Studying nucleon partonic structure with the COMPASS unpolarised Drell-Yan programme

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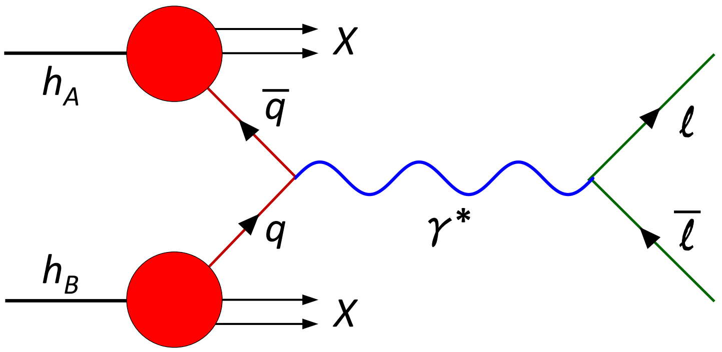
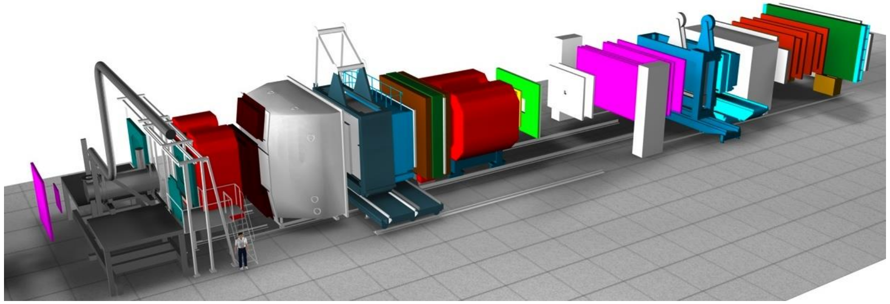
(on behalf of the COMPASS Collaboration)



MENU2016, Kyoto, Japan
27 July, 2016

Outline

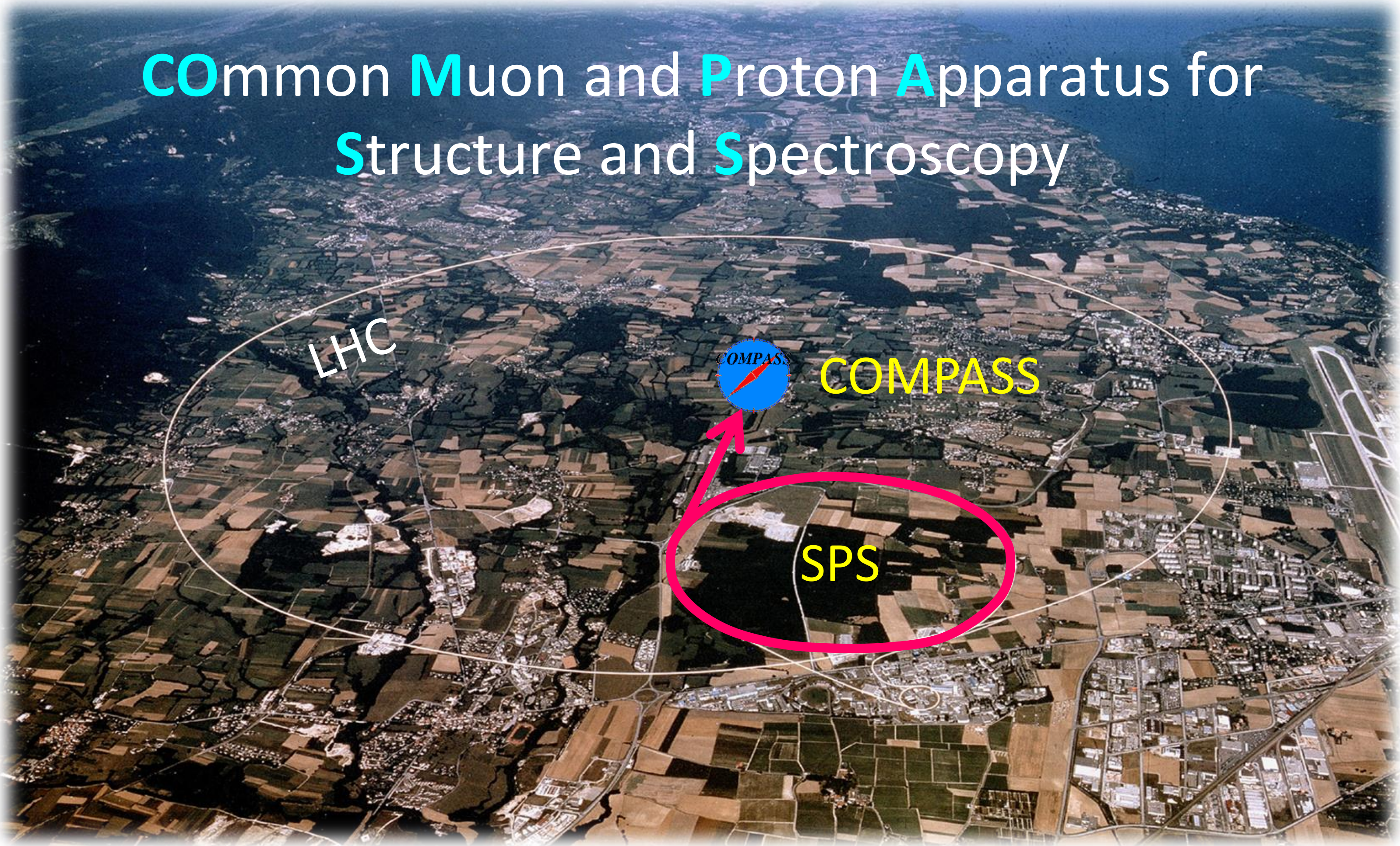
- COMPASS facility at CERN
- Nucleon Tomography at COMPASS
- Experimental Set-up
- Kinematics and Acceptance
- Physics Run in 2015
- Reachable Physics from COMPASS-DY
- Feasibility for COMPASS (beyond 2020)
- Reachable Physics from Future COMPASS-DY
- Summary



Drell-Yan experiment at COMPASS

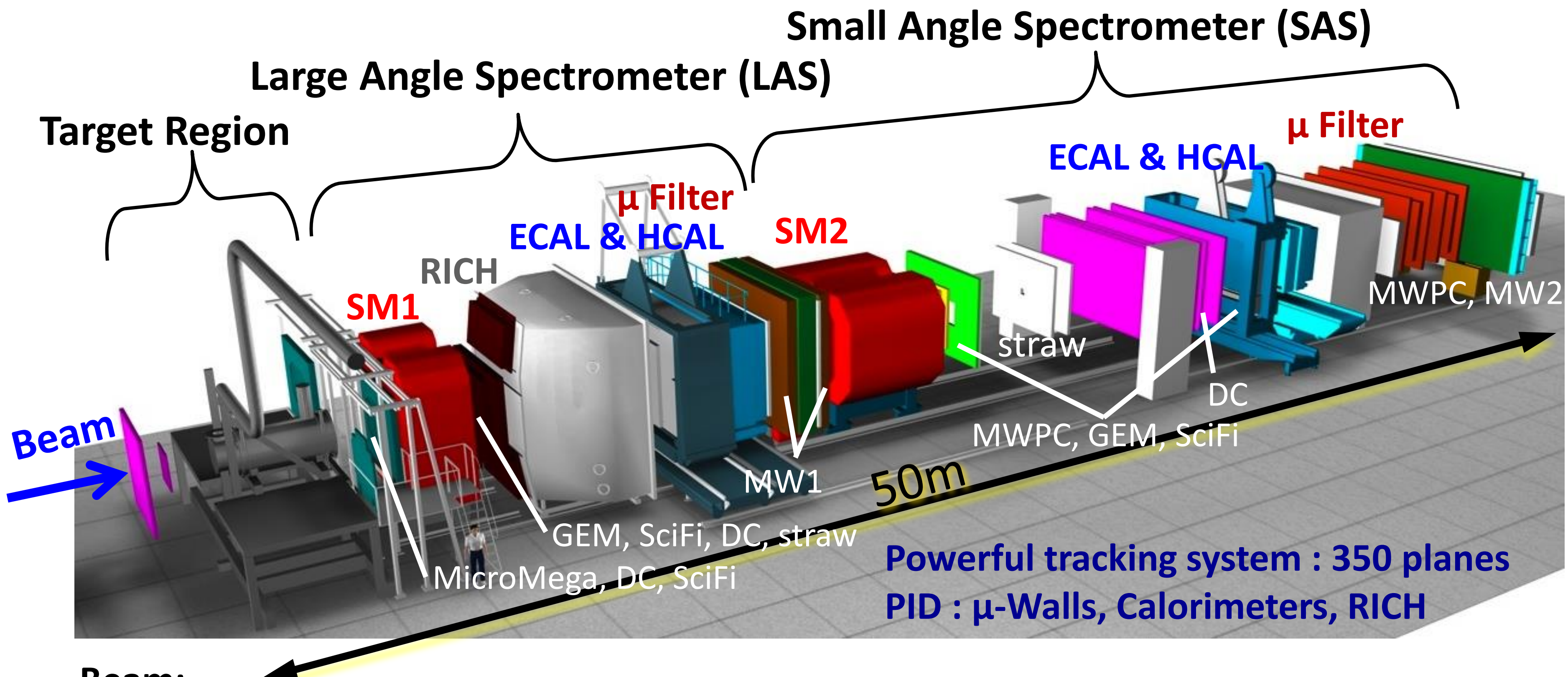
- 2014 : DY Pilot Run (without target polarisation)
  17 days of stable data taking
- 2015 : DY Physics Run (1st year)
  4 months of stable data taking
- 2016-2017 : DVCS Run
- 2018 : DY Physics Run (2nd year)

COMPASS facility at CERN



- Fixed target experiment at the end of M2 SPS beam line
- Nearly 220 physicists from 13 countries and 24 institutions

COMPASS facility at CERN



Beam:

- Polarized lepton beam : μ^+, μ^- 50-280 GeV/c
- Hadron beam : π^+, π^-, K^+, K^-, p

Target:

- Polarized proton and deuteron target
- Liquid hydrogen target
- Nuclear targets

Various Combinations of Beam & Target

Nucleon Tomography

Wigner Distributions

5D $W(x, \vec{b}_\perp, \vec{k}_\perp)$

$\int d\vec{b}_\perp$ $\int d\vec{k}_\perp$

Momentum tomography *Spatial tomography*

Transverse Momentum Dependent distribution functions

TMDs $f(x, \vec{k}_\perp)$ **3D** $H(x, \vec{b}_\perp)$ **GPDs**

Generalized Parton Distributions

$\int d\vec{k}_\perp$ $\int d\vec{b}_\perp$ $\int dx$

Longitudinal momentum density *Spatial density*

PDFs $f(x)$ **1D** $F(\vec{b}_\perp)$ **Form Factors**

Nucleon Tomography at COMPASS

Wigner Distributions

5D $W(x, \vec{b}_\perp, \vec{k}_\perp)$

$\int d\vec{b}_\perp$ $\int d\vec{k}_\perp$

Momentum tomography *Spatial tomography*

SIDIS

Drell-Yan

TMDs $f(x, \vec{k}_\perp)$ **3D** $H(x, \vec{b}_\perp)$ **GPDs** DVCS

COMPASS I (2002-2011)

- Longitudinally polarised DIS and SIDIS
- Transversely polarised SIDIS

} Muon beams

- Hadron spectroscopy
- Pion polarisability

} Hadron beams

COMPASS II (2012-2018)

- DVCS — Muon beams
- Transversely polarised Drell-Yan
- Hadron spectroscopy

} Hadron beams

This talk (unpol. DY)
Next talk (pol. DY)

COMPASS for Drell-Yan setup

Beam

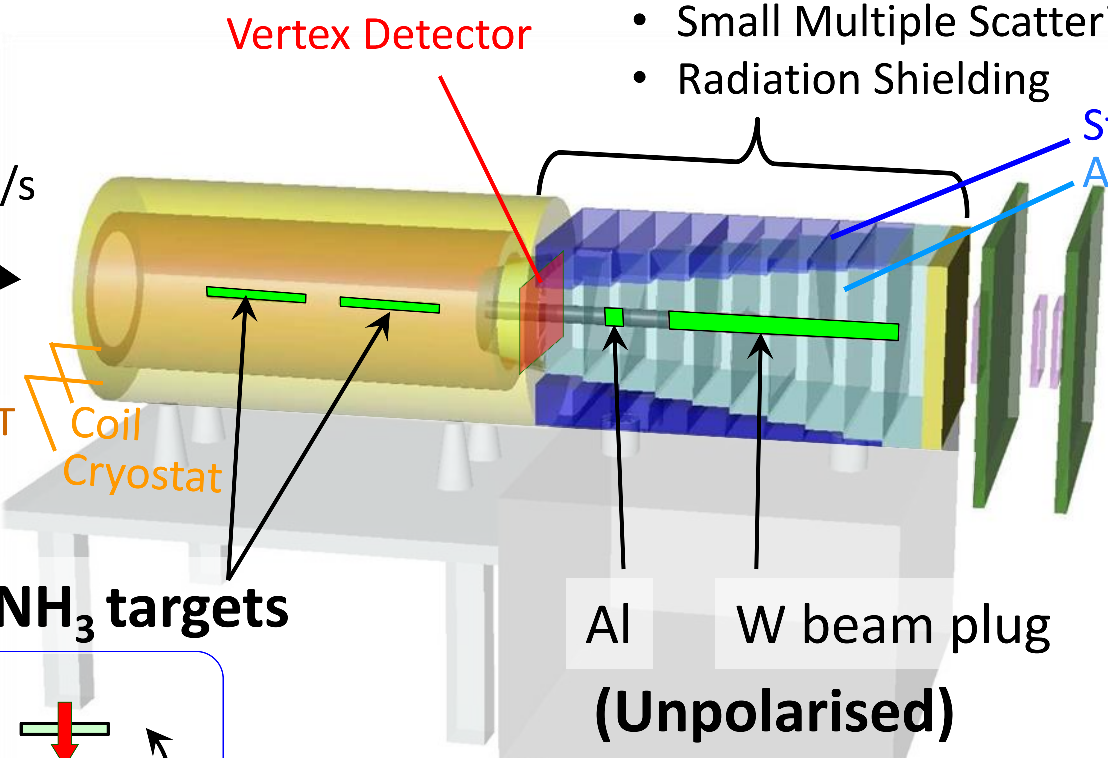
- 190 GeV/c π^-
- Intensity: 10^8 π^-/s

Magnet

- Solenoid : 2.5 T
- Dipole : 0.5 T

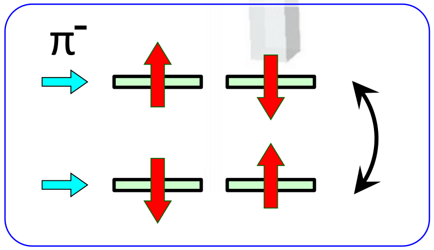
Hadron Absorber

- Large Stopping Power for hadrons
- Small Multiple Scattering for leptons
- Radiation Shielding



(Unpolarised) Nuclear Targets

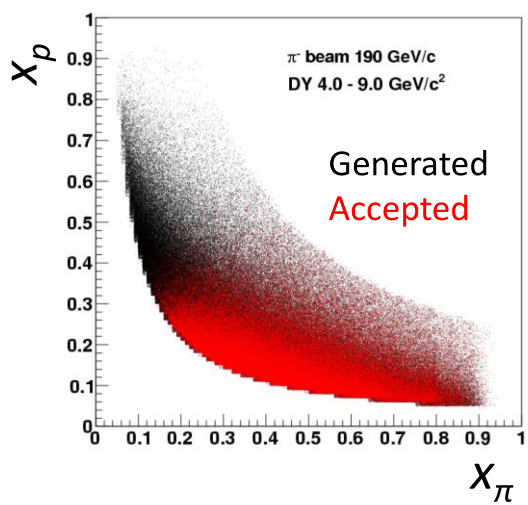
Polarized NH_3 targets



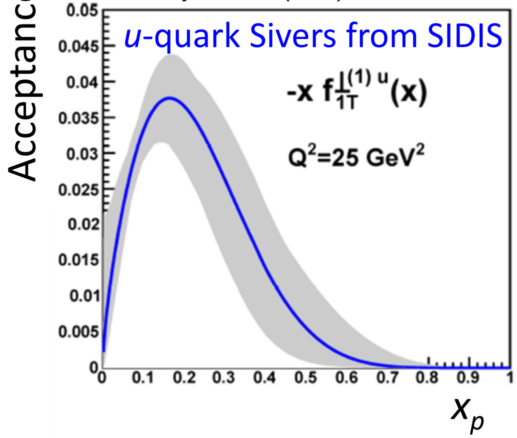
- Dilution factor: 0.22
- Polarization: > 90%

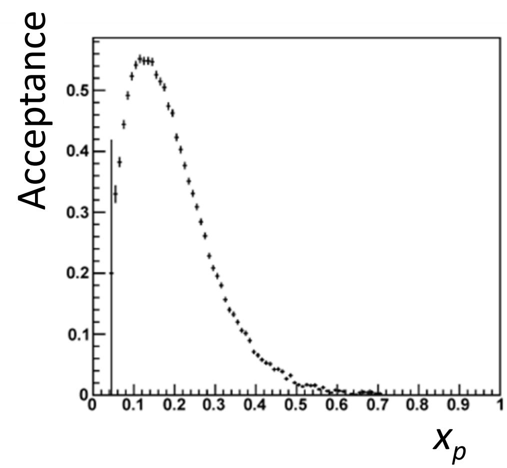
Kinematics and Acceptance

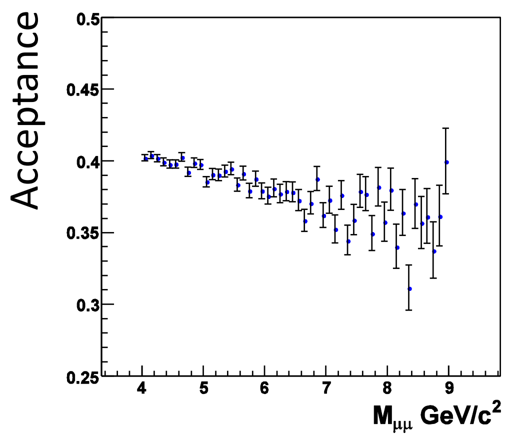
- The COMPASS acceptance covers the **valence quark region**
- $<P_T>$ ~ 1GeV – TMDs induced effects expected to be dominant with respect to the higher QCD corrections

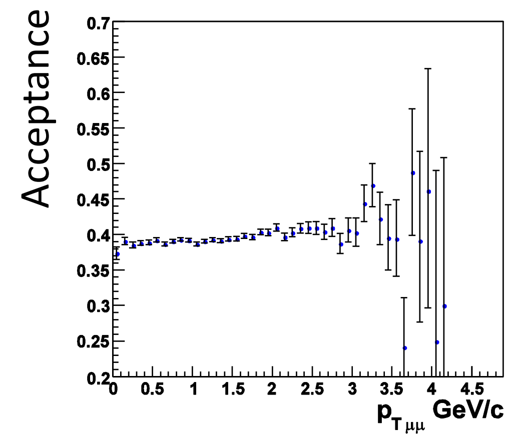


M. Anselmino et al.,
Eur. Phys. J. A39 (2009) 89









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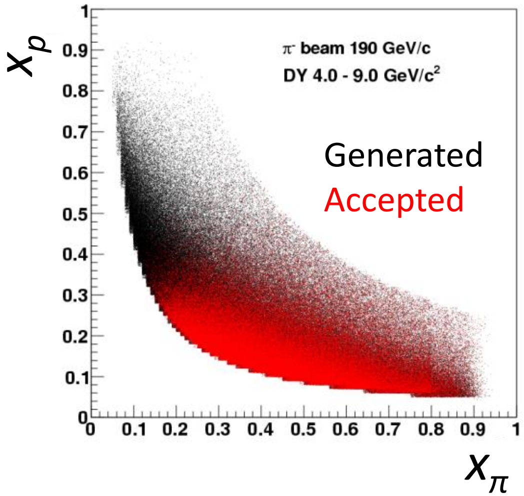

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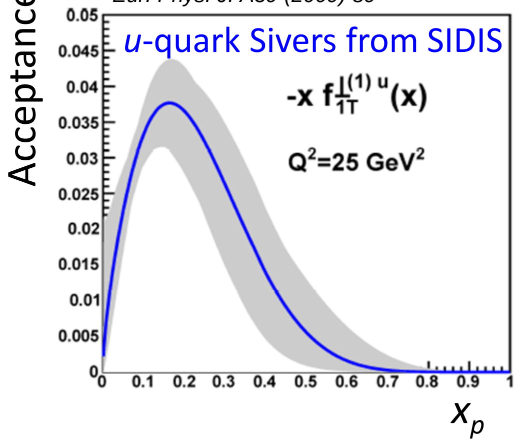
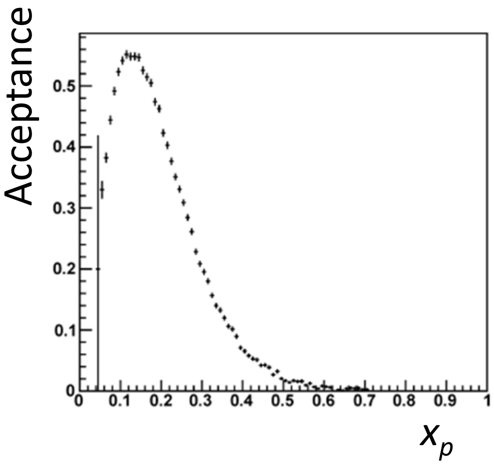
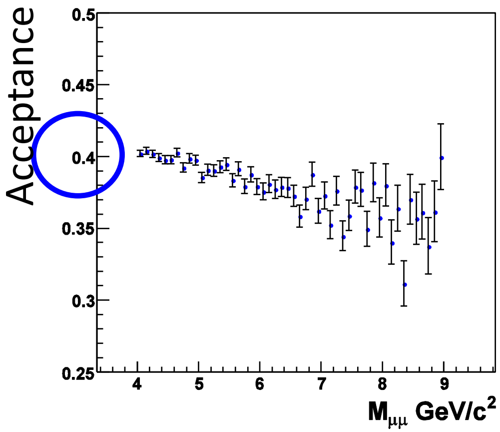
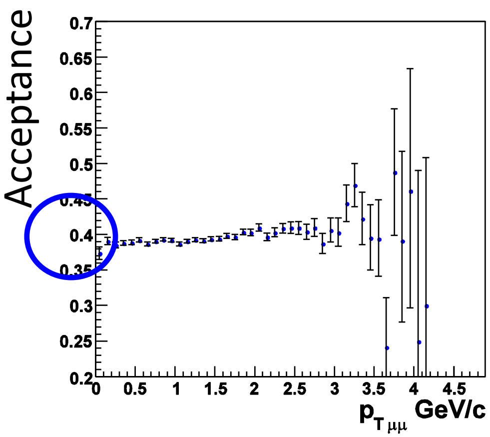






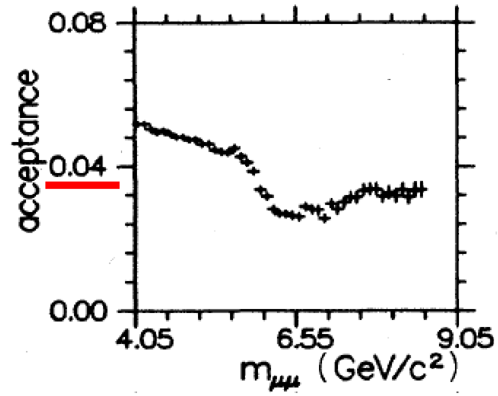


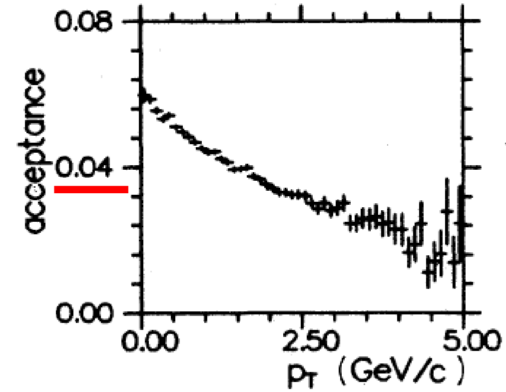
Large detector acceptance (~40%)

Kinematics and Acceptance

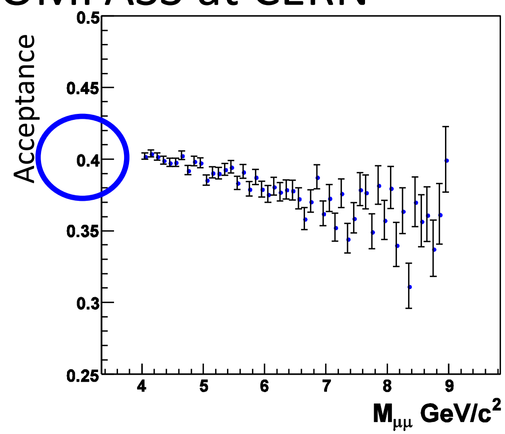
Typical acceptance of the DY experiments performed so far was 4-6% (NA10, NA50, E615)

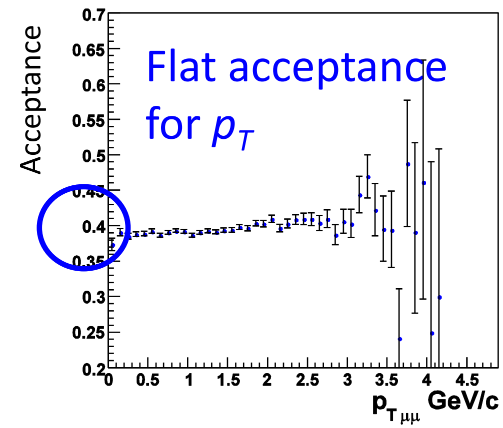
E615 at FNAL





COMPASS at CERN

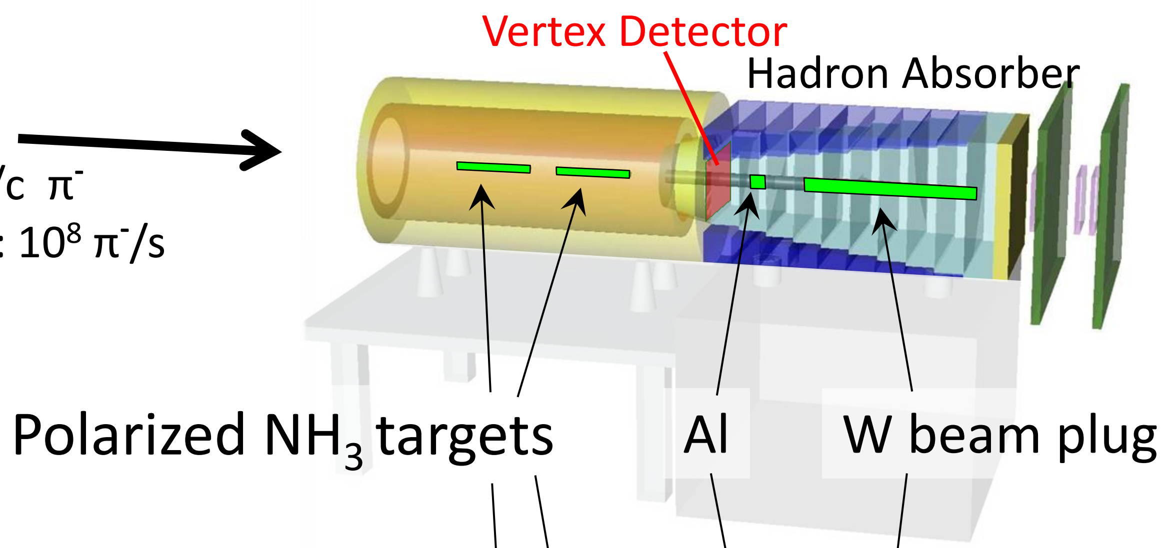




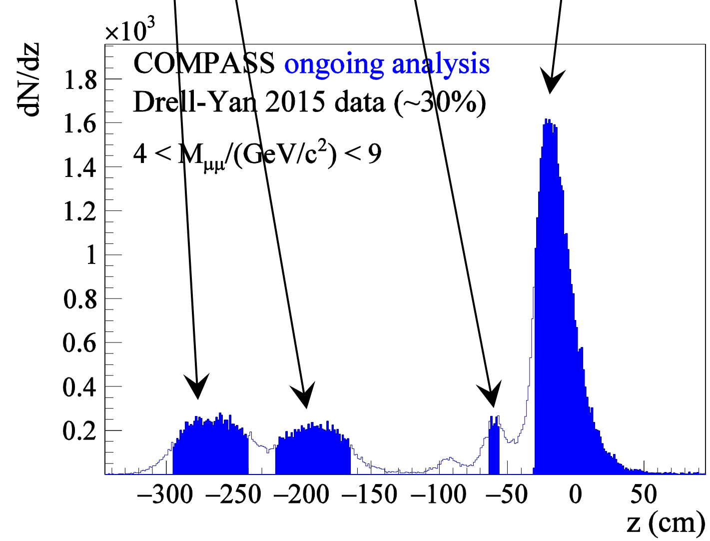
Large detector acceptance (~40%)

Drell-Yan – Physics run in 2015

Beam
- 190 GeV/c π^-
- Intensity: 10^8 π^-/s



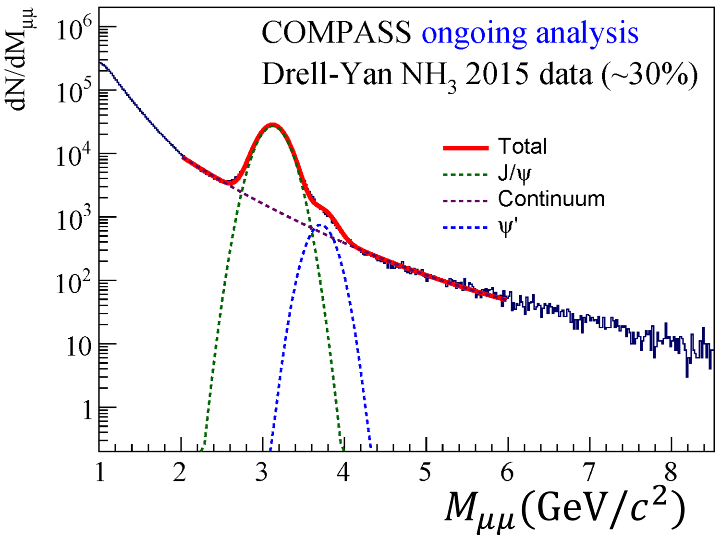
Z-coordinate of vertex distribution for $\mu^+ \mu^-$ pairs

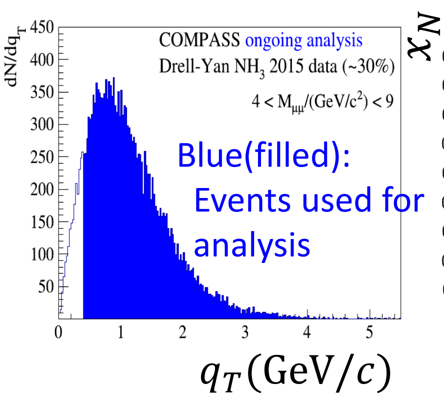


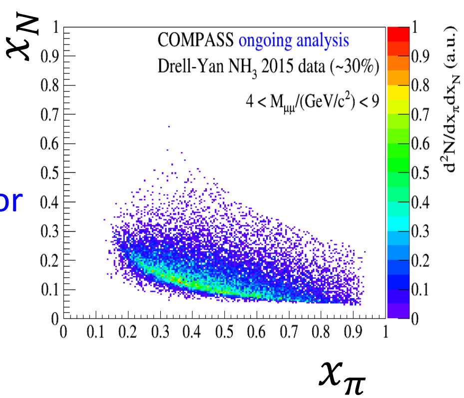
Blue(filled): Events used for analysis

Drell-Yan – Physics run in 2015

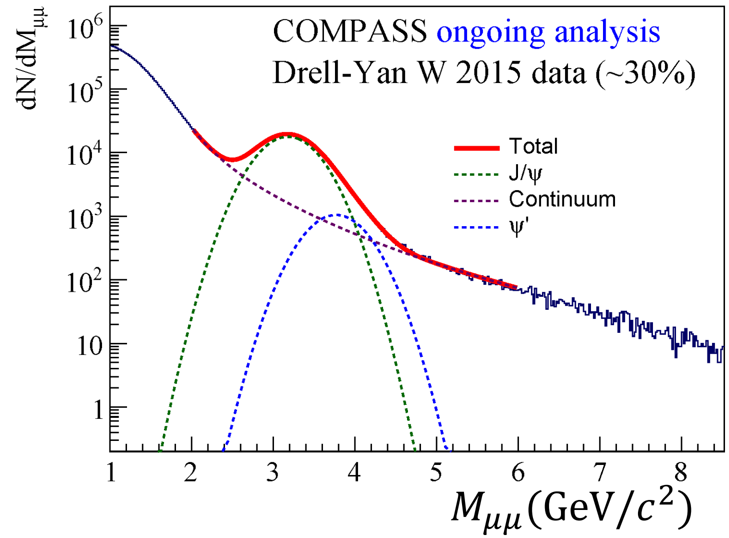
Polarized NH_3 targets

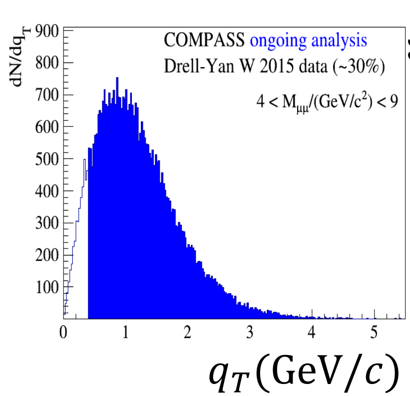


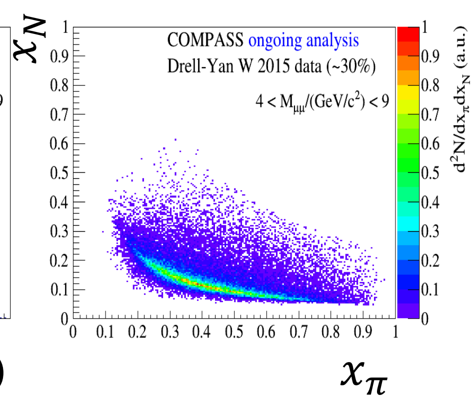




W beam plug

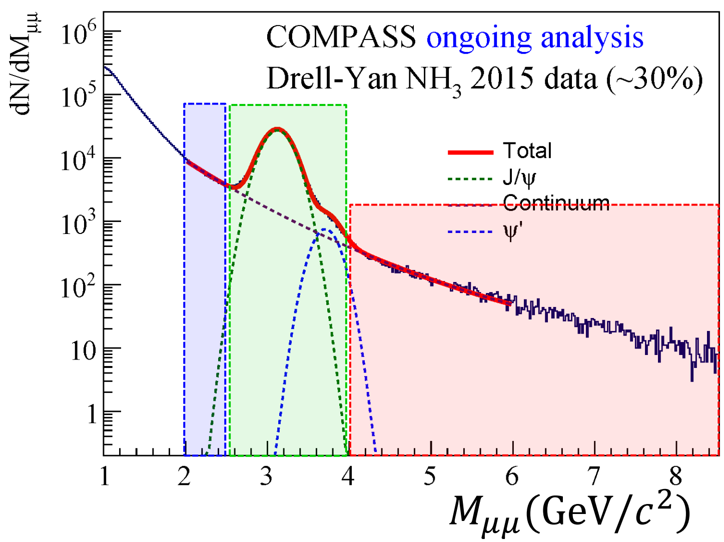




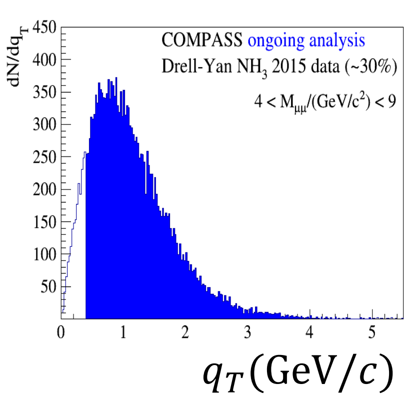


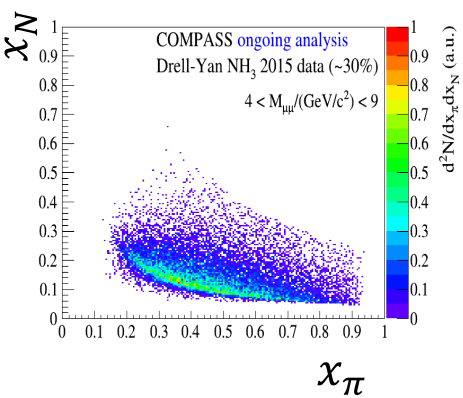
Drell-Yan – Physics run in 2015

Polarized NH_3 targets



- **Intermediate Mass Region**
  ($2 < M_{\mu\mu} < 2.5\ \mathrm{GeV}/c^2$)
  - High DY cross section
  - Open-charm
  - Combinatorial background
- **J/ψ Region** ($2.5 < M_{\mu\mu} < 4\ \mathrm{GeV}/c^2$)
  - J/ψ dominant
- **High Mass Region** ($4 < M_{\mu\mu} < 9\ \mathrm{GeV}/c^2$)
  - Clean DY signal
    (Negligible background)
  - Low cross section





Reachable Physics from Current COMPASS-DY

Beam: π^-
Target: NH_3(polarised/unpolarised), Al, W
Observable physics process:
(final state : 2mu): J/ψ, DY, (ψ'), ϒ, (open-charm)
(3mu): open-beauty
(4mu): double J/ψ

(Blue) Physics from unpolarised nucleon

Observables and physics:

Angular distributions

from polarised NH_3 target:

- Sivers functions of valence quarks in proton (DY)

from unpolarised NH3, Al, W:

- Boer-Mulders functions of valence quarks in proton (DY)
- Lam-Tung violation (DY)
- Higher Twist & Pion DA (DY at large x_1)

A-dependence of P_T distributions (DY, J/ψ):

- EMC effect
- J/ψ formation

A-dependence of x_1, x_F distributions (DY, J/ψ):

- Quark energy loss in the cold nuclear matters

Absolute production cross sections (DY, J/ψ, (double J/ψ)):

- pion PDF
- J/ψ production mechanism

ϒ and open-beauty production

Reachable Physics from Current COMPASS-DY

Beam: π^-

Target: NH_3(polarised/unpolarised), Al, W

Observable physics process:

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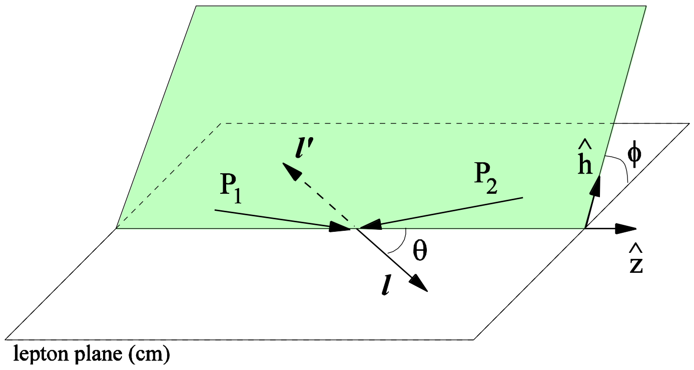
Next page

Drell-Yan decay angular distributions



Collins-Soper frame

θ and φ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest-frame

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

$$\propto (W_T(1+\cos^2\theta)+W_L(1-\cos^2\theta)+W_\Delta\sin 2\theta\cos\phi+W_{\Delta\Delta}\sin^2\theta\cos 2\phi)$$

$q\bar{q}$ annilation parton model:

$O(\alpha_s^0)$ λ=1, μ=ν=0; $W_T=1, W_L=0$

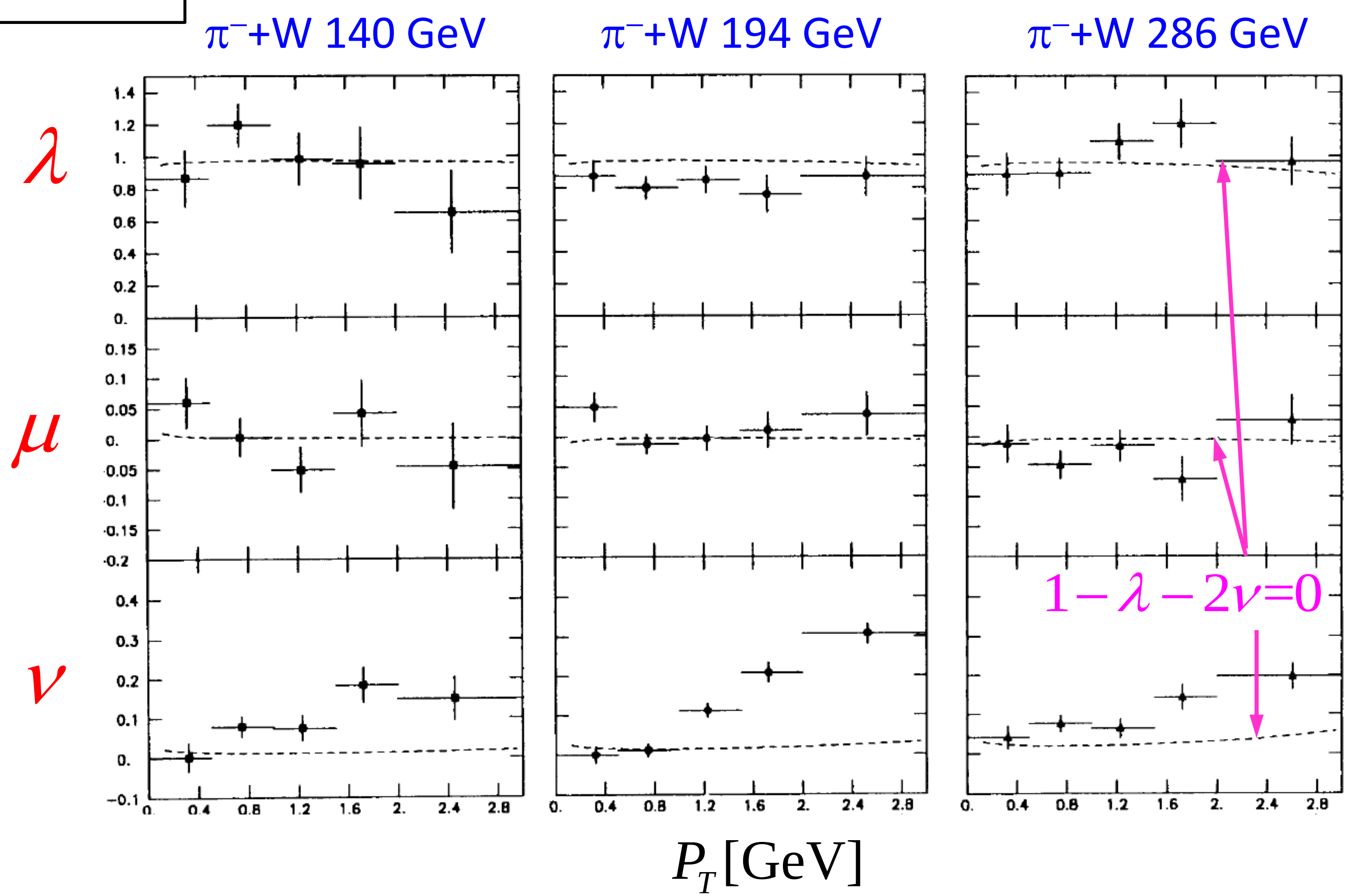
Lam-Tung relation (1978): $\boxed{\text{test of QCD effect}}$

Collinear pQCD: $O(\alpha_s^1)$, $W_L=2W_{\Delta\Delta}$; $1-\lambda-2\nu=0$

Violation of Lam-Tung Relation (1)

CERN NA10

Z. Phys. C37 (1988) 545



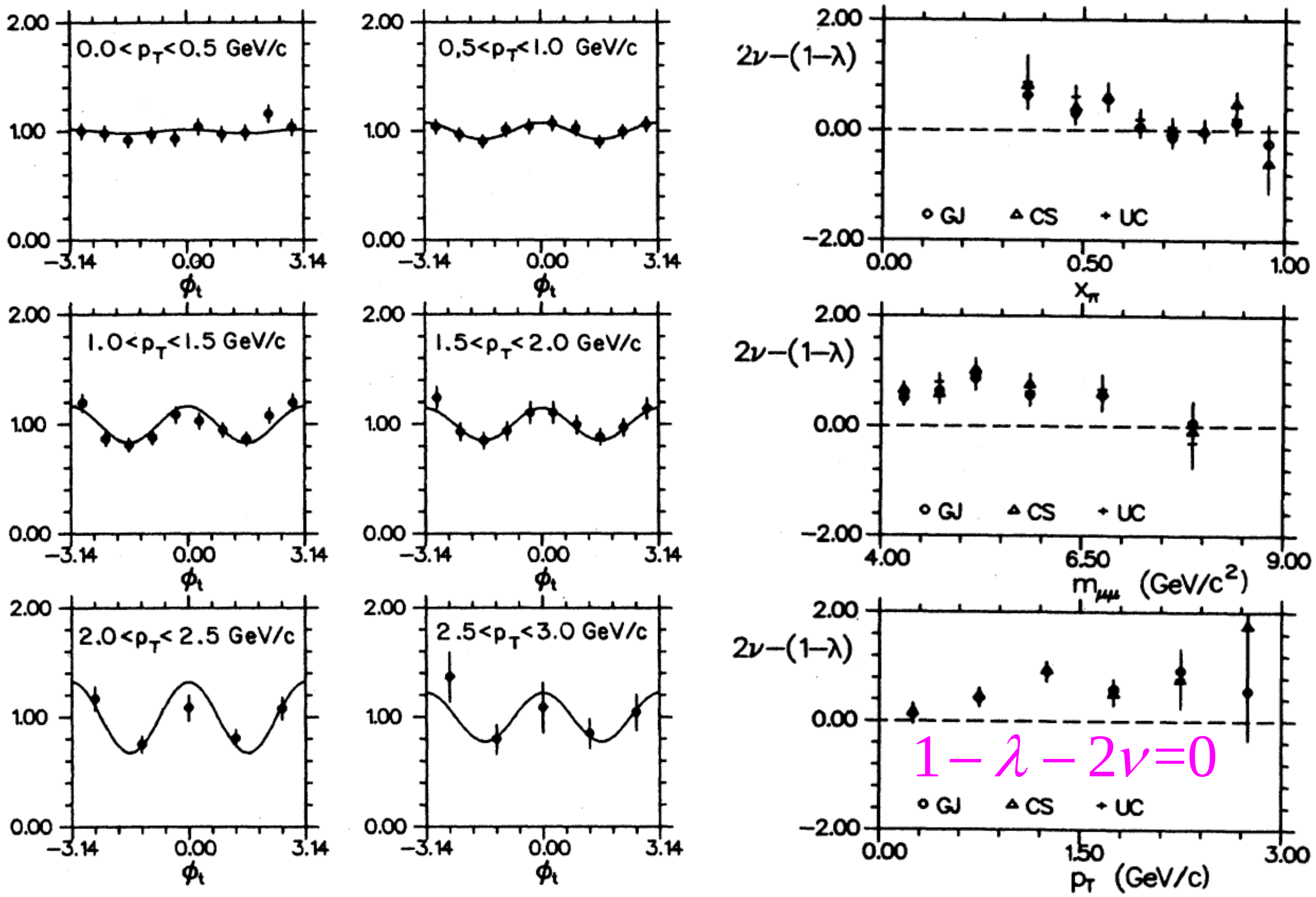
LT relation was violated at large p_T

Violation of Lam-Tung Relation (2)

FNAL E615

PRD 39, 92 (1989)

252-GeV π^{-}+W



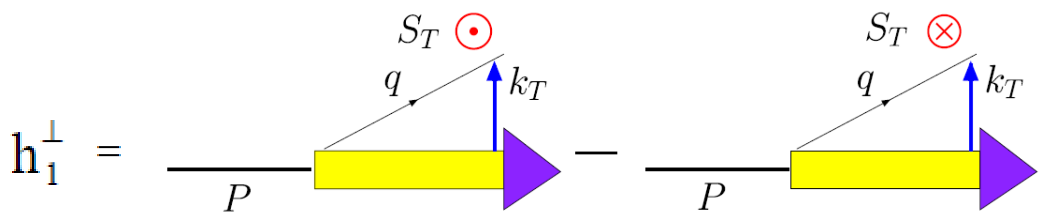
$1-\lambda-2\nu=0$

$\cos 2\phi$ modulation at large p_T

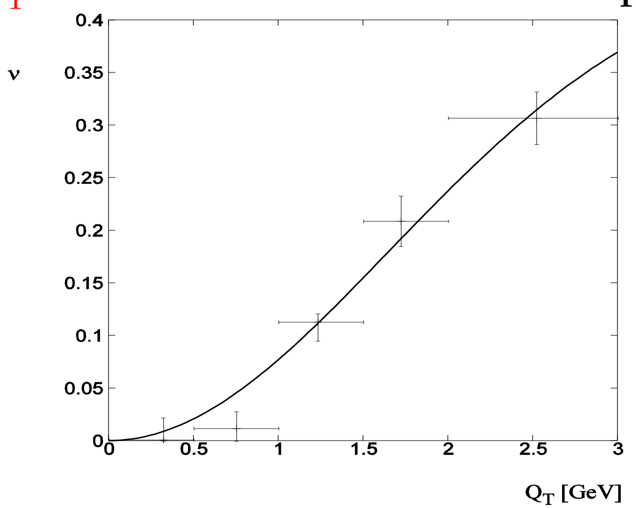
Hadronic Effect, Boer-Mulders Functions

Boer PRD 60, 014012 (1999)

Spin-orbit correlation of transversely polarized *noncollinear partons* inside an unpolarized hadron



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



$$h_1^\perp(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x),$$

$$\nu = 16\kappa_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2}, \qquad \kappa_1 = C_{H_1} C_{H_2}/2$$

$$\kappa = \frac{\nu}{2} \rightarrow 0 \text{ for large } |k_T|$$

Consistency of factorization in term of TMDs

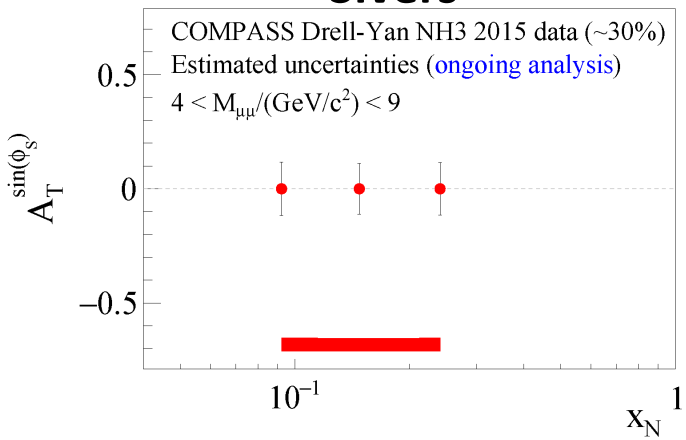
Projected Uncertainties

- 30 % of 2015 data
- π^- beam, NH_3 target
- $4 \le M_{\mu\mu} \le 9\ \mathrm{GeV}/c^2$

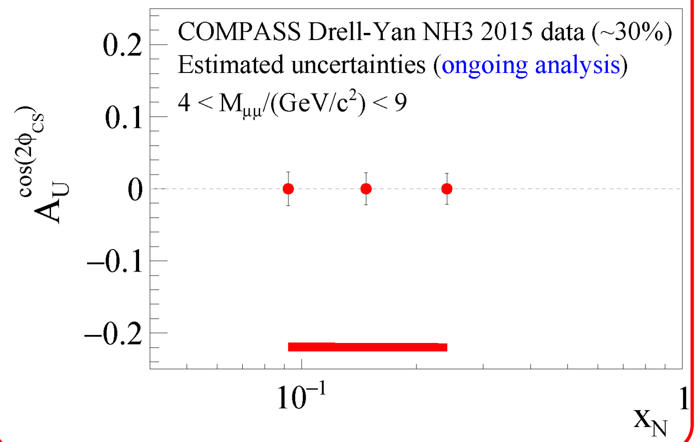
$$A_U^{cos2\varphi} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

beam BM　target BM

Sivers



Boer-Mulders



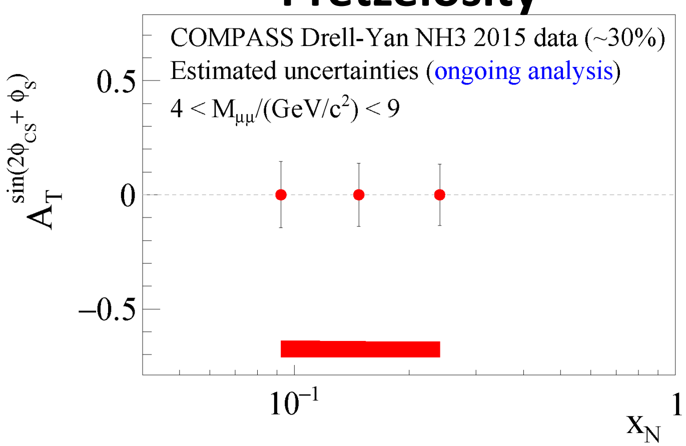
Proton BM extracted from SIDIS or pp/pd DY $\Rightarrow$ pion BM

or

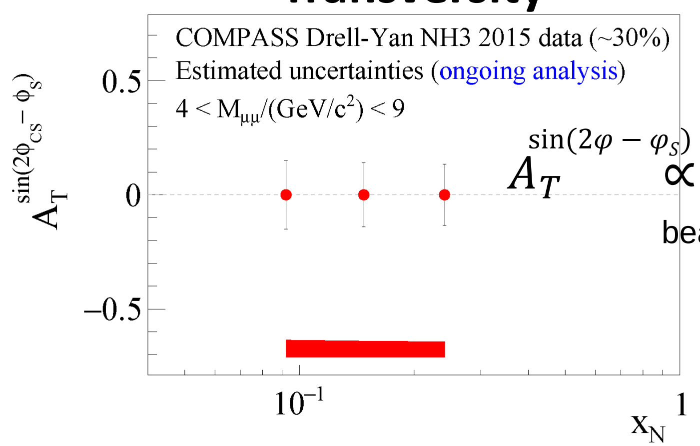
Measurement of $A_T^{\sin(2\varphi - \varphi_S)}$ and parametrization of $h_{1,p}^q$ $\Rightarrow$ proton BM

(Model dependent)

Pretzelosity



Transversity



$$A_T^{\sin(2\varphi - \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$$

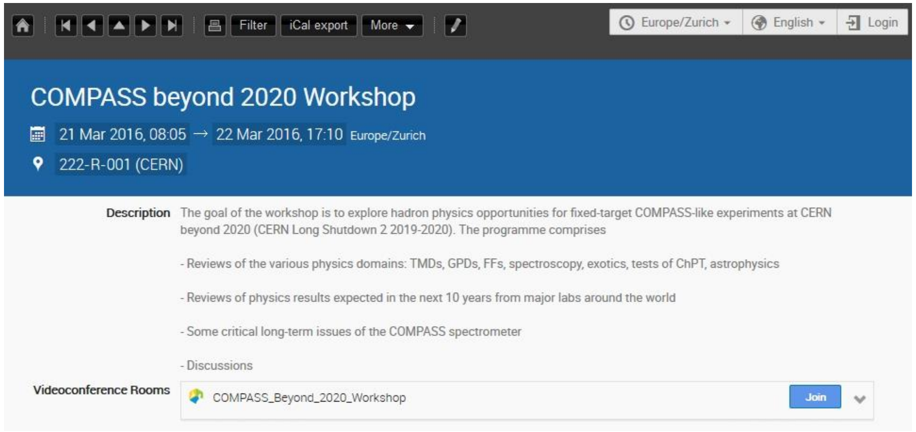
beam BM　target Transversity

Feasibility for COMPASS (beyond 2020)

First ideas: submitted to European Strategy Preparatory Group, 2012

- Hadron Spectroscopy: 280 GeV, π, K, $\bar{p}$ separation
- GPD E: Measurements with a polarised target
- SIDIS: 100 GeV, transversely polarised p and d targets
- Drell-Yan: Transversely polarised d and p targets,
  Unpolarised p, d targets,
  Nuclear targets (EMC effect),
  π, K, $\bar{p}$ separation

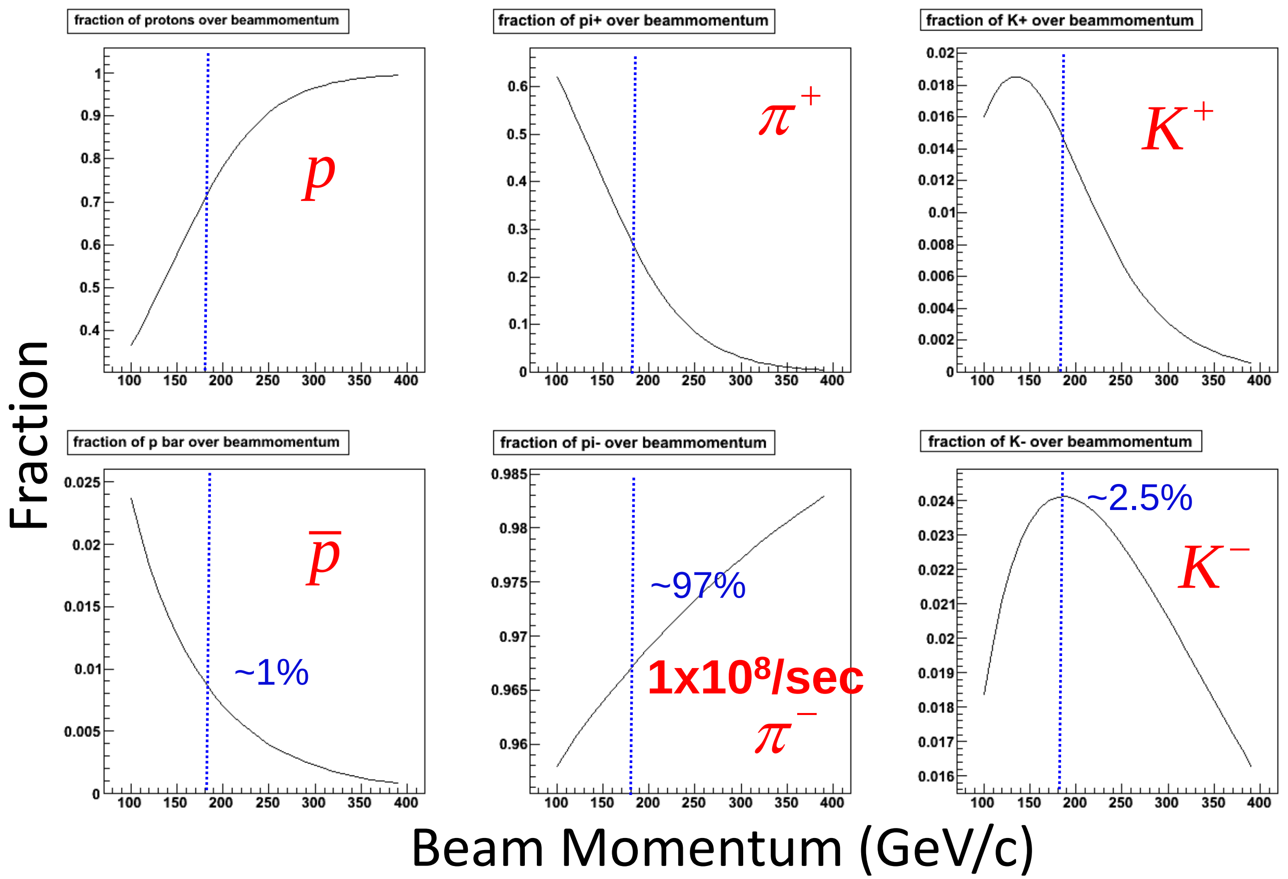
Dedicated workshop before proposal:



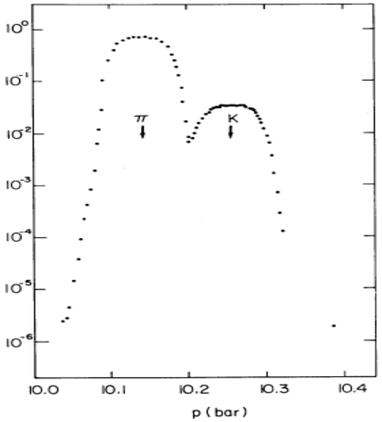
Mar. 2016

Unseparated $\pi/K/\bar{p}$ beams and beam PID

Fraction of particles in the positive or negative M2-Hadron-beam at COMPASS target



Beam PID by CEDAR (Cerenkov Differential Counters with Achromatic Ring Focus)



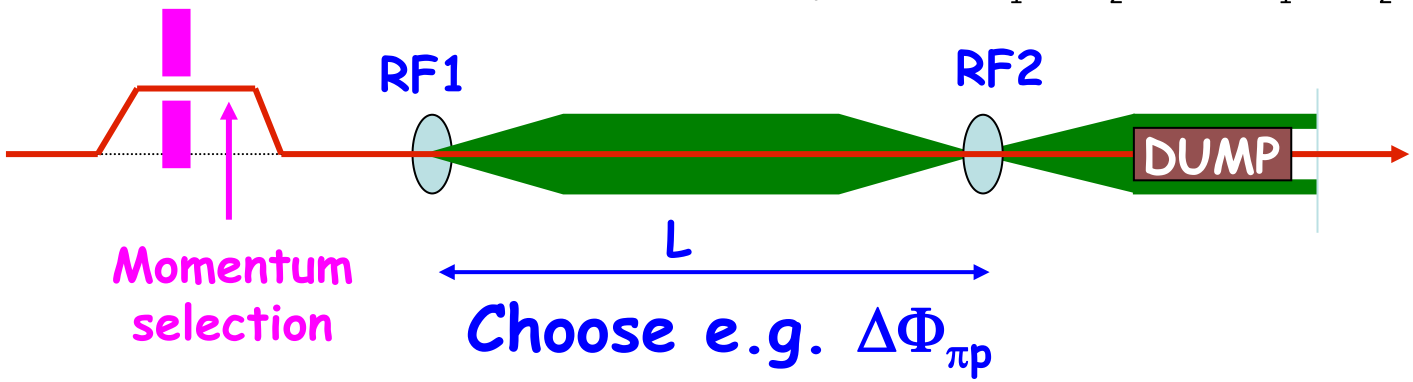
http://www.staff.uni-mainz.de/jasinsk/index.htm

Possibility of RF Separated $\pi/K/\bar{p}$ 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:

DF = 2p (L f / c) ($b_1^{-1} – b_2^{-1}$) with $b_1^{-1} – b_2^{-1}$ = (m_1^2-m_2^2)/2p^2



Particle type	From CKM beam	Antiproton beam
Beam momentum (GeV/c)	60	100
Momentum spread (%)	±1	±2
Angular emittance H,V (mrad)	±3.5, ±2.5	±3.5, ±2.5
Solid angle (μsterad)	10-12π	10-12π
% wanted particles lost on dump	37	20

Kaon and Anti-Proton Flux possibly reaching 10^7p./s

Reachable Physics from Future COMPASS-DY

Beam: π^-, K^-, $\bar{p}$
Target: polarised NH_3, ^{6}LiD
unpolarised Long-LH_2, Long-LD_2, Nuclear targets

(Blue) Physics from unpolarised nucleon

Observables and physics:

Angular distributions

with π^- beam and trans. polarised ^{6}LiD target

- flavor separation of Sivers

with $\bar{p}$ beams and trans. polarised NH3 target

- Model independent extraction of the proton Sivers- and Boer-Mulders

↓

with π^-/K^- beams

- Boer-Mulders quark distributions for Pions and Kaons

with K beam (and long-LH_2 target)

- Nucleon strange quark structure
- Kaon PDFs

with $\pi^-/K^-/\bar{p}$ beams

- Differentiating the origin of Lam-Tung violation
- $\pi/K/\bar{p}$ Distribution Amplitude

with Long-LD_2 and nuclear targets

- EMC effect

with lower momentum π^- beam

- Exclusive production near $x_F \to 1$ (DY, J/ψ): GPD and pion DA

Reachable Physics from Future COMPASS-DY

Beam: π^-, K^-, $\bar{p}$
Target: polarised NH_3, ^6LiD
unpolarised Long-LH_2, Long-LD_2, Nuclear targets

(Blue) Physics from unpolarised nucleon

Observables and physics:

Angular distributions

with π^- beam and trans. polarised ^6LiD target
- flavor separation of Sivers

with $\bar{p}$ beams and trans. polarised NH3 target
- Model independent extraction of the proton Sivers- and Boer-Mulders

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Model independent extraction of the proton BM function

Boer-Mulders from $\bar{p}\, p$ DY

$$A_U^{cos2\varphi} \propto \underbrace{h_{1,\bar{p}}^{\perp q}}_{\text{beam BM}} \otimes \underbrace{h_{1,p}^{\perp q}}_{\text{target BM}}$$

DY from anti-proton beam and (polarised) proton target can be used to achieve a model independent extraction of the proton (Sivers-) and Boer-Mulders quark distributions.

$\Downarrow$ After extracting the proton BM

DY from pion/Kaon beams and LH_2 target
→ pion/Kaon BM

Summary

- COMPASS collaboration at CERN have performed a series of Drell-Yan experiments using a high-intensity π^- beam with momentum 190-GeV/c impinging on a transversely polarised NH_3 target and unpolarised Al and W targets in 2015. A second year of data taking will be performed in 2018.
  - The experiment provides a greatly improved statistics for the unpolarised Drell-Yan and J/ψ measurements w.r.t. past experiments.
- We hope it will have a continuation as well in future (beyond 2020)
  - DY program with Improved CEDAR/RF-separated beam and LH_2/LD_2/nuclear targets will bring unique opportunities to address many important unresolved issues in understanding the flavor and TMD structures of proton, antiproton, pion, kaon and nuclei.