Drell-Yan measurements at the COMPASS experiment

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On Behalf of the COMPASS Collaboration

OUTLINE

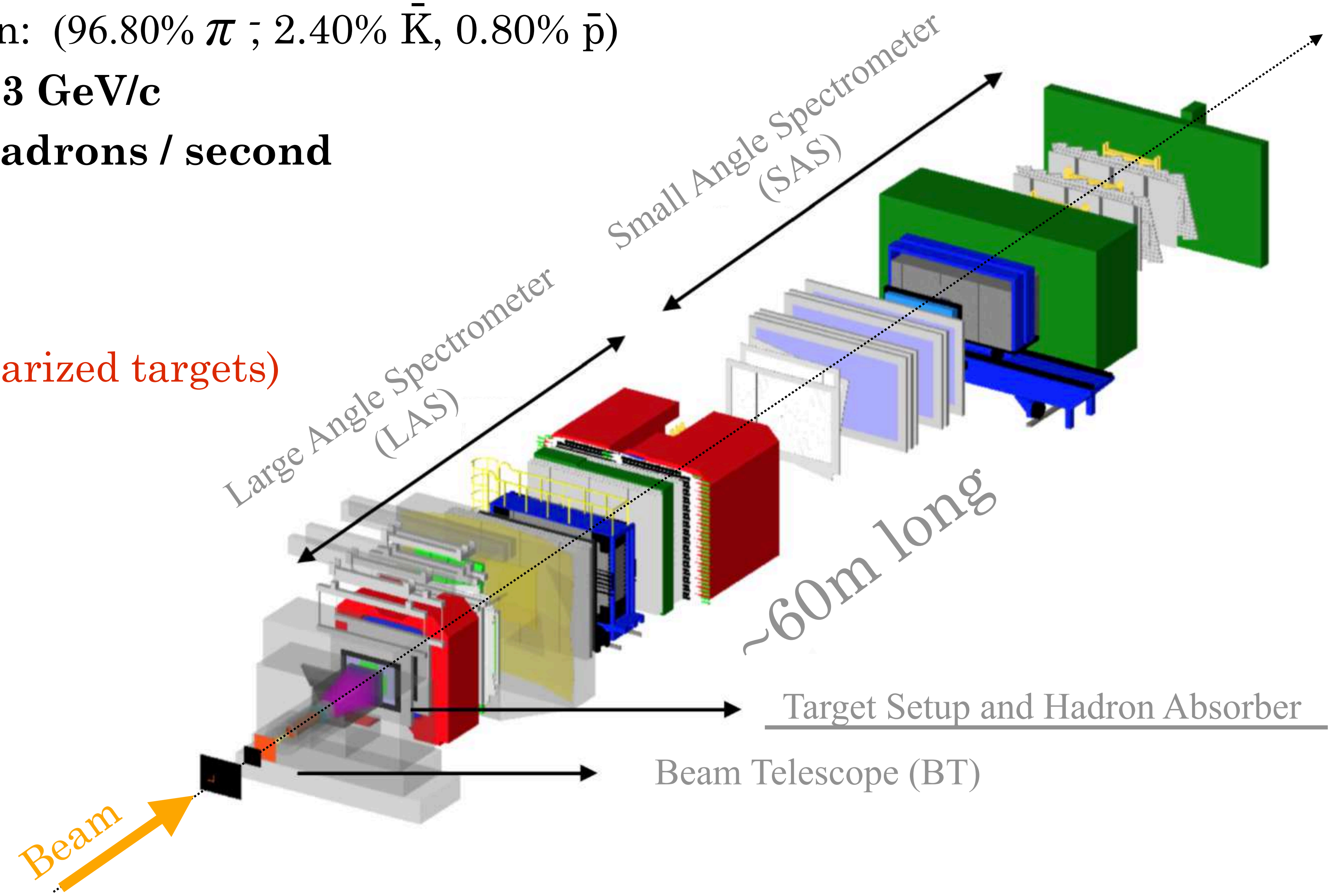
- *The COMPASS experimental setup*
- Polarized Drell-Yan measurements
- Unpolarized Drell-Yan studies
- Double J/ψ production studies
- *Summary and conclusions*

THE COMPASS DRELL-YAN (DY) SETUP

- **Versatile two-stage spectrometer:** large and small angle tracks

- **Unique hadron beam in 2015 and 2018 Drell-Yan runs:**
  — Hadron beam composition: (96.80% π^-; 2.40% $\bar{K}$, 0.80% $\bar{p}$)
  — Beam momentum: **190 ± 3 GeV/c**
  — Intensity: up to **~7x10^7 hadrons / second**

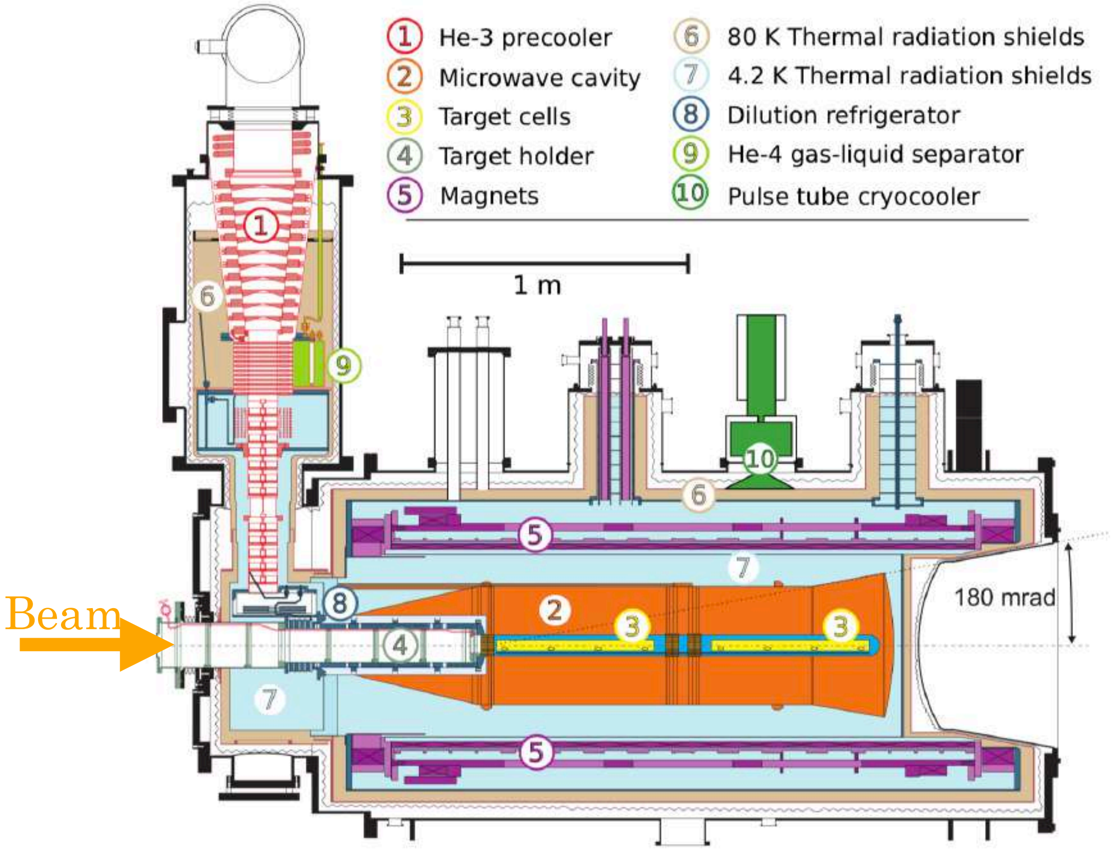
- **Drell-Yan specificities:**
  — Dilution refrigerator (Polarized targets)
  — Hardon absorber



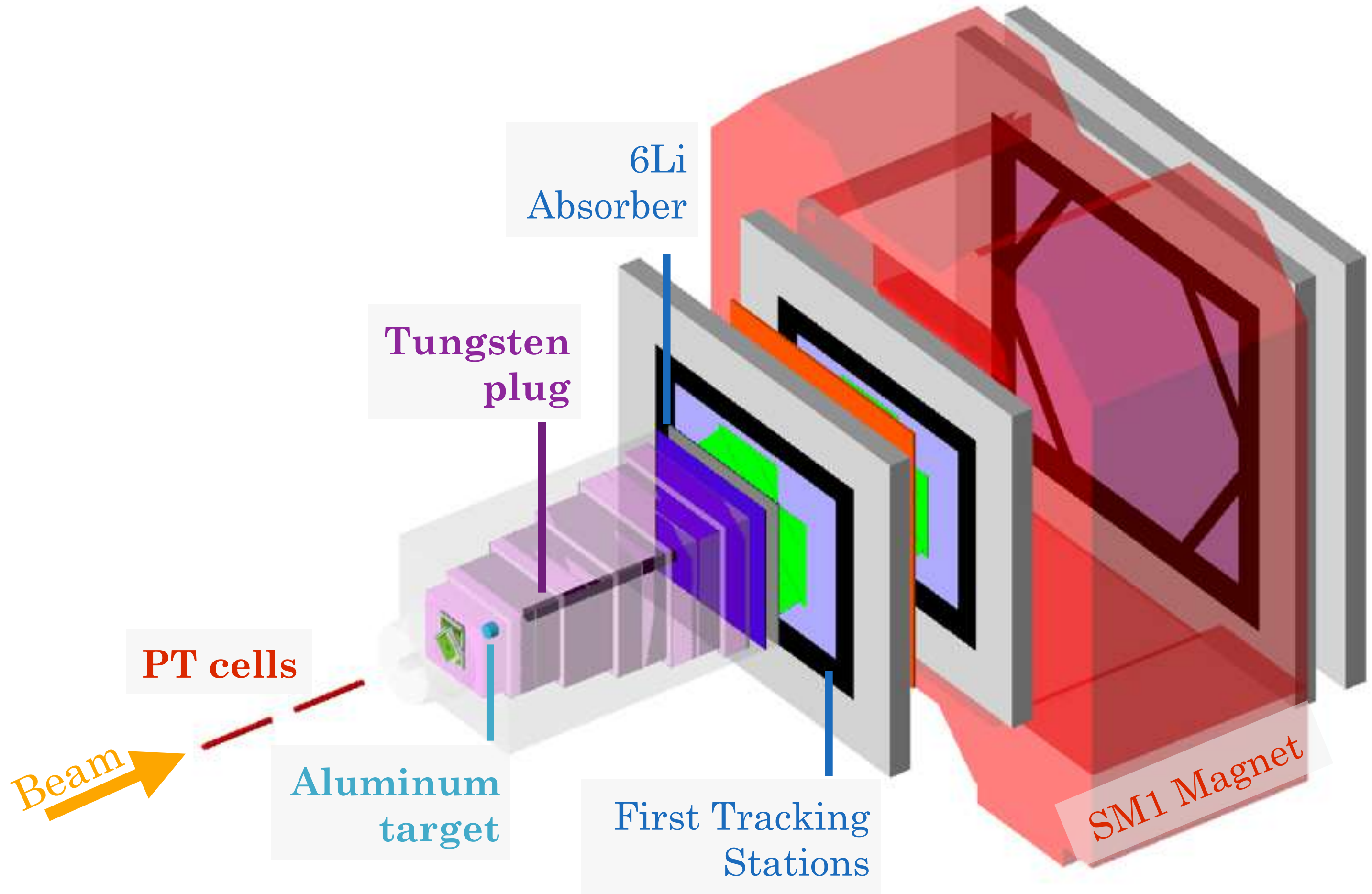
THE COMPASS DRELL-YAN (DY) SETUP

- **Dilution refrigerator:**
  — **Polarized Targets =** Solid state NH_3 beads in a LHe bath (NH3 volume fraction ~47-53%)
  — **Average spin polarization ~70%** *(Mainly H_3 protons contribute)*

- **Hadron absorber:**
  — **Alumina structure with a tungsten core** (acting as hadron absorber and beam dump)
  — Positioned dowsntream of the polarized target
  — **Nuclear targets:** Aluminum (7 cm, A~27) and Tungsten plug (10 first cm, A~184)



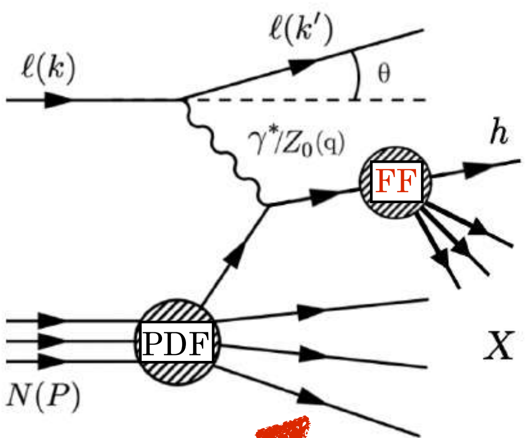
— Dilution refrigerator —



DRELL-YAN MEASUREMENT AT COMPASS

Semi-Inclusive Deep Inelastic Scattering

Phys.Lett.B717 (2012) 376–382
Phys.Lett.B717 (2012) 383–389
Phys.Rev.Lett.103 (2009) 152002

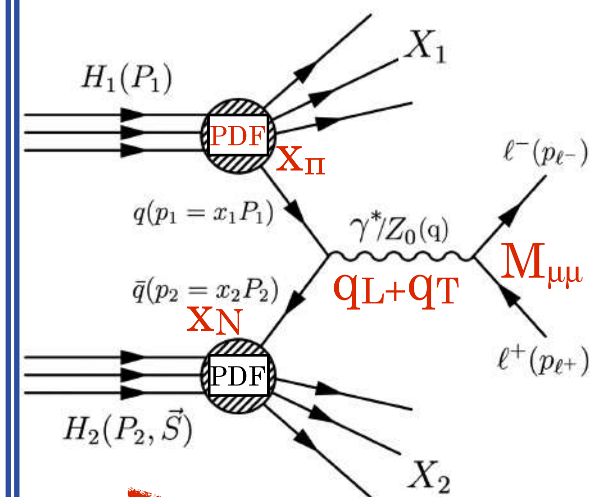


PDF⊗FF
(FF = Fragmentation Function)

Significant non-zero asymmetry (Sivers) measured in the spin structure of the nucleon by HERMES and COMPASS

Dilepton production: DY process

Phys.Lett.B770(2017)138–145



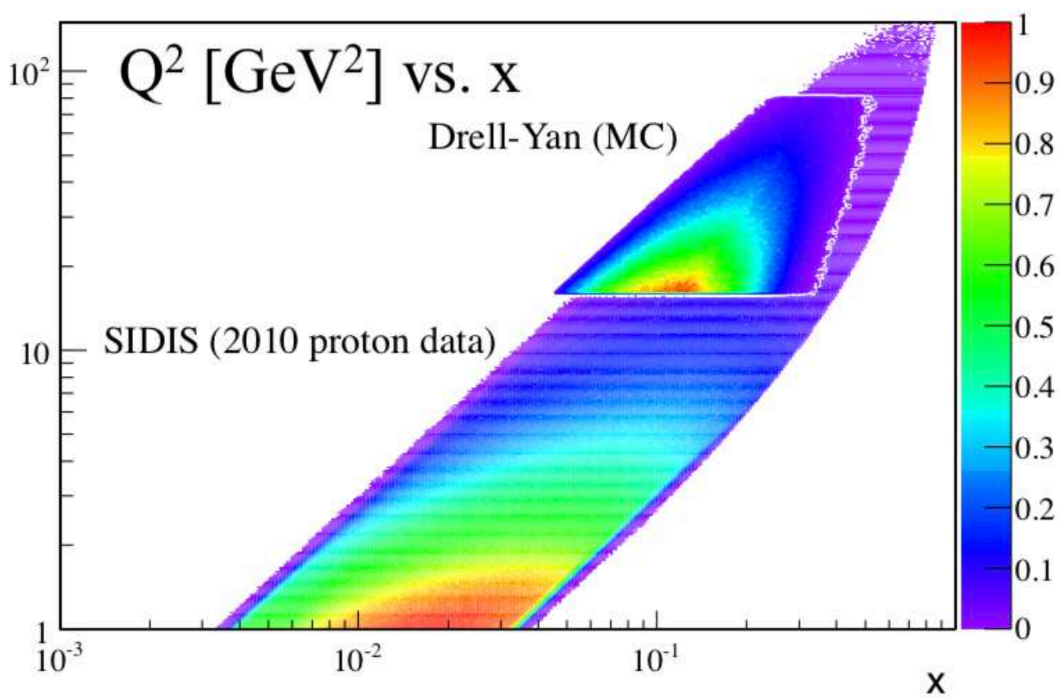
PDF⊗PDF
Beam PDF flavor sensitivity !
(valence quarks)

EM process: no fragmentation

Main variables: x_π, x_N, x_F, $M_{\mu\mu}$, q_T
$x_F = x_1 - x_2$ *(+other convention: $2p_L/\sqrt{s}$)*

T-symmetry

COMPASS DY / SIDIS data

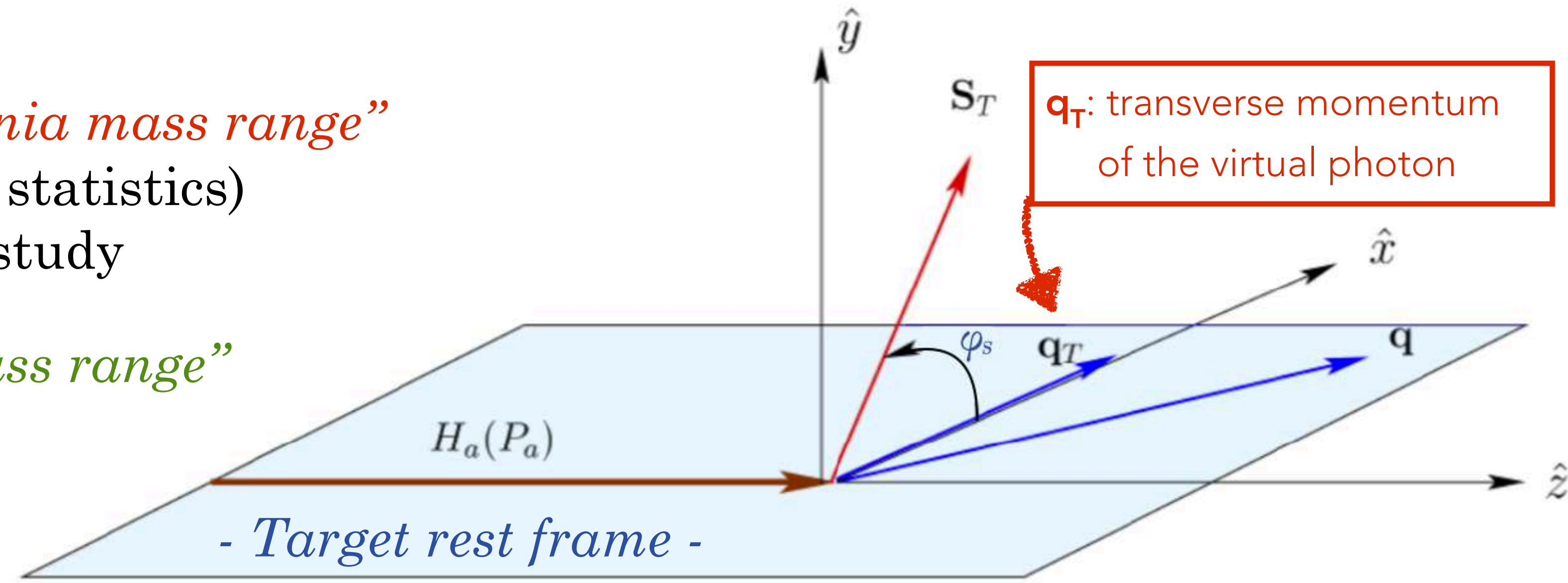


- **COMPASS** measured both target spin (in)dependent azimuthal asymmetries, via **SIDIS and Polarized DY** with **<u>the same apparatus</u>**

- **Correlation between DY and SIDIS:**
  — Initial-state/final-state interaction
  — Excepted sign change in the Sivers function of the spin structure of the nucleon

Overlapping (x,Q^2) coverage
Minimization of possible Q^2 evolution effects

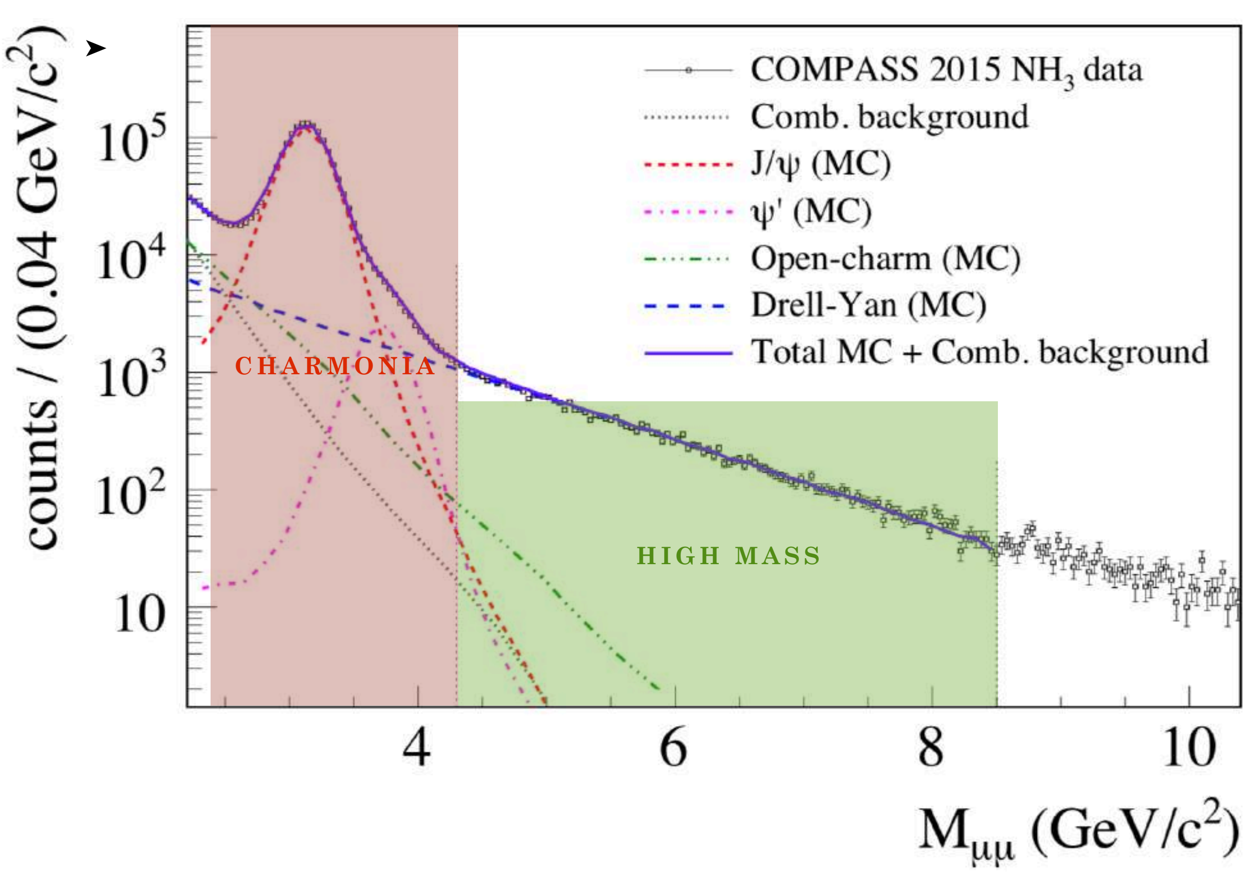
DRELL-YAN KINEMATIC COVERAGE

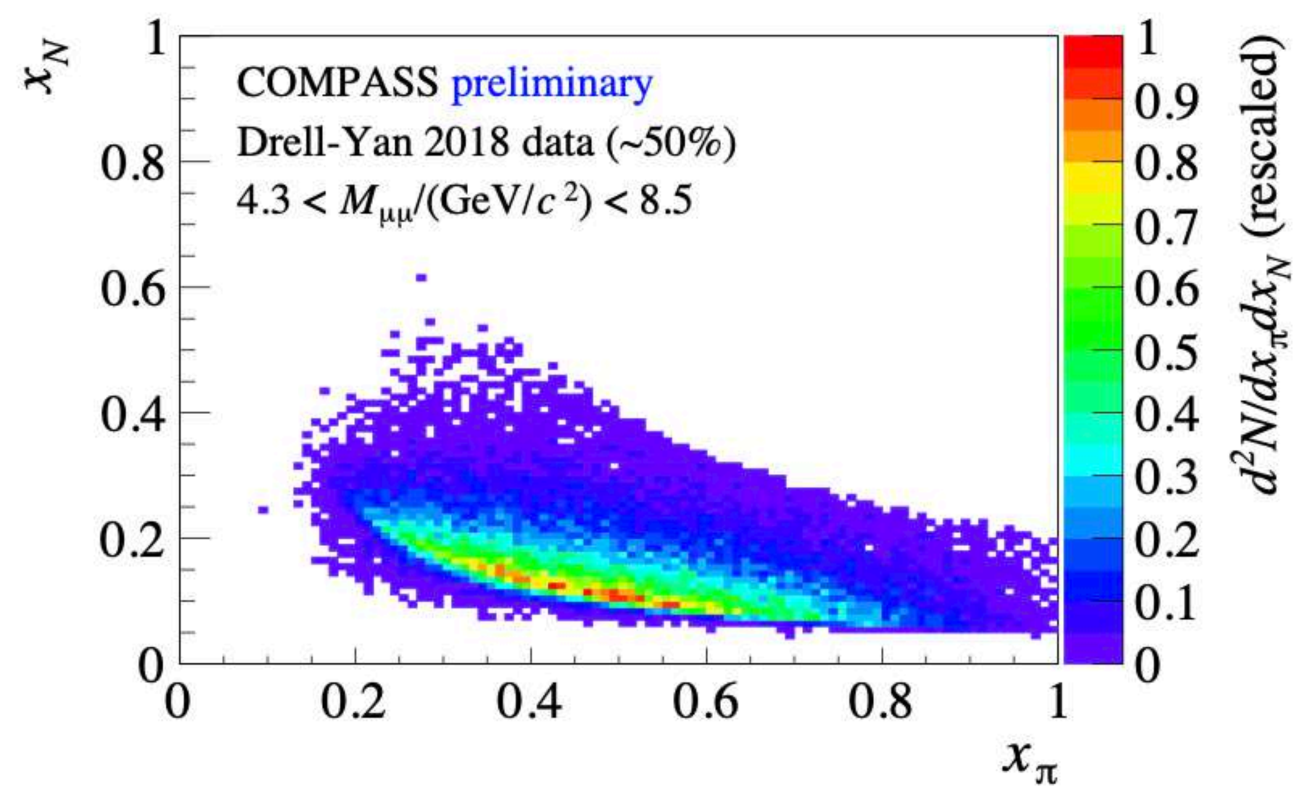


- **$2.5 < M_{\mu\mu}/(GeV/c^2) < 4.3$ — *"Charmonia mass range"***
  - Good signal/background ratio (large statistics)
  - J/ψ peak — Production mechanism study

- **$4.3 < M_{\mu\mu}/(GeV/c^2) < 8.5$ — *"High mass range"***
  - Background contamination < 4%
  - Valence-quark PDF region (Larger asymmetries)

- **Range coverage for DY:** $\langle M \rangle \sim 5.3$ GeV/c² ; $\langle q_T \rangle \sim 1.2$ GeV/c ; $\langle x_\Pi \rangle = 0.50$; $\langle x_N \rangle = 0.17$

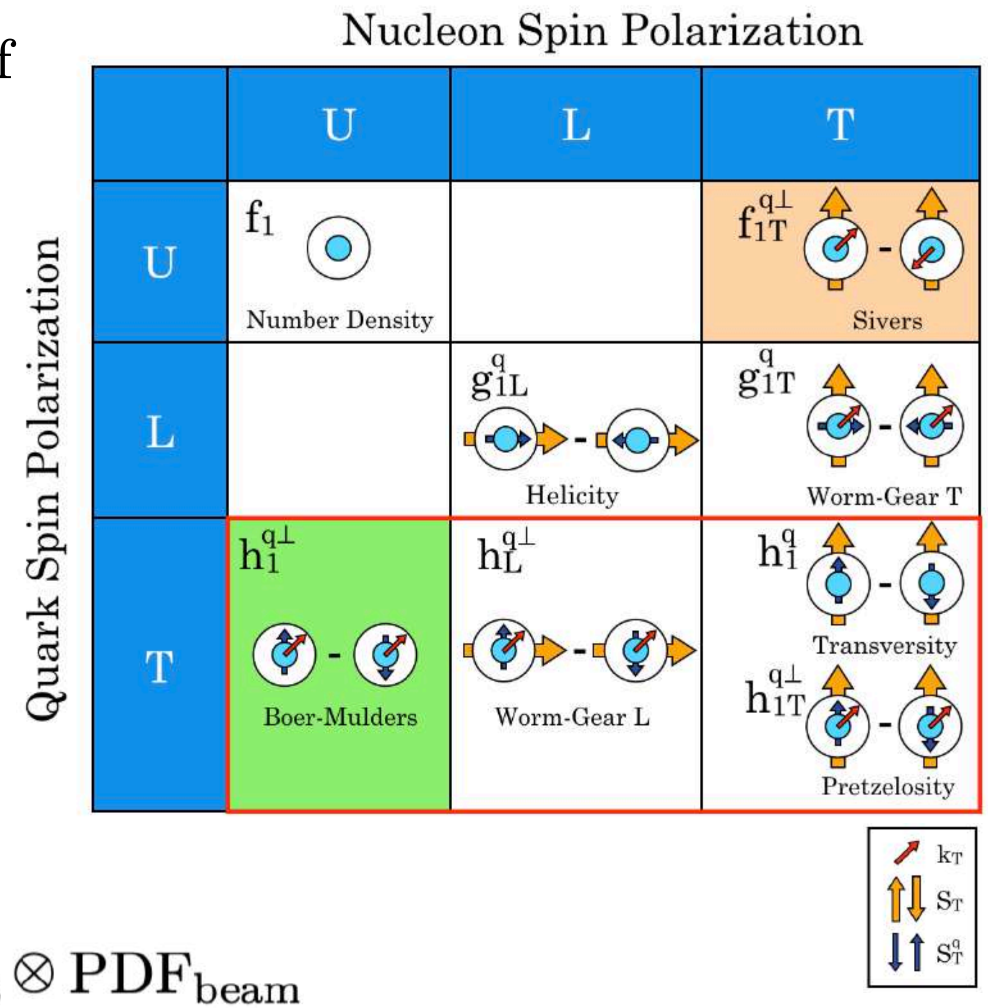




SINGLE-SPIN DRELL-YAN CROSS-SECTION

- In the QCD improved parton model at LO, the spin structure of the nucleon is parameterized in terms of 8 twist-2 TMD PDFs
- Each Twist-2 TMD PDFs depends on **the intrinsic transverse momentum k_T** of the interacting partons
- **Single-Spin DY cross-section:**

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \Big\{ 1 + D_{[\sin 2\theta_{CS}]} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}$$
$$+ S_T \Big[D_{[1+\cos^2\theta_{CS}]} A_T^{\sin\varphi_S} \sin\varphi_S$$
$$+ D_{[\sin^2\theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \right)$$
$$+ D_{[\sin 2\theta_{CS}]} \left(A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) + A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) \right) \Big] \Big\},$$



- **Access to a convoluted TMD PDF information:** $\mathrm{PDF}_{\mathrm{target}} \otimes \mathrm{PDF}_{\mathrm{beam}}$

$A_U^{\cos 2\phi} \propto h_1^{q\perp}(N) \otimes h_1^{q\perp}(\pi)$ → Boer-Mulders } Unpolarized Asymmetry → *(Ongoing analysis)*

$A_T^{\sin\phi_S} \propto f_{1T}^{q\perp}(N) \otimes f_1(\pi)$ → Sivers

$A_T^{\sin(2\phi+\phi_S)} \propto h_{1T}^{q\perp}(N) \otimes h_1^{q\perp}(\pi)$ → Pretzelosity

$A_T^{\sin(2\phi-\phi_S)} \propto h_1(N) \otimes h_1^{q\perp}(\pi)$ → Transversity

} Transverse Asymmetries *(Twist-2)*

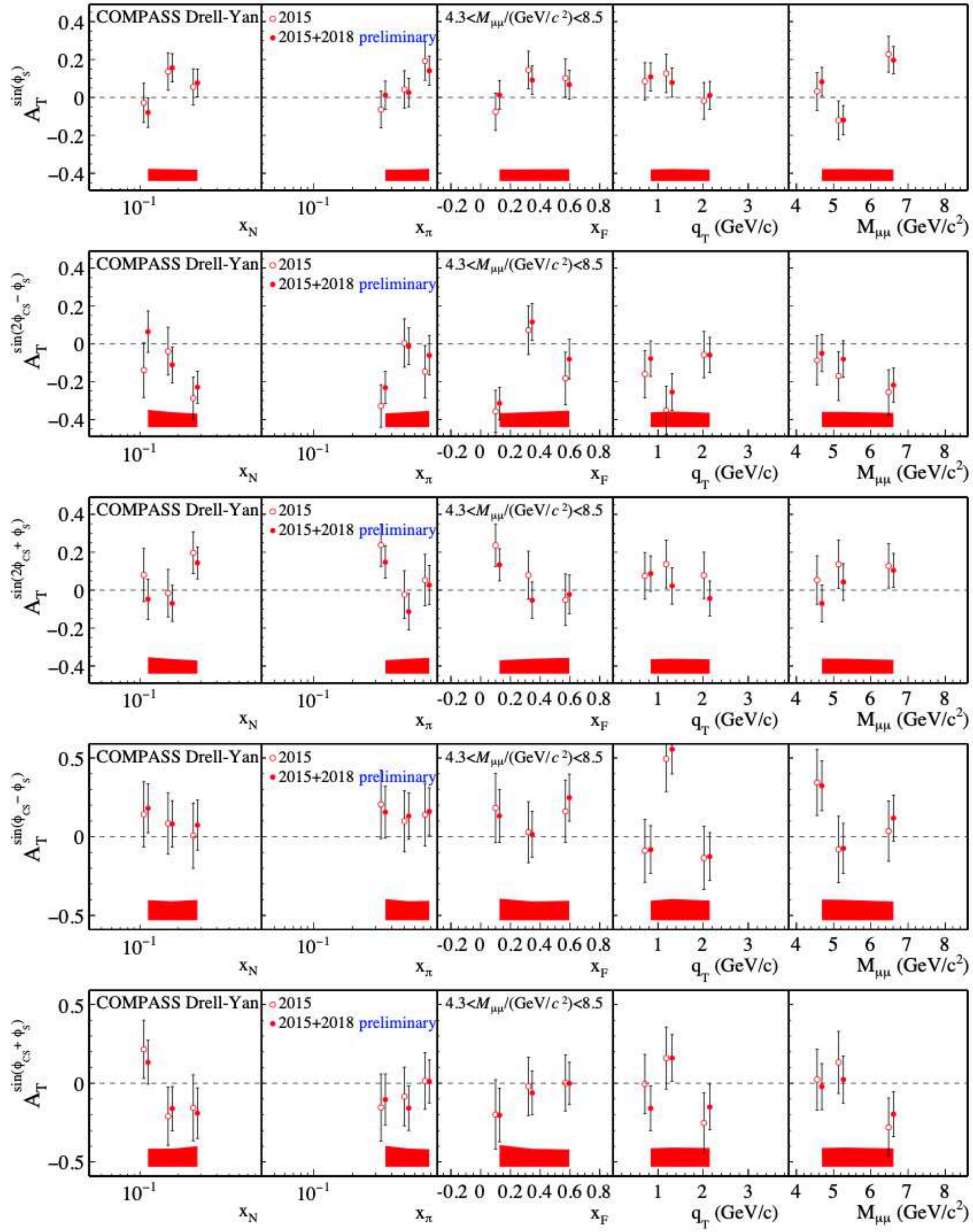
Subleading twist: $A_T^{\sin(\varphi_{CS}-\varphi_S)}$ and $A_T^{\sin(\varphi_{CS}+\varphi_S)}$ } Transverse Asymmetries *(Subleading twist)*

NB: $D_{[f(\theta)]} = \dfrac{f(\theta)}{1 + A_U^1 cos^2\theta}$

$A_U^1 \equiv F_U^1$

$A_{U,T}^{f(\phi_{CS},\phi_S)} = \dfrac{F_{U,T}^{f(\phi_{CS},\phi_S)}}{F_U^1 + F_U^2}$

ASYMMETRIES IN DRELL-YAN



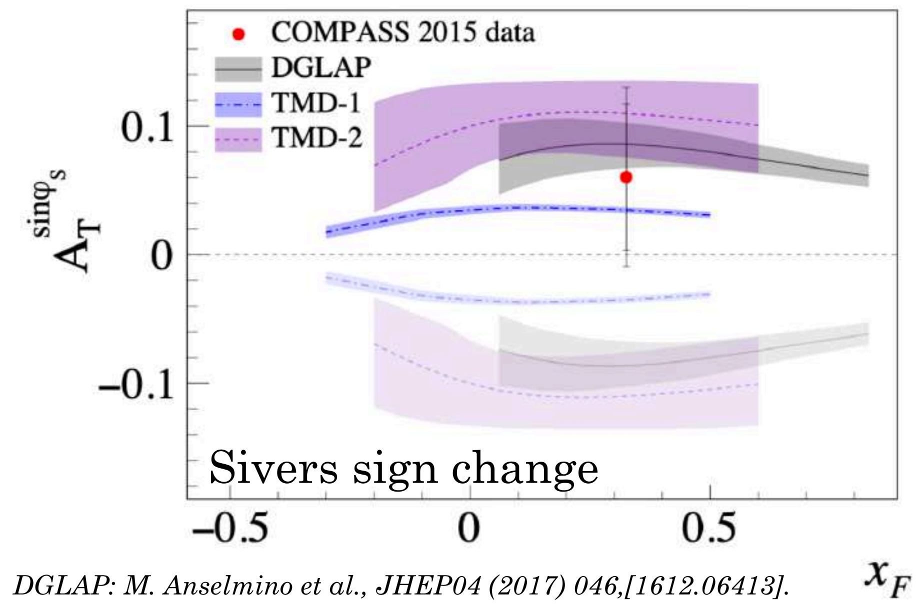
Sivers

Transversity

Pretzelosity

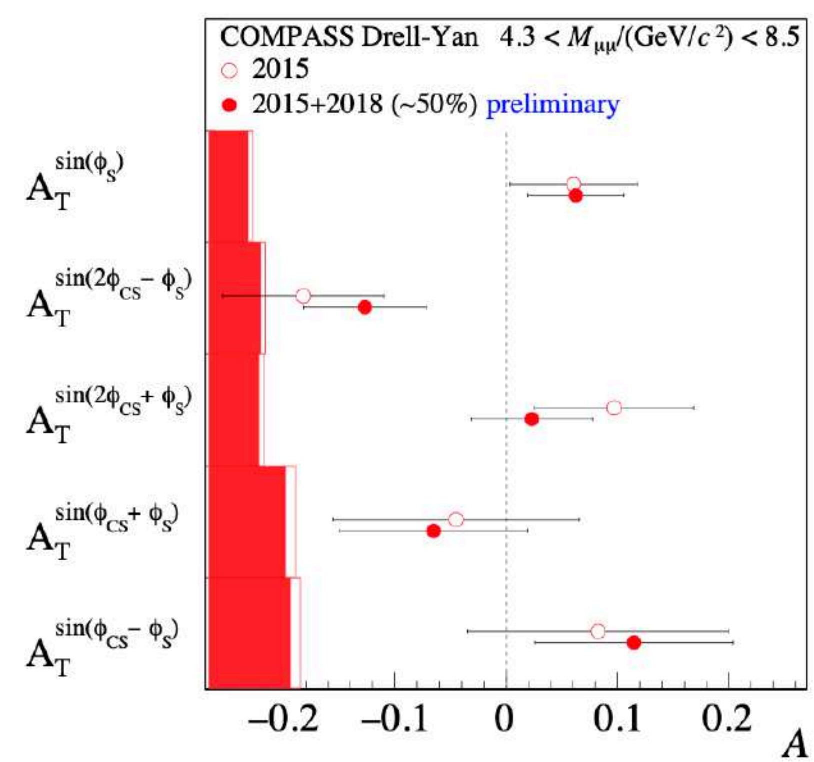
Subleading Twists

- **Results as function of x_N, x_π, x_F q_T, M**



DGLAP: M. Anselmino et al., JHEP04 (2017) 046,[1612.06413].
TMD-1: M. G. Echevarria et al., Phys.Rev.D89 (2014) 074013, [1401.5078].
TMD-2: P. Sun and F. Yuan, Phys. Rev.D88 (2013) 114012,[1308.5003].

- Compatible results between years
- Preliminary results for 2018 data (50% of available statistics)

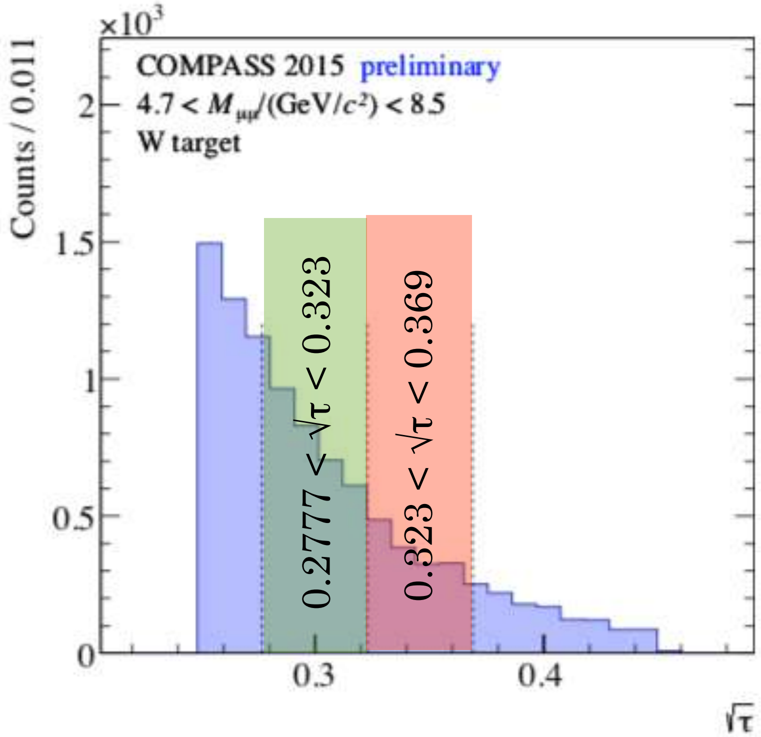


UNPOLARIZED ABSOLUTE DRELL-YAN CROSS-SECTION

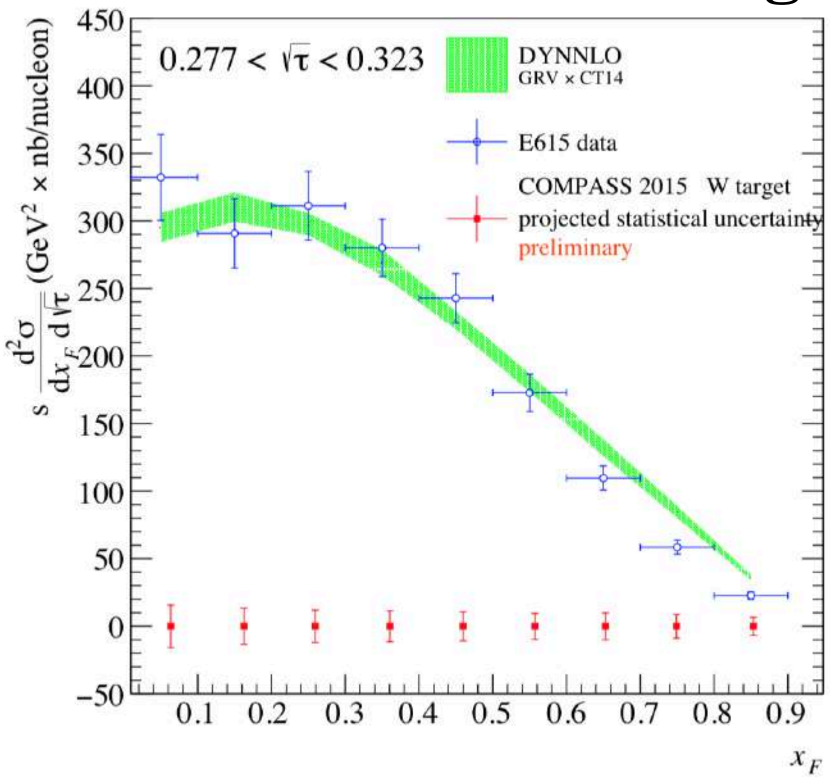
- **Projected uncertainties:**
  — Uncertainties on NH_3 data (compared with DYNNLO simulation)
  — Uncertainties for Tungsten data compared to E615 results and DYNNLO *(beam energy independent)*

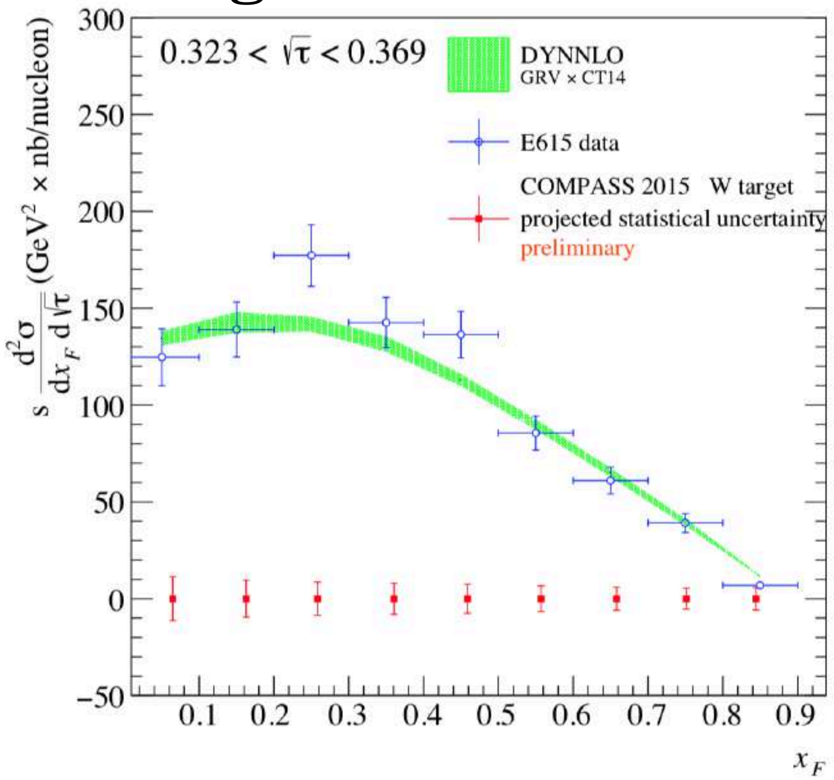
- ***Possible* comparisons with E615, NA10 experiments:**
  — Both $\pi^- + W$, E615 compared for two bins in $\sqrt{\tau}$

- Aim at systematic uncertainties: $\sigma_{sys} < 10\%$
  (Better compared to past experiments)



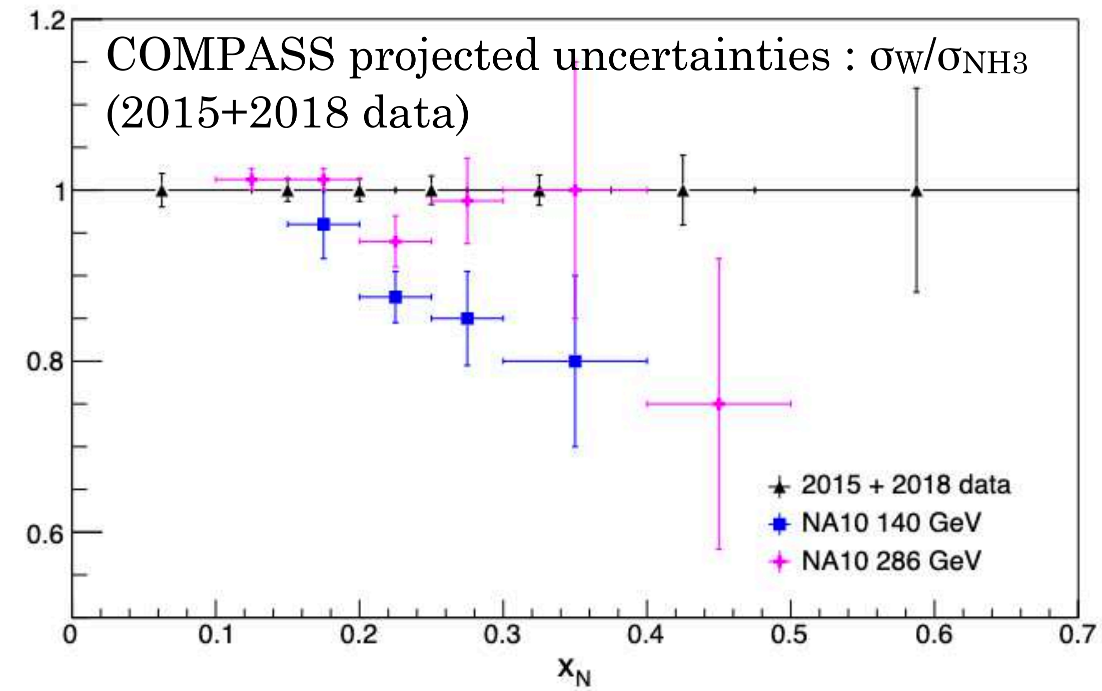
Tungsten target





A-DEPENDENCE OF THE DY AND J/ψ CROSS-SECTIONS

- In the future, **A-dependence of the cross-sections:**
  — *Polarized Target Cells: NH_3 + LHe mix (A ~ 12)*
  — *Aluminum (A ~ 27)*
  — *Tungsten (A ~ 184)*

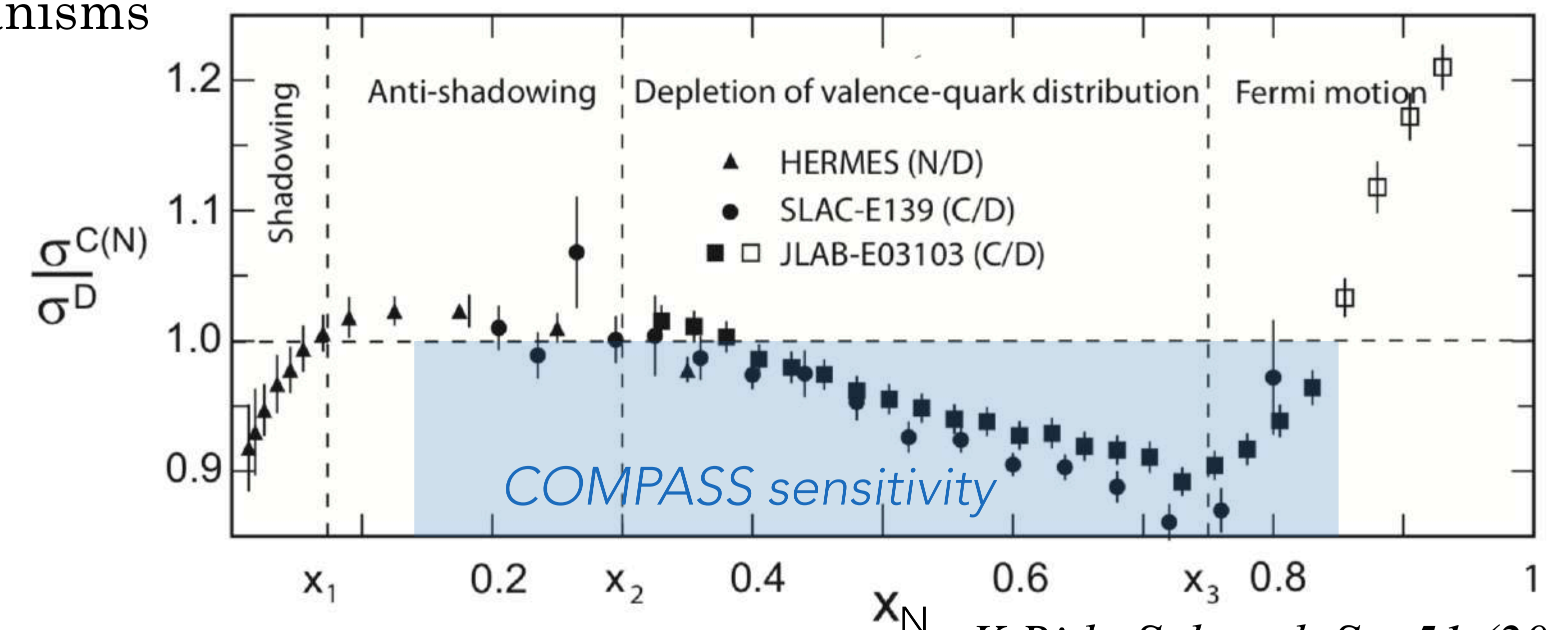


- Determination of the **Nuclear Corrective Factor R^A** of the PDF: *(Eskola et al., Eur. Phys. J.C - 1612.05741 (2017))*

$$f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q^2),$$

Modified nPDF *Proton free PDF*

- Study of the short-range mechanisms, non-perturbative effects, correlations with q_T, underlying J/ψ production mechanisms

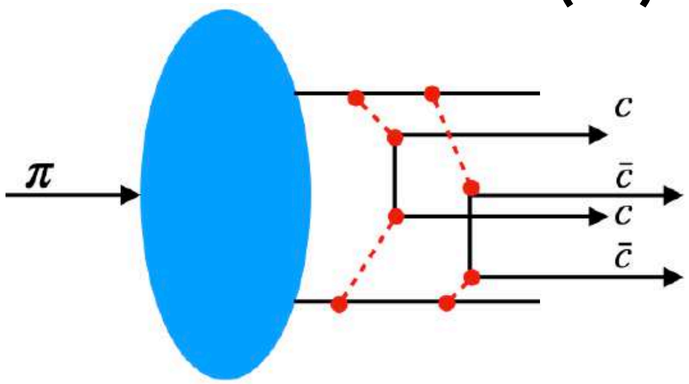


K.Rith, Subnucl. Ser.51 (2015), 431-449

DOUBLE J/ψ PRODUCTION: PAST OBSERVATIONS

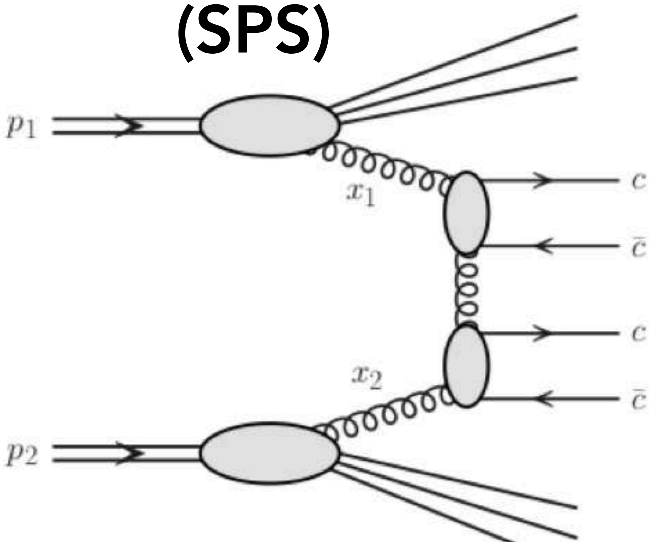
- **Double J/ψ production mechanisms**

Intrisinc charm (IC)



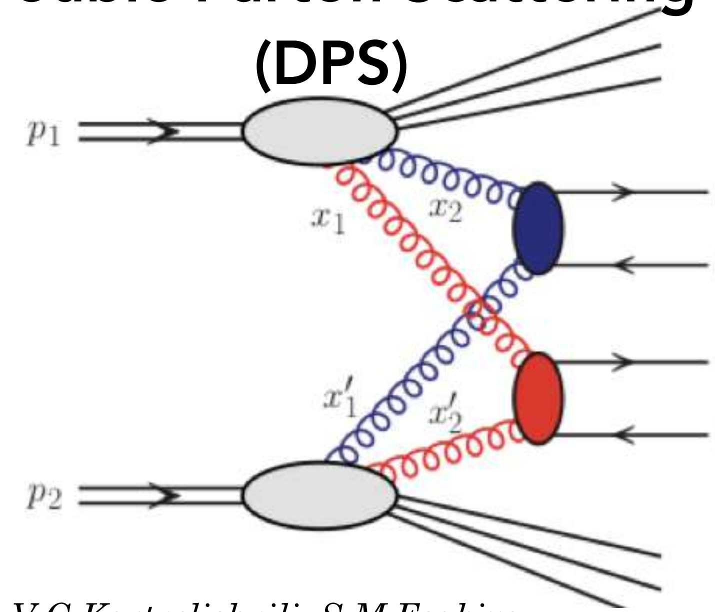
R. Vogt, S.J. Brodsky,
Phys.Lett.B349:569-575 (1995)

Single Parton Scattering (SPS)



R.E. Ecclestone, D.M. Scott
Phys. Lett. 120B (1983) 237

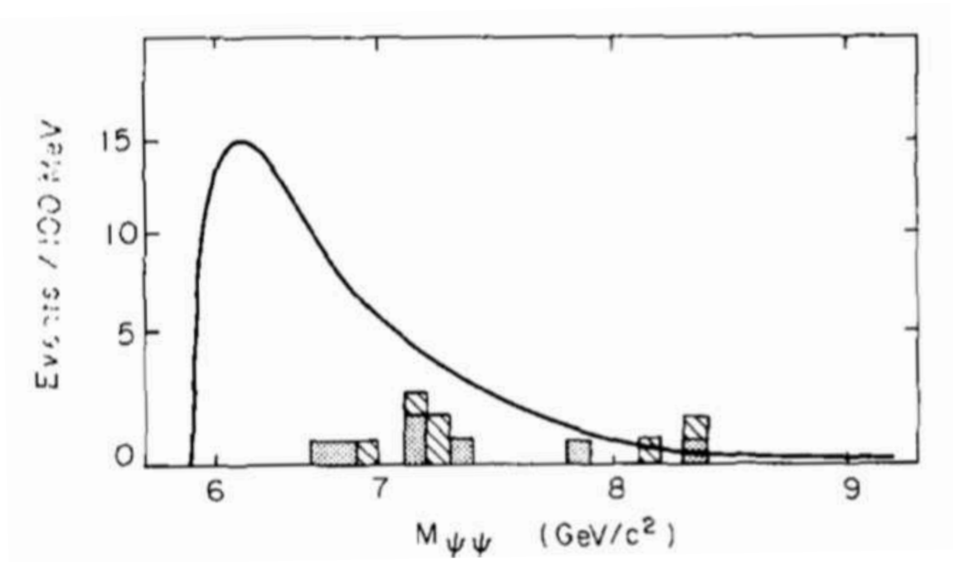
Double Parton Scattering (DPS)



V.G.Kartvelishvili, S.M.Esakiya
Yad. Fiz. 38 (1983) 722–726

- **First measurement done by NA3:**

Phys.Lett.B, 114(6) (1982)



SPS/DPS ratio known with high uncertainties

Experiment	Energy ($\sqrt{s}$)	Process	Cross-section ($\sigma_{J/\psi J/\psi}$)
NA3	16.8 GeV	$\pi^- N \to 2J/\psi + X$	18 ± 8 pb
NA3	22.9 GeV	$\pi^- N \to 2J/\psi + X$	30 ± 10 pb
NA3	27.4 GeV	$pp \to 2J/\psi + X$	27 ± 10 pb

+ other measurements at collider energies

NA3 published results without acceptance correction.

DOUBLE J/ψ PRODUCTION AT COMPASS

- **Measurement of the cross-section of double J/ψ production:**
  — COMPASS results on different targets at fixed target energies
  — Direct comparison with NA3 results
- **COMPASS data well describes the SPS+IC model**
  — SPS appears to be a dominant mechanism
  — DPS expected to be strongly suppressed at fixed target energies
- **An upper limit for IC cross-section can be determined**

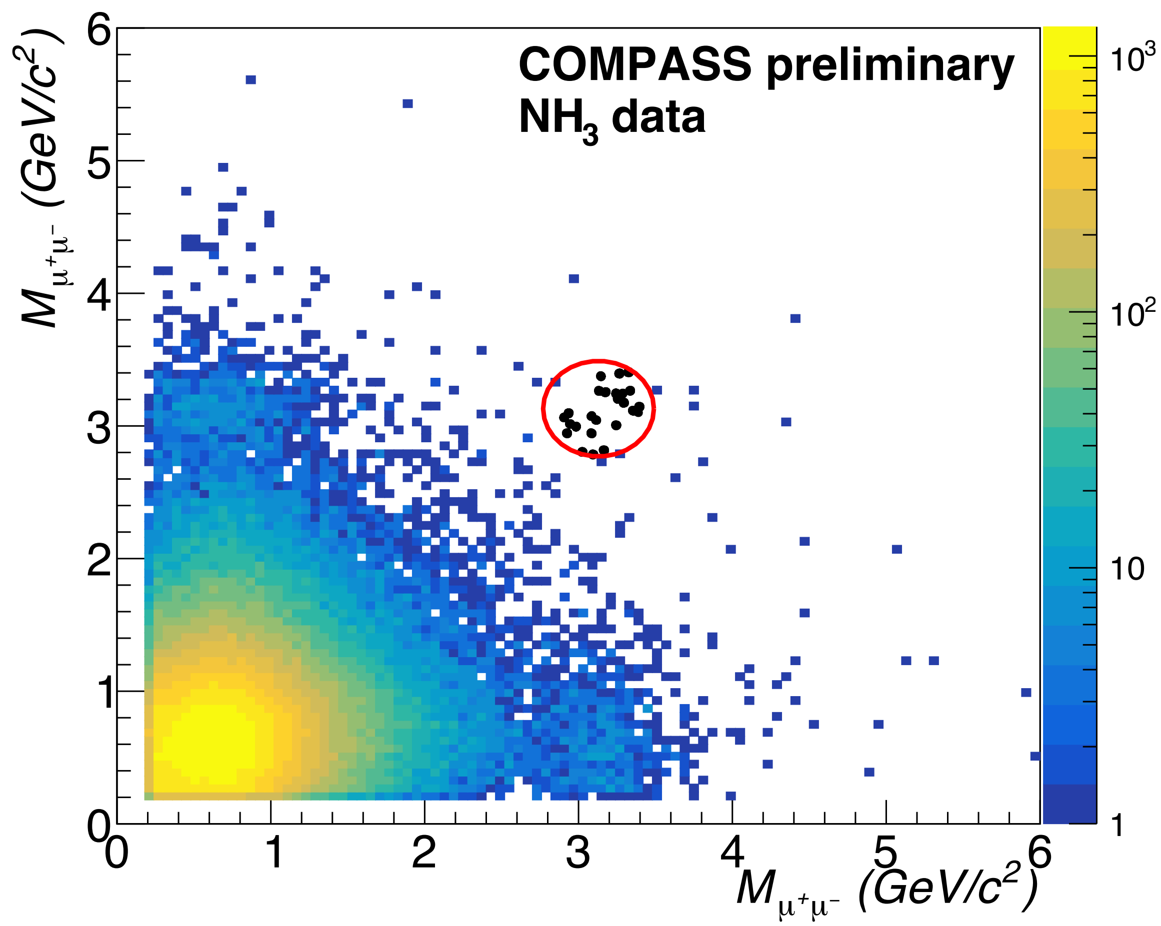
Extracted cross-section values:

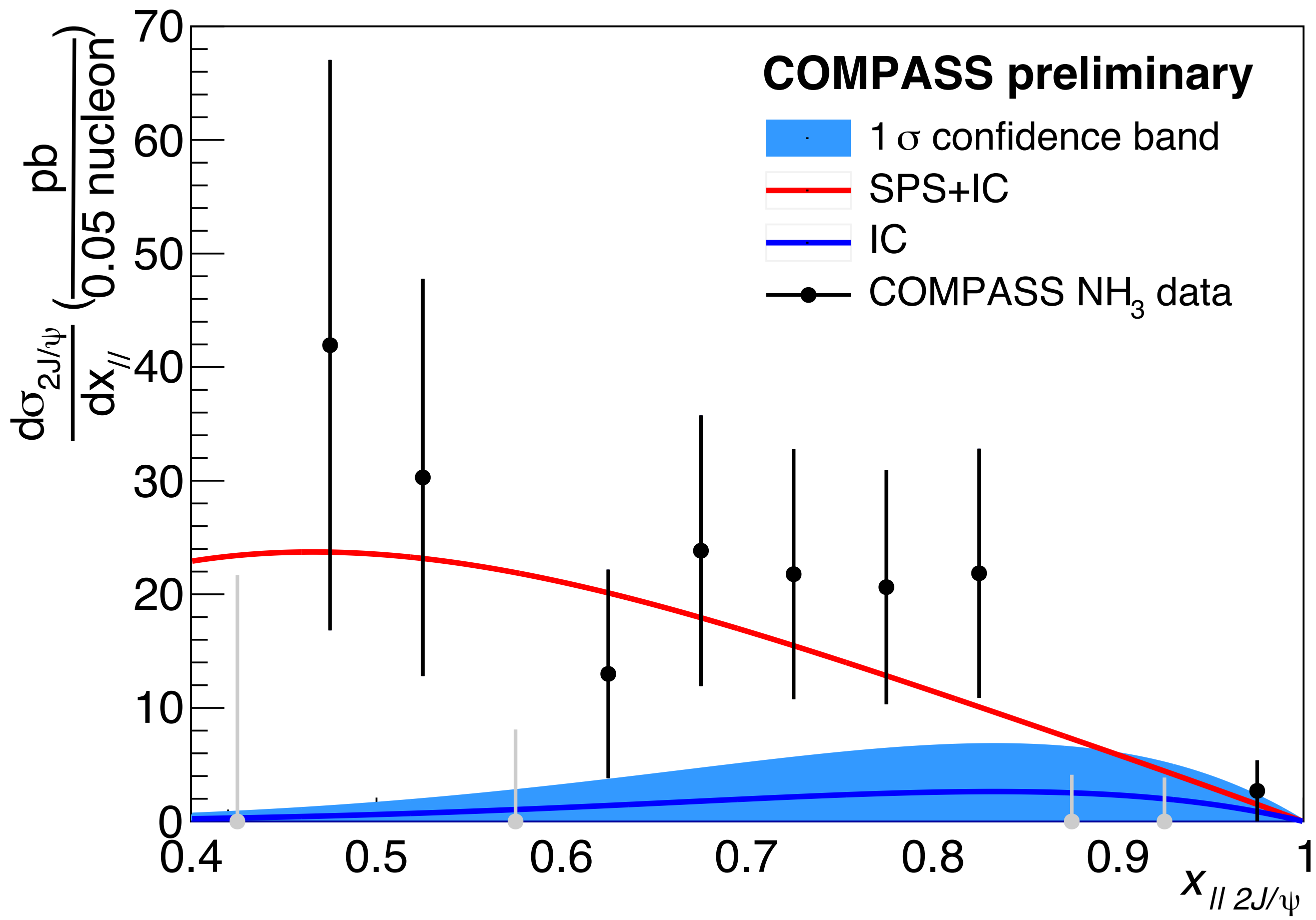
$$\left(\frac{\sigma_{2J/\psi}}{\sigma_{J/\psi}}\right)\Big|_{x_F>0} = (1.1 \pm 0.3_{\rm stat} \pm 0.2_{\rm sys}).10^{-4}$$

$$\sigma_{J/\psi J/\psi}(\mathrm{NH_3})\big|_{x_F>0} = (8.8 \pm 2.2_{\rm stat} \pm 2.4_{\rm sys})\frac{\rm pb}{\rm nucleon}$$

$$\sigma_{J/\psi J/\psi}(\mathrm{Al})\big|_{x_F>0} = (3.4 \pm 4.3_{\rm stat} \pm 5.8_{\rm sys})\frac{\rm pb}{\rm nucleon}$$

$$\sigma_{J/\psi J/\psi}(\mathrm{W})\big|_{x_F>0} = (14.3 \pm 7.7_{\rm stat} \pm 4.5_{\rm sys})\frac{\rm pb}{\rm nucleon}$$





SUMMARY & CONCLUSIONS

- **COMPASS performed polarized Drell-Yan measurements in 2015 and 2018.**
  — 2015 results were published.
  — 2018 preliminary results (50% of available statistics) are now also available.

- **TSA asymmetries:**
  — No clear trend observed for the DY TSAs, due to relatively large statistical uncertainties.
  — The hypothesis of a sign change remains compatible with the observations.

- **Unpolarized studies in full swing:**
  — Measurement of absolute Drell-Yan cross-section on 3 different targets.
  — A-dependence of the cross-section: Study of EMC effect, Energy loss, and Cronin effect.

- **Double J/ψ production:**
  — COMPASS has measured cross-section of the double J/ψ production on different targets.
  — COMPASS results compatible with SPS model: Intrinsic Charm contribution negligible.

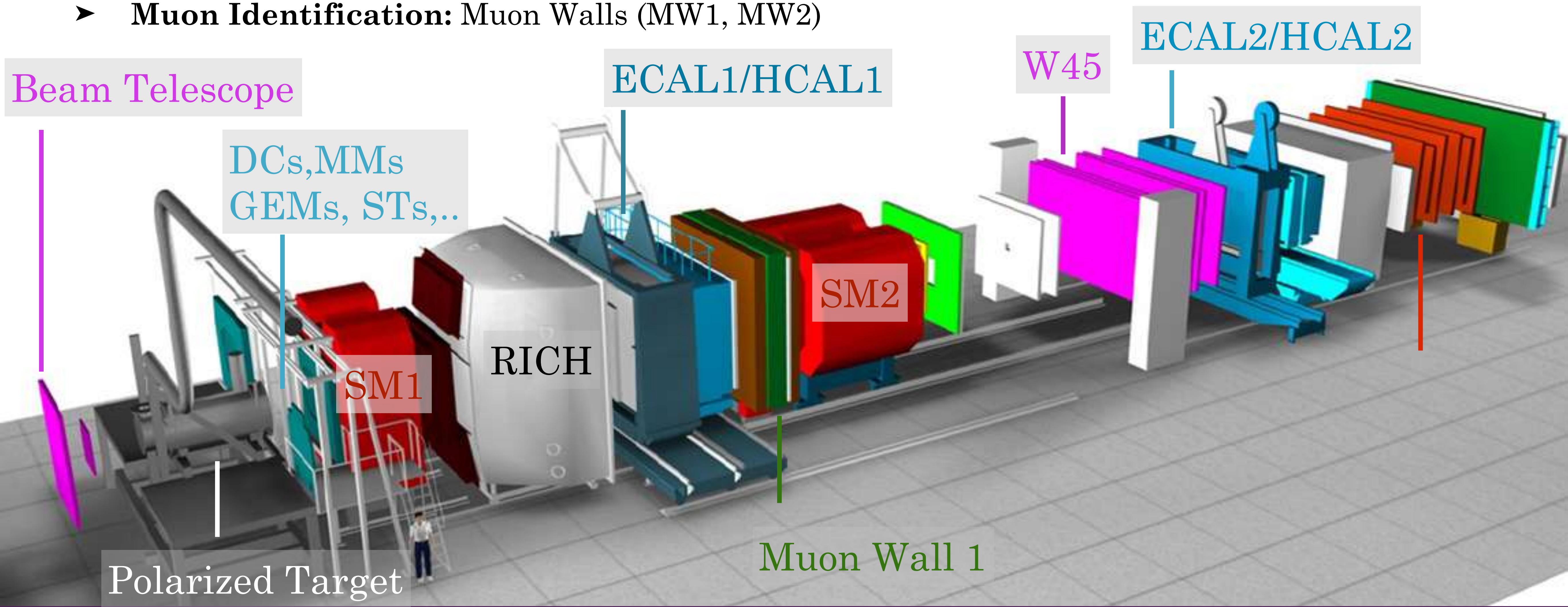
Thank you, for your attention.

Backup Slides

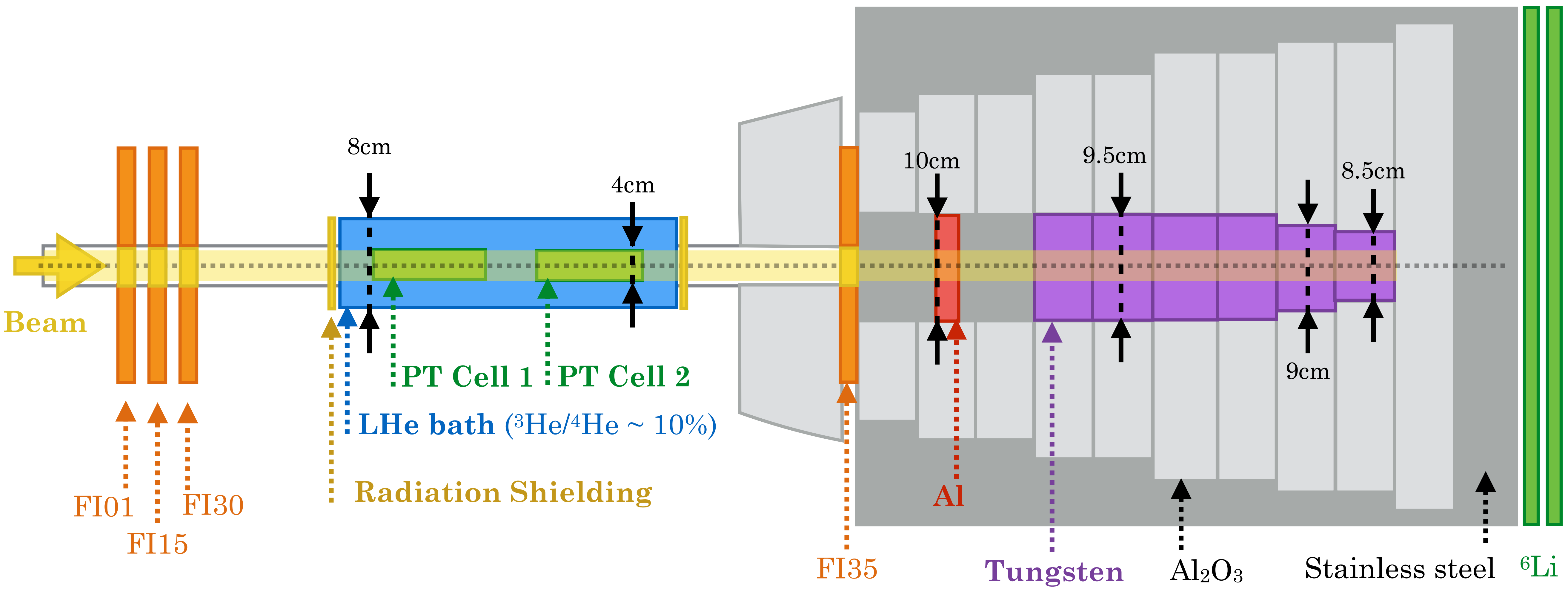
THE COMPASS DRELL-YAN APPARATUS

- **Comprising two dipole magnets:** SM1, SM2
- ***Beam Telescope Station:*** *SciFi detectors*
- **Tracking Detectors:** *(Large acceptance)*
  — Approx. 350 detection plans
  (GEMs, SciFis, DCs, MWPCs, Pixelized MicroMegas, Straw Detector..)
- **Muon Identification:** Muon Walls (MW1, MW2)

<u>**Drell-Yan Features:**</u>
- **Transversely Polarized** Target (PT)
- **Hadron Absorber** downstream PT cryostat
- Aluminum and Tungsten **Nuclear Targets**



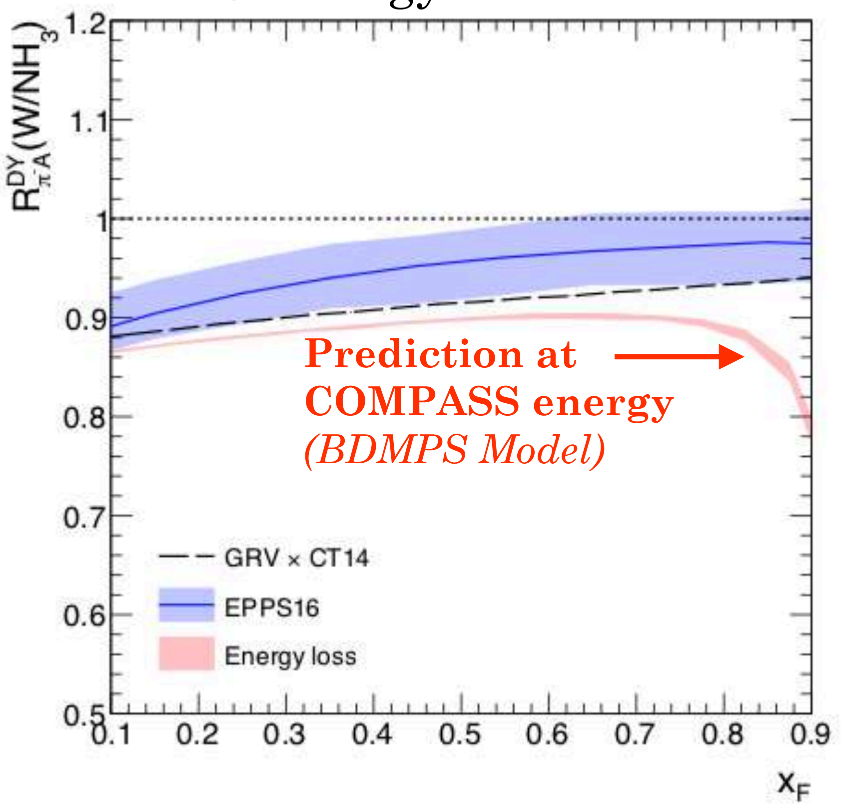
TARGET SETUP 2015



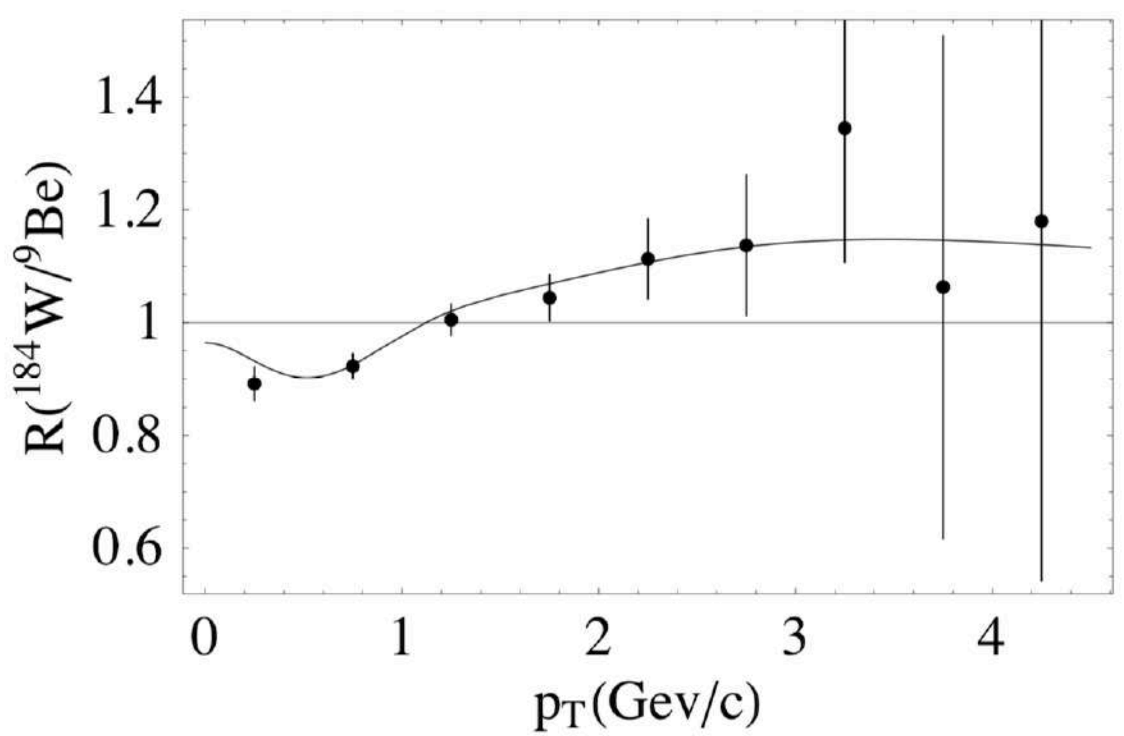
NUCLEAR DEPENDENCE OF DRELL-YAN

- **EMC Effect -** Modification of quark and gluon distributions (PDF), in bounded nucleons by a nuclear environment (1983)
- **Energy Loss Effect -** Of quarks in the pion beam while going across the nuclear target (a drop in the DY cross section at large x_F)
- **Cronin Effect -** Nuclear enhancement of high-pT hadrons, due to multiple interactions in nuclear matter.

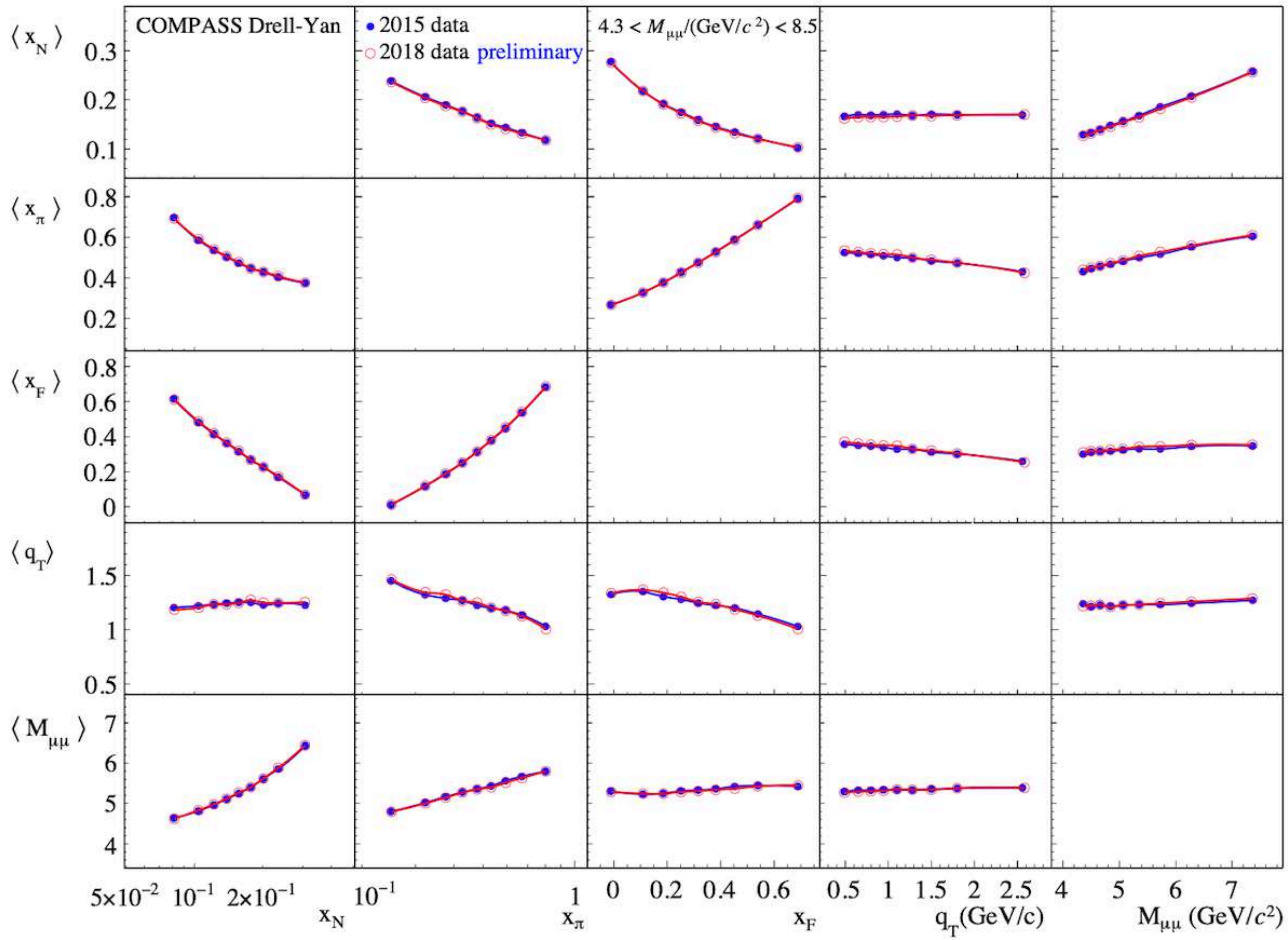
EMC/Energy Loss Prediction



Cronin Effect

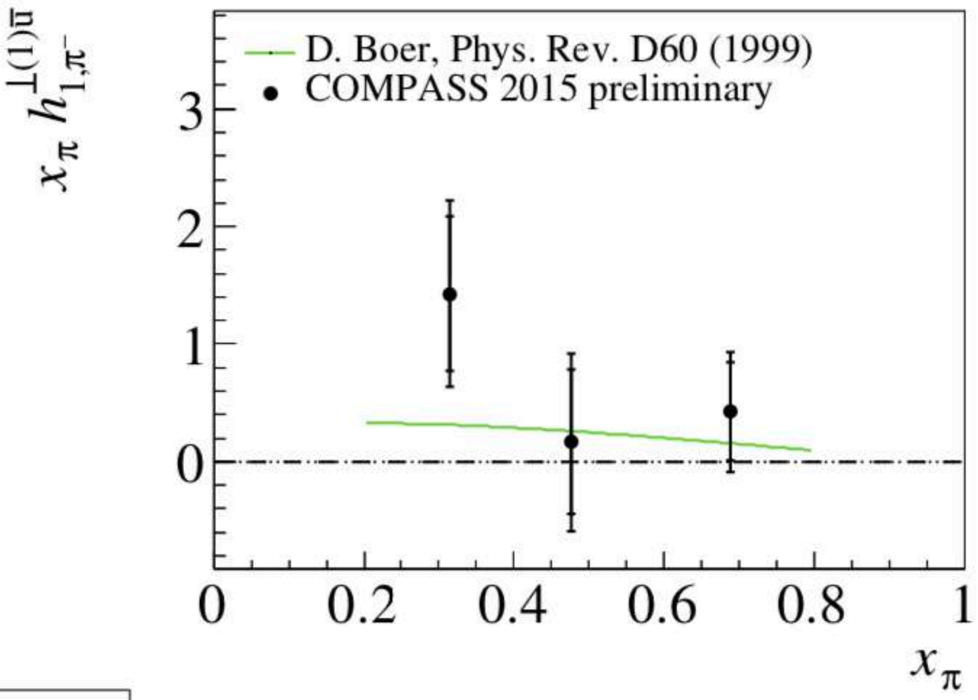


CORRELATION BETWEEN VARIABLES



BOER-MULDERS FUNCTION (WEIGHTED TSA)

- Extraction using weighted TSA method
- Preliminary results not fully estimated yet. Might be large uncertainties up to ~30%
- First moment of valence Boer-Mulders extracted with different pion PDF



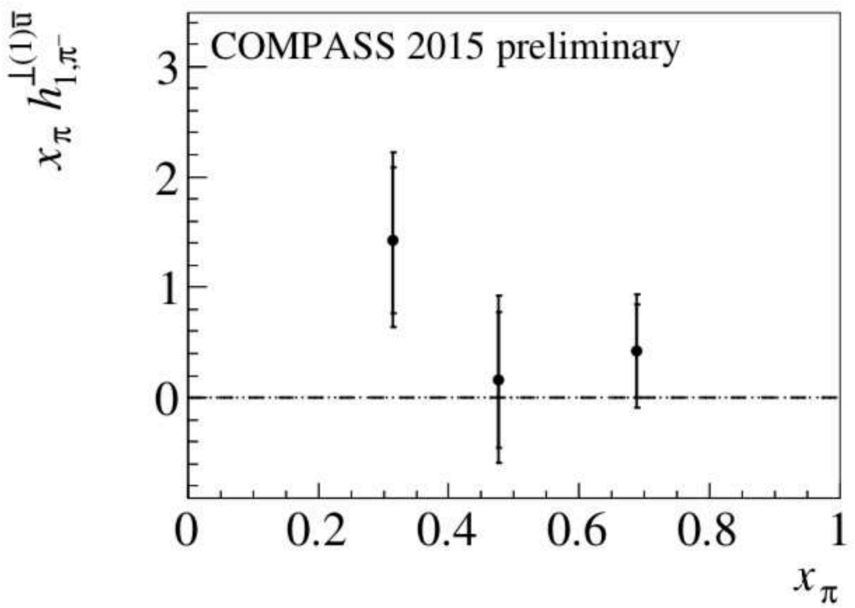


Figure 21: The extracted first transverse moment of valence Boer–Mulders function of the pion.

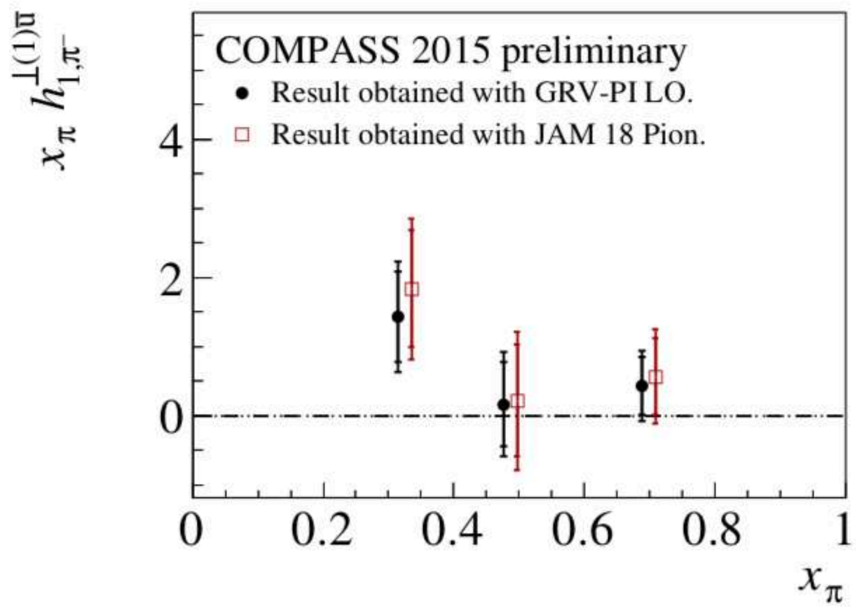
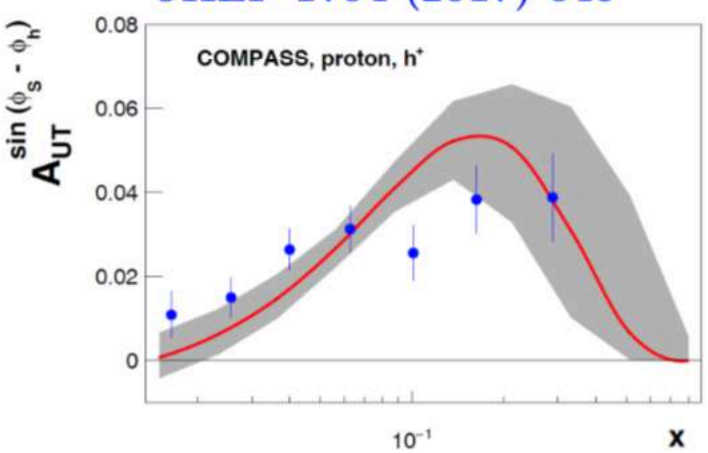


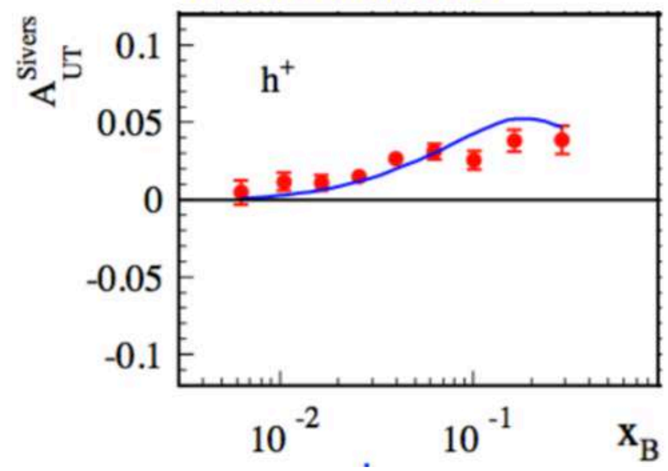
Figure 22: The results obtained using different pion PDF parametrisation.

SIVERS SIGN CHANGE

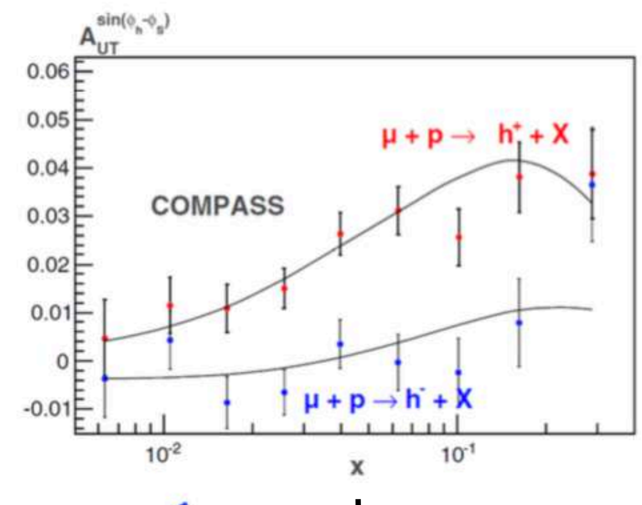
DGLAP (2016)
M. Anselmino et al.,
JHEP 1704 (2017) 046

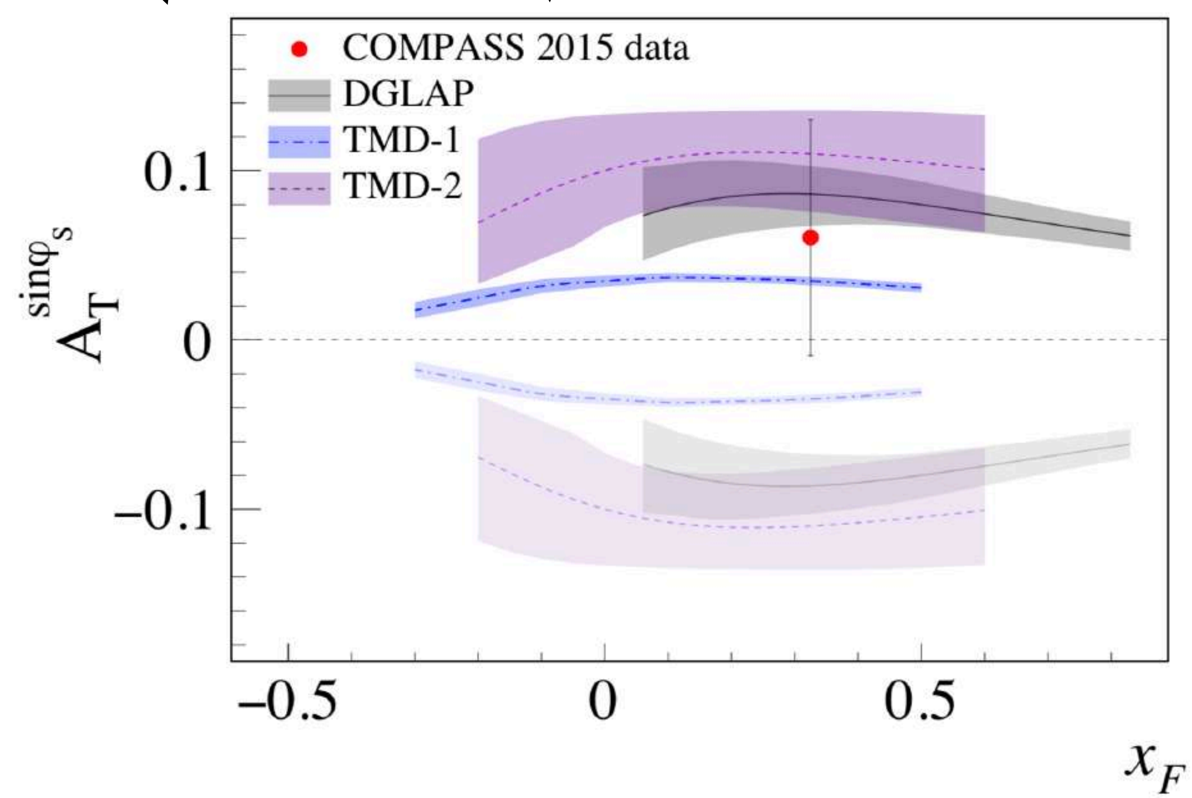


TMD-1 (2014)
M.G. Echevarria et al.,
PRD 89 074013



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





Recent theoretical predictions:

— Based on different Q2-evolution approaches.

— Positive sign of these theoretical predictions, obtained using the sign-change hypothesis for Sivers TMD PDFs

WEIGHTED SIVERS TSA IN SIDIS AND DY

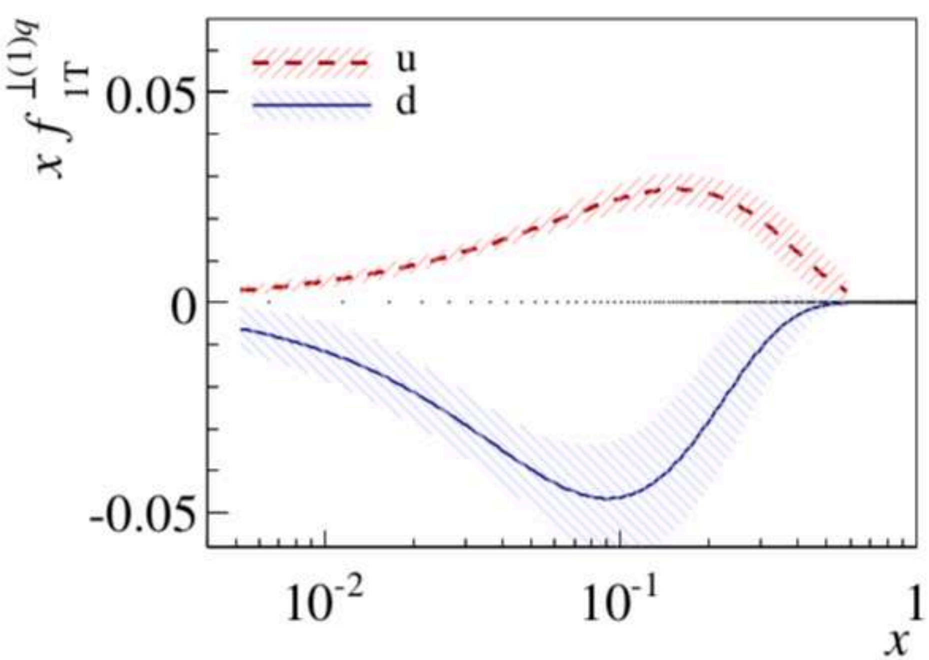
Projection from SIDIS under 3 assumptions:

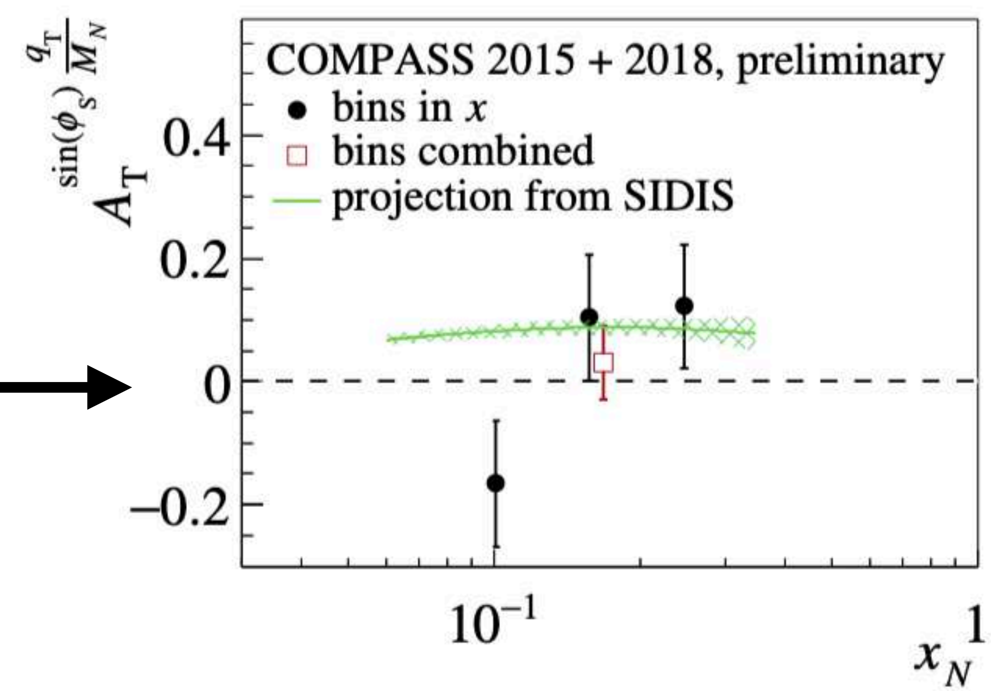
(1) $$A_T^{\sin\varphi_S \frac{q_T}{M_N}} \sim \frac{f_{1T,p}^{\perp u(1)}}{f_{1,p}^{u}}$$

(2) No Q^2 evolution for Sivers

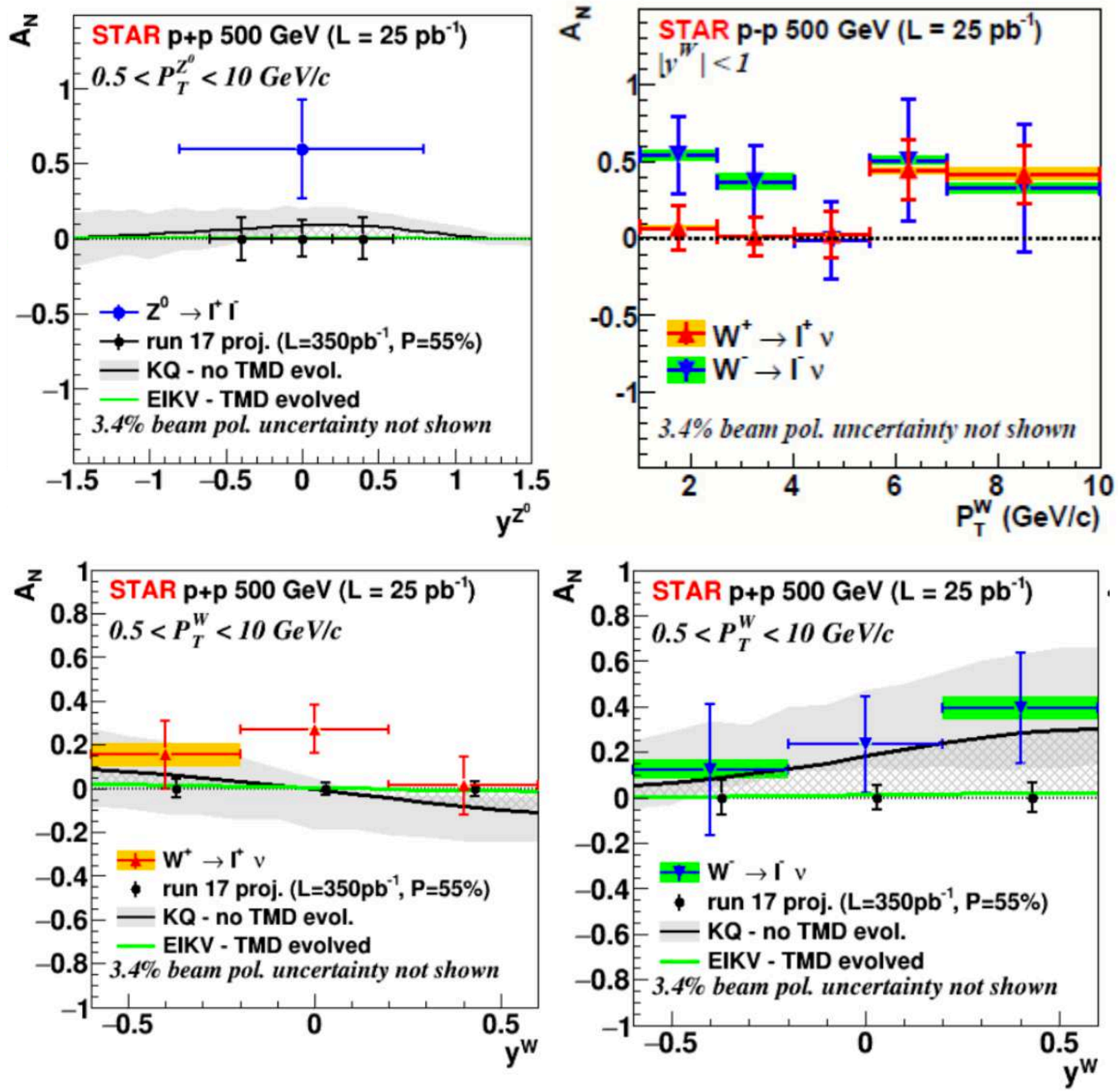
Sivers sign-change

(3) $$f_{1T,p}^{\perp u}|_{SIDIS} = -f_{1T,p}^{\perp u}|_{DY}$$





W-Boson Production in $p\uparrow + p$ at RHIC



	STAR			PHENIX			RHIC II		
	y	4 GeV	20 GeV	y	4 GeV	20 GeV	y	4 GeV	20 GeV
	-0.5	0.007	0.09	-1.8	0.008	0.2	± 2.5	0.003	0.03
δA	0.5	0.006	0.06	0.0	0.017	0.13	± 1.5	0.001	0.01
	1.5	0.007	0.11	1.8	0.008	0.2	± 0.5	0.001	0.01
$\int Ldt$	125 pb^{-1}			125 pb^{-1}			10×125 pb^{-1}		

TABLE I: *Statistical errors δA for the Sivers SSA in Drell Yan for the PHENIX and STAR detectors at RHIC: Errors are shown for dilepton masses of $Q = 4$ GeV and 20 GeV assuming an integrated luminosity of $\int Ldt = 125 pb^{-1}$ and a beam polarization of $P = 0.7$. Error estimates have been carried out using the event generator PYTHIA. Projected errors are also shown for a possible future dedicated experiment for transverse spin with large acceptance at RHIC II (luminosity upgrade); see text for details.*

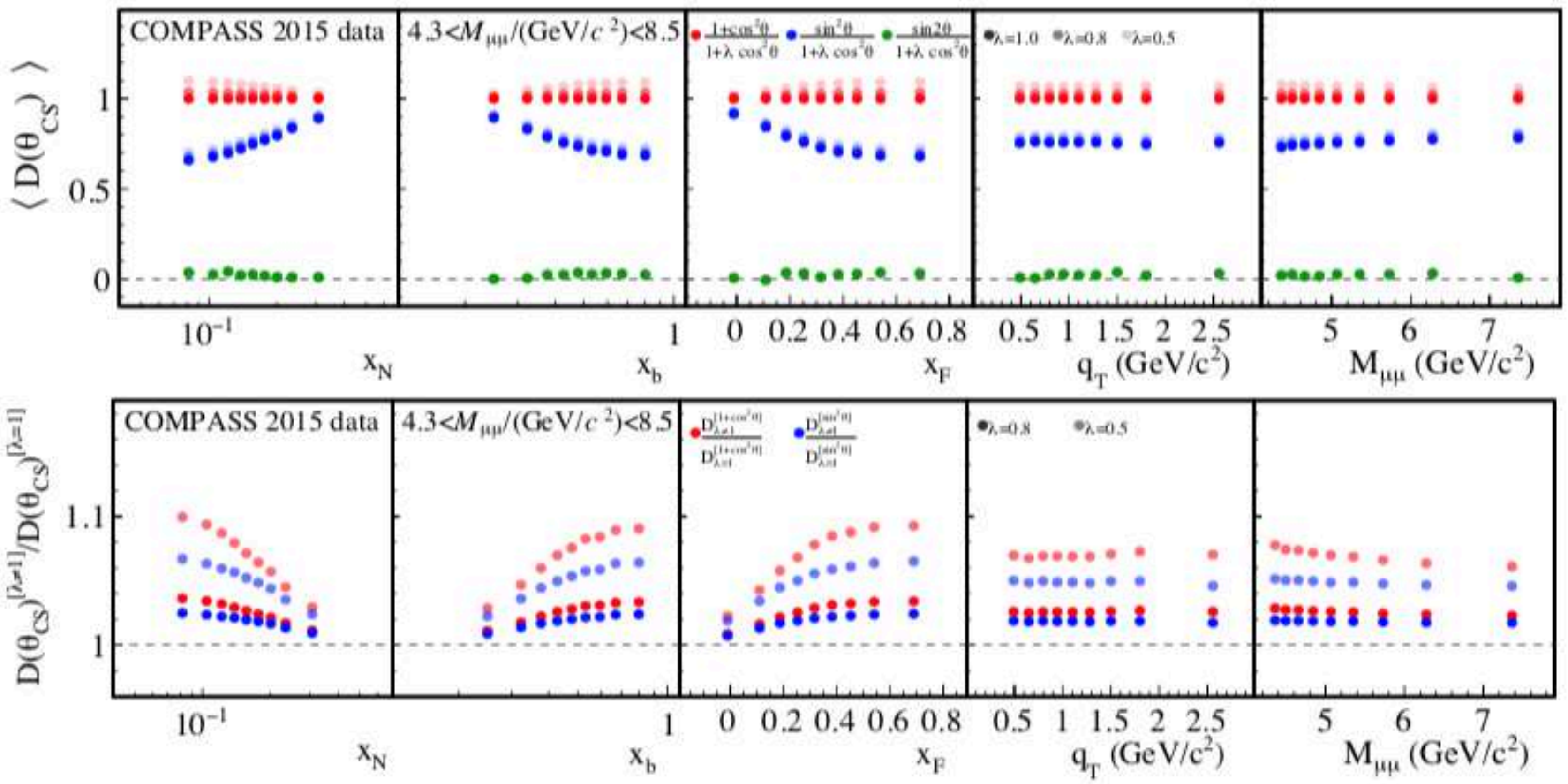
Talk from Oleg Eyser at CPHI (2019)
Phys. Rev. Lett. 116, 132301 (2016)

DEPOLARIZATION FACTOR

- **Depolarization factor:** 5 to 10% variations

Assuming $A_T^{\sin\varphi_S} \approx \tilde{A}^{\sin\varphi_S}$

$$\longrightarrow \hat{\sigma}_U = \left(F_U^1 + F_U^2\right)\left(1 + A_U^1 \cos^2\theta_{CS}\right)$$

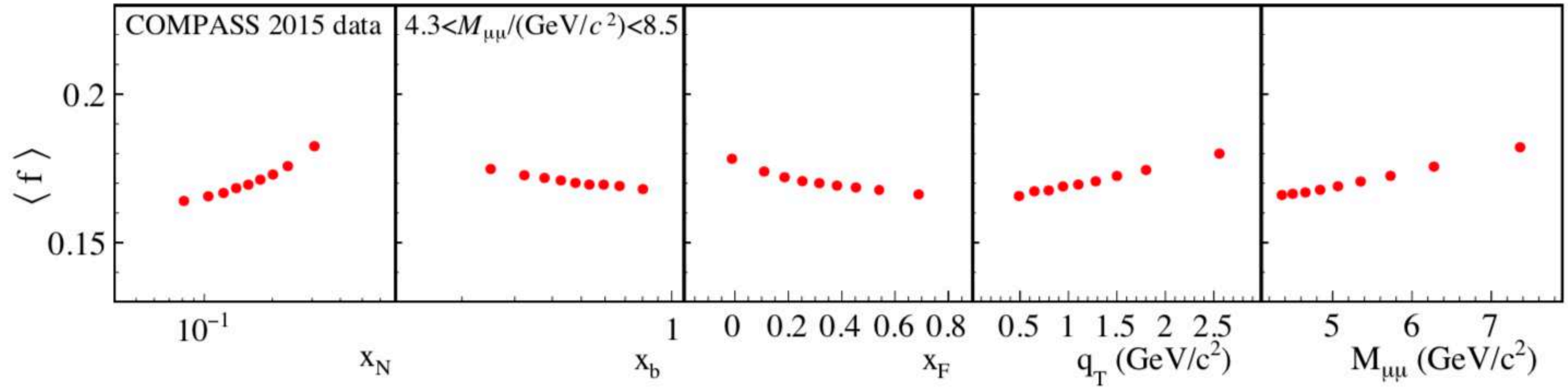


DILUTION FACTOR

- **Dilution factor accounts for the fraction of polarisable material in the target:**

$$f = \frac{n_H \sigma^{DY}_{\pi-H}}{n_H \sigma^{DY}_{\pi-H} + \Sigma_A n_A \sigma^{DY}_{\pi-A}}.$$

- **Uncertainty off by 5%:**



DOUBLE J/PSI: DPS/SPS RATIO