Measurement of transverse-spin-dependent azimuthal asymmetries in Drell-Yan process at COMPASS

M. Chiosso
on behalf of the
COMPASS Collaboration

DIS 2018
Kobe, 16-20 April

Outline

The COMPASS Experiment at CERN

Single polarized Drell-Yan at COMPASS

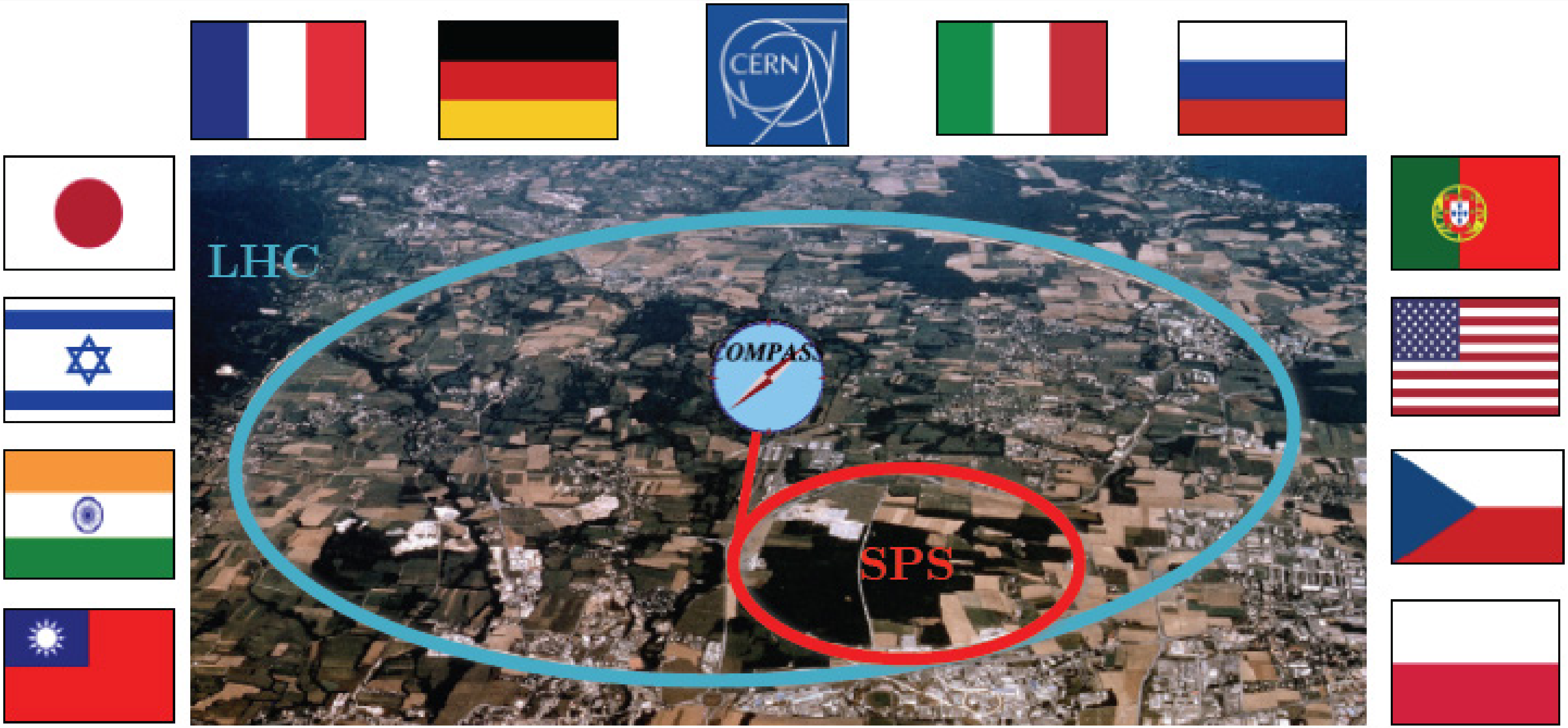
DY vs SIDIS at COMPASS

Experimental setup

Spin-dependent measurements

What about the future?

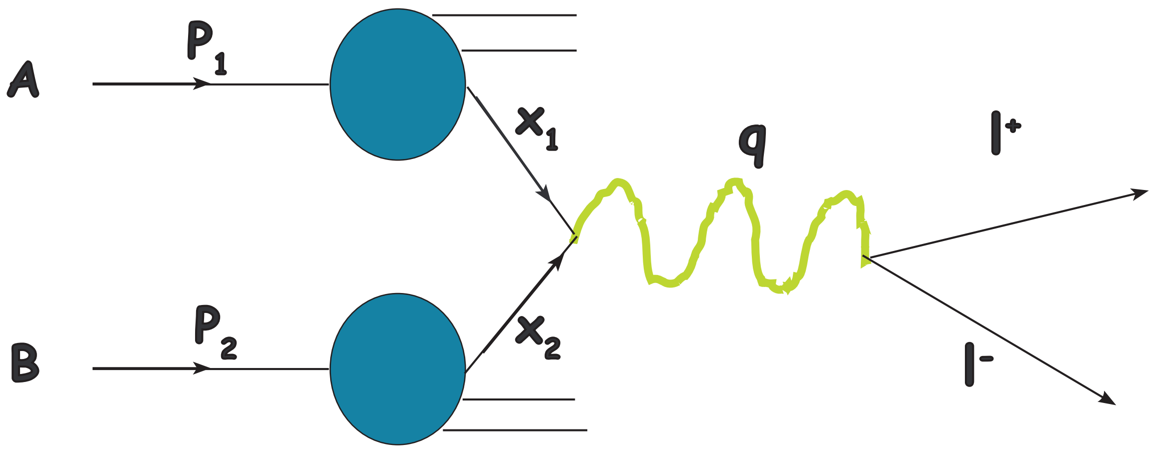
The COMPASS Experiment at CERN



Phase I
- 2002 – 2011
- Hadron spectroscopy
- Nucleon spin structure (L/T P/D Targets)

Phase II
- 2012 – 2018
- Primakoff + DVCS pilot run (2012)
- Drell-Yan (2015, 2018)
- DVCS + Unpolarized SIDIS(2016-2017)
- T-polarized SIDIS (D target) (2021 ?)

Drell-Yan process



Invariants:

$s^2 = (P_1 + P_2)^2$

$x_1 = Q^2/2P_1 \cdot q$

$x_2 = Q^2/2P_2 \cdot q$

$$x_F \approx 2p_L/\sqrt{s} = x_1 - x_2$$
$$M^2_{\mu^+\mu^-} = s x_1 x_2$$

Predictions stated in the original paper

S. D. Drell and T. M. Yan, Phys.Rev. Lett.25, 316 (1970) T. M Yan arXiv:hep-ph/9810268v1

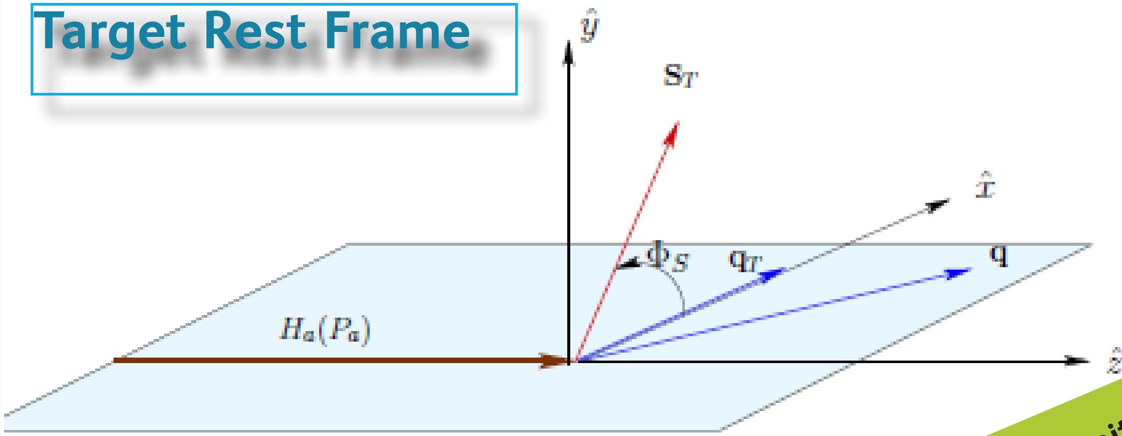
"The magnitude and shape of the cross section are determined by the parton and antiparton distributions measured in deep inelastic lepton scatterings

If a pion, kaon, or antiproton is used as the projectile, its structure functions can be measured by lepton pair production. This is the only way I know of to study the parton structure of a particle unavailable as a target."

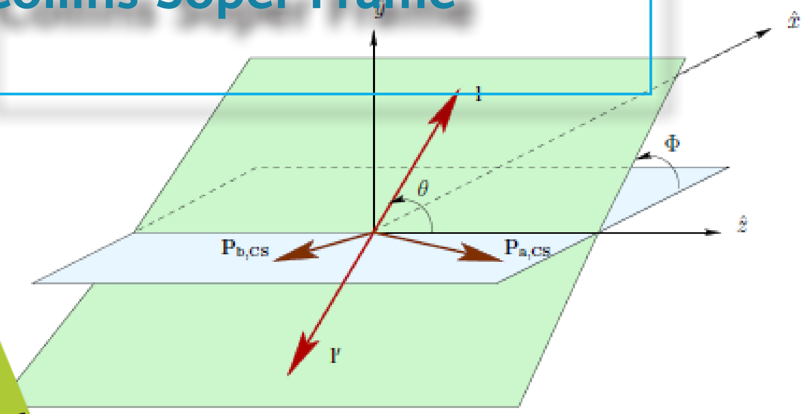
T. M Yan arXiv:hep-ph/9810268v1

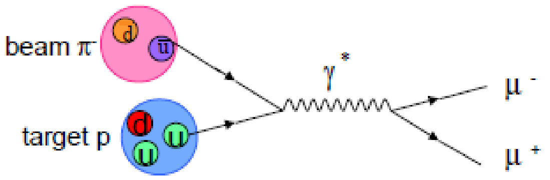
Single polarized Drell-Yan

Target Rest Frame



Collins Soper Frame





Measure magnitude of spin-(in)dependent azimuthal modulations in cross section: "Single-Spin Asymmetries"

At LO

$$\mathrm{d}\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) \propto 1 + \bar{h}_1^\perp \otimes h_1^\perp \cos(2\phi)$$
$$+ |S_T| \; \bar{f}_1 \otimes f_{1T}^\perp \sin\phi_S$$
$$+ |S_T| \; \bar{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi + \phi_S)$$
$$+ |S_T| \; \bar{h}_1^\perp \otimes h_1 \sin(2\phi - \phi_S)$$

beam target

DF ⊗ DF

$f_{\bar{u}|\pi} \otimes f_{u|p}$

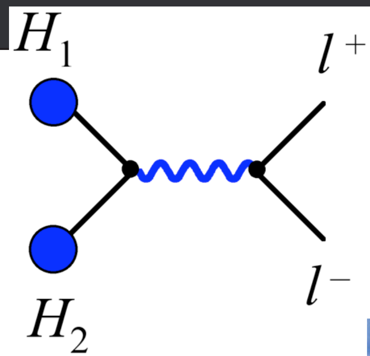
$(\mathrm{BM})_\pi \otimes (\mathrm{BM})_p$

$(f_1)_\pi \otimes (\mathrm{Sivers})_p$

$(\mathrm{BM})_\pi \otimes (\mathrm{Pretzelosity})_p$

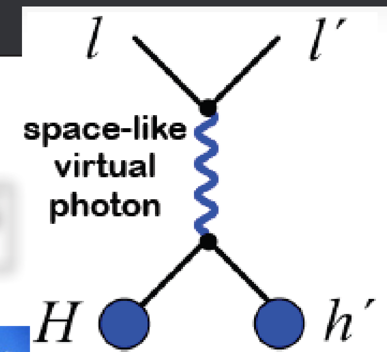
$(\mathrm{BM})_\pi \otimes (\mathrm{Transversity})_p$

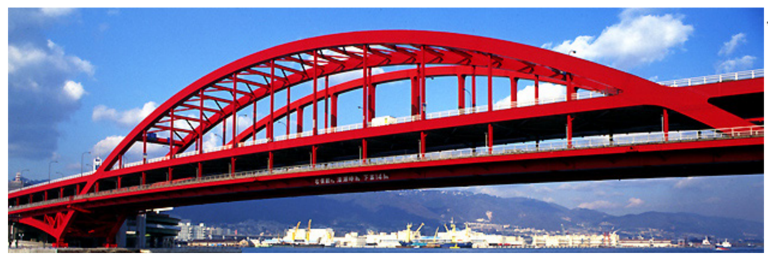
DY - SIDIS Bridge



DY

SIDIS



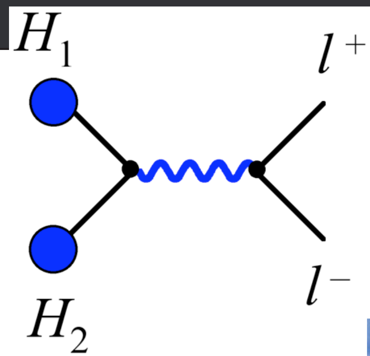


$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1+\cos^2\theta + \sin^2\theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}} + S_T \left[\begin{array}{l} \left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S} \\ +\sin^2\theta \left(\begin{array}{l} \sin\left(2\varphi_{CS}+\varphi_S\right)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

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

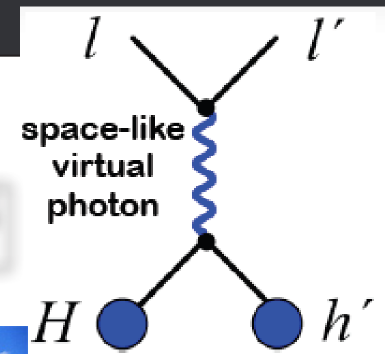
$$\times\left(F_{UU,T} + \varepsilon F_{UU,L}\right) \left\{ 1+\cos 2\phi_h \left(\varepsilon A_{UU}^{\cos 2\phi_h}\right) + S_T \left[\begin{array}{l} \sin\left(\phi_h-\phi_S\right)\left(A_{UT}^{\sin\left(\phi_h-\phi_S\right)}\right) \\ +\ \sin\left(\phi_h+\phi_S\right)\left(\varepsilon A_{UT}^{\sin\left(\phi_h+\phi_S\right)}\right)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

DY - SIDIS Bridge



DY

SIDIS



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

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

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

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

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$$

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

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

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

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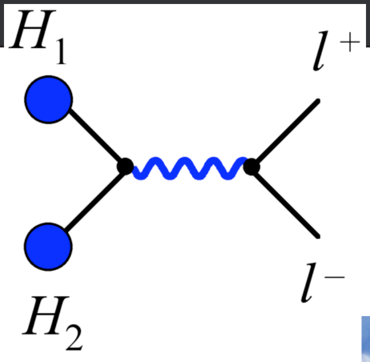

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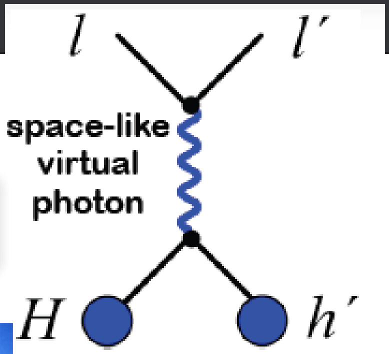

See talk by B. Parsamyan

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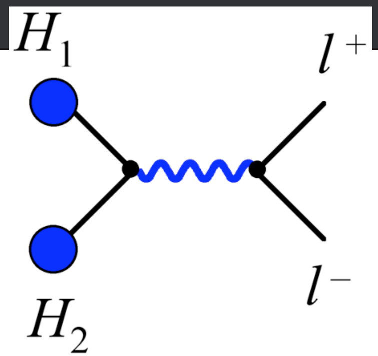
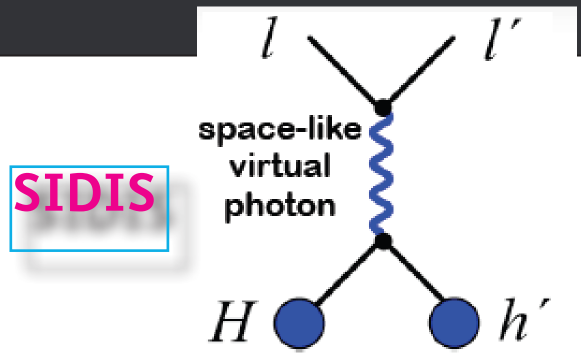
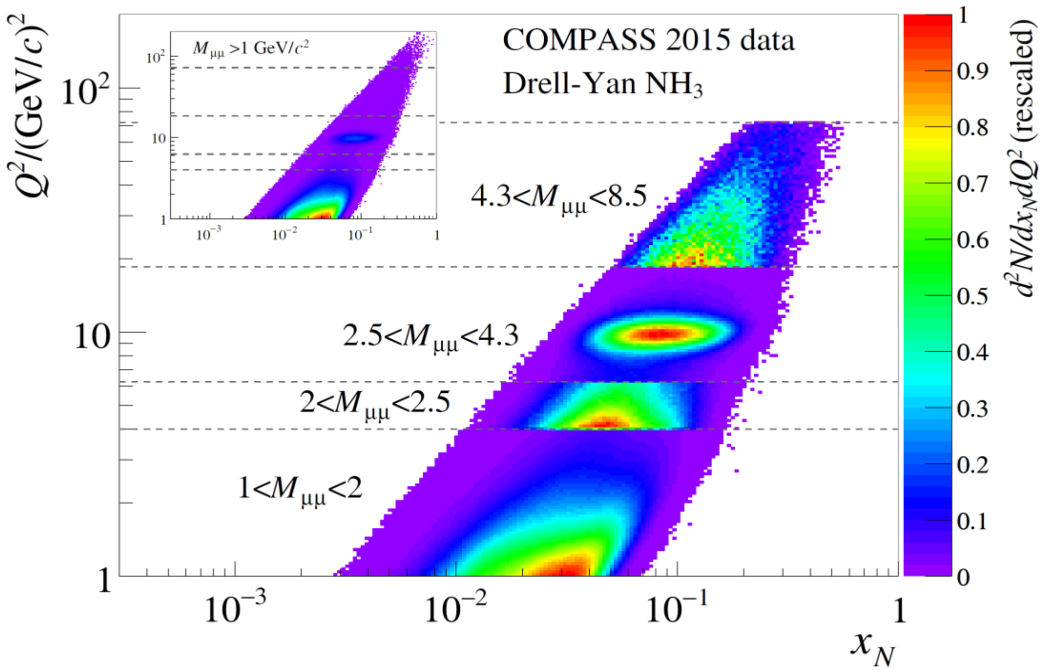
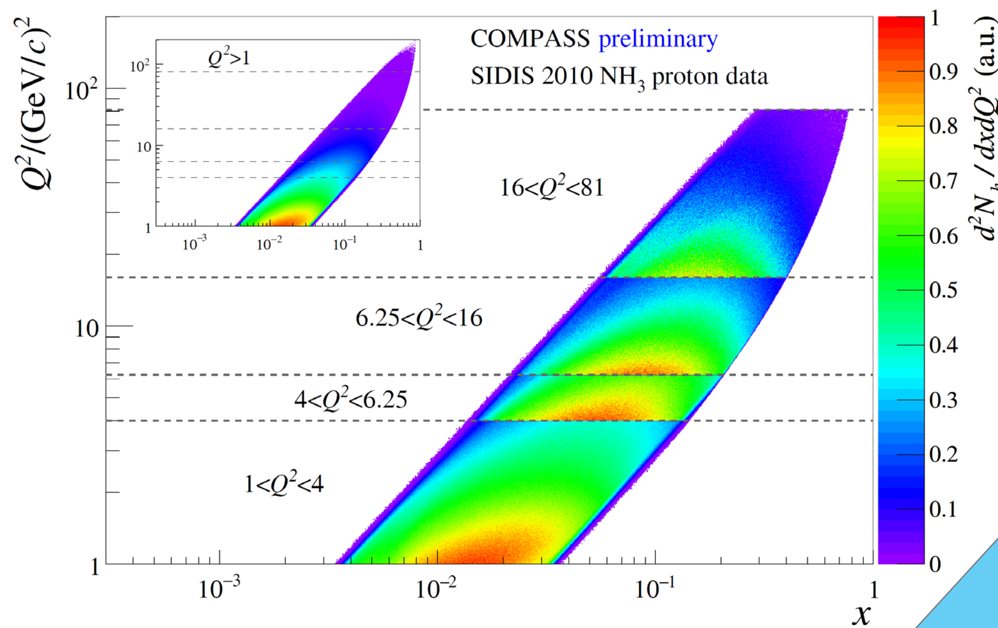








$$h_1^{q\perp}\Big|_{\mathrm{DY}} = -\,h_1^{q\perp}\Big|_{\mathrm{SIDIS}}$$
$$f_{1T}^{q\perp}\Big|_{\mathrm{DY}} = -f_{1T}^{q\perp}\Big|_{\mathrm{SIDIS}}$$

comparable x:Q^2 kinematic coverage

Unique experimental environment to perform crucial test of TMD formalism: experimental confirmation of the Sivers and the Boer-Mulders sign change prediction

minimization of possible Q^2 evolution effects

COMPASS Setup for DY

negative hadron beam (π/K/p 97/2/1%)
(from 400 GeV/c SPS protons onto conversion target)
Average Beam Intensity: 10^8 particles / sec

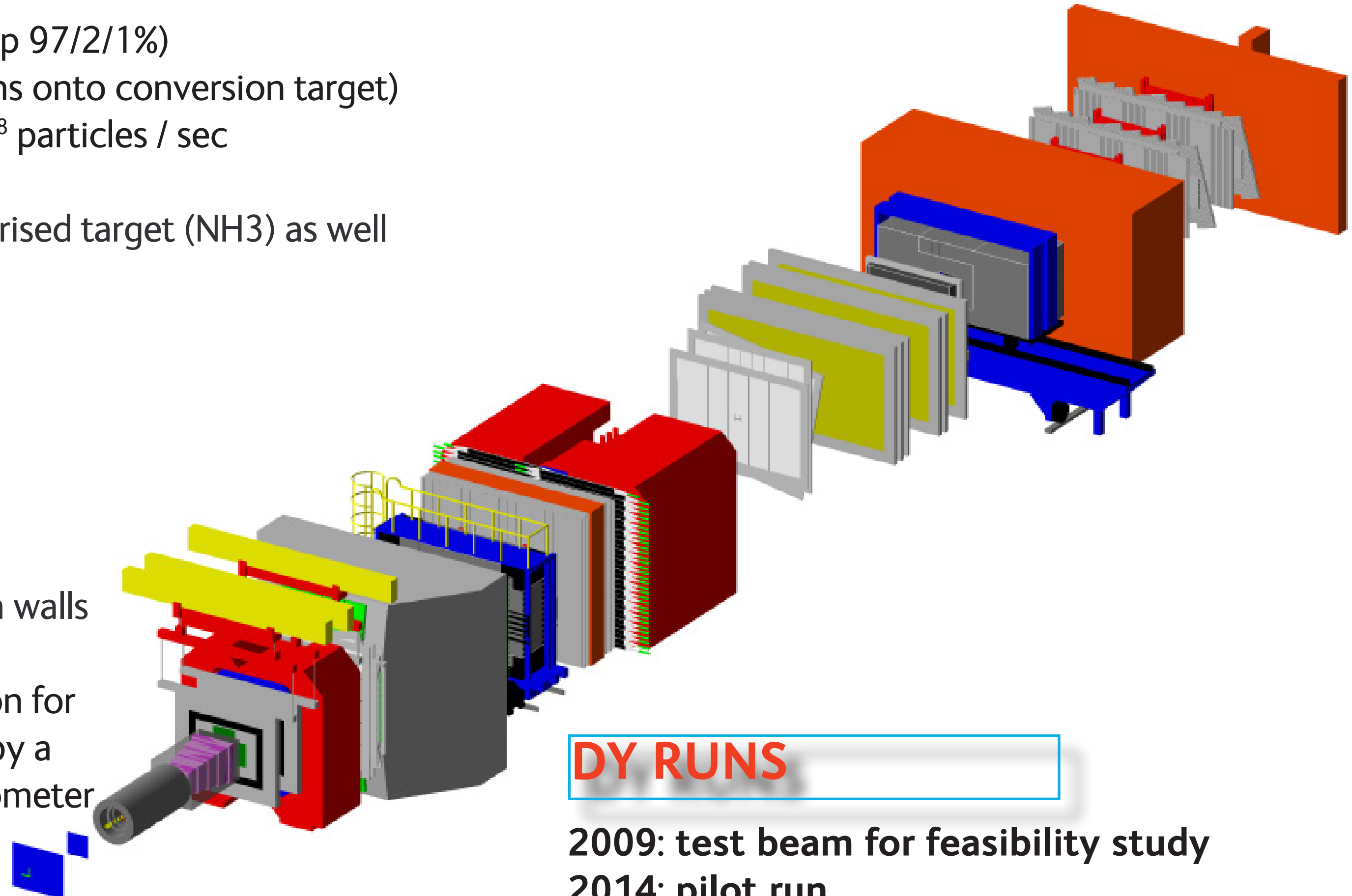
Solid state transversely polarised target (NH3) as well as nuclear targets

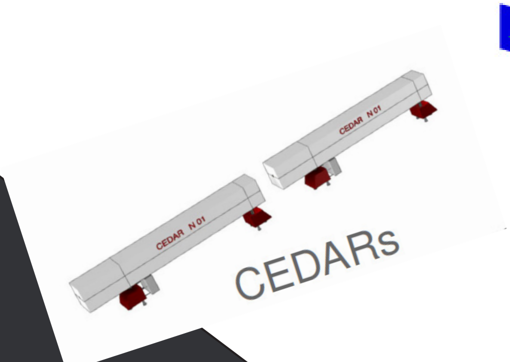
Hadron absorber

Powerful tracking system:
350 planes

Muon identification – Muon walls

A high momentum resolution for charged particles provided by a two-stage magnetic spectrometer

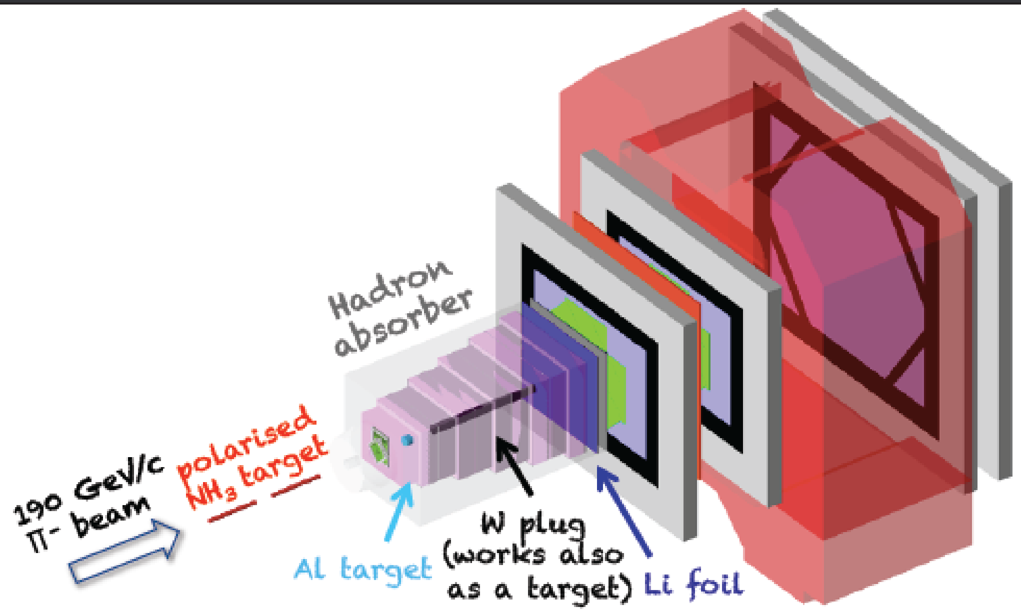




DY RUNS

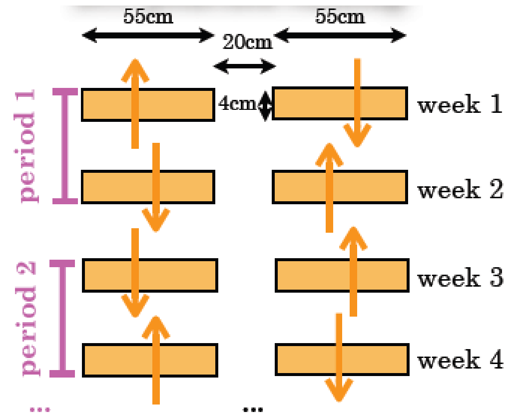
2009: test beam for feasibility study
2014: pilot run
2015: main run
(transversely polarized NH3 target)
2018: new run
(transversely polarized NH3 target)

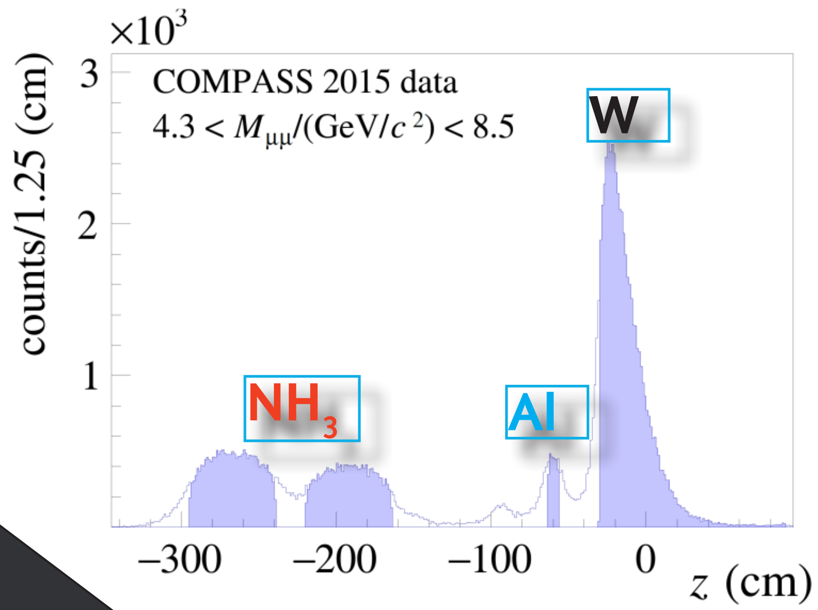
COMPASS Setup for DY



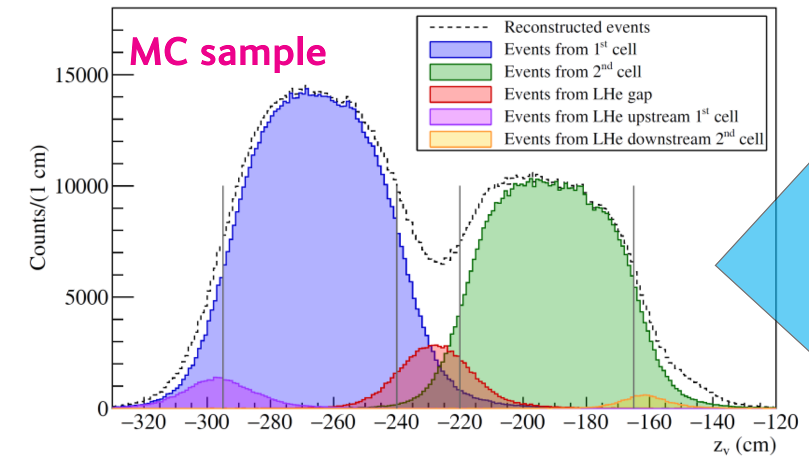
Target Polarisation ~73%

Reverse target polarization each subperiod

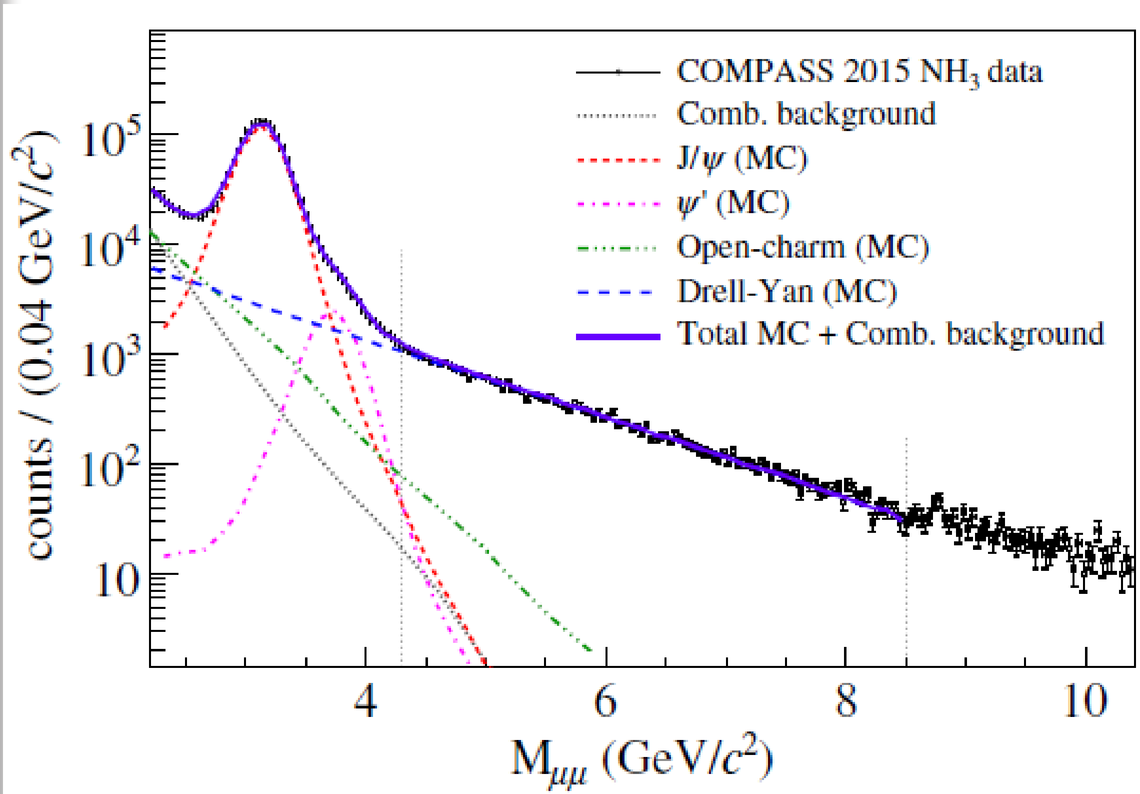




The dilution factor is corrected to account for the migration of events from one cell to the other (obtained with MC simulation)
f~0.18



The dimuon invariant mass distribution



I. 1 < Mμμ/(GeV/c²) < 2, "Low mass"
- Large background contamination

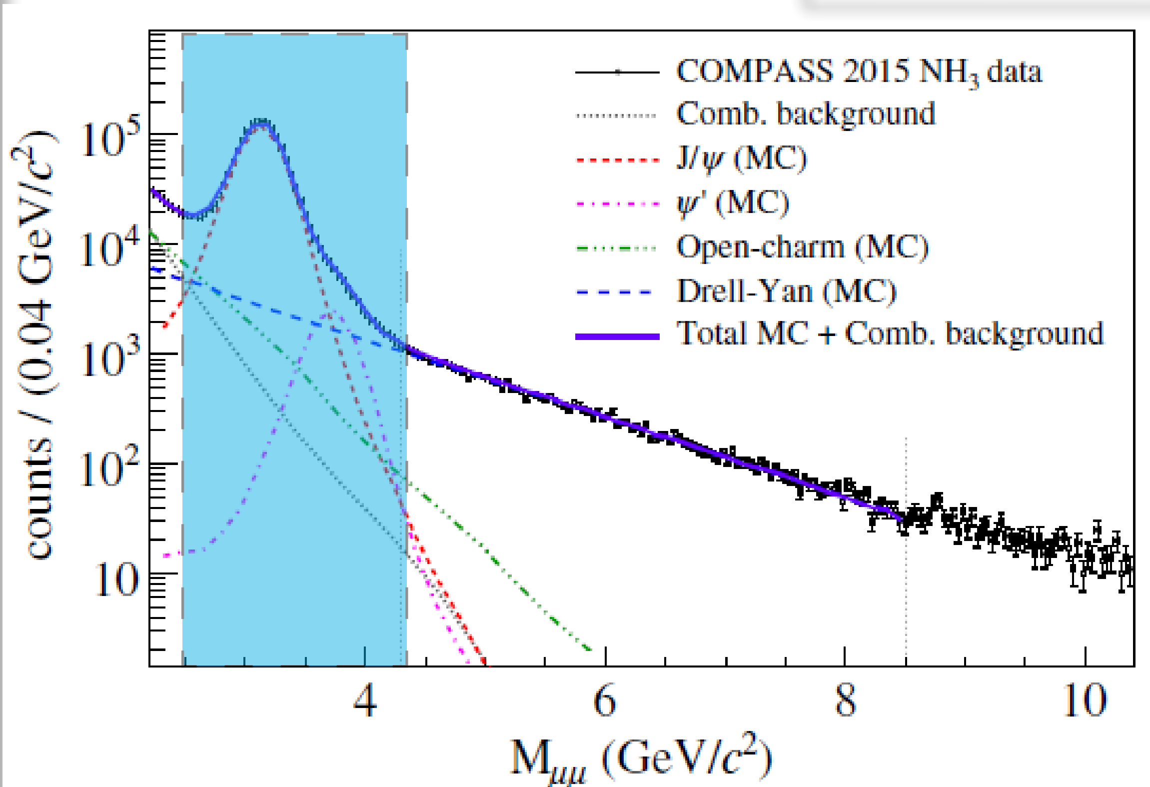
II. 2 < Mμμ/(GeV/c²) < 2.5, "Intermediate mass"
- High DY cross section.
- Still low DY-signal/background ratio.

III. 2.5 < Mμμ/(GeV/c²) < 4.3, "Charmonia mass"
- Strong J/ψ signal --> Studies of J/ψ physics.
- Good signal/background.

IV. 4.3 < Mμμ/(GeV/c2) < 8.5, "High mass"
- Beyond J/ψ and ψ' peak, background < 4%.
- Valence quark region --> Largest asymmetries!
- Low DY cross-section

The dimuon invariant mass distribution

Ongoing Analysis



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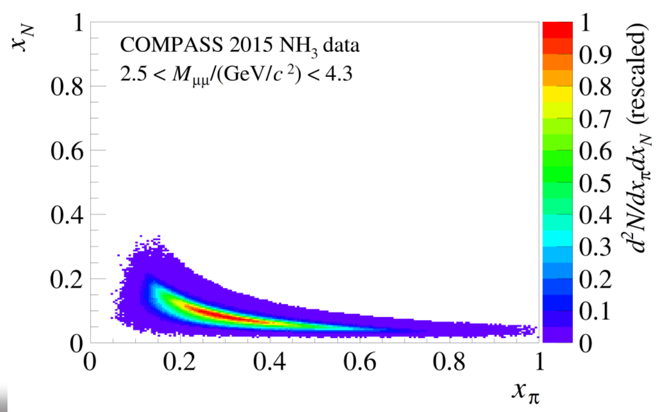
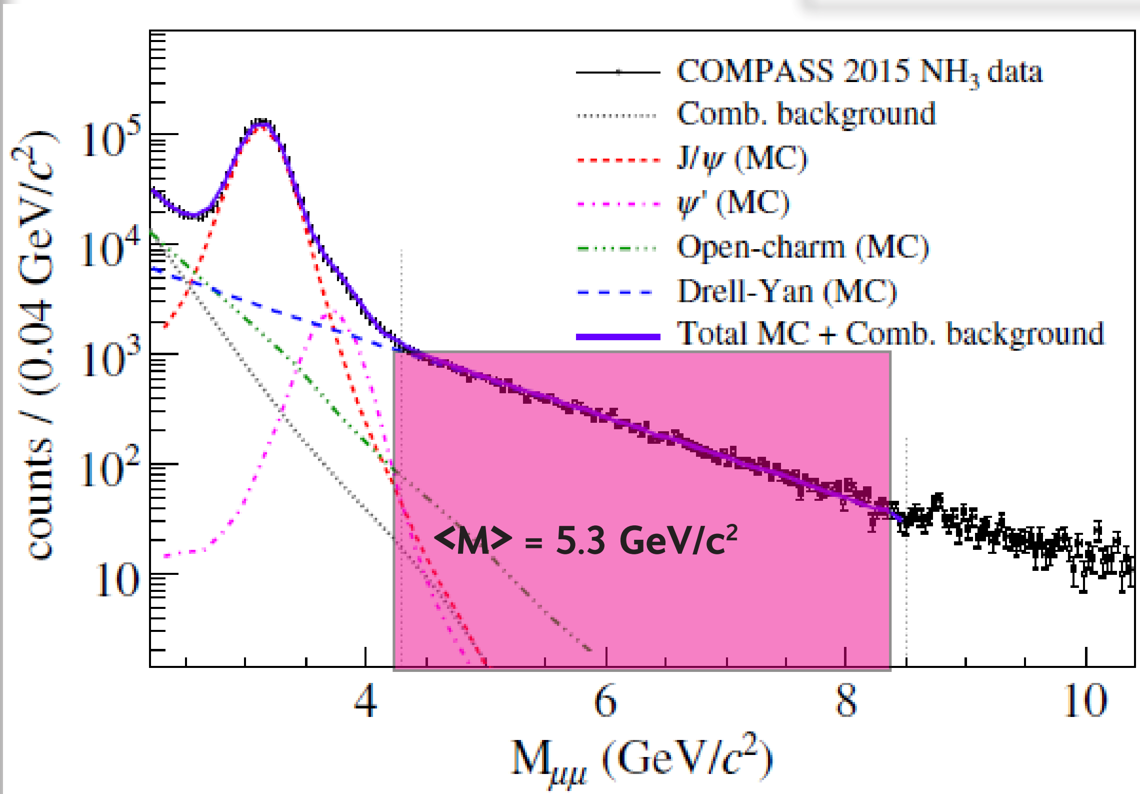
$\langle x_\pi \rangle = 0.31$
$\langle x_N \rangle = 0.009$
$\langle x_F \rangle = 0.22$
$\langle q_T \rangle = 1.1$



The dimuon invariant mass distribution

This talk



I. $1 < M_{\mu\mu}/(GeV/c^2) < 2$, "Low mass"
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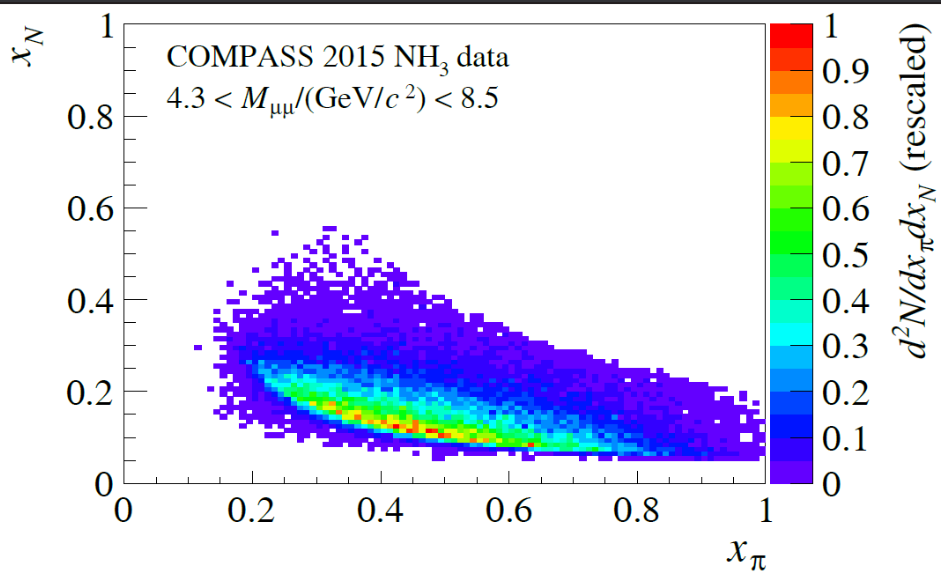
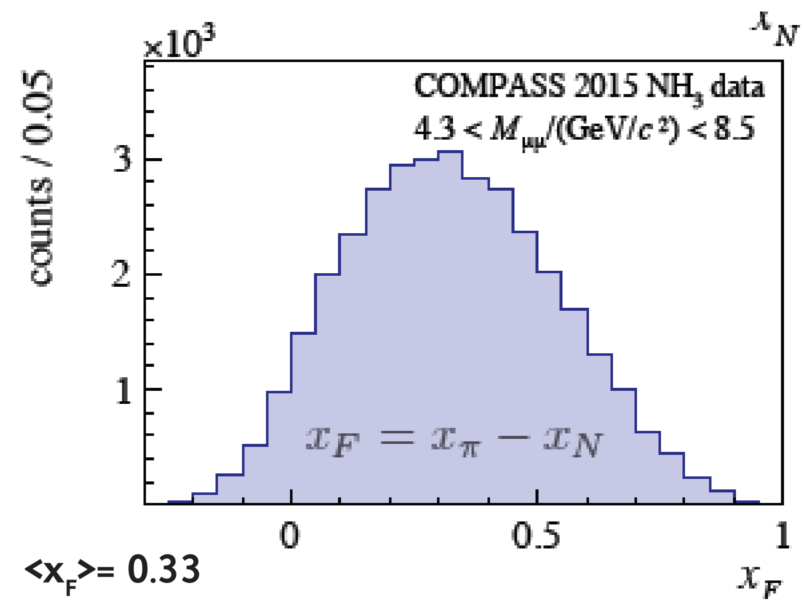
Kinematics in the high mass range



$\langle x_\pi \rangle = 0.5$

$\langle x_N \rangle = 0.17$

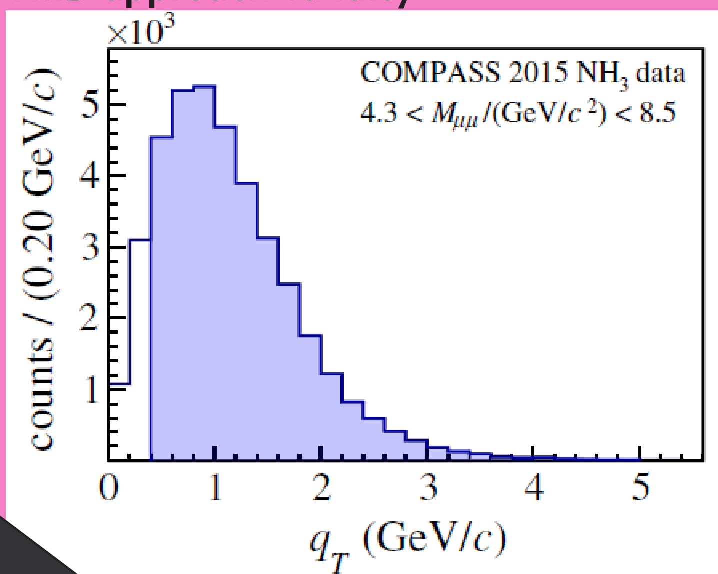
→ Valence region dominance $\bar{u}_\pi\ u_p$

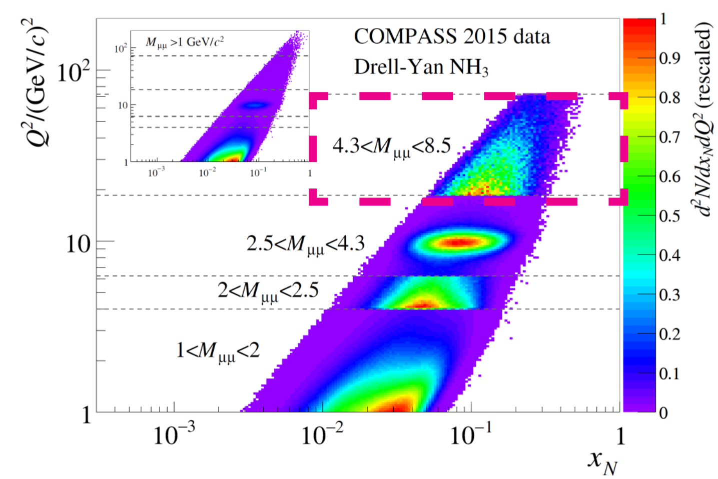


$\langle x_F \rangle = 0.33$

$\langle q_T \rangle = 1.2$ GeV/c << Mμμ = 5.3 GeV/c^2

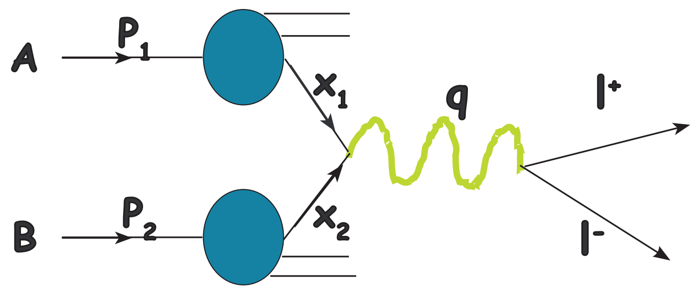
TMD approach validity





DY TSAs : Results in High Mass Range

$$d\sigma^{DY} \propto 1 + D_{[\sin 2\theta]} A_{UU}^{\cos\phi} \cos\phi + D_{[\sin^2\theta]} A_{UU}^{\cos 2\phi} \cos 2\phi$$
$$+ S_T \Big[D_{[1+\cos^2\theta]} A_{UT}^{\sin\phi_S} \sin\phi_S$$
$$+ D_{[\sin^2\theta]} \left(A_{UT}^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) + A_{UT}^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) \right)$$
$$+ D_{[\sin 2\theta]} \left(A_{UT}^{\sin(\phi-\phi_S)} \sin(\phi-\phi_S) + A_{UT}^{\sin(\phi+\phi_S)} \sin(\phi+\phi_S) \right) \Big]$$



All the 5 TSAs are extracted simultaneously using an Unbinned Maximum Likelihood Method

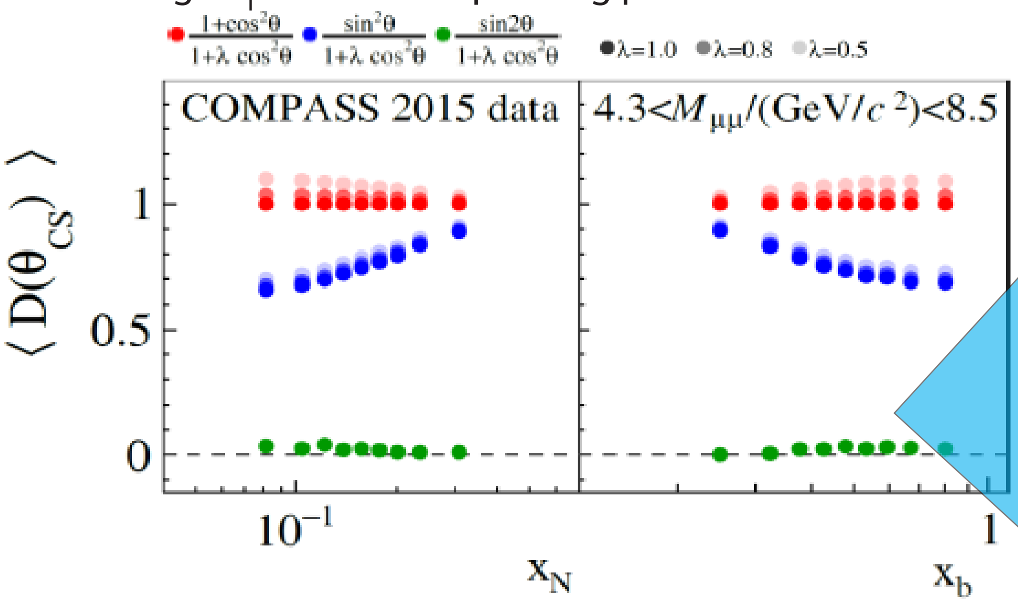
$A_{raw} = P_T f_D [f(\theta)] A_{phy}$

The asymmetries are weighted, event by event, according to the corresponding depolarization and dilution factors

The asymmetries resulting from the fit are corrected by the average P_T in the corresponding period

Depolarization factors are evaluated under assumption $\lambda = 1$

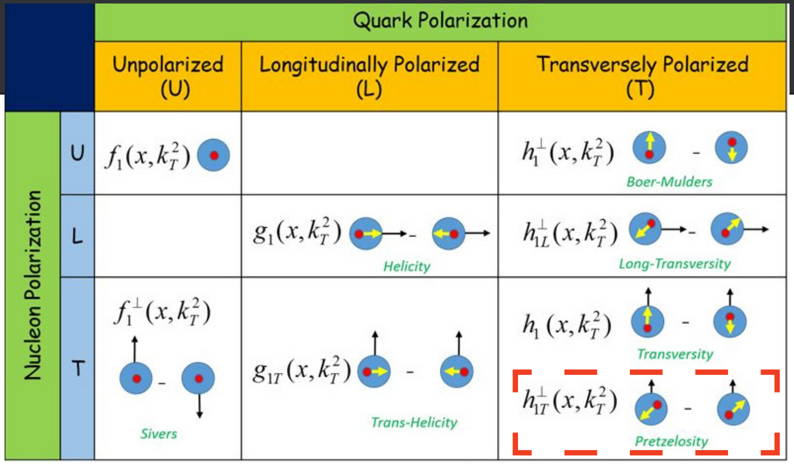
Possible impact of $\lambda \neq 1$ scenarios leads to a normalization uncertainty of at most 5%.



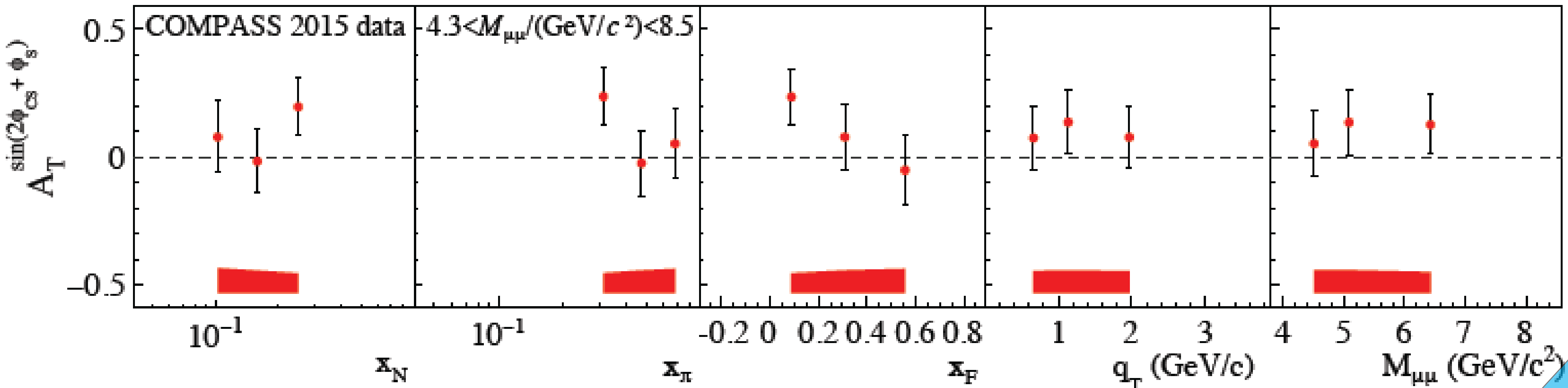
DY TSAs: results in high mass range

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

BM $\otimes$ Pretzelosity



COMPASS PRL 119, 112002 (2017)



Asymmetry from SIDIS:

Measurement compatible with zero within uncertainties

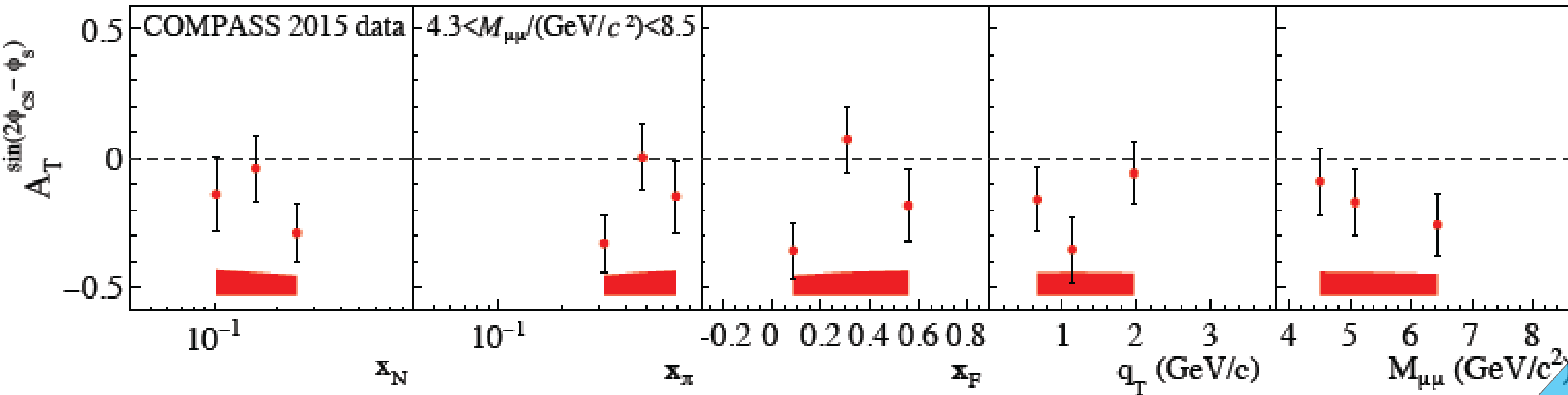
DY TSAs: results in high mass range

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

BM $\otimes$ Transversity

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$		$h_1^{\perp}(x,k_T^2)$ Boer-Mulders
	L		$g_1(x,k_T^2)$ Helicity	$h_{1L}^{\perp}(x,k_T^2)$ Long-Transversity
	T	$f_{1T}^{\perp}(x,k_T^2)$ Sivers	$g_{1T}(x,k_T^2)$ Trans-Helicity	$h_1(x,k_T^2)$ Transversity; $h_{1T}^{\perp}(x,k_T^2)$ Pretzelosity

COMPASS PRL 119, 112002 (2017)

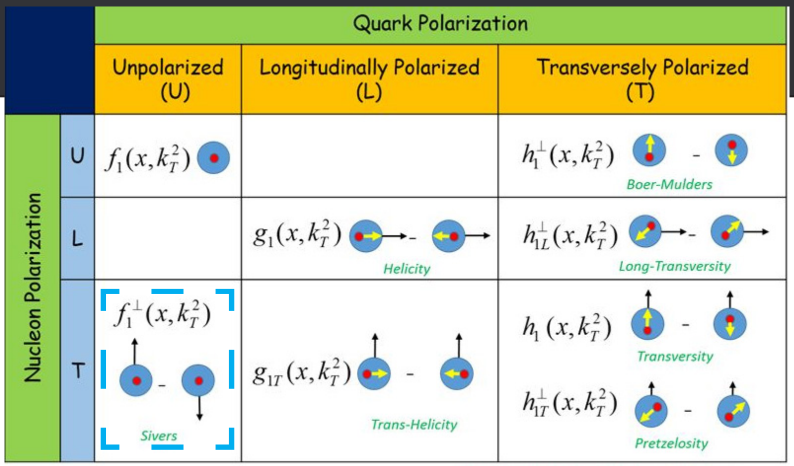


Asymmetry from SIDIS:
Measurement positive for h- and negative for h+

DY TSAs: results in high mass range

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

Unp. PDF $\otimes$ **Sivers**



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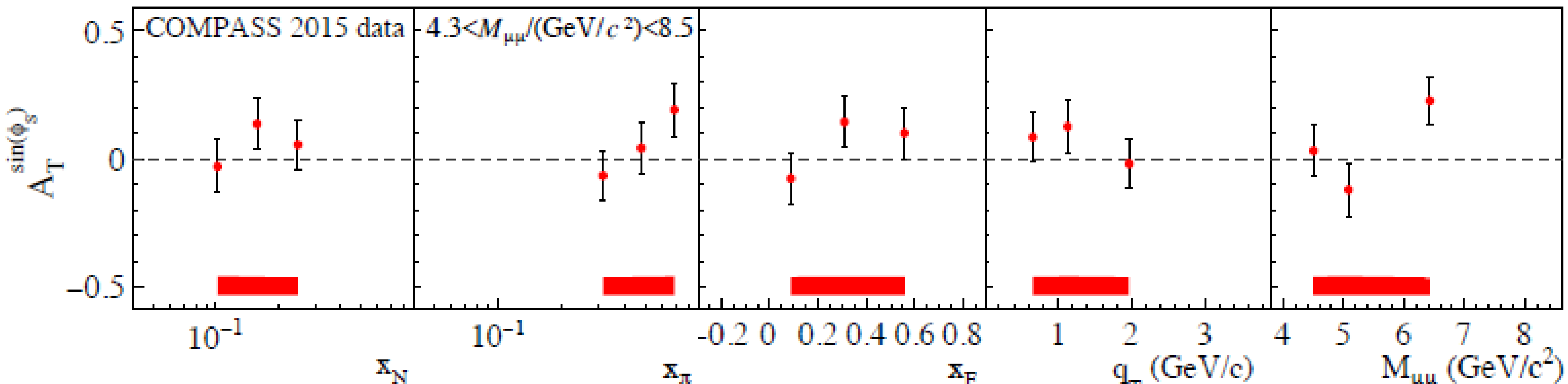
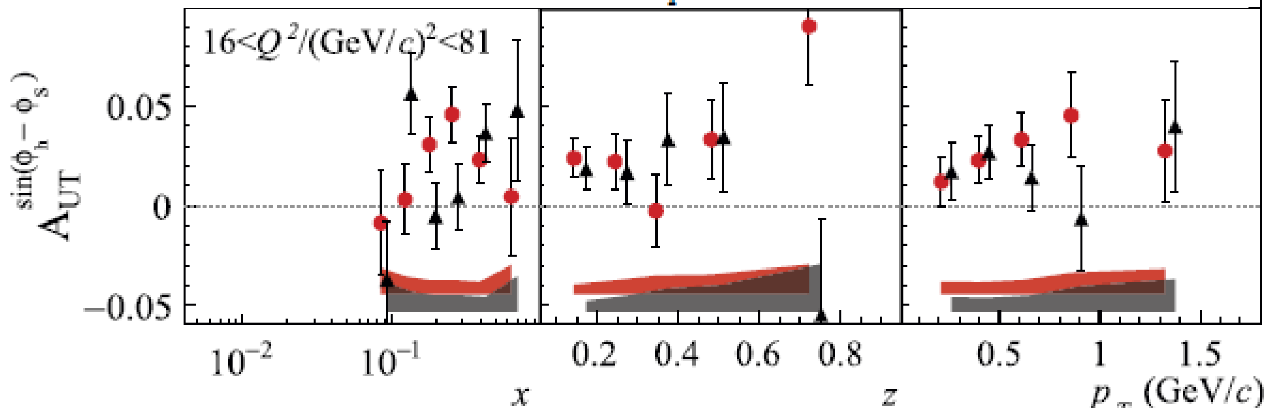


Sivers SIDIS in Drell-Yan high-mass range

COMPASS PLB 770 (2017) 138



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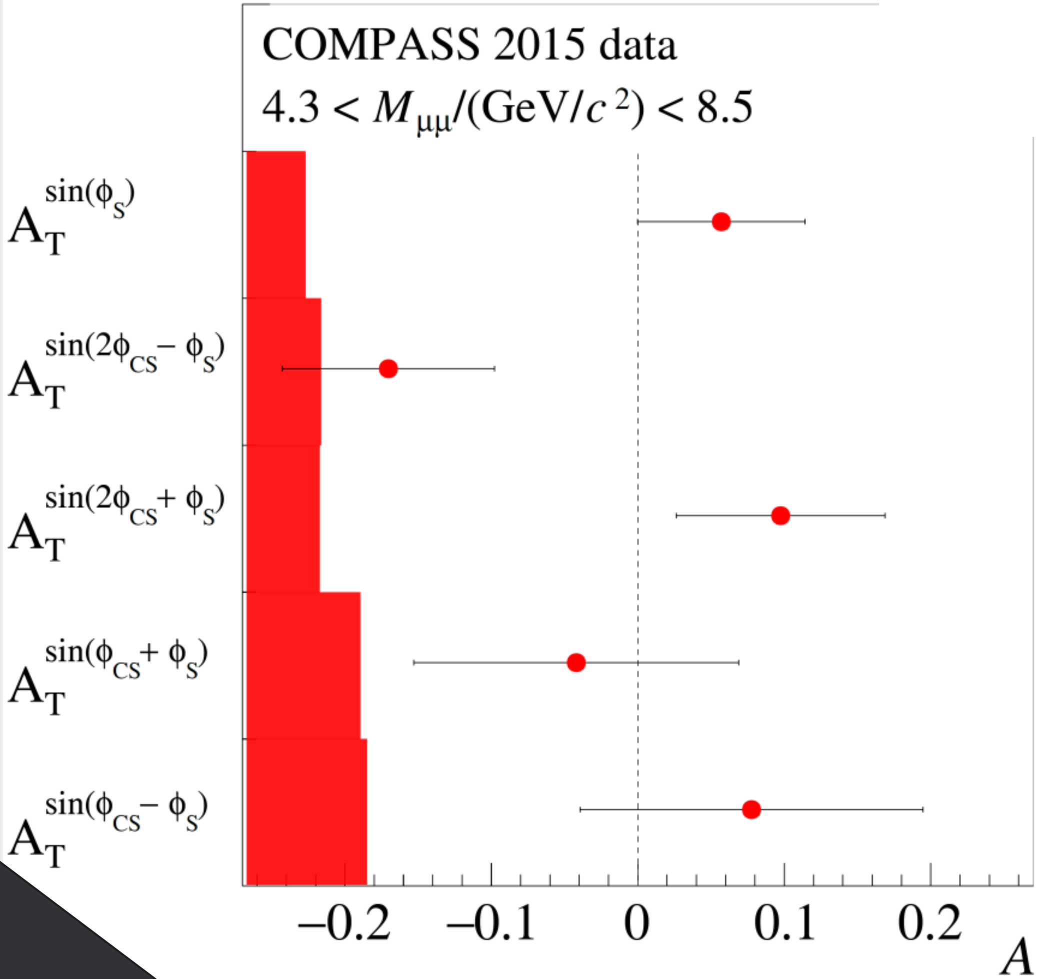
$$+ S_T \Big[D_{[1+\cos^2\theta]} A_{UT}^{\sin\phi_S}\sin\phi_S$$
$$+ D_{[\sin^2\theta]}\Big(A_{UT}^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S) + A_{UT}^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)\Big)$$
$$+ D_{[\sin 2\theta]}\Big(A_{UT}^{\sin(\phi-\phi_S)}\sin(\phi-\phi_S) + A_{UT}^{\sin(\phi+\phi_S)}\sin(\phi+\phi_S)\Big)\Big]$$

COMPASS PRL 119, 112002 (2017)



Unp. PDF ⊗ Sivers

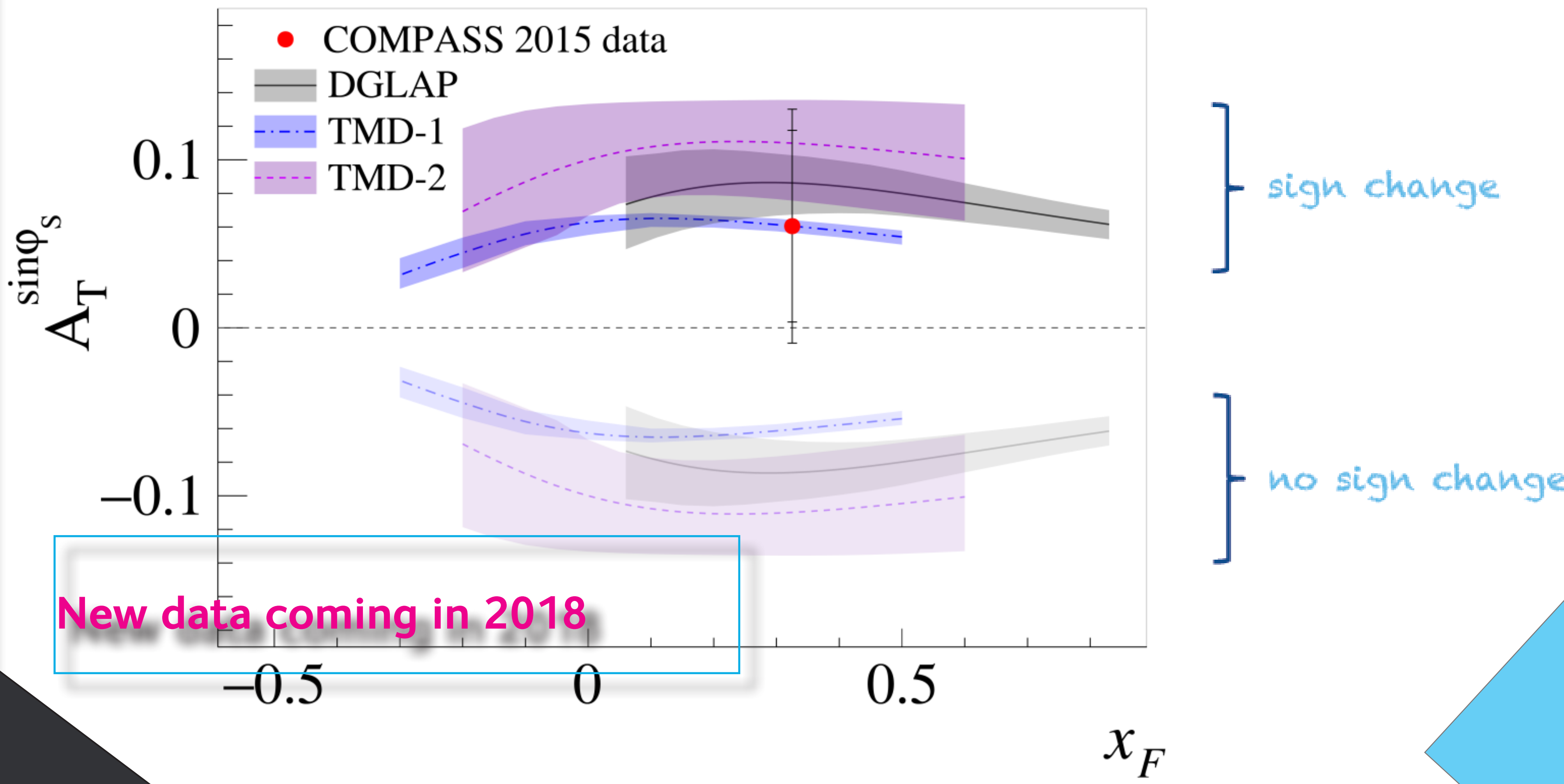
BM ⊗ Transversity

BM ⊗ Pretzelosity

Higher Twist Asymmetries

Probing the TMD formalism

The Sivers Sign Change



New data coming in 2018

DGLAP (2016) M. Anselmino et al., arXiv:1612.06413
TMD-1 (2014) M. Echevarria et al., PRD 89 (2014) 074013,
TMD-2 (2013) P. Sun and F. Yuan, PRD 88 (2013) 114012

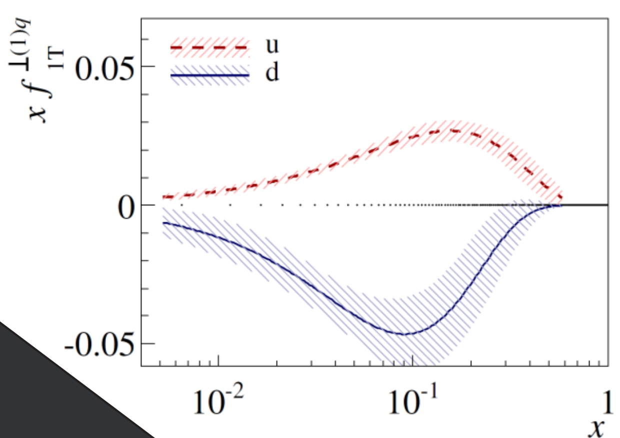
q_T weighted TSAs in Drell-Yan

- General formalism firstly developed for SIDIS [A. Kotzinian & P. Mulders, PLB 406 (1997) 373];
- It allows to avoid assumptions on k_T (e.g. gaussian);
- Recently measured in SIDIS by COMPASS;
- Formalism extended to DY [A. Efremov et al., Phys.Lett. B612 (2005) 233, A. Sissakian et al., Phys.Rev. D72 (2005) 054027];
- Using appropriate q_T weights allows to access directly the first moment of TMDs;
- Recent wTSAs extraction by COMPASS from DY 2015 data;

Sivers TSA in DY $A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$ PDF ⊗ PDF

Sivers wTSA in DY $A_T^{\sin\varphi_S \frac{q_T}{M_N}} \propto f_{1,\pi}^{q} \times f_{1T,p}^{\perp q}$ PDF X PDF

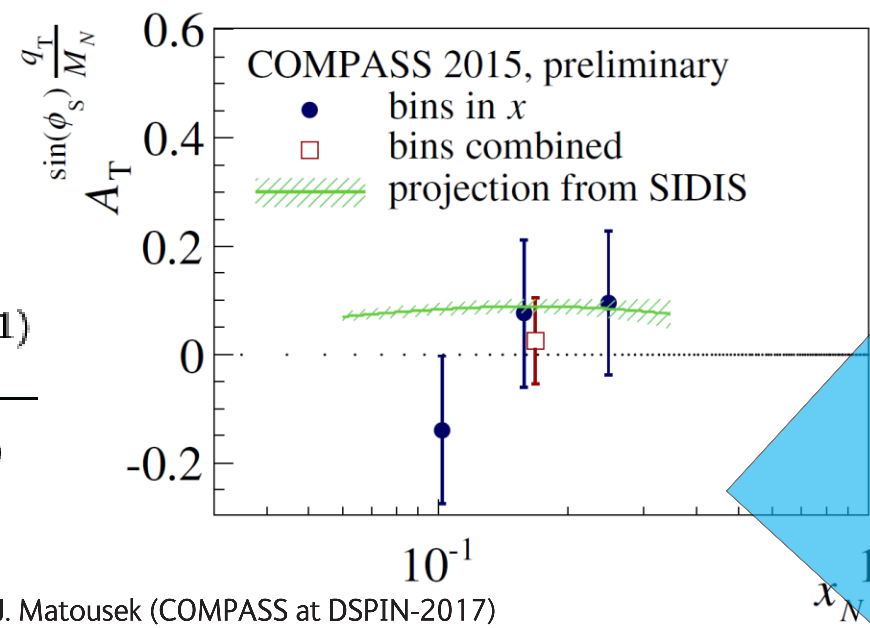
1st k_T^2 -moment of the Sivers function from SIDIS data at $Q^2 = Q^2_{SIDIS}(x)$



Valence quark dominance

No Q^2-evolution for Sivers

$$A_T^{\sin\varphi_S \frac{q_T}{M_N}} \sim \frac{f_{1T,p}^{\perp u(1)}}{f_{1,p}^{u}}$$



J. Matousek (COMPASS at DSPIN-2017)
arXiv:1710.06497 [hep-ex]

What about the future?

Coming soon

Analysis ongoing on 2015 data

• Extraction of Unpolarized Asymmetries of DY cross-section in Charmonia and High Mass ranges and test of the Lam-Tung sum rule;
• Extraction of J/ψ target spin dependent and independent azimuthal asymmetries;

2018 second year of polarized DY data taking → more data coming soon!

Beyond 2020

@ "COMPASS++" long-term future experiment (LOI to appear soon in 2018):

CERN

Physics Beyond Colliders

• A future Drell-Yan experiment is proposed, to study meson structure.
• New, precise determination of the pion structure functions: valence, sea and gluon contributions.
• The first-ever determination of the kaon PDFs, making use of RF-separated kaon beam of high intensity.
• A unique opportunity to make antiproton-induced Drell-Yan with transversely polarized proton target, and measure TSAs with signicantly reduced systematic error.

What about the future?

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Analysis ongoing on 2015 data

- Extraction of Unpolarized Asymmetries of DY cross-section in Charmonia and High Mass ranges and test of the Lam-Tung sum rule;
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Beyond 2020

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See talk by B. Badelek
18/04/2018, 16:30
WG7: Future of DIS

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- New, precise determination of the pion structure functions: valence, sea and gluon contributions.
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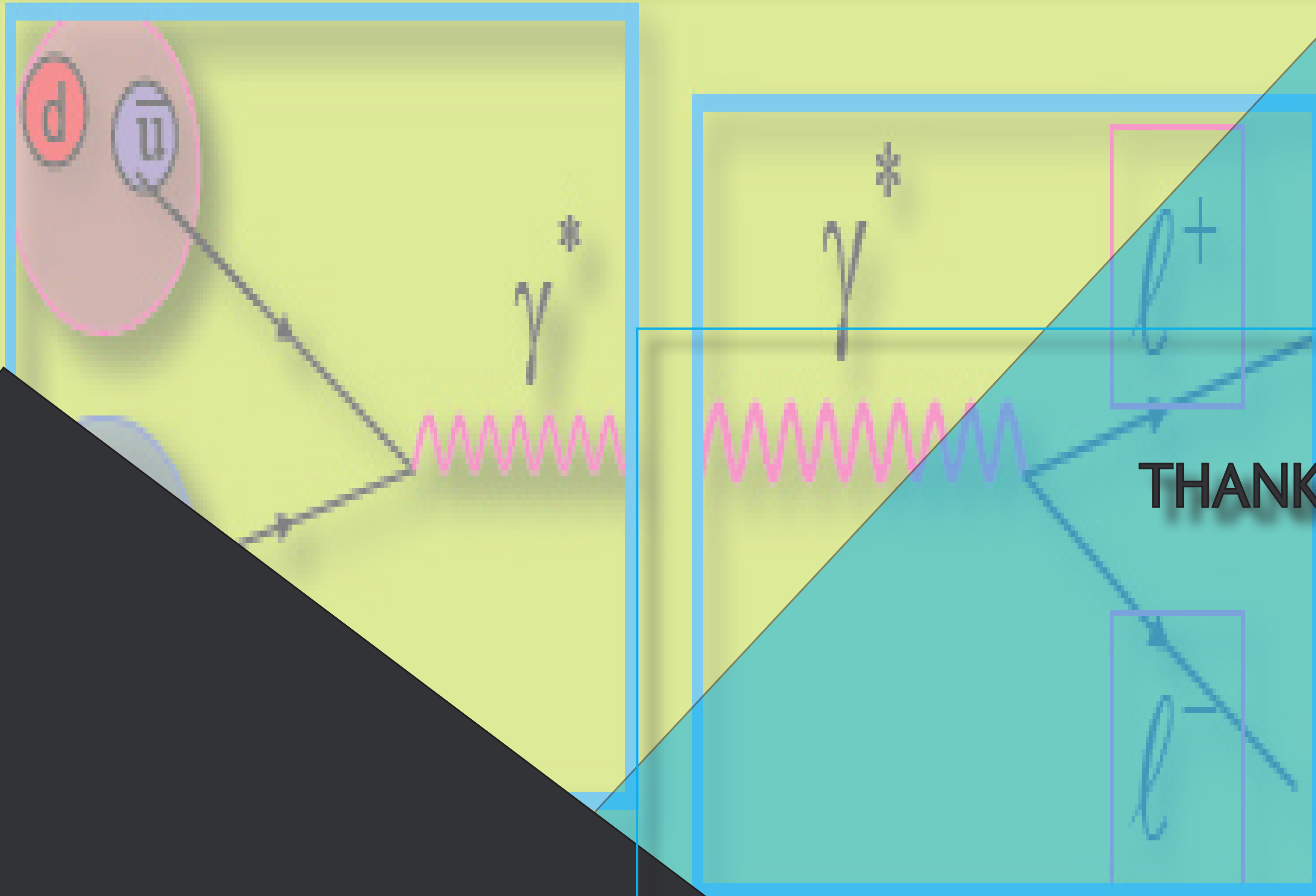
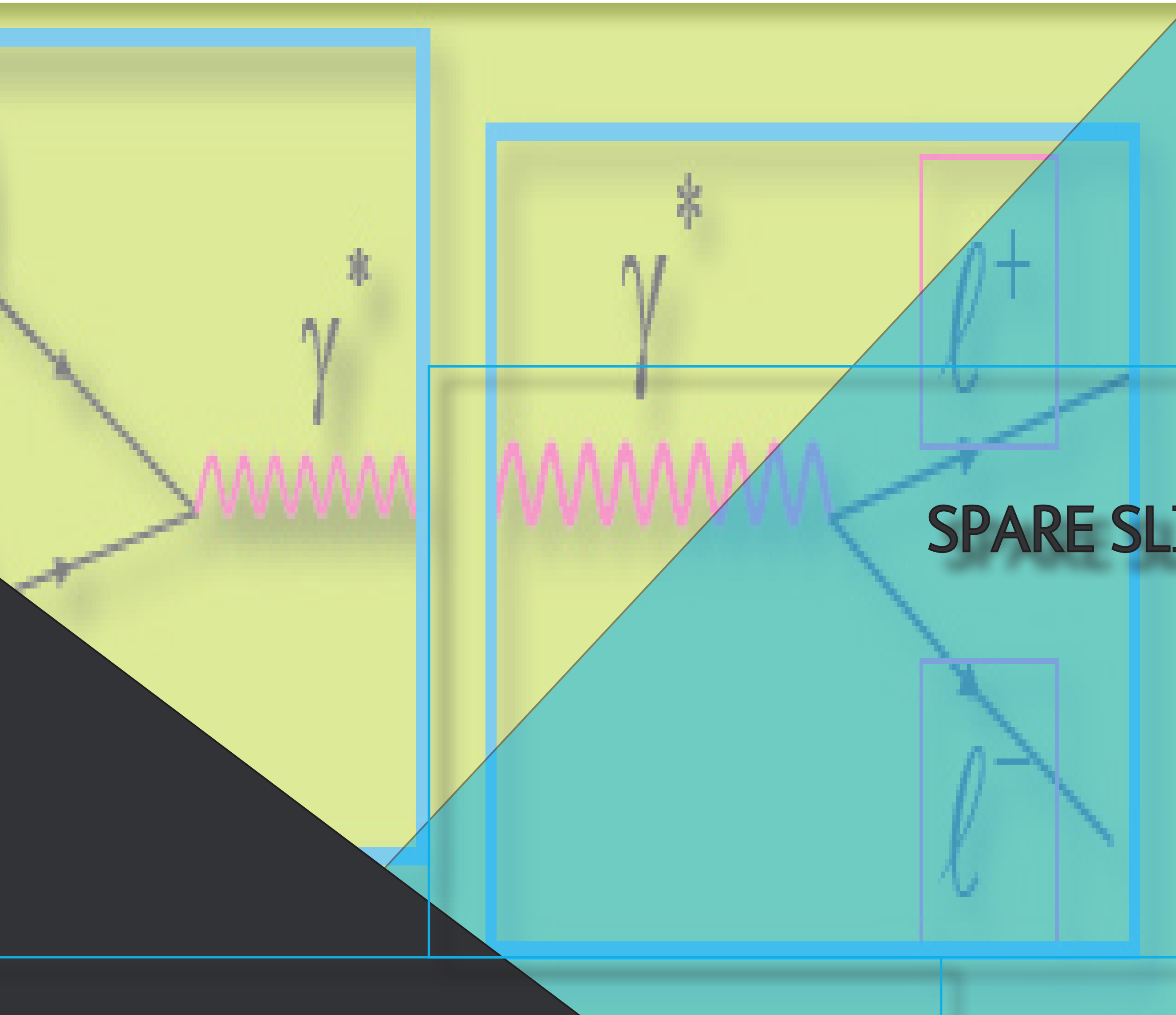


THANK YOU

DIS 2018

Kobe, 16-20 April



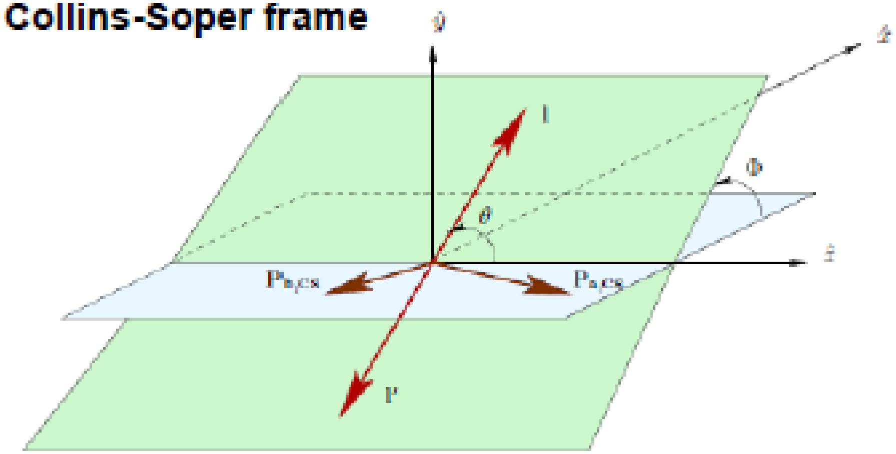
SPARE SLIDES

DIS 2018
Kobe, 16-20 April

Unpolarized Drell-Yan

Experimental tool: unpolarized Drell-Yan

Collins-Soper frame



At NLO:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U \left\{(1 + A_U^1 cos^2\theta + \sin(2\theta)\ A_U^{cos\phi} cos\phi + \sin^2\theta\ A_U^{cos2\phi} cos(2\phi)\ )\right.$$

$$\lambda = A_U^1;\ \mu = A_U^{\cos\phi};\ \nu = 2A_U^{\cos 2\phi}$$

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$ → pion (BM)$_\pi$ ⊗ proton (BM)$_p$

Lam-Tung relation $1 - \lambda = 2\nu$

Lam-Tung Relation & Boer-Mulders function

Lam-Tung relation

experimental confirmation of a universal behavior of the valence quark Boer-Mulders functions for pions and nucleons

pion and kaon pdfs

flavor and x dependencies of the Boer-Mulders functions

Boer-Mulder sign change?

Future

Lam-Tung Relation & Boer-Mulders function

$$1 - \lambda = 2\nu$$

- Proton-induced Drell-Yan (E866)
  - consistent with LT-relation
  - no $\cos(2\Phi)$ dependence
  - no p_T dependence

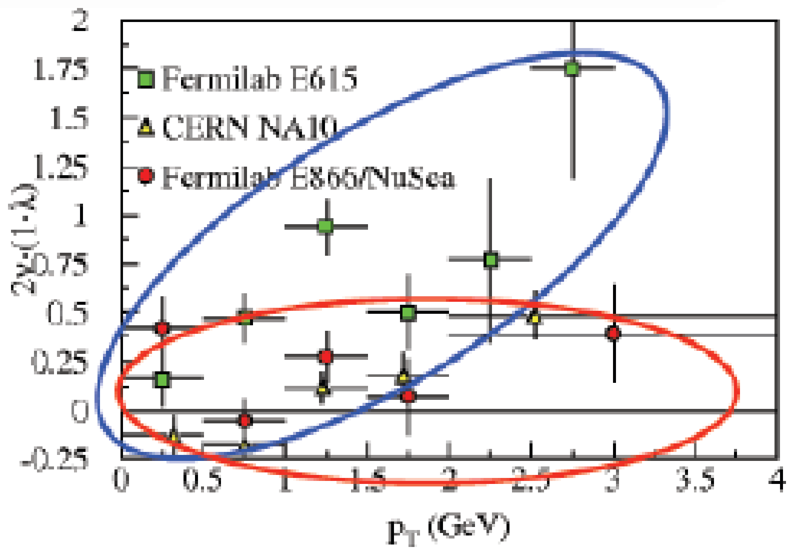
- Pion-induced Drell-Yan (NA10, E615)
  - violates LT-relation
    (independent of nucleus - no nuclear effect)
  - large $\cos(2\Phi)$ dependence
  - strong with p_T

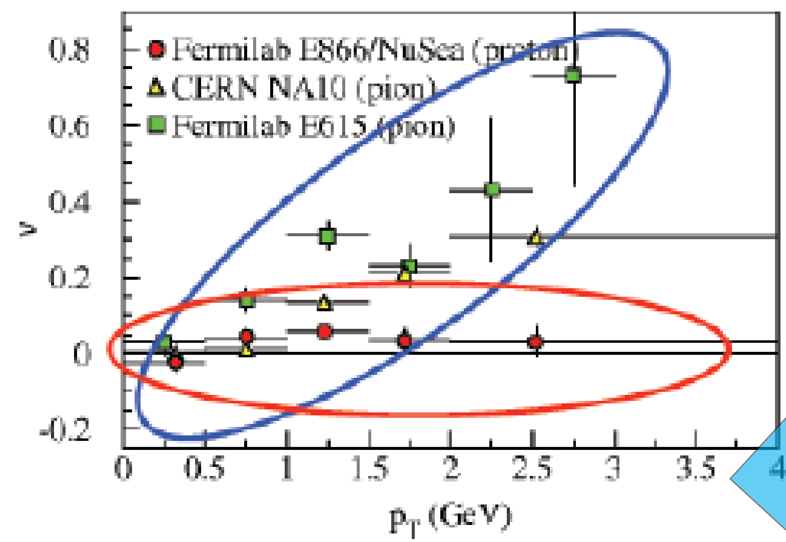
☛ **One candidate to explain LT violation: BM function**

- Pionic DY probes BM (valence), target=proton
  Protonic DY probes BM (sea), target=proton

  BM (sea) $\ll$ BM (valence)

☛ study of spin-orbit correlations





Boer-Mulders function

Obtain BM with kaon beam

$$A_{UU}^{\cos(2\phi)} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{\perp q}$$

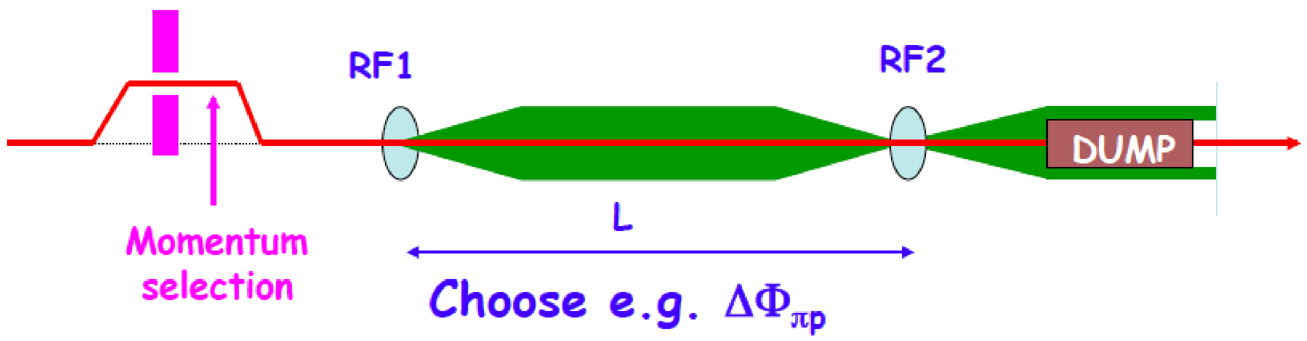
$$K^{+}p(x_f) = u^{K}(x_1)\bar{u}^{p}(x_2) + \bar{s}^{K}(x_1)s^{p}(x_2)$$

$$K^{-}p(x_f) = \bar{u}^{K}(x_1)u^{p}(x_2) + s^{K}(x_1)\bar{s}^{p}(x_2)$$

Experiment	Beam type (GeV)	Intensity (/s)	Target	DY events
NA3	K^- (150)	0.25×10^7	Pt	688
	K^- (200)	0.93×10^7		90
	K^+ (200)	0.22×10^7		170
COMPASS++	K^- (80)	1.9×10^7	C	593
	K^- (100)	2.3×10^7		1,800
	K^- (120)	2.5×10^7		3,600
COMPASS++	K^+ (80)	1.7×10^7	C	482
	K^+ (100)	2.1×10^7		1,700
	K^+ (120)	2.3×10^7		3,700

Possibility of Radio-Frequency separated beam pion, kaon and antiproton
increase by a factor of two the maximum kaon/antiproton flux actually achievable
kaon and anti-protons flux possibly reaching 10^7p/s

RF Separated Beam (CERN M2 Beam Line)



Deflection with 2 cavities
Relative phase = 0 --> dump
Deflection of wanted particle given by:

$$\Delta\Phi = 2\pi\ (L\ f\ /\ c)\ (\beta_1^{-1} - \beta_2^{-1})\ \text{with}\ \beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$$

To keep good separation, L should increase as p^2 --> limits the beam momentum

Particle type	Fraction at T6	Fraction at COMPASS
pbar	1.6 %	11.3 %
K^-	3.0 %	0 %
π^-	32.4 %	84.3 %
e^-	63.0 %	4.4 %

20 GeV/c

"Normal" h^- beam composition:
97% (π^-) 2.5%(K) 0.5% (pbar)

Boer-Mulders function

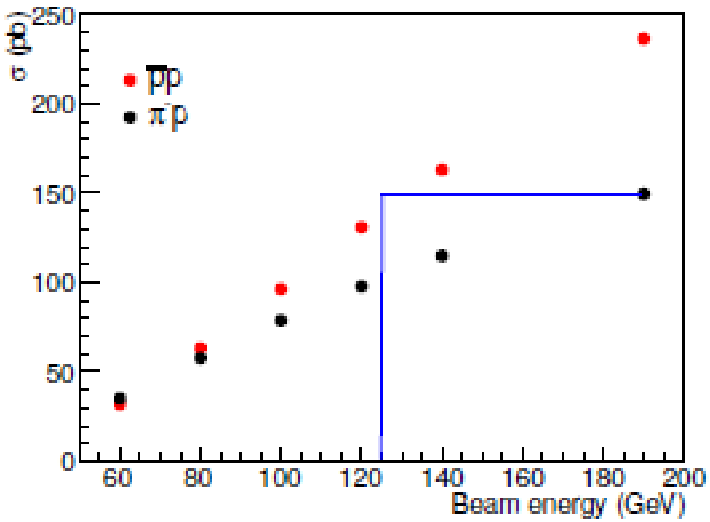
BM with antiproton beam $A_{UU}^{\cos(2\phi)} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{\perp q}$

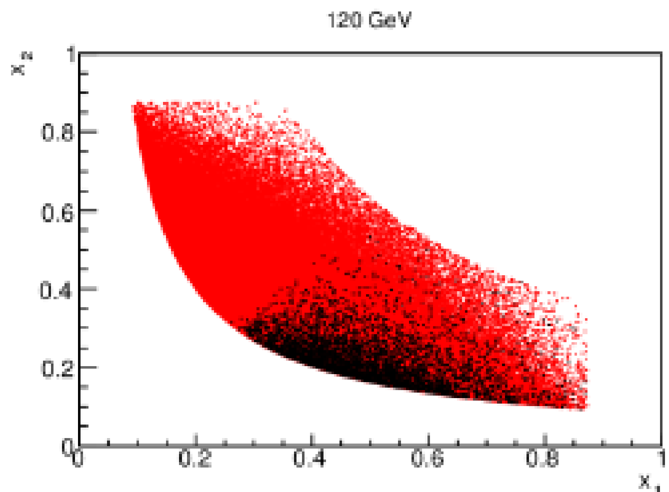
prediction of a universal behavior of the valence quark Boer-Mulders functions for pions and nucleons also awaits experimental confirmation

Combining analysis of DY data with pion and antiproton beam an indipendent extraction of pion BM is achievable

opportunity to verify the BM sign-change

Indipendent extraction of proton BM





COMPASS

Accessing e+e− DY pairs on top of μ+μ− would reinforce the feasibility of polarised measurements

Future

Active absorber

DY with antiproton beam

http://cds.cern.ch/record/2057587/files/SPSC-P-353.1.pdf

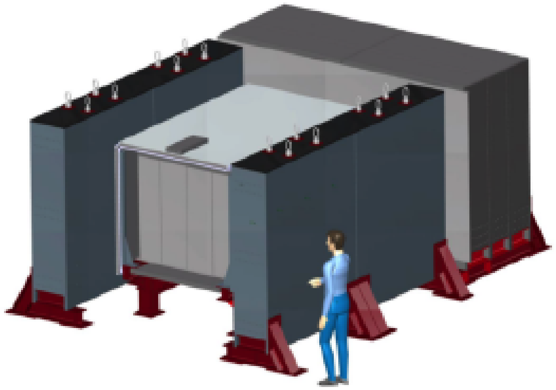


Figure 1: Baby MIND integrated into the WAGASCI experiment.

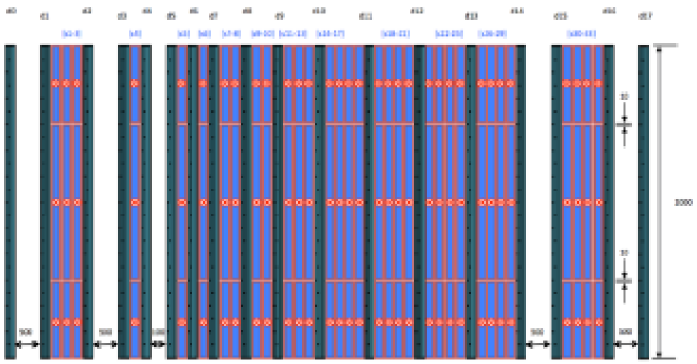
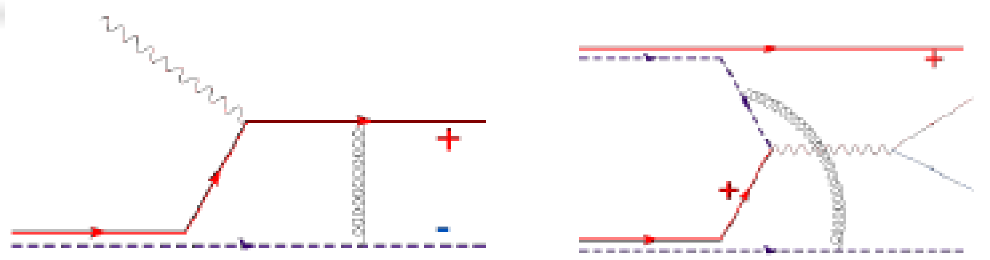


Figure 2: A side view of Baby MIND with scintillator planes (grey) and magnetised iron (blue/red).

- Basically combined tracking+SM1+calorimeter
- Instead of scintillators → High granularity detectors
- Can be placed between target and SM1
- Additional absorber in SM1 with beam dump?
- Could in principle allow also for e^+e^- detection?

Probing the TMD formalism

Sivers and BM functions sign change: first clear-cut check



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

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

$$\sigma^{DY} \propto \begin{array}{l} 1 + \bar{h}_1^{\perp} \otimes h_1^{\perp} \cos(2\phi) \\ |S_T| \; \bar{f}_1 \otimes \bar{f}_{1T}^{\perp} \sin\phi_S \end{array}$$

Still needs experimental confirmation

COMPASS at CERN, P-1027 and P-1039 at FERMILAB,
PANDA at FAIR, NICA

DY for TMDs

Future or planned Drell-Yan experiments: large variety of beam and target and kynematical ranges

Experiment	particles	beam energy (GeV)	$\sqrt{s}$ (GeV)	$x^\uparrow$	$\mathcal{L}$ (cm^{-2}s^{-1})	$\mathcal{P}_{\text{eff}}$	$\mathcal{F}$ (cm^{-2}s^{-1})
AFTER@LHCb	$p + p^\uparrow$	7000	115	$0.05 \div 0.95$	$1 \cdot 10^{33}$	80%	$6.4 \cdot 10^{32}$
AFTER@LHCb	$p + {}^3\text{He}^\uparrow$	7000	115	$0.05 \div 0.95$	$2.5 \cdot 10^{32}$	23%	$1.4 \cdot 10^{31}$
AFTER@ALICE$_\mu$	$p + p^\uparrow$	7000	115	$0.1 \div 0.3$	$2.5 \cdot 10^{31}$	80%	$1.6 \cdot 10^{31}$
COMPASS (CERN)	$\pi^\pm + p^\uparrow$ $\bar{p} + p^\uparrow$ $k^\pm + p^\uparrow$	190	19	$0.2 \div 0.3$	$2 \cdot 10^{33}$	18%	$6.5 \cdot 10^{31}$
PHENIX/STAR (RHIC)	$p^\uparrow + p^\uparrow$	collider	510	$0.05 \div 0.1$	$2 \cdot 10^{32}$	50%	$5.0 \cdot 10^{31}$
E1039 (FNAL)	$p + p^\uparrow$	120	15	$0.1 \div 0.45$	$4 \cdot 10^{35}$	15%	$9.0 \cdot 10^{33}$
E1027 (FNAL)	$p^\uparrow + p$	120	15	$0.35 \div 0.9$	$2 \cdot 10^{35}$	60%	$7.2 \cdot 10^{34}$
NICA (JINR)	$p^\uparrow + p$	collider	26	$0.1 \div 0.8$	$1 \cdot 10^{32}$	70%	$4.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	collider	200	$0.1 \div 0.5$	$8 \cdot 10^{31}$	60%	$2.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	collider	510	$0.05 \div 0.6$	$6 \cdot 10^{32}$	50%	$1.5 \cdot 10^{32}$
PANDA (GSI)	$\bar{p} + p^\uparrow$	15	5.5	$0.2 \div 0.4$	$2 \cdot 10^{32}$	20%	$8.0 \cdot 10^{30}$

Boer-Mulders function - sign change

1) From SIDIS data, one deduces that the proton B-M functions are negative for both u and d quarks:

$$h_{1,u}^{\perp,DIS}(p) < 0\ ;\ \ h_{1,d}^{\perp,DIS}(p) < 0$$

2) From NA10 pion Drell-Yan data, one deduces that the product of the pion valence quark B-M function and the proton valence quark B-M function is positive. Using u-quark dominance, we have:

$$h_{1,u}^{\perp,DY}(p) * h_{1,u}^{\perp,DY}(\pi) > 0$$

Therefore, either a) $h_{1,u}^{\perp,DY}(p) > 0;\ h_{1,u}^{\perp,DY}(\pi) > 0\quad (sign-change)$

or b) $h_{1,u}^{\perp,DY}(p) < 0;\ h_{1,u}^{\perp,DY}(\pi) < 0\quad (no\ sign-change)$

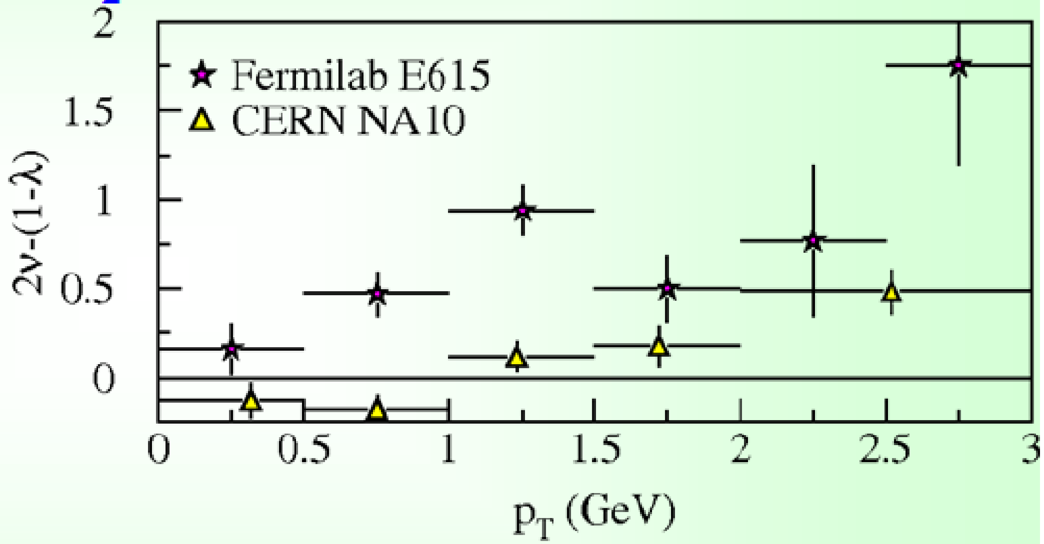
3) The crucial measurement is to determine the sign of the pion B-M function in polarized $\pi - p$ D-Y, since the $\sin(\phi+\phi_S)$ modulation is sensitive to the sign of $h_{1,u}^{\perp,DY}(\pi)$.

Lam-Tung relation

Lam-Tung Relation is theoretically robust

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

- Pionic Drell-Yan experiments see a violation which grows as a function of p_T. (Esp. NA10);
- Significant non-zero ν ($\cos 2\phi$) term



- Possible explanations?
  – Nuclear effects
  – Higher-Twist effects from quark-antiquark binding in pion
  – Factorization breaking QCD Vacuum
  – k_T dependent transverse momentum distribution (Boer Mulders $h_1^\perp$)

Lam-Tung Relation & Boer-Mulders function

origin of the Lam-Tung relation violation
Measurements with different beams over wide kinematical ranges would help differentiating the origin of Lam-Tung violation

Theoretical Interpretations of Lam-Tung Violation in pion-induced DY

	Boer-Mulders Function	QCD chromo-magnetic effect	Glauber gluon
Origin of effect	Hadron	QCD vacuum	Pion specific
Quark-flavor dependence	Yes	No	No
Hadron dependence	Yes	No	Yes
Large P_T limit	0	Nonzero	0
Violation for πp	Yes (valence quarks involved)	Yes	Yes
Violation for Kp	Yes (valence quarks involved)	Yes	Yes/No
Violation for $\bar{p}p$	Yes (valence quarks involved)	Yes	No
Violation for pp	No (sea quarks involved)	Yes	No
References	PRD 60, 014012 (1999)	Z. Phy. C 60,697 (1993)	PLB 726, 262 (2013)