Monte-Carlo simulations for Drell-Yan in COMPASS

C. Quintans, LIP-Lisbon

on behalf of the COMPASS Collaboration

26^{th} February 2014

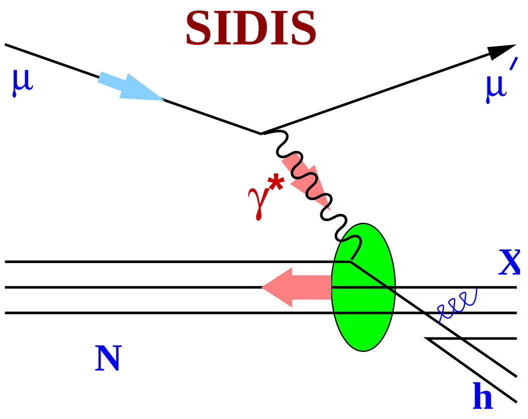
Co-financed by: Fundação para a Ciência e a Tecnologia, MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA; COMPETE; QREN, QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL; UNIÃO EUROPEIA, Fundo Europeu de Desenvolvimento Regional

Overview

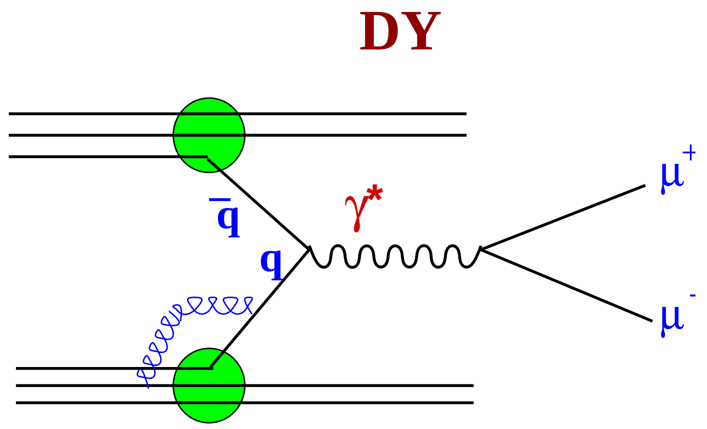
- Polarized Drell-Yan in COMPASS
- Drell-Yan process generation
- The COMPASS experiment
- Simulation of the detector
- Geometrical acceptances
- Experimental resolutions
- Expected event rates and asymmetries statistical errors
- UML extraction of asymmetries
- Summary

TMD studies in COMPASS

In COMPASS @ CERN transverse momentum dependent PDFs (TMDs) can be accessed either from semi-inclusive DIS (SIDIS), or from Drell-Yan processes, using a transversely polarized target:



Final State Interactions



Initial State Interactions

Sivers and Boer-Mulders TMDs are T-odd, thus the prediction:

$$f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS) \qquad h_1^{\perp}(DY) = -h_1^{\perp}(SIDIS)$$

- The T-odd effect is a manifestation of non-zero quarks orbital angular momentum.
- The sign change observation is considered a crucial test of non-perturbative QCD and the TMDs approach.

Polarized Drell-Yan

For a transversely polarized target, one can calculate the cross-section asymmetry between the 2 possible spin configurations.

The single polarized Drell-Yan cross-section can be written as:

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

- A: azimuthal asymmetries
- D: depolarization factors
- S: target spin component

- $F = 4\sqrt{(P_a \cdot P_b)^2 - M_a^2 M_b^2}$
- $\hat{\sigma}_U$: cross-section surviving integration over ϕ and ϕ_S.
- $\mathcal{A}$: acceptance function

Azimuthal asymmetries

The parameters entering Lam-Tung relation ($1 - \lambda - 2\nu = 0$) are:

- $\lambda = A_U^1$
- $\mu = A_U^{\cos\phi}$
- $\nu = 2A_U^{\cos 2\phi}$

The collinearity hypothesis: $\lambda = 1$, $\mu = \nu = 0$, was seen to be violated by experiments NA10(CERN) and E615(Fermilab) in the 80's.

The remaining azimuthal asymmetries contain a convolution of 2 TMDs:

- $A_U^{\cos 2\phi}$: $h_1^{\perp}(\pi) \otimes h_1^{\perp}(p)$;
- $A_T^{\sin\phi_S}$: $f_1(\pi) \otimes f_{1T}^{\perp}(p)$;
- $A_T^{\sin(2\phi+\phi_S)}$: $h_1^{\perp}(\pi) \otimes h_{1T}^{\perp}(p)$;
- $A_T^{\sin(2\phi-\phi_S)}$: $h_1^{\perp}(\pi) \otimes h_1(p)$.

All are expected to be sizeable in the valence quark region.

The MC chain

Drell-Yan process generation: Pythia

$\Downarrow$

Particles crossing the COMPASS spectrometer simulation: GEANT3

$\Downarrow$

Reconstruction as for real data

$\Downarrow$

Analysis: extraction of acceptances, efficiencies and resolutions

Note: The simulations discussed here use Pythia as Drell-Yan generator, thus polarization effects are not included in this MC.

Unpolarized Drell-Yan in Pythia

- Pythia is multi-purpose
  - Lots of parameters
  - Different versions have different parameter defaults
- Pythia is LO. NLO can be partially simulated via parton showers

Two known problems with using Pythia for Drell-Yan:

- cross-section too low
- dilepton p_T spectrum must be adjusted by a tuning of the fragmentation process

Drell-Yan data obtained over the past 30 years by different experiments can be used to tune Pythia for the COMPASS (unpolarized) case.

When COMPASS data will be available, a more precise tuning may be done.

Drell-Yan cross-section

In these simulations:

- Keep parton showers **OFF**
- Use LO PDF sets

In these conditions, the departure wrt experimentally measured cross-section is well-known (K_{DY} factor):

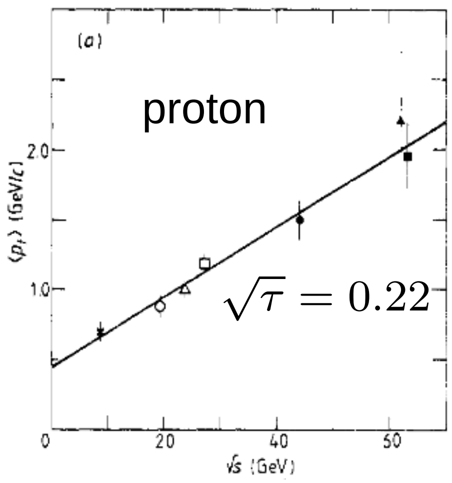
Kenyon, 1982

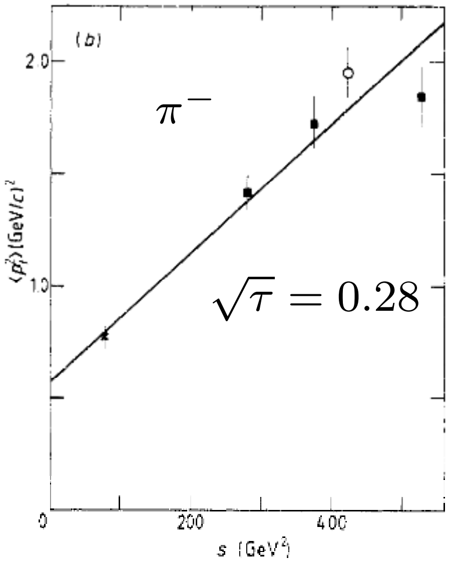
Group	Beam and target	Momentum/$\sqrt{s}$ (GeV/c)/(GeV)	Measured cross section / Naive Drell–Yan prediction
NA3 (Badier *et al* 1980b)	($\bar{p}$–p): Pt	150	2.3 ± 0.4
NA3 (Badier *et al* 1979b)	p: Pt	200	2.2 ± 0.4
CFS (Ito *et al* 1981)	p: Pt	300/400	$1.7^{+0.73}_{-0.58}$
CHFMNP (Antreasyan *et al* 1981b)	pp	44, 63	1.6 ± 0.2
MNTW (Smith *et al* 1981)	p: W	400	1.6 ± 0.3
NA3 (Lefrançois 1980)	π^-: Pt	200	2.2 ± 0.3
NA3 (Lefrançois 1980)	π^+: Pt	200	2.4 ± 0.4
NA3 (Lefrançois 1980)	(π^-–π^+): Pt	200	2.4 ± 0.4
Omega (Corden *et al* 1980a)	π^-: W	40	2.45 ± 0.42
Omega (Corden *et al* 1980a)	π^+: W	40	2.52 ± 0.49
Omega (Corden *et al* 1980a)	(π^-–π^+): W	40	2.22 ± 0.41

$\hookrightarrow$ important to estimate event rates in COMPASS.

Drell-Yan p_T spectrum

$\langle p_T^2 \rangle$ is different for DY in proton or in pion induced collisions:





- Kenyon (1982) parametrization for pions, at $\sqrt{\tau} = \sqrt{x_\pi x_p} = 0.28$, applied to the COMPASS s:

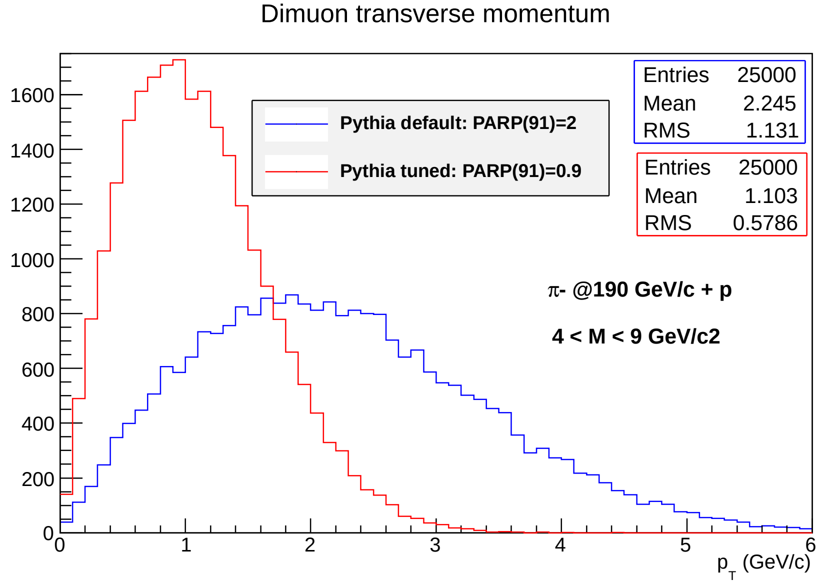
$$\langle p_T^2 \rangle \; = \; 0.59 \; + \; 0.0029 \; s = 1.6 \; (\mathrm{GeV/c})^2$$

- NA10, using π^- beam at 194 GeV on a 12 cm long W target obtained a sample of DY events in $4.05 \leq M \leq 8.5$ GeV/c^2 with $\langle p_T \rangle = 1.1$ GeV/c (NA10, CERN-EP/87-199).

- Since COMPASS uses NH$_3$ target, expect very small p_T broadening effect.

Tuning of Drell-Yan dimuon p_T in Pythia

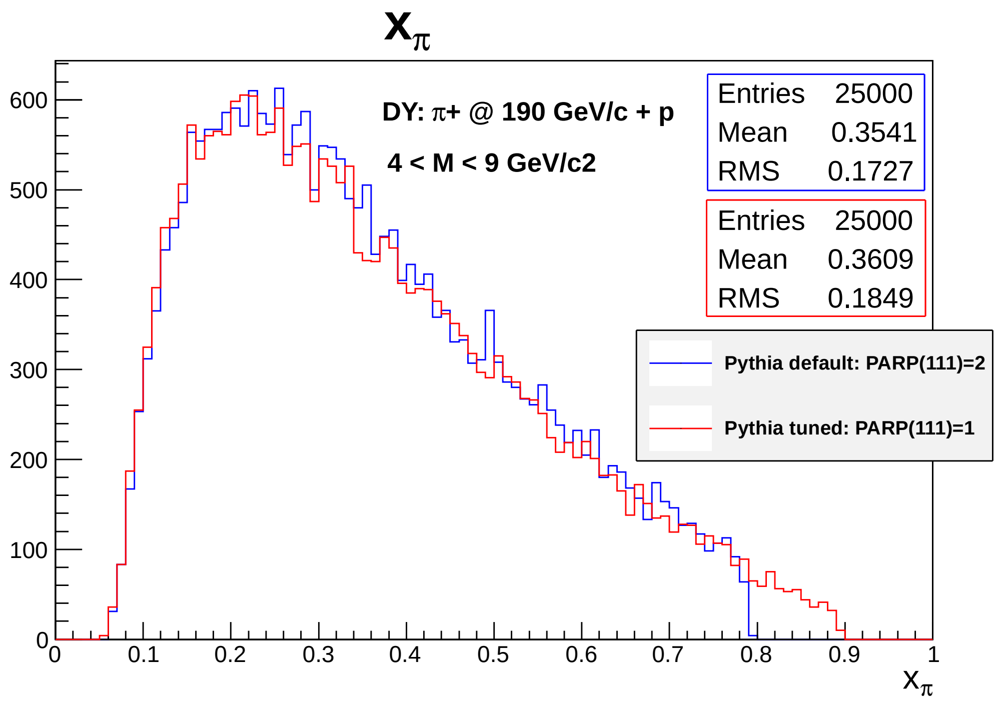
In the Pythia fragmentation, the hadrons primordial $k_\perp$ distribution is assumed gaussian. The default value for the width of this gaussian is $\sigma_{k_\perp} = 2$ GeV/c (PARP(91)), leading to a distribution too wide.



By setting $\sigma_{k_\perp} = 0.9$ GeV/c, one obtains an average dimuon $p_T = 1.1$ GeV/c, identical to the one reported by NA10.

Tuning of other parameters in Pythia

The minimum invariant mass of the remnant hadronic system (via PARP(111)) is also tuned. This parameter sets an upper limit to the momentum fraction of the interacting parton: $x < 1 - 2 * PARP(111)/E_{CM}$.



By changing this parameter, one extends to $x_\pi < 0.9$. Another consequence is that the cross-section increases by 2%.

PDF sets used

PDF sets from LHAPDF are used. Here we choose LO PDF sets, for consistency.

- pion: GRVPI0 LO (set 252)
- nucleon: GRV98 LO (set 80060)

Testing dependence of simulation on the pion PDF set (reaction π^- @190 GeV + p):

PDF set	$\sigma_{DY}^{4<M_{\mu\mu}<9}$ (nb)	$\langle p_T \rangle$	RMS$_{p_T}$	$\langle x_\pi \rangle$	RMS$_{x_\pi}$
GRVPI0	0.1454	1.105	0.584	0.365	0.186
OW-PI set1	0.1481	1.113	0.576	0.371	0.195
OW-PI set2	0.1452	1.107	0.579	0.367	0.193

Testing dependence of simulation on the nucleon PDF set (reaction π^- @190 GeV + p):

PDF set	$\sigma_{DY}^{4<M_{\mu\mu}<9}$ (nb)	$\langle p_T \rangle$	RMS$_{p_T}$	$\langle x_p \rangle$	RMS$_{x_p}$
GRV98	0.1454	1.105	0.584	0.252	0.138
MRST98 set1	0.1434	1.110	0.579	0.253	0.137

Pythia tuning summary

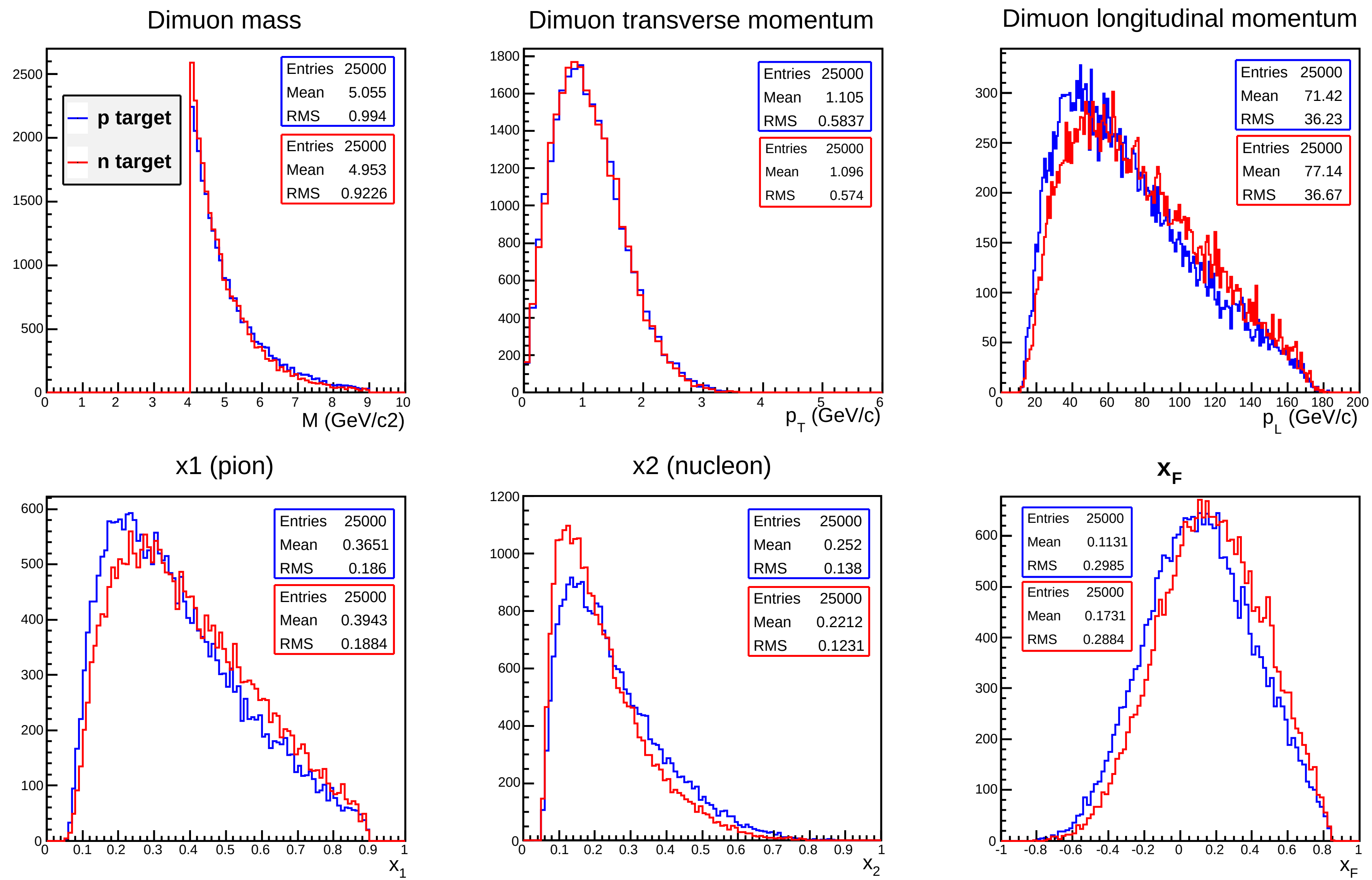
parameter	default	tuned	meaning
MSTP(61)	1	0	initial PS
MSTP(71)	1	0	final PS
MSTP(51)	–	80060	PDF set for target
MSTP(53)	–	252	PDF set for beam
PARP(111)	2	1	minimum mass of remnant
PARP(91)	2	0.9	width of $k_\perp$ gaussian

In these conditions, the Drell-Yan cross-sections obtained in Pythia for the dimuon mass range generated $4 \leq M_{\mu\mu} \leq 9$ GeV/c^2 is:

- π^- @ 190 GeV $+$ p: 0.145 nb
- π^- @ 190 GeV $+$ n: 0.074 nb

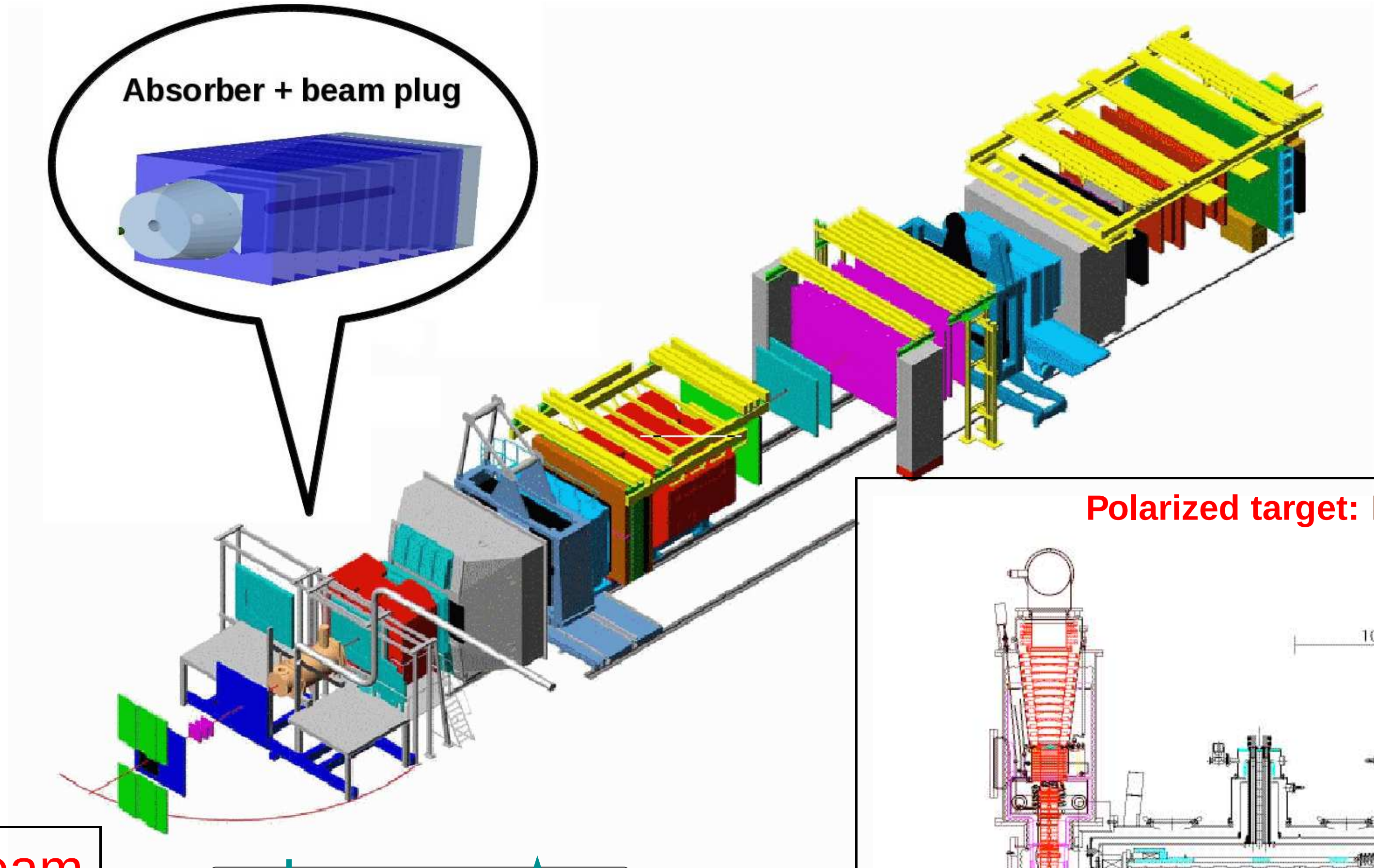
Note: the beam momentum was implemented with a gaussian spread of 2% (as we have it in COMPASS) already at generator level (PARP(171)).

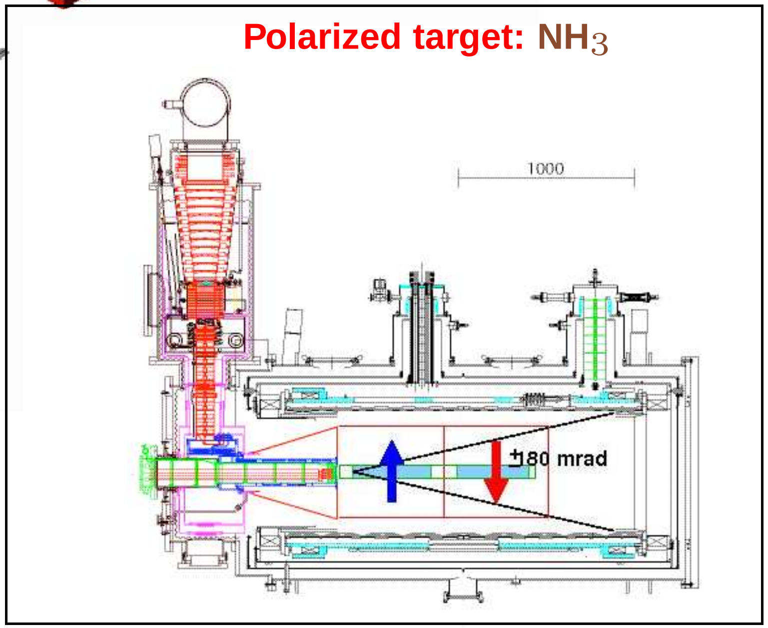
Generated distributions: proton vs neutron



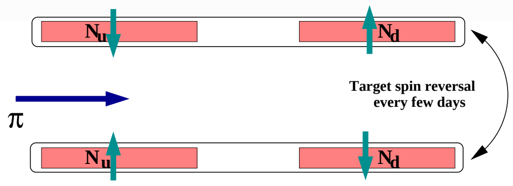
The COMPASS spectrometer

The COMPASS experiment at CERN uses a secondary beam produced from the SPS extracted protons in a production target.





π^- beam
@190 GeV/c



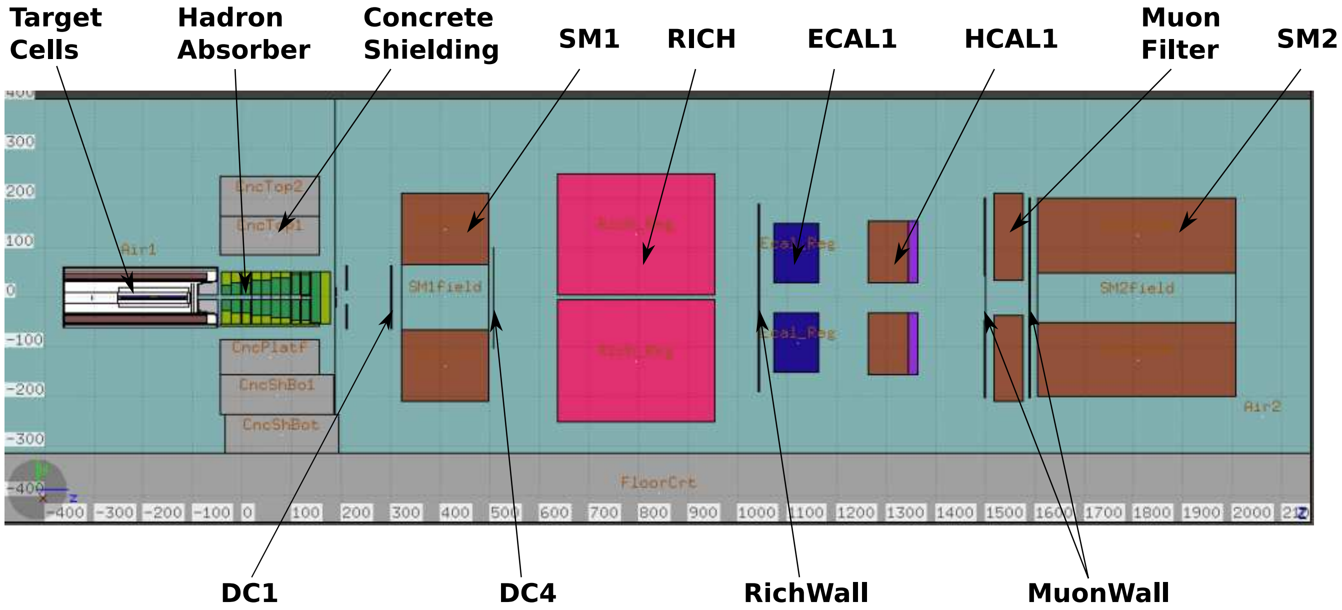
Beam and target

- The polarized Drell-Yan measurement in COMPASS will use a transversely polarized target.
- Due to the dipole field in the target (used to keep the transverse polarization), the beam must enter the hall with a tilt, in order to cross the target in all its extent.
- To avoid local heating of the target, that would destroy polarization, the beam spot must be wide ($\sigma_{x,y} = 1$ cm).
- The target cells are cylinders with 2 cm radius, to intercept most of the beam (87%).
- The target is 110 cm of solid state ammonia in a bath of liquid He (0.57 λ^{π}_{int}).
- The non-interacted beam (in this target) will be stopped by the tungsten beam plug (or interact eventually with thin nuclear target placed upstream of it).
- The DY process has low cross-section, thus the need for high luminosity. But the location of the experimental hall at ground level, the beam line characteristics and the need to limit the target heating, restrict the beam intensity to $I = 10^8$ π/s.
- COMPASS beam comes in 9.6 s long spills (flat top), in a 33.6 s extraction cycle.

Spectrometer simulation

The spectrometer simulation (propagation of particles in matter, and detectors response) is done using different packages, depending on the simulation purpose:

- For Drell-Yan geometrical acceptances, data reconstruction studies, and experimental resolutions – GEANT3
- For detector occupancy and radiation conditions studies – FLUKA
- For cross-checks (but using simplified geometry) – GEANT4



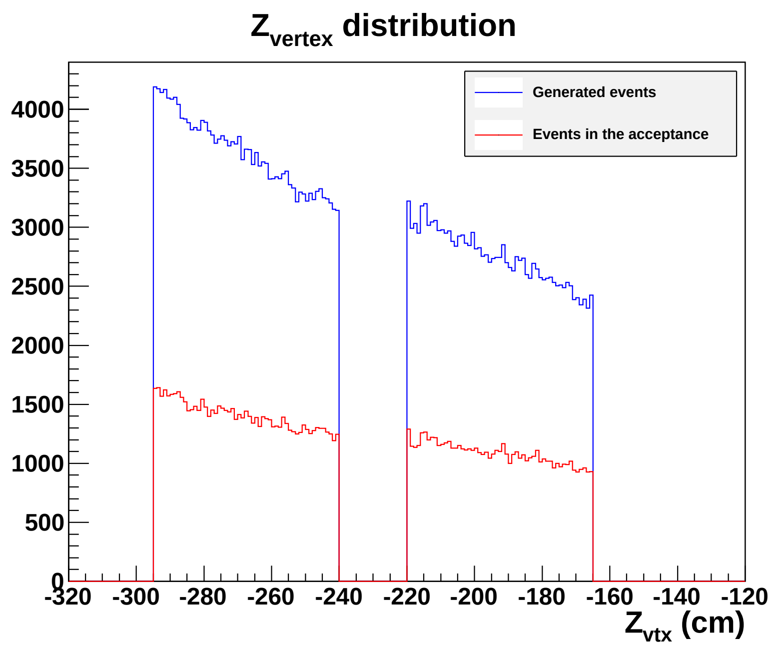
Generated events spread along target

A Pythia sample of (π^-, p) and (π^-, n), according to the proportions in NH$_3$:

$$\frac{10}{17}\,\sigma_{\pi p}^{DY} \;+\; \frac{7}{17}\,\sigma_{\pi n}^{DY}$$

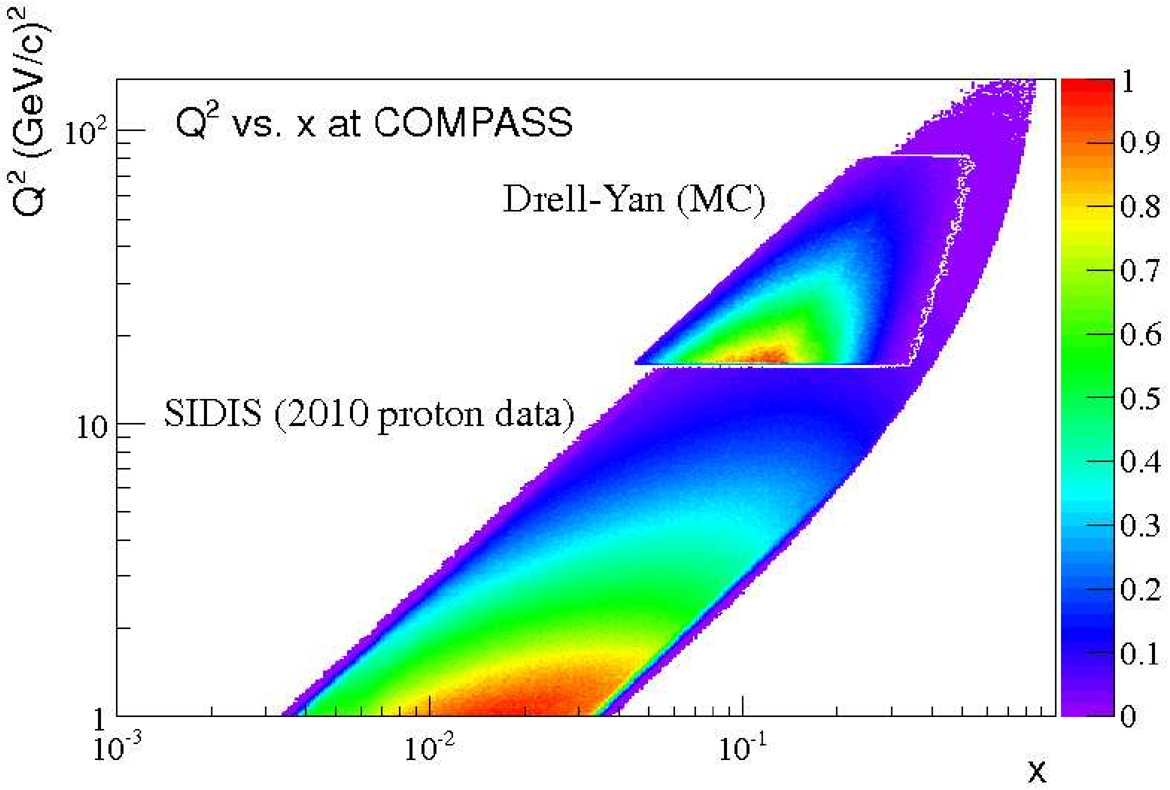
is prepared, generating Drell-Yan events with $M^{gen} > 3.5$ GeV/c^2. The wider generation window is to be able to select $4 < M^{rec} < 9$ GeV/c^2 reconstructed events with margin for experimental smearing.

The DY Pythia events are spread along the target according to the pion interaction length in NH$_3$.



COMPASS: DY and SIDIS measurements

In COMPASS we have the unique opportunity to access, using the same spectrometer, TMDs via the 2 different processes: DY and SIDIS.

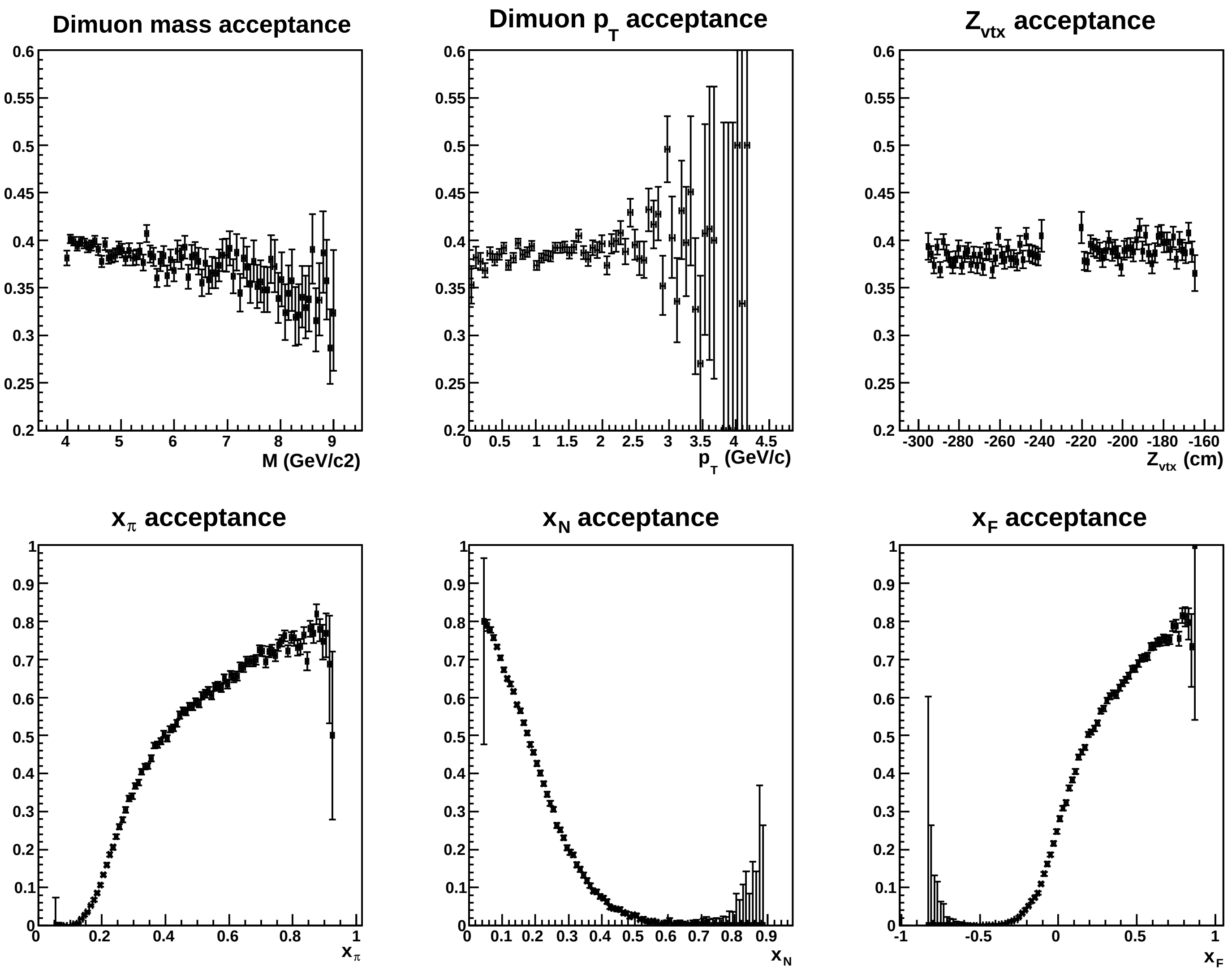


SIDIS and DY measurements have an overlapping region.

↪Check the prediction for Sivers and Boer-Mulders sign change when accessed from these 2 processes.

Acceptance

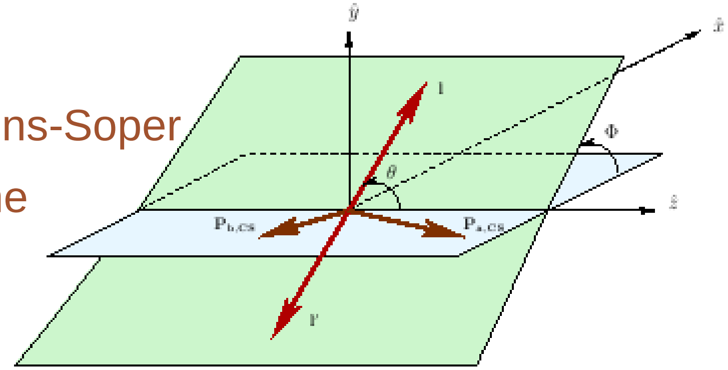
The global geometrical acceptance of DY dimuons with $4 < M < 9$ GeV/c^2 is 39%.



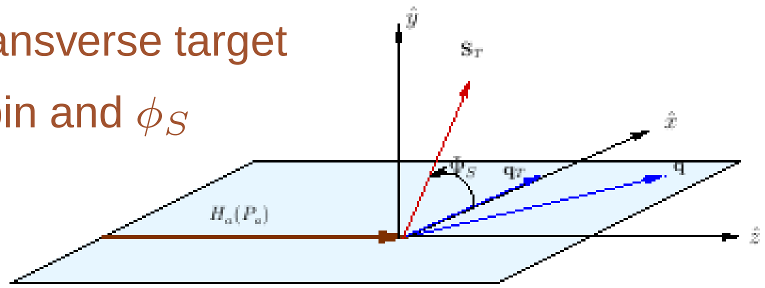
DY with π^- beam on fixed target: u-quark dominance with valence quarks interacting.

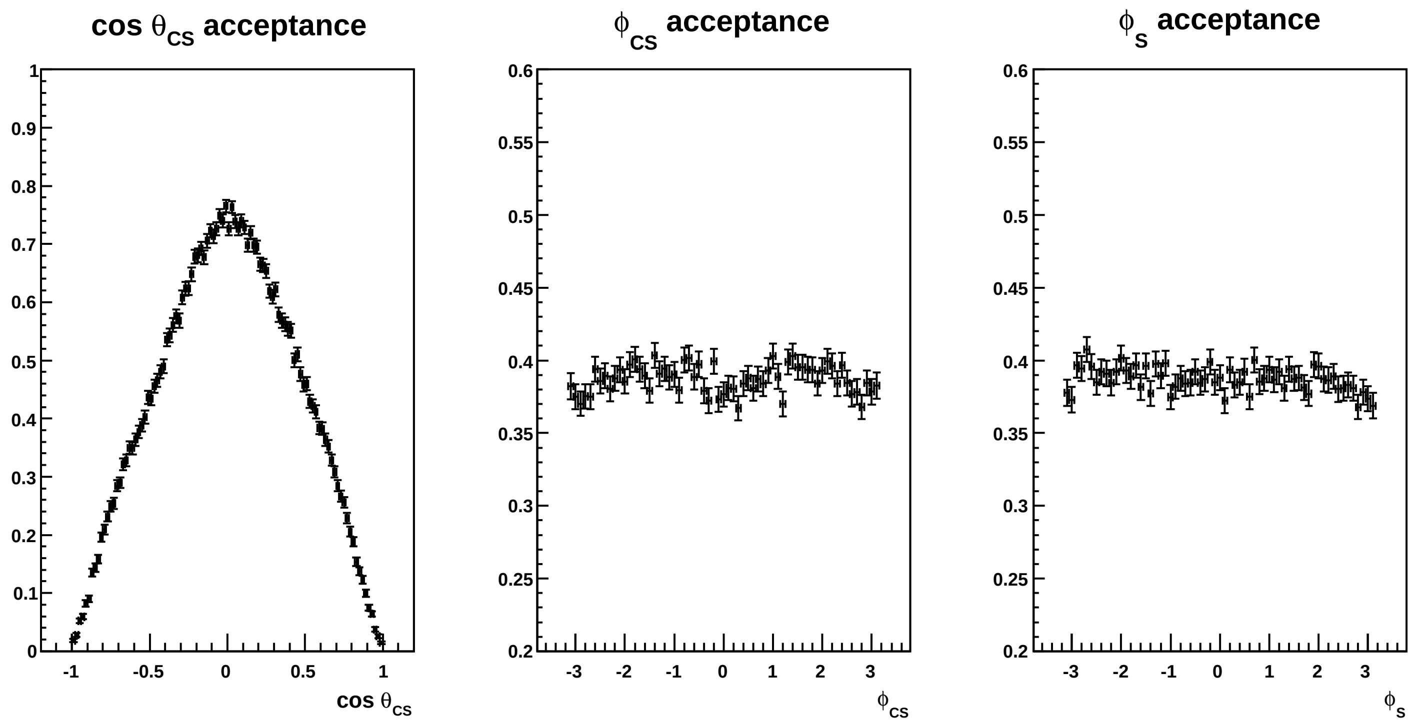
Angular acceptances

Collins-Soper frame



Transverse target spin and ϕ_S

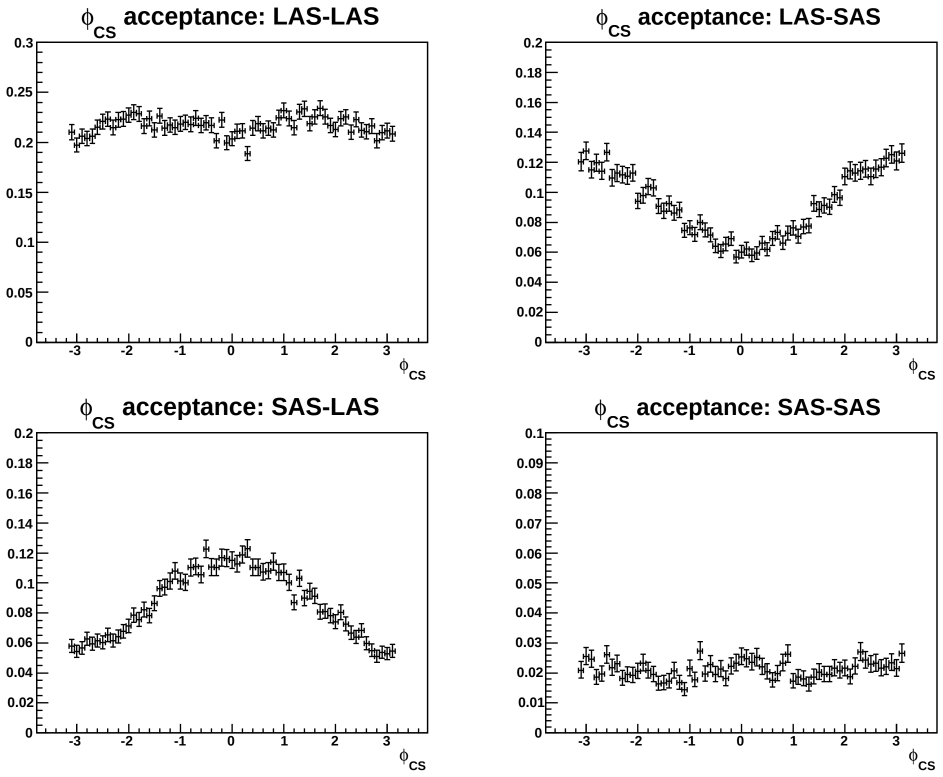




The spectrometer itself introduces a modulation in ϕ_{CS} that must be taken into account.

Acceptance per zone

The acceptance can be analysed according to the zone where μ^+ and μ^- (respectively) are accepted in the spectrometer: at large polar angle (LAS) or at small polar angle (SAS).



The geometrical acceptance is 39%

- 2 muons at Large Angle (LAS): 22%
- 2 muons at Small Angle (SAS): 2%
- one muon in LAS and another in SAS: 18%

Spectrometer related uncertainties

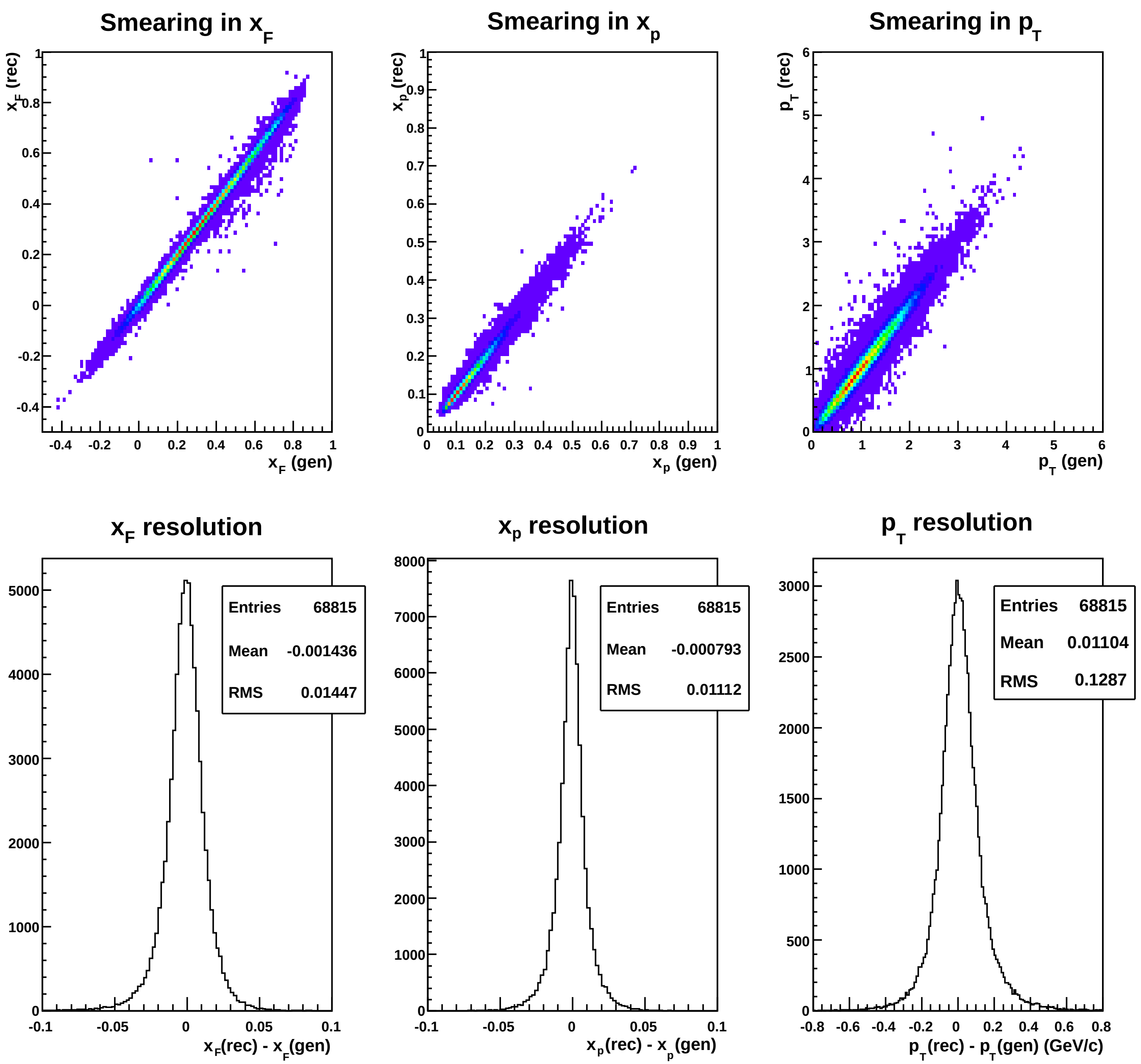
The presence of an hadron absorber downstream of the polarized target is essential to keep detector occupancies at reasonable level ($< 5\%$), and limit the combinatorial background of muons resulting from pion and kaon decays.

Muon identification is also ensured in the spectrometer by requiring the tracks to cross heavy material walls (iron or concrete).

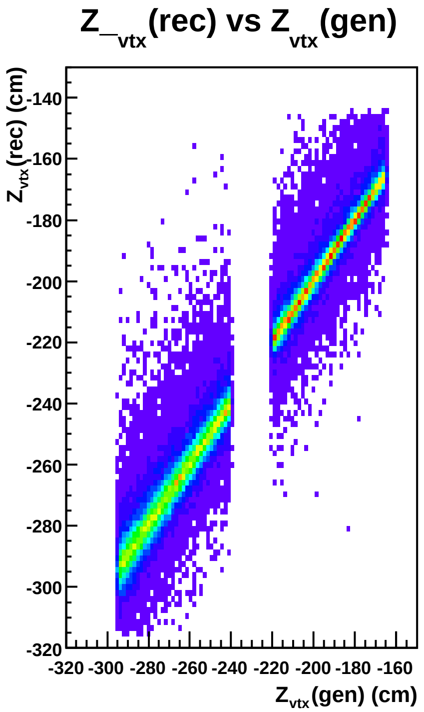
The spectrometer includes 2 sets of calorimeters, also resulting in a significant material budget.

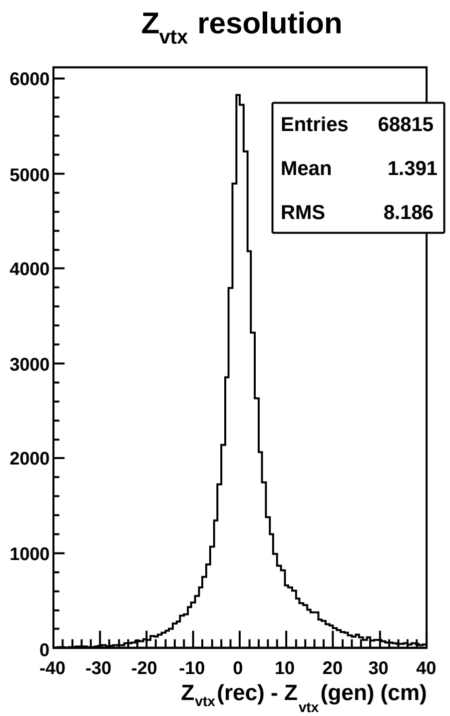
$\hookrightarrow$ A muon track in the acceptance of either spectrometer will have crossed at least 100 radiation lengths – important multiple scattering.

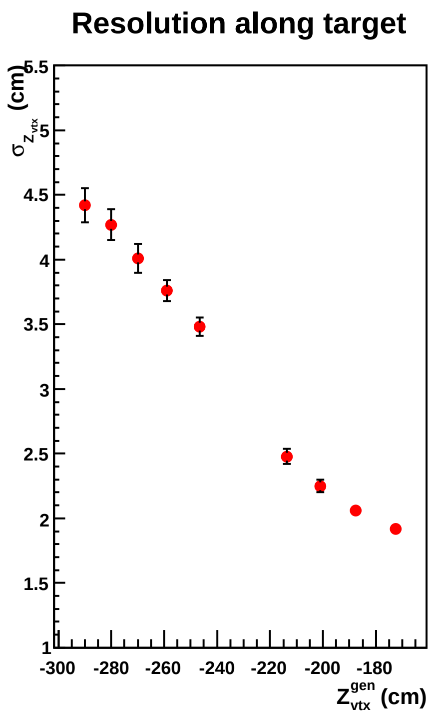
Resolutions

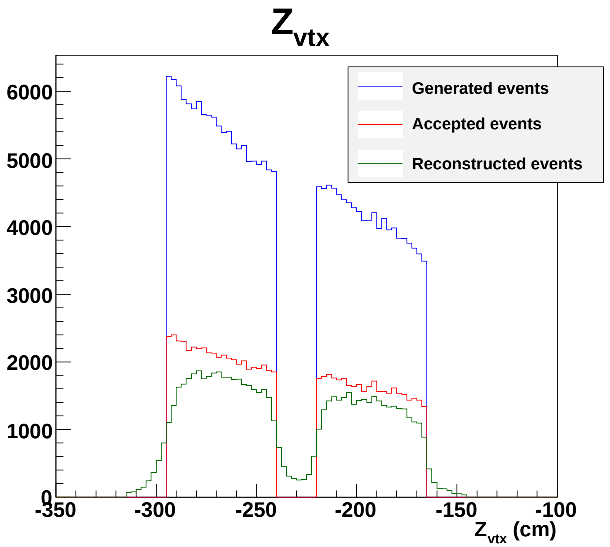


Vertex position resolution



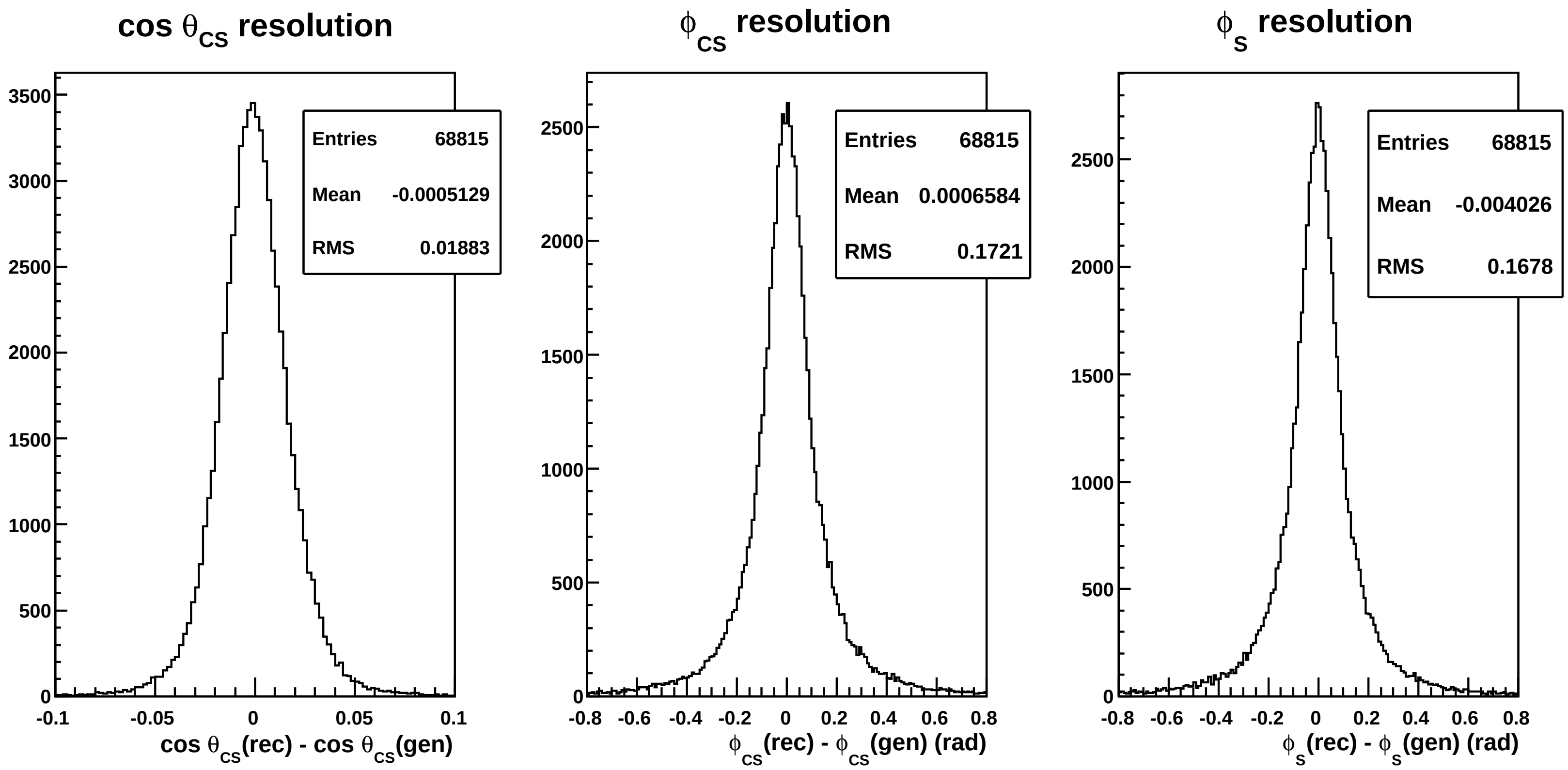






The resolution of the primary vertex position is important, since one must distinguish the events coming from each of the target cells, which are polarized in opposite directions.

Angular resolutions



Azimuthal resolutions in the order of 170 mrad are obtained from the simulation of DY events with $4 < M_{\mu\mu} < 9$ GeV/c^2 (pure Drell-Yan MC, no pile-up included).

Expected event rates

The expected events rates for Drell-Yan in the mass range $4 < M_{\mu\mu} < 9$ GeV/c^2 are:

- With a beam intensity of $I_{beam} = 6 \times 10^7$ particles/second, one expects 1000/day. In 140 days, 140 000 events.
- $\approx$ 216 000 events in one year, if $I_{beam} = 10^8$ particles/second.

Note: Used K^{DY}-factor=2. Assumed an SPS super-cycle of 33.6 s. Assumed 80% SPS efficiency (beam availability), and 85% efficiency in running of the spectrometer.

Asymmetries statistical error

The expected statistical errors in the asymmetries are given by:

$$\delta\, A_U^{\cos 2\phi} = 2\sqrt{\frac{2}{N}}; \quad \delta\, A_T^{\sin \phi_S} = \frac{1}{f S_T}\sqrt{\frac{2}{N}}; \quad \delta\, A_T^{\sin(2\phi \pm \phi_S)} = \frac{2}{f S_T}\sqrt{\frac{2}{N}}$$

Asymmetry uncertainties	Dimuon mass (GeV/c^2) $4 < M_{\mu\mu} < 9$
$\delta\, A_U^{\cos 2\phi}$	0.0056
$\delta\, A_T^{\sin \phi_S}$	0.0142
$\delta\, A_T^{\sin(2\phi+\phi_S)}$	0.0284
$\delta\, A_T^{\sin(2\phi-\phi_S)}$	0.0284

$\hookrightarrow$ Possibility to study the asymmetries in several x_F or p_T bins.

Extraction of azimuthal asymmetries

The preferred method to extract the azimuthal asymmetries is the unbinned maximum likelihood method (UML):

One maximizes the likelihood for each event characterized by (θ, ϕ, ϕ_S) to follow a probability density function:

$$P^{\pm}_{cell} = a^{\pm}_{cell} \; g^{\pm}$$

with $a^{\pm}_{cell}$: acceptance function; $g^{\pm}$: physics modulation function. In the extended maximum likelihood fit performed, the asymmetries are parameters of the fit.

The method was used in COMPASS, in particular for a simultaneous extraction of Sivers and 7 other SIDIS transverse spin asymmetries (Phys.Lett.B 692 (2010) 240). It is now adapted to the Drell-Yan case.

A toy-MC injecting sizeable asymmetries has shown the ability of the UML to recover these without bias. More studies are ongoing.

To conclude

- COMPASS polarized Drell-Yan measurement will start in a few months, in October 2014. Physics data taking continue during 2015 (full year). A second year of DY data-taking is planned, possibly in 2018.
- After 1 year of data-taking: expected statistical error in the Sivers asymmetry $\approx$2% (systematic errors will be smaller).
- Unpolarized Drell-Yan MC was done using Pythia generator and a GEANT3 simulation of the spectrometer, to extract acceptances and resolutions in all the relevant variables.
- The method to extract asymmetries (UML) in the DY case was implemented, and tested with a toy-MC.

The COMPASS measurements will contribute to the common effort of extracting the TMDs, namely Sivers, Boer-Mulders and pretzelosity, as well as the transversity PDF.