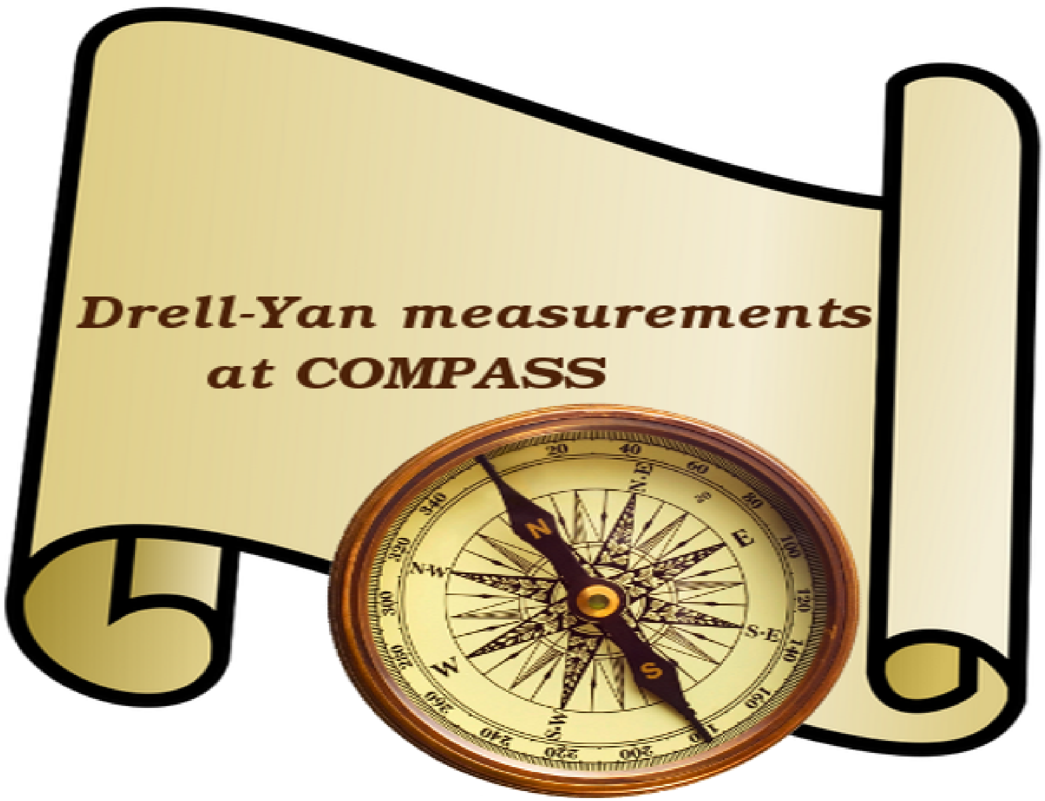


Catarina Quintans, LIP-Lisbon, Portugal

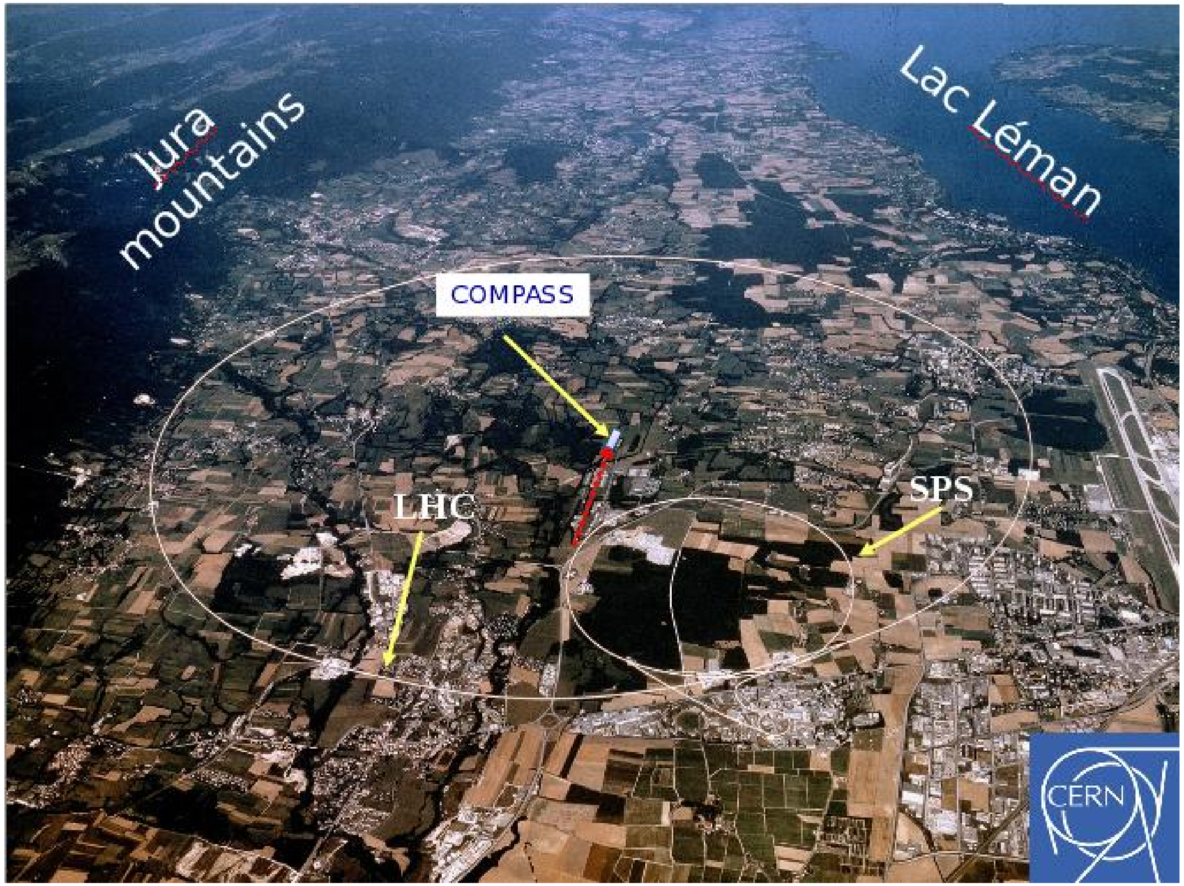
on behalf of the COMPASS Collaboration

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

CERN/FIS-NUC/0017/2015

COMPASS Collaboration

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

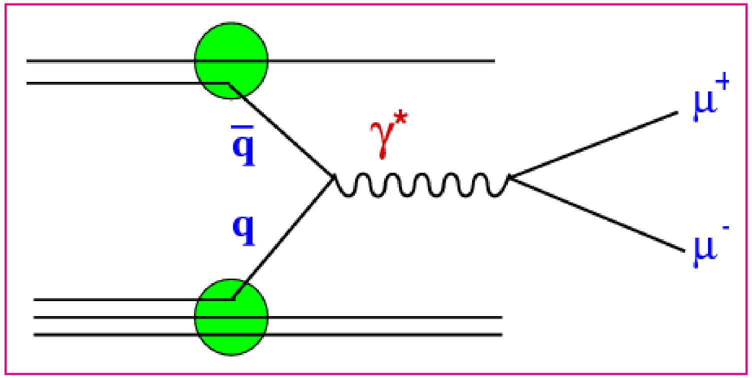


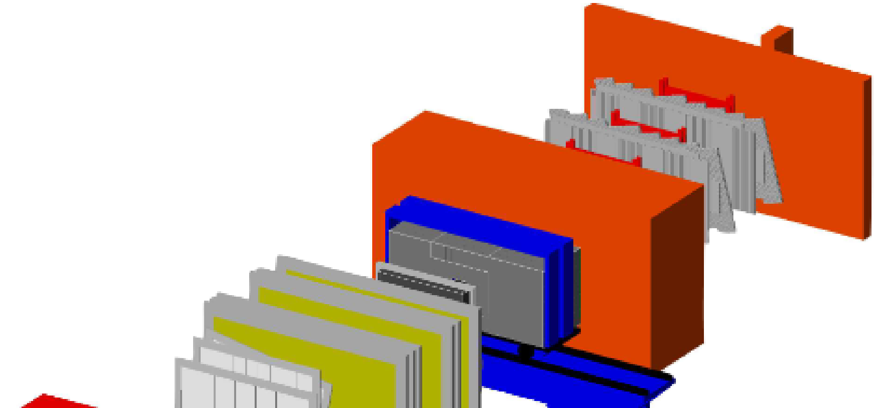
More than 200 collaborators from 12 countries.

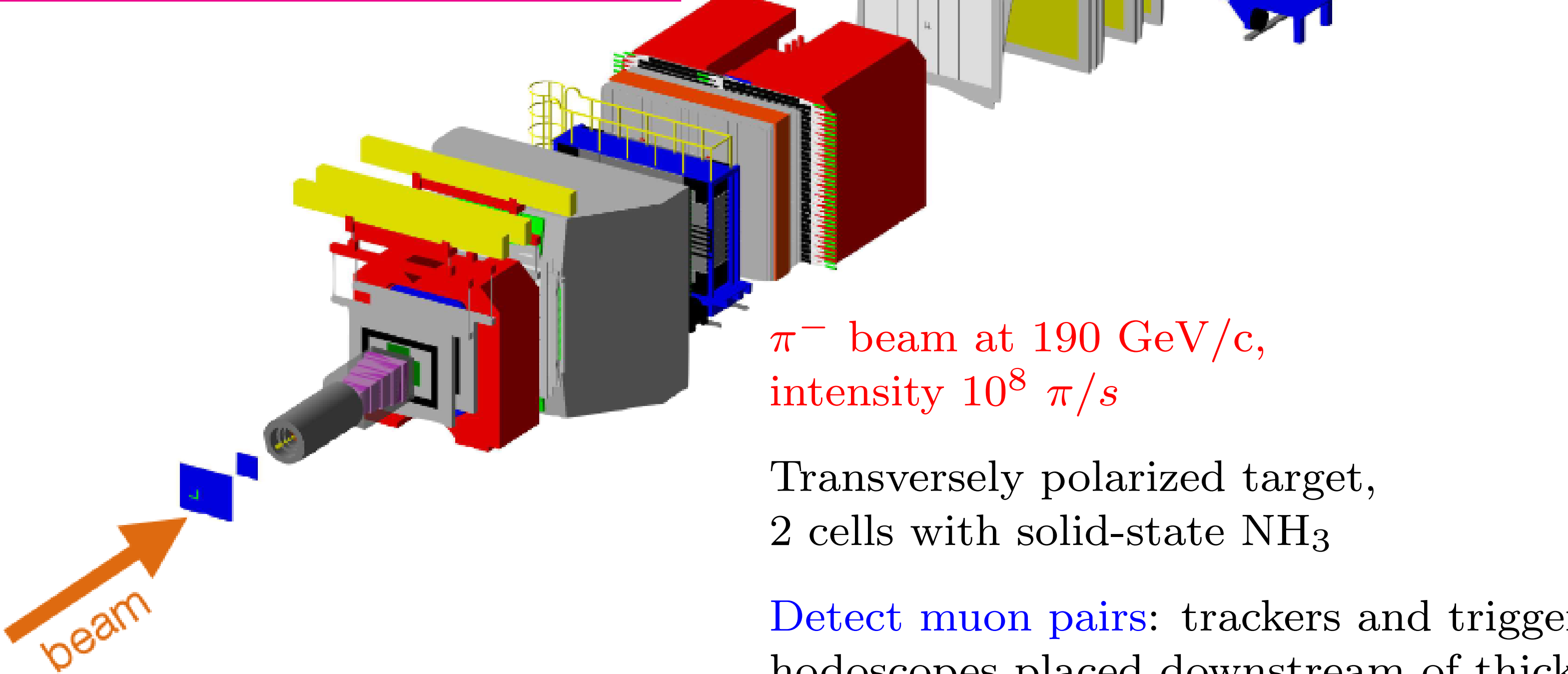
A versatile muon/hadron beam line.

A multi-purpose spectrometer.

COMPASS Drell-Yan setup





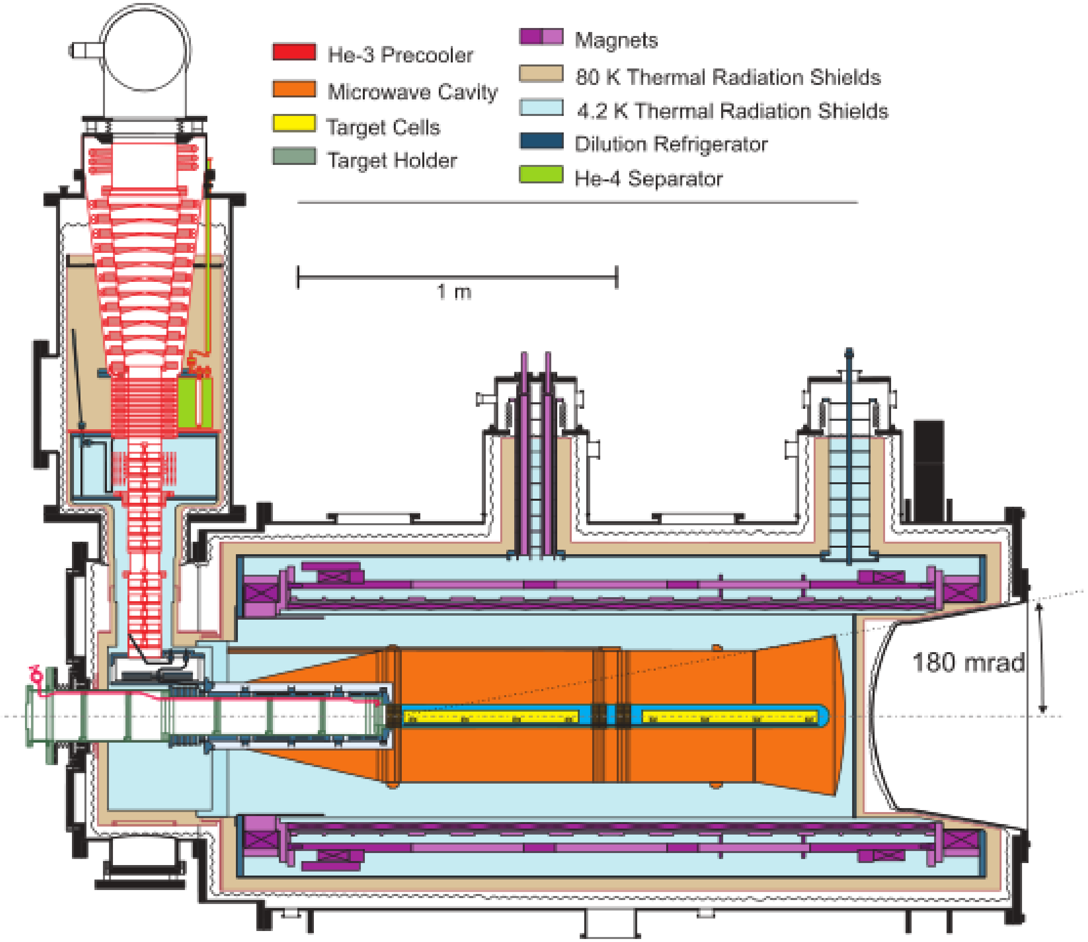


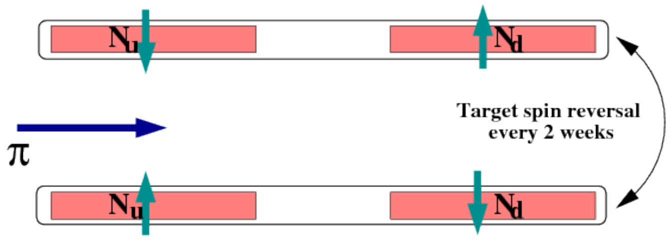
π^- beam at 190 GeV/c,
intensity 10^8 π/s

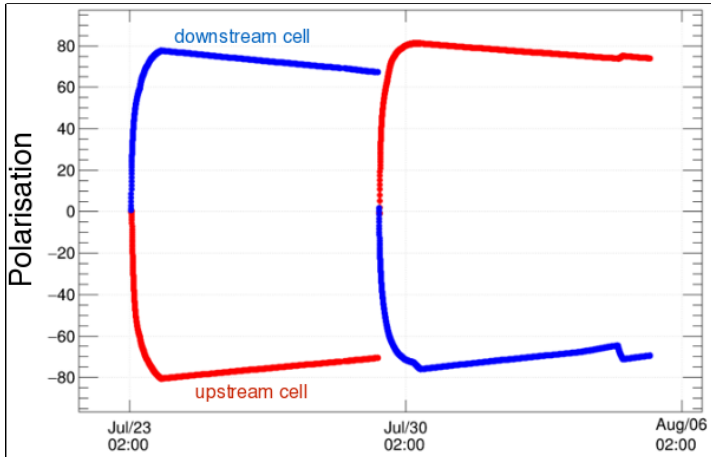
Transversely polarized target,
2 cells with solid-state NH_3

Detect muon pairs: trackers and trigger hodoscopes placed downstream of thick hadron absorbers

COMPASS polarized target

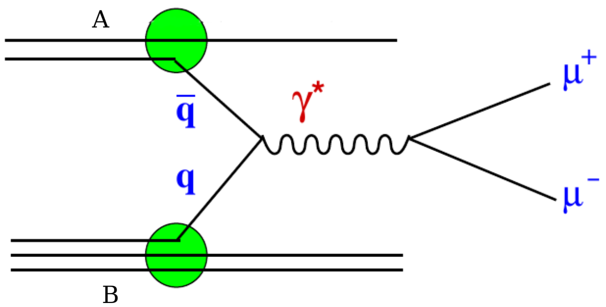






- Two cells transversely polarized NH_3 target, total 110 cm long;
- Average proton polarization in the NH_3 target ≈75%; dilution factor ≈ 0.22
- Nuclear targets downstream: 7 cm Al, and 120 cm W (beam plug)

Measuring azimuthal asymmetries in DY



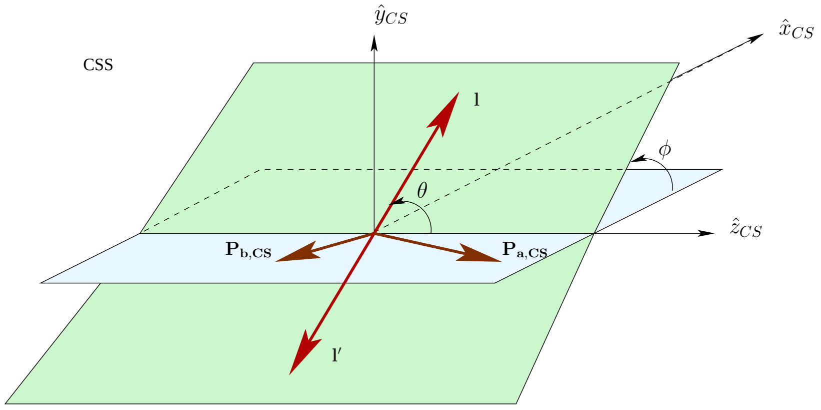
$$p_a = \frac{\sqrt{s}}{2} x_a (1, 0, 1)$$
$$p_b = \frac{\sqrt{s}}{2} x_b (1, 0, -1)$$
$$q = p_a + p_b = (q_0, 0, q_L)$$

(collinear γ^*)

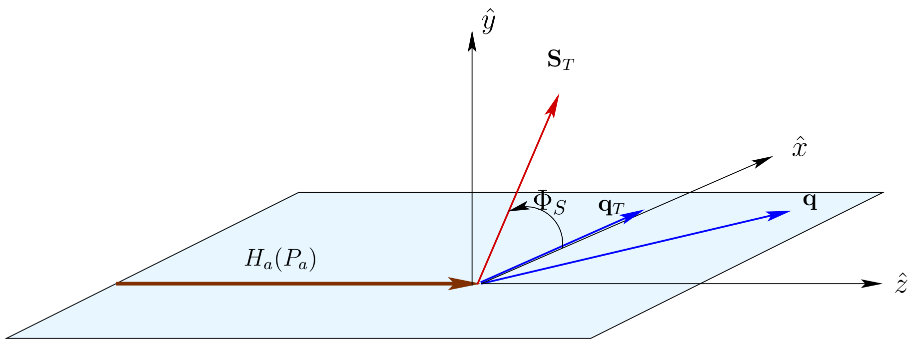
$$M_{\mu\mu} \equiv q^2 = (p_a + p_b)^2 \qquad x_{a/b} = \frac{q_0 \pm q_L}{\sqrt{s}}$$

$$\tau = x_a x_b = \frac{M_{\mu\mu}^2}{s} \qquad x_F = x_a - x_b = \frac{2q_L}{\sqrt{s}}$$

Collins-Soper frame

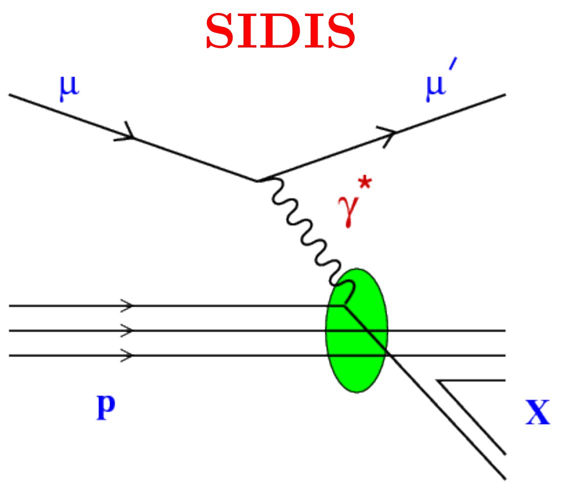


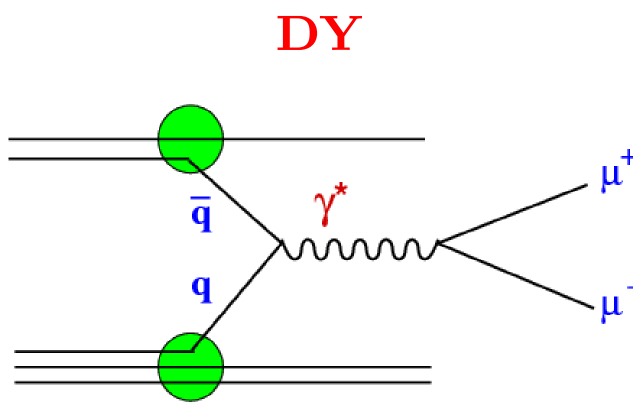
Transverse target spin and ϕ_S



TMD PDFs

Polarized Drell-Yan process: access to the transverse momentum parton distribution functions of the nucleon, complementary to semi-inclusive deep inelastic scattering.

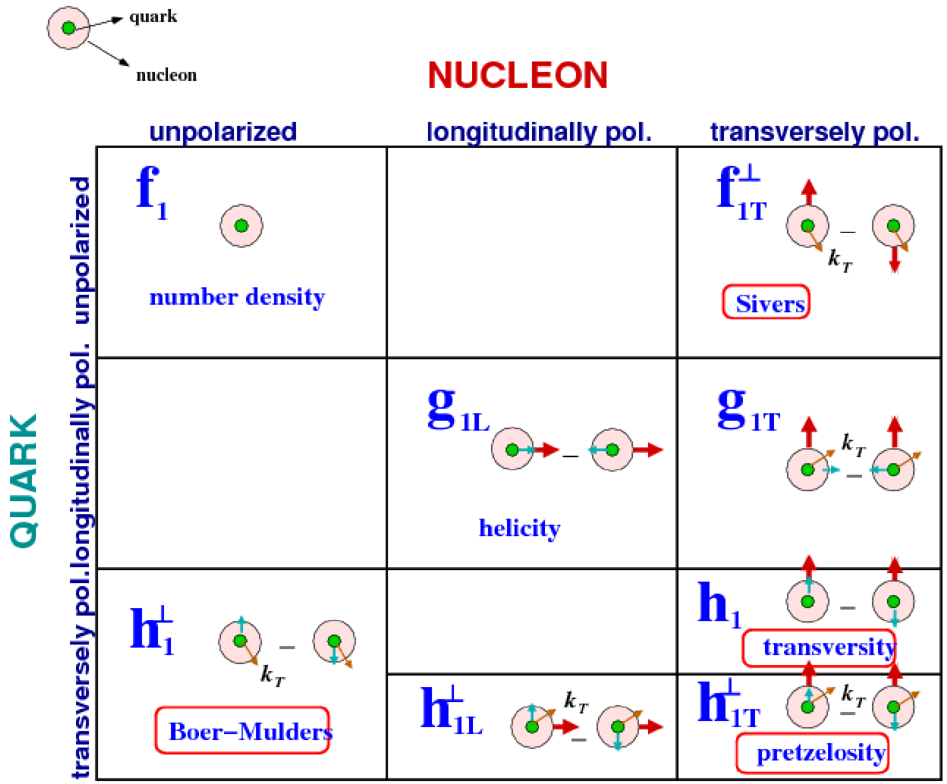




SIDIS: spin asymmetry proportional to TMD(quark) $\otimes$ FF(quark $\rightarrow$ hadron)

DY: spin asymmetry proportional to TMD(quark) $\otimes$ TMD(antiquark)

TMD PDFs



Beyond the collinear approximation:

If the intrinsic k_T of partons is taken into account, at leading twist 8 quark transverse momentum dependent PDFs are needed to describe the nucleon.

These TMD PDFs result from the correlations between the transverse momentum and the spin of quarks/nucleons.

SIDIS versus Drell-Yan

Sivers and Boer-Mulders TMD PDFs are **T-odd** – prediction of a sign change when accessed from SIDIS or from Drell-Yan processes (final state versus initial state interactions):

$$\boxed{f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)}$$

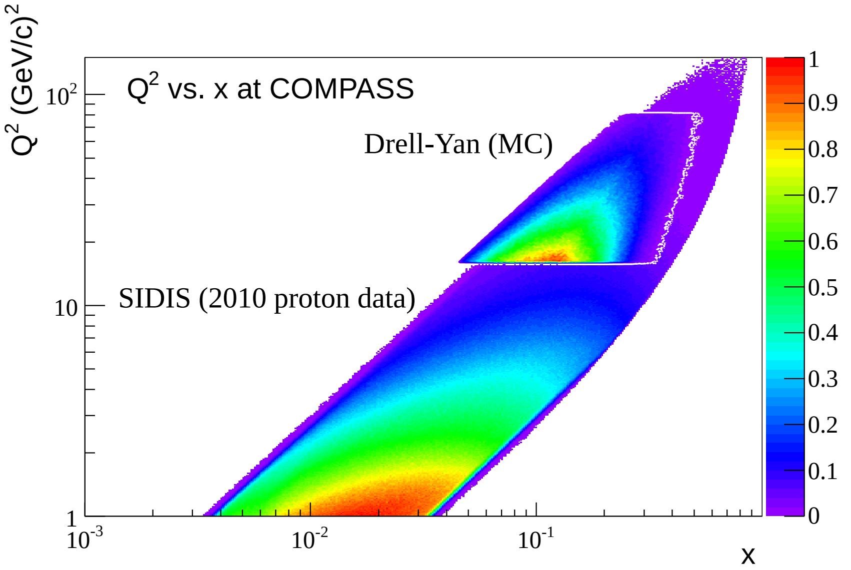
$$\boxed{h_1^{\perp}(DY) = -h_1^{\perp}(SIDIS)}$$

Its experimental confirmation is a crucial test of non-perturbative QCD.

SIDIS AND Drell-Yan in COMPASS

- In 2007 and 2010 COMPASS measured transverse single spin asymmetries (TSAs) from SIDIS process in transversely target NH_3 (and ^{6}LiD in 2004 and 2006).

- In 2015 COMPASS measured TSAs from DY process with π^- beam and transversely polarized NH_3 target.



The phase-space of the 2 measurements overlaps

↪ minimal impact (if any) of TMD evolution.

Drell-Yan cross-section

At leading twist, the single polarized Drell-Yan cross-section is:

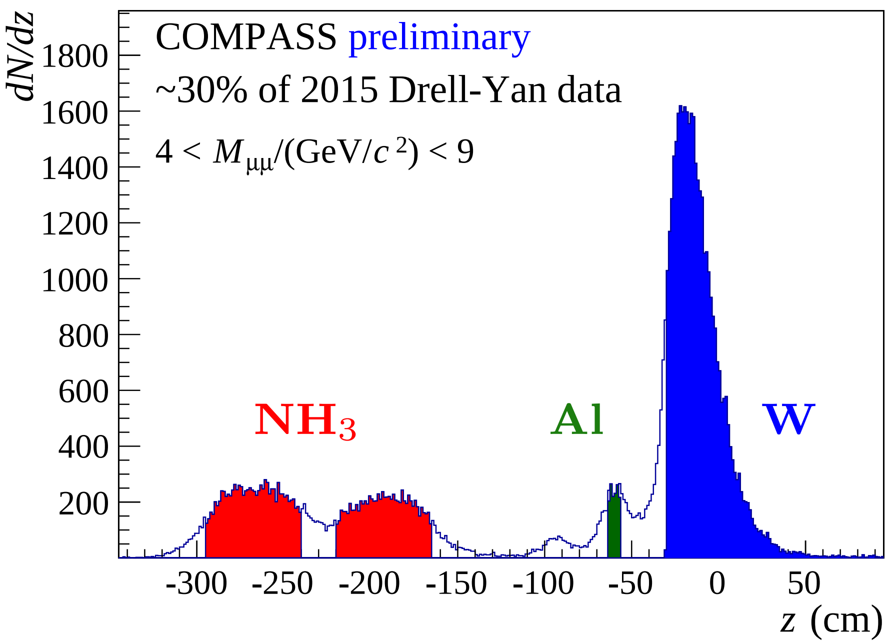
$$\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U \Big\{ (1 + D_{[\sin^2\theta]} A_U^{\cos 2\phi} \cos 2\phi)$$
$$+ |\vec{S}_T| \Big[A_T^{\sin\phi_S} \sin\phi_S + D_{[\sin^2\theta]} \Big(A_T^{\sin(2\phi+\phi_S)} \sin(2\phi + \phi_S)$$
$$+ A_T^{\sin(2\phi-\phi_S)} \sin(2\phi - \phi_S) \Big) \Big] \Big\}$$

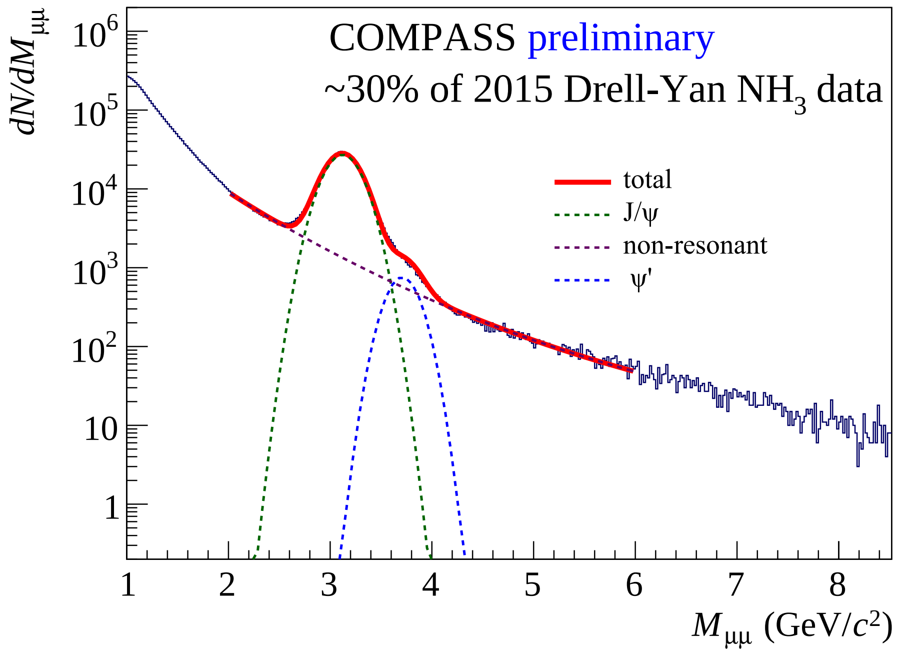
- target transverse polarization: $|\vec{S}_T|$
- depolarization factor: $D_{[\sin^2\theta]} = \frac{\sin^2\theta}{1+\cos^2\theta}$
- azimuthal asymmetries: $A_{U,T}$
  - $A_U^{\cos 2\phi}$: Boer-Mulders(π) $\otimes$ Boer-Mulders(p)
  - $A_T^{\sin\phi_S}$: unpolarized PDF(π) $\otimes$ Sivers(p)
  - $A_T^{\sin(2\phi+\phi_S)}$: Boer-Mulders(π) $\otimes$ pretzelosity(p)
  - $A_T^{\sin(2\phi-\phi_S)}$: Boer-Mulders(π) $\otimes$ transversity(p)

COMPASS Drell-Yan data

In 2015 COMPASS made its first polarized Drell-Yan measurement

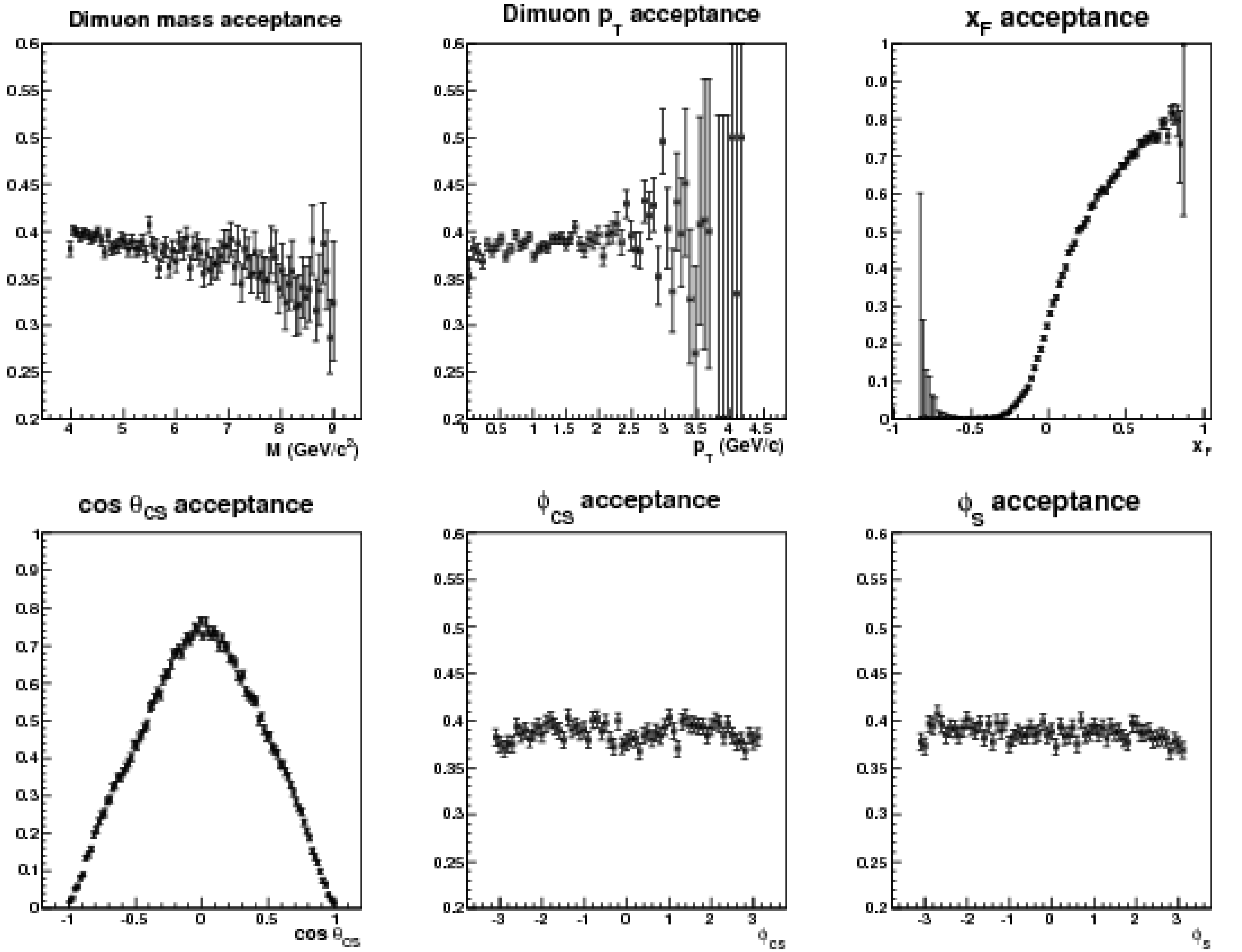
- 106 days of physics data-taking
- Target transverse spin configuration reversed every 2 weeks
- Transverse spin configuration kept by a 0.6T dipole field – relaxation time of $\approx$ 1000 hours





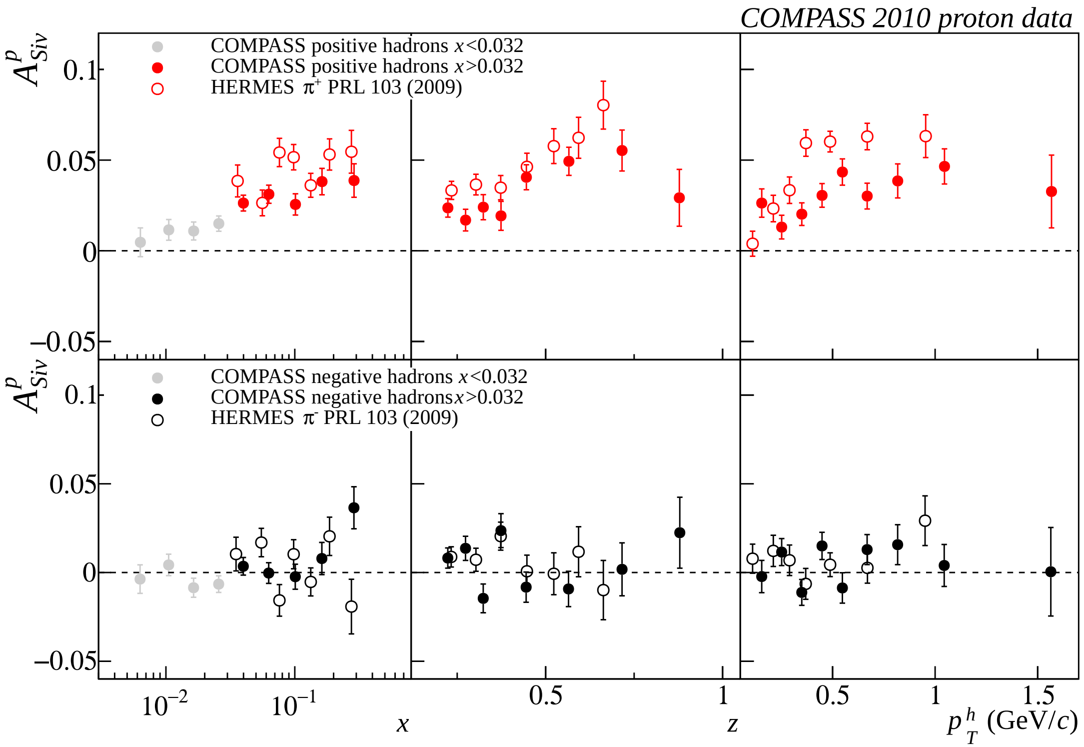
Geometrical acceptance

Global geometrical acceptance for muon pairs with $4 < M_{\mu\mu} < 9$ GeV/c^2: 39%



Sivers in SIDIS @ COMPASS

↪ See Anna Martin talk, tuesday afternoon session



The Sivers asymmetry A^p_{Siv} in SIDIS was measured by COMPASS using a transversely polarized proton target:

- positive asymmetry for h^+, compatible with zero for h^-
- asymmetry measured in COMPASS is smaller than the one from HERMES

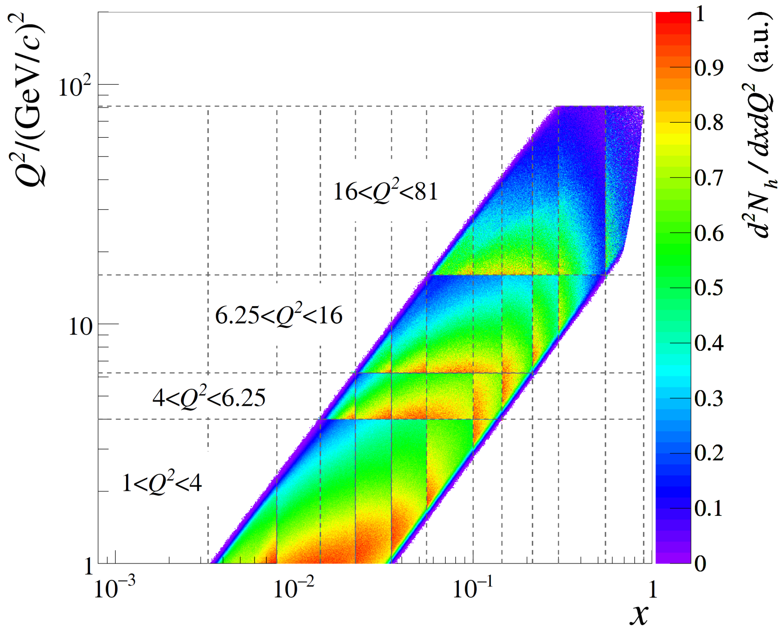
COMPASS, Phys.Lett.B 717 (2012); HERMES, Phys.Rev.Lett. 103 (2009)

The systematic difference between the 2 experiments could result from **scale dependence of the TMDs**
(factor 2-3 between COMPASS and HERMES average Q^2).

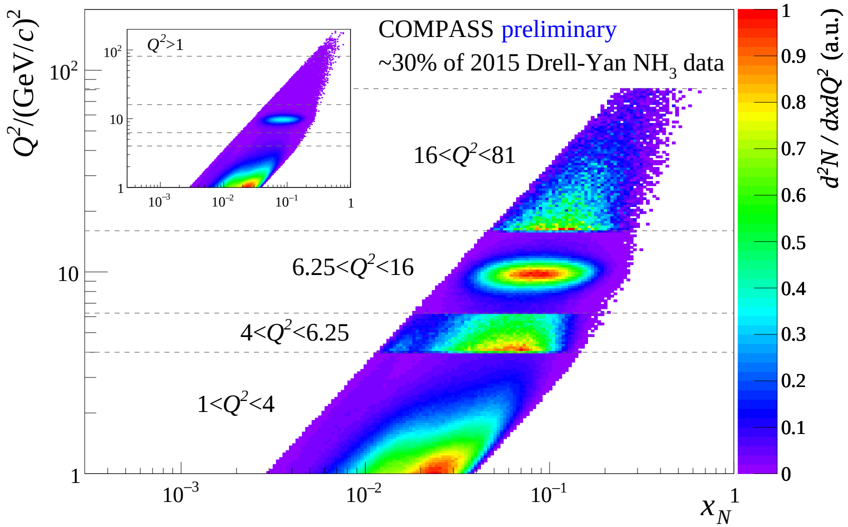
Common phase-space SIDIS – DY

4 Q^2 ranges were chosen to analyse the SIDIS data, which correspond in DY to distinct regions in terms of physics content. In the Q^2 versus x of the 2 measurements, this is:

SIDIS

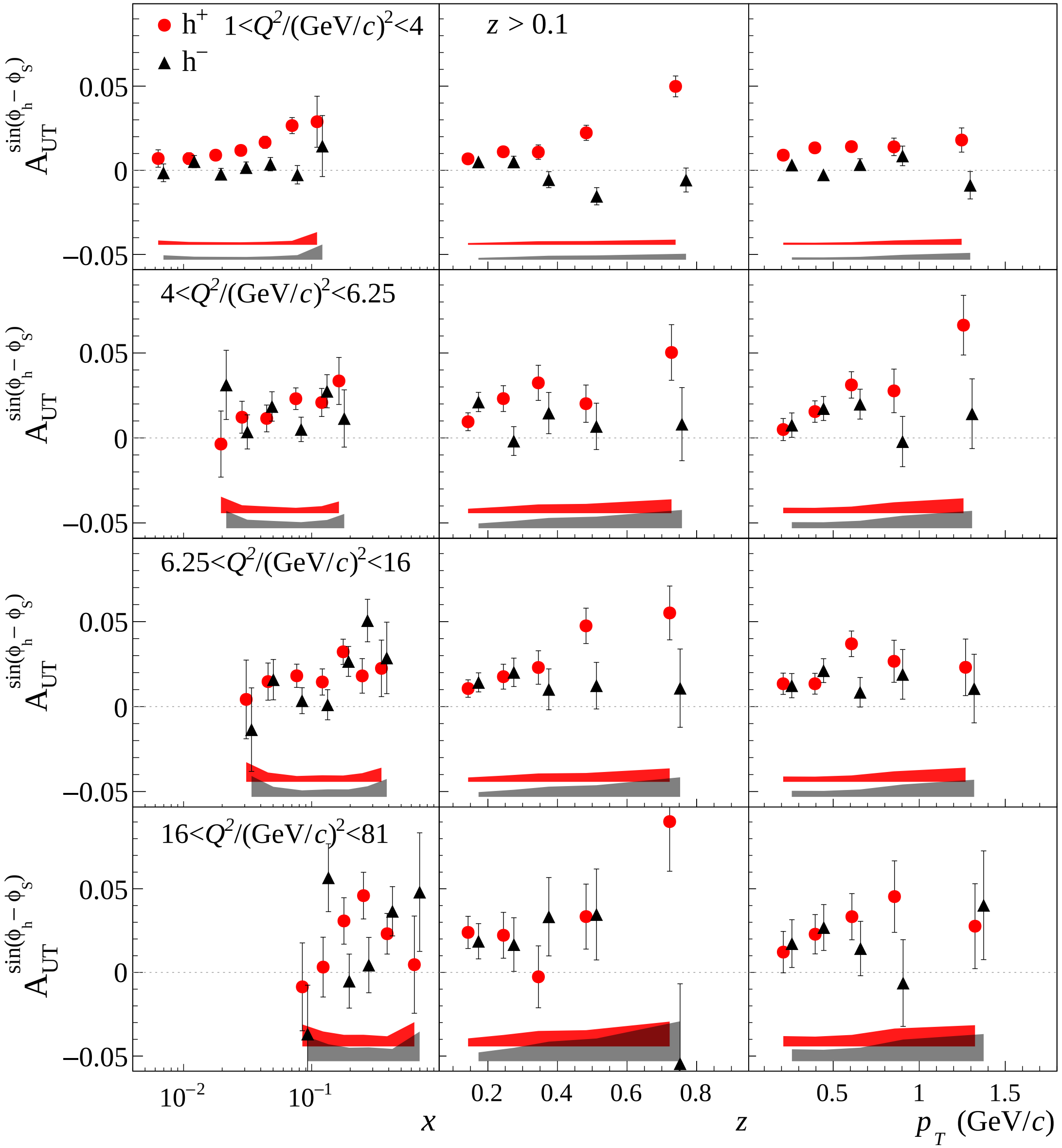


DY



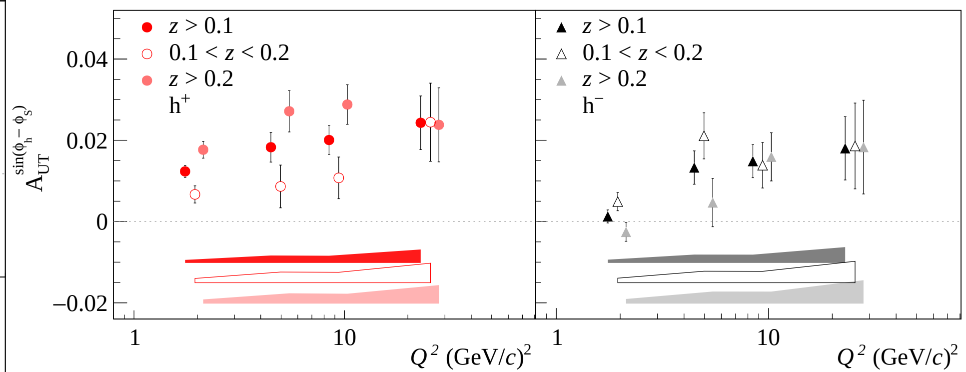
CERN-EP-2016-260; arXiv:1609.07374 [hep-ex]

SIDIS Sivers TSA in DY mass ranges

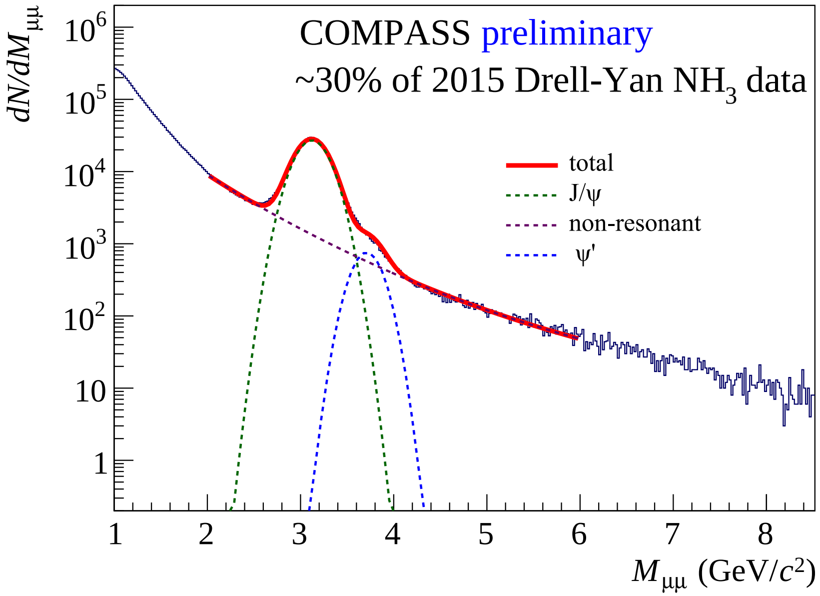


CERN-EP-2016-260;
arXiv:1609.07374 [hep-ex]

Clear Sivers signal also in the highest Q^2 bin.



Dimuon mass ranges

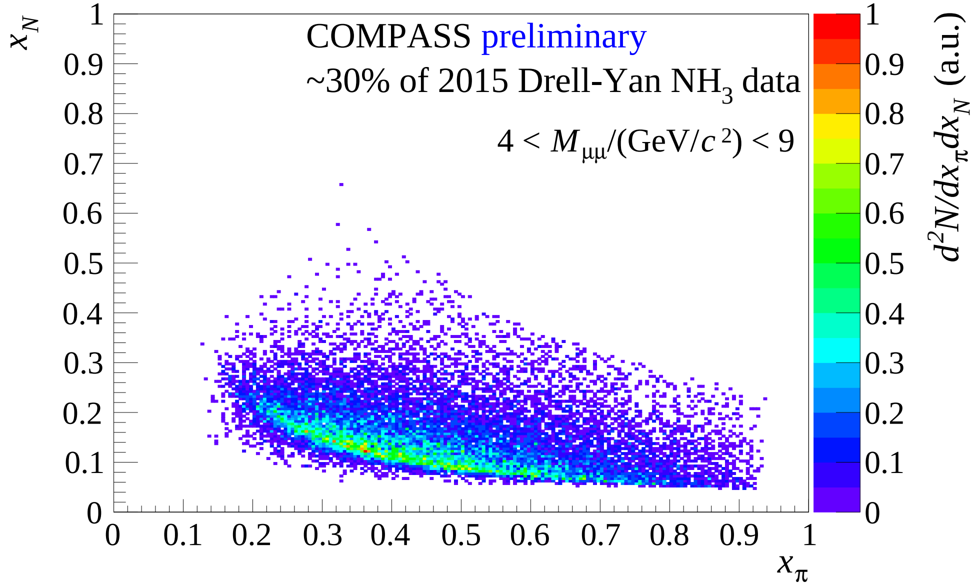


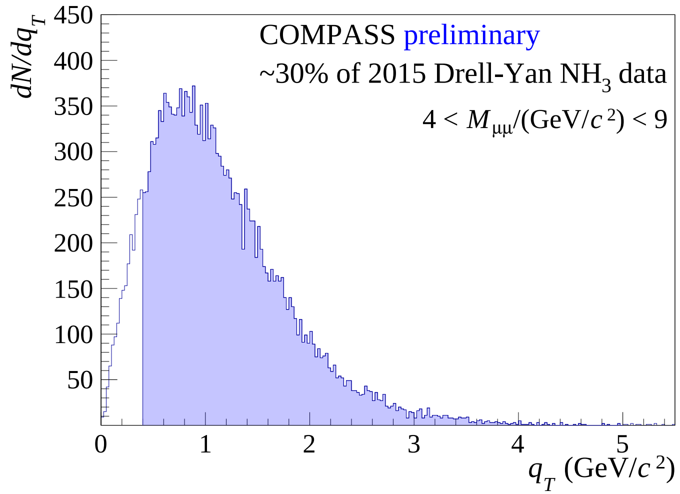
The Q^2 ranges defined for the SIDIS analysis are motivated by the physics contents in each of the DY $Q \equiv M_{\mu\mu}$ regions:

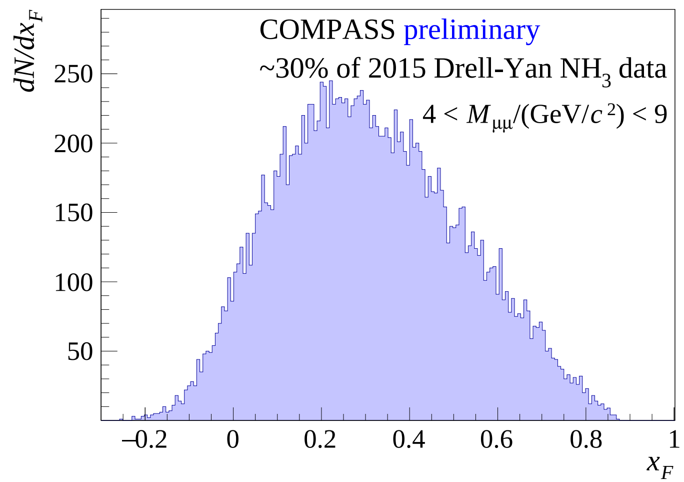
- $1 < M_{\mu\mu}/(GeV/c^2) < 2$: mix of ϕ and ρ meson tail, open charm decays, combinatorial background (uncorrelated muons) and Drell-Yan;
- $2 < M_{\mu\mu}/(GeV/c^2) < 2.5$: open charm, combinatorial background and DY;
- $2.5 < M_{\mu\mu}/(GeV/c^2) < 4$: J/$\psi$ and ψ', also DY, some open charm and combinatorial background;
- $4 < M_{\mu\mu}/(GeV/c^2) < 9$: DY dominated, also small contribution from meson tails ($< 10\%$)

Kinematical distributions (NH_3)

π^- induced DY

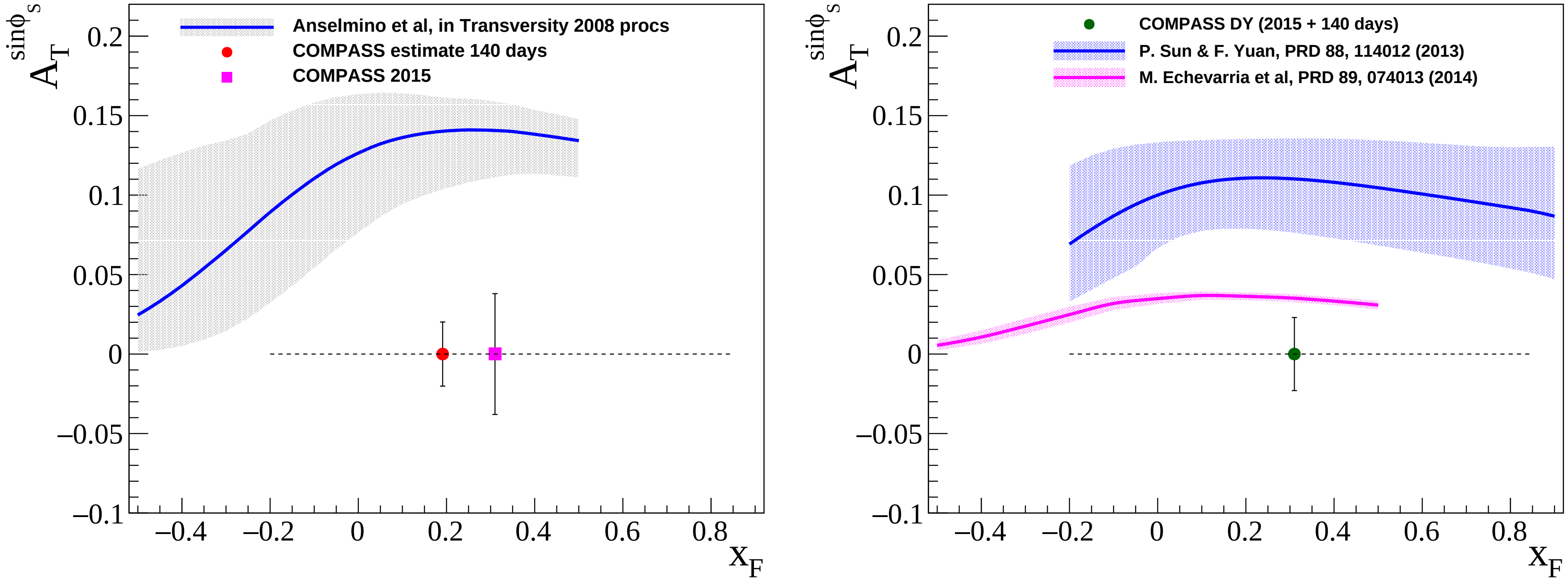






Measurement in the valence quarks region – where asymmetries are also expected to be larger.

Drell-Yan Sivers – estimates

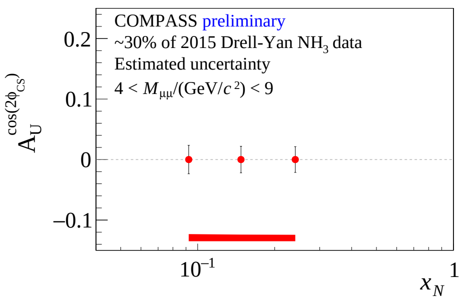


- 2015 data: statistical error of the Sivers asymmetry measurement is 4%
- Systematic error estimated smaller than the statistical one
- Enough statistics to distinguish between most extreme predictions
- One additional year of data needed to see kinematical dependencies

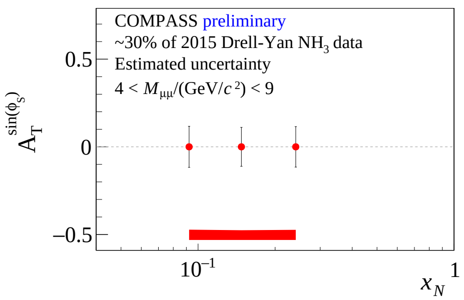
Drell-Yan TSAs – statistical precision

- Spin orientation in the cells reversed every 2 weeks for cancellation of acceptance effects.
- Quality cuts applied to guarantee the stability of the spectrometer for the data analysed
- Event selection includes muon identification, target region cuts, trigger validation, rejection of muons from pion beam decays.
- Restrict to the range where there is good angular resolution (low p_T cut)

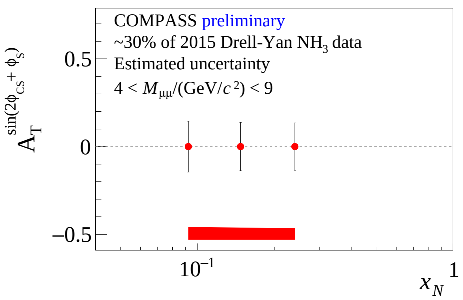
All 4 leading-twist asymmetries are extracted simultaneously, using an unbinned maximum likelihood method. Statistical accuracy:



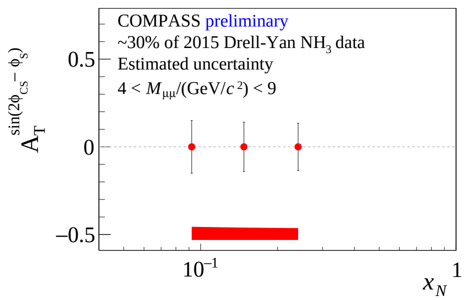
Boer-Mulders



Sivers



pretzelosity



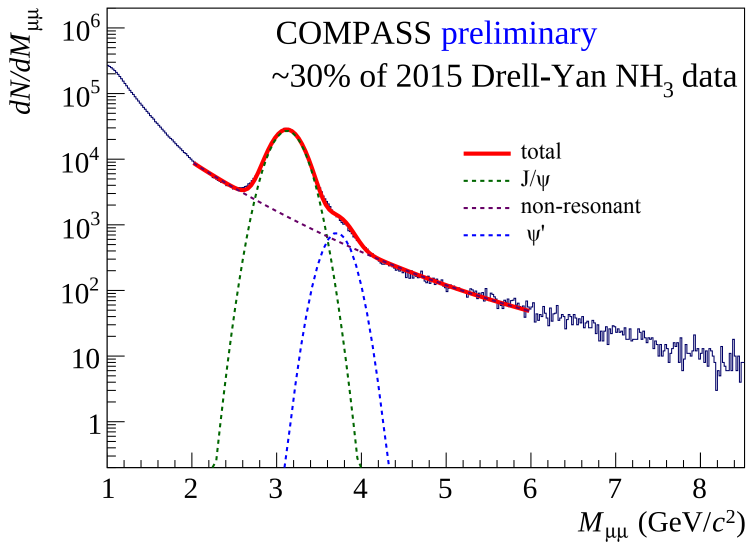
transversity

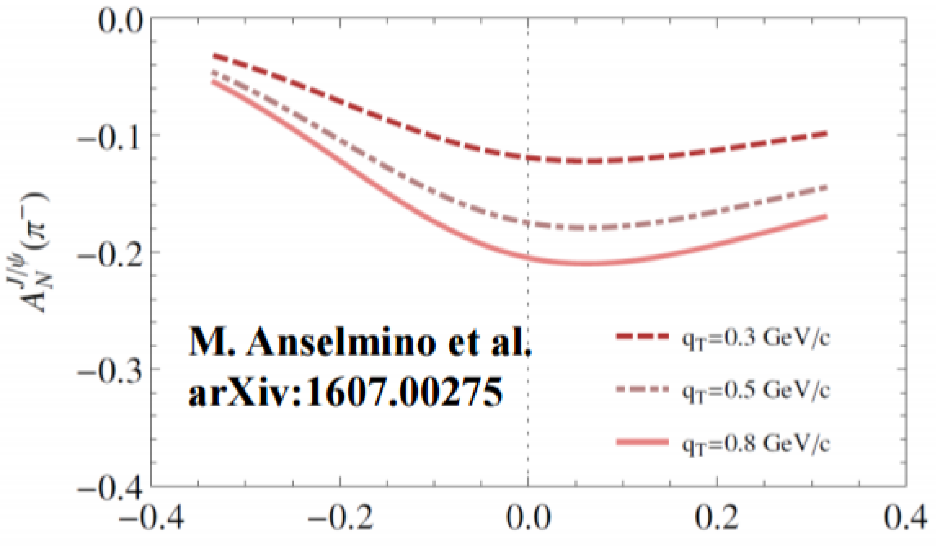
Dimuons J/ψ mass range

$\approx 50\times$ more statistics than in the high mass DY range.

At COMPASS energies, $q\bar{q}$ annihilation is believed to be the dominant mechanism of J/ψ production.

$\hookrightarrow$ access to quark Sivers (u-quark dominance) from J/ψ





Unpolarized Drell-Yan

If we now concentrate on the **unpolarized part**, at twist-3 the Drell-Yan cross-section is:

$$\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U \Big\{ (1 + A_U^1 \cos^2\theta + \sin 2\theta A_U^{\cos\phi}\cos\phi + \sin^2\theta A_U^{\cos 2\phi}\cos 2\phi$$

$$+ |\vec{S}_T| \Big((A_T^{\sin\phi_S} + \cos^2\theta \tilde{A}_T^{\sin\phi_S})\sin\phi_S$$

$$+ \sin 2\theta \left(A_T^{\sin(\phi+\phi_S)}\sin(\phi+\phi_S) + A_T^{\sin(\phi-\phi_S)}\sin(\phi-\phi_S)\right)$$

$$+ \sin^2\theta \left(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S) + A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\right)\Big)\Big\}$$

Past unpolarized Drell-Yan experiments (back in the '80s) named the modulation amplitudes: $\boxed{\lambda = A_U^1}$; $\boxed{\mu = A_U^{\cos\phi}}$; $\boxed{\nu/2 = A_U^{\cos 2\phi}}$.

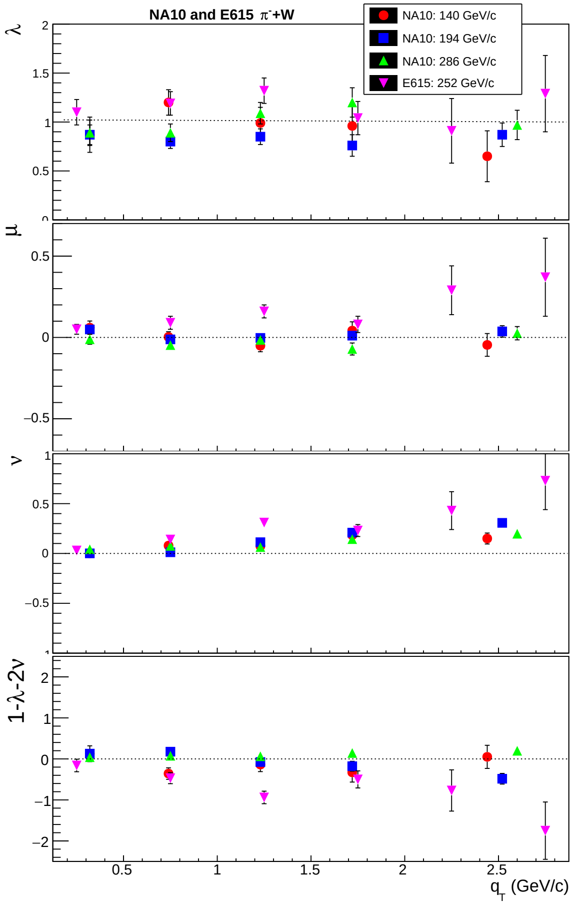
$\hookrightarrow$ Boer-mulders

Lam-Tung sum rule

The Lam-Tung relation, deriving from the fermion nature of quarks, predicts:

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

In the naive Drell-Yan model, where partons $k_T = 0$: $\lambda = 1$, $\mu = \nu = 0$.



NA10 at CERN: π^- beam of 140, 194 and 286 GeV/c on W target; also 140 and 286 GeV π^- beam on D.

E615 at Fermilab: π^- beam of 252 GeV/c on W target.

- Strong $\cos 2\phi$ modulation increasing with q_T, seen by both
- Lam-Tung relation violated in E615, not so clear in NA10 data
- Recently: ATLAS and CMS see clear Lam-Tung violation. Is its origin the same?

NA10,Z.Phys.C37,545(1988); E615,Phys.Rev.D39,92(1989); E866, CDF, ATLAS, CMS, ...

Lam-Tung measurement in COMPASS

Contrary to TSAs, the extraction of λ, μ and ν parameters requires the detailed knowledge of COMPASS acceptance.

The multidimensional acceptance of COMPASS is being evaluated with:

- Tuned Pythia generator together with a GEANT 4 full simulation of the COMPASS detector
- 2D efficiencies of the detector planes included
- Same reconstruction criteria as for real data

The Boer-Mulders related asymmetry corrected for acceptance and smearing effects can be evaluated from 2014 data (16 effective days) and 2015 data (106 effective days) with good statistical accuracy.

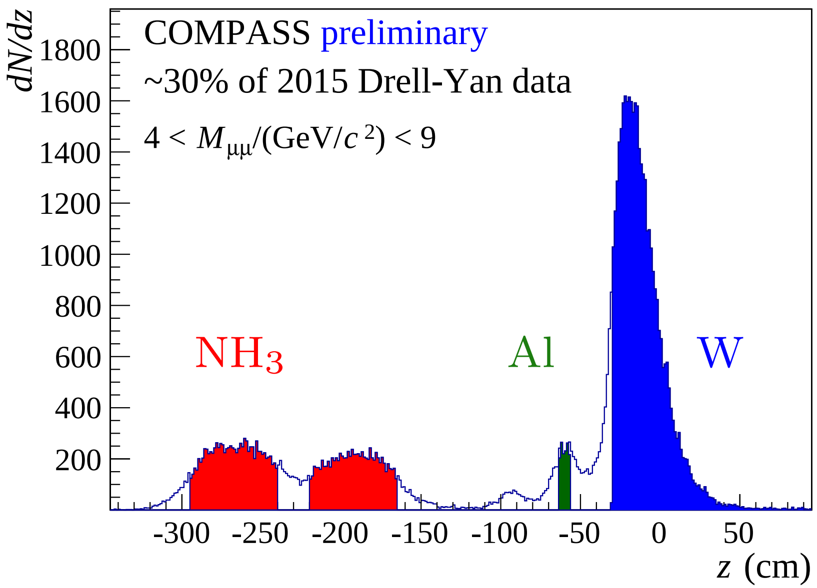
Separately extracted for the 3 targets: NH_3, W and Al – nuclear effects may become visible.

EMC effect from Drell-Yan

EMC effect: the modification of the PDFs when in nuclei. The first experimental evidence was measured by EMC@CERN, a DIS experiment.

The EMC quark flavor dependence can be investigated with pion induced Drell-Yan processes (first were NA3 and NA10 experiments).

$$\frac{\sigma_{DY}(\pi^- + A)}{\sigma_{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)} \quad ; \quad \frac{D_{DY}(\pi^- + A)}{\sigma_{DY}(\pi^- + H)} \approx \frac{u_A(x)}{u_p(x)}$$



Future Drell-Yan measurements at COMPASS

COMPASS request to continue the polarized Drell-Yan measurement in **2018**, with goals:

- Increase the statistical accuracy for π^- induced Drell-Yan in a transversely polarized NH_3 target – TSAs dependencies measurement
- Increase statistics for the measurement of unpolarized effects
- First extraction of kaon TMD PDFs, using the 2.5% K in the beam (requires CEDARs for π/K/p separation)

π^-	K^-	$\bar{p}$
97%	2.5%	<1%

★ Longer term plans include the Boer-Mulders asymmetry measurement from a long liquid hydrogen target; as well as a radio-frequency separated beam enriched in kaons and antiprotons, for TMD PDFs extraction.

Conclusions

- The COMPASS semi-inclusive DIS results from transversely polarized target have been of key importance for the extraction of TMD PDFs.
- In 2015 COMPASS made the first transversely polarized Drell-Yan measurement, with same target and spectrometer.
- These complementary measurements will allow to check the predicted sign change of the Sivers and Boer-Mulders asymmetries, between SIDIS and DY processes.
- More COMPASS polarized Drell-Yan data may be taken in 2018.
- The TSA results from COMPASS 2015 Drell-Yan data are expected soon.