COMPASS Drell-Yan Results and Future Prospect

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INT Workshop on

"The Flavor Structure of Nucleon Sea"

Oct. 2-13, 2017

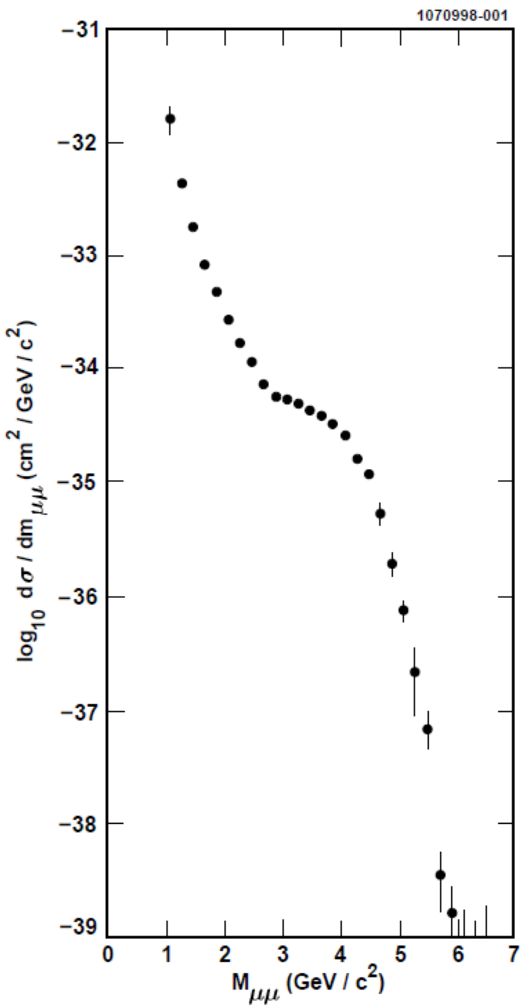
On behalf of COMPASS Collaboration

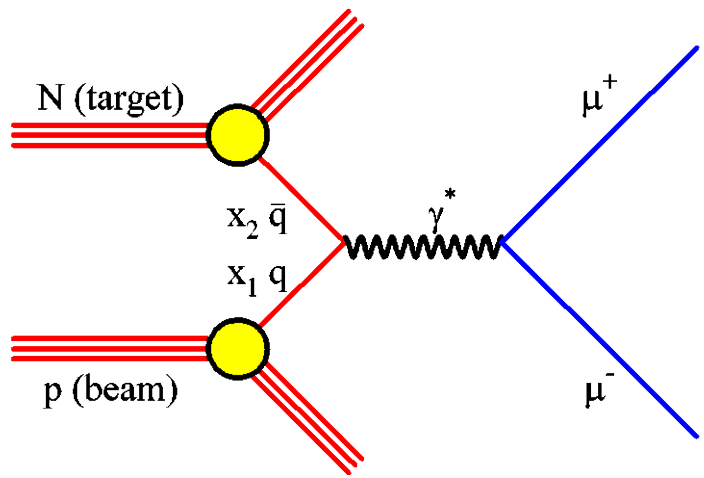
(Thanks to S. Platchkov, W.C. Chang, B. Parsamyan for some slides)

The Drell-Yan Process

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)



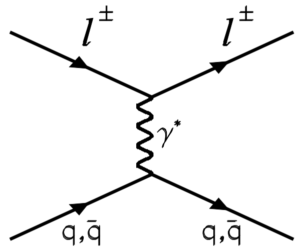


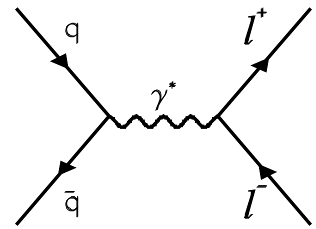
~1300 citations to date

$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2)+\bar{q}_a(x_1)q_a(x_2)\right]$$

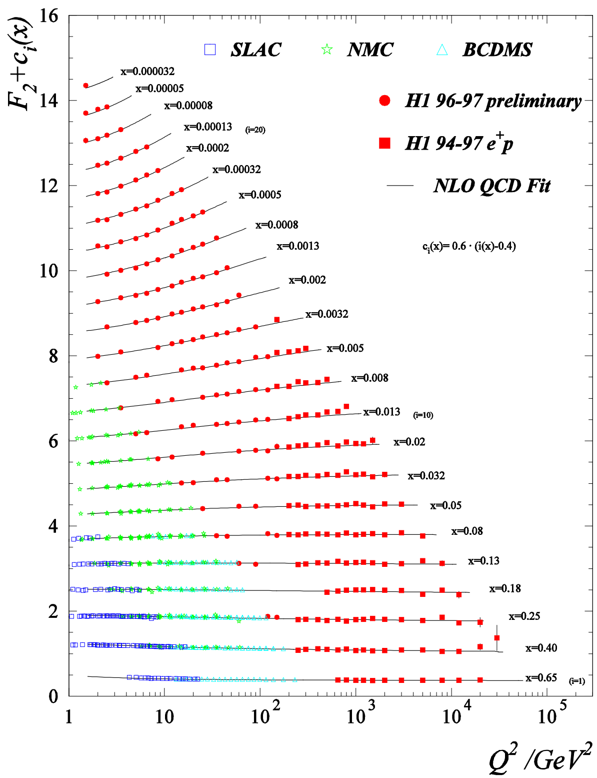
Complimentality between DIS and Drell-Yan

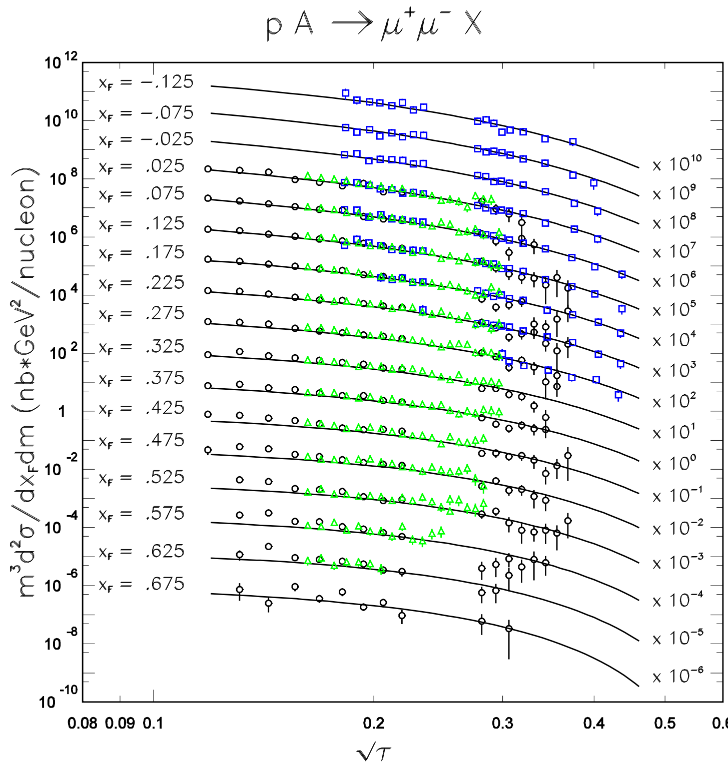
DIS





Drell-Yan





Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

Polarized Drell-Yan to Probe Transverse Momentum Dependent Quark Distributions
(45 years later!)

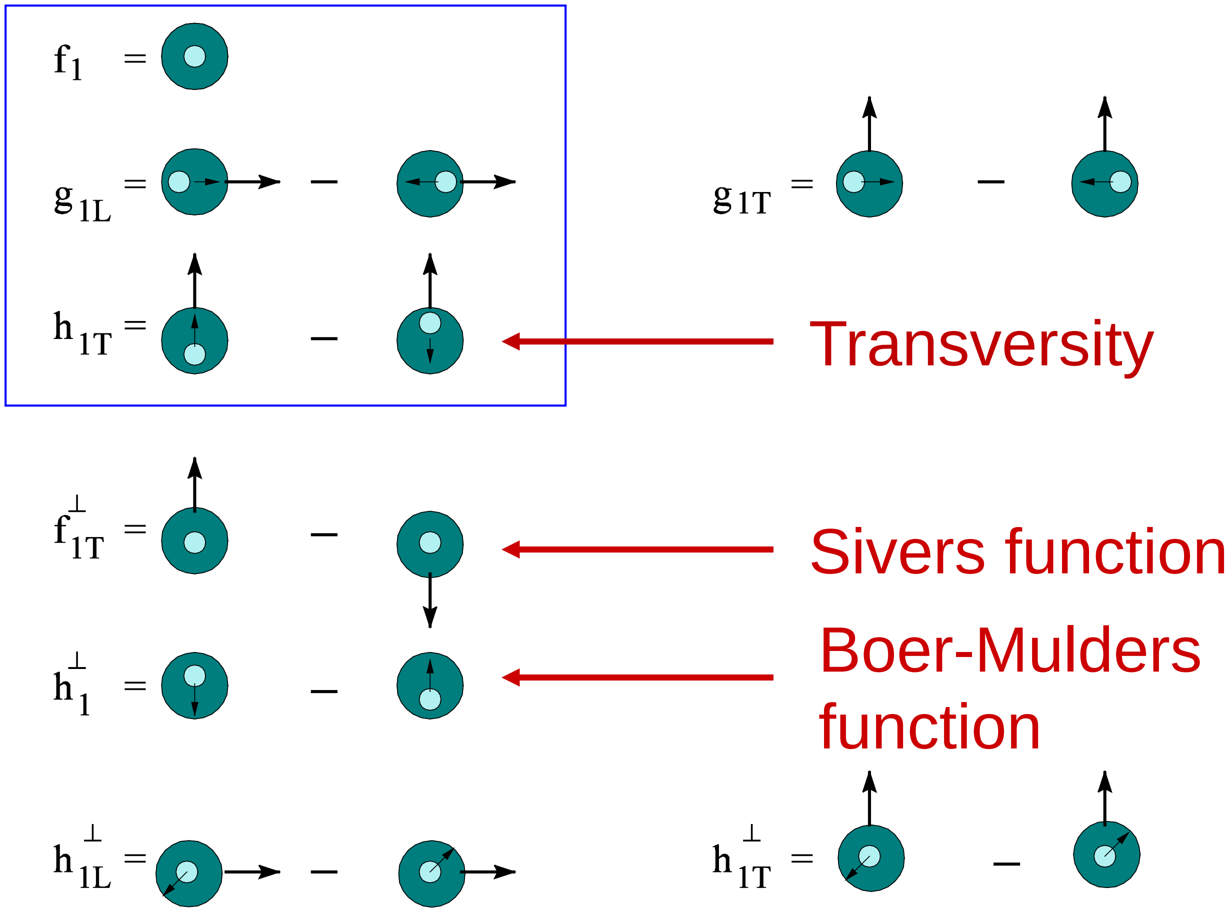
Transverse Momentum Dependent (TMD) Quark Distributions

Leading-Twist Quark Distributions

(A total of eight distributions)

Three survive after K⊥ integration

The other five are transverse momentum (K⊥) dependent (TMD)



Three parton distributions describing transverse momentum and/or transverse spin

Three transverse quantities:

1) Nucleon transverse spin

$\vec{S}_{\perp}^{N}$

2) Quark transverse spin

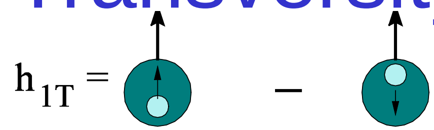
$\vec{s}_{\perp}^{q}$

3) Quark transverse momentum

$\vec{k}_{\perp}^{q}$

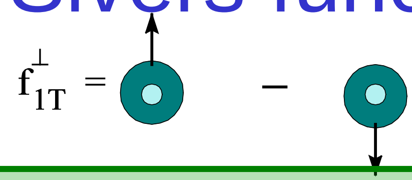
$\Rightarrow$ Three different correlations

1) Transversity



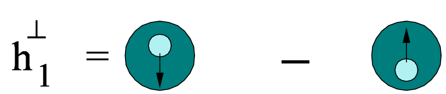
Correlation between $\vec{s}_{\perp}^{q}$ and $\vec{S}_{\perp}^{N}$

2) Sivers function



Correlation between $\vec{S}_{\perp}^{N}$ and $\vec{k}_{\perp}^{q}$

3) Boer-Mulders function



Correlation between $\vec{s}_{\perp}^{q}$ and $\vec{k}_{\perp}^{q}$

They can be measured in sem-inclusive DIS

They can also be measured in Drell-Yan process

a) Boer-Mulders functions:

- Unpolarized Drell-Yan: $d\sigma_{DY} \propto h_1^{\perp}(x_q)h_1^{\perp}(x_{\bar{q}})\cos(2\phi)$

b) Sivers functions:

- Single transverse spin asymmetry in polarized Drell-Yan:

$$A_N^{DY} \propto f_{1T}^{\perp}(x_q)\, f_{\bar{q}}(x_{\bar{q}})$$

c) Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

$$A_{TT}^{DY} \propto h_1(x_q)h_1(x_{\bar{q}})$$

- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY (Boer-Mulders and Sivers functions)

Remains to be tested experimentally!

SIDIS and single-polarized DY x-sections at twist-2 (LO)

SIDIS

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$

$$\times \left\{ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2}\, A_{LL} + S_T \left[A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \right] + S_T \lambda \left[\sqrt{(1-\varepsilon^2)}\, A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) \right] \right\}$$

DY

$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right)$$

$$\times \left\{ 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{[\sin^2\theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \right) \right] \right\}$$

where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots$ ⟷ **Boer-Mulders** ⟷ $A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$

$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$ ⟷ **Sivers** ⟷ $A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$

$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$ ⟷ **Transversity** ⟷ $A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$

$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$ ⟷ **Pretzelosity** ⟷ $A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$

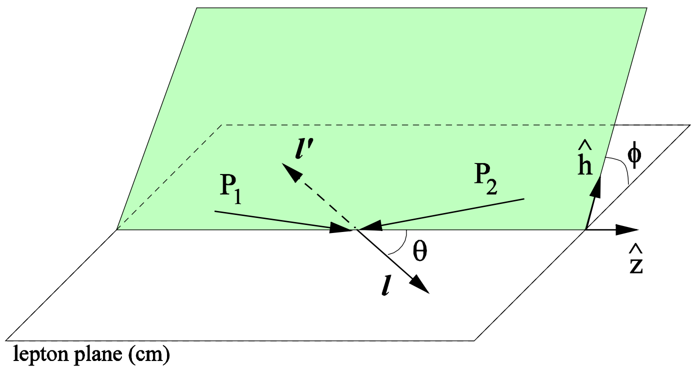
within QCD TMD-framework:

$h_1^{\perp q}$ & $f_{1T}^{\perp q}$ TMD PDFs are expected to be "conditionally" universal (SIDIS ↔ DY: sign change)

h_1^{q} & $h_{1T}^{\perp q}$ TMD PDFs are expected to be "genuinely" universal (SIDIS ↔ DY: no sign change)

The Boer-Mulders function

A long-standing puzzle in Drell-Yan angular distributions



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

A general expression for Drell-Yan decay angular distributions:

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

Lam-Tung relation: $1-\lambda=2\nu$

- Reflect the spin-1/2 nature of quarks (analog of the Callan-Gross relation in DIS)
- Insensitive to QCD - corrections

Decay angular distributions in pion-induced Drell-Yan

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

NA10 $\pi^- + W$

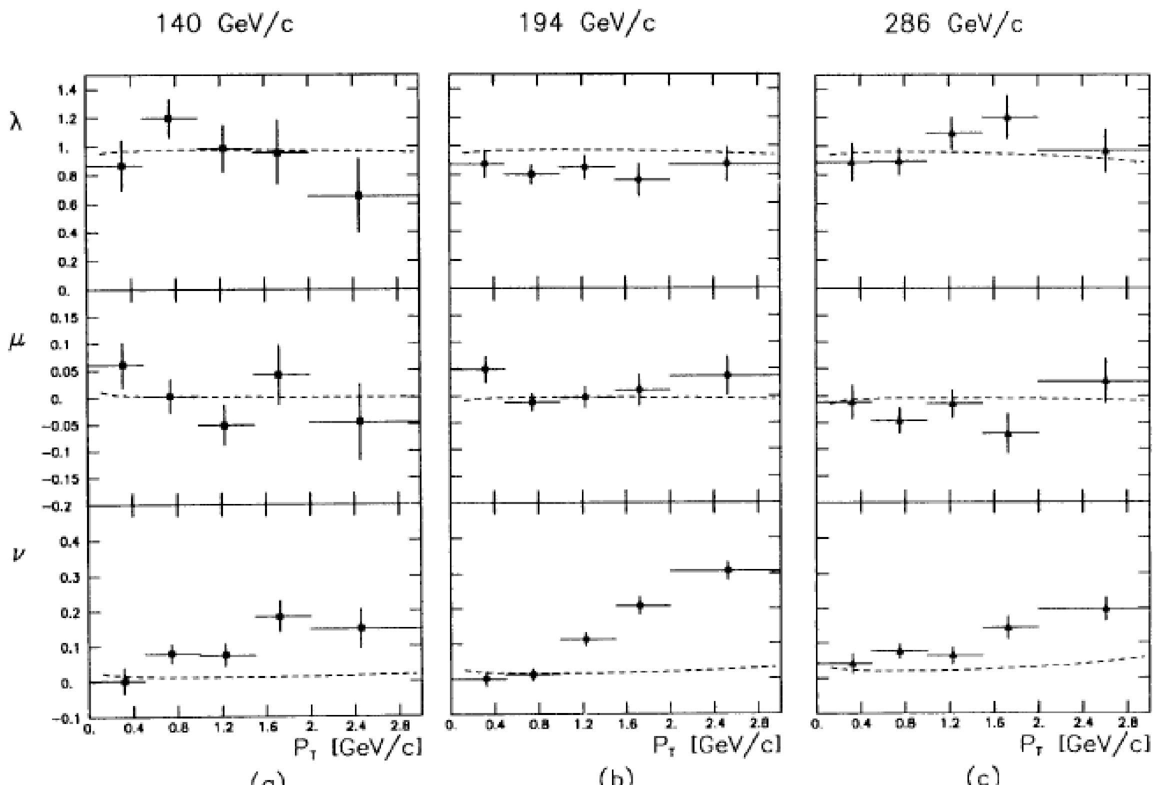


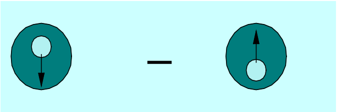
Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. a 140 GeV/c; b 194 GeV/c; c 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

Z. Phys. 37 (1988) 545

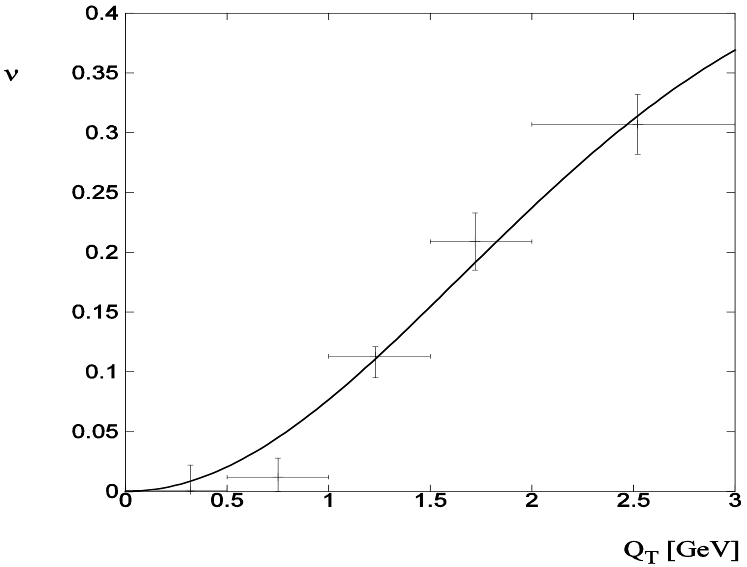
Dashed curves are from pQCD calculations

$\nu \neq 0$ and ν increases with p_T

Boer-Mulders function $h_1^{\perp}$



- $h_1^{\perp}$ represents a correlation between quark's k_T and transverse spin in an unpolarized hadron (analogous to Collins function)
- $h_1^{\perp}$ is a time-reversal odd, chiral-odd TMD parton distribution
- $h_1^{\perp}$ can lead to an azimuthal dependence with $\nu \propto \left(\frac{h_1^{\perp}}{f_1}\right)\left(\frac{\overline{h}_1^{\perp}}{\overline{f}_1}\right)$



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

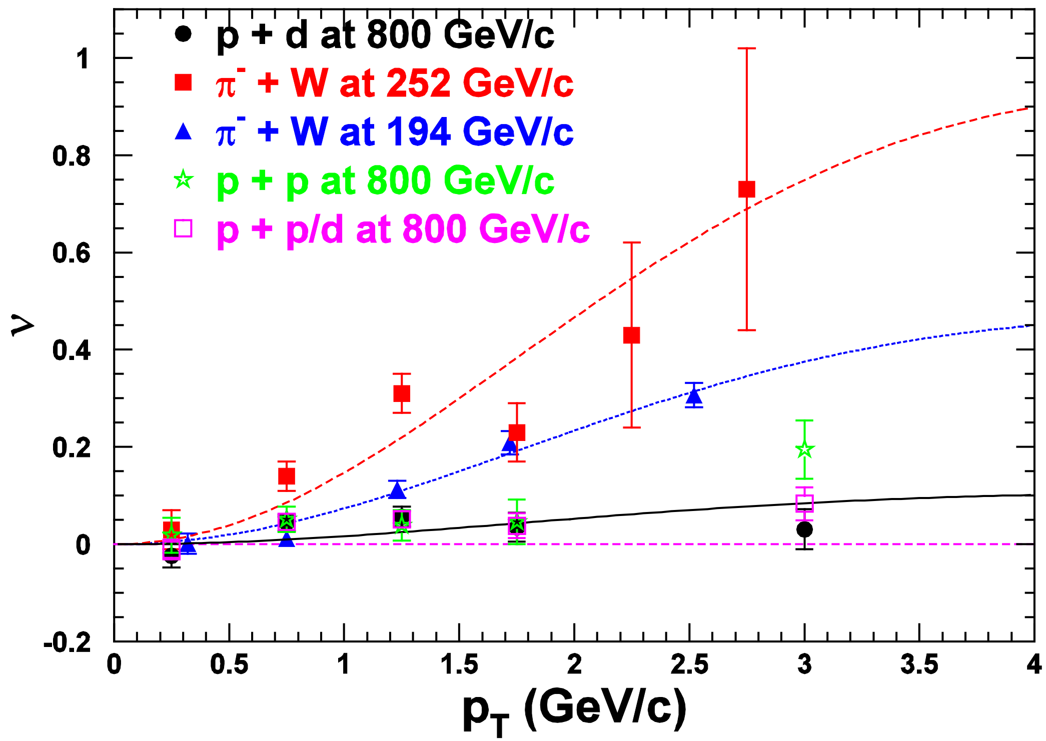
$$\nu = 16\kappa_1 \frac{Q_T^2 M_C^2}{(Q_T^2 + 4M_C^2)^2}$$

Boer, PRD 60 (1999) 014012

κ_1=0.47, M_C=2.3 GeV

ν>0 implies valence BM functions for pion and nucleon have same signs

Boer-Mulders function from cos2Φ Distribution in Drell-Yan



$$d\sigma_{DY} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi$$

$$\nu \propto h_1^{\perp}(x_q) h_1^{\perp}(x_{\bar{q}})$$

Lingyan Zhu et al., PRL 99 (2007) 082301; PRL 102 (2009) 182001

Extraction of Boer-Mulders function $h_1^{\perp}$:

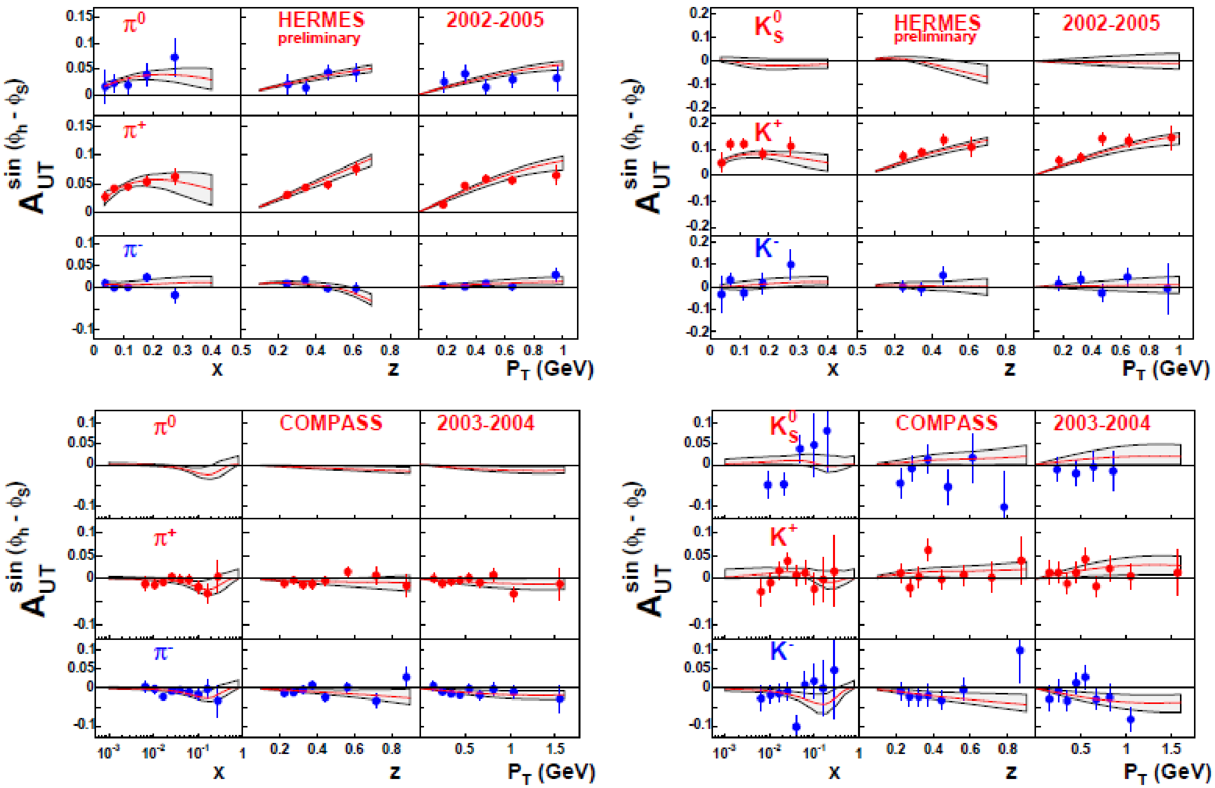
$\nu(\pi^- W \to \mu^+\mu^- X)$~ [valence $h_1^{\perp}(\pi)$] * [valence $h_1^{\perp}(p)$]

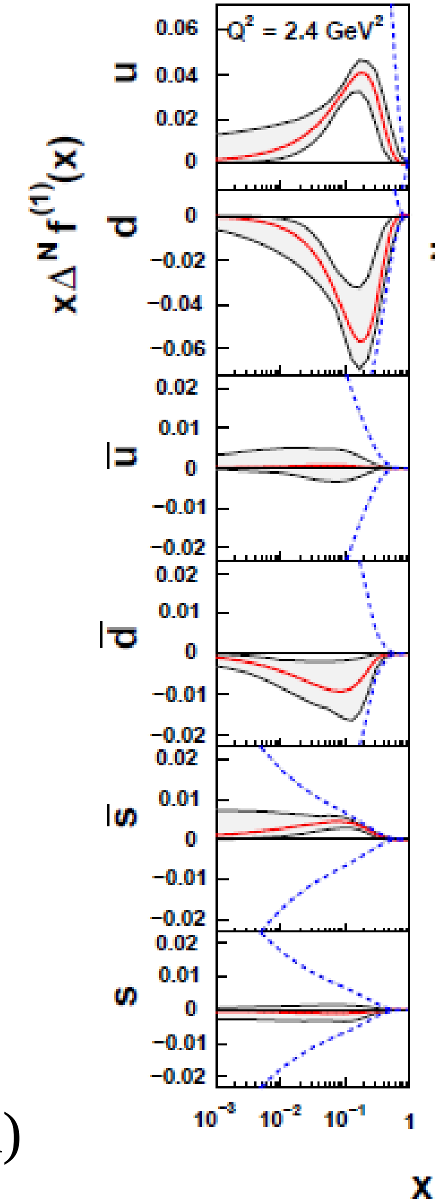
$\nu(pd \to \mu^+\mu^- X)$~ [valence $h_1^{\perp}(p)$] * [sea $h_1^{\perp}(p)$]

First extraction of BM functions in Drell-Yan has been obtained

Extraction of Sivers function from SIDIS data

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





- $u-$and d-quark Sivers functions have opposite signs
- Sea-quark Sivers functions are non-zero (from K^+ data)

SIDIS TSAs (Sivers)

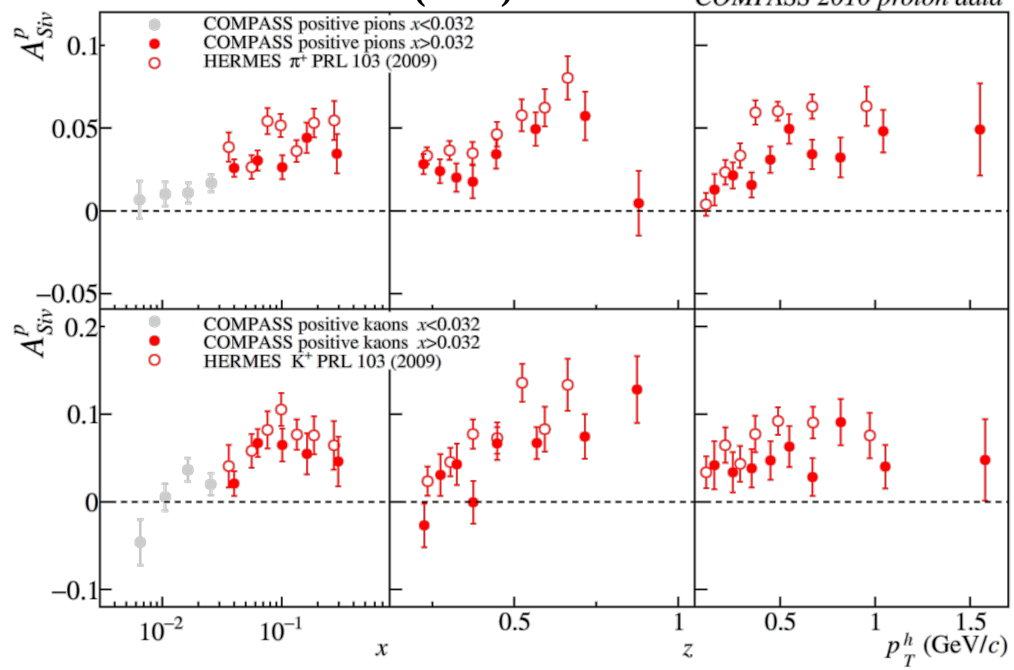
$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h} \qquad \mathrm{SSA}\left[\text{twist-2}\right]$$

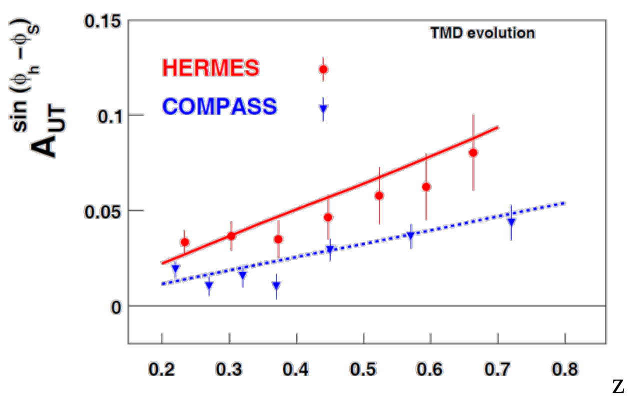
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{\begin{array}{l} 1+\ldots \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\,\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\,\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\,\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S) \end{array}\right] \\ + S_T\lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ +\,\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ +\,\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) \end{array}\right] \end{array}\right\}$$

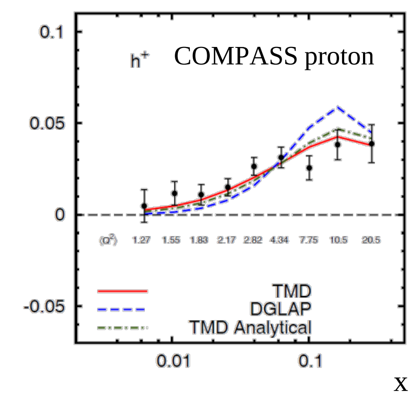
- Measured on proton and deuteron
- Gluon Sivers paper: submitted to PLB
  CERN-EP/2017-003, hep-ex/1701.02453

- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q^2 is different by a factor of ~2-3)
- **Q^2-evolution? Intriguing result!**

PLB 744 (2015) 250







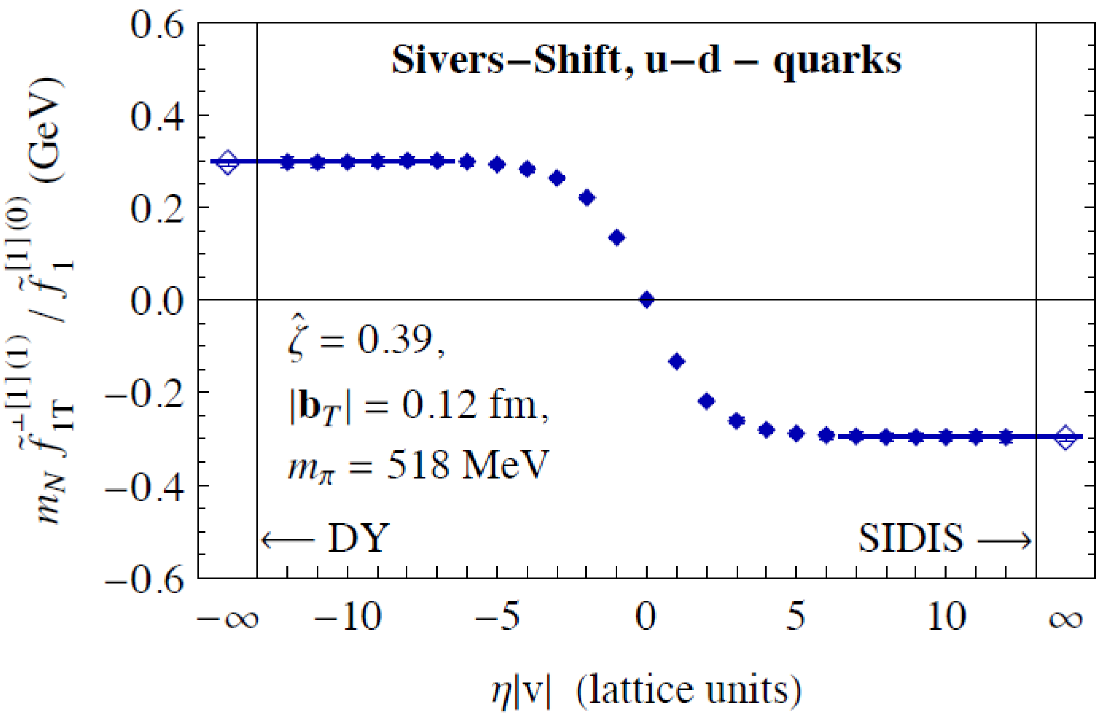
S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**

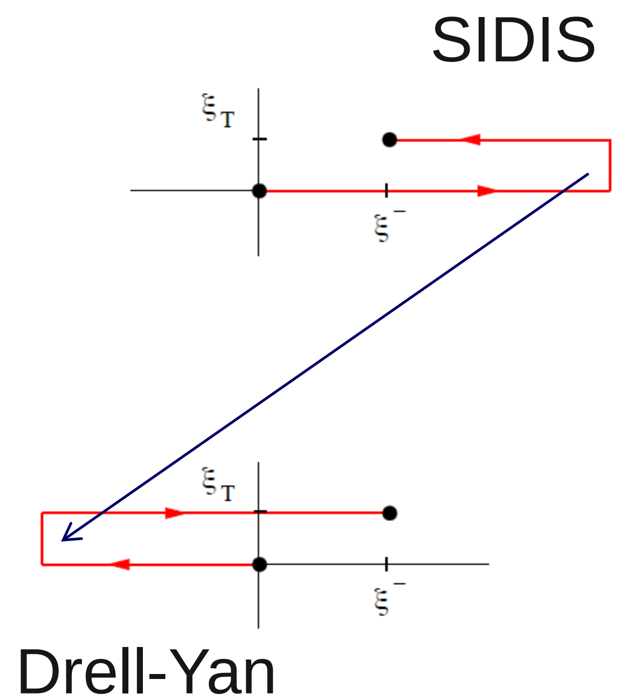
Outstanding questions on Sivers function

- Does Sivers function change sign between DIS and Drell-Yan?
- Sign and magnitude of the sea-quark Sivers functions?
- Q^2-evolution of the Sivers function?

Sivers function on the lattice

Musch, Haegler, Engelhardt, Negele & Schaeffer, PRD 85 (2012) 094510



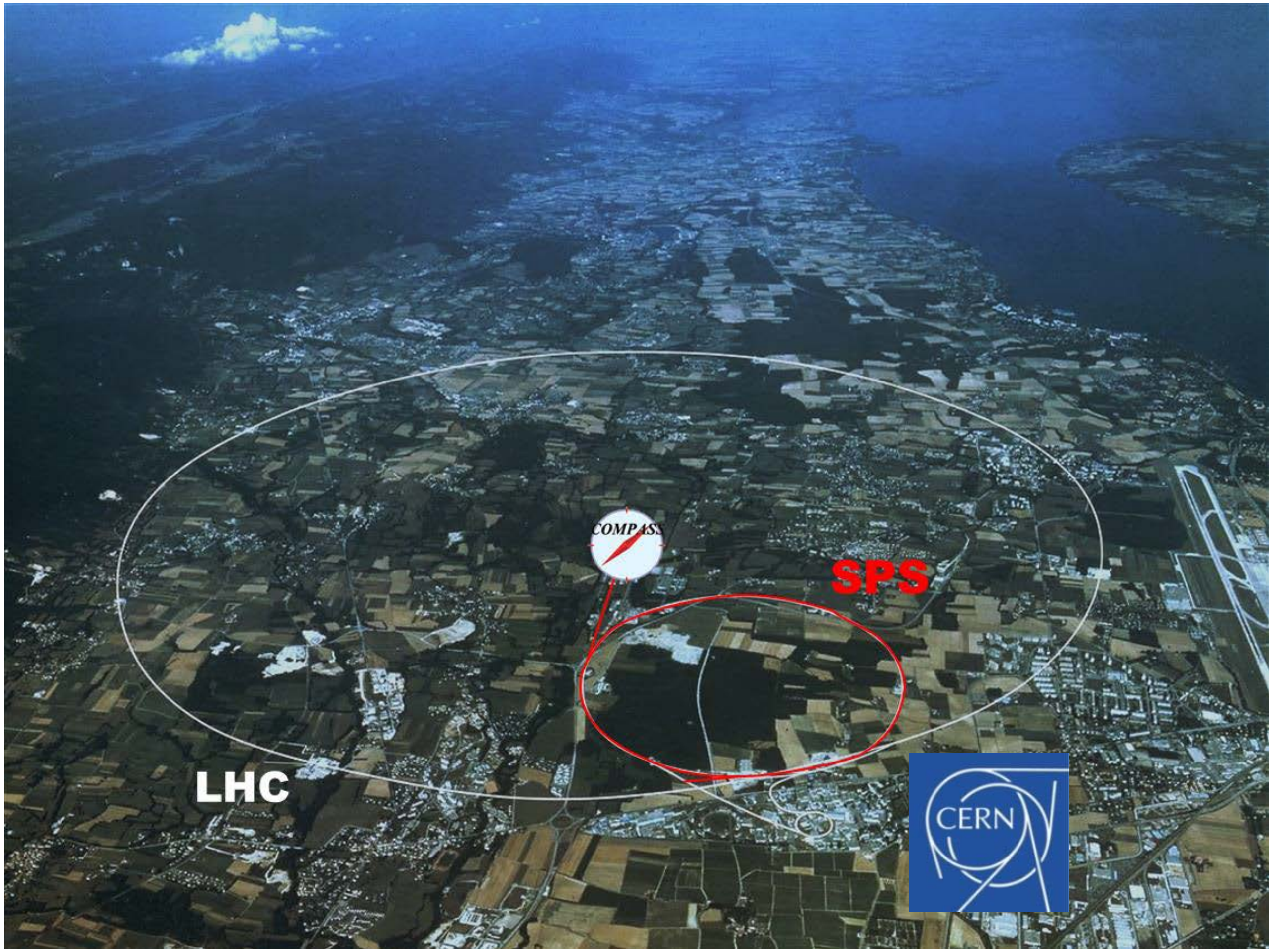


As the vertical gauge link goes from ∞ (SIDIS) to -∞ (Drell-Yan), the sign of Sivers function changes

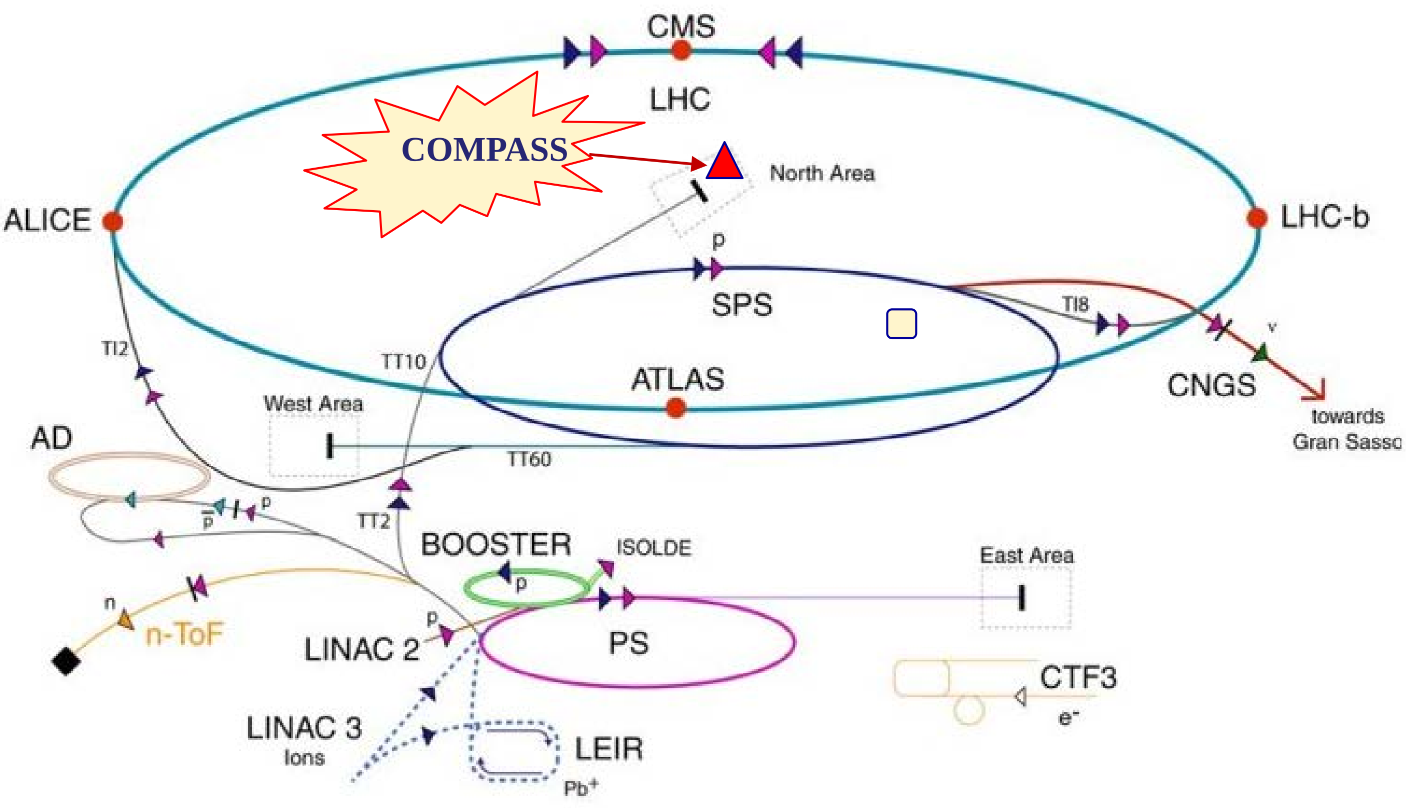
COMPASS Collaboration

(Common Muon and Proton Apparatus for Structure and Spectroscopy)

- 24 institutions from 13 countries – nearly 250 physicists
- Fixed-target experiment at SPS north area
- Physics programs:
    - Nucleon spin and partonic structures
    - Hadron spectroscopy



CERN accelerator complex

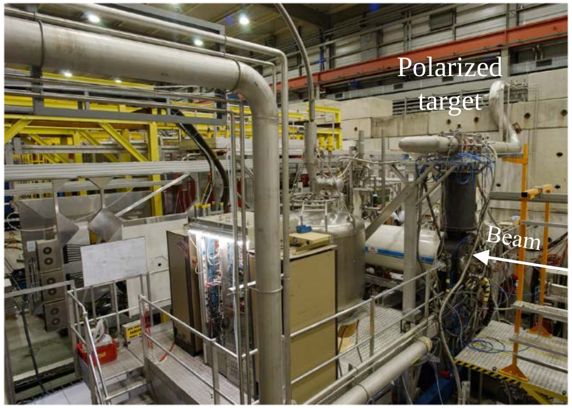


COMPASS is an “old” experiment - already two “phases”

- COMPASS I : 2002 – 2011
  - Longitudinally polarized DIS and SIDIS
  - Transversely polarized SIDIS
  - Hadron spectroscopy and chiral dynamics

Muons (Longitudinally polarized DIS and SIDIS; Transversely polarized SIDIS)

Hadrons (Hadron spectroscopy and chiral dynamics)

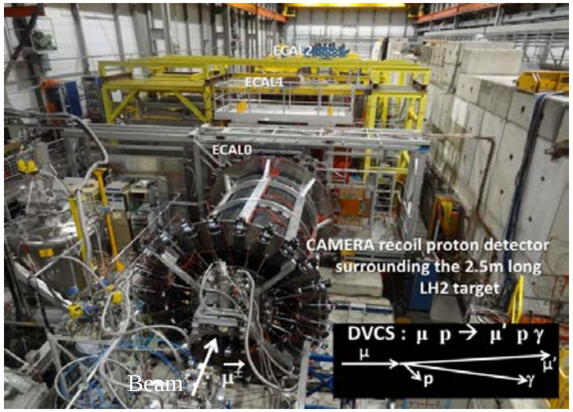


- COMPASS II : 2012 – 2018
  - Primakoff studies (2012)
  - DVCS and Meson-production (2016, 2017)
  - Polarized Drell-Yan process (2015, 2018)

Hadrons (Primakoff studies)

Muons (DVCS and Meson-production)

Hadrons (Polarized Drell-Yan process)



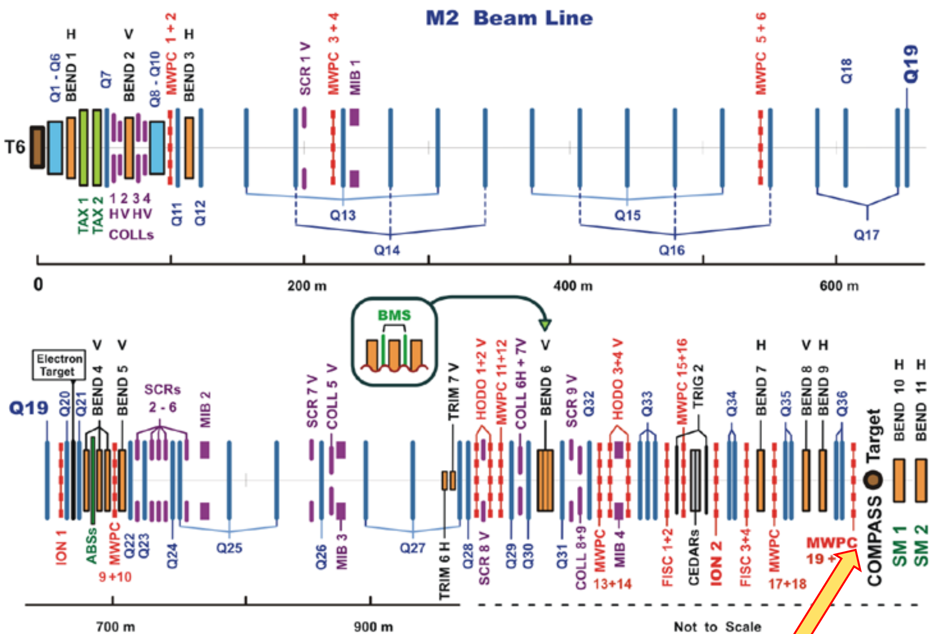
CERN M2 beam line

Abbon et al., NIM A779 (2015) 69-115

- Beams at COMPASS:
  - muons: μ^+, μ^-,
  - hadrons: $h^+(p, \pi^+, K^+)$, $h^-(\pi^-, K^- p)$
  - electrons: e^-

  - 1 or 2 spills of 5 s every 33-48 sec

SPS protons

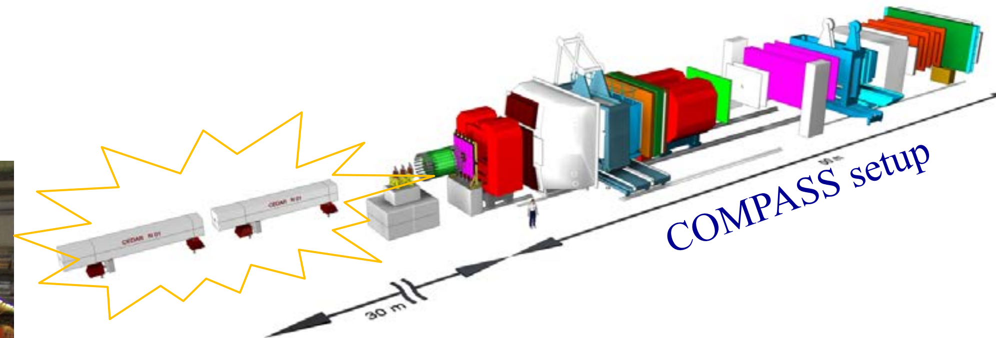


COMPASS Target

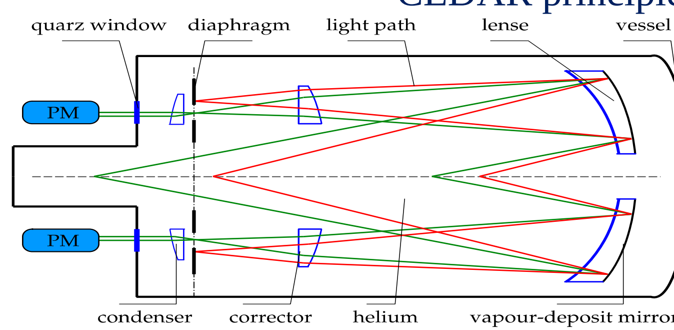
Unique combination of positive and negative beams of different species

Beam particle identification

- Differential Cerenkov counters (CEDARs) – two CEDARs



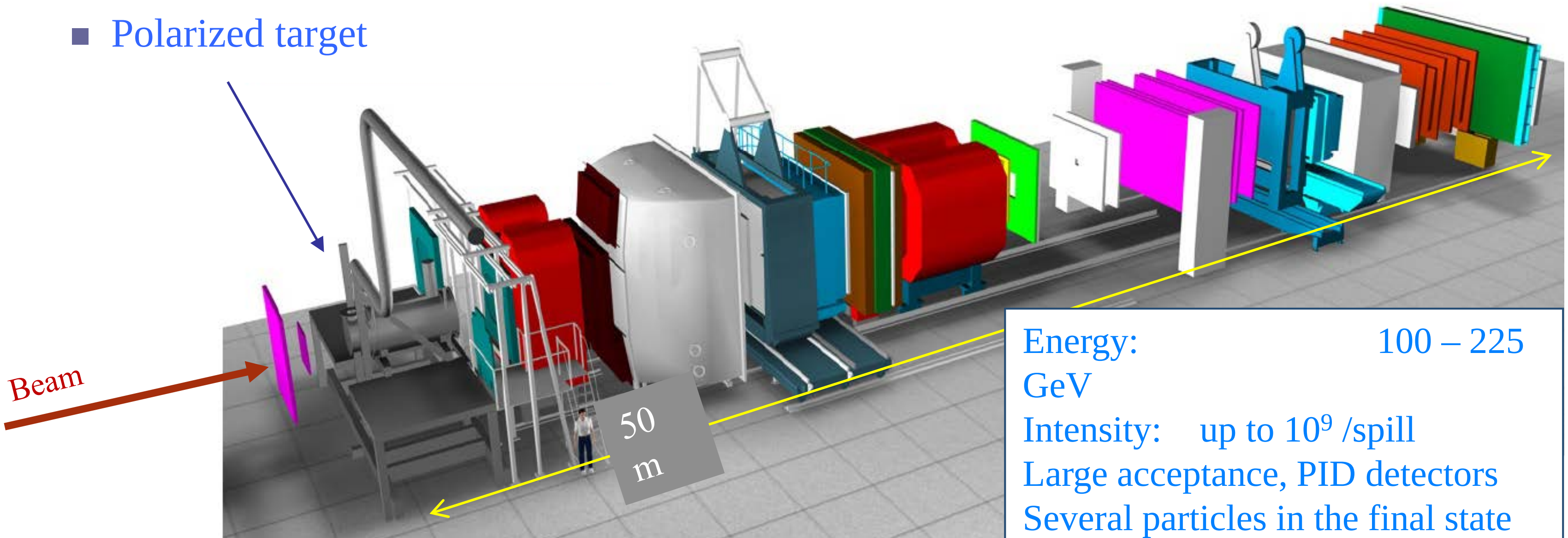
CEDAR principle



The two CEDARs are located upstream of the COMPASS experimental hall

COMPASS : a large, fixed-target, versatile setup

- COMPASS apparatus
  - Built for detecting several particles in the final state
  - Two spectrometers: Small-angle and Large-angle – large and flat acceptance
  - Polarized target

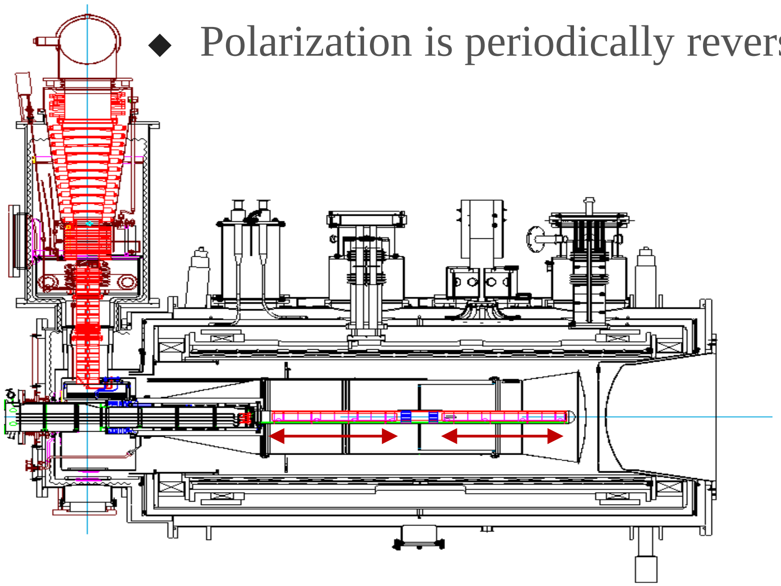


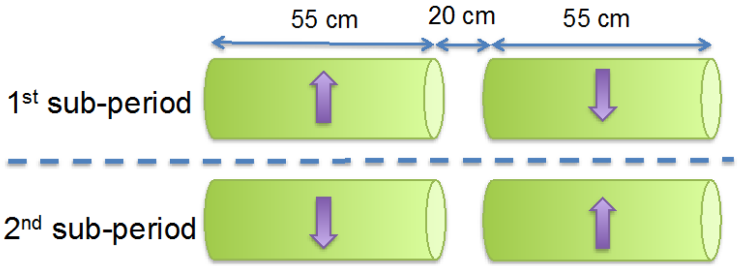
Energy: 100 – 225 GeV
Intensity: up to 10^9 /spill
Large acceptance, PID detectors
Several particles in the final state
Large (1.2 m) polarized target

"Minor" changes to the setup – switch between various physics programs
→ Same spectrometer used for SIDIS and Drell-Yan measurements

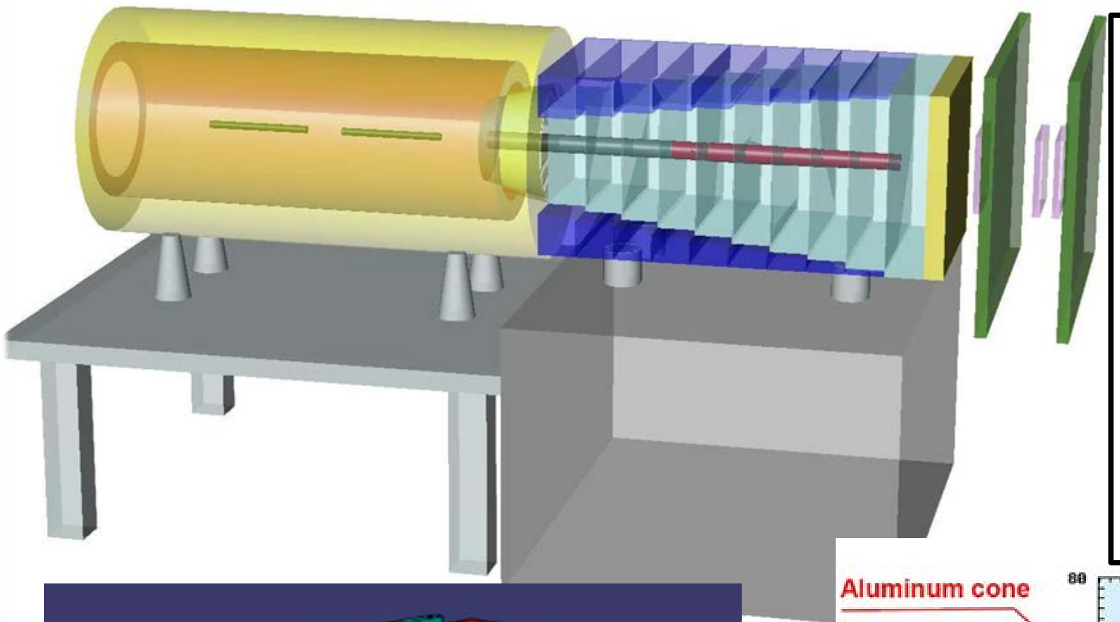
COMPASS polarized target

- Polarized target with two 55 cm long cells (for DY); three cells for SIDIS
- Superconducting magnets: solenoid + dipole
- Target filled with ammonia (NH_3) solid beads; also available: ^{6}LiD
- Polarization in longitudinal mode, data is taken in transverse mode
- Polarization is periodically reversed

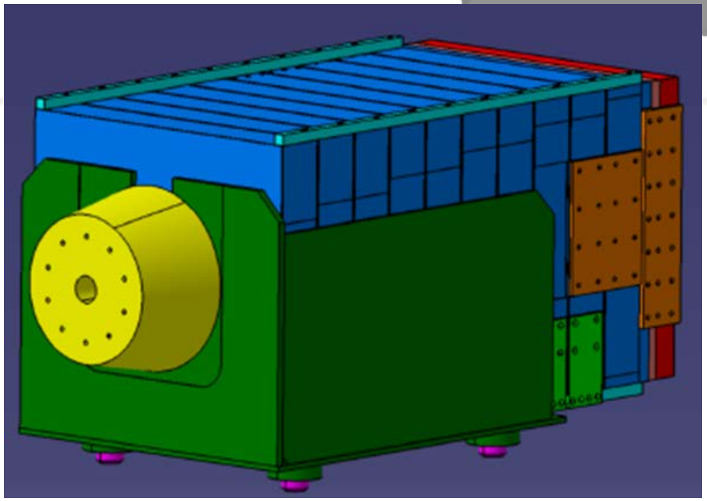


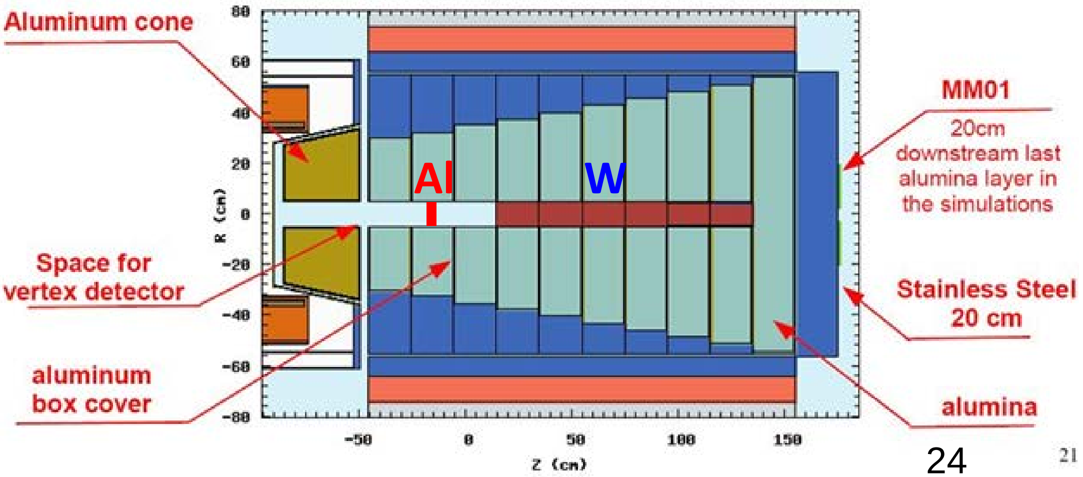


Hadron Absorber & Nuclear Targets

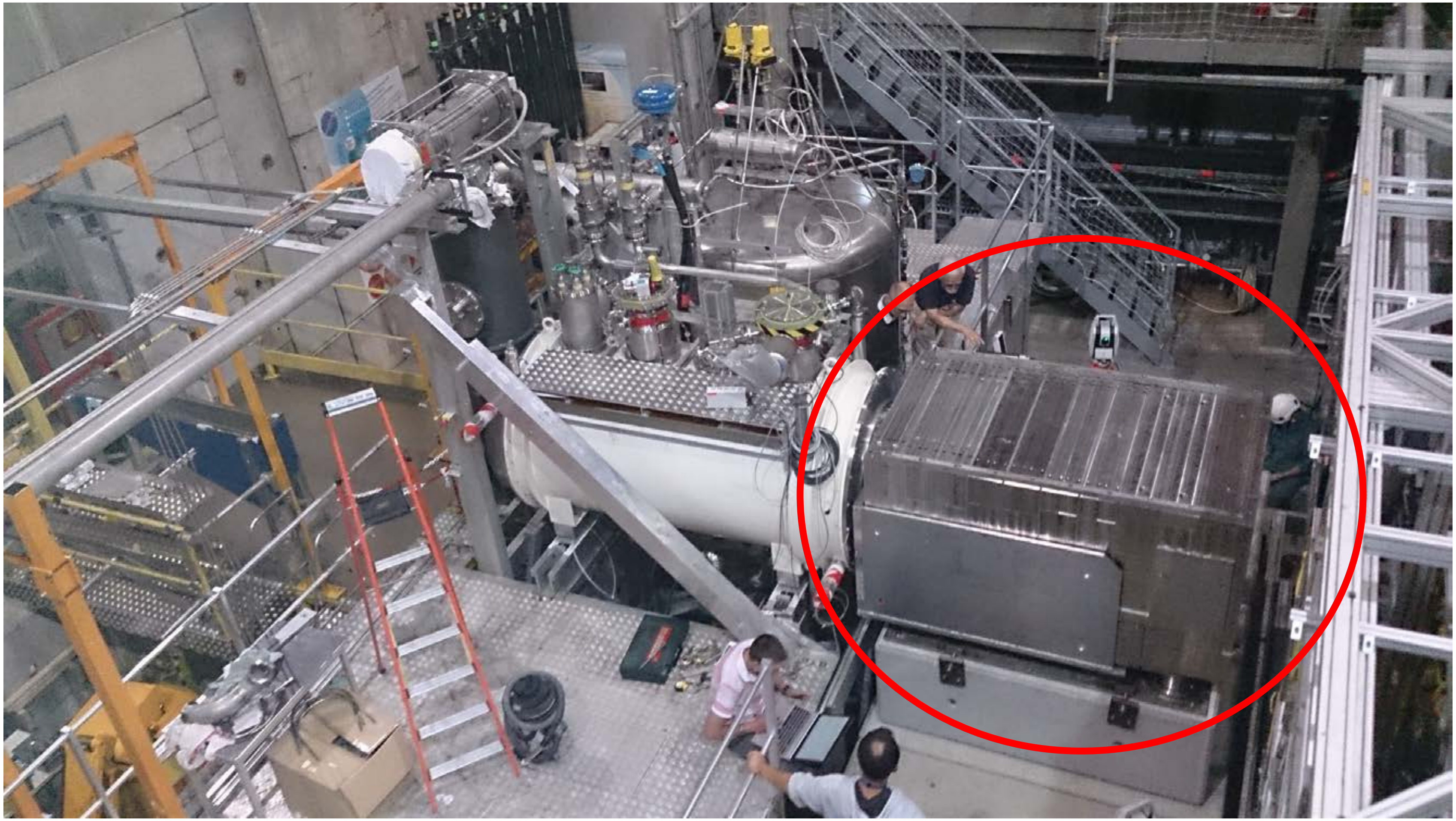


- Absorber: 236 cm long, made of Al_2O_3.
- Radiation lengths (multiple scattering for μ): $x/X_0 = 33.53$
- Hadronic interaction lengths (stopping power for π): x/λ_{int} = 7.25
- 7 cm Al target
- 120 cm W beam dump





Hadron Absorber & Nuclear Targets



COMPASS-II Transversely Polarized Drell-Yan Program

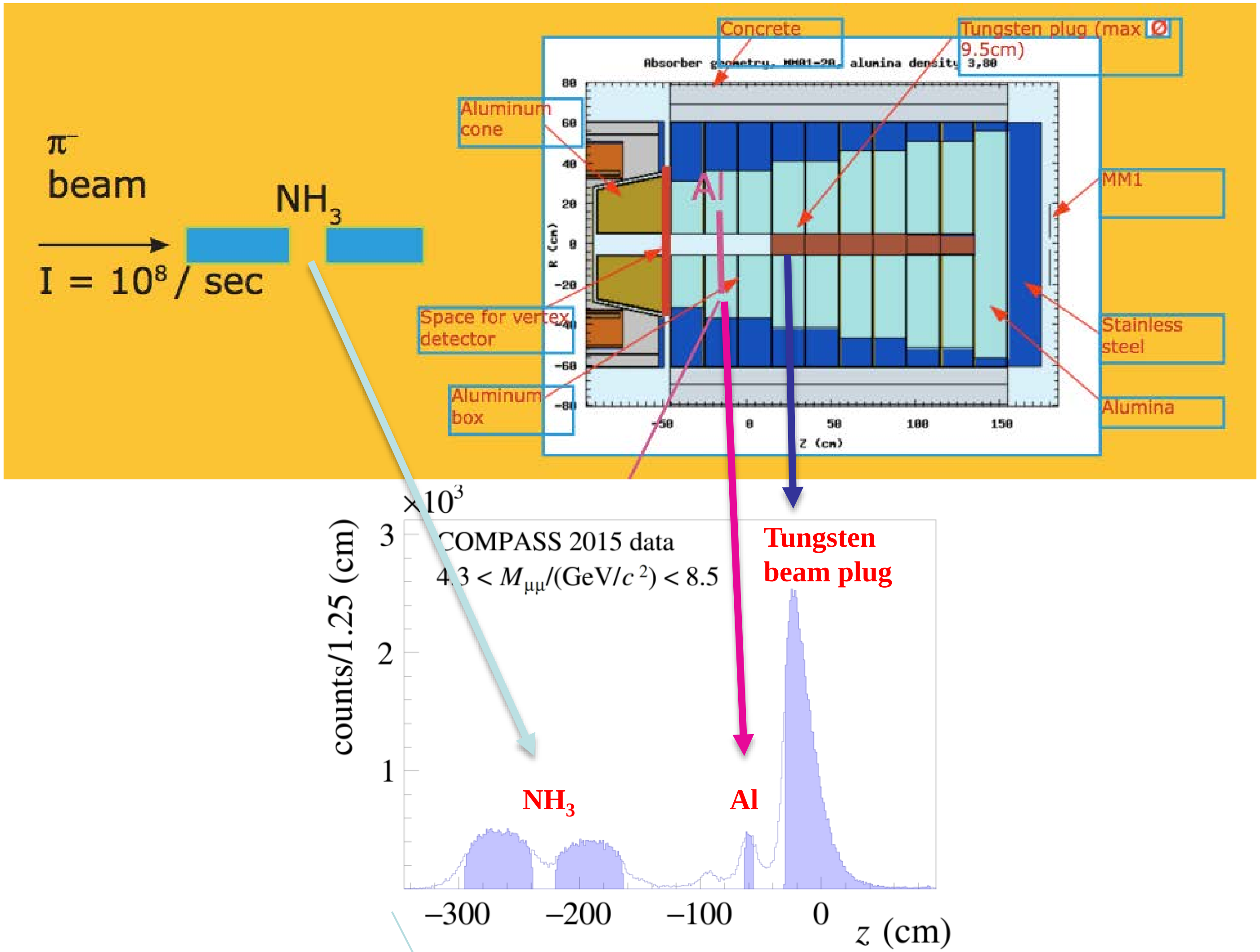
- Schedules:
  - 2014 Oct – Dec: commission Drell-Yan runs
  - 2015: first year of transversely polarized Drell-Yan runs with 190 GeV π^- beam

PRL **119,** 112002 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

First Measurement of Transverse-Spin-Dependent Azimuthal Asymmetries in the Drell-Yan Process

M. Aghasyan,[24] R. Akhunzyanov,[7] G. D. Alexeev,[7] M. G. Alexeev,[25] A. Amoroso,[25,26] V. Andrieux,[27,20] N. V. Anfimov,[7] V. Anosov,[7] A. Antoshkin,[7] K. Augsten,[7,18] W. Augustyniak,[28] A. Austregesilo,[15] C. D. R. Azevedo,[1] B. Badełek,[29] F. Balestra,[25,26] M. Ball,[3] J. Barth,[4] R. Beck,[3] Y. Bedfer,[20] J. Bernhard,[12,9] K. Bicker,[15,9] E. R. Bielert,[9] R. Birsa,[24] M. Bodlak,[17] P. Bordalo,[11,b] F. Bradamante,[23,24] A. Bressan,[23,24] M. Büchele,[8] W.-C. Chang,[21] C. Chatterjee,[6] M. Chiosso,[25,26] I. Choi,[27] S.-U. Chung,[15,c] A. Cicuttin,[24,d] M. L. Crespo,[24,d] S. Dalla Torre,[24] S. S. Dasgupta,[6]

Dimuon Vertex Distributions (2015 Trans.-pol. Drell-Yan Runs)

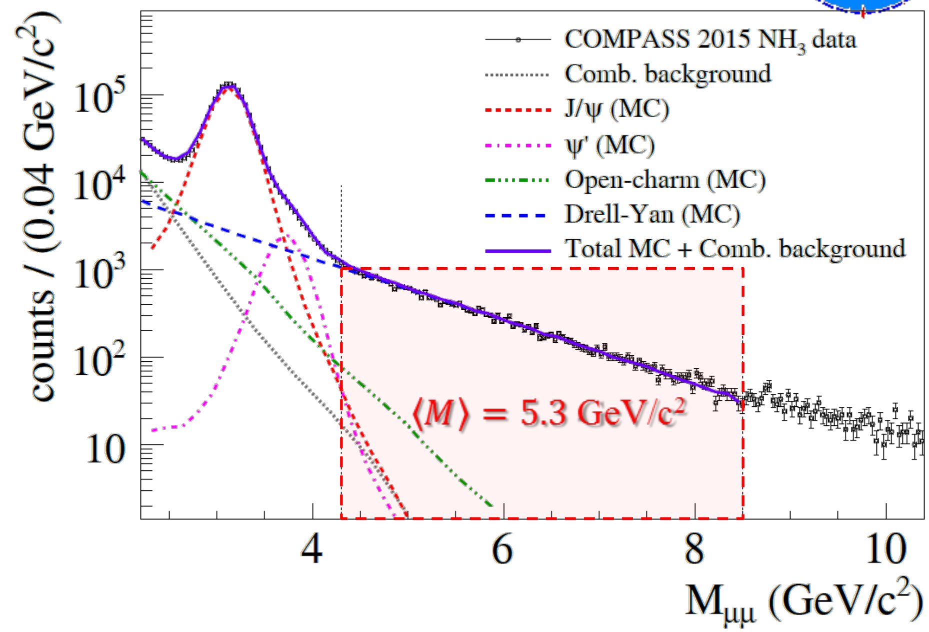


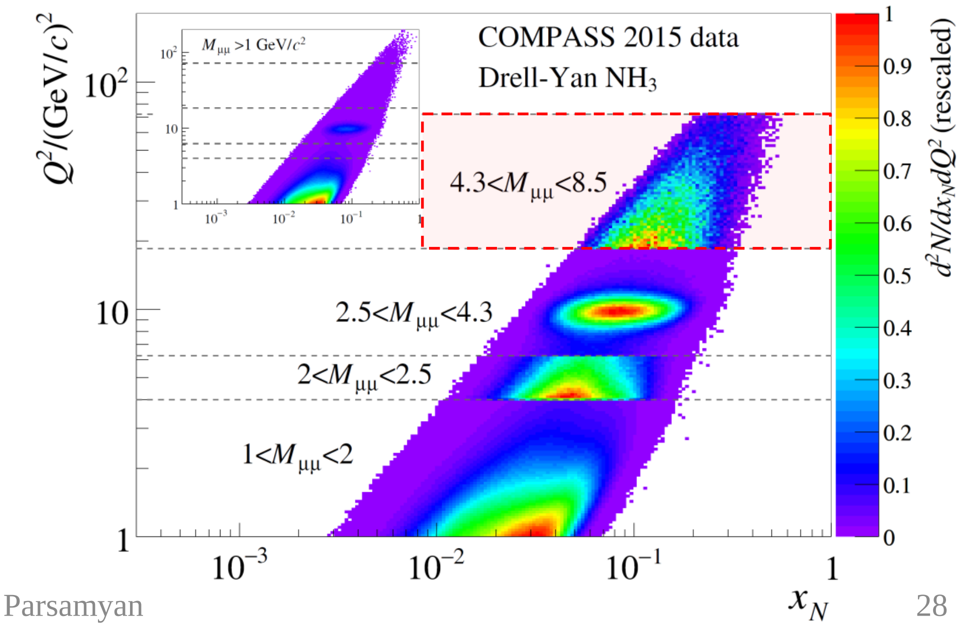
COMPASS, PRL 119 (2017) 112002

COMPASS DY: high mass range

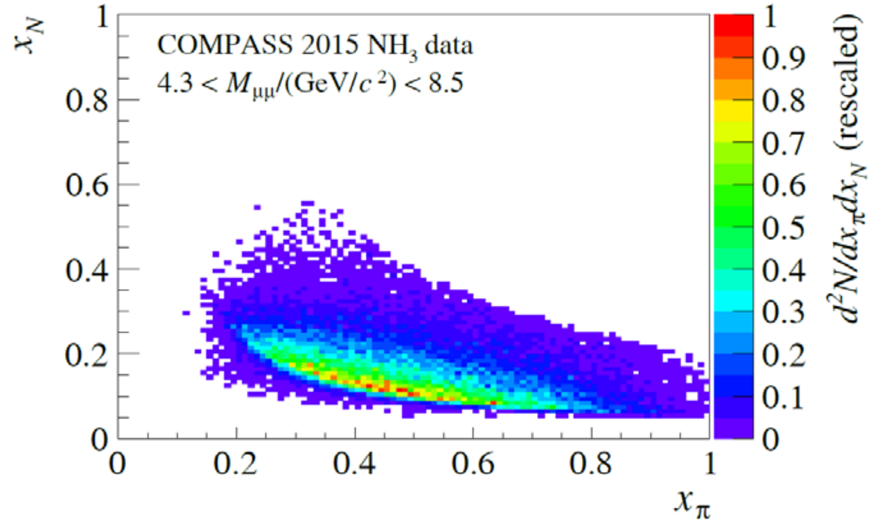
- $1.0 < M/(GeV/c^2) < 2.0$ "Low mass"
  - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π, K decays
- $2.0 < M/(GeV/c^2) < 2.5$ "Intermediate mass"
  - High DY-cross section
  - Still low DY-signal/background ratio
- $2.5 < M/(GeV/c^2) < 4.3$ "Charmonia mass"
  - Strong J/ψ-signal → study of J/ψ physics
  - Good signal/background
- $4.3 < M/(GeV/c^2) < 8.5$ "High mass"
  - Low DY cross-section
  - Beyond charmonium region, background < 3%
  - Valence region → largest asymmetries

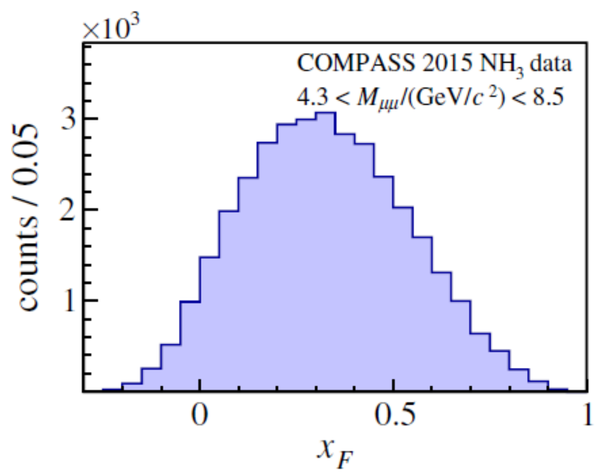
Final sample: 35 000 dimuons in HM

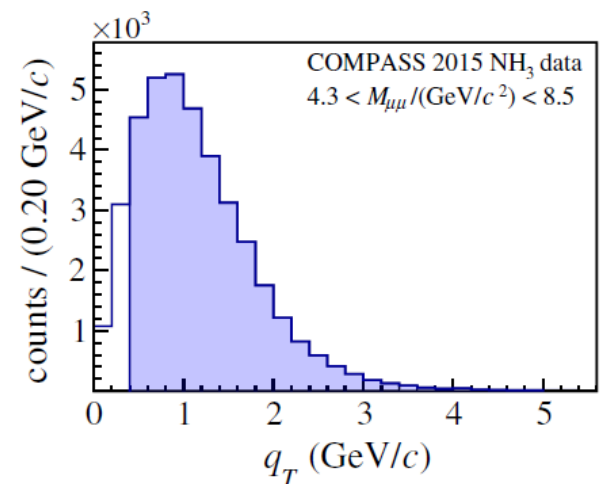




Kinematic Acceptance (2015 Trans.-pol. Drell-Yan Runs)







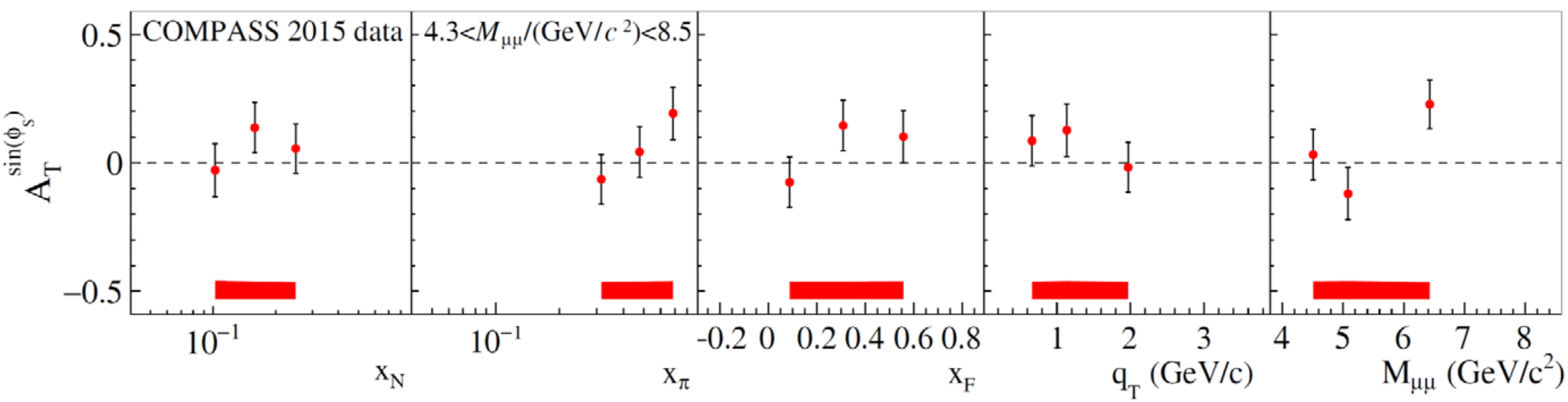
COMPASS, PRL 119 (2017) 112002

Transverse Spin Asymmetries in Trans.-pol. Drell-Yan: Sivers

$$A_T^{\sin\phi_s} \propto \text{Density } f_1|_\pi \otimes \text{Sivers } f_{1T}^\perp|_p$$

$$\frac{d\sigma^{LO}}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U^{LO}$$

$$\left\{ \left(1 + D_{[\sin^2\theta]}^{LO} A_U^{\cos 2\varphi} \cos 2\varphi\right) + \left|\vec{S}_T\right| \left[\boxed{A_T^{\sin\varphi_S}} \sin\varphi_S + D_{[\sin^2\theta]}^{LO} \left(A_T^{\sin(2\varphi-\varphi_S)} \sin(2\varphi-\varphi_S) + A_T^{\sin(2\varphi+\varphi_S)} \sin(2\varphi+\varphi_S) \right) \right] \right\}$$



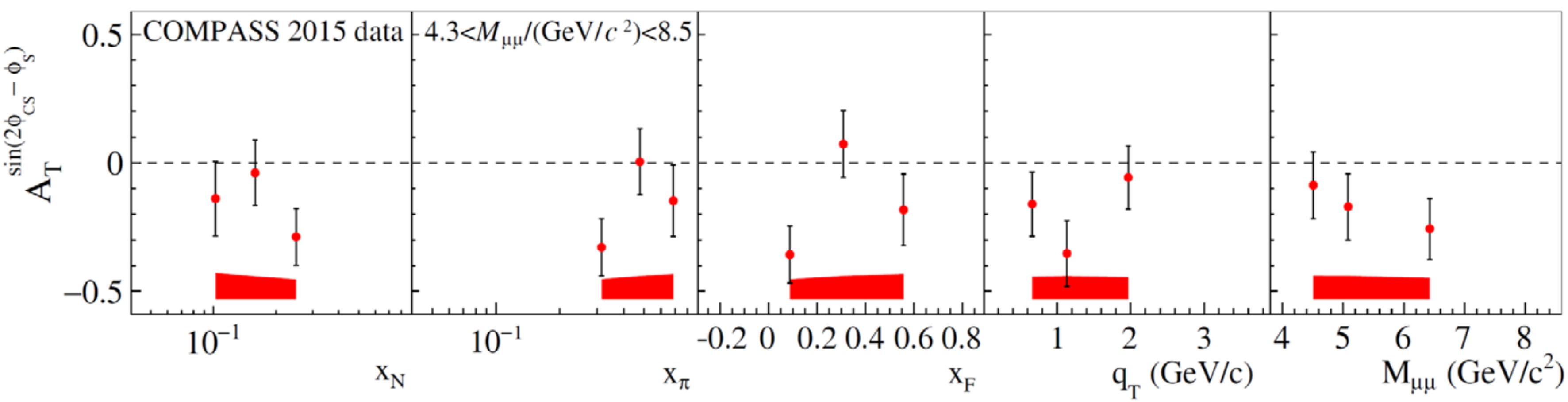
COMPASS, PRL 119 (2017) 112002

Transverse Spin Asymmetries in Trans.-pol. Drell-Yan: Transversity

$$A_T^{\sin(2\phi-\phi_s)} \propto \text{BM } h_1^{\perp}|_{\pi} \otimes \text{Transversity } h_1|_p$$

$$\frac{d\sigma^{LO}}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U^{LO}$$

$$\left\{ \left(1 + D_{[\sin^2\theta]}^{LO} A_U^{\cos 2\varphi} \cos 2\varphi\right) + \left|\vec{S}_T\right| \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{[\sin^2\theta]}^{LO} \left(A_T^{\sin(2\varphi-\varphi_S)} \sin(2\varphi-\varphi_S) + A_T^{\sin(2\varphi+\varphi_S)} \sin(2\varphi+\varphi_S) \right) \right] \right\}$$



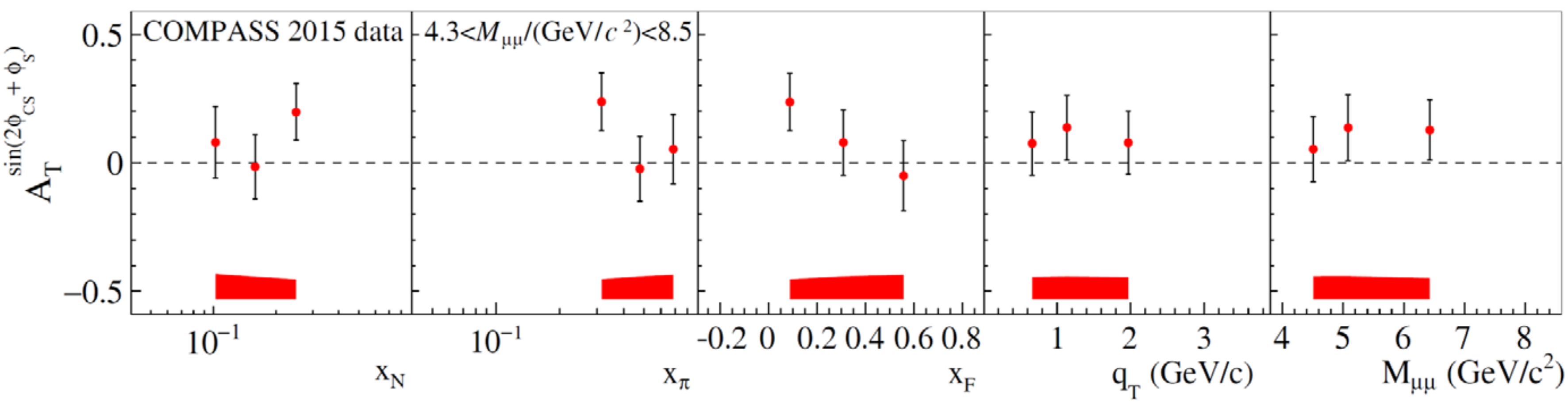
COMPASS, PRL 119 (2017) 112002

Transverse Spin Asymmetries in Trans.-pol. Drell-Yan: Pretzelosity

$$\frac{d\sigma^{LO}}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U^{LO}$$

$A_T^{\sin(2\phi+\phi_s)} \propto \text{BM } h_1^{\perp}|_{\pi} \otimes \text{Pretzelosity } h_{1T}^{\perp}|_{p}$

$$\left\{\left(1 + D_{[\sin^2\theta]}^{LO} A_U^{\cos 2\varphi}\cos 2\varphi\right) + \left|\vec{S}_T\right|\left[A_T^{\sin\varphi_S}\sin\varphi_S + D_{[\sin^2\theta]}^{LO}\left(A_T^{\sin(2\varphi-\varphi_S)}\sin(2\varphi-\varphi_S) + A_T^{\sin(2\varphi+\varphi_S)}\sin(2\varphi+\varphi_S)\right)\right]\right\}$$



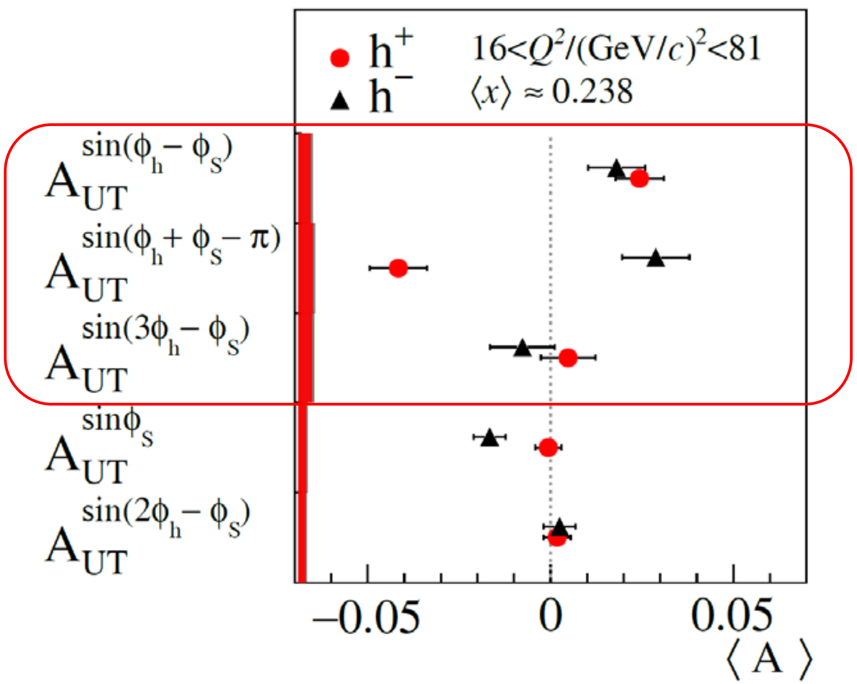
COMPASS, PRL 119 (2017) 112002

SIDIS and DY TSAs at COMPASS

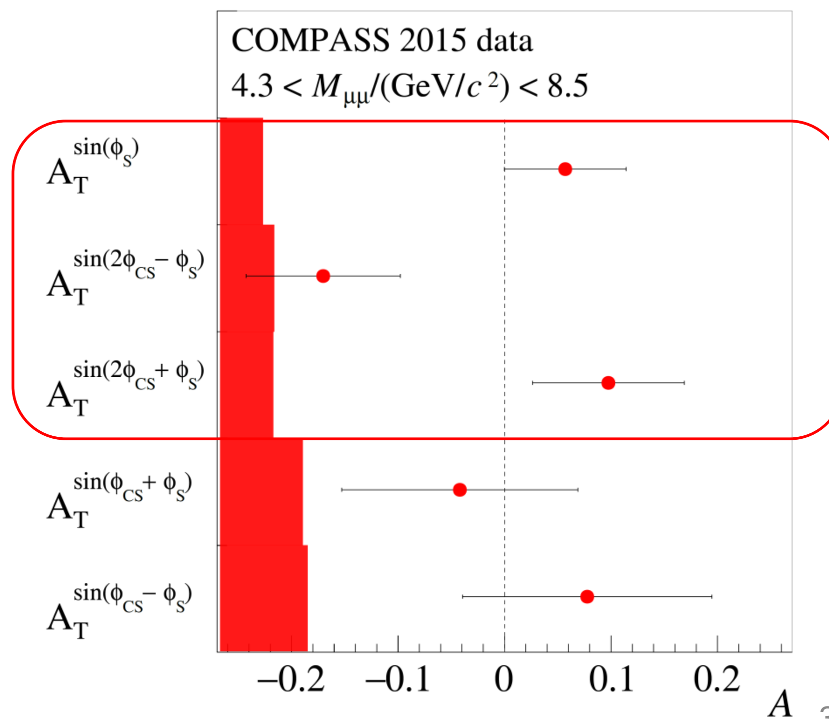
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{ 1 + \dots + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \end{array} \right] \right\}$$

$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right)\left\{ 1 + \dots + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{array} \right) \\ + D_{[\sin 2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) \end{array} \right) \end{array} \right] \right\}$$

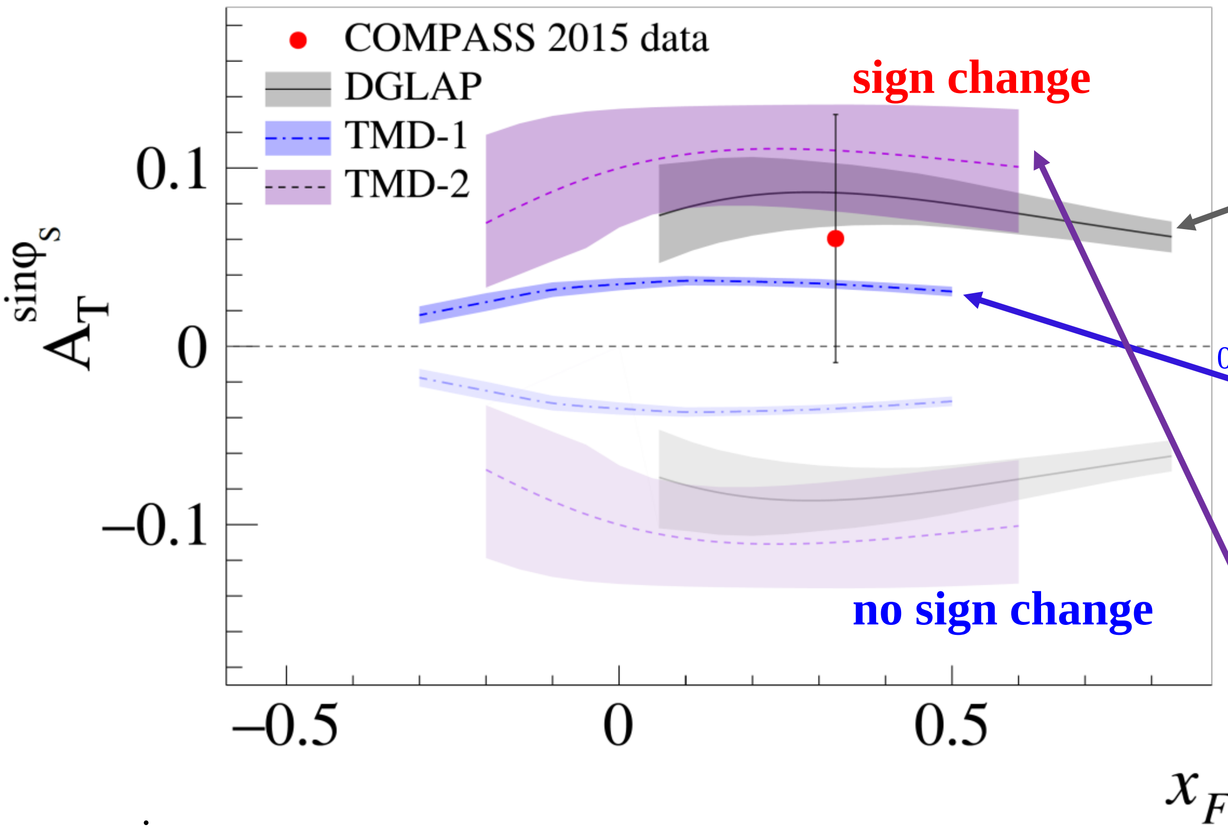
COMPASS, PLB 770 (2017) 138



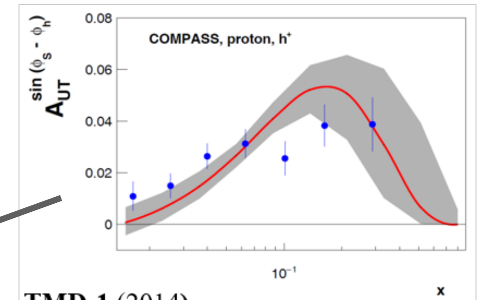
COMPASS, PRL 119 (2017) 112002



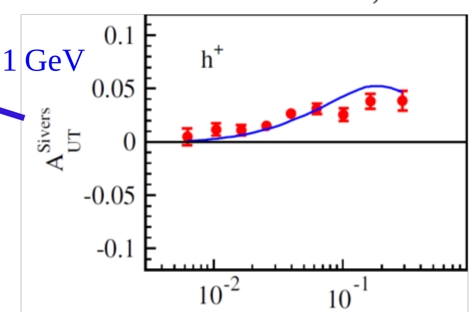
Sivers Asymmetry in Drell-Yan: Hint of Sign Change!



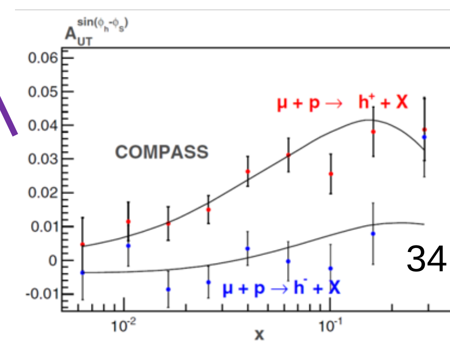
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



$$A_T^{\sin\varphi_s} = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$$

COMPASS, PRL 119 (2017) 112002

Can the existing Drell-Yan data already test the predicted sign-change of B-M function?

1) From SIDIS data, one deduces that the proton B-M functions are negative for both u and d quarks:

$$h_{1,u}^{\perp,DIS}(p) < 0 \; ; \; h_{1,d}^{\perp,DIS}(p) < 0$$

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2) From NA10 pion Drell-Yan data, one deduces that the product of the pion valence quark B-M function and the proton valence quark B-M function is positive. Using u-quark dominance, we have:

$$h_{1,u}^{\perp,DY}(p) * h_{1,u}^{\perp,DY}(\pi) > 0$$

Therefore, either a) $h_{1,u}^{\perp,DY}(p) > 0;\ h_{1,u}^{\perp,DY}(\pi) > 0 \quad (sign - change)$

or b) $h_{1,u}^{\perp,DY}(p) < 0;\ h_{1,u}^{\perp,DY}(\pi) < 0 \quad (no\,sign - change)$

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3) The crucial measurement is to determine the sign of the pion B-M function in polarized $\pi - p$ D-Y, since the $\sin(2\phi_{CS} - \phi_S)$ modulation is sensitive to the sign of $h_{1,u}^{\perp,DY}(\pi)$.

COMPASS DY: Charmonia mass range

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  - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π, K decays
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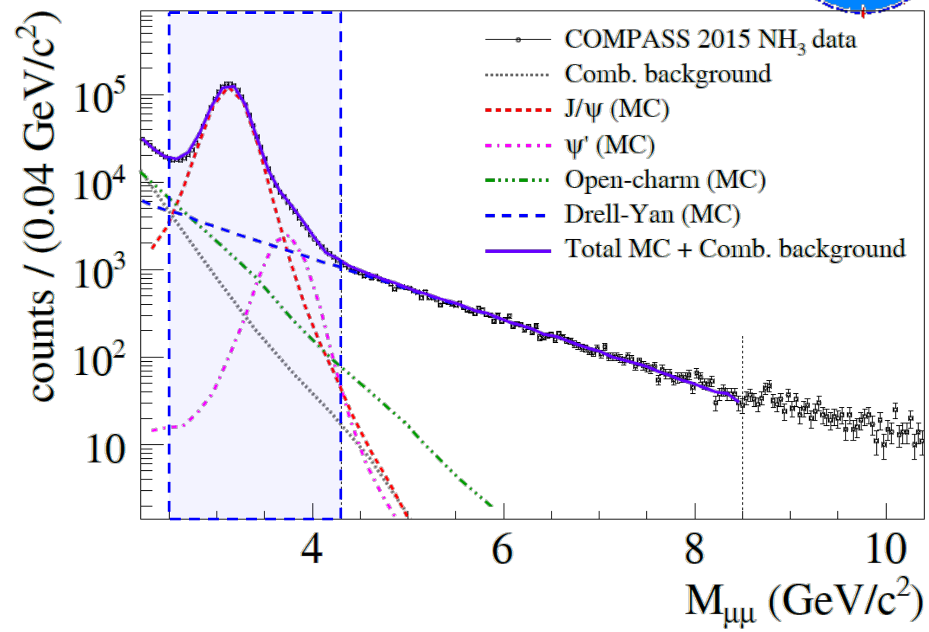
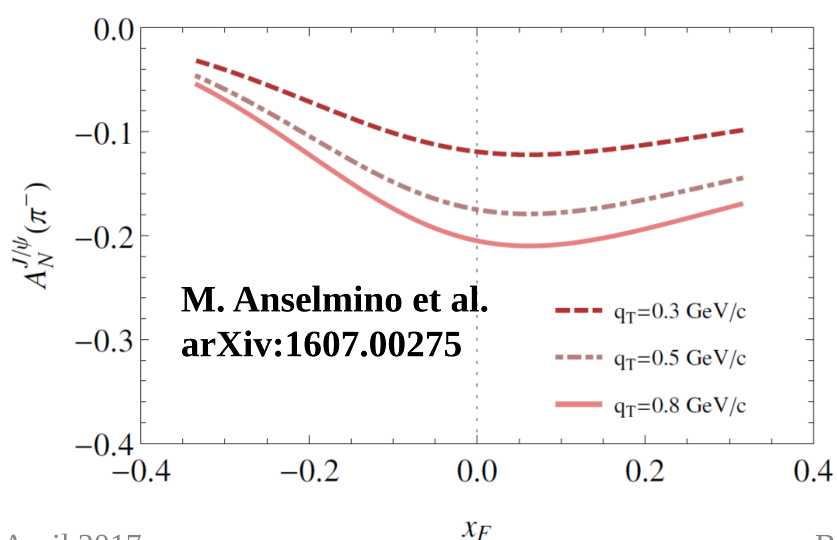
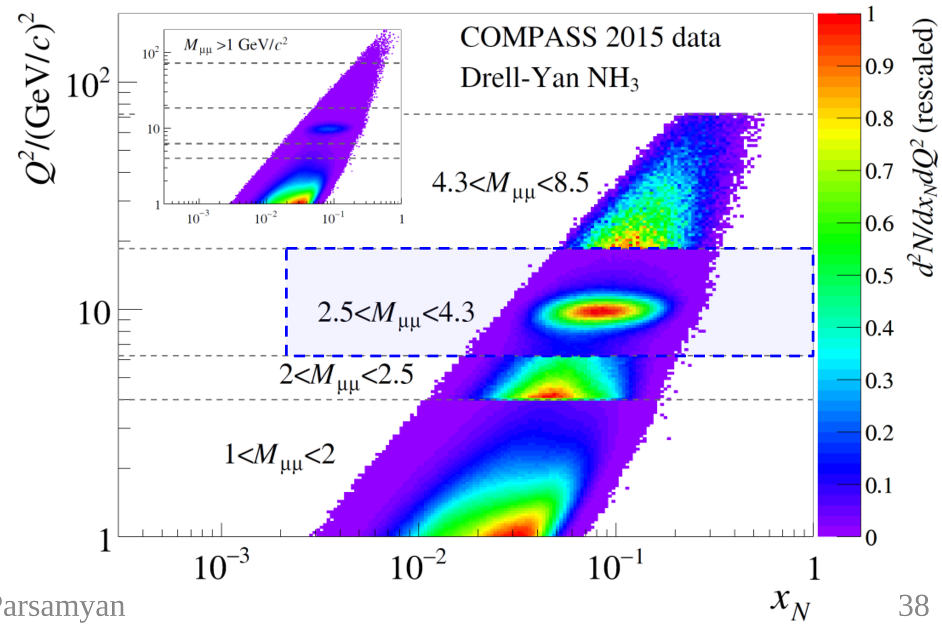


$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1$ GeV/c



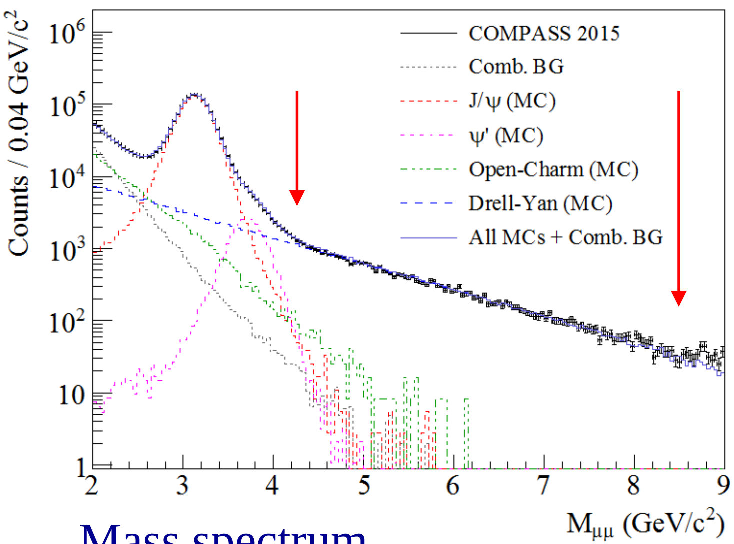


COMPASS-II Programs

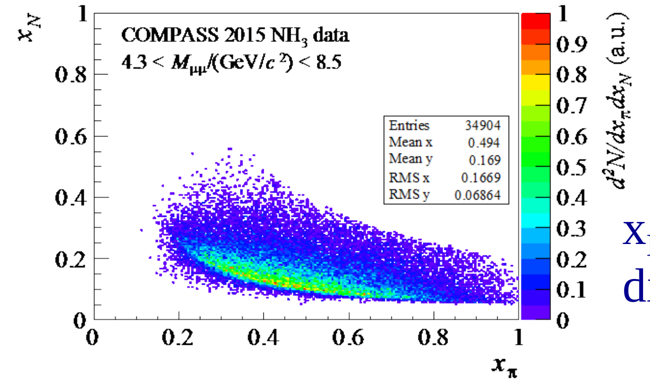
- **2014-2018:**
  - Commissioning of polarized Drell-Yan experiment started in mid-October 2014.
  - 2015: Polarized Drell-Yan program.
  - 2016-2017: DVCS program.
  - 2018: Polarized Drell-Yan program (improved statistics errors of Sivers asymmetries are expected).
- **2020-2024 (under planning) :**
  - Polarized ^{6}LiD target: flavor separation of TMD SSAs.
  - Long LH_2 and nuclei targets: un-polarized pion-induced DY.

Di-muon sample – some results from 2015

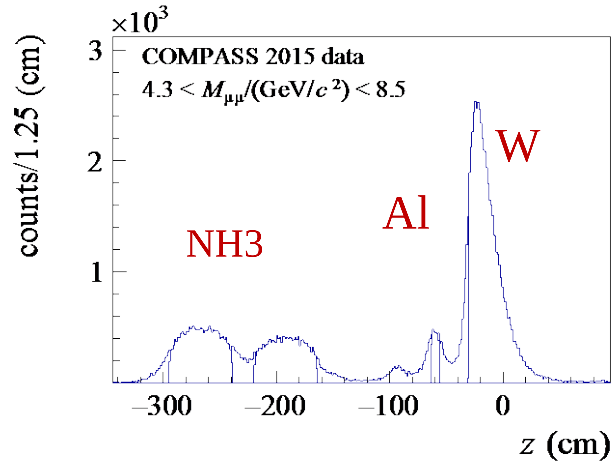
- Drell-Yan data from 2015: 4.3 – 8.5 GeV/c^2



Mass spectrum



x_N vs x_π distribution



Vertex distribution

Many dimuon events for unpolarized Drell-Yan with pion beam!

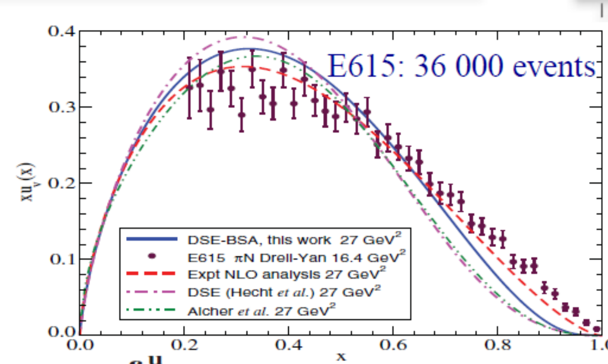
List of Drell-Yan experiments with π^- beam

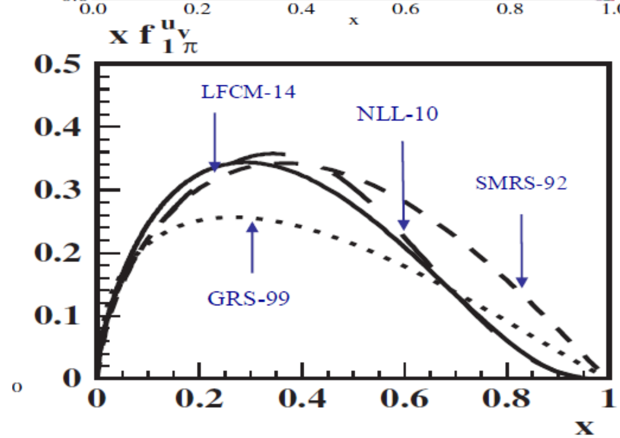
Experiments at CERN and Fermilab

Exp	P (GeV)	targets	Number of D-Y events
WA11	175	Be	500 (semi-exclusive)
WA39	40	W (H_2)	3839 (all beam, M > 2 GeV)
NA3	150, 200, 280	Pt (H_2)	21600, 4970, 20000 (535, 121, 741)
NA10	140, 194, 286	W (D_2)	~84400, ~150000, ~45900 (3200, --, 7800)
E331/E444	225	C, Cu, W	500
E326	225	W	
E615	80, 252	W	4060, ~50000

Data and (some of the) present calculations of the pion PDF

- Data (see also Jen-Chieh's talk)
  - E615 – only pseudo data (LO) available, 1989
  - NA3,1983 and NA10, 1985
- Global fits
  - SMRS, 1992
  - GRV/GRS, 1992 – 1999
- Re-analysis
  - NLO : Wijesoorija, Reimer, Holt, 2005
  - NLO/NLL : Aicher, Shaffer, Voglesang, 2010
- Model calculations
  - DSE : Nguyen et al., 2011, Chen et al., 2016
  - LFCM : Pasquini et al., 2014
  - NLChQM: Nam, 2012



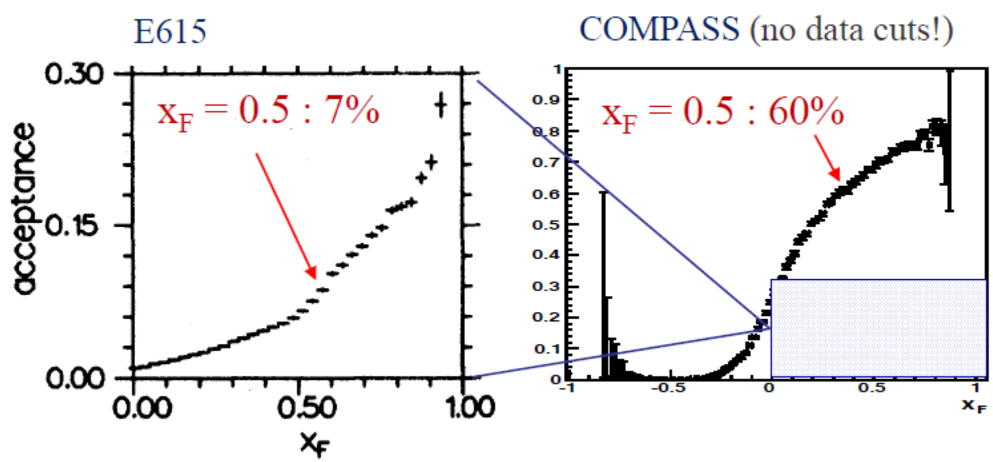


(c)

Continuous interest, no no new data since 1989

New data from COMPASS to come

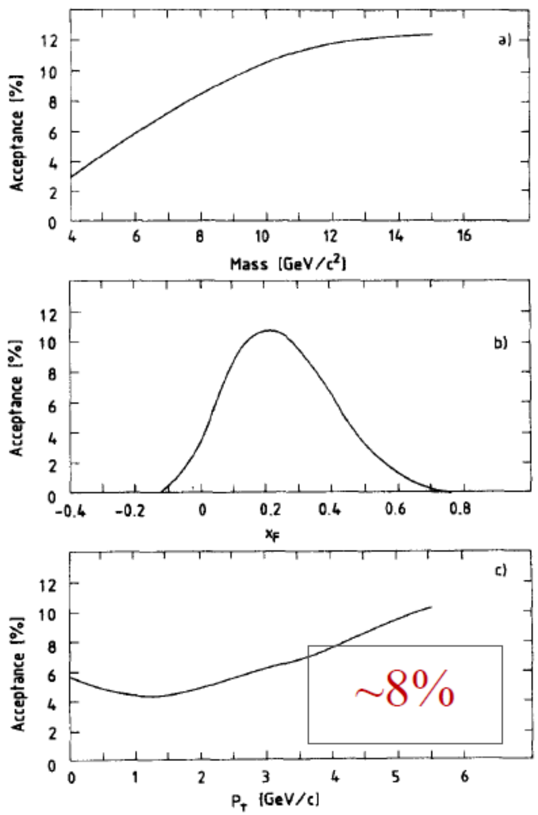
- COMPASS features
  - Better statistics on NH_3, and also W:
    - E615: 36 000; Compass 2015+2018: up to ~150 000 (x4); and about ~300 000 events on W.
  - Very good x_F resolution (~0.01)
  - Better acceptance ; large x_F coverage



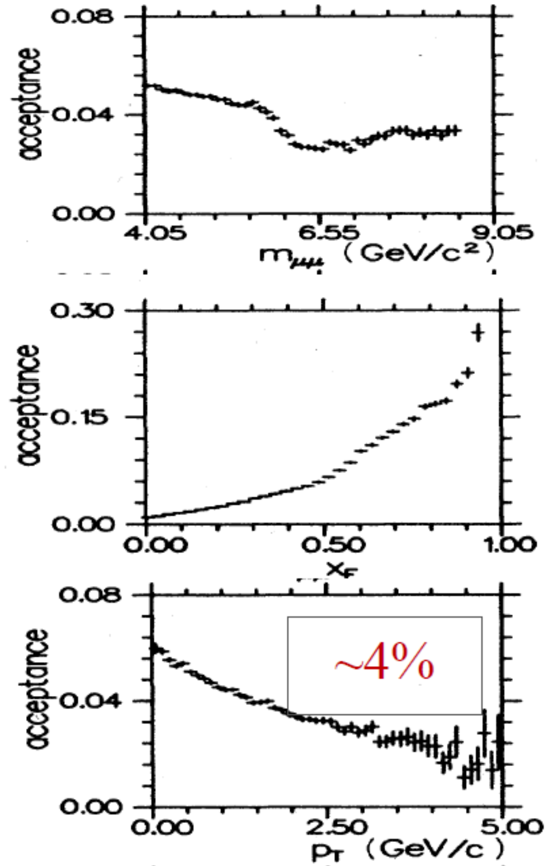
Needed is also : state-of-the-art analysis (NNLO / NLL)

Acceptances : COMPASS vs NA10 vs E615

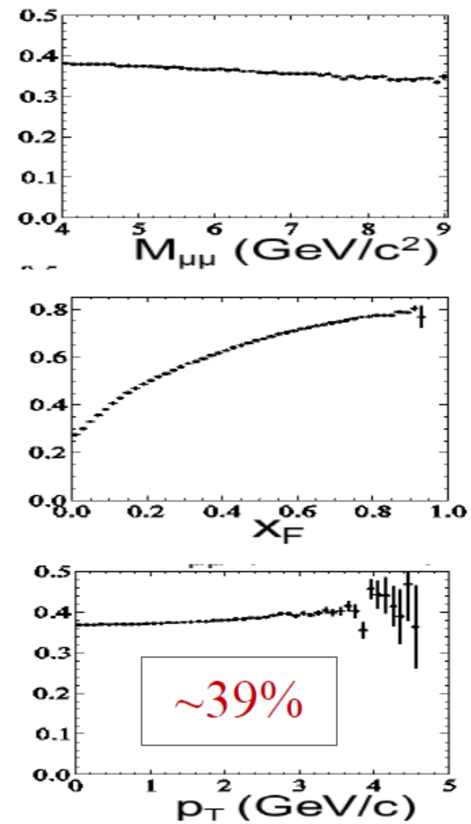
NA10



E615



COMPASS



COMPASS acceptance is relatively flat and a factor of 5 -10 better

Drell-Yan experiments with K^- beam

Exp	P (GeV)	targets	D-Y events
WA39	40	W (H_2)	
NA3	150, 200	Pt	688, 90

Drell-Yan experiments with K^+ beam

Exp	P (GeV)	targets	D-Y events
WA39	40	W (H_2)	
NA3	200	Pt	170

Drell-Yan experiments with $\bar{p}$ beam

Exp	P (GeV)	targets	D-Y events
WA39	40	W (H_2)	
NA3	150, 200	Pt	275, 32
E537	125	W, Cu, Be	380

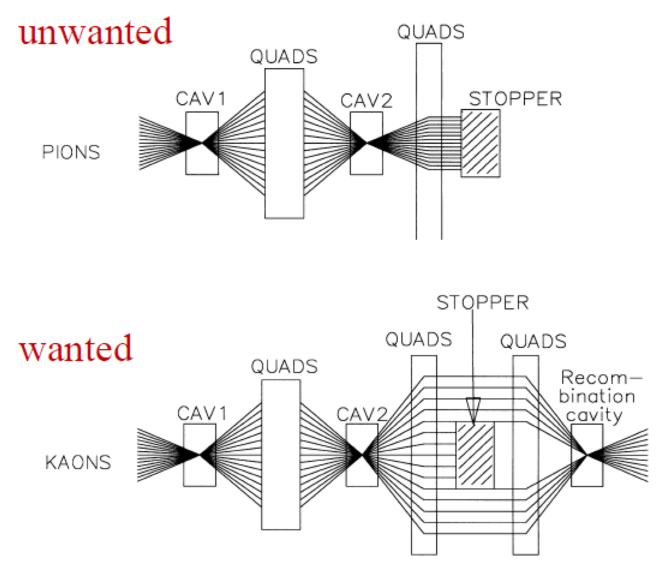
RF-separated beams

- Idea: Panofsky and Wenzel, 1956
- Studies for Triumph (~1998) and at CERN (~2005) for rare kaon decay experiments
- Method:
  - particles with same momenta have different velocities – small TOF differences
  - produce a time-dependent transverse kick with RF cavities
  - select particles by the phase space difference:

$$\Delta\Phi = 2\pi(Lf/c)(\beta_1^{-1} - \beta_2^{-1})$$

  - available length at CERN: up to 900 meters
  - working frequency: 3.9 GHz

J. Doornbos, NIM A455, 253 (2000)



CERN strategy : support physics other than LHC

- "Physics Beyond Colliders" initiative – meetings Sept. 6/7, 2016; March 1st 2017
  - Initiated by CERN' DG as part of the CERN's future
  - Exploit the full potential of CERN's accelerator complex; complement the LHC programme
  - Set working groups with deliverables for each project that include:
    - evaluation of the physics case
    - detector building and optimizations
    - CERN's uniqueness
  - Physics QCD subgroup (among others) :
    - COMPASS++, LHC Fixed-target, other experiment
  - Conventional beams subgroup
    - comprises studies for RF-separated beams fro COMPASS

Info at: http://pbc.web.cern.ch//

Deliverables due end 2018

In time for the European Strategy for Particle Physics update in 2019/2020

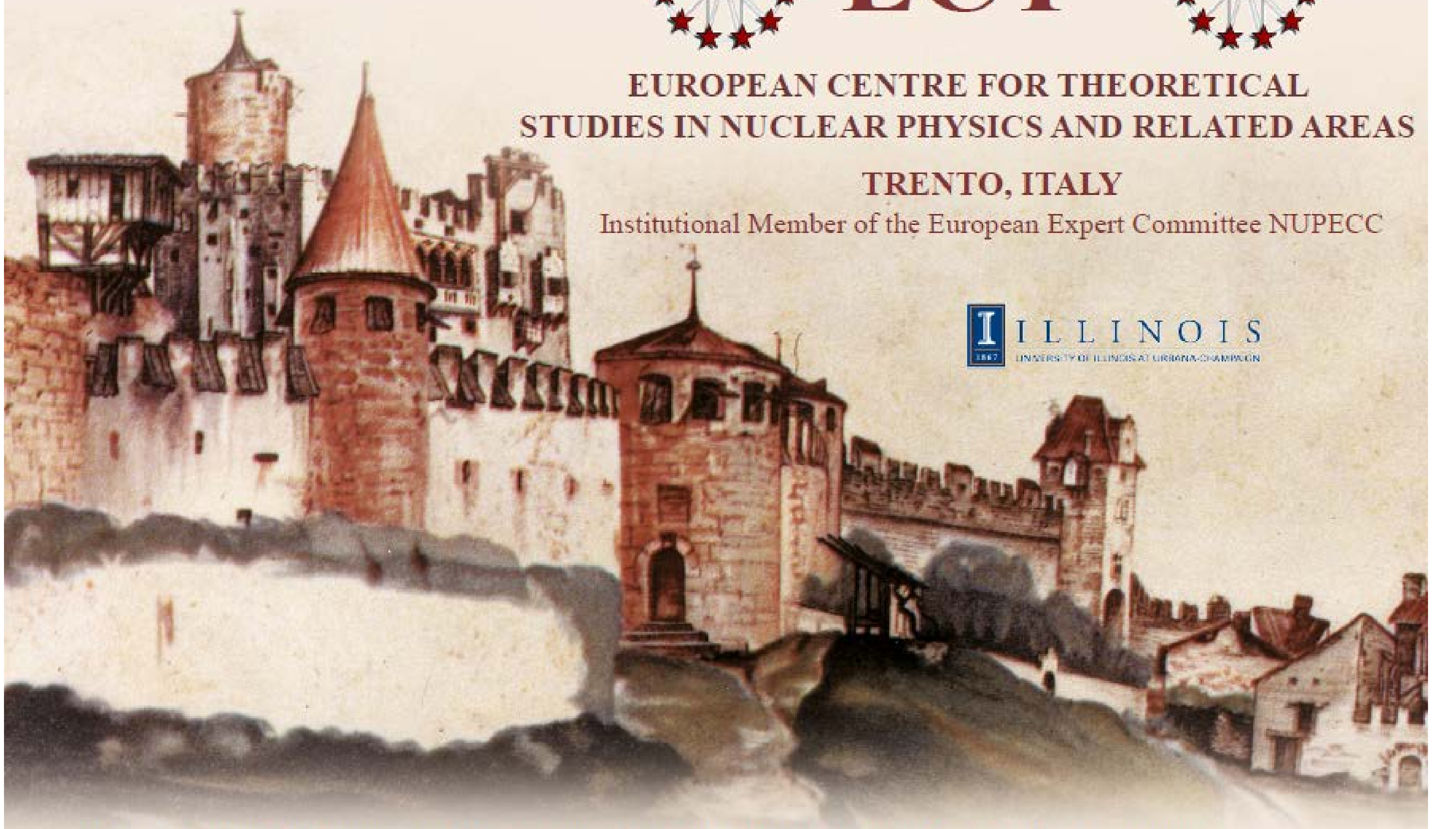
ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

TRENTO, ITALY

Institutional Member of the European Expert Committee NUPECC

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN



Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum,

Dilepton Production with Meson and Antiproton Beams

Trento, November 6-10, 2017

Main Topics

Theoretical and experimental aspects of high-mass dilepton production with meson and antiproton beams.

Physics of partonic structures of pion and kaon.

Exclusive Drell-Yan process.

Opportunities to carry out new measurements on high-mass lepton pairs productions using meson and antiproton beams.

Summary

- COMPASS has successfully collected first ever transversely polarized Drell-Yan data in 2015:
  - Sivers asymmetry is found to be above zero at about 1 sigma.
  - DY Sivers asymmetry is consistent with the predicted sign change!
- A second year of polarized DY run in 2018 will provide more stringent test of Sivers non-universality.
- New unpolarized DY data on nuclear targets with pion beam are being analyzed
- Future DY experiments with RF-separated kaon and antiproton beams are under consideration