



# Highlights from COMPASS SIDIS and Drell-Yan programs

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on behalf of the COMPASS Collaboration  
INFN section of Turin and University of Turin



102° Congresso SIF  
Padova, Italy  
26 – 30 September  
2016

# Transverse Momentum Dependent Parton Distribution Functions,



## TMD PDFs

In the leading order QCD parton model nucleon spin-structure can be parametrized in terms of in total 8 twist-2 intrinsic transverse momentum ( $\mathbf{k}_T$ ) dependent TMD PDFs.

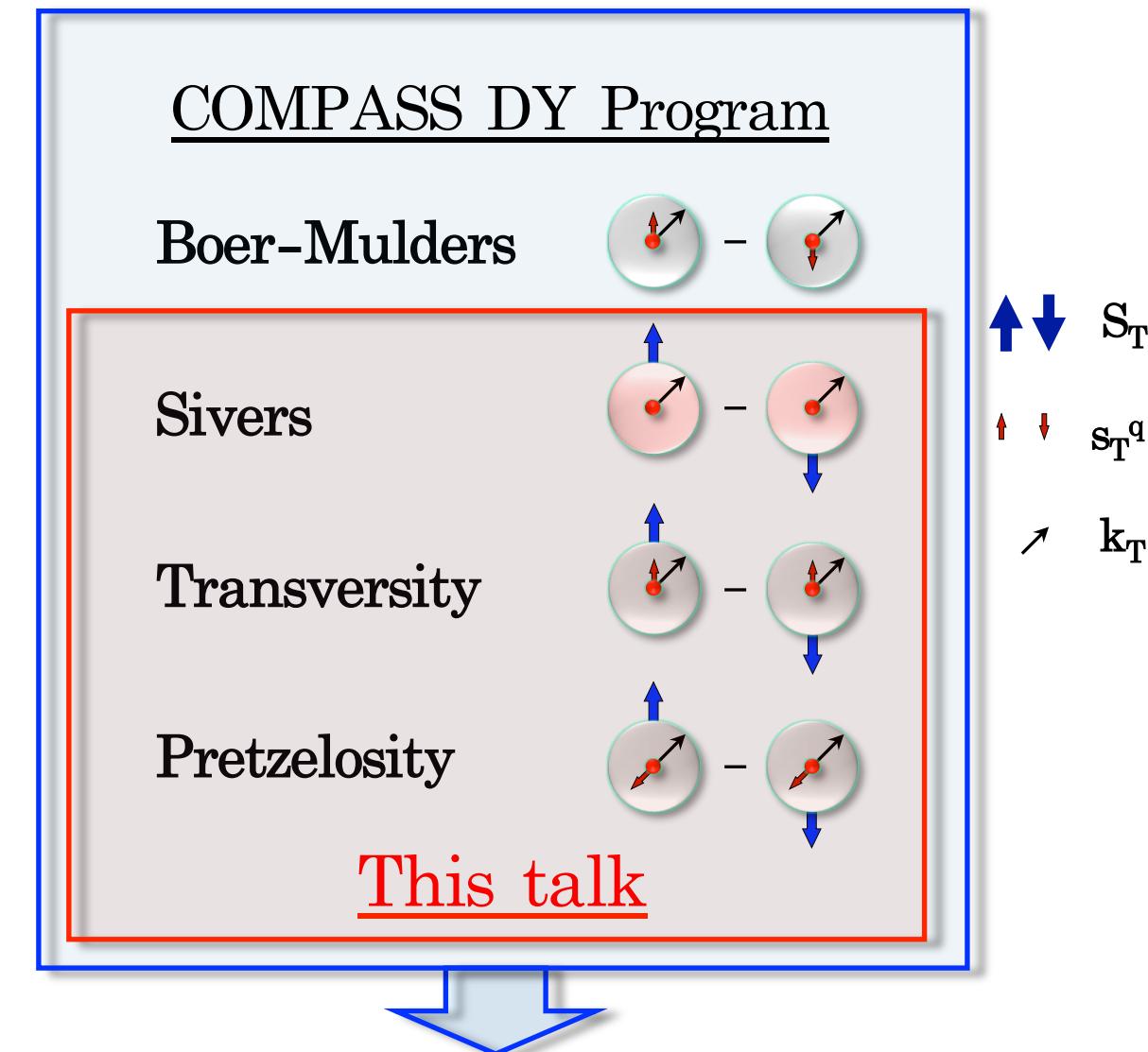
<i>Nucleon Quark</i>	<b>U</b>	<b>L</b>	<b>T</b>
<b>U</b>	$f_I^q(x, \mathbf{k}_T^2)$ Number density		$f_{IT}^{q\perp}(x, \mathbf{k}_T^2)$ Sivers
<b>L</b>		$g_I^q(x, \mathbf{k}_T^2)$ Helicity	$g_{IT}^{q\perp}(x, \mathbf{k}_T^2)$ Kotzinian-Mulders or Worm-gear T
<b>T</b>	$h_I^{q\perp}(x, \mathbf{k}_T^2)$ Boer-Mulders	$h_{IL}^{q\perp}(x, \mathbf{k}_T^2)$ Worm-gear L	$h_{IT}^{q\perp}(x, \mathbf{k}_T^2)$ Pretzelosity

# Transverse Momentum Dependent Parton Distribution Functions, TMD PDFs



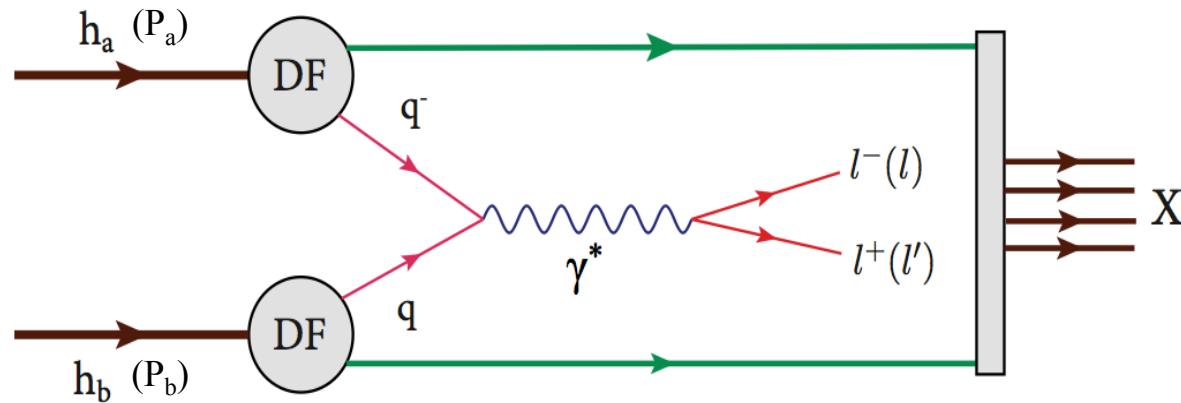
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TMD PDFs can be accessed through measurement of target spin (in)dependent azimuthal asymmetries both in SIDIS and Drell-Yan

# Single Polarized Drell-Yan process



DY @ COMPASS:  
 $h_a = \pi^- (190 \text{ GeV}/c)$   
 $h_b = p \uparrow$

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1 + \cos^2 \theta + \sin^2 \theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}}$$

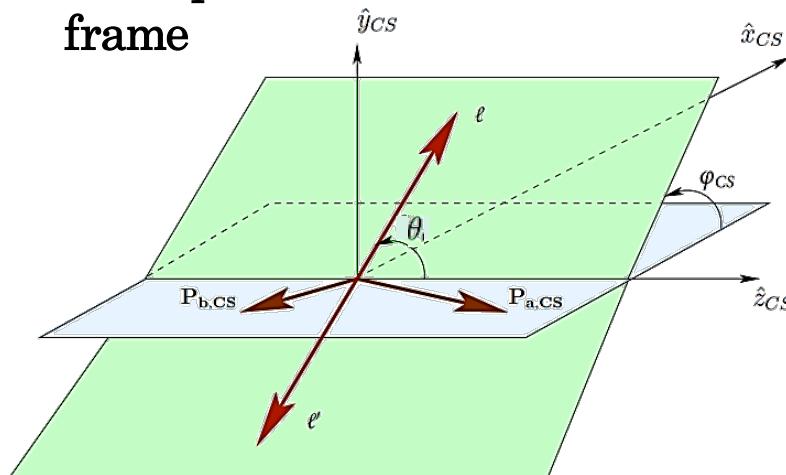
$$+ S_T \left[ \begin{aligned} & (1 + \cos^2 \theta) \sin \varphi_S A_T^{\sin \varphi_S} \\ & + \sin^2 \theta \left( \sin(2\varphi_{CS} + \varphi_S) A_T^{\sin(2\varphi_{CS} + \varphi_S)} \right. \\ & \quad \left. + \sin(2\varphi_{CS} - \varphi_S) A_T^{\sin(2\varphi_{CS} - \varphi_S)} \right) \end{aligned} \right] \rightarrow \begin{aligned} & h_{1,\pi}^{\perp q} \otimes h_1^{\perp q} \\ & f_{1,\pi}^q \otimes f_{1T}^{\perp q} \\ & h_{1,\pi}^{\perp q} \otimes h_1^q \\ & h_{1,\pi}^{\perp q} \otimes h_{1T}^{\perp q} \end{aligned}$$

- General leading order QCD parton model expression of the Single Polarized DY cross-section
- Azimuthal asymmetries

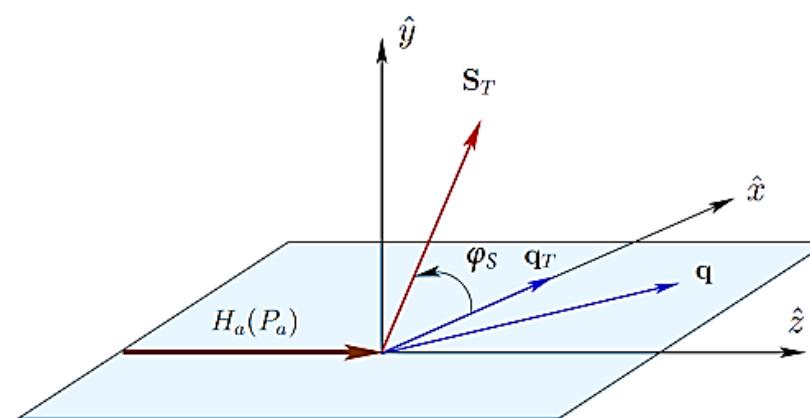
$$A_{U,T}^{w(\varphi_{CS}, \varphi_S)} = \frac{F_{U,T}^{w(\varphi_{CS}, \varphi_S)}}{F_U^1 + F_U^2} \propto PDF \otimes PDF$$

- At LO
  - 1 *Unpolarized Asymmetry*
  - 3 *Single Spin Asymmetries*
- Measurements of these azimuthal asymmetries provide an access to specific convolutions of TMD PDFs of  $h_a$  and  $h_b$

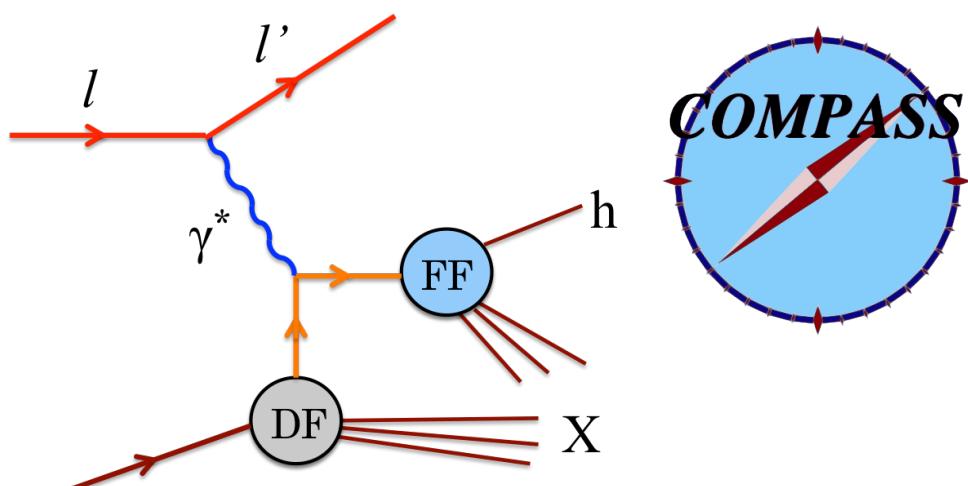
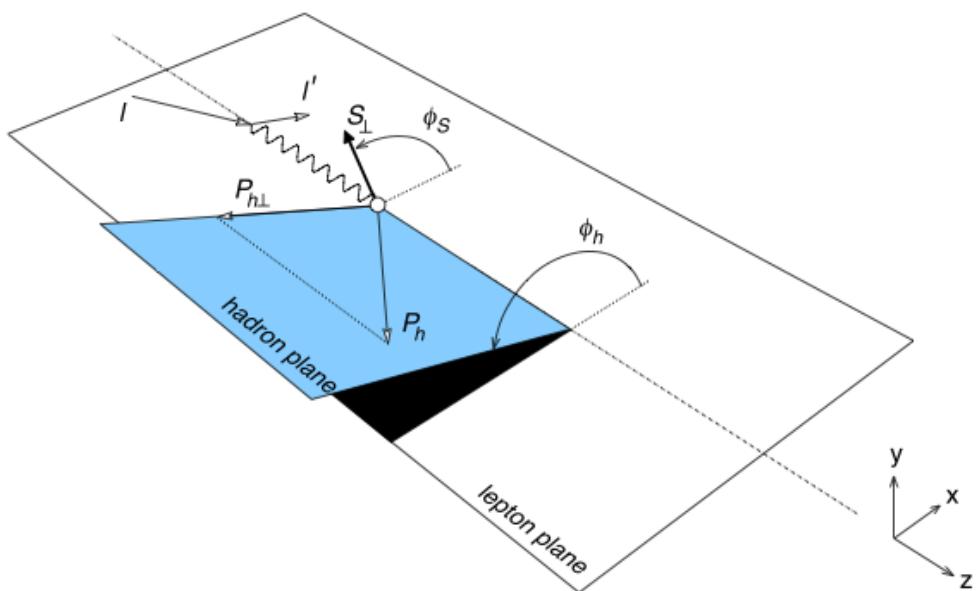
Collins-Soper  
frame



Target rest  
frame



# The SIDIS process



$$\frac{d\sigma_{SIDIS}^{LO}}{dxdydzdp_T^2d\varphi_h d\psi} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] \times (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ \begin{array}{l} h_1^{\perp q} \otimes H_{1q}^{\perp h} \\ f_{1T}^{\perp q} \otimes D_{1q}^h \\ h_1^q \otimes H_{1q}^{\perp h} \\ h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} \\ g_{1T}^q \otimes D_{1q}^h \end{array} \right. \begin{array}{l} \sin(\phi_h - \phi_s) (A_{UT}^{\sin(\phi_h - \phi_s)}) \\ + S_T \sin(\phi_h + \phi_s) (\varepsilon A_{UT}^{\sin(\phi_h + \phi_s)}) \\ + \sin(3\phi_h - \phi_s) (\varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)}) \\ + S_T \lambda \cos(\phi_h - \phi_s) \left[ \sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \right] \end{array} \right\}$$

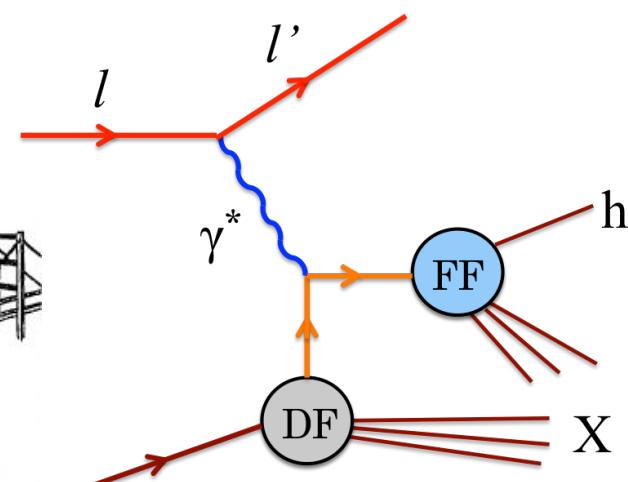
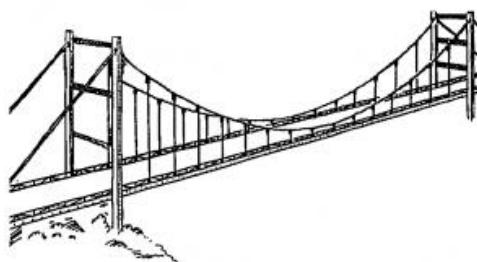
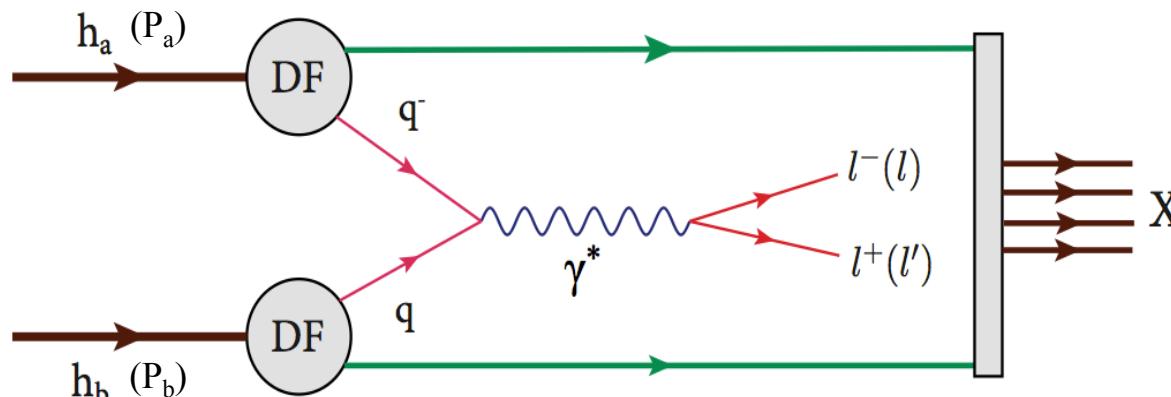
- General leading order expression of the transversely polarized SIDIS process
- At LO:
  - 1 Unpolarized Asymmetry;
  - 3 Single Spin Asymmetries;
  - 1 Double Spin Asymmetry;
- Measurement of SIDIS azimuthal asymmetries provides an access to specific convolutions of TMD and Fragmentation functions (FFs).

$$A_{U(L),T}^{w(\phi_h, \phi_s)} = \frac{F_{U(L),T}^{w(\phi_h, \phi_s)}}{F_{UU,T} + \varepsilon F_{UU,L}}$$

$\propto$  PDF  $\otimes$  FF

$$\gamma = \frac{2Mx}{Q}; \quad \varepsilon = \frac{1 - y - \frac{1}{4}\gamma^2 y^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2 y^2};$$

# DY-SIDIS Bridge



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

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Within the concept of generalized universality (time-reversal modified process-independence) of TMD PDFs it appears that same parton distribution functions can be accessed both in SIDIS and Drell-Yan

DP – DY only

TMD Universality

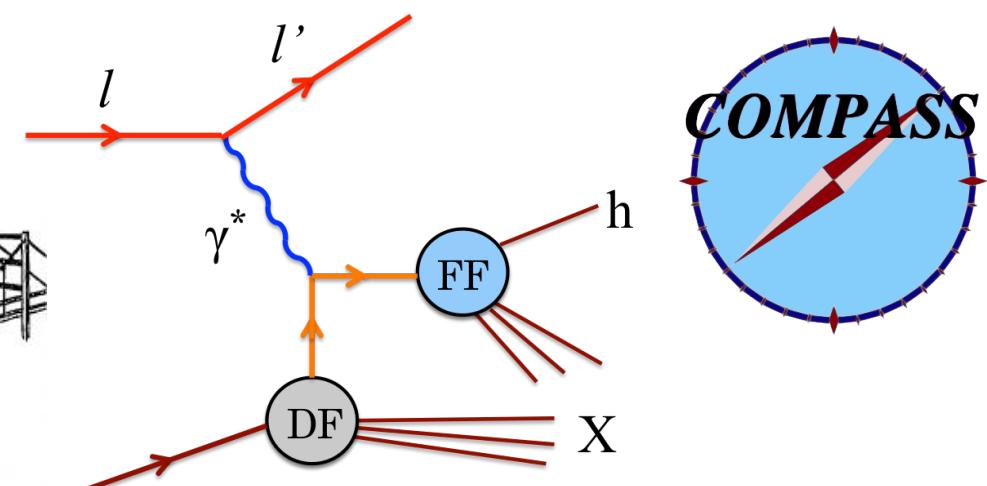
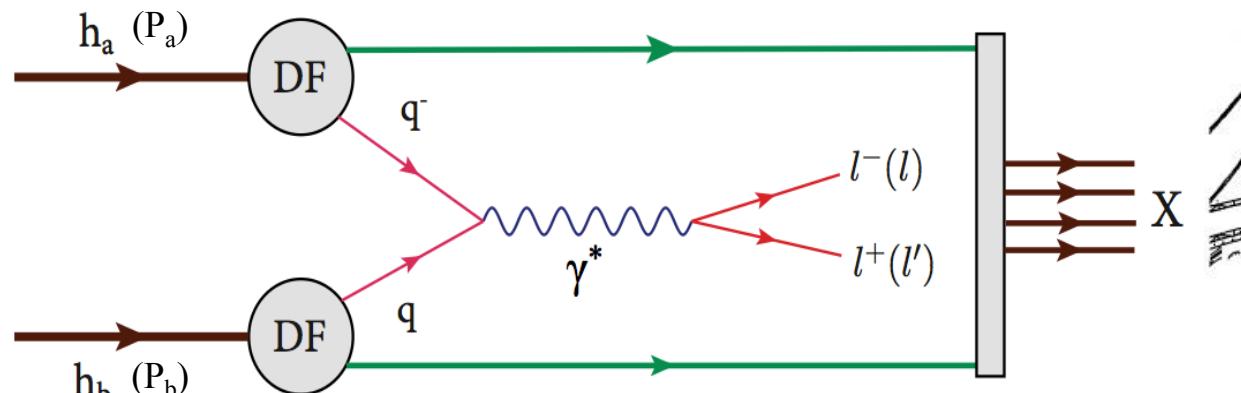
Sivers and BM sign change

$$f_{IT}^{\perp q}|_{DY} = - f_{IT}^{\perp q}|_{SIDIS}$$

$$h_I^q|_{DY} = - h_I^q|_{SIDIS}$$

$h_I^q$      $h_{IT}^{\perp q}$

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Within the concept of generalized universality (time-reversal modified process-independence) of TMD PDFs it appears that same parton distribution functions can be accessed both in SIDIS and Drell-Yan

Polarized DY data are needed for the verification!

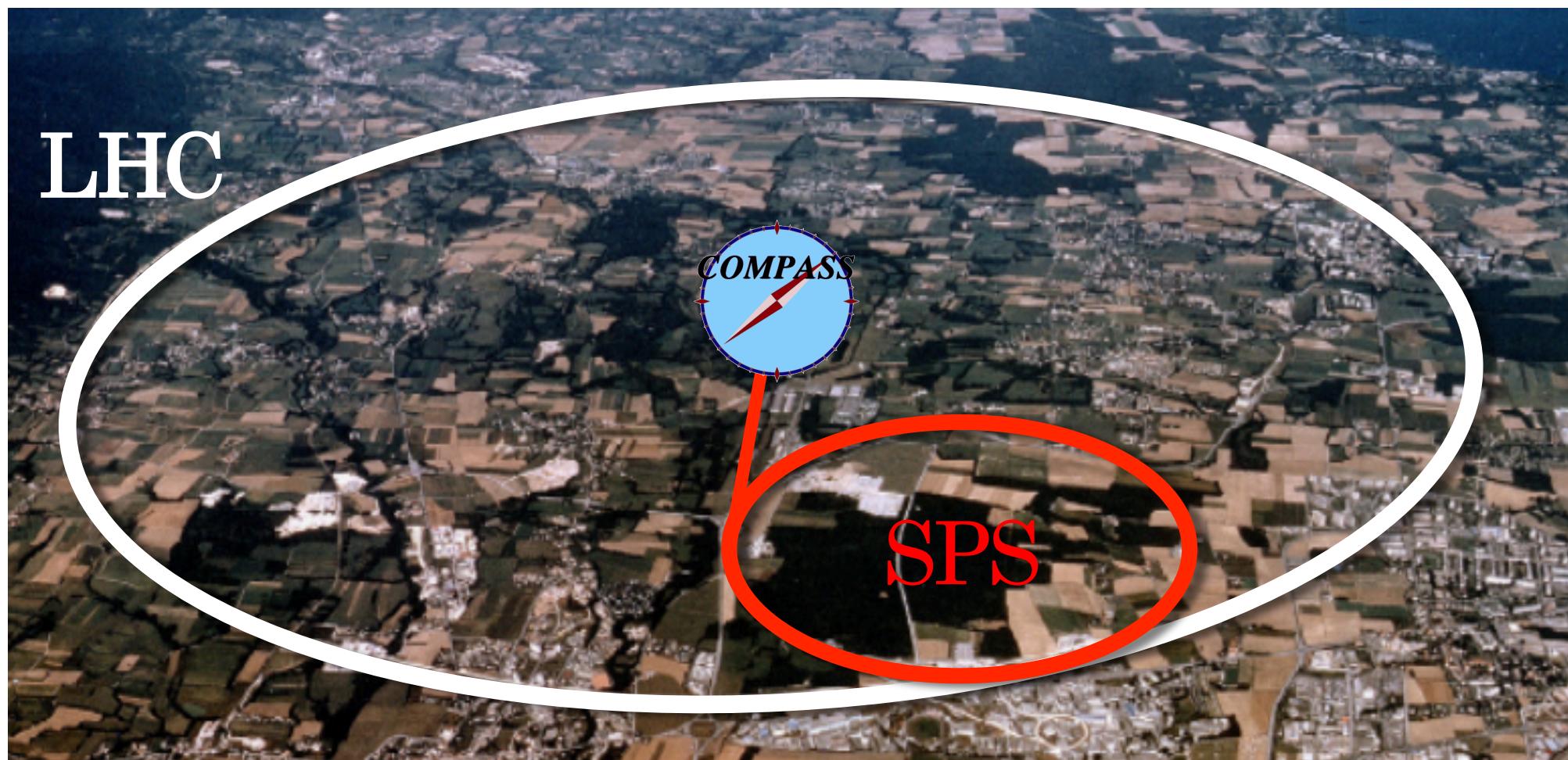
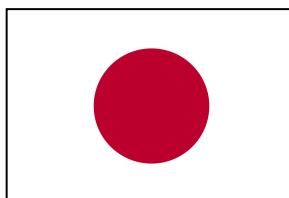
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# The COMPASS collaboration



- SPS North Area

- Fixed target experiment

- First data taking in 2002

## Phase I

- 2002 – 2011
- Hadron spectroscopy
- Nucleon spin structure studies

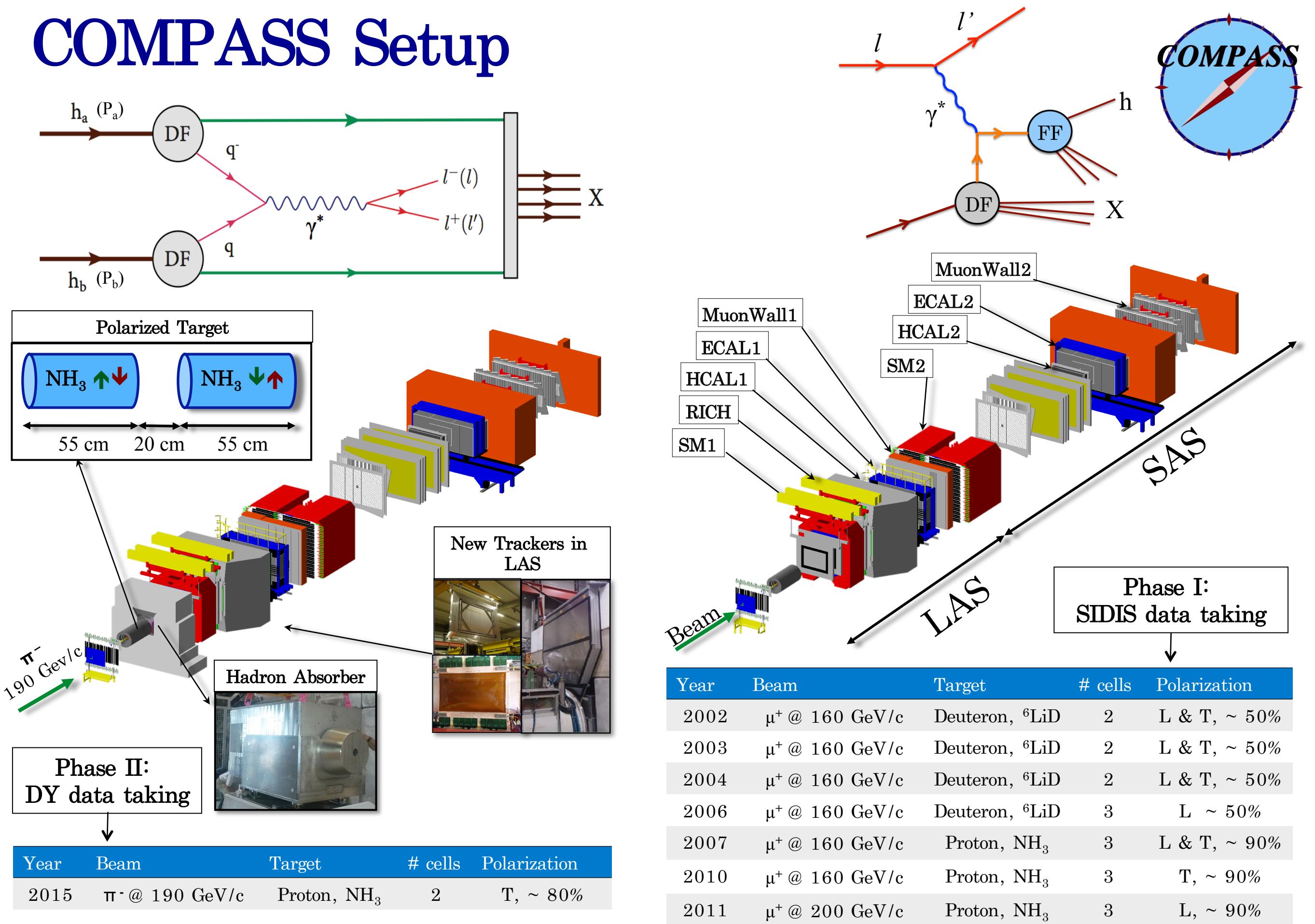
A. Ivanov → in 10 min!



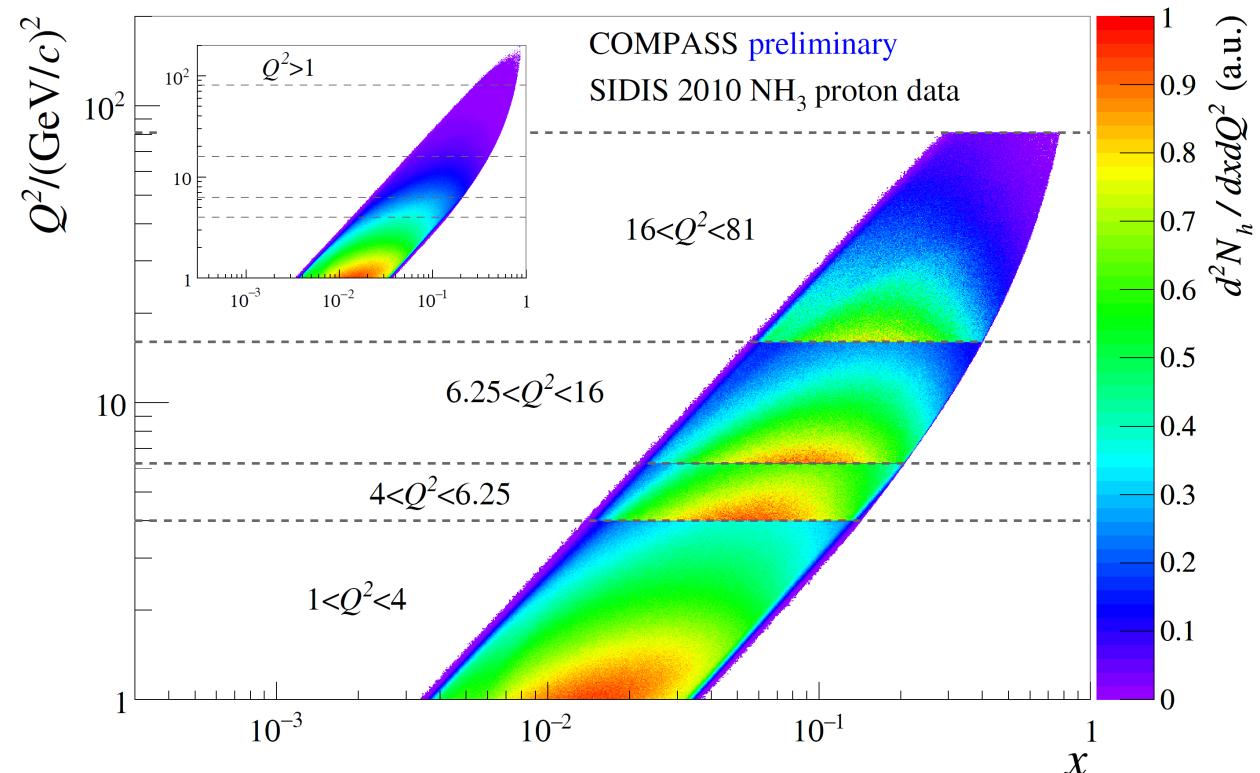
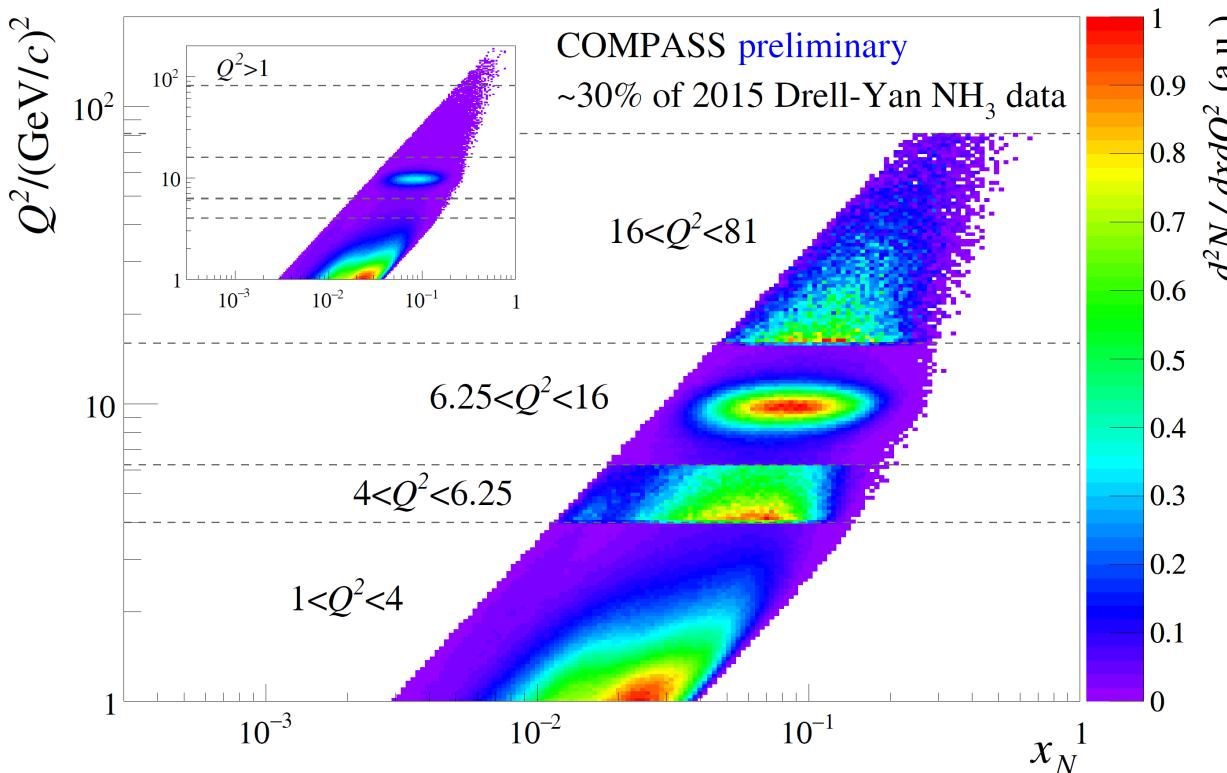
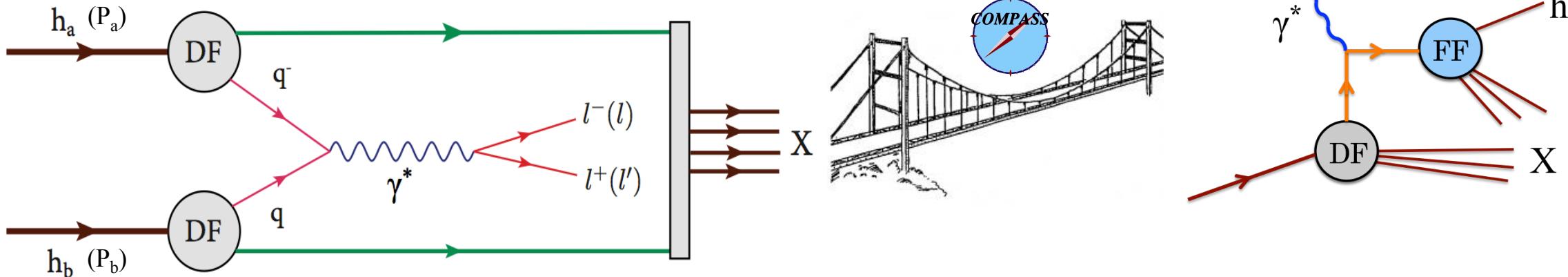
## Phase II

- 2012 – 2018
- Primakoff + DVCS pilot run (2012)
- Drell-Yan (2015, 2018)
- DVCS (GPD + Unpolarized SIDIS 2016-2017)

# COMPASS Setup



# COMPASS DY-SIDIS Bridge



- The COMPASS experiment has measured both SIDIS and polarized DY asymmetries exploring comparable  $x:Q^2$  phase space and using essentially the same spectrometer;

# COMPASS DY ranges

Four  $Q^2$  (or mass) ranges

I.  $1 < Q^2 / (\text{GeV}/c^2) < 4$ , “Low mass”

- Large combinatorial background:
  - Pion and Kaon decays.
  - Open charm (bottom) semi-leptonic decays  $D\bar{D}$ ,  $B\bar{B}$
- Smaller Asymmetries.

II.  $4 < Q^2 / (\text{GeV}/c^2) < 6.25$ , “Intermediate”

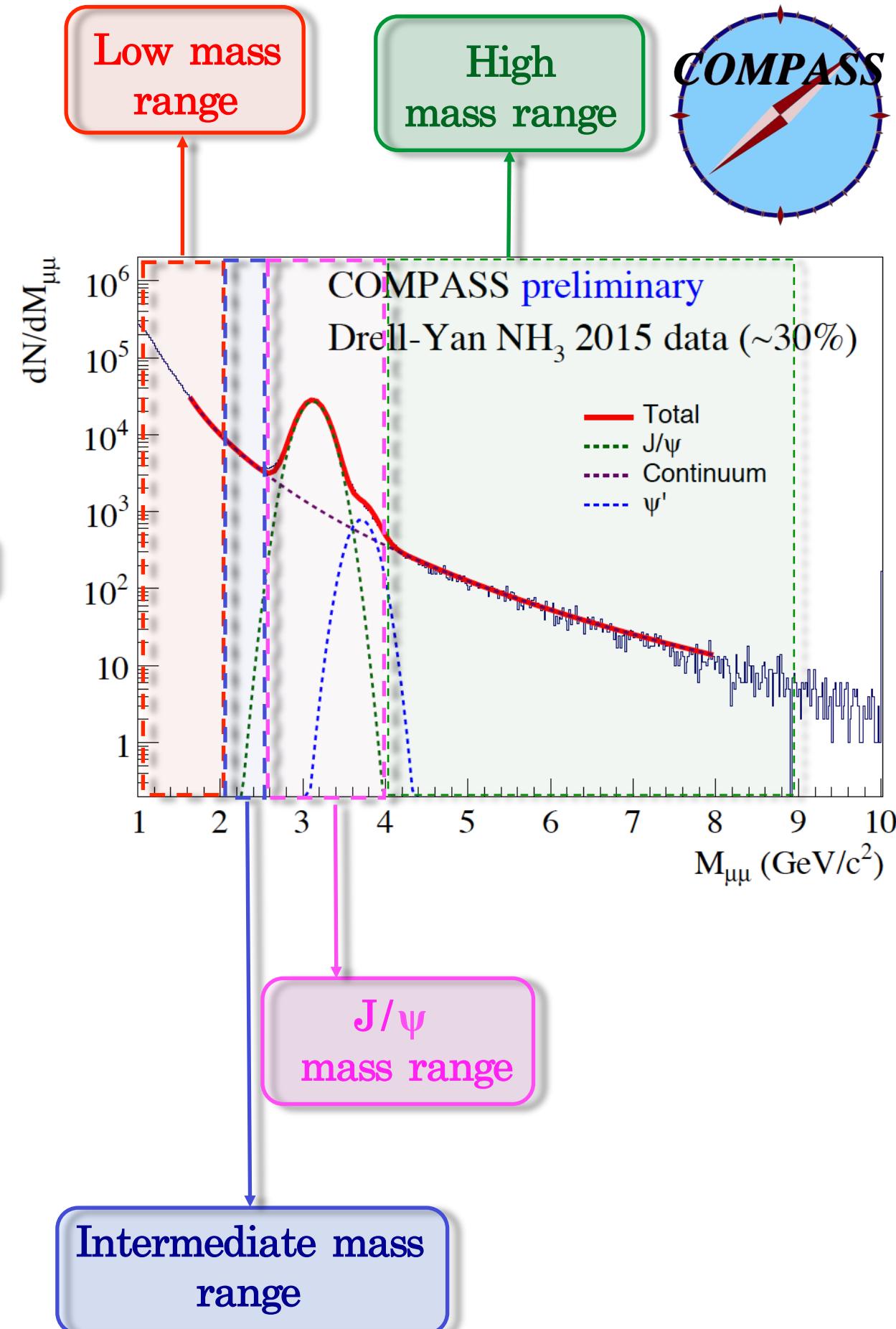
- High DY cross section.
- Still low signal/background

III.  $6.25 < Q^2 / (\text{GeV}/c^2) < 16$ , “ $J/\psi$ ”

- Strong  $J/\psi$  signal → Studies of  $J/\psi$  physics.
- Lower background
- Difficult to disentangle DY

IV.  $16 < Q^2 / (\text{GeV}/c^2) < 81$ , “High Mass”

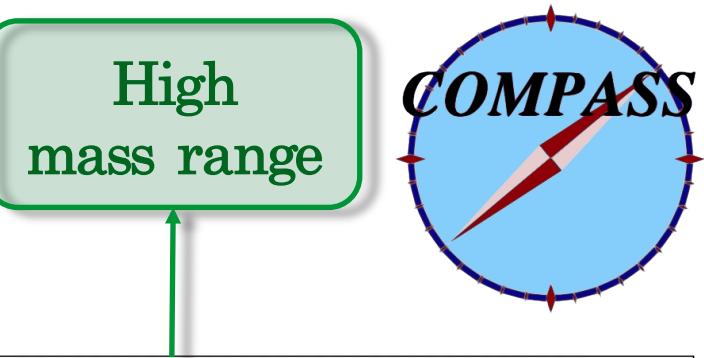
- Beyond  $J/\psi$  and  $\psi'$  peak.
- Negligible background
- Valence quark region → Larger asymmetries! But ...
- Low cross-section



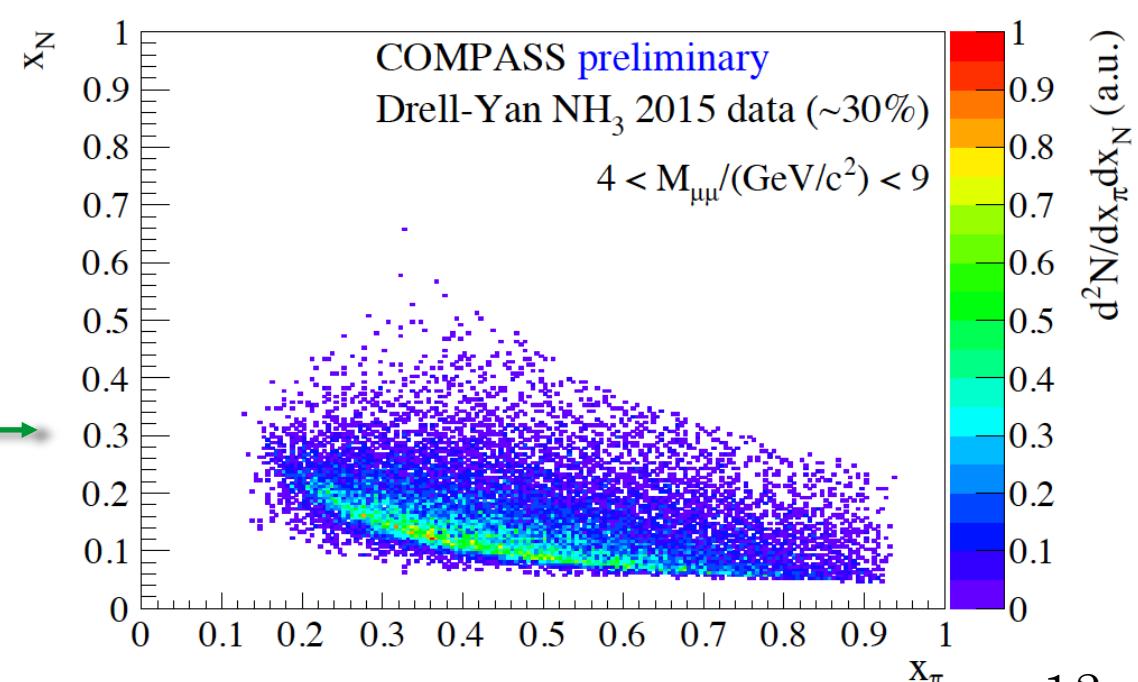
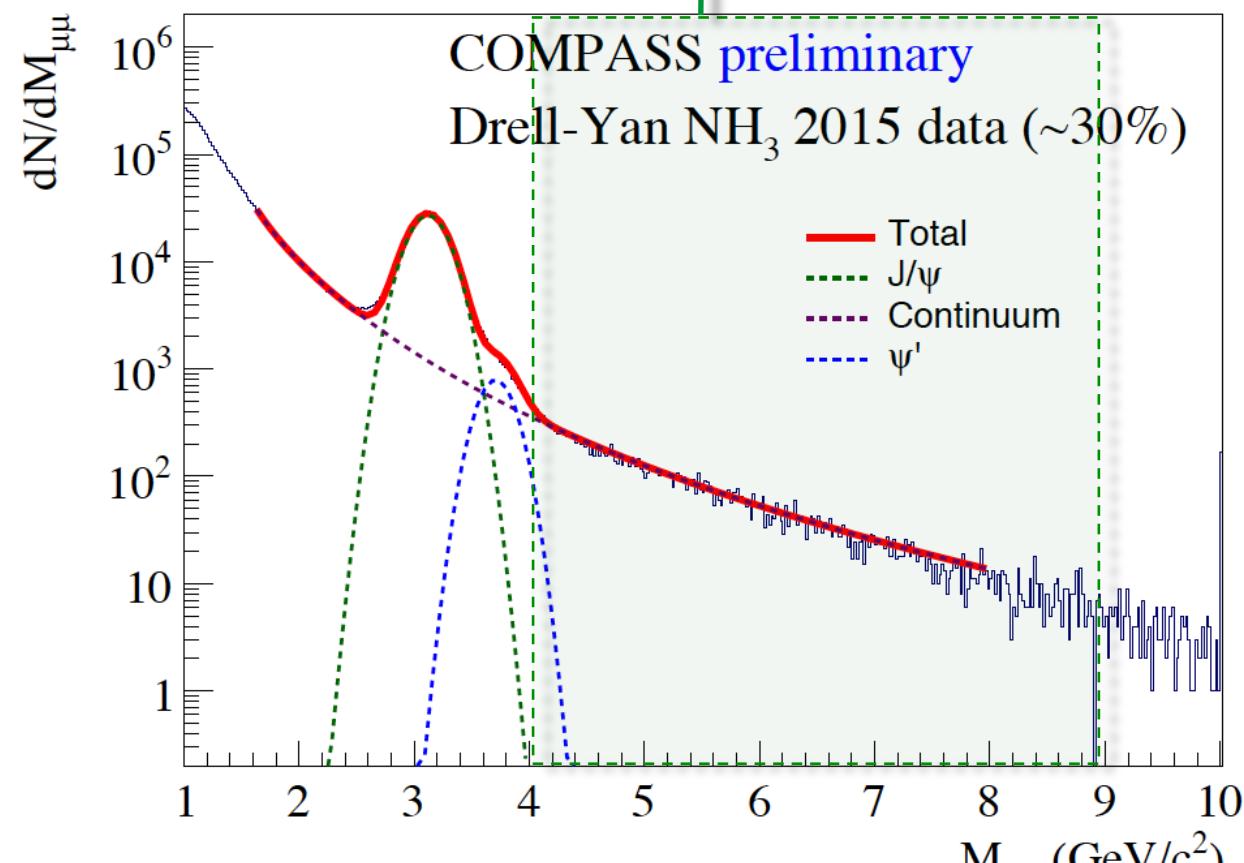
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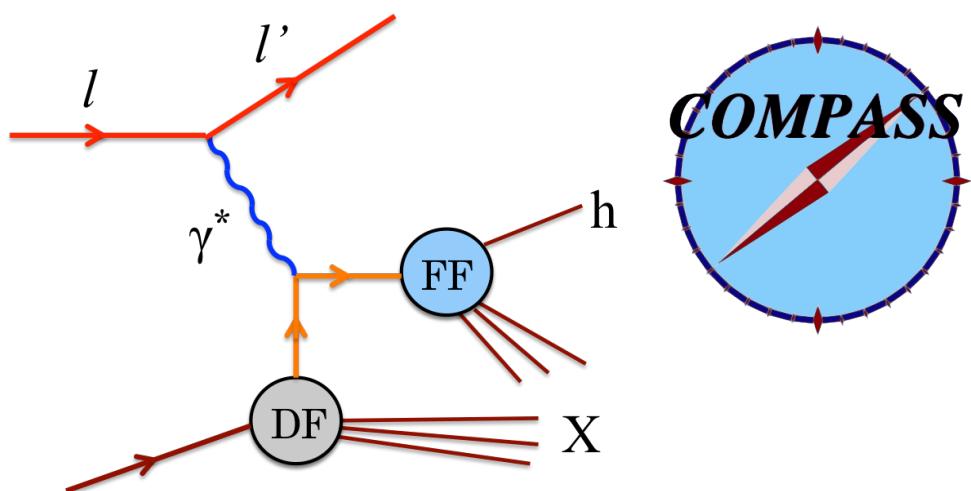
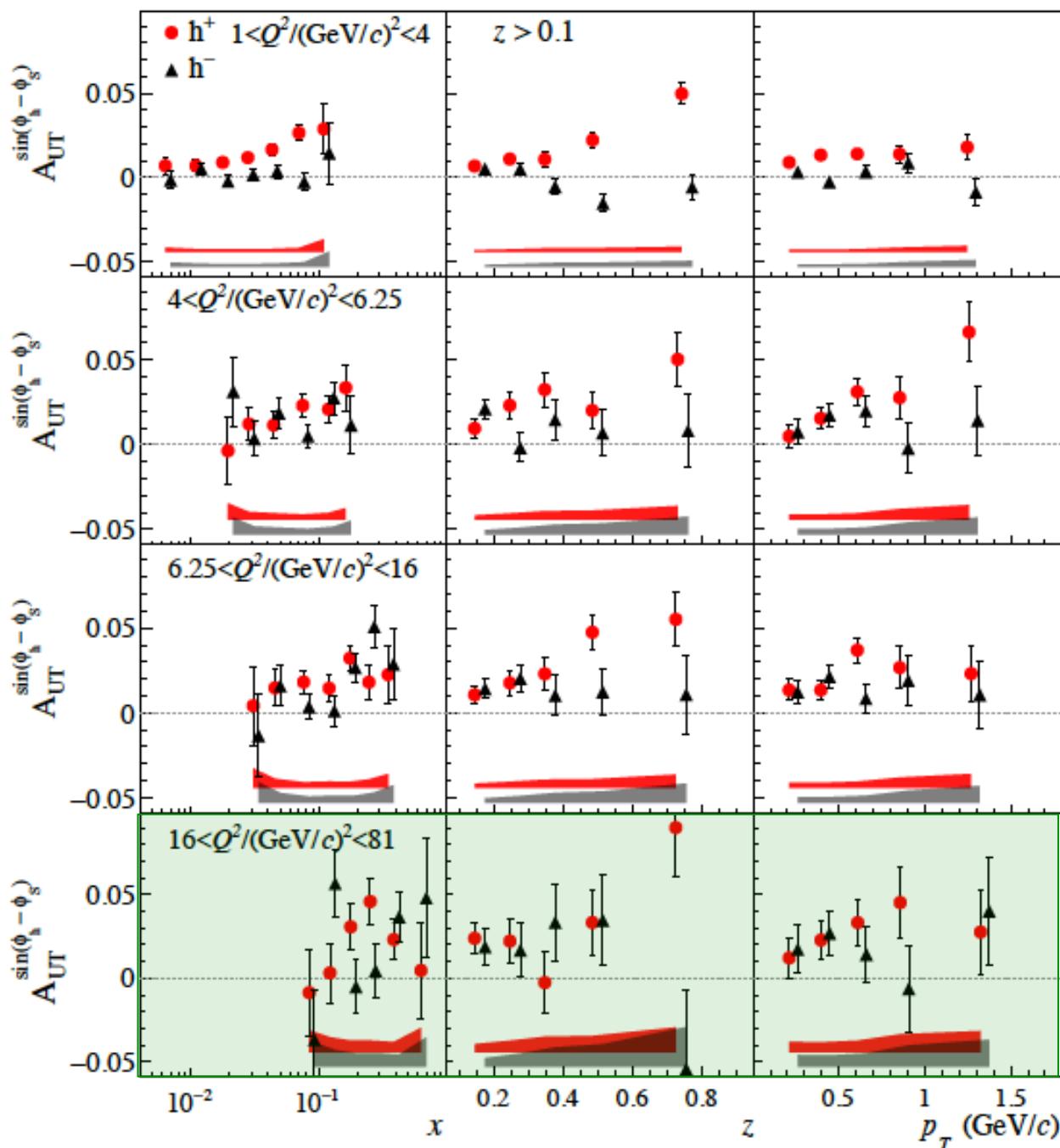
High  
mass range



# COMPASS SIDIS results in DY ranges

**NEW!** [CERN-EP-2016 – 250](#)  
[arXiv:1609.07374 \[hep-ex\]](#)

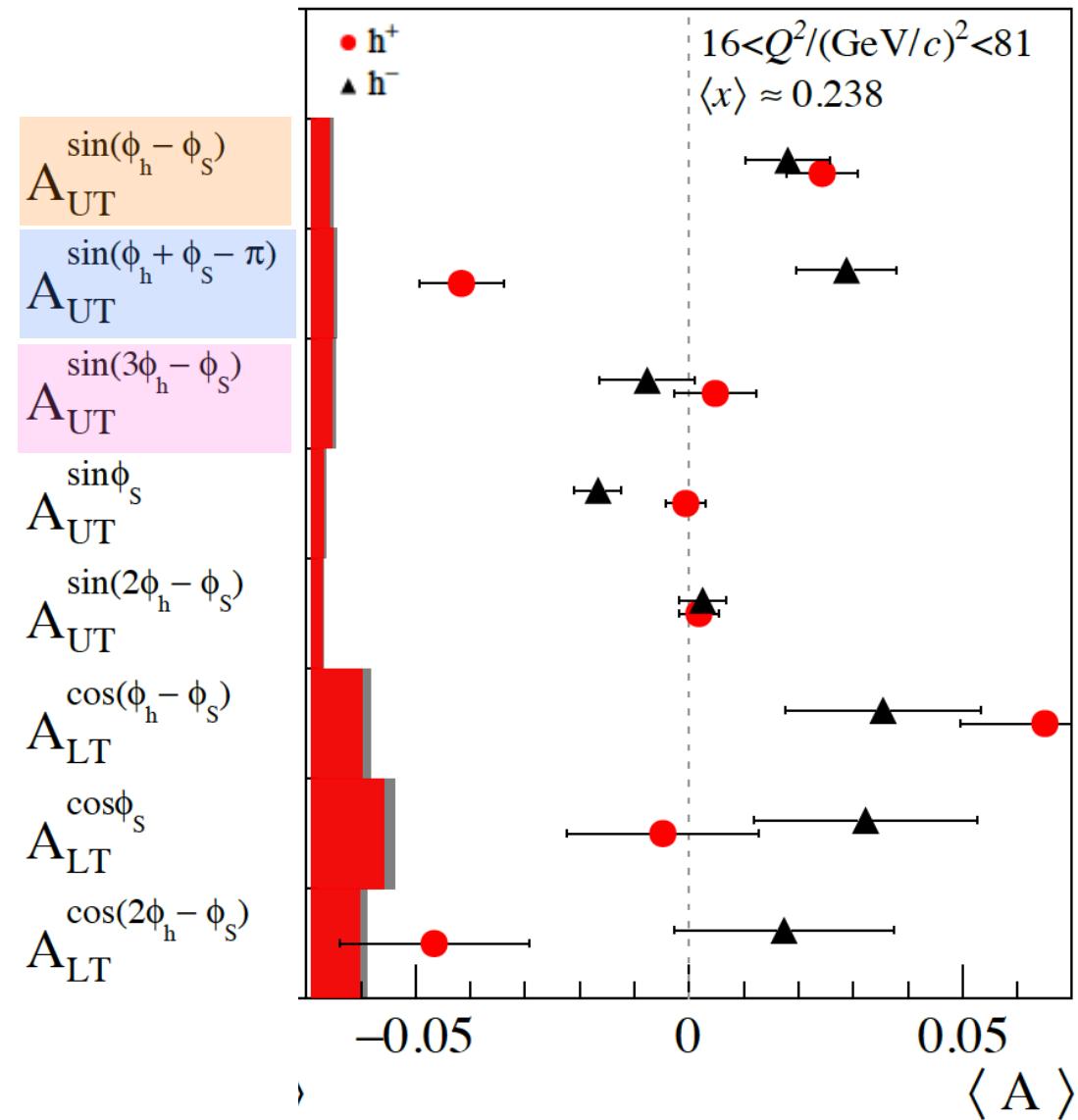
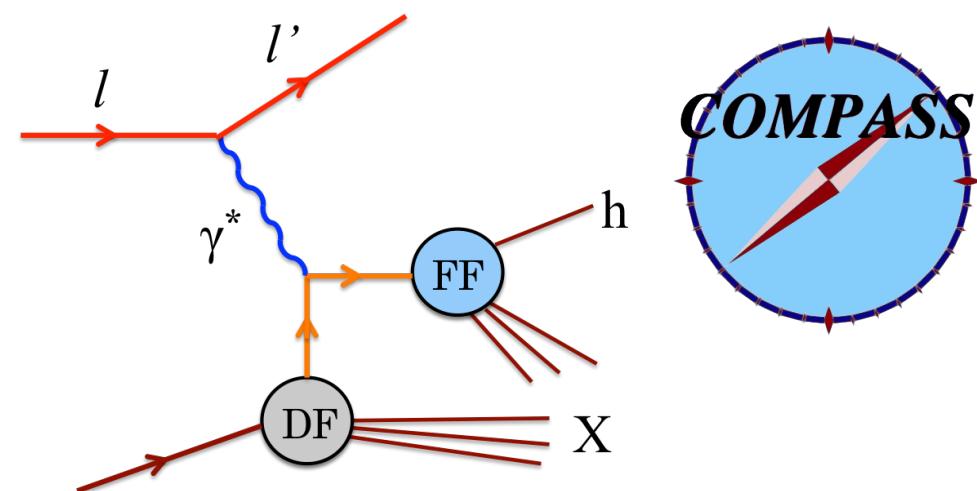
$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$



$$\frac{d\sigma_{SIDIS}^{LO}}{dxdydzdp_T^2d\varphi_h d\psi} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] \times (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ \begin{array}{l} \sin(\phi_h - \phi_s) \left( A_{UT}^{\sin(\phi_h - \phi_s)} \right) \\ + S_T \left[ \begin{array}{l} \sin(\phi_h + \phi_s) \left( \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \right) \\ + \sin(3\phi_h - \phi_s) \left( \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \right) \end{array} \right] \\ + S_T \lambda \left[ \cos(\phi_h - \phi_s) \left( \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \right) \right] \end{array} \right\}$$

- Sivers asymmetry extracted for each  $Q^2$  range;
- COMPASS divided Proton 2010 data sample into the 4  $Q^2$  DY ranges and extracted all the azimuthal asymmetries of the SIDIS cross section in each one of them;
- Results for the Sivers asymmetry in DY **High mass range** in SIDIS are already available;

# COMPASS SIDIS results in DY HM range



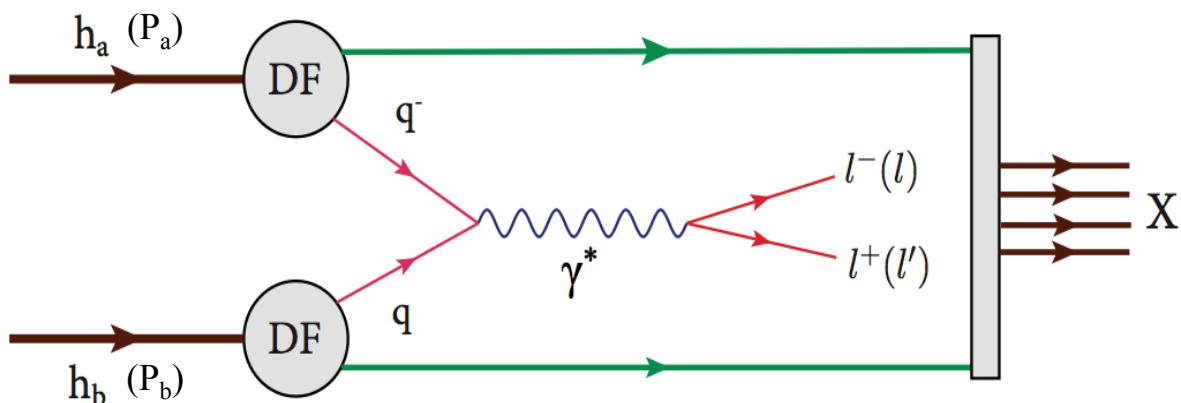
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NEW! [CERN-EP-2016-250](https://cds.cern.ch/record/2016-250)  
[arXiv:1609.07374 \[hep-ex\]](https://arxiv.org/abs/1609.07374)

In High Mass range:

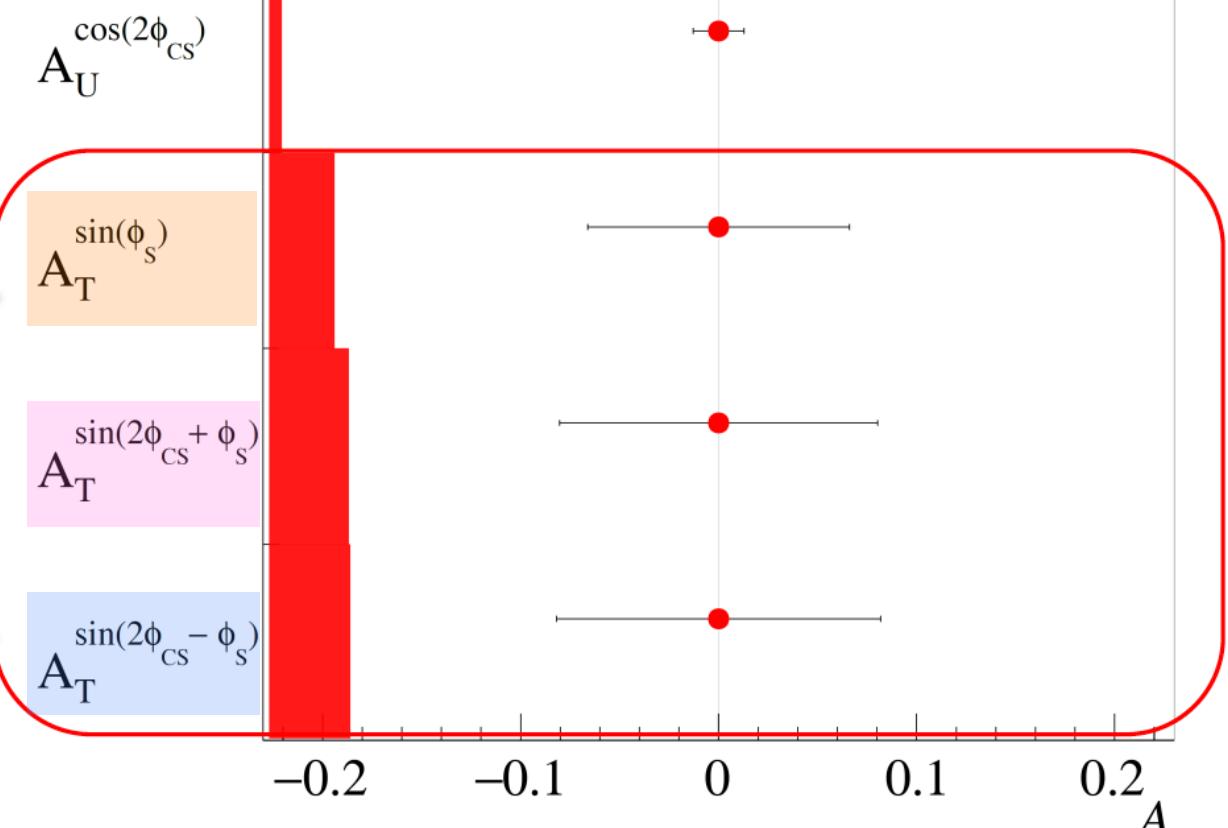
- Clear signal for **Sivers** and **Transversity**;
- **Pretzelosity** compatible with zero;
- SIDIS results in DY ranges are already available;
- Just DY part of the puzzle is missing, analysis ongoing, new results very soon!

# Expected accuracy in HM

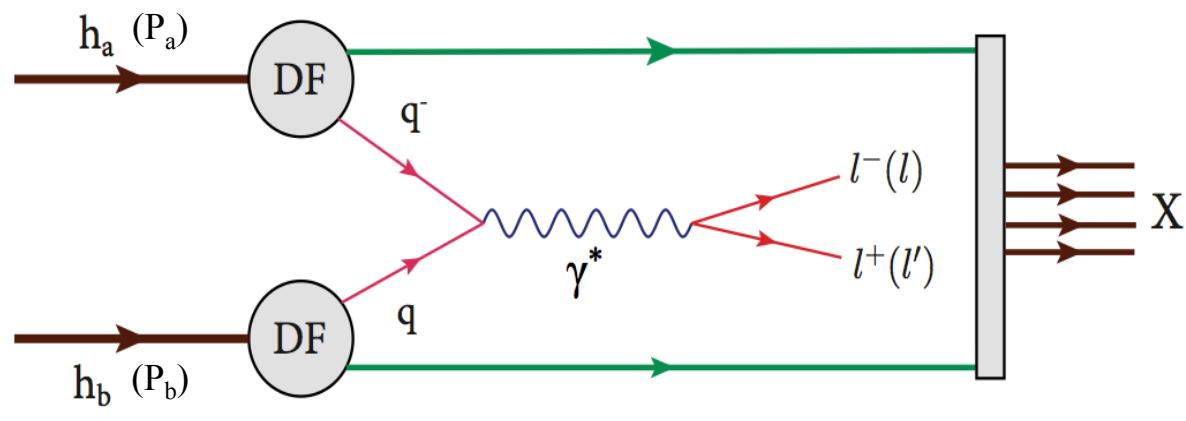


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$$+ S_T \left[ (1 + \cos^2 \theta) \sin \varphi_S A_T^{\sin \varphi_S} \right. \\ \left. + \sin^2 \theta \left( \sin(2\varphi_{CS} + \varphi_S) A_T^{\sin(2\varphi_{CS} + \varphi_S)} \right. \right. \\ \left. \left. + \sin(2\varphi_{CS} - \varphi_S) A_T^{\sin(2\varphi_{CS} - \varphi_S)} \right) \right]$$

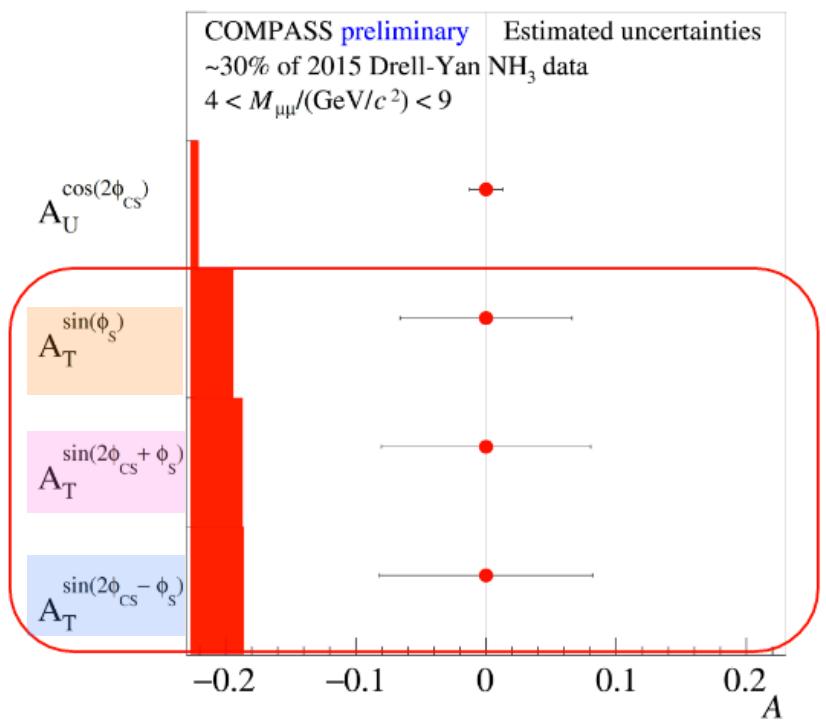


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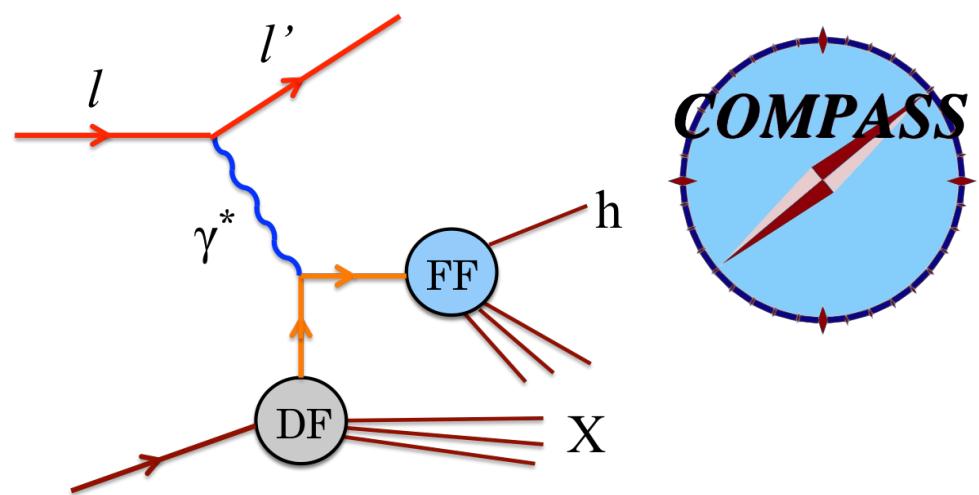
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30 September 2016

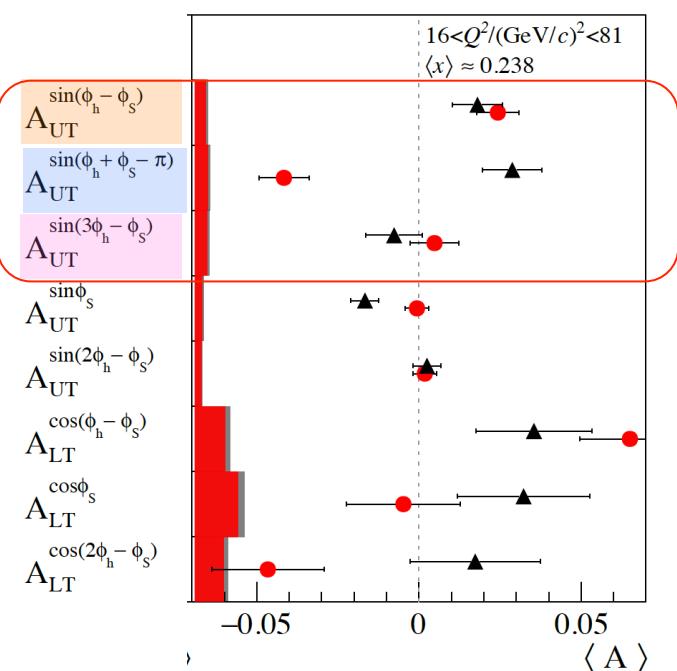
Riccardo Longo



$$\frac{d\sigma_{SIDIS}^{LO}}{dx dy dz dp_T^2 d\varphi_h d\psi} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right]$$

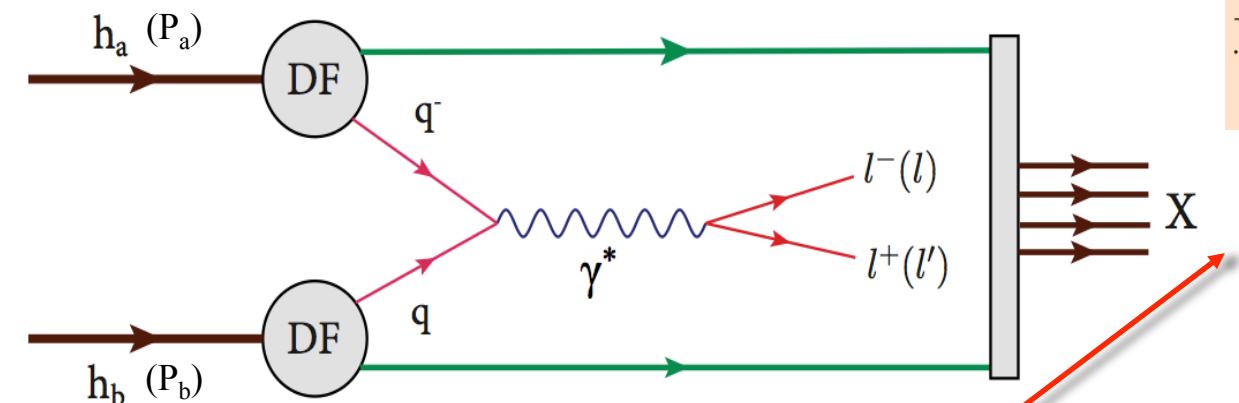
$$\times \left( F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \cos 2\phi_h \left( \varepsilon A_{UU}^{\cos 2\phi_h} \right) \right\}$$

$$\begin{aligned} & \left[ \sin(\phi_h - \phi_S) \left( A_{UT}^{\sin(\phi_h - \phi_S)} \right) \right. \\ & + S_T \left[ \begin{aligned} & \sin(\phi_h + \phi_S) \left( \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \right) \\ & + \sin(3\phi_h - \phi_S) \left( \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \right) \end{aligned} \right] \\ & \left. + S_T \lambda \left[ \cos(\phi_h - \phi_S) \left( \sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \right) \right] \right\} \end{aligned}$$



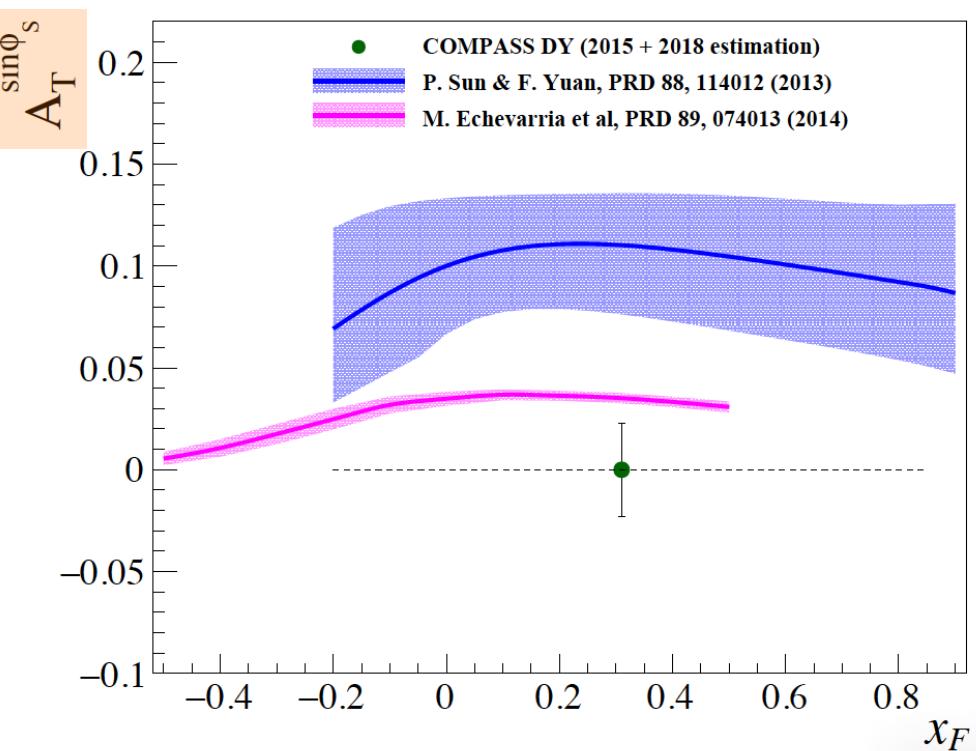
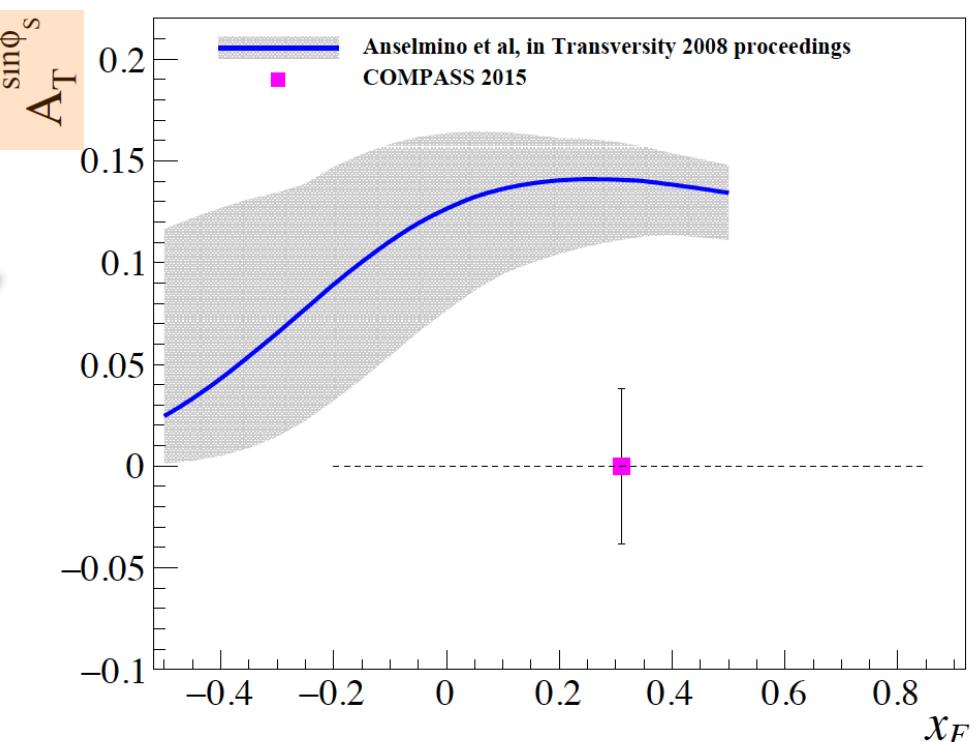
16

# Expected accuracy in HM



$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1 + \cos^2 \theta + \sin^2 \theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}}$$

$$+ S_T \left[ (1 + \cos^2 \theta) \sin \varphi_S A_T^{\sin \varphi_S} + \sin^2 \theta \left( \sin(2\varphi_{CS} + \varphi_S) A_T^{\sin(2\varphi_{CS} + \varphi_S)} + \sin(2\varphi_{CS} - \varphi_S) A_T^{\sin(2\varphi_{CS} - \varphi_S)} \right) \right]$$



- There is a variety of models giving largely spread theoretical predictions.
- Experimental data are the necessary input to constrain the models



# Conclusions



- The DY and SIDIS processes are complementary ways to access TMD PDFs.
- The COMPASS Collaboration took a considerable amount of SIDIS data during the Phase I.
- The experiment has taken the first ever polarized DY data in 2015.
- **COMPASS is the first experiment that has measured both SIDIS and polarized DY using essentially the same spectrometer!**
  - Cross SIDIS-DY studies are already available.
  - Exploration of the same  $x:Q^2$  phase space both in SIDIS and DY.
  - **First opportunity to test TMD universality and the sign change between SIDIS and DY for Sivers and Boer-Mulders PDFs.**
- **Several analyses are ongoing, new results will be available soon!**

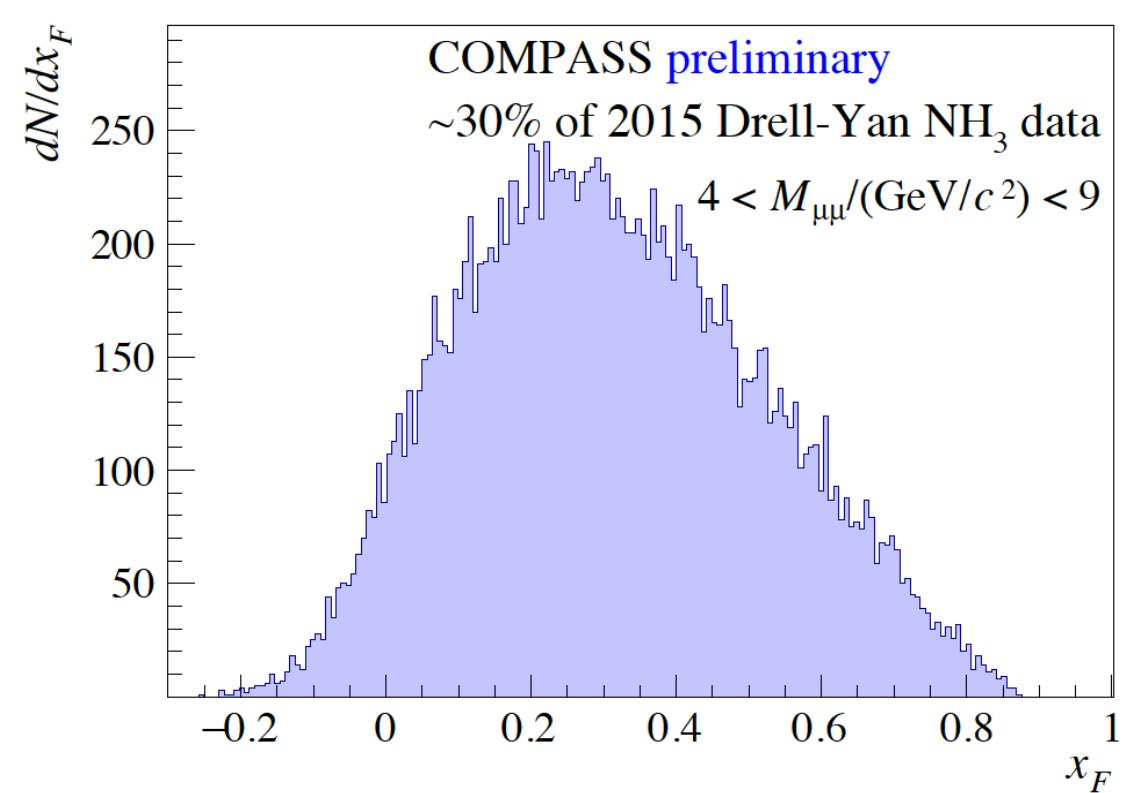
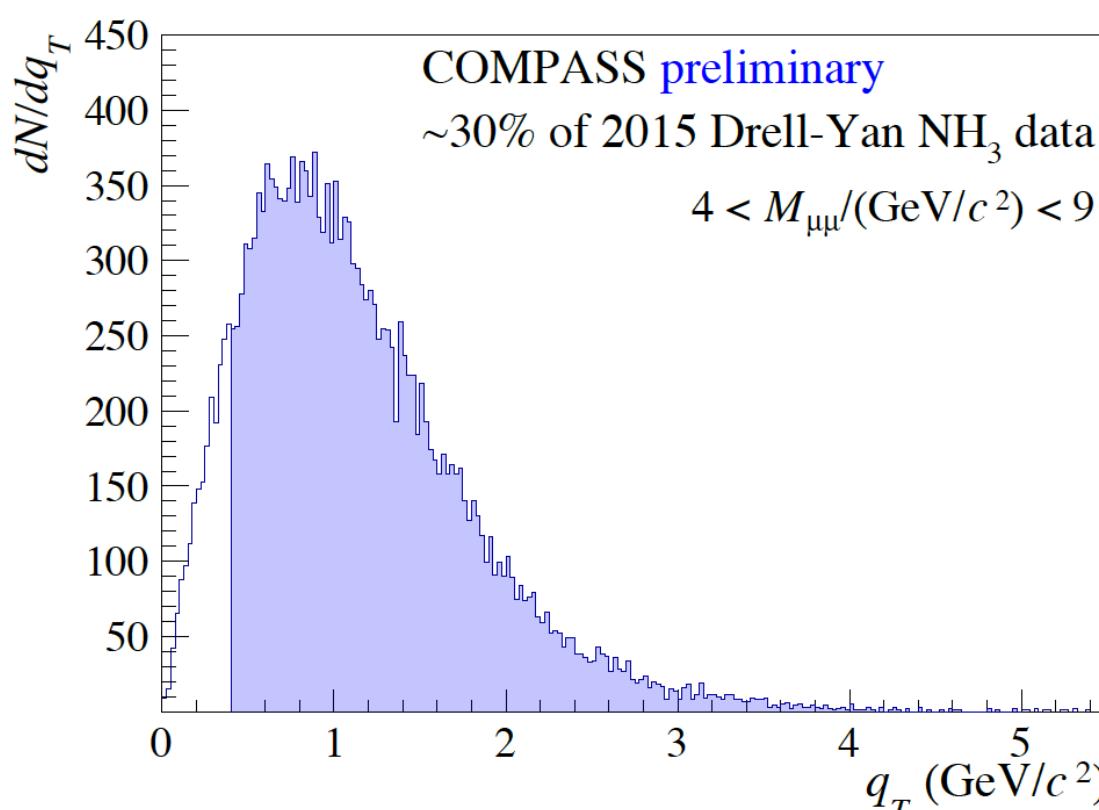
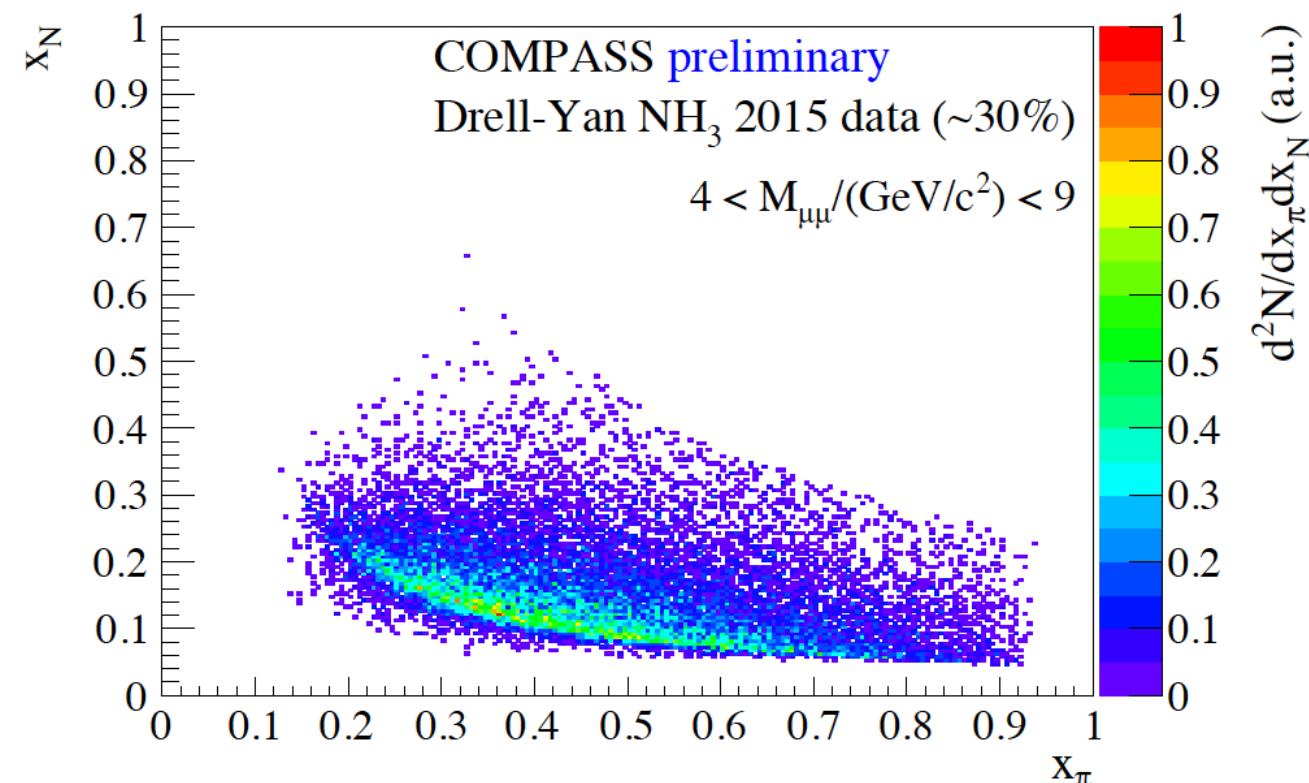
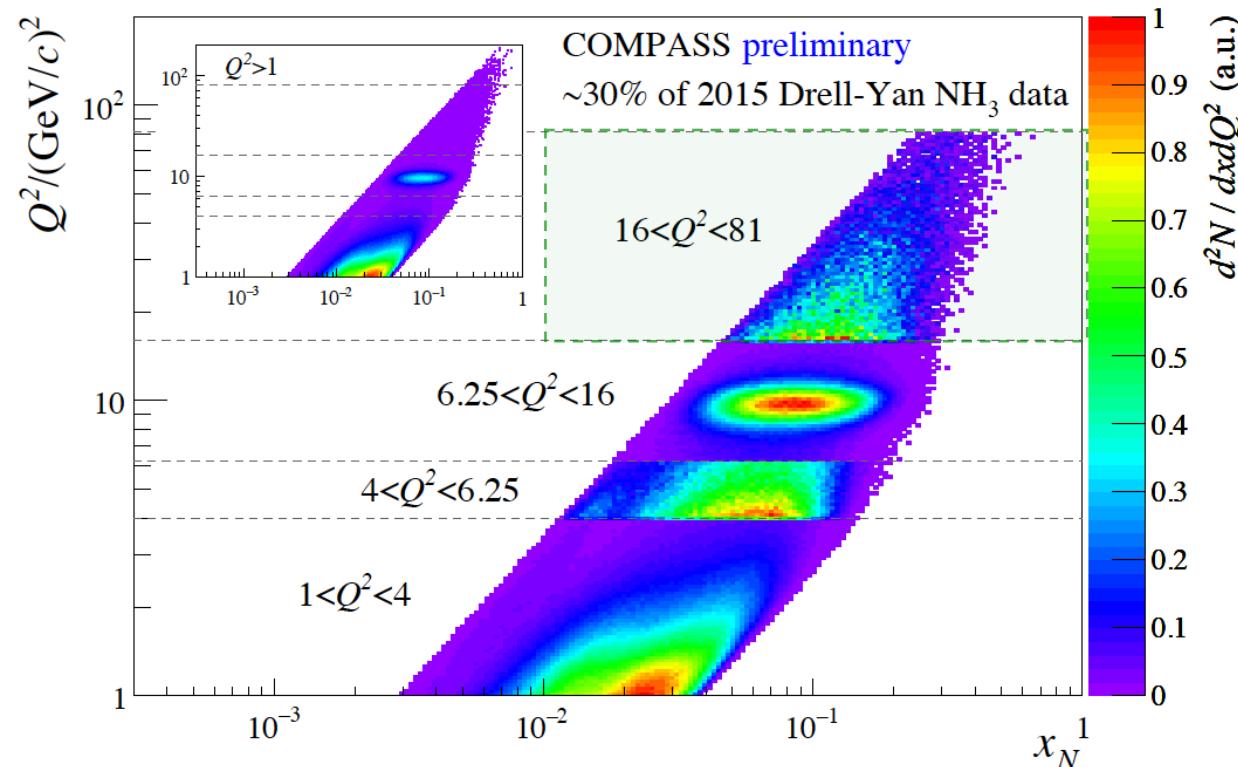
Thank you!  
Grazie!



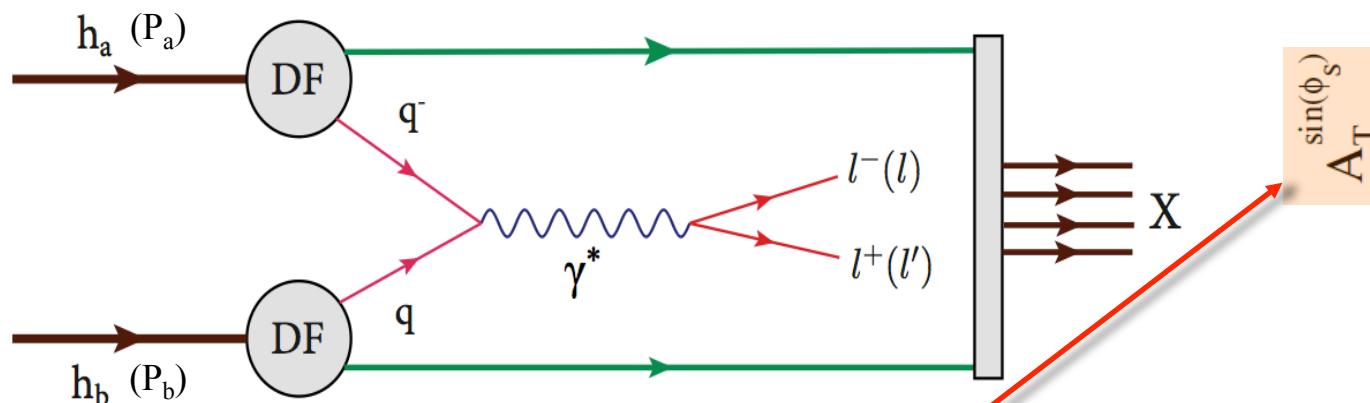


# Spare Slides

# COMPASS DY run 2015 kinematics: $x_\pi$ , $x_N$ , $x_F$ and $q_T$ in HM range



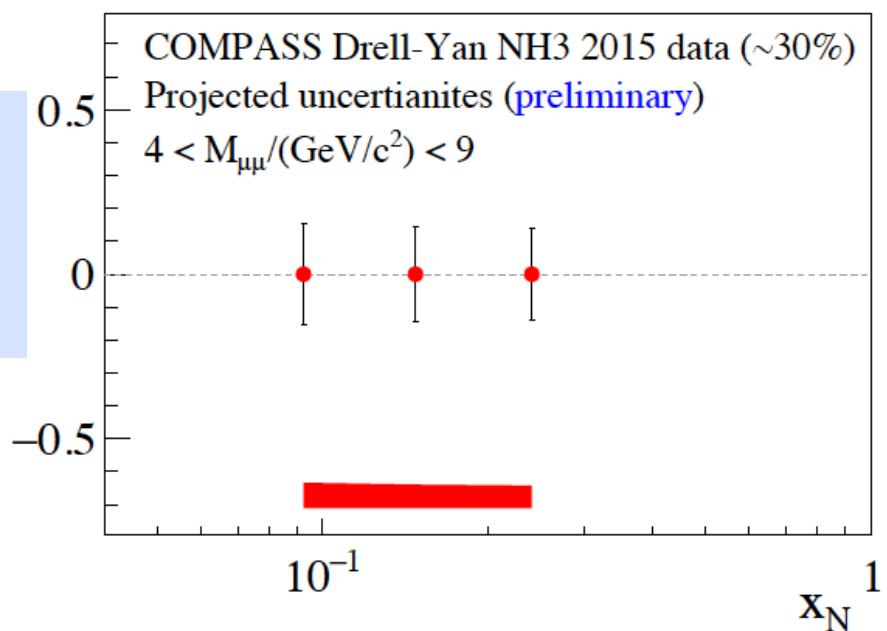
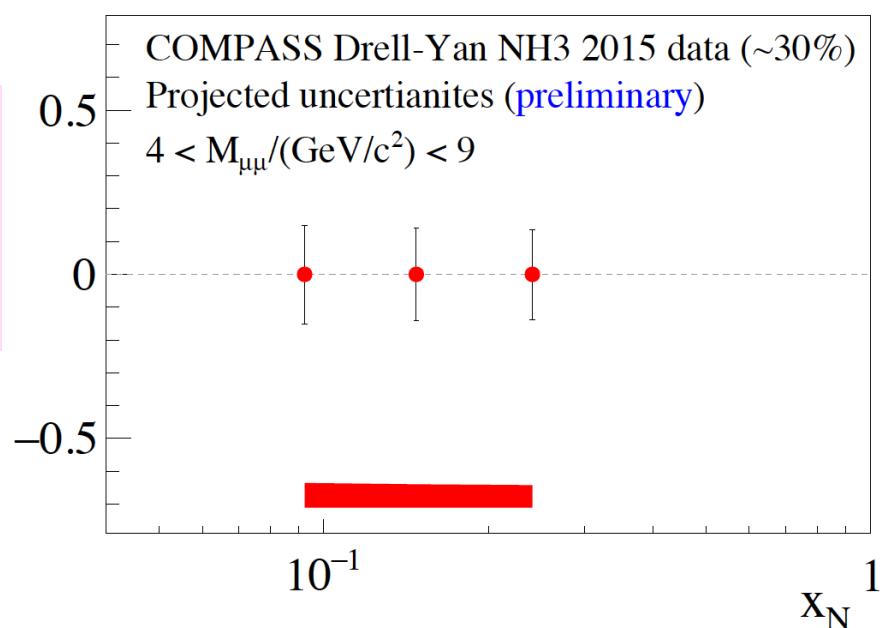
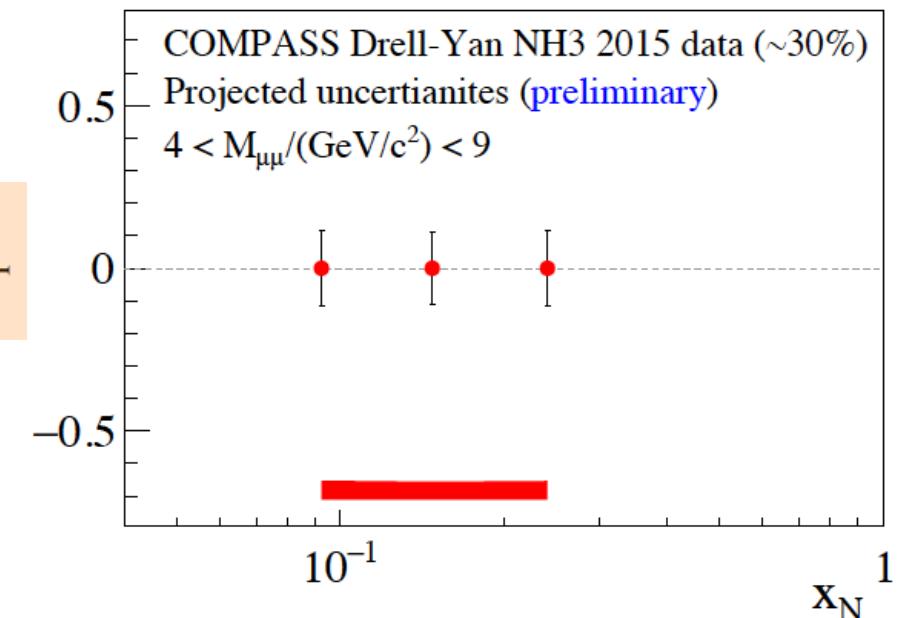
# Expected accuracy



$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1 + \cos^2 \theta + \sin^2 \theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}}$$

$$+ S_T \left[ \begin{aligned} & (1 + \cos^2 \theta) \sin \varphi_S A_T^{\sin \varphi_S} \\ & + \sin^2 \theta \left( \sin(2\varphi_{CS} + \varphi_S) A_T^{\sin(2\varphi_{CS} + \varphi_S)} \right. \\ & \left. + \sin(2\varphi_{CS} - \varphi_S) A_T^{\sin(2\varphi_{CS} - \varphi_S)} \right) \end{aligned} \right]$$

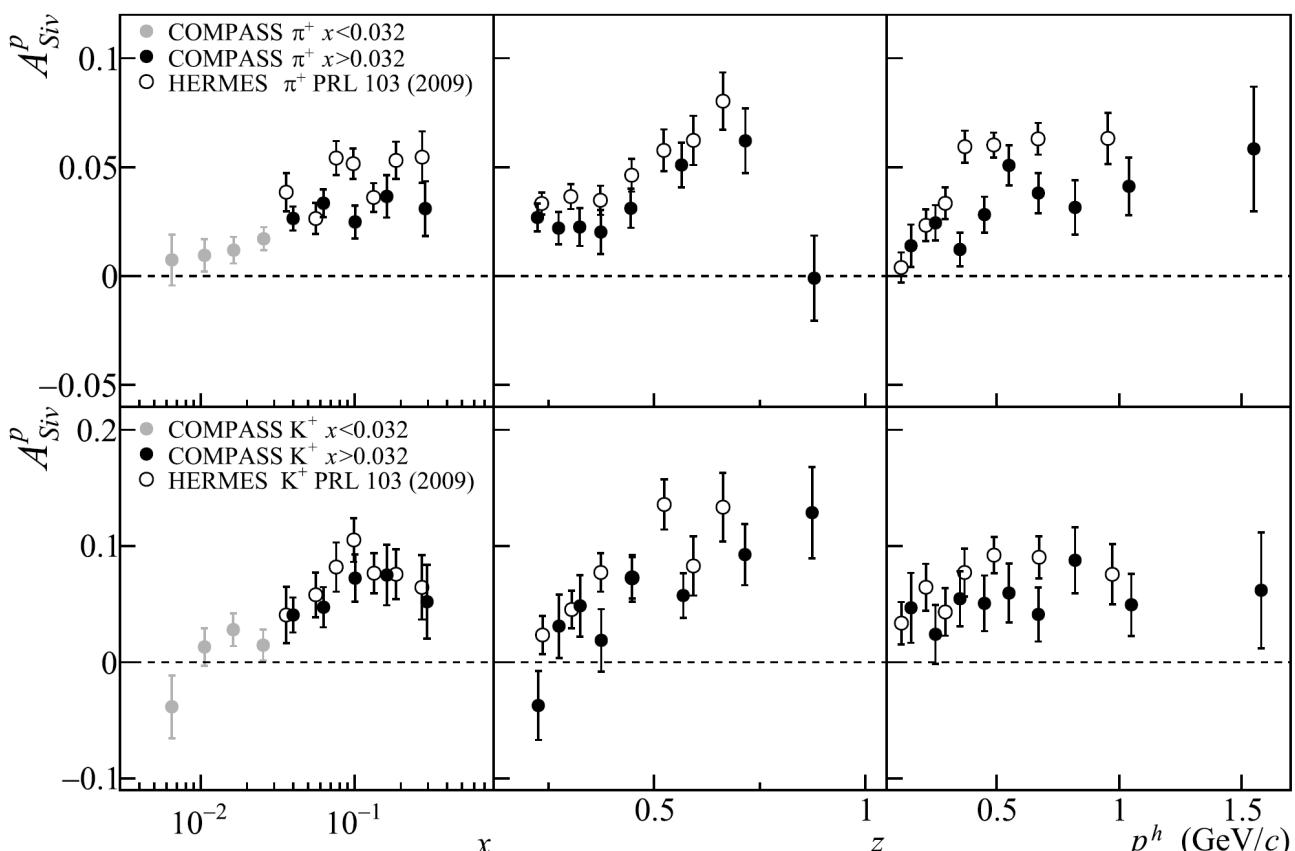
Estimated accuracies for  
COMPASS DY-Run of 2015  
using 3 bins in  $x_N$



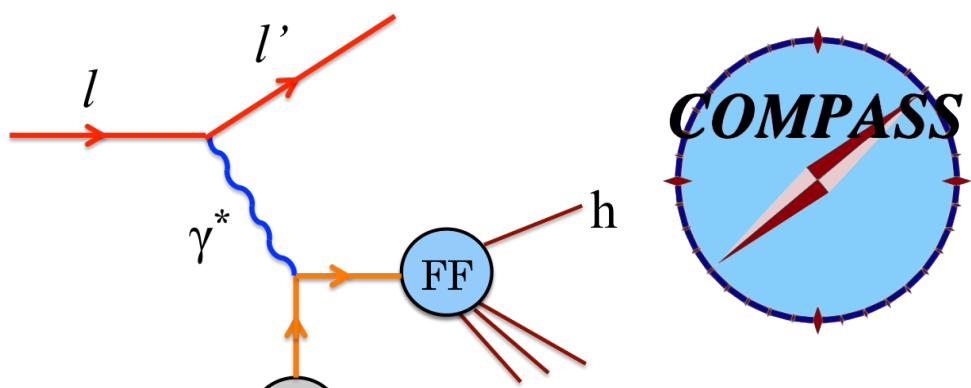
# SIDIS results: Sivers

PLB 744 (2015) 250

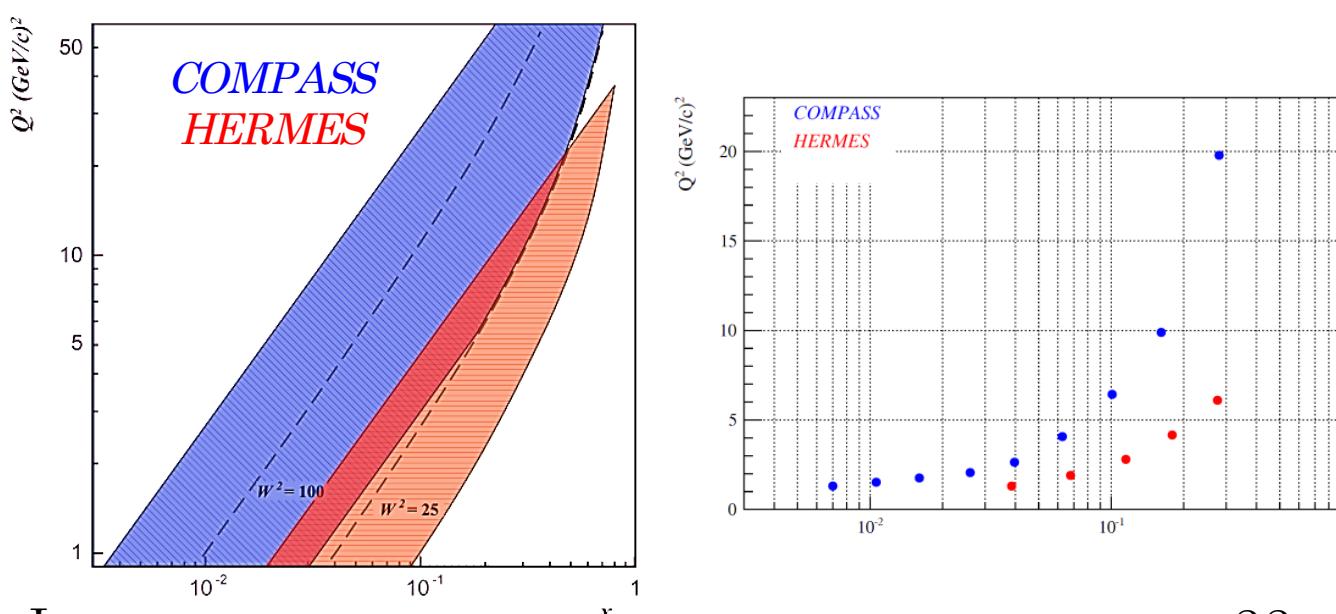
$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$



- Sivers asymmetry for  $\pi^+$  and  $K^+$ : COMPASS proton 2010 vs HERMES proton 2002-2005.
- Sivers asymmetry measured in COMPASS is lower than the one from HERMES, for both  $\pi^+$  and  $K^+$ .
- Different  $x:Q^2$  phase spaces.
- For given  $x$  COMPASS operates with larger mean  $Q^2$  values (factor 2-3).
- Can the differences in the Sivers amplitude be an evidence of **TMD evolution effects?**



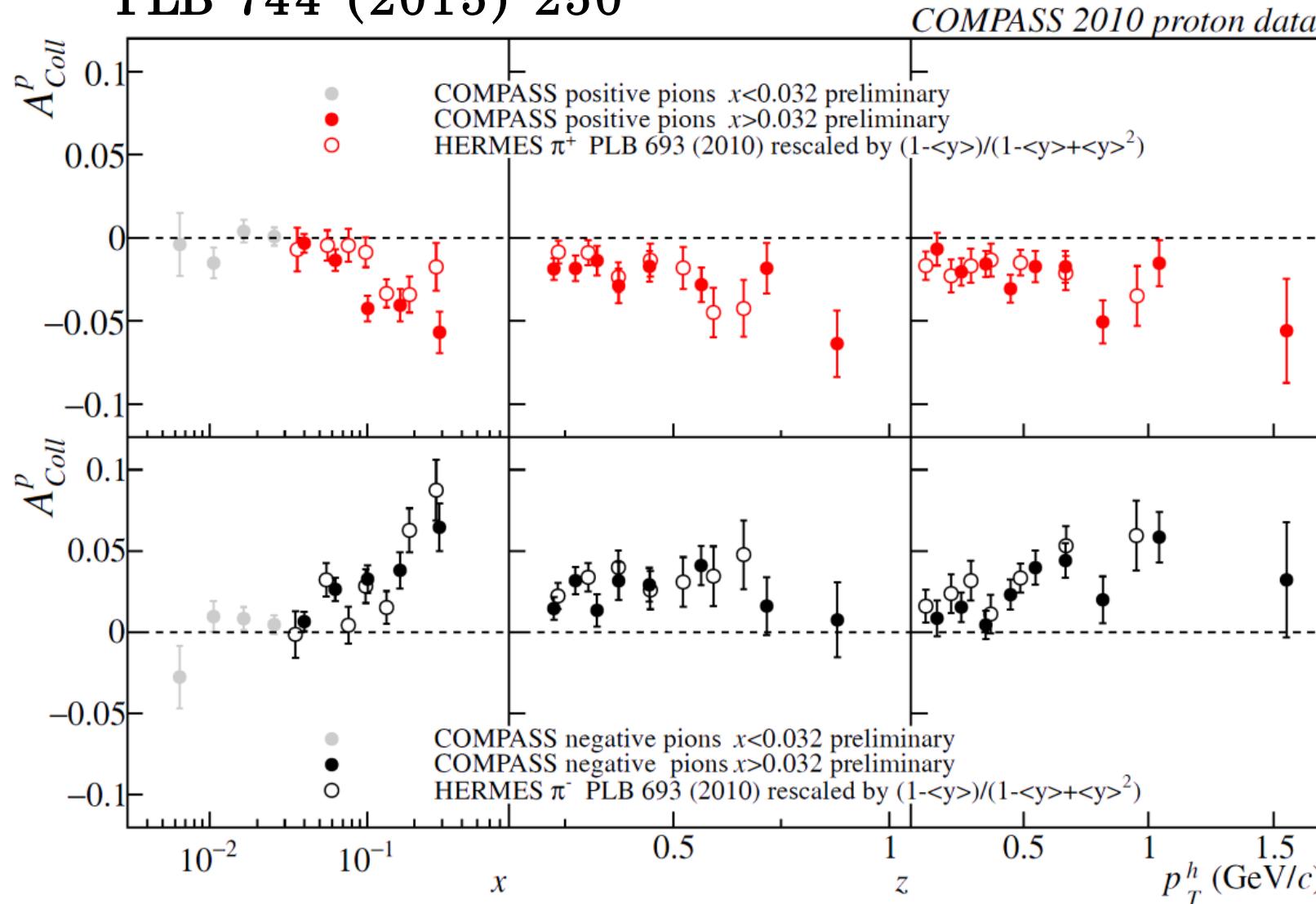
$$\frac{d\sigma_{SIDIS}^{LO}}{dxdydzdp_T^2d\varphi_h d\psi} = \left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] \times (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ \begin{array}{l} 1 + \cos 2\phi_h (\varepsilon A_{UU}^{\cos 2\phi_h}) \\ \sin(\phi_h - \phi_s) (A_{UT}^{\sin(\phi_h - \phi_s)}) \\ + \sin(\phi_h + \phi_s) (\varepsilon A_{UT}^{\sin(\phi_h + \phi_s)}) \\ + \sin(3\phi_h - \phi_s) (\varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)}) \\ + S_T \lambda [\cos(\phi_h - \phi_s) \left( \sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \right)] \end{array} \right\}$$



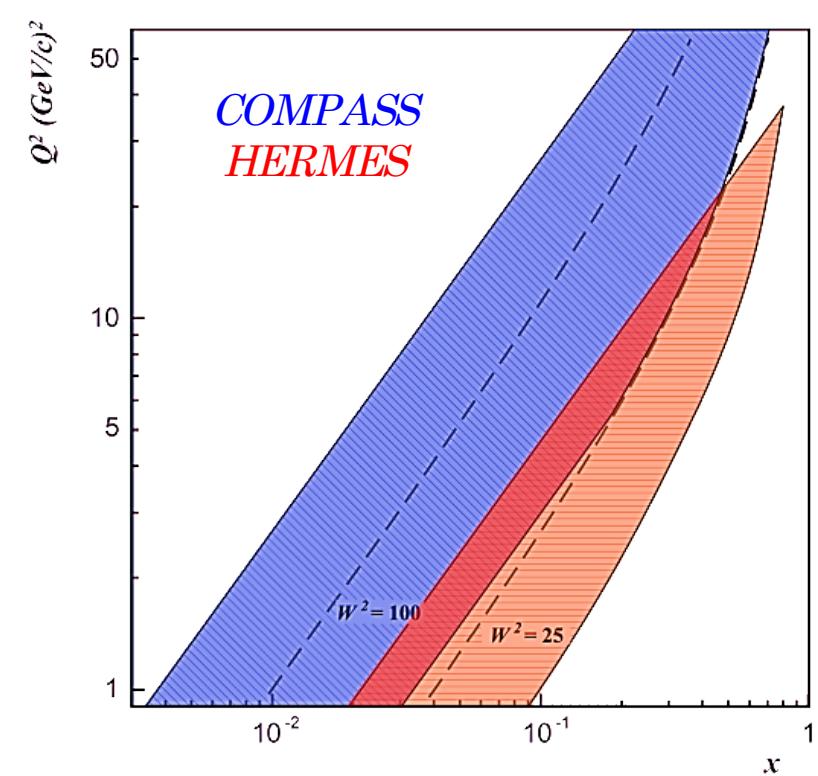
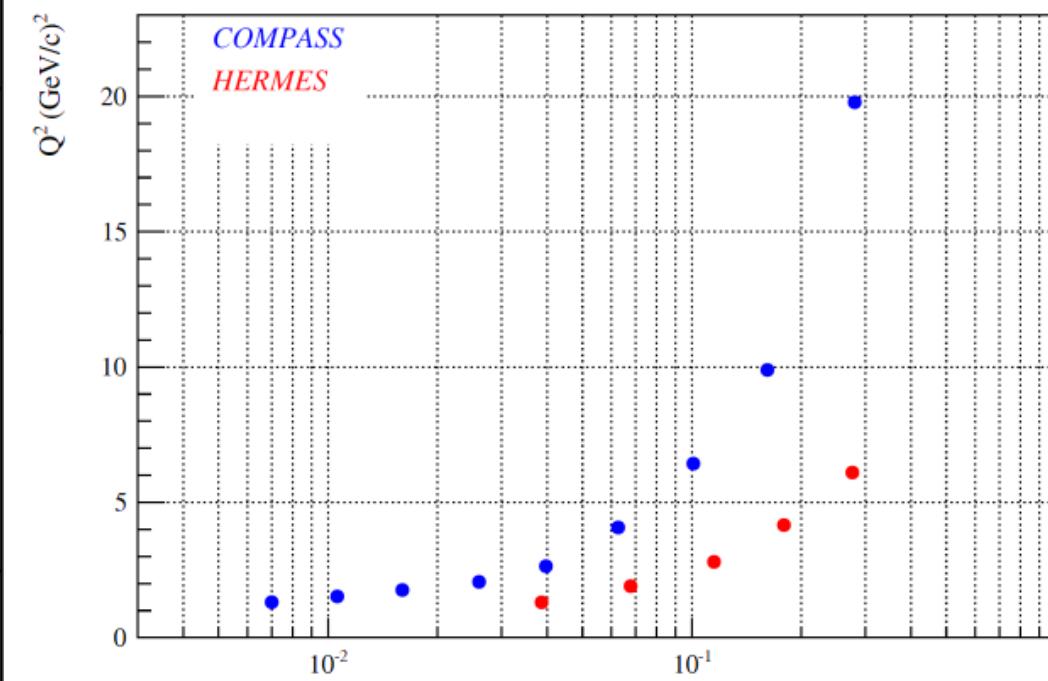
# COMPASS SIDIS results: Collins



PLB 744 (2015) 250



$$A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

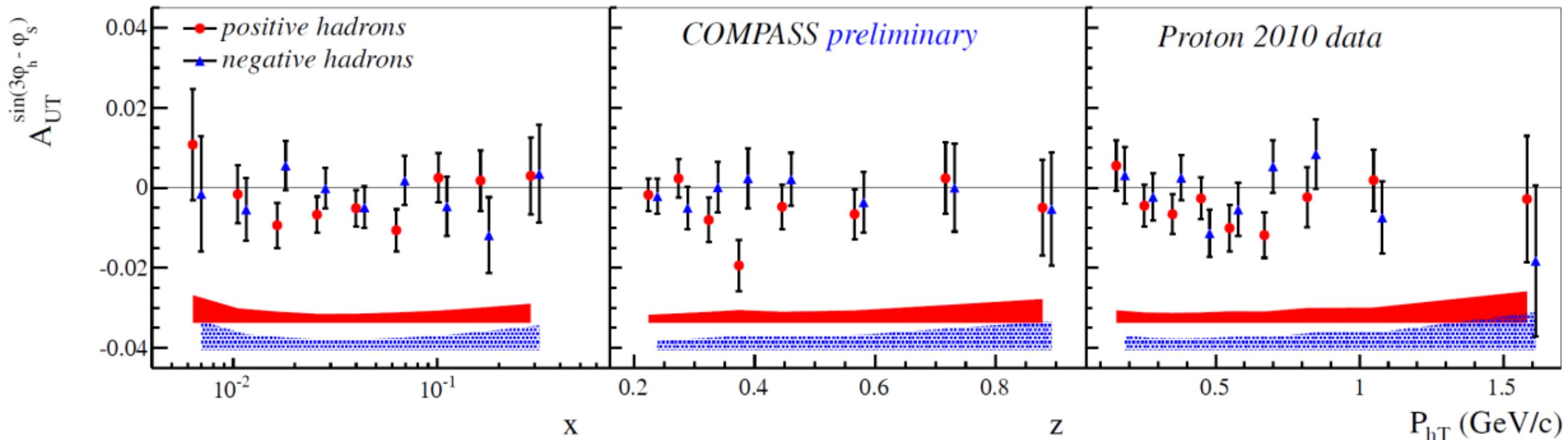


- Collins asymmetry : COMPASS proton vs Hermes proton.
- Clear effect at large  $x$ .
- Collins amplitudes for  $\pi^+$  and  $\pi^-$  are mirror symmetric (favoured unfavoured Collins FF).
- Even taking into account different  $Q^2$  coverage of the experiments, asymmetries appeared to be compatible.

# COMPASS SIDIS results: Pretzelosity

B.Parsamyan, PoS DIS2013 (2013), 2013

$$A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$



- Asymmetry is small and compatible with zero within statistical accuracy;
- It still can provide some information about the PDF;

Ch. Lefky, A. Prokudin Phys.Rev.  
D91 (2015) 034010

