COMPASS Drell-Yan measurements: testing the universality of TMD PDFs

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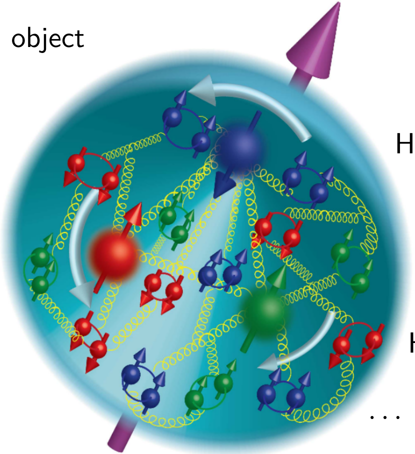
Outline

Picture of the proton

A complicated QCD object



How is the mass described dynamically?

How are quarks and gluons confined?

How are they distributed ?

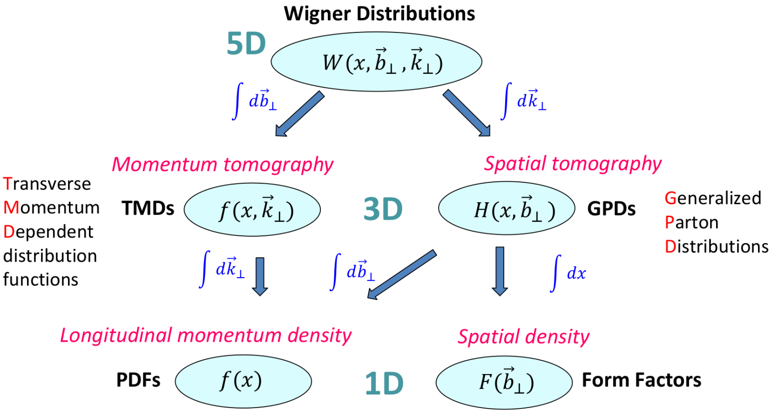
How do they contribute to the nucleon spin ?

...

Figure taken from arXiv:1212.1701 [nucl-ex]

Nucleon tomography

General description of nucleon structure



x: fraction of longitudinal momentum

$k_\perp$: Parton transverse momentum

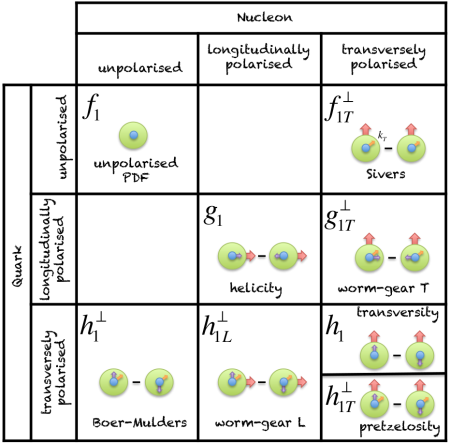
$b_\perp$: Impact parameter

1D picture is relatively well known,. . .

. . . efforts are focussing on the 3D picture

Transverse momentum dependent PDFs

Nucleon structure at leading order QCD is described with
8 Tranverse momentum dependent PDFs:

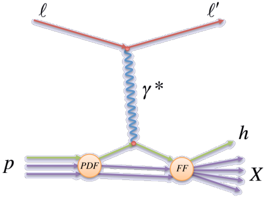


- f_1, g_1 and h_1 survive k_T integration
- Other distributions describe correlations among quark's k_T, nucleon's spin and quark's spin

→ Accessible at COMPASS via Semi-inclusive DIS and Drell-Yan processes

Drell-Yan and Semi-inclusive DIS processes

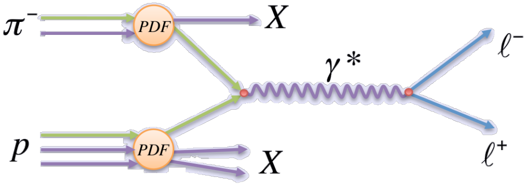
SIDIS:



Variables:

- $Q^2 = -M^2_{\gamma*}$
- $x = Q^2/(2p\cdot q)$
- $z = E_h/E_{\gamma^*}$

DY:



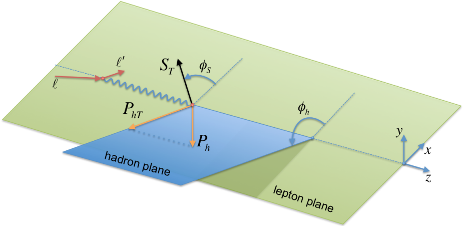
Variables:

- $Q^2 = M^2_{l^+l^-}$
- $x_{1,2} = Q^2/(2p_{1,2}\cdot q)$
- q_T = virtual photon transverse momentum

Drell-Yan and SIDIS cross-section modulations

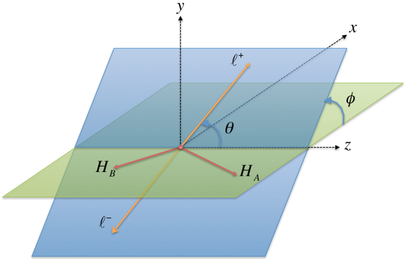
SIDIS:

$$\frac{d\sigma}{dxdydzd\phi_S d\phi_h dP_{hT}^2} \overset{\text{LO}}{=} \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1\frac{\gamma^2}{2x}\right)\hat{\sigma_U}\Big\{1+\epsilon A_{UU}^{\cos(2\phi_h)}\cos(2\phi_h)$$
$$+S_T\Big[A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)+\epsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h-\phi_S)$$
$$+\epsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\Big]$$
$$+S_T P_l\left[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)A_{LT}^{\cos\phi_h-\phi_S}\right]\Big\}$$



DY:

$$\frac{d\sigma}{d^4qd\Omega} \overset{\text{LO}}{=} \frac{\alpha^2}{Fq^2}\hat{\sigma_U}\Big\{\left(1+\cos^2(\theta)+\sin^2(\theta)A_{UU}^{\cos(2\phi)}\cos(2\phi)\right)$$
$$+S_T\Big[(1+\cos^2(\theta))A_{UT}^{\sin(\phi_S)}\sin(\phi_S)$$
$$+\sin^2(\theta)\left(A_{UT}^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)+A_{UT}^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\right)\Big]\Big\}$$



Modulation amplitudes

DY:					SIDIS:			
$A_{UU}^{\cos(2\phi)}$	$\propto h_{1,\pi}^{\perp q}$	$\otimes$	$h_{1,p}^{\perp q}$	Boer-Mulders	$A_{UU}^{\cos(2\phi_h)}$	$\propto h_{1,p}^{\perp q}$	$\otimes$	$H_{1q}^{\perp h}$
$A_{UT}^{\sin(\phi_S)}$	$\propto f_{1,\pi}^{q}$	$\otimes$	$f_{1T,p}^{\perp q}$	Sivers	$A_{UT}^{\sin(\phi_h-\phi_S)}$	$\propto f_{1T,p}^{\perp q}$	$\otimes$	D_{1q}^{h}
$A_{UT}^{\sin(2\phi-\phi_S)}$	$\propto h_{1,\pi}^{\perp q}$	$\otimes$	$h_{1,p}^{q}$	Transversity	$A_{UT}^{(\sin\phi_h+\phi_S)}$	$\propto h_{1,p}^{q}$	$\otimes$	$H_{1q}^{\perp h}$
$A_{UT}^{\sin(2\phi+\phi_S)}$	$\propto h_{1,\pi}^{\perp q}$	$\otimes$	$h_{1T,p}^{\perp q}$	Pretzelosity	$A_{UT}^{(\sin 3\phi_h-\phi_S)}$	$\propto h_{1T,p}^{\perp q}$	$\otimes$	$H_{1q}^{\perp h}$

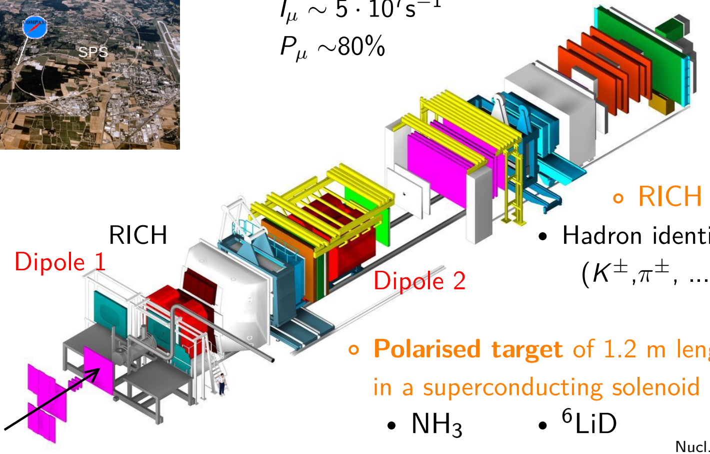
TMD PDFs are **universal** but
final state interaction (SIDIS) *vs.* initial state interaction (DY) $\rightarrow$ **Sign flip** for naive T-odd TMD PDFs

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

Crucial test of TMD framework in QCD

COMPASS-I SIDIS setup

- **Polarised μ^+ beam** from CERN SPS
  200 GeV/160 GeV
  $I_\mu \sim 5 \cdot 10^7 s^{-1}$
  $P_\mu \sim 80\%$



- RICH :
  - Hadron identification ($K^\pm$, $\pi^\pm$, ...)

- **Polarised target** of 1.2 m length in a superconducting solenoid
  - NH_3
  - ^6LiD

Nucl. Instr. Meth. A577 (2007) 455

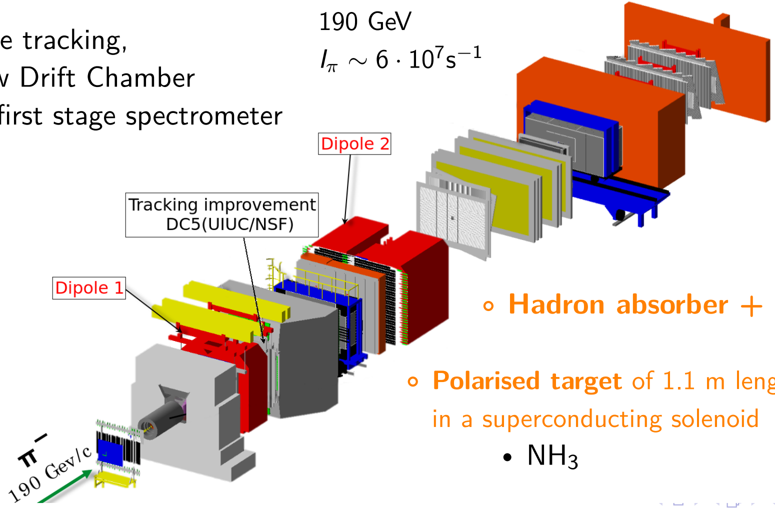
COMPASS-II Drell-Yan setup

Almost the same tracking, except for a new Drift Chamber detector in the first stage spectrometer

- π^- **beam** from CERN SPS

  190 GeV

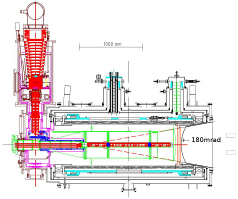
  $I_\pi \sim 6 \cdot 10^7 s^{-1}$



- **Hadron absorber + nuclear targets**
- **Polarised target** of 1.1 m length in a superconducting solenoid
  - NH_3

Polarised target and hadron absorber

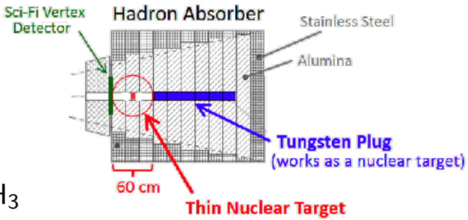
Polarised target



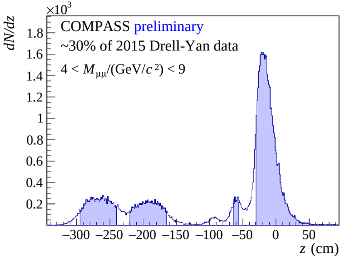
- Two cells of NH_3
- Polarisation ∼80%
- Dilution factor f∼22%

⇒ Two spin states recorded simultaneously: minimisation of systematic effects

Hadron absorber



Primary vertex distribution



- Due to small cross-section and high luminosity
- Improve resolutions → Vertex detector
- Used as nuclear targets: Al & W

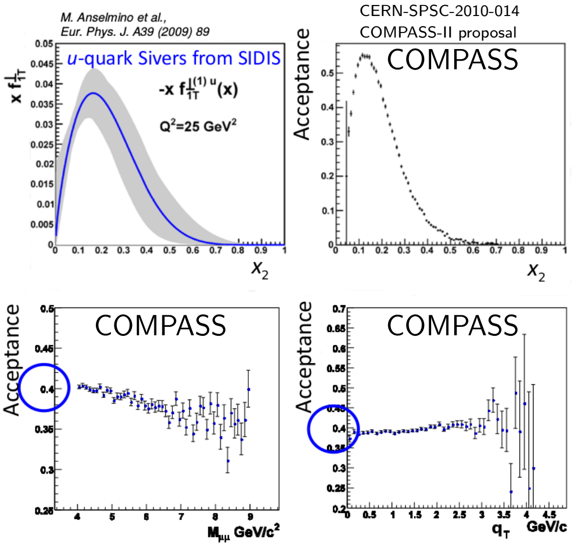
COMPASS data taking with polarised target

Year	Beam	Target	Polarisation	
2002	μ	^{6}LiD	L & T ∼50%	
2003	μ	^{6}LiD	L & T ∼50%	
2004	μ	^{6}LiD	L & T ∼50%	
2006	μ	^{6}LiD	L ∼50%	
2007	$\boldsymbol{\mu}$	**NH_3**	L & **T** ∼80%	→ PLB 744 (2015) 250
2010	$\boldsymbol{\mu}$	**NH_3**	**T** ∼80%	
2011	μ	NH_3	L ∼80%	
2014	$\boldsymbol{\pi}$	**NH_3**	unpol.	First unpolarised DY data
2015	$\boldsymbol{\pi}$	**NH_3**	**T** ∼80%	First ever polarised DY data

Focus in this talk on Boer-Mulders and Sivers related measurements.
Many other COMPASS results available!

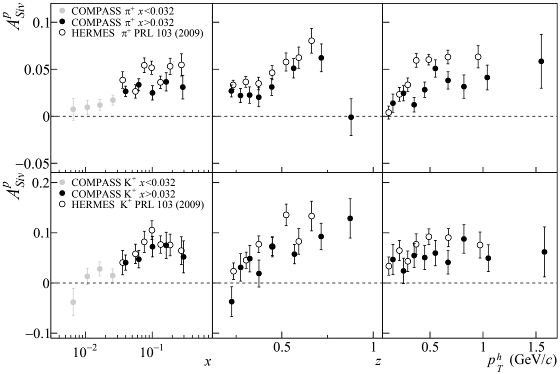
Acceptance in DY

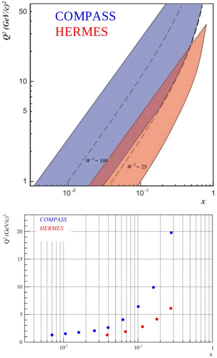
- COMPASS acceptance high where $f_{1T}^{\perp}$ is expected to be large
- High acceptance: 40% to be compared to previous experiments $\leqslant$ 10% (*e.g.* NA10, NA50 at CERN, E615 at FNAL)
- Acceptance flat in q_T



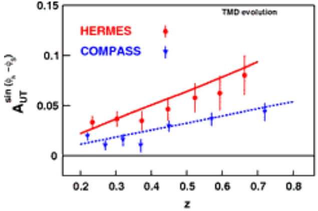
Evolution effects

PLB 744 (2015) 250





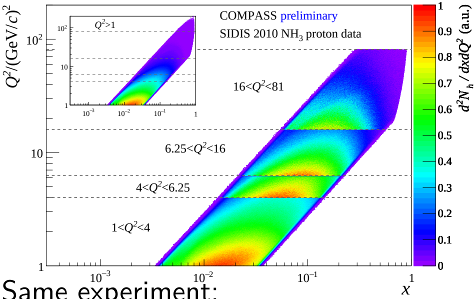
S. M. Aybat, A. Prokudine, T. C. Rogers PRL 108, (2012) 242003



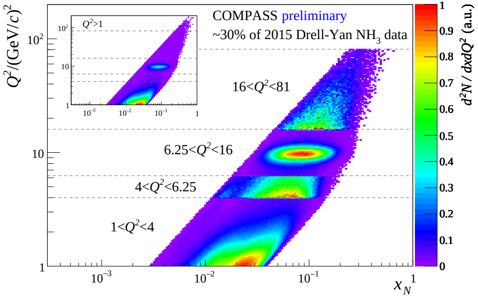
- COMPASS Sivers asymmetries found significantly smaller than HERMES A^p_{Siv}
- Non-trivial Q^2-dependence

COMPASS kinematics

SIDIS



DY

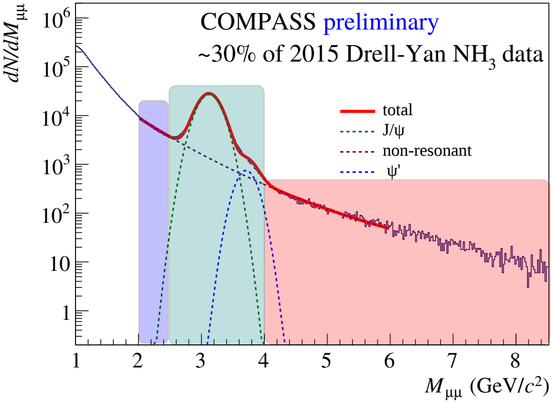


Same experiment:

- ≈ Same acceptance
- ≈ Same kinematics
- ≈ Same systematic effects

→ **minimisation** of Q^2 **evolution** effects and **systematics effects** in the comparison of the two processes

DY invariant mass



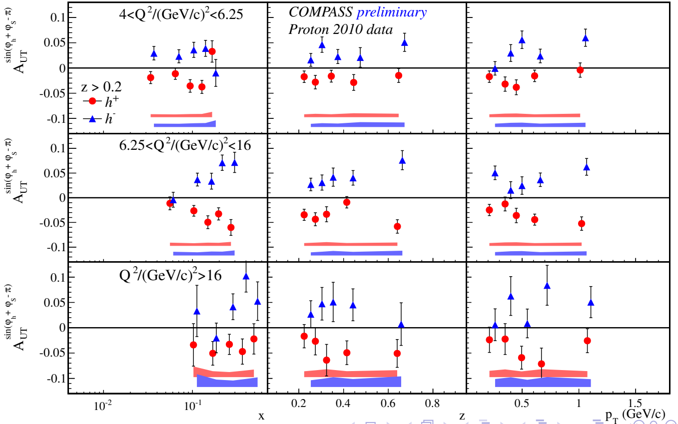
- Intermediate mass: $2 < M_{\mu\mu}/(GeV/c^2) < 2.5$
  - High Drell-Yan cross-section
  - Low DY-signal/background ratio
- J/ψ mass: $2.5 < M_{\mu\mu}/(GeV/c^2) < 4$
  - Strong J/ψ signal
  - Lower background
- High mass: $4 < M_{\mu\mu}/(GeV/c^2)$
  - Low DY cross-section
  - Low background

SIDIS Transversity in DY Q^2 ranges

$h^q_{1,p}$: correlation between transversely polarised quark in a transversely polarised nucleon

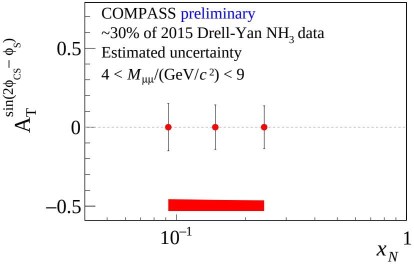
$$A_{UT}^{sin(\phi_h+\phi_S)} \propto h^q_{1,p} \otimes H^{\perp h}_{1q}$$

- Sizable in all Q^2 range
- Azymuthal modulation have opposite sign for h^+ & h^-

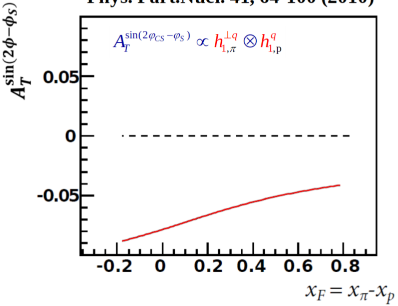


Projection for DY transversity in COMPASS

$$A_{UT}^{sin(2\phi-\phi_S)} \propto h_{1,p}^{q} \otimes h_{1,\pi}^{\perp q}$$



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



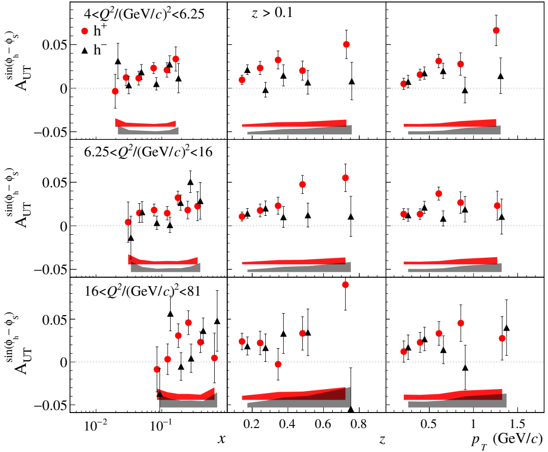
- Estimated uncertainties for 2015 DY run
- Expect a sizable DY asymmetry based on SIDIS results

SIDIS Sivers in DY Q^2 ranges

$f_{1T,p}^{\perp q}$: Correlation between quark transverse momentum and transverse nucleon spin

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

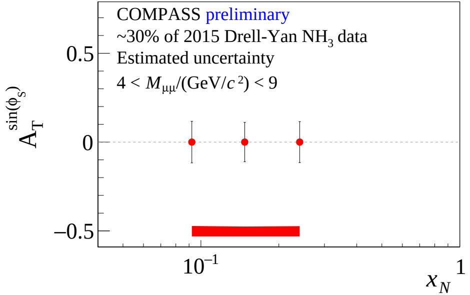
- Sizable in all Q^2 ranges for h^+
- Asymmetry becomes positive with Q^2 for h^-

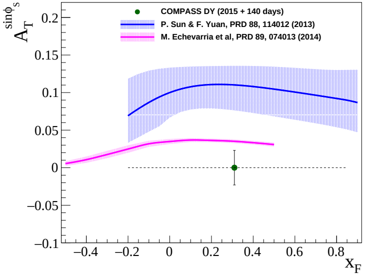


arXiv: 1609.07374 [hep-ex]

Projection for DY Sivers in COMPASS

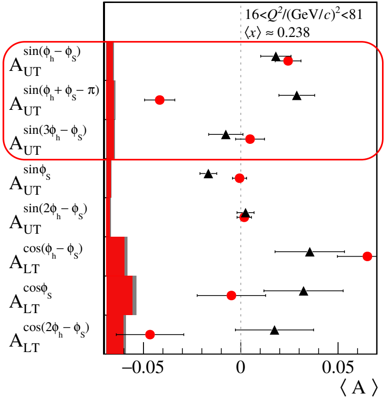
$$A_{UT}^{(\sin\phi_S)} \propto f_{1T,p}^{\perp q} \otimes f_{1,\pi}^{q}$$

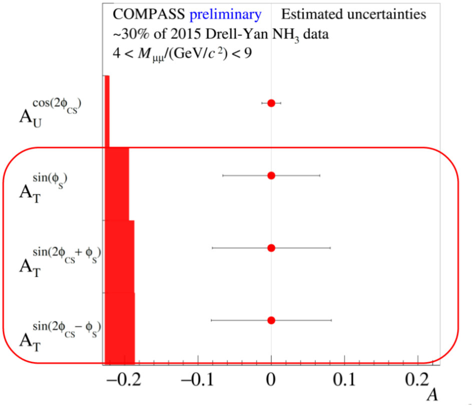




- Estimated uncertainties for 2015 DY run
- Expect a sizable DY asymmetry based on SIDIS results
- Many models exist, experimental data are necessary: COMPASS results awaited

SIDIS and projected DY TSA in COMPASS





- Except for Pretzelosity, all LO TSA common between SIDIS and DY are sizable in SIDIS
- Estimated uncertainties for 2015 DY run
- Another polarised DY run is scheduled for 2018

Unpolarised Drell-Yan angular dependencies

$$\frac{dN}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2(\theta)+\mu\sin(2\theta)\cos(\phi)+\frac{\nu}{2}\sin^2(\theta)\cos(2\phi)\right)$$

In naive Drell-Yan model, no k_T and no QCD processes involving gluons:

$$\lambda = 1,\ \ \mu = 0,\ \ \nu = 0$$

The Lam-Tung relation, derived from the fermionic nature of quarks, predicts:

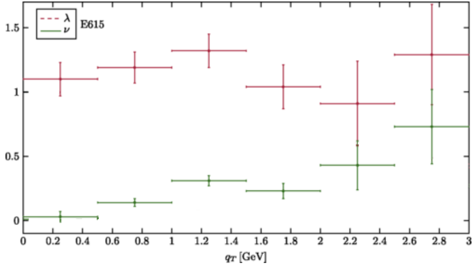
$$1-\lambda-2\nu = 0$$

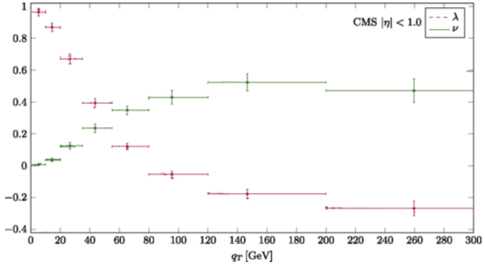
Analog of DIS Callan-Gross relation for Drell-Yan

C.S. Lam and W.K. Tung, Phys. Rev. D 18, 2447 (1978)

Lam-Tung relation

Data:





E615 PRD 39, 92 (1989)

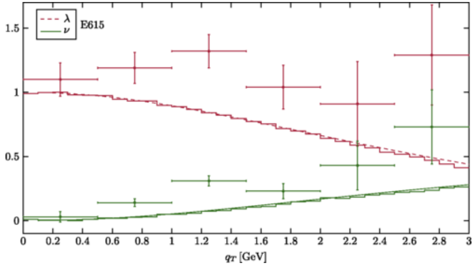
CMS PLB 750, 154 (2015)

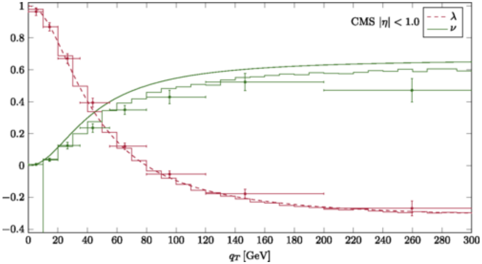
- Clear departure from $\nu = 0$ and violation of Lam-Tung
- Boer Mulders effects: $\nu = 2A_{UT}^{\cos(2\phi)}$

Lam-Tung relation

Data and QCD radiative effects:

Lambertsen *et al.* PRD 93 (114013)





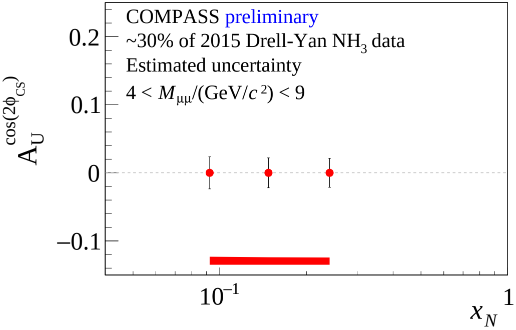
E615 PRD 39, 92 (1989)

CMS PLB 750, 154 (2015)

- Recent interpretations in terms of QCD radiative effects describe pretty well the data
  - J.-C. Peng *et al.* PLB 758, 384 (2016)
  - M. Lambertsen and W. Vogelsang PRD93, 114013 (2016)
- Boer-Mulders effects are not excluded
- Better precision for fixed target regime would be appreciated

COMPASS DY Boer-Mulders

- Estimated uncertainties for 2015 DY run
- Sizable asymmetry expected from QCD radiative effect
- Positive signal also seen in SIDIS at COMPASS and HERMES with ^{6}LiD, D and H target



Conclusions

- COMPASS is the only experiment able to measure TSA in SIDIS and in DY
  - Direct comparison between SIDIS and DY Sivers without TMD evolution
  - Minimisation of experimental systematic effect between SIDIS and DY
- SIDIS proton TSAs within DY mass ranges are measured
  - Sizable Sivers and Transversity
  - Prezelosity SIDIS TSA is found compatible with zero
- Estimated DY statistical uncertainties would allow a discriminating power between models and a possible verification of the sign change
- **Ongoing analysis, results will be available soon!**

COMPASS future plans

- 2016-2017: Exclusive physics with muon beams on liquid hydrogen target
- 2018: Drell-Yan with transversely polarised NH_3 target

- 2017: Preparation for a possible physics program for 2020 and beyond

Beyond 2020 workshop

COMPASS beyond 2020 Workshop

21 Mar 2016, 08:05 → 22 Mar 2016, 17:10 Europe/Zurich

222-R-001 (CERN)

Description The goal of the workshop is to explore hadron physics opportunities for fixed-target COMPASS-like experiments at CERN beyond 2020 (CERN Long Shutdown 2 2019-2020). The programme comprises

- Reviews of the various physics domains: TMDs, GPDs, FFs, spectroscopy, exotics, tests of ChPT, astrophysics

- Reviews of physics results expected in the next 10 years from major labs around the world

- Some critical long-term issues of the COMPASS spectrometer

- Discussions

Outcome

- RF separated $\bar{p}/K$ beam would provide a unique opportunity for future fixed target COMPASS-like program at CERN
- Existing muon/hadron beam allows to extend current COMPASS program by doing unique or first class measurements of exclusive processes, SIDIS and Drell-Yan

Physics at the SPS M2 beam line at CERN beyond 2020

Non exhaustive list:

	Physics item	Key aspects of the measurement
DY	Flavour separation	transversely pol. ^{6}LiD target
	EMC effect	LD_2 & Nuclear target
	Universality of TMD PDFs	$\bar{p}$ with transversely pol NH_3 target
	Model free TMD PDFs	$\bar{p}$ beam
	Lam-Tung	For K and $\bar{p}$ beam
	Meson structure	π and K beams
GPD	E	Tansversely pol. NH_3 target with RPD
SIDIS	Precision h_1^d	Transversely pol. ^{6}LiD target
	f_1 evolution	100 GeV beam with transversely pol. NH_3 target
Hadron	Spectroscopy	High intensity π, K and $\bar{p}$ beams

New collaborators are welcome

IWHSS whorkshop

IWHSS 2017

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- Announcements
- Registration
- Participants
- How to reach
- Accommodation
- For speakers
- Cortona
- Map of Cortona

Announcements

The workshop occurs when a community of physicists is exploring hadron physics opportunties for fixed-target experiments at CERN beyond 2020 (CERN Long Shutdown 2 2019-2020). These discussions already started with the workshop COMPASS beyond 2020 in March 2016 and the workshop Physics Beyond Collider organized by CERN in September 2016. The physics discussed at the Workshop will mainly be related to the most recent results, open issues and short and long future programs on Spectroscopy, Drell-Yan, DVCS and SIDIS, remaining open-minded to new possible programms.

Physics topics:

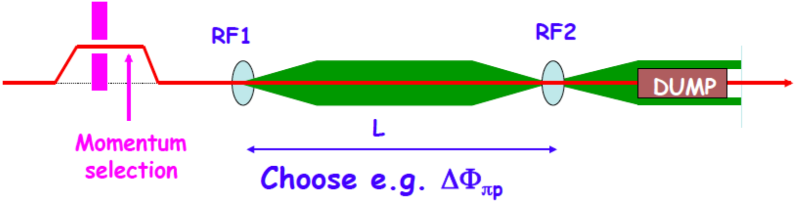
- Longitudinal and Transverse Spin Structure of the Nucleon
- Fragmentation Functions
- Meson Spectroscopy
- Search for Glueballs, Hybrid Mesons and Multiquark States
- TMDs, GPDs and GTMDs
- New opportunities for physics beyond collider
- Cosmic rays and accelerator physics

BACKUP

RF separated beam

Current hadron beam composition:

- 97% $\pi \rightarrow I_{beam} = 10^7\ \mathrm{s}^{-1}$
- 2.5% $K \rightarrow I_{beam} = 2 \times 10^6\ \mathrm{s}^{-1}$
- 0.5% $\bar{p} \rightarrow I_{beam} = 5 \times 10^5\ \mathrm{s}^{-1}$



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

RF-separated beam composition:

Current and to come Drell-Yan experiments

Experiment	Particles	Energy	x_t	Luminosity		P_b/P_t	rFOM	Timeline
COMPASS	$\pi^- \ p^\uparrow$	190 Gev	x_t= 0.1-0.3	2×10^{33}	0.14	P_t = 80%	1.0×10^{-3}	2014-2015
PANDA	$\bar{p} \ p^\uparrow$	15 GeV	x_t= 0.2-0.4	2×10^{32}	0.07	P_t = 90%	1.1×10^{-4}	>2025
AFTER	$p^\uparrow \ p$	7 TeV	x_b= 0.1-0.9	2×10^{32}	0.06	P_t = 100%?	2.3×10^{-5}	>2020
NICA	$p^\uparrow \ p$	collider	x_b= 0.1-0.8	1×10^{32}	0.04	P_t = 70%	6.8×10^{-5}	>2023
PHENIX/STAR	$p^\uparrow \ p^\uparrow$	collider	x_b= 0.05-0.1	2×10^{32}	0.08	P_b = 60%	1.0×10^{-3}	>2018
fsPHENIX	$p^\uparrow \ p^\uparrow$	collider	x_b= 0.05-0.6	6×10^{32}	0.08	P_b = 50%	2.1×10^{-3}	>2021
SeaQuest	$p \ p$	120 GeV	x_t= 0.1-0.45	3.4×10^{35}				2012-2017
E1039	$p \ p^\uparrow$	120 GeV	x_b= 0.1-0.45	4.4×10^{35}	0-0.2*	P_t = 85%?	0.15	2018-2019