













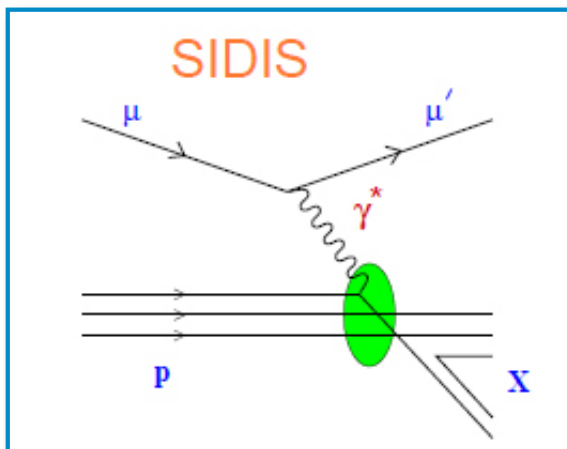




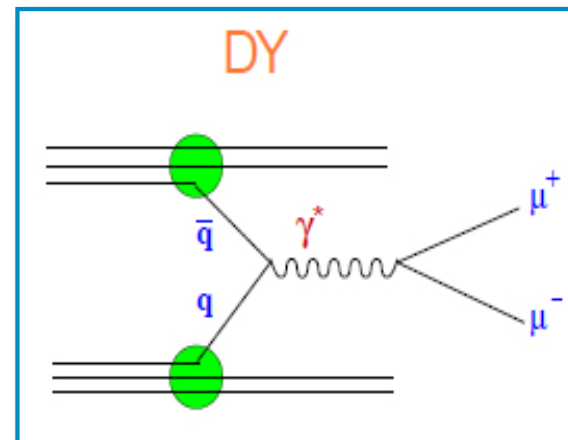
# Single polarized Drell-Yan

- Transversity and TMD PDFs
- TMDs universality
- J/ $\psi$ -Drell-Yan duality

TMD PDFs, like Sivers, can be accessed both from semi-inclusive DIS (SIDIS) and from the Drell-Yan process (DY).



the amplitudes of azimuthal modulations are convolutions of PDFs and FFs



the amplitudes of azimuthal modulations are convolutions of PDFs only

# Single polarized Drell-Yan

In a recent paper Arnold, Metz and Schlegel derived the full expression of the Drell-Yan cross-section, including unpolarized, transversely and longitudinally polarized terms [S. Arnold et al, Phys.Rev. D79 (2009)034005].

In single polarized DY, with transversely polarized target nucleons, the general expression of the cross-section (LO) is:

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

A: azimuthal asymmetries; D: depolarization factor; S: target spin components; F: flux of incoming hadrons;  $\sigma_U$ : part of the cross-section surviving integration over  $\phi$  and  $\phi_S$

$\phi_S$ : azimuthal angle of transverse target spin  $S_T$  in the target rest frame  
 $\phi$ : azimuthal angle of the lepton momenta in the Collins-Soper frame



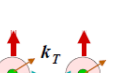






# Single Polarized Drell-Yan

$A_U^{\cos 2\phi}$  gives access to the Boer-Mulders functions of the incoming hadrons

$A_T^{\sin\phi_S}$  to the Sivers function of the target nucleon

$A_T^{\sin(2\phi+\phi_S)}$  to the Boer-Mulders function of the beam hadron and to the pretzelocity function of the target nucleon

$A_T^{\sin(2\phi-\phi_S)}$  to the Boer-Mulders function of the beam hadron and to the transversity function of the target nucleon

		NUCLEON		
		unpolarized	longitudinally pol.	transversely pol.
QUARK	unpolarized	$f_1$  number density		$f_{1T}^+$  Sivers
	longitudinally pol.		$g_{1L}$  helicity	$g_{1T}$  pretzelocity
	transversely pol. longitudinally pol.	$h_1^+$  Boer-Mulders	$h_{1L}^+$ 	$h_1$  transversity
	transversely pol. transversely pol.		$h_{1T}^+$ 	$h_{1T}$  pretzelocity

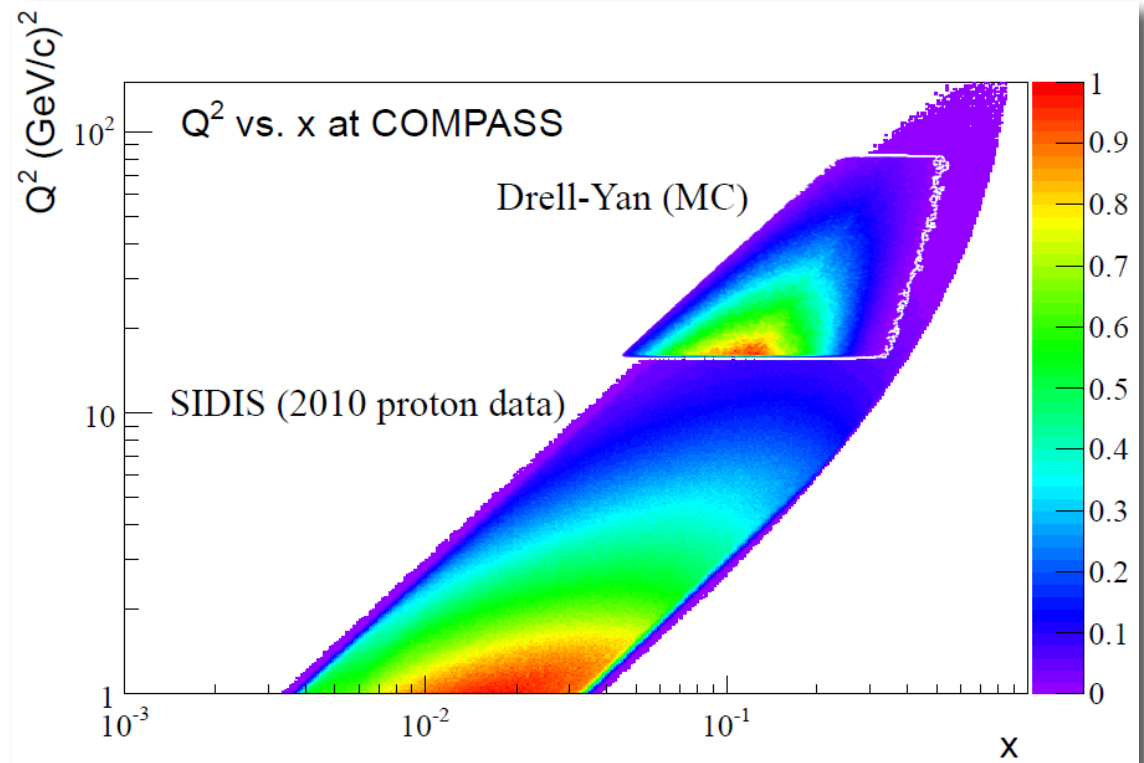
# DY vs SIDIS

Change of sign of Sivers and Boer-Mulders functions?

$$f_{1T}^{\perp}|_{DY} = -f_{1T}^{\perp}|_{DIS} \quad \text{and} \quad h_1^{\perp}|_{DY} = -h_1^{\perp}|_{DIS}$$

Critical test of universality of TMD factorization approach for the description of SSA.

In COMPASS, we have the opportunity to test this sign change using the same spectrometer and a transversely polarized target.



# J/Ψ-DY duality

In spite of the large amount of experimental data on J/ψ production in various reaction, the production mechanism is still unclear.

J/Ψ-DY duality → model based on close analogy between Drell-Yan and J/Ψ production mechanism: occurs when the gluon-gluon fusion mechanism of the J/Ψ production is dominated by the q-q annihilation mechanism

$$\pi^- p^\uparrow \rightarrow J/\psi X \rightarrow \mu^+ \mu^- X$$

$$\pi^- p^\uparrow \rightarrow \gamma^* X \rightarrow \mu^+ \mu^- X$$

From the study of J/ψ production in the dileptons decay channel:

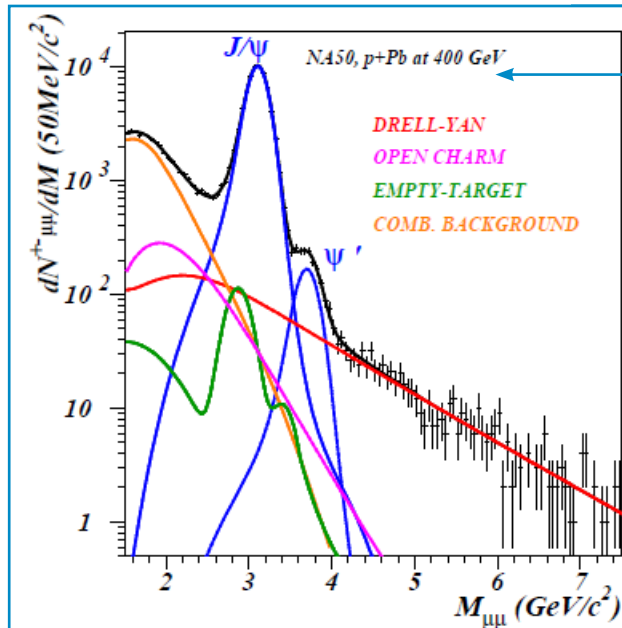
- Check duality hypothesis – polarized J/ψ production cross-section
- Access PDFs from J/ψ events – larger statistics available

# Polarized Drell-Yan experiments

## What do we need to access spin dependent PDFs through DY?

Polarized Drell-Yan experiments:

- High luminosity (DY Cross Section is a fraction of nanobarns) and large angular acceptance
- Sufficiently high energy to access 'safe' background free M range ( $4 \text{ GeV}/c^2 < M_{\mu\mu} < 9 \text{ GeV}/c^2$ )
- Good acceptance in the valence quark range
- Good figure of merit (FoM), which can be represented as a product of the luminosity, target polarisation (dilution factor f) and beam (target) polarisation



NA50: p @ 400 GeV/c in a Pb target; I about  $10^9$  particles/sec

Even if the cross-section is low, M range  $4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$  is the ideal sample to study azimuthal asymmetries in Drell-Yan, due to negligible background contamination.

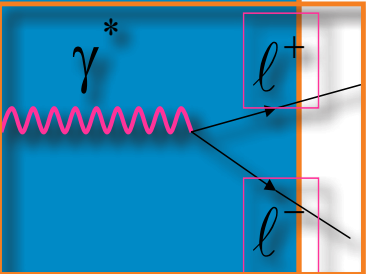
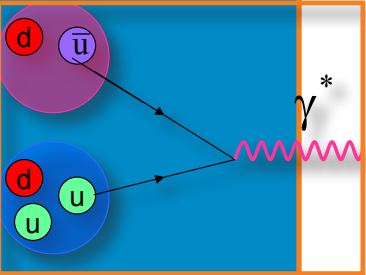
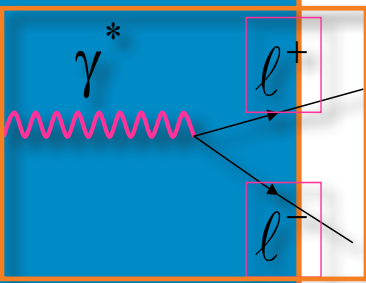
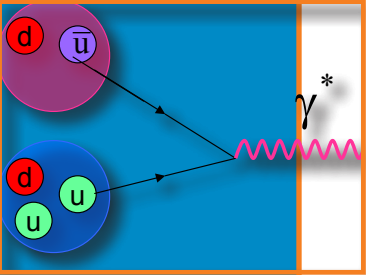
The combinatorial background is kept under control by the presence of a hadron absorber downstream of the target.

@ COMPASS:  $\pi^-$  @ 190 GeV/c in a  $\text{NH}_3$  target; I up to  $10^8$  particles/sec:

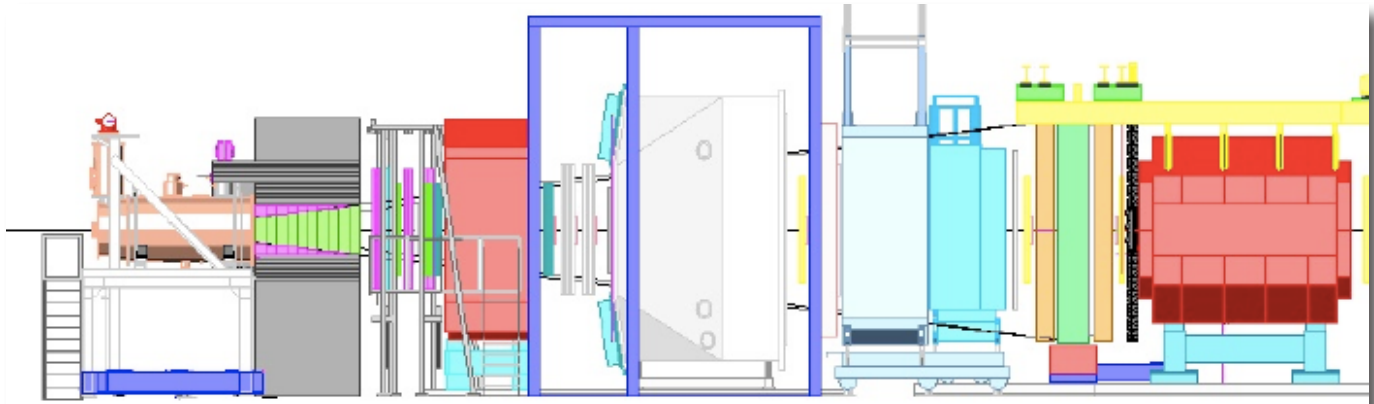
comb. background 100 times lower (50% of total in intermediate M range  $2. < M_{\mu\mu} < 2.5 \text{ GeV}/c^2$ )

open charm contributes only at 15%

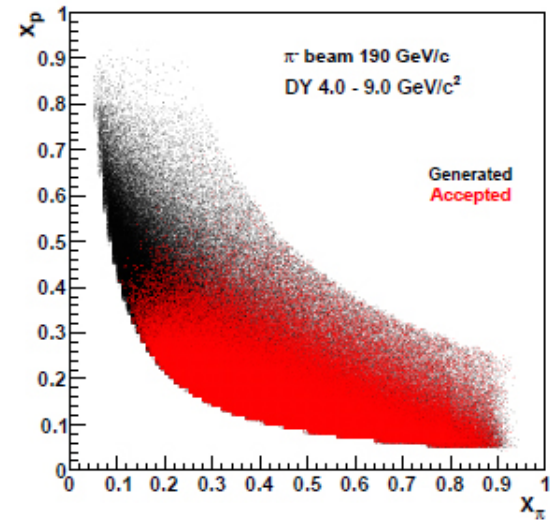
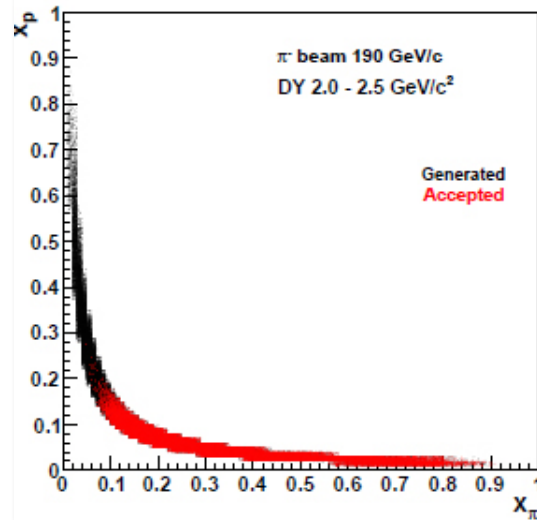
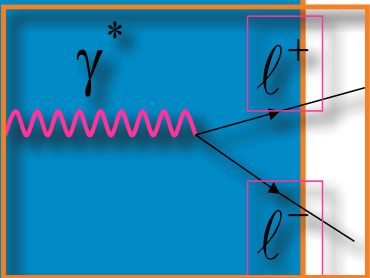
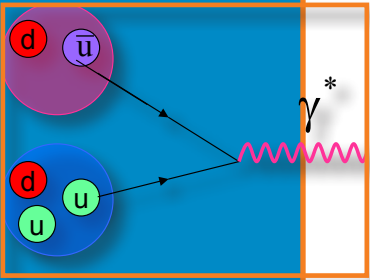
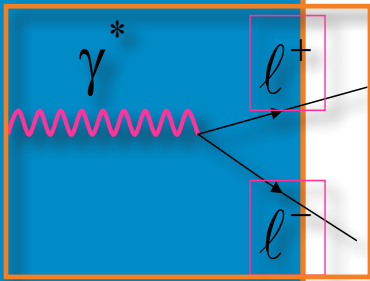
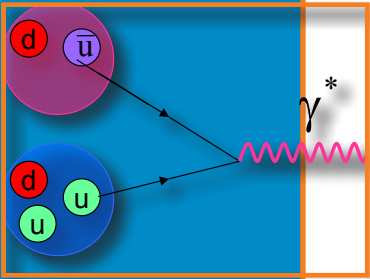
# Drell-Yan @ COMPASS-II



- Large angular acceptance spectrometer
- $\pi^-$  beam at 190 GeV/c with the intensity up to  $1 \times 10^8$  particles/second
- Large acceptance COMPASS Superconducting Solenoid Magnet
- Transversely polarized  $\text{NH}_3$  target working in frozen spin mode with long relaxation time
- Hadron absorber downstream of the target
- A detection system designed to stand relatively high particle fluxes
- A Data Acquisition System (DAQ) that can handle large amounts of data at large trigger rates
- Trigger based on hodoscope signals coincidence, homothetic and pointing to the target

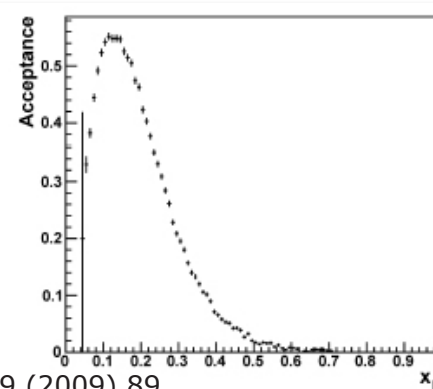
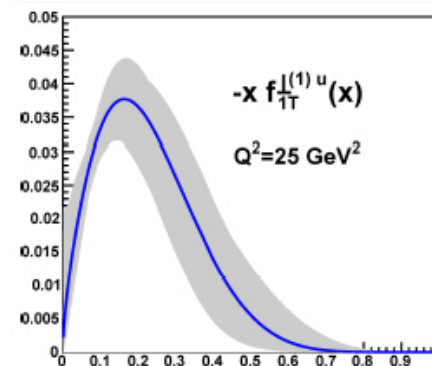


# COMPASS-II DY Acceptance



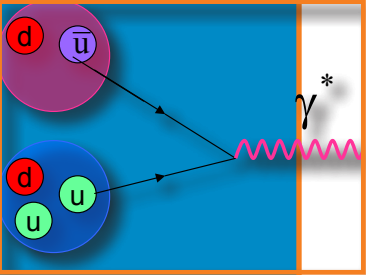
COMPASS acceptance is in the valence quarks region

For  $DY$  4 <  $M_{\mu\mu}$  < 9 GeV/c<sup>2</sup>, we have  $x_p > 0.05$  --> also the best region to measure spin asymmetries



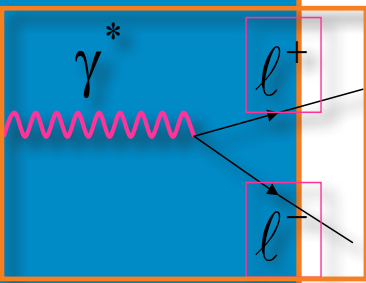
M. Anselmino et al., Eur. Phys. J. A39 (2009) 89.

# Drell-Yan @ COMPASS-II: Feasibility



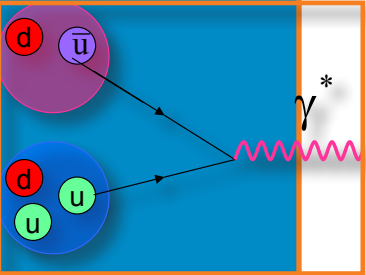
In 2007, 2008 and 2009 short Drell-Yan beam tests were performed, to check the feasibility of the measurement

In 2007, with a  $\pi^-$  beam of 160 GeV/c on a  $\text{NH}_3$  target, and without hadron absorber:  $\approx 90000$  dimuon events ( $< 12$  hours data-taking)

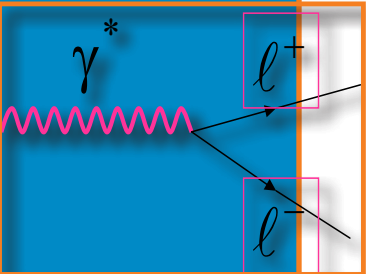


In 2008 a second beam test was performed, also with an open configuration of the spectrometer, a  $\pi^-$  beam of 190 GeV/c, and a polyethylene target

- The target temperature does not seem to increase significantly with the hadron beam, long polarization relaxation times measured (2007 beam test)

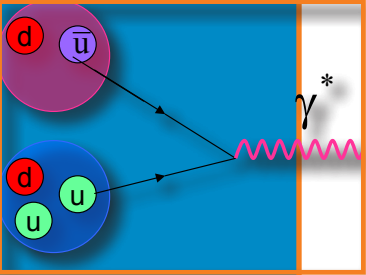


- Reasonable occupancies in the detectors closer to the target can only be achieved if a hadron absorber and beam plug is used (2008 beam test)

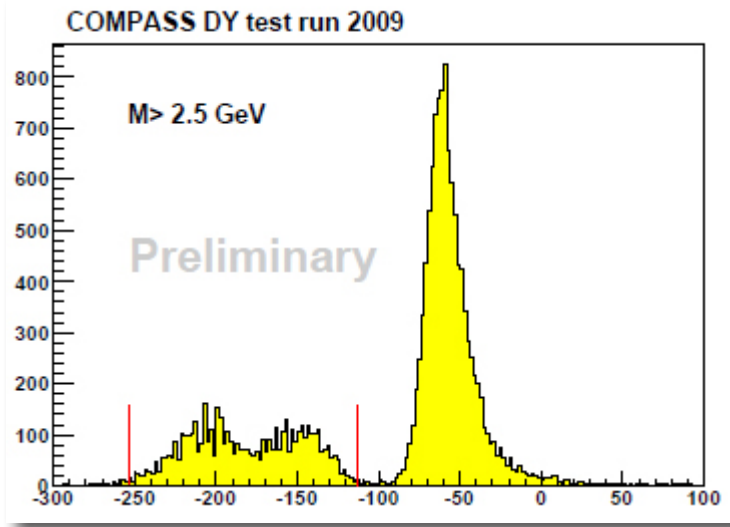
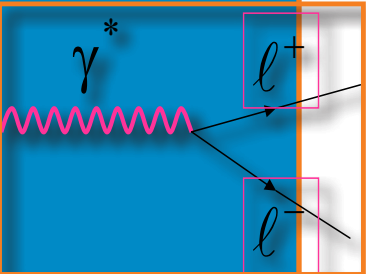
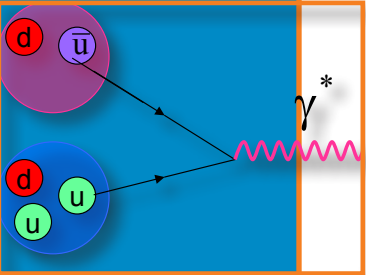
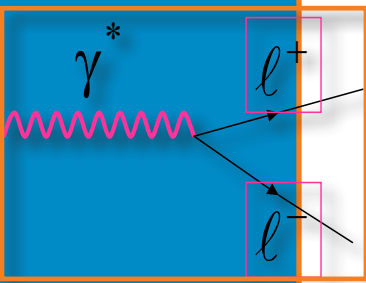


- Physics simulation were validated, within statistical errors ( $J/\psi$  peak and combinatorial background, in 2007 and 2009 beam tests)

# Beam test 2009

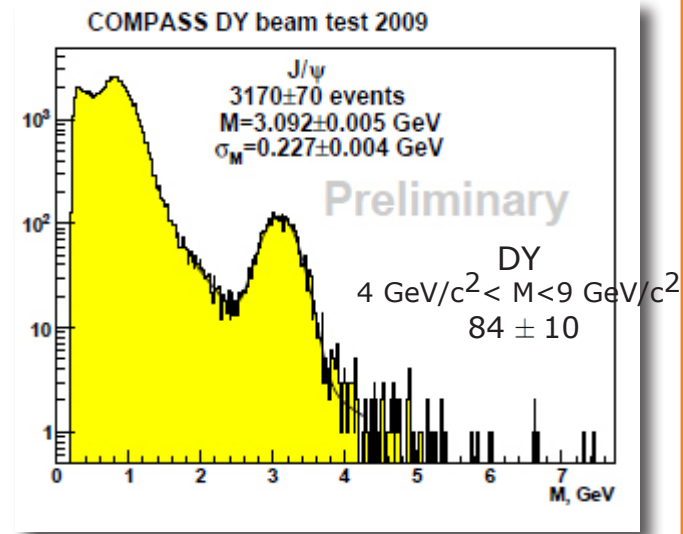


$\pi^-$  beam of 160 GeV/c on 2-cells polyethylene target. Setup including hadron absorber and a beam plug (3 days of data-taking)



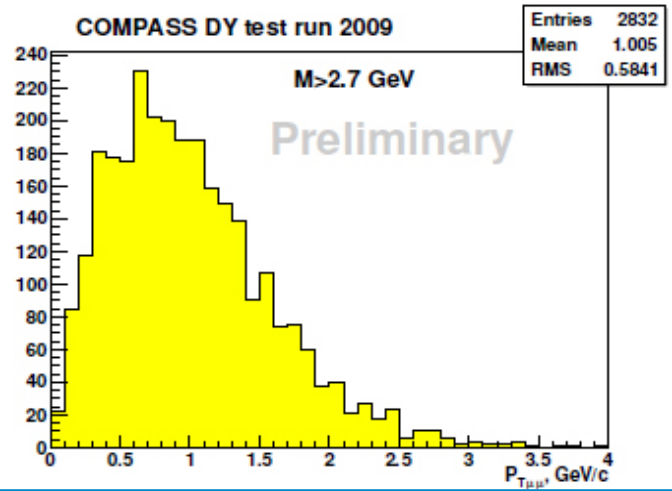
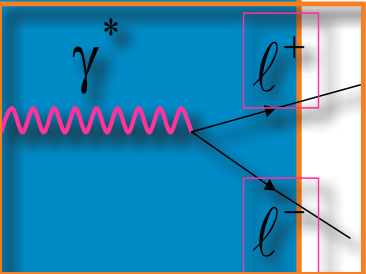
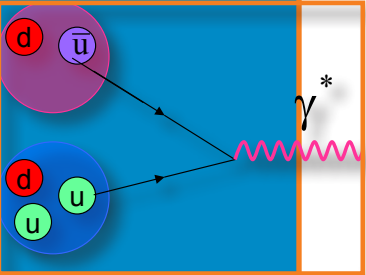
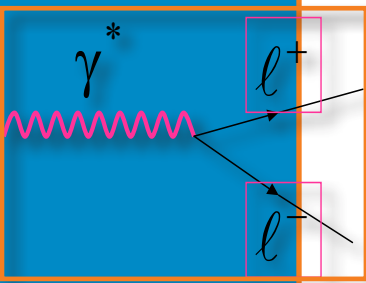
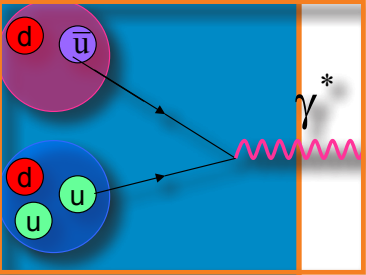
Reasonable Zvertex separation, allowing to distinguish the 2 target cells and the absorber

Data taken without the optimised dimuon trigger with target pointing capability

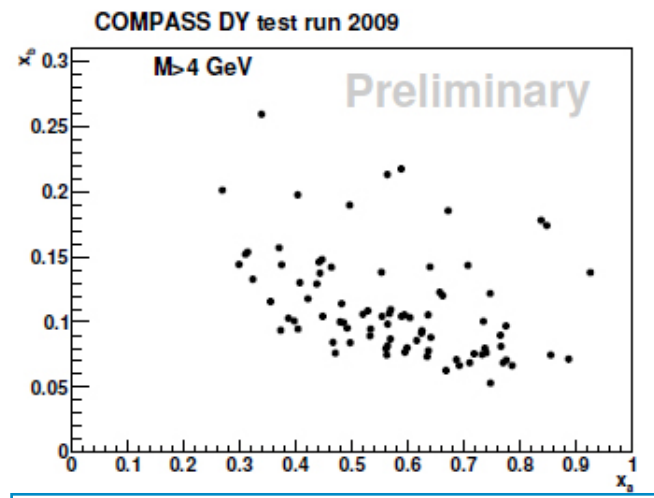


The expected number of  $J/\Psi$  and DY events from Monte-Carlo was confirmed:  
 expected  $J/\Psi$ : 3600  $\pm$  600  
 expected DY events ( $4 \text{ GeV}/c^2 < M < 9 \text{ GeV}/c^2$ ): 110  $\pm$  22

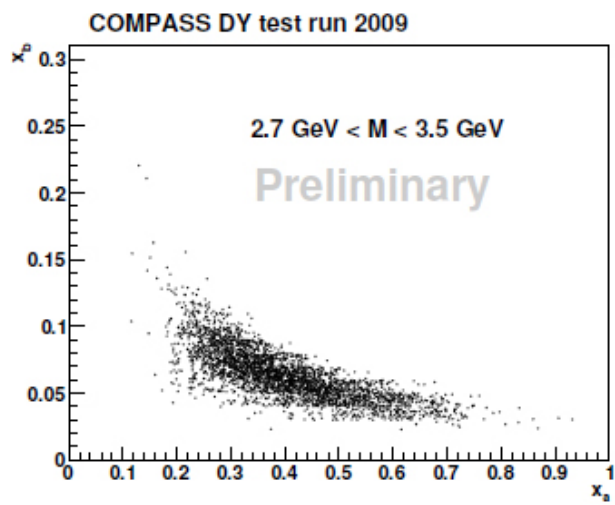
# Beam test 2009



The mean value of  $p_T$  is about 1 GeV/c. This makes Compass sensitive to TMDs, which are expected to be accessible up to  $p_T = 2 \text{ GeV}/c$ .

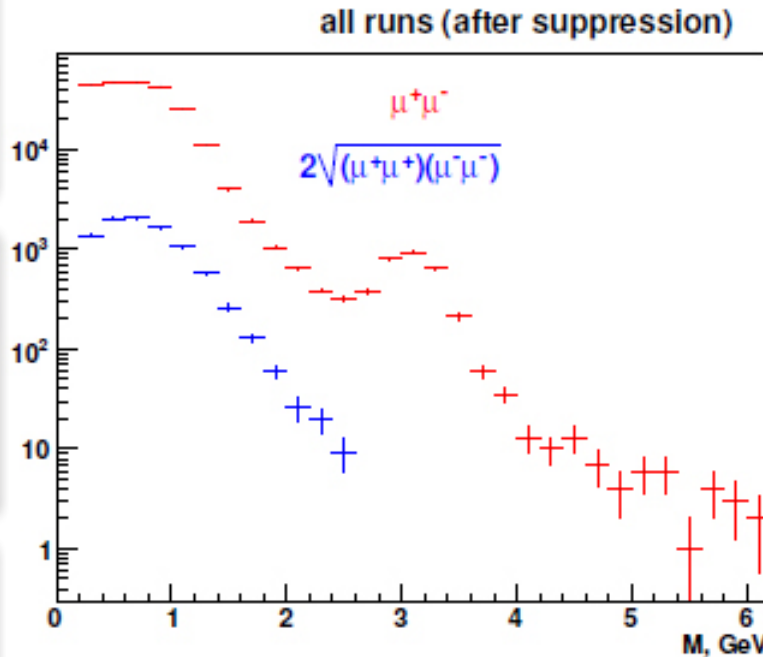
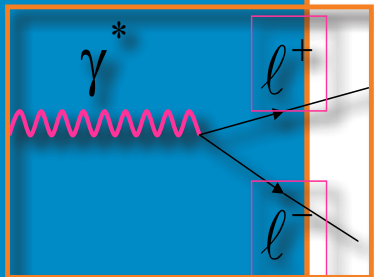
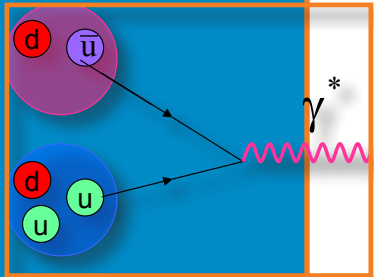
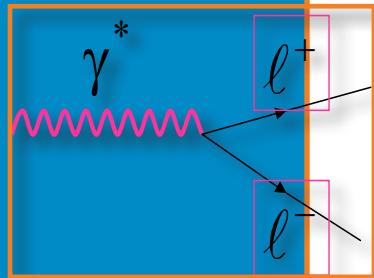
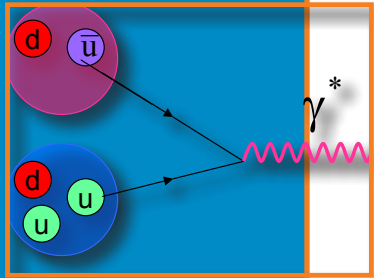


In the high mass range of the dimuon,  $M_{\mu\mu} > 4 \text{ GeV}/c$ , both annihilating quarks belong to the valence quark range



In case of the  $J/\psi$  the contribution of valence quarks is also dominant

# Beam test 2009



- 4.  $< M_{\mu\mu} < 9$ . GeV/ $c^2$  (HMR): clean DY signal
- 2.  $< M_{\mu\mu} < 2.5$  GeV/ $c^2$  (IMR): contaminated with:

→ combinatorial background (a contribution that can be subtracted by using the like-sign muon pairs samples),

→ physics background mostly from uncorrelated decays of open-charm mesons (in the IMR:  $N_{D D} / N_{DY} = 0.14$ )

Combinatorial background (from uncorrelated  $\pi$  decays) is estimated using the measured like-sign  $\mu^\pm\mu^\pm$  distributions: the absorber reduces the background by a factor 10 at  $M_{\mu\mu} = 2$  GeV/ $c^2$

# Expected event rates and statistical precision

With a beam intensity of  $I_{\text{beam}} = 6 \times 10^7$  particles/second, a luminosity of  $L = 1.2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  can be obtained

In 280 days one can collect:

250.000 DY events with  $4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$ .

$1.4 \times 10^6$  events DY events with  $2 < M_{\mu\mu} < 2.5 \text{ GeV}/c^2$ .

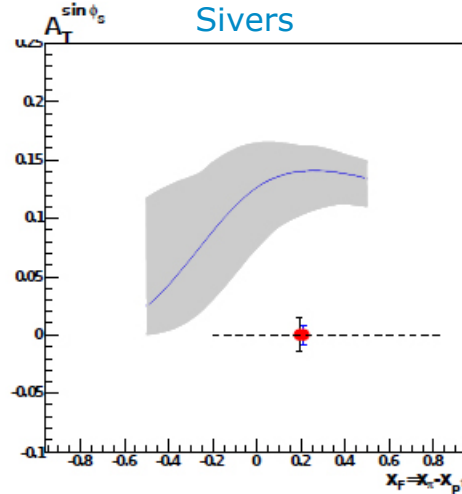
The expected statistical error in the asymmetries is:

Asymmetry	Dimuon mass ( $\text{GeV}/c^2$ )		
	$2 < M_{\mu\mu} < 2.5$	$J/\psi$ region	$4 < M_{\mu\mu} < 9$
$\delta A_U^{\cos 2\phi}$	0.0020	0.0013	0.0045
$\delta A_T^{\sin \phi_S}$	0.0062	0.0040	0.0142
$\delta A_T^{\sin(2\phi + \phi_S)}$	0.0123	0.0080	0.0285
$\delta A_T^{\sin(2\phi - \phi_S)}$	0.0123	0.0080	0.0285

# Asymmetries: comparing with theory prediction

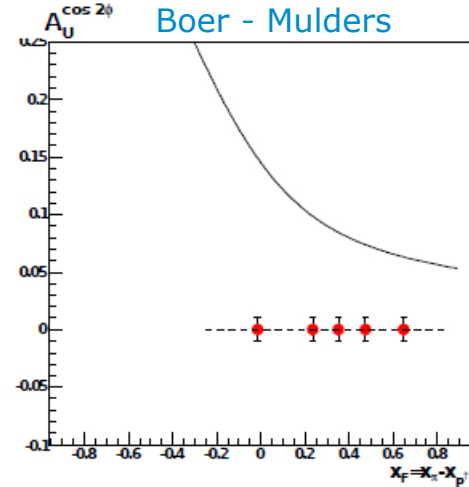
2 years of data taking  
DY 4.-9. GeV/c<sup>2</sup>

Sivers



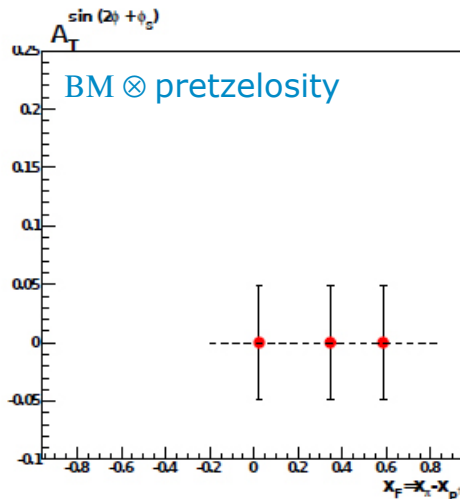
M. Anselmino et al., in Proceedings of Transversity 2008, 2009, ISBN:978-981-4277-77-8, p. 138

Boer - Mulders

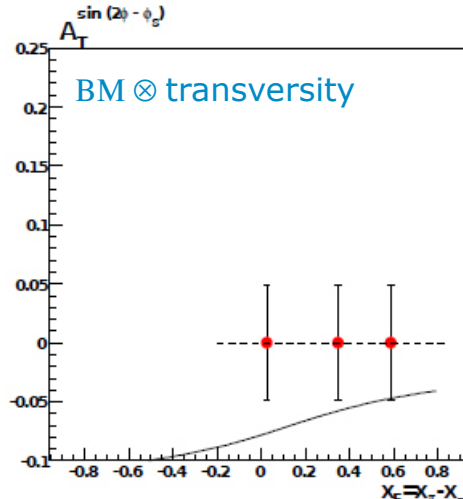


D. Boer, Phys. Rev. D60 (1999) 014012.  
B. Zhang et al., Phys. Rev. D77 (2008) 054011.

BM  $\otimes$  pretzelocity



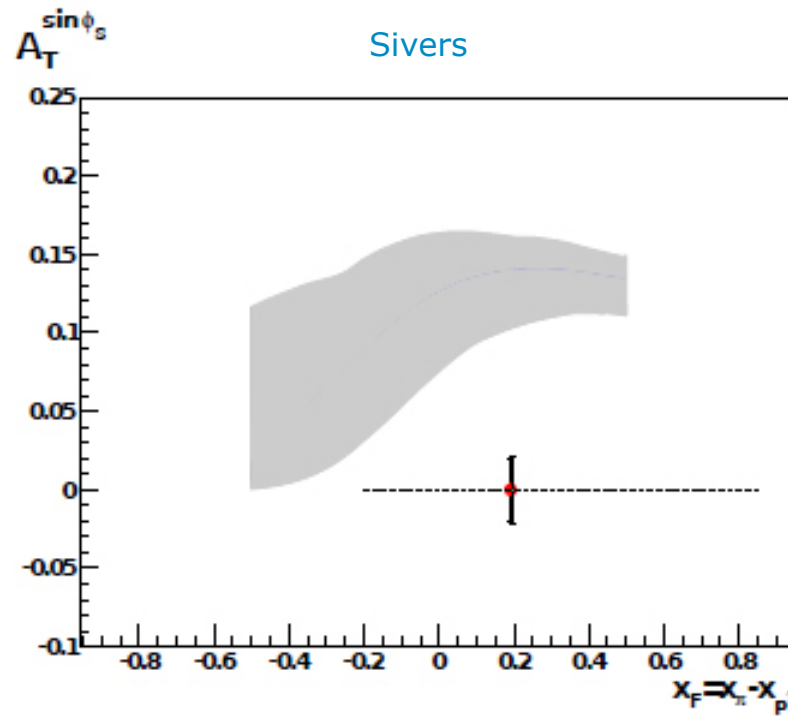
BM  $\otimes$  transversity



V. Barone et al., Phys. Rept. 359 (2002) 1.  
V. Barone et al., Phys. Rev. D56 (1997) 527.

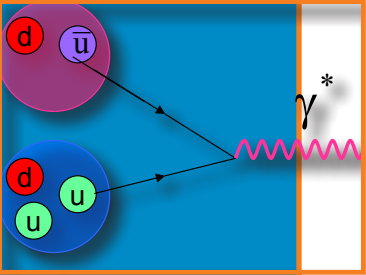
# Asymmetries: comparing with theory prediction

1 year of data taking  
DY 4.-9.  $\text{GeV}/c^2$



M. Anselmino et al.

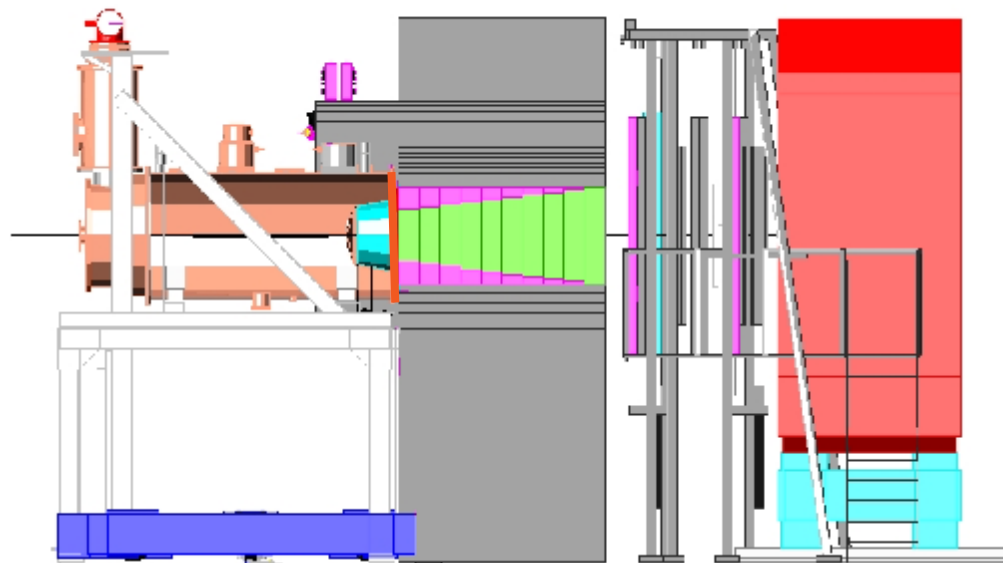
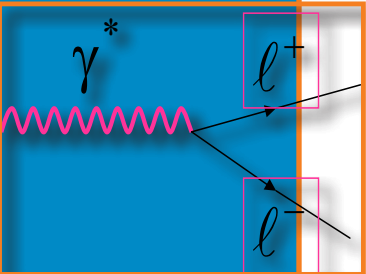
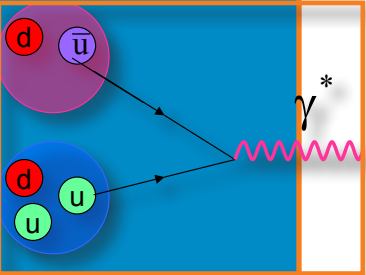
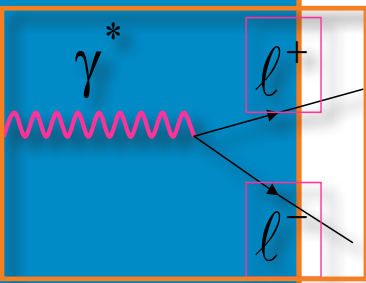
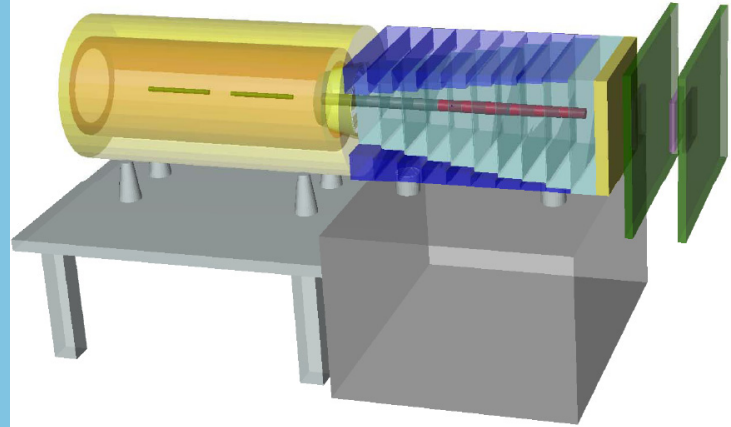
# DY setup: new hardware developments



Two target cells (NH<sub>3</sub>) inside the dipole (55 cm length, 4 cm diameter, spaced by 20 cm)

An absorber 236 cm long, downstream the target

Possibility to place a scintillator fibers detector between target and absorber to improve vertex resolution



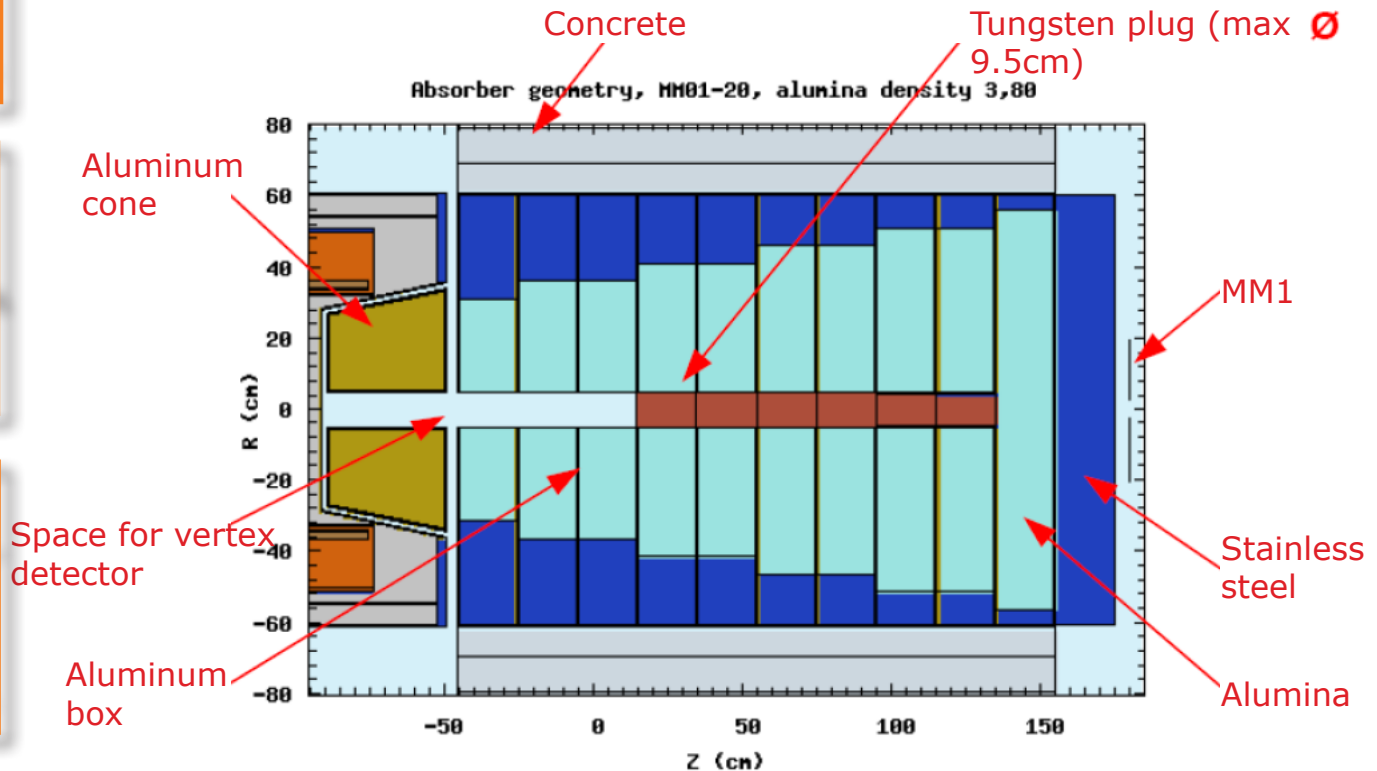
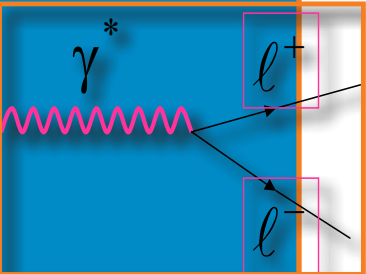
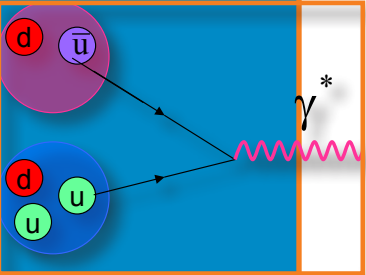
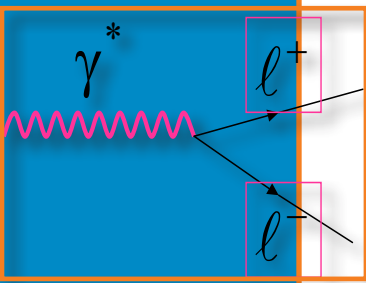
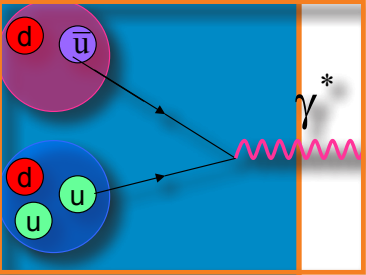
# DY setup: the absorber

The absorber is 236 cm long, made of  $\text{Al}_2\text{O}_3$

The plug is made of 6 discs of W 20 cm long each and 20 cm of Alumina in the most downstream part (total of 140 cm)

Number of radiation lengths (multiple scattering for muons):  
 $x/X_0 = 33.53$

Number of interaction lengths (stopping power for pions):  
 $x/\lambda_{\text{int}} = 7.25$



# Summary

- Transversity and Sivers PDFs of the nucleon are addressed in COMPASS presently from semi-inclusive DIS.
- The opportunity to study, with the same spectrometer, the TMD PDFs from the Drell-Yan process is unique.
- COMPASS experimental conditions probe the valence quarks region, where TMD effects are expected to be sizable.
- The feasibility of the measurement was proven, after a series of beam tests.
- The COMPASS-II Proposal has been recommended by SPSC and is approved by the Research Board for a first period of 3 years including 1 year for Drell-Yan.

2014 Single polarised Drell-Yan with  $\pi^-$  beam --> TMDs (Sivers and Boer-Mulders) sign change

2015+16 DVCS with  $\mu^+$  and  $\mu^-$  beams on unpolarised protons

in parallel unpolarised SIDIS --> PDFs, TMDs, FFs (in particular for strange)

Second year of Drell-Yan data taking?

...beyond 2016 --> TMDs (Sivers, Boer-Mulders, and Pretzelosity), transversity PDF