Nucleon spin structure at COMPASS

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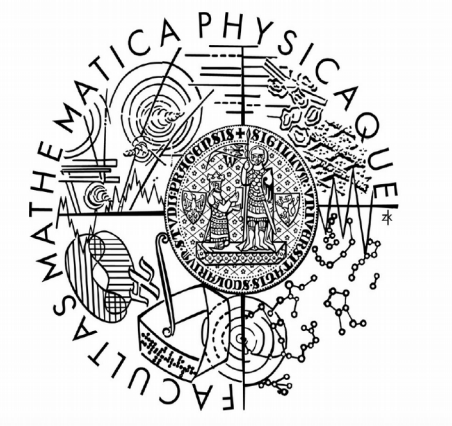
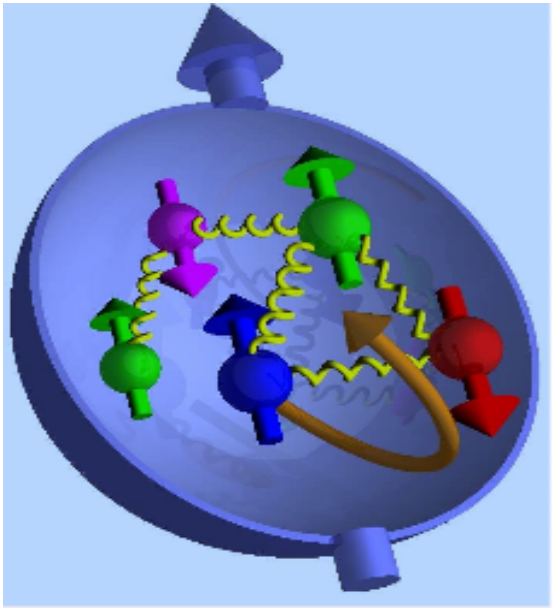


Malá Skála 19.04.2017

Outline

- Nucleon spin structure
- SIDIS & Drell-Yan processes
- COMPASS experiment at CERN
- COMPASS SIDIS results
- J/Ψ production in SIDIS and DY
- Conclusion

Nucleon spin structure



- Proton spin $\frac{1}{2}=\frac{1}{2}\Delta\Sigma+\Delta G+ L_{q,g}$
- Naive parton model expects ΔΣ=1
- EMC(1988) ΔΣ compatible with zero
- Precision data today ΔΣ~0.3
- Recently ΔG non-zero, positive at x_g range accessed (RHIC, COMPASS) $\Delta G=0.2^{+0.06}_{-0.07}$

de Florian et al.Phys.Rev.Lett. 113 (2014) no.1, 012001

- $L_{q,g}$ still unexplored, accessible e.g. via Generalized PDFs (DVCS & DVMP & SIDIS at COMPASS, JLAB, future EIC)

"You think you understand something? Now add spin..." R. Jaffe

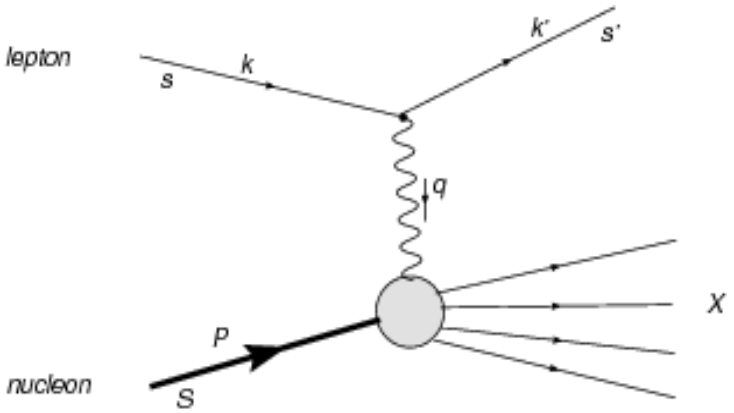
Nucleon (spin) structure

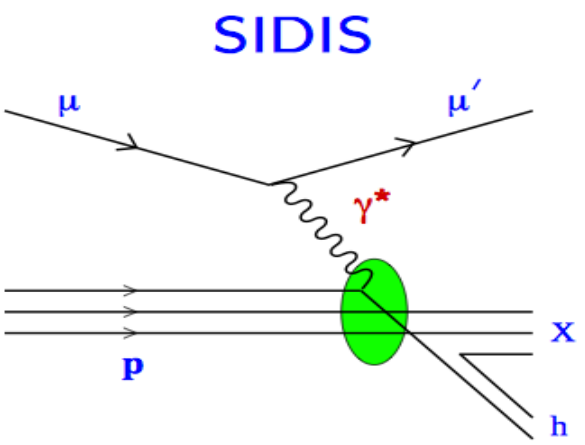
At leading-twist (LO), neglecting parton transverse momentum (collinear aproximation):

- 3 funtions f_1(number density), g_1(helicity), h_1(transversity)
- f_1, g_1 well measured in (inclusive) Deep Inelastic Scattering

  (EMC, NMC, Hermes, HERA, COMPASS, CLASS)
- h_1 is chiral-odd and cannot be measured in inclusive DIS (Semi-inclusive reaction needed)

h_1 extraction requires knowledge of Collins fragmentation function





$lepton + p \rightarrow lepton' + X$

$lepton + p \rightarrow lepton' + h + X$

Nucleon structure continued

$$s \equiv (k+P)^2 = M^2 + 2\mathrm{k}\cdot P = M(2E_{lab} + M)$$

$$Q^2 \equiv -q^2 \equiv -(k-k')^2 = 2\mathrm{k}\cdot k' = 4EE'\sin^2(\theta_{lab}/2)$$

$$y \equiv \frac{q\cdot P}{k\cdot P} = \frac{E_{lab} - E'_{lab}}{E_{lab}} = \frac{\nu}{E_{lab}}$$

$$x \equiv \frac{Q^2}{2\mathrm{P}\cdot q} = \frac{Q^2}{2\mathrm{M}\nu}$$

$$W^2 \equiv (q+P)^2 = \frac{Q^2(1-x)}{x} + M^2 .$$

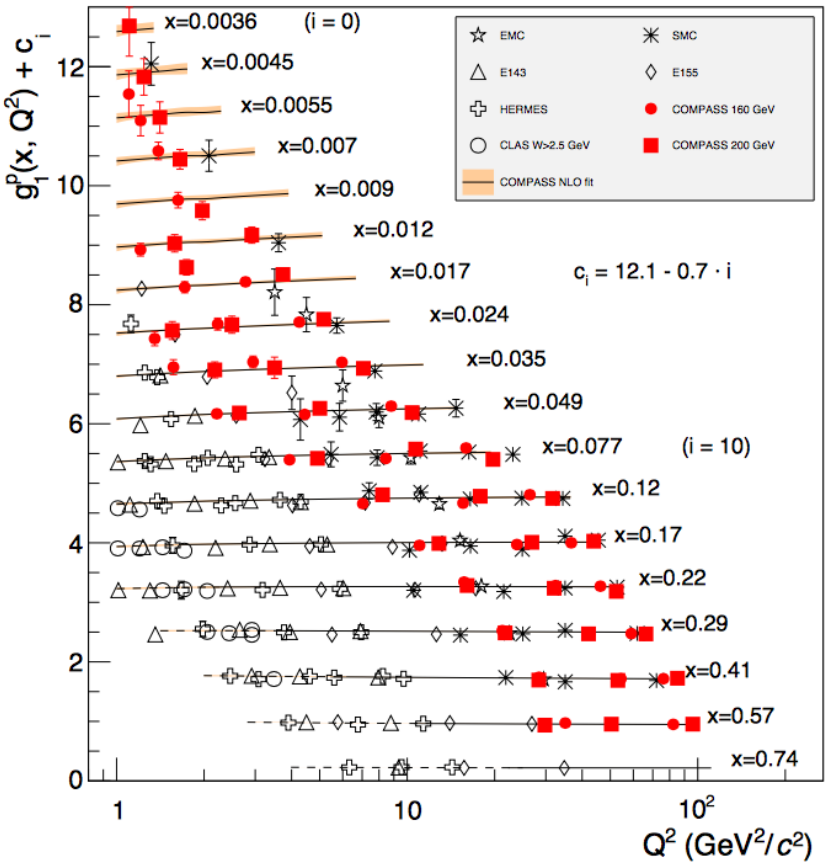
$$\frac{d\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{M^2 xy}{s}\right)\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right],$$

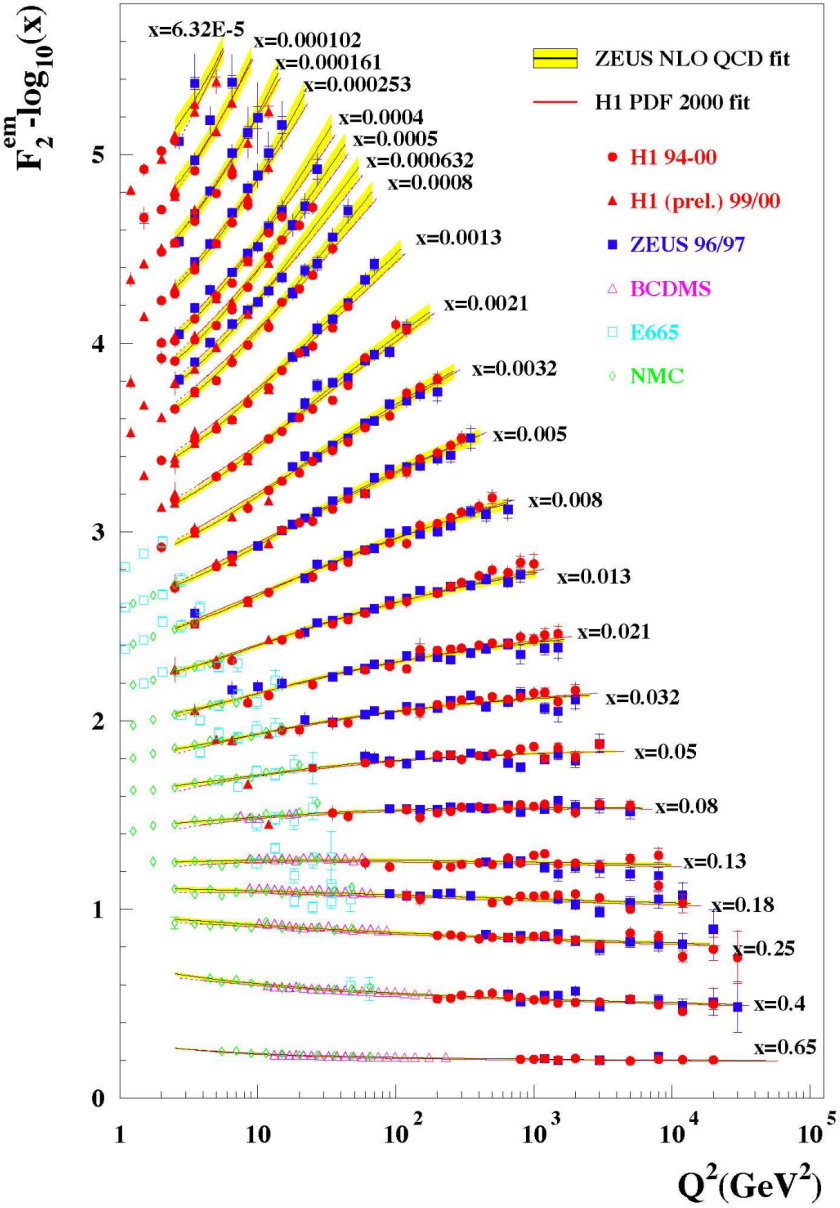
$$A_1 = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} .$$

$$F_2(x,Q^2) = F_2(x) = x\sum_i e_i^2 f_i(x) .$$

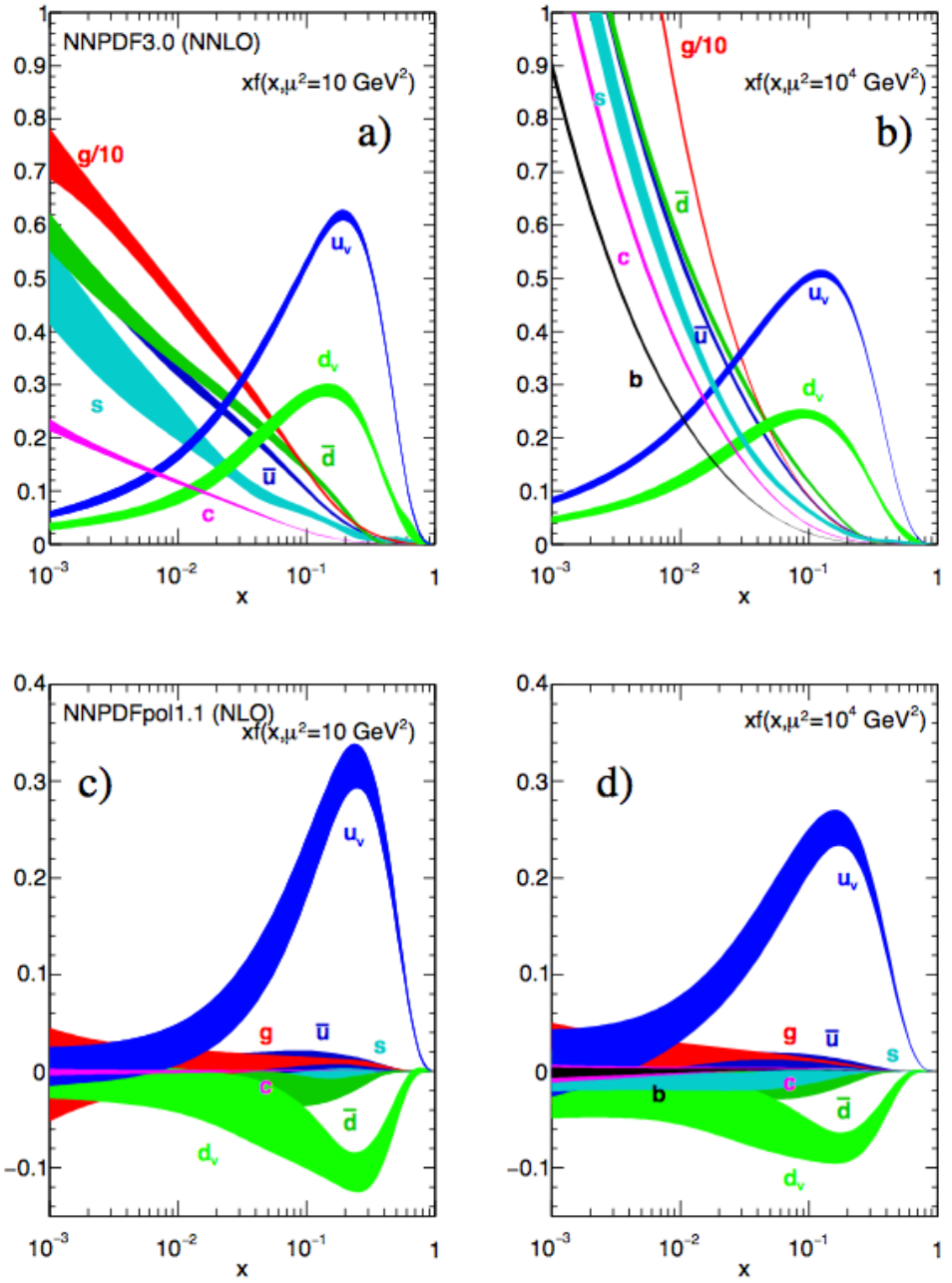
$$A_1(x) = \frac{(1-(1-y)^2)}{(1+(1-y)^2)}\frac{x}{F_2(x)}\sum_i e_i^2 \Delta q_i$$

Nucleon structure – experimental results





Nucleon structure – experimental results



Twist-2 TMD PDFs

Nucleon / Quark	U	L	T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **Number density**		$f_{1T}^{q\perp}(x,\boldsymbol{k}_T^2)$ **Sivers**
L		$g_1^q(x,\boldsymbol{k}_T^2)$ **Helicity**	$g_{1T}^{q\perp}(x,\boldsymbol{k}_T^2)$ **Kotzinian-Mulders or Worm-gear T**
T	$h_1^{q\perp}(x,\boldsymbol{k}_T^2)$ **Boer-Mulders**	$h_{1L}^{q\perp}(x,\boldsymbol{k}_T^2)$ **Worm-gear L**	$h_1^q(x,\boldsymbol{k}_T^2)$ **Transversity** $h_{1T}^{q\perp}(x,\boldsymbol{k}_T^2)$ **Pretzelosity**

+ two FFs: $D_{1q}^h(z,P_\perp^2)$ and $H_{1q}^{\perp h}(z,P_\perp^2)$

Beyond collinear approximation if we consider partons transverse momentum k_T

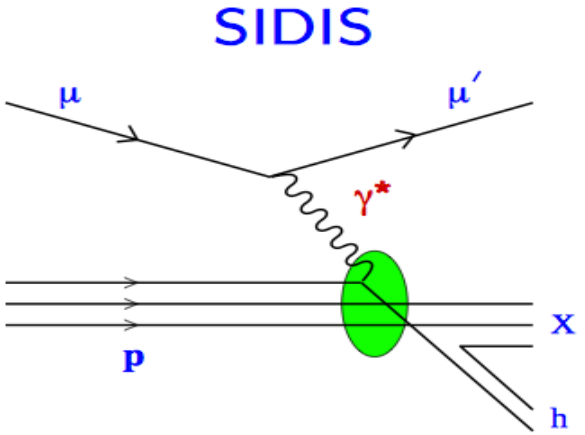
(LO QCD parton model with TMD-factorization):

- The nucleon spin-structure can be parametrized by 8 twist-2 TMD PDFs
- They can be accessed by measuring azimuthal asymmetries in DY or SIDIS processes

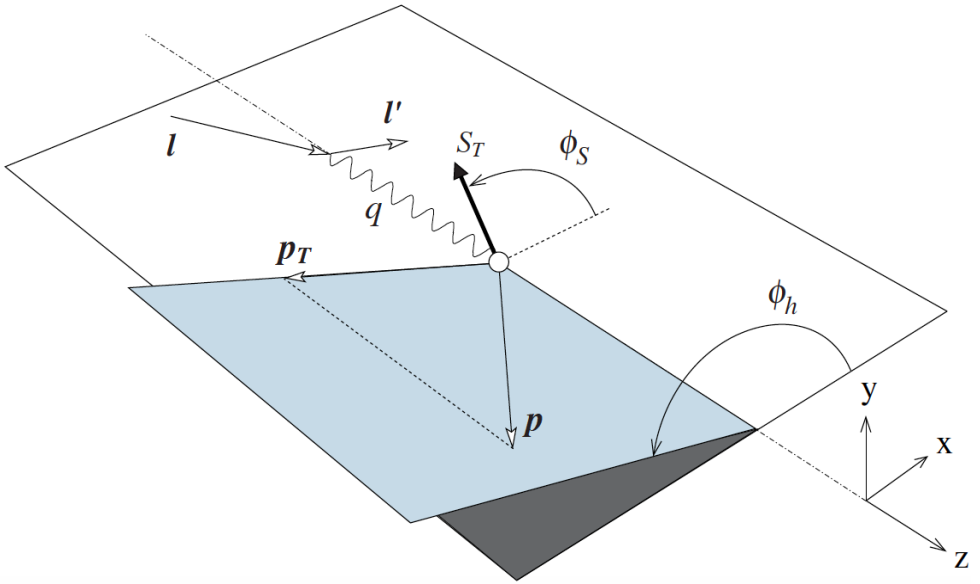
- Complementarity
- Posibility to test the TMD approach

See Marketa's talk later today

Polarized SIDIS cross-section



SIDIS involves both Fragmentation Functions and TMD PDFs



$$\frac{d\sigma^{LO}_{SIDIS}}{dxdydzdp_T^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]$$

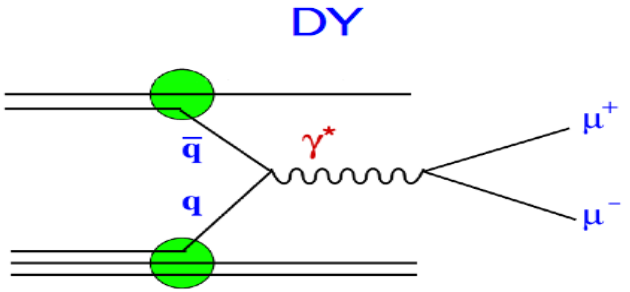
$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{\ 1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)\right.$$

$$+\ \mathrm{S_T}\left[\begin{array}{l}\sin\left(\phi_h-\phi_S\right)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\ +\ \sin\left(\phi_h+\phi_S\right)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\ +\ \sin\left(3\phi_h-\phi_S\right)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{array}\right]$$

$$\left.+\ \mathrm{S_T}\lambda\left[\cos\left(\phi_h-\phi_S\right)\left(\sqrt{\left(1-\varepsilon^2\right)}A_{LT}^{\cos(\phi_h-\phi_S)}\right)\right]\ \right\}$$

For transversely polarized nucleons

Drell-Yan process



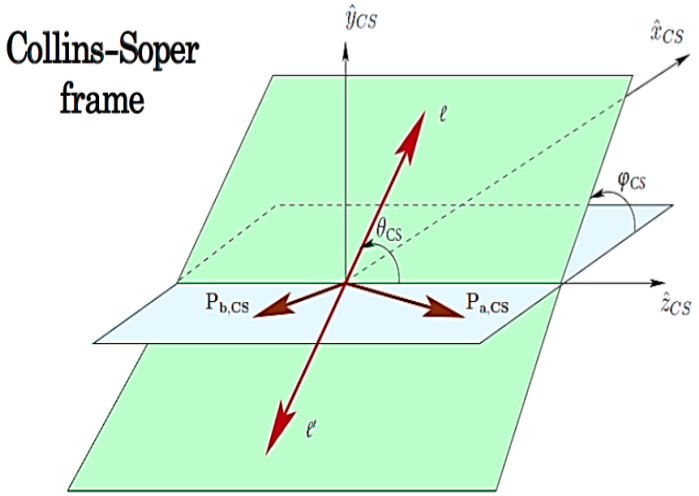
- Cross-section involves no FFs, only TMD PDFs (pion/nucleon)
- Dilepton final state
- Gives possibility to study pion or kaon structure

$$hadron1 + hadron2 \rightarrow \mu + \mu + X$$

At COMPASS: $\pi^- + p \rightarrow \mu + \mu + X$

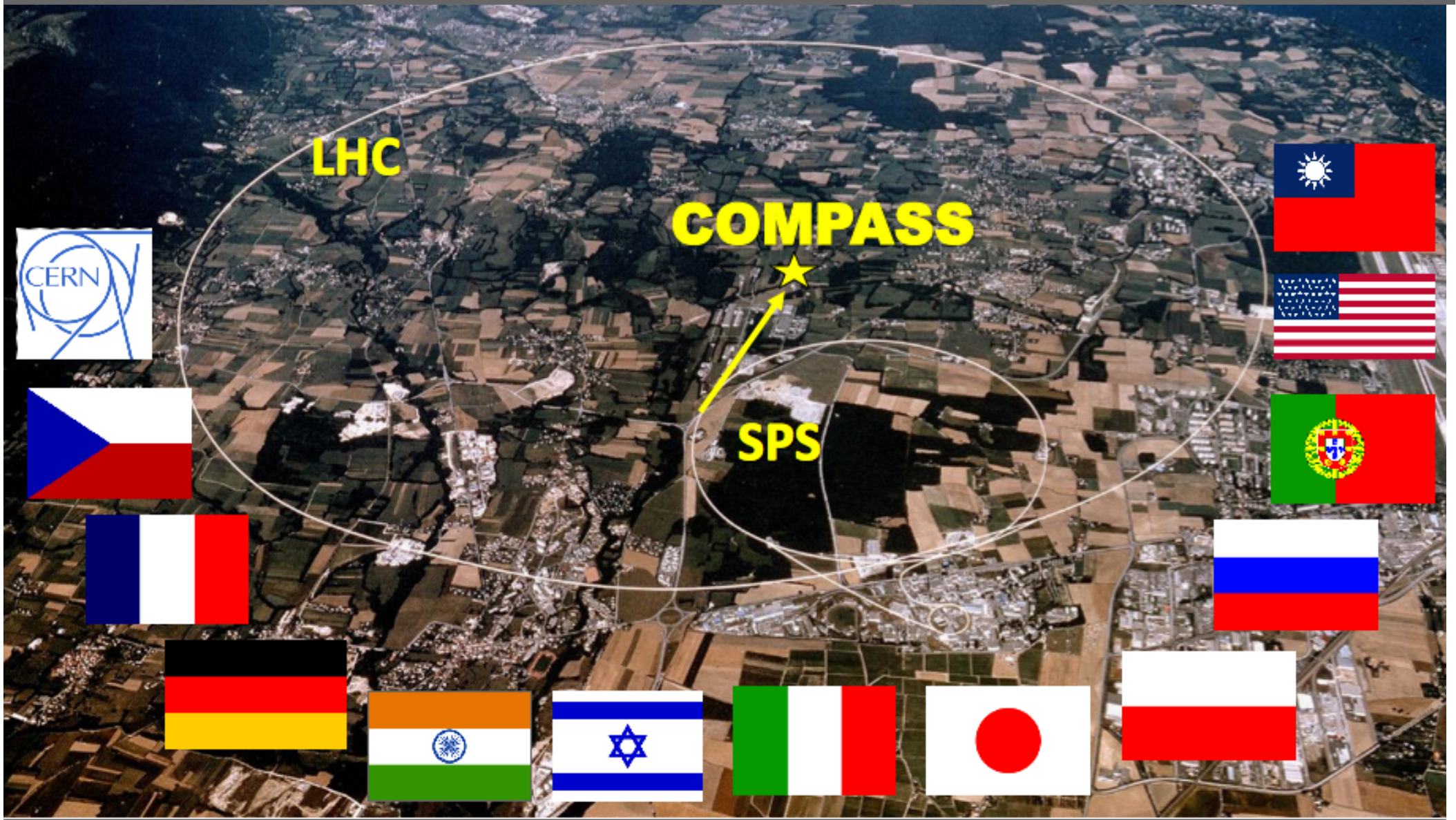
$$s = (P_1 + P_2)^2$$
$$x_{1,2} = q^2/(2q \cdot P_{1,2})$$
$$x_F = x_1 - x_2$$
$$Q^2 = q^2 = M^2_{\mu\mu} = s x_1 x_2$$

Unpolarized cross-section: $$\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\varphi_{CS} + \frac{\nu}{2} \sin^2\theta \cos 2\varphi_{CS}\right)$$



See Marketa's talk later today

COMPASS: Versatile facility to study QCD with hadron (pions, kaon, antiprotons) and muon beams for hadron spectroscopy and hadron structure studies using SIDIS, DY, DVCS, DVMP, ...

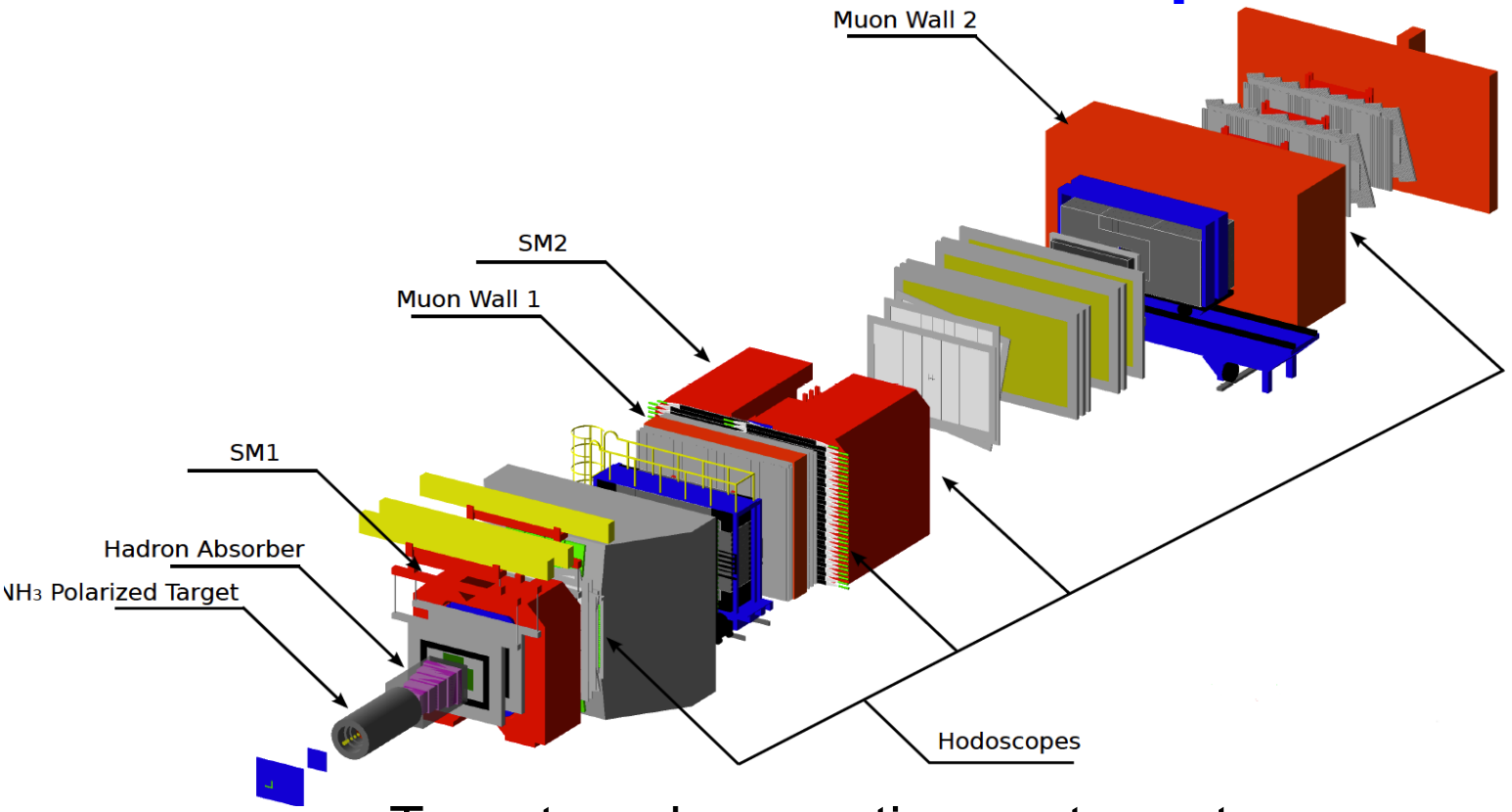


History of data taking

- 1997 COMPASS approved at CERN
- 2001 commissioning run
- 2002-2004 muon run with ^{6}LiD (T)
- 2005 Long Shutdown
- 2006 muon run with ^{6}LiD (T)
- 2007 muon run (L & T)
- 2008-2009 Hadron spectroscopy
- 2010 Muon run (T)
- 2011 Muon run (L)

  COMPASS II phase
- 2012 Primakoff & DVCS Pilot
- 2013-2014 Long Shutdown
- 2014-2015 Polarized Drell-Yan
- 2016-2017 DVCS
- 2018 Polarized Drell-Yan
- 2019-2020 Long Shutdown
- 2021-?? LoI & Proposal in preparation

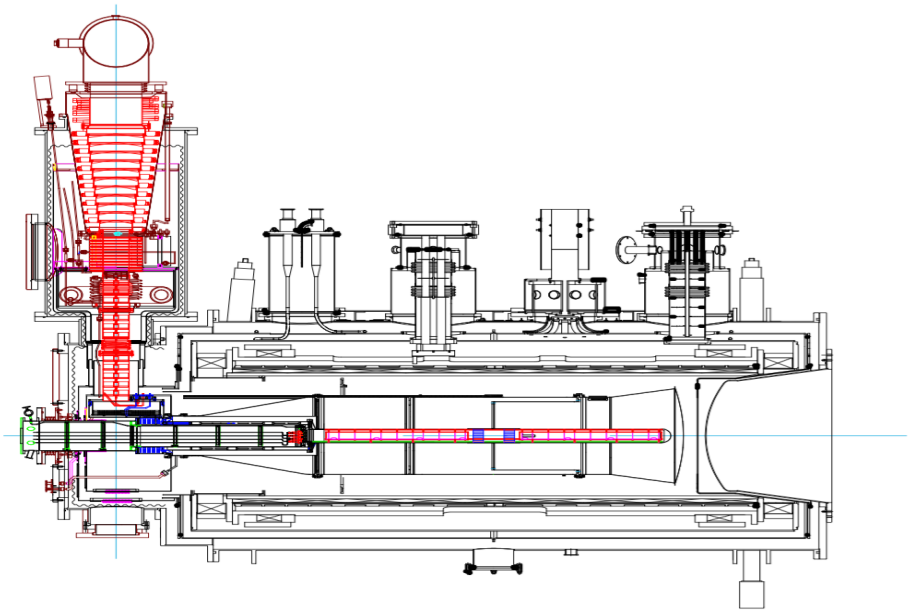
COMPASS experiment



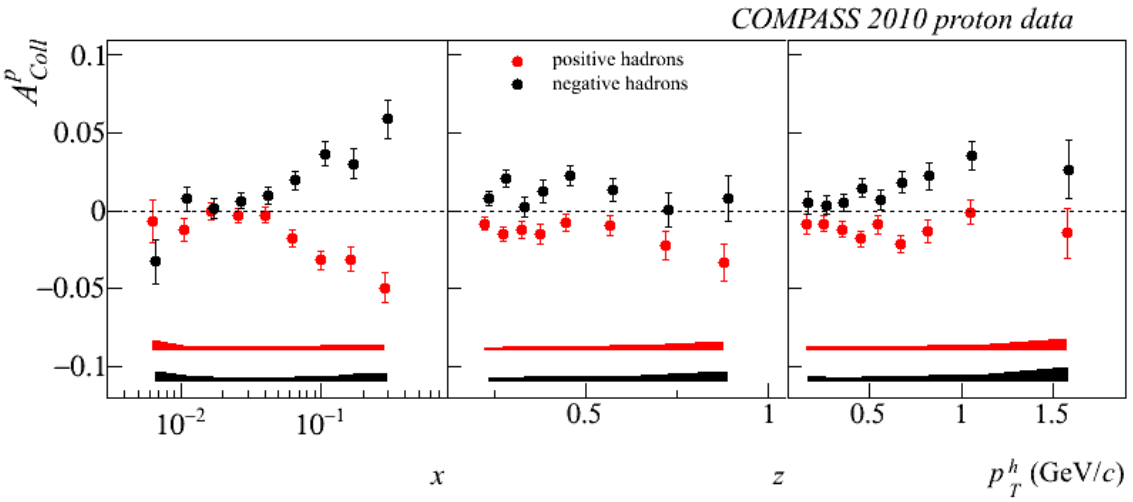
- Two staged magnetic spectrometer
- Calorimeters in both stages
- PID in first stage
- Lepton & hadron beams, polarized NH_3 , ^6LiD targets or various unpolarized nuclear targets(Al, Pb, C, W,..)
- ~300 tracking planes
- Hadron absorber for DY running
- Hadron beam ~97 % pion,~ 2 % kaons, ~1 % antiprotons

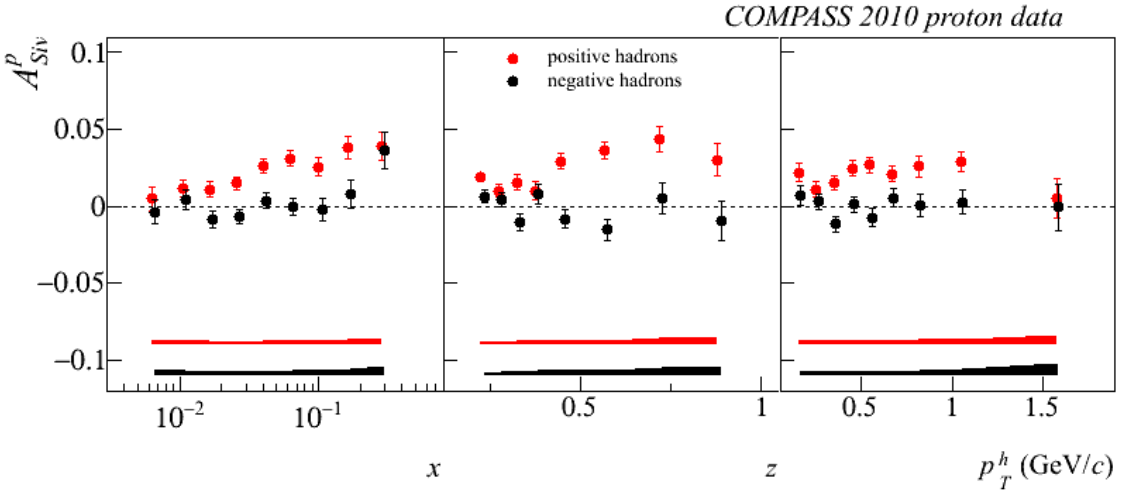
Polarized target

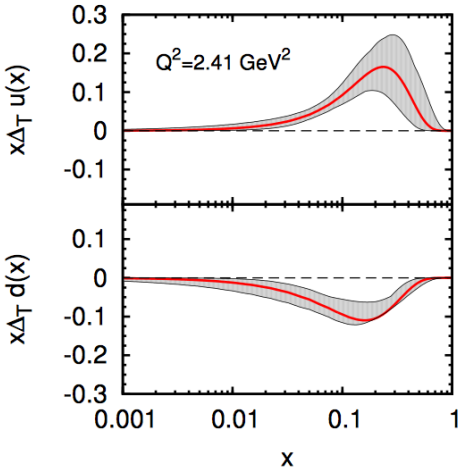
- 1,5 l of material (=solid ammonia, or ^{6}LiD in the past)
- Dilution refrigerator for frozen spin mode, T~60 mK
- SC magnet 2 in 1 - 2.5 T solenoid for polarizing the material
  0,6 T dipole to keep the transverse polarization
- Two cell design with 10 NMR coil for polarization measurement
- Relaxation time ~5000-10000 h (muon running T & L)
- Heating by hadron beam leads to relaxation time ~1000 h
- Typical P=80 %

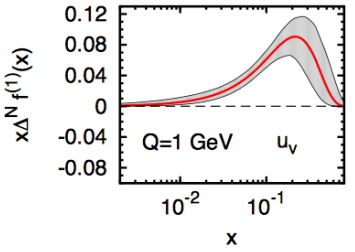


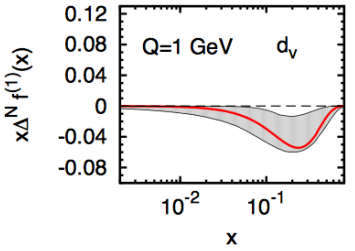
Some COMPASS SIDIS results







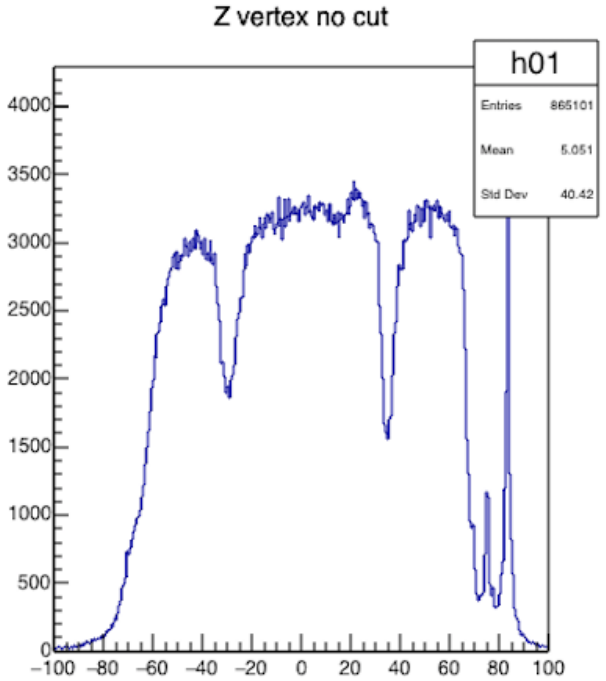


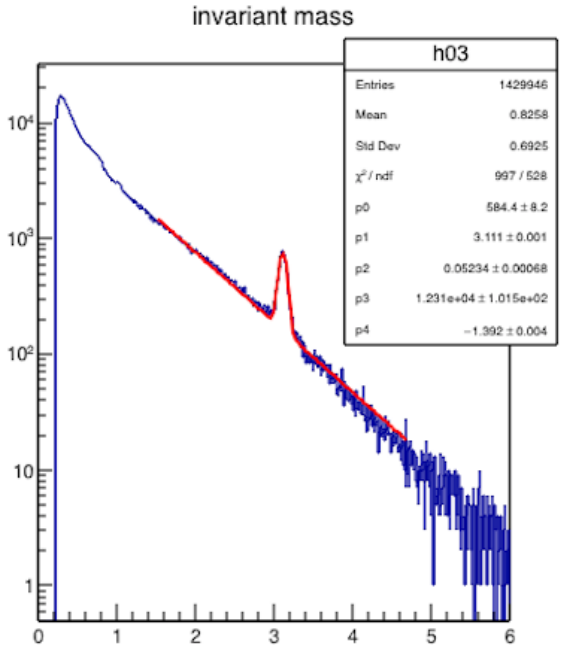


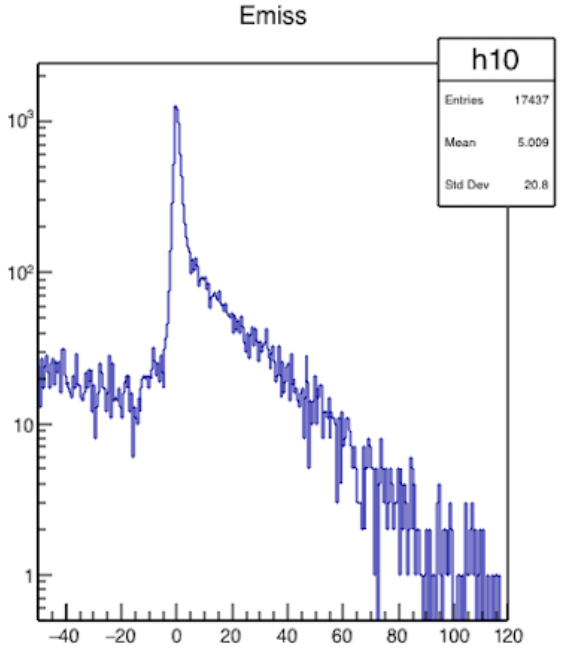
Extrated transversity & first moment of Sivers by Anselmino et al.

SIDIS with h=J/ψ

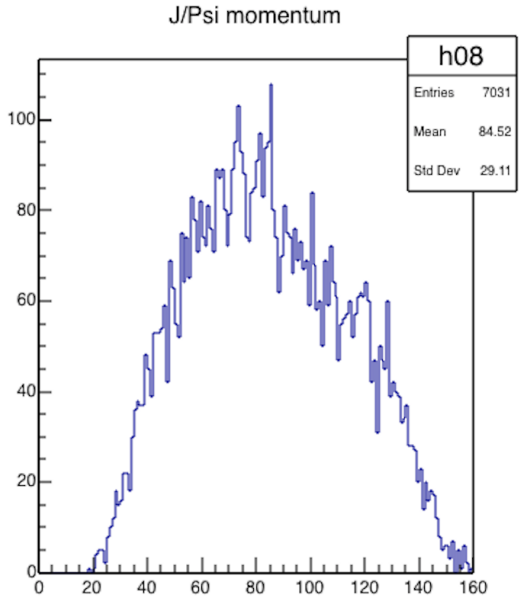
- μ+p→ μ+J/Ψ+X , J/Ψ→μμ, 2010 transverse proton data
- Some basic quality cuts on tracks & target position
- Reconstruct invariant mass of μμ pair
- Total 17500 pairs within J/Ψ peak
- 3 different samples – exclusive (cut on E_{miss}) , inclusive, all
- Evaluate 8 transverse asymmetries (double ratio method)

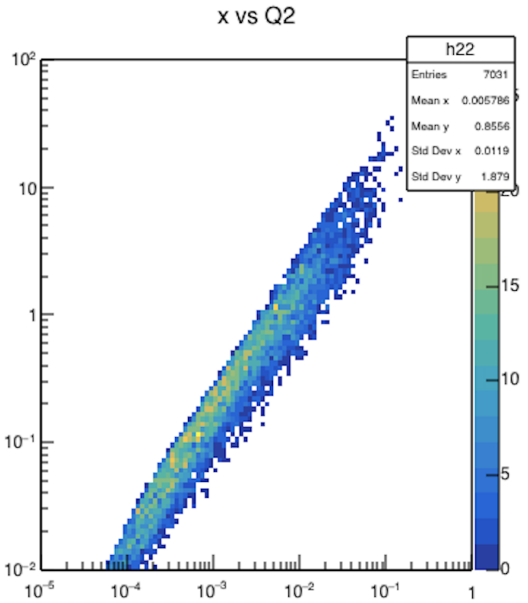


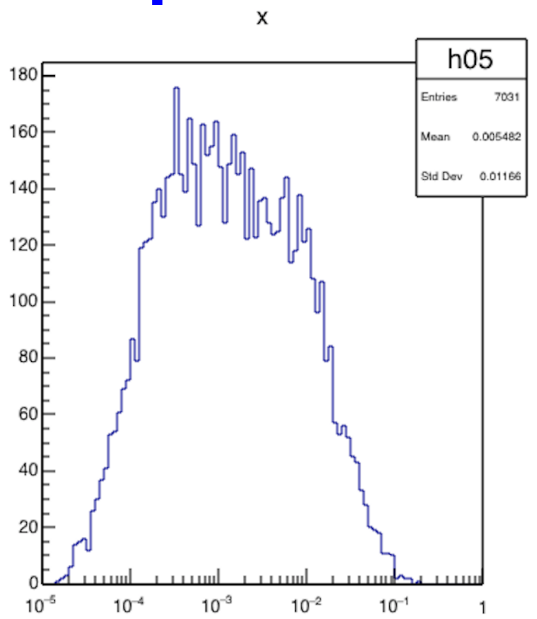




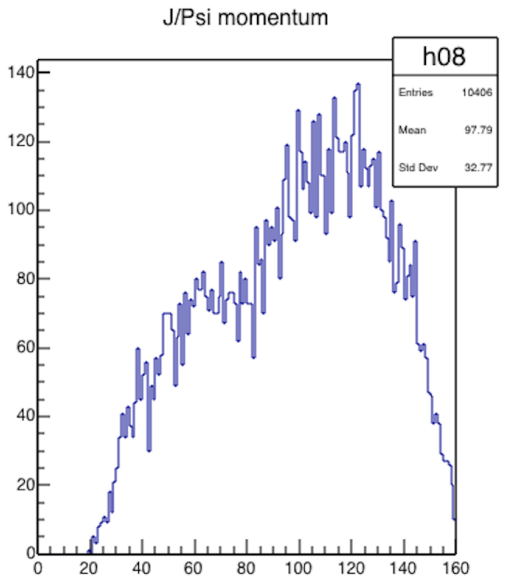
SIDIS with h=J/ψ

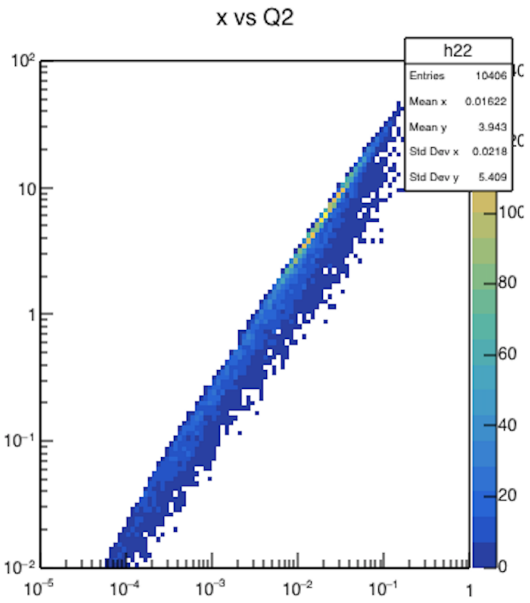


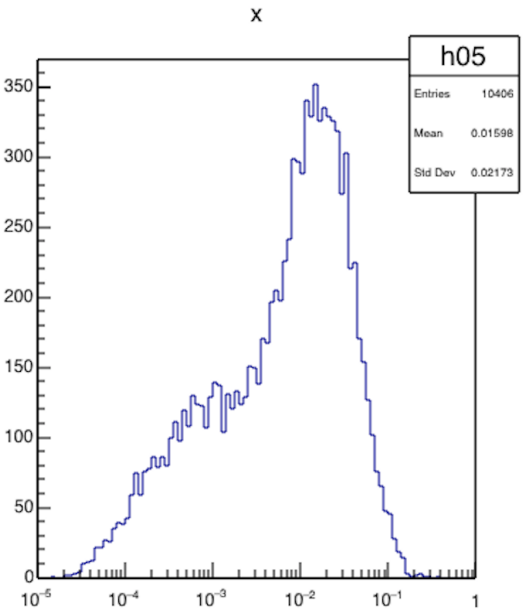




Exclusive sample



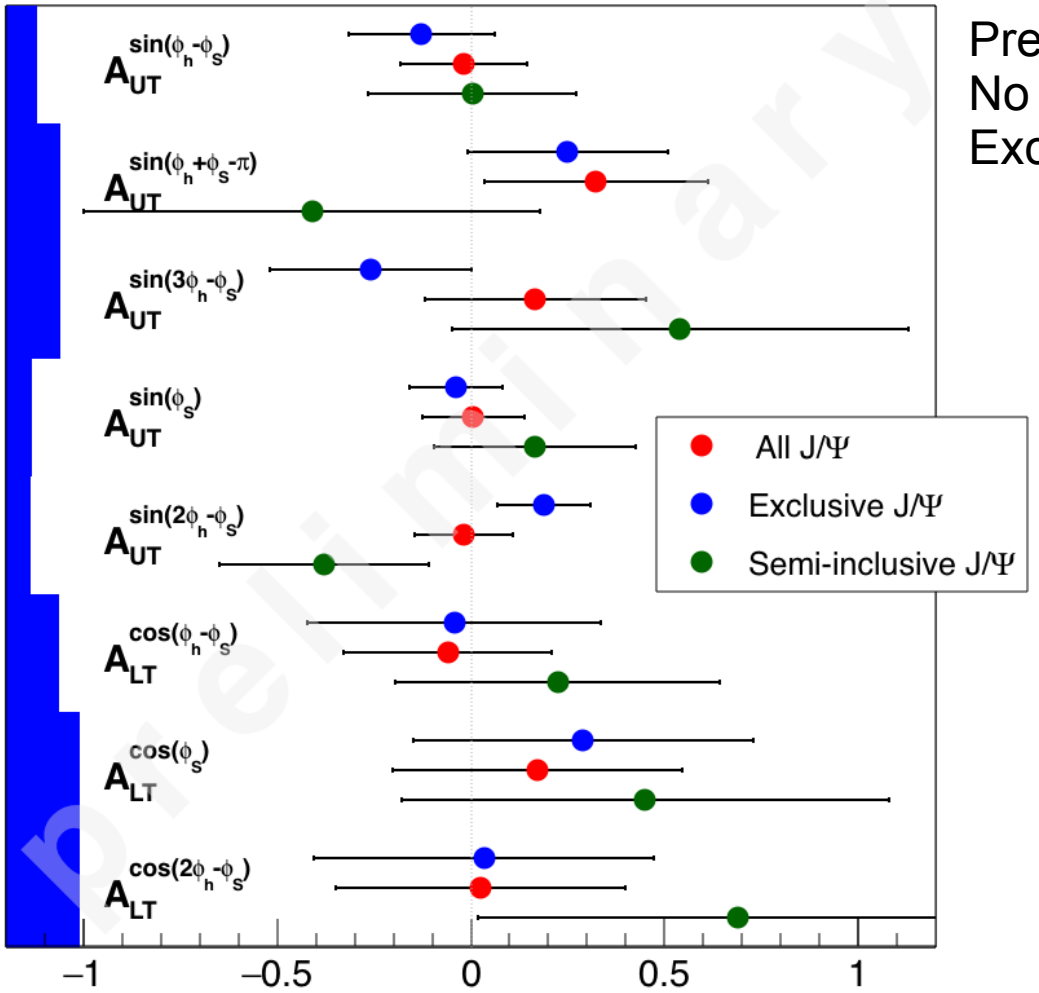




Inclusive sample

SIDIS with h=J/ψ

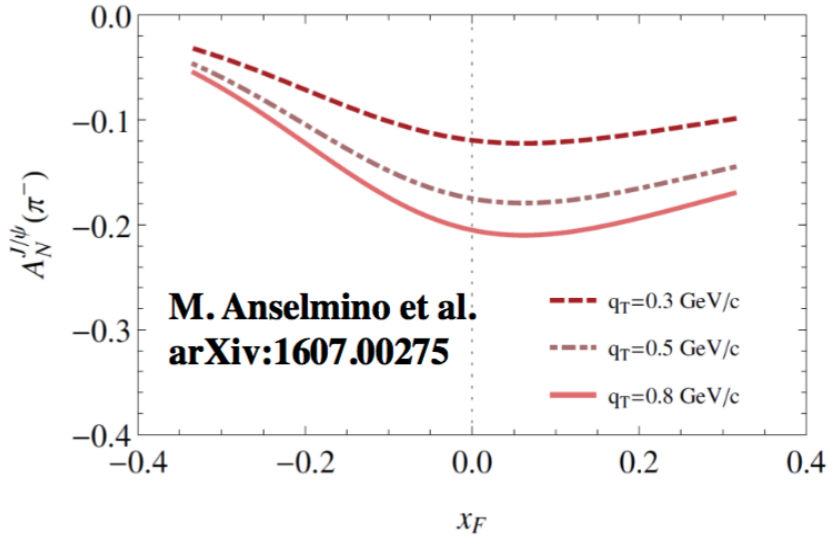
8 J/Ψ Asymmetries (all 2010 data)



Precision statistically limited
No asymmetry significantly non-zero
Exclusive might be useful for constraining GPDs

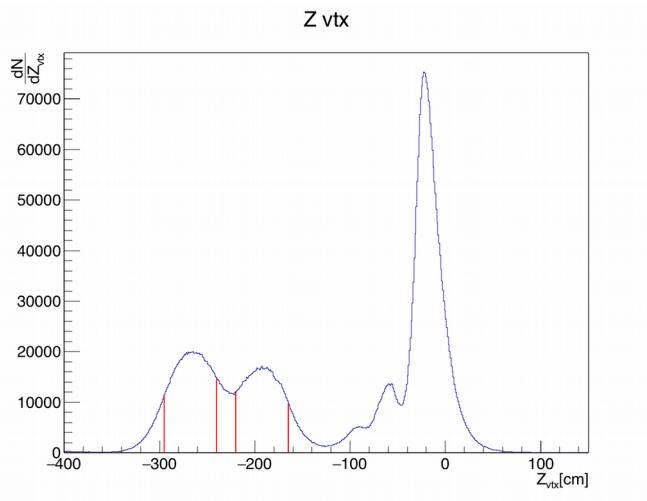
J/ψ production in DY data

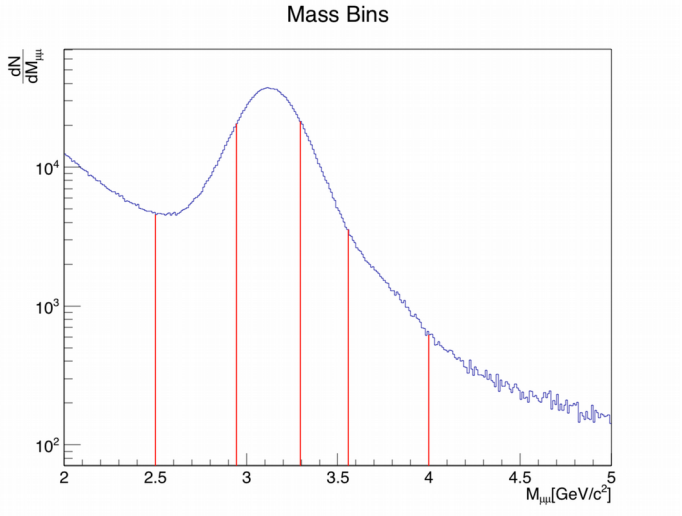
Recent, very interesting prediction for COMPASS kinematics by Anselmino et al.:

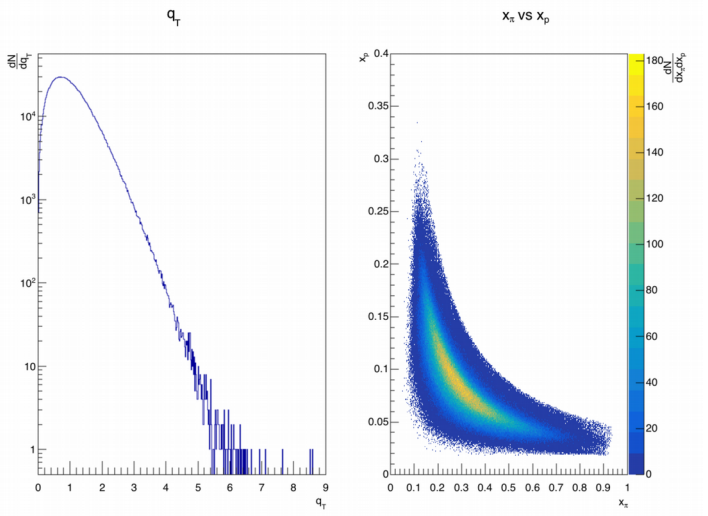


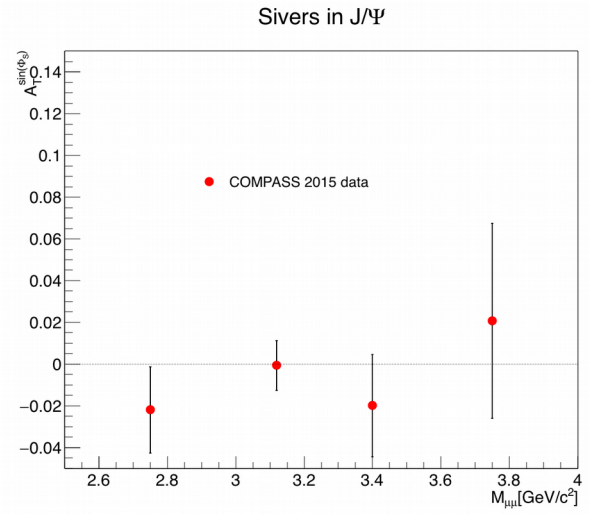
About 1 million of J/ψs in COMPASS 2015 DY data, more to come in 2018
Ongoing work – worse vertex resolution, many contributions in given mass range,...

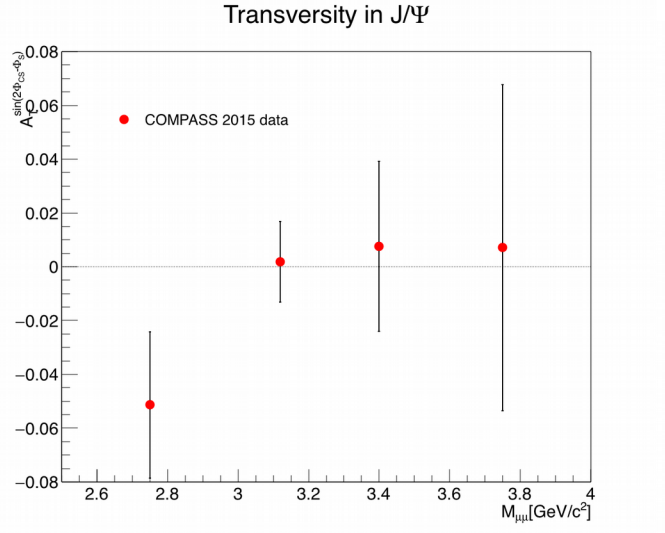
J/ψ production in DY data

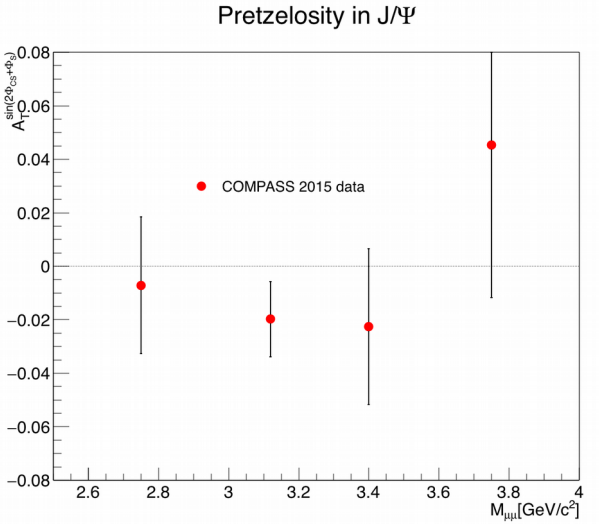












Conclusion

- Nucleon spin structure still has many unanswered questions
- Many results provided by COMPASS
- Many new measurements to come in near/far future

  (PANDA , RHIC, JLAB, NICA, COMPASS, EIC)

Thank you for your attention!

Questions?

Spares

Recent STAR measurement

Recently STAR measured the left-right asymmetry of dilepton production in p-p collisions with one of the beams polarized

Mass region of Z-boson

Data favors a Sivers TMD with sign-change between DY and SIDIS.

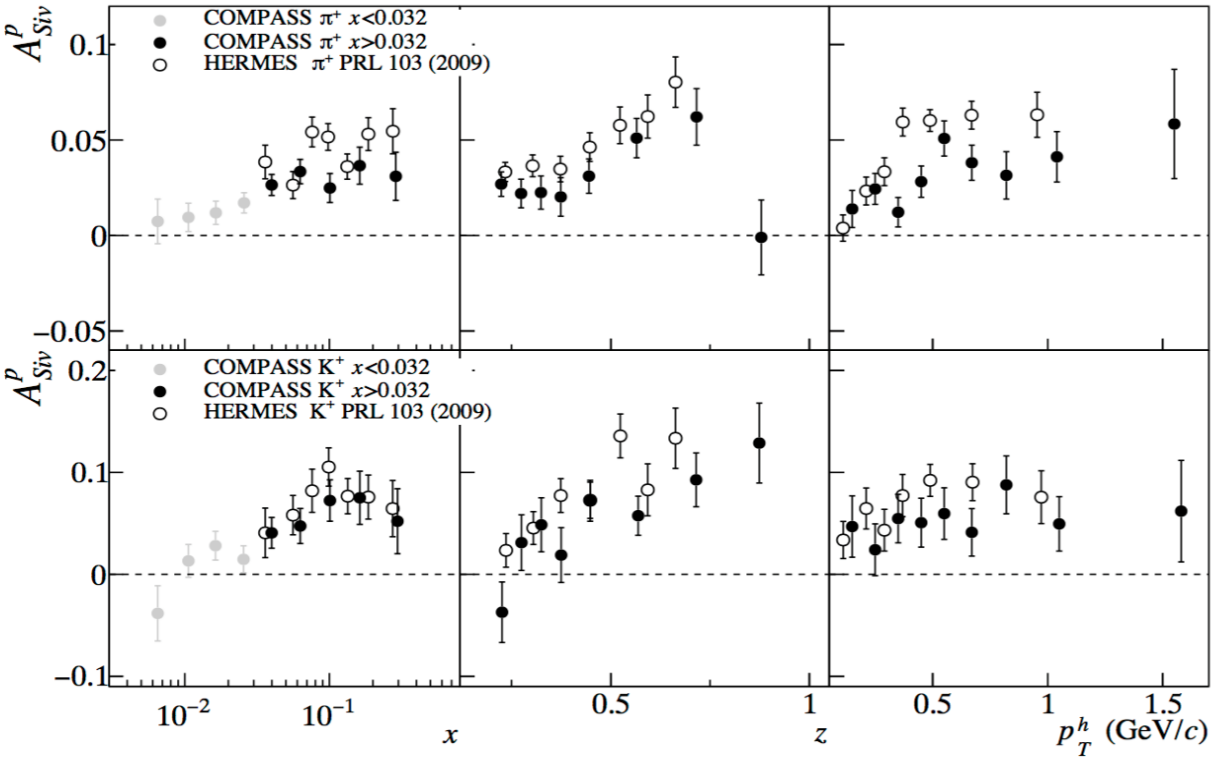
But they performed the measurement of Sivers in very different energy regime from SIDIS measurements, effects of evolution likely to be non- negligible.

The advantage of COMPASS is to acess the Sivers asymmetry in a comparable x-Q^2 phase space , with similar target and spectrometer, both in SIDIS and DY, thus minimizing possible Q^2 evolution effects

Hardware modifications for DY data taking

- Hadron absorber+beam plug
- SciFi Vertex detector downstream the target
- Dimuon trigger based on hodoscopes
- New PMM stations
- New large-area DC chamber
- “Proton-free” target cells
- New DAQ system
- Target magnet refurbishment

COMPASS SIDIS results



- Clear effect seen for both pions & kaons
- Smaller than HERMES
- Q^2 2-3x higher than HERMES->TMD evolution??


GAMS
COMPASS