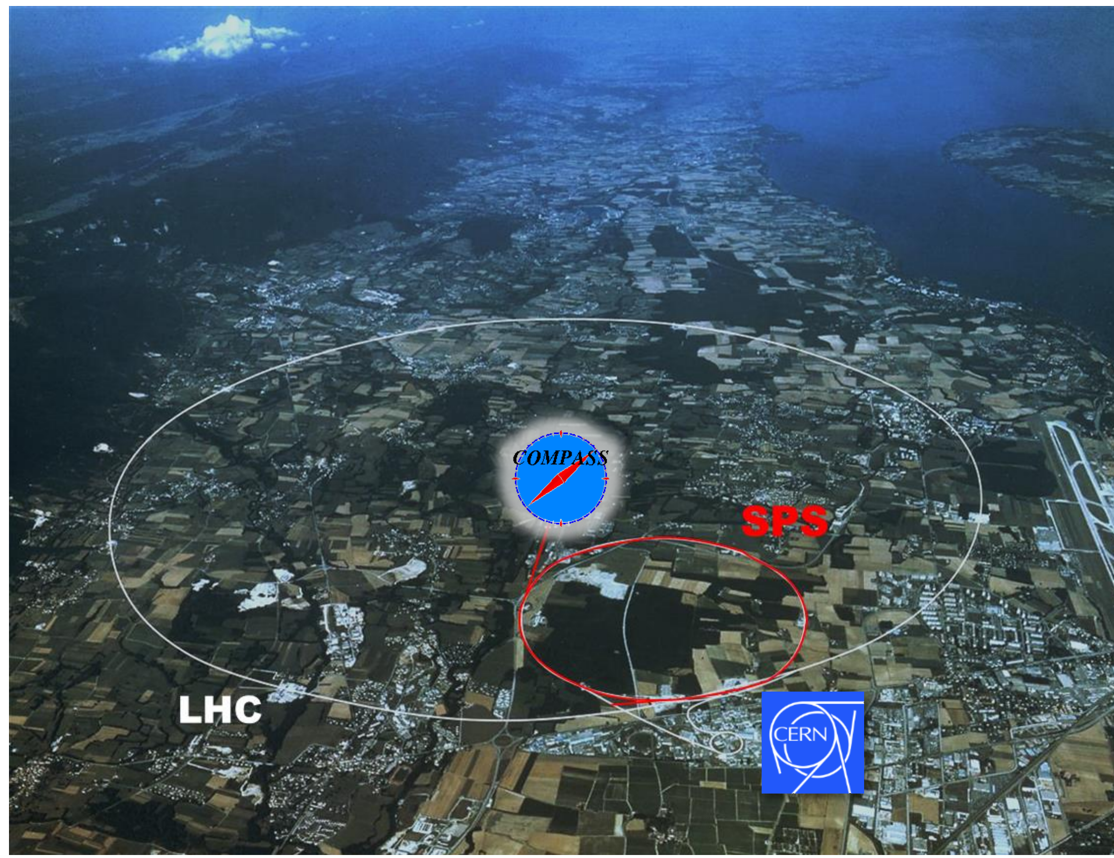
21.10.14 - M. Stolarski, F. Kunne
22.10.14 - K. Kurek, A. Martin, B. Parsamyan,
N. Makke, F. Kunne, G. Sbrizzai, F. Bradamante
24.10.14 - F.Bradamante, J. Ter Wolbeek, K. Kurek

COMPASS-II

- **Data taking 2012-2017**
- **Primakoff**
- **DVCS**
- **Polarized Drell-Yan**

COMPASS-II talks at SPIN2014:

24.10.14 – A. Ferrero, B. Parsamyan, W.Ch. Chang



COMPASS web page: http://wwwcompass.cern.ch

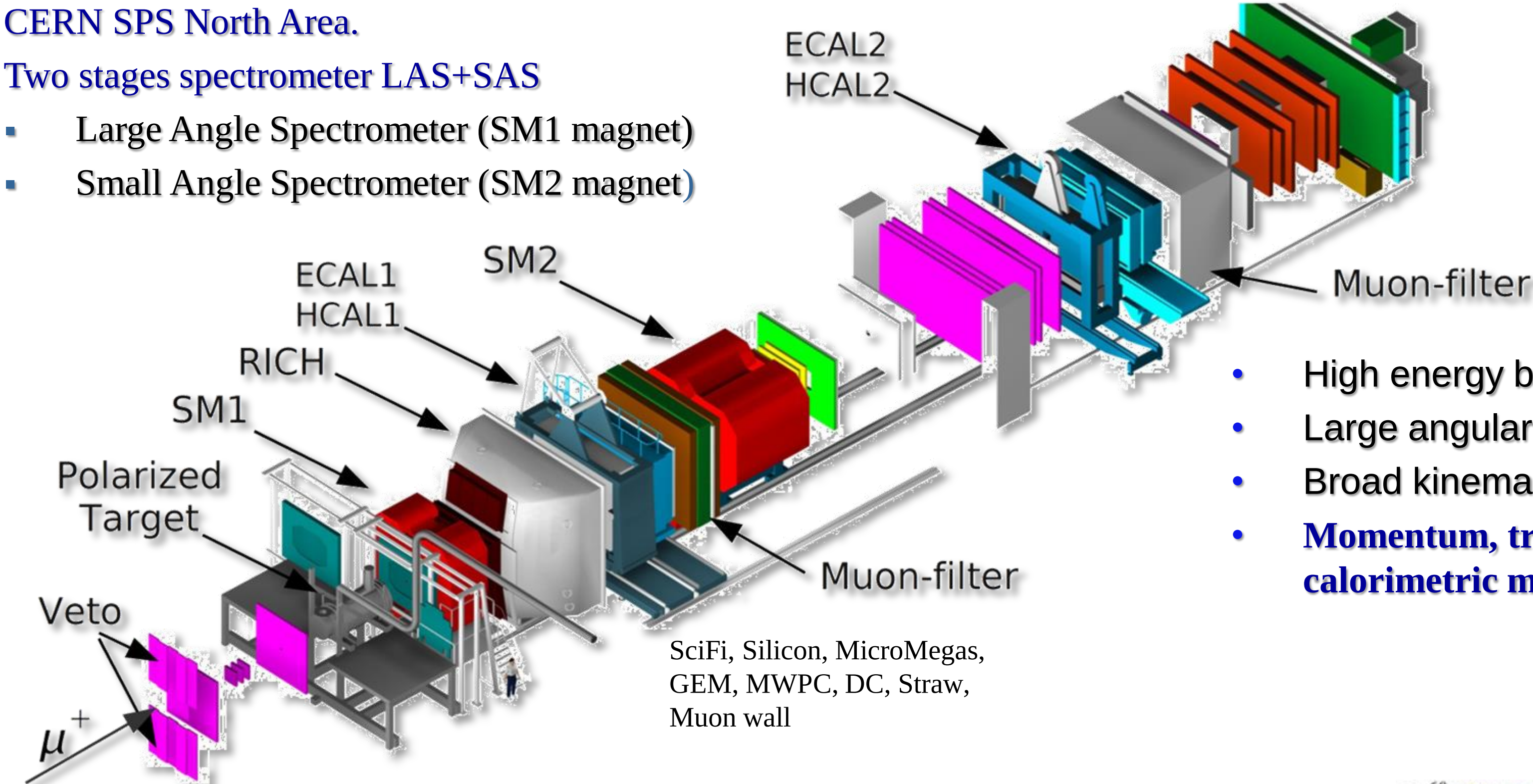
COMPASS experimental setup: Phase I (muon program)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area.

Two stages spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



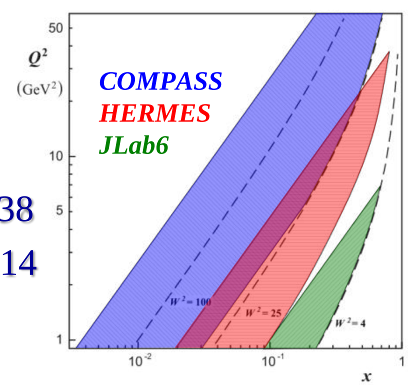
- High energy beam
- Large angular acceptance
- Broad kinematical range
- **Momentum, tracking and calorimetric measurements, PID**

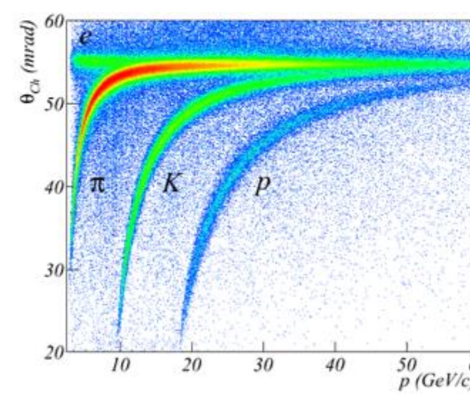
Longitudinally polarized (80%) μ^+ beam:

Energy: 160 GeV/c, Intensity: $2 \cdot 10^8$ μ^+/spill (4.8s).

Target: Solid state (*^6LiD or NH_3*)

- ^{6}LiD 2-cell configuration. Polarization (L & T) ~ 50%, f ~ 0.38
- NH_3 3-cell configuration. Polarization (L & T) ~ 80%, f ~ 0.14





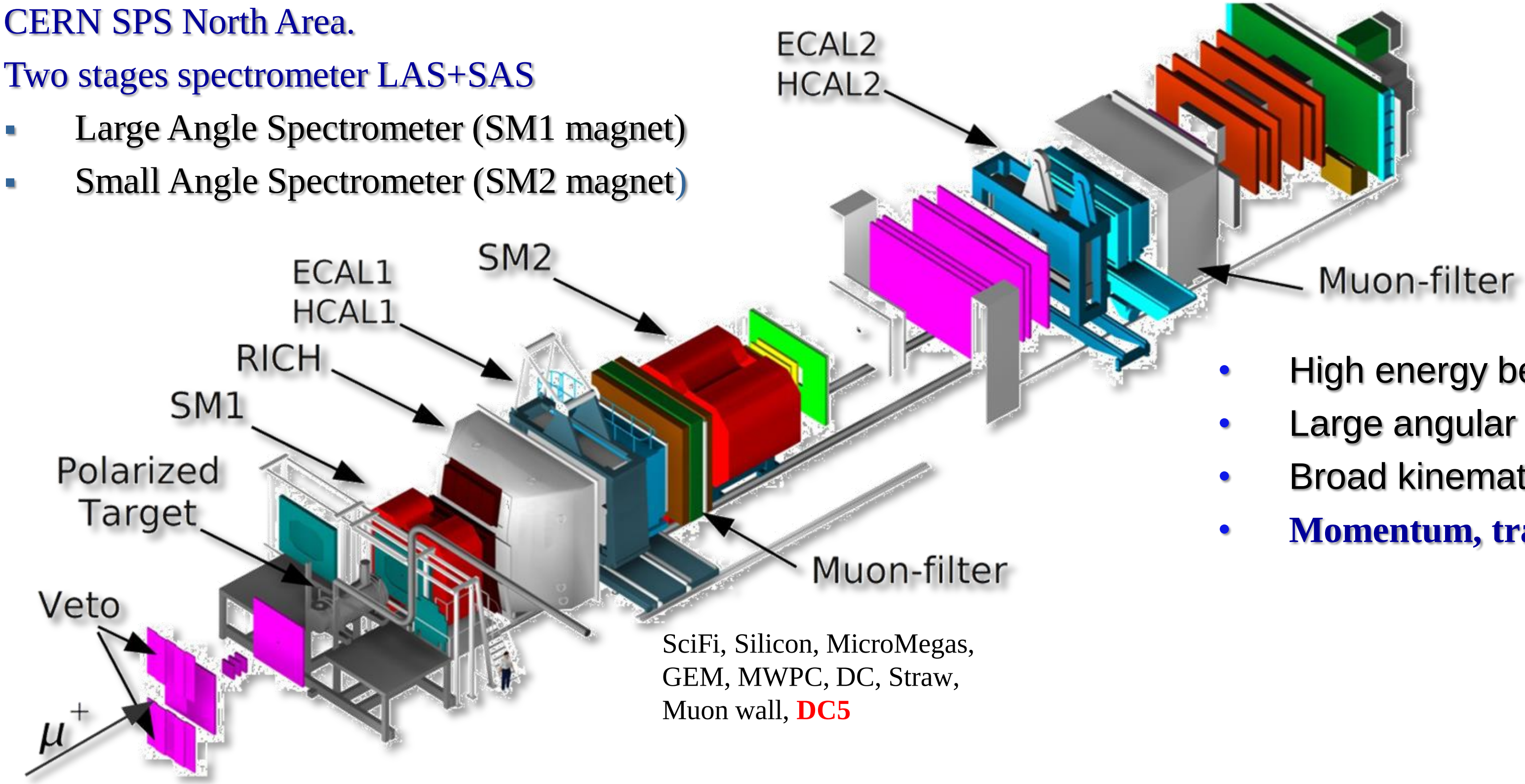
COMPASS experimental setup: Phase II (DY program)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area.

Two stages spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



- High energy beam
- Large angular acceptance
- Broad kinematical range
- **Momentum, tracking**

High energy π^- beam:

Energy: 190 GeV/c, Intensity: 10^8 π/s

Target: Solid state

- NH_3 2-cell configuration. Polarization T ~ 90%, f ~ 0.22

COMPASS experimental setup: Phase II (DY program)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

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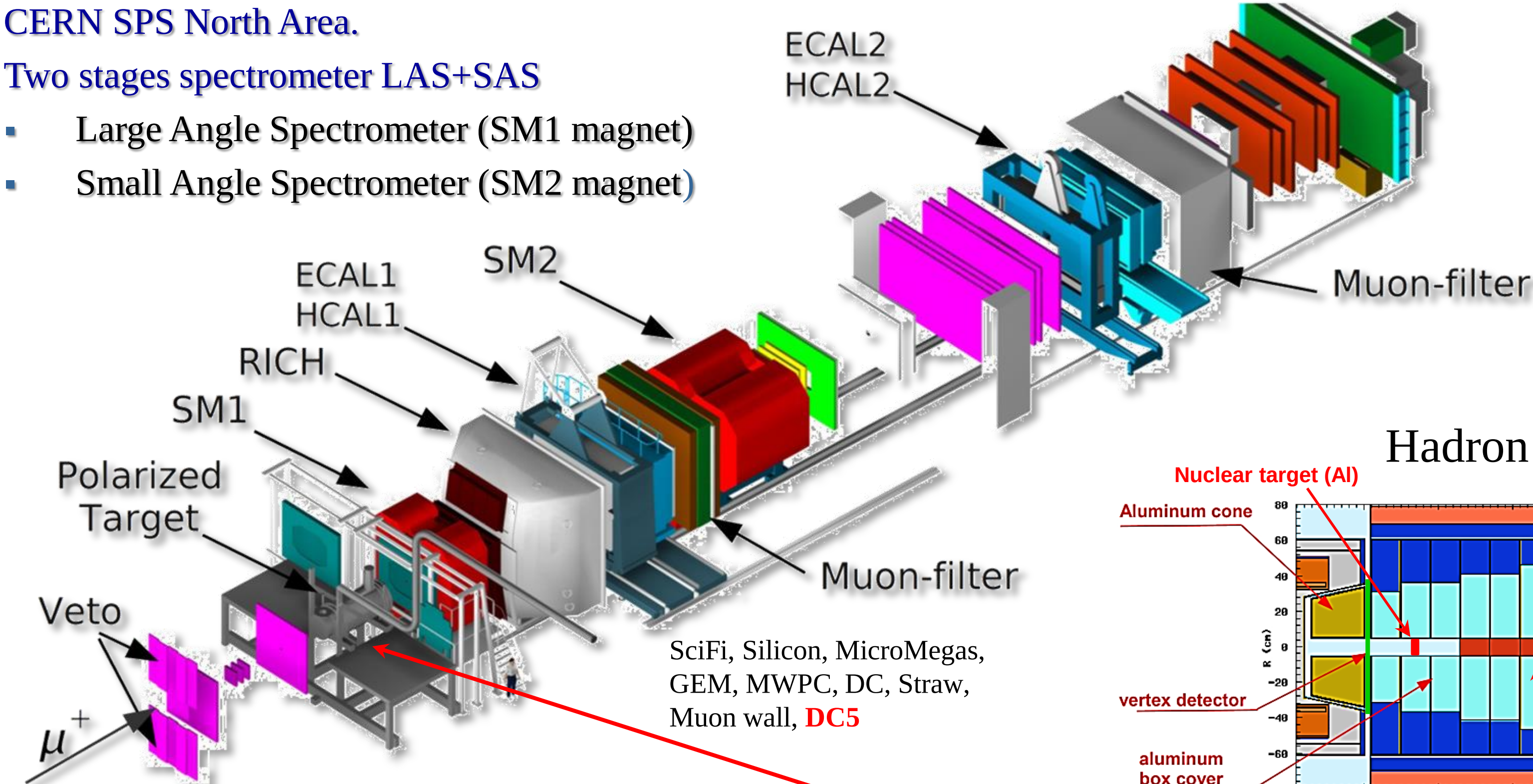

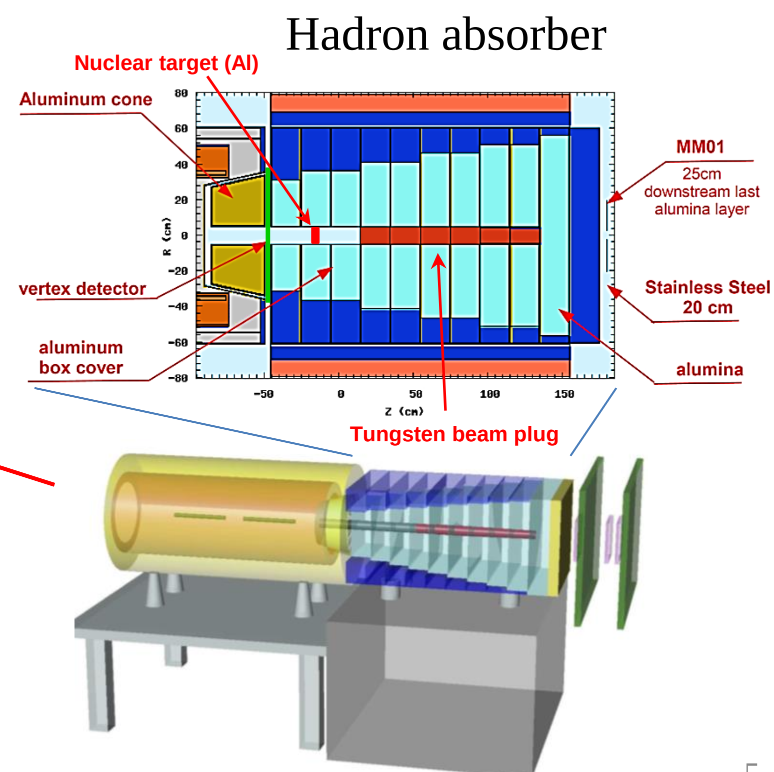

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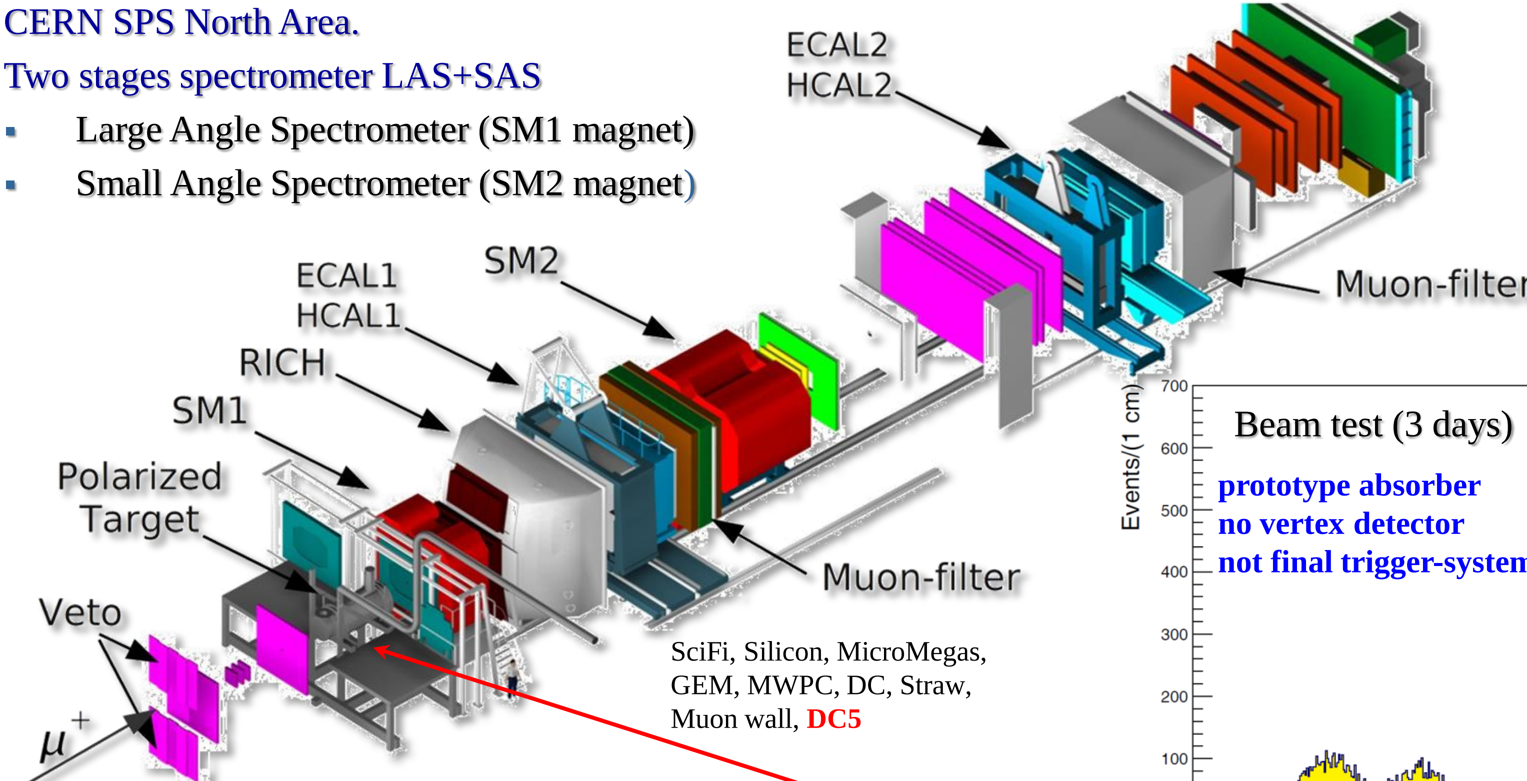

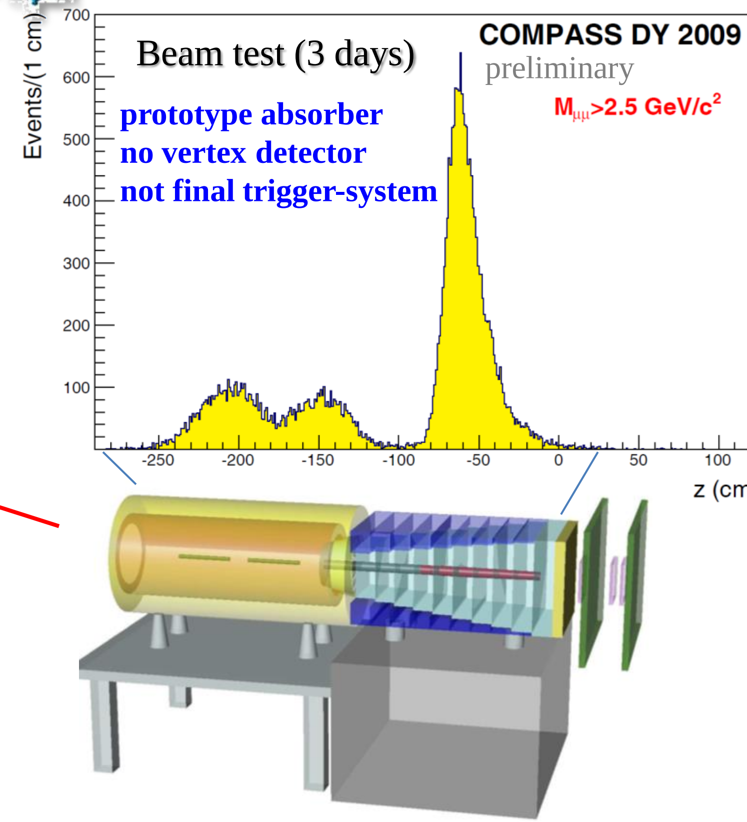

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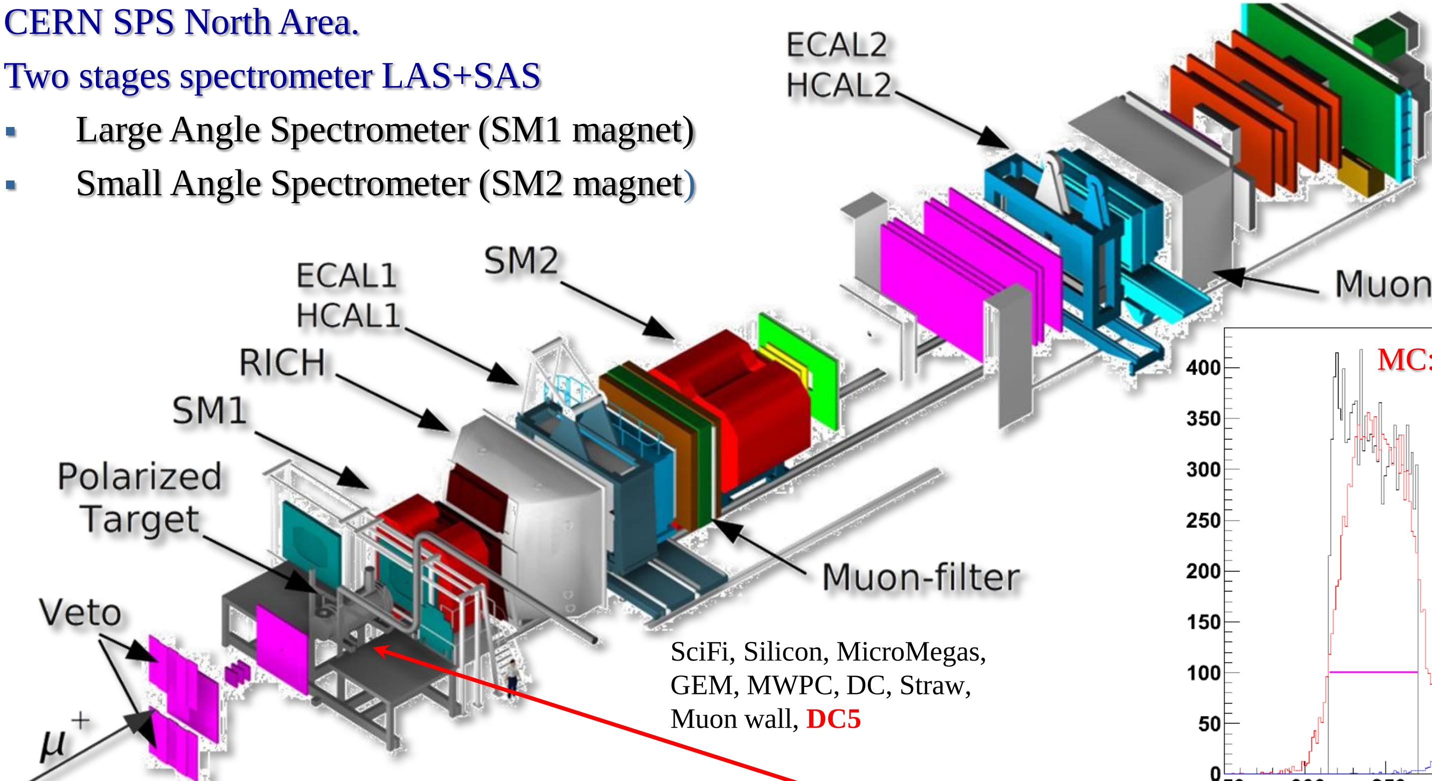

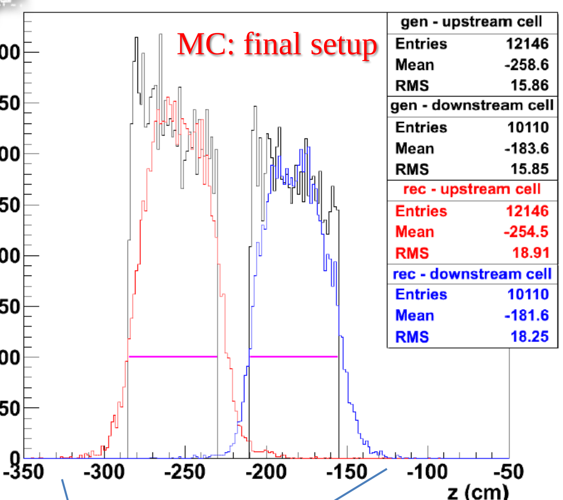

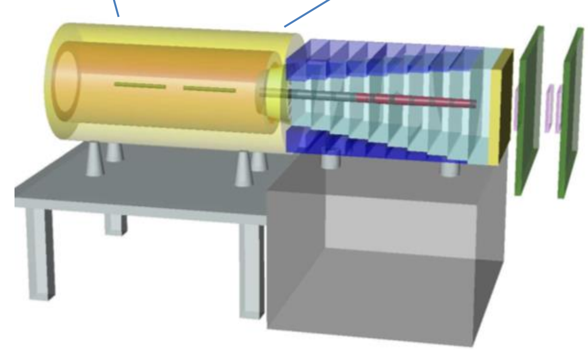

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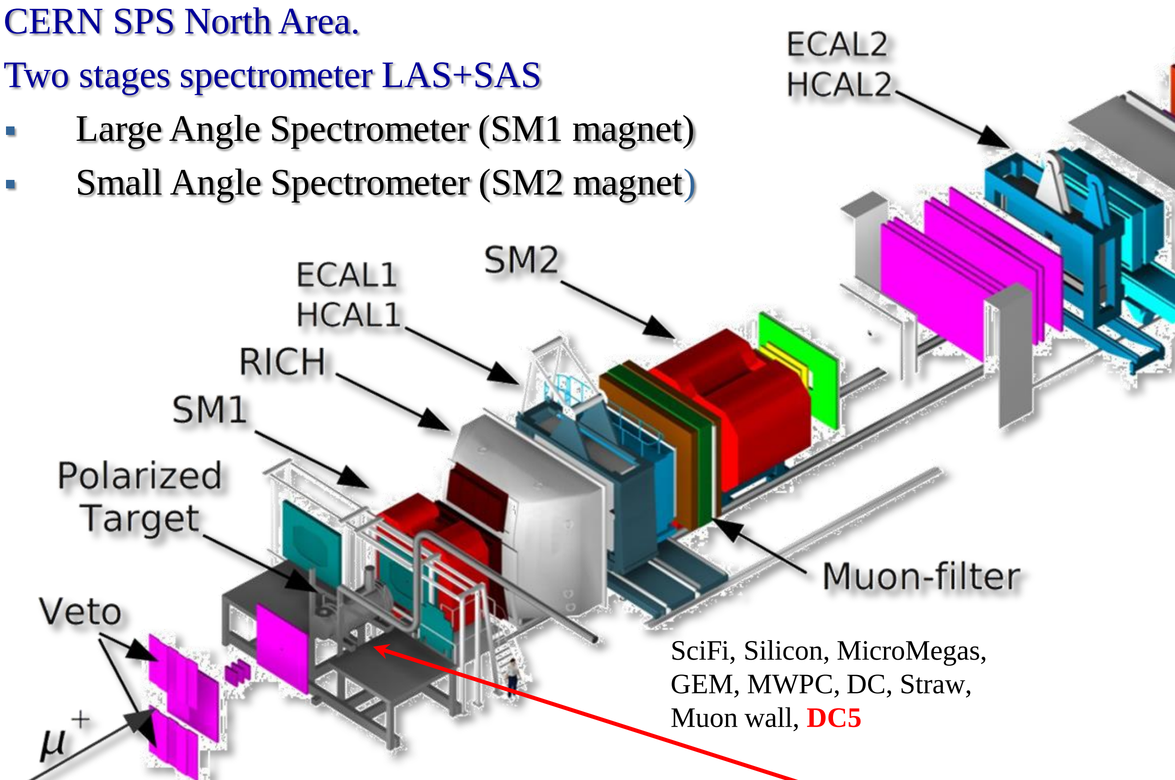
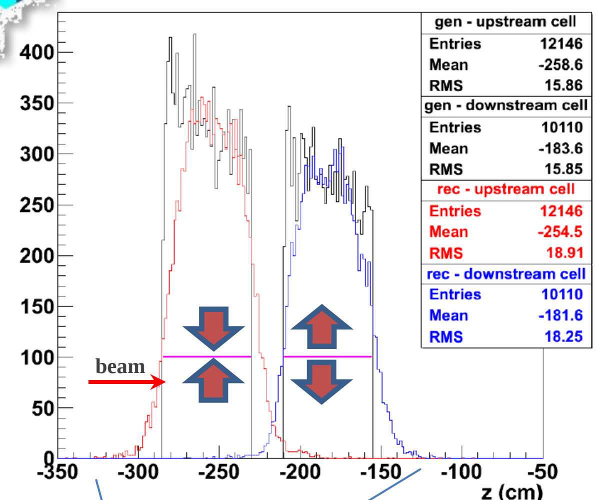
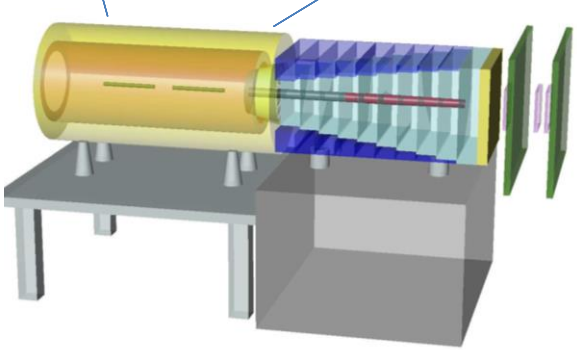






High energy π^- beam:

Energy: 190 GeV/c, Intensity: 10^8 π/s

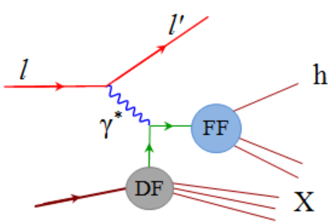
Target: Solid state

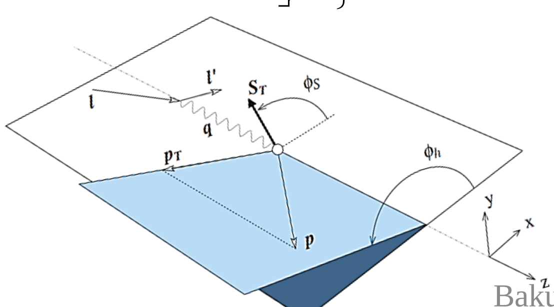
- NH_3 2-cell configuration. Polarization T ~ 90%, f ~ 0.22

SIDIS x-section

$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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



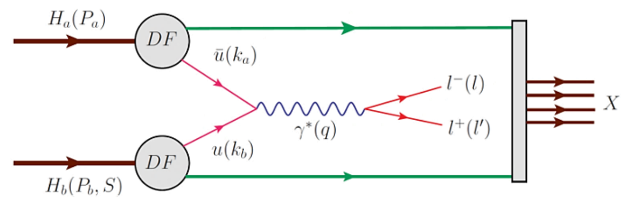


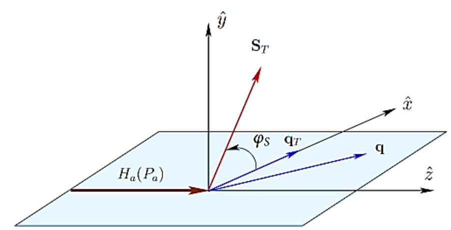
DY x-section

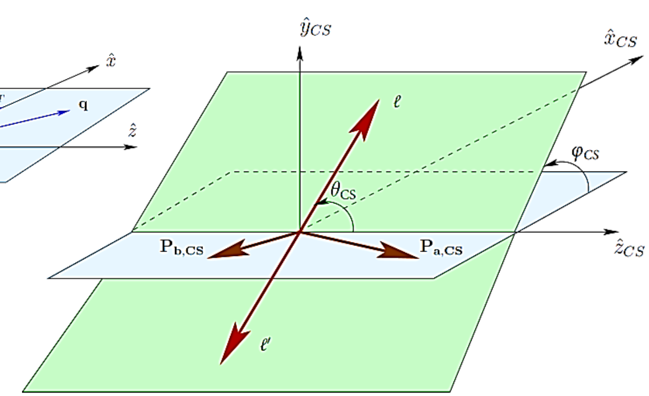
LO single polarized

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\times$$

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





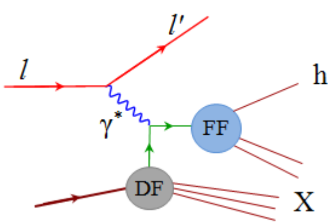


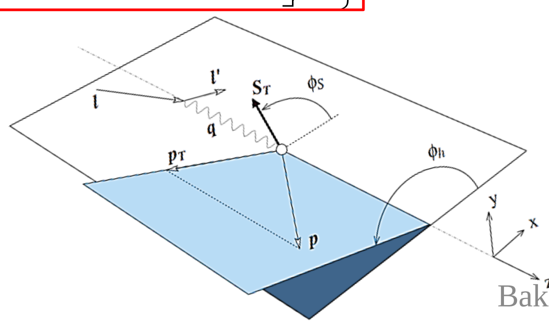
SIDIS x-section

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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

This talk





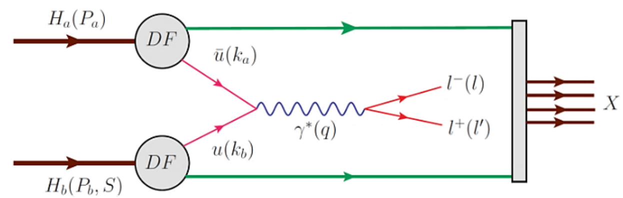
DY x-section

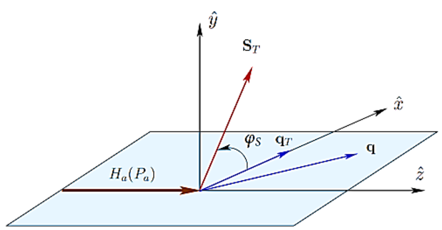
LO single polarized

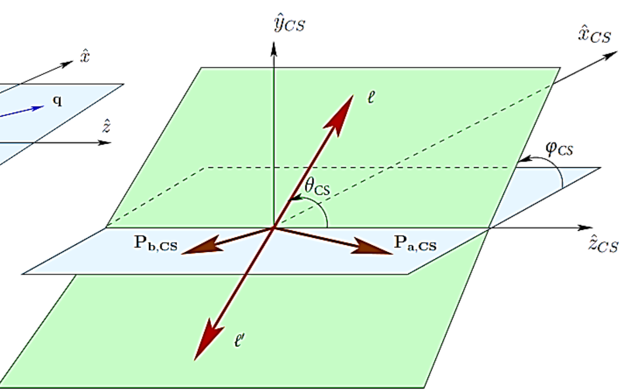
Wen-Chen's talk

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}F_U^1\times$$

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







TMDs accessed in SIDIS and DY

COMPASS

SIDIS

$$A_{UU}^{\cos\phi_h} \propto Q^{-1}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots \right)$$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1}\left(f_1^q \otimes D_{1q}^h + \ldots \right)$$

$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_s)} \propto Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots \right)$$

$$A_{UT}^{\sin(2\phi_h - \phi_s)} \propto Q^{-1}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots \right)$$

$$A_{LT}^{\cos(\phi_s)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots \right)$$

$$A_{LT}^{\cos(2\phi_h - \phi_s)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots \right)$$

Single polarized DY (LO)

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{\perp q}$$

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,\mathrm{p}}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^q$$

$$A_T^{\sin(2\varphi_{CS} + \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,\mathrm{p}}^{\perp q}$$

Nucleon \ Quark	U	L	T
U	$f_1^q(x, \mathbf{k}_T^2)$ **number density**		$h_1^{q\perp}(x, \mathbf{k}_T^2)$ **Boer-Mulders**
L		$g_1^q(x, \mathbf{k}_T^2)$ **helicity**	$h_{1L}^{q\perp}(x, \mathbf{k}_T^2)$ **worm-gear L**
T	$f_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ **Sivers**	$g_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ **worm-gear T**	$h_1^q(x, \mathbf{k}_T^2)$ **transversity** $h_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ **pretzelosity**

Nucleon TMD PDFs accessed in SIDIS and DY

SIDIS

$$A_{UU}^{\cos\phi_h} \propto Q^{-1}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots\right)$$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1}\left(f_1^q \otimes D_{1q}^h + \ldots\right)$$

$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_s)} \propto Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

$$A_{UT}^{\sin(2\phi_h-\phi_s)} \propto Q^{-1}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

$$A_{LT}^{\cos(\phi_s)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$$

$$A_{LT}^{\cos(2\phi_h-\phi_s)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$$

Single polarized DY (LO)

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{\perp q}$$

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,\mathrm{p}}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^q$$

$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,\mathrm{p}}^{\perp q}$$

Nucleon \ Quark	U	L	T
U	$f_1^q(x,\mathbf{k}_T^2)$ number density		$h_1^{q\perp}(x,\mathbf{k}_T^2)$ Boer-Mulders
L		$g_1^q(x,\mathbf{k}_T^2)$ helicity	$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$ worm-gear L
T	$f_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ Sivers	$g_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ worm-gear T	$h_1^q(x,\mathbf{k}_T^2)$ transversity $h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ pretzelosity

Nucleon TMD PDFs accessed in SIDIS and DY

SIDIS

$$A_{UU}^{\cos\phi_h} \propto Q^{-1}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots \right)$$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1}\left(f_1^q \otimes D_{1q}^h + \ldots \right)$$

$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_s)} \propto Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots \right)$$

$$A_{UT}^{\sin(2\phi_h - \phi_s)} \propto Q^{-1}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots \right)$$

$$A_{LT}^{\cos(\phi_s)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots \right)$$

$$A_{LT}^{\cos(2\phi_h - \phi_s)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots \right)$$

Single polarized DY (LO)

Boer-Mulders

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

Boer-Mulders

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

Sivers

$$A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$$

Transversity

$$A_T^{\sin(2\varphi_{CS} + \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

Pretzelosity

Nucleon \ Quark	U	L	T
U	$f_1^q(x, \mathbf{k}_T^2)$ number density		$h_1^{q\perp}(x, \mathbf{k}_T^2)$ Boer-Mulders
L		$g_1^q(x, \mathbf{k}_T^2)$ helicity	$h_{1L}^{q\perp}(x, \mathbf{k}_T^2)$ worm-gear L
T	$f_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ Sivers	$g_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ worm-gear T	$h_1^q(x, \mathbf{k}_T^2)$ transversity $h_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ pretzelosity

Nucleon TMD PDFs accessed in SIDIS and DY

SIDIS

$A_{UU}^{\cos\phi_h} \propto Q^{-1}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots\right)$

$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1}\left(f_1^q \otimes D_{1q}^h + \ldots\right)$

$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$

$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$

$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$

$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$

$A_{UT}^{\sin(\phi_s)} \propto Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$

$A_{UT}^{\sin(2\phi_h-\phi_s)} \propto Q^{-1}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$

$A_{LT}^{\cos(\phi_s)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$

$A_{LT}^{\cos(2\phi_h-\phi_s)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$

Single polarized DY (LO)

Boer-Mulders: $A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$

Boer-Mulders

Sivers: $A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$

Transversity: $A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$

Pretzelosity: $A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$

Nucleon \ Quark	U	L	T
U	$f_1^q(x,\mathbf{k}_T^2)$ number density		$h_1^{q\perp}(x,\mathbf{k}_T^2)$ Boer-Mulders
L		$g_1^q(x,\mathbf{k}_T^2)$ helicity	$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$ worm-gear L
T	$f_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ Sivers	$g_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ worm-gear T	$h_1^q(x,\mathbf{k}_T^2)$ transversity $h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ pretzelosity

Nucleon TMD PDFs accessed in SIDIS and DY

SIDIS

$$A_{UU}^{\cos\phi_h} \propto Q^{-1}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots\right)$$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1}\left(f_1^q \otimes D_{1q}^h + \ldots\right)$$

$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

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$$A_{UT}^{\sin(2\phi_h-\phi_s)} \propto Q^{-1}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

$$A_{LT}^{\cos(\phi_s)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$$

$$A_{LT}^{\cos(2\phi_h-\phi_s)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$$

Single polarized DY (LO)

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$$

$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

Boer-Mulders

Boer-Mulders

Sivers

Transversity

Pretzelosity

All the answers are encoded in the data...
In few years many new asymmetries measured by different experiments in different reactions, at different energies and kinematical ranges will wait for a "global analysis"…

Nucleon TMD PDFs accessed in SIDIS and DY

SIDIS $\ell^{\rightarrow}N^{\uparrow}$	Nucleon TMD PDF	Drell-Yan $\pi N^{\uparrow}$ (LO)
$A_{UU}^{\cos 2\phi_h}$, $A_{UU}^{\cos\phi_h}$	$h_1^{\perp q}$ - "Boer-Mulders"	$A_U^{\cos 2\varphi_{CS}}$
$A_{UT}^{\sin(\phi_h-\phi_s)}$, $A_{UT}^{\sin\phi_s}$, $A_{UT}^{\sin(2\phi_h-\phi_s)}$	$f_{1T}^{\perp q}$ - "Sivers"	$A_T^{\sin\varphi_S}$
$A_{UT}^{\sin(\phi_h+\phi_s-\pi)}$, $A_{UT}^{\sin\phi_s}$	h_1^q - "Transversity"	$A_T^{\sin(2\varphi_{CS}-\varphi_S)}$
$A_{UT}^{\sin(3\phi_h-\phi_s)}$, $A_{UT}^{\sin(2\phi_h-\phi_s)}$	$h_{1T}^{\perp q}$ - "Pretzelosity"	$A_T^{\sin(2\varphi_{CS}+\varphi_S)}$
$A_{LT}^{\cos(\phi_h-\phi_s)}$, $A_{LT}^{\cos\phi_s}$, $A_{LT}^{\cos(2\phi_h-\phi_s)}$	g_{1T}^q - "Worm-Gear" (T)	Double-polarized DY

DY measurements at COMPASS are complementary to the previous COMPASS SIDIS results. Unique opportunity to access TMD PDFs via two mechanisms and test their universality and key features.

$$f_{1T,p}^{\perp q}(DY) = -f_{1T}^{\perp q}(SIDIS)$$

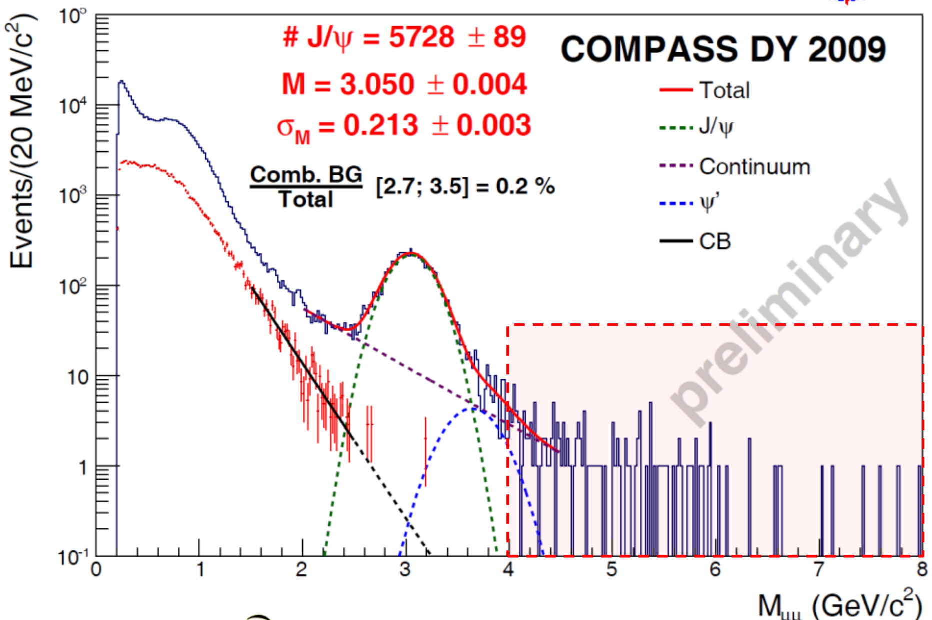
$$h_{1,p}^{\perp q}(DY) = -h_1^{\perp q}(SIDIS)$$

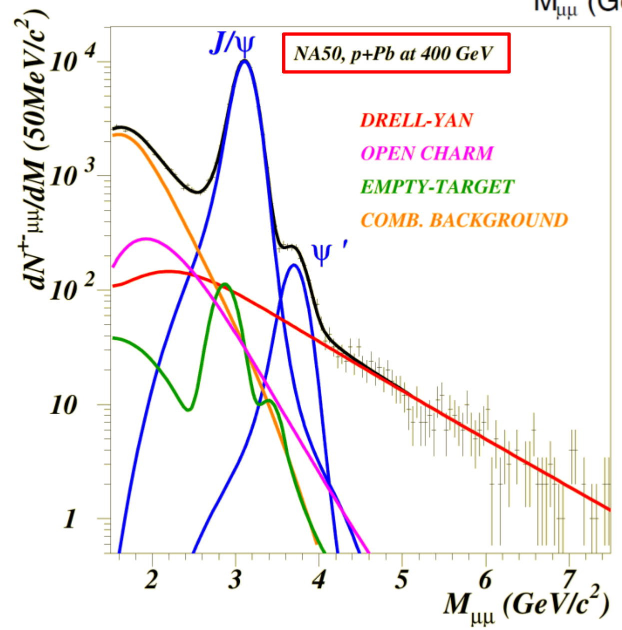
red - "twist-2", blue - "twist-3"

COMPASS x:Q^2 phase-space: SIDIS – Drell-Yan

Four Q^2(or mass)-ranges:

- $1 < Q^2/(GeV/c)^2 < 4$ "Low mass"
  - Large combinatorial background
    - Pion and kaon decays
    - Open-charm (bottom) semi-leptonic decays $D\bar{D}$, $B\bar{B}$
  - smaller asymmetries
- $4 < Q^2/(GeV/c)^2 < 6.25$ "Intermediate"
  - High DY-cross section
  - Still low signal/background
- $6.25 < Q^2/(GeV/c)^2 < 16$ "J/ψ"
  - Strong J/ψ-signal → study of J/ψ physics
  - Difficult to disentangle DY
  - Lower background
- $Q^2/(GeV/c)^2 > 16$ "High mass"
  - Beyond J/ψ peak
  - Negligible background
  - Low cross-section
  - Valence region → largest asymmetries





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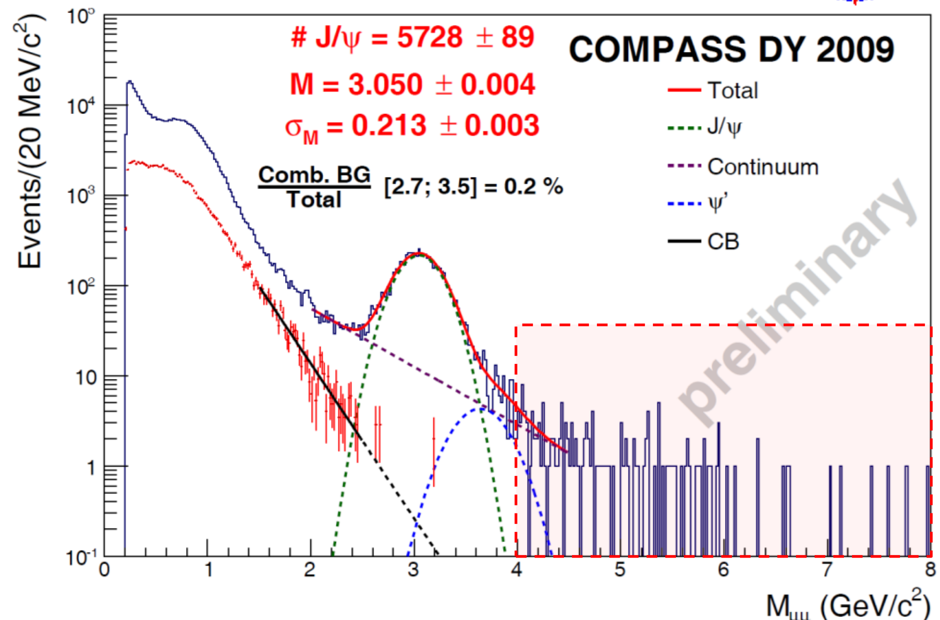

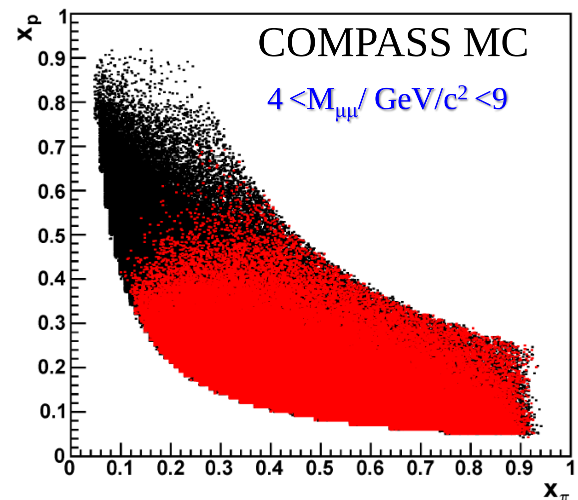

COMPASS x_p:x_π. Accepted events are in the valence quark range ($x > 0.1$)

COMPASS x:Q^2 phase-space: SIDIS – Drell-Yan

Four Q^2(or mass)-ranges:

- $1 < Q^2/(GeV/c)^2 < 4$ "Low mass"
  - Large combinatorial background
    - Pion and kaon decays
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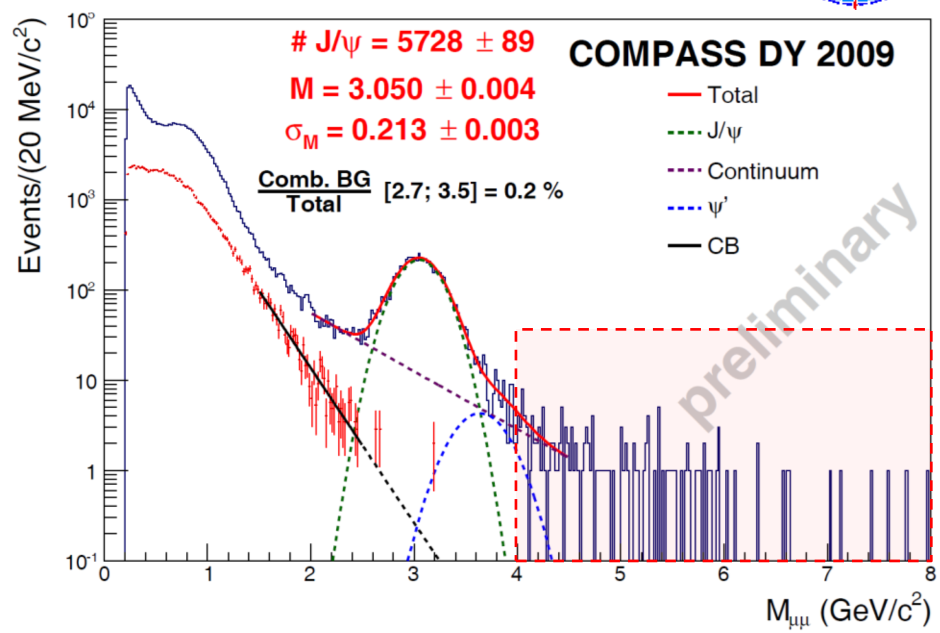

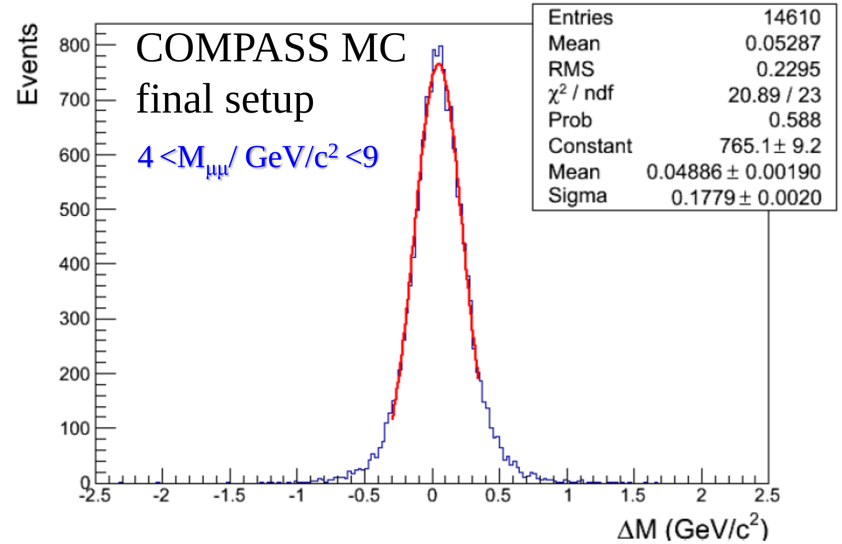

Good mass resolution $\Delta M \approx 180$ MeV/c^2

COMPASS $x{:}Q^2$ phase-space: SIDIS – Drell-Yan

Four Q^2(or mass)-ranges:

- $1 < Q^2/(\text{GeV}/c)^2 < 4$ "Low mass"
  - Large combinatorial background
    - Pion and kaon decays
    - Open-charm (bottom) semi-leptonic decays $D\bar{D}$, $B\bar{B}$
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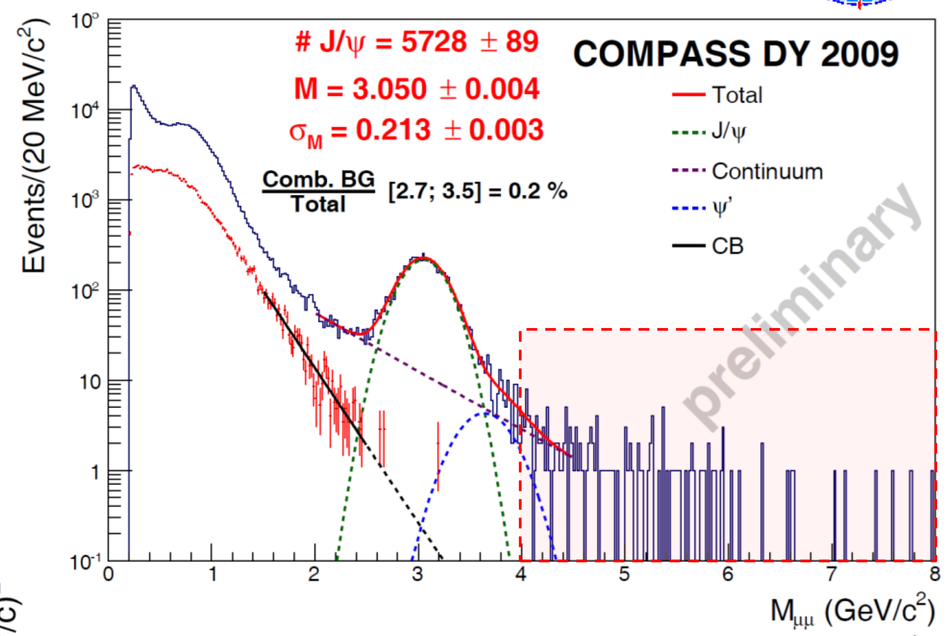
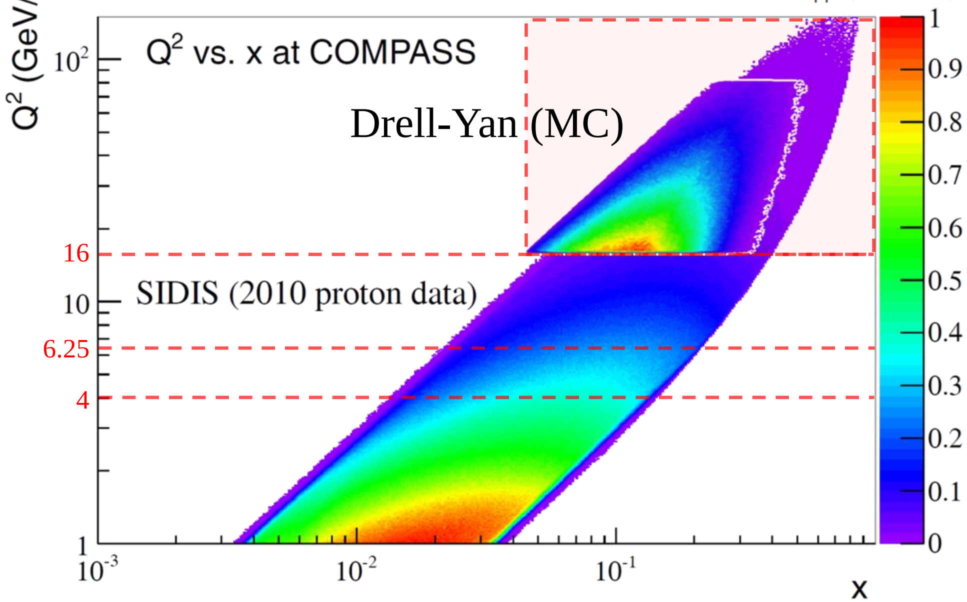
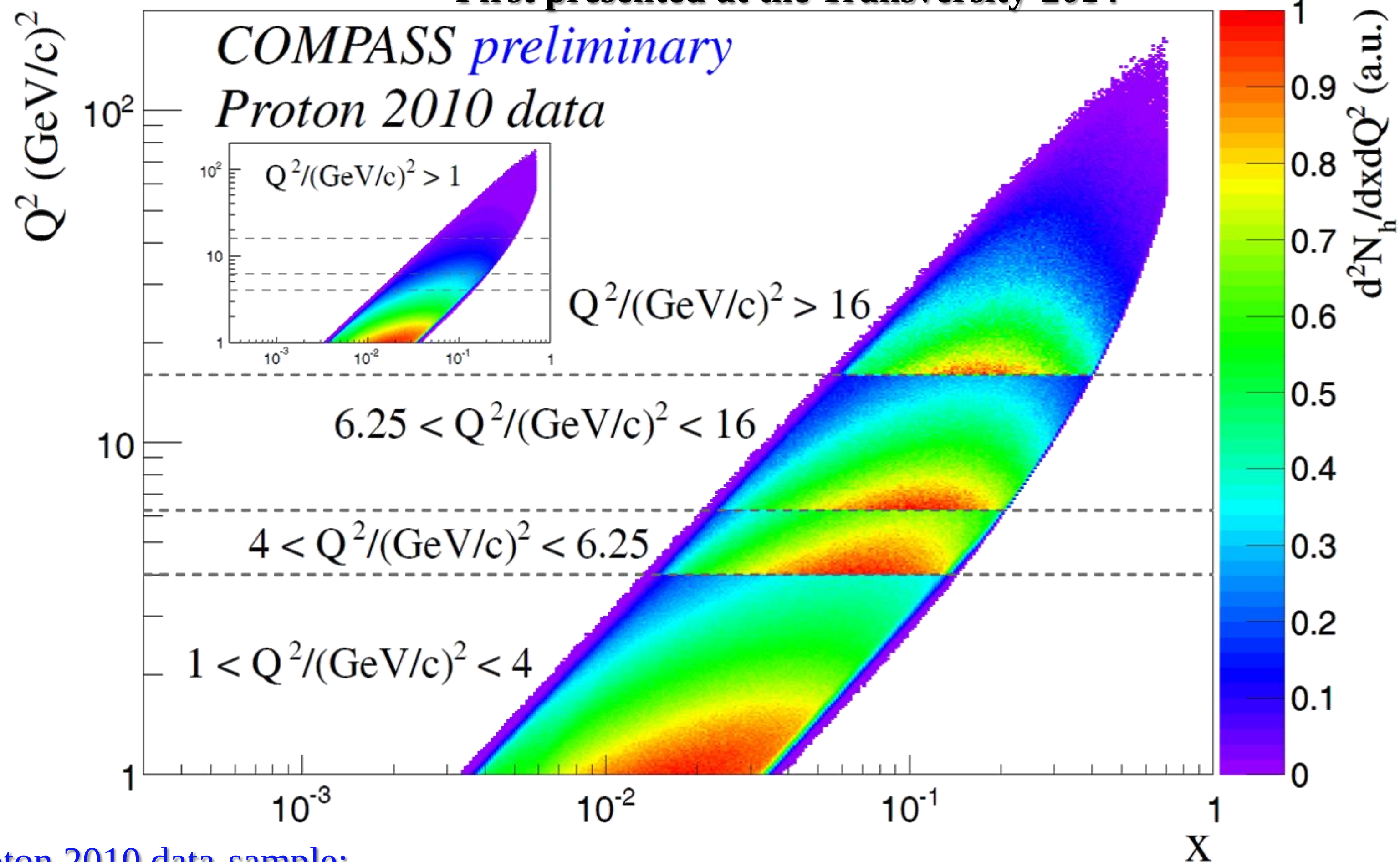
  - Negligible background
  - Low cross-section
  - Valence region → largest asymmetries





COMPASS SIDIS phase-space x:Q^2 (“DY” Q^2-ranges)

First presented at the Transversity-2014



Proton 2010 data-sample:

$Q^2 > 1$ (GeV/c)^2; $0.1 < y < 0.9$; $W > 5$ GeV, $z > 0.1$, $p_T > 0.1$ GeV/c

Four Q^2-bins:

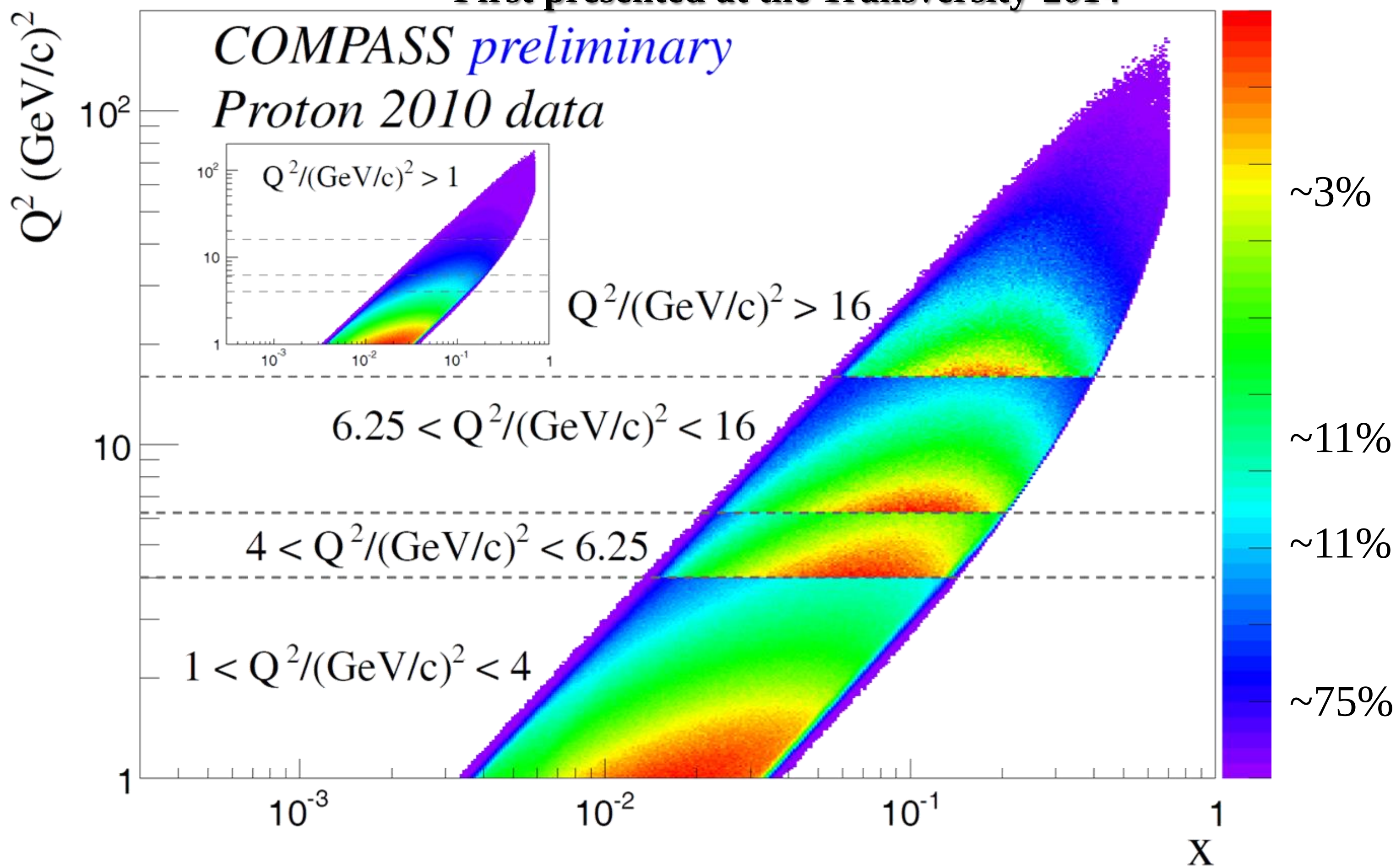
$1 < Q^2/(\text{GeV}/c)^2 < 4$, $4 < Q^2/(\text{GeV}/c)^2 < 6.25$, $6.25 < Q^2/(\text{GeV}/c)^2 < 16$, $Q^2/(\text{GeV}/c)^2 > 16$

Two z-ranges:

$z>0.2$; $z>0.1$

COMPASS SIDIS phase-space x:Q^2 ("DY" Q^2-ranges)

First presented at the Transversity-2014

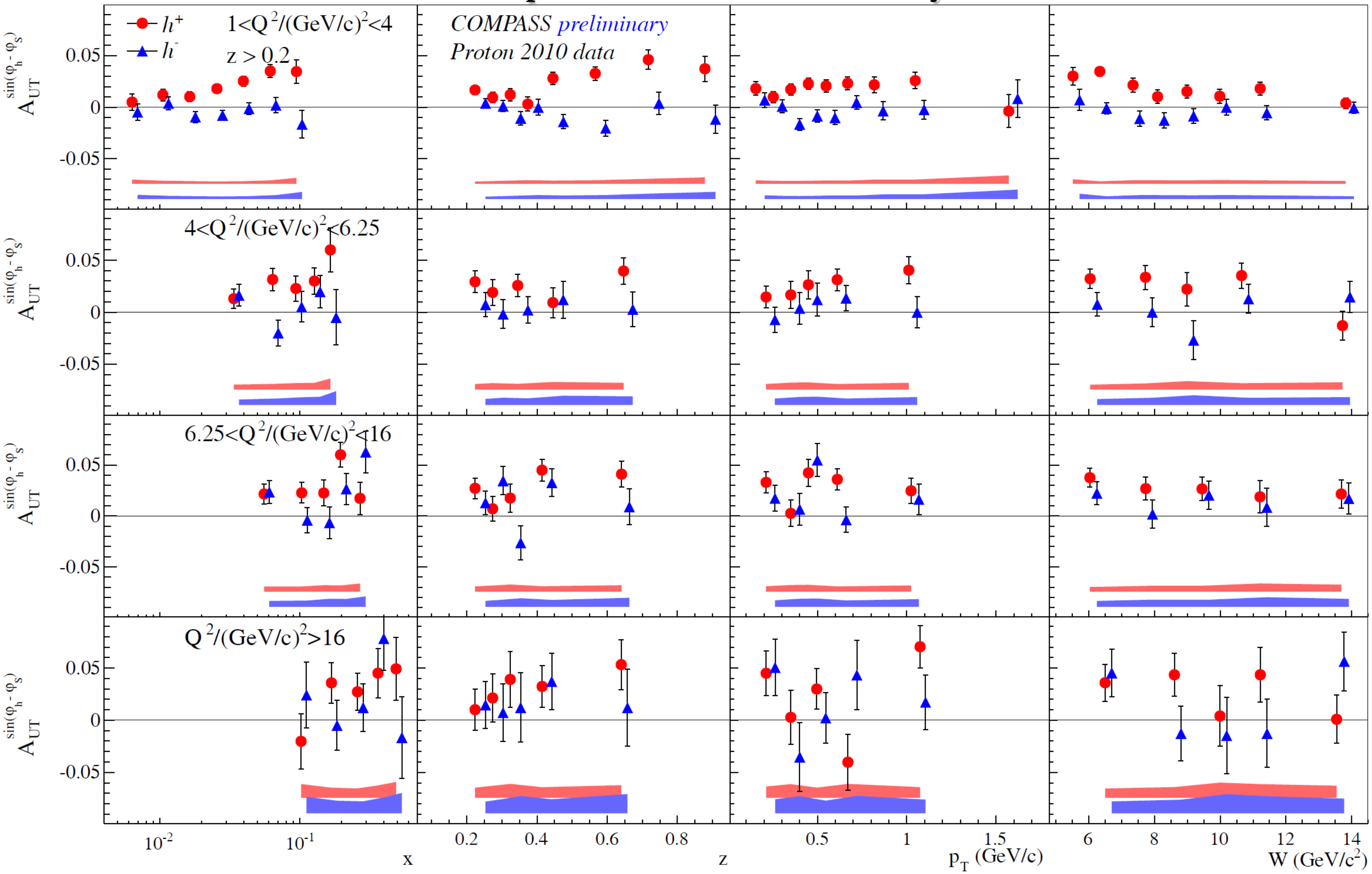


- In SIDIS with z>0.2 and $Q^2 > 16$ (GeV/c)^2: $\delta A_{UT}^{\sin(\phi_h - \phi_s)} \approx$ **0.01** (for h^+) and $\approx$ **0.012** (for h^-)
- $\delta A_T^{\sin\varphi_s}$ in DY "high mass" range with 2.85 10^5 events (140 days) $\approx$ **0.013**

DY event rate expectations have been recently updated/improved (longer SPS-cycle and higher intensity).

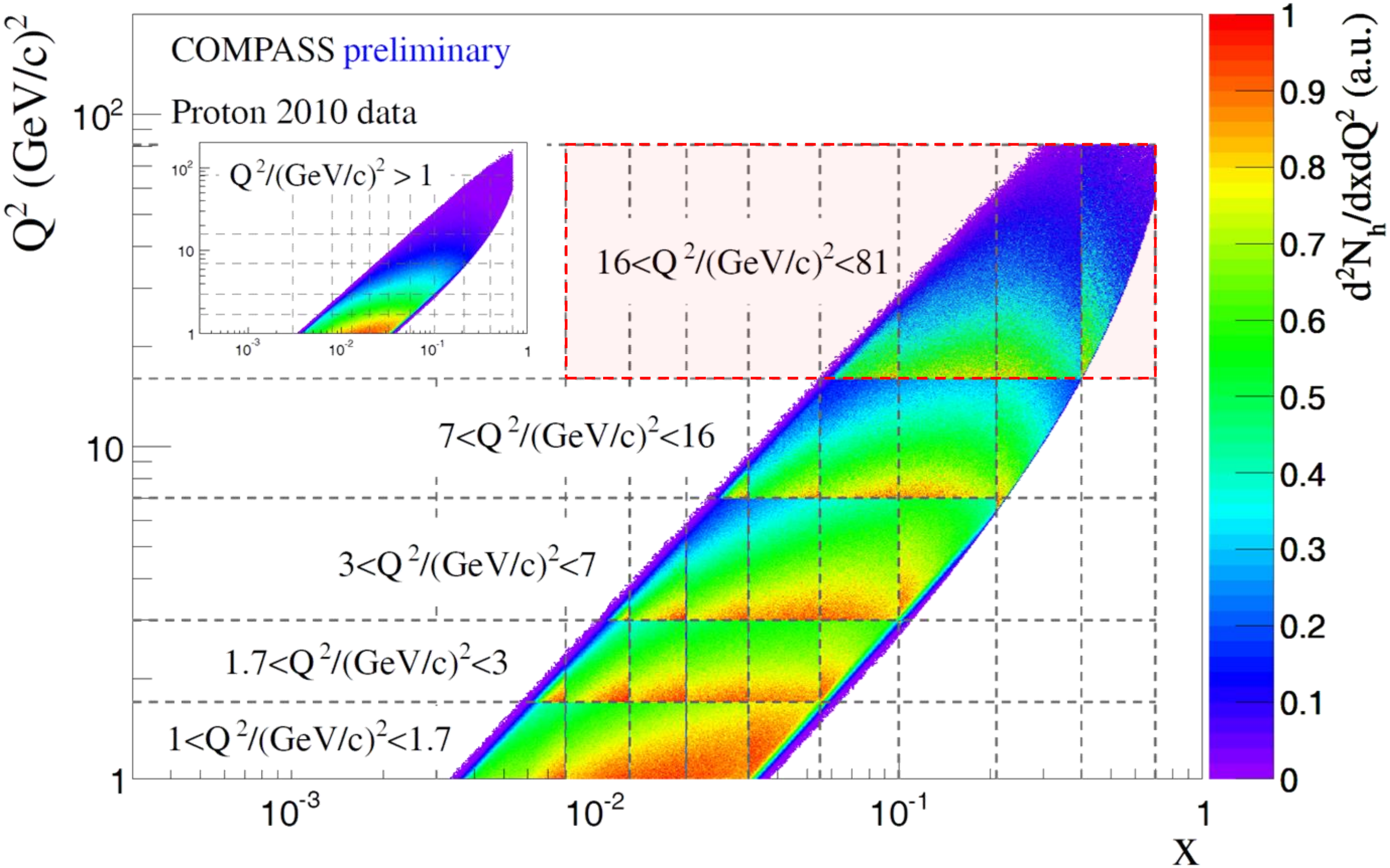
Sivers in SIDIS in DY Q^2-bins: $z > 0.2$

First presented at the Transversity-2014



- **First input for future DY-SIDIS comparison and Sivers sign-change studies!**
- **First attempt to extract "Q^2-evolution" related information from data of one experiment.**

Multidimensional approach concept I ($x:Q^2$)



NEW!

Shown for the first time!

3D

For details see talk by B. Parsamyan given on 22.10.2014

Q^2 ranges:
- **$1 < Q^2 < 1.7$**
- **$1.7 < Q^2 < 3$**
- **$3 < Q^2 < 7$**
- **$7 < Q^2 < 16$**
- **$16 < Q^2 < 81$**

z ranges:
- **$z > 0.1$**
- **$z > 0.2$**
- **$0.1 < z < 0.2$**
- **$0.2 < z < 0.4$**
- **$0.4 < z < 1.0$**

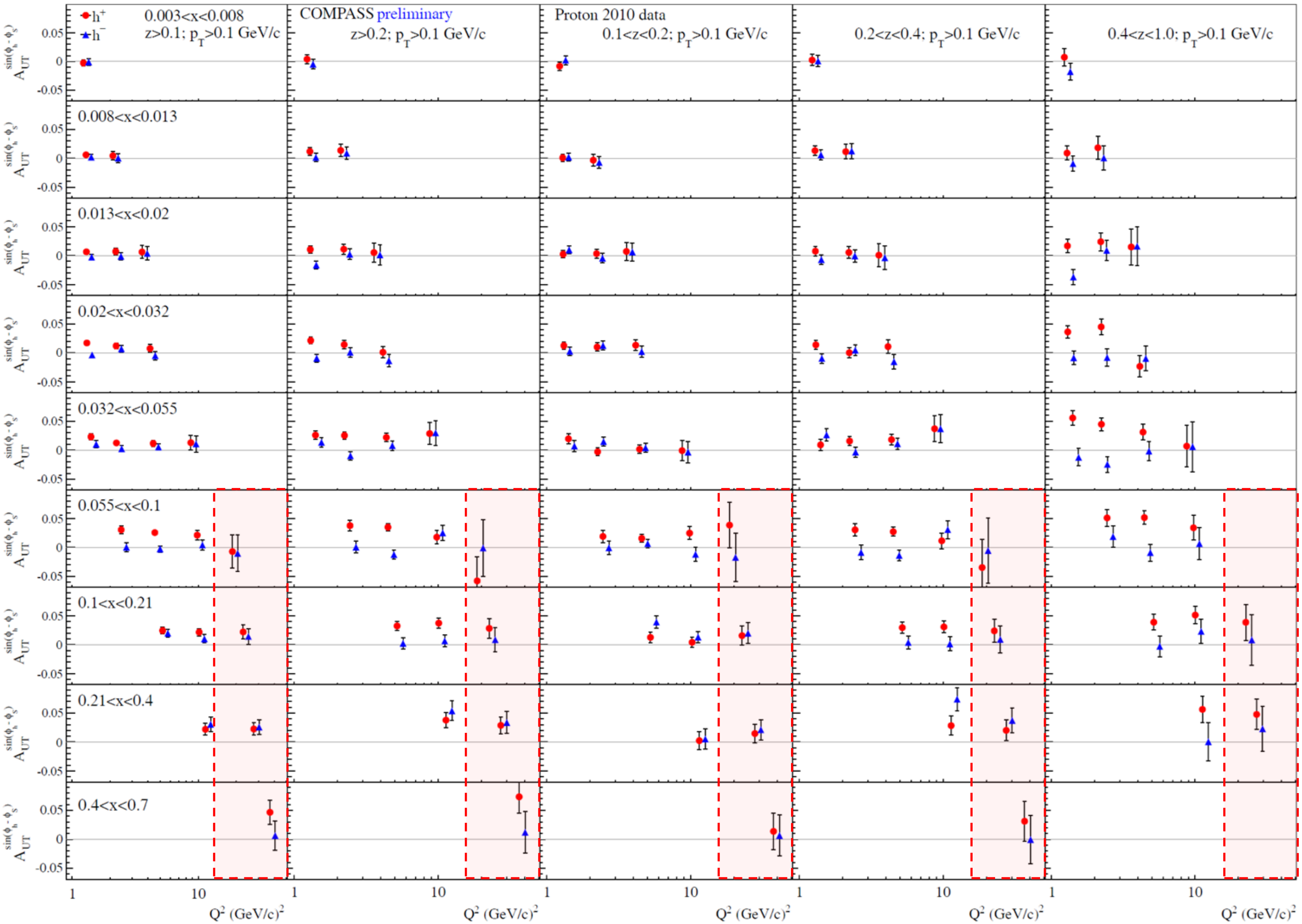
p_T ranges:
- **$p_T > 0.1$**
- **$0.1 < p_T < 0.75$**
- **$0.1 < p_T < 0.3$**
- **$0.3 < p_T < 0.75$**
- **$p_T > 0.75$**

x bins: 0.003, 0.008, 0.013, 0.02, 0.032, 0.055, 0.10, 0.21, 0.40, 0.7

Sivers asymmetry: 3D x-z-Q^2 dependency

For details see talk by B. Parsamyan given on 22.10.2014

COMPASS



NEW!

Shown for the first time!

3D

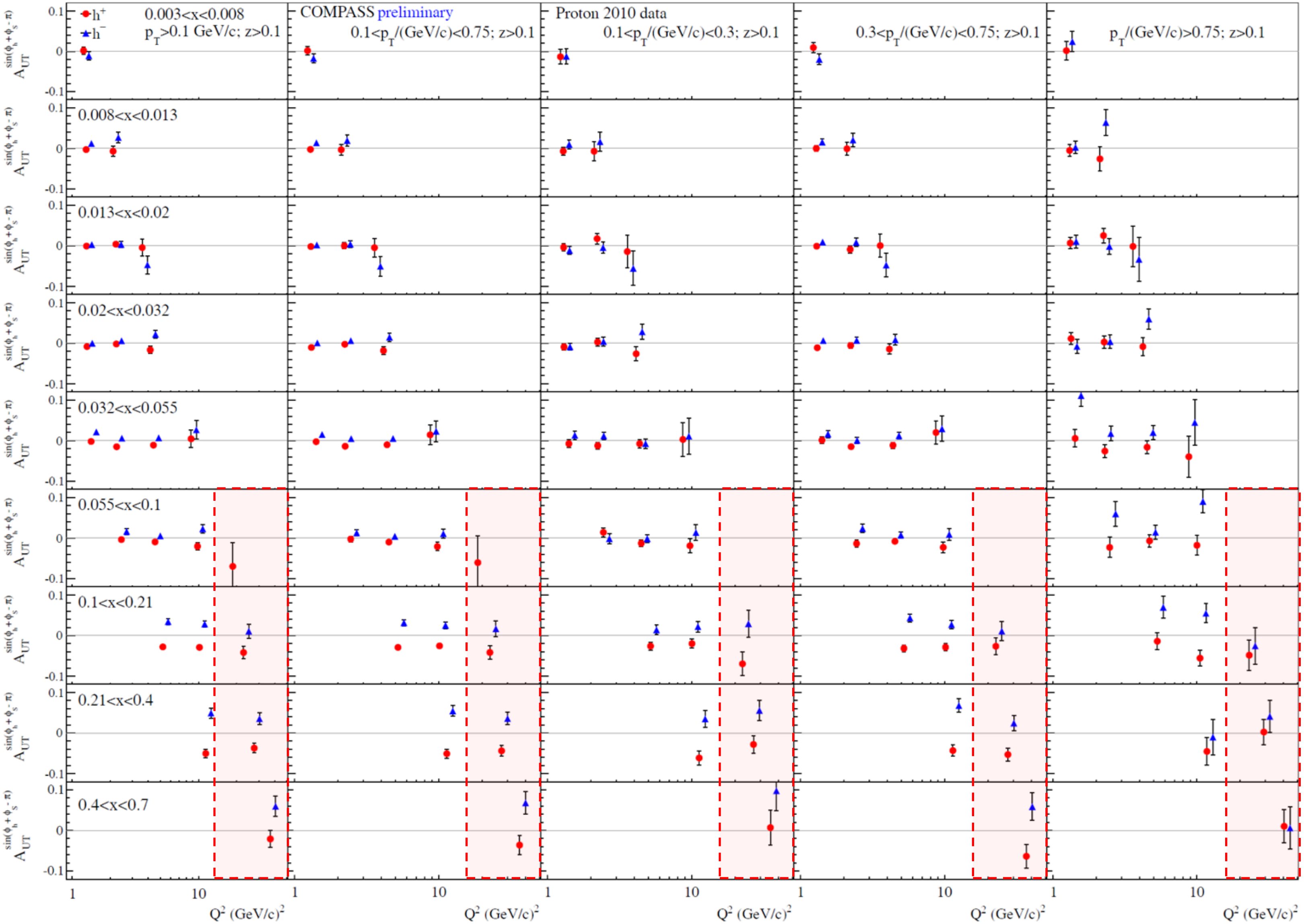
16<Q^2<81

- **In several x-bins some hints for possible Q^2-dependence for positive hadrons (decrease) more evident at large z**
- **At low z effect for h^+ is smaller in general**
- **No clear picture for negative hadrons**

Important input for Q^2-evolution and DY-SIDIS related studies

Collins asymmetry: 3D x-p_T-Q^2 dependency

For details see talk by B. Parsamyan given on 22.10.2014



NEW!

Shown for the first time!

3D

16<Q^2<81

- **Both h^+ and h^- amplitudes are compatible with zero at low x and become sizable (opposite in sign) from x>0.032**
- **Both h^+ and h^- amplitudes tend to increase with x, but with some "irregularities"**
- **Both h^+ and h^- amplitudes tend to increase with p_T. Some weak Q^2-dependencies. Not clear.**

Expected DY event rates and statistical uncertainties

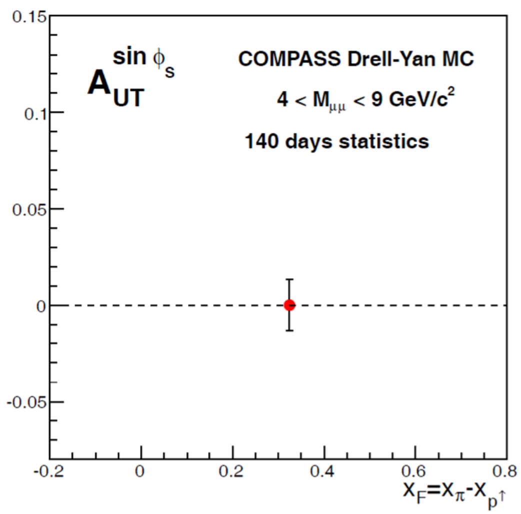
Thanks to a shorter SPS-supercycle COMPASS will have more integrated beam time than it was initially foreseen in the proposal. In addition we will have higher beam intensity.

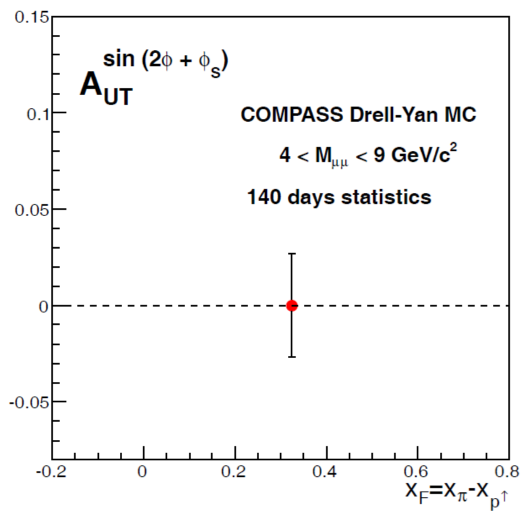
Updated expectations for the Drell-Yan events rate with masses 4 GeV/c^2 < $M_{\mu\mu}$ < 9 GeV/c^2 are:

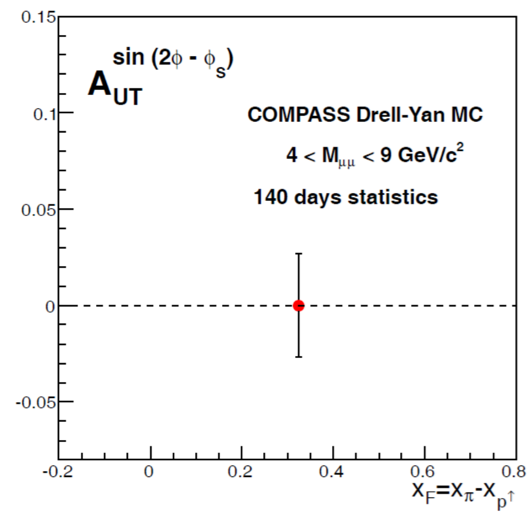
- 2000 events/day - beam intensity of $I_{beam} = 10^8$ π/s, and 9.6s long spills every 34 seconds
- 285 000 events in 140 days of data-taking.

Expected statistical errors of the asymmetries after one year run (140 days) are:

Asymmetry	Statistical error ($4 < M_{\mu\mu} < 9$ GeV/c^2)
$\delta\ A_{UU}^{\cos 2\phi}$	0.005
$\delta\ A_{UT}^{\sin \phi_S}$	0.013
$\delta\ A_{UT}^{\sin(2\phi+\phi_S)}$	0.027
$\delta\ A_{UT}^{\sin(2\phi-\phi_S)}$	0.027

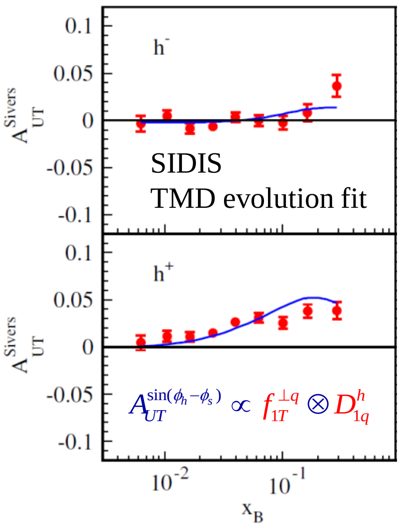


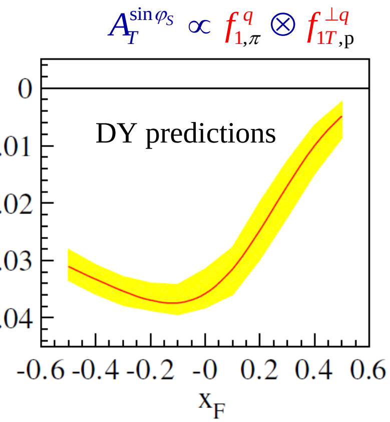




TSAs in SIDIS and Drell-Yan: fits, predictions

M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev,
"QCD Evolution of the Sivers Asymmetry"
PRD 89 074013 (2014)





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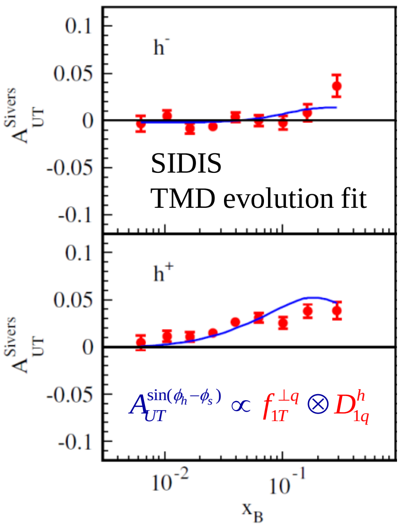
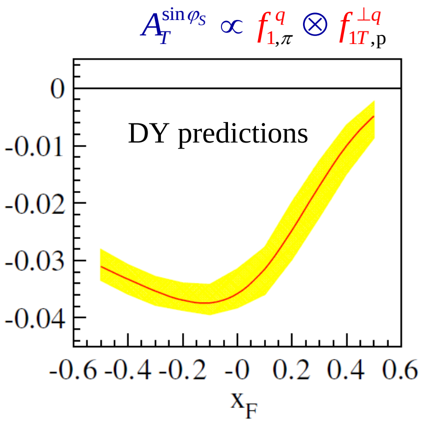
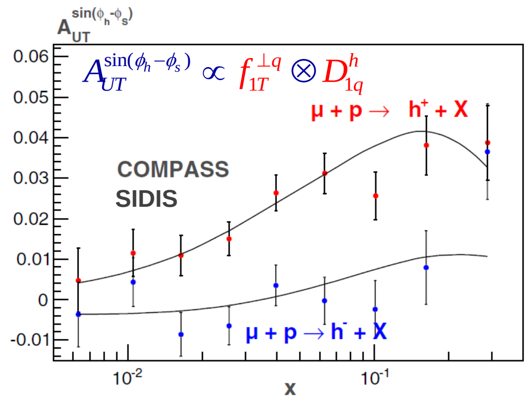
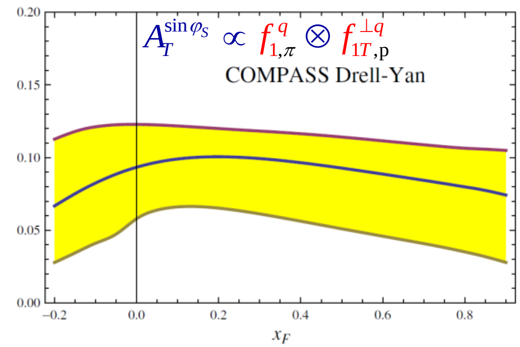




P. Sun and F. Yuan,
"Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production".
PRD 88 11, 114012 (2013)





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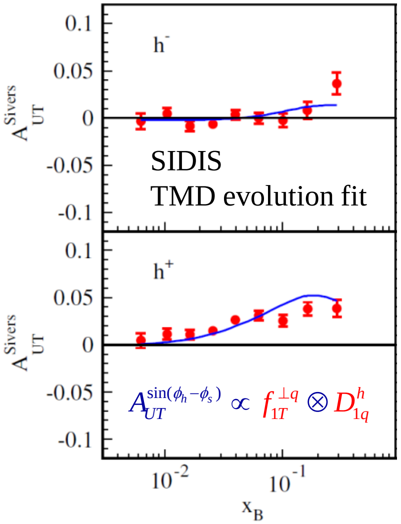
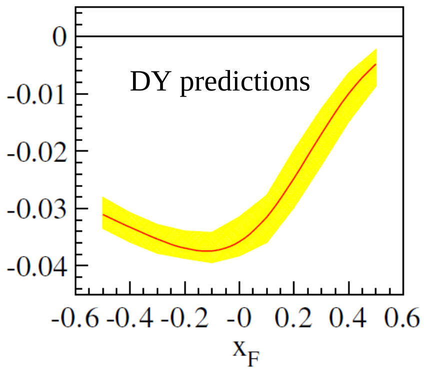
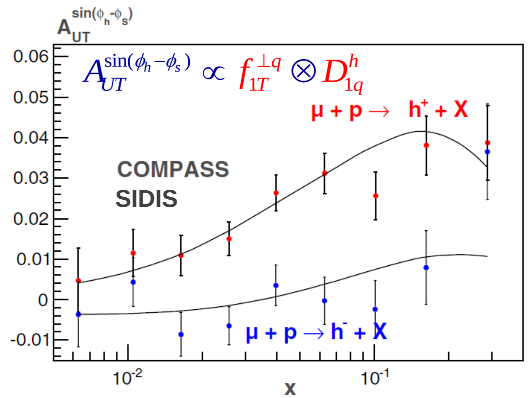
PRD 89 074013 (2014)

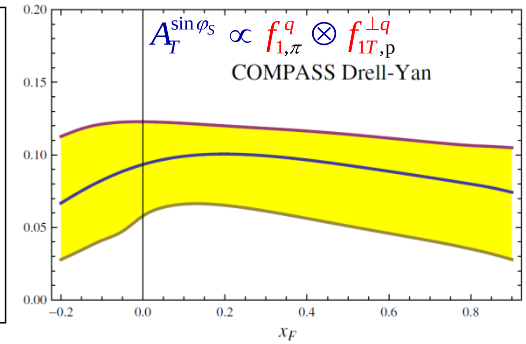
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$



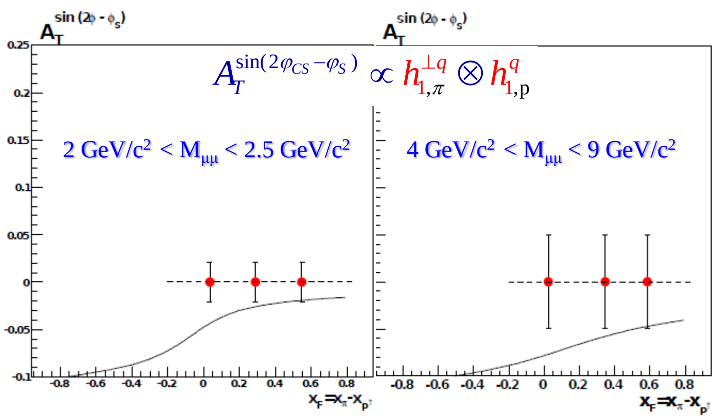


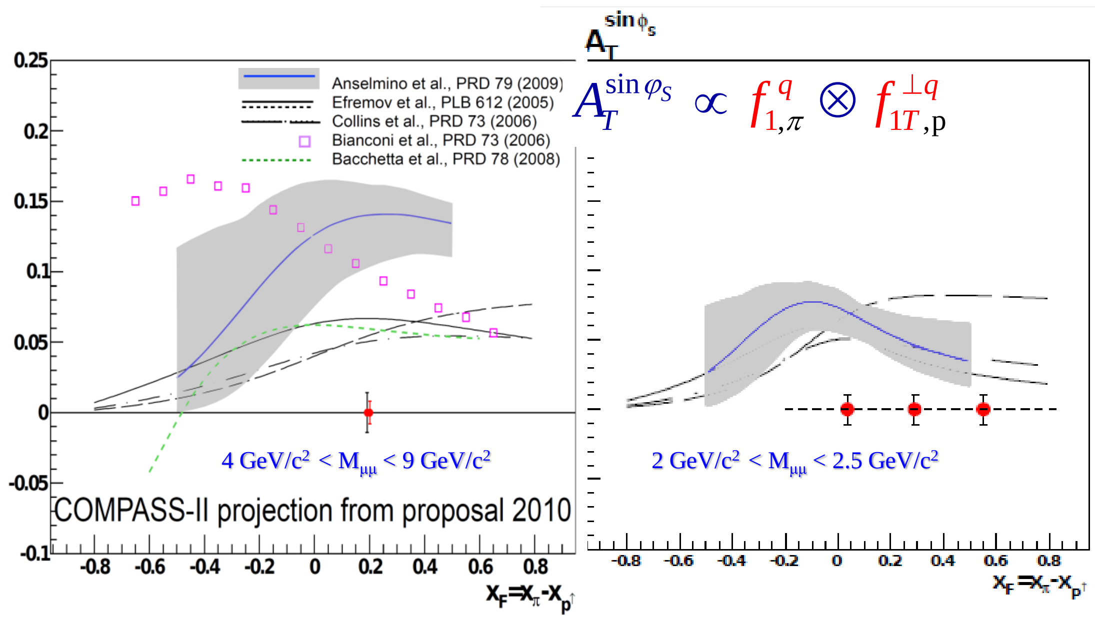
P. Sun and F. Yuan,
"Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production".
PRD 88 11, 114012 (2013)





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





Current status

- COMPASS Drell-Yan program has started in October by a pilot run.
  - After final commissioning of the magnets, detectors and polarized target first polarized Drell-Yan physics data will be recorded from beginning of November till the end of the run (December 2014)
- Main purposes of the pilot run are:
  - to put back in operation COMPASS setup after long shut-down
  - to test all the new and old detectors under new working conditions
  - to make final tunings of upgraded DAQ system
  - to test and tune trigger systems
  - to work out data taking strategy
  - to test reconstruction software
  - to have a look into first Drell-Yan data
- This pilot run will be followed by the one year long (140 days) full-time Drell-Yan data taking period starting in 2015.

- A second year of DY data-taking is planned, possibly in 2018 – to be approved..

Conclusions

- COMPASS will be the first ever experiment to measure polarized Drell-Yan!
  - Also first experiment to measure both SIDIS and polarized Drell-Yan!
  - Also first and only experiment to measure meson-induced Drell-Yan in past 25 years!
- Feasibility of measurement has been proven by the series of beam-tests.
- Final pilot run has already started and hopefully soon first data will be recorded.
- COMPASS has provided first input for future SIDIS - Drell-Yan cross-studies.
  - Measurement of DY-TSAs in 2015 compared with COMPASS SIDIS results will hopefully give first so long desired answers to several hot topics raised in QCD.
  - Expected statistical accuracy of Sivers asymmetry should allow to test sign-change and to study the effect in several kinematical bins.
  - Several important studies are defined also for the "unpolarized" part of COMPASS DY program (see talk by Wen-Chen Chang)

- A second year of data-taking is planned in near future. To be approved.

Thank you!

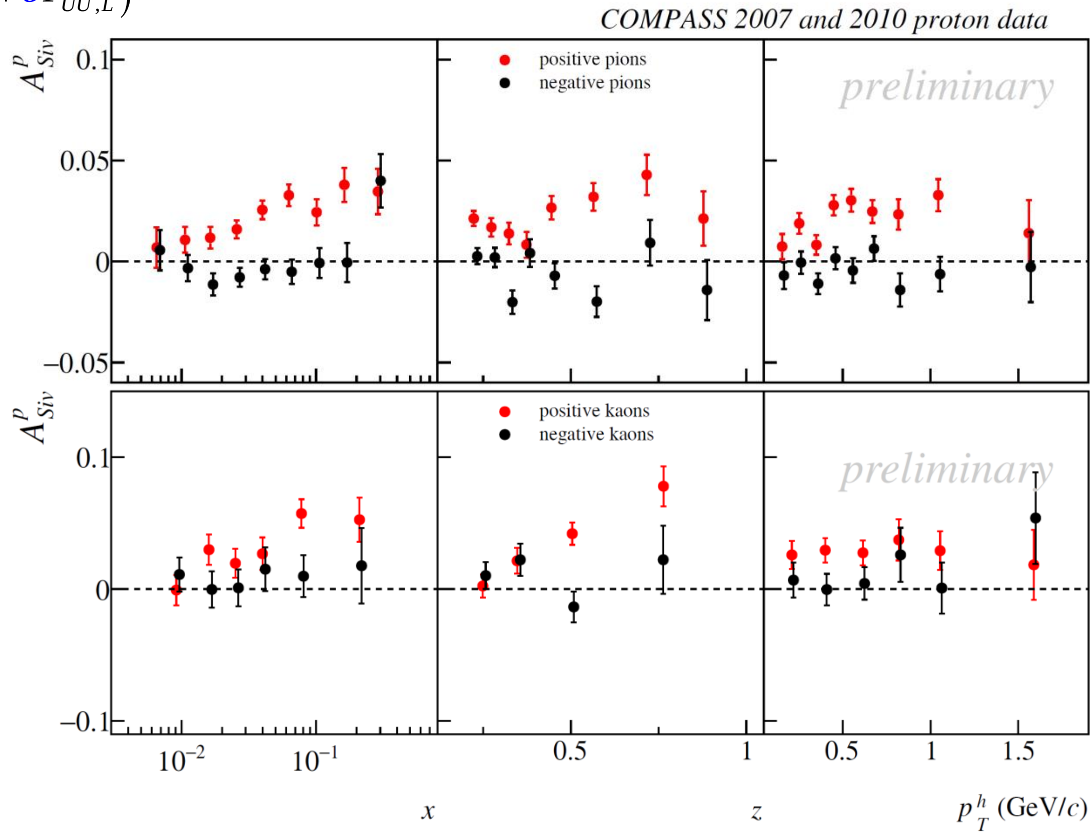
Spare slides

SIDIS x-section

$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$ SSA[twist-2]

$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right] \times \left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times$$

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



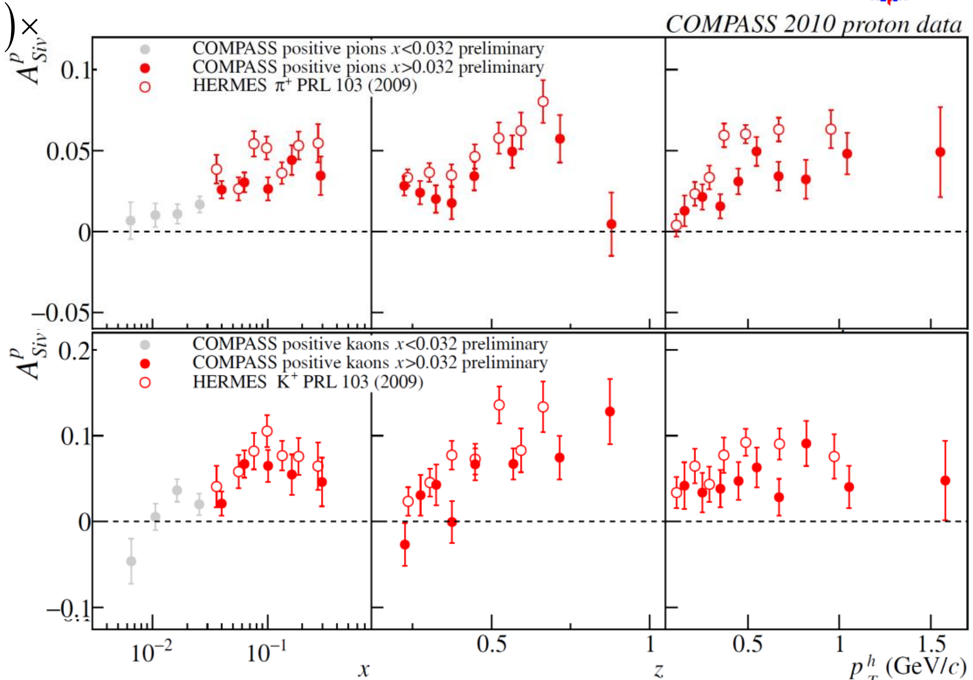
- Significantly large amplitude for π^+ and K^+ in whole range of *x*
- Compatible with zero for π^- and K^-
  - (maybe except the last bin of *x* for π^-).
- Compatible with zero on deuteron

SIDIS x-section

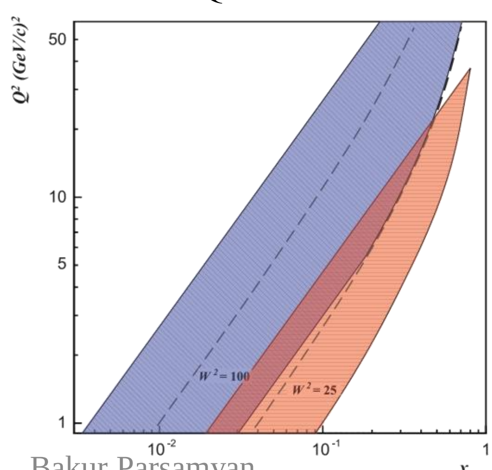
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$ SSA[twist-2]

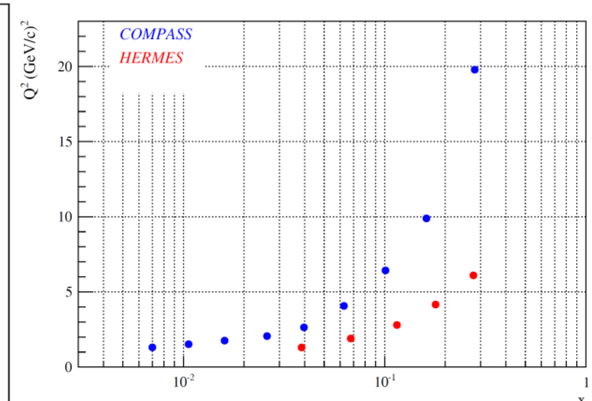
$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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



- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results… Q^2-evolution?





SIDIS x-section

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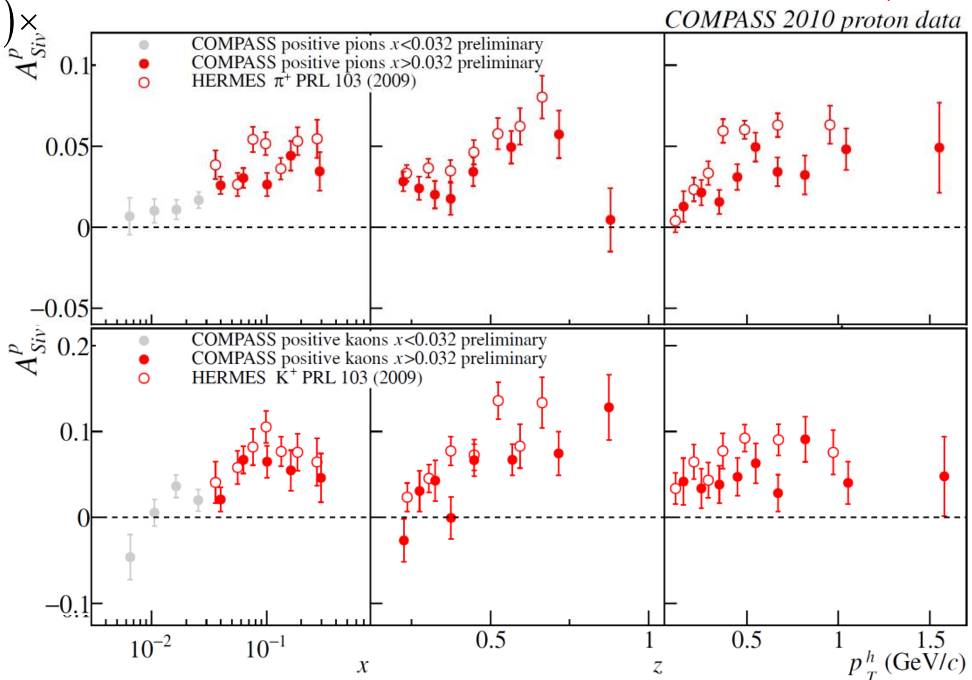
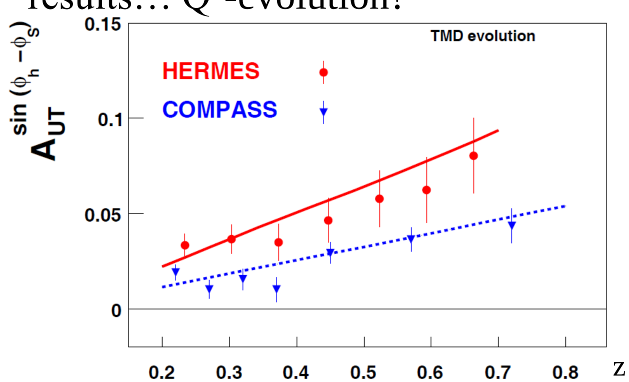
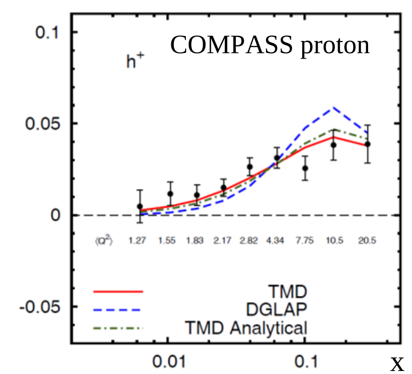
$$
\begin{aligned}
\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = & \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times \\
\Bigg\{ & 1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\varphi_h}+\cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)}+ \\
& \lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h}+ \\
& S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h A_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)A_{UL}^{\sin(2\phi_h)}\right]+ \\
& S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h A_{LL}^{\cos\phi_h}\right]+ \\
& S_T\left[\begin{aligned}
&\sin(\varphi_h-\varphi_S)\times\left(A_{UT}^{\sin(\varphi_h-\varphi_S)}\right)+ \\
&\sin(\varphi_h+\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}\right)+ \\
&\sin(3\varphi_h-\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)+ \\
&\sin\varphi_S\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+ \\
&\sin(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}\right)+
\end{aligned}\right]+ \\
& S_T\lambda\left[\begin{aligned}
&\cos(\varphi_h-\varphi_S)\times\left(\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\varphi_h-\varphi_S)}\right)+ \\
&\cos\varphi_S\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}\right)+ \\
&\cos(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)
\end{aligned}\right]\Bigg\}
\end{aligned}
$$



- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results… Q^2-evolution?





S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**