COMPASS Drell-Yan Program

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on behalf of the COMPASS Collaboration

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Outline

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  - The Drell-Yan process
  - The SIDIS process
  - Drell-Yan SIDIS bridge
- The COMPASS experiment
  - Selected SIDIS results from Phase I
  - COMPASS Multi-D analysis approach
- The COMPASS DY program
  - Four COMPASS – Drell-Yan mass-ranges
  - Theoretical predictions
  - COMPASS DY Experimental setup
  - Pilot run 2014: first glance at the data
- Conclusions

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 ($\mathbf{k}_\mathrm{T}$) dependent TMD PDFs.

Quark \ Nucleon	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

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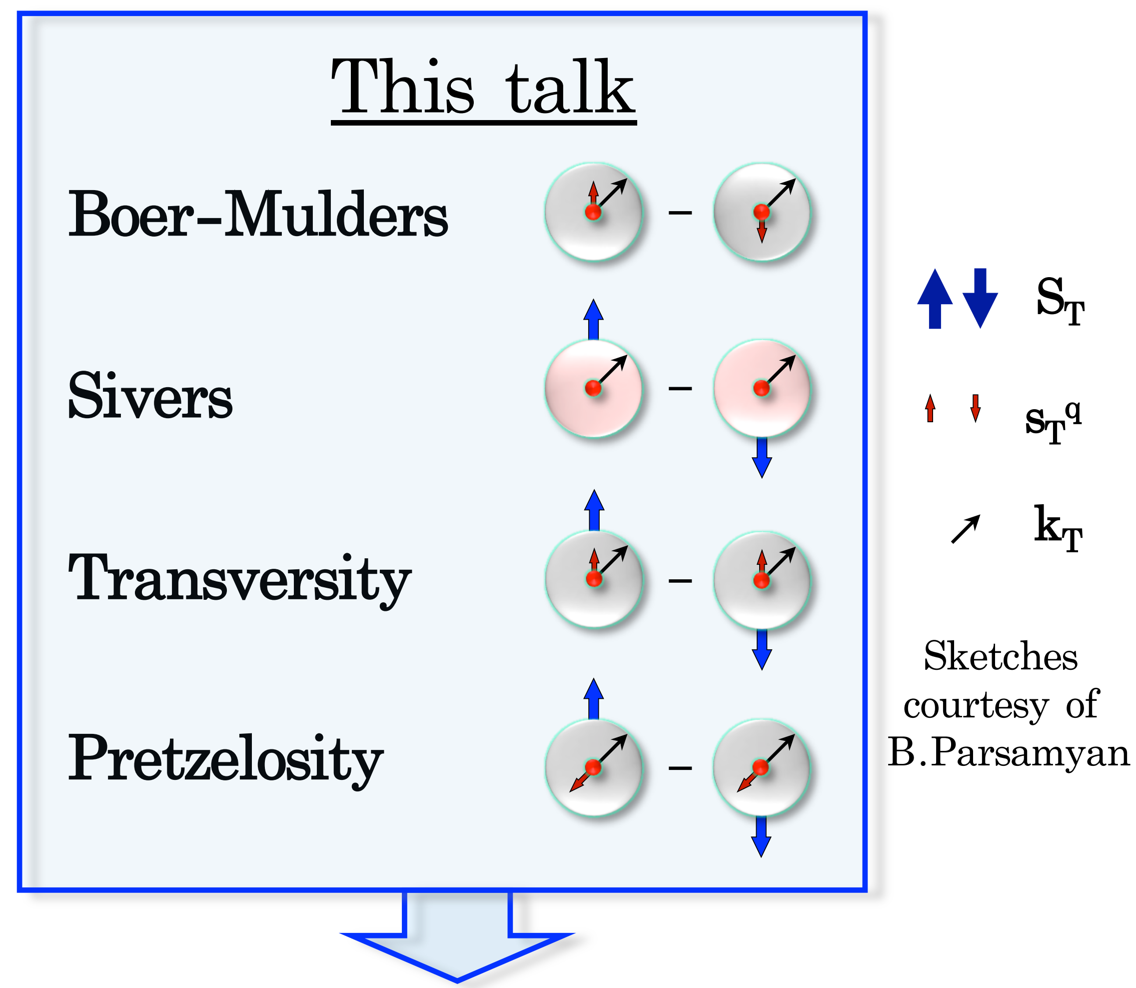
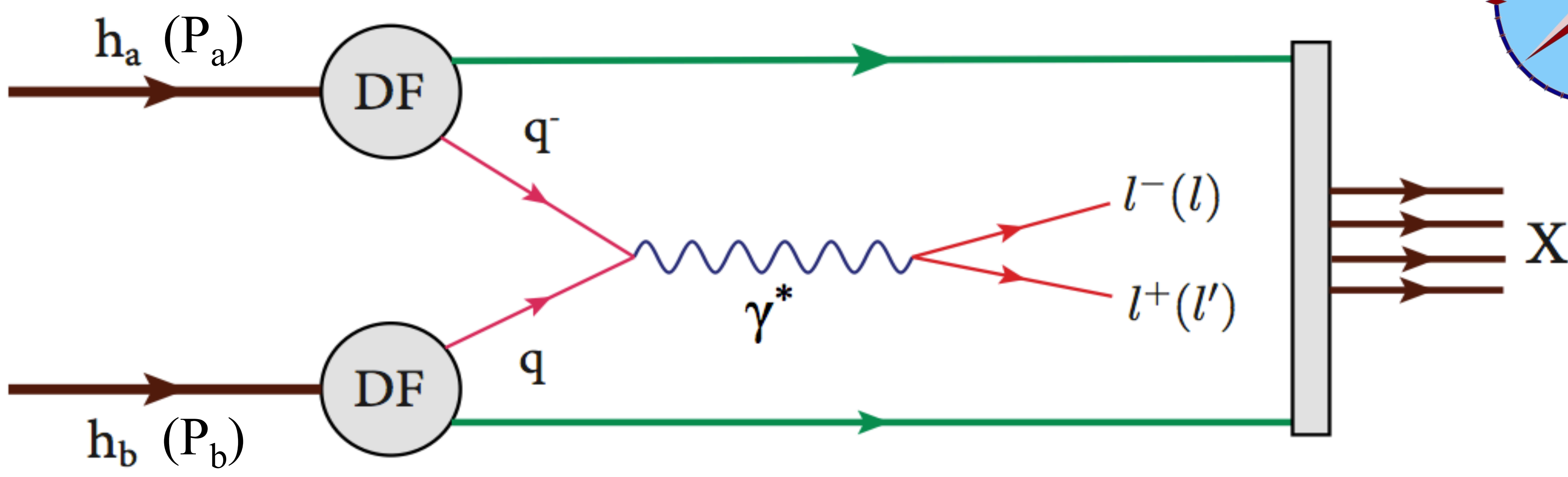


TMD PDFs can be accessed through measurement of target spin (in)dependent azimuthal asymmetries both in **SIDIS** and **Drell-Yan**

The Drell-Yan Process



Standard notations

$$s = (P_a+P_b)^2$$

$$x_{a(b)} = \frac{q^2}{2P_{a(b)}\cdot q}$$

$$x_F = x_a - x_b$$

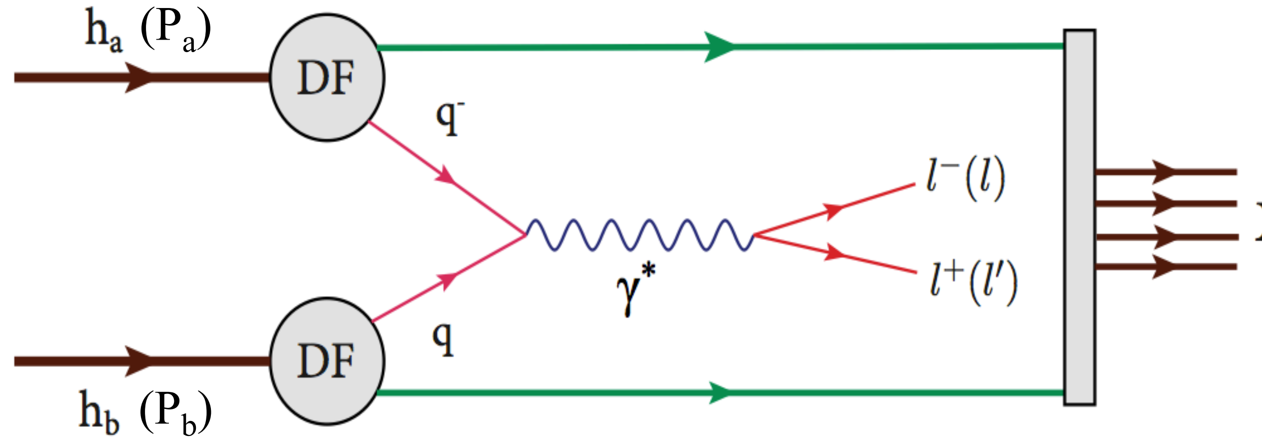
$$Q^2 = q^2 = M_{\mu\mu}^2 = s x_a x_b$$

- Quark-antiquark annihilation with two leptons in the final state.
- Experimentally challenging, because of the **small cross section**

$$\frac{d\sigma}{dM_{\mu\mu}} \approx \frac{10^{-32}}{M_{\mu\mu}^5} \cdot \frac{cm^2}{GeV^2}$$

- Therefore, DY measurement is a task for **high luminosity** experiments.
- Using different beams (p, π, K...) different quark flavors and phase space regions can be explored.

Single Polarized Drell-Yan



General **leading order** QCD parton model expression of the SP DY **cross-section**

$$\frac{d\sigma^{LO}}{d\Omega d^4 q} \propto \left\{ 1 + D_{[\sin^2\theta]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_T \times \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{[\sin^2\theta]} \left(A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \right) \right] \right\}$$

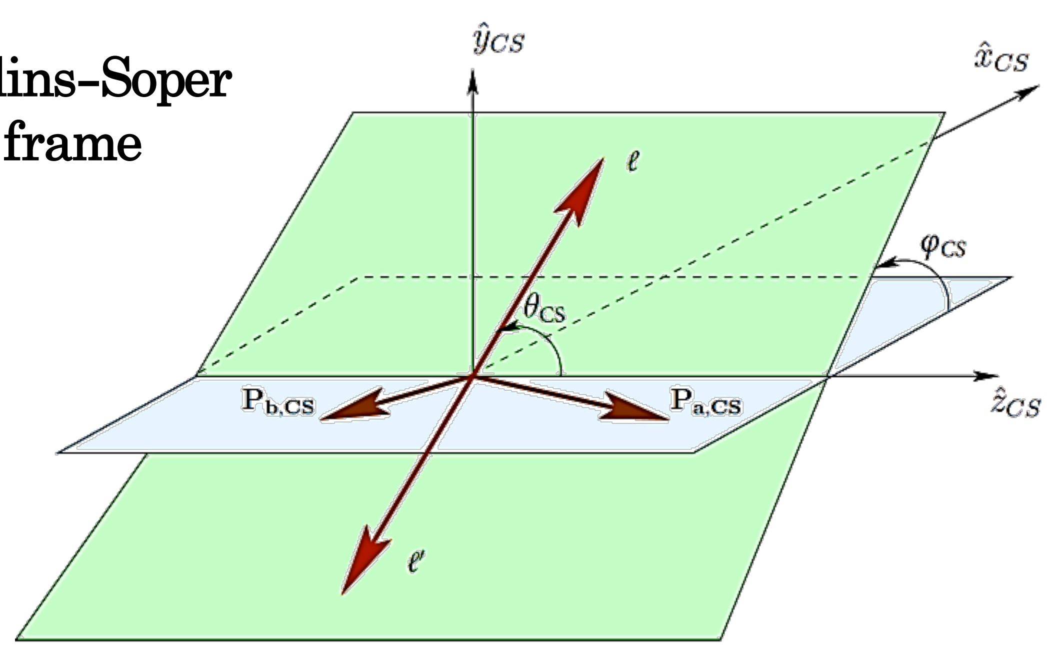
$$D_{[f(\theta)]}^{LO} = \frac{f(\theta)}{1+\cos^2\theta}$$

D-factors

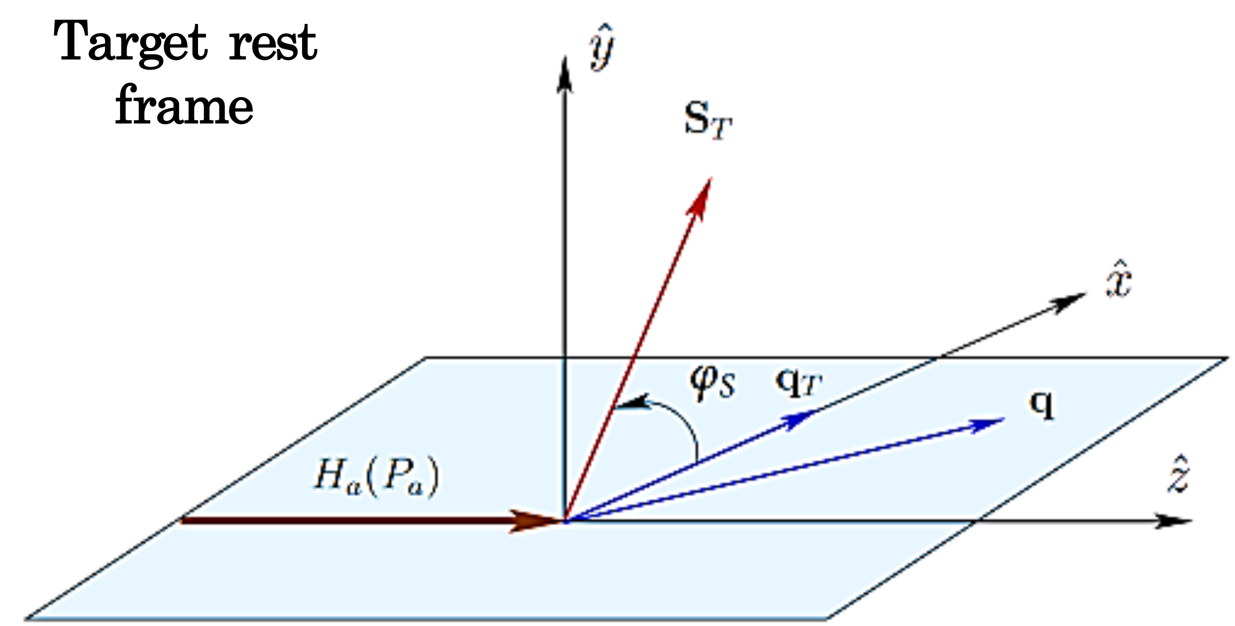
$$A_{U,T}^{w(\varphi_{CS},\varphi_S)} = \frac{F_{U,T}^{w(\varphi_{CS},\varphi_S)}}{F_U^1 + F_U^2}$$

Azimuthal asymmetries

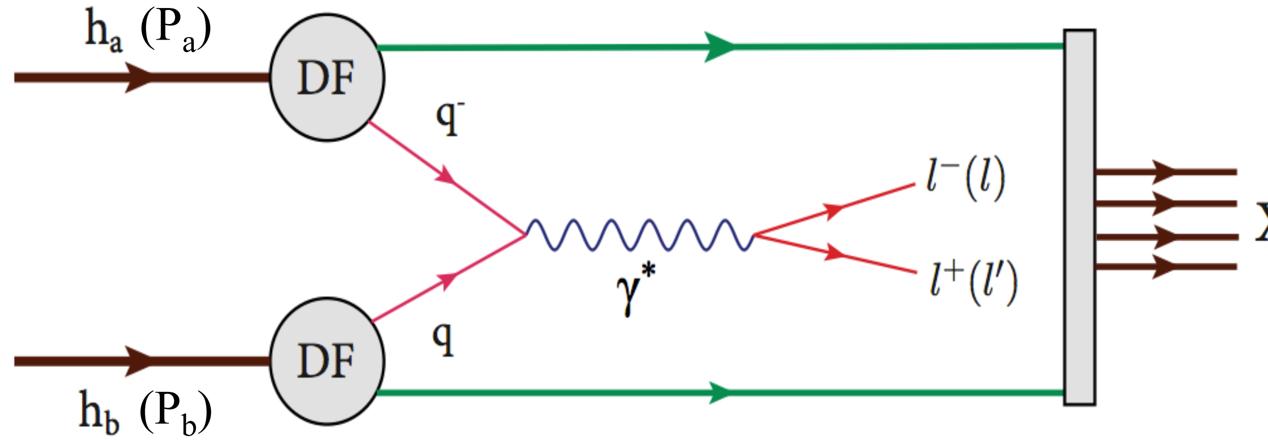
Collins-Soper frame



Target rest frame



Single Polarized Drell-Yan



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$$D^{LO}_{[f(\theta)]} = \frac{f(\theta)}{1+\cos^2\theta}$$

D-factors

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

Azimuthal asymmetries

@COMPASS: $h_a = \pi^-$ (190 GeV/c^2) $h_b = p^{\uparrow}$

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

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

- 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

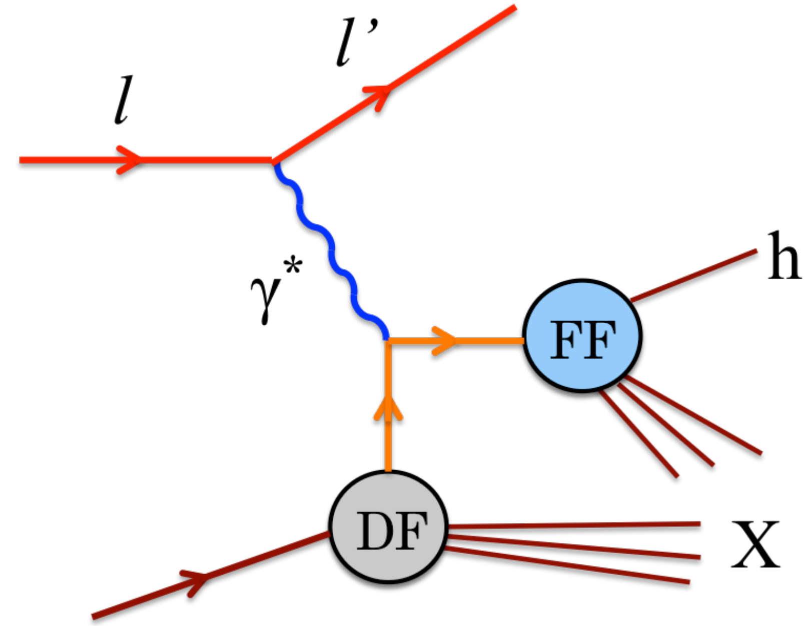
The SIDIS process

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

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

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

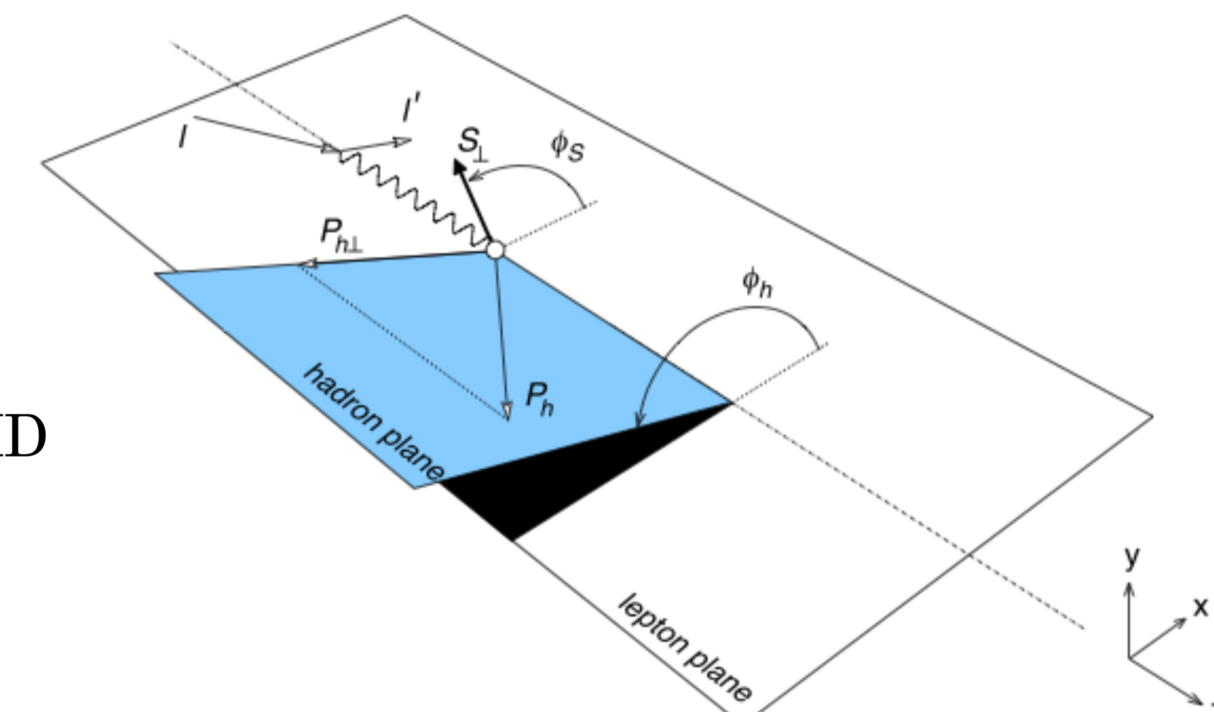
$$+\;S_T\lambda\left[\cos(\phi_h-\phi_S)\left(\sqrt{(1-\varepsilon^2)}\,A_{LT}^{\cos(\phi_h-\phi_S)}\right)\right]\Bigg\}$$



$$A^{w(\phi_h,\phi_S)}_{U(L),T} = \frac{F^{w(\phi_h,\phi_S)}_{U(L),T}}{F_{UU,T}+\varepsilon F_{UU,L}}; \quad \gamma=\frac{2Mx}{Q};$$

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

- At LO, 1 Unpolarized, 3 Single Spin and 1 Double Spin Asymmetries.
- Measurement of SIDIS azimuthal asymmetries provides an access to specific convolutions of TMD and Fragmentation functions (FFs).



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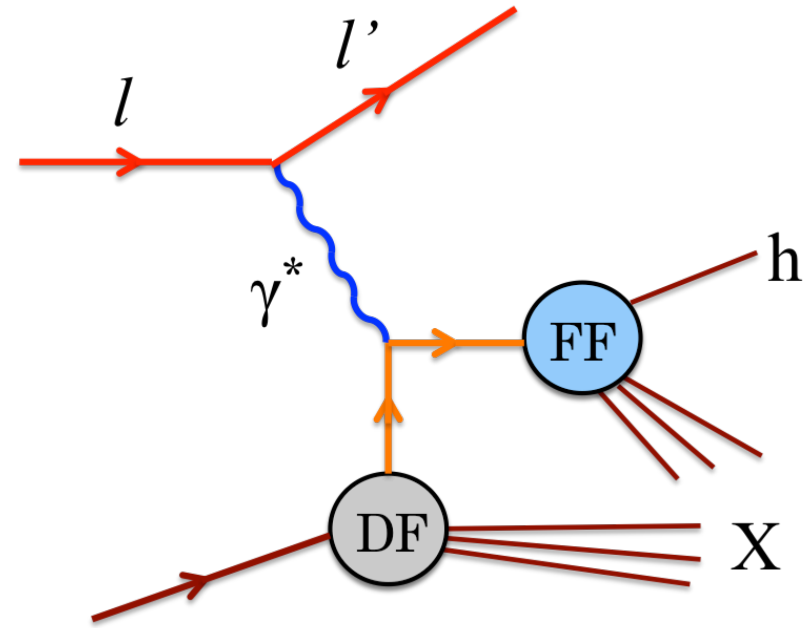
$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\Big\{\; 1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)$$

$$+\; S_T \begin{bmatrix} \sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right) \\ +\;\sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right) \\ +\;\sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{bmatrix}$$

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

- **At LO, 1 Unpolarized, 3 Single Spin and 1 Double Spin Asymmetries.**
- Measurement of SIDIS azimuthal asymmetries provides an access to specific convolutions of TMD and Fragmentation functions (FFs).



$$A_{U(L),T}^{w(\phi_h,\phi_S)} = \frac{F_{U(L),T}^{w(\phi_h,\phi_S)}}{F_{UU,T}+\varepsilon F_{UU,L}}; \quad \gamma = \frac{2Mx}{Q};$$

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

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$$

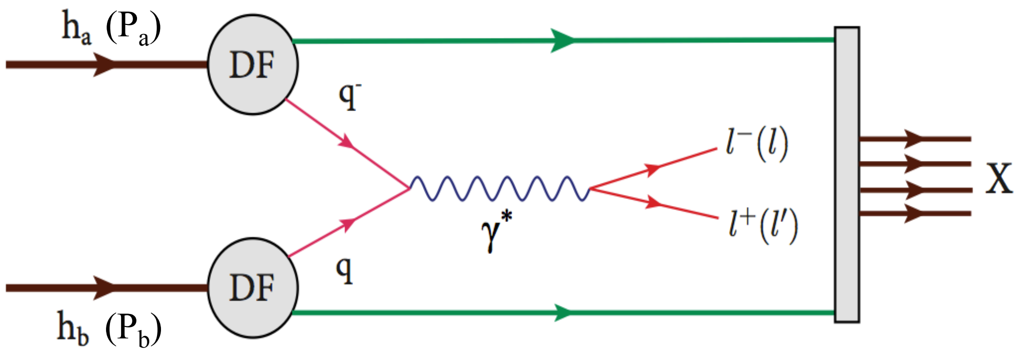
$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$$

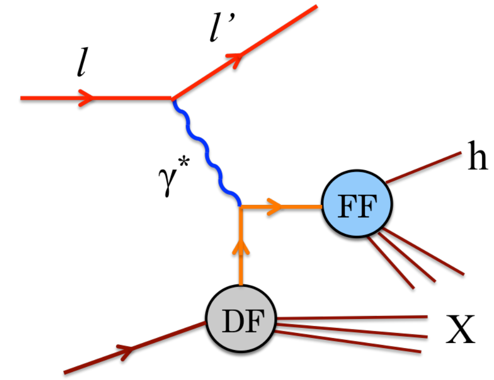
$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$$

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

$$A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

DY-SIDIS Bridge





COMPASS

Single Polarized DY (LO)

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1+\cos^2\theta + \sin^2\theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}} + S_T \left[\begin{array}{l} \left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S} \\ + \sin^2\theta \left(\begin{array}{l} \sin(2\varphi_{CS}+\varphi_S) A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ + \sin(2\varphi_{CS}-\varphi_S) A_T^{\sin(2\varphi_{CS}-\varphi_S)} \end{array} \right) \end{array} \right] \right\}$$

Transversely polarized SIDIS (LO)

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

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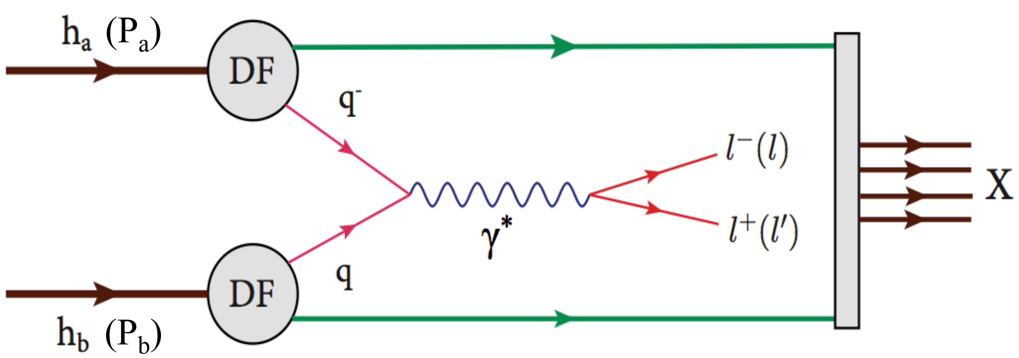

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$$\left. + S_T \left[\left(1+\cos^2\theta\right) \sin\varphi_S A_T^{\sin\varphi_S} + \sin^2\theta \left(\sin\left(2\varphi_{CS}+\varphi_S\right) A_T^{\sin(2\varphi_{CS}+\varphi_S)} + \sin\left(2\varphi_{CS}-\varphi_S\right) A_T^{\sin(2\varphi_{CS}-\varphi_S)}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

$h_{1,\pi}^{\perp q} \otimes h_1^{\perp q}$

$f_{1,\pi}^{q} \otimes f_{1T}^{\perp q}$

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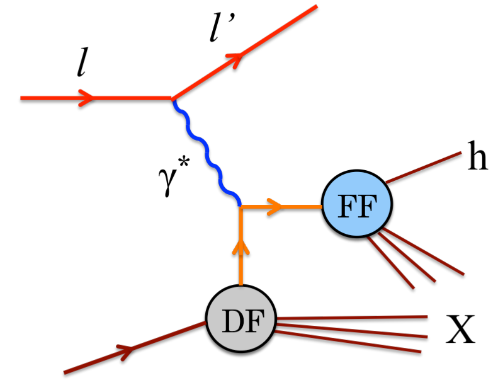

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$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right) \right.$$

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

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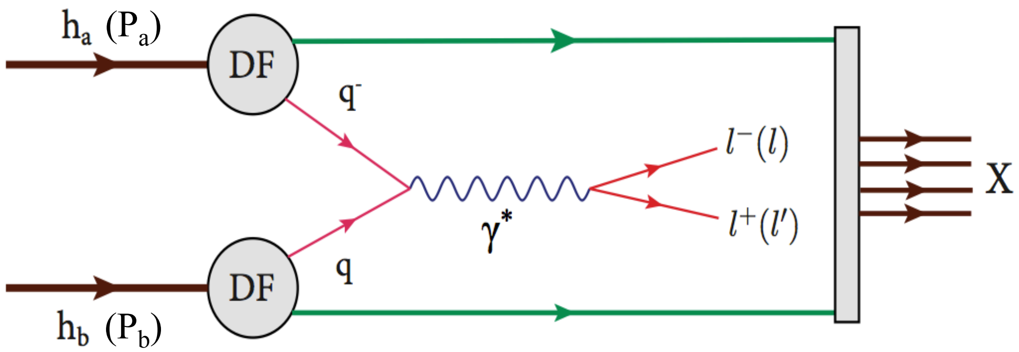

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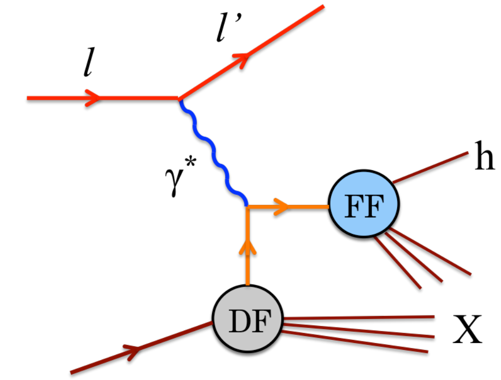

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$$\left. + S_T\lambda\left[\cos\left(\phi_h-\phi_S\right)\left(\sqrt{\left(1-\varepsilon^2\right)} A_{LT}^{\cos(\phi_h-\phi_S)}\right)\right] \right\}$$

$h_1^{\perp q} \otimes H_{1q}^{\perp h}$

$f_{1T}^{\perp q} \otimes D_{1q}^{h}$

$h_1^{q} \otimes H_{1q}^{\perp h}$

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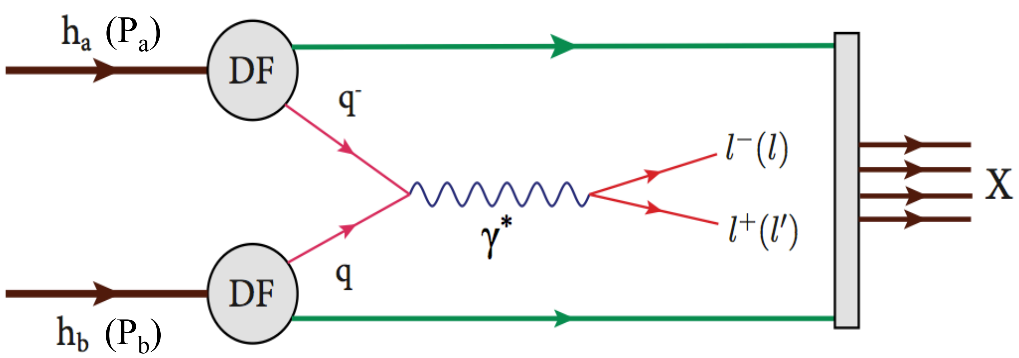

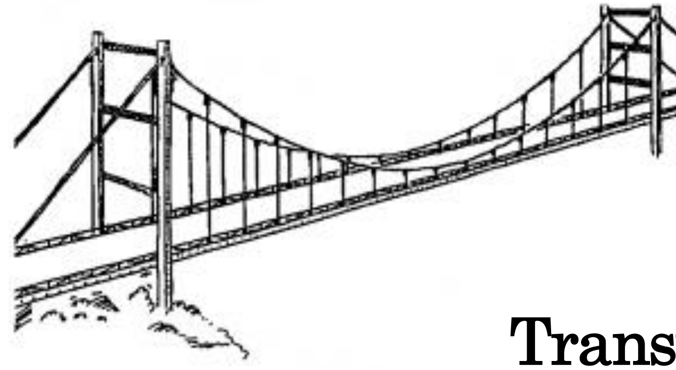

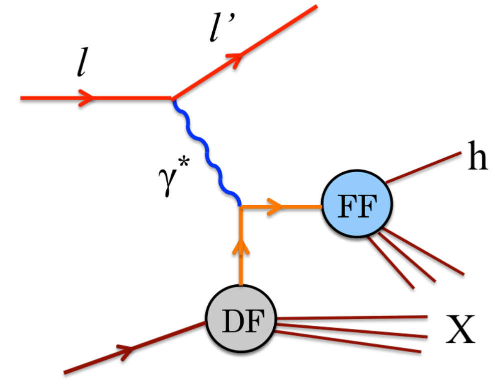

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$$+ S_T\left[\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right) + \sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right) + \sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\right]$$
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$h_1^{\perp q}$

$f_{1T}^{\perp q}$

h_1^q

$h_{1T}^{\perp q}$

DP – DY only g_{1T}^q

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

TMD Universality

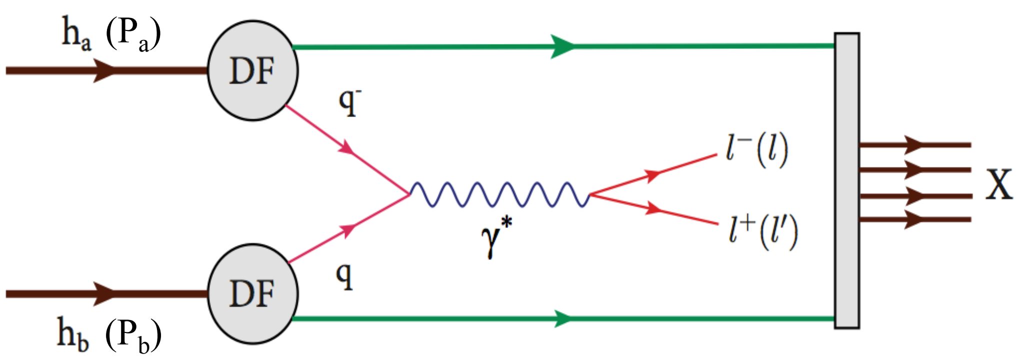
Sivers and BM sign change

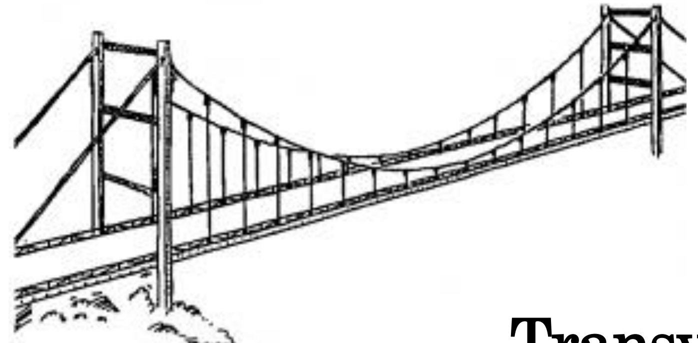
$$f_{1T}^{\perp q}\big|_{DY} = -\,f_{1T}^{\perp q}\big|_{SIDIS}$$

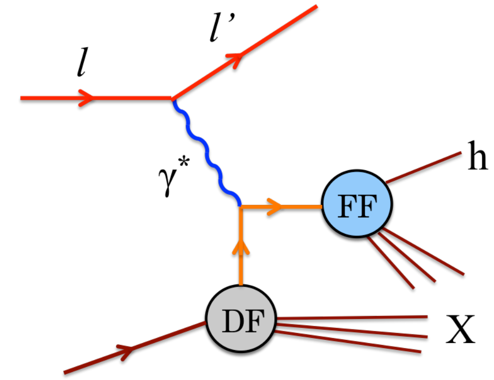
$$h_1^q\big|_{DY} = -\,h_1^q\big|_{SIDIS}$$

h_1^q $\quad$ $h_{1T}^{\perp q}$

DY-SIDIS Bridge







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

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

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

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

$h_1^{\perp q}$

$f_{1T}^{\perp q}$

h_1^q

$h_{1T}^{\perp q}$

DP – DY only g_{1T}^q

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!

TMD Universality

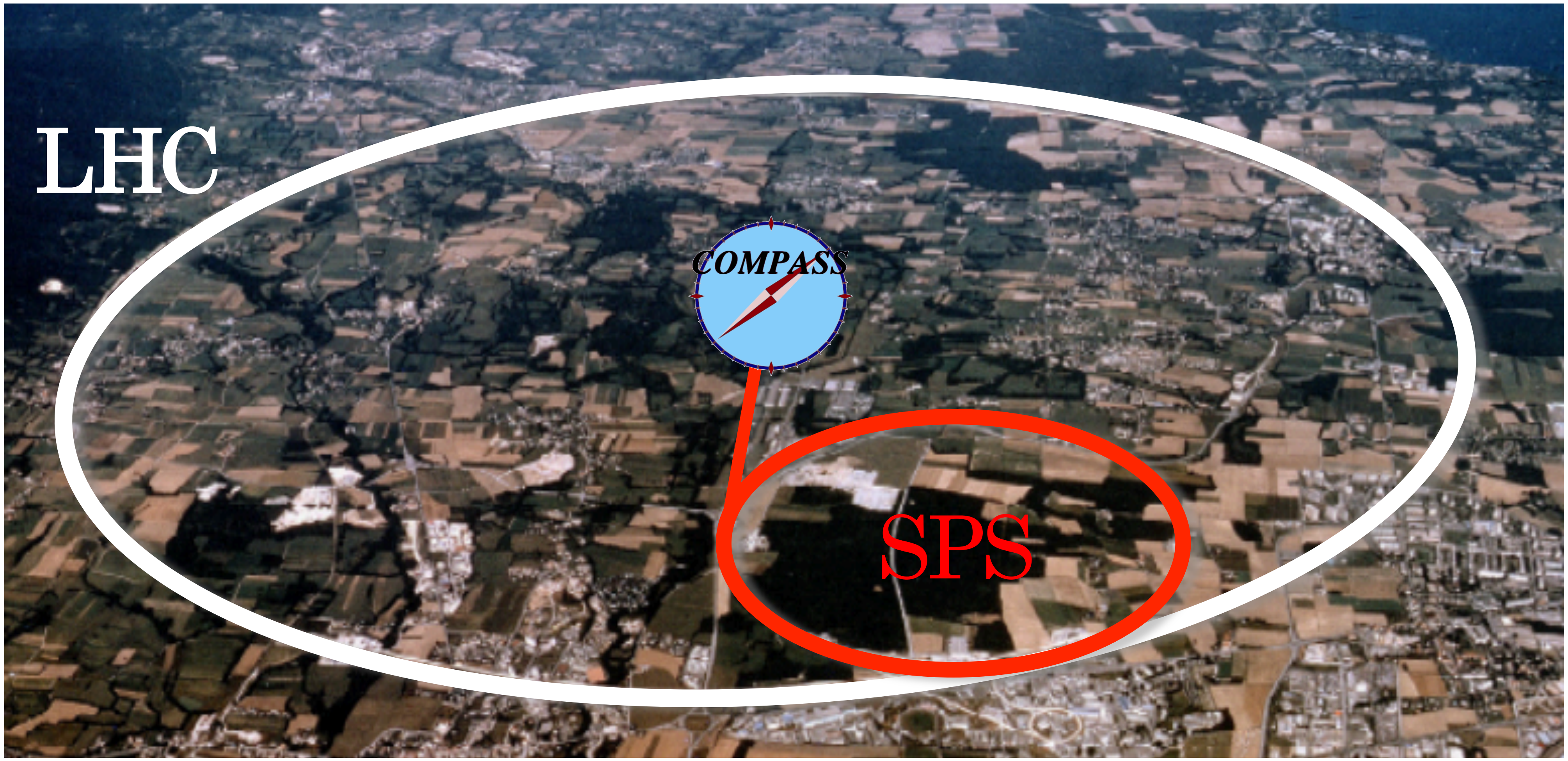
Sivers and BM sign change

$$f_{1T}^{\perp q}\big|_{DY} = - f_{1T}^{\perp q}\big|_{SIDIS}$$

$$h_1^{q}\big|_{DY} = - h_1^{q}\big|_{SIDIS}$$

h_1^q $h_{1T}^{\perp q}$

The COMPASS collaboration

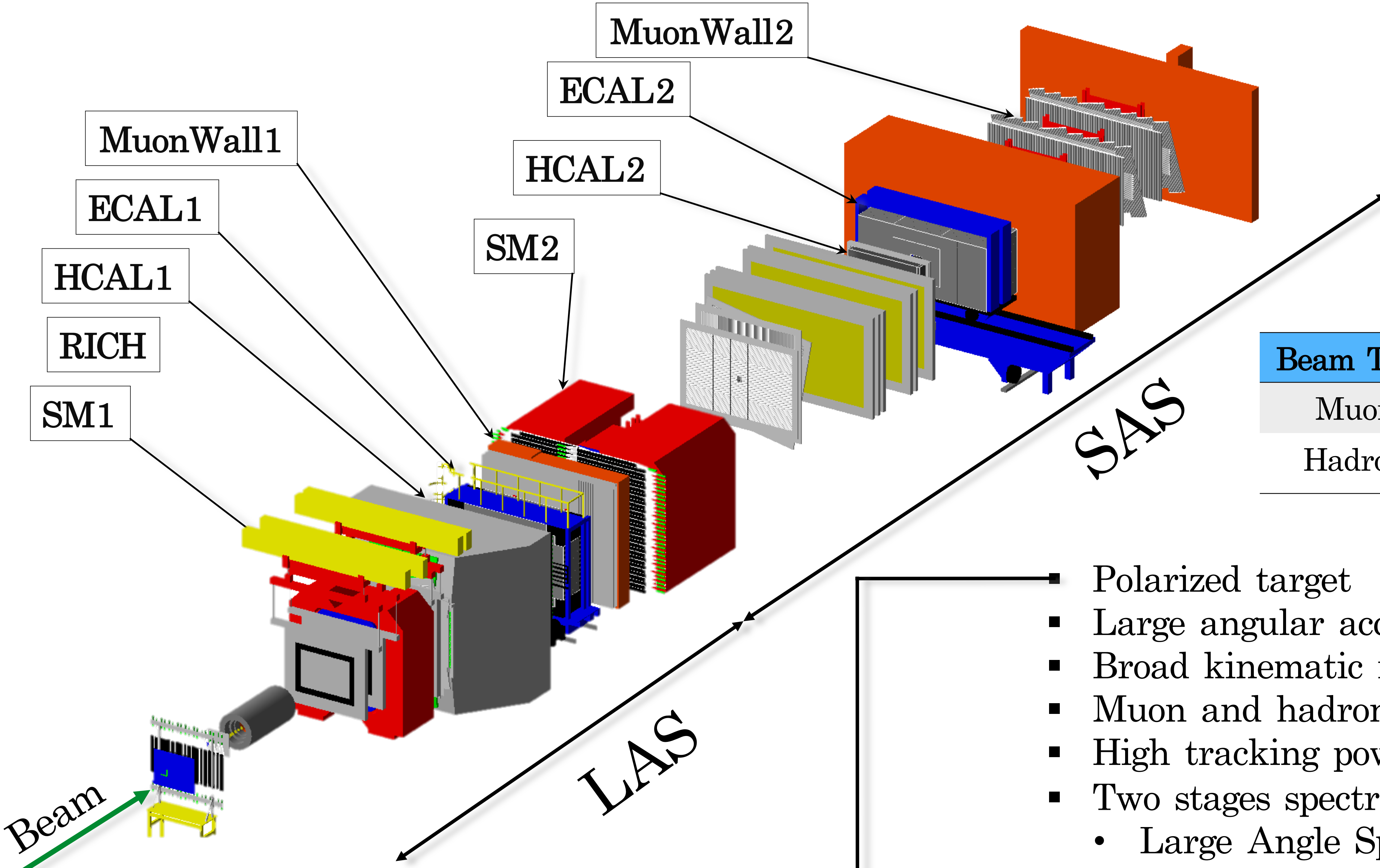


- SPS North Area
- Fixed target experiment
- First data taking in 2002

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

Phase II
- 2012 – 2018
- Primakoff + DVCS pilot run (2012)
- Drell-Yan (ongoing)
- DVCS (2016-2017)

COMPASS experimental setup



Beam Type	Details
Muon	L polarized
Hadron	π, p , K

- Polarized target
- Large angular acceptance
- Broad kinematic range covered
- Muon and hadron beam
- High tracking power (~350 planes)
- Two stages spectrometer
  - Large Angle Spectrometer (LAS)
    - 35 mrad < θ < 180 mrad
    - SM1 magnet (1 T · m)
  - Small Angle Spectrometer (SAS)
    - 18 mrad < θ < 35 mrad
    - SM2 magnet (4.4 T · m)

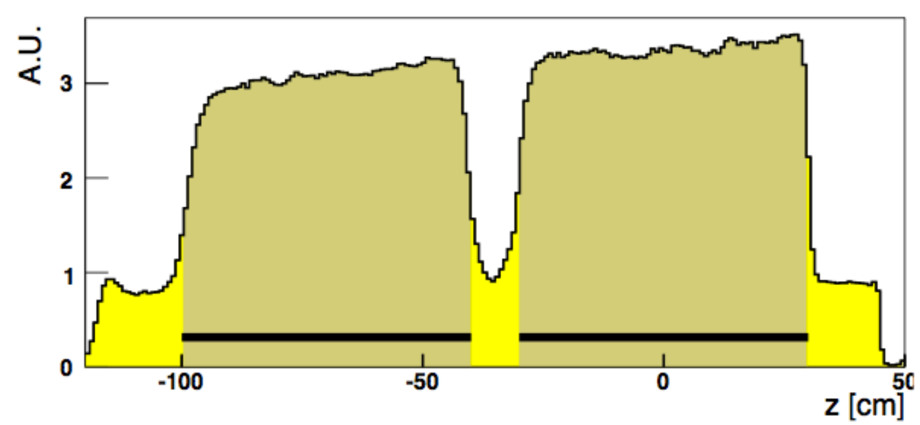
Target	# of cells	Polarization
NH_3	3	L&T, ~80-90 %
^6LiD	2,3	L&T, ~50 %

COMPASS SIDIS data taking

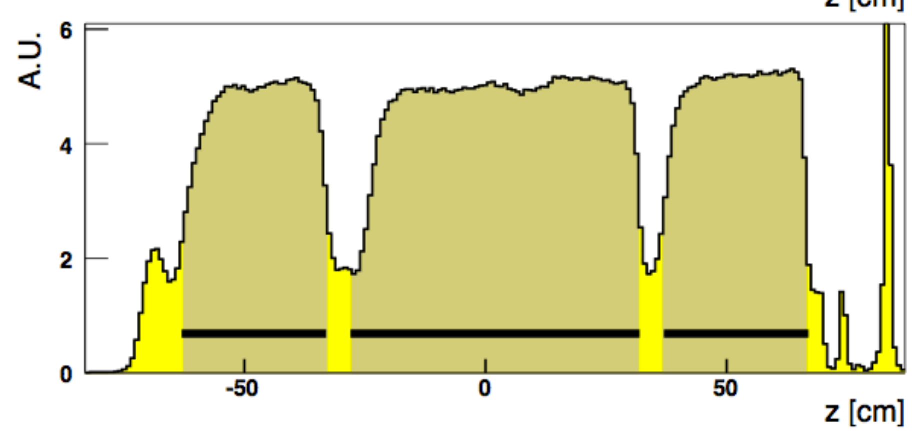
Year	Beam	Target	# cells	Polarization
2002	μ^+ @ 160 GeV/c	Deuteron, ^{6}LiD	2	L & T, ~ 50%
2003	μ^+ @ 160 GeV/c	Deuteron, ^{6}LiD	2	L & T, ~ 50%
2004	μ^+ @ 160 GeV/c	Deuteron, ^{6}LiD	2	L & T, ~ 50%
2006	μ^+ @ 160 GeV/c	Deuteron, ^{6}LiD	3	L ~ 50%
2007	μ^+ @ 160 GeV/c	Proton, NH_3	3	L & T, ~ 90%
2010	μ^+ @ 160 GeV/c	Proton, NH_3	3	T, ~ 90%
2011	μ^+ @ 200 GeV/c	Proton, NH_3	3	L, ~ 90%

- During Phase I, the COMPASS collaboration collected a considerable amount of **SIDIS data**, using L&T polarized proton and deuteron targets.
- Many interesting and important **results** and still more to come from several ongoing analysis…

For more details see talk by [Anna Martin](#) (Session 6)



2002 - 2004



2006 - 2011

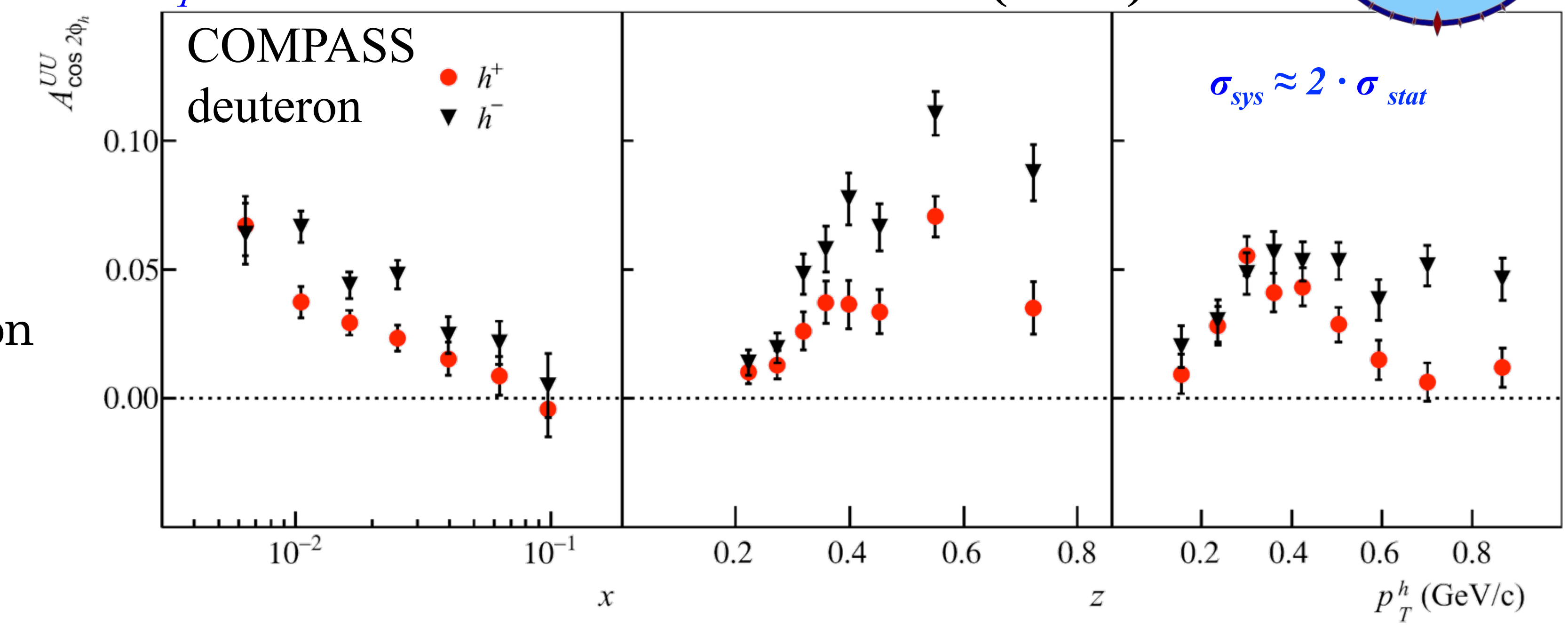
COMPASS SIDIS results: BM

Boer-Mulders effect + "twist-4" Cahn effect

$$A_{UU}^{\cos 2\phi_h} \propto -h_1^{\perp q} \otimes H_{1q}^{\perp h} + \left(\frac{M}{Q}\right)^2 f_1^q \otimes D_{1q}^h + \ldots.$$

- Large positive amplitudes decreasing with x for both h^+/h^-.
- Clear differences between h^+/h^-
- Slightly larger amplitude for h^-
- Similarity between proton and deuteron results for $A_{UU}^{\cos 2\phi_h}$ has been previously observed at HERMES collaboration.

NPB 886 (2014) 1046



COMPASS SIDIS results: BM

Boer-Mulders effect + 2"twist-4" Cahn effect

$$A_{UU}^{\cos 2\phi_h} \propto -h_1^{\perp q} \otimes H_{1q}^{\perp h} + \left(\frac{M}{Q}\right)^2 f_1^q \otimes D_{1q}^h + \ldots$$

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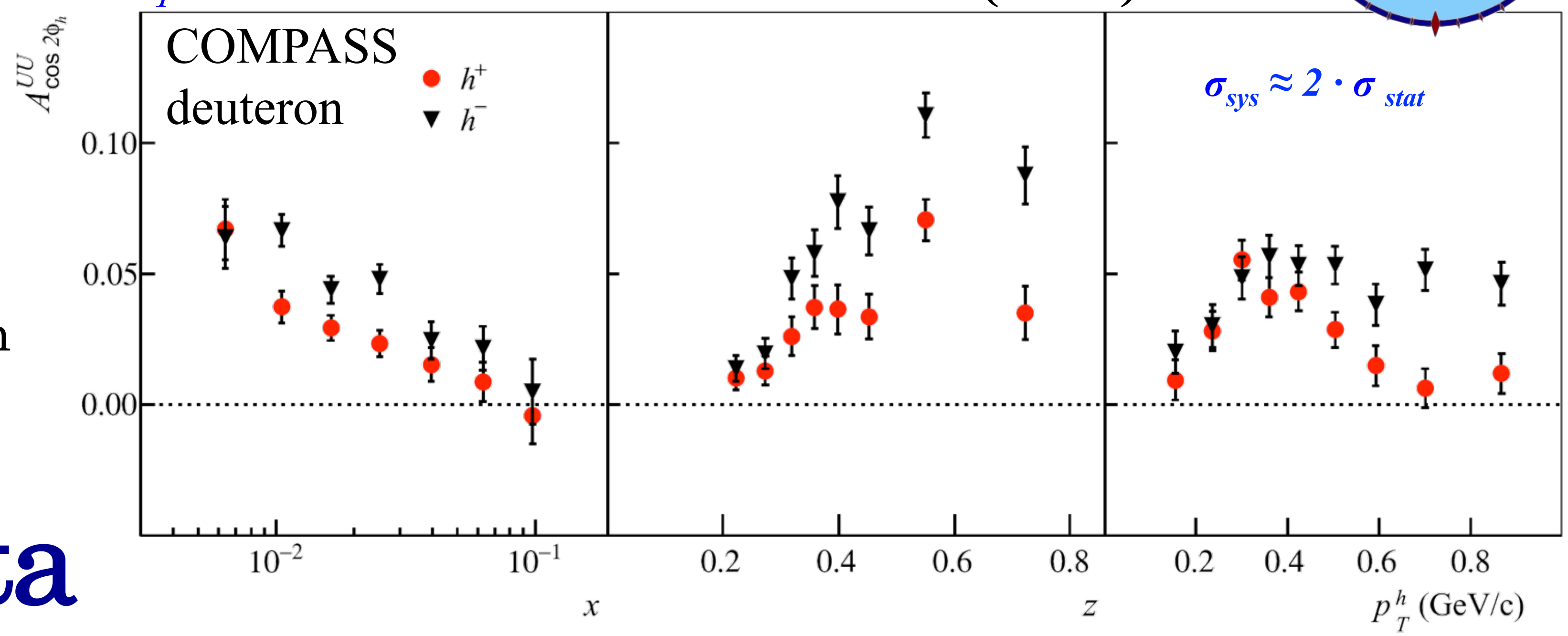
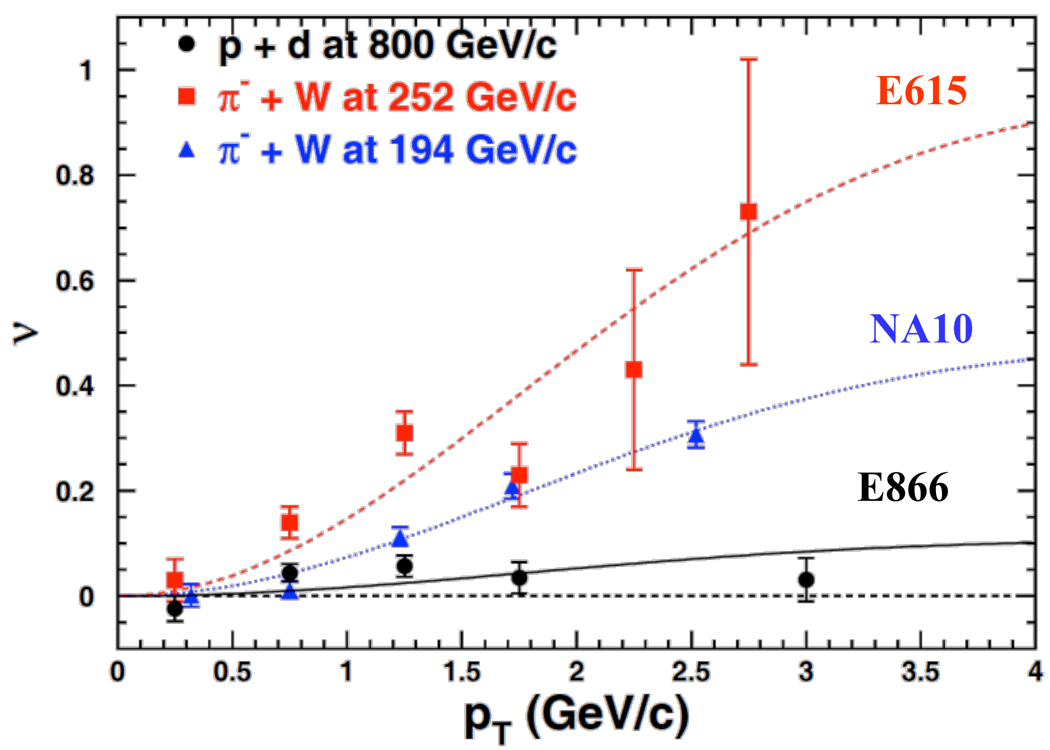


Available DY data

$$\nu = 2A_U^{\cos 2\varphi} \propto h_{1q}^{\perp} \otimes h_{1\bar{q}}^{\perp}$$



- Clear effect in Drell-Yan
- Energy and quark flavour dependence
  - Smaller effect for sea quarks

E866, PRL99, 082301 (2007)

COMPASS SIDIS results: BM

Boer-Mulders effect + 2"twist-4" Cahn effect

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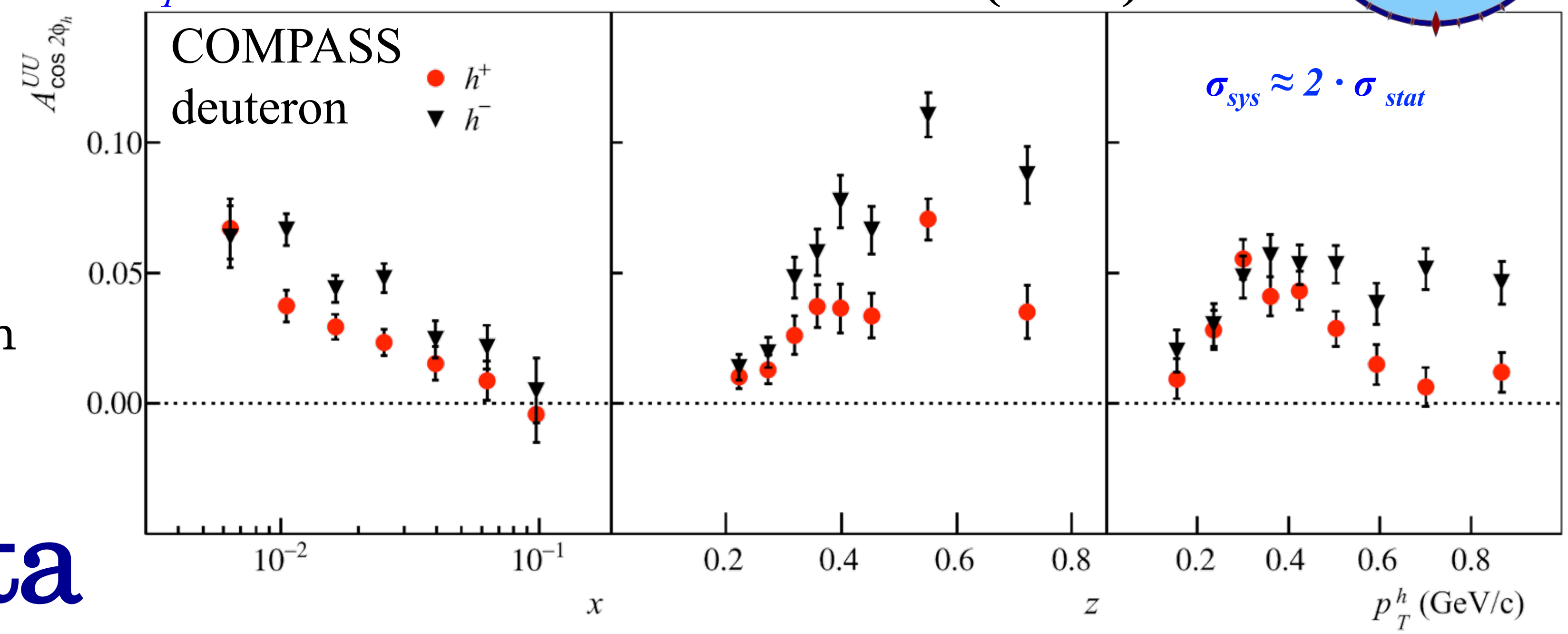
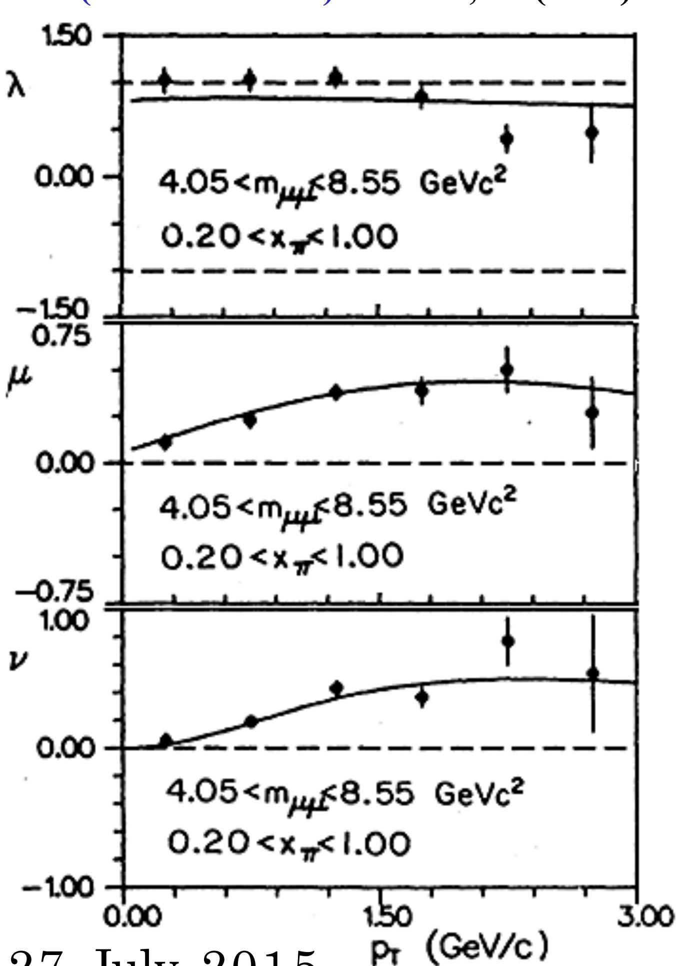
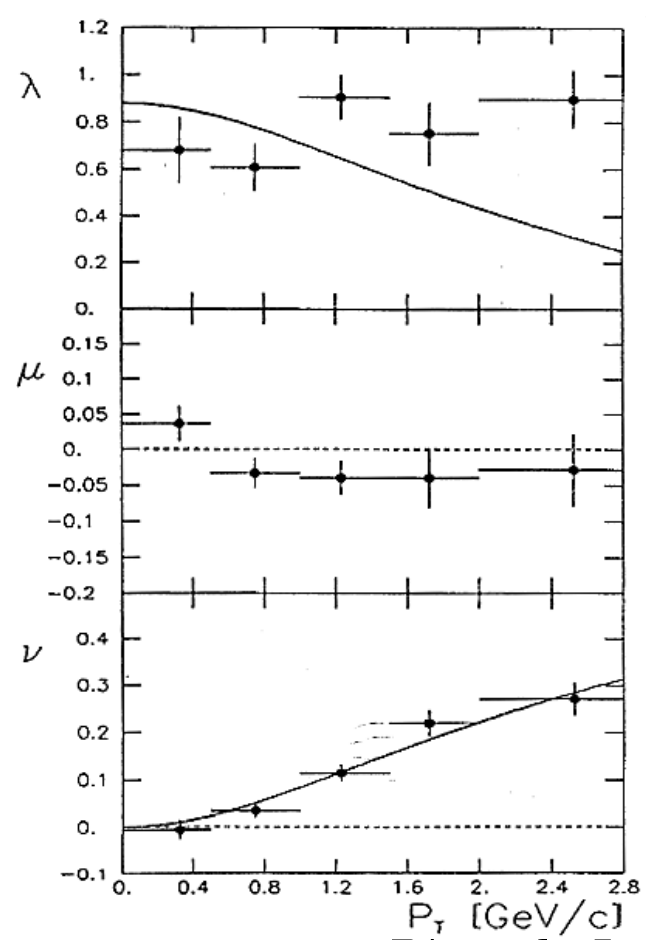


Available DY data

E615 (π^-W 252 GeV) PRD 39, 92 (1989)



NA10 (π^-W 194 GeV) Z.Phys.C 31, 513 (1986)



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

Lam Tung relation (collinear LO pQCD)

$1 - \lambda - 2\nu = 0 \longrightarrow \lambda = 1, \ \mu = 0, \ \nu = 0$

Violation of L-T relation:
Data from E615 (FNAL) and NA10 (CERN) experiments.

COMPASS is collecting higher precision π^-NH_3, π^-W, π^-Al data

COMPASS SIDIS results: BM

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NPB 886 (2014) 1046

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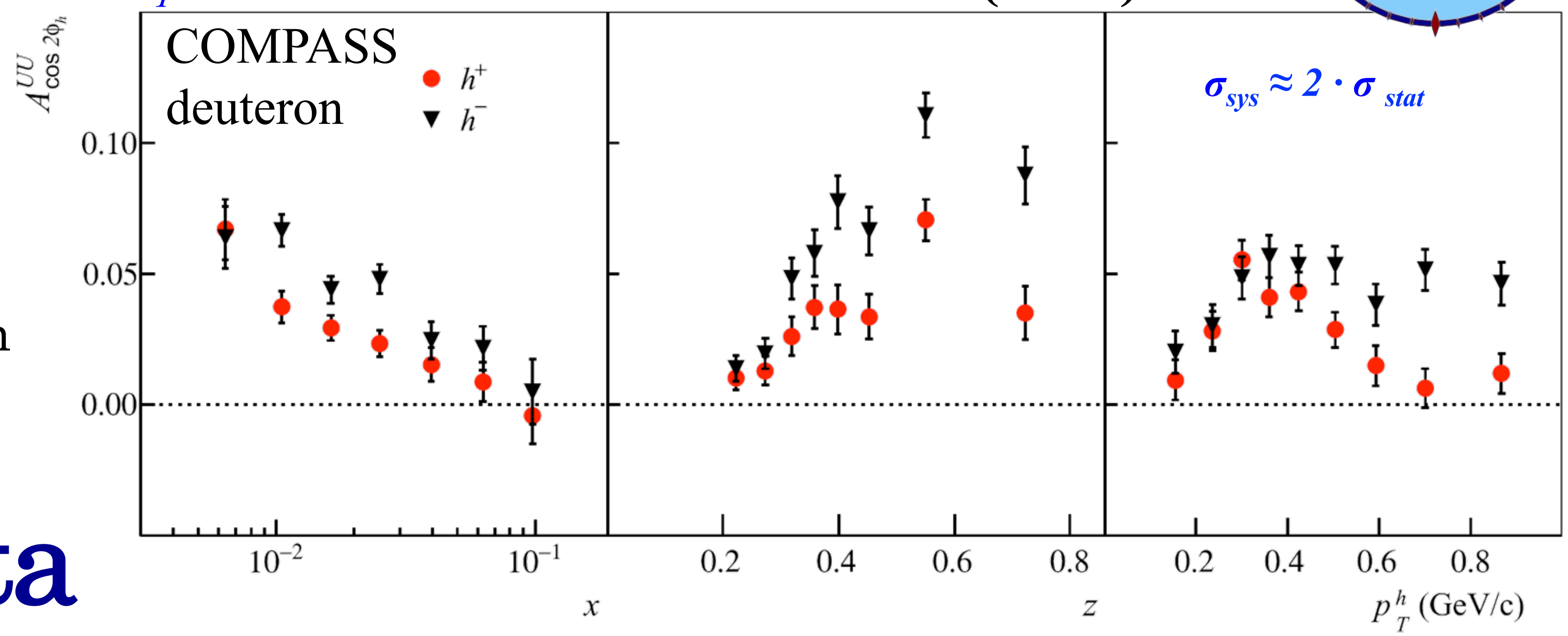

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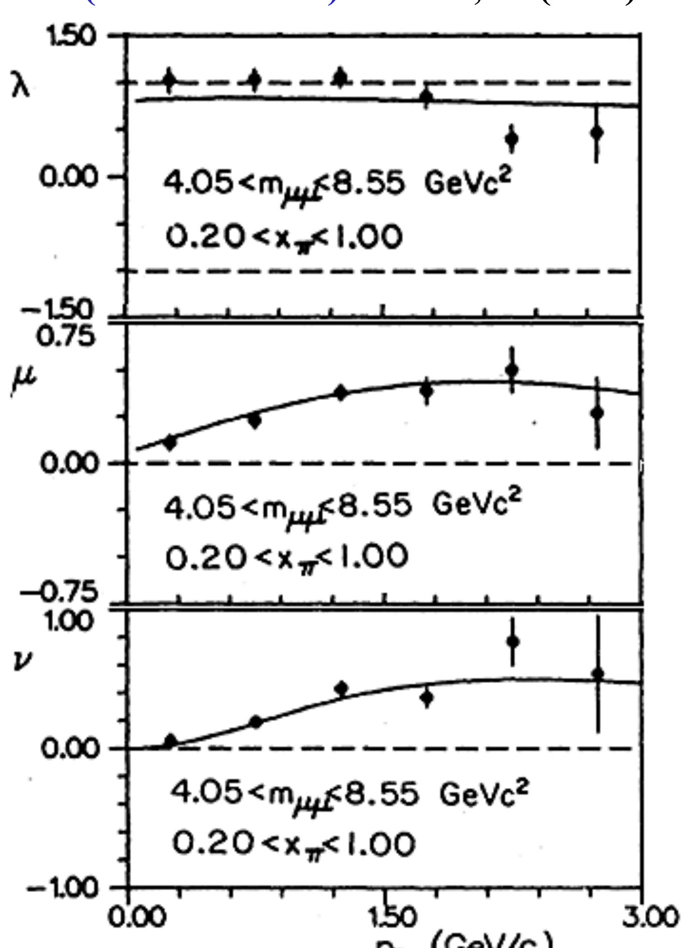

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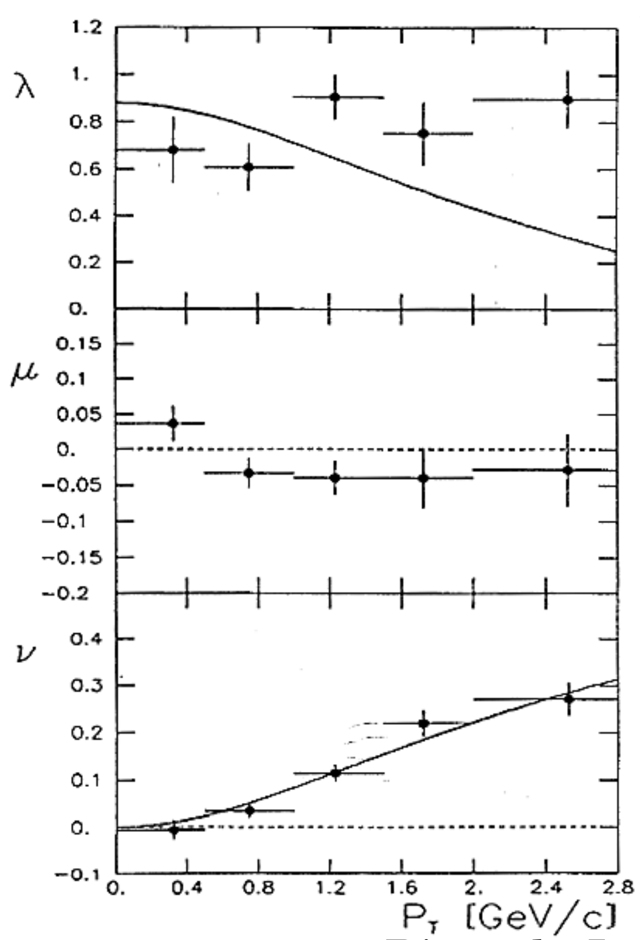

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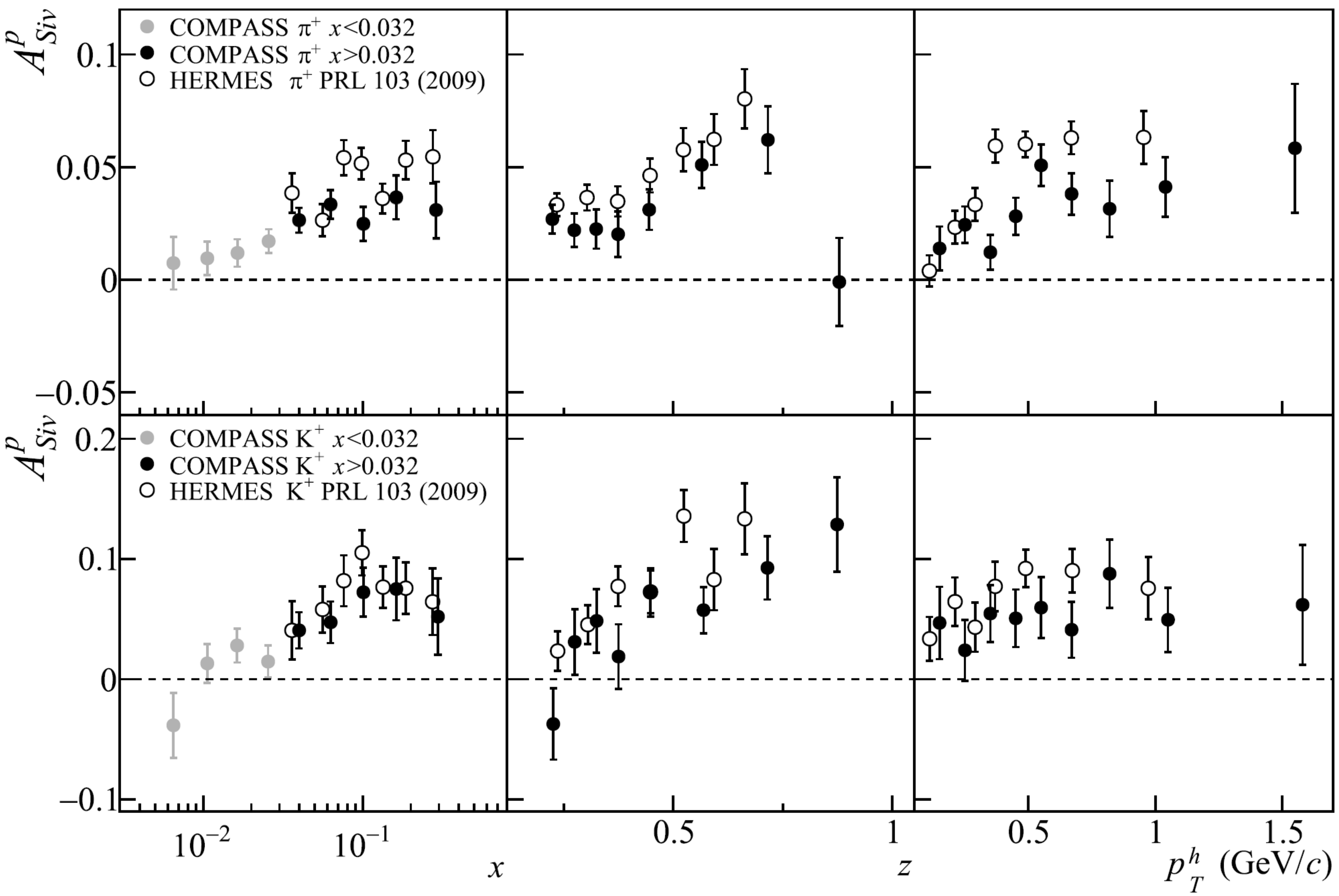
Lam Tung relation (collinear LO pQCD)

$1 - \lambda - 2\nu = 0 \longrightarrow \lambda = 1, \ \mu = 0, \ \nu = 0$

Boer-Mulders PDF's sign-change between SIDIS and Drell-Yan and deep analysis of the LT-relation violation are one of the main issues addressed by COMPASS.

COMPASS SIDIS results: Sivers

PLB 744 (2015) 250

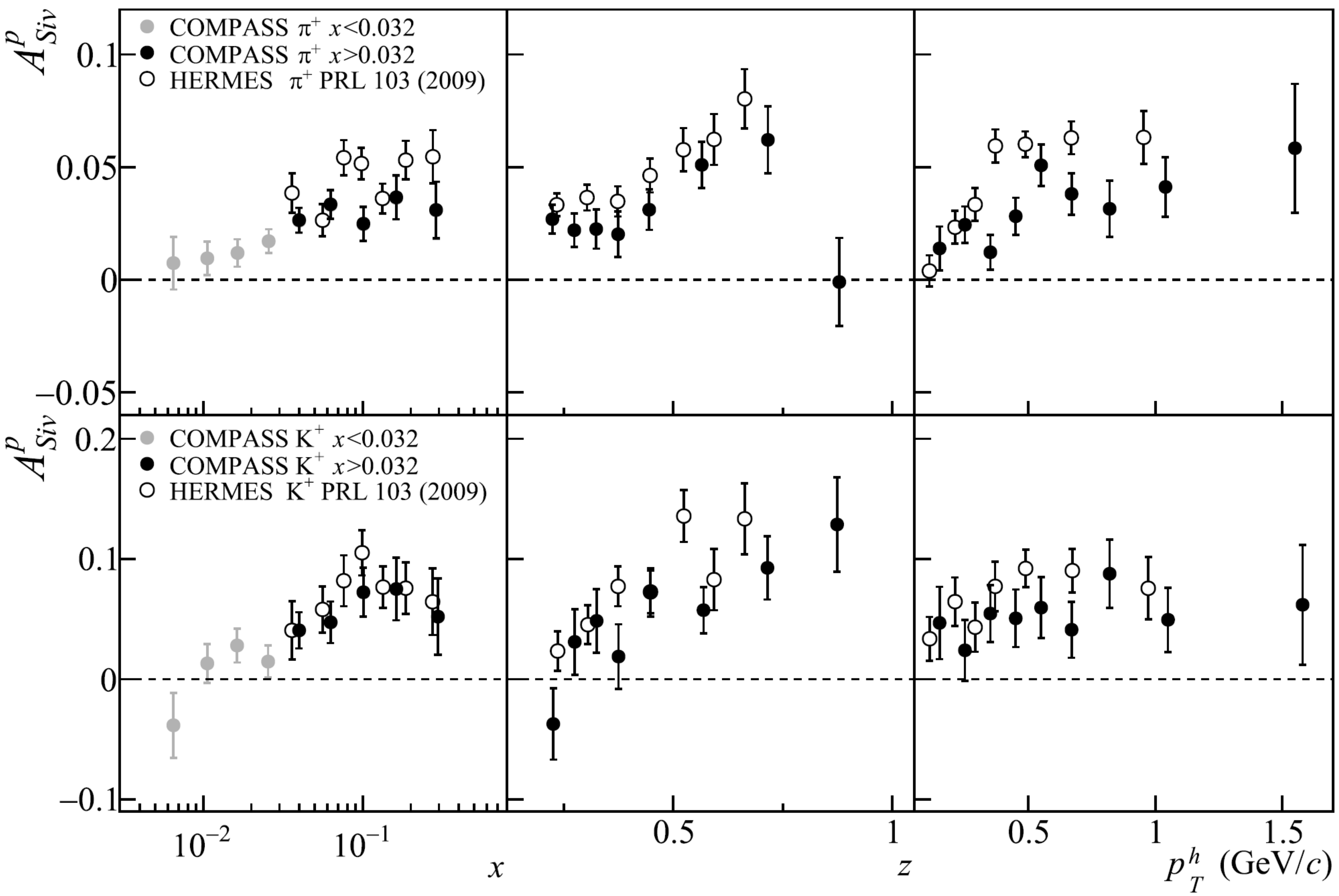


For more details see talk by Anna Martin (Session 6)

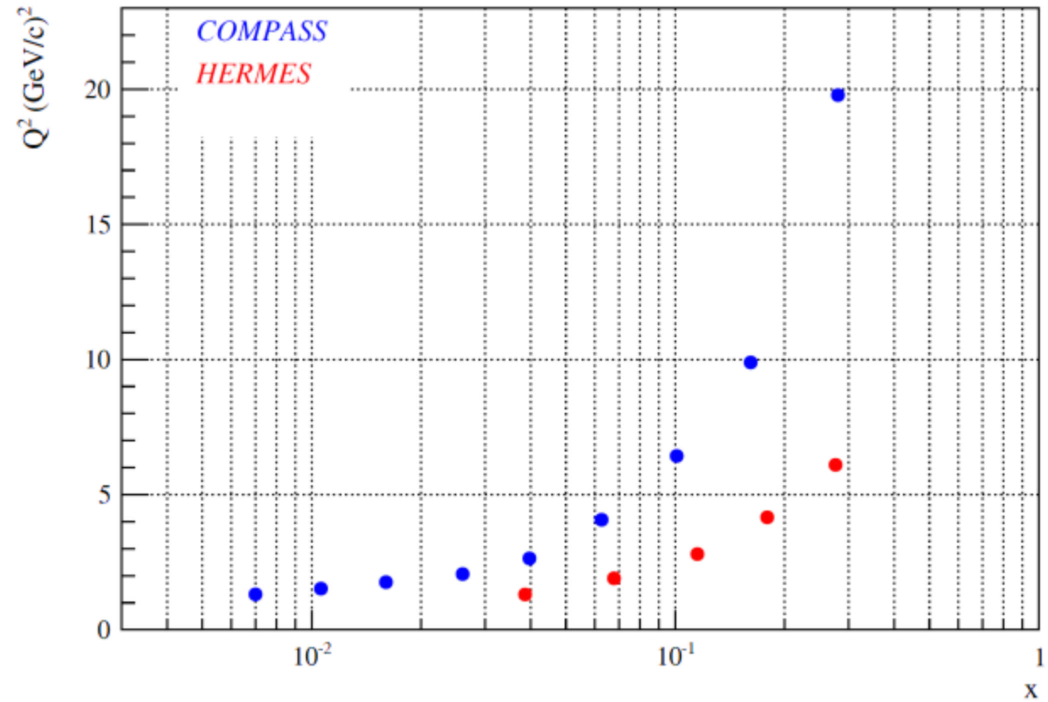
- Sivers asymmetry for π^+ and K^+ : COMPASS proton 2010 vs Hermes proton 2002-2005.
- Sivers asymmetry measured in COMPASS is lower than the one from HERMES, for both π^+ and K^+.

COMPASS SIDIS results: Sivers

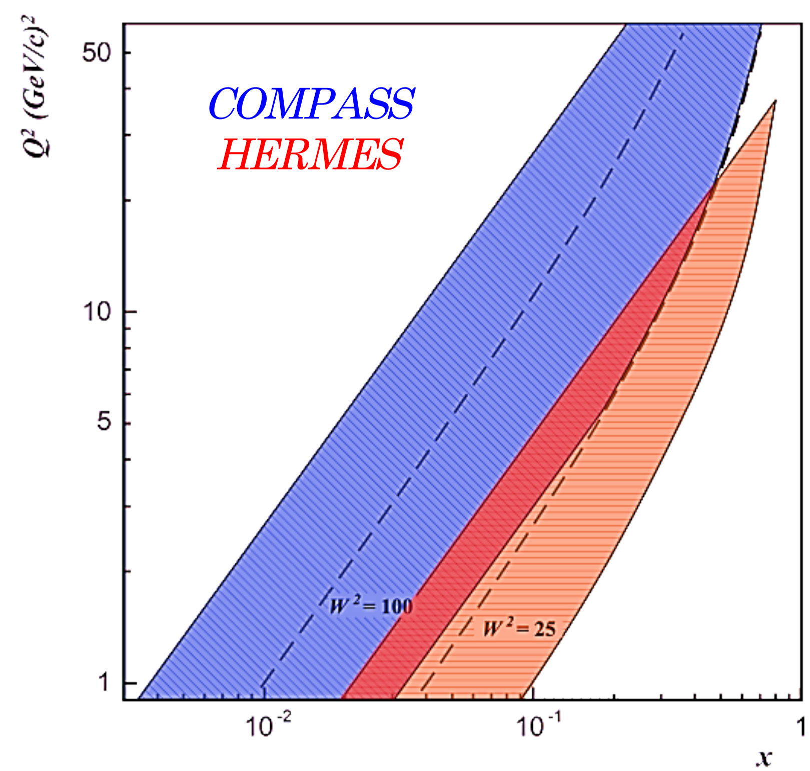
PLB 744 (2015) 250



For more details see talk by Anna Martin (Session 6)



- Sivers asymmetry for π^+ and K^+ : COMPASS proton 2010 vs Hermes proton 2002-2005.
- Sivers asymmetry measured in COMPASS is lower than the one from HERMES, for both π^+ 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?**



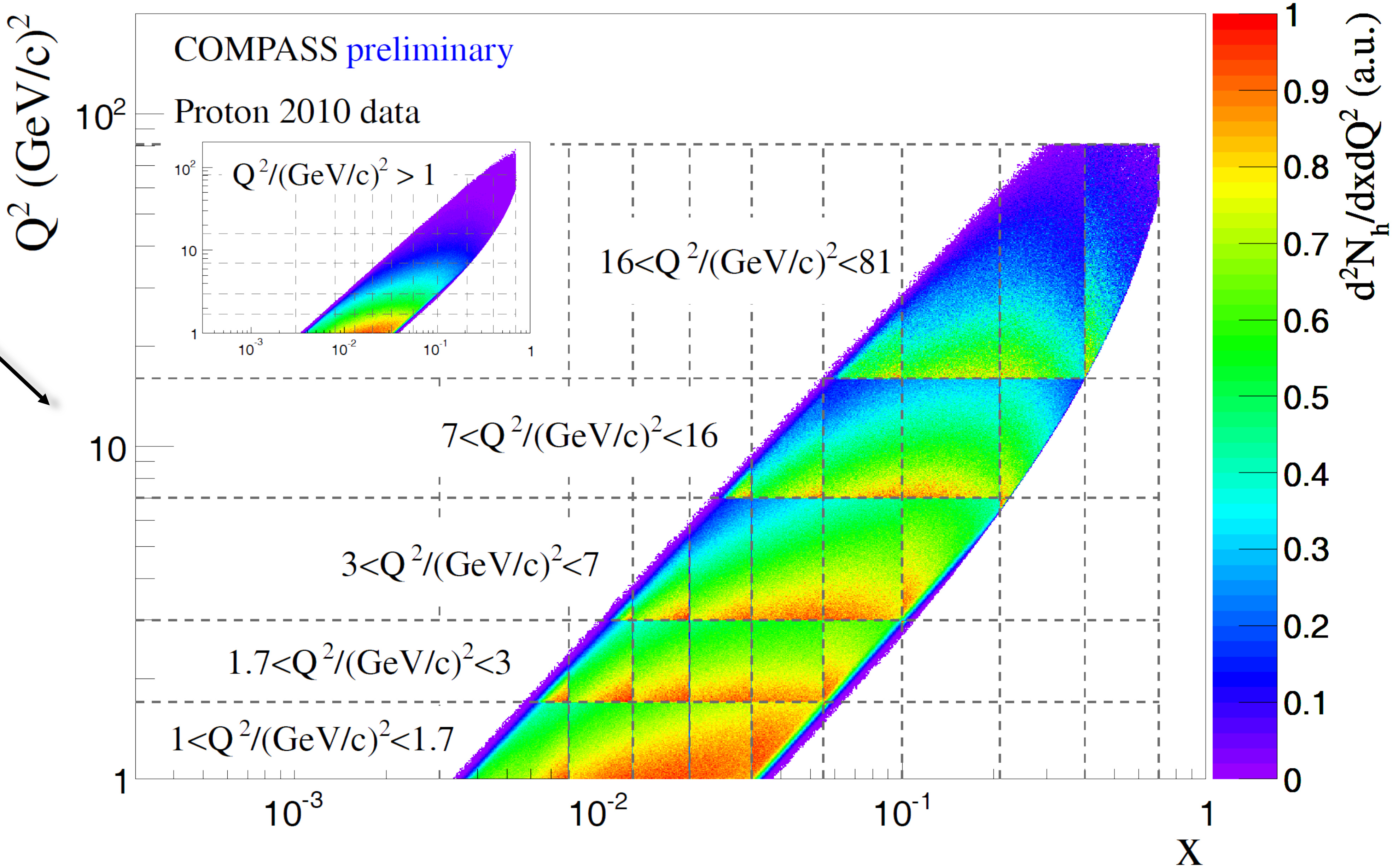
SIDIS Multi-D: an input to TMD evolution studies …

Results first shown at the SPIN-2014 conference,
B.Parsamyan (OBO COMPASS), arXiv:1504.01599 [hep-ex]

Q^2 ranges:
- $1 < Q^2 < 1.7$
- $1.7 < Q^2 < 3$
- $3 < Q^2 < 7$
- $7 < Q^2 < 16$
- $16 < Q^2 < 81$

z ranges:
- $z > 0.1$
- $z > 0.2$
- $0.1 < z < 0.2$
- $0.2 < z < 0.4$
- $0.4 < z < 1.0$

p_T ranges:
- $p_T > 0.1$
- $0.1 < p_T < 0.75$
- $0.1 < p_T < 0.3$
- $0.3 < p_T < 0.75$
- $p_T > 0.75$

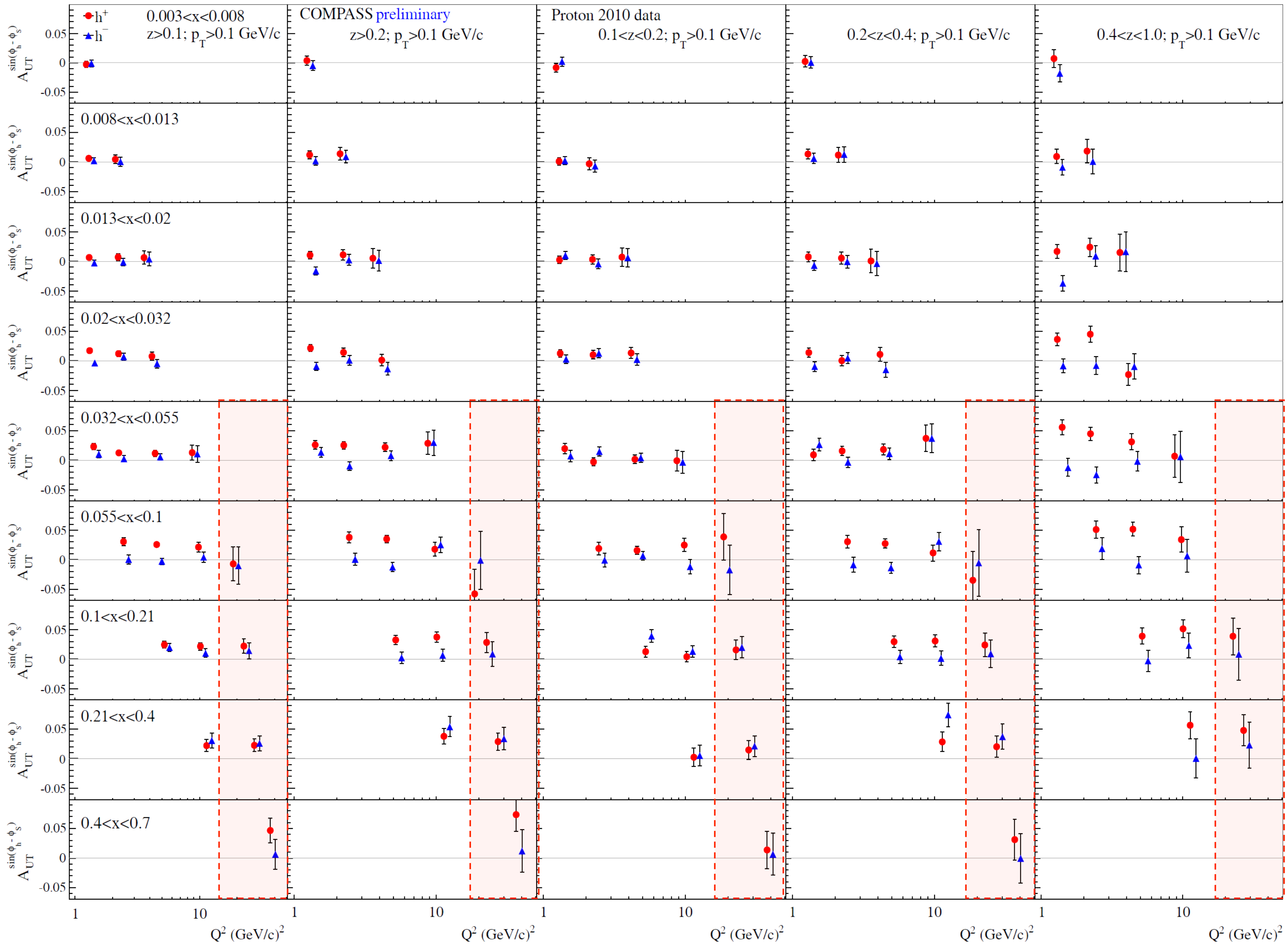


x bins: 0.003, 0.008, 0.013, 0.02, 0.032, 0.055, 0.10, 0.21, 0.40, 0.7

- First ever x-Q^2-z-p_T multidimensional analysis from the real data.
- Direct input for **TMD evolution related studies.**

SIDIS Multi-D in DY Q^2 ranges

Results first shown at the SPIN-2014 conference,
B.Parsamyan (OBO COMPASS), arXiv:1504.02599 [hep-ex]



Sivers asymmetry: 3D x-z-Q^2 dependence

$16<Q^2<81$

DY High Mass range

- Important input for Q^2-evolution and DY-SIDIS related studies

COMPASS DY ranges

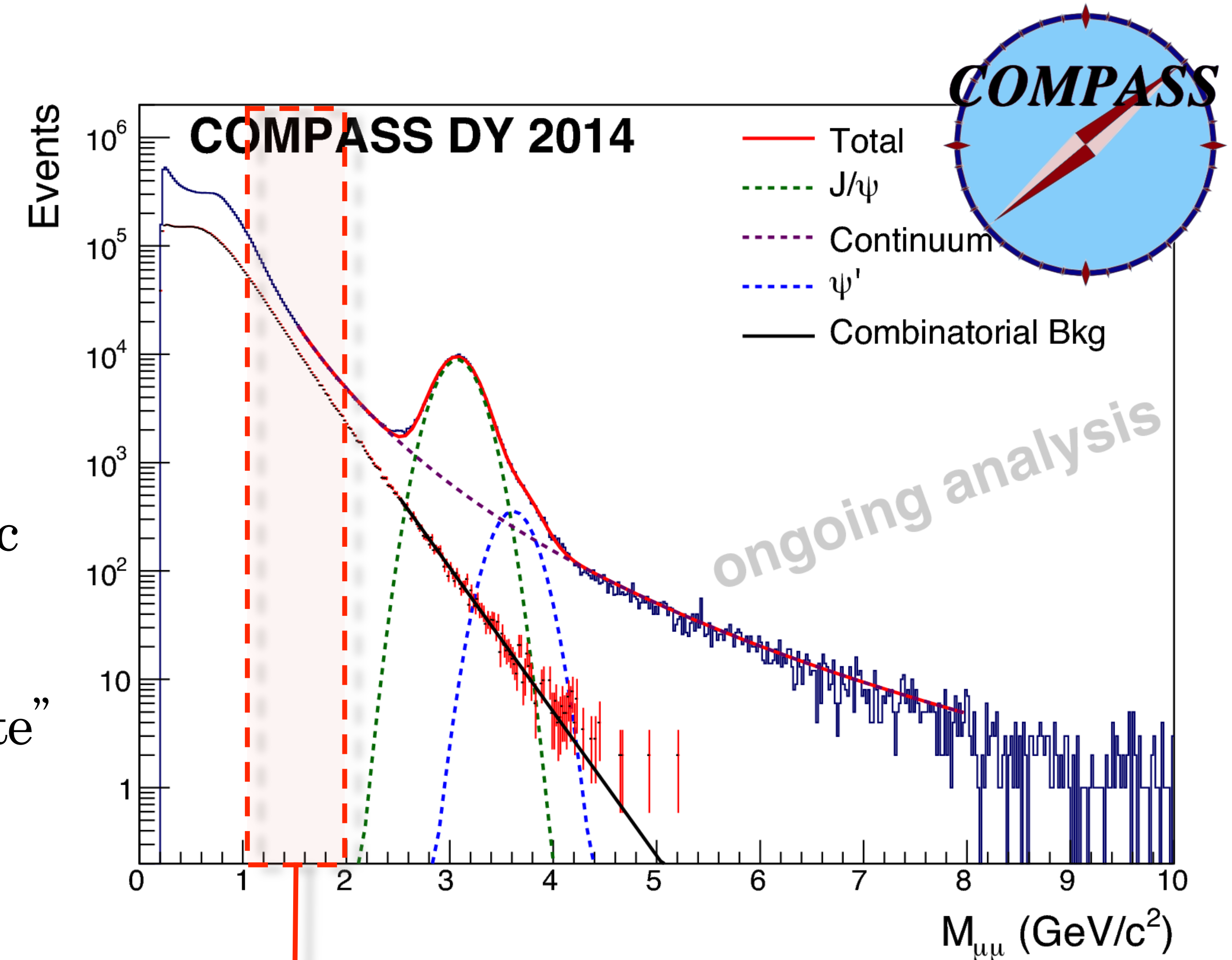
Four Q^2 (or mass) ranges

I. $1 < Q^2/(GeV/c^2) < 4$, "Low mass"
  - Large combinatorial background:
    - Pion and Kaon decays.
    - Open charm (bottom) semi-leptonic decays $D\overline{D}$, $B\overline{B}$
  - Smaller Asymmetries.

II. $4 < Q^2/(GeV/c^2) < 6.25$, "Intermediate"
  - High DY cross section.
  - Still low signal/background

III. $6.25 < Q^2/(GeV/c^2) < 16$, "$J/\psi$"
  - Strong J/ψ signal ➔ Studies of J/ψ physics.
  - Lower background
  - Difficult to disentangle DY

IV. $16 < Q^2/(GeV/c^2) < 81$, "High Mass"
  - Beyond J/ψ and ψ' peak.
  - Low background and just in the region $16 < Q^2/(GeV/c^2) < 25$
  - Valence quark region ➔ Larger asymmetries! But …
  - Low cross-section



Low mass range

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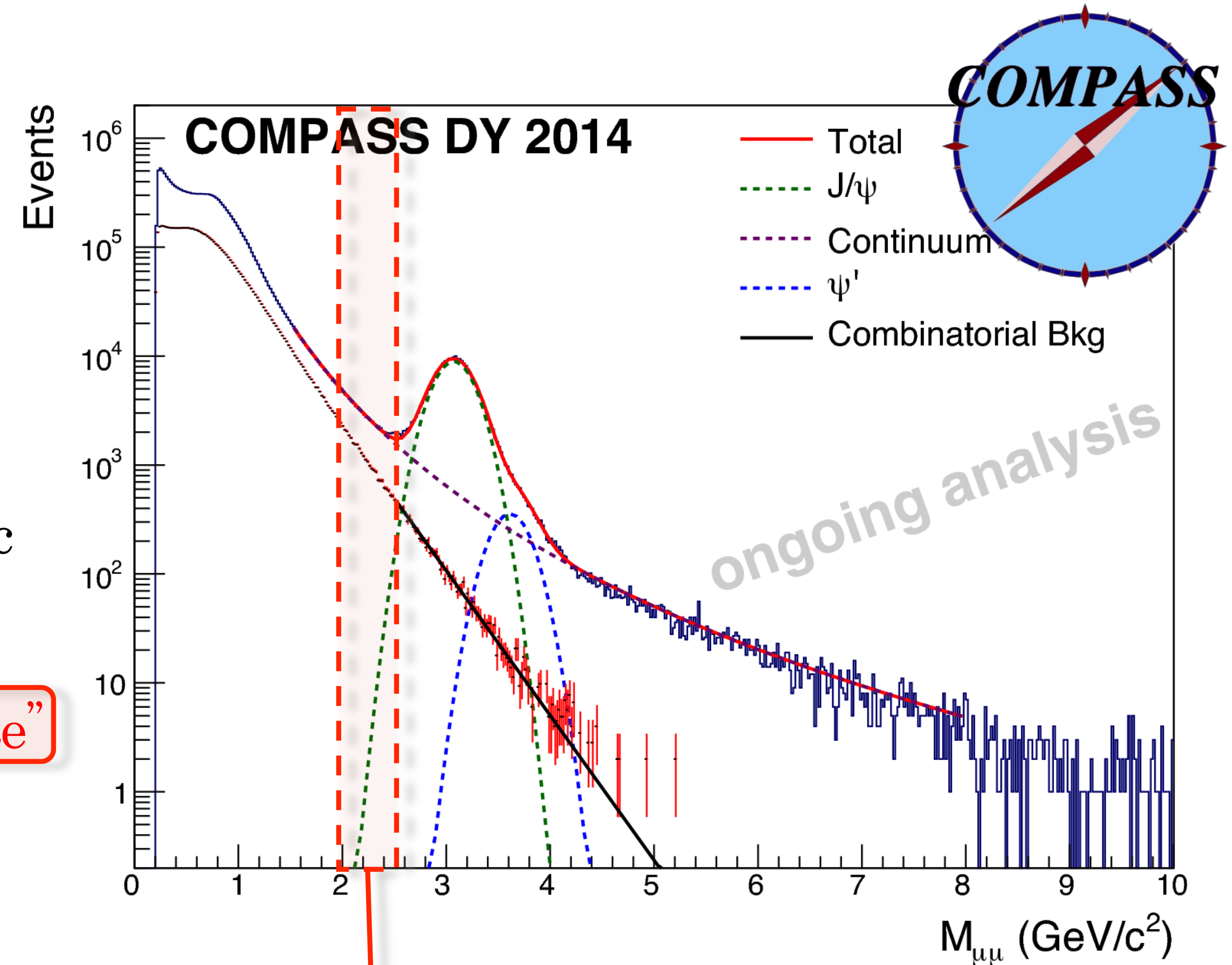

Intermediate mass range

COMPASS DY ranges

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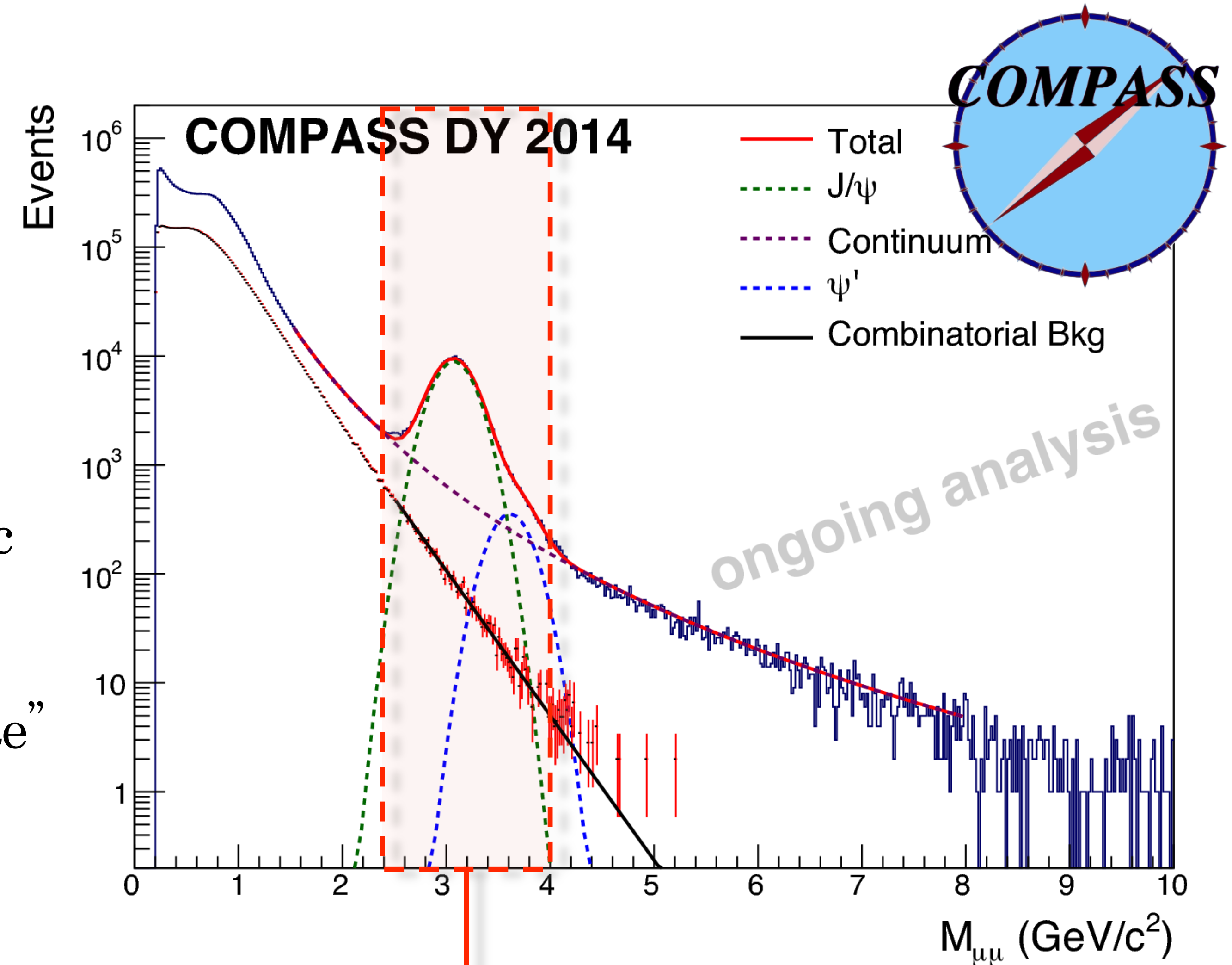

J/ψ mass range

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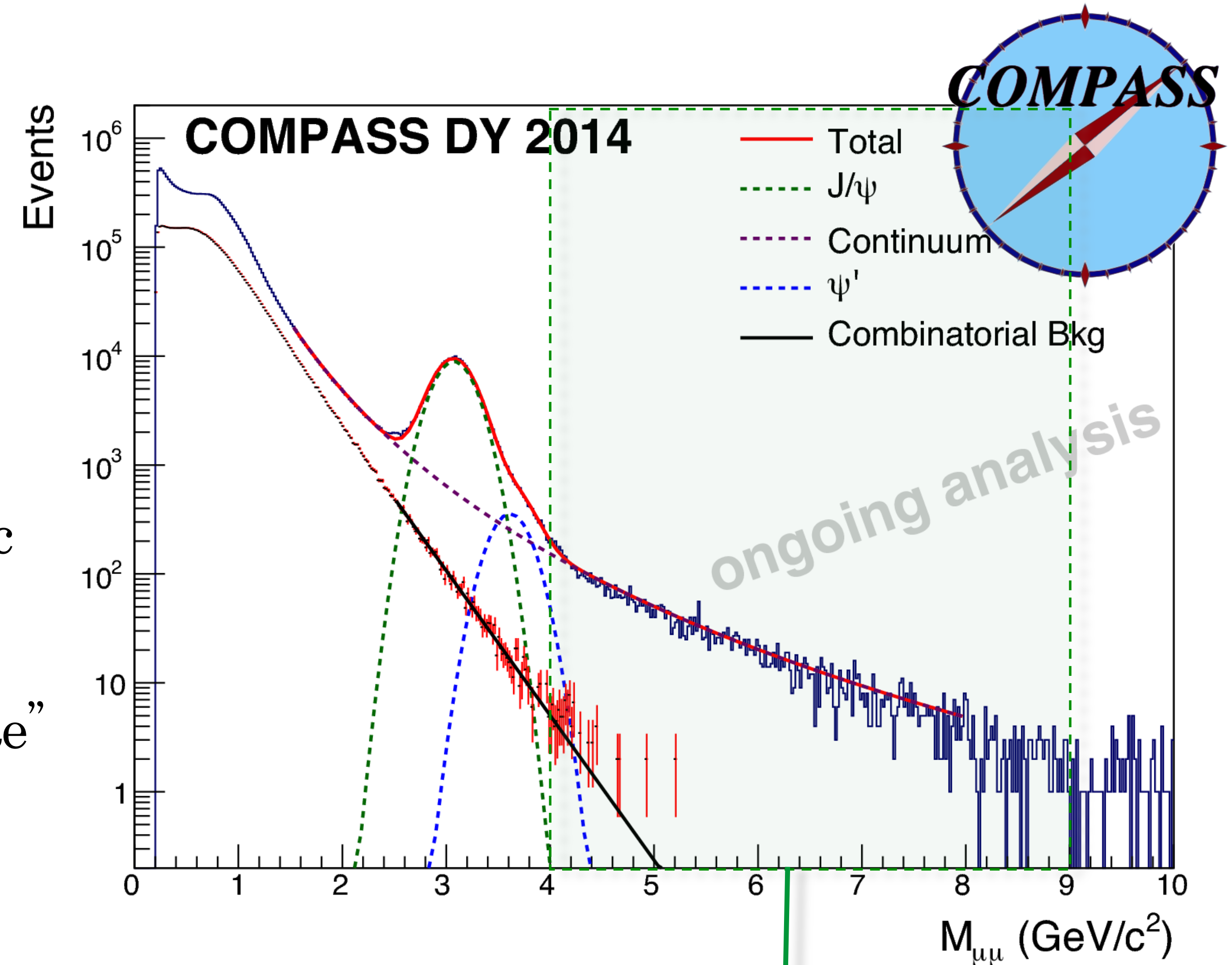

High mass range

COMPASS DY ranges

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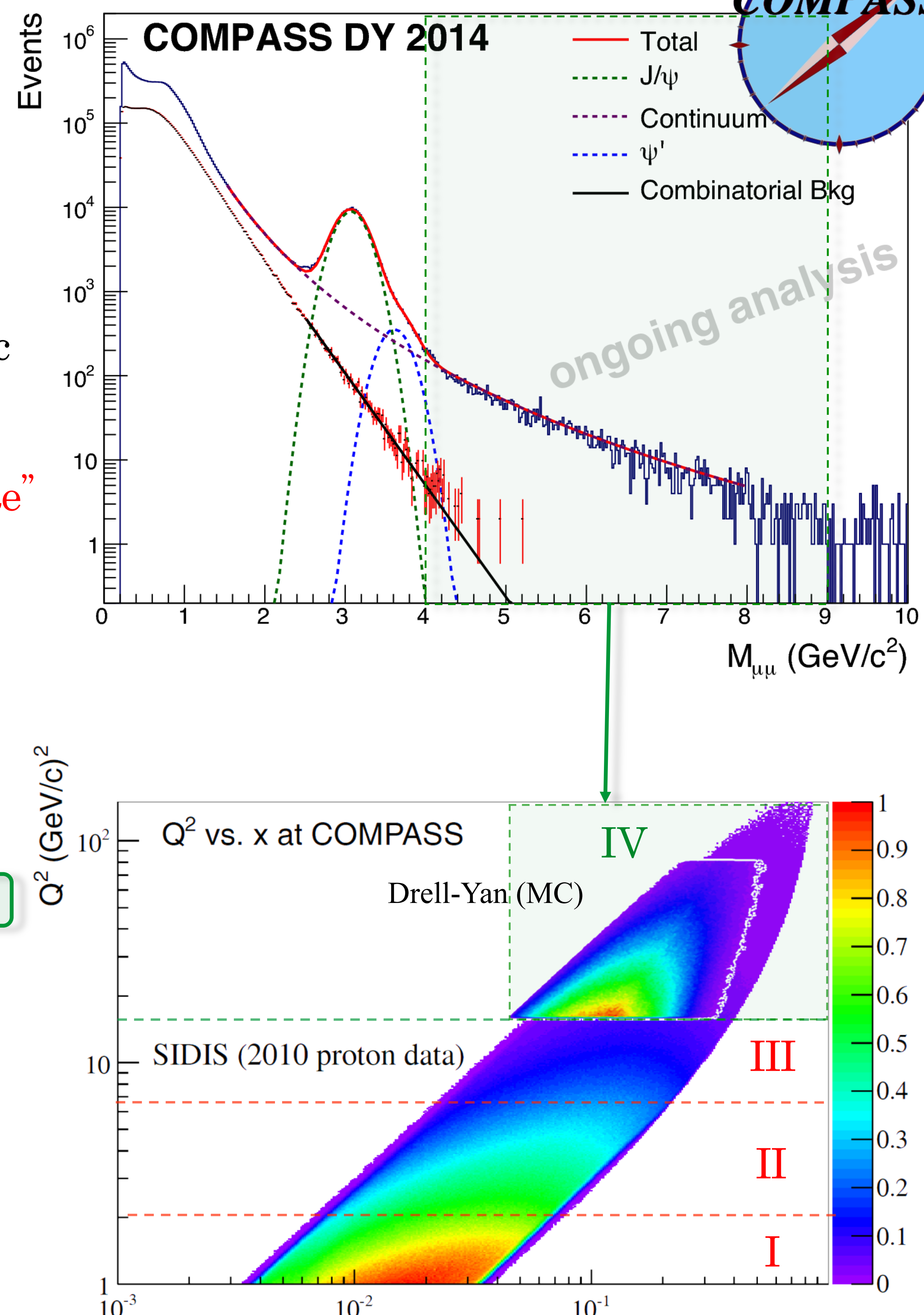
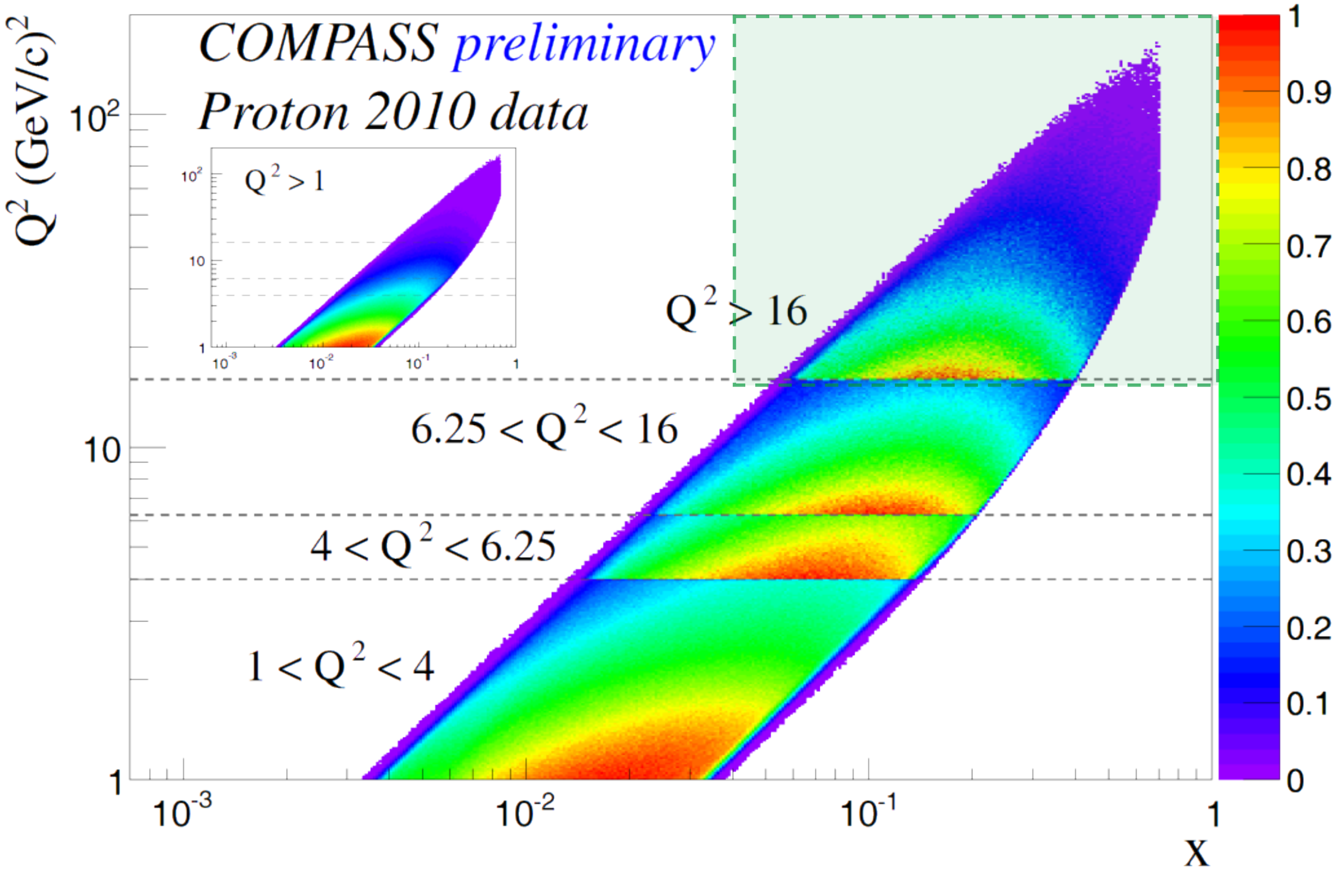
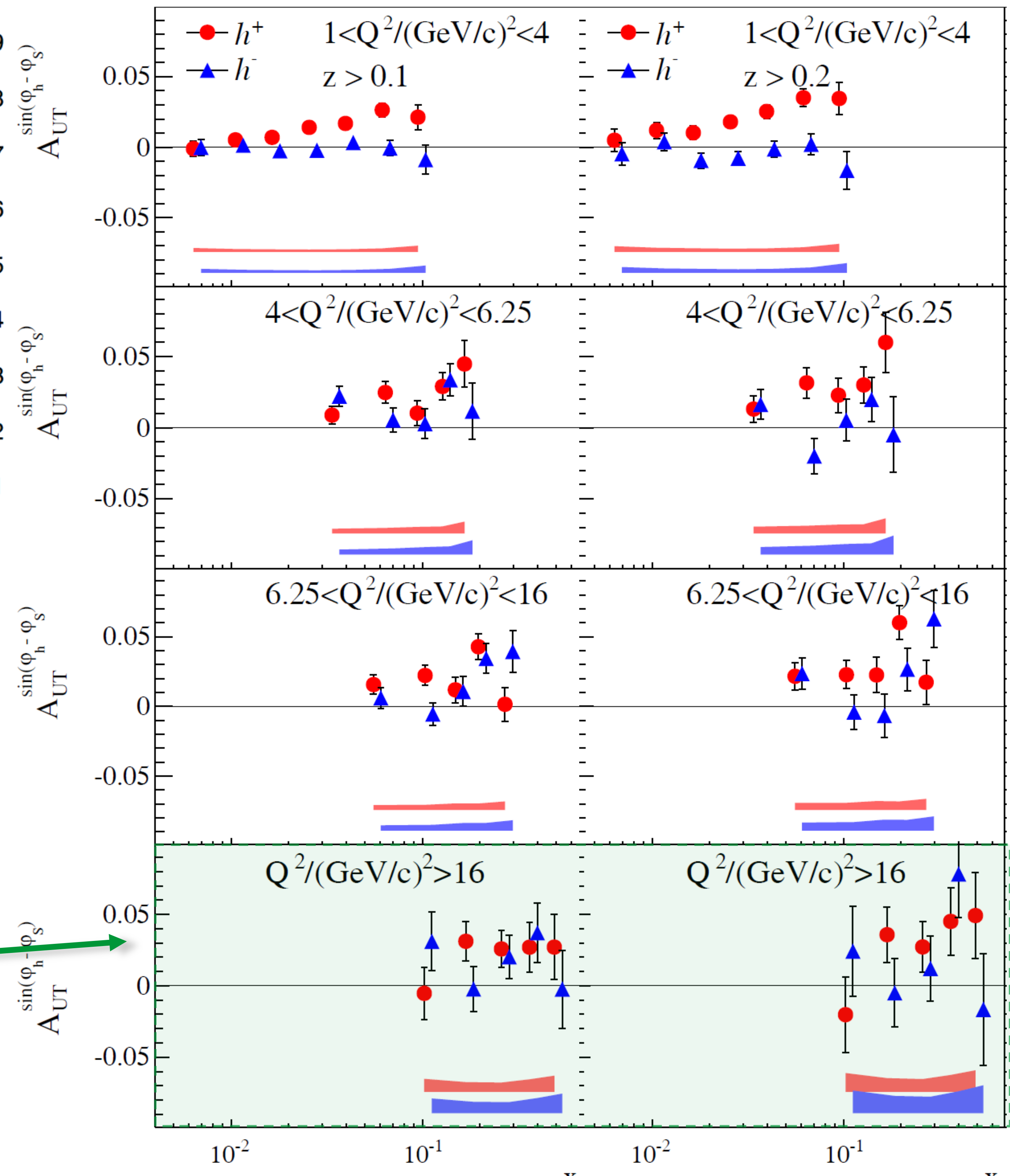


SIDIS results in DY ranges

First shown at the Transversity-2014 conference,
B.Parsamyan (OBO COMPASS) arXiv:1411.1568 [hep-ex]



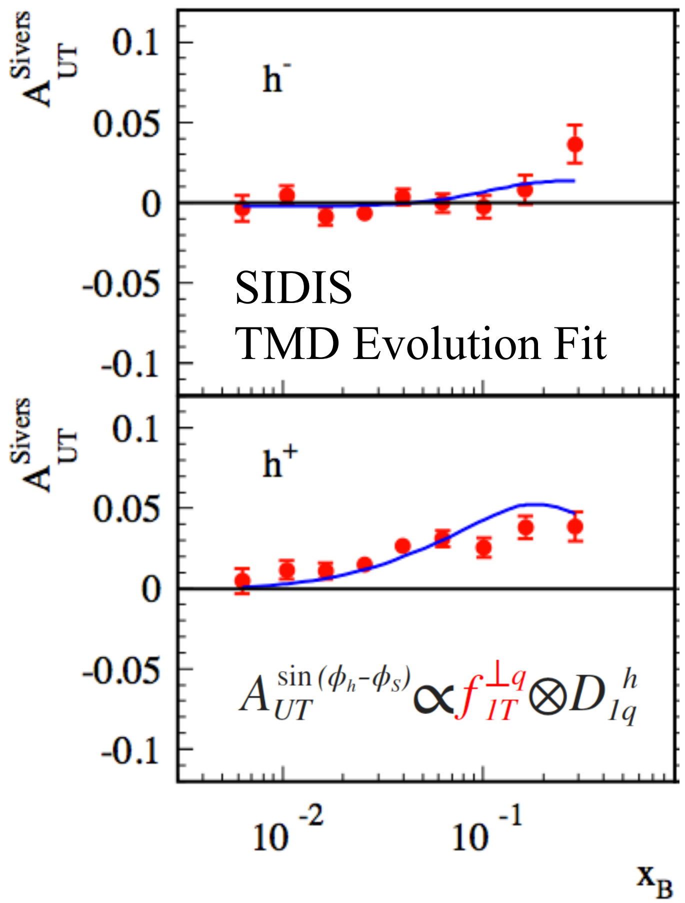


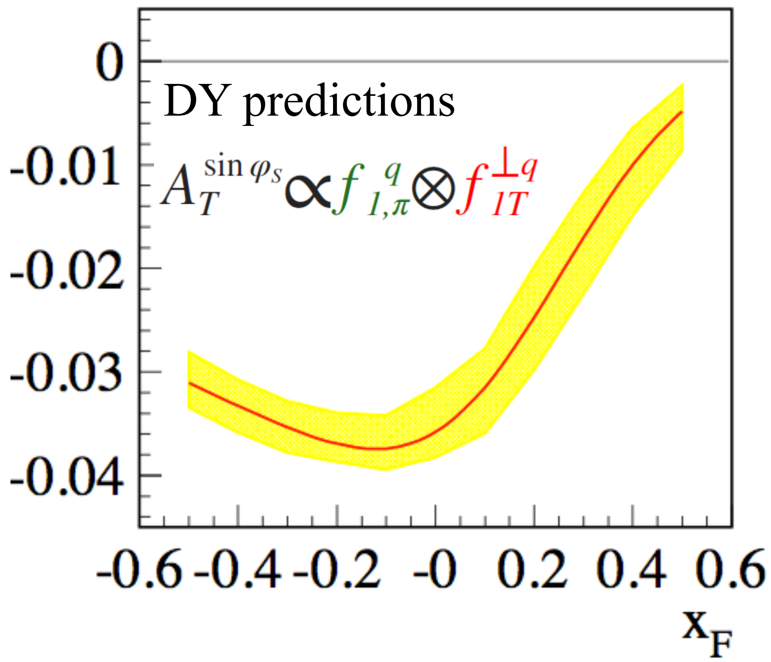
- COMPASS Proton 2010 data sample divided into the 4 Q^2 DY ranges.
- Sivers asymmetry extracted for each Q^2 range, using two different z-ranges
- Results for the Sivers asymmetry in DY High mass range in SIDIS are already available!
- Only DY part of the puzzle is missing.

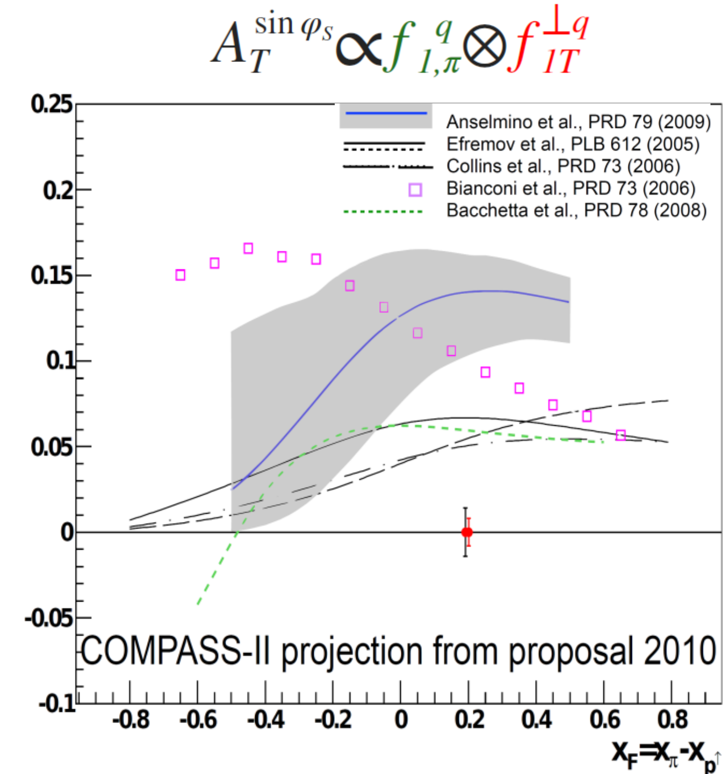
DY predictions

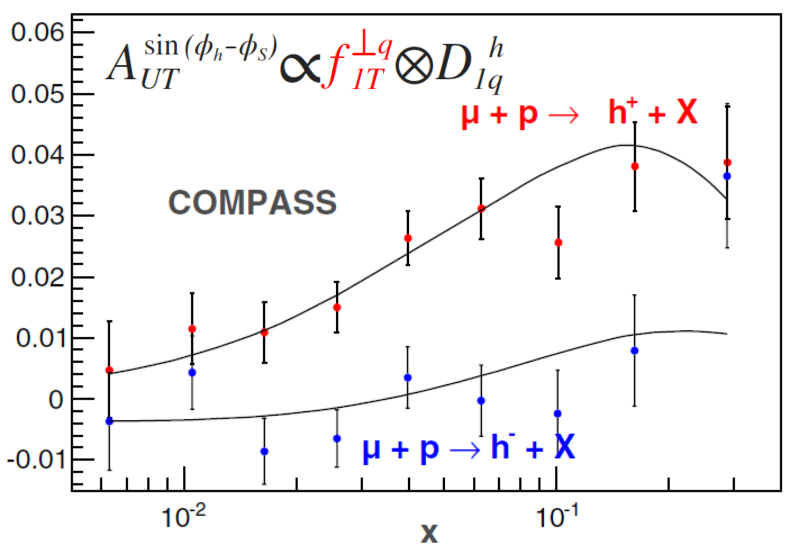
M.G. Echevarria et al., "*QCD Evolution of the Sivers Asymmetry*" , PRD 89 074013 (2014)

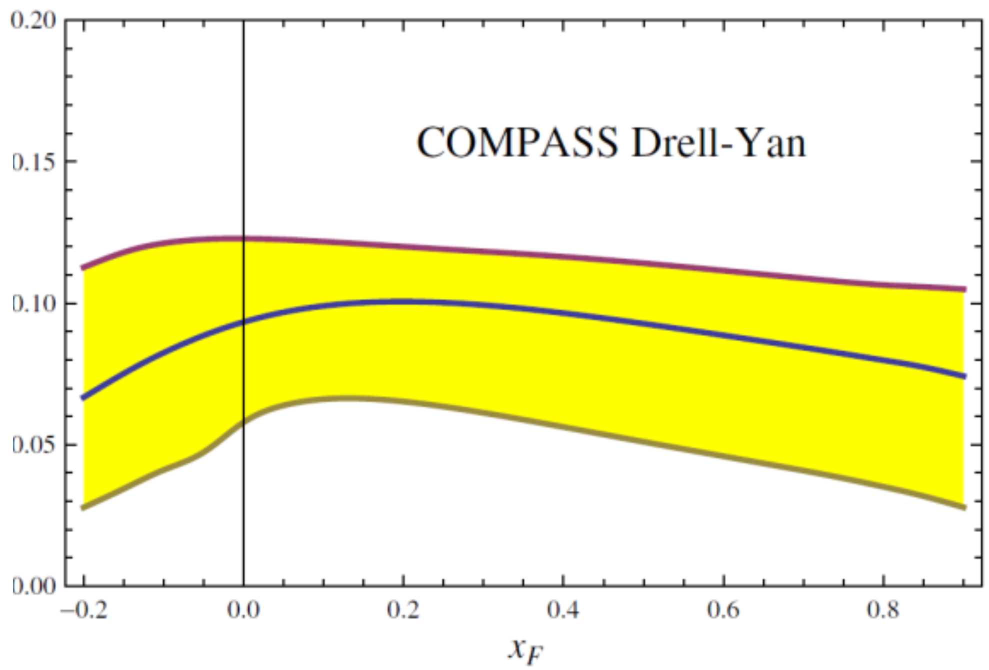
- Variety of models giving largely spread theoretical predictions.
- Experimental data is the necessary input to constrain the models

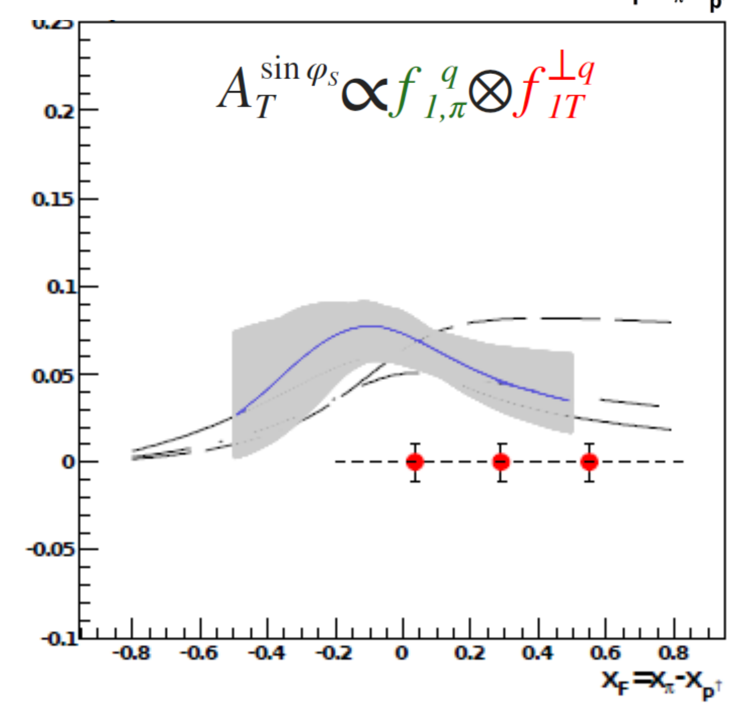












P. Sun and F. Yuan, "*Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production*" . PRD 88 11, 114012 (2013)

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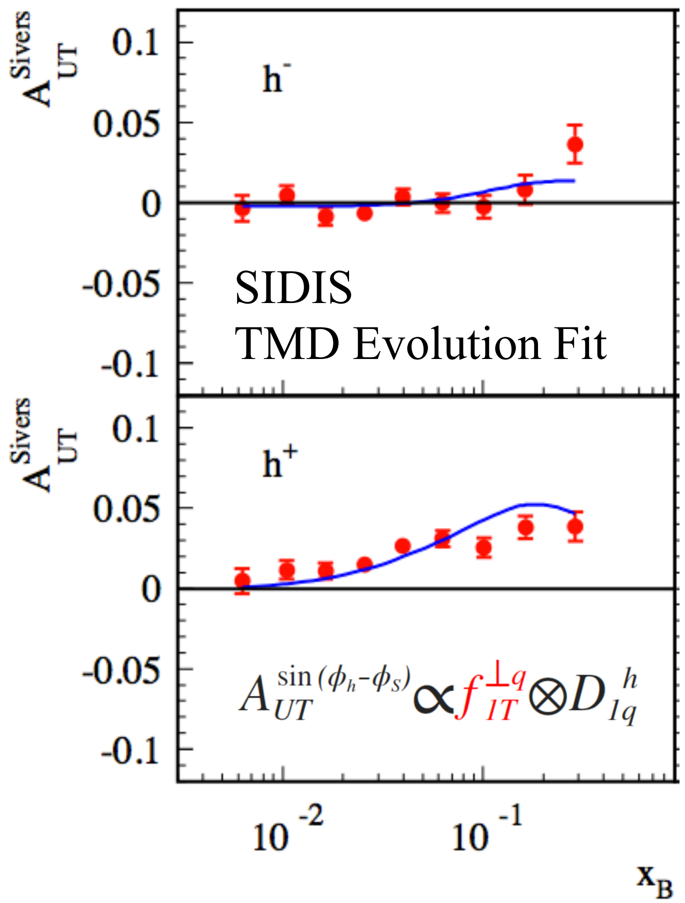
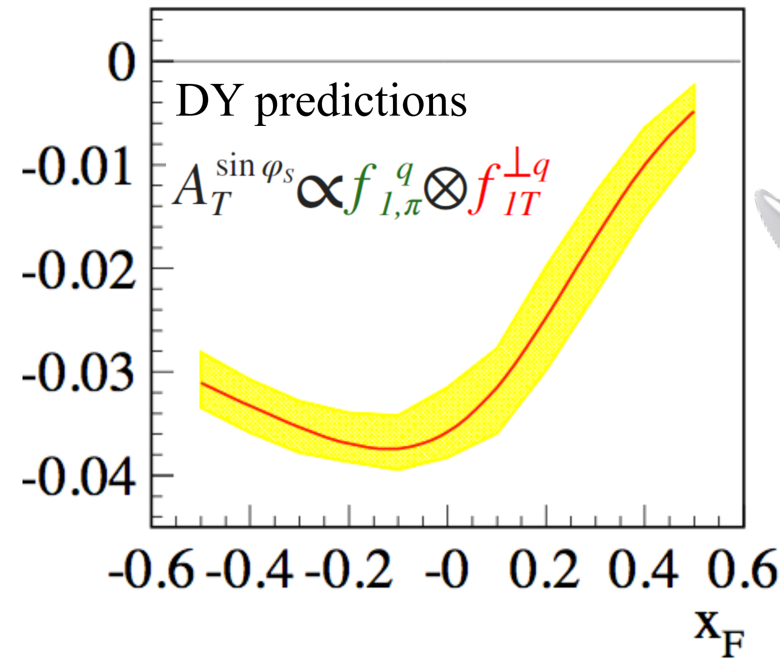
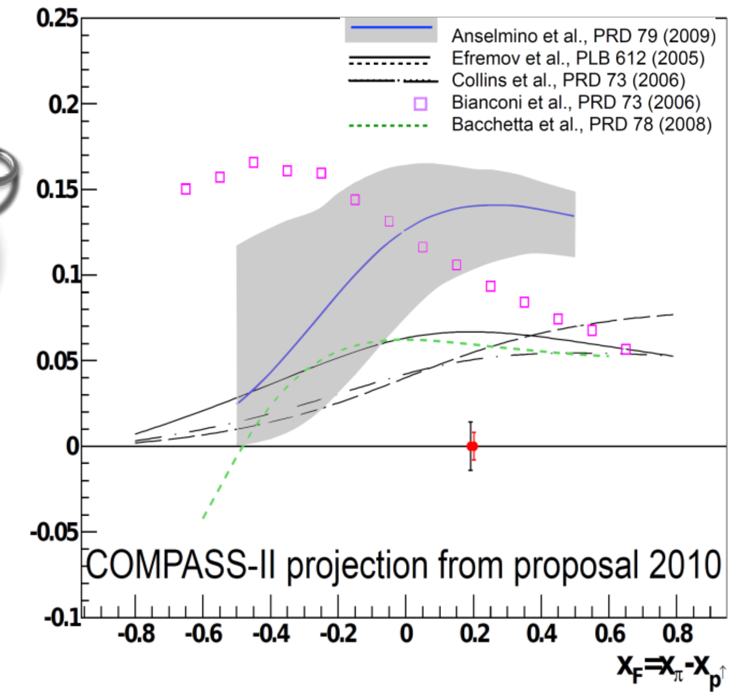
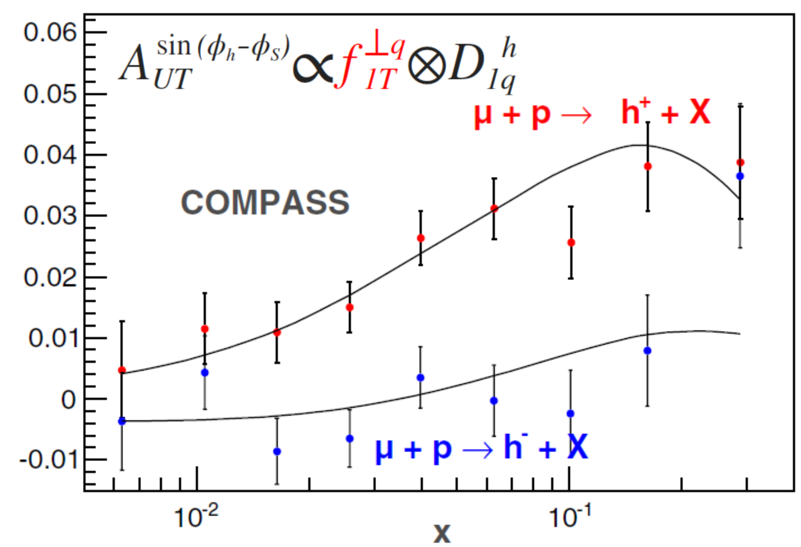
- Variety of models giving largely spread theoretical predictions.
- Experimental data is the necessary input to constrain the models

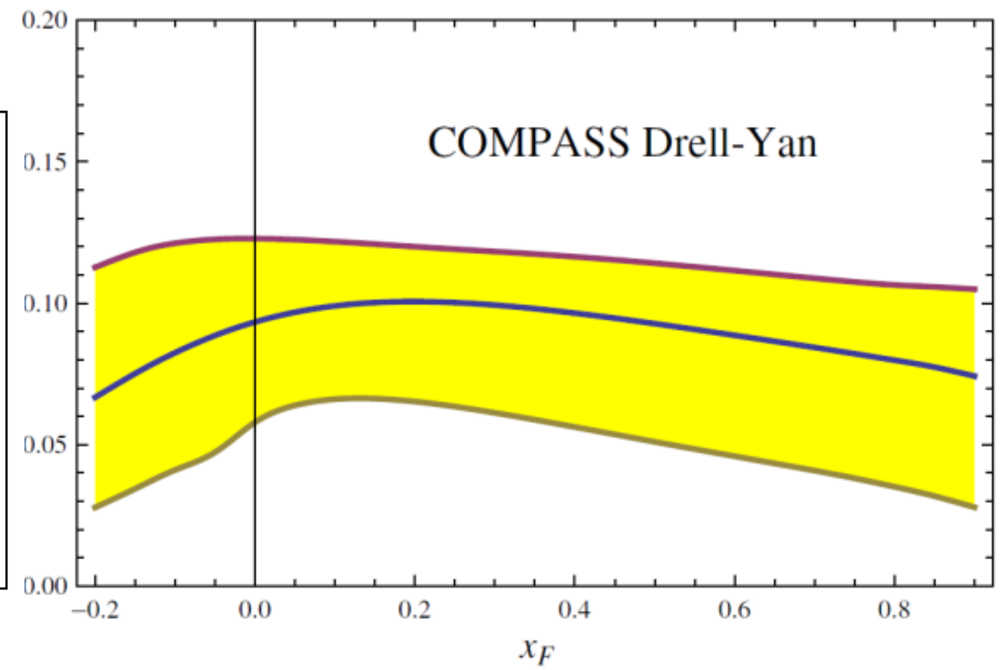


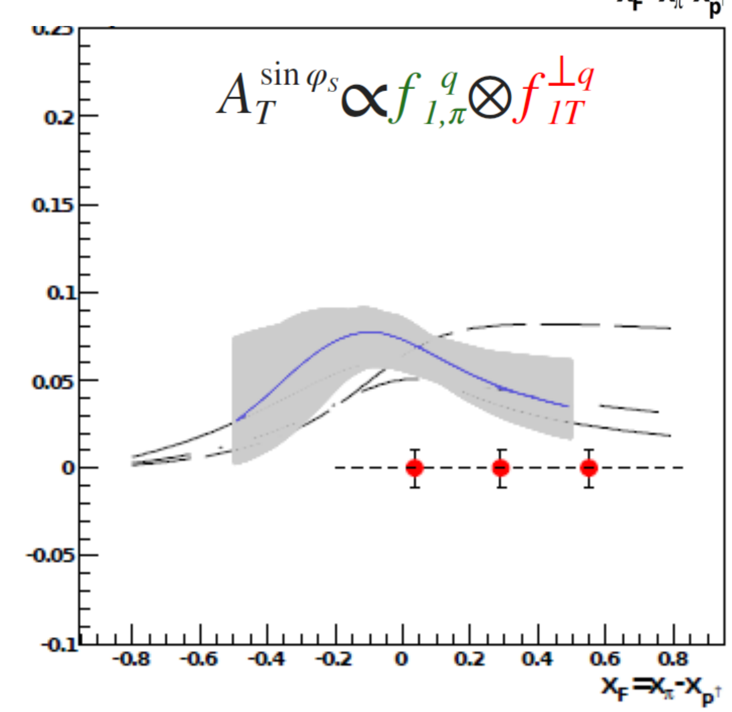
COMPASS is NOW collecting 1st ever polarized DY data!







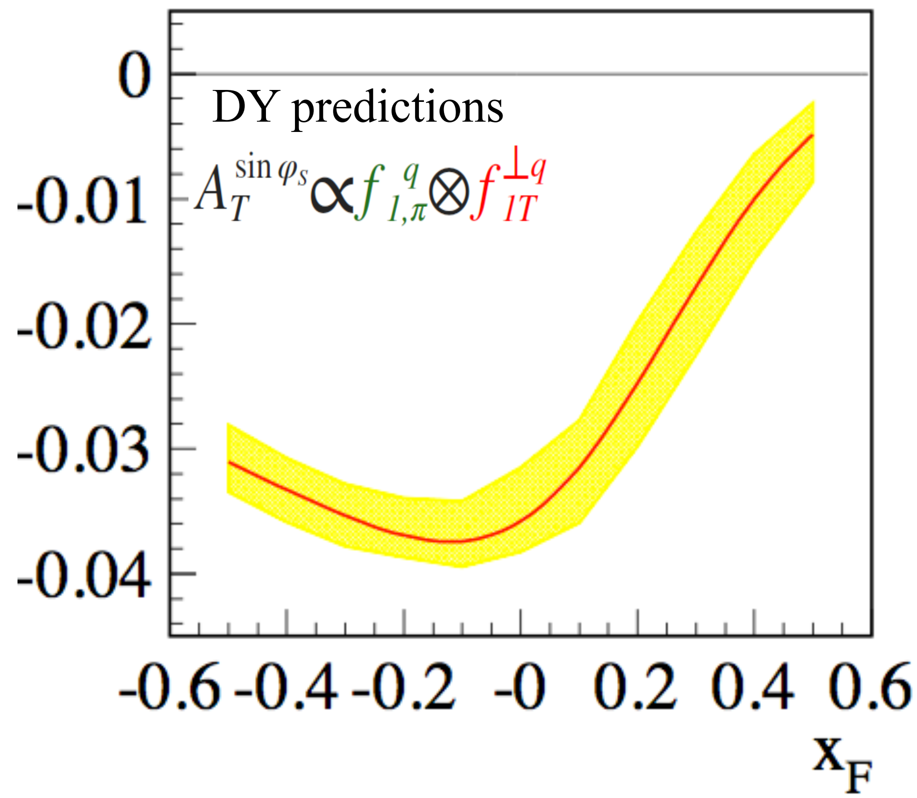


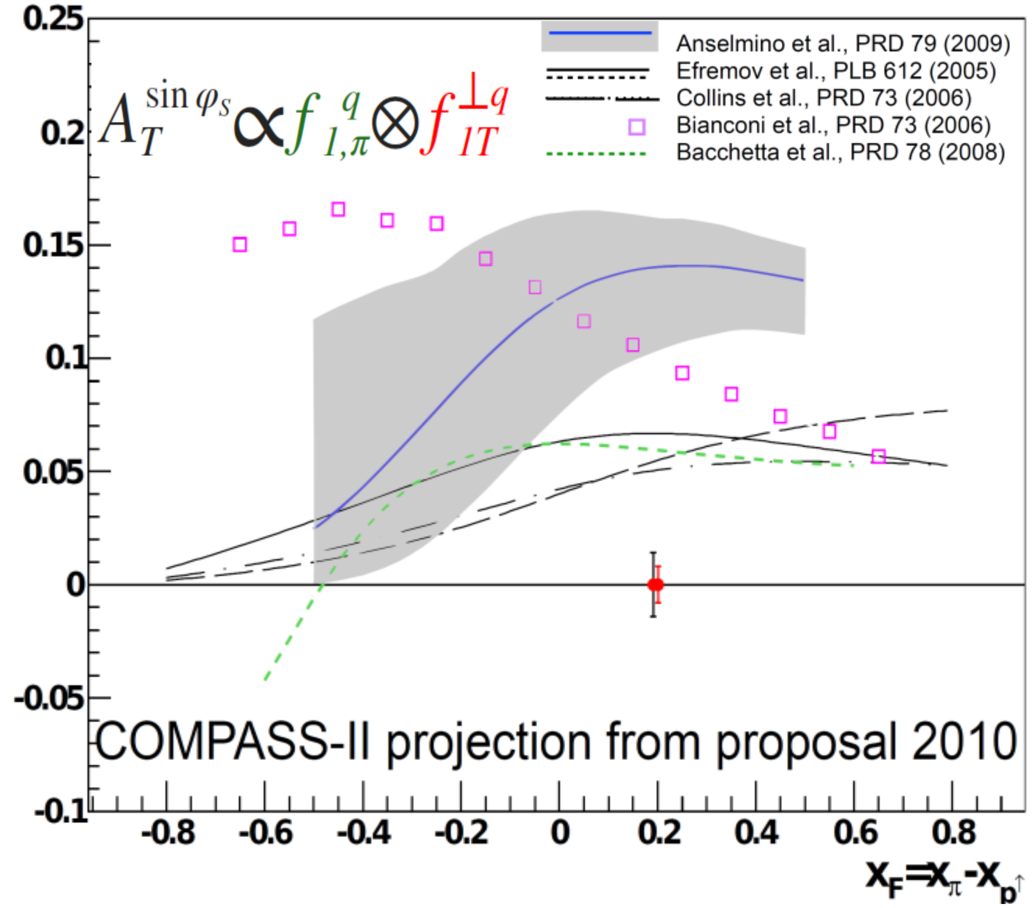


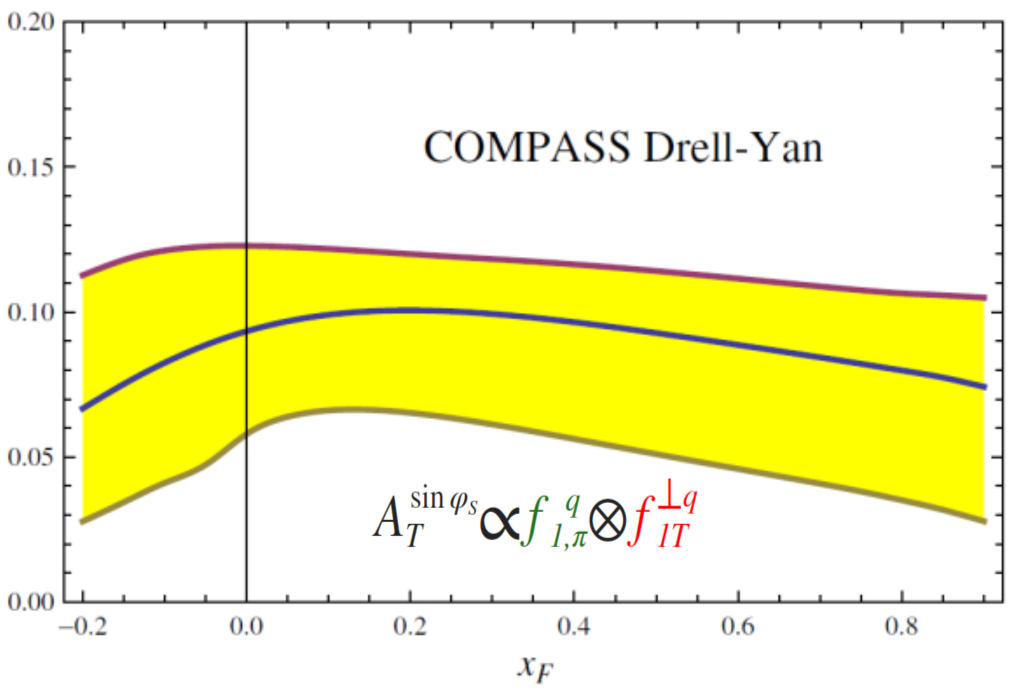
P. Sun and F. Yuan, "*Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production*". PRD 88 11, 114012 (2013)

COMPASS acceptance

M.G. Echevarria et al., *"QCD Evolution of the Sivers Asymmetry"*, PRD 89 074013 (2014)

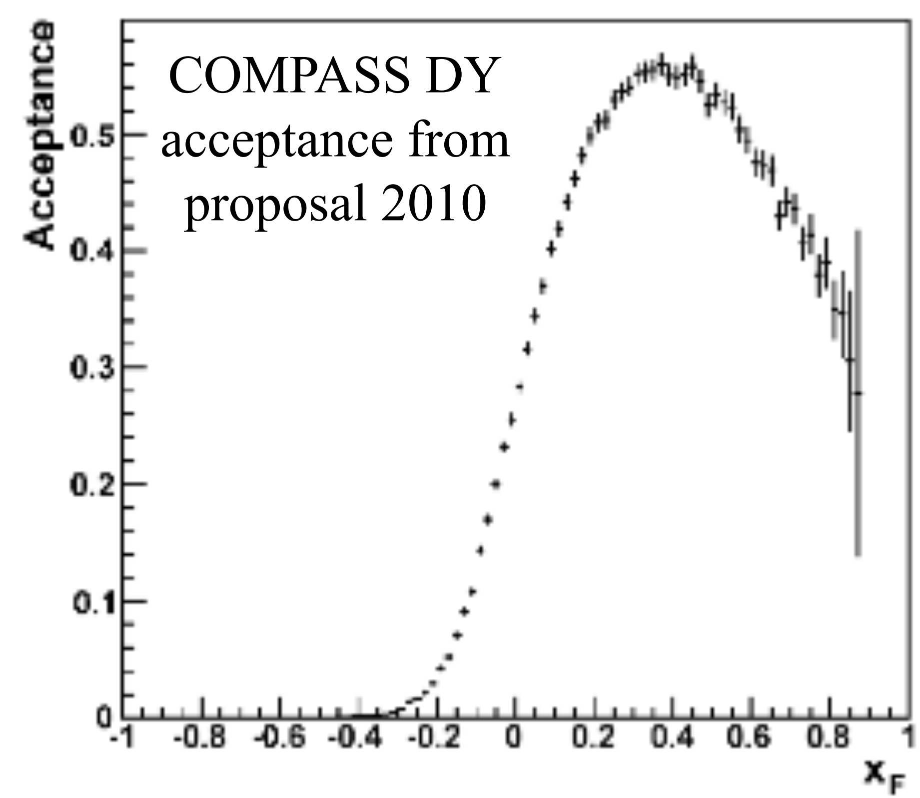






P. Sun and F. Yuan, *"Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production"*. PRD 88 11, 114012 (2013)

COMPASS will work in the **valence region** where the **Sivers** asymmetry is expected to **maximize**!



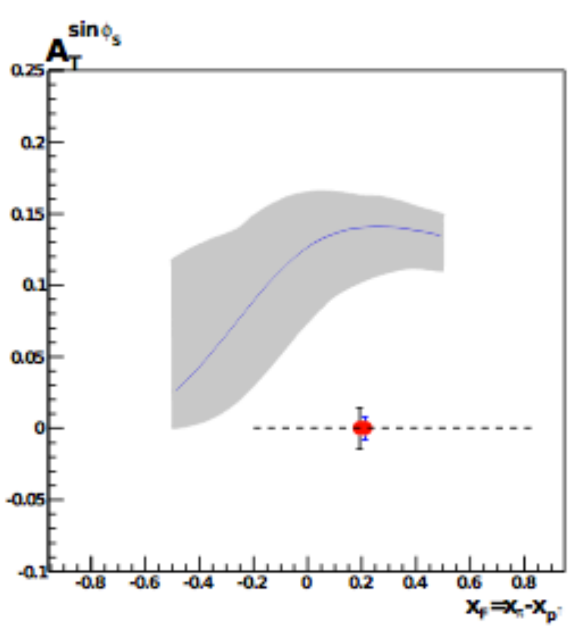
Expected accuracy

Values for expected statistical accuracies for different asymmetries as estimated in the COMPASS II Proposal

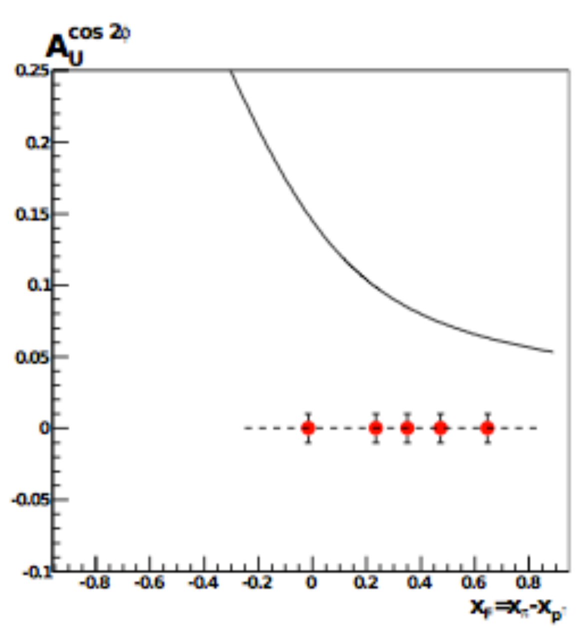
Asymmetry	Dimuon mass (GeV/c^2)		
	$2 < M_{\mu\mu} < 2.5$	J/ψ region	$4 < M_{\mu\mu} < 9$
$\delta A_U^{\cos 2\phi}$	0.0020	0.0013	0.0045
$\delta A_T^{\sin \phi_S}$	0.0062	0.0040	0.0142
$\delta A_T^{\sin(2\phi+\phi_S)}$	0.0123	0.008	0.0285
$\delta A_T^{\sin(2\phi-\phi_S)}$	0.0123	0.008	0.0285

Expected DY rate in HM range:
~ 700 – 800 DY/day

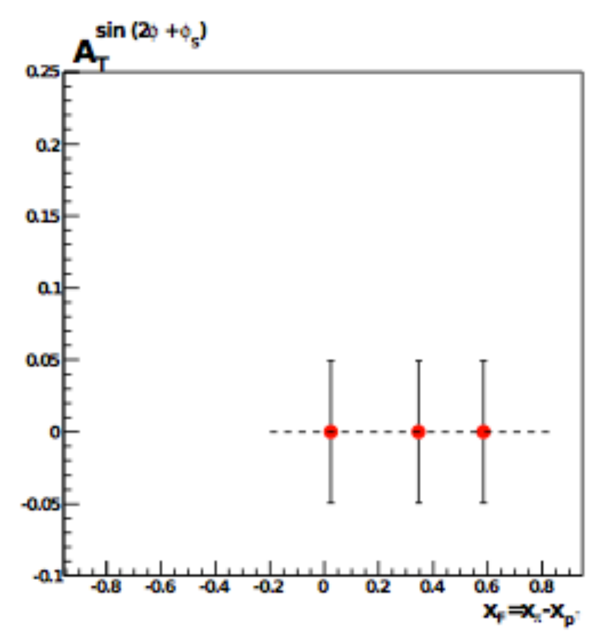
Expected statistical uncertainties for <u>TWO YEARS</u> of data taking



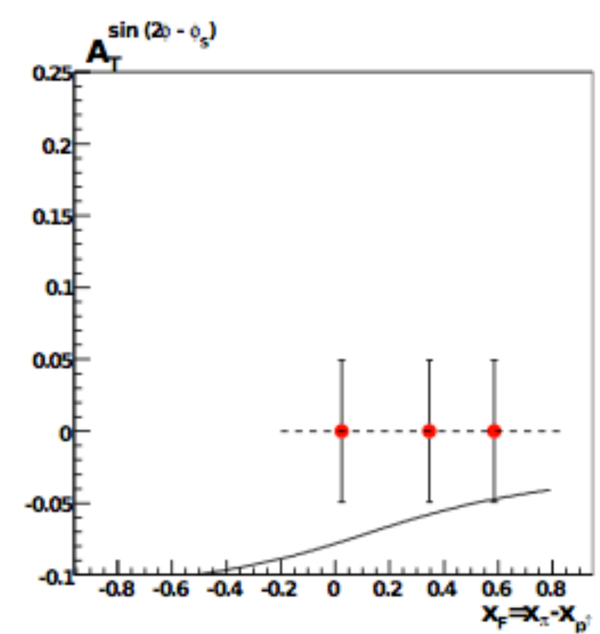
Sivers



Boer – Mulders



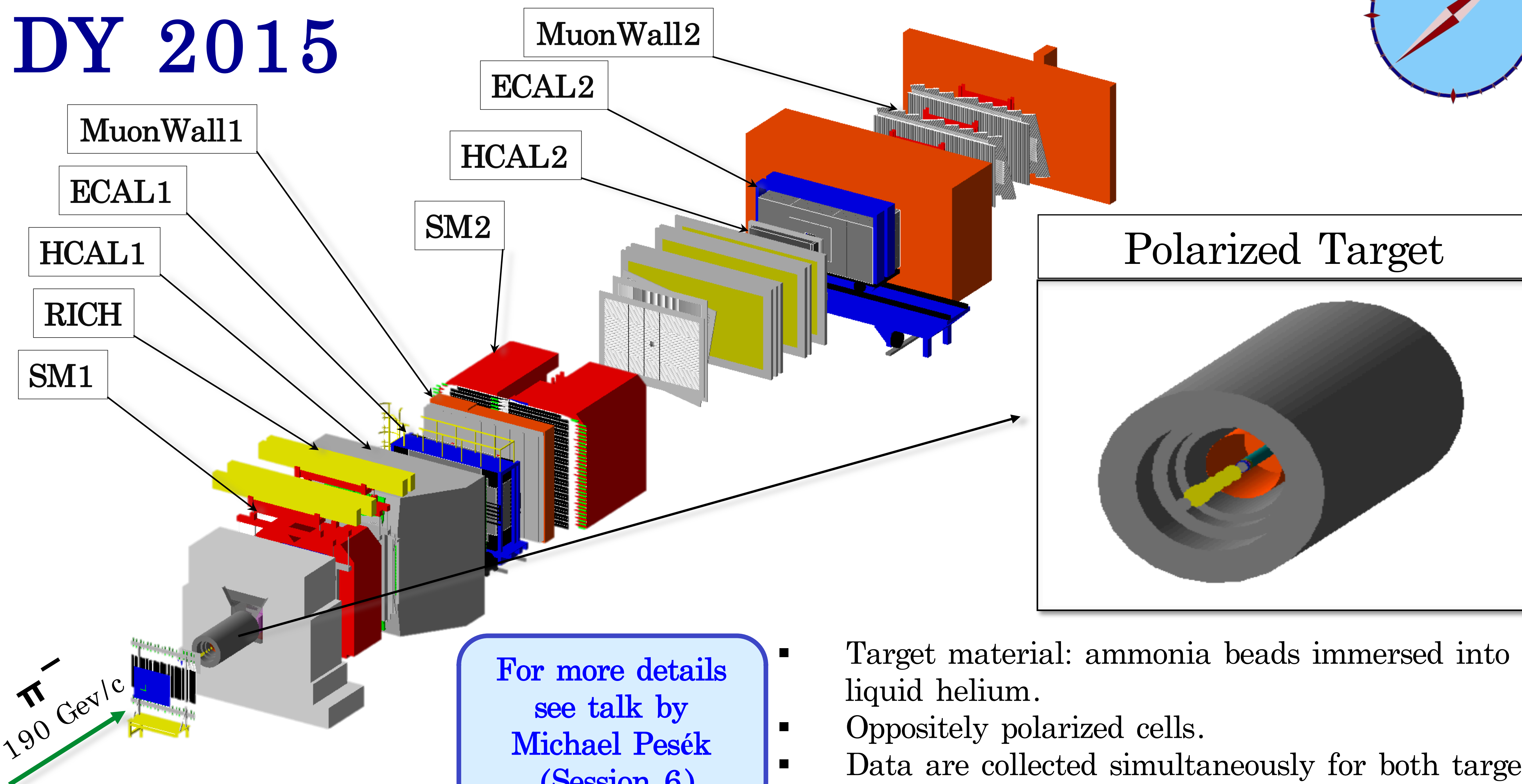
Transversity



Pretzelosity

$4 < M\mu\mu / (GeV/c^2) < 9$
High mass range

COMPASS experimental setup: DY 2015

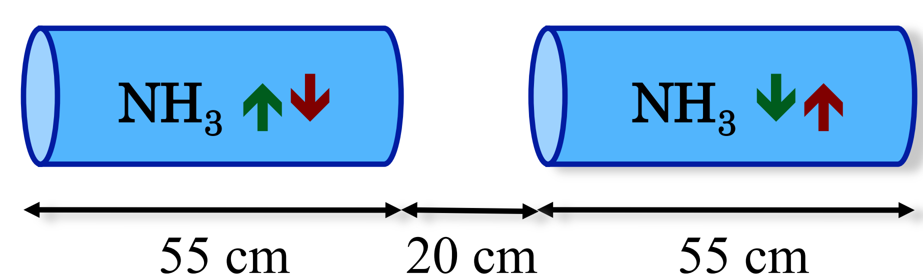


For more details see talk by Michael Pesék (Session 6)

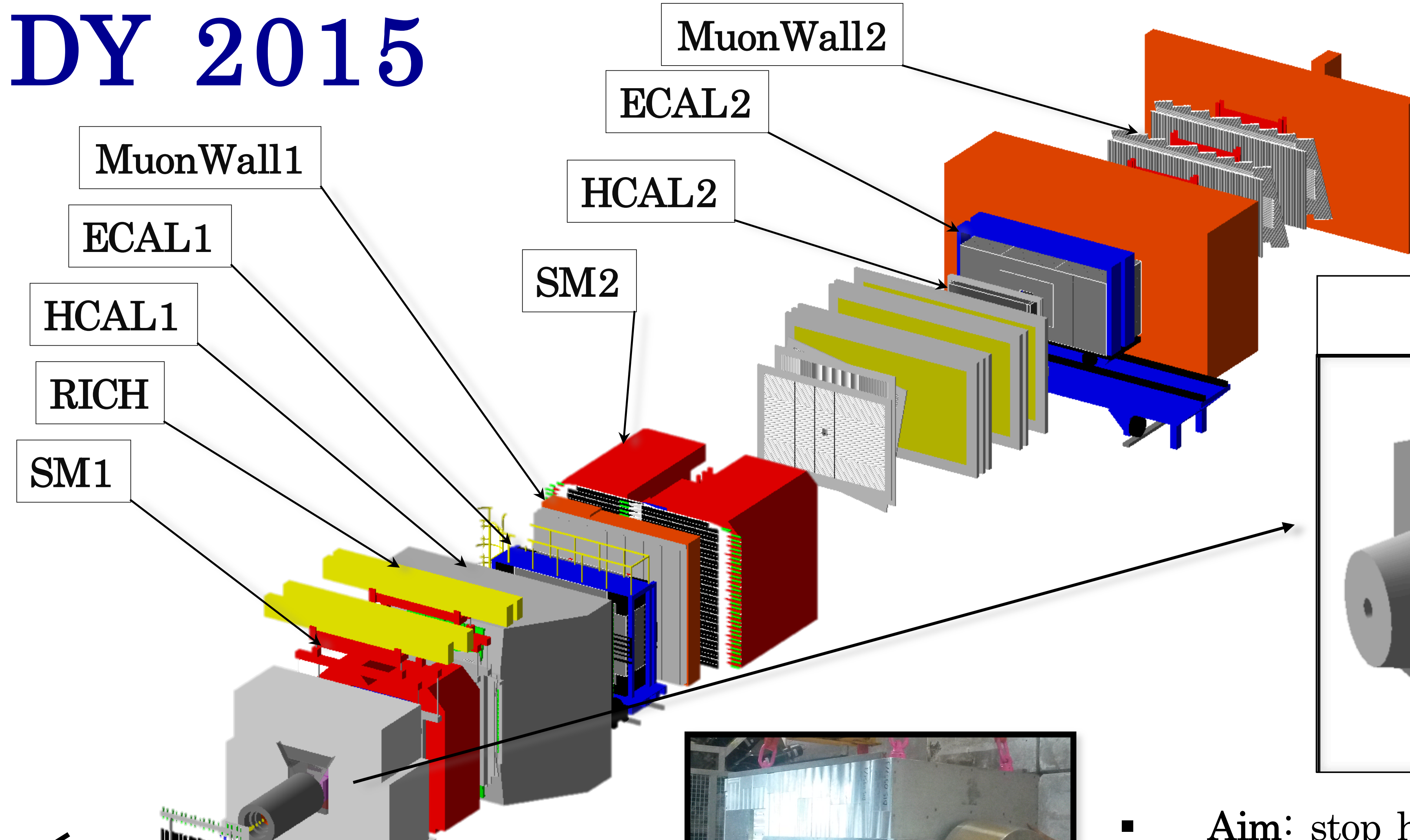
Setup for DY, $\pi^- + p^\uparrow \longrightarrow \mu^+\mu^- + X$

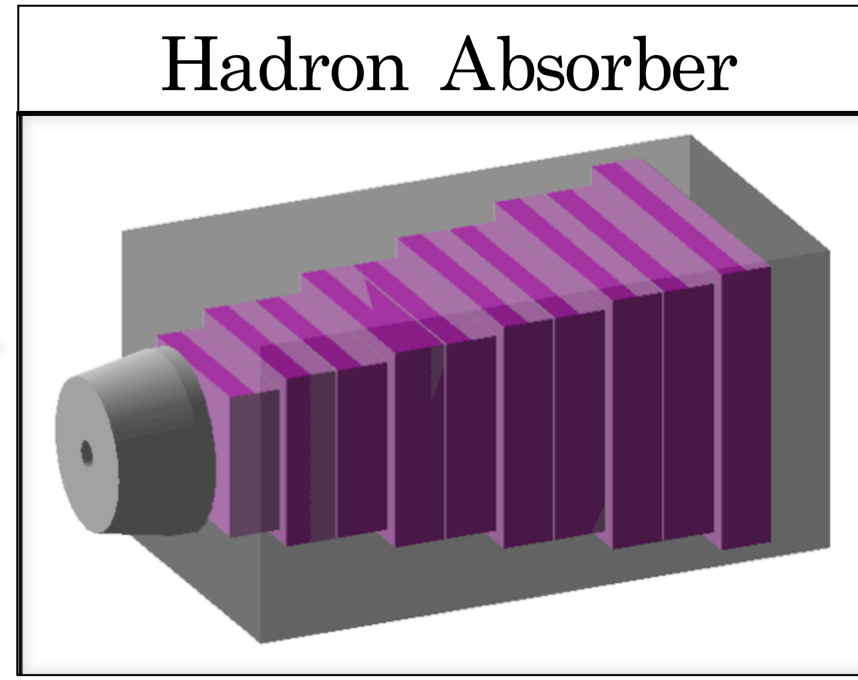
- Polarized Target

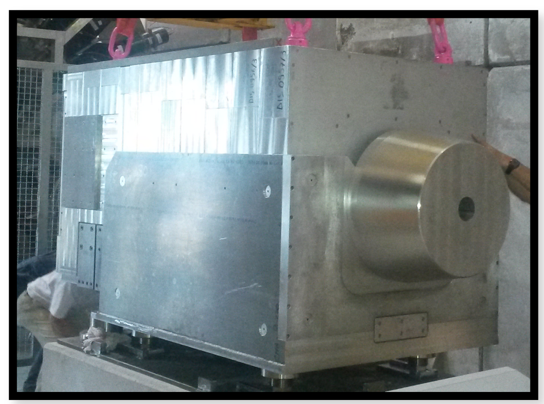
- Target material: ammonia beads immersed into liquid helium.
- Oppositely polarized cells.
- Data are collected simultaneously for both target spin orientation.
- Polarization reversal each 5 days, which allows to reduce possible systematics.
- Average polarization per cell ~ 80 %.



COMPASS experimental setup: DY 2015





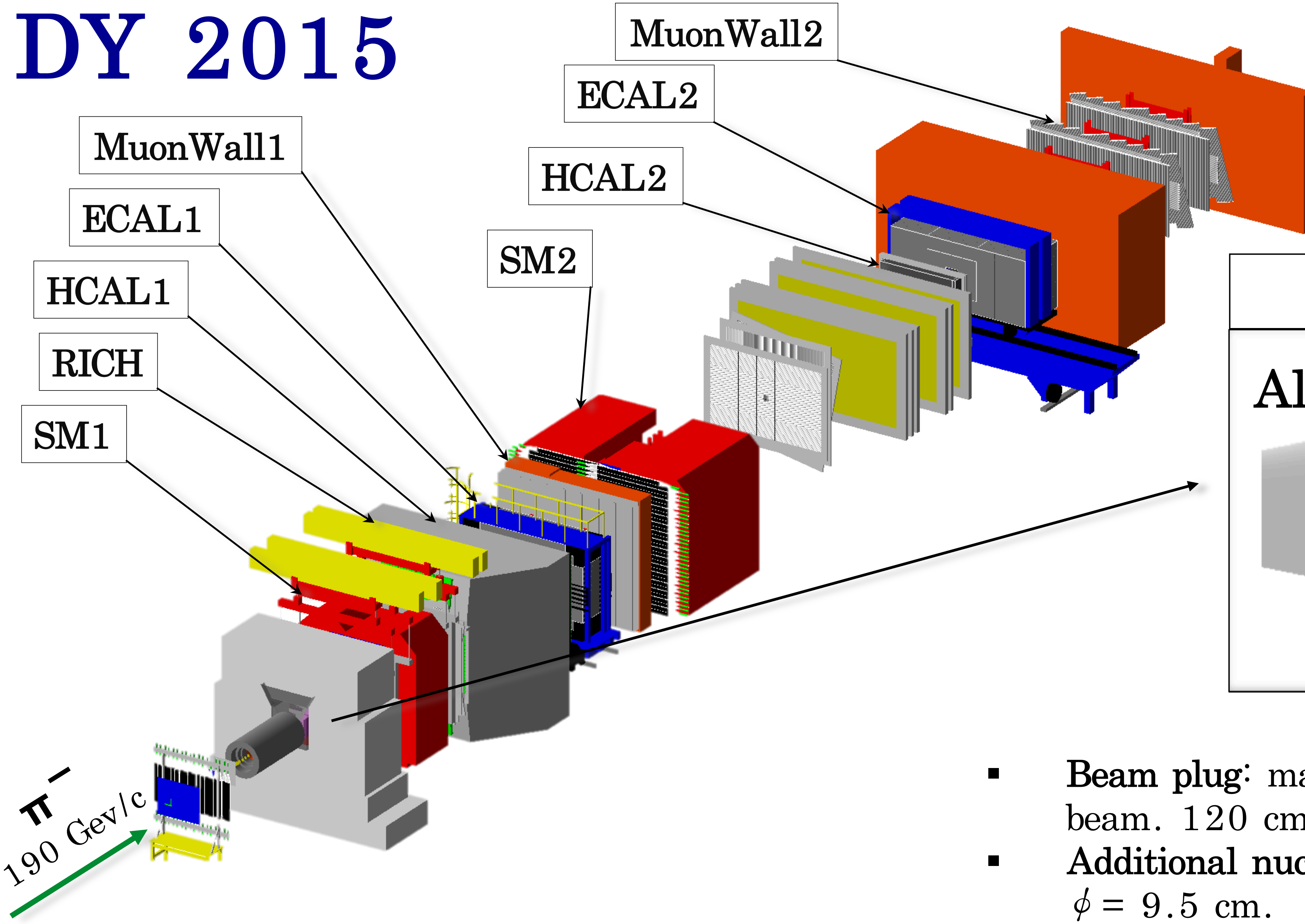


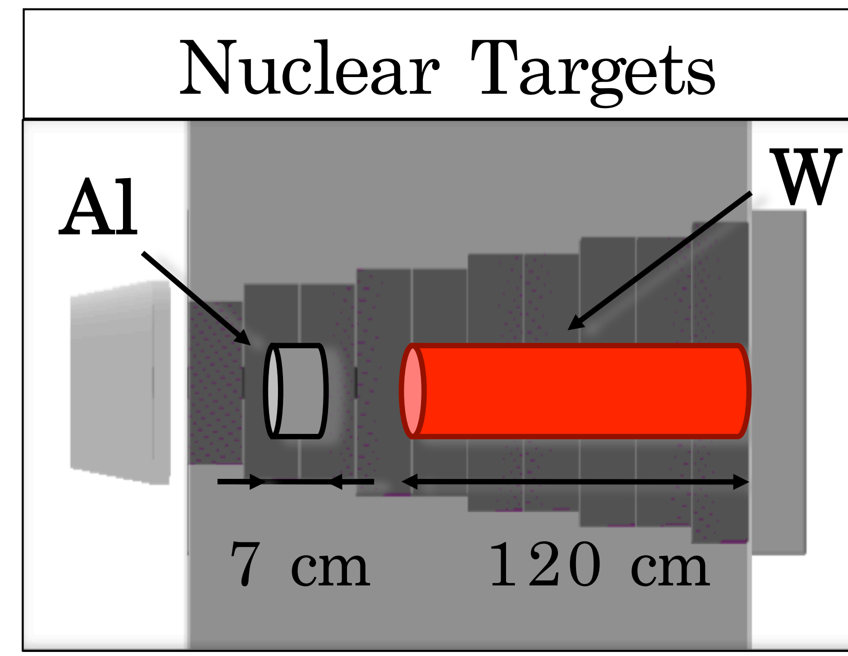
Setup for DY, $\pi^- + p^\uparrow \longrightarrow \mu^+\mu^- + X$

- Polarized Target
- Hadron Absorber

- **Aim**: stop hadron component of the secondary particles flux.
- **Requirements**: maximize hadron stopping power in the meanwhile keeping as low as possible multiple scattering and energy losses for leptons.
- **Structure**: stainless steel frames filled with alumina tiles; Two berillium and one polyethilene sheets before the last frame to stop n flux.

COMPASS experimental setup: DY 2015



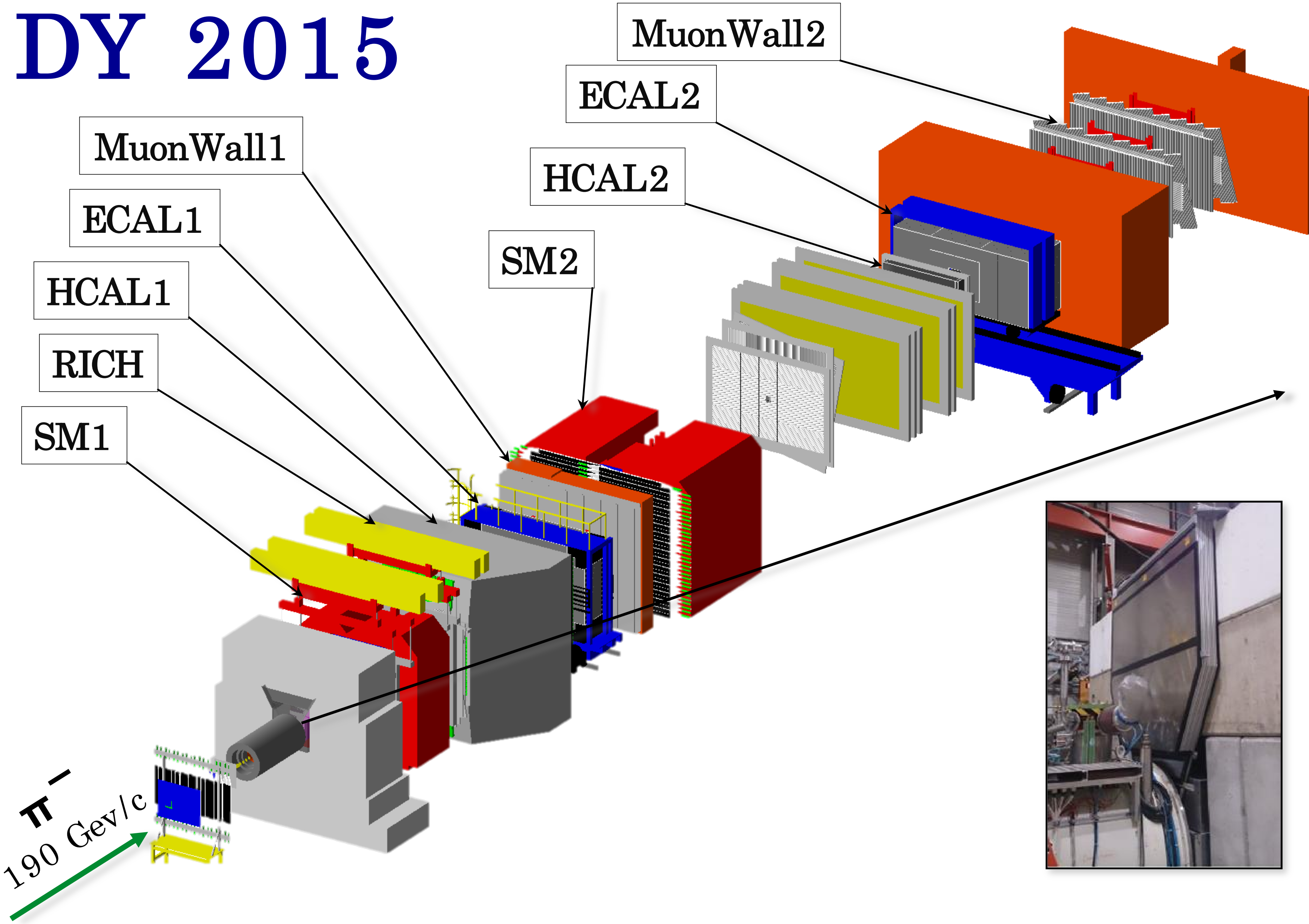


- **Beam plug**: made of tungsten, to stop the beam. 120 cm long, $\phi = 9.5 - 8.5$ cm.
- **Additional nuclear target**: Al, 7 cm long, $\phi = 9.5$ cm.
- Al + W plug → along with NH_3 is another source for unpolarized DY data.
- Higher yield due to density of the materials.
- Lower reconstruction and vertex resolution with respect to NH_3

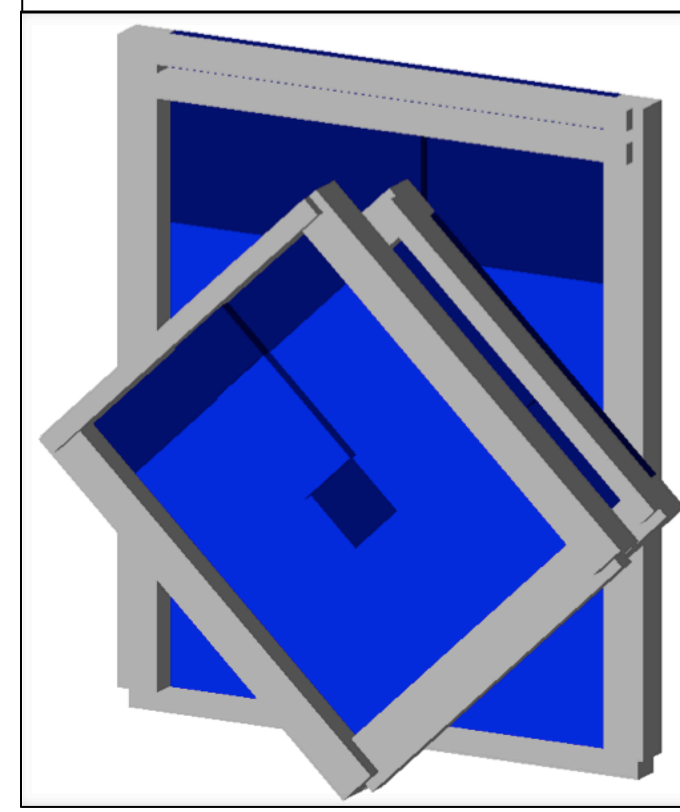
Setup for DY, $\pi^- + p^\uparrow \longrightarrow \mu^+\mu^- + X$

- Polarized Target
- Hadron Absorber
- Nuclear Targets

COMPASS experimental setup: DY 2015



Vertex Detector

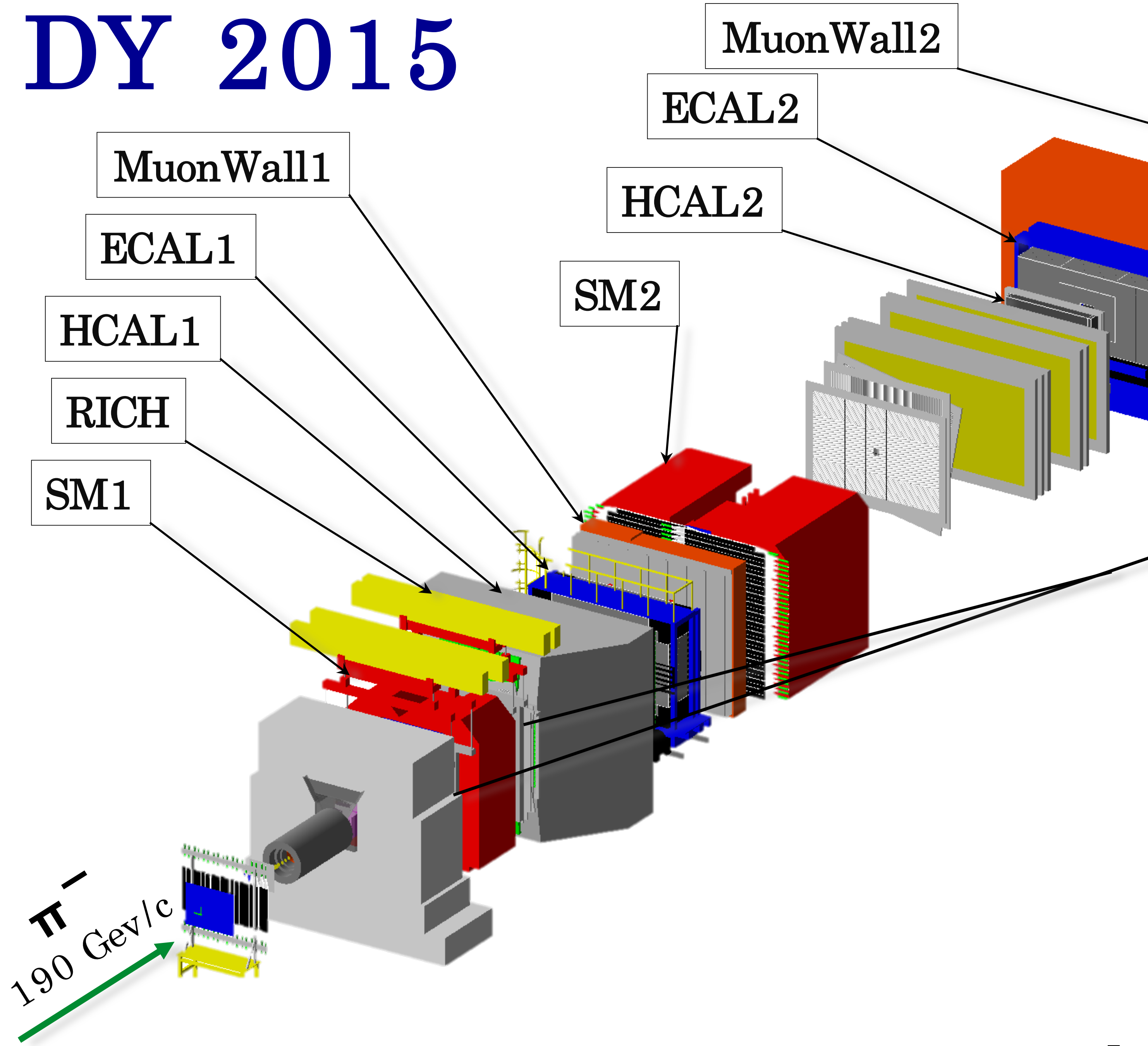


- Made by scintillating fiber planes (X,V,U).
- Time resolution ~ 700 ps → capability to operate at high event rate.
- Inserted in the gap between the absorber and its nose (~6 cm).
- **Aim**: improvement of the vertex resolution in NH_3 ~15 cm → ~4 cm.

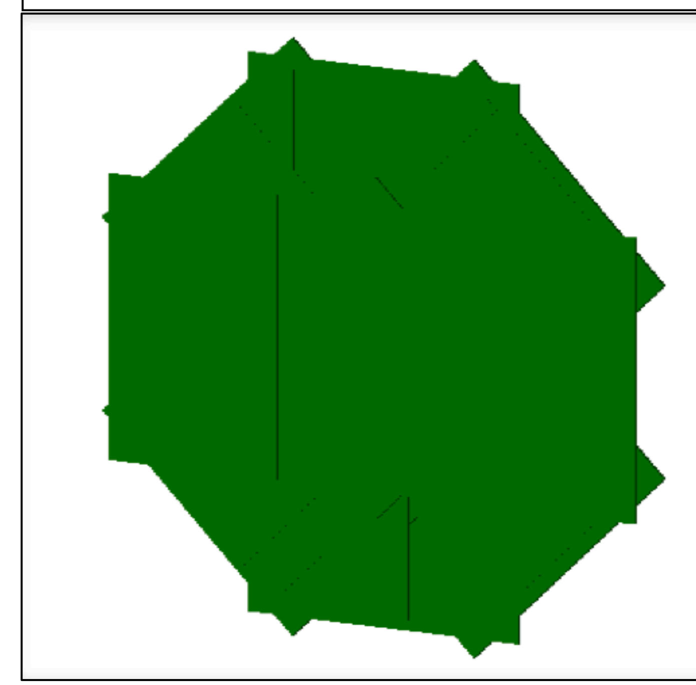
Setup for DY, $\pi^- + p^\uparrow \longrightarrow \mu^+\mu^- + X$

- Polarized Target
- Hadron Absorber
- Nuclear Targets
- Vertex detector

COMPASS experimental setup: DY 2015



Pixel Micromegas

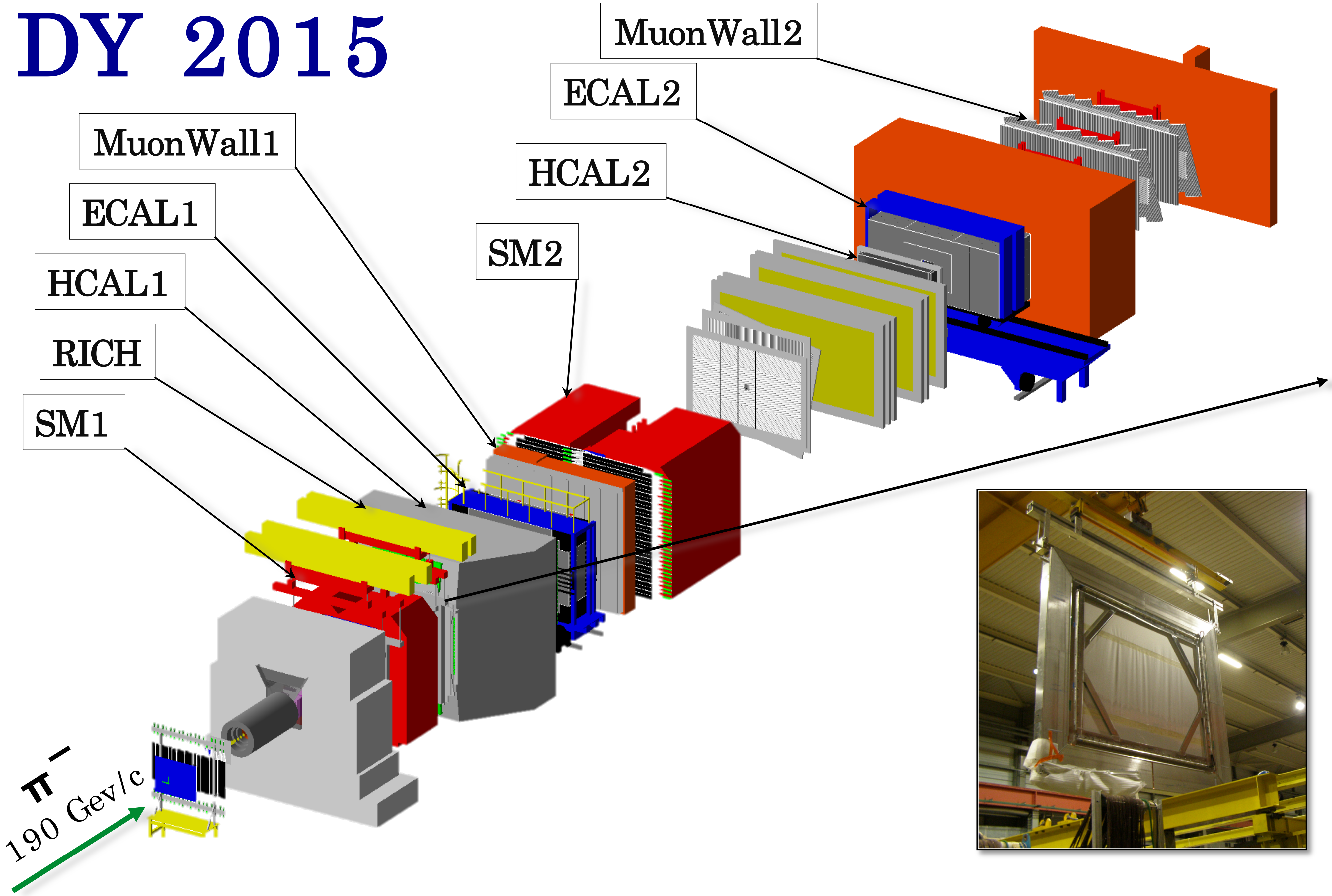


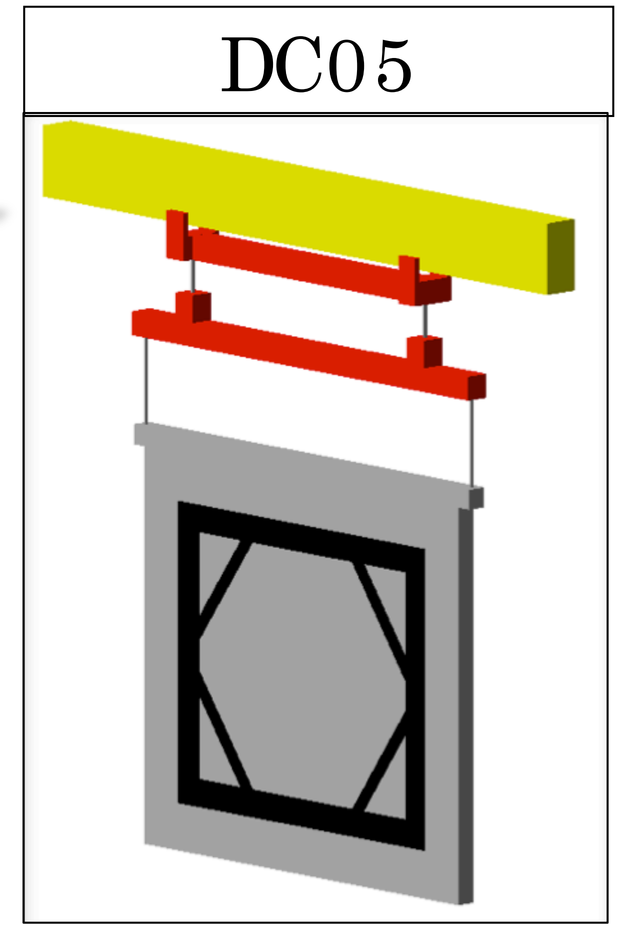
Setup for DY, $\pi^- + p^\uparrow \longrightarrow \mu^+\mu^- + X$

- Polarized Target
- Hadron Absorber
- Nuclear Targets
- Vertex detector
- Pixel Micromegas

- Tracking detector
- Hybrid MM with GEM foil.
- 3 stations (just 1 during the pilot run 2014) with 4 planes each one (X,Y,U,V) installed in LAS.
- Spatial resolution: 60 um.
- Time resolution: 9 ns.

COMPASS experimental setup: DY 2015





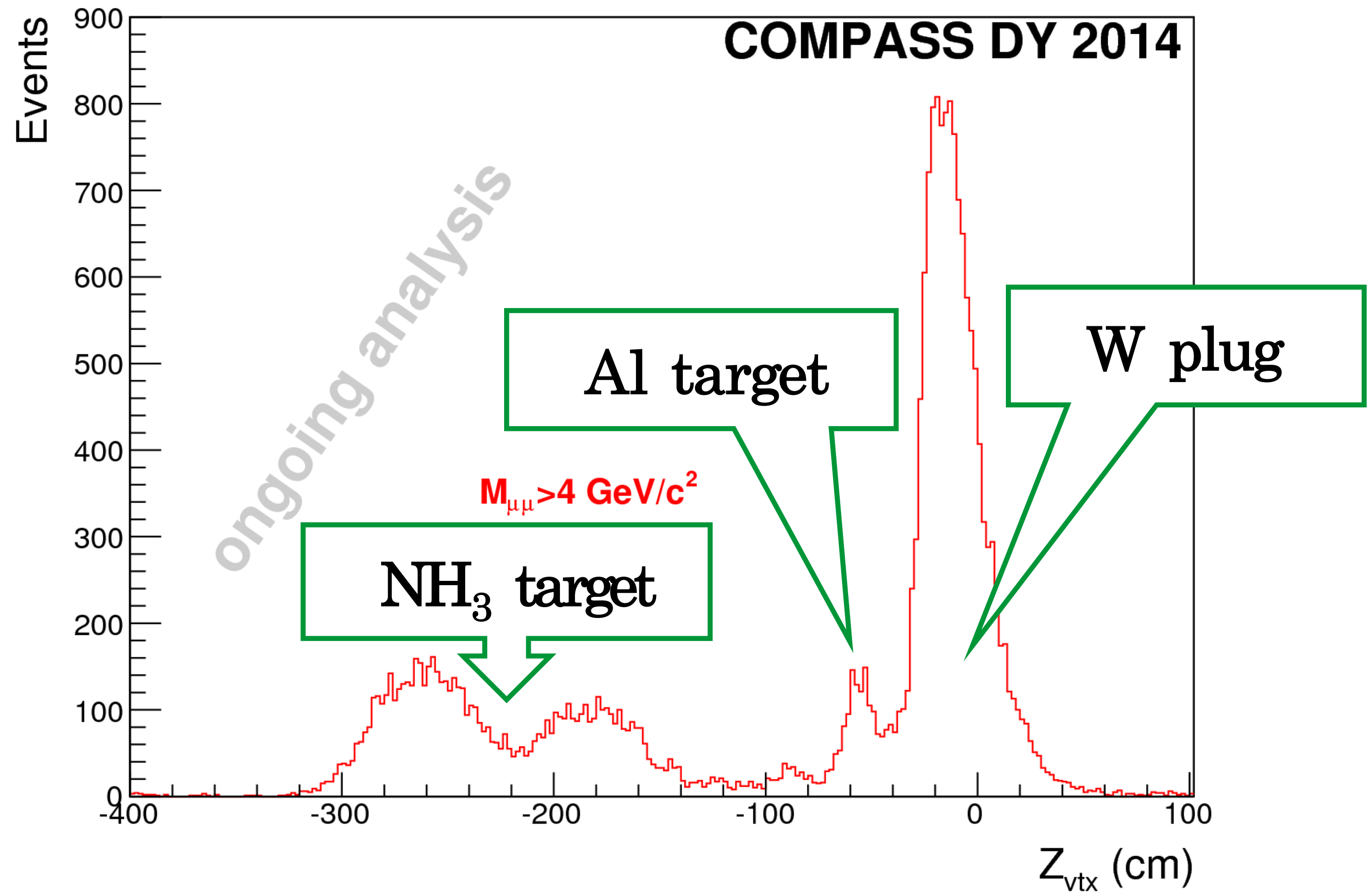
Setup for DY, $\pi^- + p^{\uparrow} \longrightarrow \mu^+\mu^- + X$

- Polarized Target
- Hadron Absorber
- Nuclear Targets
- Vertex detector
- Pixel Micromegas
- DC05

- New large area Drift Chamber in LAS.
- Aim to increase the tracking power.
- Installed in April 2015.
- 8 planes.
- 6 available now and 2 more from 2016.

DY Pilot Run 2014

- To prepare the spectrometer for the 2015 run, two months of pilot run have been done in October-November 2014. The experimental conditions were not exactly the final ones:
  - No target polarization.
  - DC05 and 2 stations of PMM were not yet installed.
  - Different beam conditions (beam intensity ~ $7 \cdot 10^7$ π^-/s).
  - ~ 10 days of stable data taking have been performed. The **analysis is ongoing**!



z vertex distribution

- Clear signal from all the targets (NH_3, Al, W).
- Good enough vertex z-resolution. To be improved with fully operational VD in 2015 and tuned reconstruction algorithms

DY Pilot Run 2014

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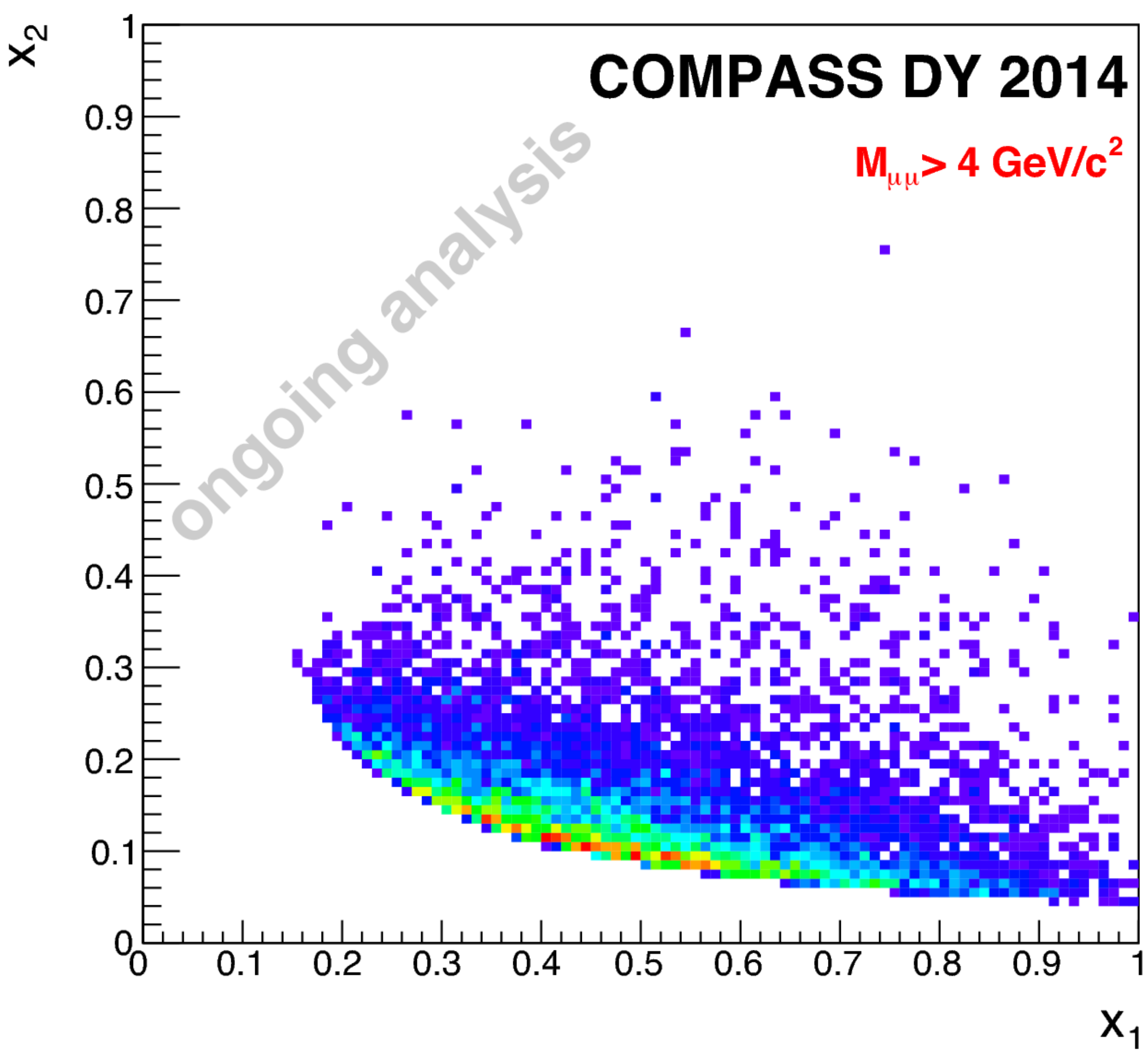
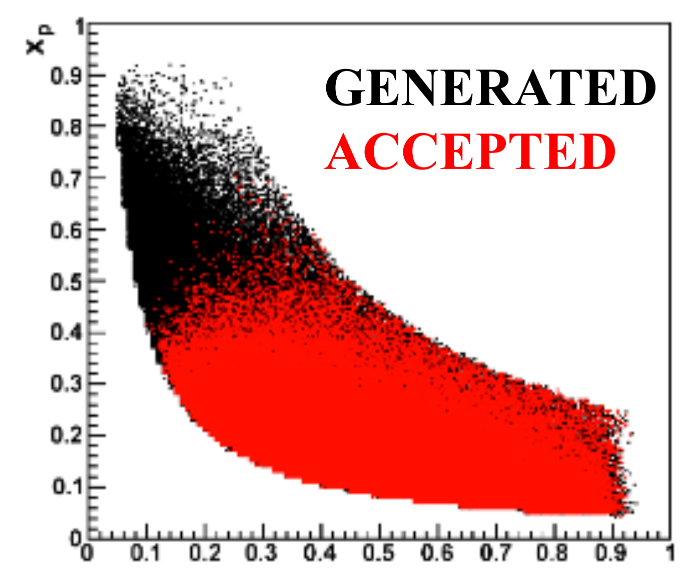


x1:x2 phase space

- Valence quark region (x_1, x_2 > 0.05)
- In agreement with MC simulations



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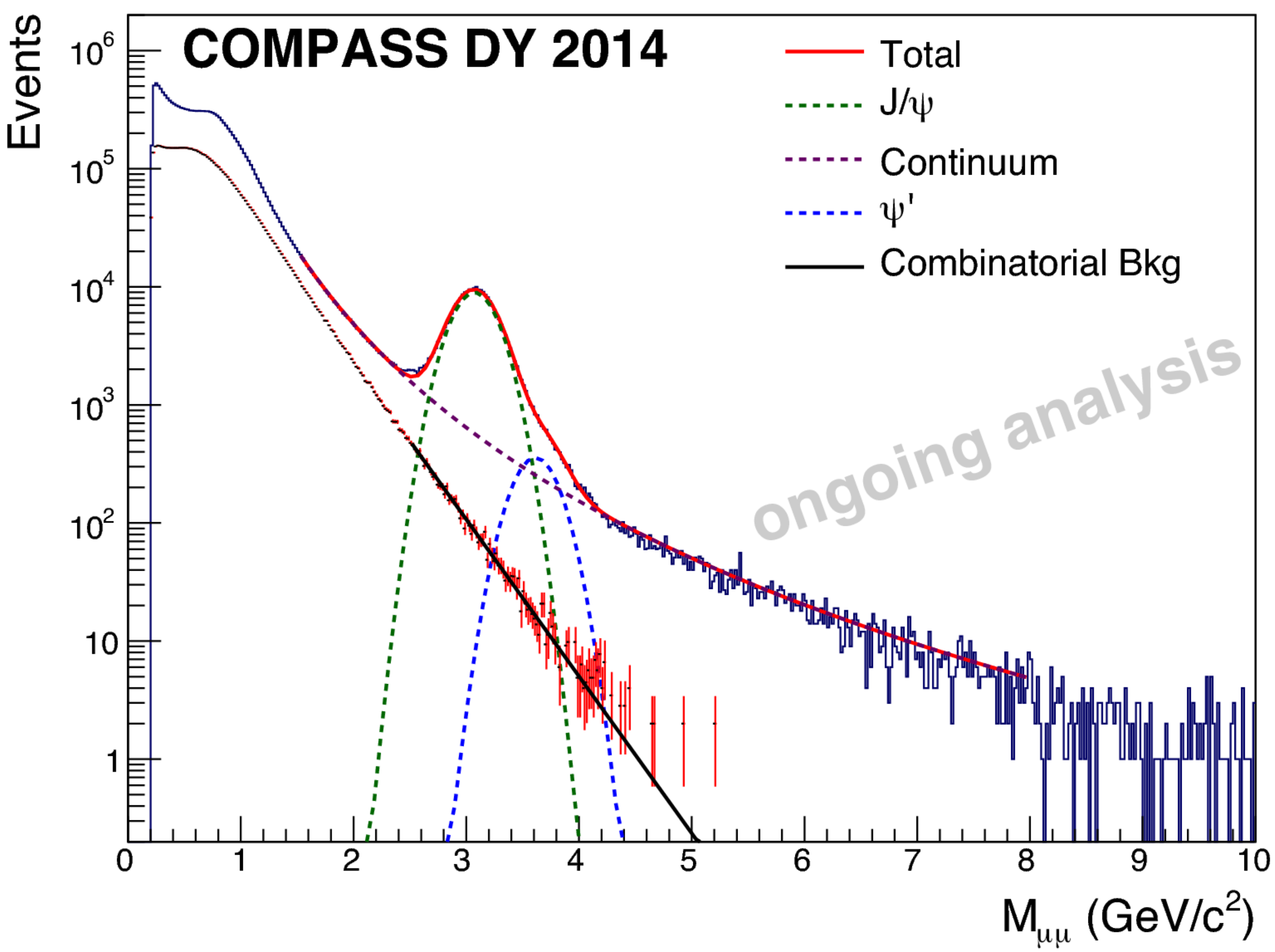
  - $\sim$ 10 days of stable data taking have been performed. The **analysis is ongoing**!



Invariant mass spectrum

- Clear J/ψ signal

DY Pilot Run 2014

- To prepare the spectrometer for the 2015 run, two months of pilot run have been done in October-November 2014. The experimental conditions were not exactly the final ones:
  - No target polarization.
  - DC05 and 2 stations of PMM were not yet installed.
  - Different beam conditions (beam intensity ~ $7 \cdot 10^7\ \pi^- / s$).
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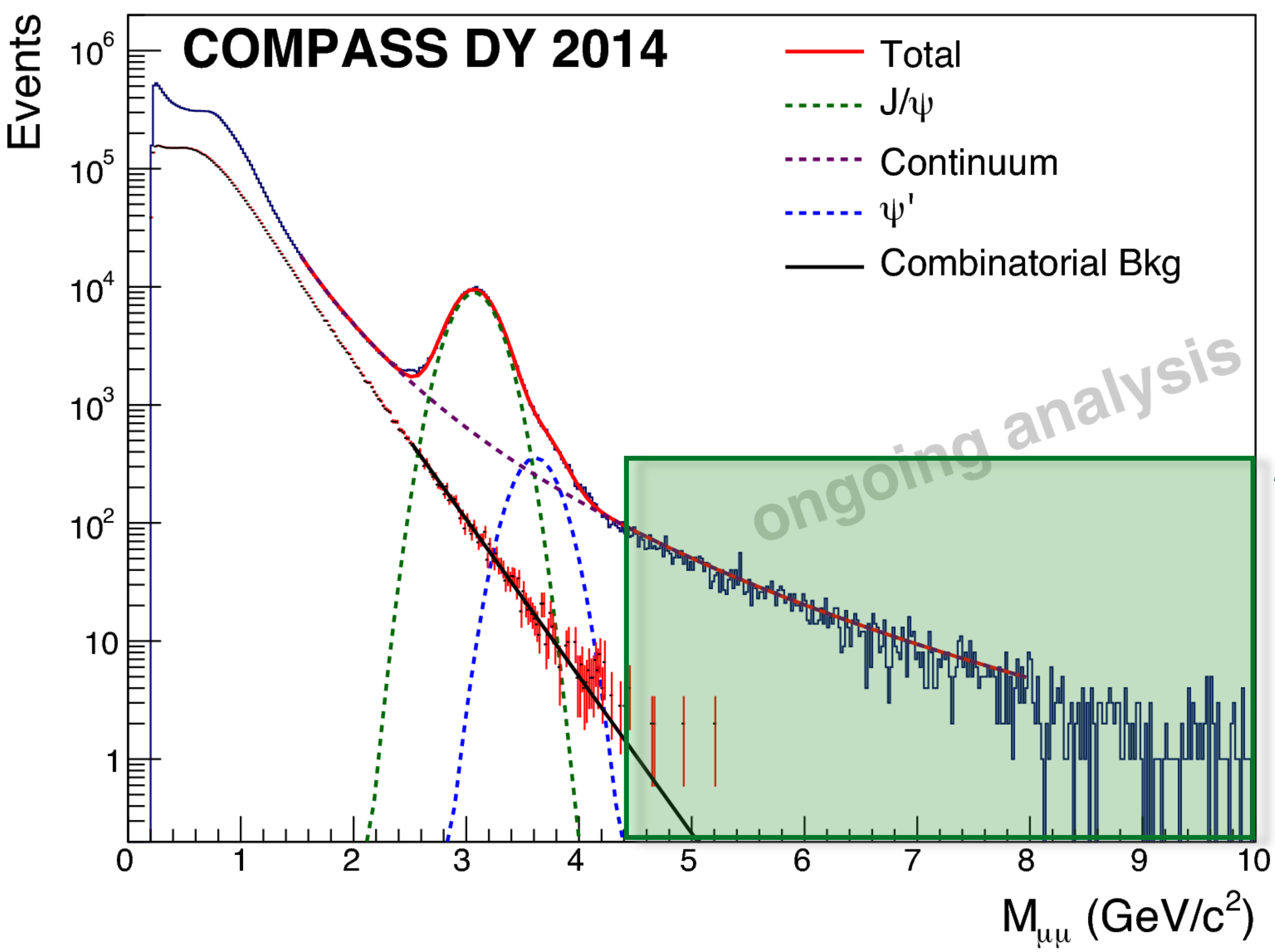


Invariant mass spectrum

- Clear J/ψ signal.
- First COMPASS unpolarized DY data finally are here!

At this very moment COMPASS is recording first ever polarized DY data!

Conclusions

- The DY and SIDIS process are complementary ways to access TMD PDFs.
- The COMPASS Collaboration took a considerable amount of SIDIS data during the Phase I.
- Variety of theoretical models have been developed in past years. Experimental data are needed to constrain them.
- COMPASS will be the first experiment to measure 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 studies with *unpolarized*-data from different nuclear targets
- Two months of pilot run have been made in October-November 2014, to tune experimental setup for 2015 run.
- The experiment is taking the first ever single polarized DY data at this very moment!

The COMPASS SIDIS-DY bridge

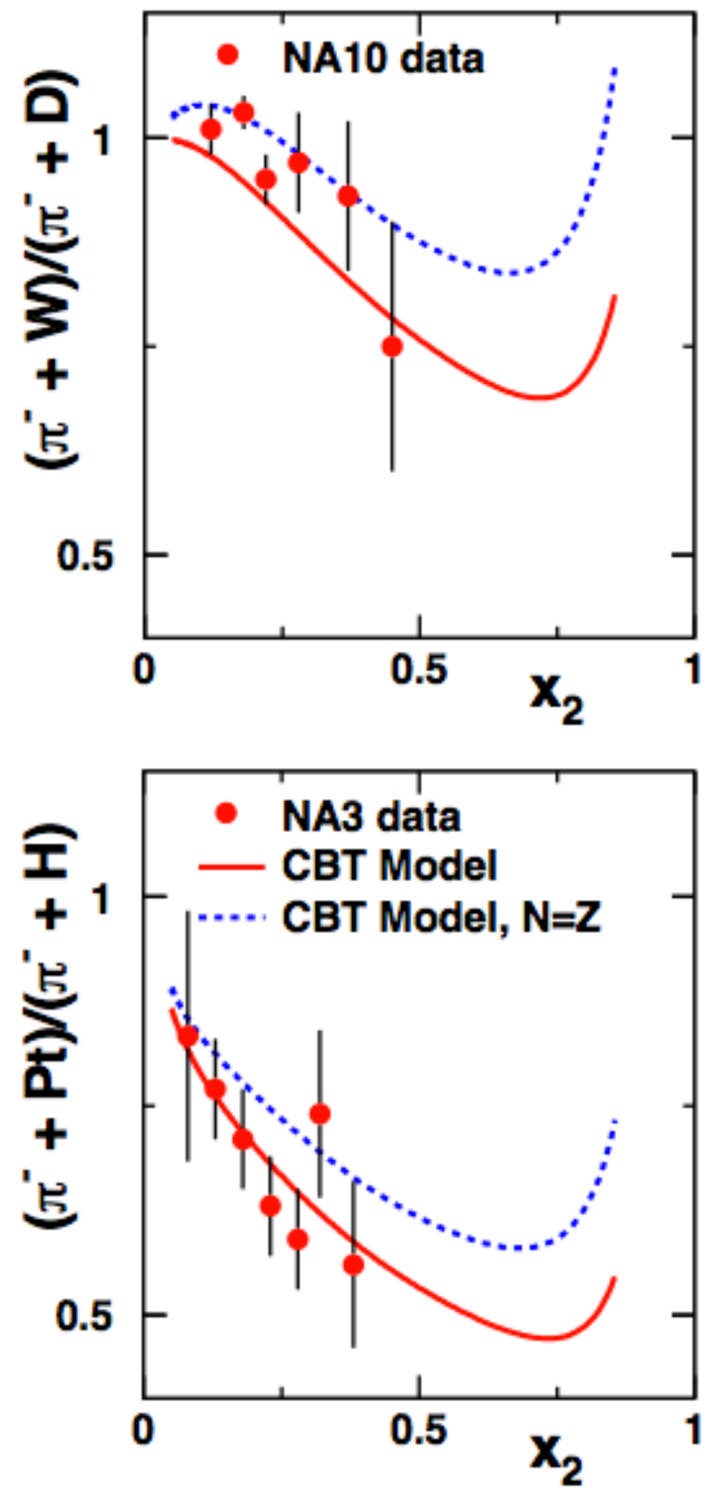
Thank you!

Spare Slides

Beyond polarized program…

- Several studies beyond the polarised DY measurements are possible, thanks to the use of nuclear targets:
  - Unpolarized analysis → measurements of λ, μ, ν
  - Flavor dependent EMC effect:
    - EMC effect → Observed modifications in quark distribution inside nuclei.
    - Cloet, Bentz and Thomas (CBT) model try to explain this effect on a flavor dependence basis.
    - u and d quarks have distinct nuclear modifications for N ≠ Z nuclei.
    - A way to study the flavor dependence is via the A dependence, where the rations proton/neutron (and then u/d) is different.
    - More data are needed to get a conclusion

D.Dutta et al., "*Pion-induced Drell-Yan processes and the flavor-dependent EMC effect*", PHISICAL REVIEW C 83,04220

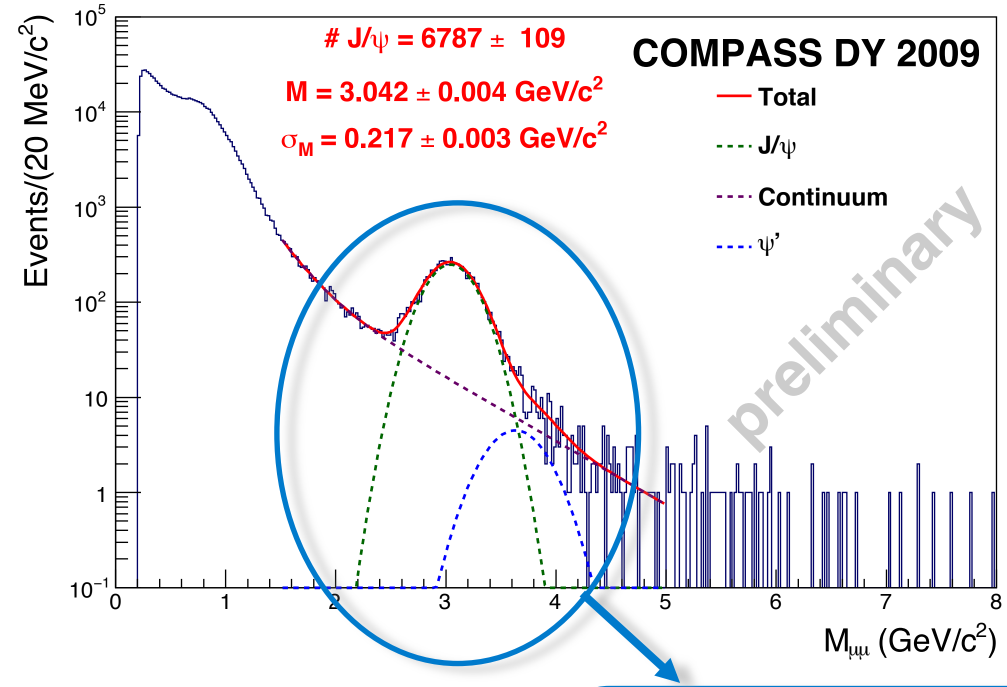


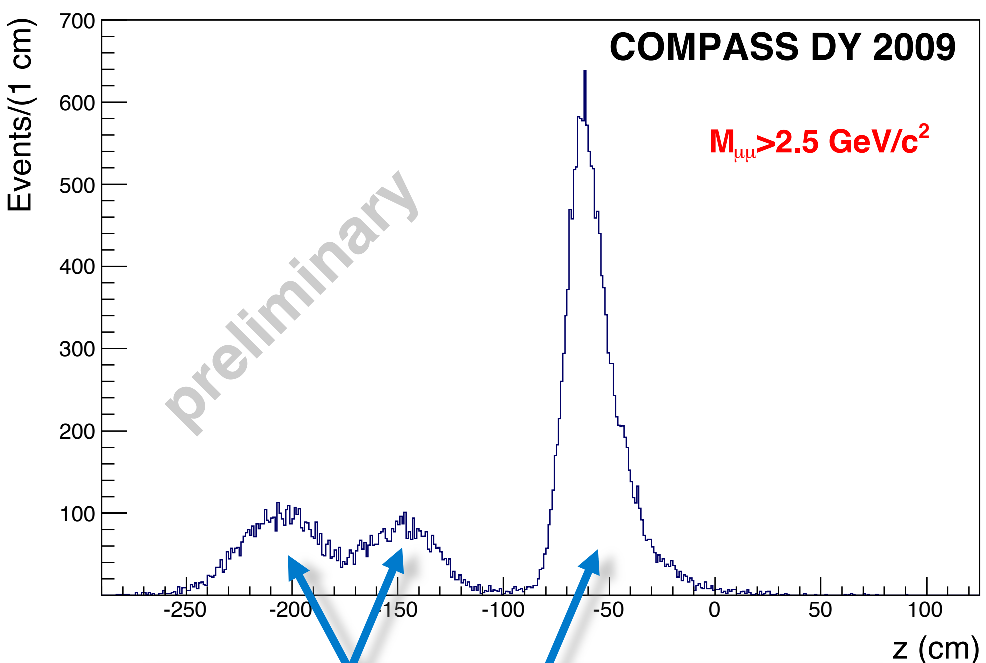
Target	N	Z	A
NH_3	7	10	17
Al	14	13	27
W	110	74	184

Making use of several targets, COMPASS can add useful informations to test the models!

Feasibility: beam test 2009

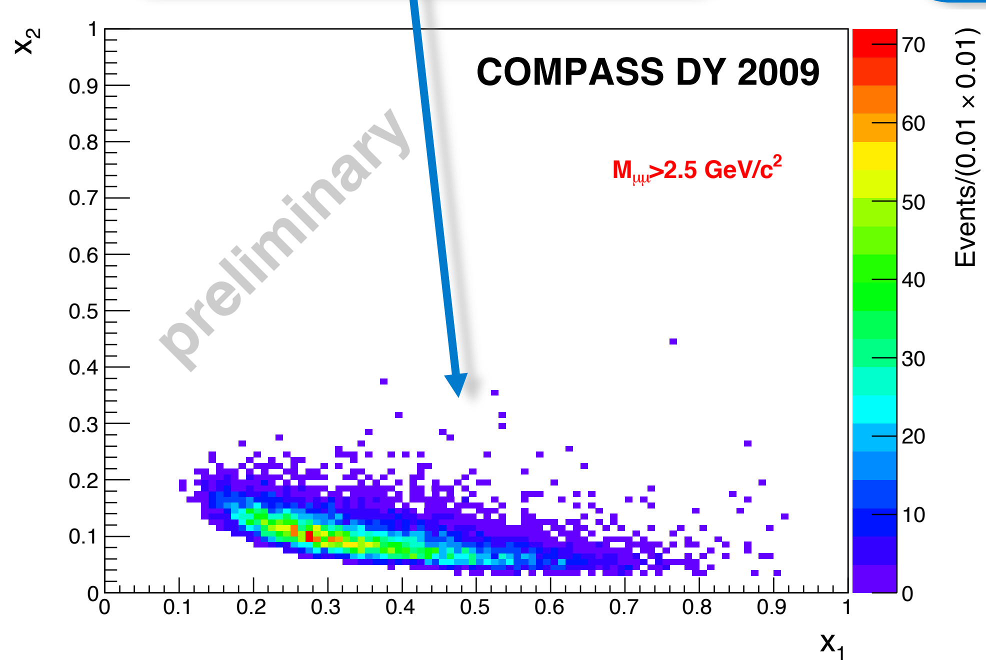
- 3 days of data taking in 2009, using:
  - A hadron absorber prototype.
  - Two cells polyethilene target.
  - π^- @ 190 GeV/c and I = $1.5 \cdot 10^7\ \pi^-$/s.
  - Double trigger based on calorimeter signal.





Expected J/Ψ yield (taking into account low efficiencies)

Valence quark region explored



Target cells and W plug clearly visible even if the absorber wwas just a prototype.

Required improvements:
- Vertexing
- Absorber
- Tracking
- Trigger

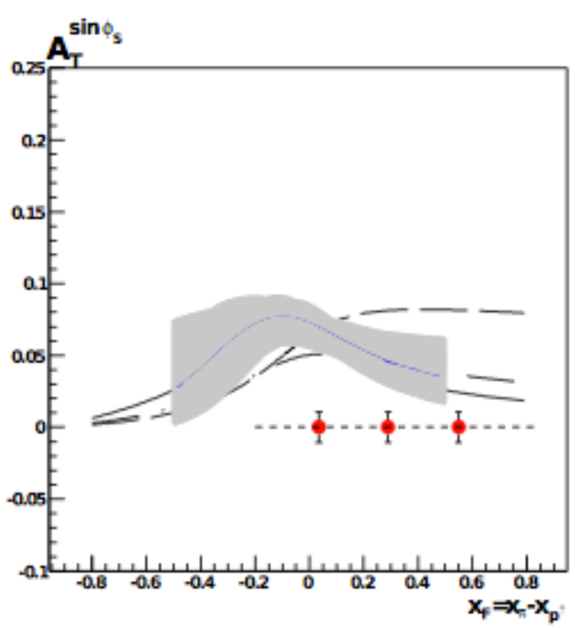
Expected accuracy

Values for expected statistical accuracies for different asymmetries as estimated in the COMPASS II Proposal

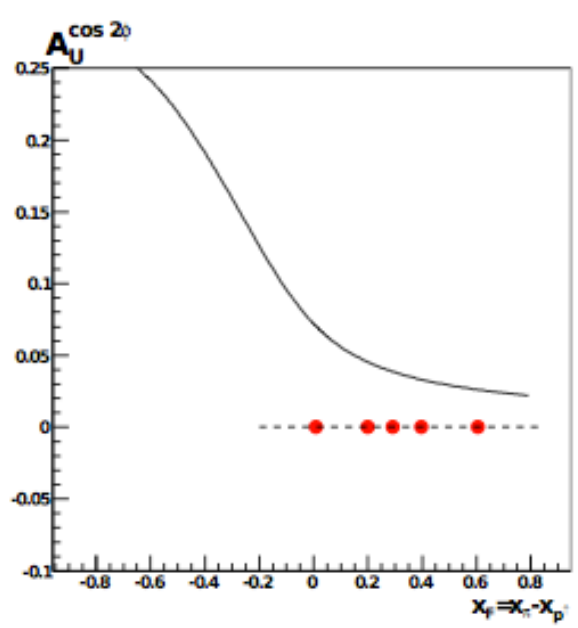
Asymmetry	Dimuon mass (GeV/c^2)		
	$2 < M_{\mu\mu} < 2.5$	J/ψ region	$4 < M_{\mu\mu} < 9$
$\delta\, A_U^{\cos 2\phi}$	0.0020	0.0013	0.0045
$\delta\, A_T^{\sin \phi_S}$	0.0062	0.0040	0.0142
$\delta\, A_T^{\sin(2\phi+\phi_S)}$	0.0123	0.008	0.0285
$\delta\, A_T^{\sin(2\phi-\phi_S)}$	0.0123	0.008	0.0285

Expected DY rate in IM range: ~ 4800 DY/day

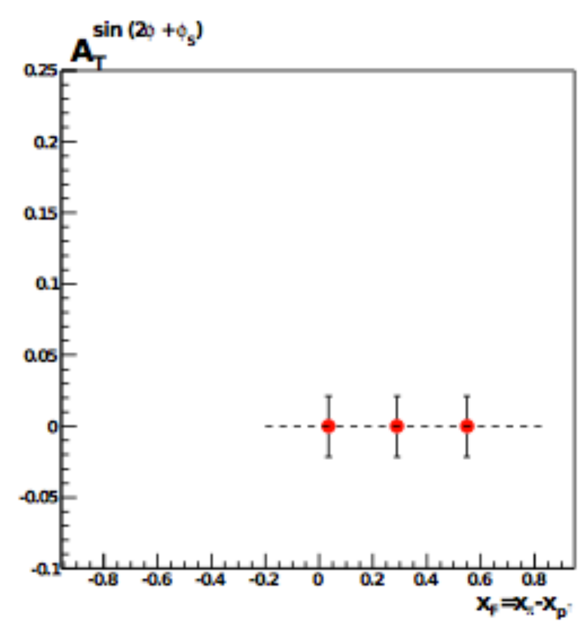
Expected statistical accuracy for two years of data taking



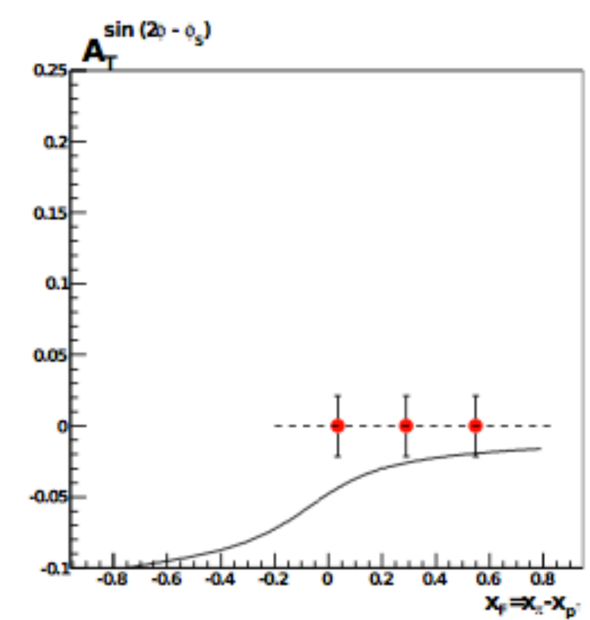
Sivers



Boer - Mulders



Transversity



Pretzelosity

2 < Mμμ / (GeV/c²) < 2.5
Intermediate mass range

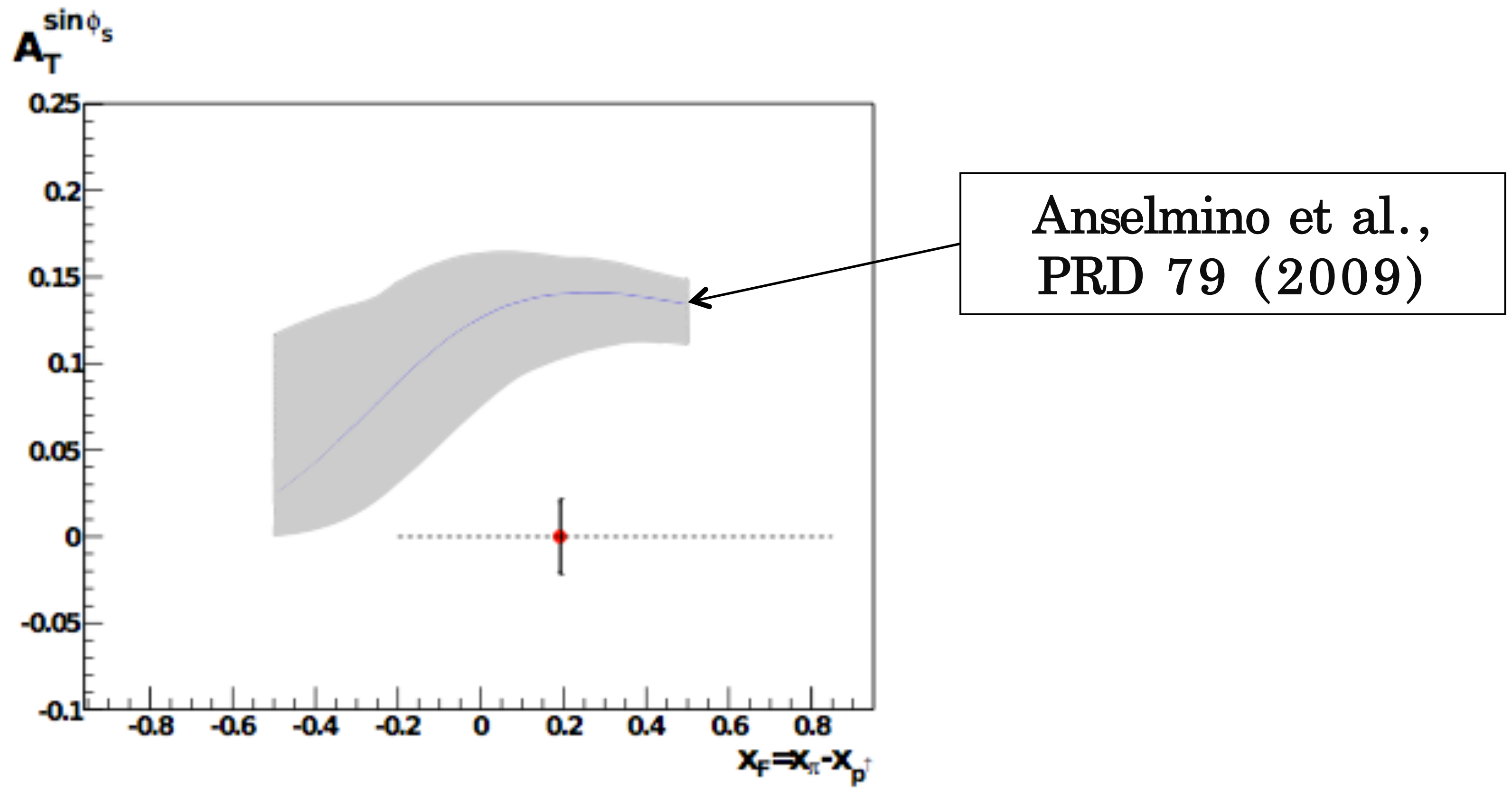
Expected accuracy

Values for expected statistical accuracies for different asymmetries as estimated in the COMPASS II Proposal

Expected DY rate in HM range: ~ 700 - 800 DY/day

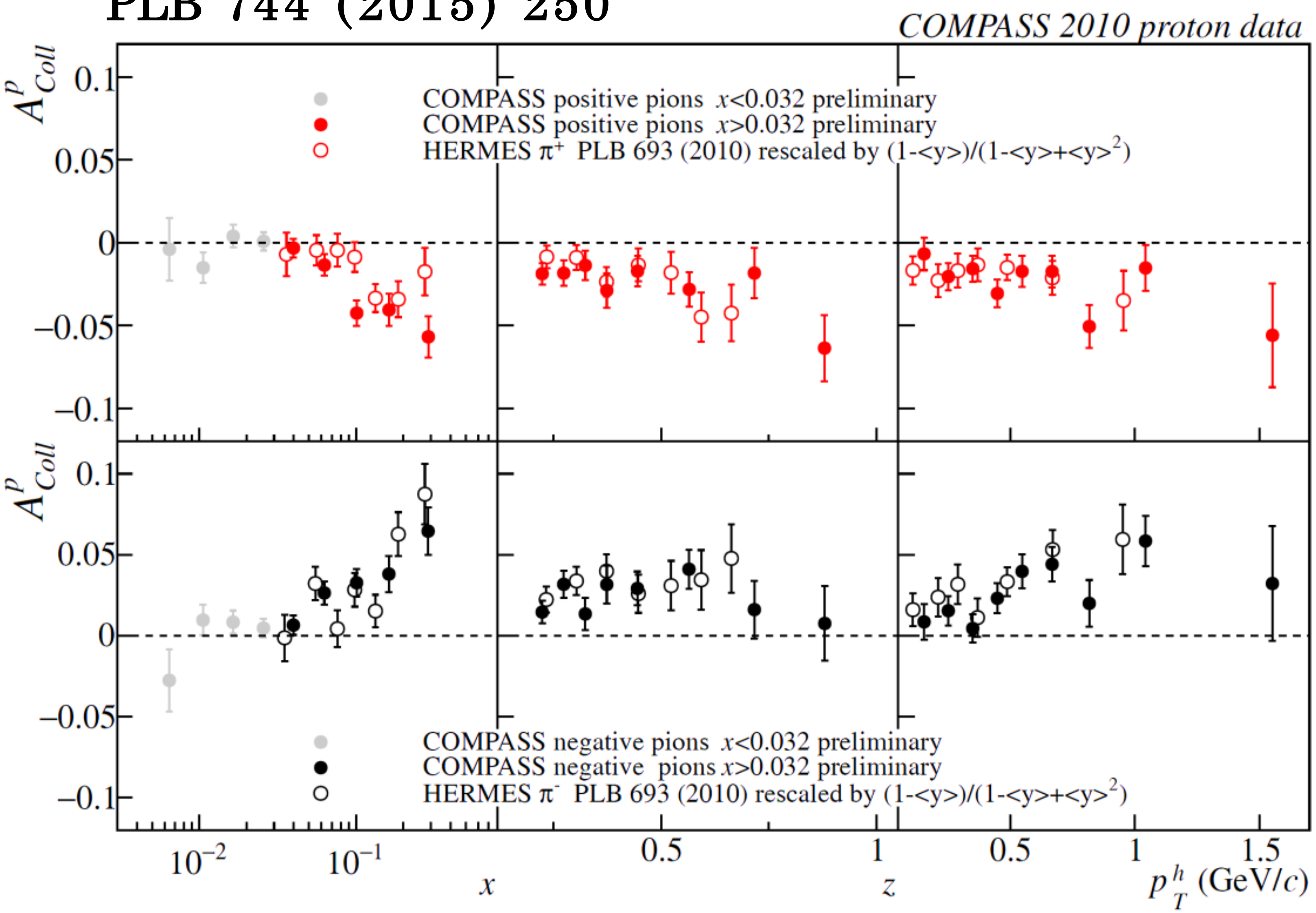
Expected statistical accuracy for one year of data taking

Sivers



COMPASS SIDIS results: Collins

PLB 744 (2015) 250

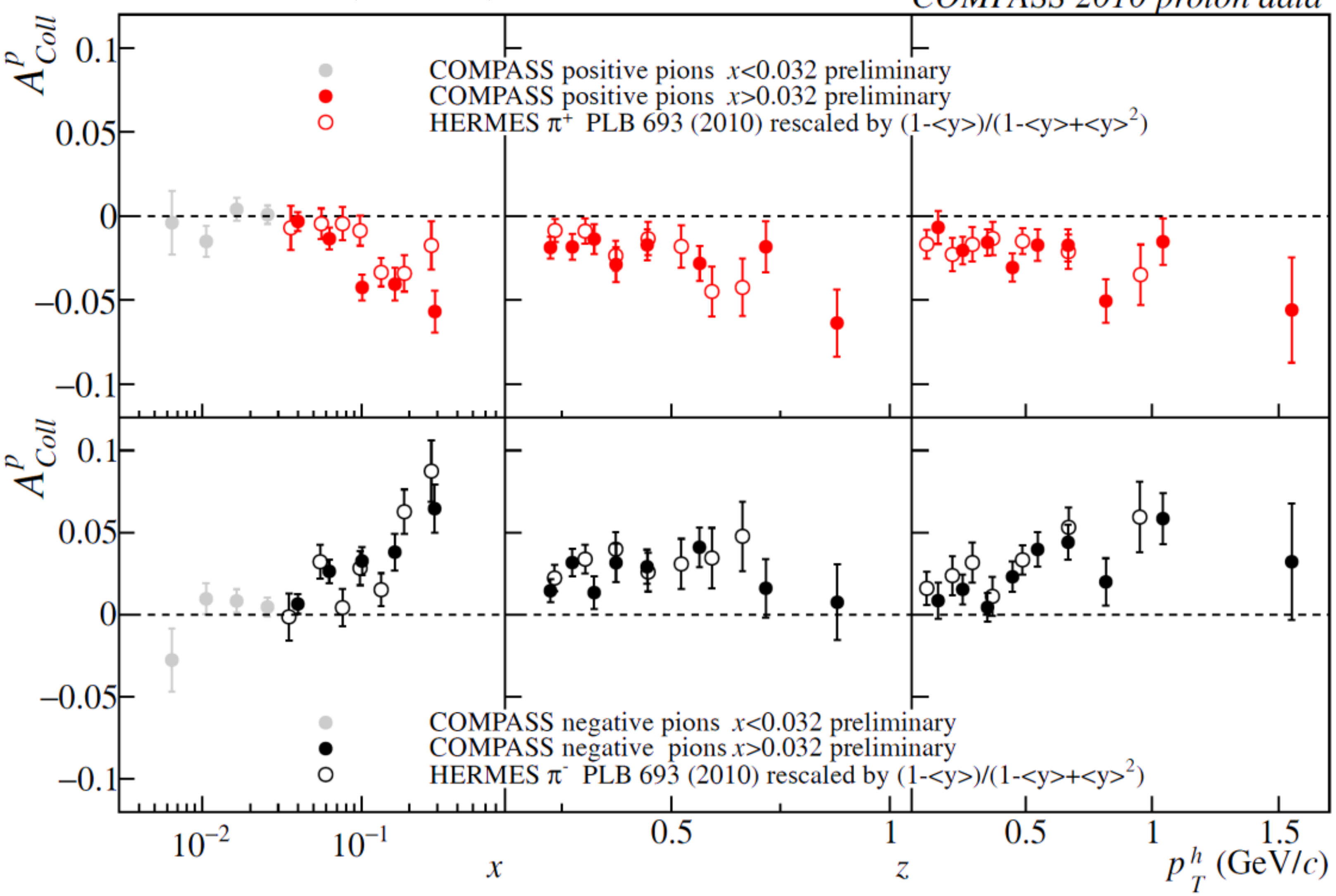


For more details see talk by Anna Martin (Session 6)

- Collins asymmetry : COMPASS proton vs Hermes proton.
- Clear effect at large x.
- Collins amplitudes for π^+ and π^- are mirror symmetric (favoured unfavoured Collins FF).

COMPASS SIDIS results: Collins

PLB 744 (2015) 250



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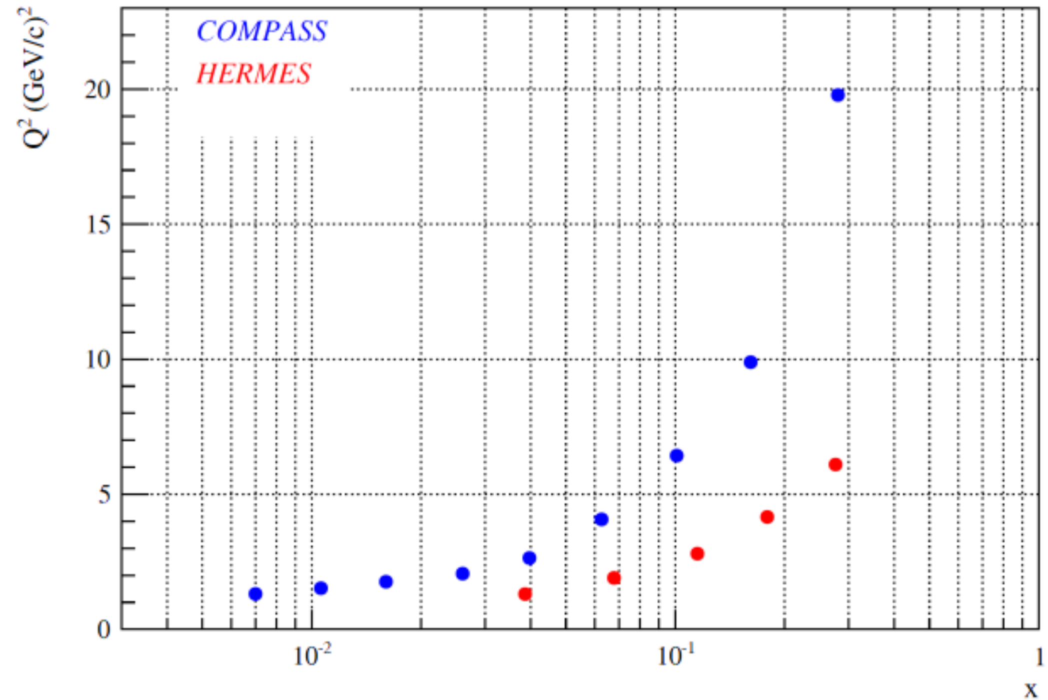
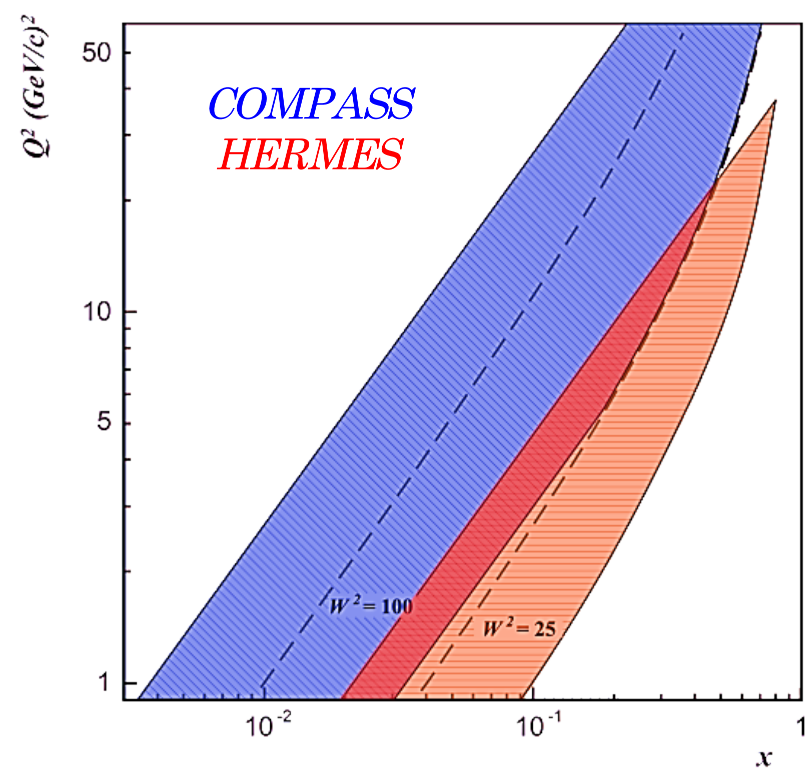
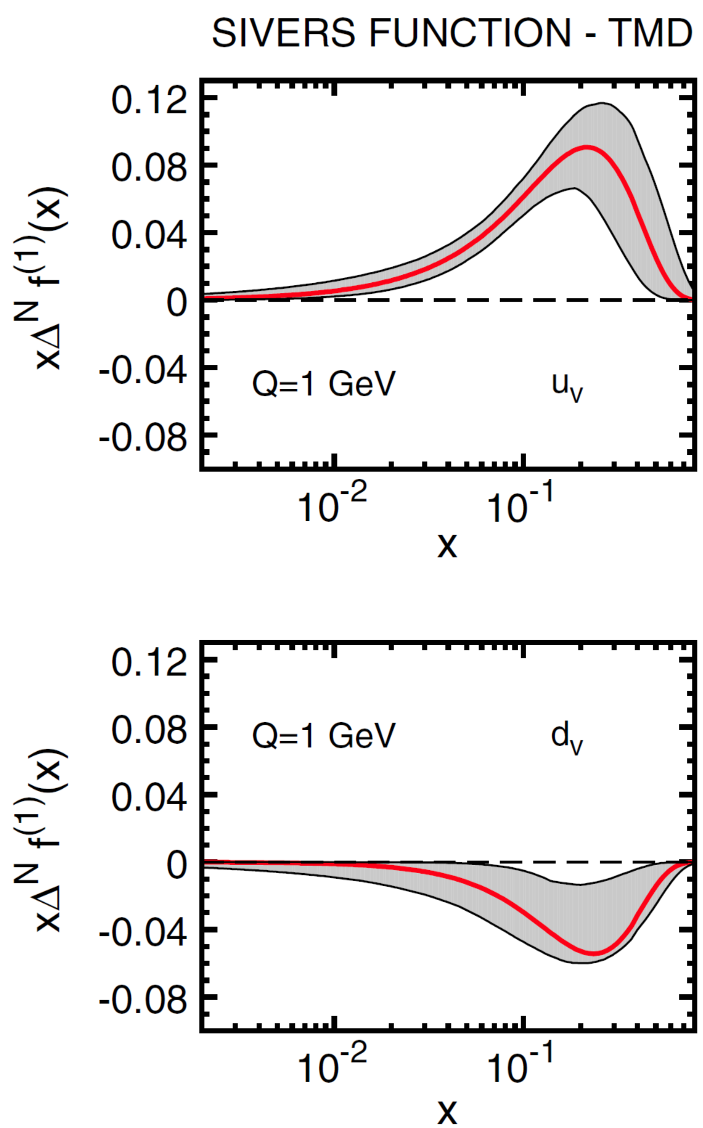


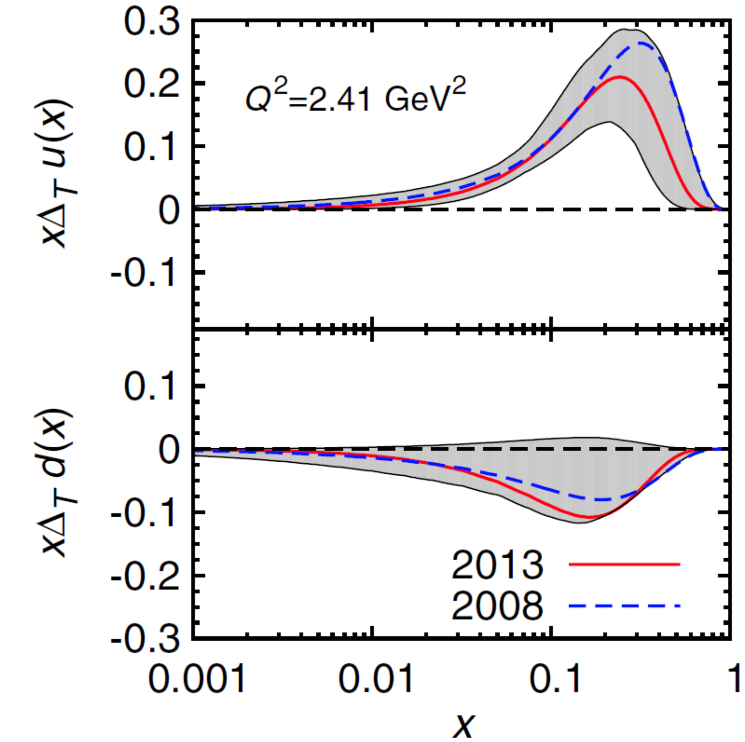


- Collins asymmetry : COMPASS proton vs Hermes proton.
- Clear effect at large x.
- Collins amplitudes for π^+ and π^- are mirror symmetric (favoured unfavoured Collins FF).
- Even taking into account **different Q^2 coverage** of the experiments, asymmetries appeared to be **compatible**.

COMPASS SIDIS: fit to results

Anselmino et al. Phys.Rev. D86 (2012) 014028





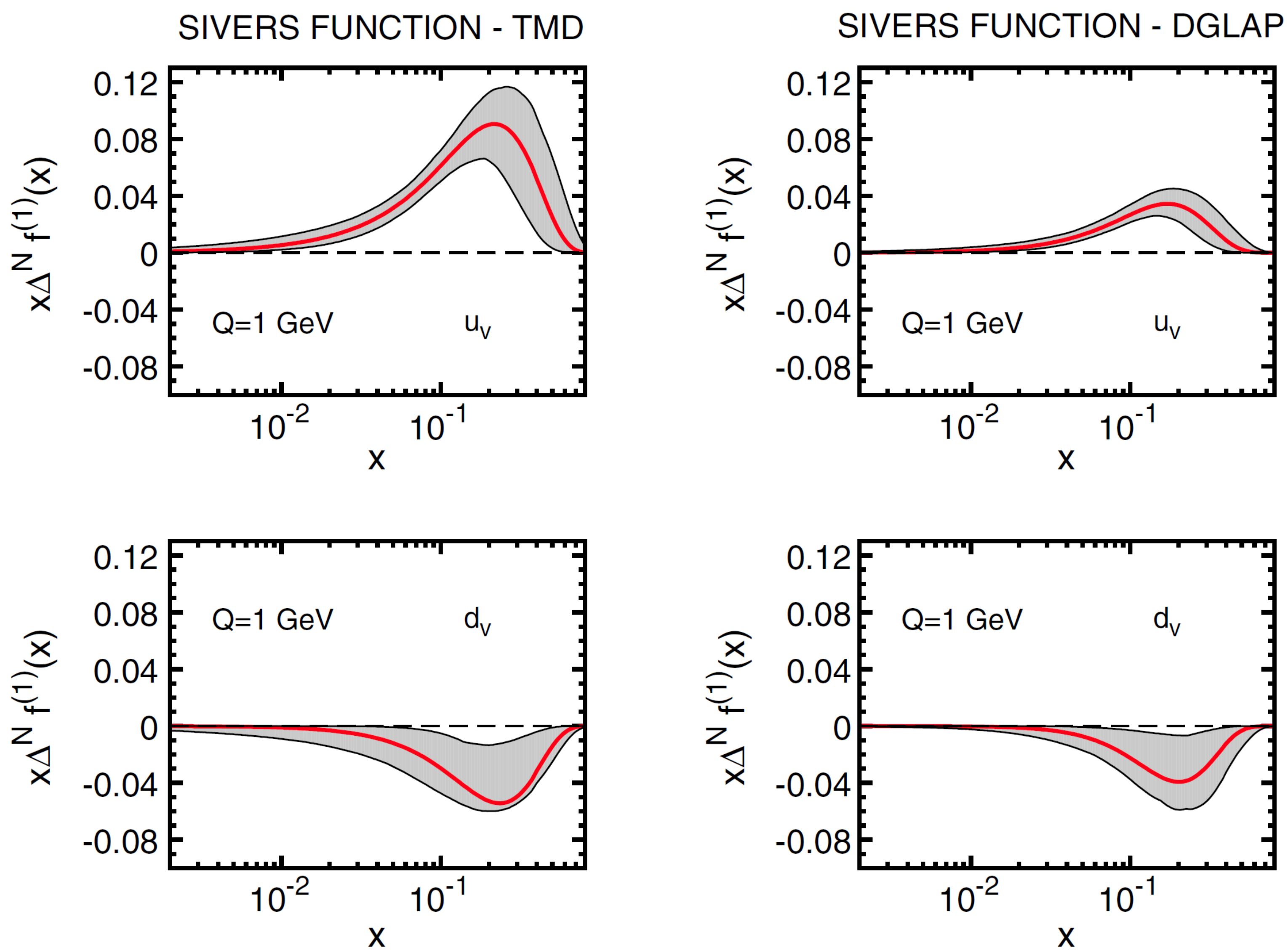
Anselmino et al. Phys.Rev. D87 (2013) 094019

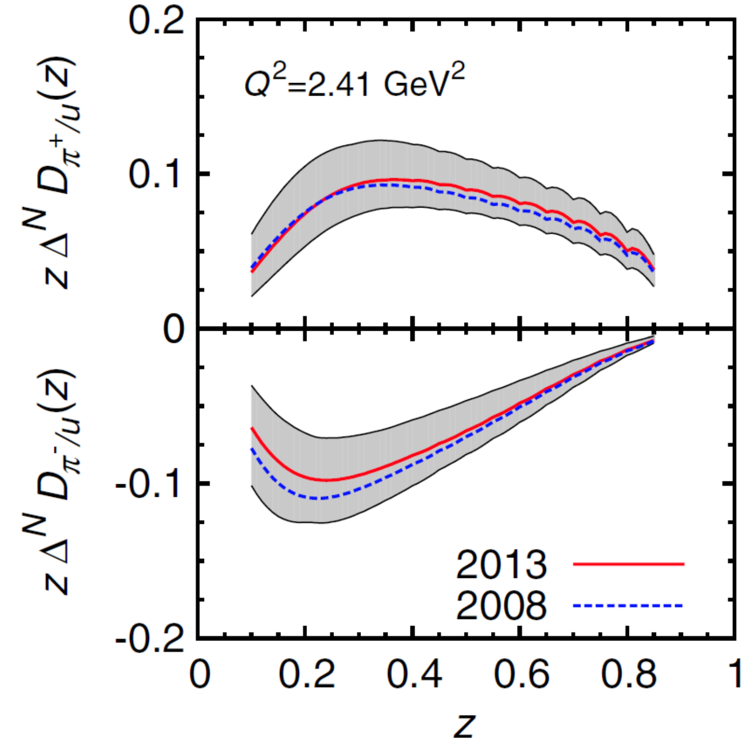
Examples of global fits to the experimental data:

- COMPASS results play an important role in TMD studies.
- Several attempts have been done to perform global fit of the data from different experiments, also modeling TMD evolution.
- Additional experimental data are highly desirable to better constrain the fits (COMPASS, JLAB12, EIC ...).

COMPASS SIDIS: fit to results

Anselmino et al. Phys.Rev. D86 (2012) 014028





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Examples of global fits to the experimental data:

- COMPASS results play an important role in TMD studies.
- Several attempts have been done to perform global fit of the data from different experiments, also modeling TMD evolution.
- Additional experimental data are highly desirable to better constrain the fits (COMPASS, JLAB12, EIC ...).


COMPASS