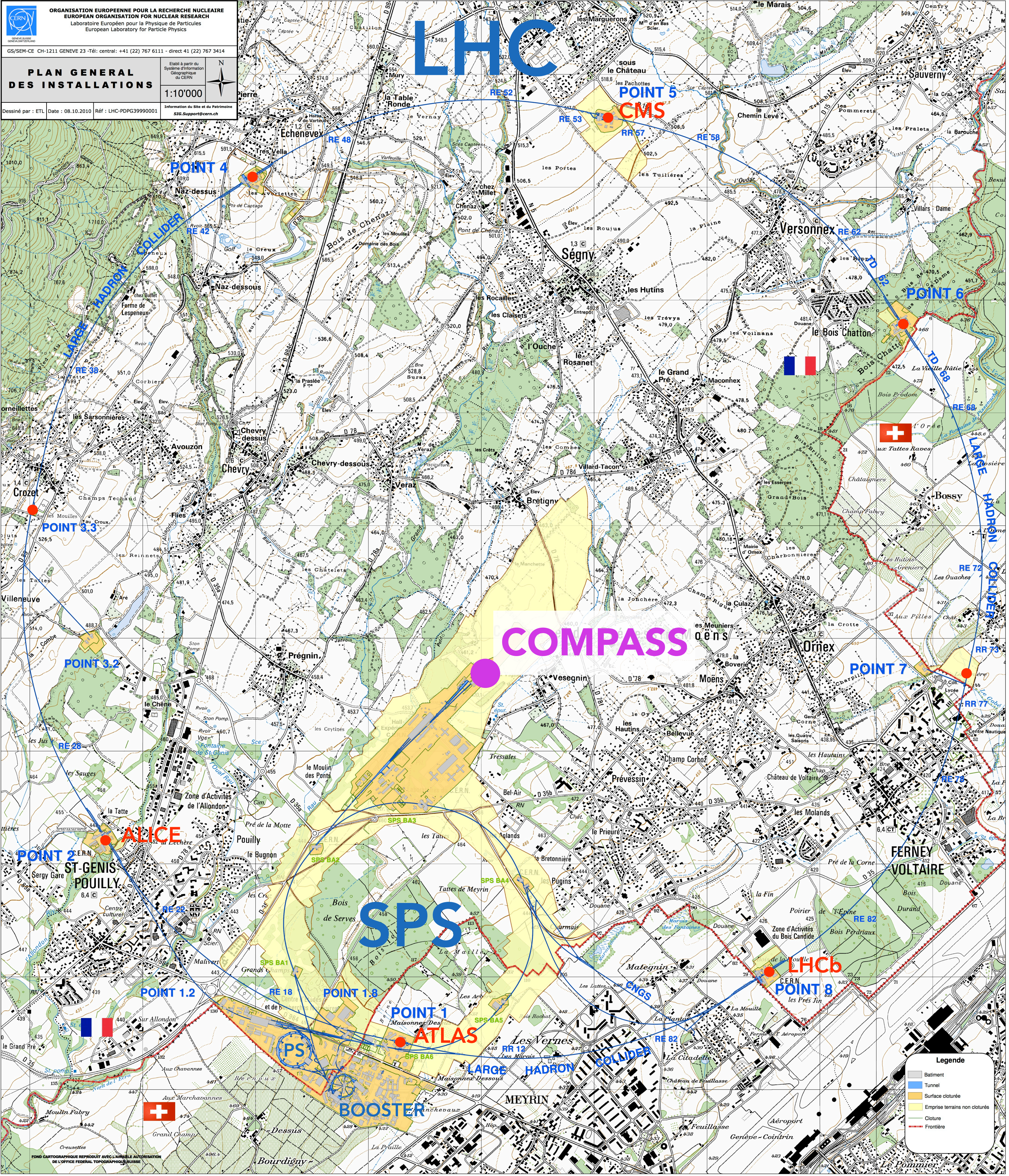
Recent Drell-Yan Results from COMPASS

Aveiro, Portugal - IWHSS 2019 - June 24, 2019

Marco Meyer-Conde
On Behalf of the COMPASS Collaboration

OUTLINE

- The COMPASS experiment
- Results from the polarized Drell-Yan measurement
- Perspectives for unpolarized Drell-Yan studies
- Summary and conclusions



COMPASS Experiment
(SPS North Area)

COmmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

Phase I (2002-2011)

- Nucleon Spin Structure
- Hadron Spectroscopy (2008-2009)

Phase II (2012-2018)

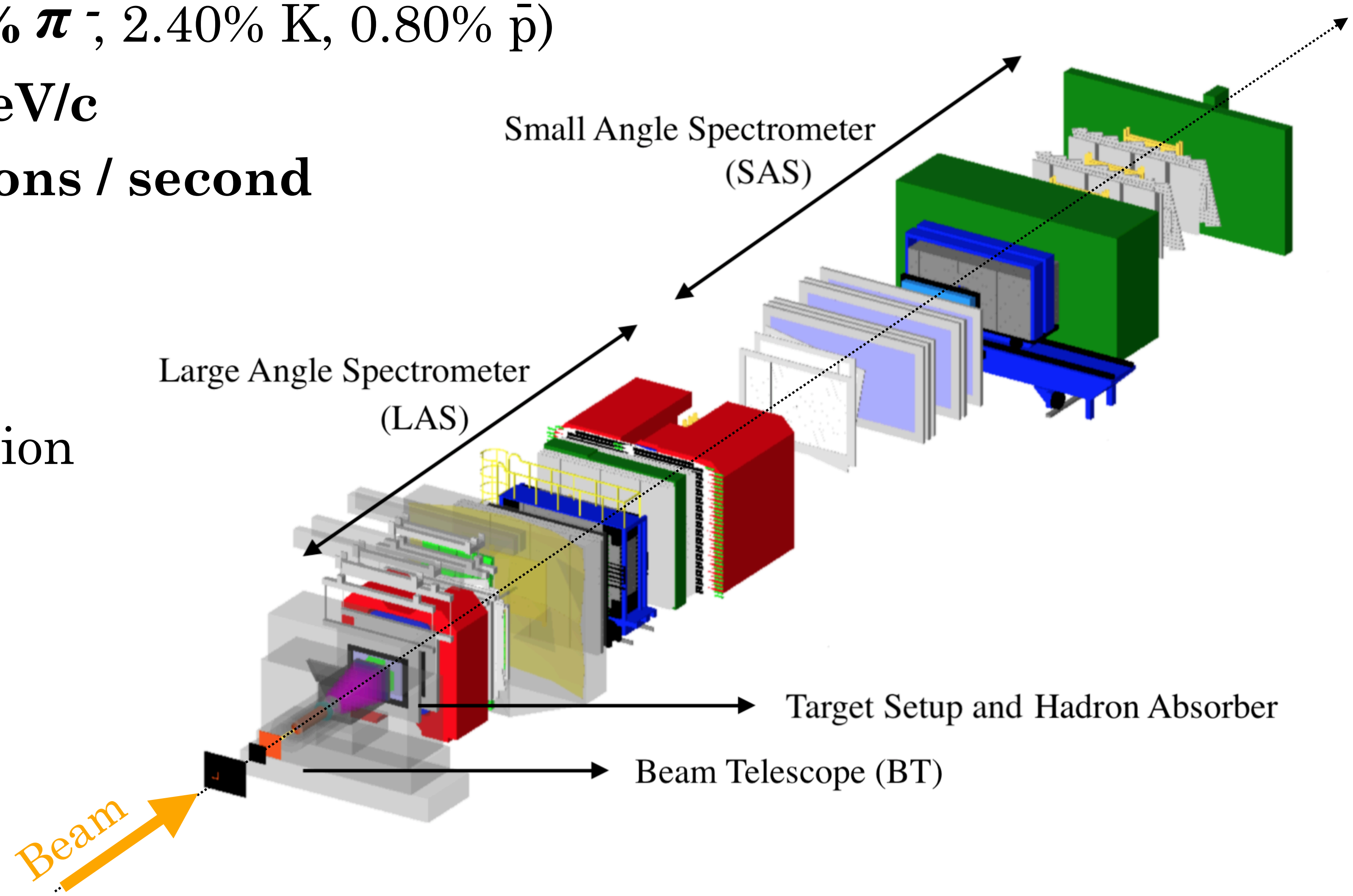
- Primakoff (2012)
- DVCS, SIDIS (2012, 2016, 2017)
- **Drell-Yan (2014, 2015, 2018)**

THE COMPASS DRELL-YAN APPARATUS

- **Two Stage Apparatus :**
  - Large Angle Spectrometer *(35 mrad - 180 mrad)*
  - Small Angle Spectrometer *(18 mrad - 35 mrad)*

- **Unique Hadron Beam in DY runs :**
  - Hadron beam made of (**96.80% π^-**, 2.40% $\bar{K}$, 0.80% $\bar{p}$)
  - Beam momentum : **190 ± 3 GeV/c**
  - Intensity : up to **~7x10^7 hadrons / second**

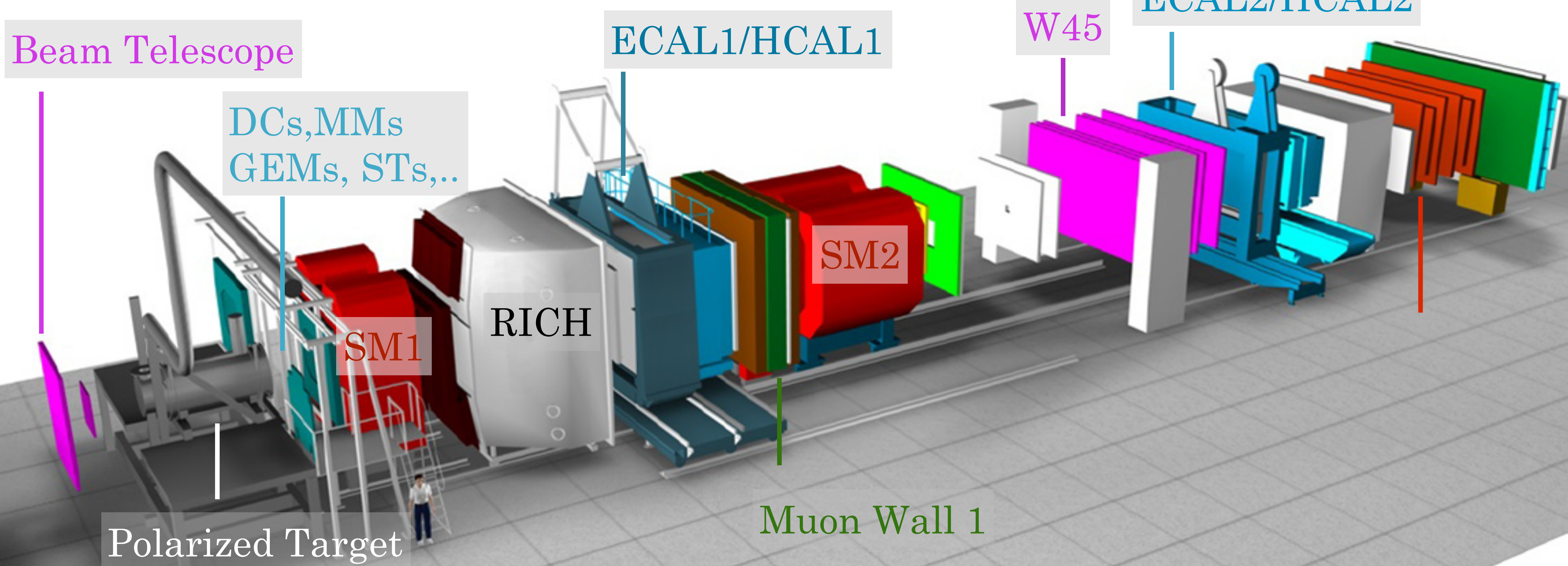
- **Spectrometer Features:**
  - Track and Vertex Reconstruction
  - Momentum Reconstruction
  - Particle Identification



THE COMPASS DRELL-YAN APPARATUS

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

- **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)

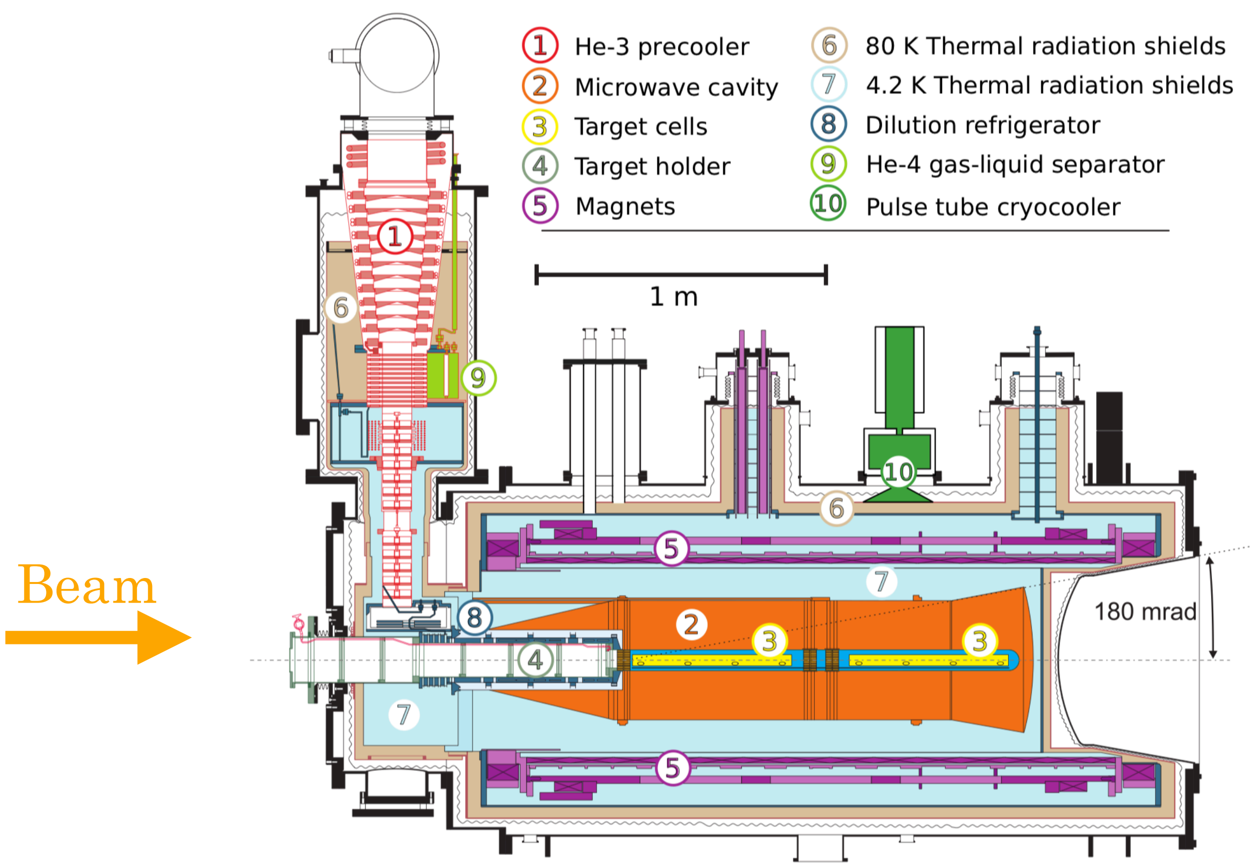


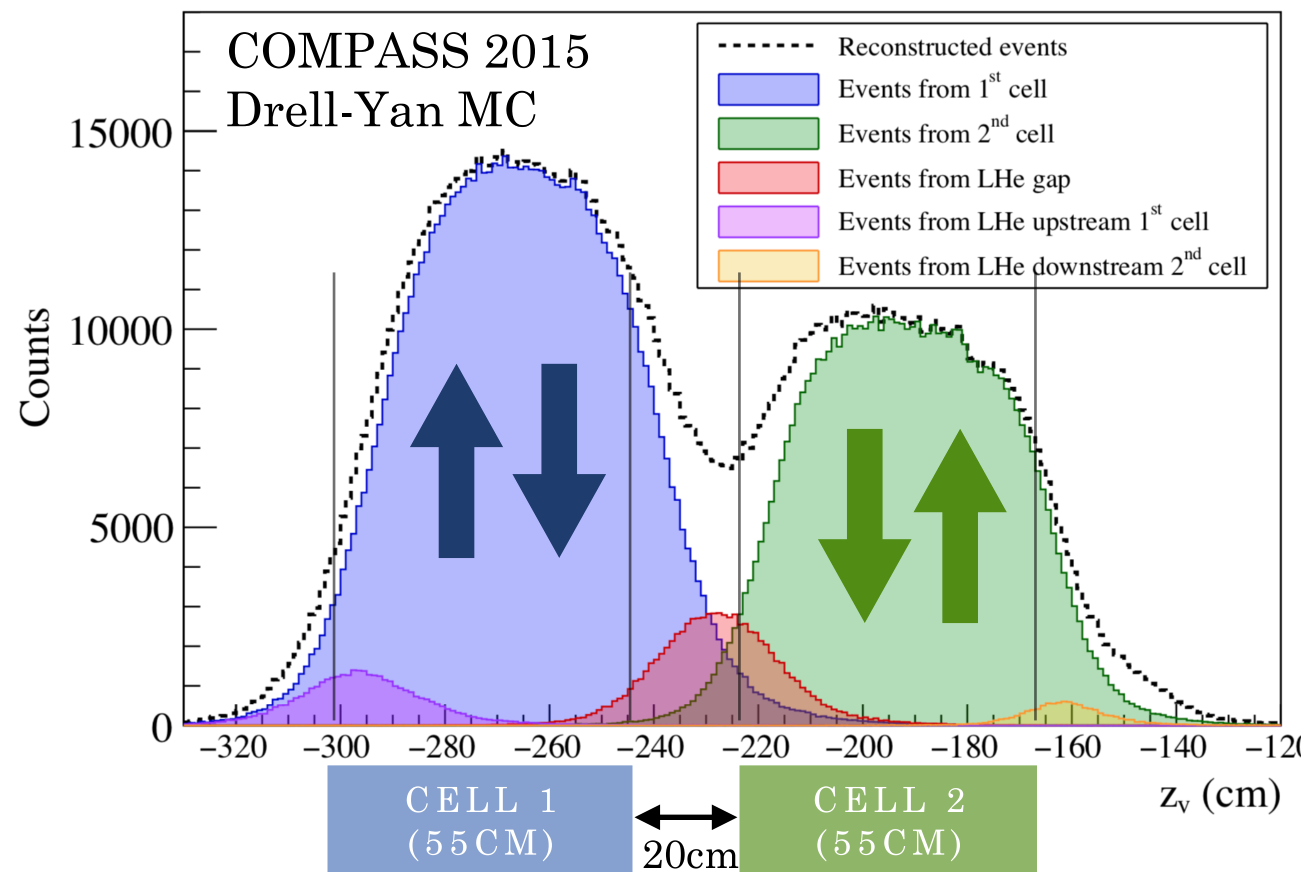
THE POLARIZED TARGET

➤ **Composition of the PT target :** Solid state NH_3 beads in a LHe bath *(Packing factor of 47%-56%)*

➤ **Average polarization ~70%** *(Only H_3 protons are polarized)*
Polarization reversed ↑↓ each week to minimize systematic uncertainties

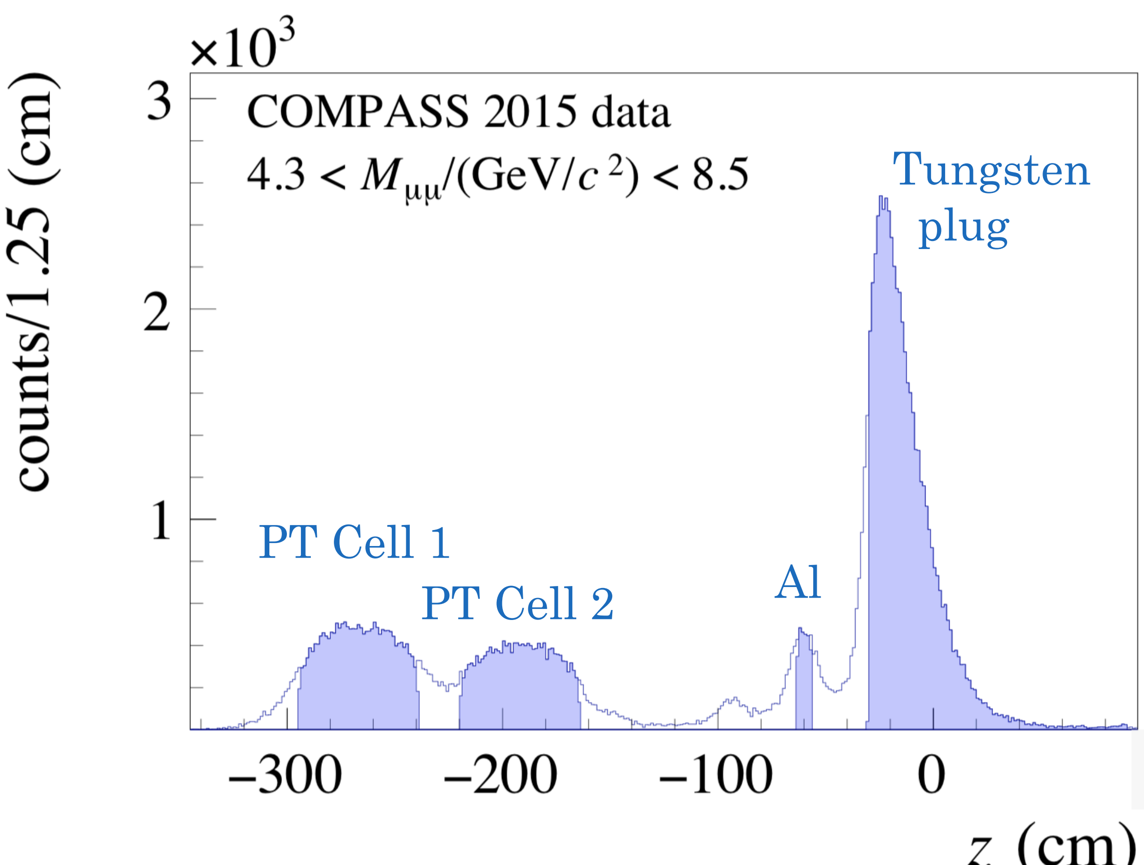
➤ **Physics Data taking :**
- 2014 Pilot DY run ~ Few weeks of data taking
- 2015 Polarized DY run ~ 4 months of data taking
- 2018 Polarized DY run ~ 5 months of data taking

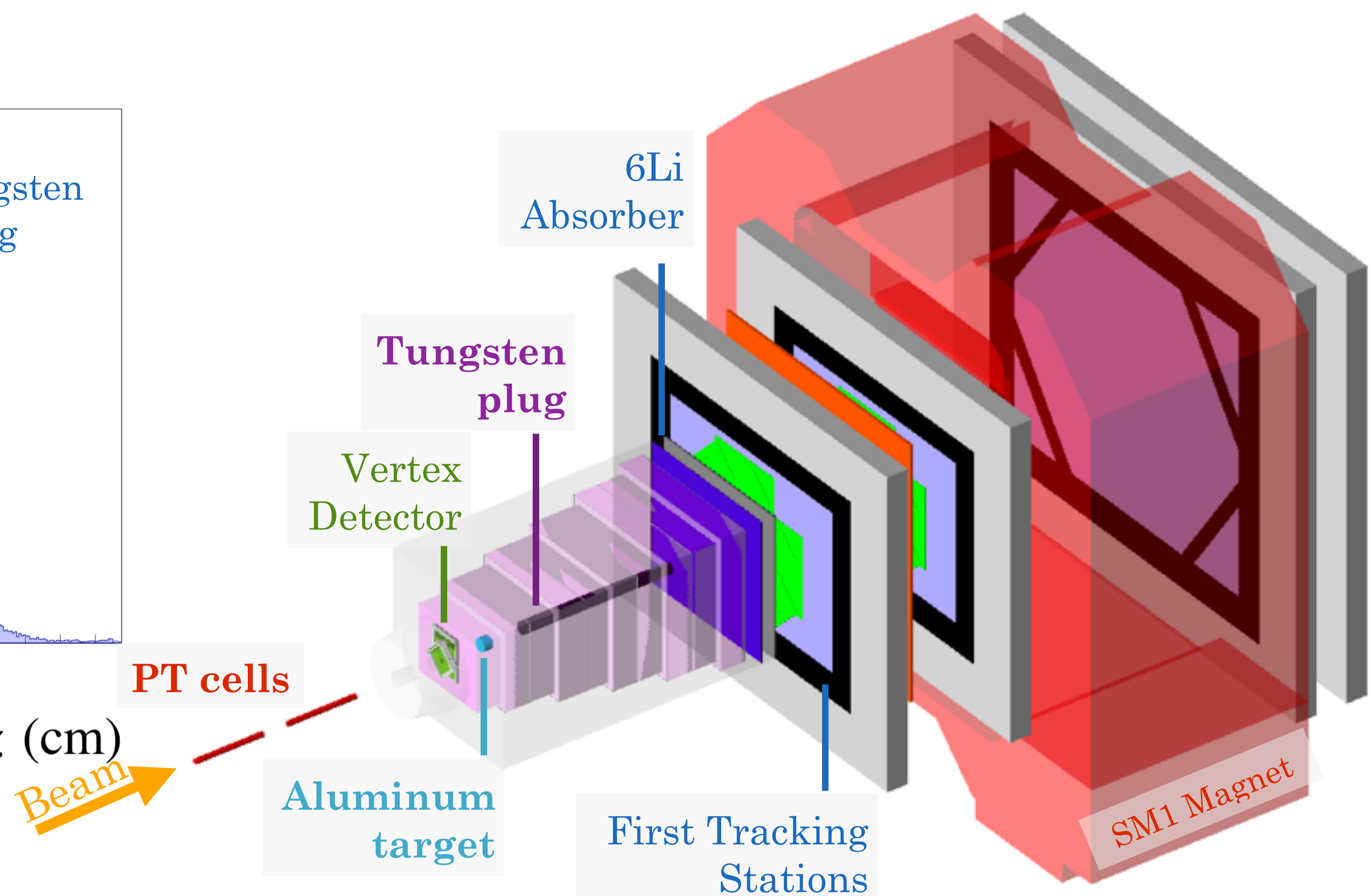




THE HADRON ABSORBER AND NUCLEAR TARGETS

- **Goal:** Remove hadrons upstream of the absorber *(originating from target interactions or beam)*
- Aluminum and Tungsten plug used as **hadron absorbers**.
- **Additional Nuclear Targets available:** *(Good separation of targets)*
  - Aluminum 7cm length target — *Intermediate A ~ 27*
  - Tungsten first 10 cm used for physics analysis — *Large A ~ 184*





THE DRELL-YAN PROCESS

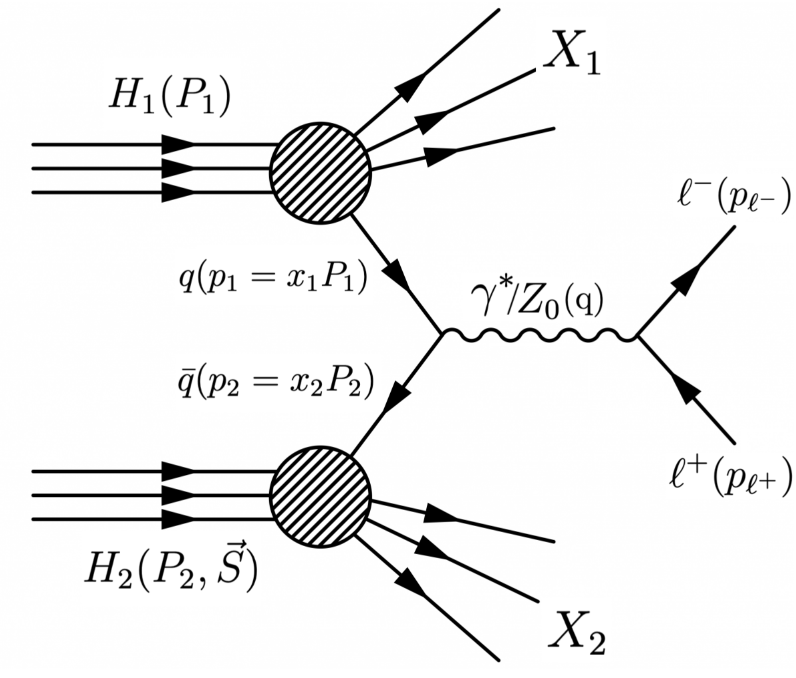
- **Leading Order Feynman diagram for the Drell-Yan process :**

$$H_1(P_1) + H_2(P_2, \vec{S}) \longrightarrow \ell^-(p_{\ell^-}) + \ell^+(p_{\ell^+}) + X_1 + X_2$$

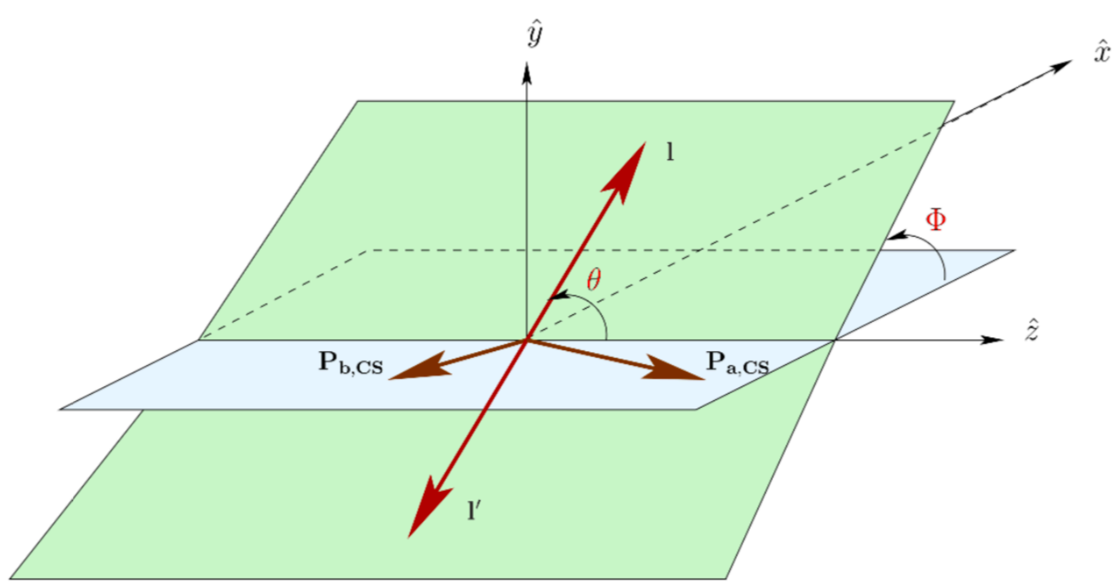
<u>Drell-Yan hard cross-section</u> : QED process + QCD corrections
<u>Soft part</u>: Non-perturbative hadron structure

- No fragmentation function required in DY (cf. SIDIS)

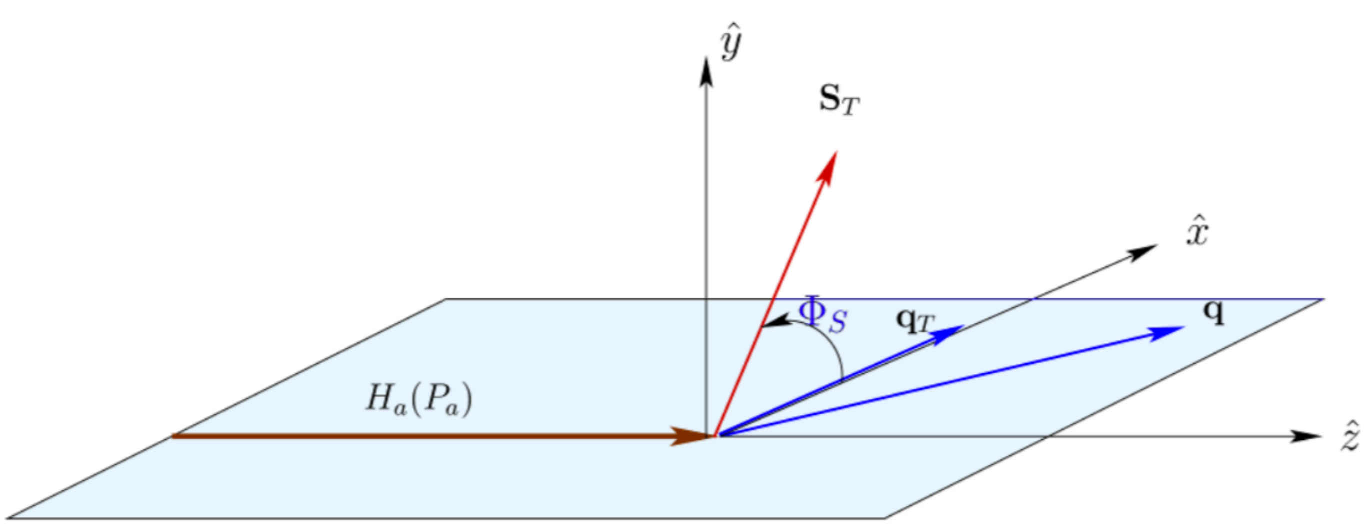
- **<u>Experimentally:</u>** Measuring momentum of both muons.
  Six degrees of freedom : (M, x_F, q_T, ϕ_s, θ_{CS}, ϕ_{CS})



- Drell-Yan Feynman Diagram -



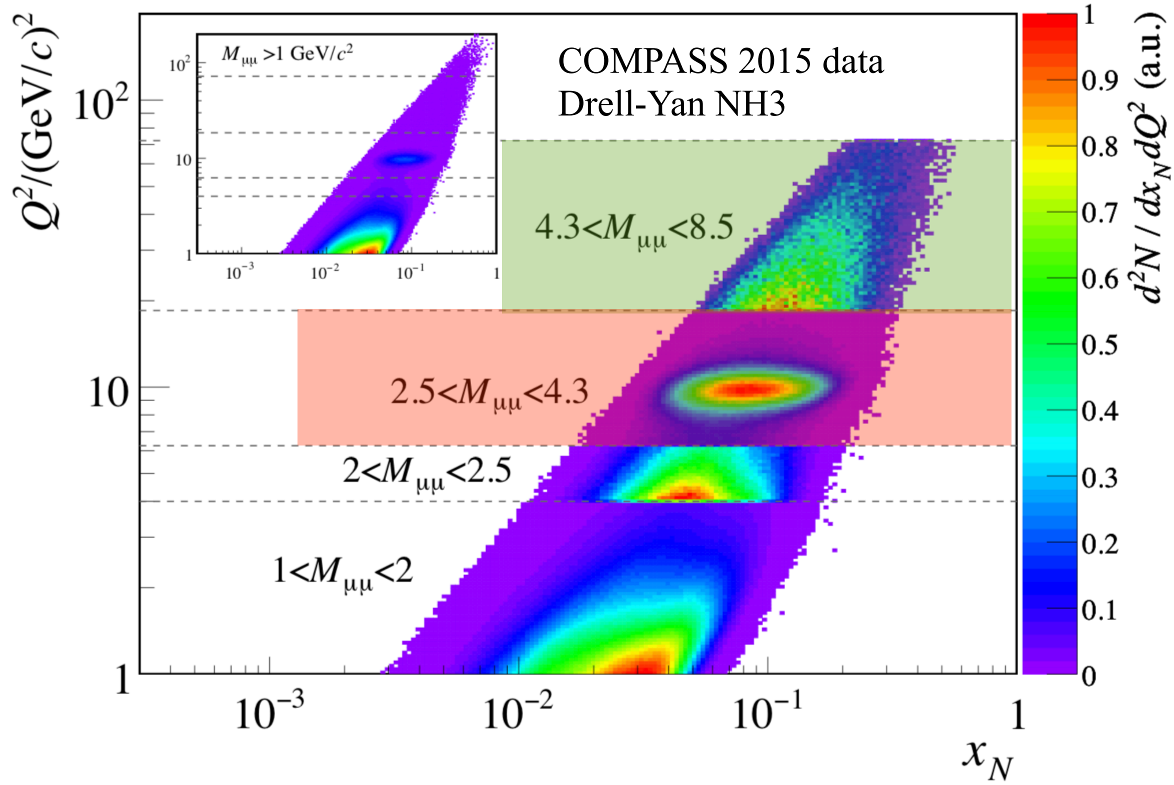
- Collins-Soper Frame Definition -

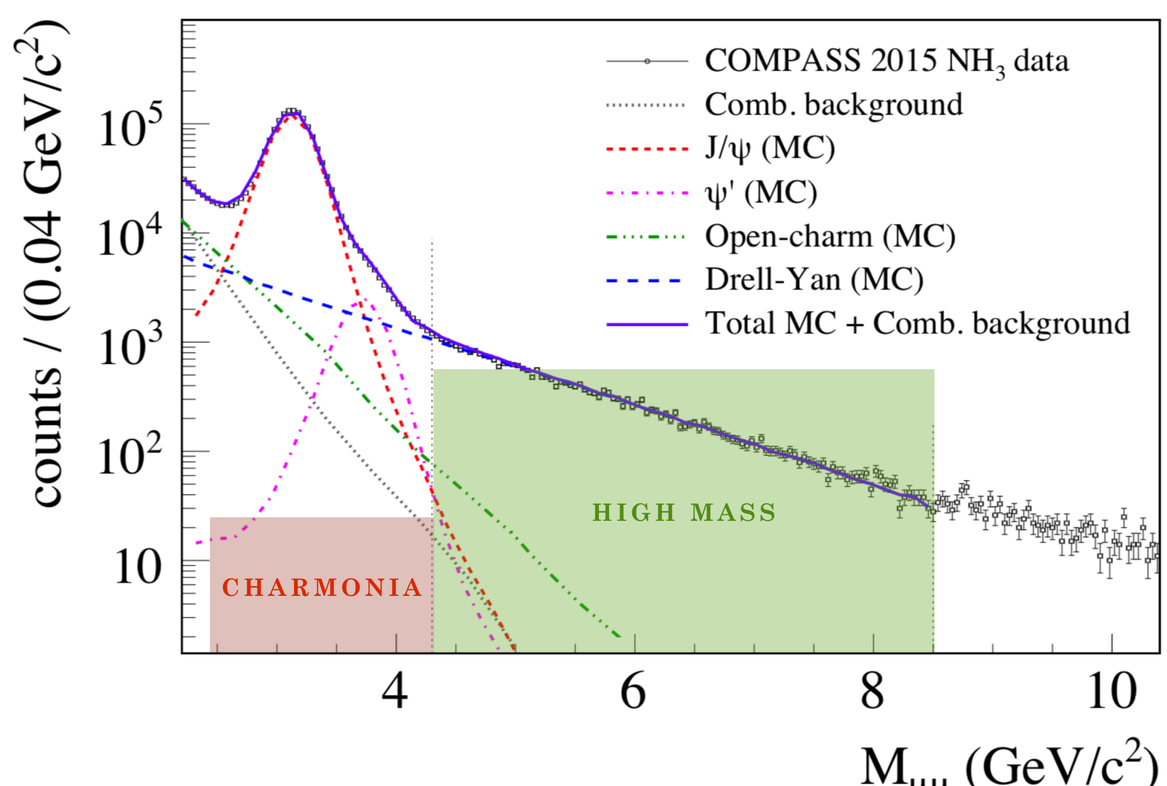


- Target Rest Frame Definition -

KINEMATIC COVERAGE

- **1 < $M_{\mu\mu}$/(GeV/c²) < 2** — *"Low Mass Region"*
  - Large background contamination
- **2 < $M_{\mu\mu}$/(GeV/c²) < 2.5** — *"Intermediate mass"*
- **2.5 < $M_{\mu\mu}$/(GeV/c²) < 4.3** — *"Charmonia mass"*
  - Good signal/background ratio (large statistics)
  - J/ψ peak — Production mechanism study
- **4.3 < $M_{\mu\mu}$/(GeV/c²) < 8.5** — *"High mass range"*
  - Background contamination < 4%
  - Valence-quark region (Larger asymmetries)





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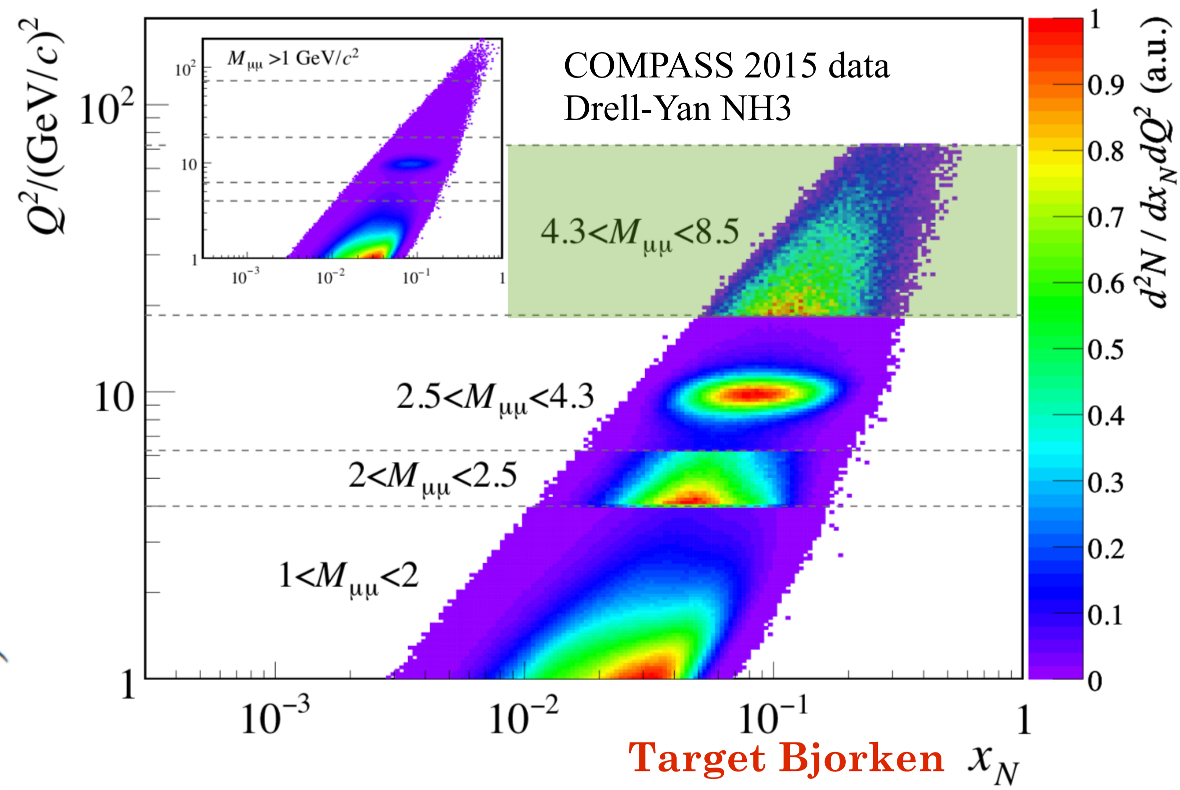

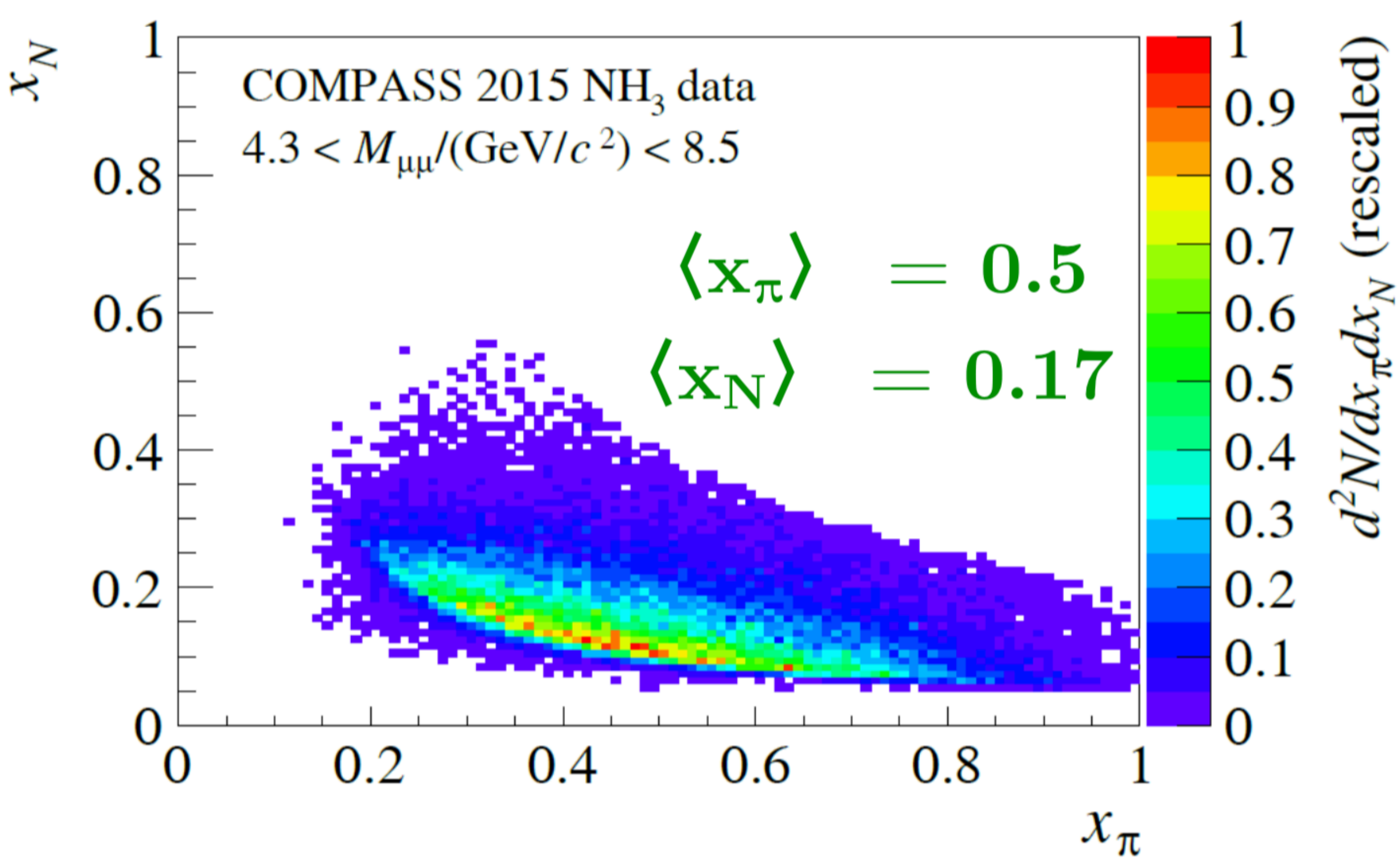

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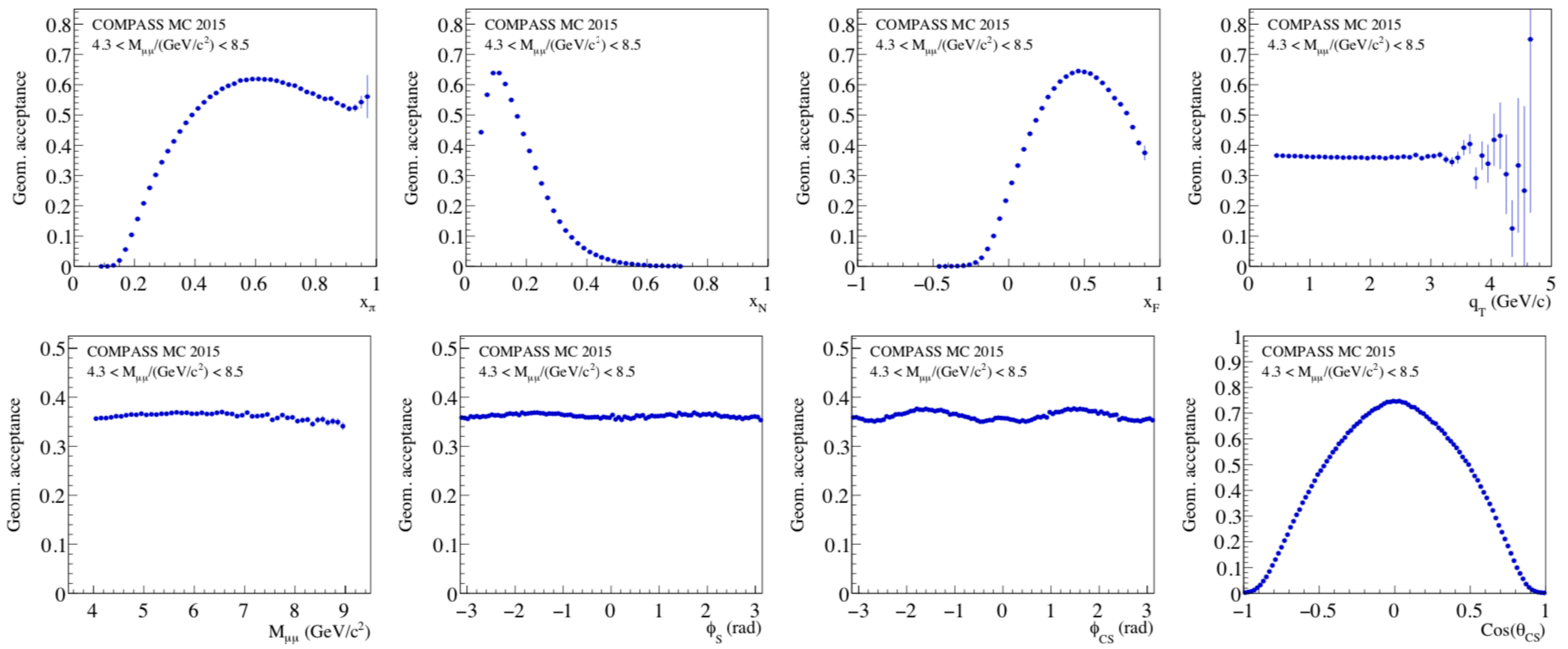
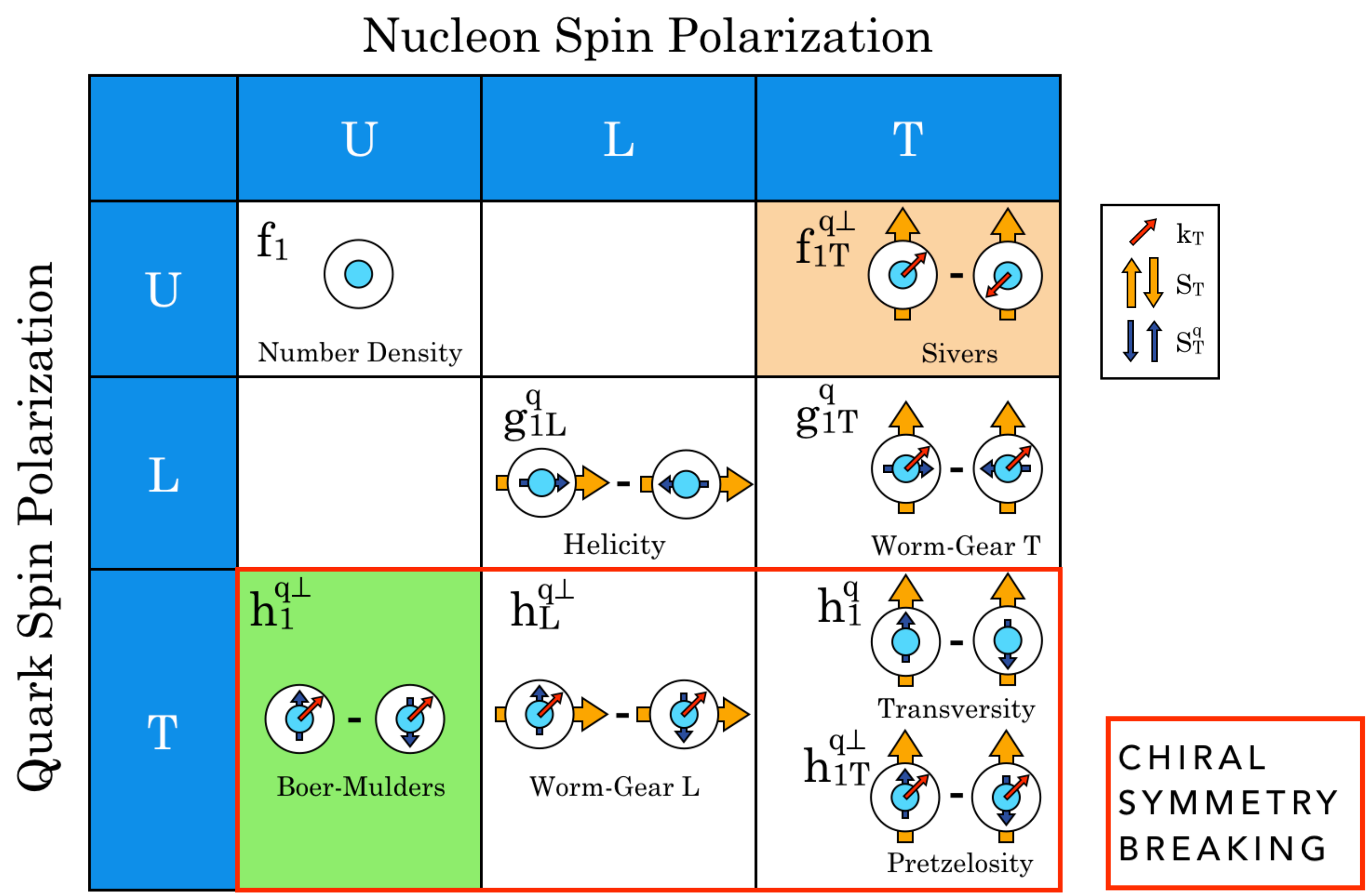
Geometrical Acceptance



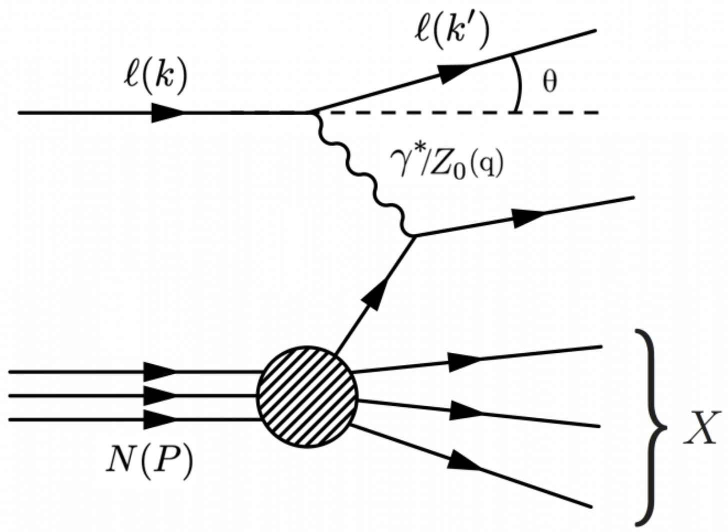
TRANSVERSE MOMENTUM DEPENDENT PARTON DISTRIBUTION FUNCTIONS

- At leading twist, pQCD is parametrized by **8 TMD PDFs**
- Each Twist-2 TMD PDFs depends on **the intrinsic transverse momentum k_T** of the interacting partons
- **Sivers and Boer-Mulders :**
  - A particular interest in Drell-Yan — Change of sign expected compared to SIDIS.
  - Crucial test of the TMD factorization



BRIDGE DIS / DRELL-YAN

- **Deep Inelastic Scattering process :** PDF⊗FF
  Drell-Yan process : PDF⊗PDF (Beam flavor sensitivity)

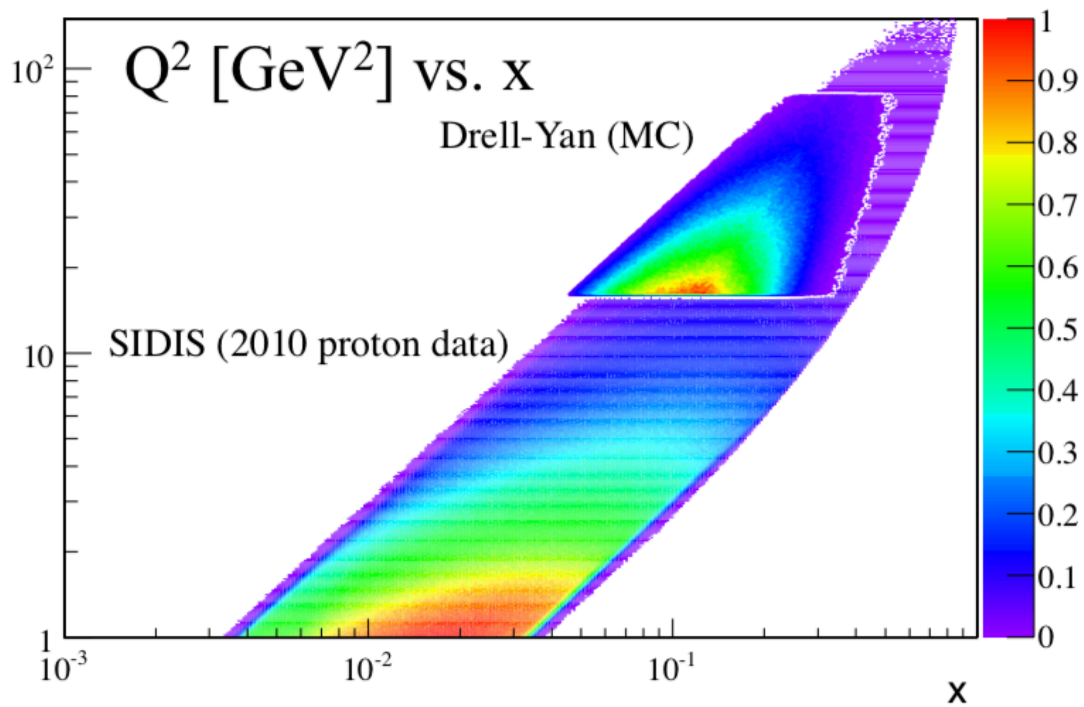


- DIS Feynman Diagram -

- **Since 2005:** Significant non-zero Sivers asymmetry was measured by HERMES and COMPASS in SIDIS

- **COMPASS Experiment :** Access to convoluted TMD PDFs via Polarized DY and SIDIS with the same apparatus

COMPASS DY / SIDIS data



Sign change relations DY/SIDIS:

$$f_{1T}^{q\perp}\Big|_{DY} = -f_{1T}^{q\perp}\Big|_{SIDIS} \quad \text{(Sivers)}$$

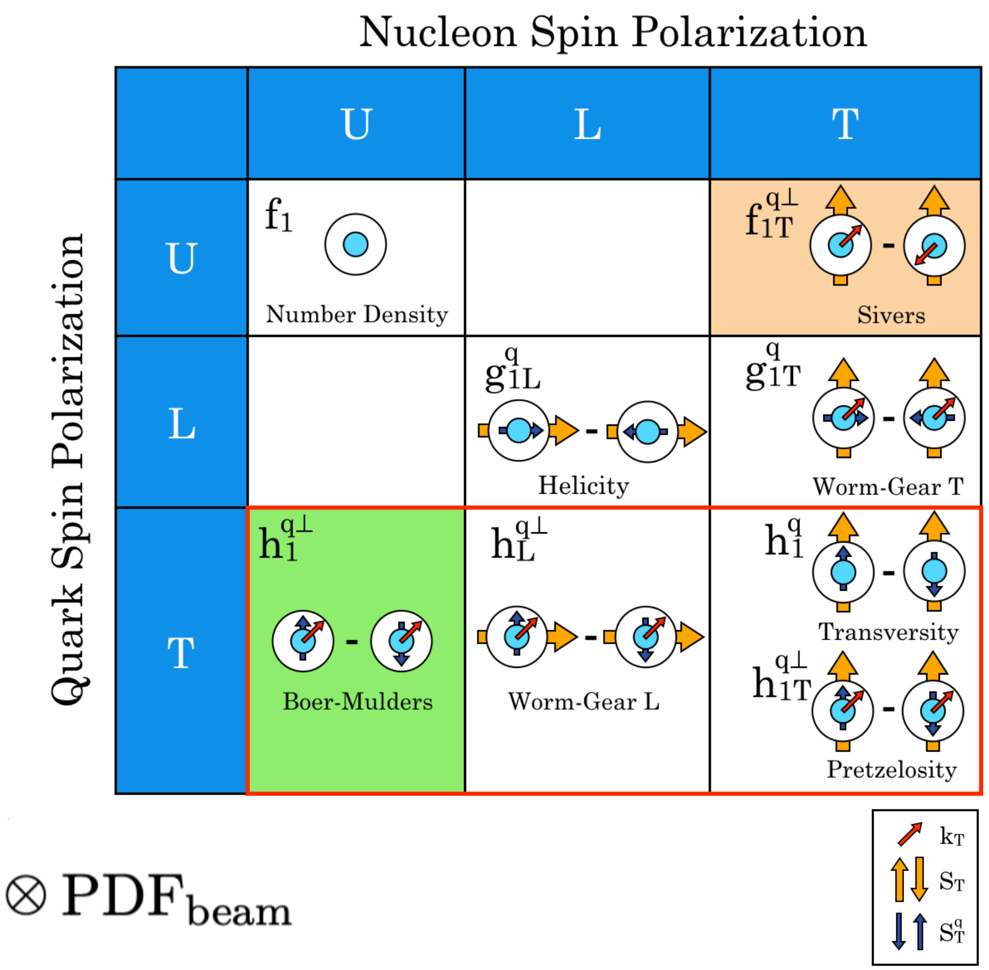
$$h_{1}^{q\perp}\Big|_{DY} = -h_{1}^{q\perp}\Big|_{SIDIS} \quad \text{(Boer-Mulders)}$$

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

SINGLE POLARIZED DRELL-YAN CROSS-SECTION

- **Single-Spin Drell-Yan cross-section at Leading Twist :**

$$\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha_{em}^2}{q^2 F} \times A_U^1 (1 + cos^2\theta) \left[\left(1 + D_{[\sin^2\theta]} A_U^{\cos 2\phi} \cos 2\phi\right) + |S_T| \left\{ \begin{array}{l} A_T^{\sin\phi_S} \sin\phi_S \\ + D_{[\sin^2\theta]} \left\{ \begin{array}{l} A_T^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) \\ + A_T^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) \end{array} \right\} \end{array} \right. \right]$$



- **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

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

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

$A_U^1 = F_U^1$

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

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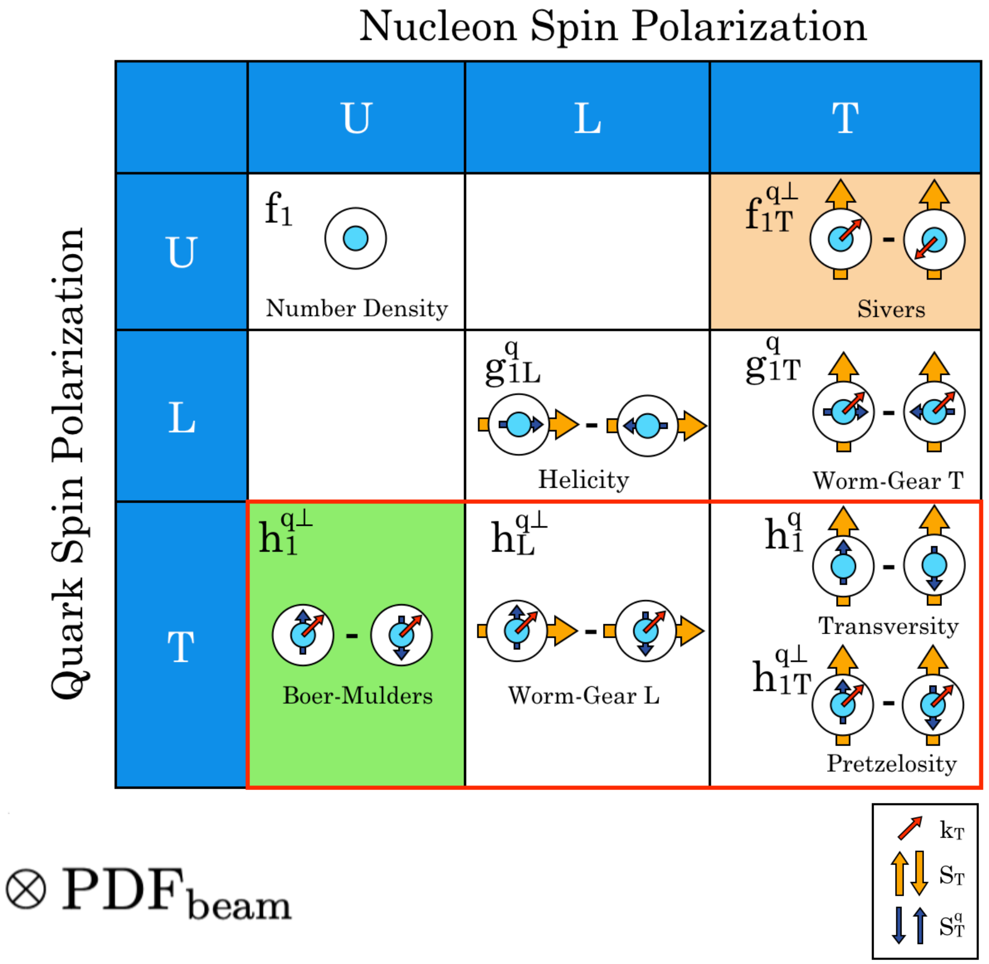

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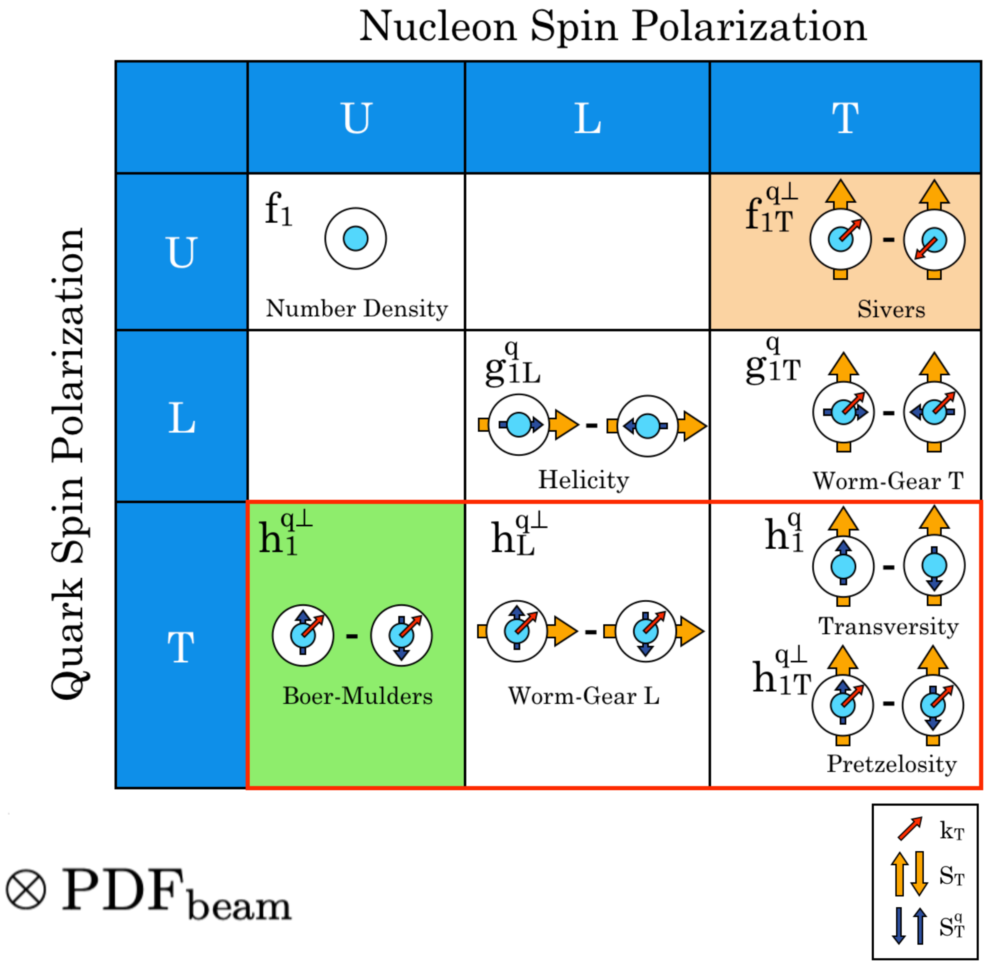

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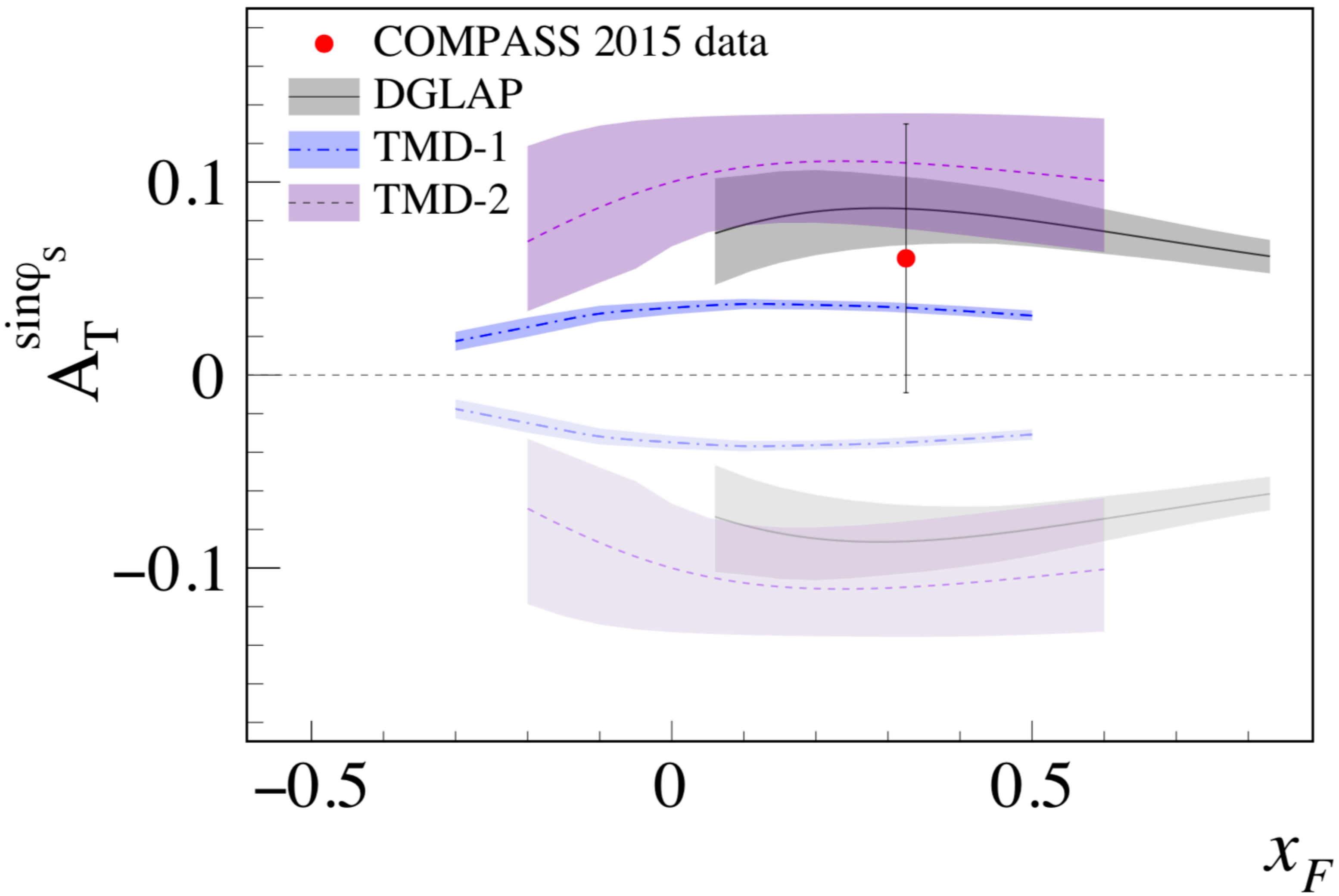
} Transverse Asymmetries (Sivers, Pretzelosity, Transversity)

SIVERS ASYMMETRY IN DRELL-YAN

- **Sivers Asymmetry from COMPASS 2015 data:**

  — $\langle A_T^{\sin \phi_S} \rangle = 0.060 \pm 0.057(\text{stat}) \pm 0.040(\text{sys})$

- **Requires more Drell-Yan data:** *Successful year of data taking in 2018*

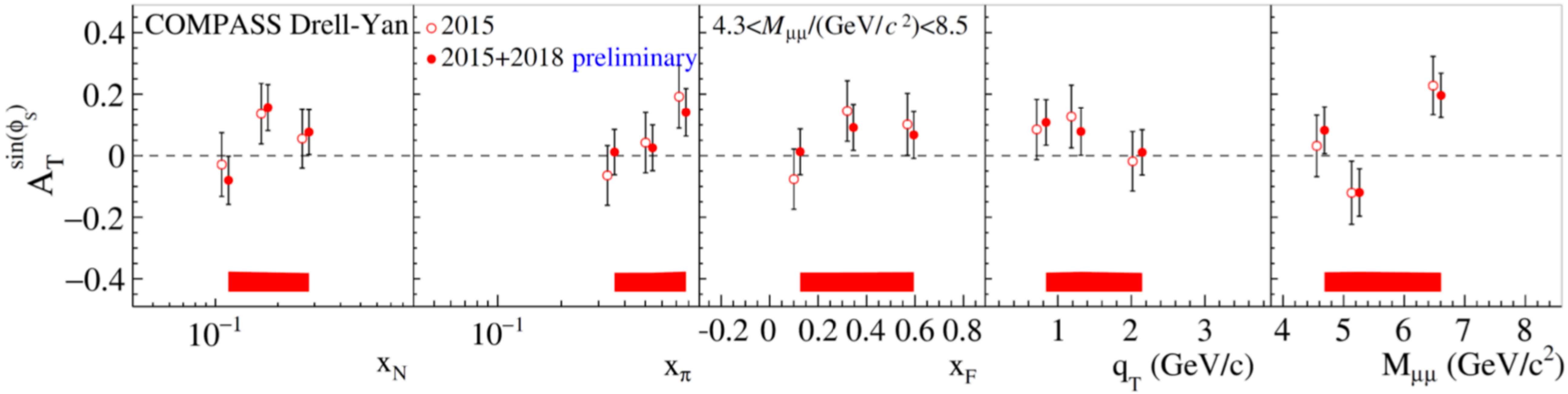


Phys. Rev. Lett. 119, 112002 (2017)
DGLAP (2016) M. Anselmino et al., JHEP 1704 (2017) 046
TMD-1 (2014) M.G. Echevarria et al., PRD 89 074013
TMD-2 (2013) P. Sun, F. Yuan, PRD88, 114012

SIVERS DISTRIBUTION FUNCTION

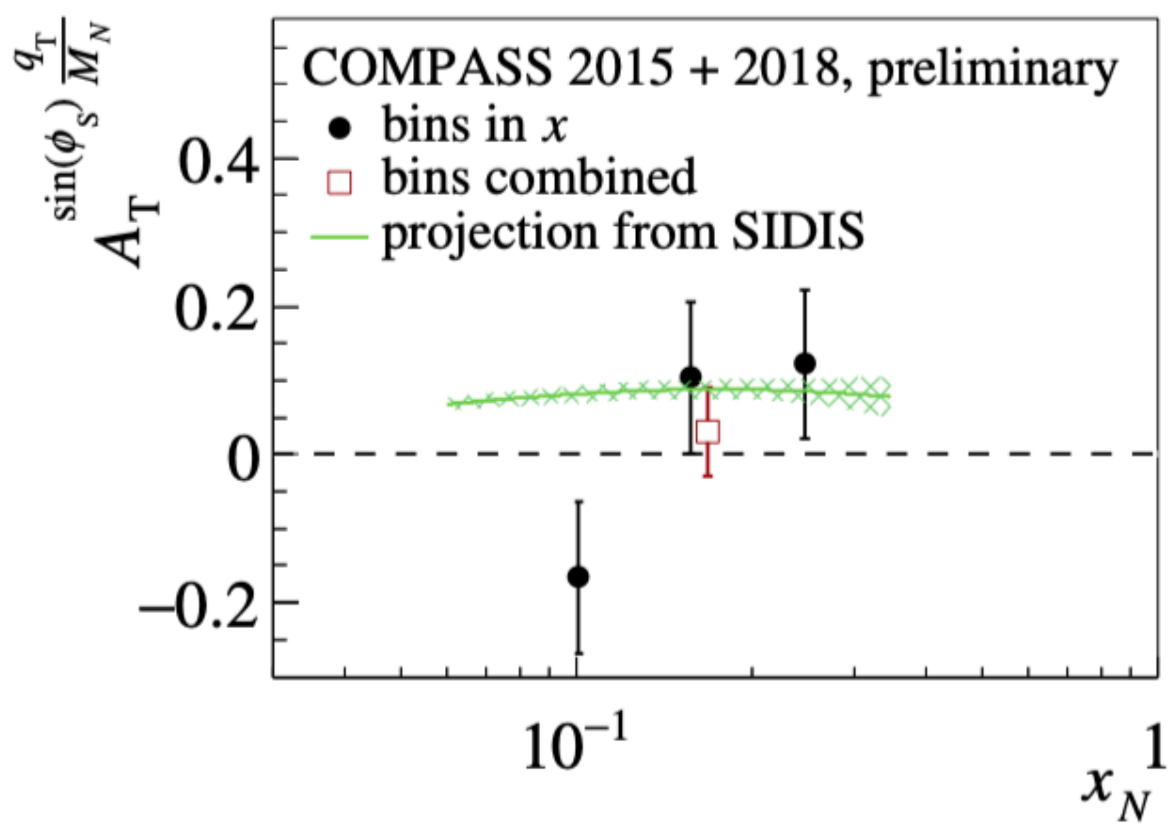
- **Updated results as function of x_N, x_π, x_F q_T, M**
- Preliminary results including 50% of the 2018 data
  (2015 = 4 months; 2018 = 5 months of data taking)

COMPASS 2015 (*PRL 119, 112002 (2017)*) + 2018 (~50%)



WEIGHTED SIVERS TSA IN DRELL-YAN

- **qT weighted transverse spin asymmetries in Drell-Yan:**
  A. Efremov et al., Phys.Lett. B612 (2005) 233
  A. Sissakian et al., Phys.Rev. D72 (2005) 054027
- **Directly access to the first moment of TMDs :** $A_T^{\sin\varphi_S \frac{q_T}{M_N}} \propto f_{1,\pi}^{q} \times f_{1T,p}^{\perp q(1)}$
  - No assumption on k_T dependence of the TMDs
  - Access to the direct product of the TMD PDFs

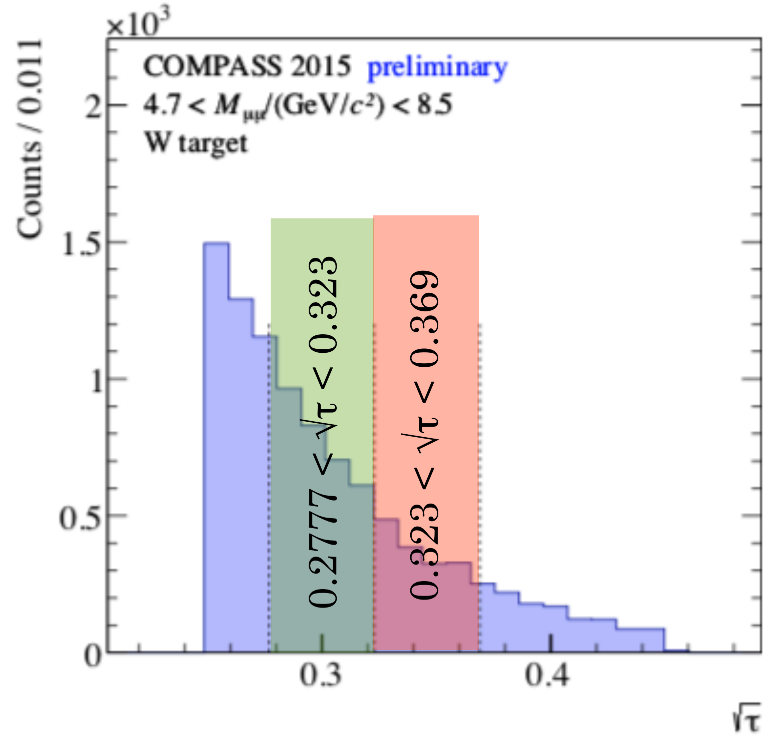


MOTIVATIONS OF THE UNPOLARIZED DRELL-YAN

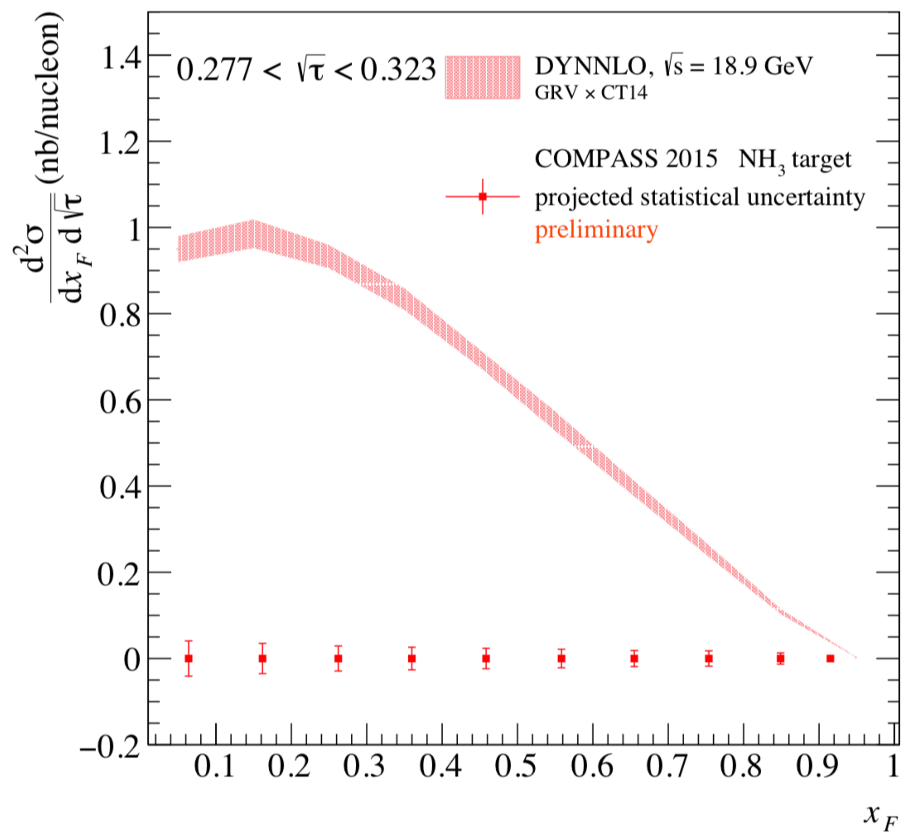
- **Three targets available :** PT cells, Al (A~27), W (A ~184)
- **Unique results using a negatively charged pion beam at 190 GeV/c**
- **Motivations of unpolarized DY studied :**
  (1) Extraction of the valence quark distributions for pion
  (2) Boer-Mulders TMD extraction
  (3) Lam-Tung Violation
  (4) Nuclear dependence as a function of x_F, and q_T
  (EMC effect, Energy loss effect and Cronin effect)

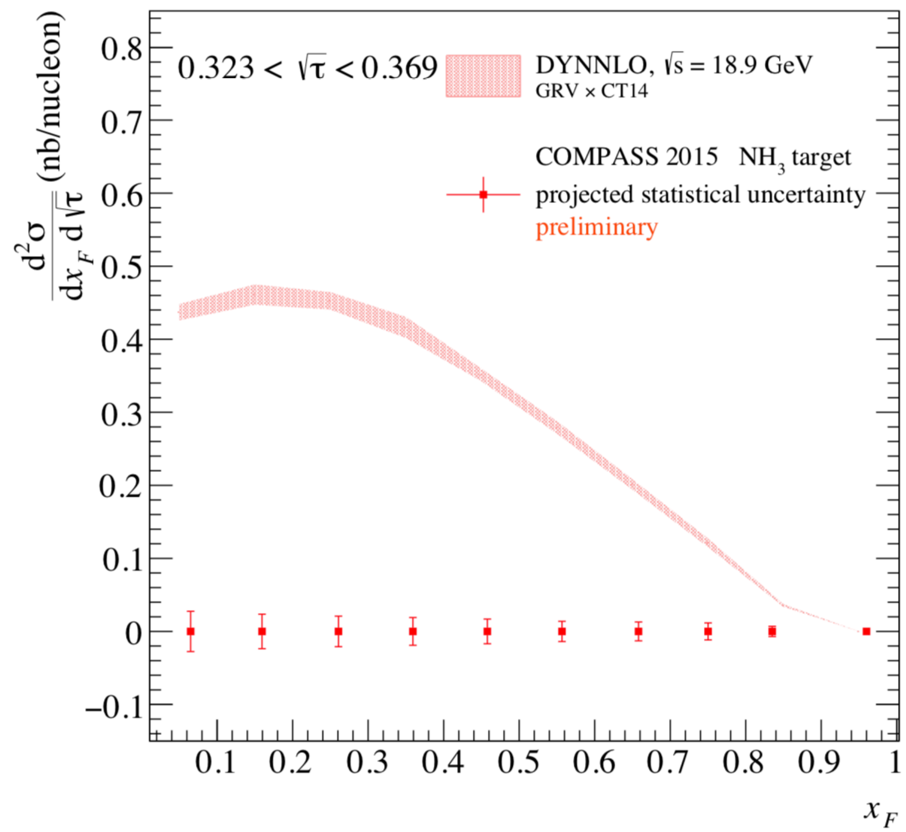
UNPOLARIZED ABSOLUTE DRELL-YAN CROSS-SECTION

- **Comparison with E615, NA10 experiment :**
  — Both $\pi^- + W$, compared for two bins in $\sqrt{\tau}$
- **Projected uncertainties recently released (Nov. 2018) :**
  — Uncertainties for PT NH_3 target compared with DYNNLO simulation
  — Uncertainties for Tungsten target compared with E615 and DYNNLO *(beam energy rescaling)*
- **Aim at better systematic uncertainties**



PT cells





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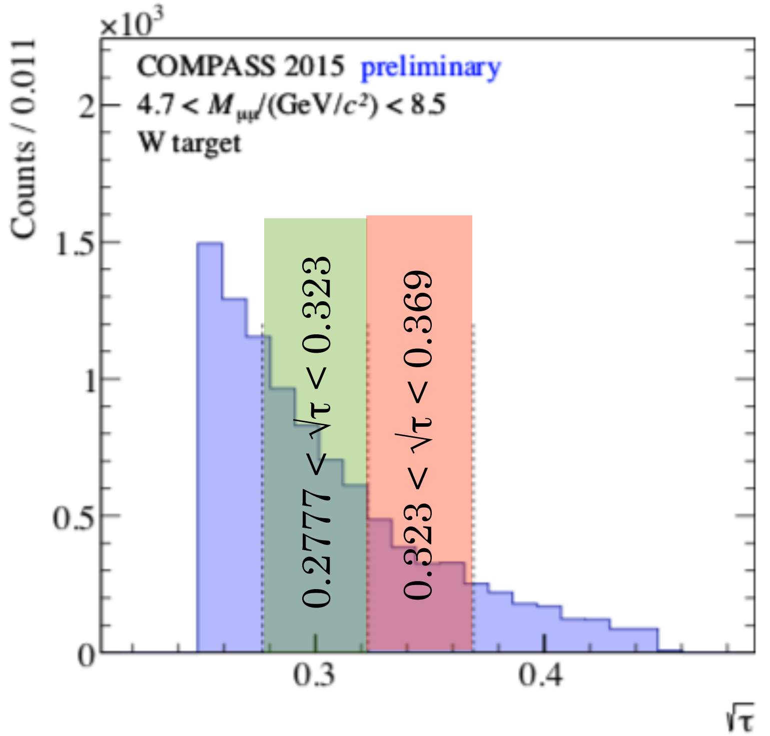
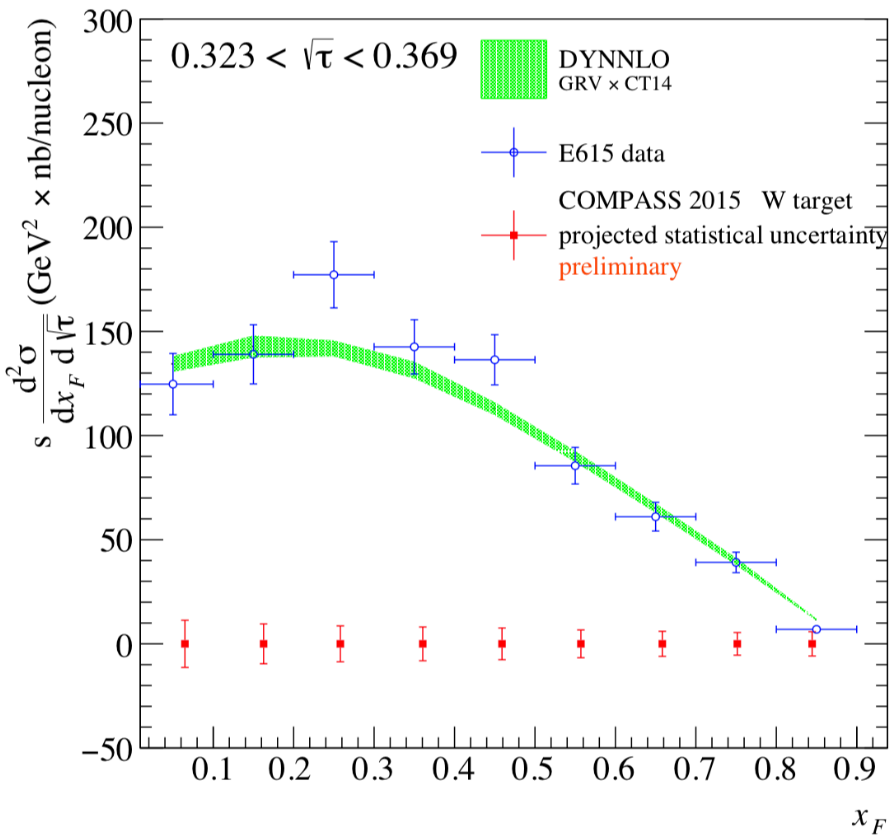
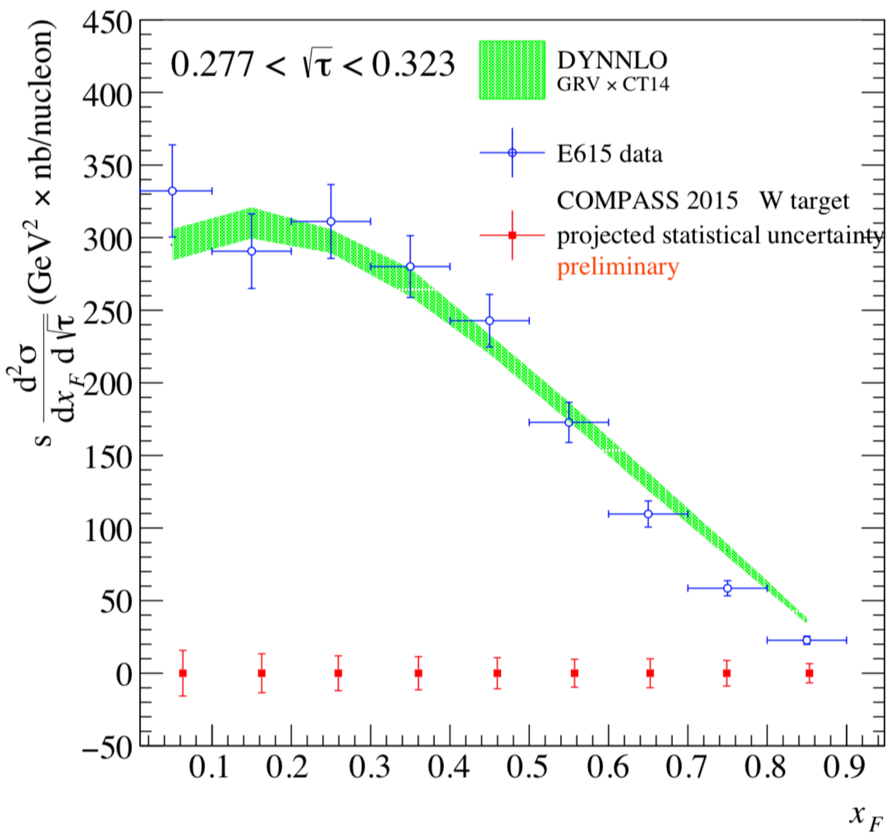


Tungsten target

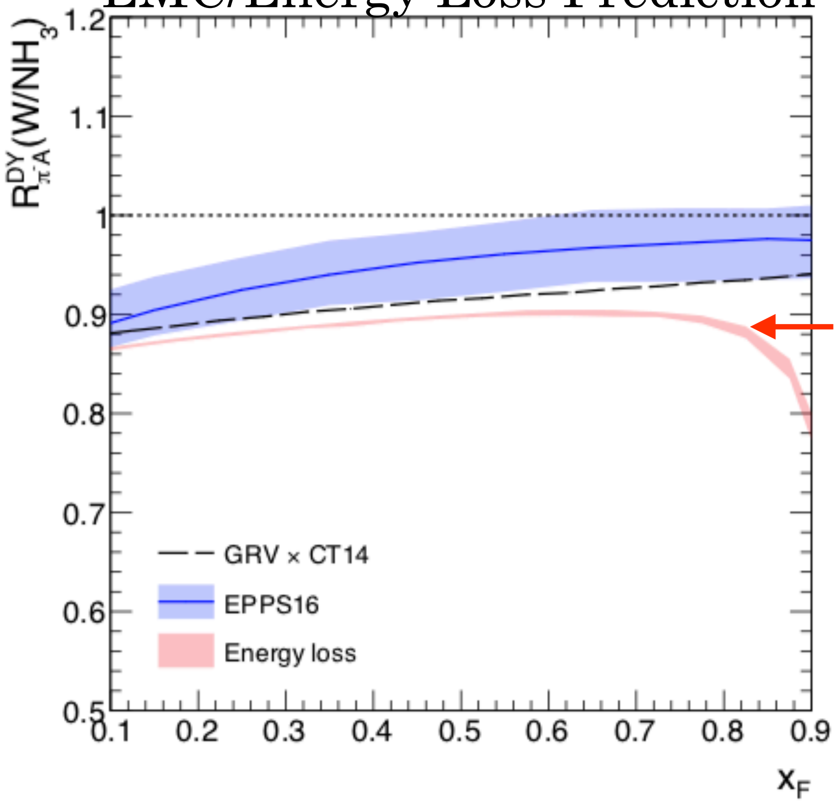




NUCLEAR DEPENDENCE OF DRELL-YAN

- **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.

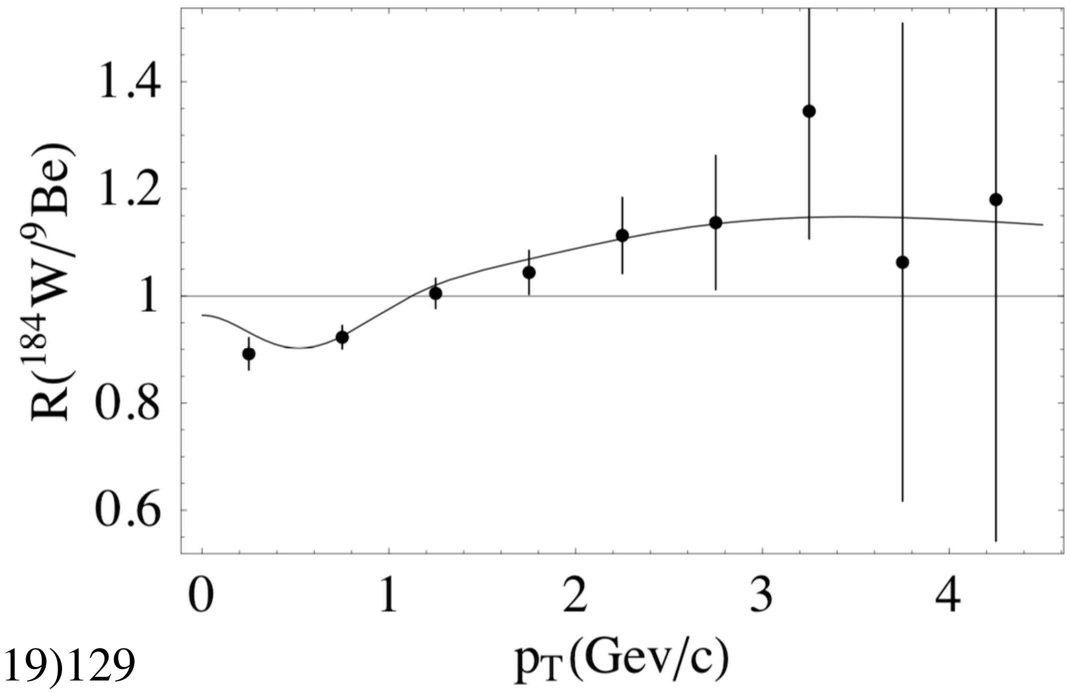
EMC/Energy Loss Prediction



Prediction at COMPASS energy *(BDMPS Model)*

Arleo et al. 10.1007/JHEP01(2019)129

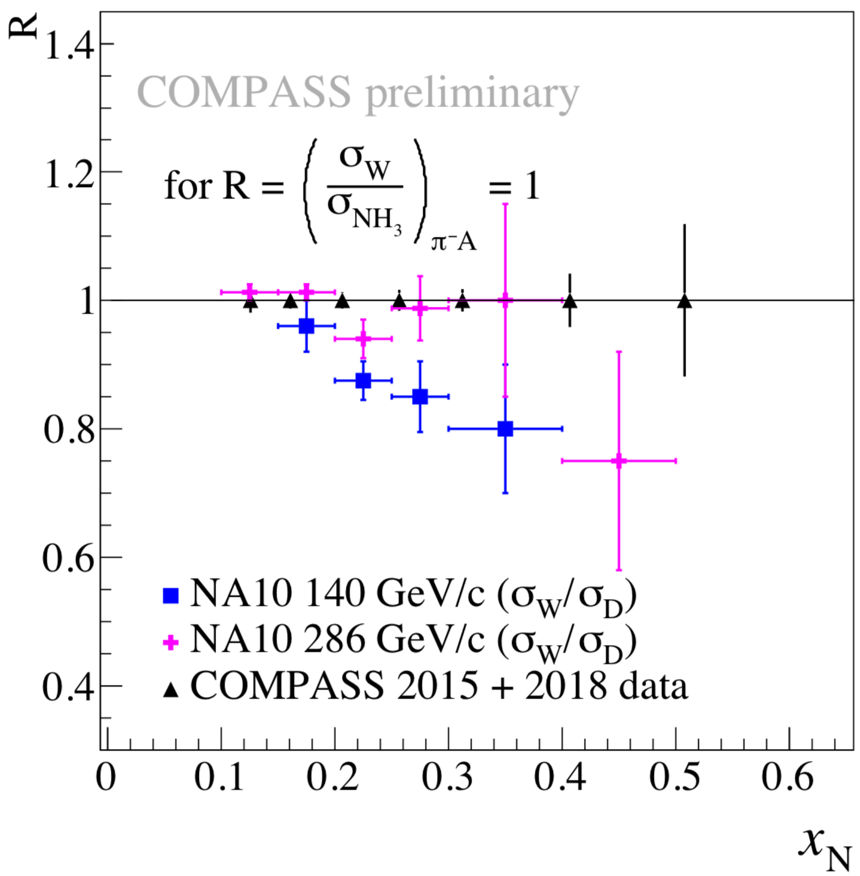
Cronin Effect

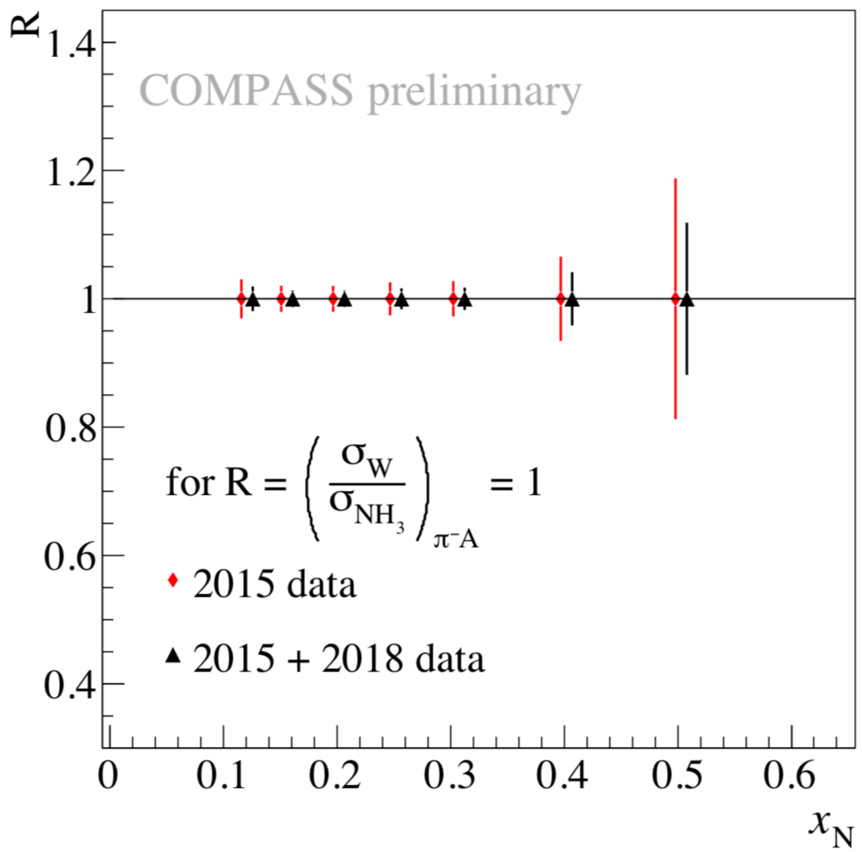


Johnson et al. (Phys.Rev.C75:064905,2007)
Data are from the FermiLab E772/E866 collaboration

NUCLEAR DEPENDENCE OF DRELL-YAN

- **Study of the A-dependence :** Cross Section per nucleon Ratio R
  — *PT Cells (A_N, A_H, A_{Lhe}); Aluminum (A ~ 27); Tungsten (A ~ 184)*
- Recent release of the COMPASS preliminary **projected uncertainties**, ratio between NH_3 and W.
- Projected 2015 uncertainties + expected statistical uncertainty in 2018 (not from real data based on simulation) compared with NA10



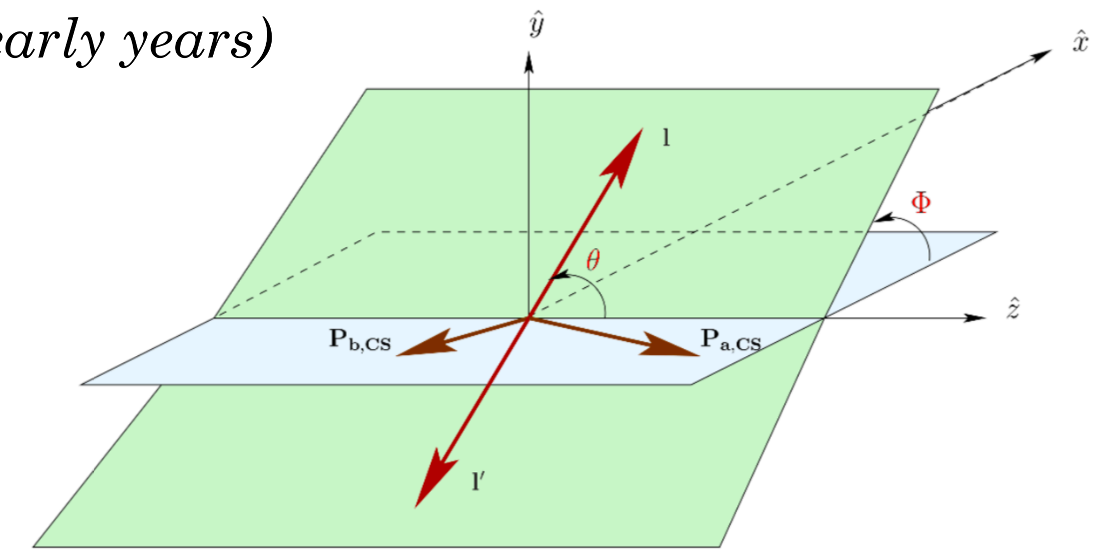


UNPOLARIZED AZIMUTHAL ASYMMETRIES

➤ **Expression of the angular (μ⁻) cross-section :**

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

➤ **Collinear hypothesis :** **λ = 1, μ = ν = 0** *(assumed in early years)*



- Collins-Soper Frame -

➤ **Experimental results from :**
— CERN (NA10) (Z. Phys. C37 (1988) 545)
— Fermilab (E615) (PRD 39,(1989) 92)

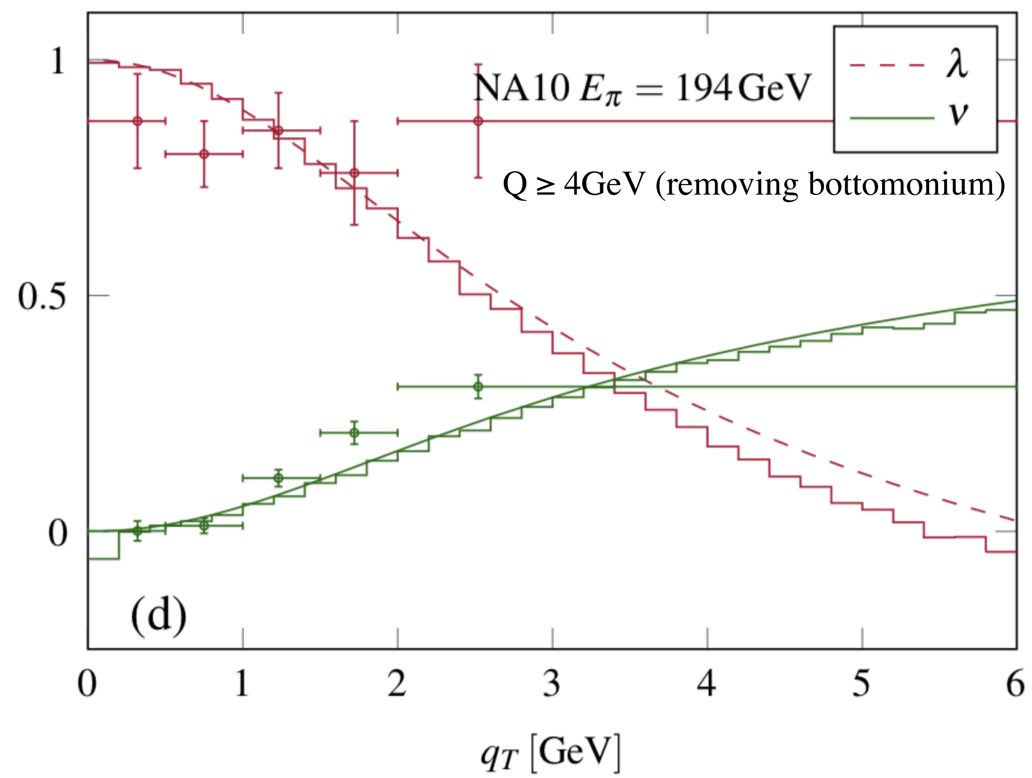
➤ **Consequently, cannot neglect intrinsic k_T of quarks (QCD corrections) :**
— **λ ≠ 1, μ ≠ 0, ν ≠ 0**
— $\gamma^\star$ transverse momentum: $q_T = k_{T1} + k_{T2} \neq 0$

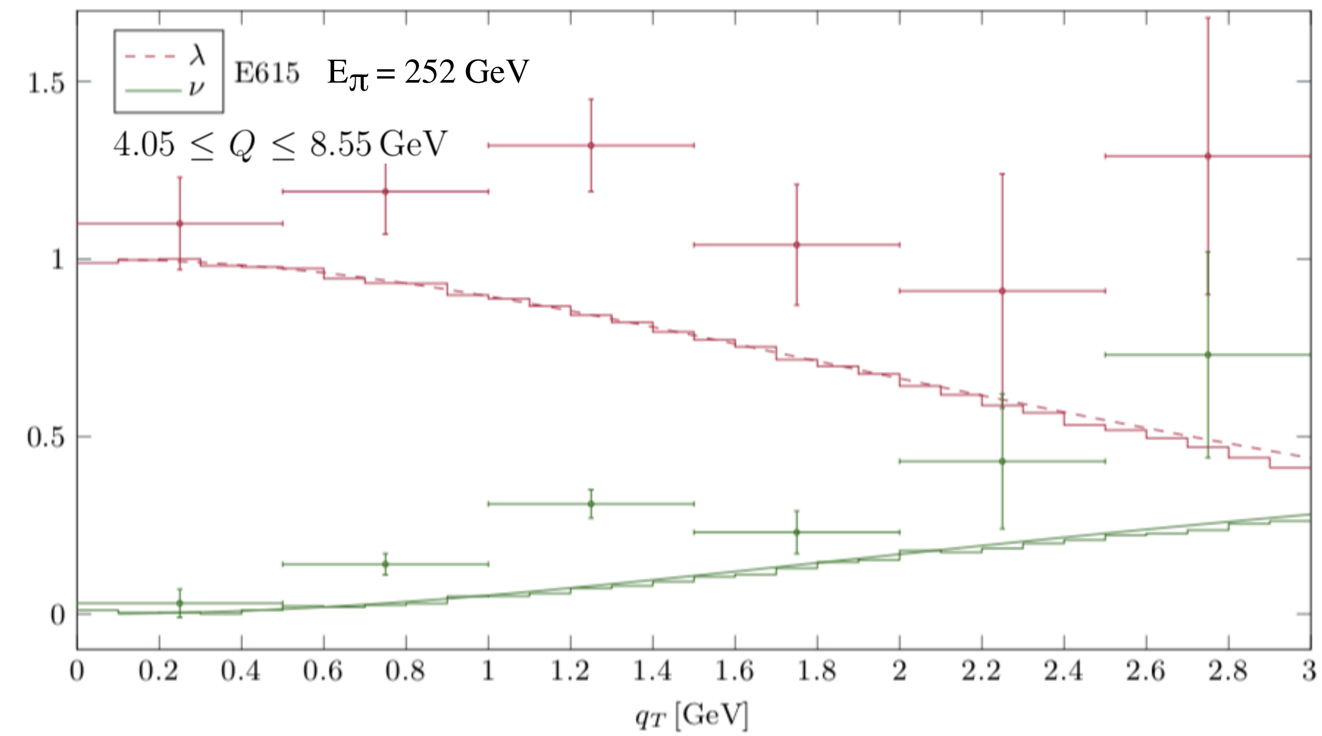
➤ **Lam-Tung relation in DY** *(e.g. conserved when q_T~0)* **: 1 - λ = 2ν**
(Analog to Callan-Gross relation in DIS)

UNPOLARIZED AZIMUTHAL ASYMMETRIES

- **NA10 and E615 measured sizable deviations of the Lam-Tung relation:**
  — Initial interpretation (80's): Sizable deviations about 30% larger than QCD corrections.
  — Violation of the Lam-Tung relation : **$1 - \lambda \neq 2\nu$**

(Line = LO, Dash = NLO)





- **More recently : cos 2ϕ modulation believed to arise from product of 2 TMD Boer-Mulders:**
  — *Possibly a non-perturbative origin is expected*
  — $\nu \propto h_1^{q\perp}(p) \otimes h_1^{q\perp}(\pi)$

J-C Peng et al. Physics Letters B Volume 758, 10 July 2016, Pages 384-388
M.Lambertsen and W.Vogelsang Phys. Rev. D 93, 114013 (2016)

SUMMARY & CONCLUSIONS

- **COMPASS successfully collected new dimuon data in 2018:**
  — The new 2018 Drell-Yan data are under analysis
  (preliminary results including 50% of these data were shown)

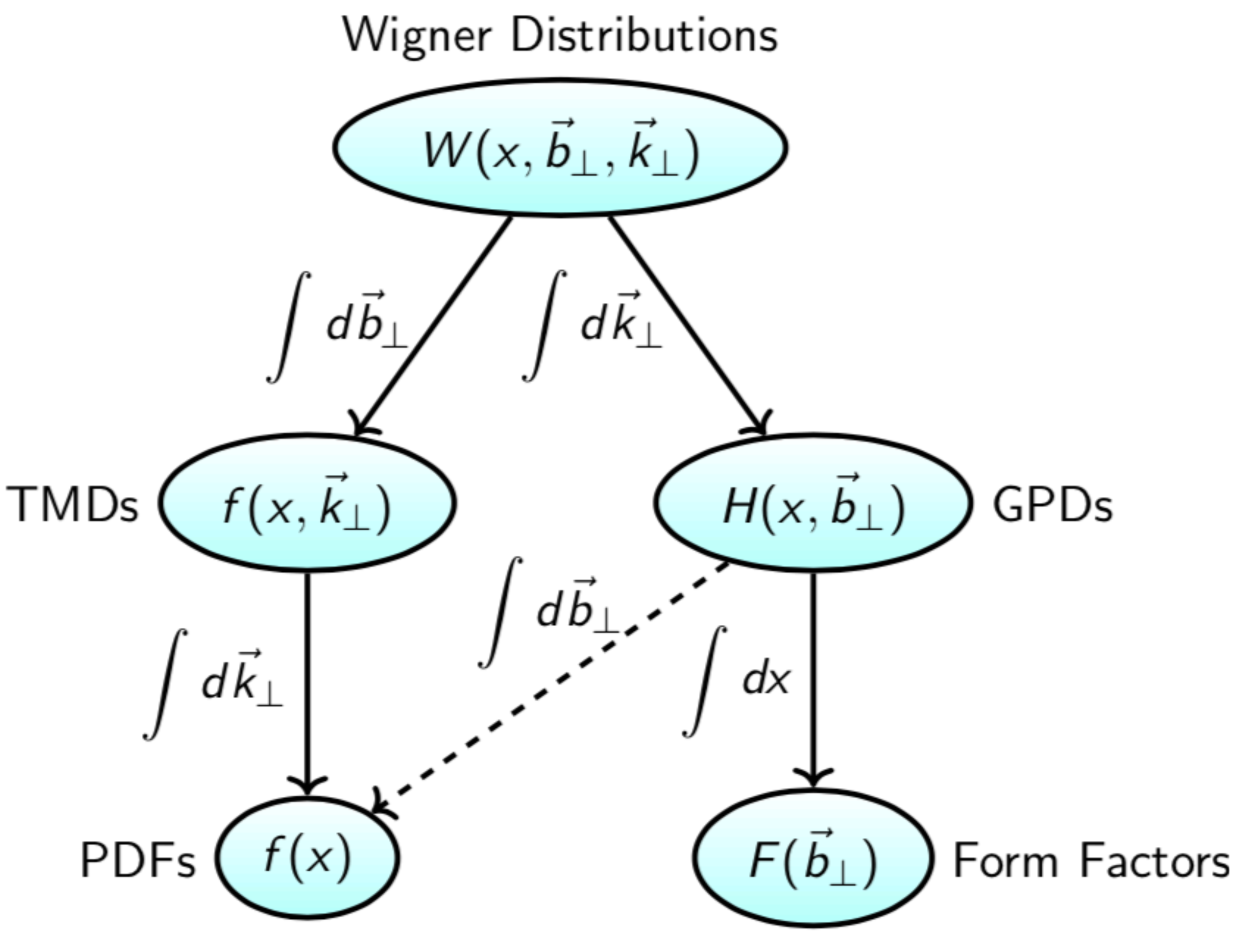
- **Sivers asymmetry :**
  — Sivers asymmetry measured both in polarized Drell-Yan and SIDIS processes
  — Measurement performed with the same apparatus.

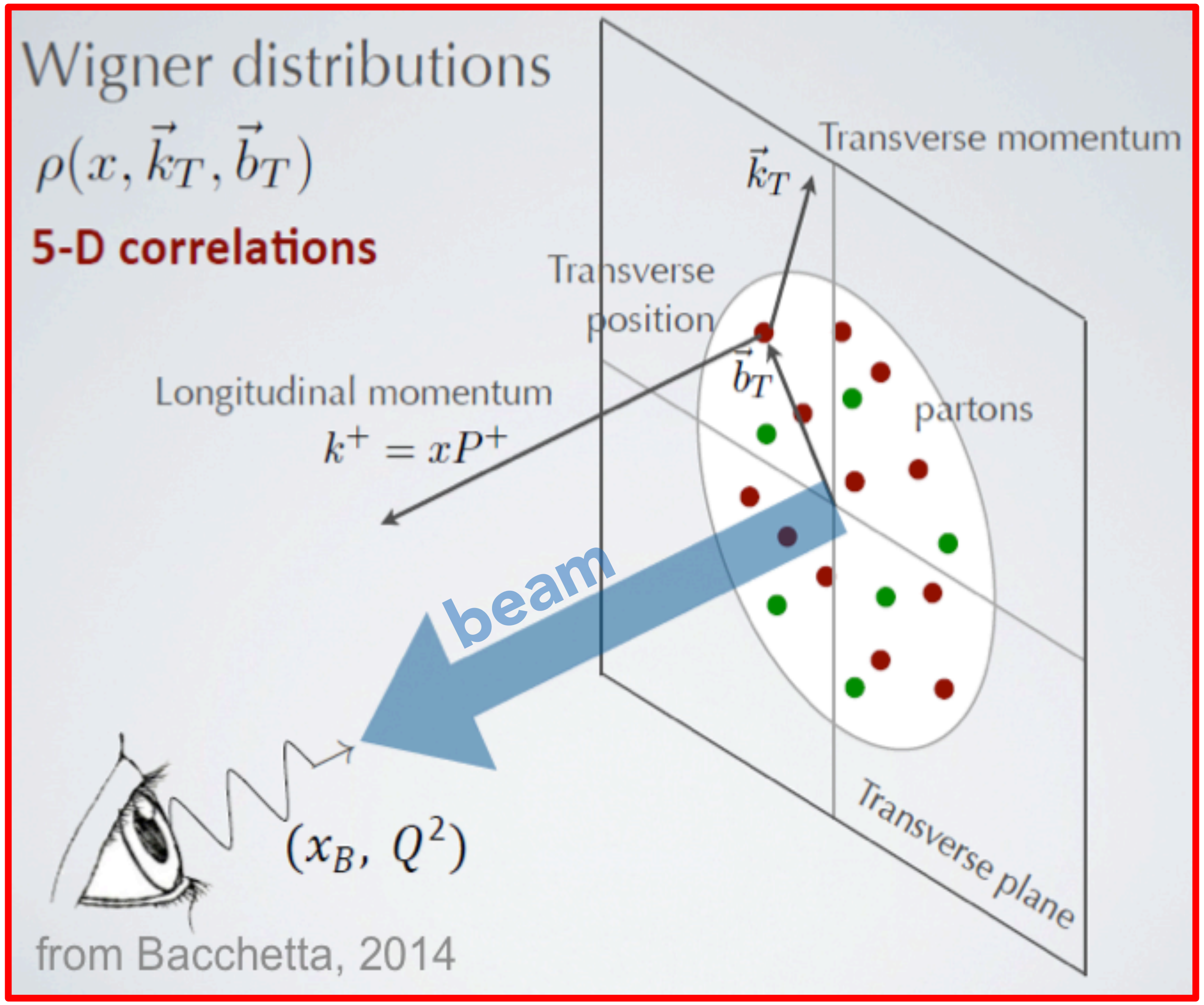
- **Unpolarized studies in full swing :**
  — Measurement of absolute Drell-Yan cross-section on 3 different targets.
  — EMC effect, Energy loss and Cronin effect.
  — Study of unpolarized asymmetries, violation of the Lam-Tung relation.

Thank you, for your attention.

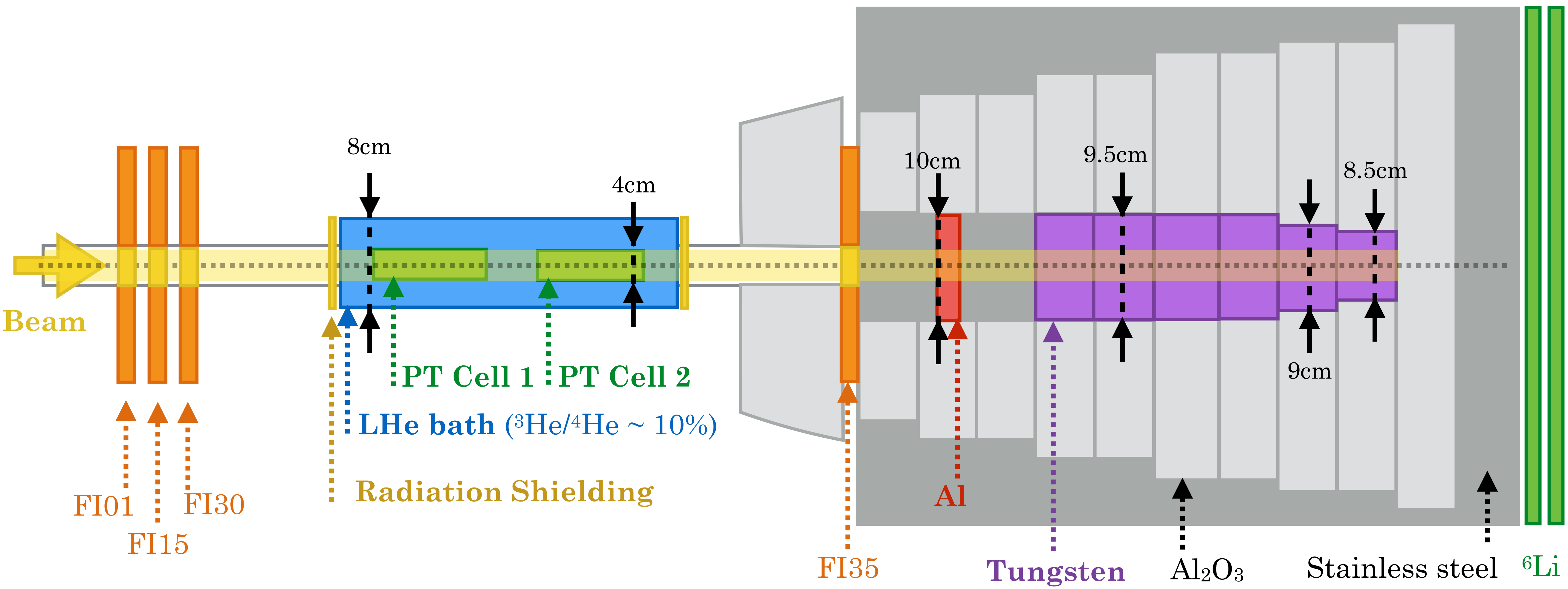
Backup Slides

- Representation in 3D of the nucleon structure





TARGET SETUP 2015



Nucleon Spin Polarization

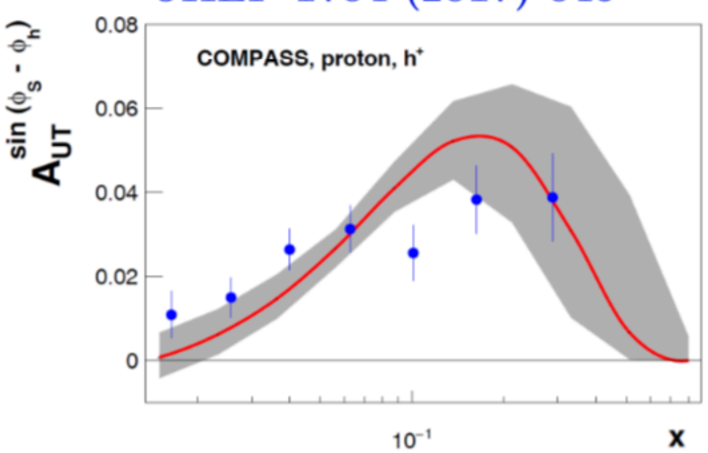
Quark Spin Polarization	U	L	T
U	f_1^q Number Density		$f_{1T}^{q\perp}$ Sivers
L		g_{1L}^q Helicity	g_{1T}^q Worm-Gear T
T	$h_1^{q\perp}$ Boer-Mulders	$h_L^{q\perp}$ Worm-Gear L	h_1^q Transversity $h_{1T}^{q\perp}$ Pretzelosity

k_T
S_T
S_T^q

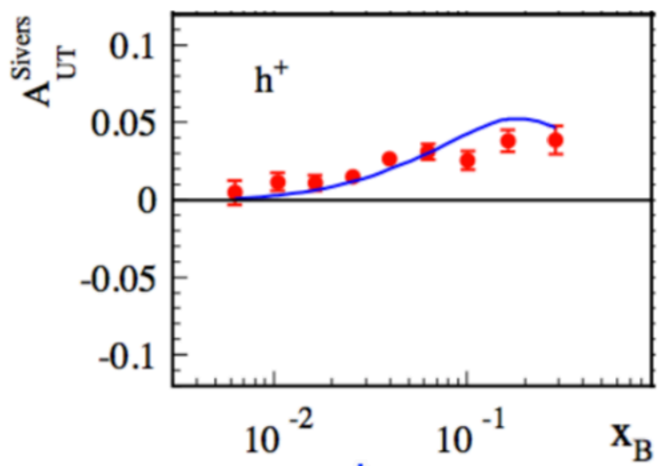
CHIRAL SYMMETRY BREAKING

SIVERS SIGN CHANGE

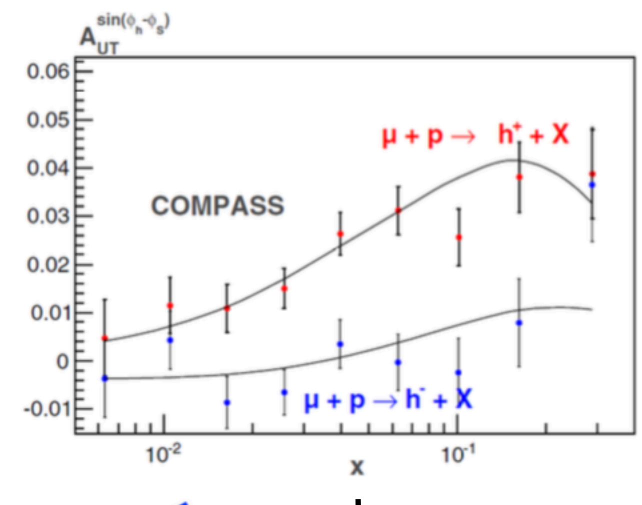
DGLAP (2016)
M. Anselmino et al.,
JHEP 1704 (2017) 046

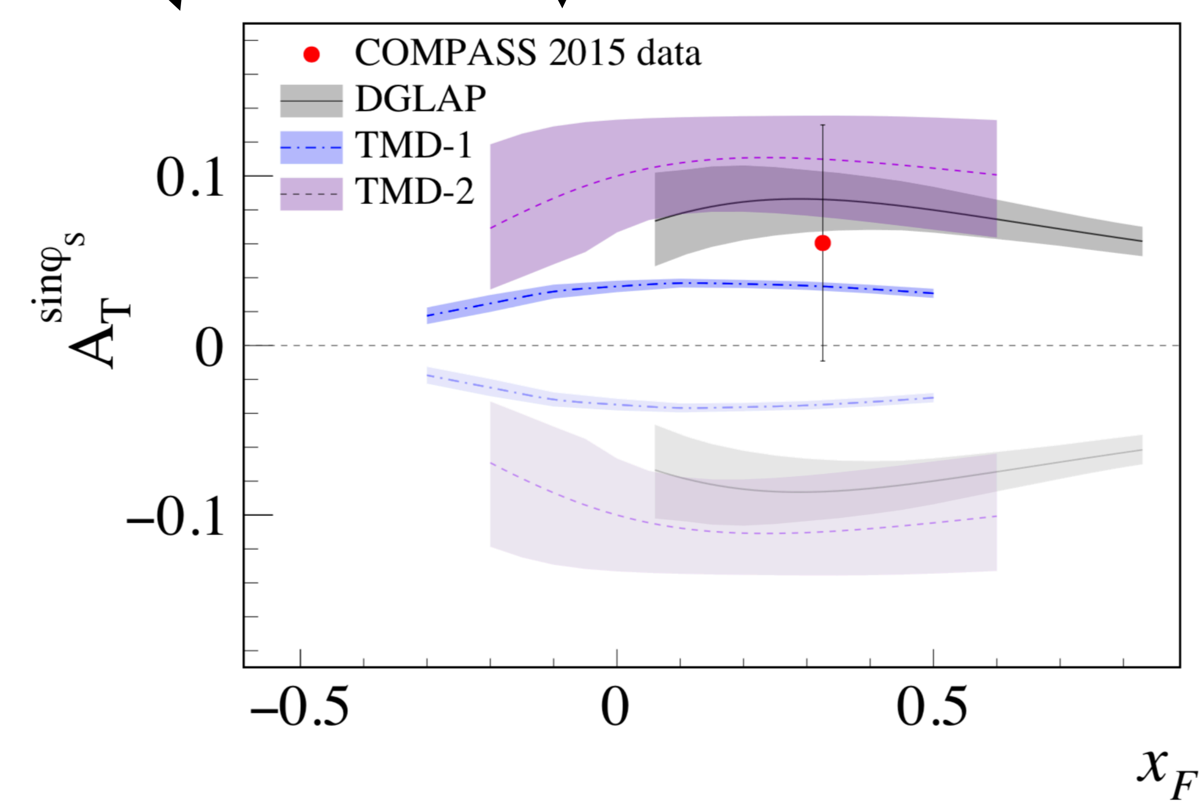


TMD-1 (2014)
M.G. Echevarria et al.,
PRD 89 074013



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





<u>Recent theoretical predictions :</u>

— Based on different Q2-evolution approaches.
— Positive sign of these theoretical predictions, obtained using the sign-change hypothesis for Sivers TMD PDFs

A-DEPENDENCE OF THE J/Ψ AND DY CROSS-SECTION

- **Study of the A-dependence :**
  —*Polarized Target Cells,*
  —*Aluminum (A ~ 27g/mol),*
  —*Tungsten (A ~ 184g/mol)*

- Study of the underlying J/ψ production mechanisms

- Determination of the **Nuclear Corrective Factor R_i^A**

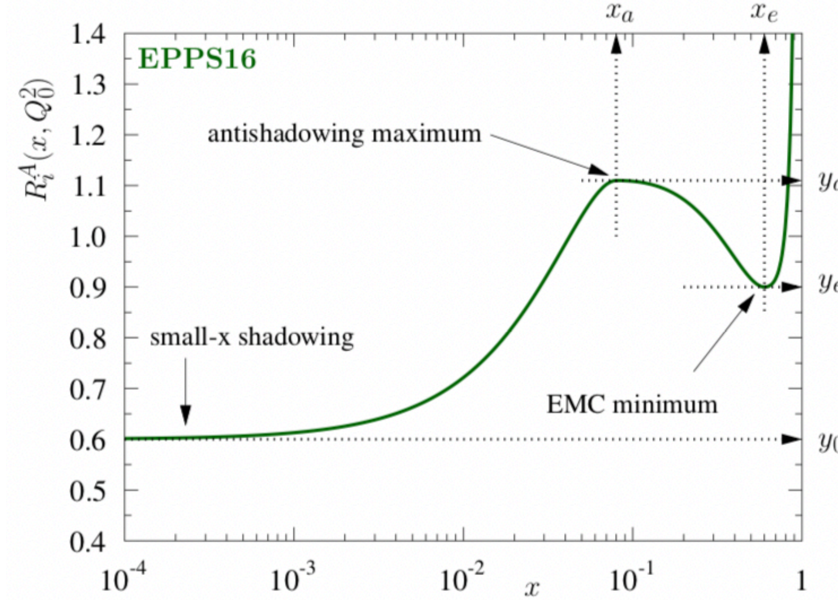
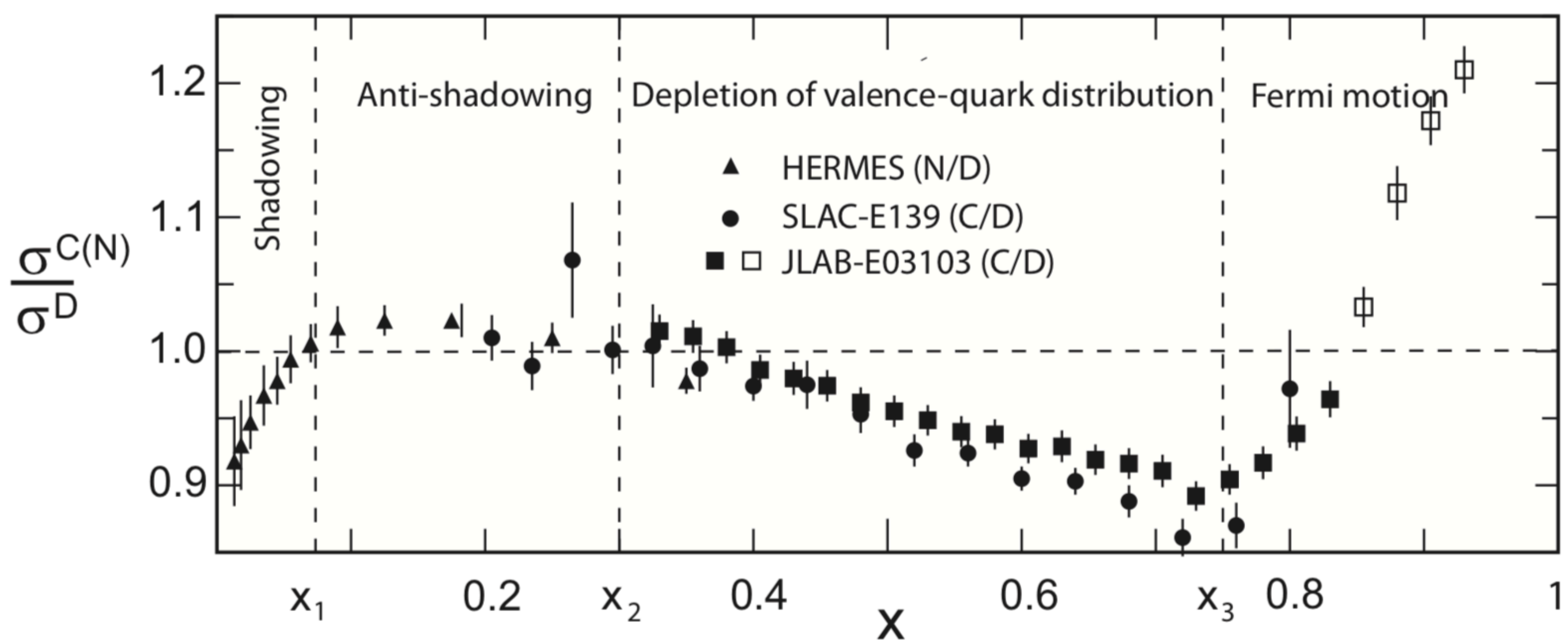


Fig. 1 Illustration of the EPPS16 fit function $R_i^A(x, Q_0^2)$.



WEIGHTED SIVERS TSA IN SIDIS AND DY

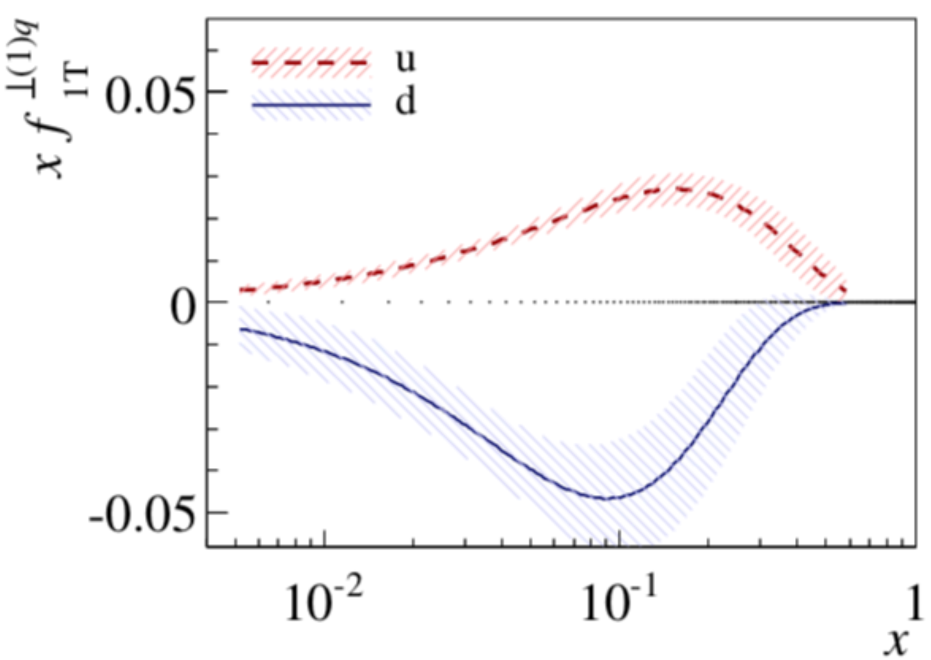
Projection from SIDIS under 3 assumptions:

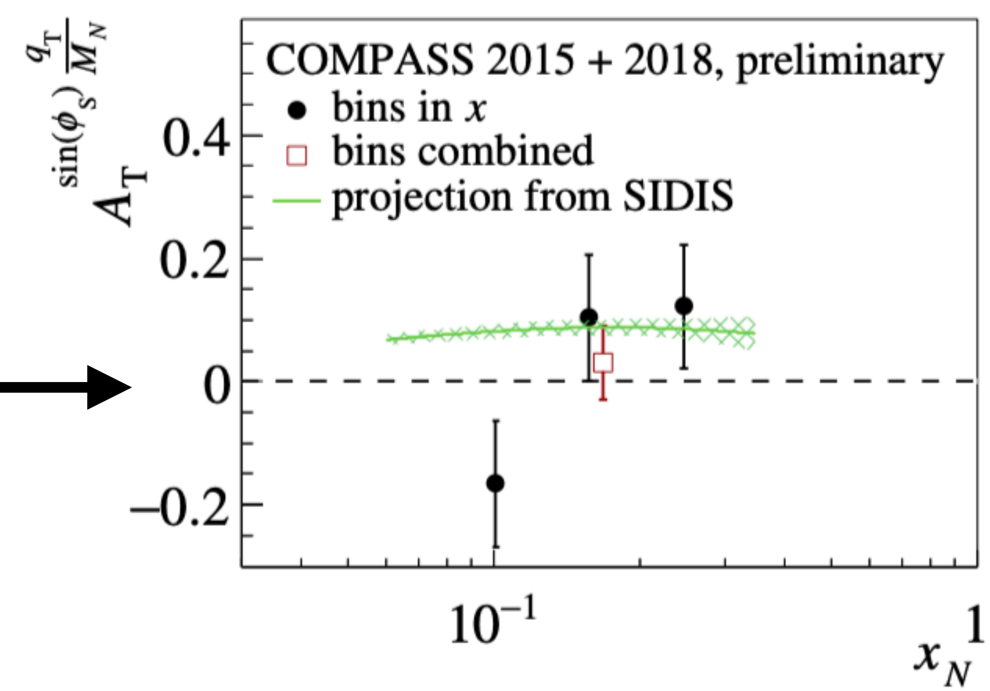
(1) $A_T^{\sin\varphi_S \frac{q_T}{M_N}} \sim \frac{f_{1T,p}^{\perp u(1)}}{f_{1,p}^{u}}$

(2) No Q^2 evolution for Sivers

Sivers sign-change

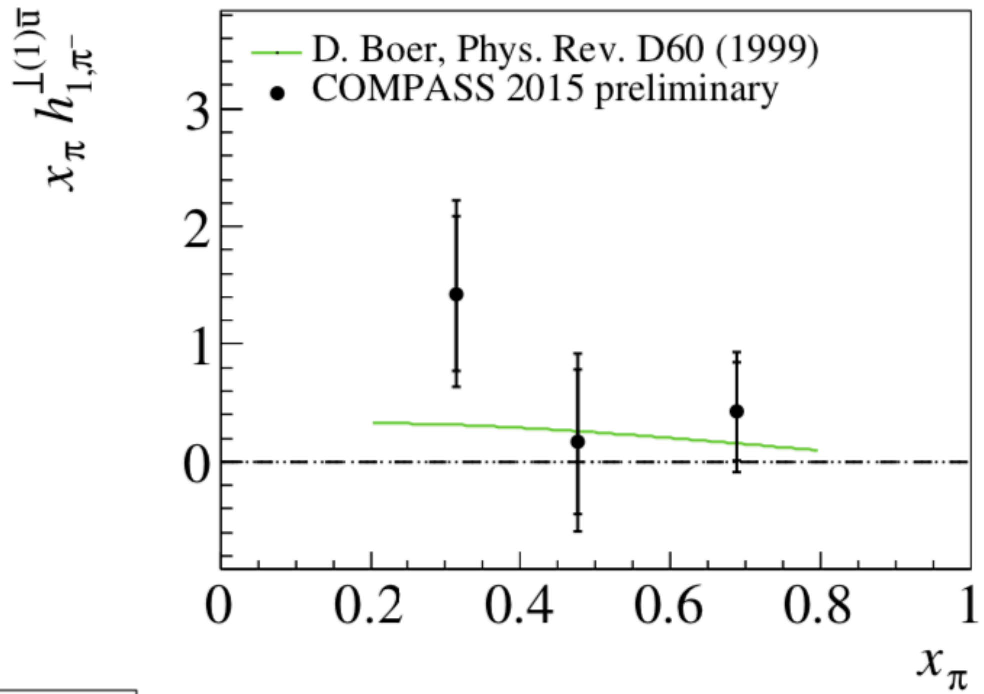
(3) $f_{1T,p}^{\perp u}|_{SIDIS} = -f_{1T,p}^{\perp u}|_{DY}$





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



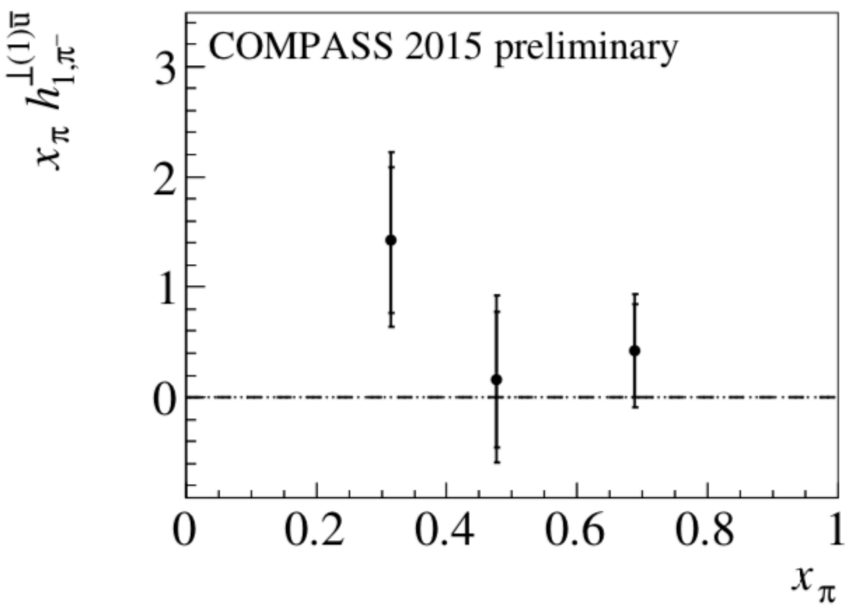


Figure 21: The extracted first transverse moment of valence Boer–Mulders function of the pion.

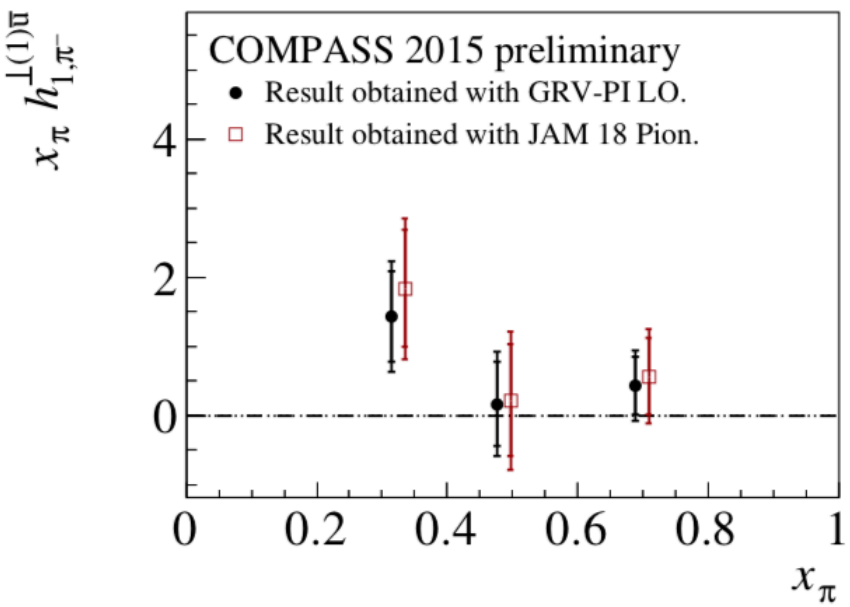
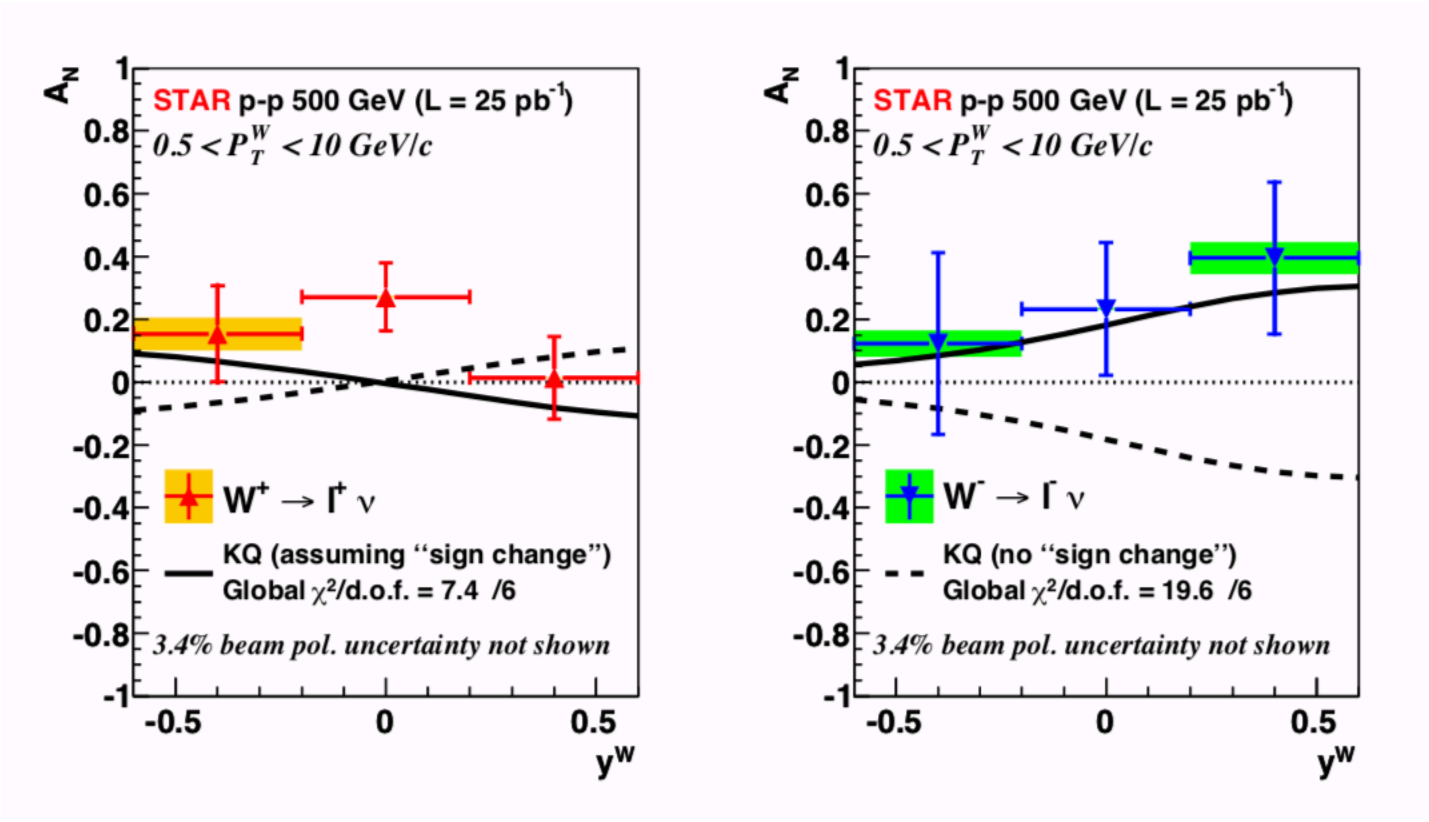


Figure 22: The results obtained using different pion PDF parametrisation.

RHIC ASYMMETRIES DRELL-YAN RESULTS

- RHIC extracted asymmetries : $p^{\uparrow}p \rightarrow l^{+}l^{-}X$



	STAR			PHENIX			RHIC II		
	y	4 GeV	20 GeV	y	4 GeV	20 GeV	y	4 GeV	20 GeV
δA	-0.5	0.007	0.09	-1.8	0.008	0.2	± 2.5	0.003	0.03
	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}		

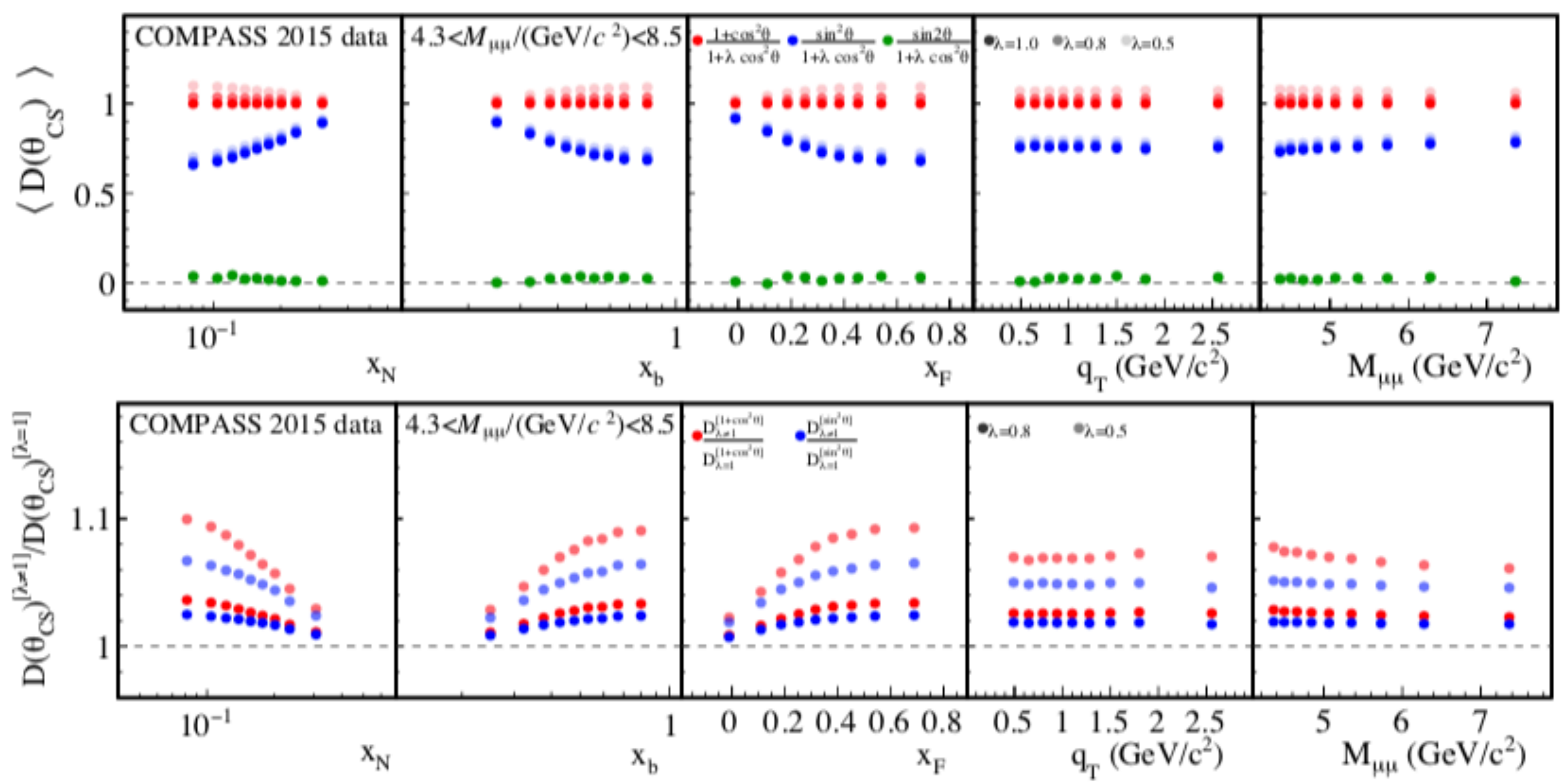
TABLE I: *Statistical errors δA for the Sivers SSA in Drell Yan for the PHENIX and STAR detectors at RHIC: Errors are shown for dilepton masses of $Q = 4$ GeV and 20 GeV assuming an integrated luminosity of $\int Ldt = 125 pb^{-1}$ and a beam polarization of $P = 0.7$. Error estimates have been carried 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.*

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 to be off by 5% :**