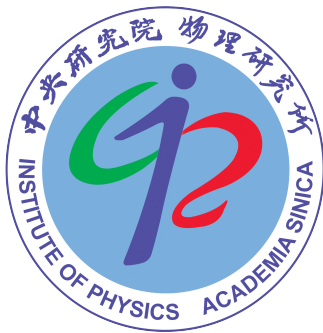




Measurement of Target Spin (in)dependent Asymmetries in Dimuon Production in Pion-Nucleon Collisions at COMPASS

DIS 2021 Conference

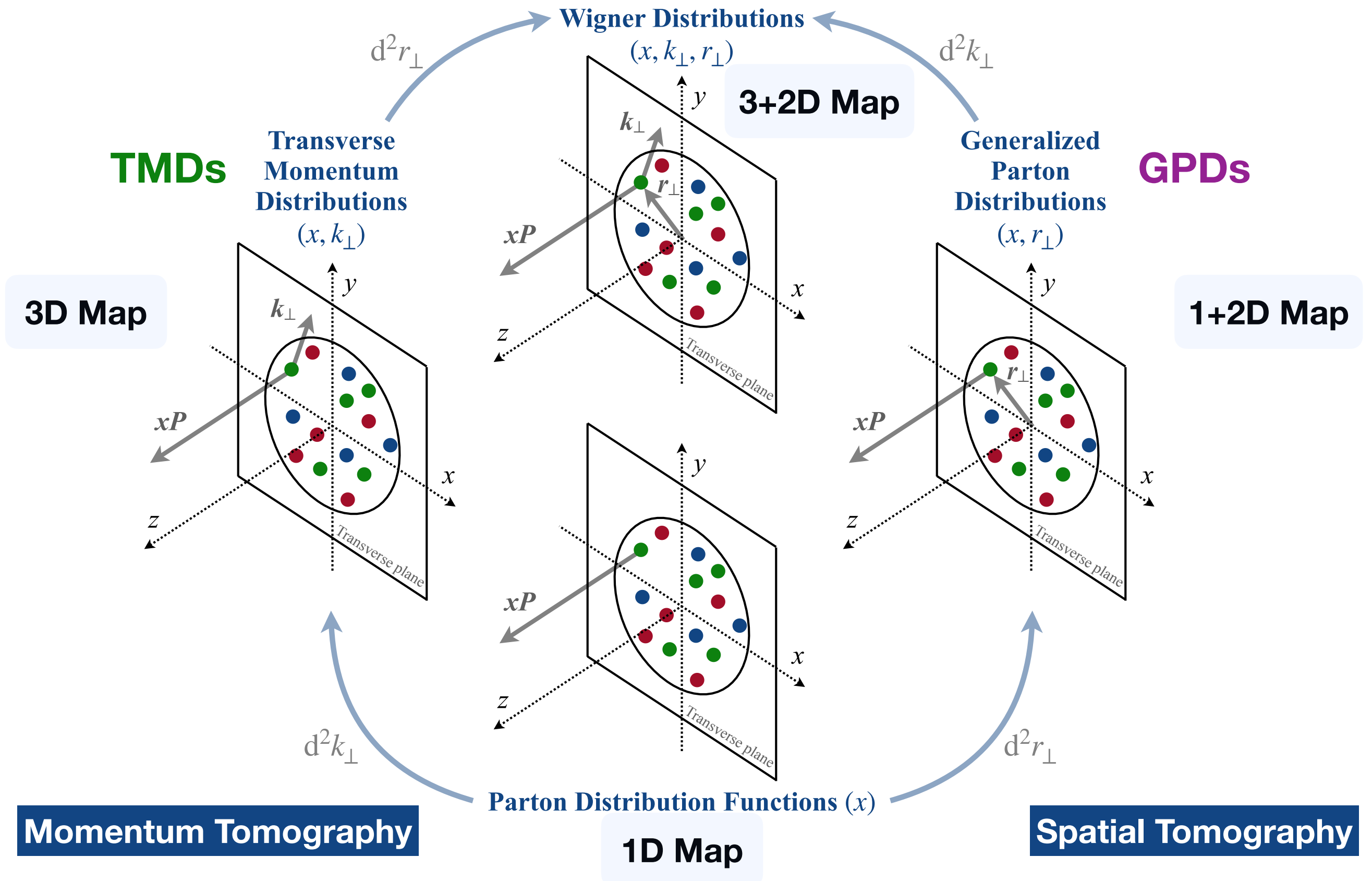


Yu-Hsiang Lien^{1,2}, Alexandr Chumakov^{3,4}

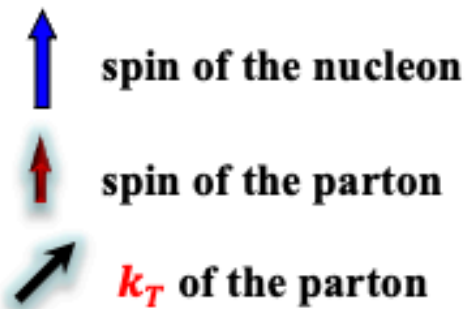
on behalf of the COMPASS Collaboration

1. Academia Sinica, Taiwan
2. National Kaohsiung Normal University, Taiwan
3. National Research Tomsk Polytechnic University, Russia
4. University of Turin, Italy

Multi-dimensional Partonic Structures



Transverse-Momentum Dependent PDFs



Quark \ Nucleon	U	L	T
U	 number density $f_1^{q,g}(x, k_T^2)$		 Boer-Mulders $h_1^{\perp q,g}(x, k_T^2)$
L		 Helicity $g_{1L}^{q,g}(x, k_T^2)$	 worm-gear L $h_{1L}^{\perp q,g}(x, k_T^2)$
T	 Sivers $f_{1T}^{\perp q,g}(x, k_T^2)$	 Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x, k_T^2)$	 Transversity $h_1^{q,g}(x, k_T^2)$ Pretzelosity $h_{1T}^{\perp q,g}(x, k_T^2)$

- The TMD PDFs are sorted according to the nucleon polarization and individual polarization of partons.

Drell-Yan (DY) Angular Distributions



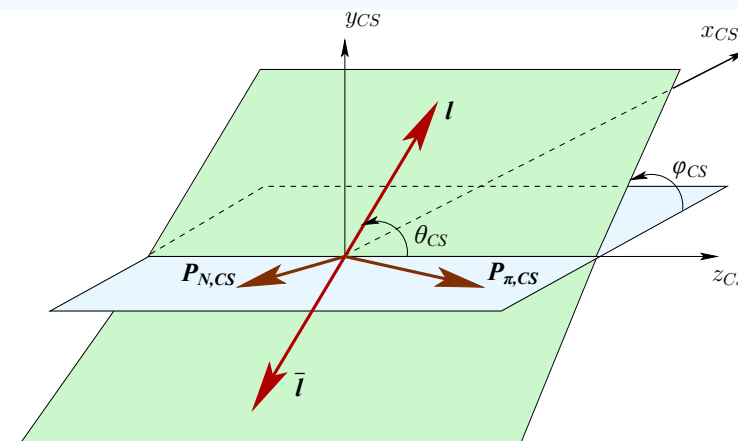
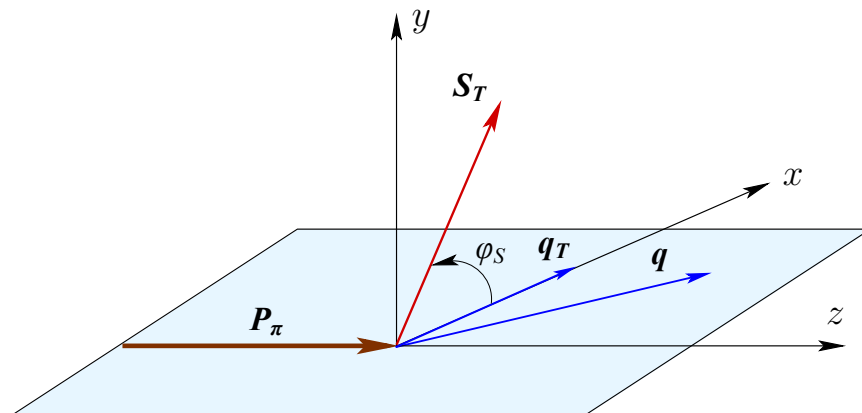
- The angular distribution of DY process is an important source of information to probe the spin and transverse momentum of partons.
- The LO differential cross-section for single-polarized DY angular distribution is:

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \left\{ \begin{array}{l} \text{Spin independent} \\ 1 + A_U^1 \cos^2 \theta_{CS} + \sin 2\theta_{CS} A_U^{\cos \varphi_{CS}} \cos \varphi_{CS} + \sin^2 \theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ \text{Transverse spin dependent} \\ + S_T \left[(A_T^{\sin \varphi_S} + \cos^2 \theta_{CS} \tilde{A}_T^{\sin \varphi_S}) \sin \varphi_S \right. \\ + \sin 2\theta_{CS} \left(A_T^{\sin(\varphi_{CS} + \varphi_S)} \sin(\varphi_{CS} + \varphi_S) + A_T^{\sin(\varphi_{CS} - \varphi_S)} \sin(\varphi_{CS} - \varphi_S) \right) \\ \left. + \sin^2 \theta_{CS} \left(A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) + A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right) \right] \end{array} \right\}$$

Spin Independent

$$\begin{aligned} A_U^1 &= \lambda \\ A_U^{\cos \varphi_{CS}} &= \mu \\ A_U^{\cos 2\varphi_{CS}} &= \frac{\nu}{2} \end{aligned}$$

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



SIDIS and Single-Polarized Drell-Yan



Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

$$\frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L})$$

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

SIDIS-DY bridge

Drell-Yan process (DY)

$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

$$\times \left\{ \begin{aligned} &1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ &+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ &+ S_T \left[\begin{aligned} &A_T^{\sin \varphi_S} \sin \varphi_S \\ &+ D_{[\sin^2 \theta_{CS}]} \left(\begin{aligned} &A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\ &+ A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{aligned} \right) \end{aligned} \right] \end{aligned} \right\}$$

where $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$

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

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

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

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

$$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$$

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

Boer-Mulders

Sivers

Transversity

Pretzelosity

Worm-gear L

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

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

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

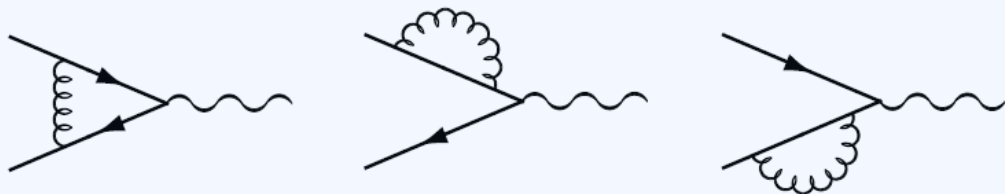
$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

$$A_L^{\sin 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1L,p}^{\perp q}$$

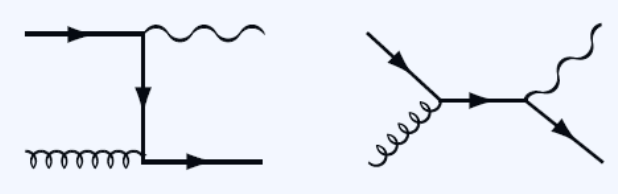
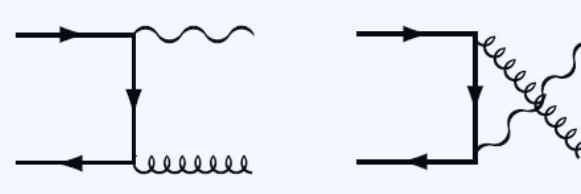
Double polarized DY only

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

- The angular coefficients λ , μ , ν are often referred to as **Unpolarized Asymmetries (UAs)**.
- **[LO]** In the naïve DY model, virtual photon is produced by the electromagnetic quark-antiquark annihilation. ($\lambda = 1, \mu = 0, \nu = 0$, because of $\vec{s}_{q,\bar{q}} = \frac{1}{2}$)
- **[NLO]** The **Lam–Tung relation** ($1 - \lambda = 2\nu$) [PRD 18(1978) 2447], valid in NLO(α_s) QCD corrections
 ⇒ **non-zero $\cos 2\varphi$ dependence.**



NLO(α_s)
annihilation diagram



NLO(α_s)
Compton diagram

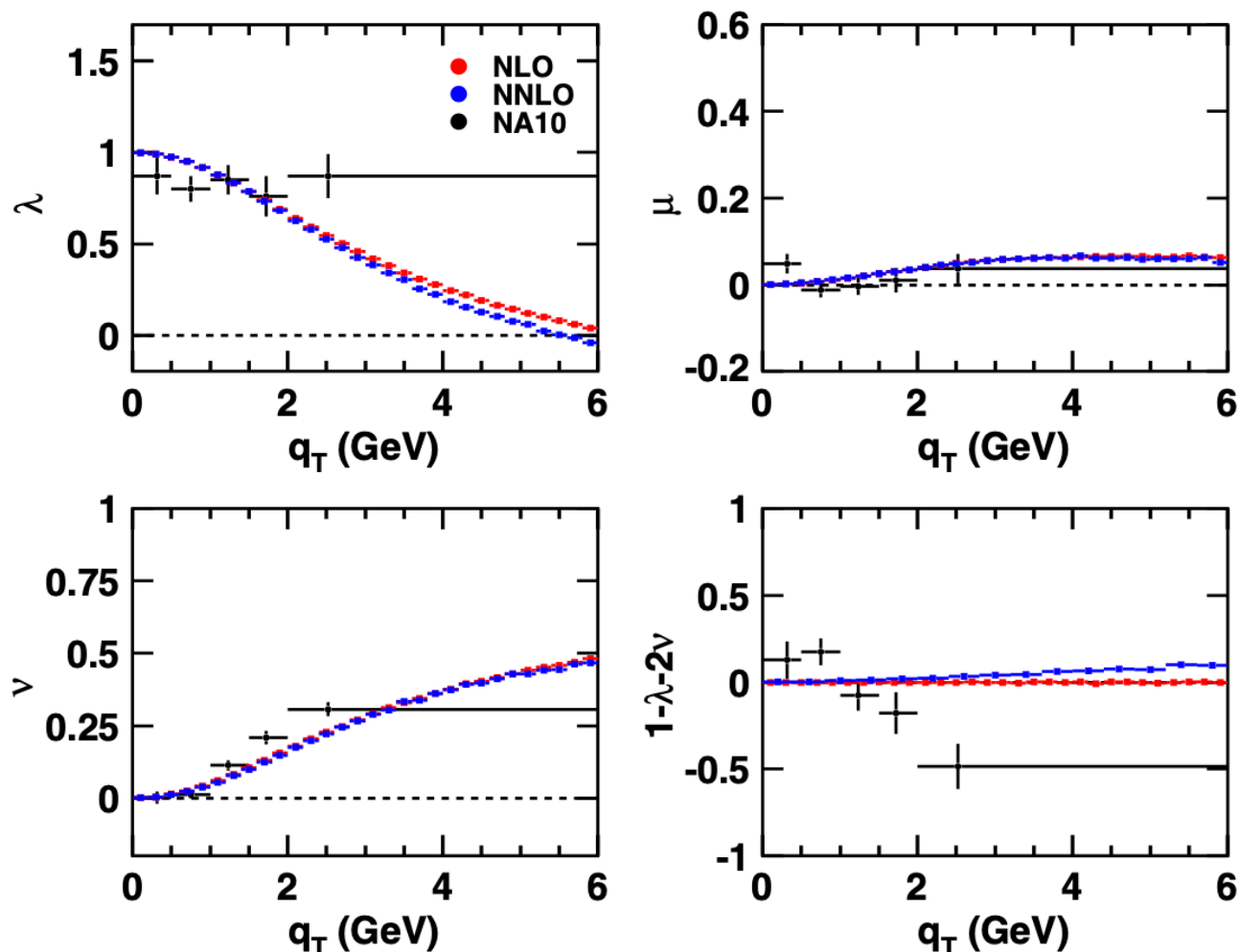
Angular Distribution in Pion-induced Drell-Yan



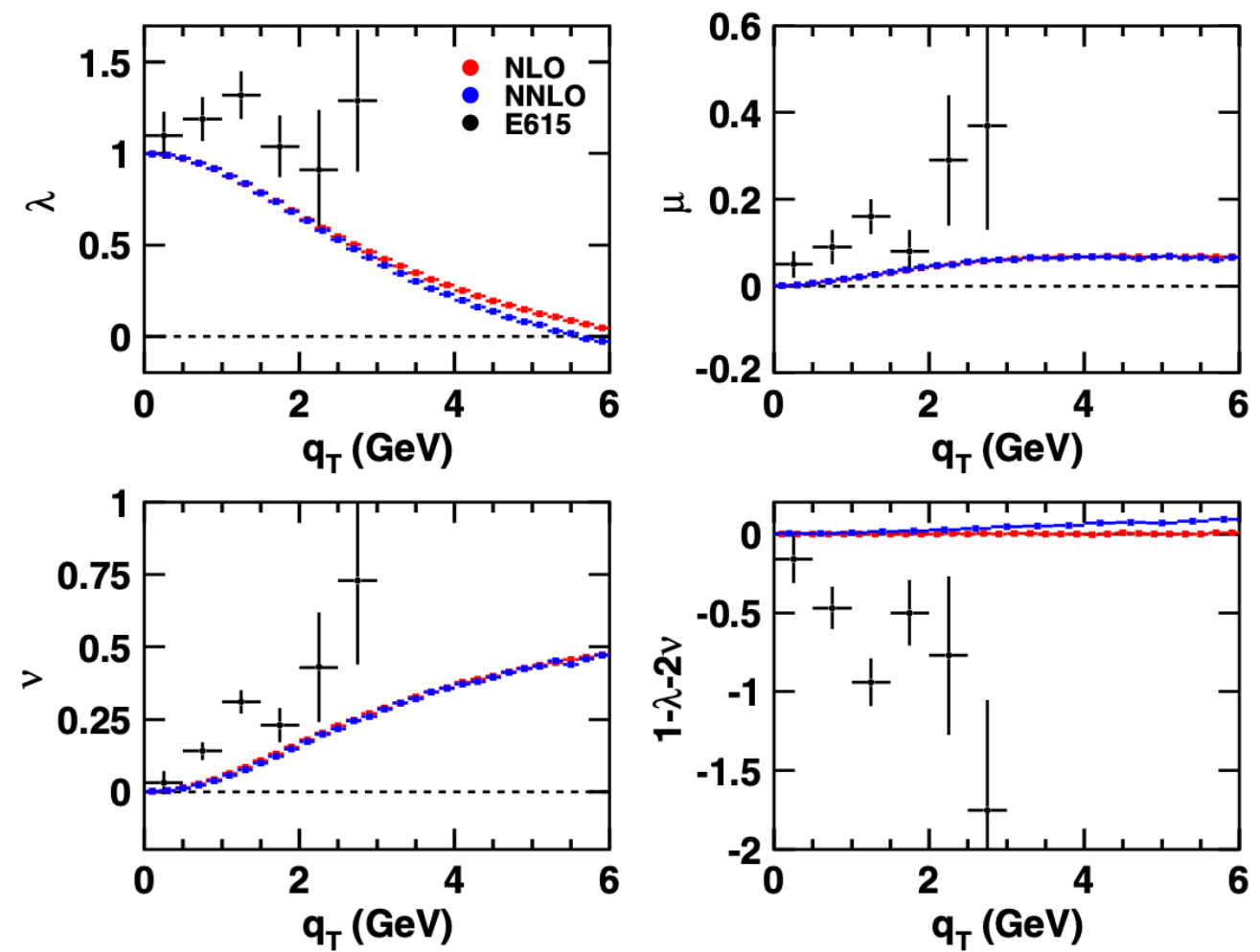
NA10: ZPC 31, 513(1986); E615: PRD 39, 92(1989); W-C. Chang, et.al, PRD 99, 014032 (2019)

- The Lam-Tung relation was found to be **violated** in past **pion-induced** DY experiments.
- Significant discrepancy between **pQCD** calculations and experimentally measured ν as a function of dimuon transverse momentum q_T .

NA10 $\pi^- + W$ at 194 GeV



E615 $\pi^- + W$ at 252 GeV

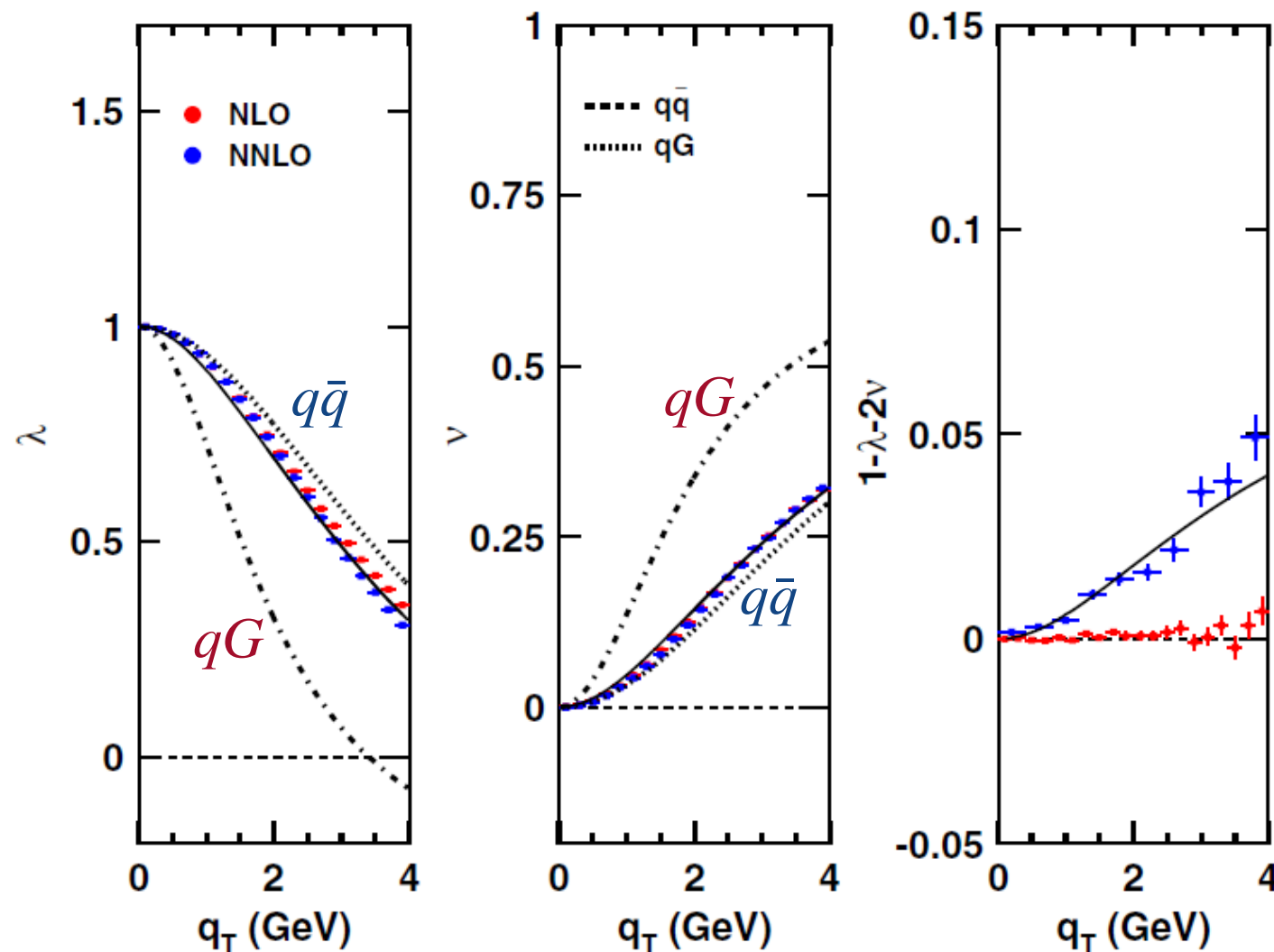


Violation of Lam-Tung Relation



W-C. Chang, R. E. McClellan, J-C. Peng, O. Teryaev, PRD 99, 014032 (2019)

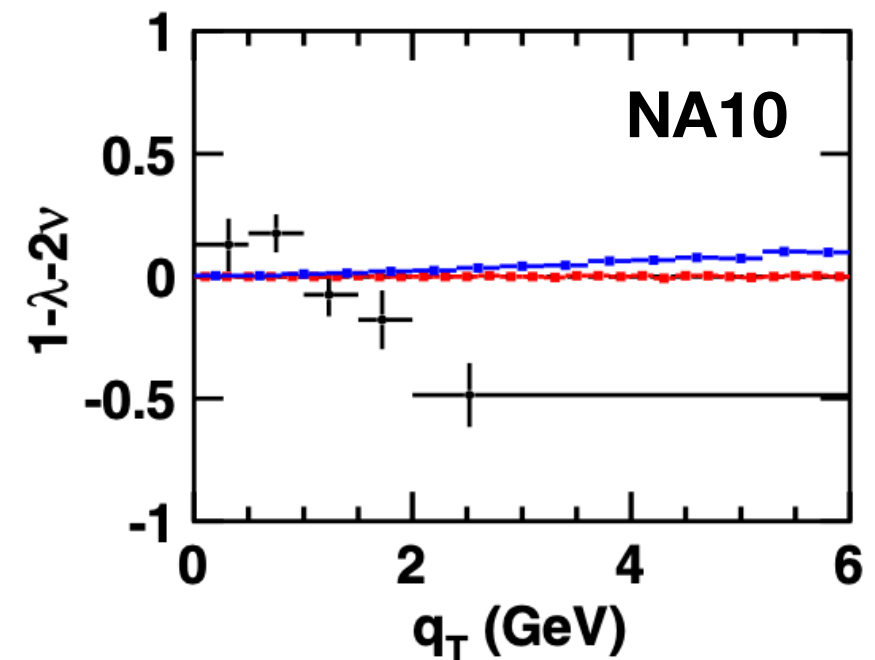
COMPASS $\pi^- + W$ at 190 GeV



$NLO : O(\alpha_s^1); NNLO : O(\alpha_s^2)$

$4 < M_{\mu\mu}/(\text{GeV}/c^2) < 9$

$0.2 < x_F < 0.4$



- Including NNLO contributions in pQCD violates Lam-Tung relation.
- Opposite sign for Lam-Tung relation from NNLO pQCD calculations and experiments.

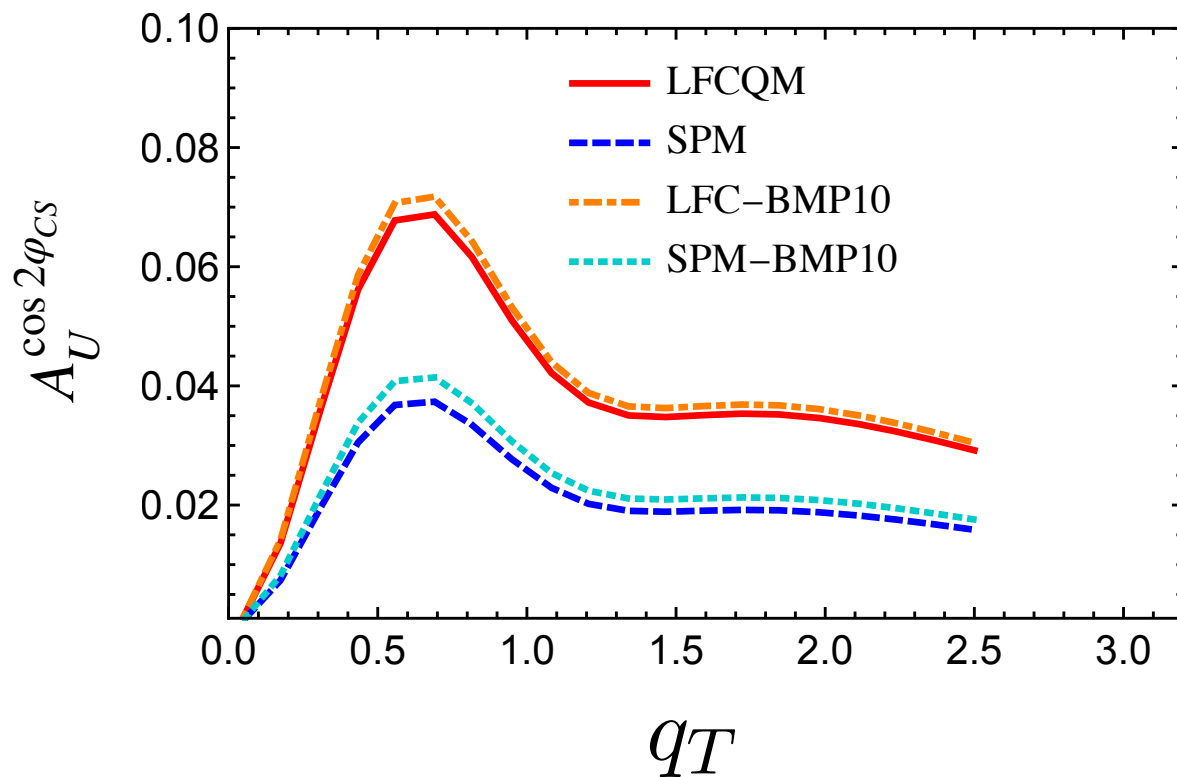
The Boer–Mulders Function



Boer, PRD 60 (1999) 014012; S. Bastami, et.al, JHEP 02 (2021) 166

- An explanation to the $\cos 2\varphi$ dependence observed in the DY process was proposed, by introducing a non-perturbative TMD **Boer–Mulders function**.
- The Boer–Mulders function $h_1^\perp$ represents a correlation between quark's intrinsic **transverse momentum** k_T and **transverse spin** S_T (transversely polarized quark) in an unpolarized hadron.

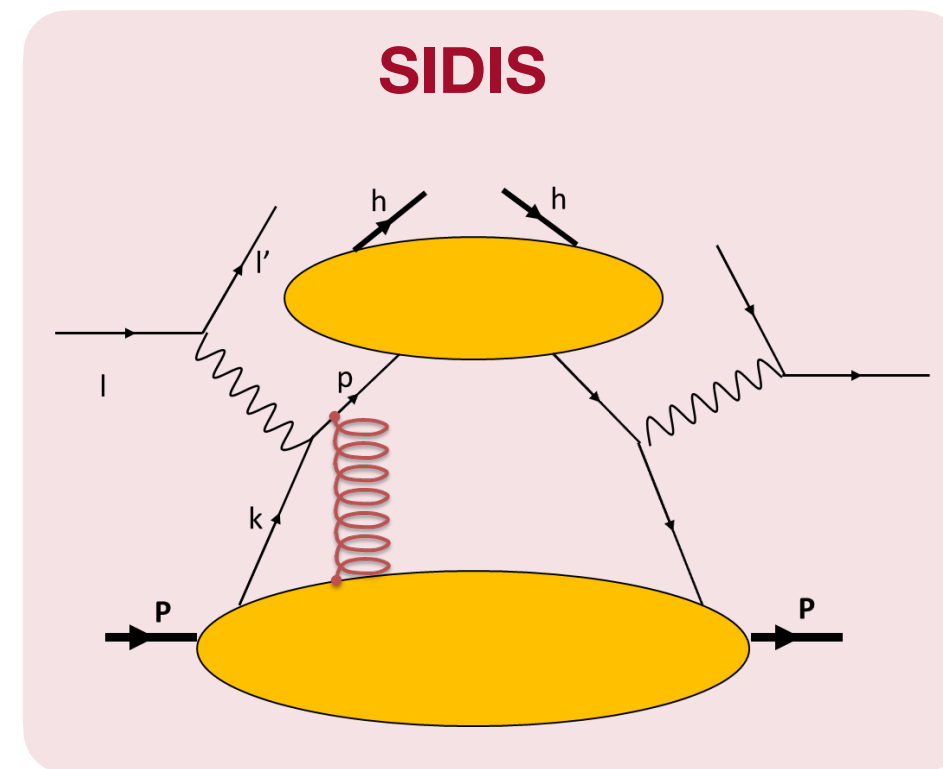
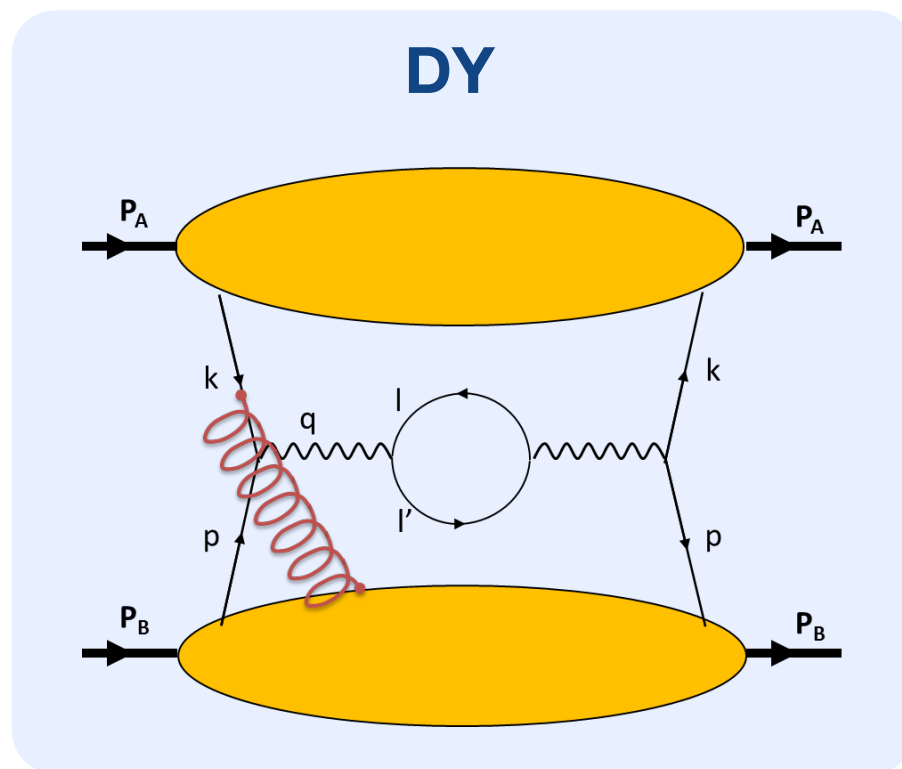
$$A_U^{\cos 2\varphi_{CS}} = \frac{\nu}{2} \propto h_1^\perp(N) \bar{h}_1^\perp(\pi)$$



spin of the nucleon
 spin of the parton
 k_T of the parton

Quark \ Nucleon	U	L	T
U	 number density $f_1^{q,g}(x, k_T^2)$		 Boer-Mulders $h_1^{\perp,q,g}(x, k_T^2)$
L		 Helicity $g_{1L}^{q,g}(x, k_T^2)$	 worm-gear L $h_{1L}^{\perp,q,g}(x, k_T^2)$
T	 Sivers $f_{1T}^{\perp,q,g}(x, k_T^2)$	 Kotzinian-Mulders worm-gear T $g_{1T}^{\perp,q,g}(x, k_T^2)$	 Transversity $h_1^{q,g}(x, k_T^2)$ Pretzelosity $h_{1T}^{\perp,q,g}(x, k_T^2)$

Non-Universality of TMD Functions



To be tested by COMPASS experiment!

$$\text{Sivers}|_{DY} = -\text{Sivers}|_{SIDIS}$$

- QCD gluon gauge link (Wilson line) in the initial state (DY) v.s. final state interactions (SIDIS).
- Fundamental predictions from TMD framework of QCD.

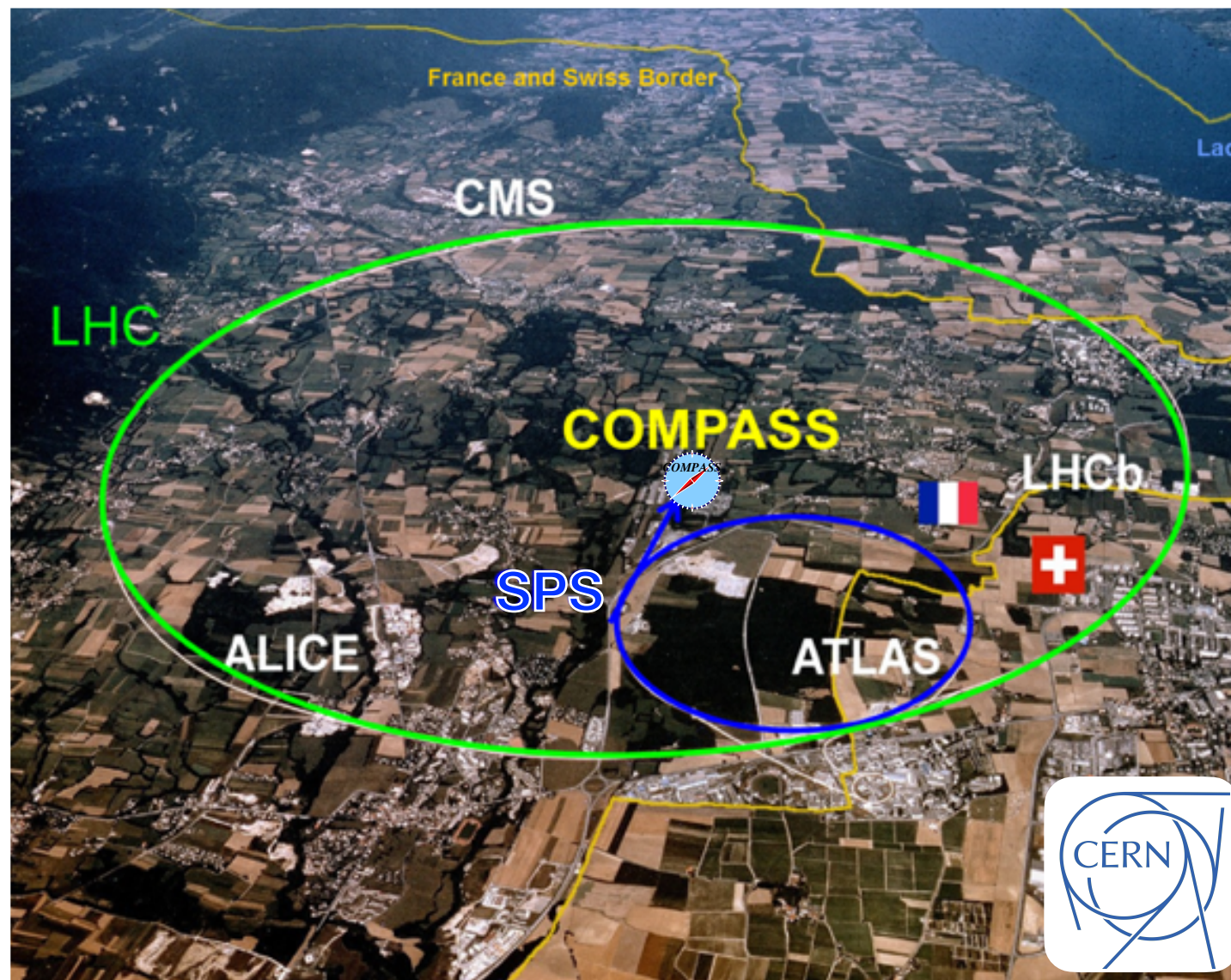
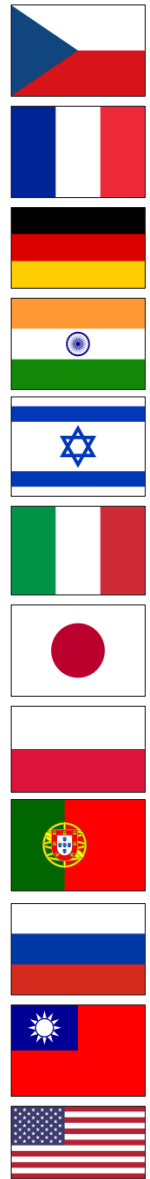
spin of the nucleon
 spin of the parton
 k_T of the parton

Quark \ Nucleon	U	L	T
U	 number density $f_1^{q,g}(x, k_T^2)$		 Boer-Mulders $h_1^{\perp q,g}(x, k_T^2)$
L		 Helicity $g_{1L}^{q,g}(x, k_T^2)$	 worm-gear L $h_{1L}^{\perp q,g}(x, k_T^2)$
T	 Sivers $f_{1T}^{\perp q,g}(x, k_T^2)$	 Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x, k_T^2)$	 Transversity $h_1^{q,g}(x, k_T^2)$ Pretzelosity $h_{1T}^{\perp q,g}(x, k_T^2)$

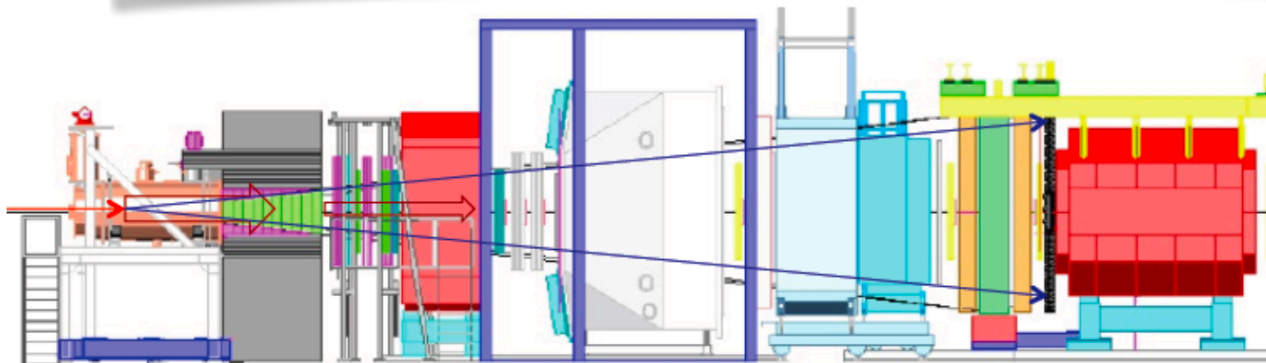
COMPASS/CERN Collaboration



Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS)

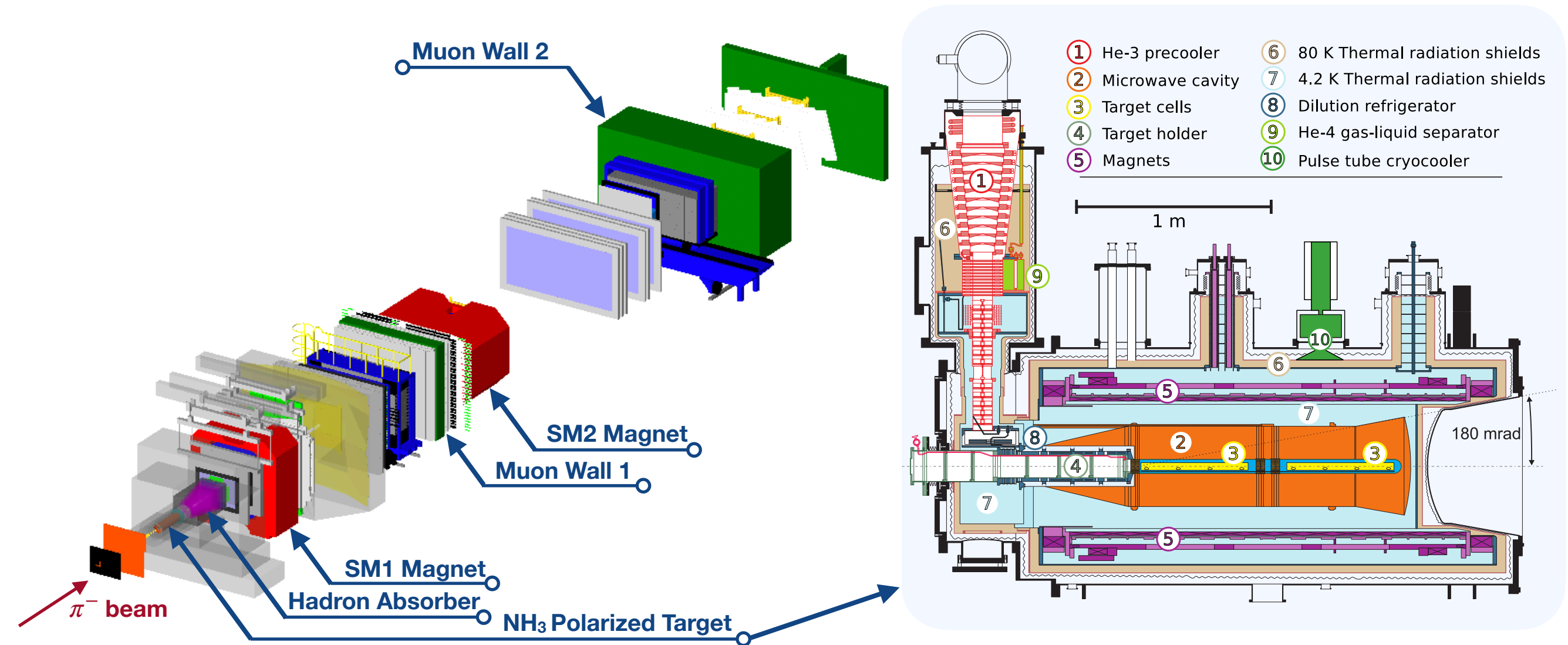


- A fixed-target experiment at SPS north area.
- 24 participating institutions from 13 countries.
- Physics programs:
 - Nucleon spin and partonic structure.
 - Hadron spectroscopy
 - TMDs + pion structure
- Taking data since 2002.
- Last run will take place in 2022.
- To be superseded by **AMBER** experiment.



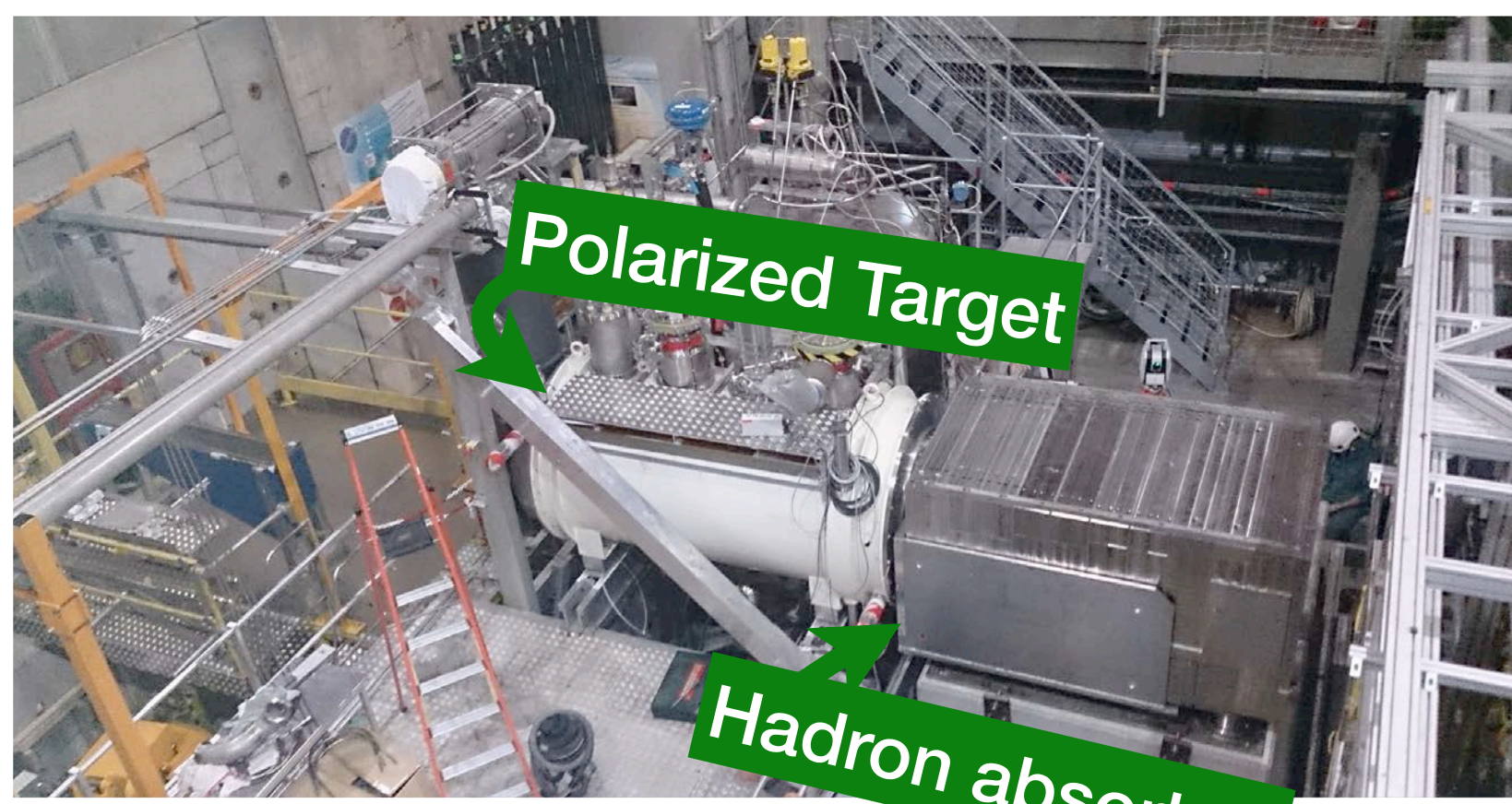
...

Drell-Yan Program in COMPASS



- First ever polarized DY measurements were performed by COMPASS in 2015 and 2018.
- π^- beam at **190 GeV/c** with average beam intensity **$7 \times 10^7 \text{ s}^{-1}$** from **CERN SPS M2 beam line**.
- Transversely polarized NH₃ target cells (55+55 cm) + Al target (7 cm) + W beam plug (120 cm)**

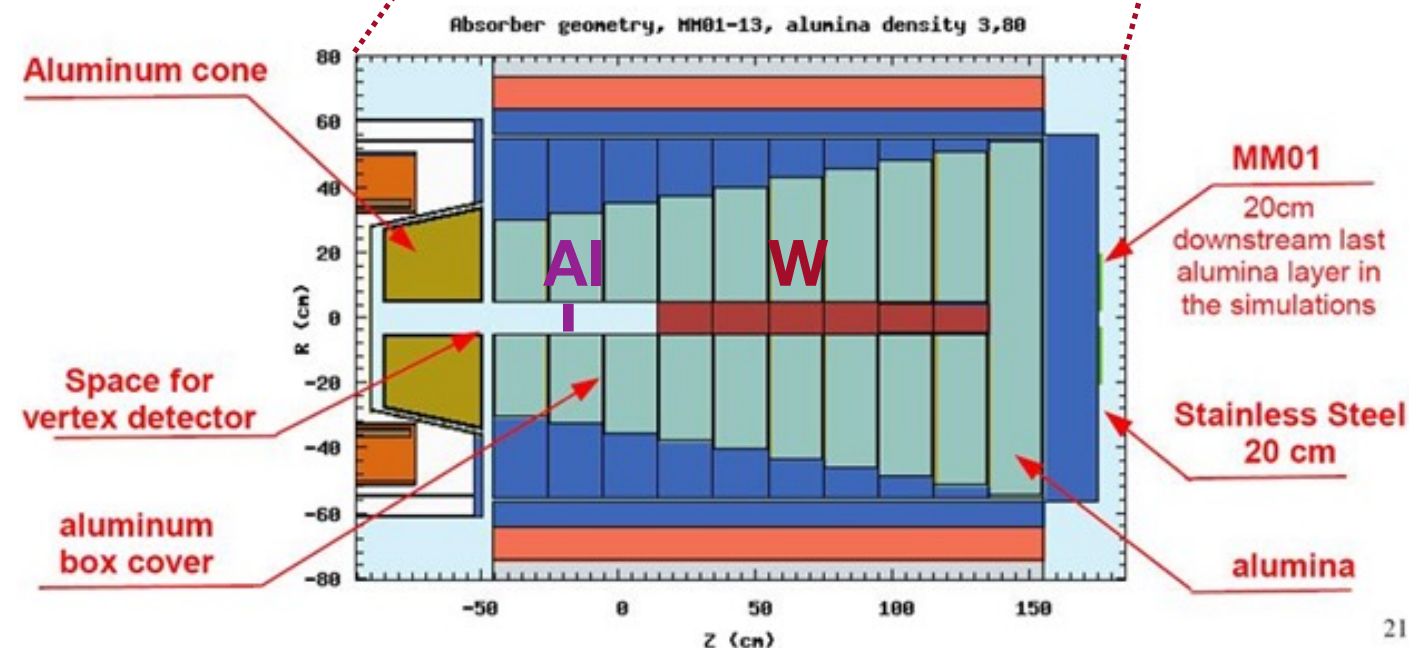
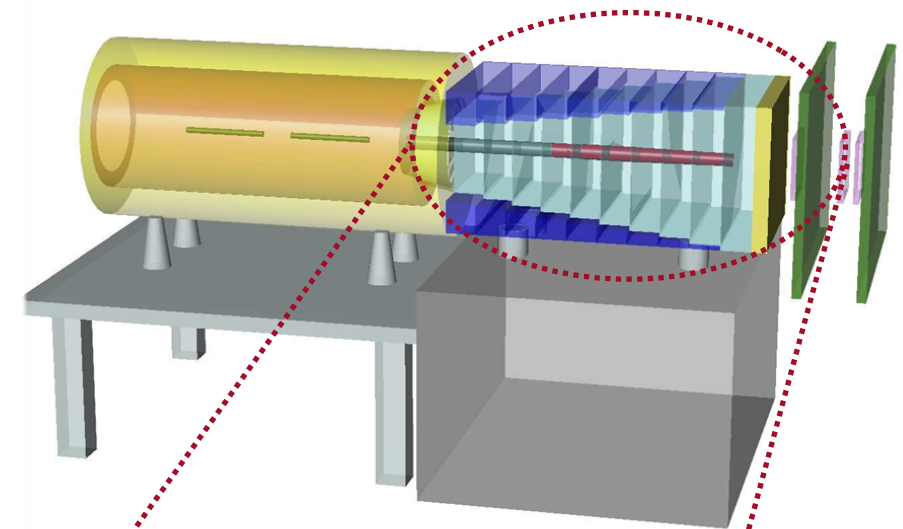
Hadron Absorber

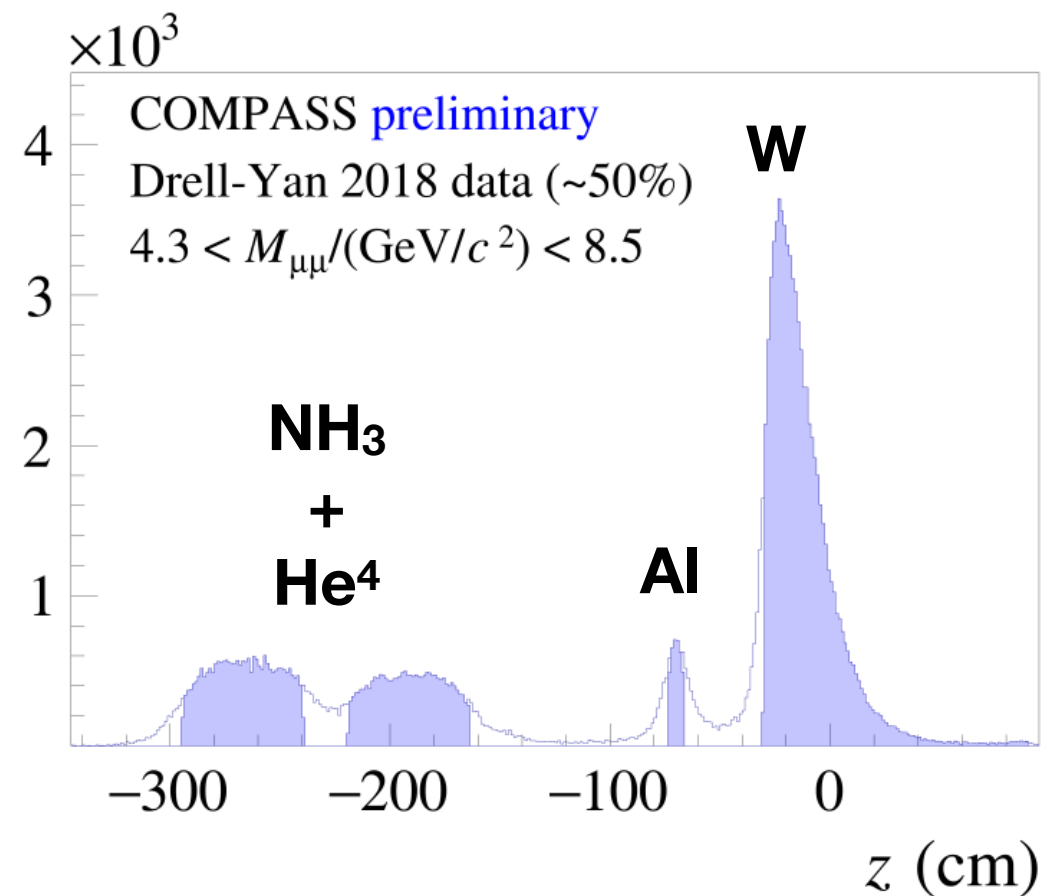
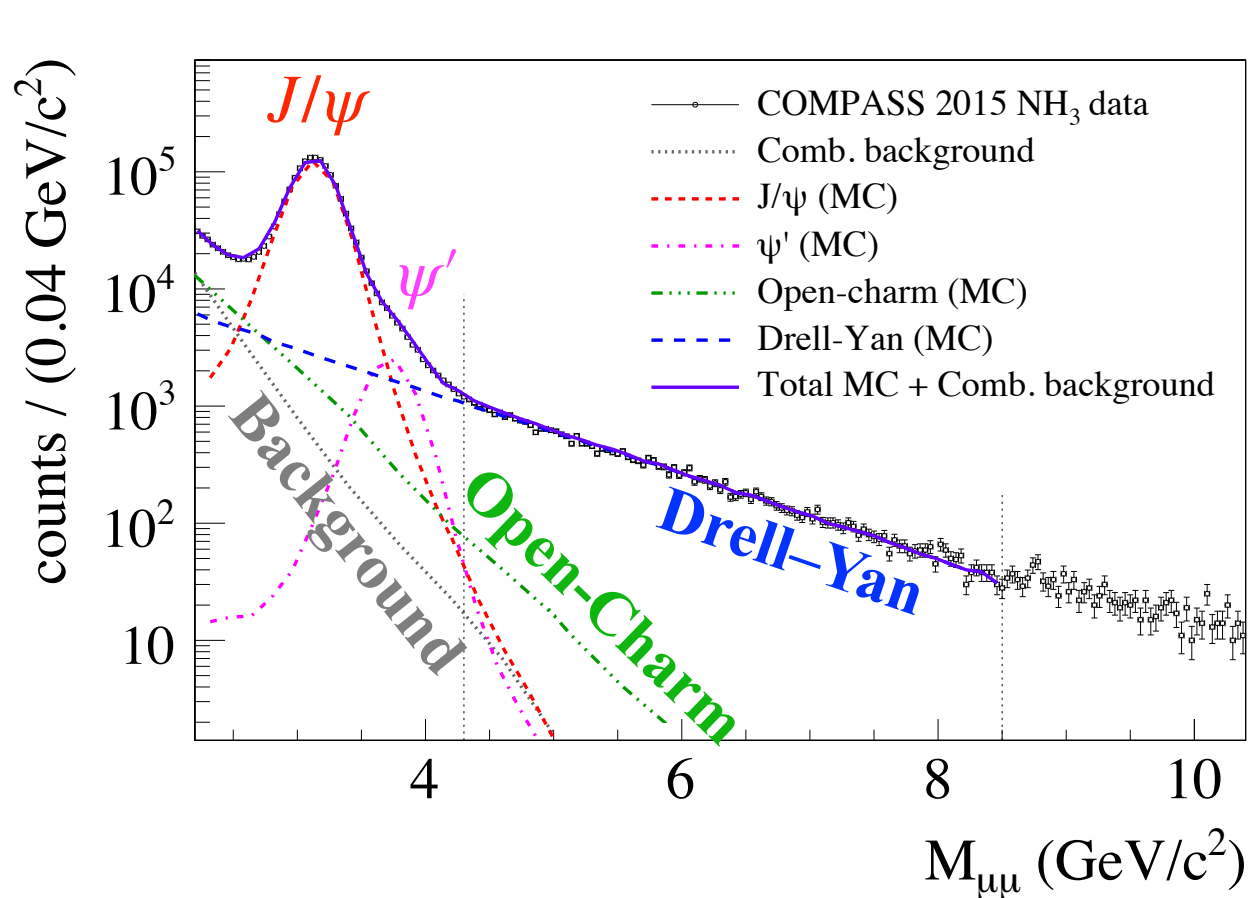


Polarized Target

Hadron absorber

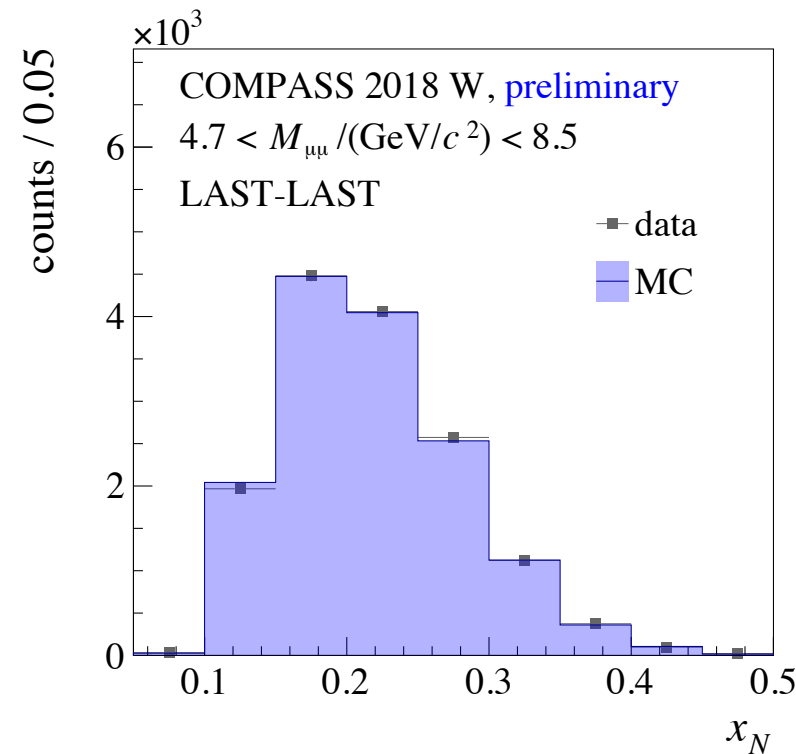
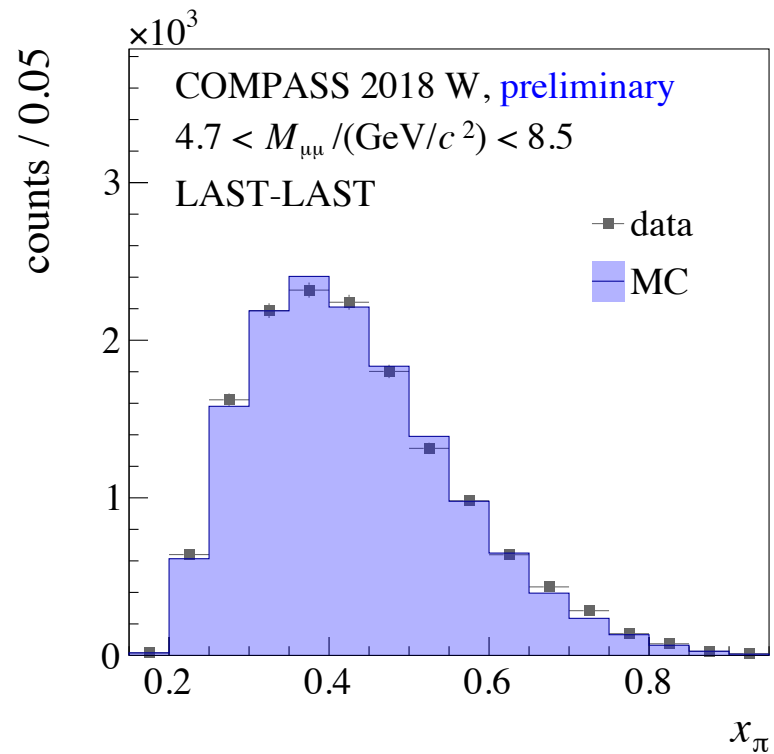
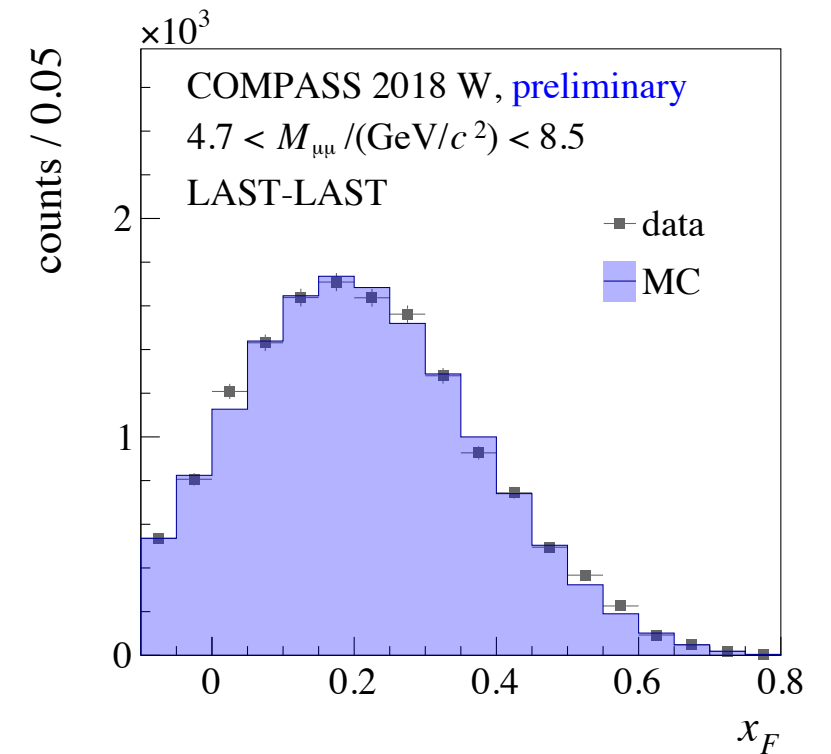
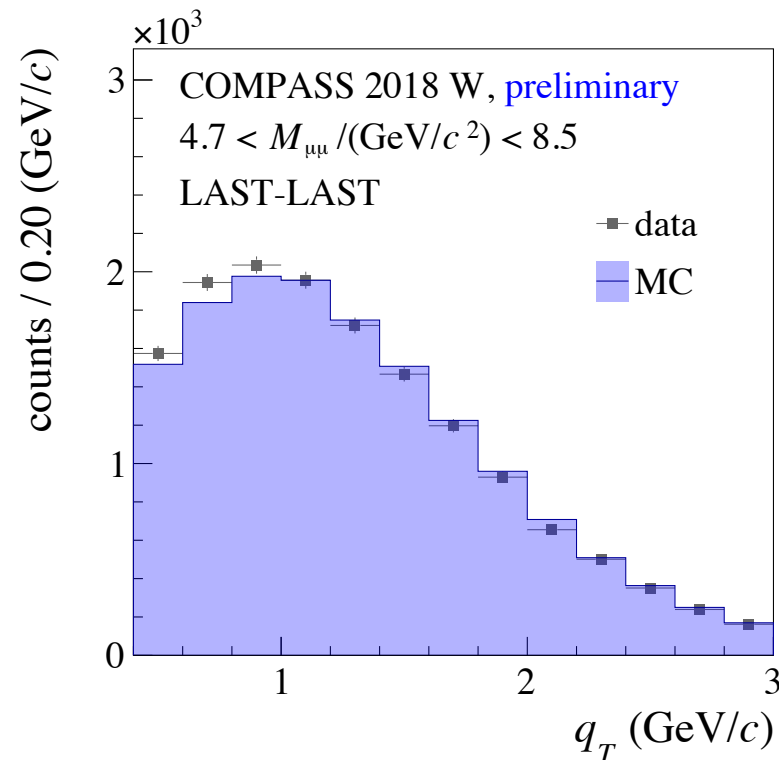
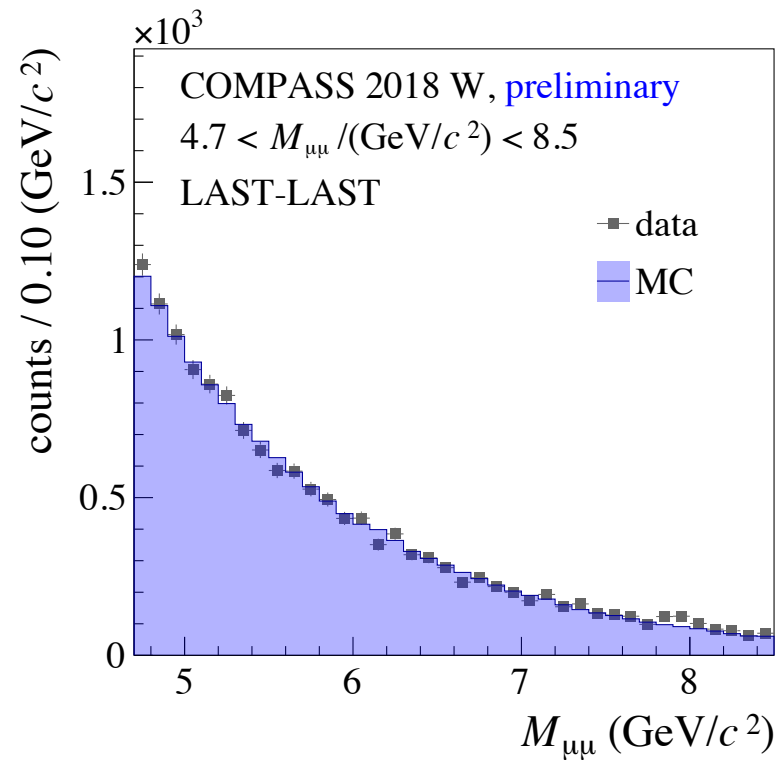
- The total length of the hadron absorber is 240 cm
- It incorporates 120 cm W beam plug and 7 cm Al target.





- Dimuons produced via **DY process** are mixed with muon pairs from **open-charm**, J/ψ , ψ' channels and **combinatorial background**.
- 96% purity of DY** in the selected mass region is concluded based on MC studies.

Verify MC Simulation

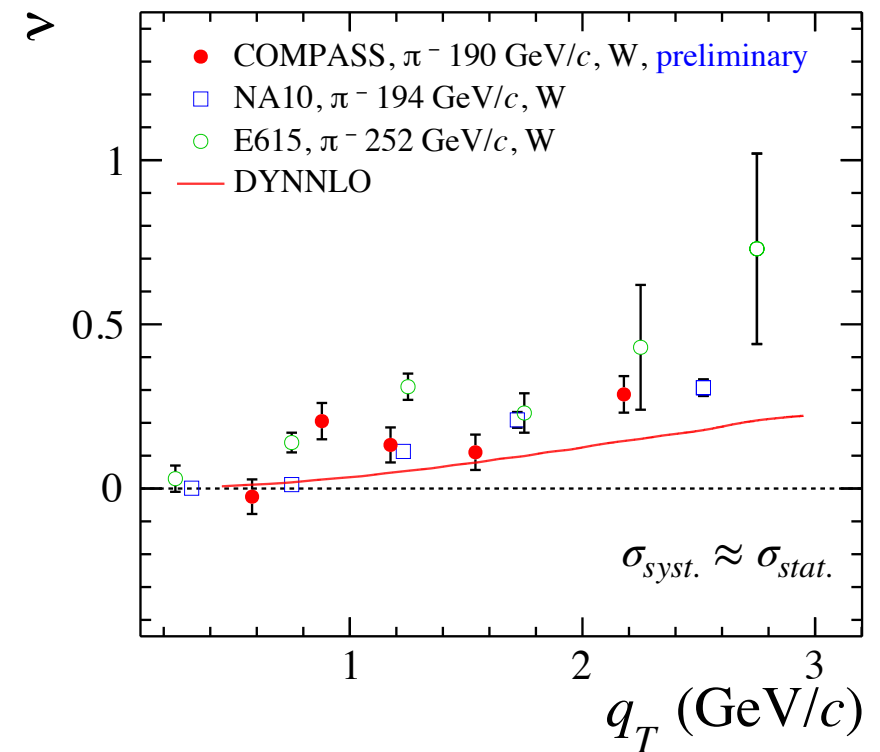
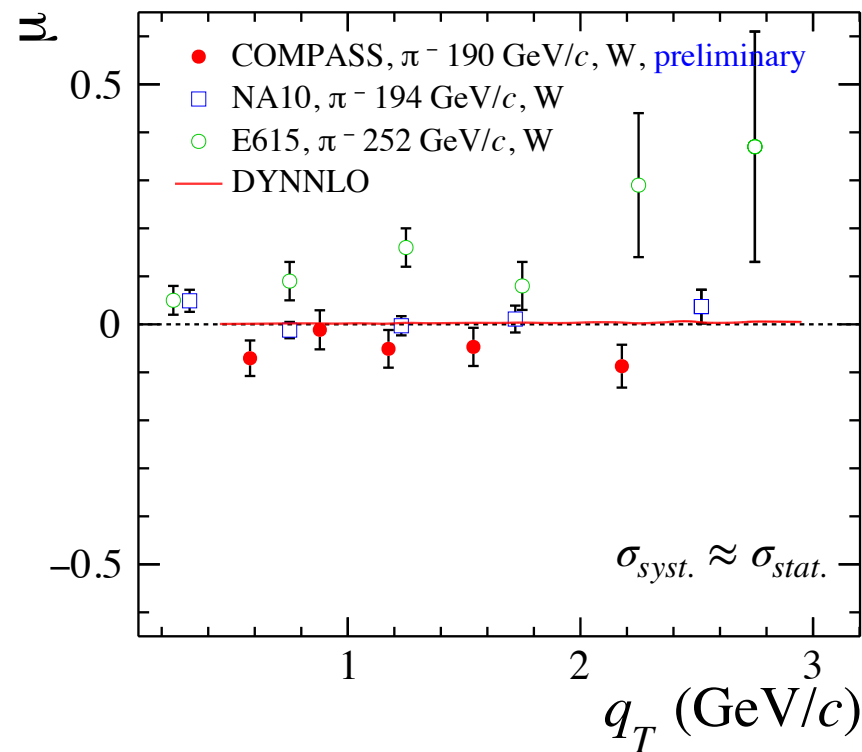
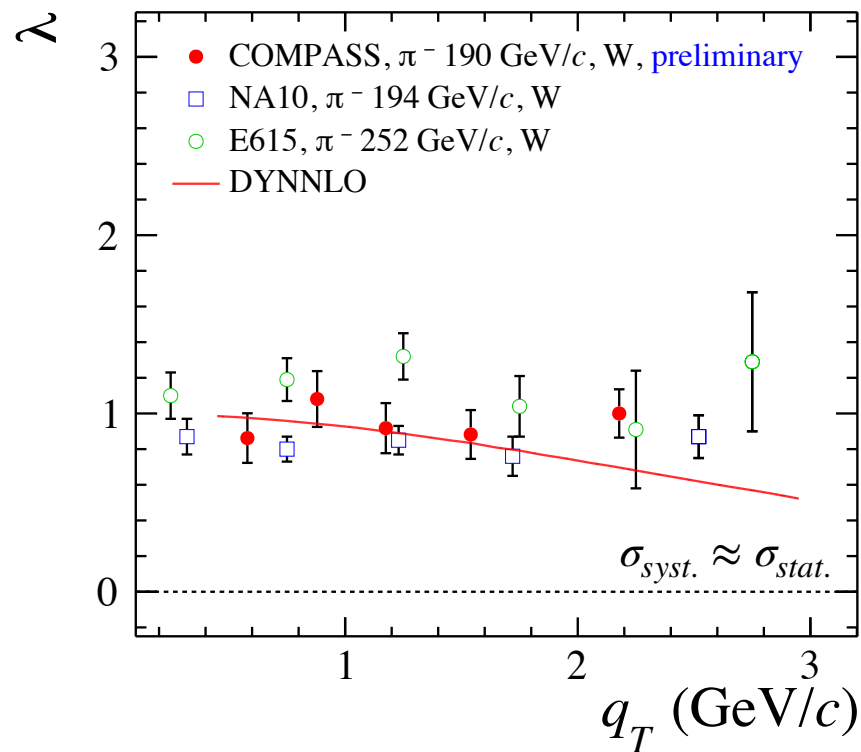


- Good data/MC agreement is achieved for all key kinematic distributions!

Unpolarized Asymmetries

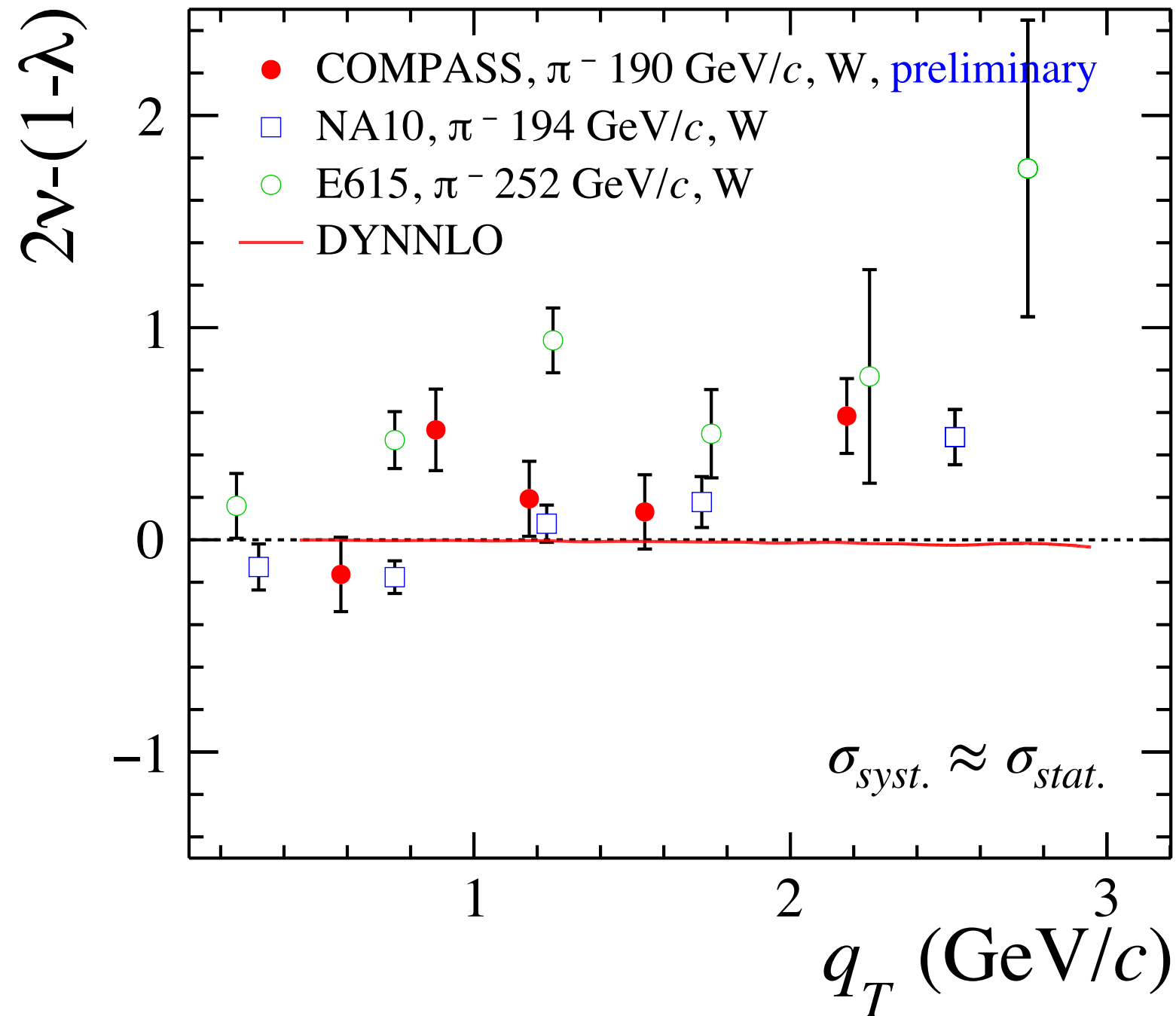


$$\frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi} \frac{1}{\lambda + 3} \left[1 + \lambda \cos^2 \theta_{CS} + \mu \sin 2\theta_{CS} \cos \varphi_{CS} + \frac{\nu}{2} \sin^2 \theta_{CS} \cos 2\varphi_{CS} \right]$$



- Preliminary COMPASS results for ν tend to deviate from pQCD calculation at large q_T . An indication for a presence of a non-zero TMD Boer-Mulders effect.
- Preliminary results are based on ~70% of COMPASS tungsten data collected in 2018.

Result of Lam-Tung Violation

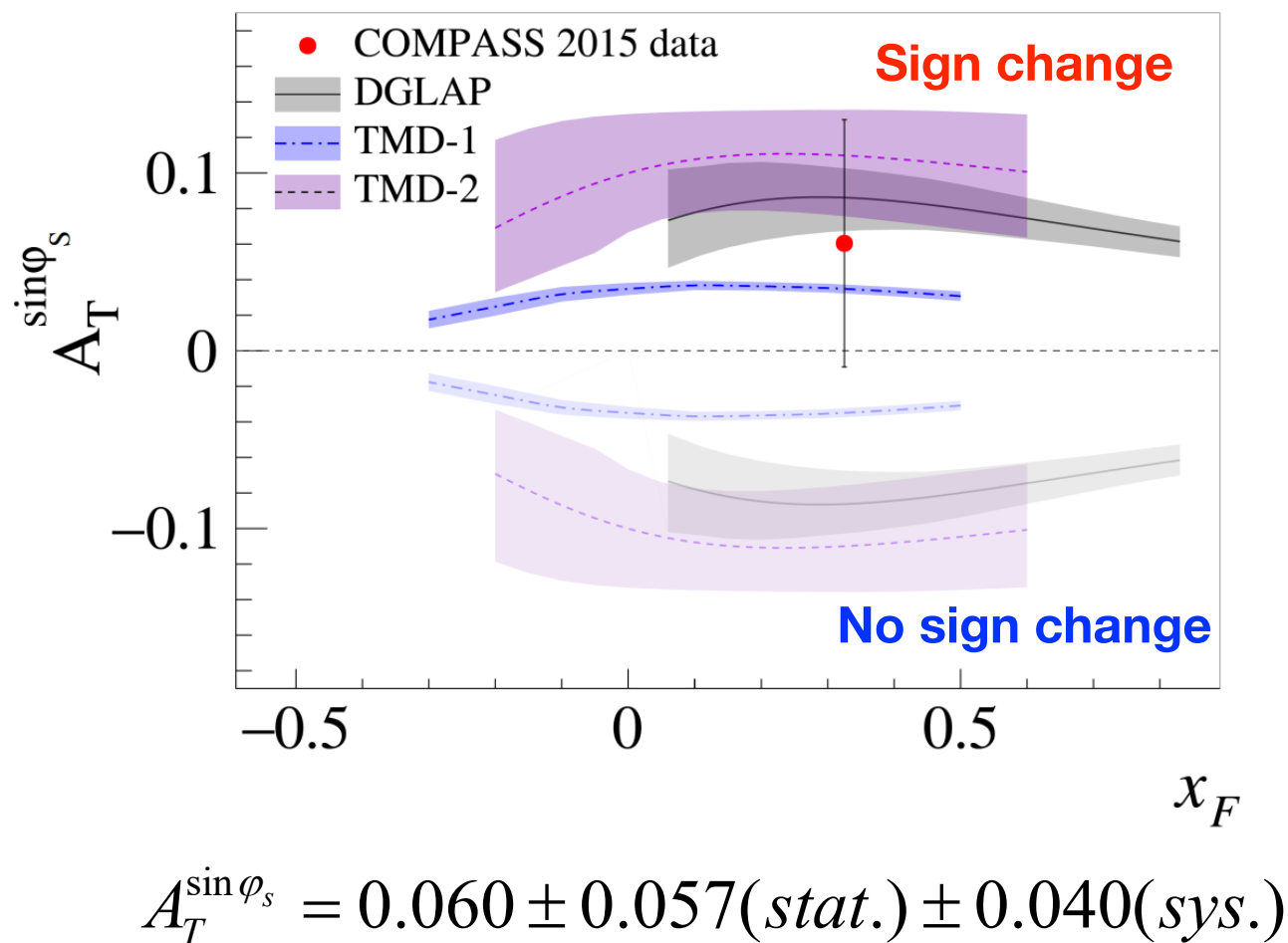


- COMPASS preliminary results indicate possible violation of the Lam-Tung relation.
- Consistent with results obtained by past pion-induced DY experiments.

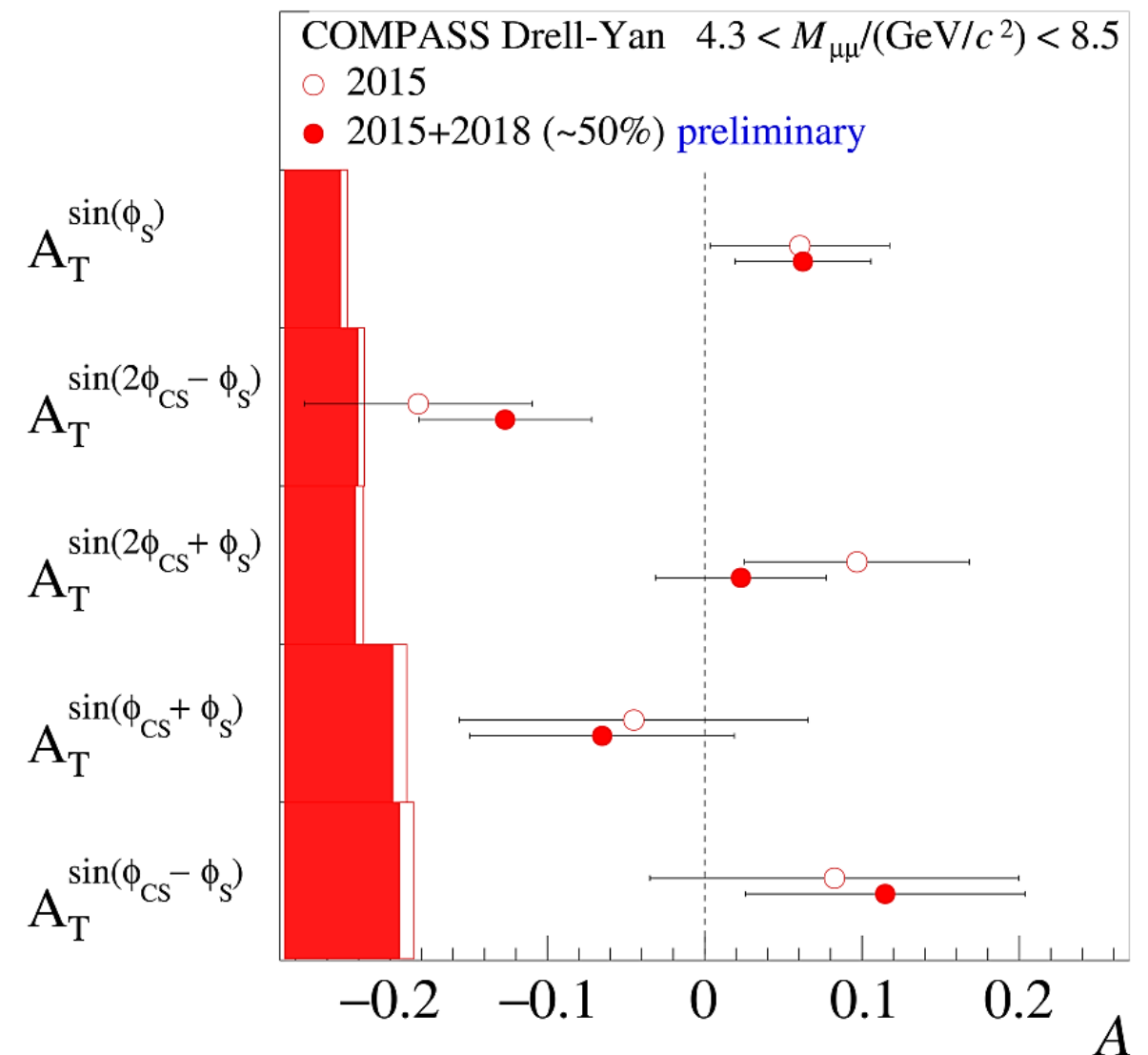
Sivers Asymmetry in Drell-Yan



COMPASS, PRL 119 (2017) 112002



COMPASS 2015 + 2018 (~50%)



- First COMPASS published results from 2015 run and preliminary results from 2018 favor the sign change hypothesis!
- Final analysis of combined 2015-2018 data is ongoing.



- COMPASS study the spin and partonic structure of the nucleon via SIDIS and Drell-Yan channels employing muon and pion beams impinging on different polarized and unpolarized targets.
- In 2017 COMPASS has published the results of Sivers asymmetry from the first ever polarized DY measurements. [PRL 119, 112002 (2017)]
- The preliminary results of DY angular distributions from COMPASS tungsten data may indicate the presence of TMD Boer-Mulders function.
- Various ongoing analyses: cross-section and EMC-effect, polarization (in)dependent asymmetries, J/psi asymmetries etc.

Thank you for your attention!



Back Up

Rotational Invariant Quantities

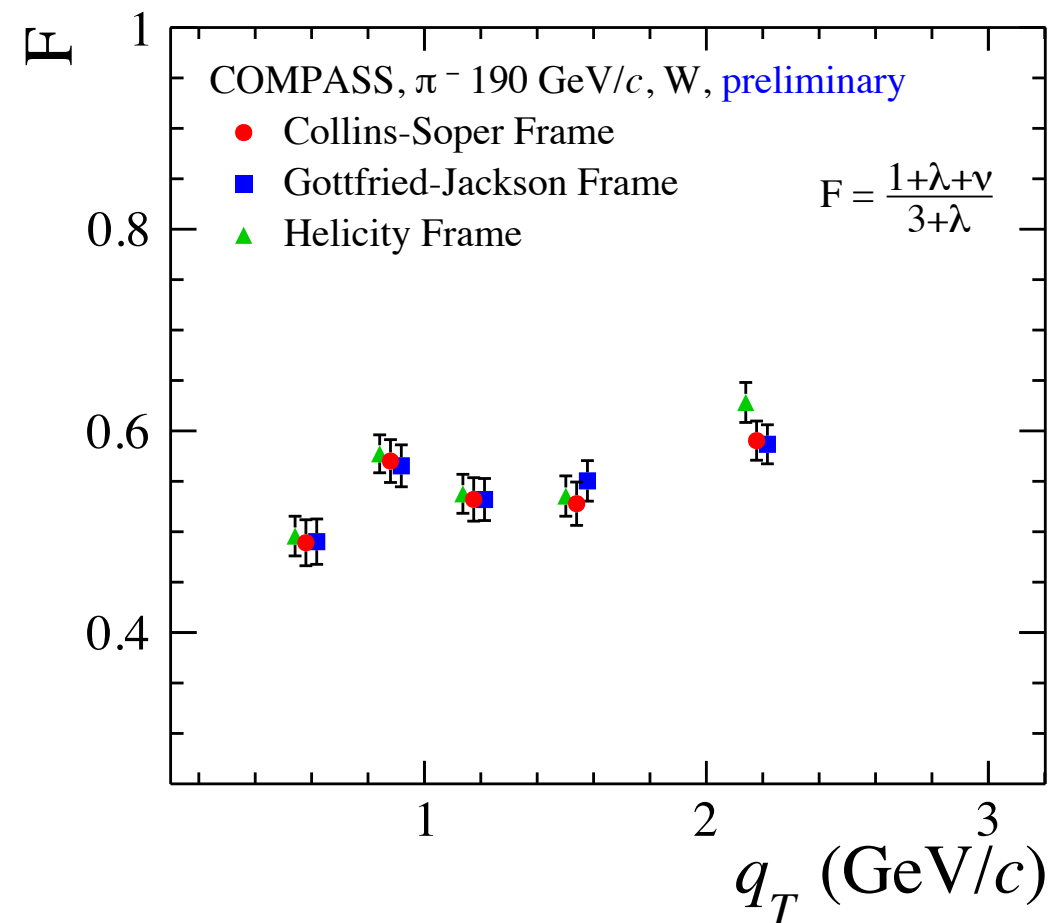
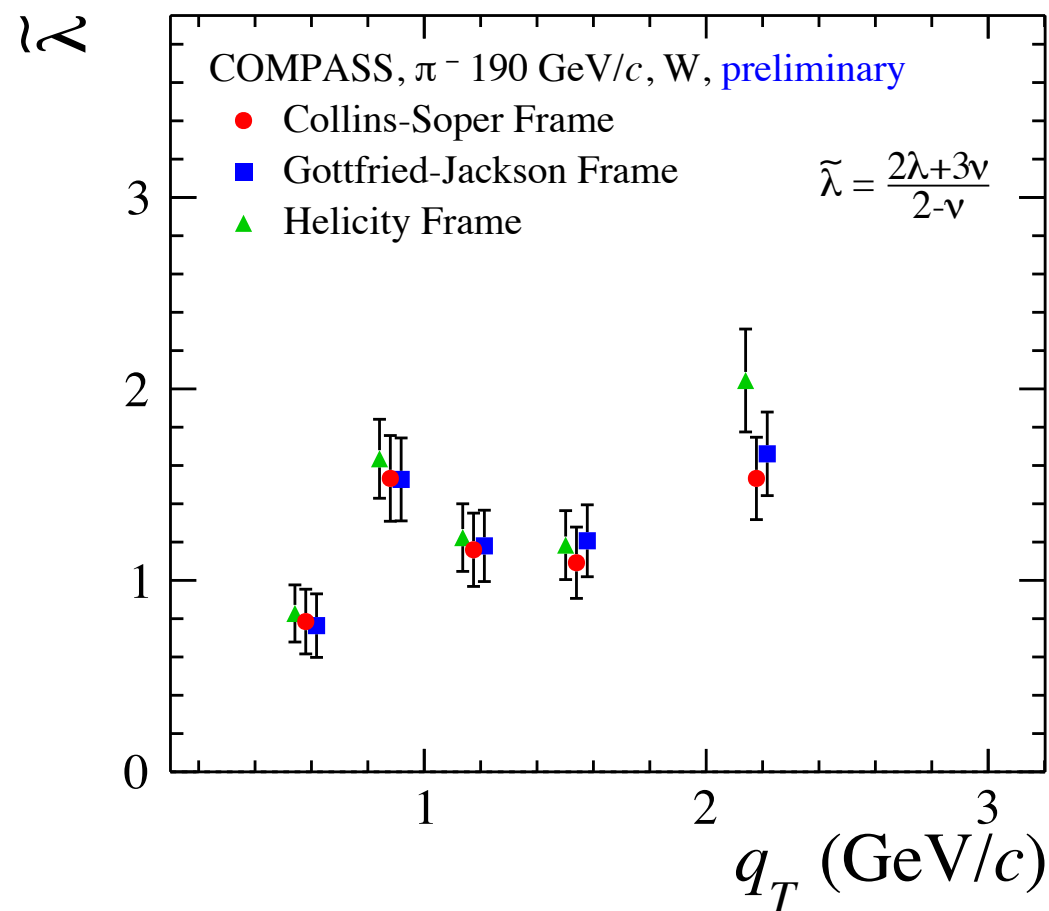


P. Faccioli, C. Lourenco, J. Seixas, H. Wohri, Phys. Rev. D 83 (2011) 056008.

- Rotational invariant quantities (rotated along the **y** axis):

$$\tilde{\lambda} = \frac{2\lambda + 3\nu}{2 - \nu}$$

$$\mathcal{F} = \frac{1 + \lambda + \nu}{3 + \lambda}$$



- Rotational invariant quantities is a good testing ground of overall systematic uncertainties of angular analysis.