TMDs at future DY experiments

(COMPASS at CERN)

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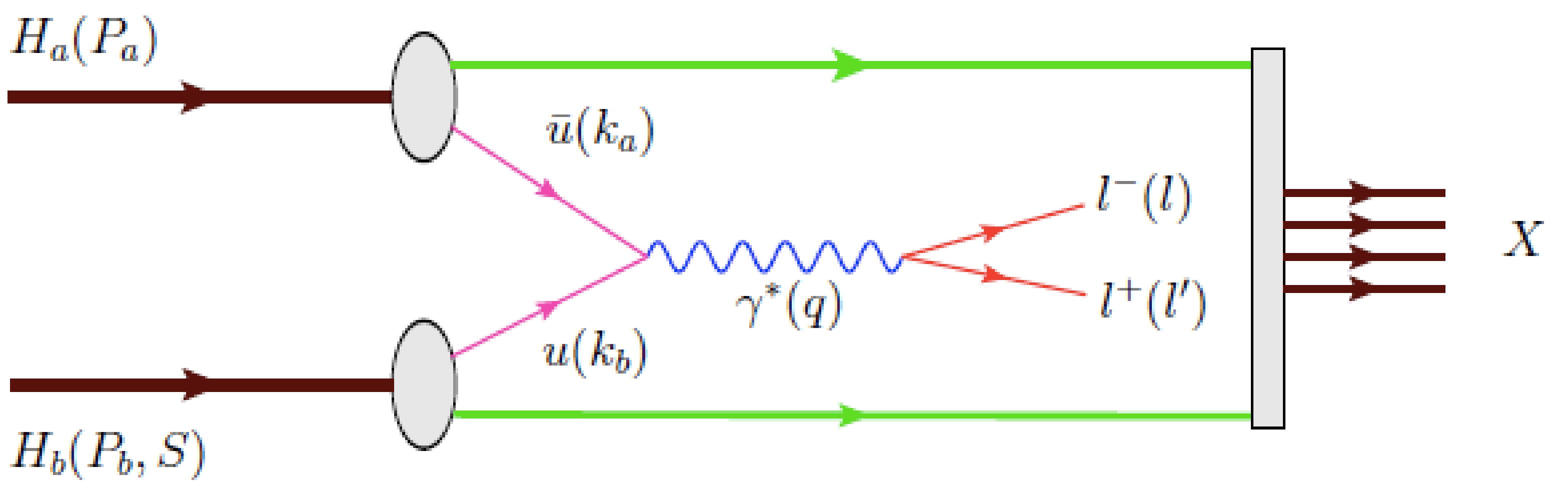
Outline

- Drell-Yan kinematics
- Choice of the kinematic domain
- Drell-Yan Cross Sections at LO
- TMDs at Drell-Yan – unpolarised and single polarised case
- Sivers and Boer-Mulders SIDIS←→DY
- Some indications for the future Drell-Yan experiments
- Future Drell-Yan experiments:
  - Fixed target experiments (COMPASS, E906, J-Park, RHIC P2(II))
  - Collider experiments (RHIC, NICA SPD (Dubna), PAX (GSI))
- Some conclusions

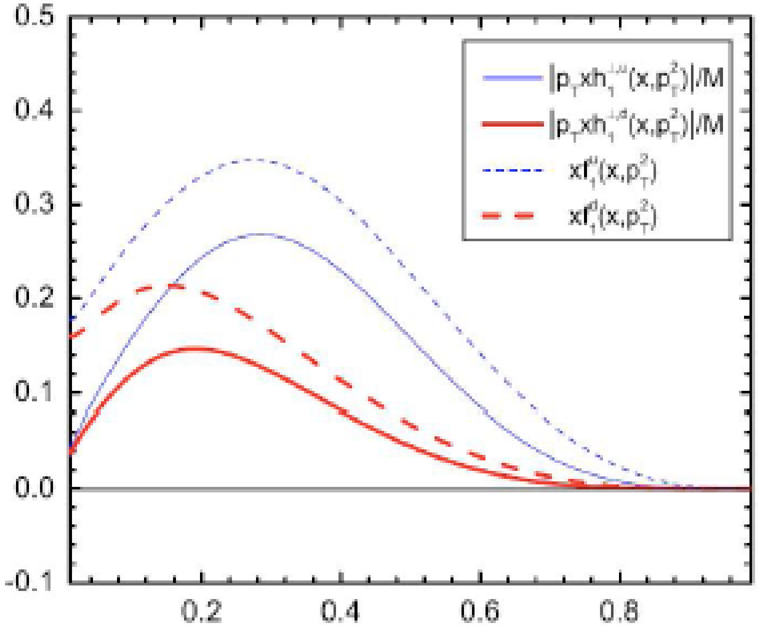
Drell-Yan Kinematics

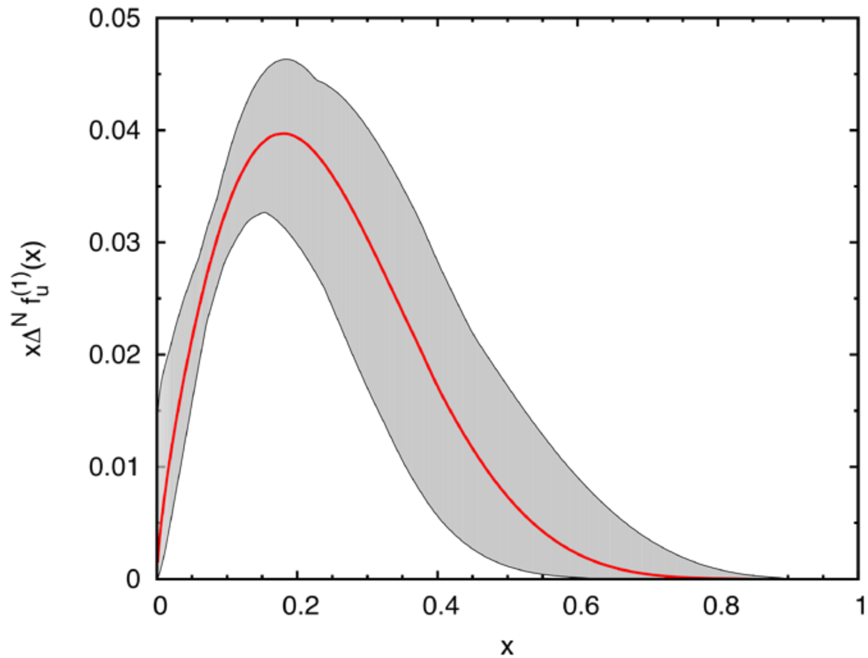


$P_{a(b)}$	the momentum of the beam (target) hadron,
$s = (P_a + P_b)^2,$	the total centre-of-mass energy squared,
$x_{a(b)} = q^2/(2P_{a(b)} \cdot q),$	the momentum fraction carried by a parton from $H_{a(b)}$,
$x_F = x_a - x_b,$	the Feynman variable,
$M^2_{\mu\mu} = Q^2 = q^2 = s\ x_a\ x_b,$	the invariant mass squared of the dimuon,
$\mathbf{k}_{Ta(b)}$	the transverse component of the quark momentum,
$\mathbf{q}_T = \mathbf{P}_T = \mathbf{k}_{Ta} + \mathbf{k}_{Tb}$	the transverse component of the momentum of the virtual photon.

Some indications for the future Drell-Yan experiments

TMD PDFs – ALL are sizable in the valence quark region





► Boer-Mulder function for u and d quarks as extracted from $p + D$ data from Zhang *et al Phys. Rev.* D77,0504011]

Sivers effect in Drell-Yan processes. M. Anselmino, M. Boglione U. D'Alesio, S. Melis, F. Murgia, A. Prokudin Published in Phys.Rev.D79:054010, 2009

Drell-Yan Kinematics (transverse motion)

- If we consider the transverse motion of partons then:

$$p_a = \frac{\sqrt{s}}{2} x_a \left(1 + \frac{k^2_{\perp a}}{x_a^2 s}, \frac{2\boldsymbol{k}_{\perp a}}{x_a \sqrt{s}}, 1 + \frac{k^2_{\perp a}}{x_a^2 s}\right)$$

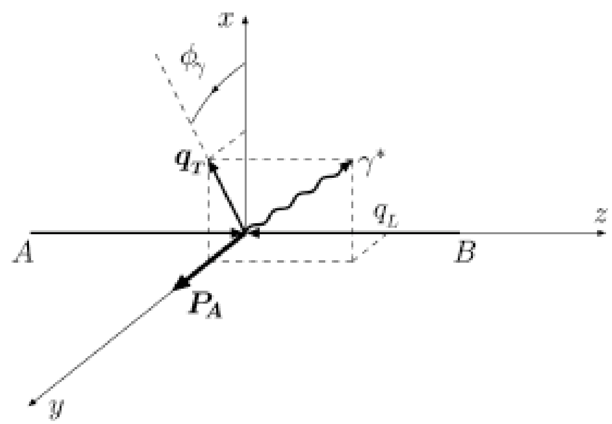
$$p_b = \frac{\sqrt{s}}{2} x_b \left(1 - \frac{k^2_{\perp b}}{x_b^2 s}, \frac{2\boldsymbol{k}_{\perp b}}{x_b \sqrt{s}}, -1 + \frac{k^2_{\perp b}}{x_b^2 s}\right)$$

- ... and the γ^* (dilepton) momentum has a transverse component in the h.c.m. frame

$$q = p_a + p_b = (q_0, \boldsymbol{q}_T, q_L)$$

$$\boxed{\boldsymbol{q}_T = \boldsymbol{k}_{\perp a} + \boldsymbol{k}_{\perp b}}$$

Only low q_T ($q_T^2 \ll q^2$) have a non-perturbative origins



Choice of the kinematic domain in order to be sensitive to the contribution from TMDs

Mauro Anselmino (DY@CERN Workshop concluding remarks):

ideal machines:

x-range including the valence region,

Q^2, M^2 high enough to control higher-twist corrections

P_T, Q_T ranges large enough to see transition from TMDs to collinear factorization

plenty of challenging theoretical issues....

Drell-Yan cross section

Very recent paper by Arnold, Metz and Schlegel arXiv:0809.2262

$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{F\,q^2}\times$$
$$\Big\{\Big((1+\cos^2\theta)\,F_{UU}^1 + (1-\cos^2\theta)\,F_{UU}^2 + \sin 2\theta\cos\phi\,F_{UU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{UU}^{\cos 2\phi}\Big)$$
$$+\ S_{aL}\Big(\sin 2\theta\sin\phi\,F_{LU}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{LU}^{\sin 2\phi}\Big)$$
$$+\ S_{bL}\Big(\sin 2\theta\sin\phi\,F_{UL}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{UL}^{\sin 2\phi}\Big)$$
$$+\ |\vec{S}_{aT}|\Big[\sin\phi_a\Big((1+\cos^2\theta)\,F_{TU}^1 + (1-\cos^2\theta)\,F_{TU}^2 + \sin 2\theta\cos\phi\,F_{TU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{TU}^{\cos 2\phi}\Big)$$
$$+\cos\phi_a\Big(\sin 2\theta\sin\phi\,F_{TU}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TU}^{\sin 2\phi}\Big)\Big]$$
$$+\ |\vec{S}_{bT}|\Big[\sin\phi_b\Big((1+\cos^2\theta)\,F_{UT}^1 + (1-\cos^2\theta)\,F_{UT}^2 + \sin 2\theta\cos\phi\,F_{UT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{UT}^{\cos 2\phi}\Big)$$
$$+\cos\phi_b\Big(\sin 2\theta\sin\phi\,F_{UT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{UT}^{\sin 2\phi}\Big)\Big]$$
$$+\ S_{aL}\,S_{bL}\Big((1+\cos^2\theta)\,F_{LL}^1 + (1-\cos^2\theta)\,F_{LL}^2 + \sin 2\theta\cos\phi\,F_{LL}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{LL}^{\cos 2\phi}\Big)$$

Single-polarised DY cross-section: Leading order QCD parton model, TMD PDFs universality

At LO the general expression of the DY cross-section simplifies to (Aram Kotzinian) :

$$
\begin{aligned}
\frac{d\sigma^{LO}}{d^4q\, d\Omega} &= \frac{\alpha_{em}^2}{F\, q^2}\hat{\sigma}_U^{LO}\Big\{\Big(1 + D^{LO}_{[\sin^2\theta]}\, A_U^{\cos 2\phi}\cos 2\phi\Big) \\
&+ S_L D^{LO}_{[\sin^2\theta]}\, A_L^{\sin 2\phi}\sin 2\phi \\
&+ |\vec{S}_T|\Big[A_T^{\sin\phi_S}\sin\phi_S + D^{LO}_{[\sin^2\theta]}\Big(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S) \\
&+ A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\Big)\Big]\Big\},
\end{aligned}
$$

Thus the measurement of 4 asymmetries (modulations in the DY cross-section):

- $A_U^{\cos 2\phi}$ 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 functions of the beam hadron and to $h_{1T}^{\perp}$, the pretzelosity function of the target nucleon,
- $A_T^{\sin(2\phi-\phi_S)}$ – to the Boer-Mulders functions of the beam hadron and h_1, the transversity function of the target nucleon.

TMDs UNIVERSALITY TO BE PROVEN

Sivers, Boer-Mulders functions SIDIS ←→ DY

Mauro Anselmino (DY@CERN):

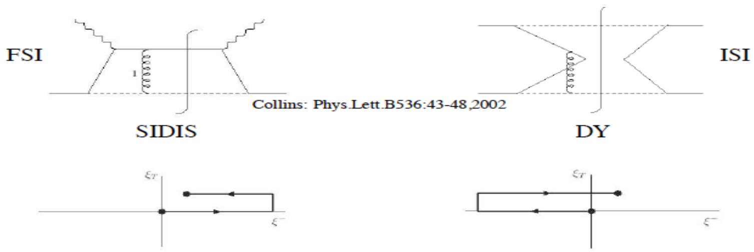
in all models one has:

$$[f_{1T}^{q\perp}]_{\text{SIDIS}} = -[f_{1T}^{q\perp}]_{\text{DY}}$$

whatever the reason, check it!

gauge-link was introduced (intrinsic feature of PDF). The presence of gauge-link provides the possibility of existence of non-zero T-odd TMD PDFs

Direction of the gauge-link of the k_T dependent PDF is process-dependent (gauge-link is resummation of all collinear soft gluons) and it changes to the opposite in SIDIS wrt DY



Sivers and Boer-Mulders functions are T-odd, and to provide the time-invariance they change the sign in SIDIS wrt DY due to the opposite direction of the gauge-link

$$f_{1T}^{\perp}(x, \mathbf{k}_T)\Big|_{SIDIS} = -f_{1T}^{\perp}(x, \mathbf{k}_T)\Big|_{DY}$$

$$h_{1}^{\perp}(x, \mathbf{k}_T)\Big|_{SIDIS} = -h_{1}^{\perp}(x, \mathbf{k}_T)\Big|_{DY}$$

J.C. Collins, Phys. Lett. B536 (2002) 43

J. Collins, talk at LIGHT CONE 2008

Some indications for the future Drell-Yan experiments

$$\delta A = \frac{1}{P_b f} \frac{1}{\sqrt{N_{sig}}} \sqrt{1 + \frac{N_{sig}}{N_{backg}}}$$

$$\tau = x_a x_b = M^2 / s$$

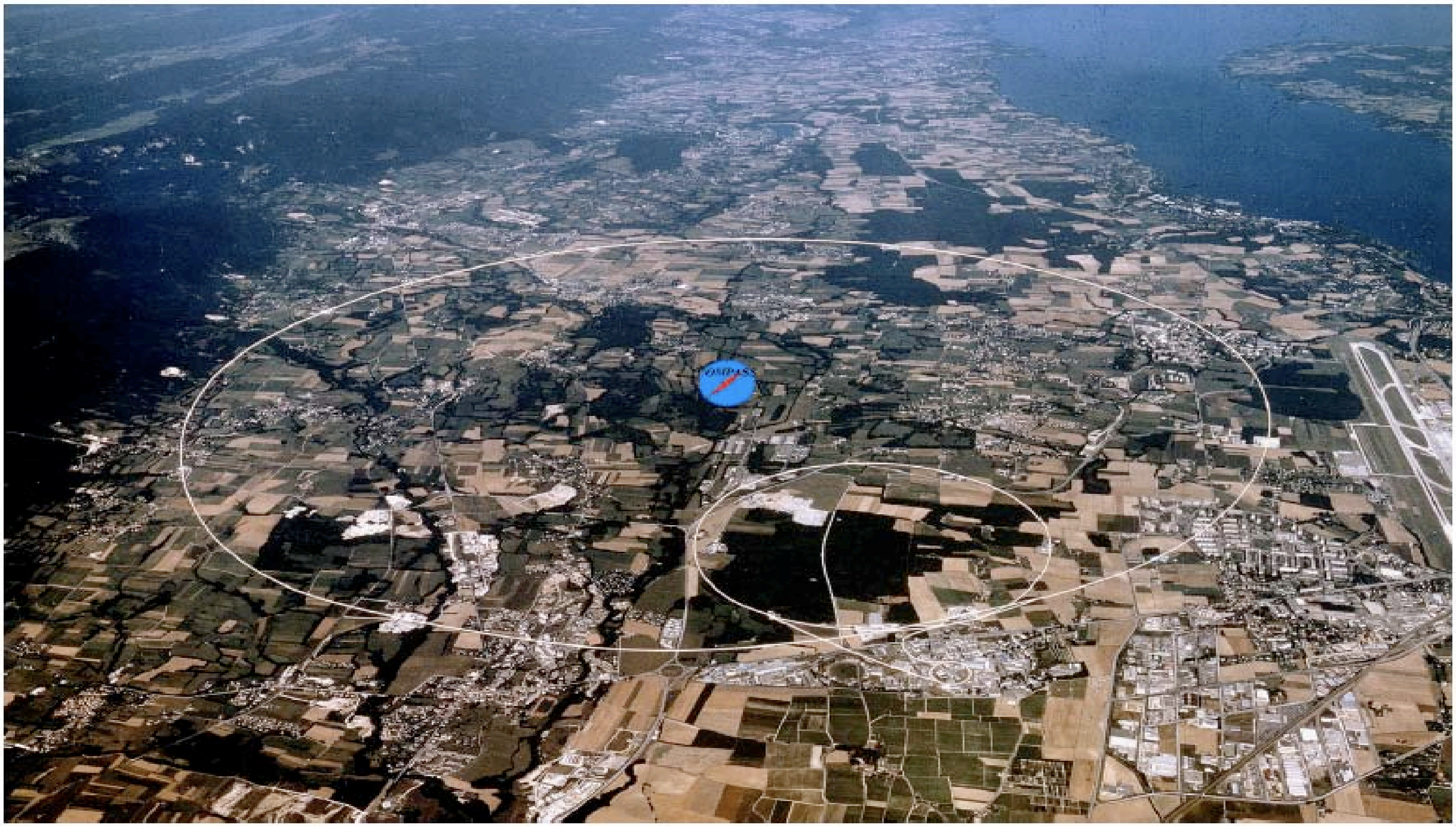
1. Drell-Yan experiments:
   - High luminosity (DY Cross Section is a fractions of nanobarns) and large angular acceptance, better pion or antiproton beams (valence anti-quark)
   - Sufficiently high energy to access 'safe' of background free M_{ll} range (4 GeV/c < M_{ll} < 9 GeV/c)
   - Good acceptance in the valence quark range $x_B > 0.05$ and kinematic range: $\tau = x_A x_B = M^2/s > 0.1$
2. Polarised Drell-Yan:
   - Good factor of merit (F_m), which can be represented as a product of the luminosity and beam (target) polarisation (dilution factor) ($F_m \sim L \times P_{beam}\ (f)$)

Future Drell-Yan experiment

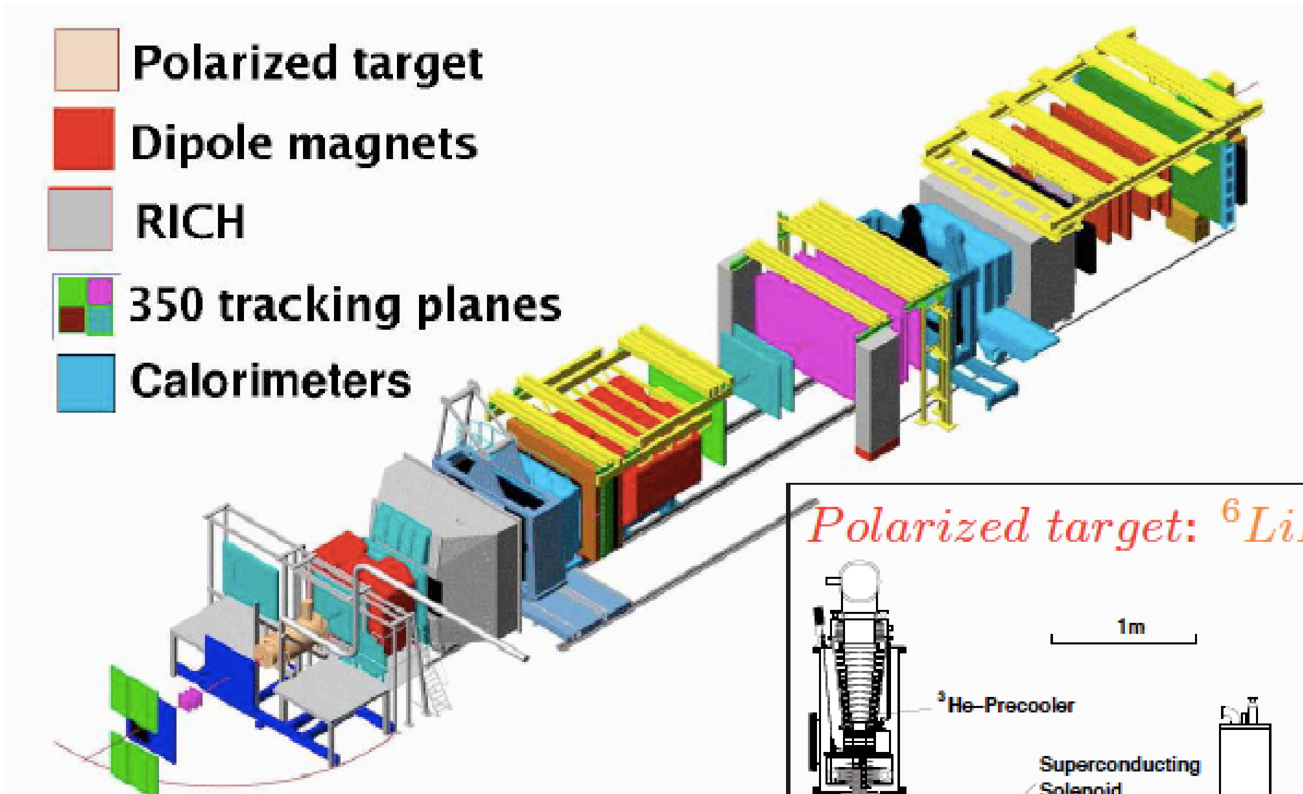
- Fixed target experiments (COMPASS, E906, J-Park, PANDA, RHIC P2) characterised by:
  - Very high luminosity (>10^{33} $cm^{-2}s^{-1}$ apart of RHIC and PANDA))
  - Only muon in the final state (hadron absorber has to be used because of the ‘all forward’ geometry and high luminosity)
  - Light unpolarised targets (liquid hydrogen and deuterium) and solid state polirised targets (NH_3, ^6LD)
  - Pion, proton and antiproton (PANDA and probably COMPASS) beams
- Collider experiments (RHIC, NICA SPD, PAX)
  - Moderate luminosity
  - High universality (not only TMD PDFs, J/Psi and related aspect but also formfactors, various hard processes – not a topic of this talk)

COMPASS facility at CERN (SPS)

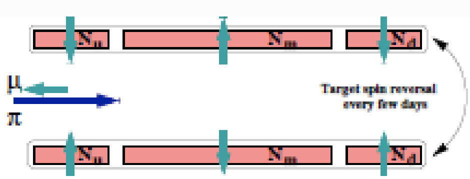
COmmon Muon Proton Apparatus for Structure and Spectroscopy



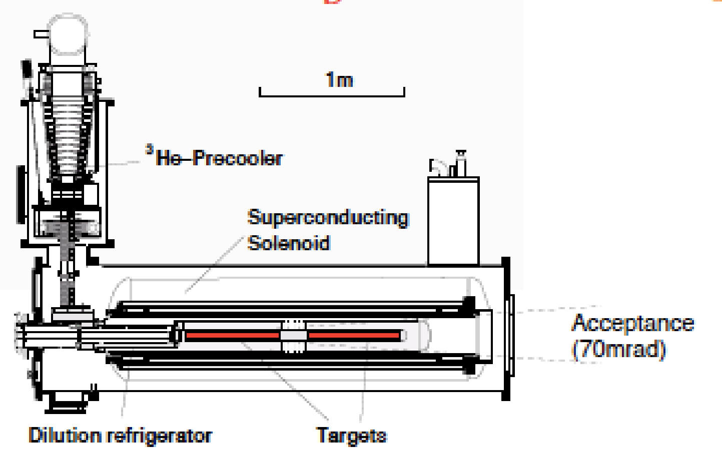
COMPASS experiment at CERN



μ or π beam



Polarized target: ^6LiD or NH_3



Why Drell-Yan @ COMPASS

1. Large angular acceptance spectrometer
2. SPS M2 secondary beams with the intensity up to 10^8 particles per second
3. Large acceptance COMPASS Superconducting Toroidal Magnet
4. Transversely polarized solid state proton target with a large relaxation time and high polarization, when going to spin frozen mode;
5. a detection system designed to stand relatively high particle fluxes;
6. a Data Acquisition System (DAQ) that can handle large amounts of data at large trigger rates;
7. The dedicated muon trigger system

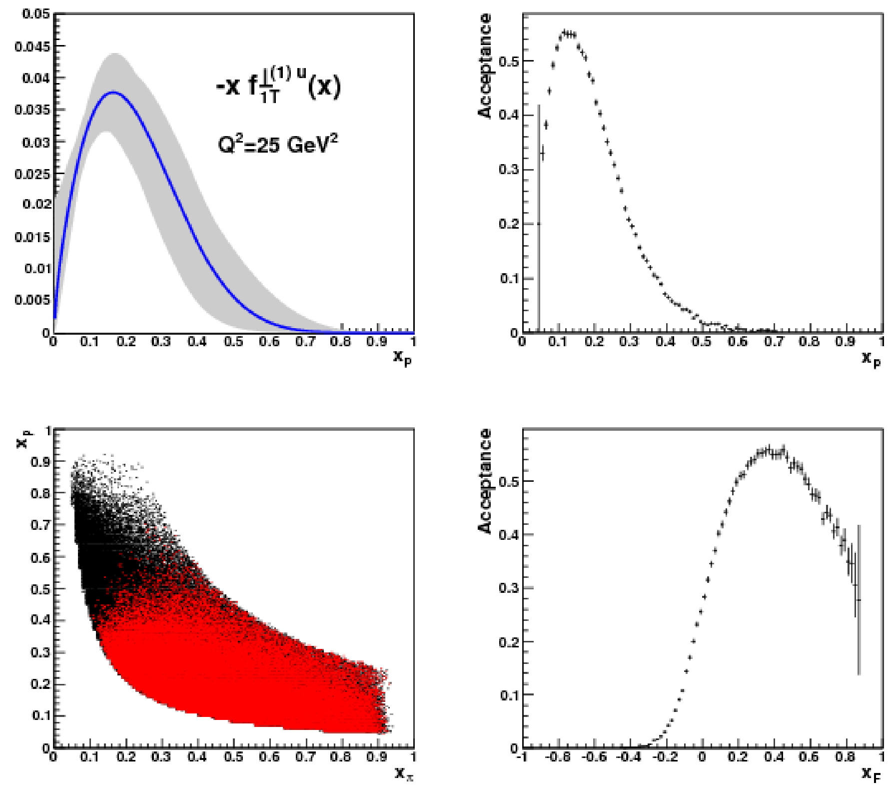
For the moment we consider two step DY program:

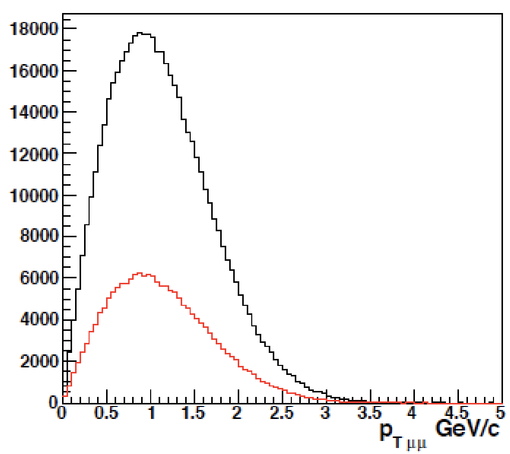
- The program with high intensity pion beam
- The program with Radio Frequency separated antiproton beam

DY@COMPASS – kinematics - valence quark range

$\pi^- p \rightarrow \mu^- \mu X$

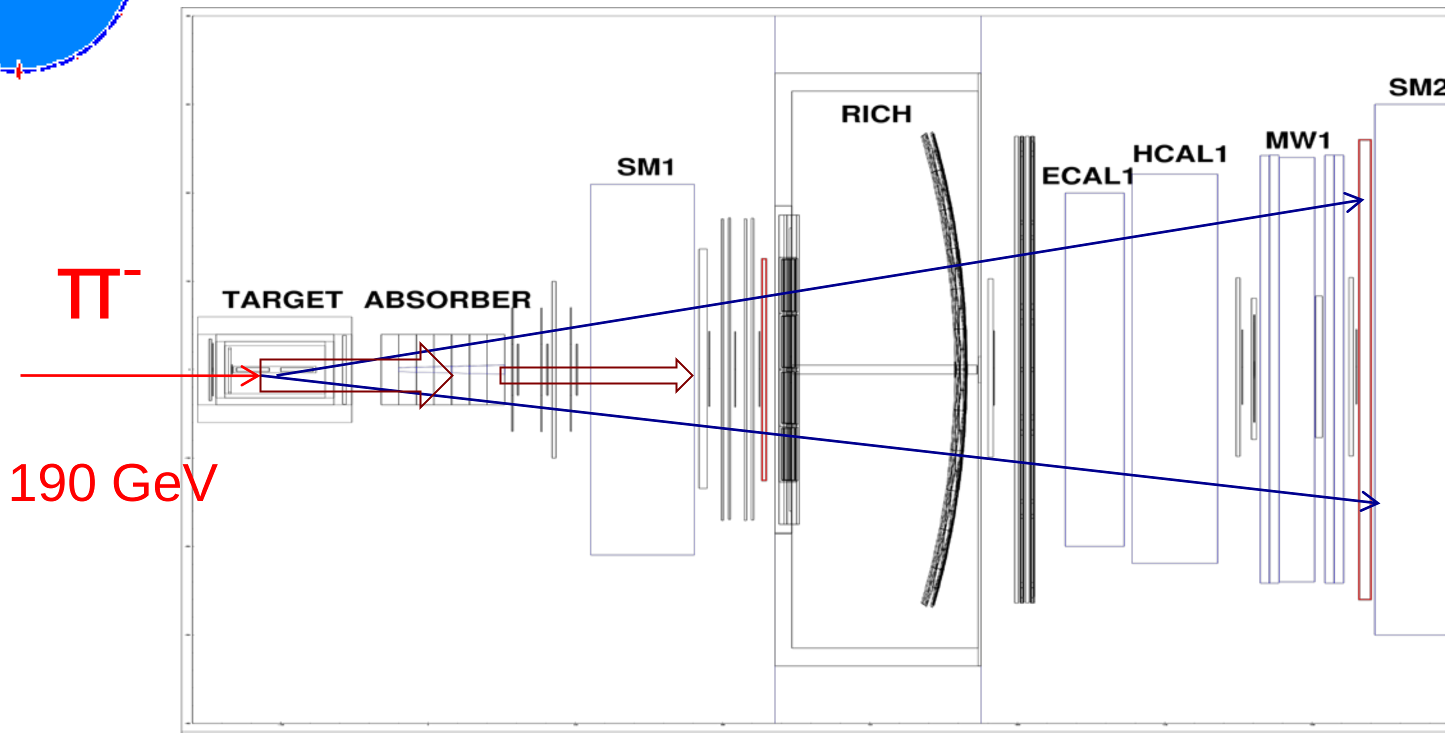
- In our case ($\pi^- p \rightarrow \mu^- \mu X$) contribution from valence quarks is dominant
- In COMPASS kinematics u-ubar dominance
- $\langle P_T \rangle \sim$ 1GeV – TMDs induced effects expected to be dominant with respect to the higher QCD corrections





DY@COMPASS - set-up

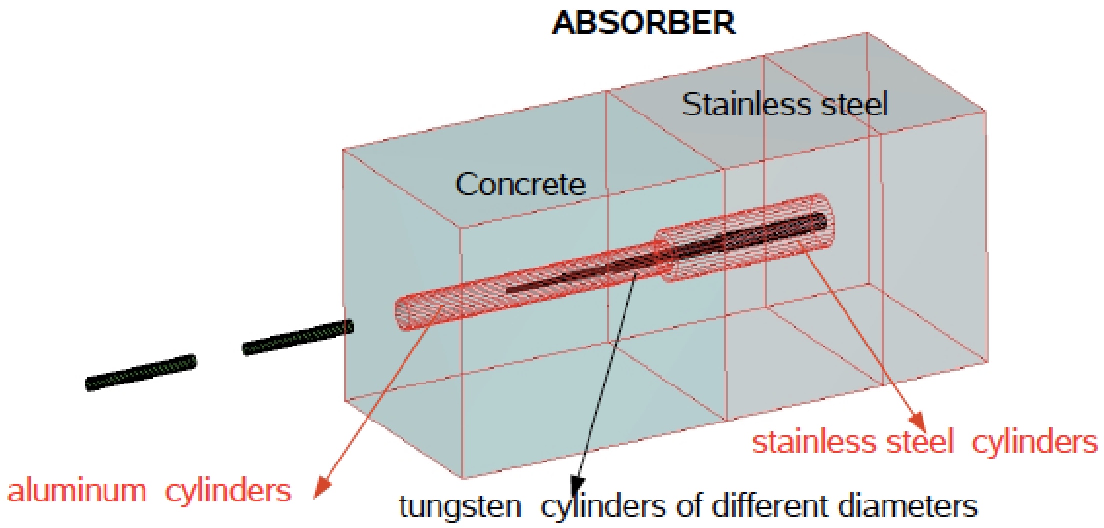
$\pi^- p \rightarrow \mu^- \mu X$



Key elements:

1. COMPASS PT
2. Tracking system (both LAS abs SAS) and beam telescope in front of PT
3. Muon trigger (in LAS is of particular importance - 60% of the DY acceptance)
4. RICH1, Calorimetry – also important to reduce the background (the hadron flux downstream of the hadron absorber ~ 10 higher then muon flux)

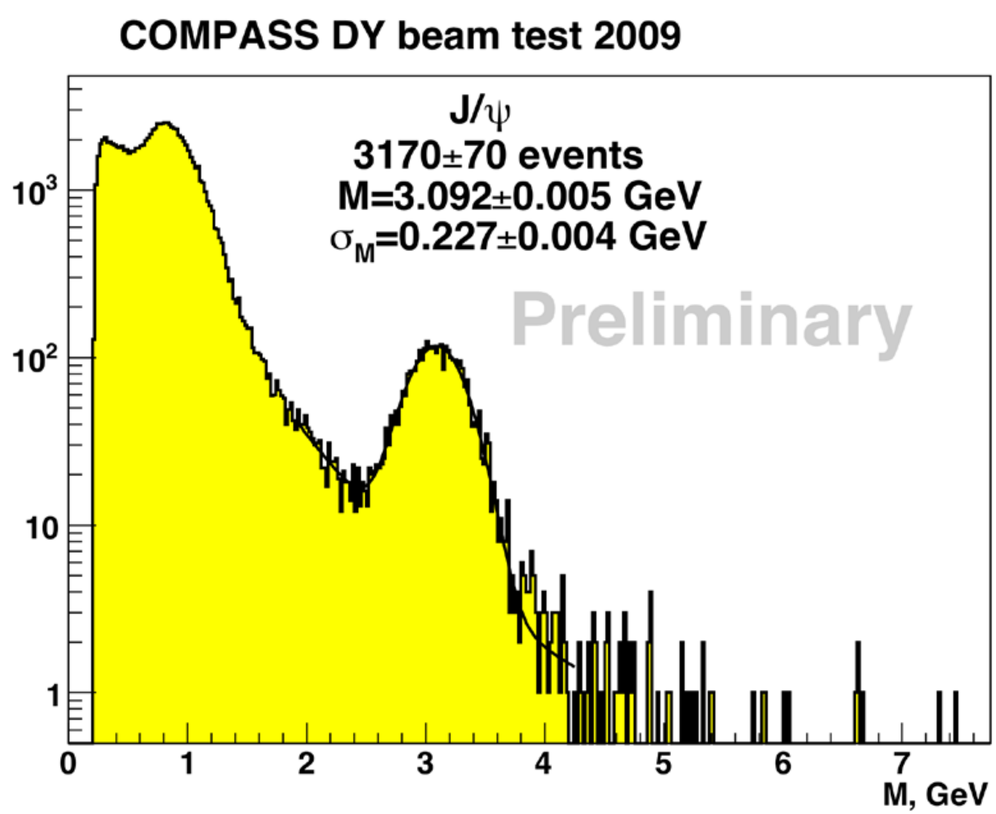
DY Feasibility@COMPASS
Beam Test 2009 – very important (2007, 2008)



DY Feasibility@COMPASS
Beam Test 2009 (with hadron absorber III)

DY@COMPASS - feasibility - Signal

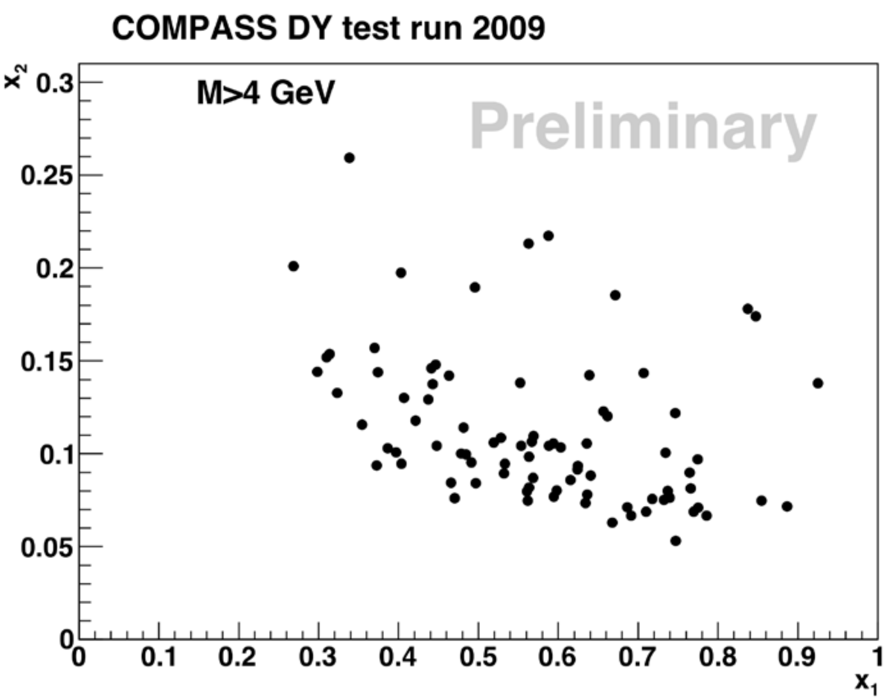
- Expected according to the proposal J/Psi and Drell-Yan yields: 3600 ± 600 and 110 ± 22 (normalized to 2009 beam flux ~3.7 x 10^{11})
- Measured in 2009 beam test J/Psi yield is 3170 ± 70, and DY yield is 84

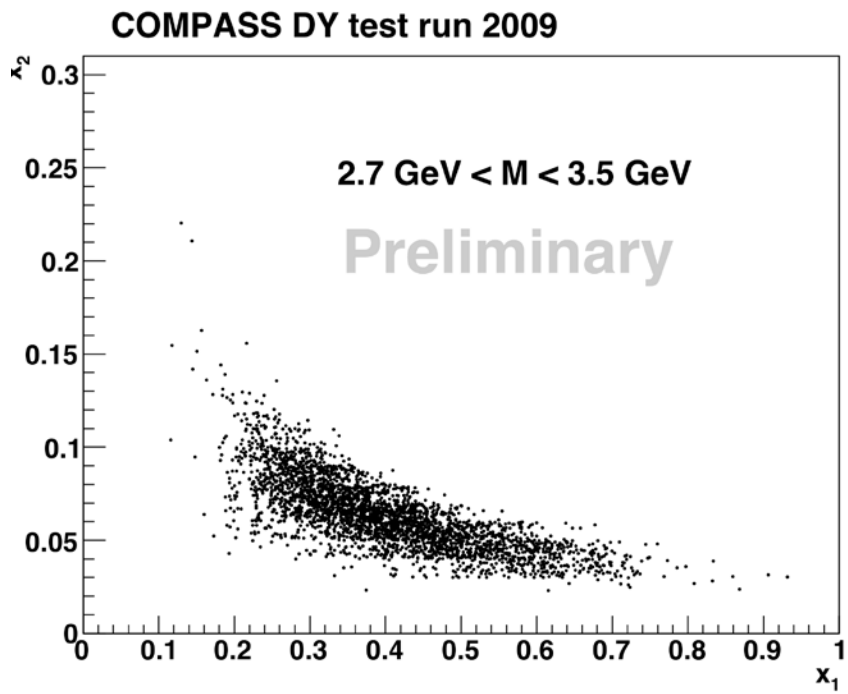


DY@COMPASS - feasibility – Kinematics I

- Valence quark range for both J/Psi and DY

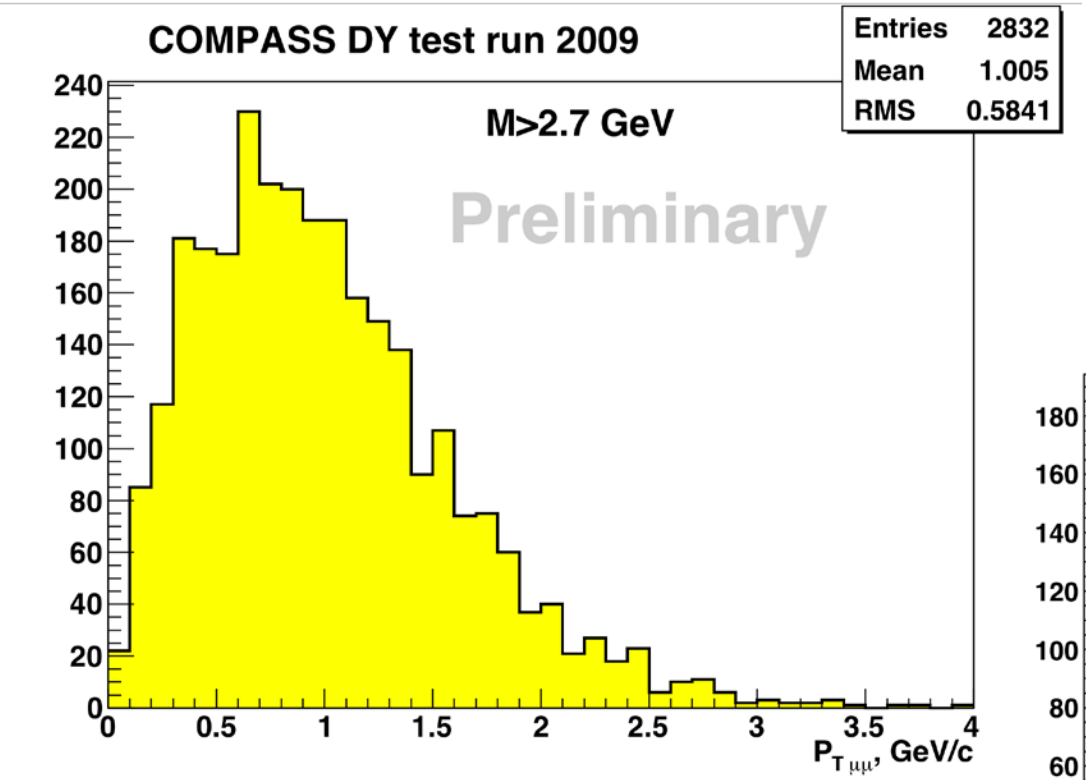
$$x_1 = \frac{Q^2}{P_1 q},$$
$$x_2 = \frac{Q^2}{P_2 q},$$
$$x_f = x_1 - x_2,$$

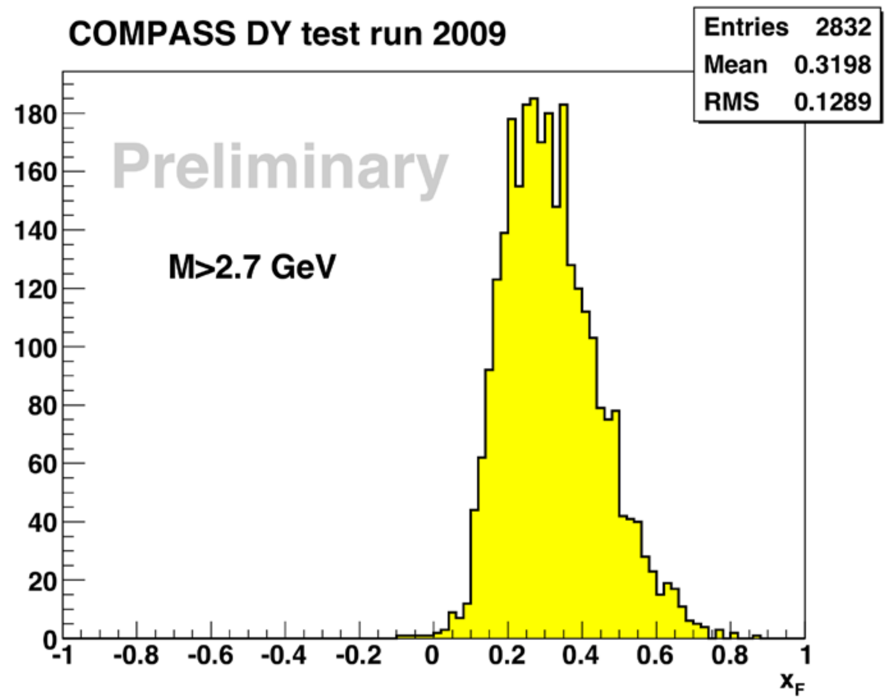




DY@COMPASS - feasibility – Kinematics II

q_T and x_F ranges





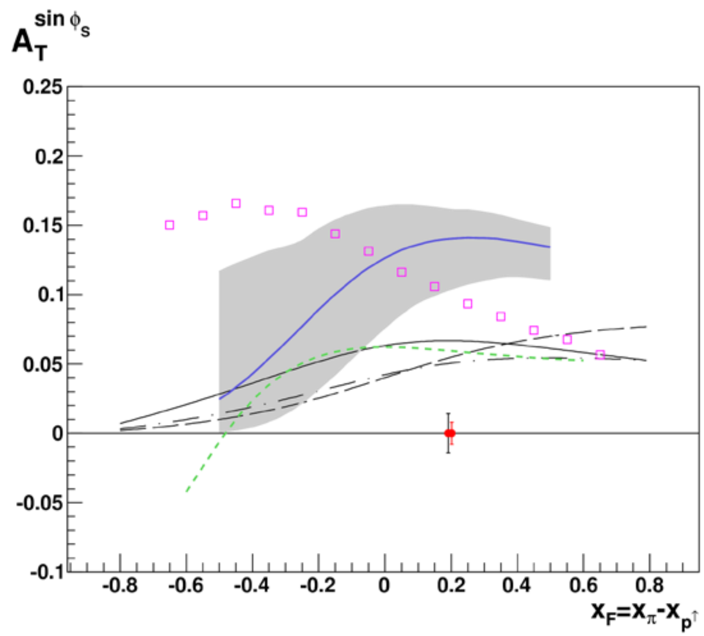
DY@COMPASS projections I

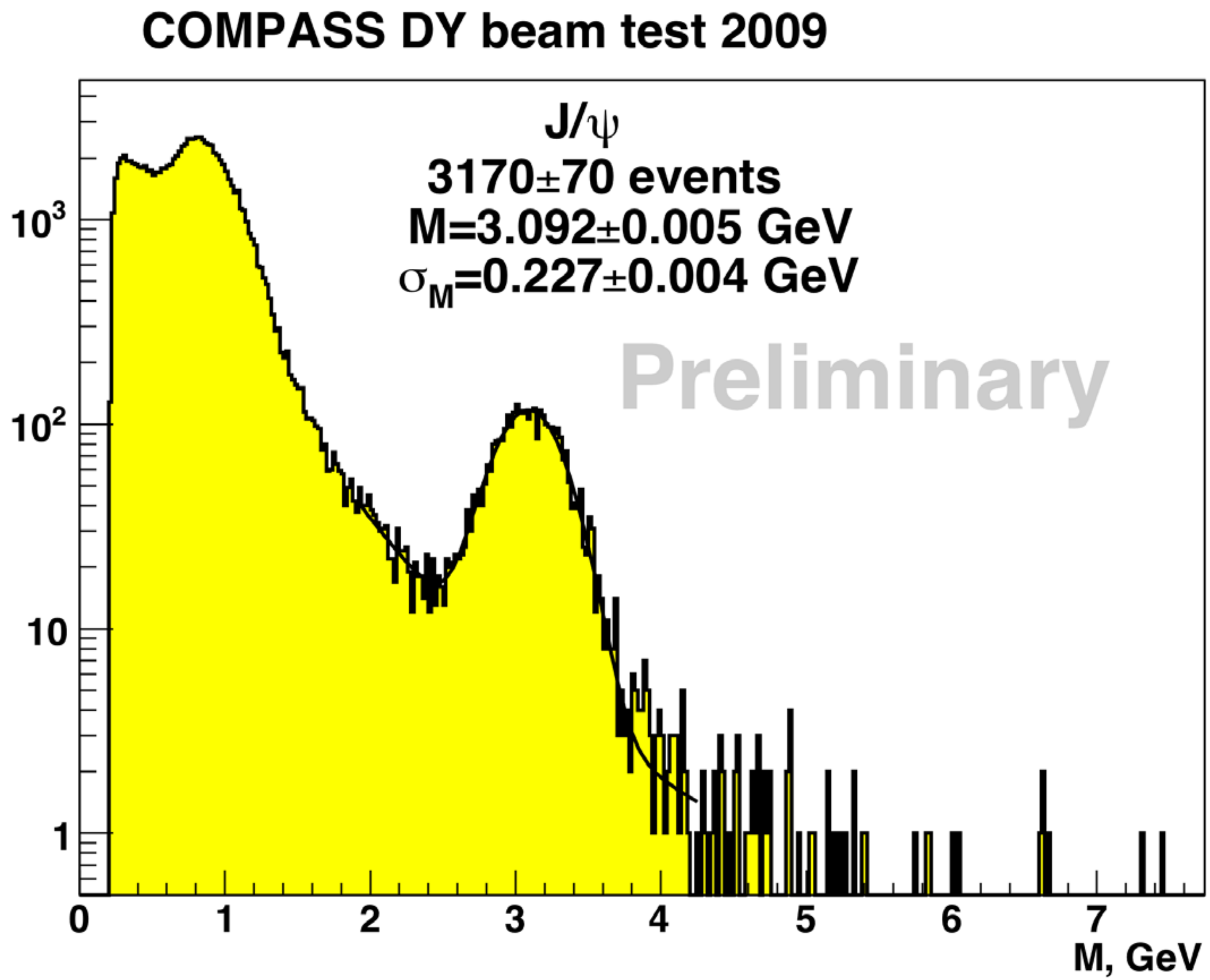
With a beam intensity $I_{beam} = 6 \times 10^7$ particles/second,
a luminosity of $L = 1.7 \times 10^{33}\ cm^{-2}s^{-1}$ can be obtained.

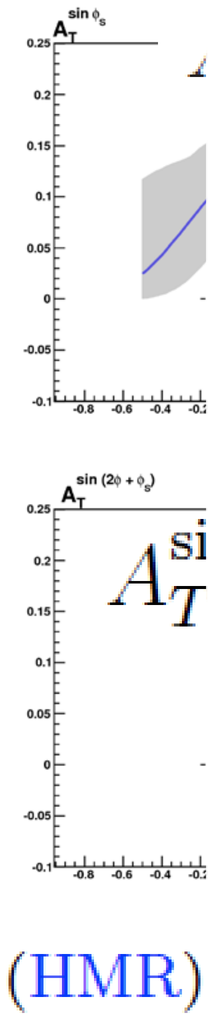
↪ Assuming 2 years of data-taking, one can collect > 200000 DY events in the region $4 < M_{\mu\mu} < 9.$ GeV/c^2.

Predictions for the Sivers asymmetry in the COMPASS phase-space, for the mass region $4. < M < 9.$ GeV/c^2, compared to the expected statistical errors of the measurement:

- solid and dashed: Efremov et al, PLB612(2005)233;
- dot-dashed: Collins et al, PRD73(2006)014021;
- solid, dot-dashed: Anselmino et al, PRD79(2009)054010;
- boxes: Bianconi et al, PRD73(2006)114002;
- short-dashed: Bacchetta et al, PRD78(2008)074010.

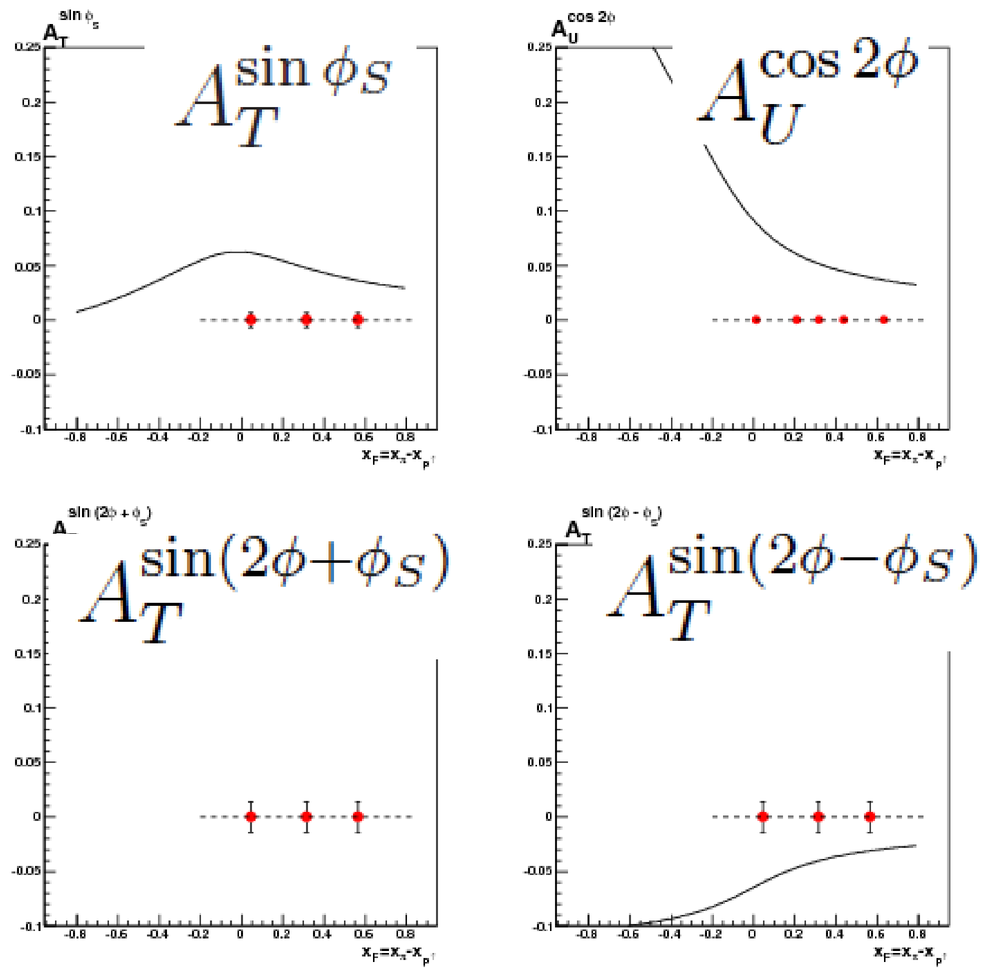



COMPASS DY beam test 2009
J/ψ
3170±70 events
M=3.092±0.005 GeV
σ_M=0.227±0.004 GeV
Preliminary
10^3
10^2
10
1
0
1
2
3
4
5
6
7
M, GeV


(HMR)

DY@COMPASS projections III

J/ψ region: $2.9 \leq M_{\mu\mu} \leq 3.2\ \mathrm{GeV/c^2}$



COMPASS: Summary

- Pion and, later, antiproton beams (50-200 GeV), Drell-Yan process dominated by the contribution from the valence quarks (both beam and target), $\tau = x_1 x_2 = Q^2/s \cong 0.05 \div 0.3$
- Solid state polarised targets, NH_3 and ^6LD, in case of hydrogen target – pure u-dominance
- Statistical error on single spin asymmetries is on the level $1 \div 2\%$
- Proposal has been submitted to the committee on May 17th
- The presentation of the proposal and first discussion in the SPS Committee is scheduled on Tuesday June 29th.
- Start date ≥ 2013

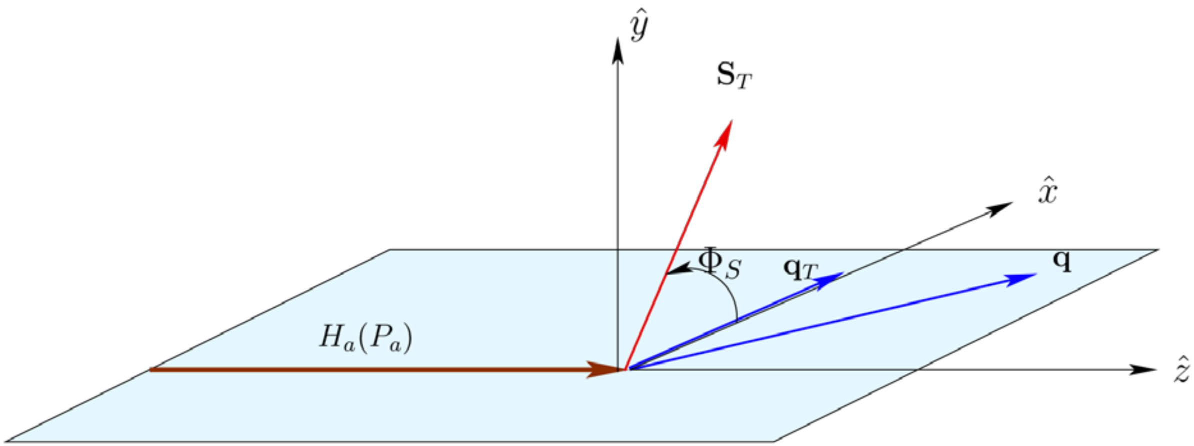
TMDs at Drell-Yan: road map

- 2010 – COMPASS polarised SIDIS data (Sivers, transversity via global data fit)
- 2010 – 2013? E906 (SeaQuest) – pp Drell-Yan – Boer-Mulders of the proton
- 2013 - 2016 COMPASS polarised Drell-Yan pi-p data – TMDs universality and T-odd TMDs sign change SIDIS←→DY (for Boer-Mulders funtion study the input from E906 as well as new transversity fit from the global data analysis is very welcome)
- 2015 → …… RHIC, NICA pp (un)polarised DY data – very welcome – complimentary to COMPASS
- 2020 → GSI antiproton data
- MANY NEW data - just behind the corner

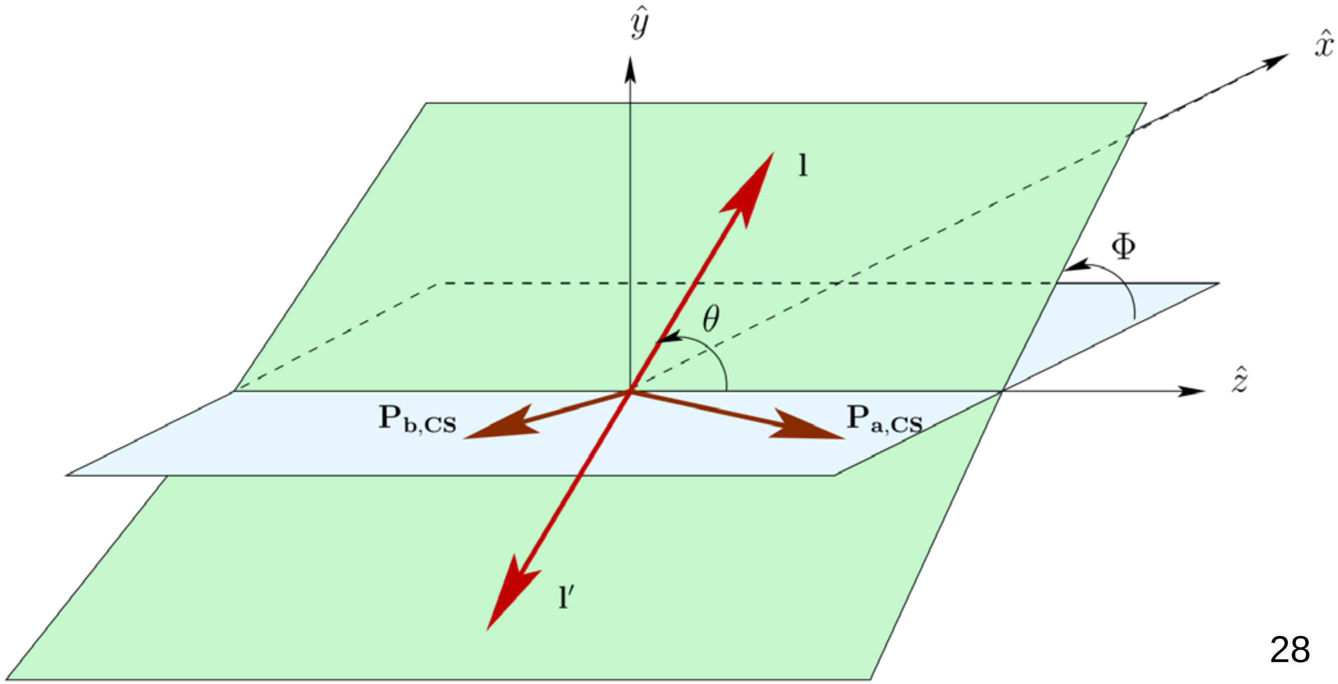
- Spares

Coordinate systems

TF



Collins-Soper



Drell-Yan Workshop at CERN, April 26-27

Studying the hadron structure in Drell-Yan reactions

26-27 April 2010 *CERN*

Since a long time the Drell-Yan (DY) process is considered to be a powerful tool to study hadron structure. In the past, several experiments were successfully carried out using unpolarised beams and targets. Nowadays, taking into account the much advanced understanding of the spin structure of the nucleon, we are discussing a new generation of DY measurements using polarised beams and/or targets.

The COMPASS collaboration is currently preparing a proposal for future studies of nucleon structure beyond 2011. One of the main aims is a first measurement of transverse-momentum-dependent parton distributions (TMDs) using the Drell-Yan process on a transversely polarised proton target hit by a pion beam. Among the distributions to be studied are Sivers, Boer-Mulders and pretzelosity TMDs as well as transversely polarised quark distributions.

The workshop will review ongoing theoretical and experimental efforts related to the Drell-Yan process. Detailed presentations and discussions of the theoretical aspects will be complemented by descriptions of planned fixed-target and collider experiments.

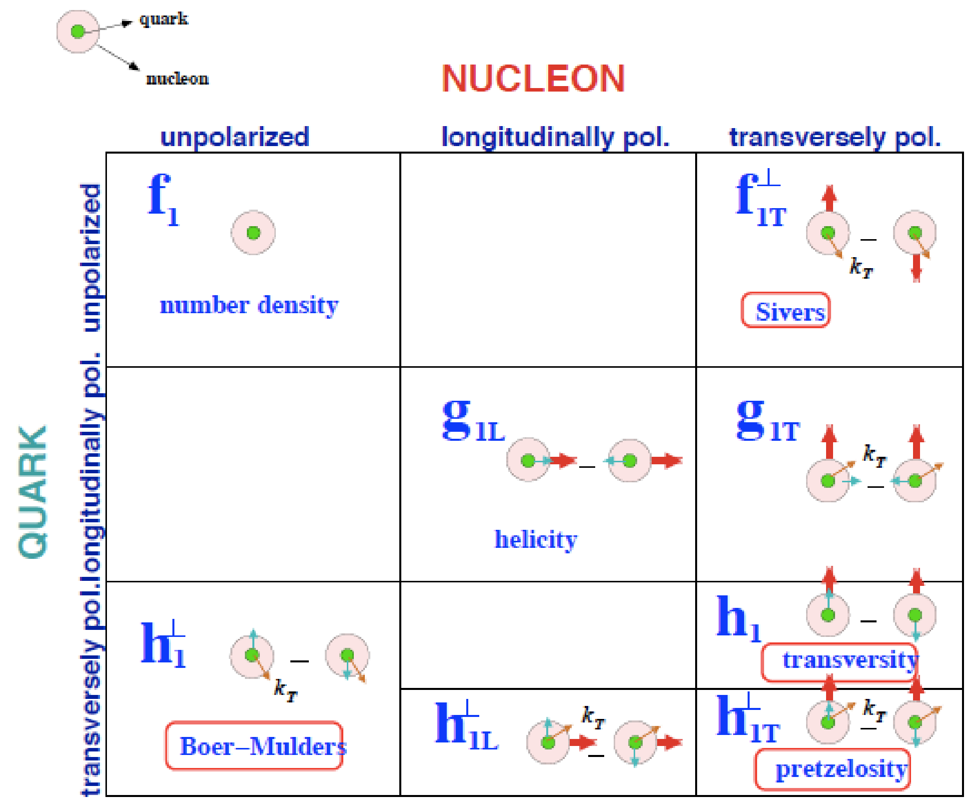
Organizers: Paula Bordalo (LIP-Lisbon and IST/UTL)
Oleg Denisov (CERN/INFN-Torino)
Eva-Maria Kabuss (Mainz)
Fabienne Kunne (CEA Saclay)
Alain Magnon (CEA Saclay)
Gerhard Mallot (CERN)
Anna Martin (Univ. Trieste and INFN-Trieste)
Wolf-Dieter Nowak (CERN)
Daniele Panzieri (Univ. Alessandria and INFN-Torino)

Dates: from 26 April 2010 09:00 to 27 April 2010 18:00

Location: *CERN*
Salle Andersson
Room: 40-S2-A01

Parton distribution functions

Taking into account the intrinsic transverse momentum k_T of quarks, at LO **8 PDFs** are needed for a full description of the nucleon:

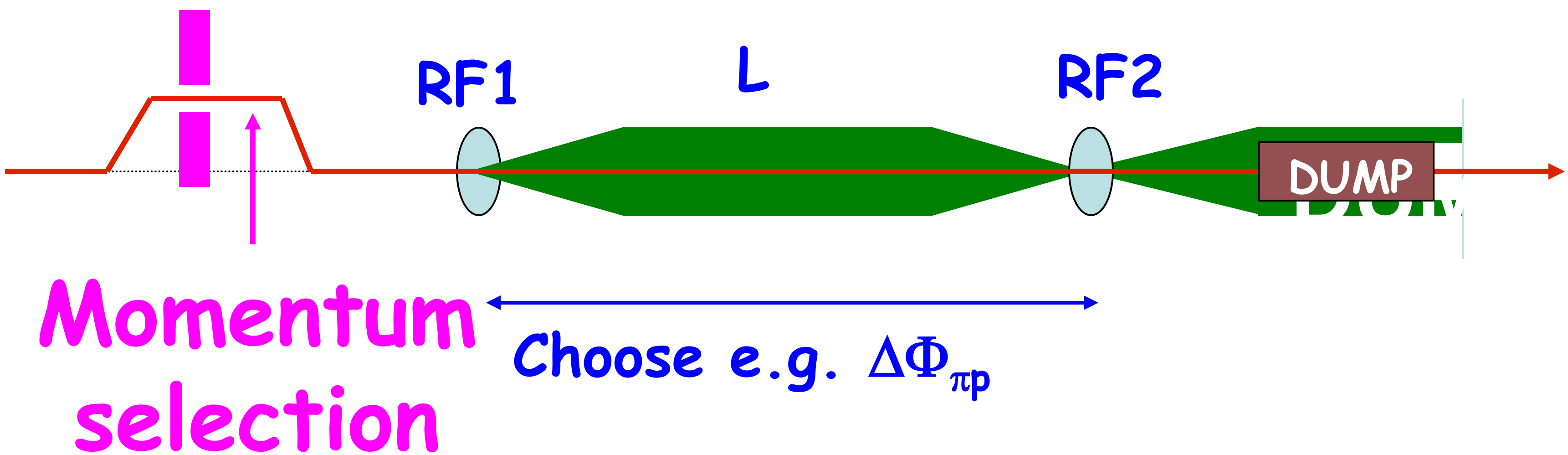


WHAT ABOUT A RF SEPARATED $\bar{p}$ BEAM ???

First and very preliminary thoughts, guided by

- recent studies for P326
- CKM studies by J.Doornbos/TRIUMF, e.g. http://trshare.triumf.ca/~trjd/rfbeam.ps.gz

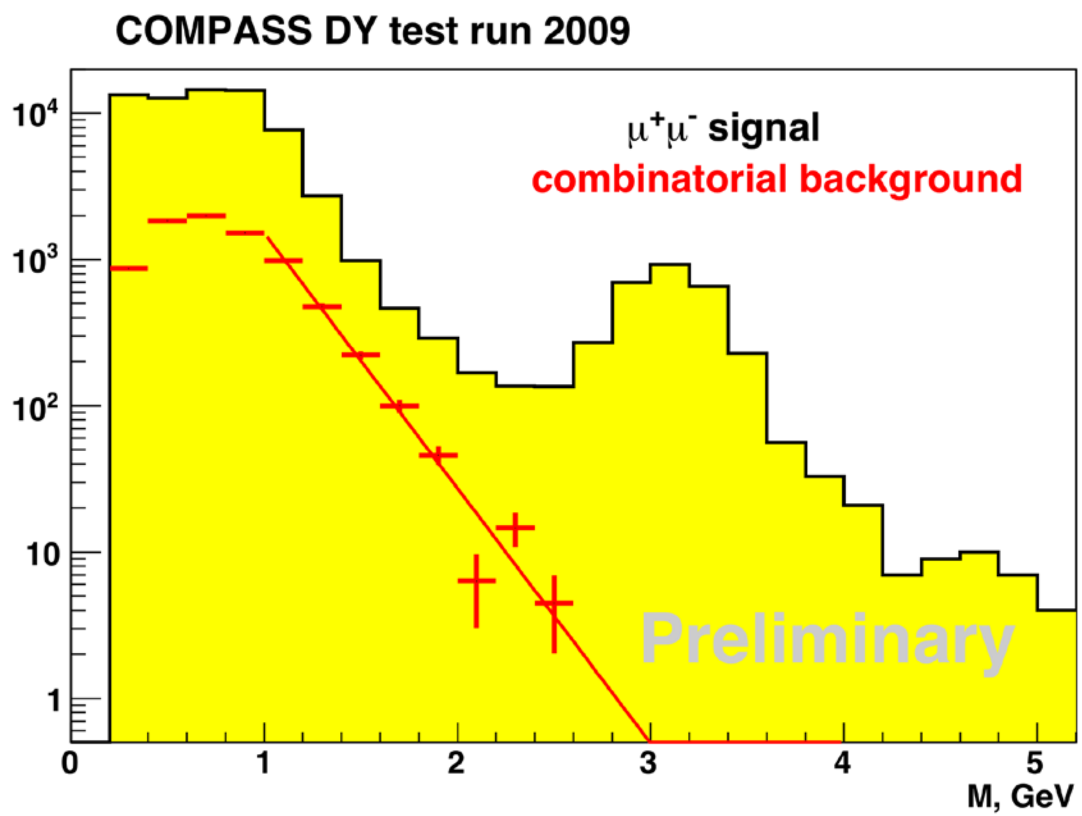
E.g. a system with two cavities:



$$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1}) \text{ with } \beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$$

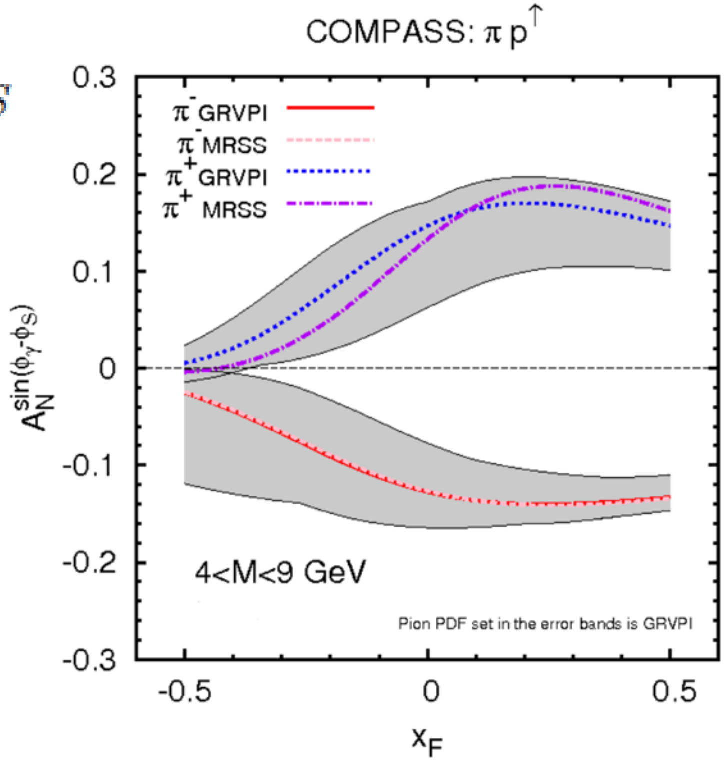
DY@COMPASS - feasibility – Background II – Combinatorial

- 2009 beam test id very important
- Combinatorial background suppressed by ~10 at 2.0 GeV/c dimuon invariant mass (beam intensity ~8 times lower wrt Proposal)



DY@COMPASS uncertainty coming from the pion PDFs

$A_T^{\sin \phi_S}$



In case of $\pi^- p$ scattering the valence pion $\bar{u}$ unpolarised PDF is well known and there is no difference between two pdf sets. In case of $\pi^+ p$ scattering there is a little contamination coming from sea $\bar{u}$ of the pion, which annihilates with valence u quark of the proton, because the distribution functions are weighted in the cross section with e_q^2, and the $\bar{u}u$ contribution is multiplied by factor 4/9 while the $\bar{d}d$ by factor 1/9. Thus, the contribution from the sea $\bar{u}$ of the pion can not be neglected, it is less known with respect to valence PDFs and it explains the difference from one data set (GRVPI) to another (MRSS).