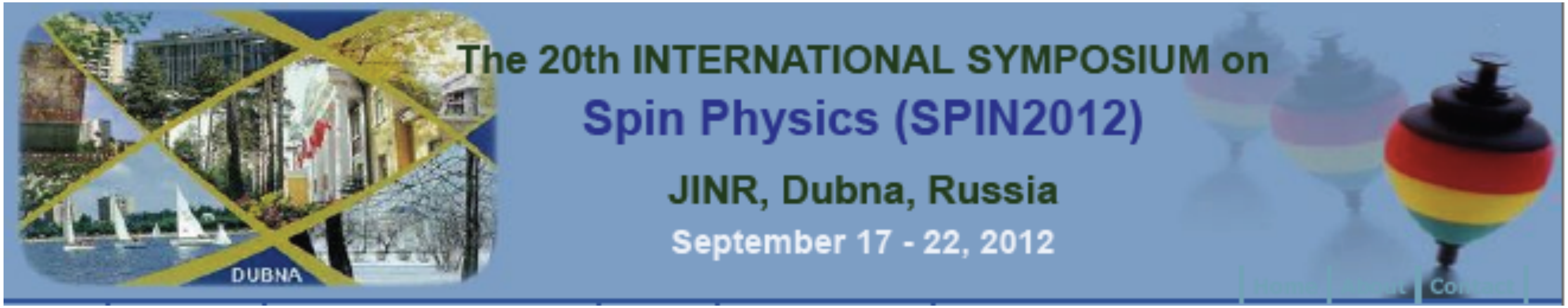


Unpolarised Drell-Yan physics at COMPASS-II

Oleg Denisov
INFN section of Turin
(INFN sezione di Torino)
21.09.2012

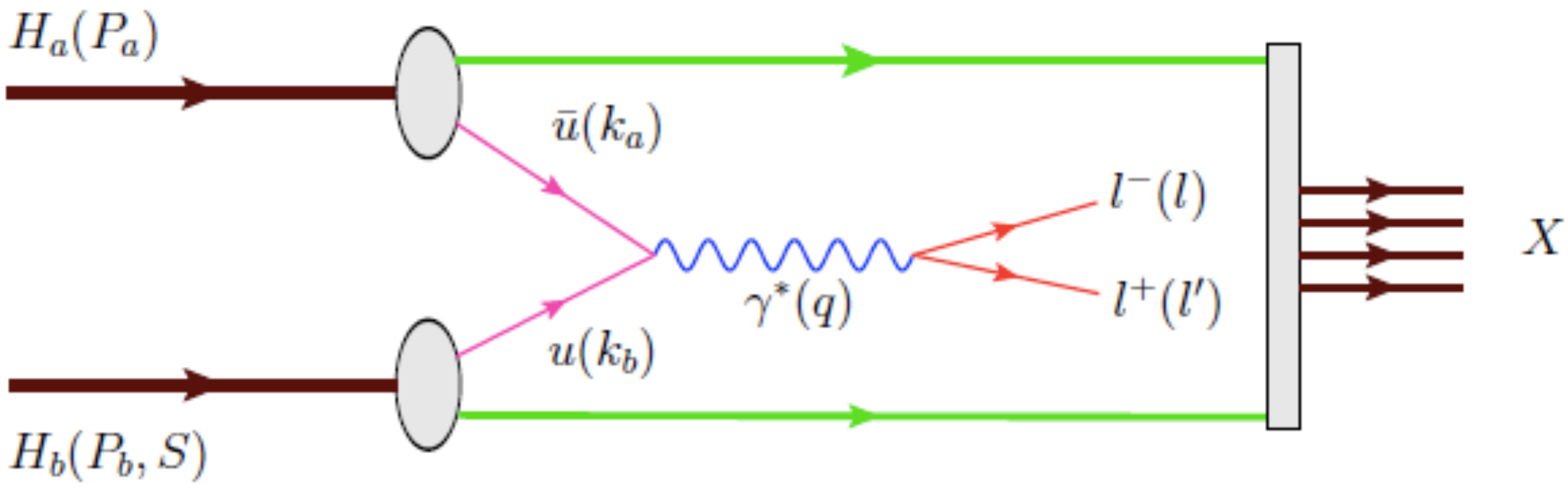
Outline

- Pion-induced Drell-Yan, unpolarised case:
  - Pion structure:
    - Pion PDFs
    - Pion Distribution Amplitude
  - Quark Transverse Momentum Dependent (TMD) effects
    - Higher twist effect
    - Boer-Mulders effect
  - EMC effects – flavour dependence
- Kaon and Antiproton induced DY
- COMPASS-II Drell-Yan experiment
- COMPASS.vs.Past Pion-induced DY experiments
- Very preliminary sensitivity/feasibility study
  - Pion DA
  - Lam-Tung and Higher Twist
  - Boer-Mulders
  - Kaon & (anti)proton structure
- Some conclusions

Drell-Yan at COMPASS

- Main focus is of course on the polarised DY program – first ever polarised DY experiment
- Two logical questions:
  - what kind of unpolarised DY physics we can do in parallel to the polarised DY measurements at NH_3 target (2014 and, most probable 2017)
  - What kind of unpolarised DY physics we can do in longer term future, using liquid hydrogen or liquid deuterium targets
- One have to underline that discussing unpolarised DY program during data taking with polarised target only minimal modifications can be done to the set-up to optimise it for the unpolarised physics

Drell-Yan Process Kinematics

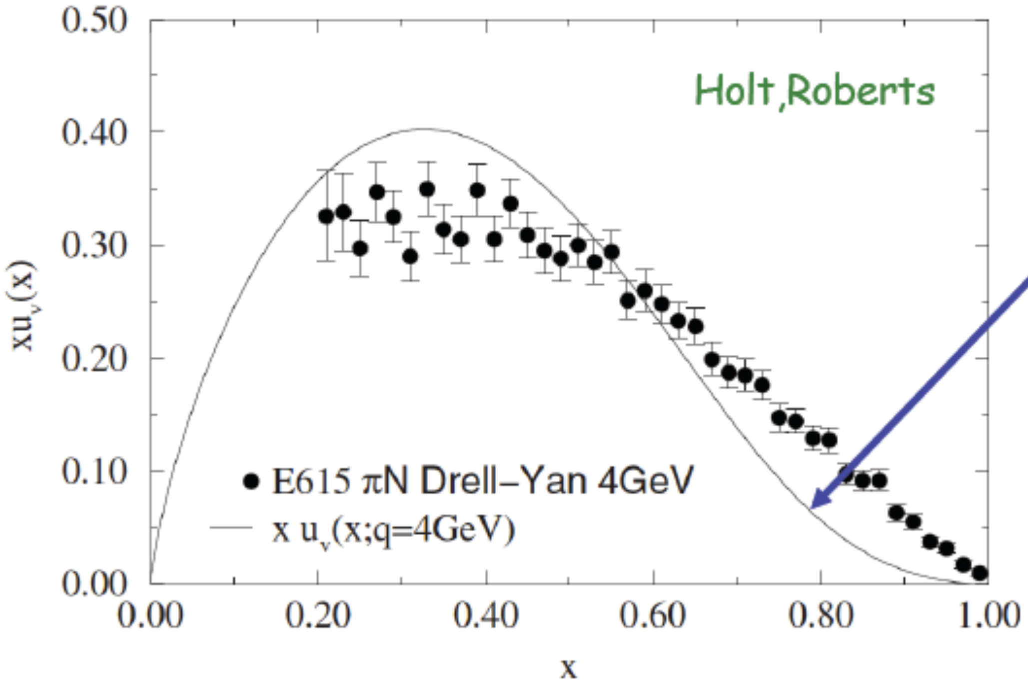


$P_{a(b)}$	the momentum of the beam (target) hadron,
$s = (P_a + P_b)^2$,	the total centre-of-mass energy squared,
$x_{a(b)} = q^2/(2P_{a(b)} \cdot q)$,	the momentum fraction carried by a parton from $H_{a(b)}$,
$x_F = x_a - x_b$,	the Feynman variable,
$M_{\mu\mu}^2 = Q^2 = q^2 = s\ x_a\ x_b$,	the invariant 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.

Pion-induced DY, DY Cross section calculations theoretical calculations I

LO – factor ~ 2 missing compare to the real data

- LO extraction of u_v from E615 data: $\sqrt{S} = 21.75\,\mathrm{GeV}$



$\sim (1-x)^2$

QCD counting rules

Farrar, Jackson; Berger, Brodsky; Yuan Blankenbecler, Gunion, Nason

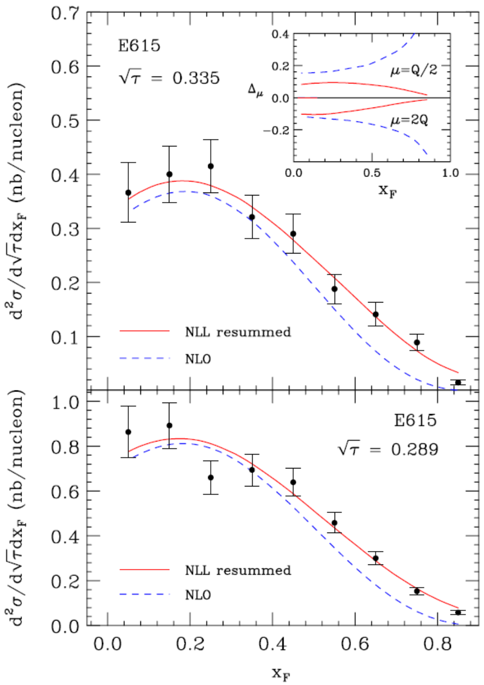
Dyson-Schwinger

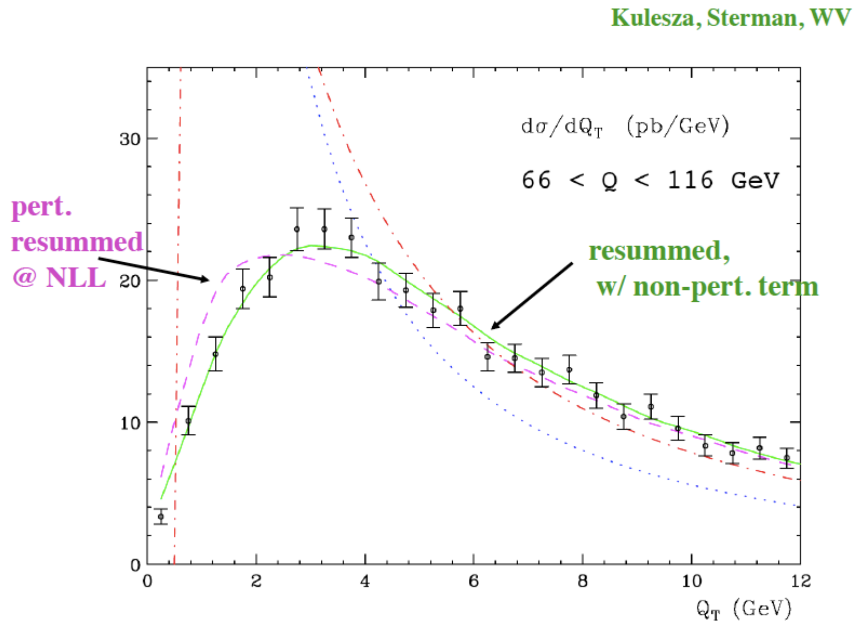
Hecht et al.

Pion-induced DY, DY Cross section calculations theoretical calculations II

Very big progress recently achieved: NLO threshold re-summation mechanism with non-perturbative term (Vogelsang and collab.) - good experimental data description

Aicher et al. (PRL 105, 252003 (2010))

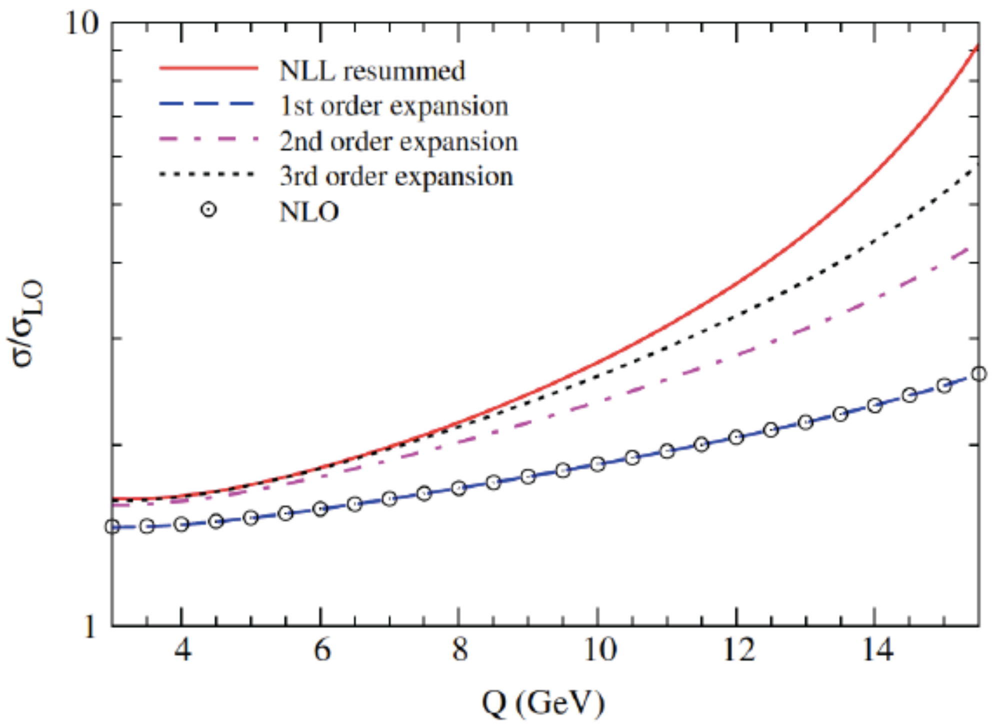




Pion-induced DY, DY Cross section calculations theoretical calculations III - COMPASS

(Compass kinematics)

$$\sqrt{S} = 19\,\mathrm{GeV}$$

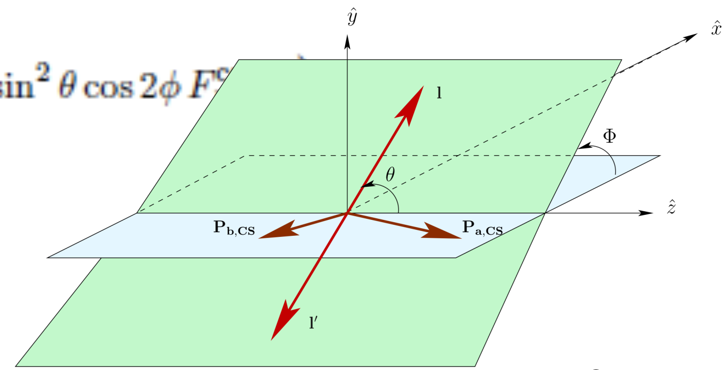


Aicher, Schäfer, WV
(earlier studies: Shimizu, Sterman, WV, Yokoya)

Drell-Yan cross-section – general (full) angular distribution

2008: S. Arnold, (Ruhr U., Bochum) , A. Metz, (Temple U.) , M. Schlegel, (Jefferson Lab)
Phys.Rev.D79:034005,2009, e-Print: **arXiv:0809.2262**

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



Pion-induced DY, Pion structure functions I

The only way to access pion PDFs

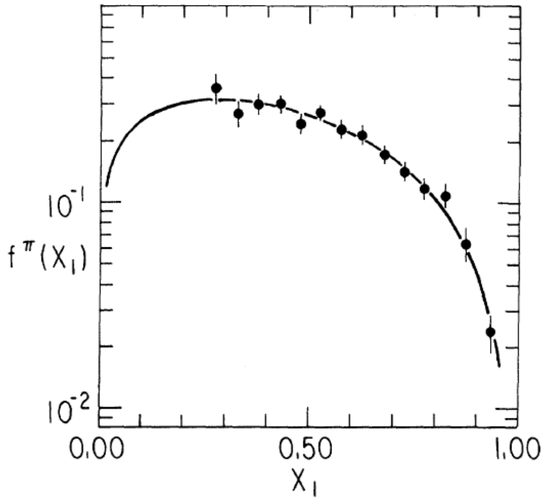
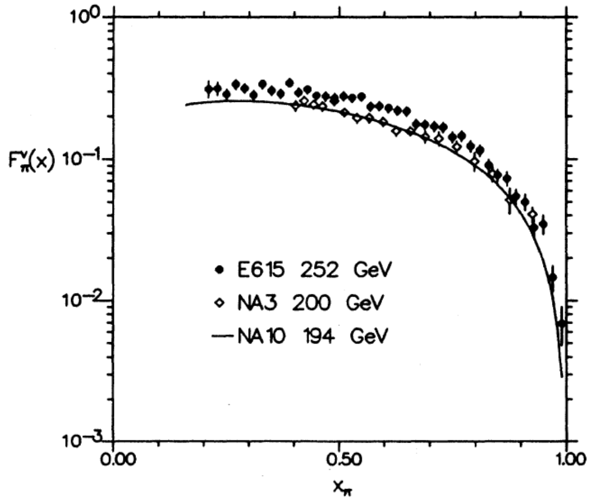


FIG. 3. The pion structure function $f^{\pi}(x_1) = x_1 \bar{u}^{\pi^-}(x_1)$.

CIP (PRL 42, 951, (1979))



E615 (PRD 39, 92 (1989)):

Pion-induced Drell-Yan access to DA I

Very preliminary – feasibility is under discussion now, some indications:

- see talk by O.Teryaev (Friday, Sep. 2): Drell-Yan pair production in the pion-nucleon collisions for large x_F (the region whose exploration is favourable in COMPASS kinematics) is sensitive to such an important and hot ingredient of pion structure as its light-cone distribution amplitude (DA). In other words in this kinematic range pion participate in the interaction coherently (as a two-quark system) rather then by only one of its quark.

References:

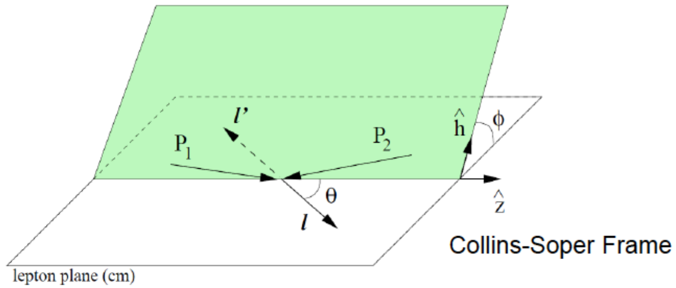
A.Brandenburg, S.J.Brodsky, V.V.Khoze and D.Mueller, Phys.Rev.Lett. 73, 939 (1994)
A.Brandenburg, D.Mueller and O.V.Teryaev, Phys.Rev.D 53, 6180 (1996)
A.P. Bakulev, N.G. Stefanis, O.V.Teryaev, Phys.Rev.D76:074032,2007.

- B.Pire, O.Teryaev: Semi-exclusive DY – crucial test of the GPDs universality (time-like process contrary to the Deep Inelastic scattering)

Reference:

B.Pire, L. Szymanowski, arXiv:0905.1258v1 [hep-ph] 8 May 2009

Pion-induced Drell-Yan, angular distributions of lepton pair, higher twist effects I



$$\frac{d\sigma}{d\Omega} \propto (1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi)$$

LO - $O(\alpha_s^0)\ \lambda=1,\ \mu=\nu=0$

NLO - pQCD: $O(\alpha_s^1)\ 1-\lambda-2\nu=0$

Lam-Tung Relation (1978)

$$\frac{d\sigma}{d\Omega} \propto [W_T(1+\cos^2\theta)+W_L(1-\cos^2\theta)+W_\Delta\sin 2\theta\cos\phi+W_{\Delta\Delta}\sin^2\theta\cos 2\phi]$$

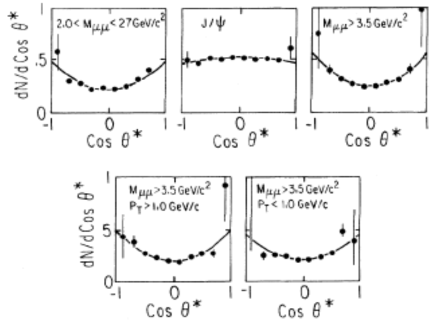
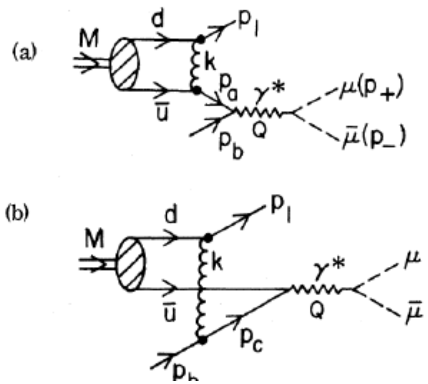
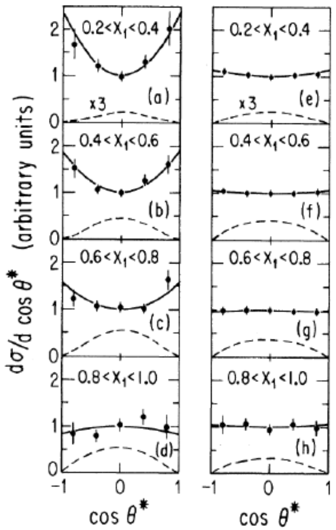


FIG. 3. Helicity angular distributions in three different mass intervals. The $M>3.5$ GeV/c^2 interval is also shown divided in two p_T intervals. The Collins-Soper angle (θ^*) is defined in the text.

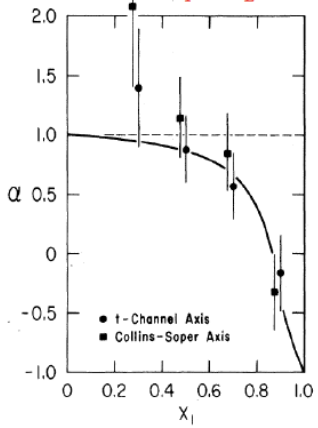
CIP (PRL 42, 948, (1979)) : Transversely Polarized Photon & Scaling of M²/s

$$d\sigma(\Omega) \propto (1+\cos^2\theta)$$





$$\alpha = \frac{W_T-W_L}{W_T+W_L}$$



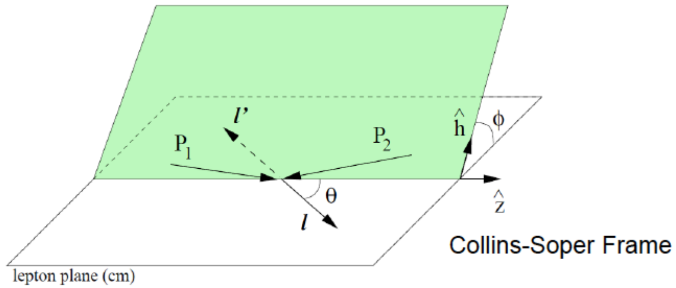
CIP (PRL 43, 1219, (1979)) : Longitudinally Polarized Photon at large x_1

$$d\sigma \propto (1-x_\pi)^2(1+\cos^2\theta)+\frac{4x_\pi^2\langle k_T^2\rangle}{9m_{\mu\mu}^2}\sin^2\theta$$

Berger and Brodsky (PRL 42, 940, (1979)) : Higher Twist Effect at large x_1

10

Pion-induced Drell-Yan, angular distributions of lepton pair, higher twist effects II



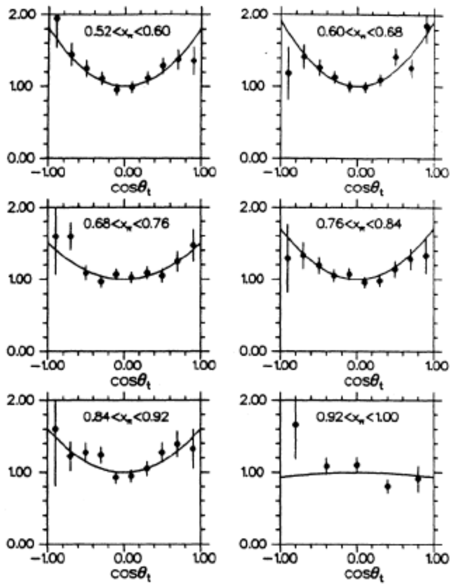
$$\frac{d\sigma}{d\Omega} \propto (1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi)$$

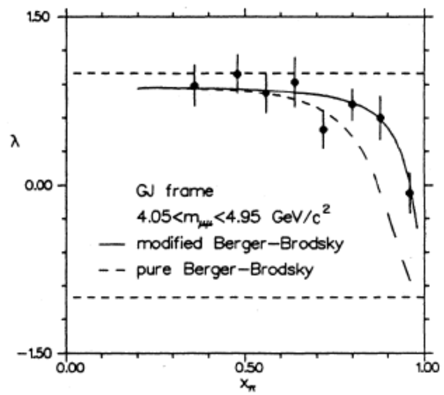
$$O(\alpha_s^0)\ \lambda=1,\ \mu=\nu=0$$

NLO - pQCD: $O(\alpha_s^1)\ 1-\lambda-2\nu=0$

Lam-Tung Relation (1978)

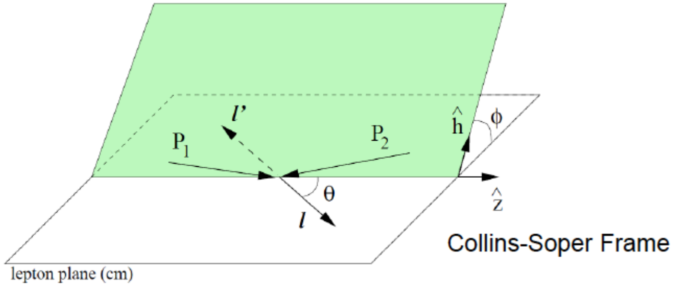
In late 80s NA10 (NA10 (Z. Phys. C 37, 545 (1988)), and E615 (E615 (PRD 39, 92 (1989)) has shown the violation of LT relation





E615 (PRD 39, 92 (1989)):
Higher Twist Effect

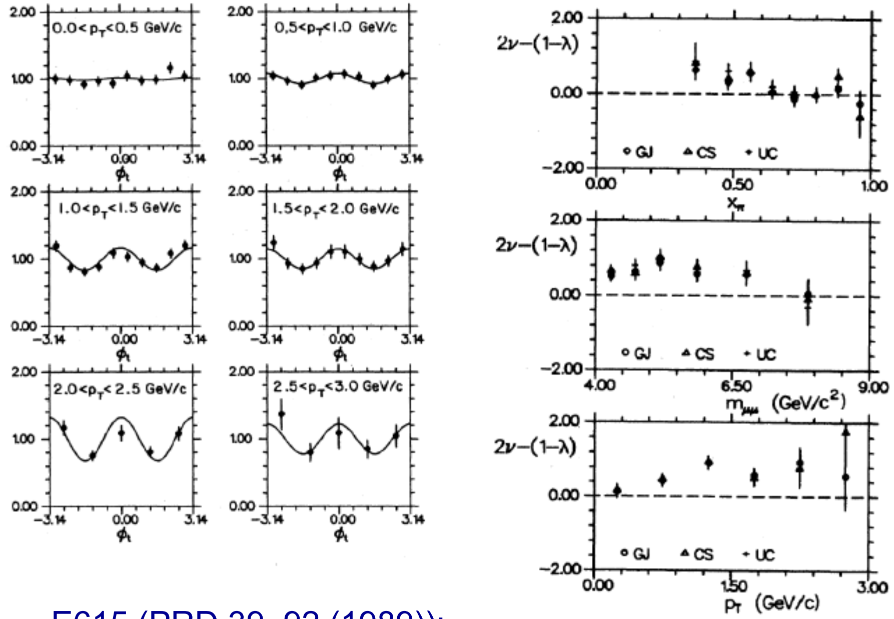
Pion-induced Drell-Yan, angular distributions of lepton pair, Boer-Mulders effect I



$$\frac{d\sigma}{d\Omega} \propto (1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi)$$

NLO - pQCD: $O(\alpha_s^1)$ $1-\lambda-2\nu=0$

Lam-Tung Relation (1978)

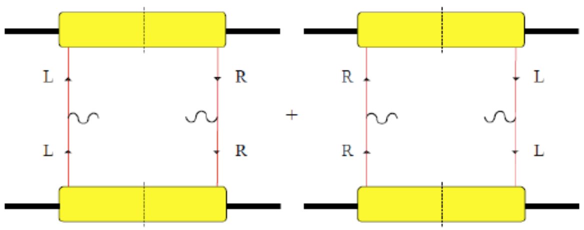


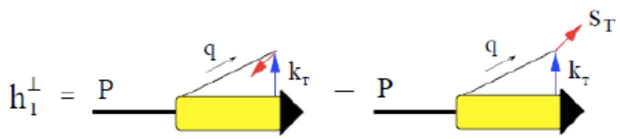
E615 (PRD 39, 92 (1989)): Violation of LT Relation

D. Boer

Angular asymmetry requires helicity flip

The $\cos 2\phi$ asymmetry arises from an interference between $+1$ and -1 photon helicities





- $h_1^\perp$ represents a correlation between quark's k_T and transverse spin in an unpolarized hadron
- $h_1^\perp$ can lead to an azimuthal dependence with $\frac{\nu}{2} \propto h_1^\perp(N)\bar{h}_1^\perp(\pi)$

Hadronic effect →

Pion-induced Drell-Yan, angular distributions of lepton pair, Boer-Mulders effect II

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

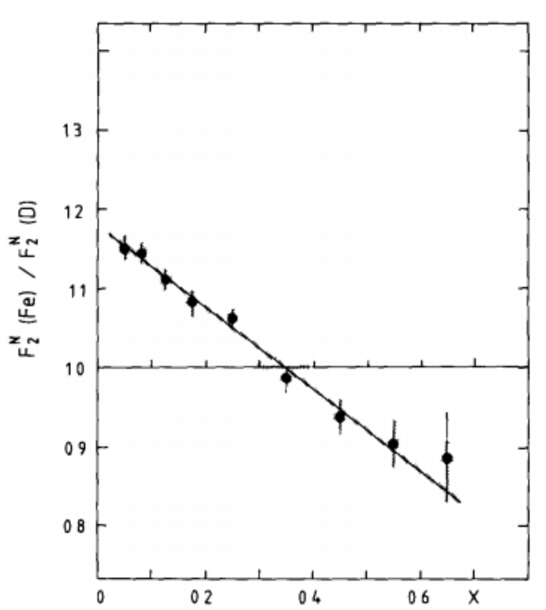
$$
\begin{aligned}
\frac{d\sigma^{LO}}{d^4q\,d\Omega} &= \frac{\alpha_{em}^2}{F\,q^2}\hat{\sigma}_U^{LO}\Big\{\Big(1 + D_{[\sin^2\theta]}^{LO}\,A_U^{\cos 2\phi}\cos 2\phi\Big) \\
&+ S_L D_{[\sin^2\theta]}^{LO}\,A_L^{\sin 2\phi}\sin 2\phi \\
&+ |\vec{S}_T|\Big[A_T^{\sin\phi_S}\,\sin\phi_S + D_{[\sin^2\theta]}^{LO}\Big(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)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

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.

Pion-induced DY, flavour-dependent EMC effect I

EMC effect - experiment



Cloet et. al (PRL 102, 252301, 2009):
Flavor dependence of the EMC effects ?

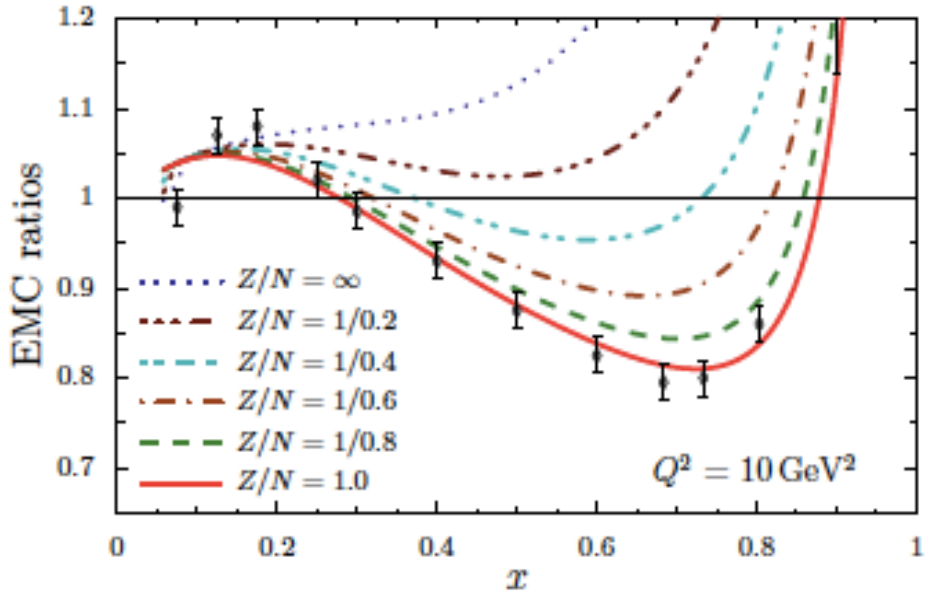
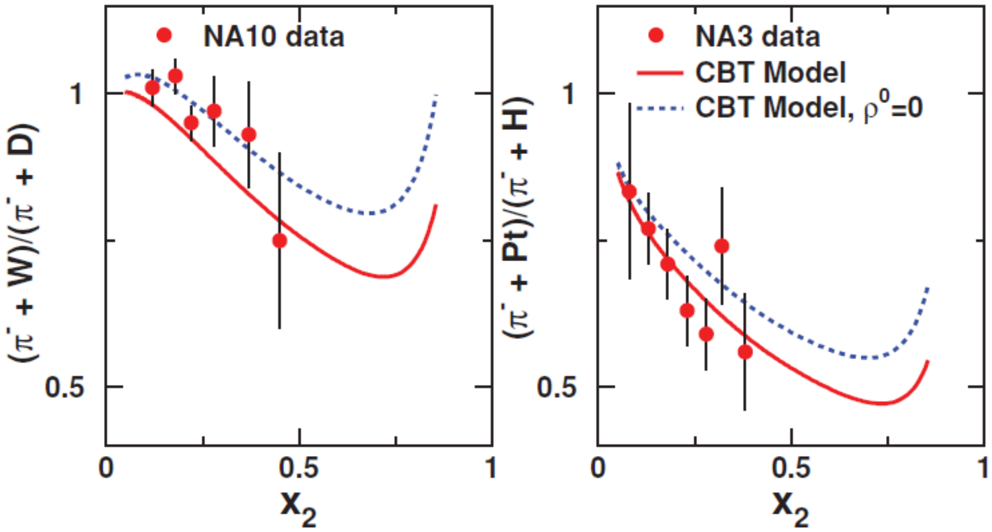


FIG. 1: Isospin dependence of the EMC effect for proton-neutron ratios greater than one. The data is from Ref. [24] and corresponds to $N = Z$ nuclear matter.

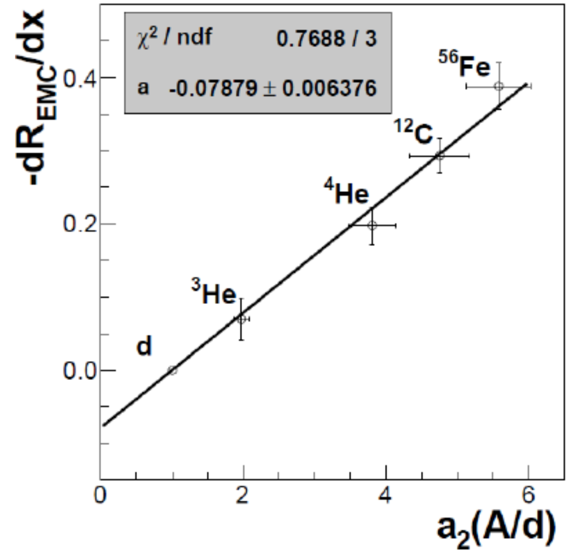
The isovector ρ^0 mean-field generated in Z≠N nuclei can modify nucleon's *u* and *d* PDFs in nuclei.

Pion-induced DY, flavour-dependent EMC effect II

$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$



Dutta et al. (PRC 83, 042201, 2011):
Pion-induced Drell-Yan and the flavor-dependent EMC effect



SRC is related with isoscalar p-n interaction.
→ NO flavor-dependence of EMC effect

Weinstein et al. (PRL 106 , 052301 (2011)):
EMC & Short Range Correlation (SRC)

Kaon and antiproton induced Drell-Yan I

ANY data on kaon or antiproton induced DY will bring us an unique information on kaon and (anti)proton structure.
Very high discovery potential

COMPASS facility at CERN (SPS)

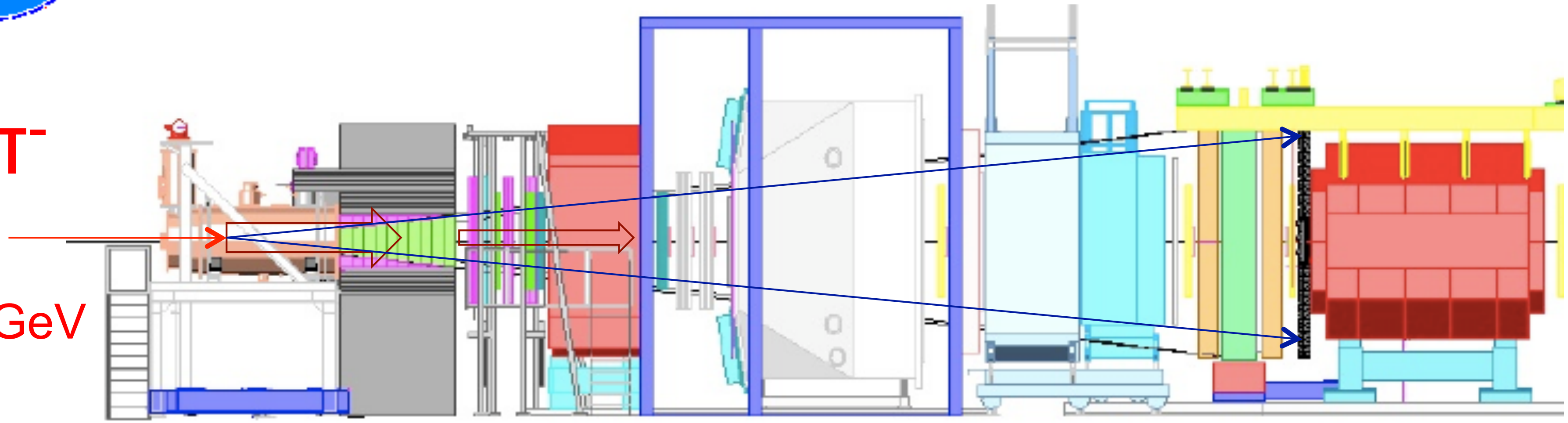
COmmon Muon Proton Apparatus for Structure and Spectroscopy

DY@COMPASS - set-up

$\pi^- p^\uparrow \to \mu^- \mu X$

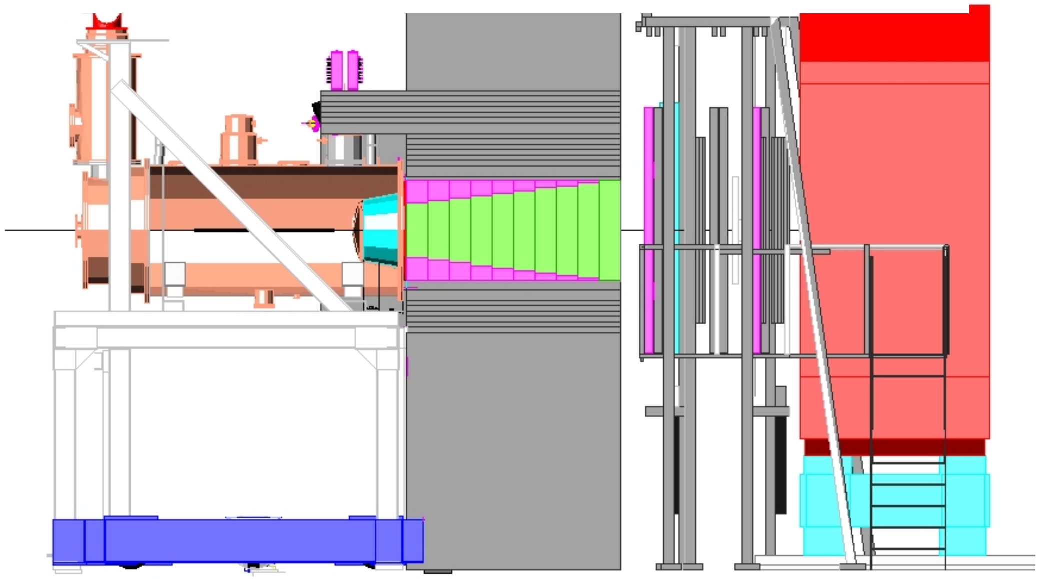
π^-

190 GeV

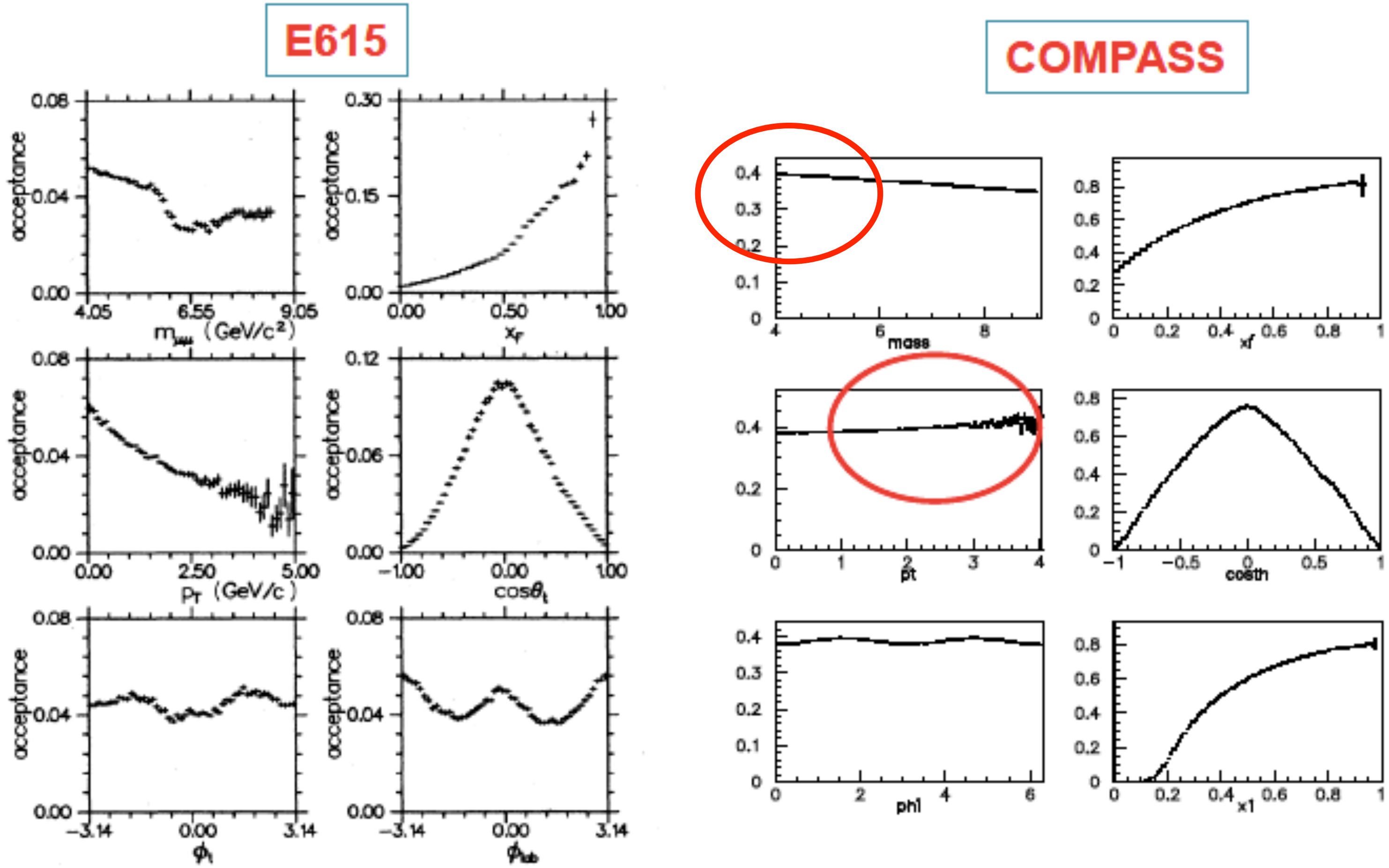


Key elements:

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)



COMPASS.vs.Past Pion-induced DY experiments



The strike back of CERN DY experiment!

Expected statistics at COMPASS-II after 2 years of Drell-Yan running on NH_3

With a beam intensity of $I_{beam} = 6 \times 10^7$ particles/second,
a luminosity of $L = 1.2 \times 10^{32}\ cm^{-2}s^{-1}$ can be obtained
$\Longrightarrow$ expect 900/day DY events with $4 < M_{\mu\mu} < 9$ GeV/c^2.

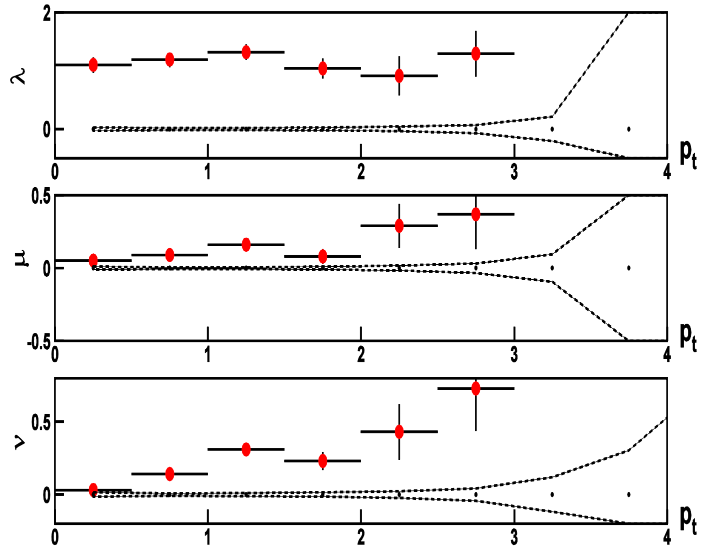
In 280 days one can collect 250 000 events in the DY HMR.
($\approx$ 420 000 events if $I_{beam} = 1 \times 10^8$ particles/second)

E615 (252 GeV π^- + W): ~36.000 events
NA3 (150 GeV π^- + W): ~21.000 events

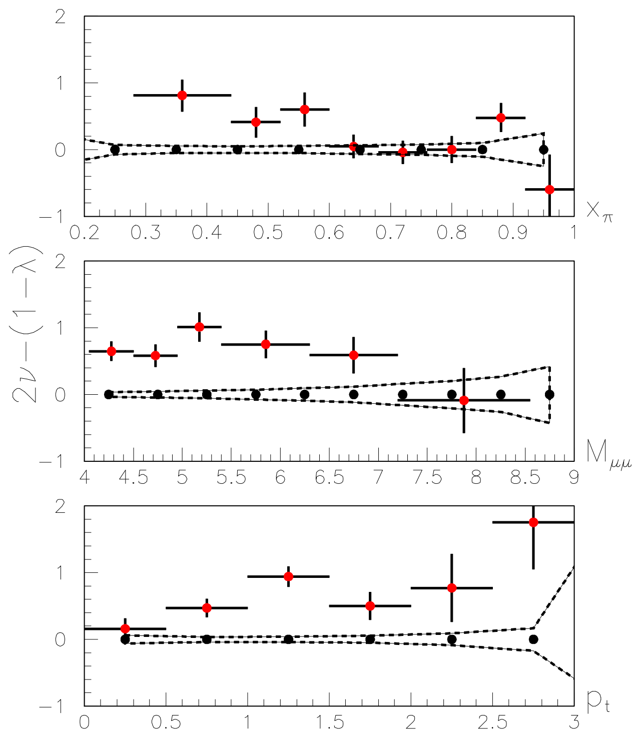
Some statistical error projections, Lam-Tung and Higher Twist

• :E615

Dashed band: COMPASS



Sensitivity on p_t dependence of λ, μ, and ν

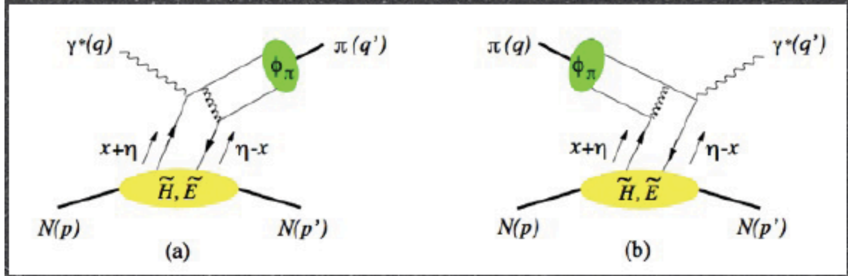


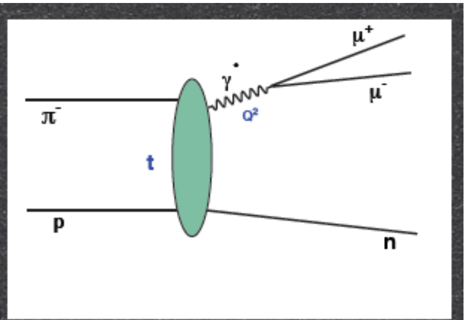
Sensitivity on LT violation

Pion-induced Drell-Yan access to DA I

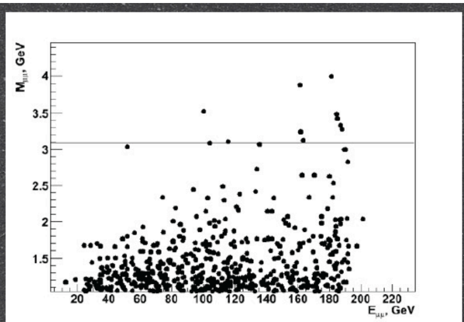
Feasibility study

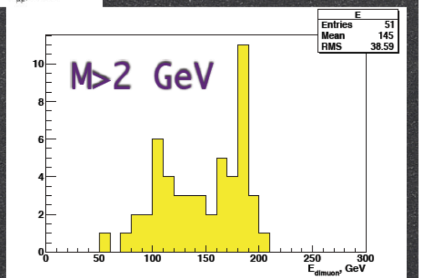
$\pi^- + p \rightarrow \mu^+ + \mu^- + n$



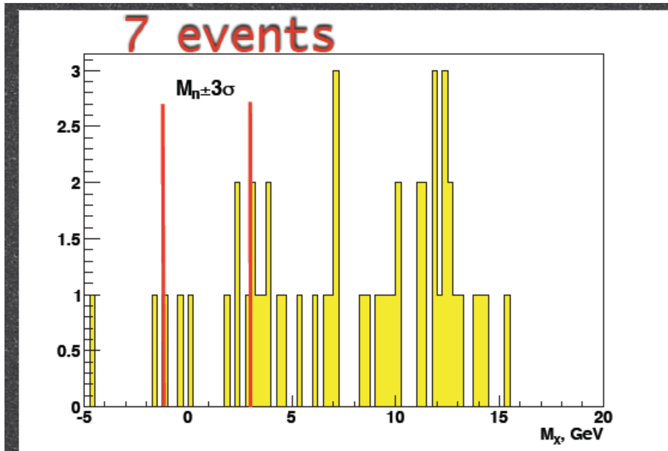


Access to GPD





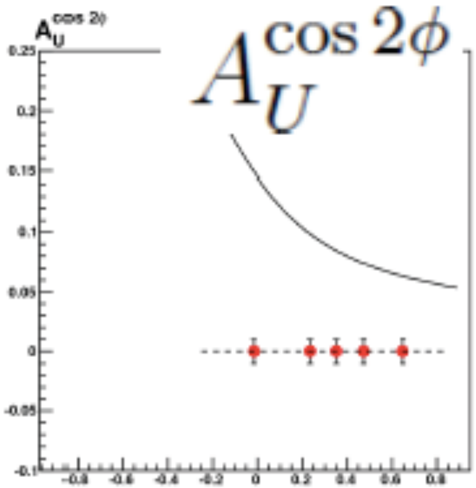
15-20 events where dimuon energy is about the beam energy



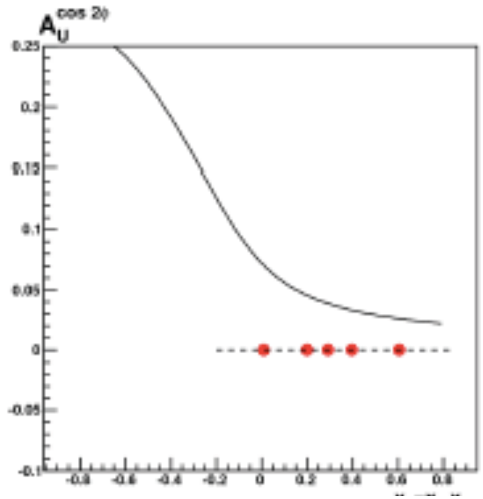
Setup resolution for M_X is about 0.7 GeV

~20.000 events in 2 years of running

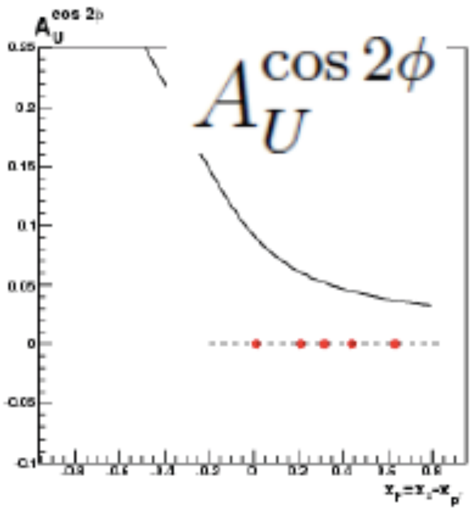
Some statistical error projections, Boer-Mulders function



(HMR): $4. \leq M_{\mu\mu} \leq 9.$ GeV/c^2



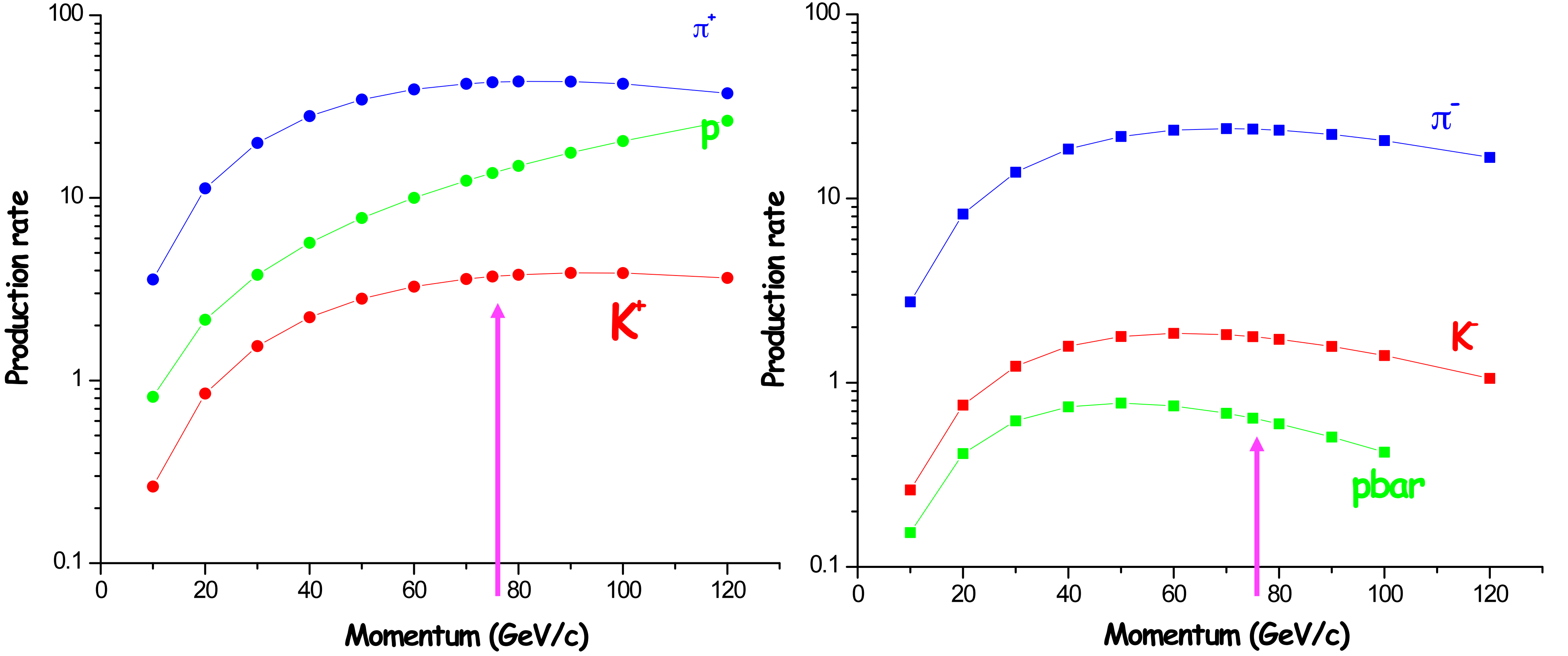
(IMR): $2.0 \leq M_{\mu\mu} \leq 2.5$ GeV/c^2



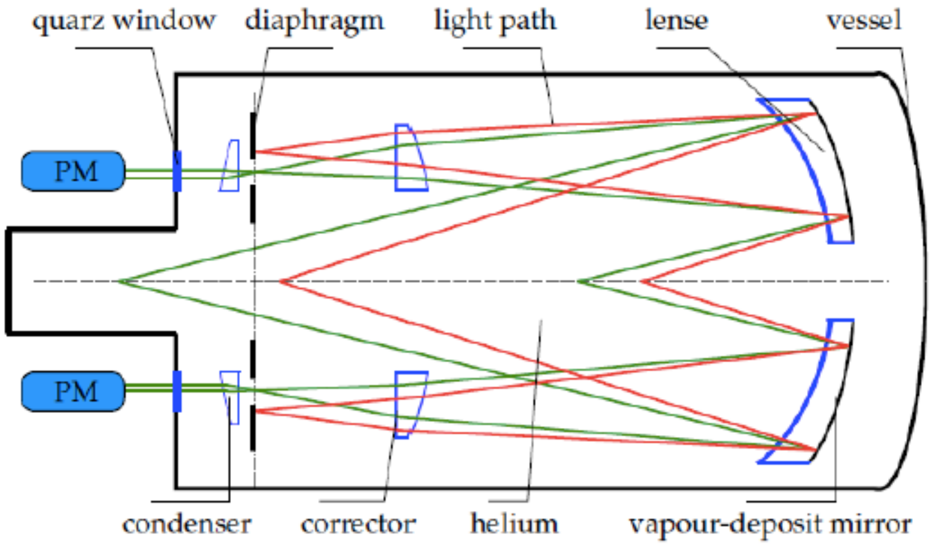
J/ψ region: $2.9 \leq M_{\mu\mu} \leq 3.2$ GeV/c^2

Some statistical error projections, Kaon and Antiproton induced Drell-Yan I

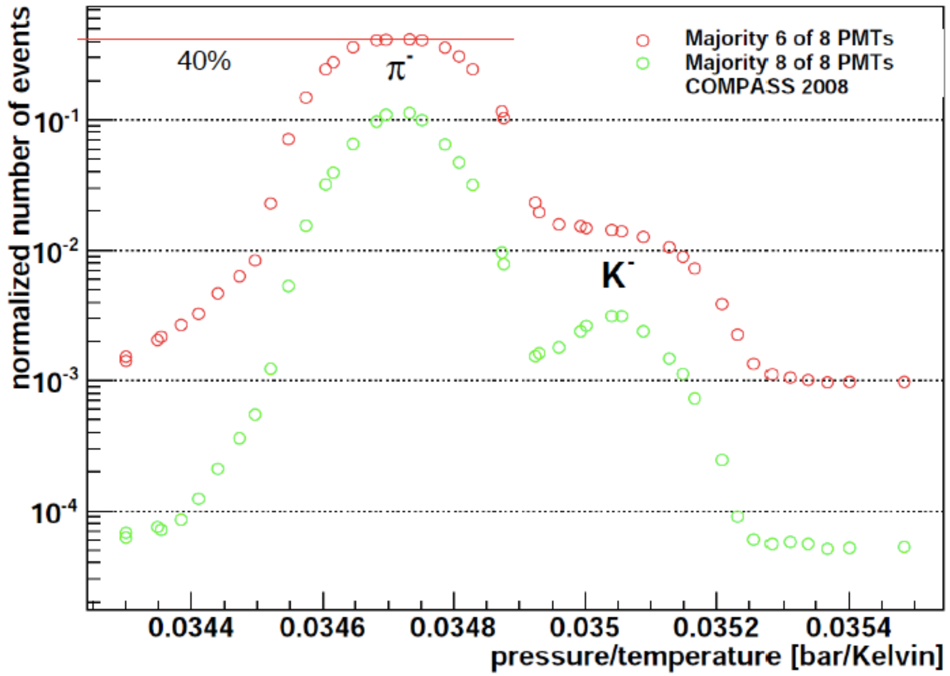
Particle production at 0 mrad



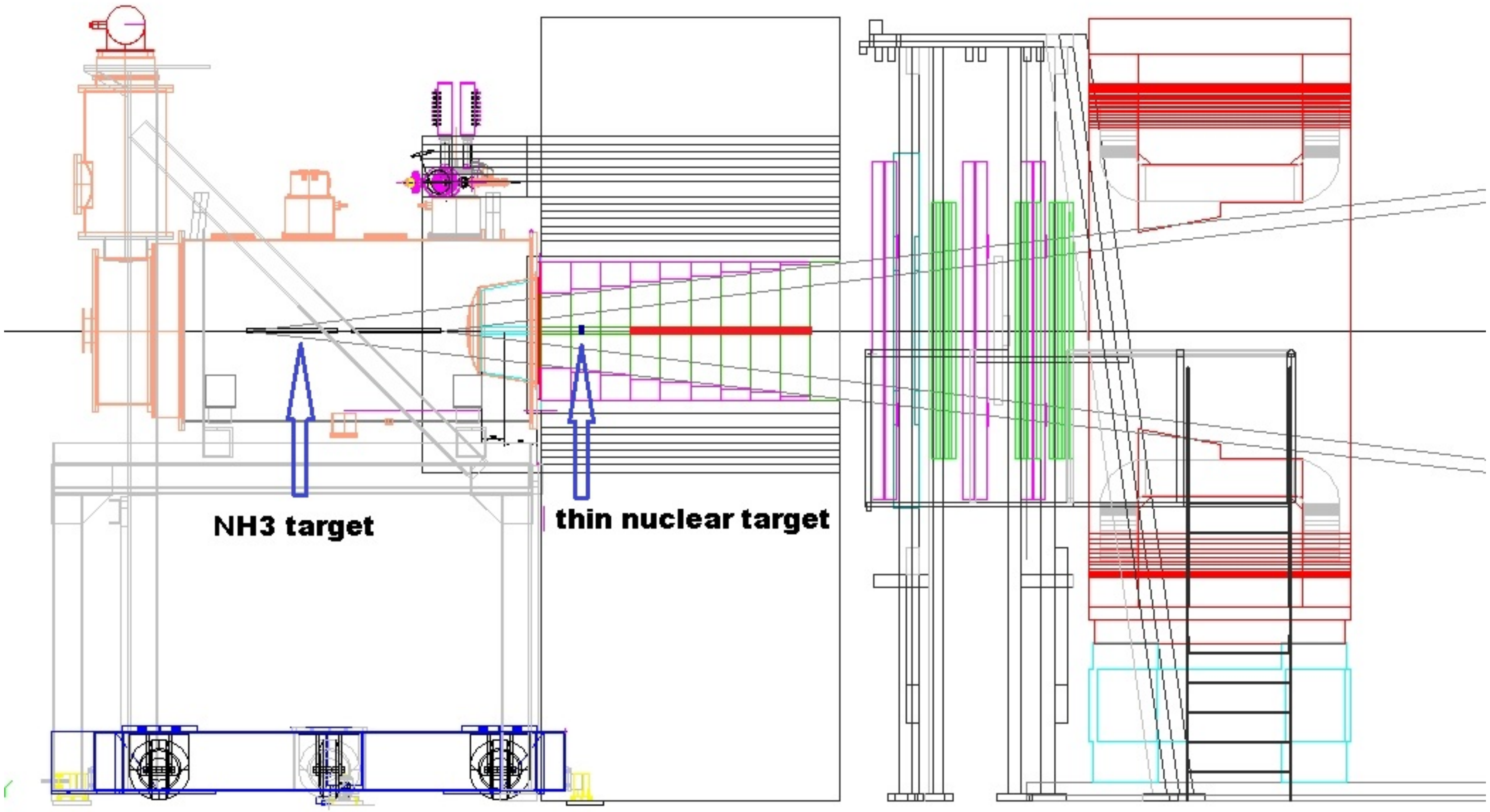
Some statistical error projections, Kaon and Antiproton induced Drell-Yan III



If one assume 70% efficiency of the CEDARs 'kaon/antiproton' tagging We can expect up to 10.000 DY events induced by the K^- and pbar



Flavour-dependent EMC effect study, possible set-up



Feasibility and set-up optimization still has to be completed

COMPASS: Summary

- In addition to the spin-dependent effects (first priority) the spin averaged effects can be studied at COMPASS-II:
  - Pion structure:
    - Pion PDFs
    - Pion Distribution Amplitude
  - Quark Transverse Momentum Dependent (TMD) effects
    - Higher twist effect
    - Boer-Mulders effect
  - EMC effects – flavour dependence
  - Kaon and Antiproton structure
- In the next 12 month we will concentrate on the feasibility study of all physics topics listed above
- In a long-term future we hope to have a dedicated unpolarised DY data taking on liquid hydrogen/deuterium targets

- Spares

Some statistical error projections, Kaon and Antiproton induced Drell-Yan II

At -100 GeV/c one may expect the following beam composition (in %):

Particle type	Fraction at T6	Fraction at COMPASS
pbar	1.7	2.1
K^-	5.8	1.6
π^-	84.5	86.3
e^-	8.0	10.0

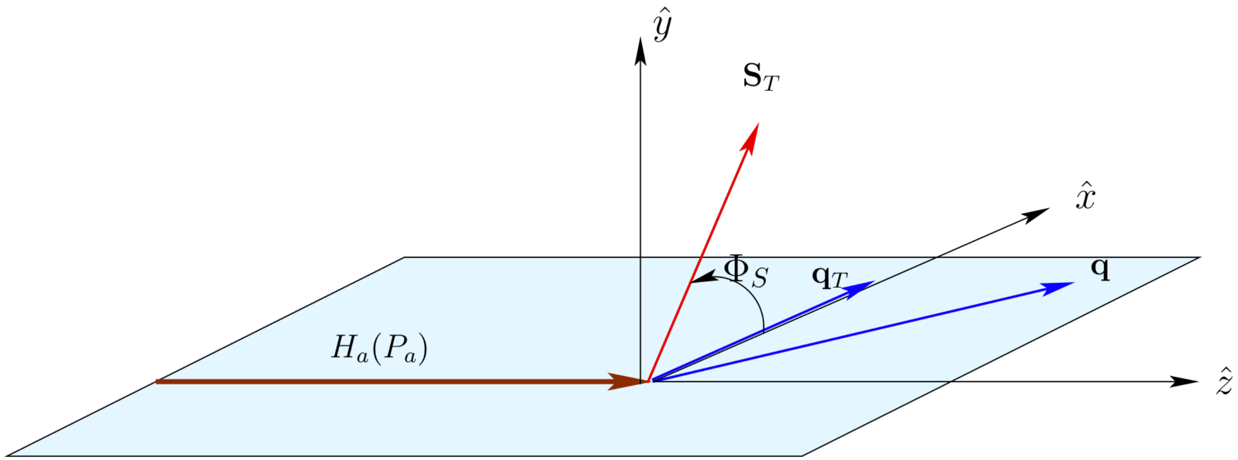
In present M2 hadron beam ≤ 2 10^7pbar

(due to 10^8 limit on total beam flux for RP)

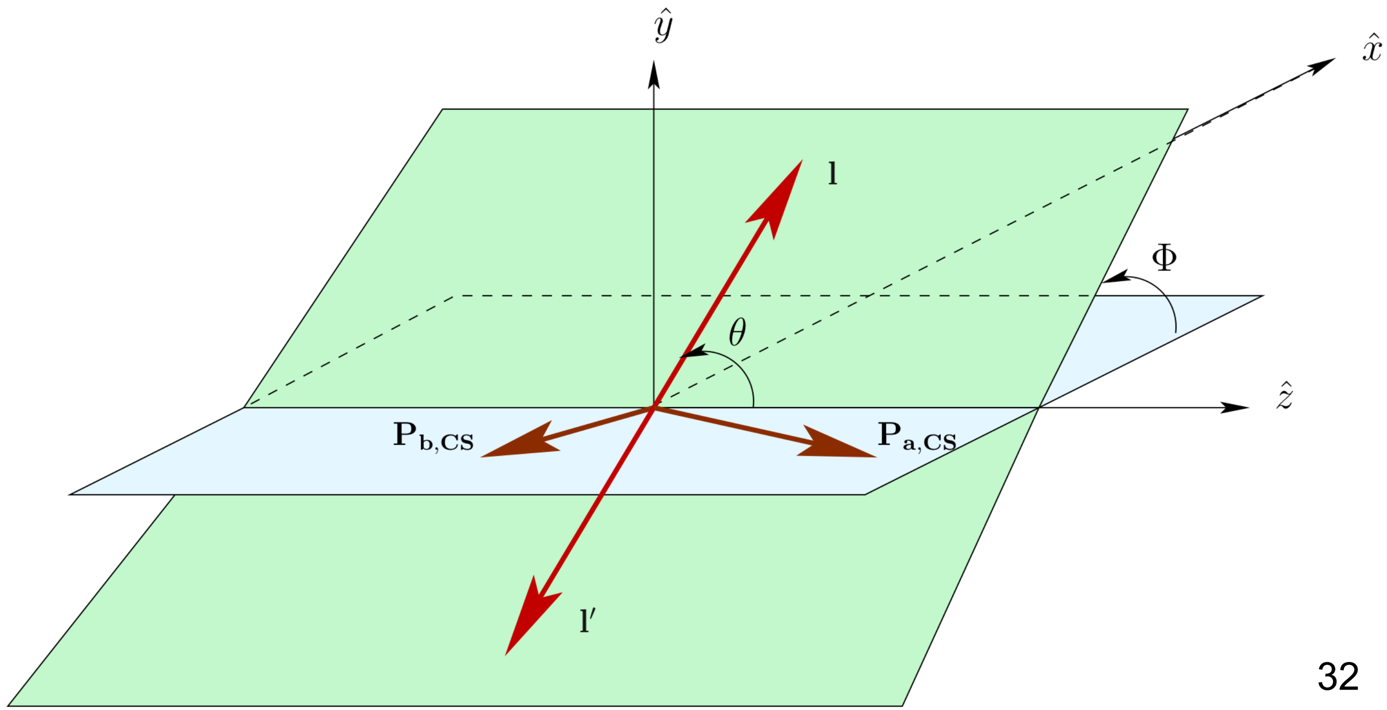
TMDs at Drell-Yan: road map

- 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
- 2017 → more COMPASS data, antiprotons?.....
- MANY NEW data - just behind the corner

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.

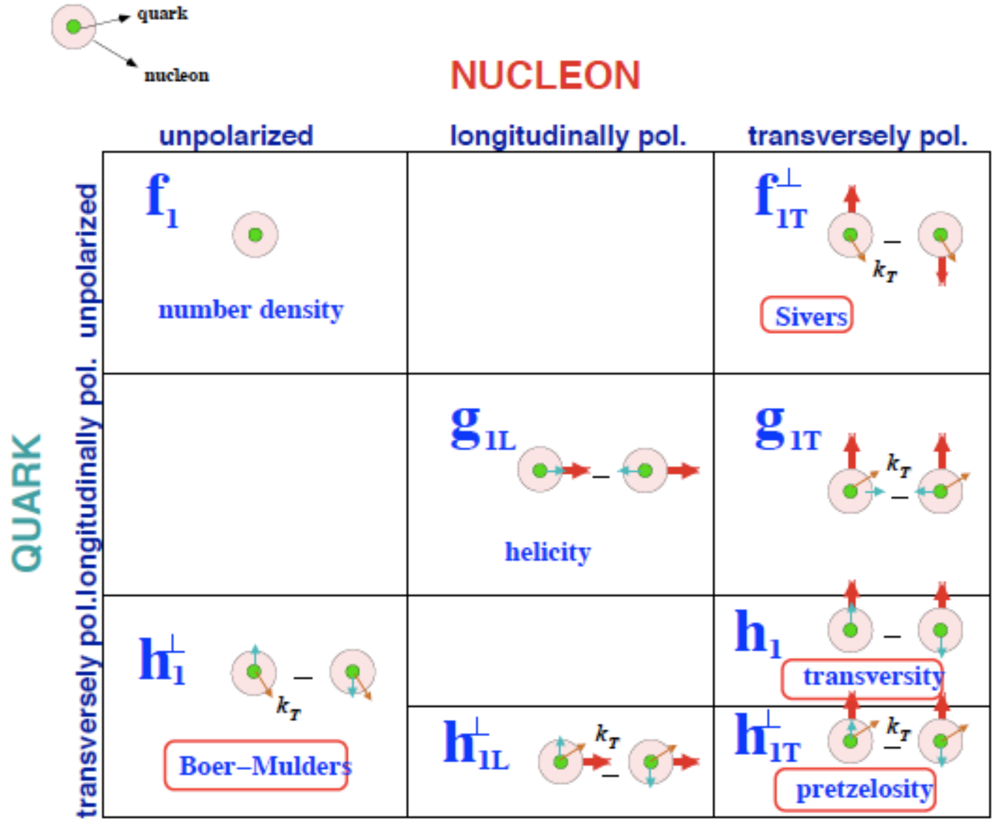
Organizers: Paula Bordalo (LIP-Lisbon and IST/UTL)
Oleg Denisov (CERN/INFN-Torino)
Eva-Maria Kabuss (Mainz)
Fabienne Kunne (CEA Saclay)
Alain Magnon (CEA Saclay)
Gerhard Mallot (CERN)
Anna Martin (Univ. Trieste and INFN-Trieste)
Wolf-Dieter Nowak (CERN)
Daniele Panzieri (Univ. Alessandria and INFN-Torino)

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:



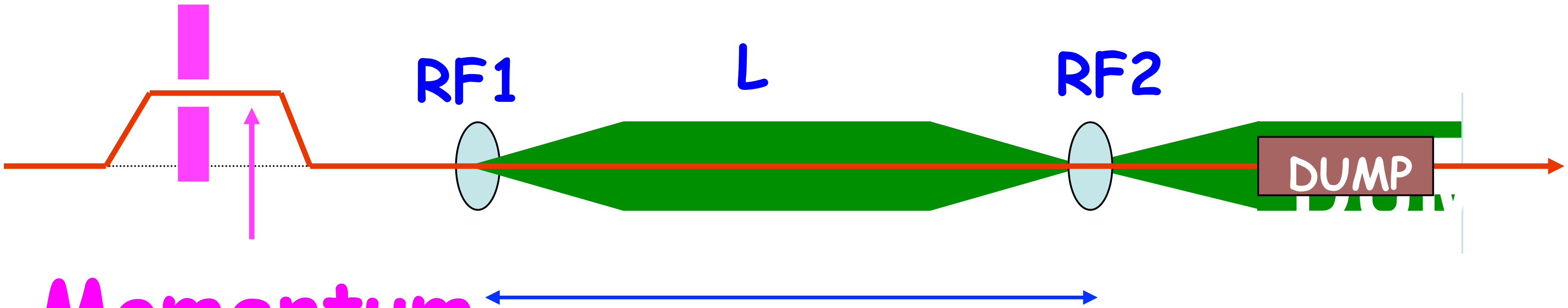
COMPASS

WHAT ABOUT A RF SEPARATED⌧p BEAM ???

INFN
Istituto Nazionale di Fisica Nucleare Sezione di Torino

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:



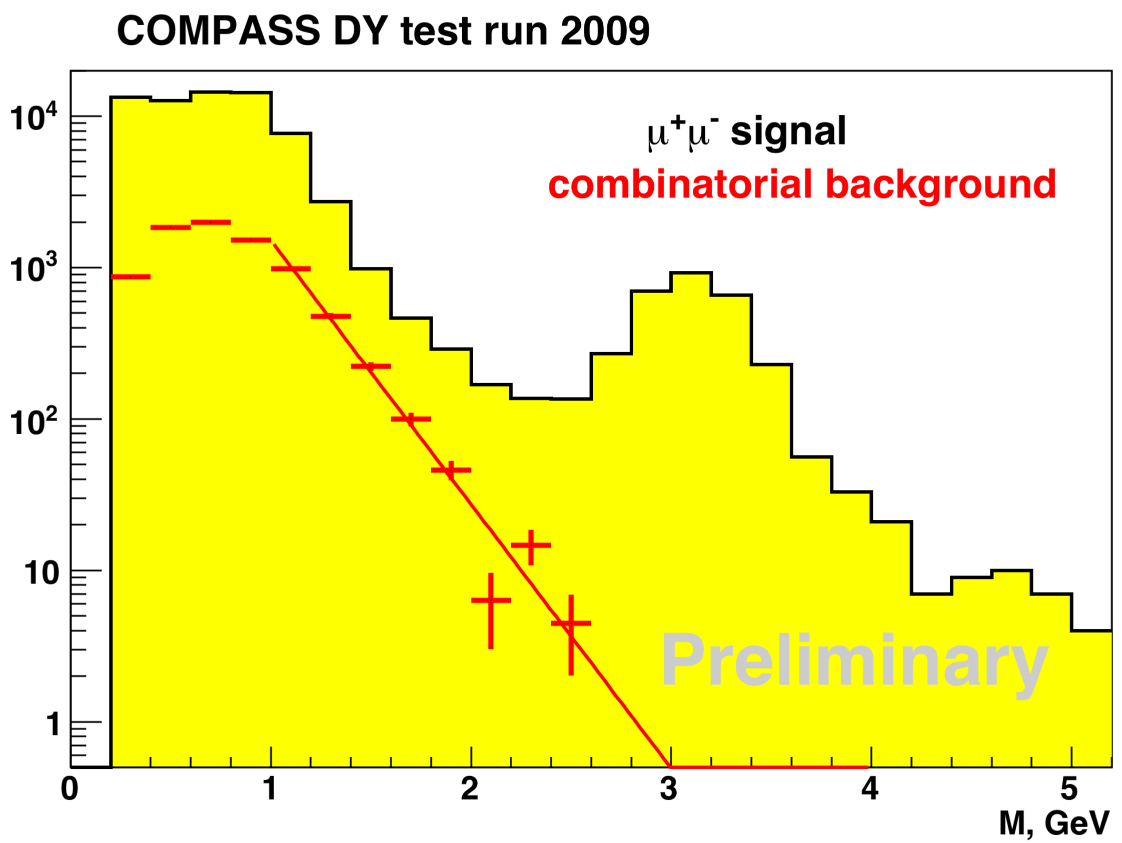
Momentum selection

Choose e.g. $\Delta\Phi_{\pi p}$

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

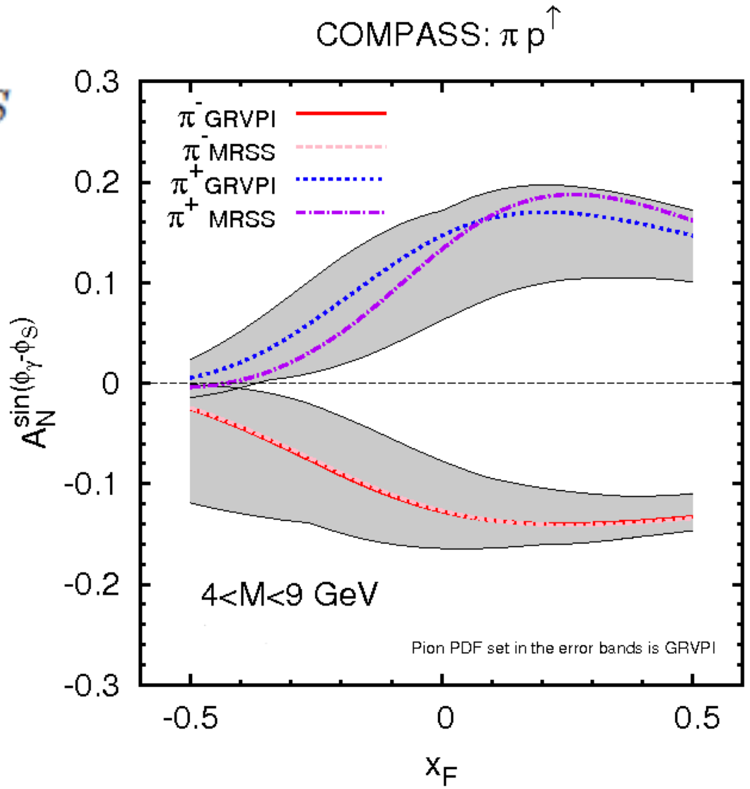
DY@COMPASS - feasibility – Background II – Combinatorial

- 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

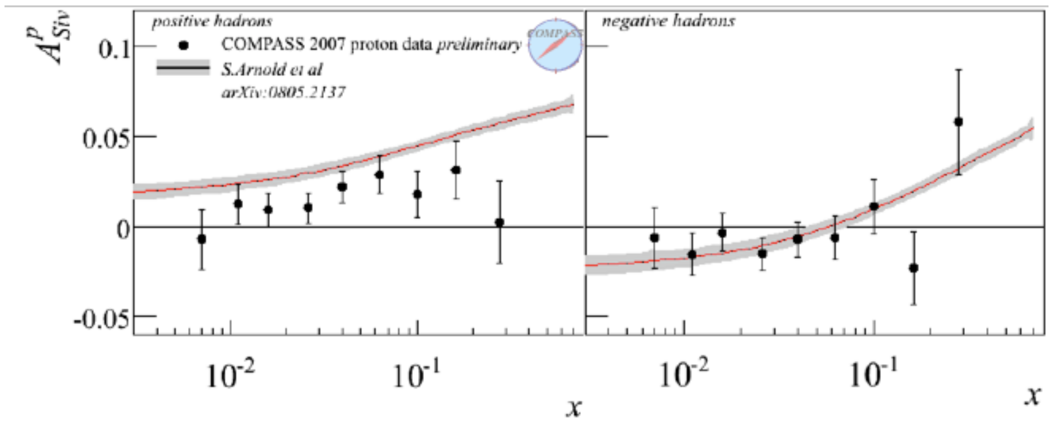
$A_T^{\sin\phi_S}$

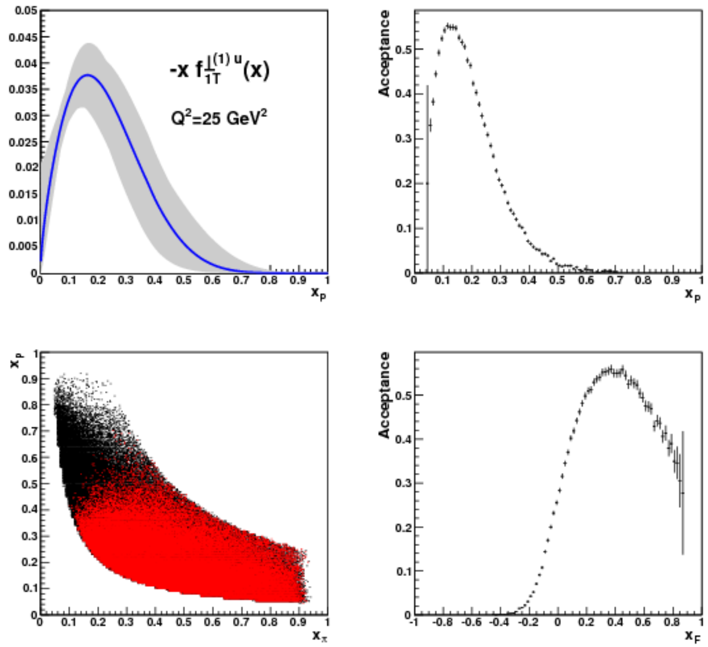


In case of $\pi^- p$ scattering the valence pion $\bar{u}$ unpolarised PDF is well known and there is no difference between two pdf sets. In case of $\pi^+ p$ scattering there is a little contamination coming from sea $\bar{u}$ of the pion, which annihilates with valence u quark of the proton, because 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).

DY@COMPASS ➔ SIDIS complemenatrity

- TMD PDFs study in SIDIS is an important part of the COMPASS-I program
- COMPASS-II, TMDs study in Drell-Yan processes:
  - We change the probe (elementary process)
  - We upgrade the spectrometer and we change its lay-out
  - We change the kinematic range





Some indications for the future Drell-Yan experiments

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

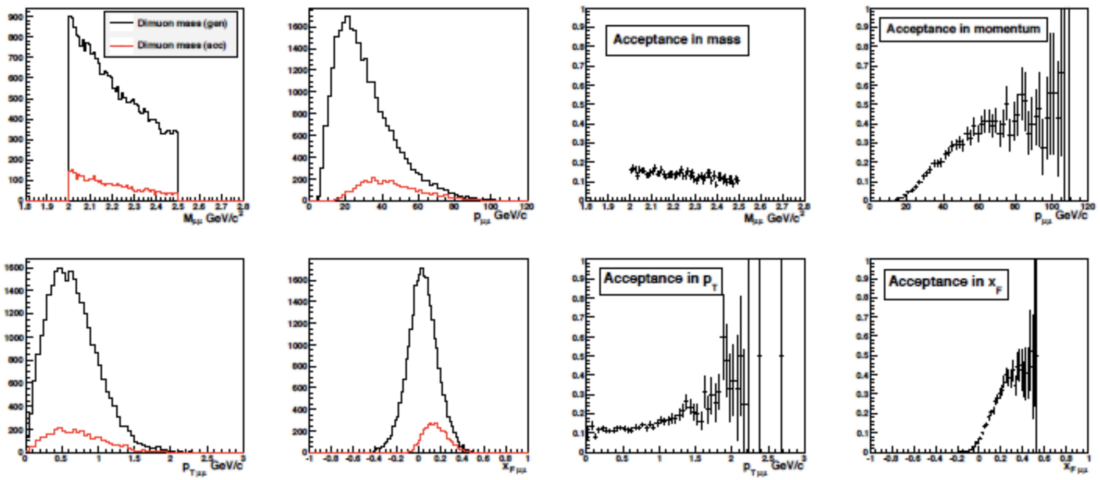
$$\tau = x_a x_b = M^2/s$$

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)*)

DY@COMPASS - feasibility – Background I – D-Dbar

- Calculated by MC
- Negligible in both HM and IM ranges (~15% contribution in IM)

Acceptance for open-charm 2.0 - 2.5 GeV/c^2



As in the IMR the acceptances are 14% for open-charm and 43% for DY, the ratio of observable events in the dimuon mass spectra will be $N_{DD}/N_{DY} = (5.47 \times 0.14)/(12.46 \times 0.43) = 0.14$.

Sivers, Boer-Mulders functions SIDIS ←→ DY

QCD

QCD factorization, valid for hard processes only (Q, q_T are large)

$\sigma_h \cong \sigma_p \times$ PDF

Cross-sections are gauge-invariant objects, to provide the gauge invariance of the PDFs the 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