Transverse spin asymmetries in J/ψ production at COMPASS

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CHARLES UNIVERSITY
Faculty of mathematics
and physics

Outline

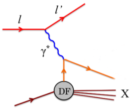
Nucleon structure: Parton distribution functions

- Parton model
  - Born in the late 60's,
  - to describe electron–proton scattering $e(k) + p(P) \to e(k') + X$

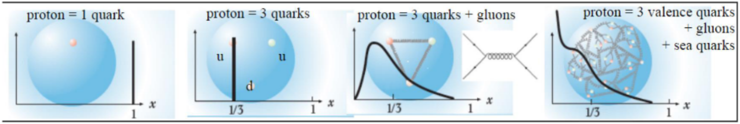
$$Q^2 = -q^2 = -(k' - k)^2, \qquad x = \frac{Q^2}{2P \cdot q}$$

  - Deeply-Inelastic Scattering (DIS) limit and "infinite momentum frame": $P \to \infty$, $Q^2 \to \infty$, x stays finite.

$$\frac{d\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4} D(x, Q^2) \sum_i e_i^2 f_1^i(x)$$



  - Point-like constituents (partons) with momentum and charge: $k = xP$, $e = 2/3, -1/3$.
  - $f_1(x)$ – Parton Distribution Function (PDF),



  - Drell–Yan reaction (1970)

$$\frac{d\sigma}{dx_a dx_b} = \frac{4\pi\alpha^2}{9q^2} \sum_i e_i^2 f_1^i(x_a) f_1^{\bar{i}}(x_b)$$

- QCD
  - $f = f(x, Q^2)$, but the dependence on Q^2 is calculable (DGLAP equations).

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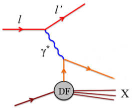

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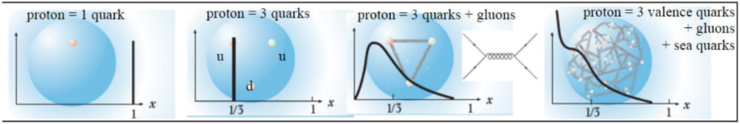

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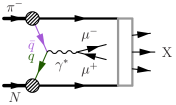

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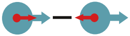
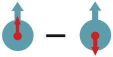
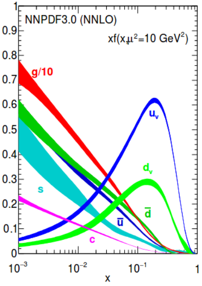
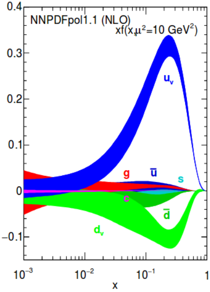
Number density	Helicity	Transversity
		



NNPDF 3 number density



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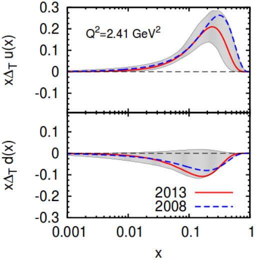
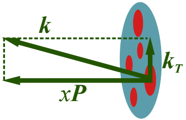
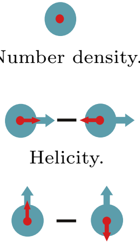


Transversity from Anselmino *et al.*.

COMPASS



- If parton intrinsic $\boldsymbol{k}_\mathrm{T}$ is not integrated over,
- "three-dimensional" objects $f(x, k_\mathrm{T}^2, Q^2)$.
- Accessible in
  - semi-inclusive deep-inelastic scattering (SIDIS),
  - Drell–Yan dilepton production,
  - proton–proton collisions...



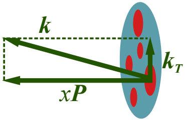
Number density.

Helicity.

Transversity.

Parton polarisation		Parent hadron polarization: Unpolarised	Longitudinal	Transverse
	U	$f_1(x, k_\mathrm{T}^2)$ (number density)		$f_{1T}^\perp(x, k_\mathrm{T}^2)$ (Sivers)
	L		$g_1(x, k_\mathrm{T}^2)$ (helicity)	$g_{1T}(x, k_\mathrm{T}^2)$ (Kotzinian–Mulders)
	T	$h_1^\perp(x, k_\mathrm{T}^2)$ (Boer–Mulders)	$h_{1L}^\perp(x, k_\mathrm{T}^2)$ (worm-gear)	$h_1(x, k_\mathrm{T}^2)$ (transversity) $h_{1T}^\perp(x, k_\mathrm{T}^2)$ (pretzelosity)

Nucleon structure: Transverse momentum dependent PDFs



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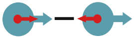
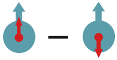


Helicity.



Transversity.

Sivers PDF.

Boer–Mulders PDF.

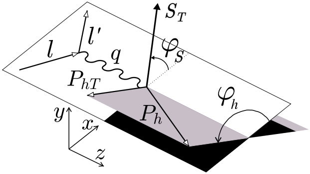
Pretzelosity PDF.

Nucleon structure: Measuring the TMD PDFs

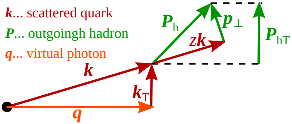
- Semi-Inclusive Deep-Inelastic Scattering (SIDIS) off polarised nucleons

$$\ell + \overrightarrow{N} \to \ell' + h + X, \qquad \ell + N^{\uparrow} \to \ell' + h + X$$

  - Q^2, x, z (fraction of available energy transferred to h), $\boldsymbol{P_{\mathrm{T}}}$ (transverse momentum of h).



γN frame.



Transverse momenta in target rest frame.

  - $\boldsymbol{k_{\mathrm{T}}}$ is not directly observable, only convolutions of TMD PDFs and fragmentation functions (FFs) over $\boldsymbol{k_{\mathrm{T}}}$ and $\boldsymbol{p_{\perp}}$.
  - Measured since ≈ 2000: HERMES, COMPASS, JLab.

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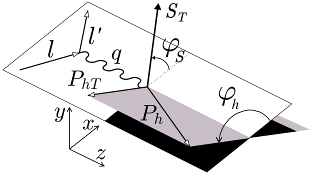

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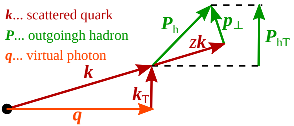

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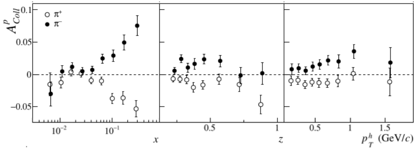
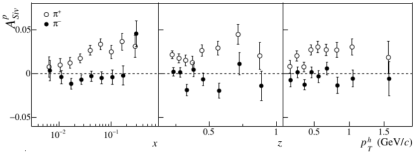
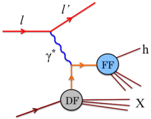


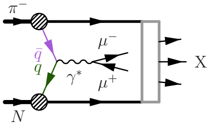
Collins asymmetry at COMPASS.
Arises from transverse polarisation of q in $\mathrm{p}^{\uparrow}$ (transversity PDF h_1), and anisotropic fragmentation of $q^{\uparrow}$ (Collins TMD FF $H_1^{\perp}$).



Sivers asymmetry at COMPASS.
From correlation of $\boldsymbol{k_\mathrm{T}}$ of q with the spin of $\mathrm{p}^{\uparrow}$ (Sivers TMD PDF $f_{1\mathrm{T}}^{\perp}$)

Nucleon structure: SIDIS and Drell–Yan





SIDIS on transversely polarised nucleons

- Structure functions F:
  $F = \mathrm{PDF}_{q,\mathrm{p}} \otimes \mathrm{FF}_{q\to h}$.
- For example:
  - $F_{UU}^{\cos\phi_h}$ and $F_{UU}^{\cos 2\phi_h}$ linked to $h_{1,\mathrm{p}}^{\perp}$,
  - $F_{UT,T}^{\sin(\phi_h-\phi_S)} = f_{1\mathrm{T},\mathrm{p}}^{\perp} \otimes D_1$.
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  - $F_{T}^{\sin(2\phi-\phi_S)} = h_{1,\pi}^{\perp} \otimes h_{1,\mathrm{p}}$.

A sign change predicted for Sivers and Boer–Mulders functions:

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

$$h_{1}^{\perp q}\big|_{\mathrm{SIDIS}} = -h_{1}^{\perp q}\big|_{\mathrm{DY}}$$

[J. Collins, Phys.Lett. B536 (2002) 43]

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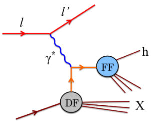

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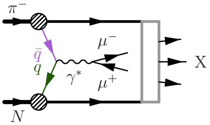

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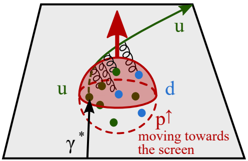

Sivers effect in SIDIS
(as described by [M. Burkardt, Nucl.Phys. A735 (2004) 185].

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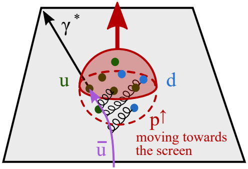
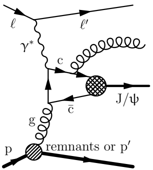
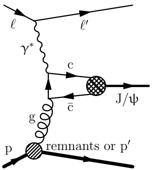


Sivers effect in Drell–Yan drawn in the same manner.

In lepton–nucleon scattering



Color singlet model.



Color evaporation model (CEM) or color octet model (COM).

- Color singlet model: $c\bar{c}$ has to be in color singlet state to form the J/ψ.
- CEM: the color 'evaporates' from $c\bar{c}$ via soft gluon interactions.
- COM: NRQCD factorisation, different transition probabilities from different inital states (more free parameters than CEM).
- These processes give access to gluon TMD PDFs via the 'photon–gluon fusion' (PGF).
- Diffractive production: via exchange of a color-less particle.
- Also the diffractive production could be approached by perturbative QCD, but contains different information.
- Feed-down: decay of heavier charmonia – any information on nucleon structure is lost.

Nucleon structure: J/ψ production

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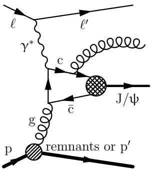

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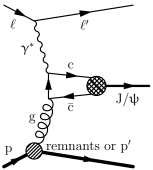

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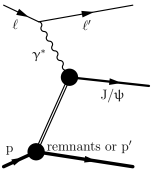

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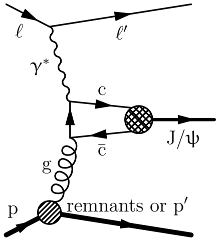
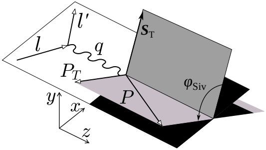


J/ψ formed in PGF.

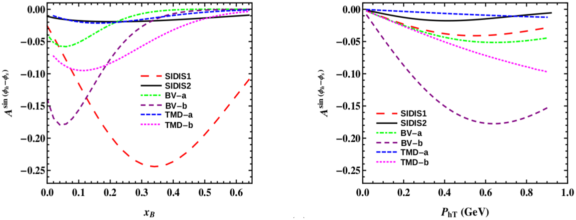


The Sivers angle
(here $P = P_{J/\psi}$).

- Assuming PGF process (plus CEM or COM),
- azimuthal distribution of g preserved, $\phi_g = \phi_{J/\psi}$,
- → Sivers-like modulation in φ_{Siv}

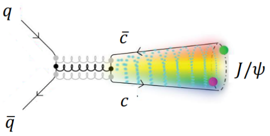
$$\sigma(\phi_{Siv}) = \sigma_0\left(1 + f P_{tar.} A^{p}_{Siv} \sin(\varphi_{Siv})\right)$$

- [Mukherjee and Rajesh, Eur.Phys.J.C77 (2017)], [Bacchetta et al., Eur.Phys.J.C80 (2020)].

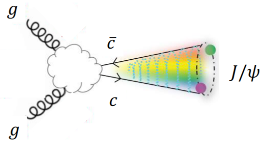


Projections for COMPASS energy, [Mukherjee and Rajesh, Eur.Phys.J.C77 (2017)].

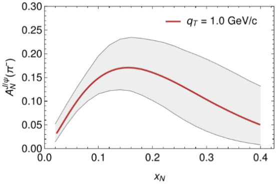
In pion–nucleon scattering



Quark–antiquark annihilation[1].



Gluon–gluon fusion[1], the cloud = several perturbative contributions.



[Anselmino *et al.*. Phys.Lett.B770 (2017)]

- The rainbow area represents CEM or COM J/ψ production from $c\bar{c}$.
- $q\bar{q}$ annihilation: access to quark TMD PDFs.
  - A large Sivers asymmetry in $\pi^- p^\uparrow \to \mu^- \mu^+ X$ at COMPASS was predicted, assuming only $q\bar{q}$ [Anselmino *et al.*. Phys.Lett.B770 (2017)].
- gg fusion: access to gluon TMD PDFs.
  - For example, to d-type Sivers function if produced in $\pi^- p^\uparrow$ scattering.
- Feed-down: decay of heavier charmonia – any information on nucleon structure is lost.
- The result is a mix of the processes. The ratio depends on J/ψ production mechanism.
  - Studies suggest that gg fusion dominates at COMPASS [Chang *et al.*, Phys.Rev.D102 (2020)]

[1] Diagrams: courtesy of Pietro Faccioli.

Nucleon structure: Drell–Yan and J/ψ cross-section

[S. Arnold *et al.*, Phys.Rev.D79 (2009) 034005]

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

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

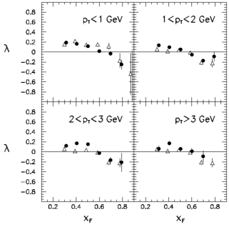
$$D_{[f(\theta_{CS})]} = f(\theta_{CS}) / \left(1 + A_U^1 \cos^2\theta_{CS}\right)$$

Cross-section with unpolarised target:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+1}\left(1 + \lambda\cos^2\theta_{\mathrm{CS}} + \mu\sin 2\theta\cos\varphi_{\mathrm{CS}} + \frac{\nu}{2}\sin^2\theta\cos 2\varphi_{\mathrm{CS}}.\right)$$

$\lambda = A_{\mathrm{U}}^1$, $\mu = A_{\mathrm{U}}^{\cos\varphi_{\mathrm{CS}}}$ and $\nu = 2A_{\mathrm{U}}^{\cos 2\varphi_{\mathrm{CS}}}$

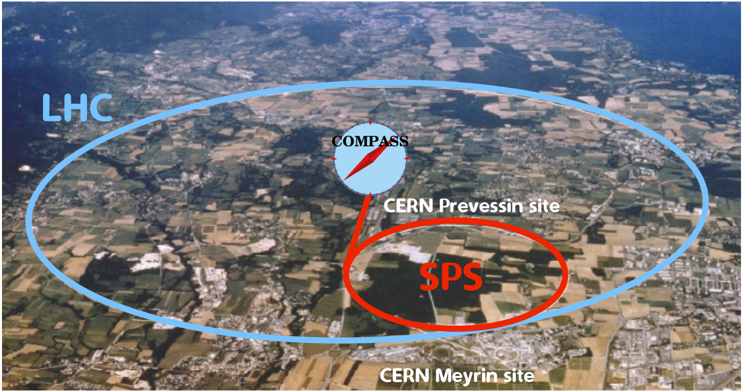
- The same parametrisation describes Drell–Yan and J/ψ cross-section.
- The interpretation of the structure functions F differs.
- 'Naive' Drell–Yan model: $\lambda = 1$, $\mu = \nu = 0$.
- Lam–Tung relation for Drell–Yan: $\lambda + 2\nu = 1$.
- λ plays role in the kinematic factors D.
- Drell–Yan: $\lambda \approx 1$ from experiments.
- J/ψ: kinematically dependent.



λ measured by NuSea experiment [NuSea, Phys.Rev.Lett. 91 (2003)].

COMPASS experiment: Introduction

- COMPASS Collaboration: 24 institutions from 13 countries ($\approx$ 220 physicists).
- Experimental area: CERN Super Proton Synchrotron (SPS) North Area.
- Multi-purpose apparatus with rich physics program since 2002 aimed at hadron structure and spectroscopy.



COMPASS experiment: SIDIS and Drell–Yan setups

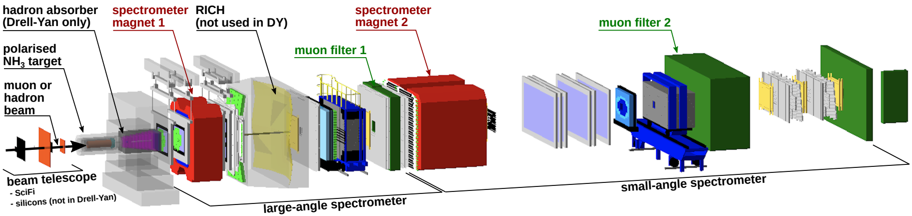
- Large polarised solid-state target with 2 or 3 oppositely-polarised cells.
- Two-stage spectrometer, about 350 detector planes, μ identification.

SIDIS with transversely-polarised target

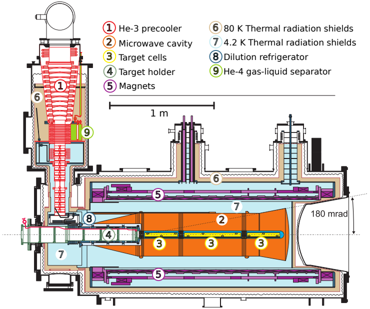
- 2002–2004 with $d^{\uparrow}$ (^{6}LiD, old magnet).
- 2007 and 2010 with $p^{\uparrow}$ (NH_3, new mag.)
- 2021–2022 with $d^{\uparrow}$ (^{6}LiD, new mag.)
- 160 GeV/c μ^{+} beam (about 3.5×10^{8} μ/spill of 10 s).
- Triggering on the scattered μ.

Drell–Yan with transversely-polarised target

- 2015 and 2018 with $p^{\uparrow}$ (NH_3, new mag.)
- 190 GeV/c π^{-} beam (about 10^{9} π/spill of 10 s).
- With a hadron absorber.
- Triggering on 2μ.



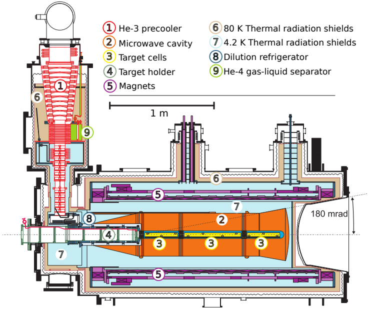
COMPASS Drell–Yan setup.
The SIDIS setup has beam momentum stations, silicon beam telescope and no hadron absorber.



Polarised target (new magnet).

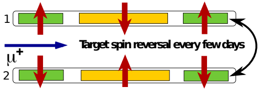
Large solid-state polarised target

- Super-conducting magnets:
  - 2.5 T solenoid, 0.6 T dipole.
  - Old (SMC) target magnet: 70 mrad acceptance.
  - New (COMPASS) target magnet: 180 mrad.
- MW system for dynamic nuclear polarisation.
- Polarisation is measured by NMR.
- Dilution refrigerator → frozen spin mode at 70 mK.
- The target contains also unpolarised nuclei
  - Dilution of the signal by fP_N.
  - f: fraction of cross-section on polarisable nuclei.
  - P_N: polarisation of the polarisable nuclei.
  - Polarised d: ^{6}LiD, $f = 0.4$, $P_d = 0.5$
  - Polarised p: NH_3, $f = 0.16$, $P_p = 0.9$
- Acceptance in polarisation-dependent azimuthal angles is cancelled in combinations of target cells and data taking periods.



Polarised target (new magnet).

Operation with 2 cells.



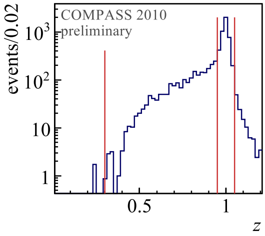
Operation with 3 cells.

Large solid-state polarised target

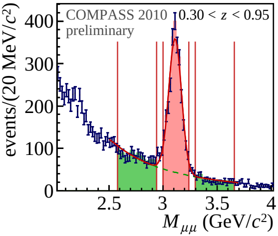
- Super-conducting magnets:
  - 2.5 T solenoid, 0.6 T dipole.
  - Old (SMC) target magnet: 70 mrad acceptance.
  - New (COMPASS) target magnet: 180 mrad.
- MW system for dynamic nuclear polarisation.
- Polarisation is measured by NMR.
- Dilution refrigerator → frozen spin mode at 70 mK.
- The target contains also unpolarised nuclei
  - Dilution of the signal by fP_N.
  - f: fraction of cross-section on polarisable nuclei.
  - P_N: polarisation of the polarisable nuclei.
  - Polarised d: ^{6}LiD, $f = 0.4$, $P_d = 0.5$
  - Polarised p: NH_3, $f = 0.16$, $P_p = 0.9$
- Acceptance in polarisation-dependent azimuthal angles is cancelled in combinations of target cells and data taking periods.

TSAs in J/ψ leptoproduction: Data analysis

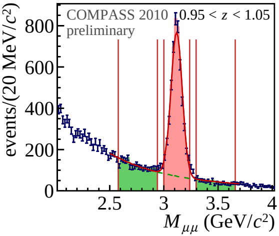
- $\mu^+ p^\uparrow \to \mu^+ J/\psi\, X \to \mu^+ \mu^+ \mu^- X$.
- Both possible combinations of $\mu^+\mu^-$ used.
- 2010 proton data.
- No Q^2 cut imposed (hard scale = $c\bar{c}$ mass).
- Two bins z: inclusive, exclusive.
- Clear J/ψ signal (3.1 GeV/c^2, $\sigma \approx 55$ MeV/c^2).
- Small background, limited statistics (≈ 2300 incl., 4500 excl.).



Energy fraction transferred to J/ψ.

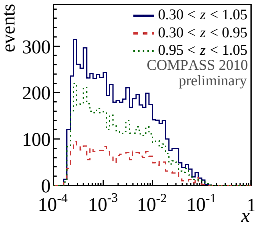


Invariant mass, inclusive bin.

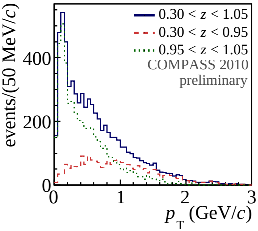


Invariant mass, exclusive bin.

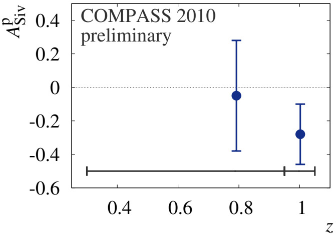
TSAs in J/ψ leptoproduction: Results



The $x_{\mathrm{Bj.}}$ distribution.



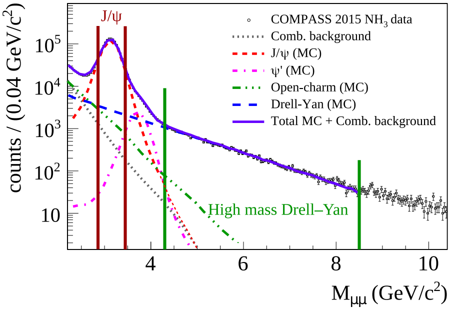
The P_{T} distribution.



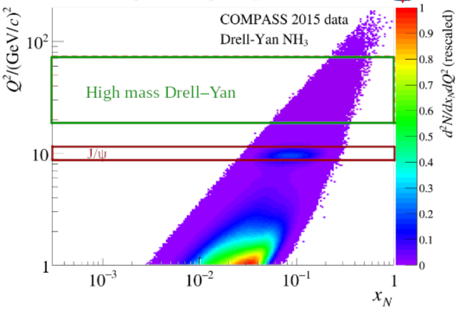
The measured Sivers-like asymmetry.

- $A^{\mathrm{p}}_{\mathrm{Siv}} = -0.28 \pm 0.18$ (preliminary, exclusive J/ψ).
- Prospects for improving statistics:
  - e^+e^- channel: spectrometer not optimal for electrons, probably high background...
  - 2002–2004 ^{6}LiD data: rather small statistics,
  - 2007 NH_3 data could bring something,
  - Planned 2022 ^{6}LiD data: $\approx$ 2010 statistics.
- We are considering analysing other J/ψ asymmetries and writing a paper.

TSAs in $\pi^- p^\uparrow$ scattering: Data analysis



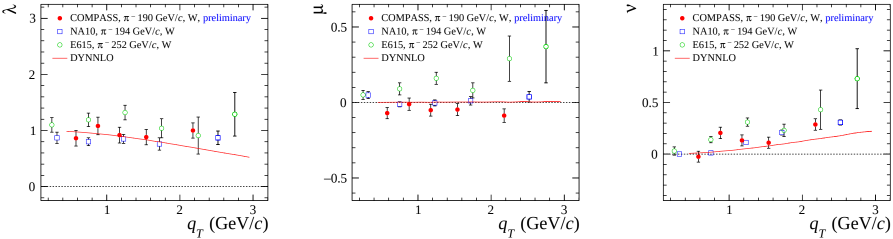
2015 data and reconstructed MC.



Kinematic coverage in x_N and Q^2

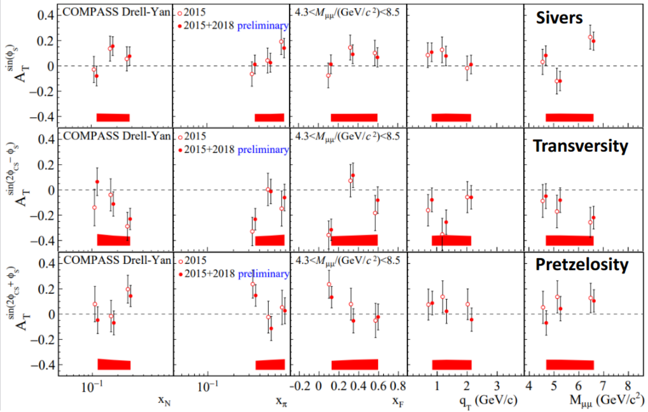
- $\pi^- p^\uparrow \to \mu^+\mu^-$.
- Invariant mass distribution is smeared by the hadron absorber.
- Combinatorial background evaluated from like-sign μμ in the data.
- Open-charm background evaluated from Monte Carlo.
- $M_{\mu\mu} \in [4.3, 8.5]$ GeV/c^2: High mass Drell–Yan region (96% pure Drell–Yan)
  - TSAs from 2015 data published [COMPASS, Phys.Rev.Lett.119(11), 112002 (2017)].
- $M_{\mu\mu}$ in J/ψ region: more than 90% pure J/ψ, depending on the precise cut.
  - Ongoing analysis of the TSAs.
  - About 30× more data with respect to high-mass Drell–Yan.

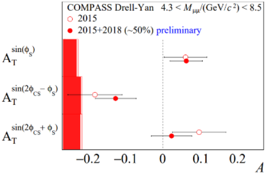
TSAs in $\pi^- p^\uparrow$ scattering: Results in the Drell–Yan range



- Unpolarised asymmetries in line with previous experiments.
- In line with Lam–Tung relation, within uncertainties.
- Obtained using 2018 data (better Monte Carlo description than 2015).
- J/ψ analysis is ongoing.

TSAs in $\pi^- p^\uparrow$ scattering: Results in the Drell–Yan range





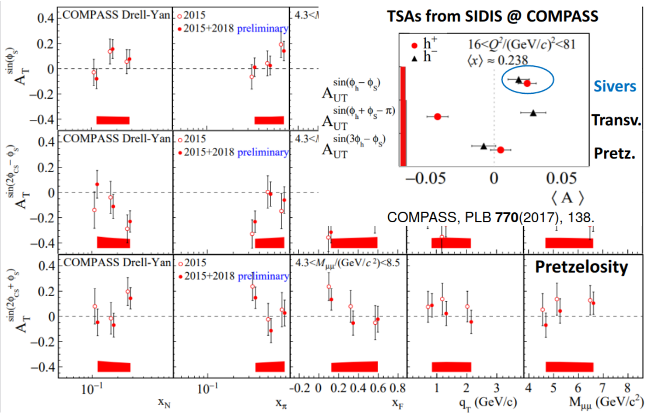
Sivers ~1σ above zero

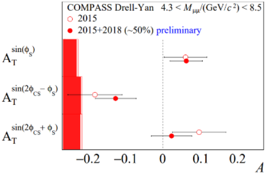
Transversity ~2σ below zero

Pretzelosity ~1σ above zero

TSAs in the high-mass Drell–Yan range [COMPASS, Phys.Rev.Lett.119(11), 112002 (2017)].

- The results support the sign-change prediction, although with a limited precision.
- Obtained using 2015 and part of 2018 data.
- J/ψ analysis is ongoing.





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Conclusions

- COMPASS is studying the TMD PDFs in muon–nucleon and pion–nucleon scattering.
- It can thus address the universality of the TMDs.
- J/ψ production in these processes can bring important information.
- However, the interpretation is challenging
  - Different production mechanisms,
  - Feed-down contributions.
- Resutls on the TSAs can be expected soon.

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Thank you for your attention!