SPIN2021
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Measurement of target spin (in)dependent asymmetries in dimuon production in pion-nucleon collisions at COMPASS

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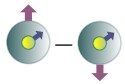
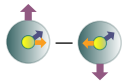
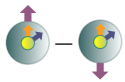
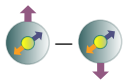
on behalf of the COMPASS Collaboration

TOMSK
POLYTECHNIC
UNIVERSITY

Transverse Momentum Dependent Parton Distribution Functions (TMD PDFs) at twist-2

Correlations between quark transverse momentum and the parton/nucleon polarization

Quark polarization	Nucleon polarization: unpolarized	Nucleon polarization: longitudinal	Nucleon polarization: transverse
unpolarized	 $f_1(x, \mathbf{k}_T^2)$ Number Density		 $f_{1T}^{\perp}(x, \mathbf{k}_T^2)$ Sivers
longitudinal		 $g_{1L}^{\perp}(x, \mathbf{k}_T^2)$ Helicity	 $g_{1T}^{\perp}(x, \mathbf{k}_T^2)$ Kotzinian-Mulders Worm-Gear T
transverse	 $h_1^{\perp}(x, \mathbf{k}_T^2)$ Boer-Mulders	 $h_{1L}^{\perp}(x, \mathbf{k}_T^2)$ Worm-Gear L	 $h_1(x, \mathbf{k}_T^2)$ Transversity  $h_{1T}^{\perp}(x, \mathbf{k}_T^2)$ Pretzelosity

spin of the nucleon spin of the parton $\mathbf{k}_T$ of the parton

This talk

Asymmetries giving access to

Boer-Mulders

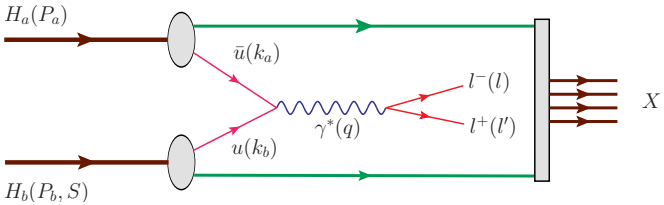
Sivers

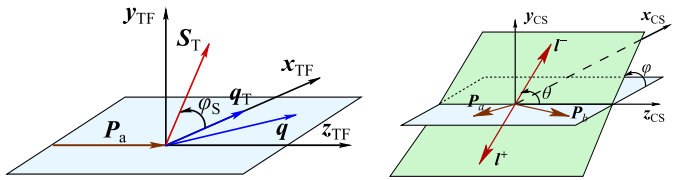
Transversity

Pretzelosity

TMD PDFs

Probing nucleon structure via Drell-Yan process





Differential cross section of pion-induced Drell-Yan (DY) lepton-pair production off a transversely polarized nucleon

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}'_U \Big\{1 + A_U^1 \cos^2\theta_{CS} + \sin 2\theta_{CS} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} +$$
$$+ S_T \Big[(A_T^{\sin\varphi_S} + \cos^2\theta_{CS} \tilde{A}_T^{\sin\varphi_S}) \sin\varphi_S +$$
$$+ \sin 2\theta_{CS} \left(A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) + A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \right) +$$
$$+ \sin^2\theta_{CS} \left(A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \right) \Big] \Big\}$$

COMPASS accesses

Boer-Mulders	$A_U^{\cos 2\varphi_{CS}}$	$= \frac{F_{UU}^{\cos 2\varphi}}{F_{UU}^1 + F_{UU}^2}$	$\propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{\perp q}$
Sivers	$A_T^{\sin\varphi_S}$	$= \frac{F_{UT}^1 + F_{UT}^2}{F_{UU}^1 + F_{UU}^2}$	$\propto f_{1,\pi}^{q} \otimes f_{1T,\mathrm{p}}^{\perp q}$
Transversity	$A_T^{\sin(2\varphi_{CS}-\varphi_S)}$	$= \frac{F_{UT}^{\sin 2\varphi} - F_{UT}^{\cos 2\varphi}}{2(F_{UU}^1 + F_{UU}^2)}$	$\propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{q}$
Pretzelosity	$A_T^{\sin(2\varphi_{CS}+\varphi_S)}$	$= \frac{F_{UT}^{\sin 2\varphi} + F_{UT}^{\cos 2\varphi}}{2(F_{UU}^1 + F_{UU}^2)}$	$\propto h_{1,\pi}^{\perp q} \otimes h_{1T,\mathrm{p}}^{\perp q}$

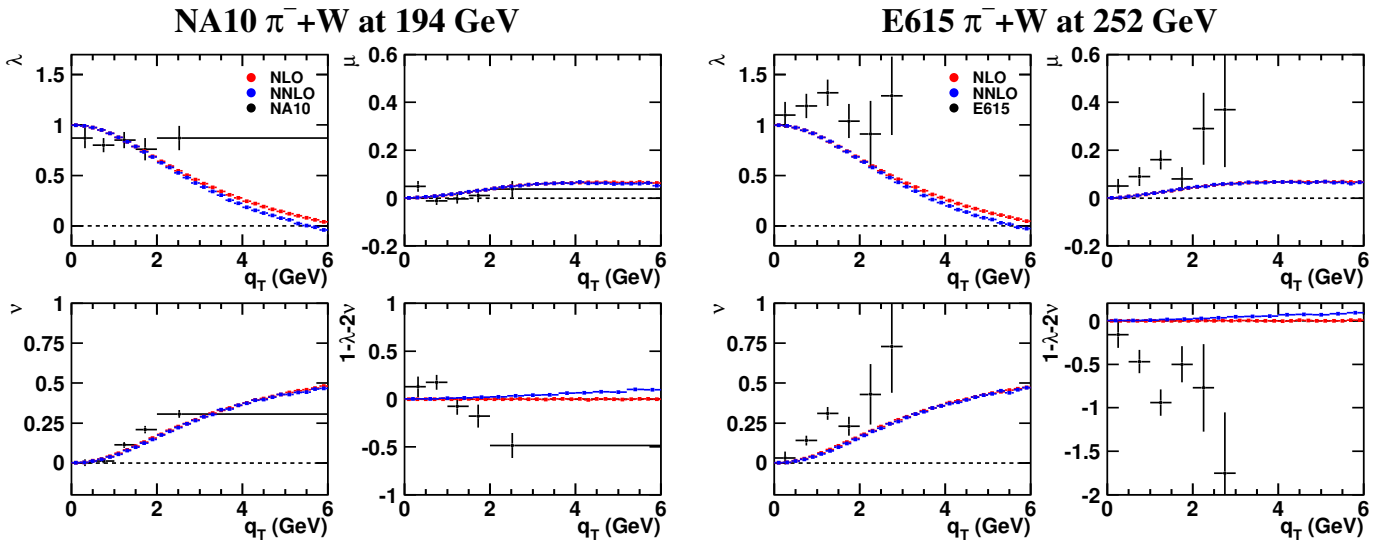
Probing nucleon structure via Drell-Yan process

Unpolarized part of the differential cross-section

$$\frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\cos^2\theta_{CS}+\mu\sin 2\theta_{CS}\cos\varphi_{CS}+\frac{\nu}{2}\sin^2\theta_{CS}\cos 2\varphi_{CS}\right]$$

$$\lambda = A_U^1 \qquad \mu = A_U^{\cos\varphi_{CS}} \qquad \nu = 2A_U^{\cos 2\varphi_{CS}}$$

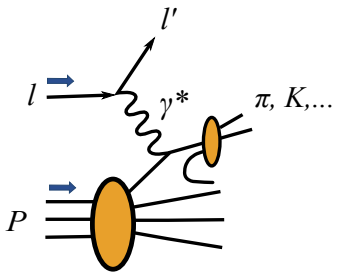
Prediction from pQCD at the NLO – Lam-Tung relation $1-\lambda=2\nu$ (PRD **18**(1978) 2447).



NA10: ZPC 31, 513(1986); **E615**: PRD 39, 92(1989); **NNLO**: W-C. Chang *et al.*, PRD 99, 014032 (2019);

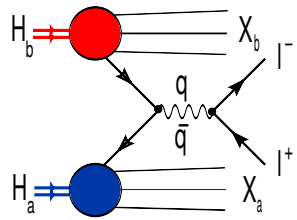
TMD PDFs in Drell-Yan and SIDIS

COMPASS SIDIS-DY "Bridge"



Based on (pseudo-)universality of the TMD PDFs

Semi-Inclusive Deep-Inelastic Scattering (SIDIS)		Drell-Yan (DY)	
$A_U^{\cos 2\phi_h}$	$\propto \mathbf{h_1^{\perp q}} \otimes H_{1q}^{\perp h} + \dots$	$A_U^{\cos 2\varphi_{CS}}$	$\propto h_{1,\pi}^{\perp q} \otimes \mathbf{h_{1,p}^{\perp q}}$
$A_T^{\sin(\phi_h - \phi_s)}$	$\propto \mathbf{f_{1T}^{\perp q}} \otimes D_{1q}^h$	$A_T^{\sin \varphi_S}$	$\propto f_{1,\pi}^q \otimes \mathbf{f_{1T,p}^{\perp q}}$
$A_T^{\sin(\phi_h + \phi_s)}$	$\propto \mathbf{h_1^q} \otimes H_{1q}^{\perp h}$	$A_T^{\sin(2\varphi_{CS} - \varphi_S)}$	$\propto h_{1,\pi}^{\perp q} \otimes \mathbf{h_{1,p}^q}$
$A_T^{\sin(3\phi_h - \phi_s)}$	$\propto \mathbf{h_{1T}^{\perp q}} \otimes H_{1q}^{\perp h}$	$A_T^{\sin(2\varphi_{CS} + \varphi_S)}$	$\propto h_{1,\pi}^{\perp q} \otimes \mathbf{h_{1T,p}^{\perp q}}$



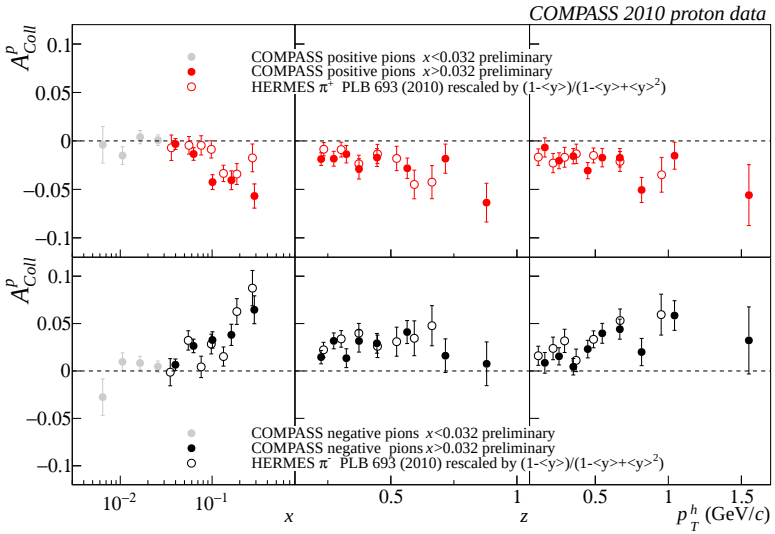
Prediction due to the T-odd property of the Sivers and Boer-Mulders TMD functions

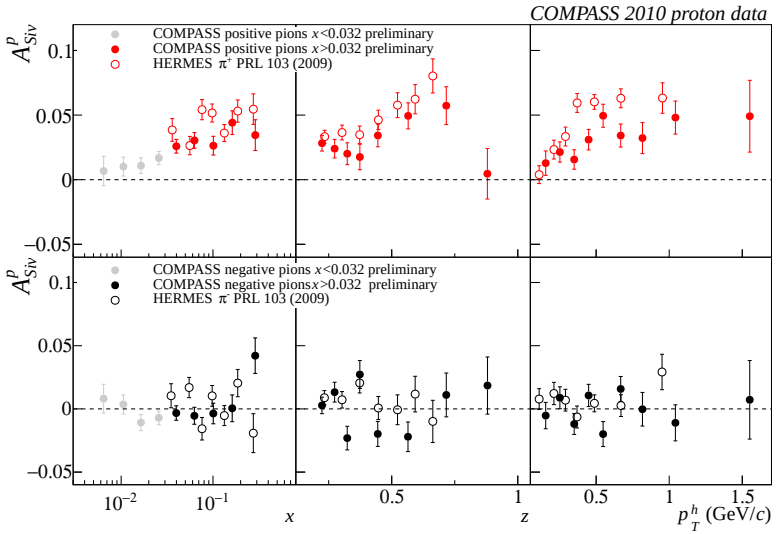
$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{SIDIS} \quad \text{for Sivers TMD PDF}$$

$$h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{SIDIS} \quad \text{for Boer-Mulders TMD PDF}$$

one of the tests of the TMD QCD-framework

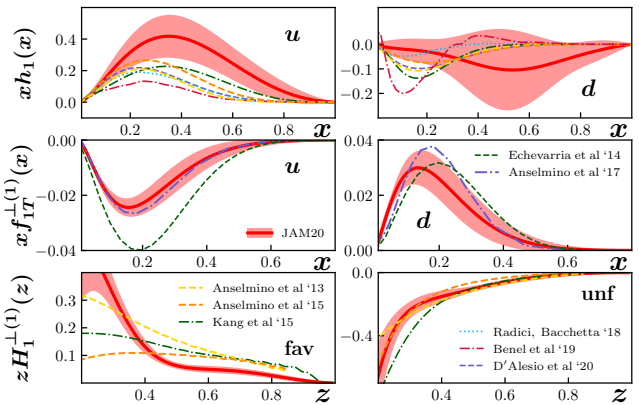
SIDIS measurements: Collins and Sivers asymmetries





PLB 744 (2015) 250

- Complementary measurements with proton and deuteron targets (COMPASS, HERMES)
- Significant non-zero Sivers and Collins asymmetries
- COMPASS vs. HERMES: compatible results for Collins effect, lower amplitude at COMPASS for Sivers effect (TMD-evolution effect?)
- Extensive phenomenological studies and various global fits by different theory groups



JAM Collaboration, PRD 102 (2020) 5

COMPASS experiment

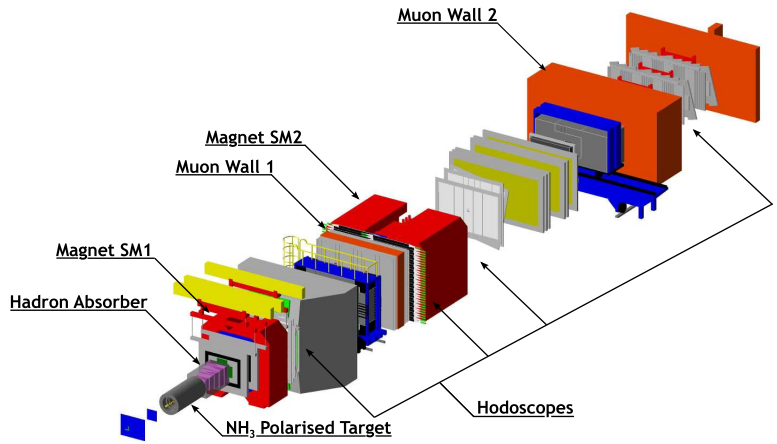
- Fixed target experiment in SPS North Area (CERN)
- 25 participating institutions from 13 countries
- First data taking in 2002
- Two phases

Phase I

- 2002 – 2011
- Hadron spectroscopy
- Nucleon spin structure using L/T P/D targets

Phase II

- 2012 – 2018
- Primakoff + DVCS pilot run (2012)
- **Drell-Yan (2015, 2018)** ← **this talk!**
- DVCS + Unpolarized SIDIS(2016-2017)
- T-polarized SIDIS (D target) (2021-2022)

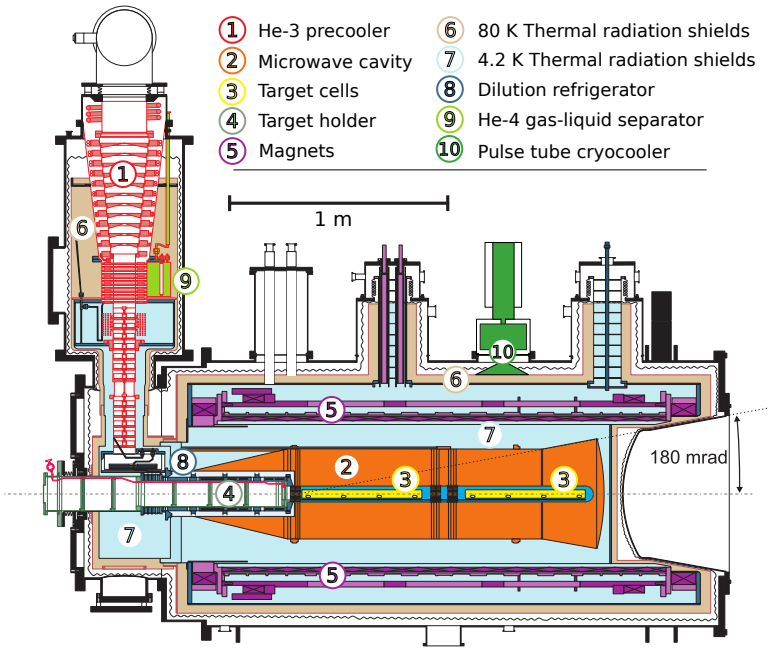


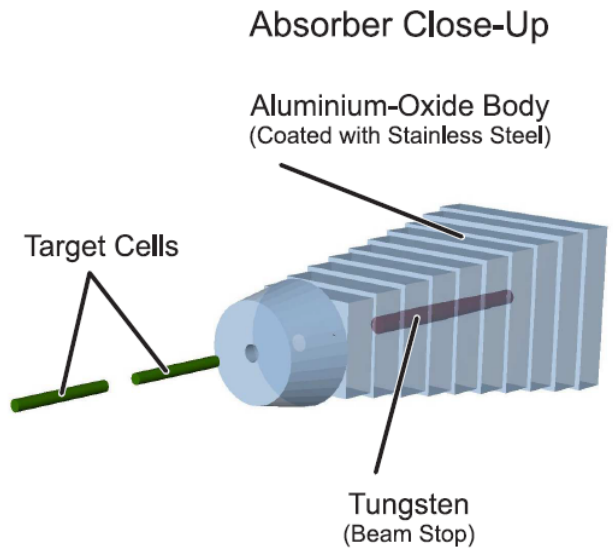
COMPASS Drell-Yan Programme

- π^- beam scattered off a transversely polarized proton target
- 190 GeV/c, intensity 10^8 π^-/s
- two cells of the polarized NH_3 target + hadron absorber
- ∼350 tracking planes (SciFis, GEMs, DCs, MWPCs, MicroMegas, Straws, Muon Walls etc.)
- 2015: 4 months of data taking
- 2018: 5 months of data taking

COMPASS Drell-Yan Programme

Polarized target and hadron absorber





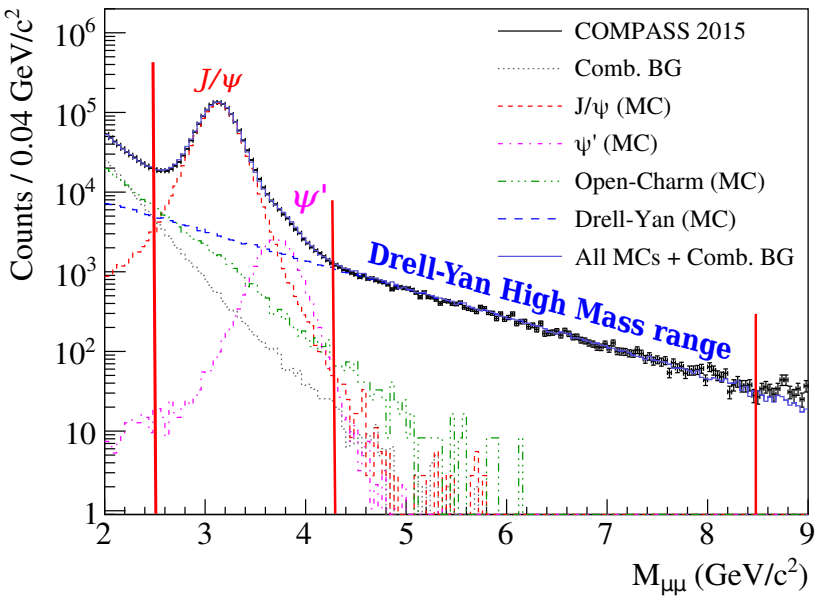
- Protons in the two NH_3 cells were polarized in opposite directions
- Periodic reversal of polarization directions once in 1-2 weeks:

$$(1^{\text{st}} \text{ cell} \downarrow;\ 2^{\text{nd}} \text{ cell} \uparrow) \longleftrightarrow (1^{\text{st}} \text{ cell} \uparrow;\ 2^{\text{nd}} \text{ cell} \downarrow)$$

- Target polarization $\sim$70%
- Events collected in the W and Al material are also used for unpolarized studies

Pion-induced Drell-Yan production at COMPASS

Dimuon mass spectrum



1. $M_{\mu\mu} \in (1.0;\ 2.0)$ GeV/c^2
   "**low mass**" range
   Large background contamination

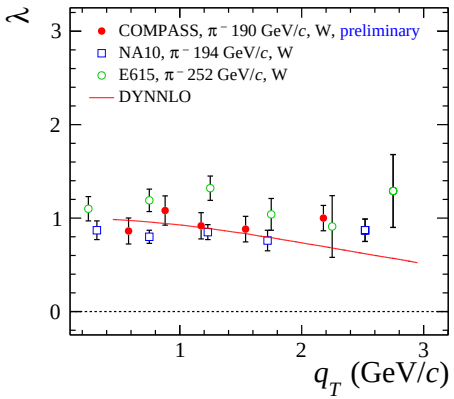
2. $M_{\mu\mu} \in (2.0;\ 2.5)$ GeV/c^2
   "**intermediate mass**" range
   High DY cross section,
   but low DY-signal/background ratio

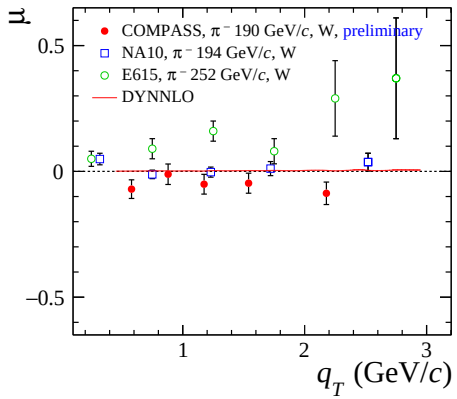
3. $M_{\mu\mu} \in (2.5;\ 4.3)$ GeV/c^2
   "**J/ψ (or charmonium) mass**" range
   Strong J/ψ-signal ($> 90\%$ purity)

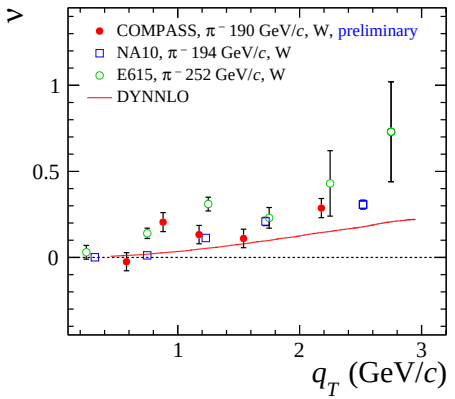
4. $M_{\mu\mu} \in (4.3;\ 8.5)$ GeV/c^2
   "**high mass**" range
   valence quark region with $\sim$96% purity of DY events

Spin independent asymmetries

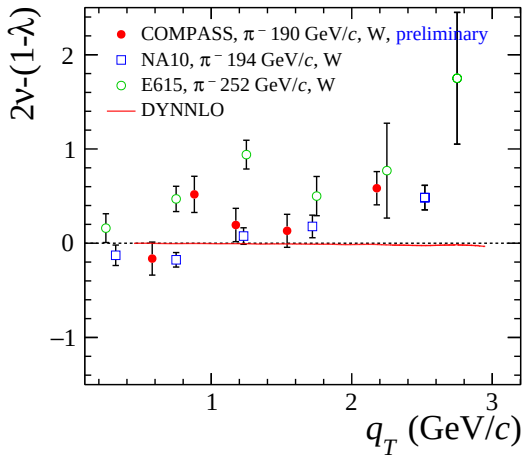
in pion-induced DY production at COMPASS





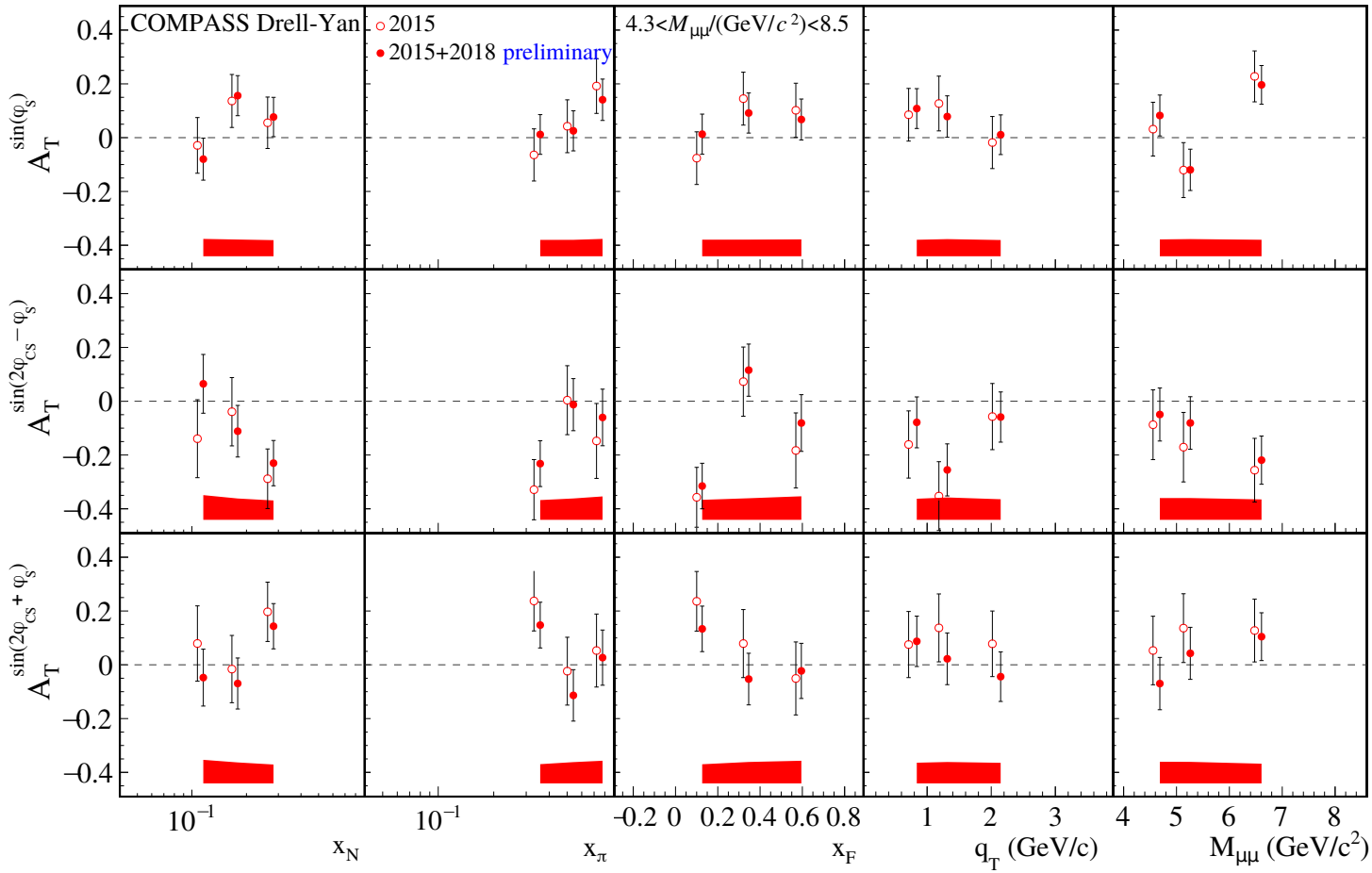


- Results are **consistent with past pion-induced DY measurements** on W targets
- Preliminary COMPASS results for ν:
  a room for possible Boer-Mulders effect?
- Indication of **possible violation of the Lam-Tung relation**



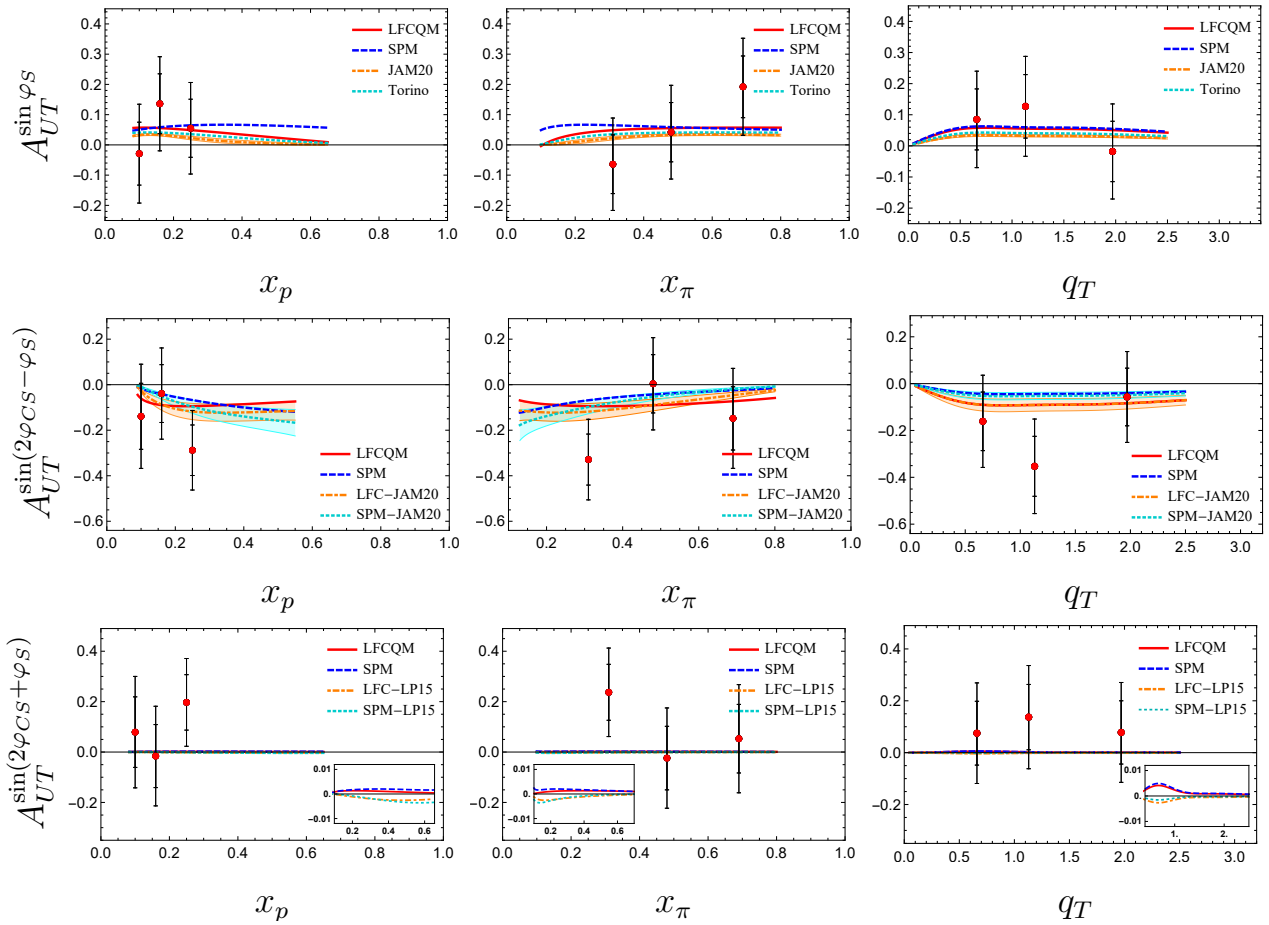
DYNNLO: W-C. Chang *et al.*, PRD 99, 014032 (2019); **NA10**: ZPC 31, 513(1986); **E615**: PRD 39, 92(1989);

Drell-Yan transverse spin asymmetries at COMPASS



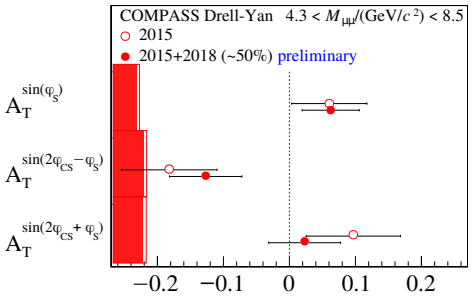
COMPASS, PRL **119**(2017), 112002;
+2018 (50% of statistics) preliminary results (PoS DIS2019 (2019) 195; 1908.01727 [hep-ex]).

Drell-Yan transverse spin asymmetries at COMPASS

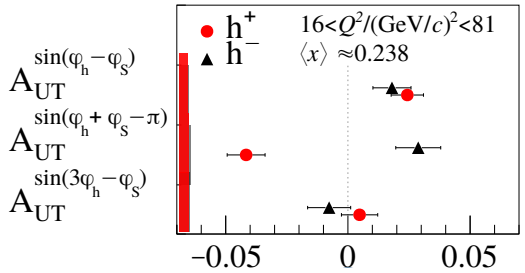


S. Bastami *et al.*, JHEP **02** (2021) 166;
Red points: COMPASS, PLB **770**(2017), 138.

Drell-Yan transverse spin asymmetries at COMPASS

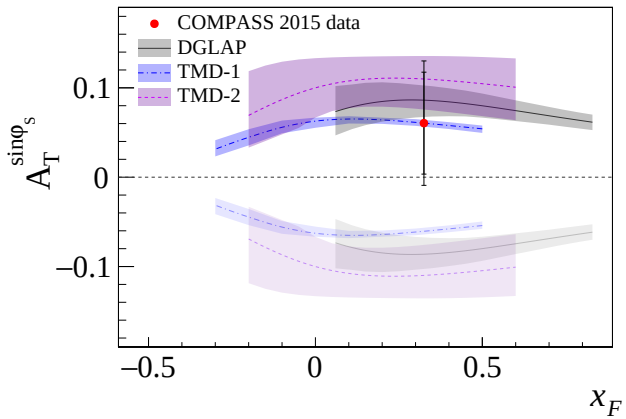


COMPASS, PRL **119**(2017), 112002,
+2018 (50% of statistics) preliminary results
(PoS DIS2019 (2019) 195).



COMPASS, PLB **770**(2017), 138.

- Sivers $\sim 1\sigma$ above zero
- Transversity $\sim 2\sigma$ below zero
- Pretzelosity compatible with zero
- Results from 2015 run and preliminary results from 2018 favor the sign change hypothesis

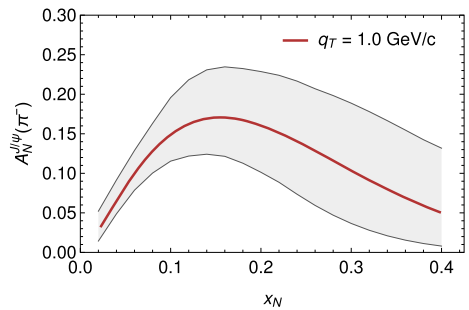


Spin dependent asymmetries

from J/ψ production in pion-nucleon collisions at COMPASS

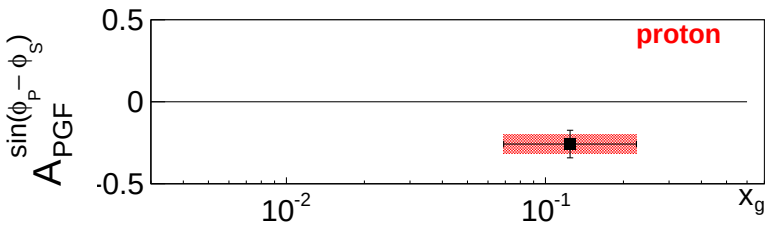
Two subprocesses for J/ψ production at the LO:

- $q\bar{q}$ annihilation – impact on quark TMD PDFs
- gg-fusion – sensitive to gluon TMD PDFs



Anselmino *et al.*, PLB **770**(2017), 302-306.

Large Sivers asymmetry in COMPASS J/ψ production assuming only $q\bar{q}$ annihilation



COMPASS, PLB **772**(2017), 854.

Sivers asymmetry for gluons is $\sim 2\sigma$ below zero in photon-gluon fusion from COMPASS SIDIS data

Possible dominant gg-fusion at COMPASS (Chang *et al.*, PRD **102**(2020), 054024)

COMPASS analysis on transverse asymmetries in J/ψ-production is in progress!

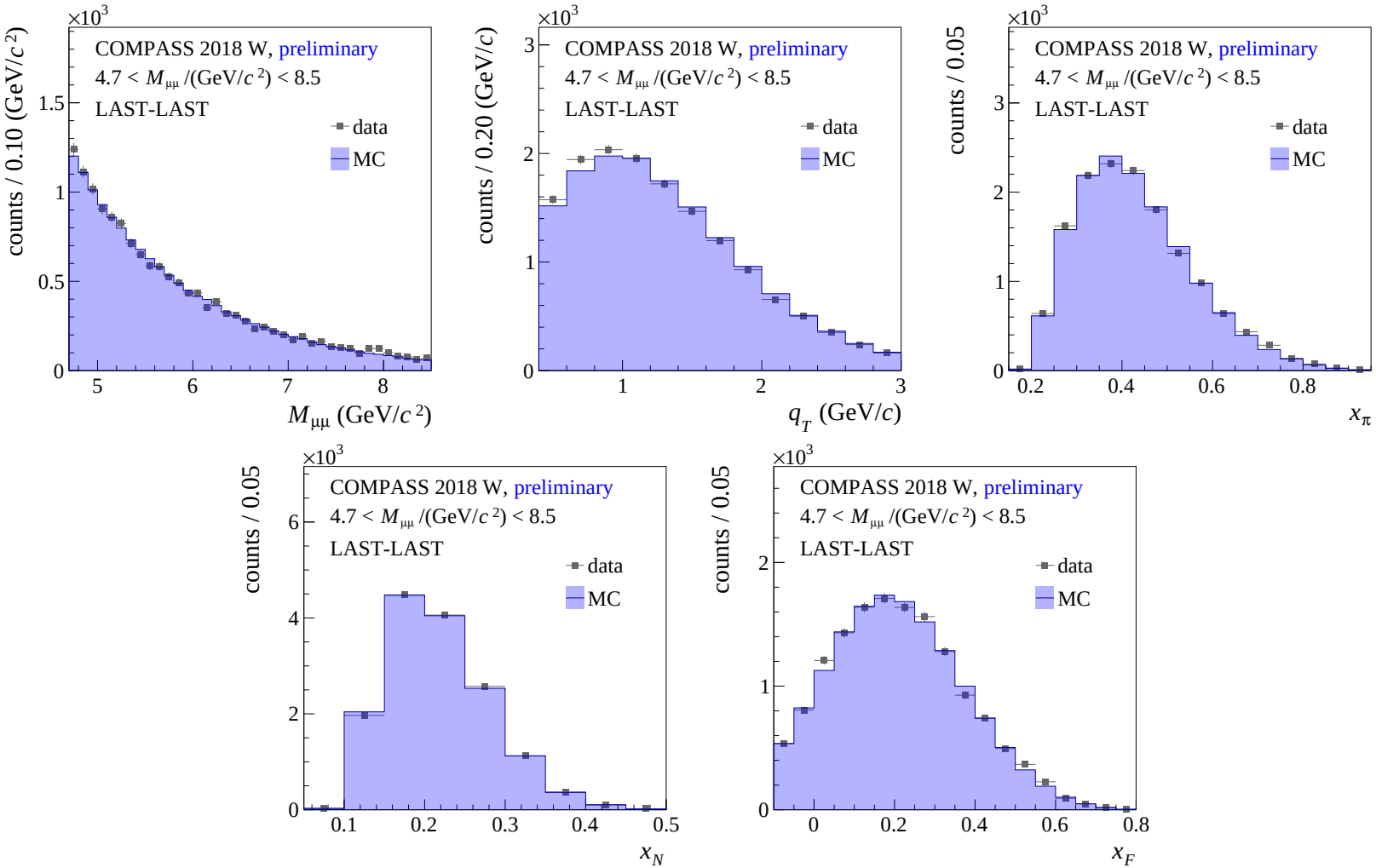
Summary

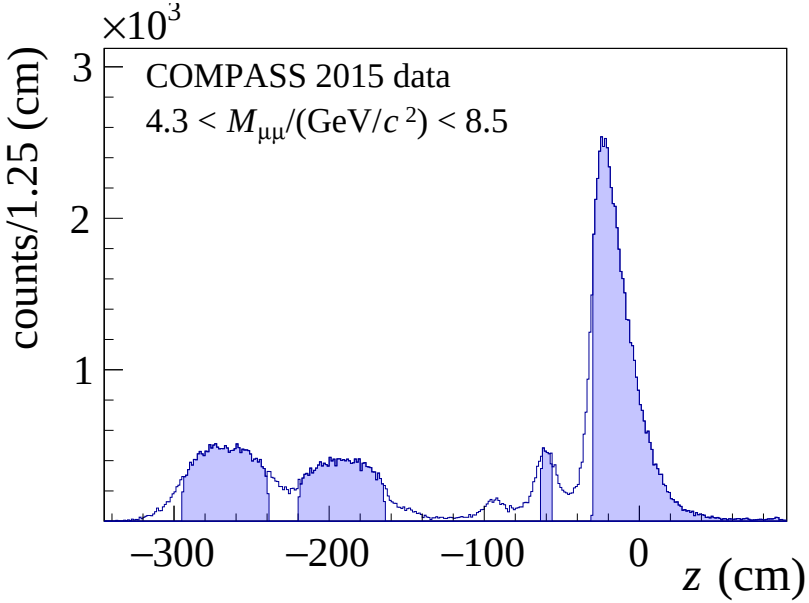
- COMPASS DY measurements on azimuthal asymmetries offer a unique opportunity, when comparing to corresponding COMPASS SIDIS results, to investigate the process dependence of TMD PDFs at practically the same hard scale, thereby minimising possible bias introduced by TMD evolution.
- COMPASS preliminary results on DY spin-independent azimuthal asymmetries on the W target:
  - possibly hint at a non-zero Boer-Mulders effect;
  - possibly indicate violation of the Lam-Tung relation.
- Various analyses on azimuthal effects are ongoing:
  - final (using full 2015+2018 data sample) transverse spin-dependent azimuthal DY asymmetries;
  - transverse spin-(in)dependent azimuthal asymmetries in J/ψ production;
  - final results on spin-independent azimuthal asymmetries on the W and the NH_3 targets, EMC effect *etc.*

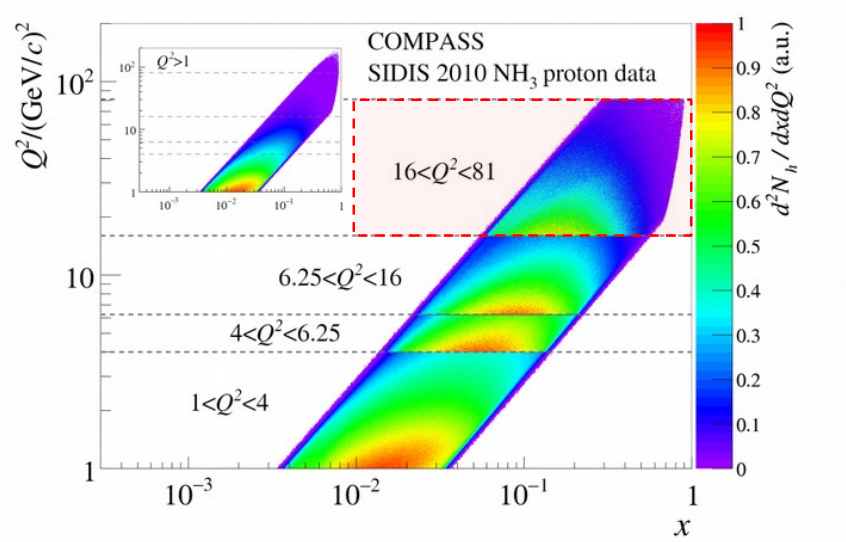
Thank you for your attention!

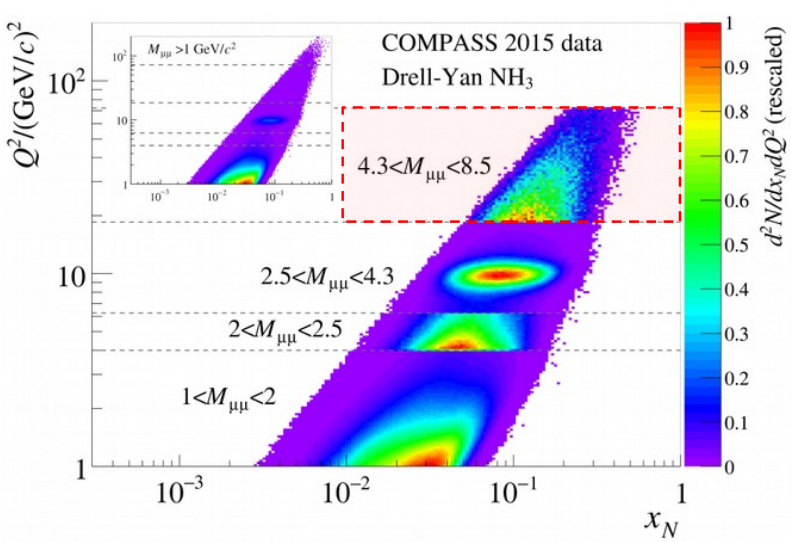
Back up slides

Monte-Carlo agreement with data




×10^3
counts/1.25 (cm)
COMPASS 2015 data
4.3 < Mμμ/(GeV/c 2) < 8.5
z (cm)


COMPASS
SIDIS 2010 NH3 proton data
Q2>1
16<Q2<81
6.25<Q2<16
4<Q2<6.25
1<Q2<4
Q2/(GeV/c)2
x
d2Nh / dxdQ2 (a.u.)


COMPASS 2015 data
Drell-Yan NH3
Mμμ >1 GeV/c2
4.3<Mμμ<8.5
2.5<Mμμ<4.3
2<Mμμ<2.5
1<Mμμ<2
Q2/(GeV/c)2
xN
d2N/dxNdQ2 (rescaled)