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

DIS 2021 Conference

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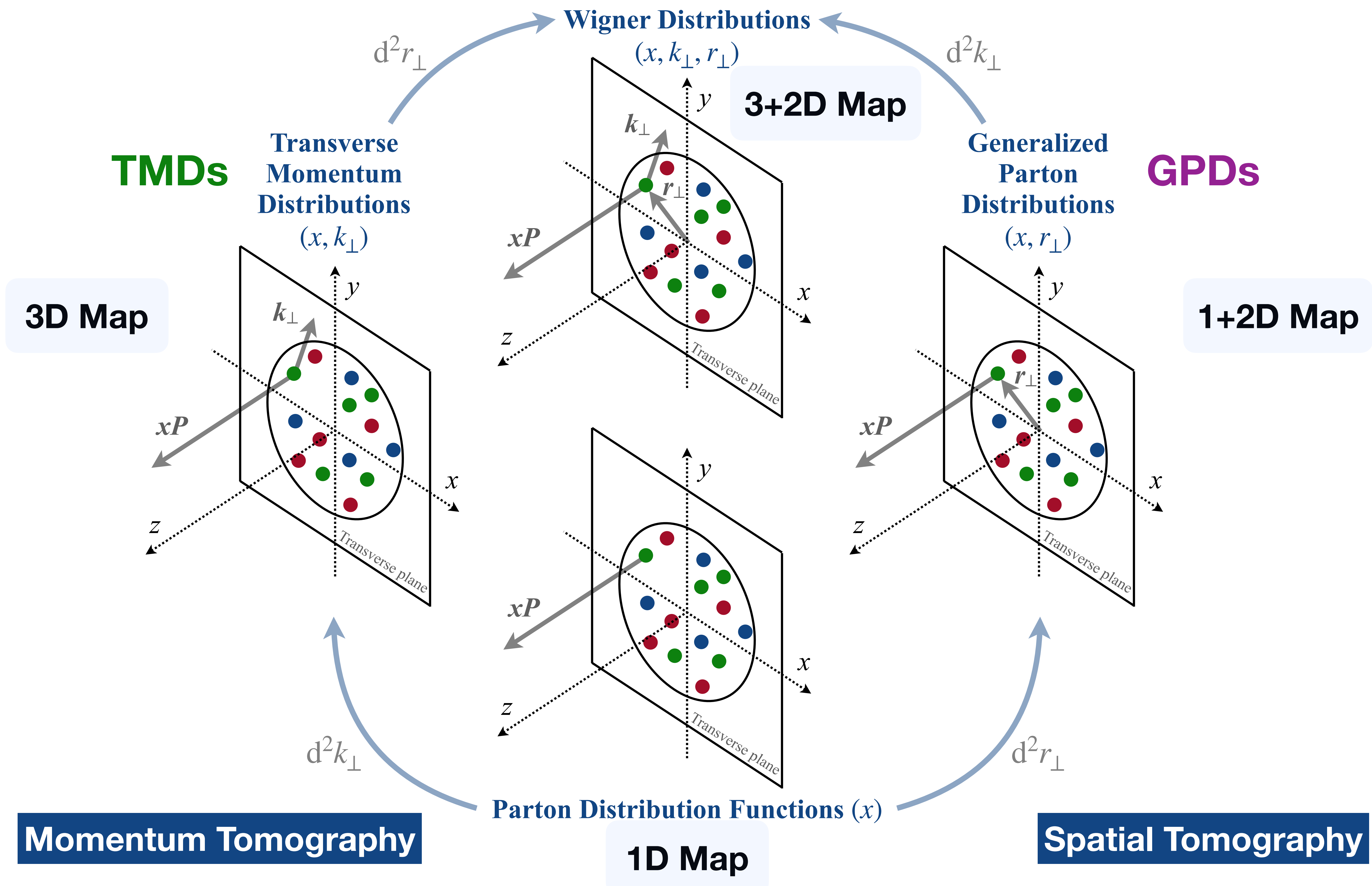
Multi-dimensional Partonic Structures



Transverse-Momentum Dependent PDFs

- 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 $h_{1T}^{\perp q,g}(x, k_T^2)$

- 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:

Spin independent

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \Big\{ 1 + A_U^1 \cos^2\theta_{CS} + \sin 2\theta_{CS}\, A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS}\, A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}$$

Transverse spin dependent

$$+ S_T \Big[(A_T^{\sin\varphi_S} + \cos^2\theta_{CS} \tilde{A}_T^{\sin\varphi_S}) \sin\varphi_S$$

$$+ \sin 2\theta_{CS} \left(A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) + A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \right)$$

$$+ \sin^2\theta_{CS} \left(A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \right) \Big] \Big\}$$

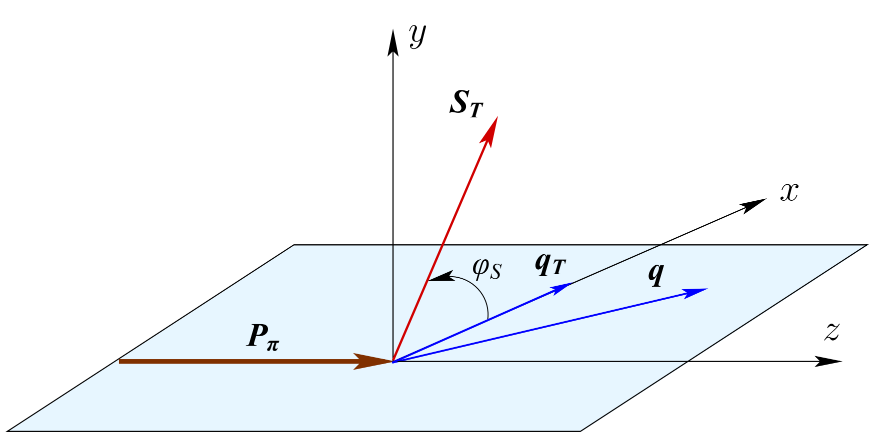
Spin Independent

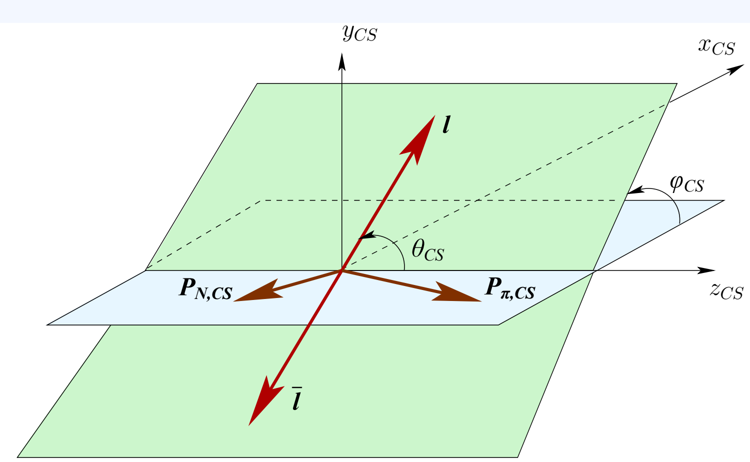
$$A_U^1 = \lambda$$

$$A_U^{\cos\varphi_{CS}} = \mu$$

$$A_U^{\cos 2\varphi_{CS}} = \frac{\nu}{2}$$

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





SIDIS and Single-Polarized Drell–Yan

Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$
$$\times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \end{array} \right] \\ + S_T \lambda \left[\sqrt{\left(1-\varepsilon^2\right)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \right] \end{array} \right\}$$

SIDIS-DY bridge

Drell–Yan process (DY)

$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 \left(1 + \cos^2\theta_{CS}\right)$$
$$\times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\ + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

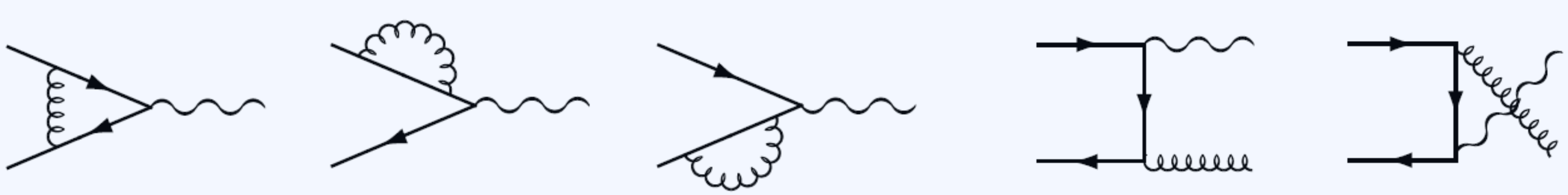
where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1 + \cos^2\theta_{CS}\right)$

SIDIS		DY
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \dots$	← **Boer-Mulders** →	$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$	← **Sivers** →	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$	← **Transversity** →	$A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$
$A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	← **Pretzelosity** →	$A_T^{\sin(2\varphi_{CS} + \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$
$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$	← **Worm-gear L** →	$A_L^{\sin 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1L,p}^{\perp q}$
$A_{LL} \propto g_{1L}^q \otimes D_{1q}^h,\ A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$	← →	**Double polarized DY only**

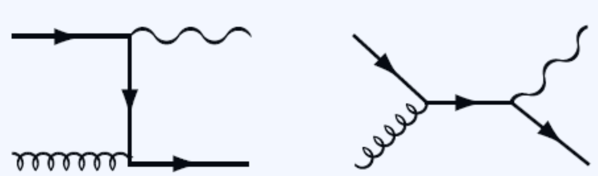
Unpolarized Asymmetries

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

- 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

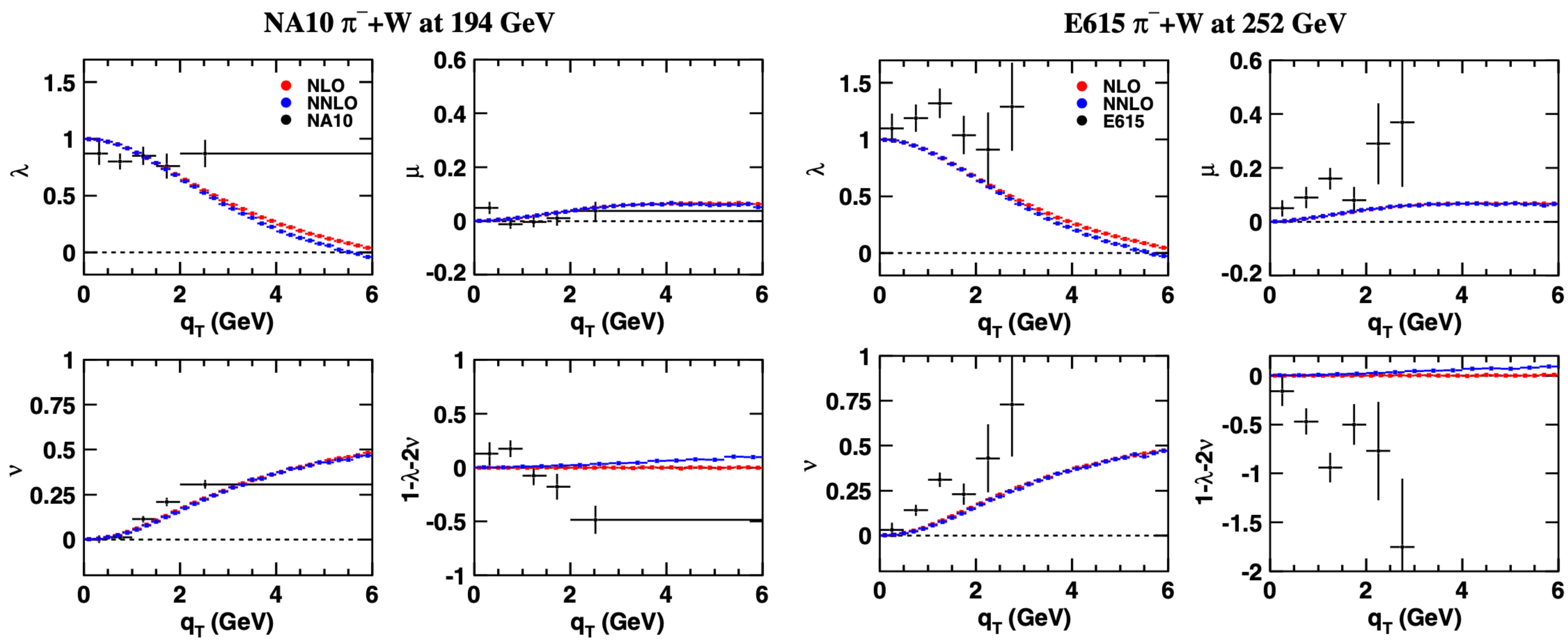


NLO(α_s)
Compton diagram

Angular Distribution in Pion-induced Drell–Yan

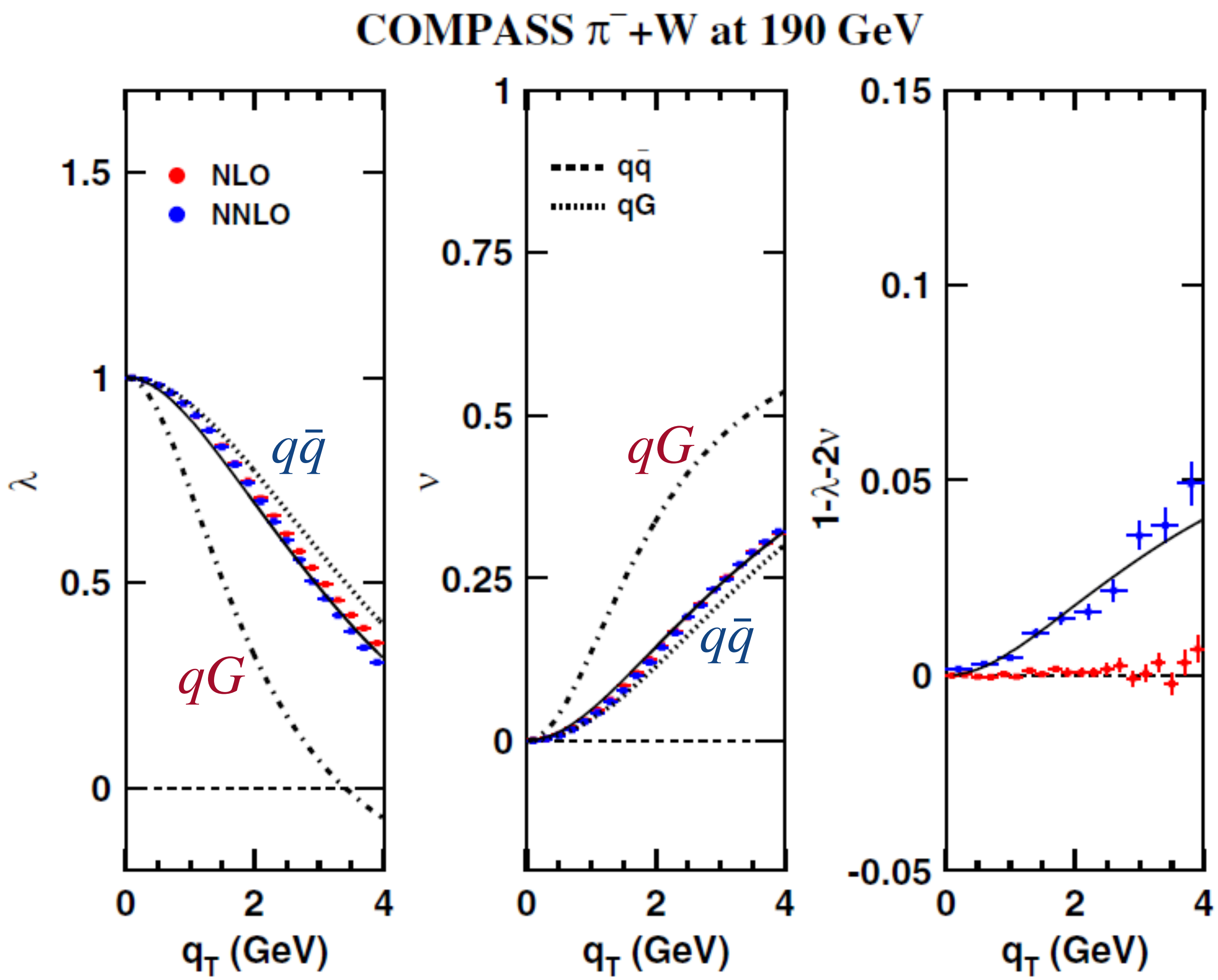
NA10: ZPC 31, 513(1986); E615: PRD 39, 92(1989); W-C. Chang, et.al, PRD 99, 014032 (2019)

- 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.



Violation of Lam-Tung Relation

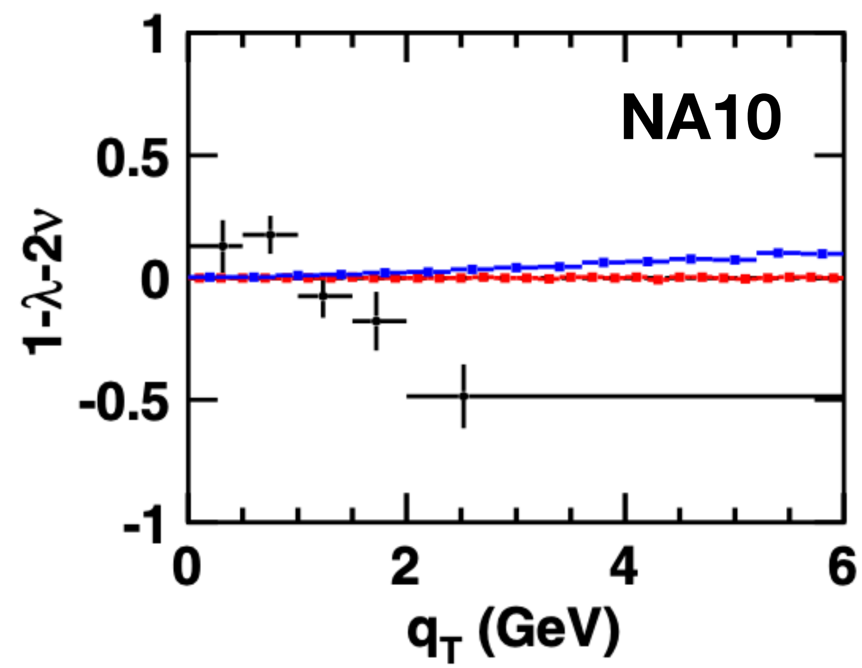
W-C. Chang, R. E. McClellan, J-C. Peng, O. Teryaev, PRD 99, 014032 (2019)



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

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

$0.2 < x_F < 0.4$



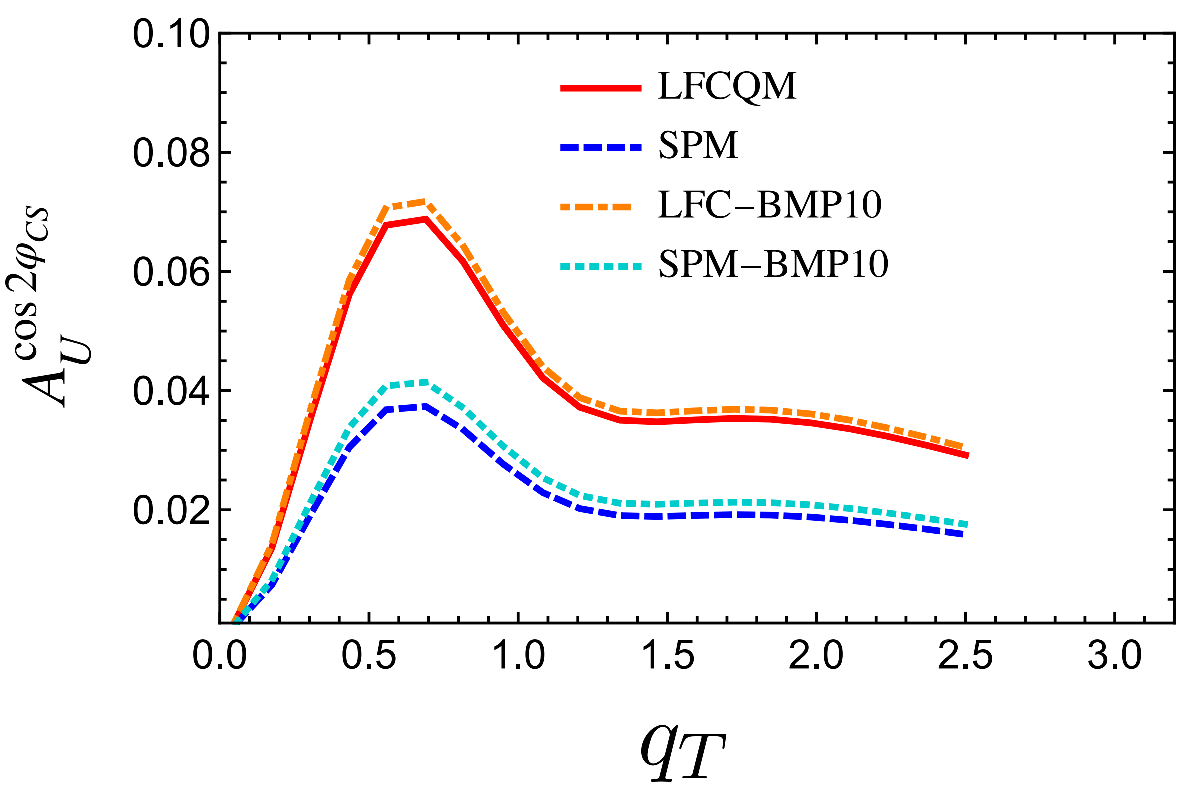
- Including NNLO contributions in pQCD violates Lam-Tung relation.
- Opposite sign for Lam-Tung relation from NNLO pQCD calculations and experiments.

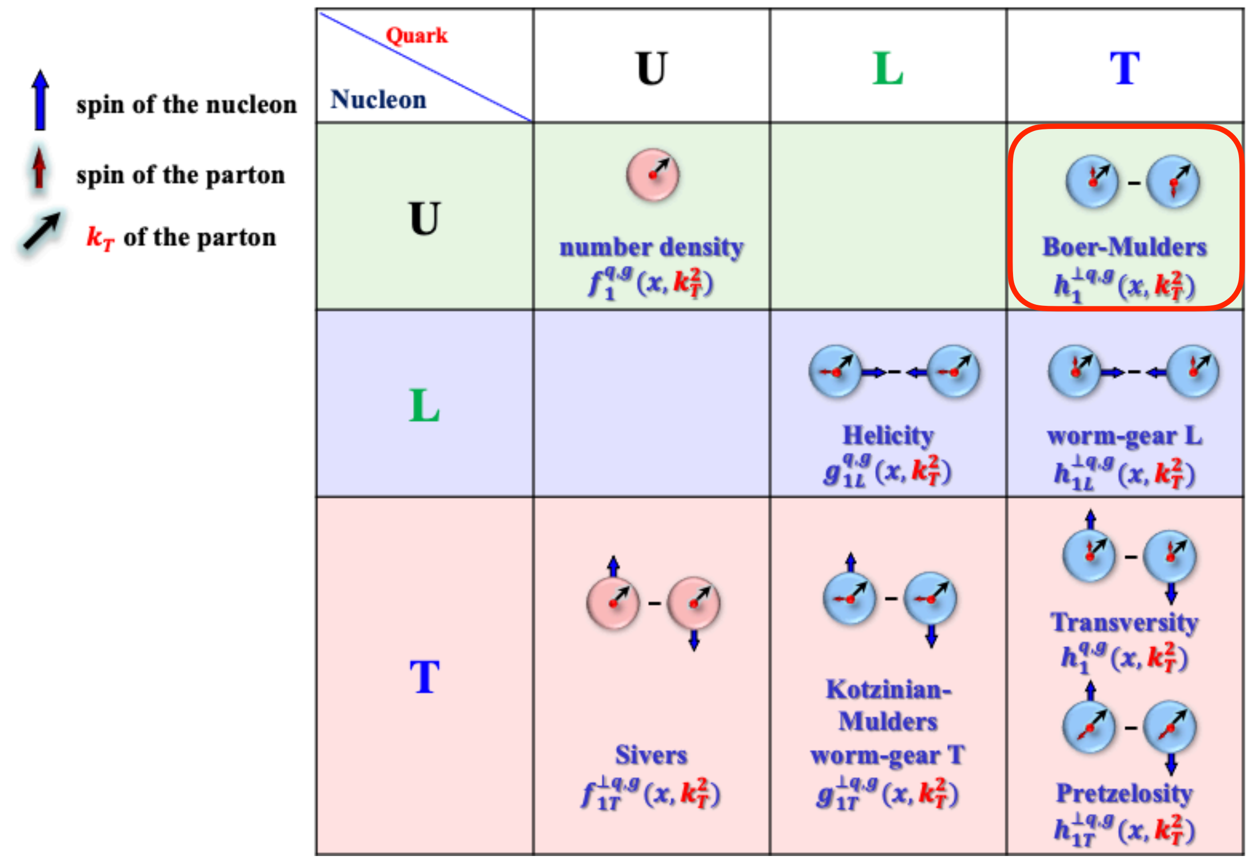
The Boer–Mulders Function

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.

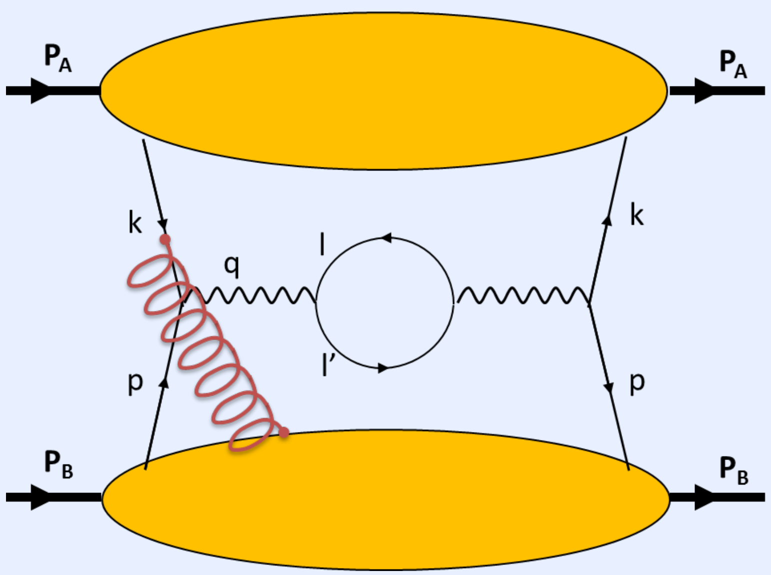
$$A_U^{\cos 2\varphi_{CS}} = \frac{\nu}{2} \propto h_1^\perp(N)\bar{h}_1^\perp(\pi)$$



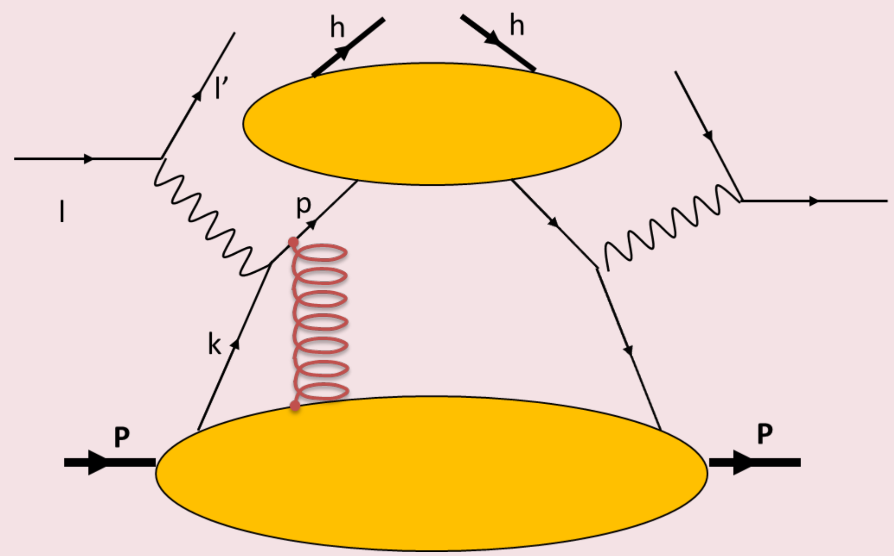


Non-Universality of TMD Functions

DY



SIDIS



To be tested by COMPASS experiment!

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

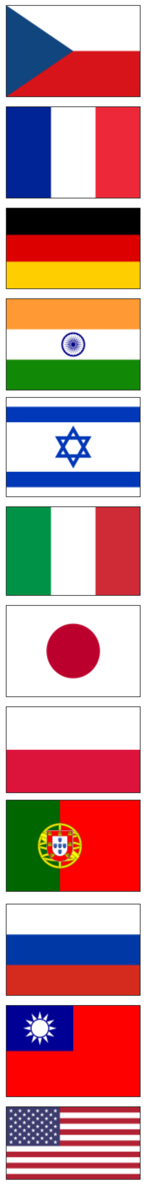
- QCD gluon gauge link (Wilson line) in the initial state (DY) v.s. final state interactions (SIDIS).
- Fundamental predictions from TMD framework of QCD.

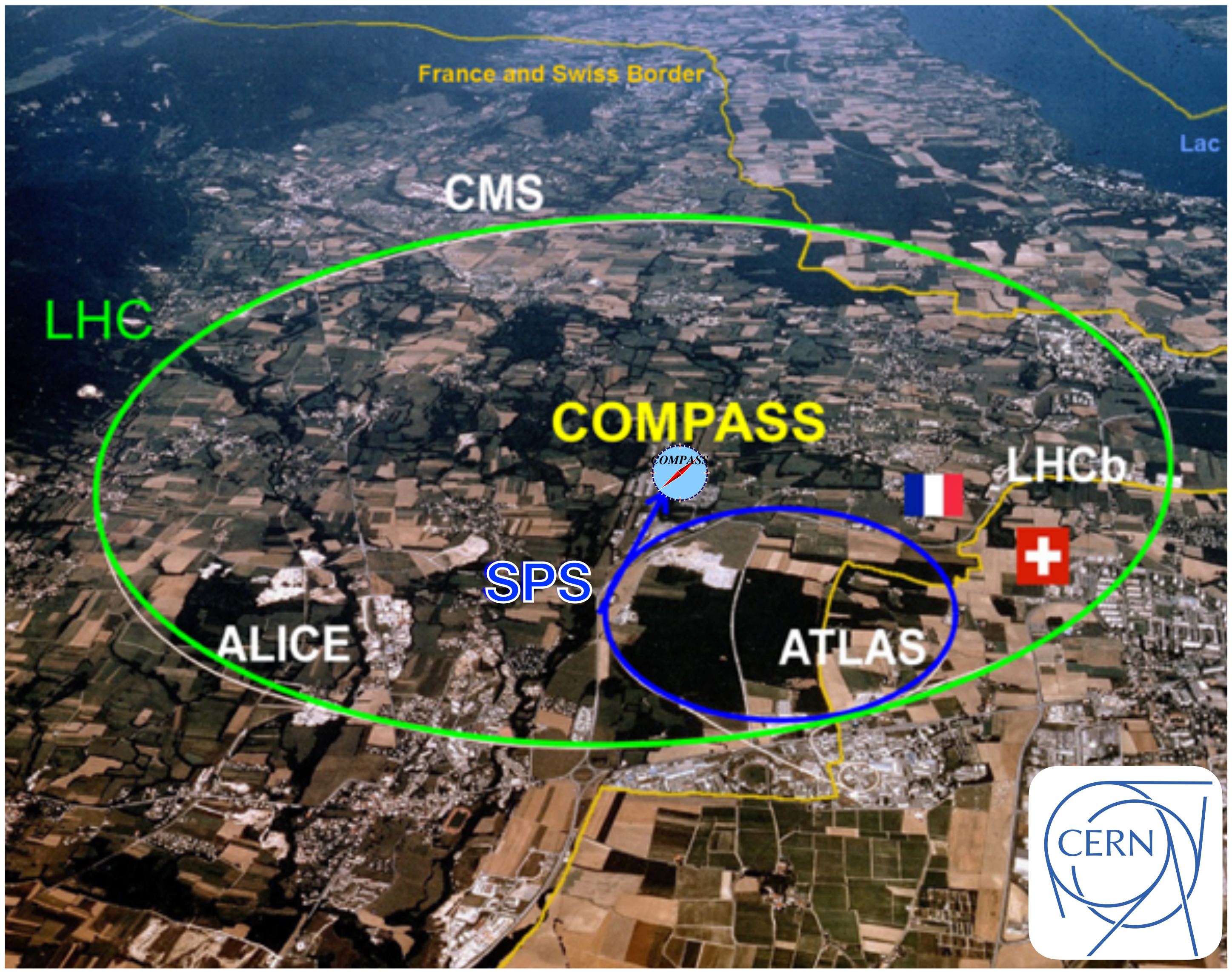
spin of the nucleon
spin of the parton
k_T of the parton

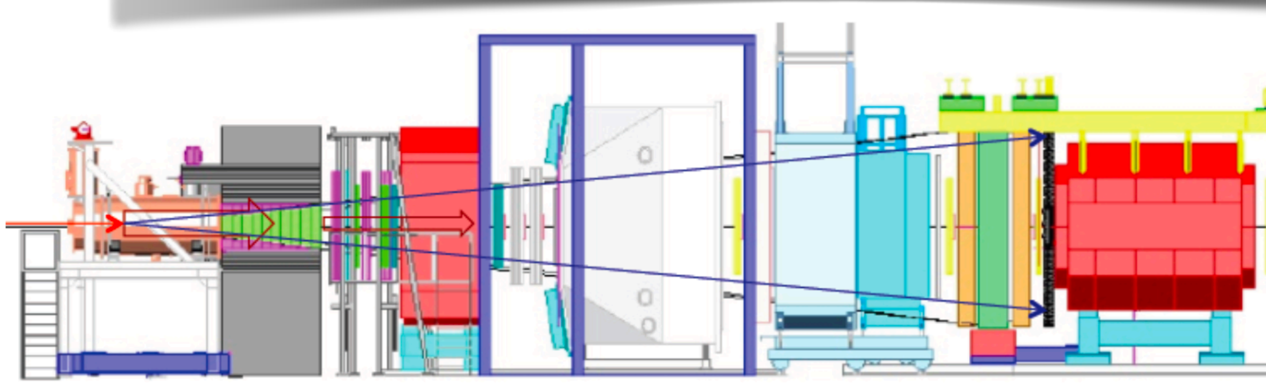
Nucleon \ Quark	U	L	T
U	number density $f_1^{q,g}(x, k_T^2)$		Boer-Mulders $h_1^{\perp q,g}(x, k_T^2)$
L		Helicity $g_{1L}^{q,g}(x, k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x, k_T^2)$
T	Sivers $f_{1T}^{\perp q,g}(x, k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x, k_T^2)$	Transversity $h_1^{q,g}(x,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

COMPASS/CERN Collaboration

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



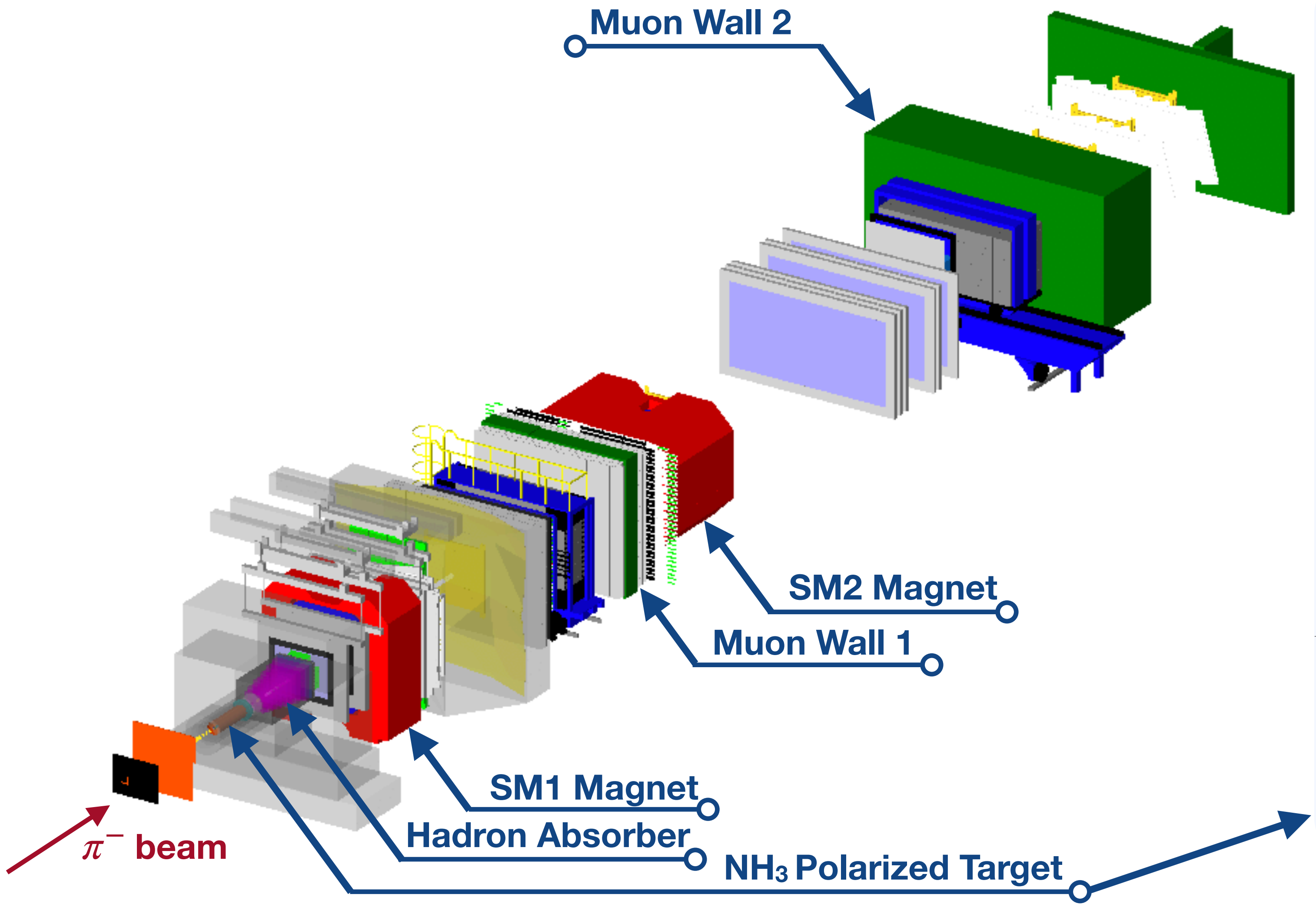


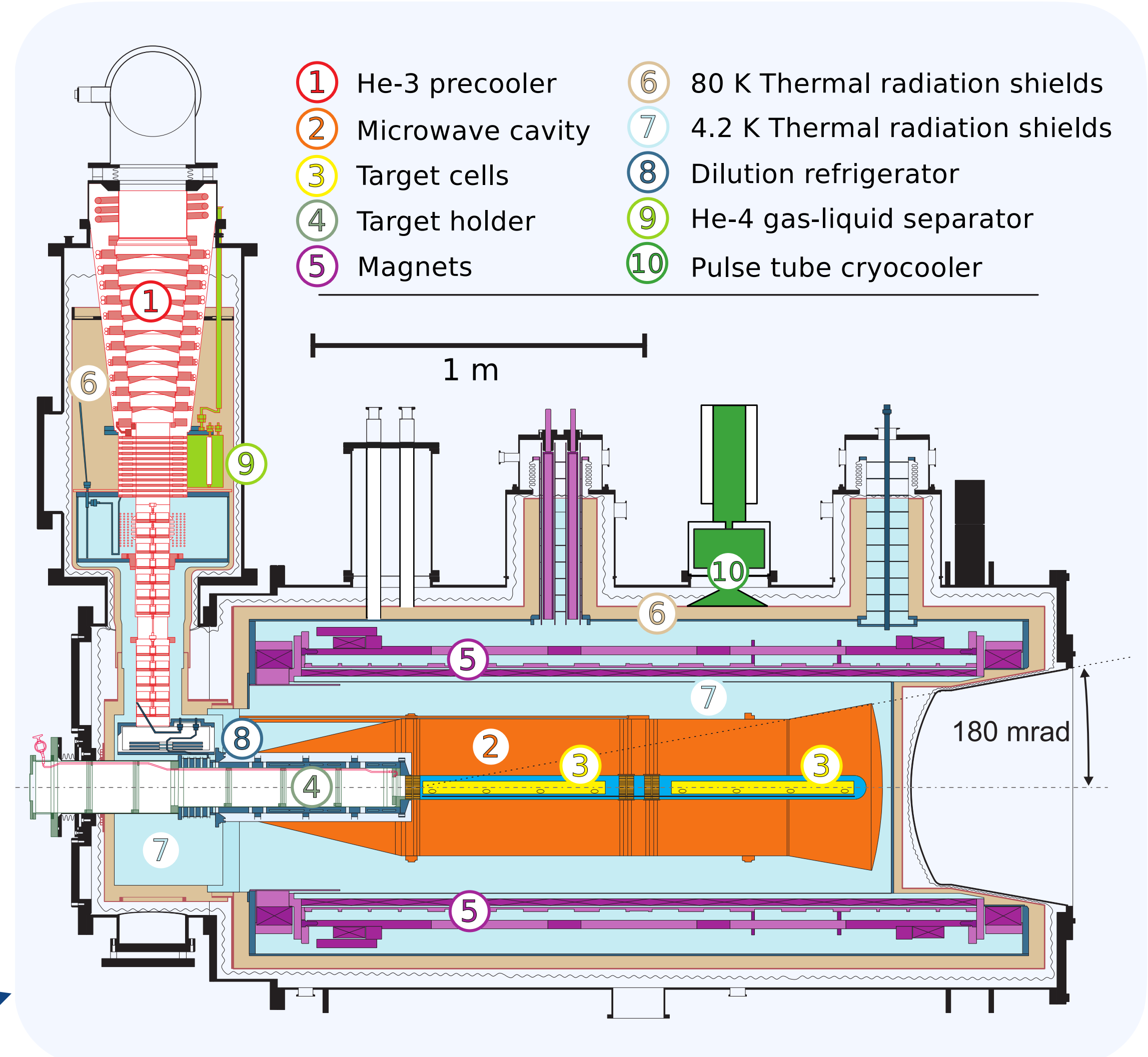


…

- 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.

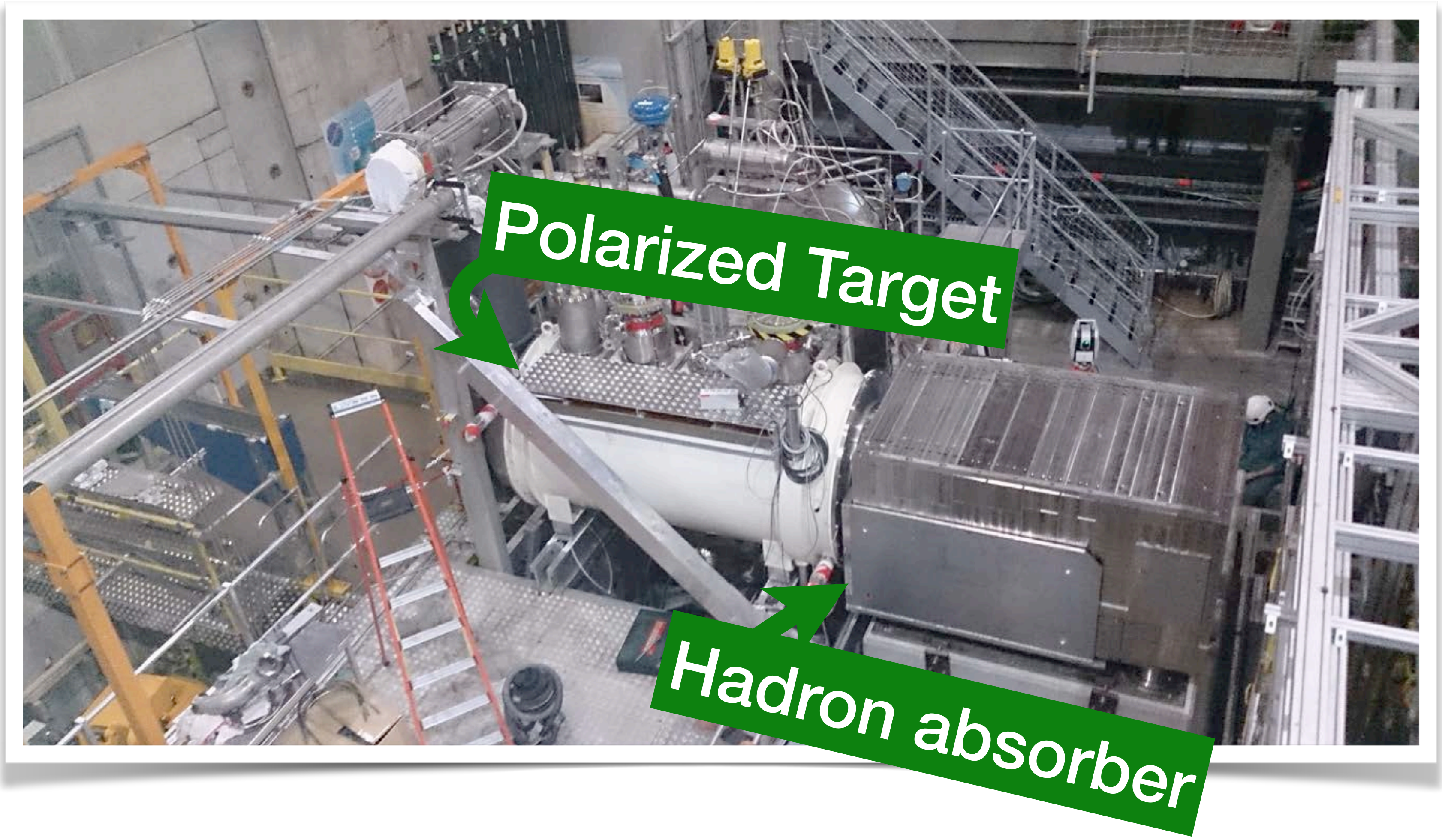
Drell-Yan Program in COMPASS

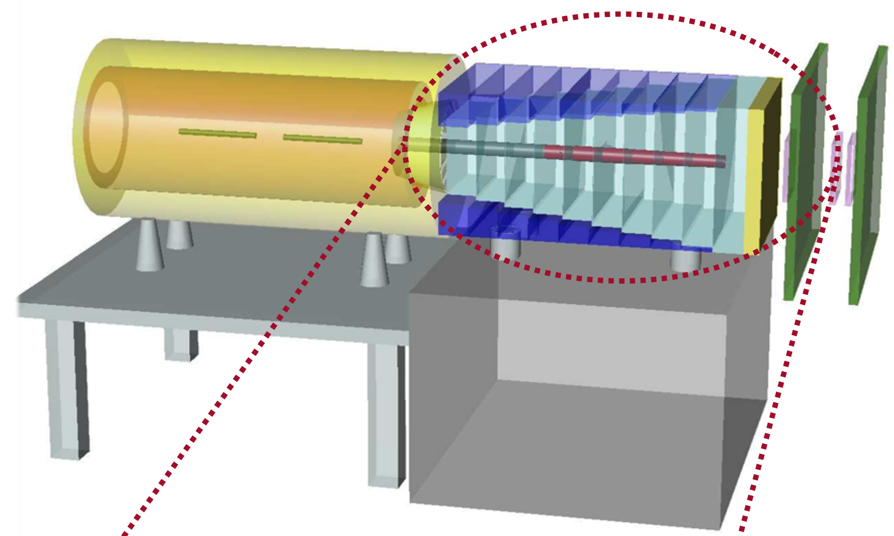


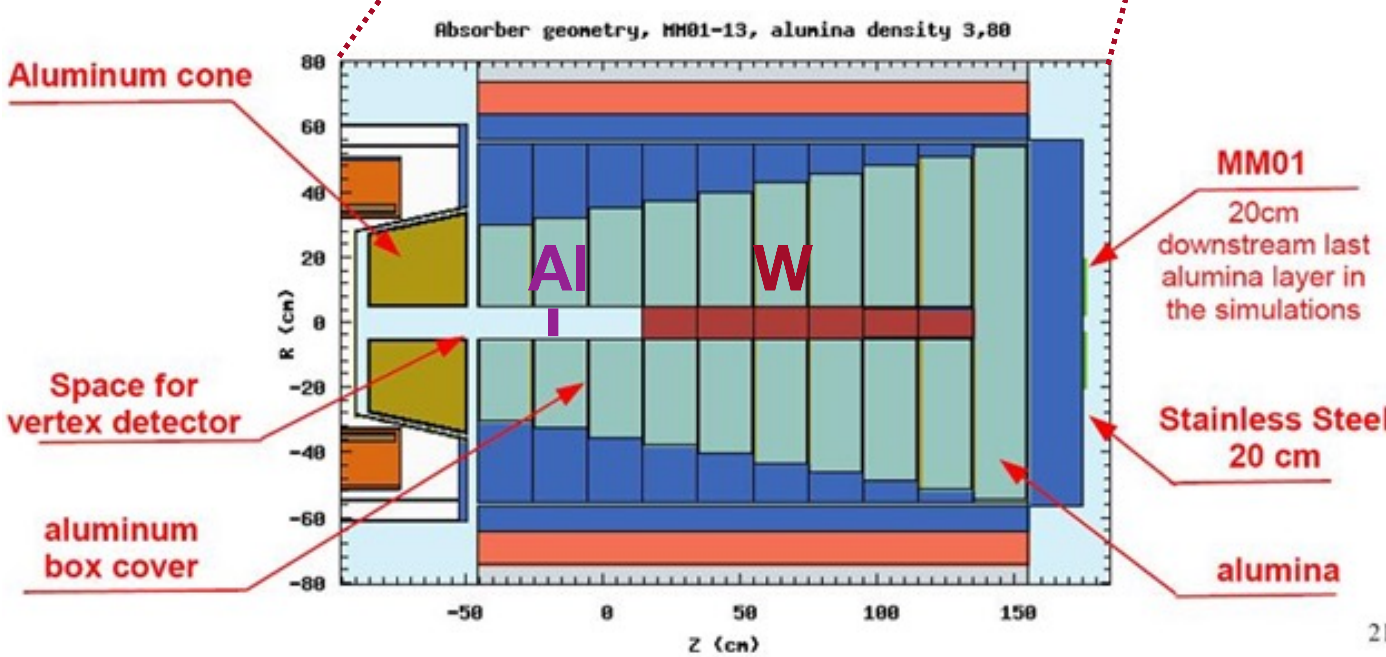


- First ever polarized DY measurements were performed by COMPASS in 2015 and 2018.
- π^- beam at 190 GeV/c with average beam intensity 7×10^7 s^{-1} from **CERN SPS M2 beam line**.
- **Transversely polarized NH_3 target cells** (55+55 cm) + **Al target** (7 cm) + **W beam plug** (120 cm)

Hadron Absorber

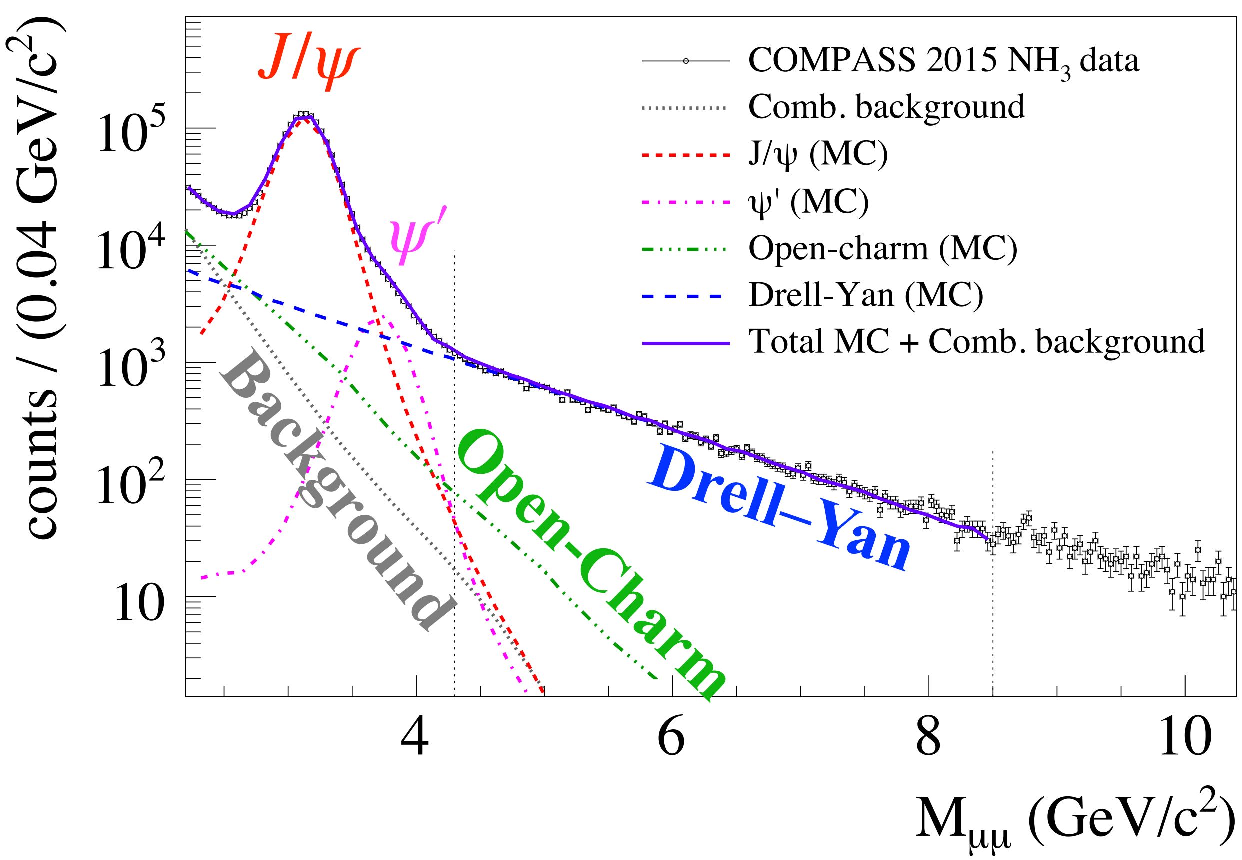


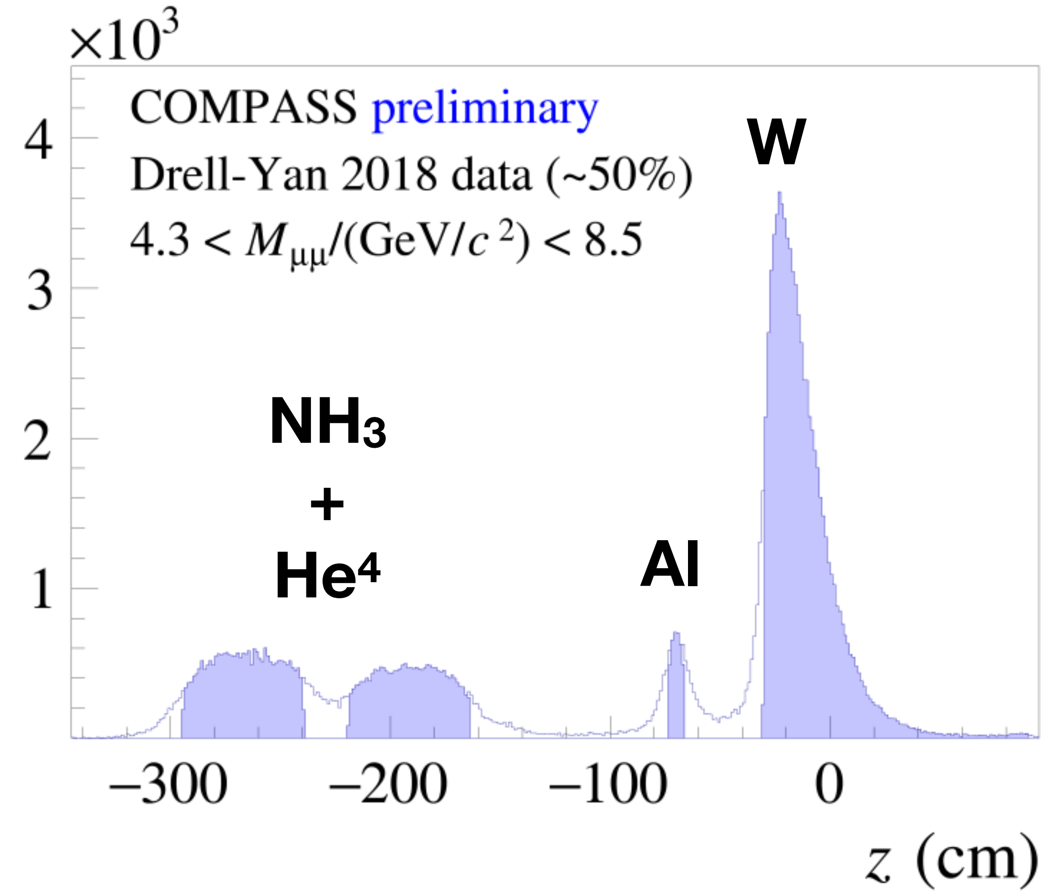




- The total length of the hadron absorber is 240 cm
- It incorporates 120 cm W beam plug and 7 cm Al target.

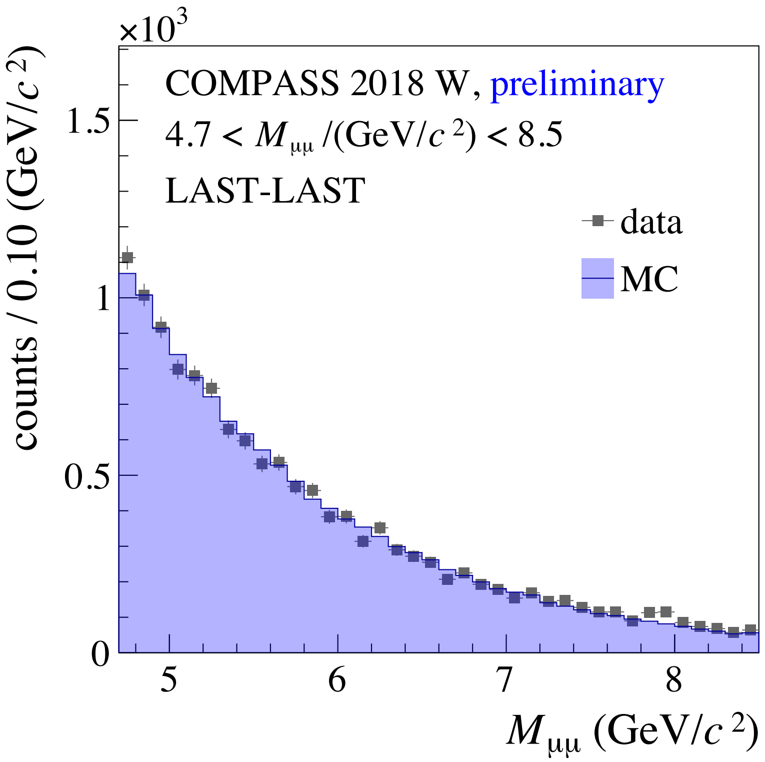
Data Analysis — Background Estimation

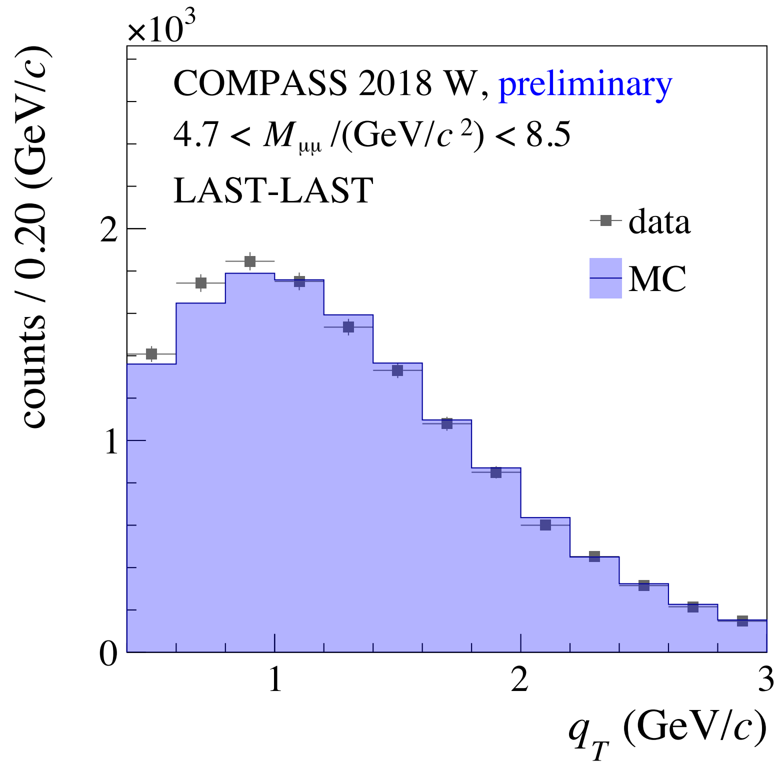


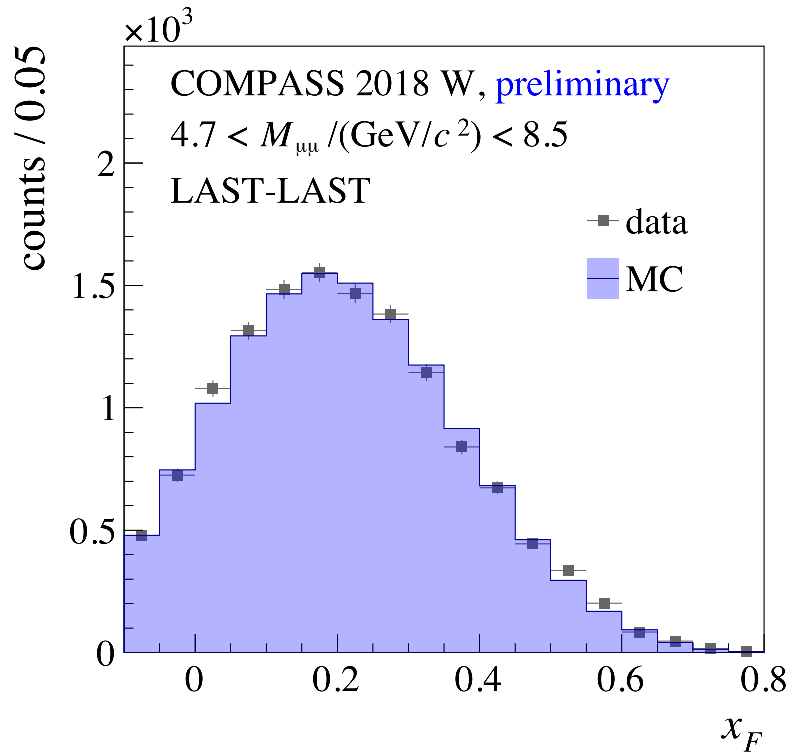


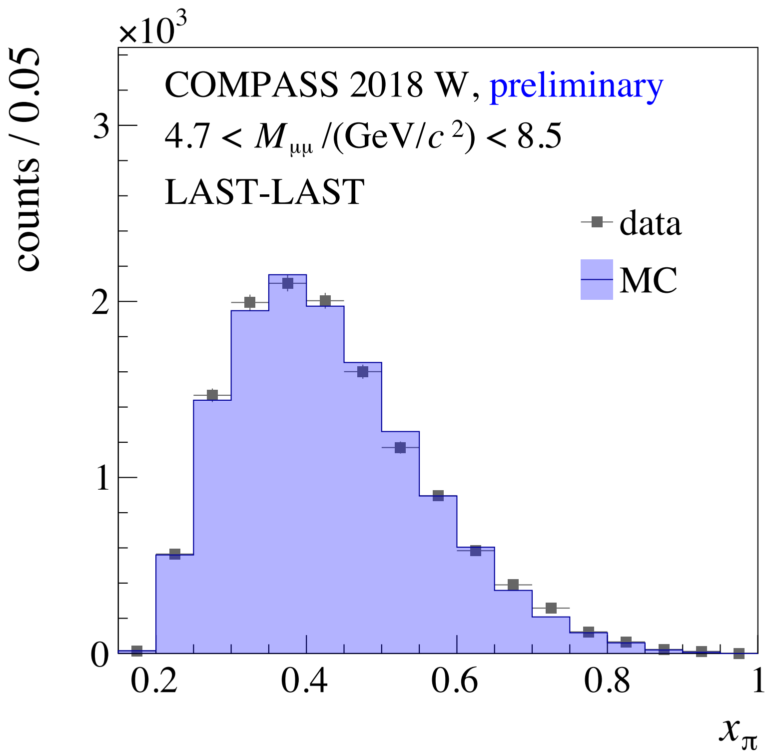
- Dimuons produced via **DY process** are mixed with muon pairs from **open-charm**, J/ψ, ψ' channels and **combinatorial background**.
- **96% purity of DY** in the selected mass region is concluded based on MC studies.

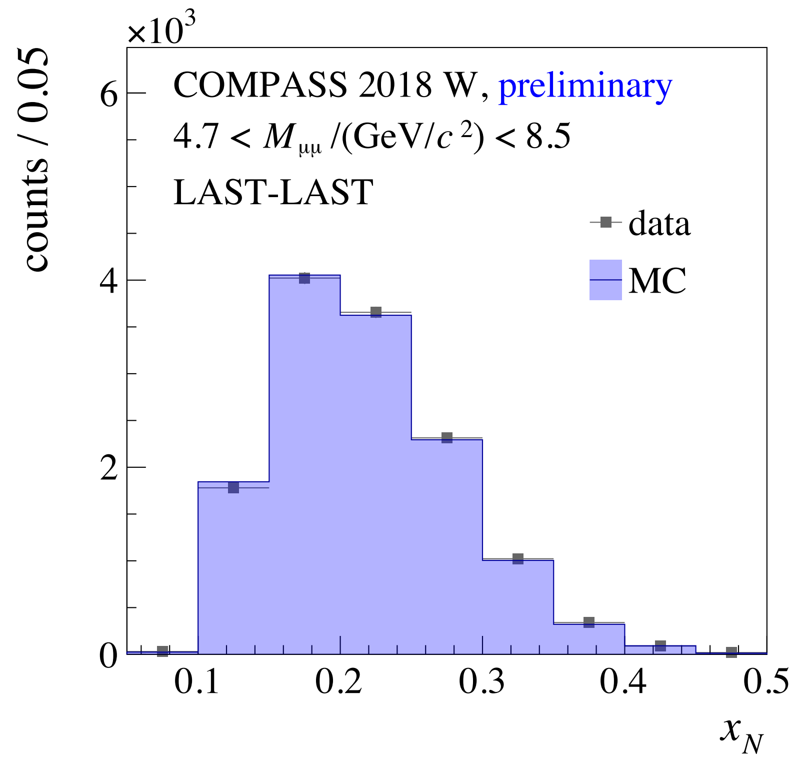
Verify MC Simulation







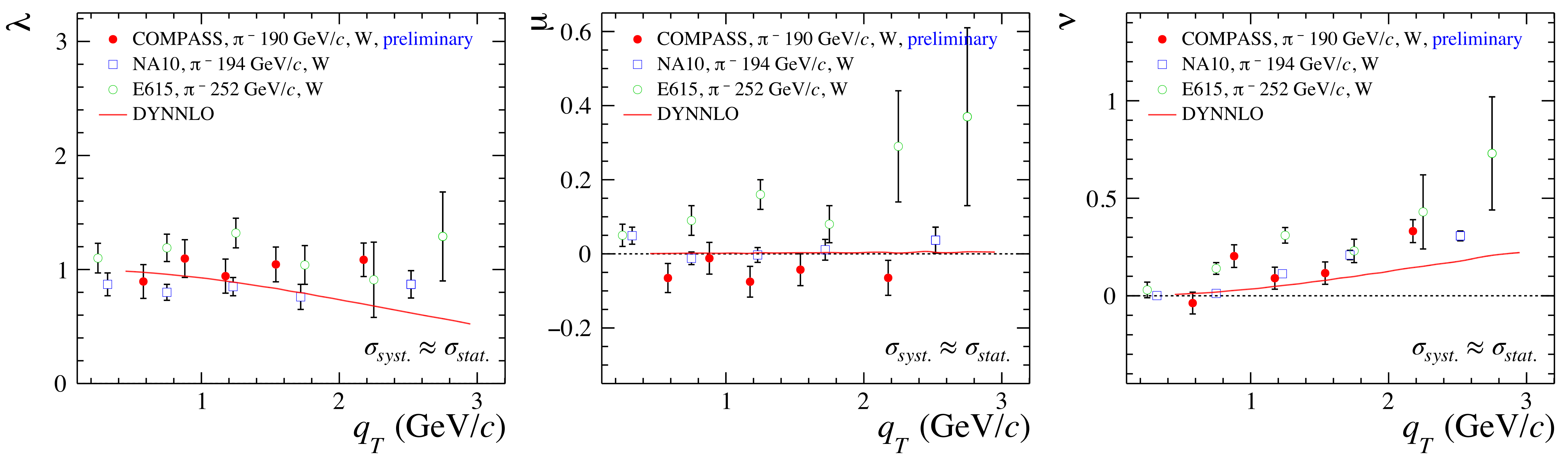




- Good data/MC agreement is achieved for all key kinematic distributions!

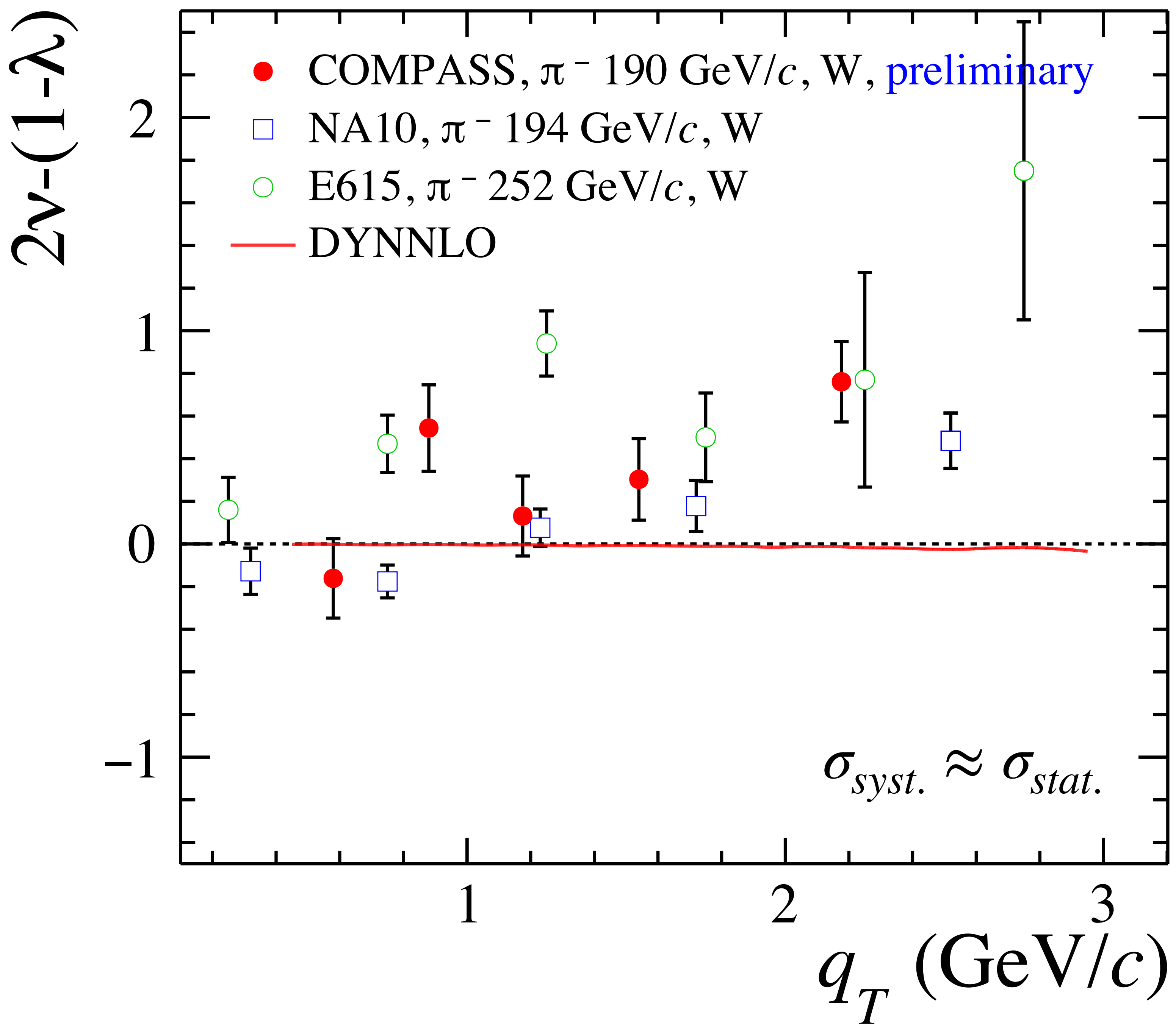
Unpolarized Asymmetries

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



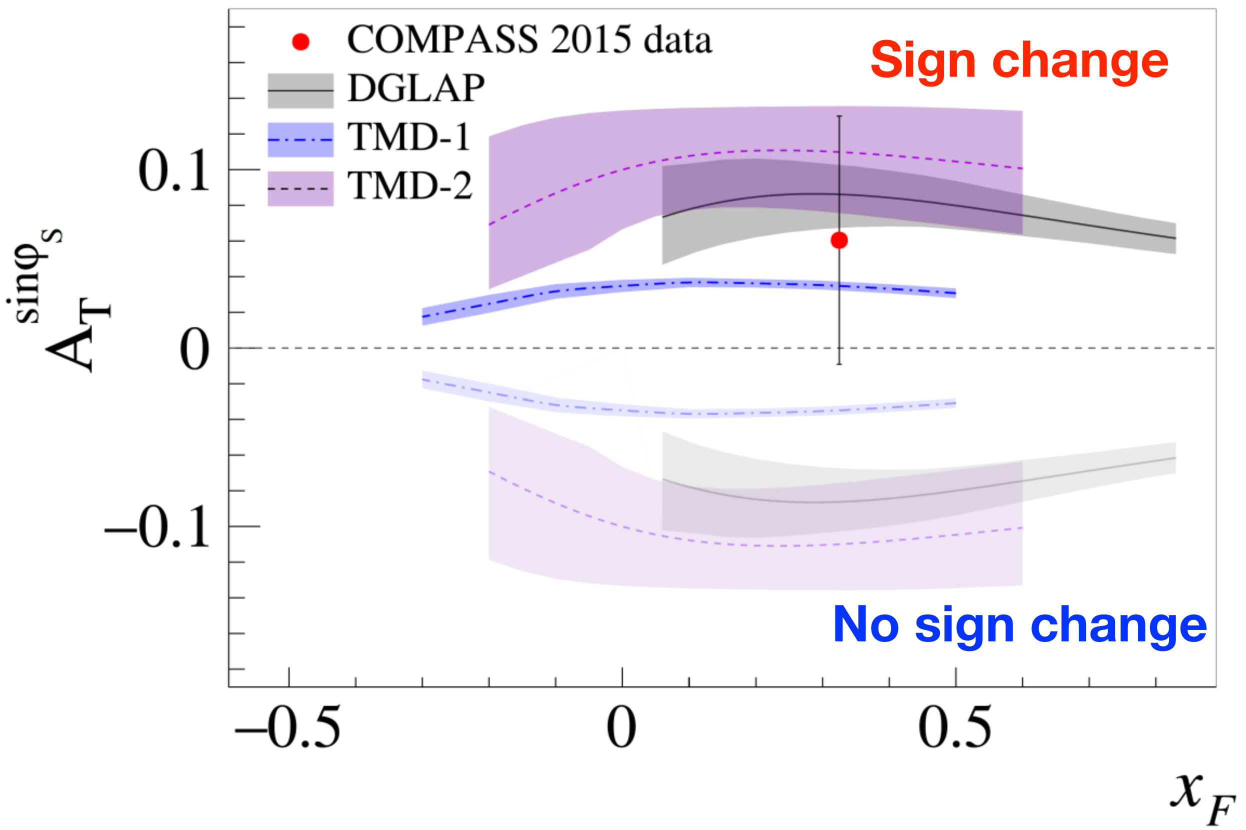
- Preliminary COMPASS results for ν tend to deviate from pQCD calculation at large q_T. An indication for a presence of a non-zero TMD Boer-Mulders effect.
- Preliminary results are based on ~70% of COMPASS tungsten data collected in 2018.

Result of Lam-Tung Violation



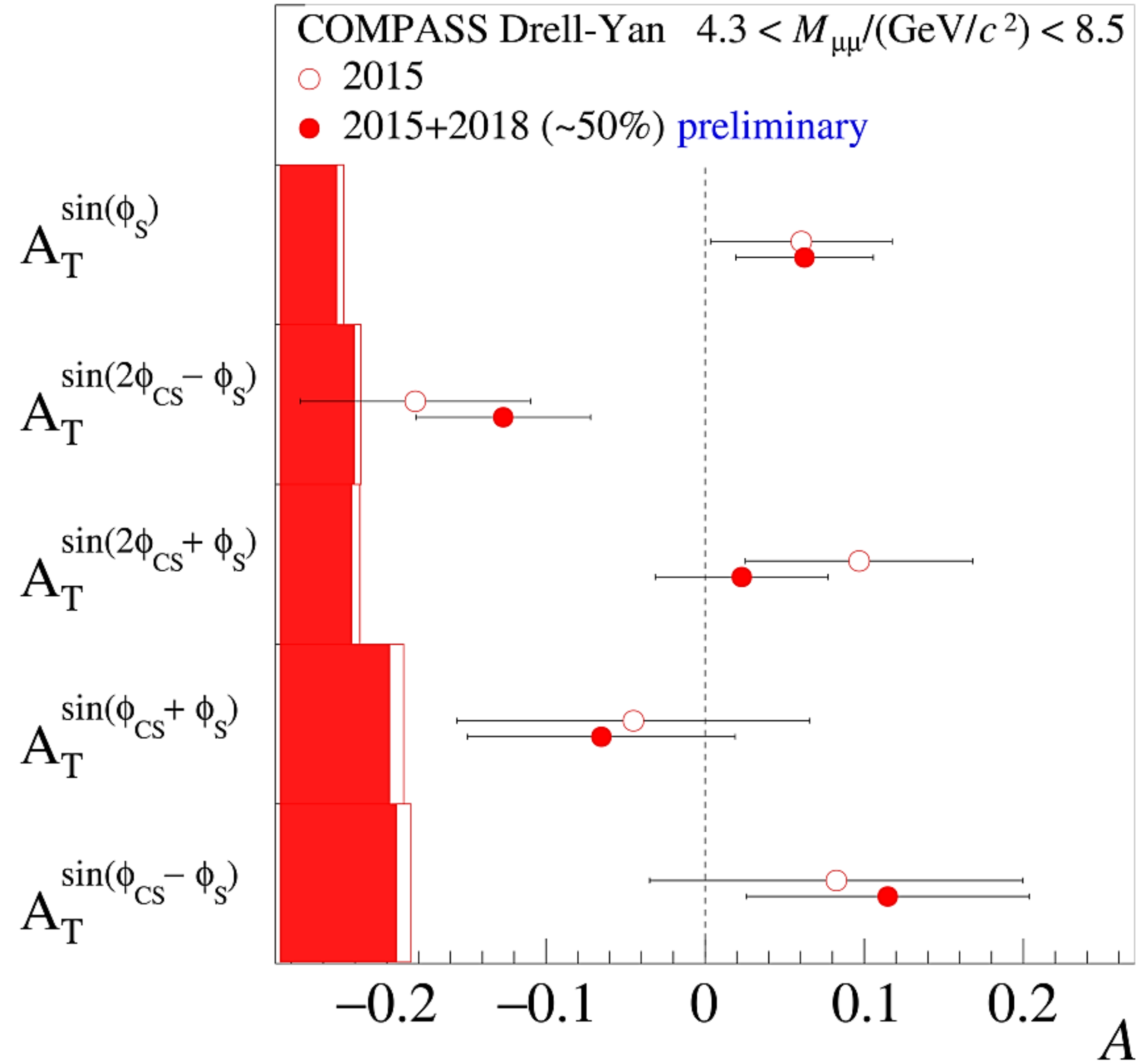
- COMPASS preliminary results indicate possible violation of the Lam-Tung relation.
- Consistent with results obtained by past pion-induced DY experiments.

COMPASS, PRL 119 (2017) 112002



$$A_T^{\sin\varphi_s} = 0.060 \pm 0.057(stat.) \pm 0.040(sys.)$$

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.

Summary and Outlook

- 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

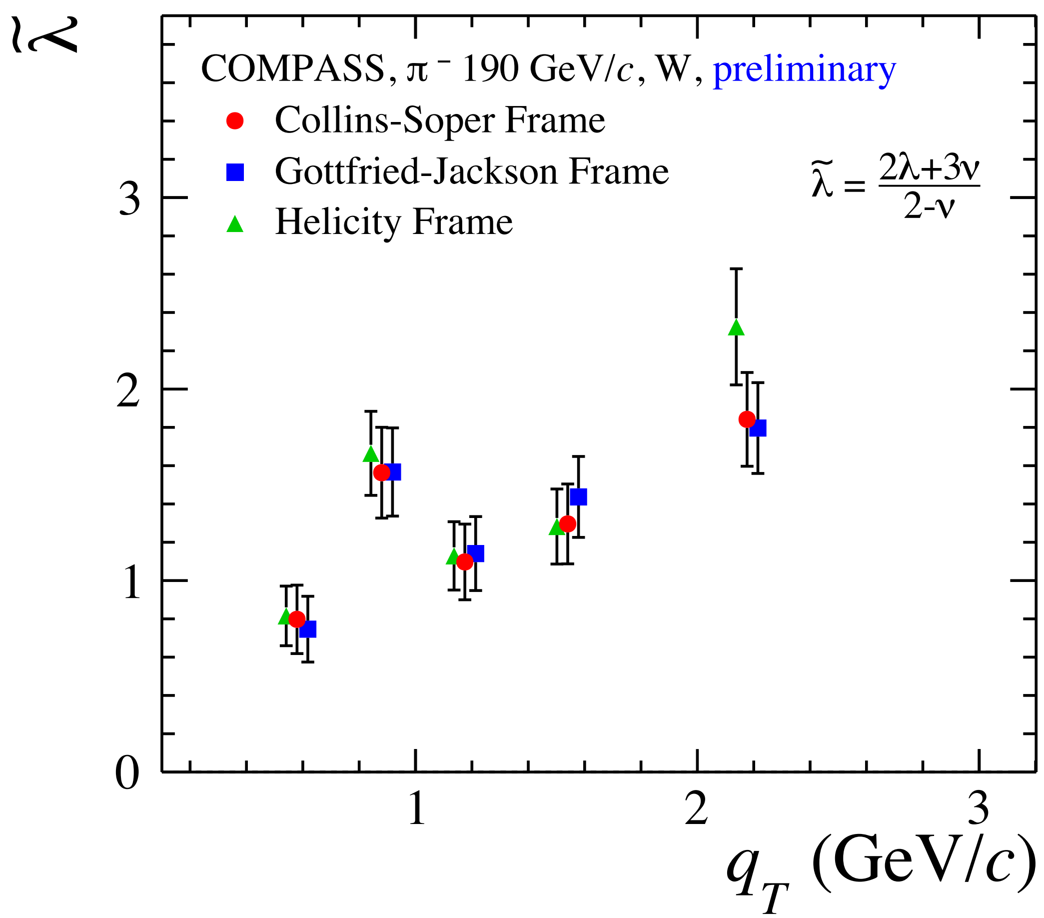
Rotational Invariant Quantities

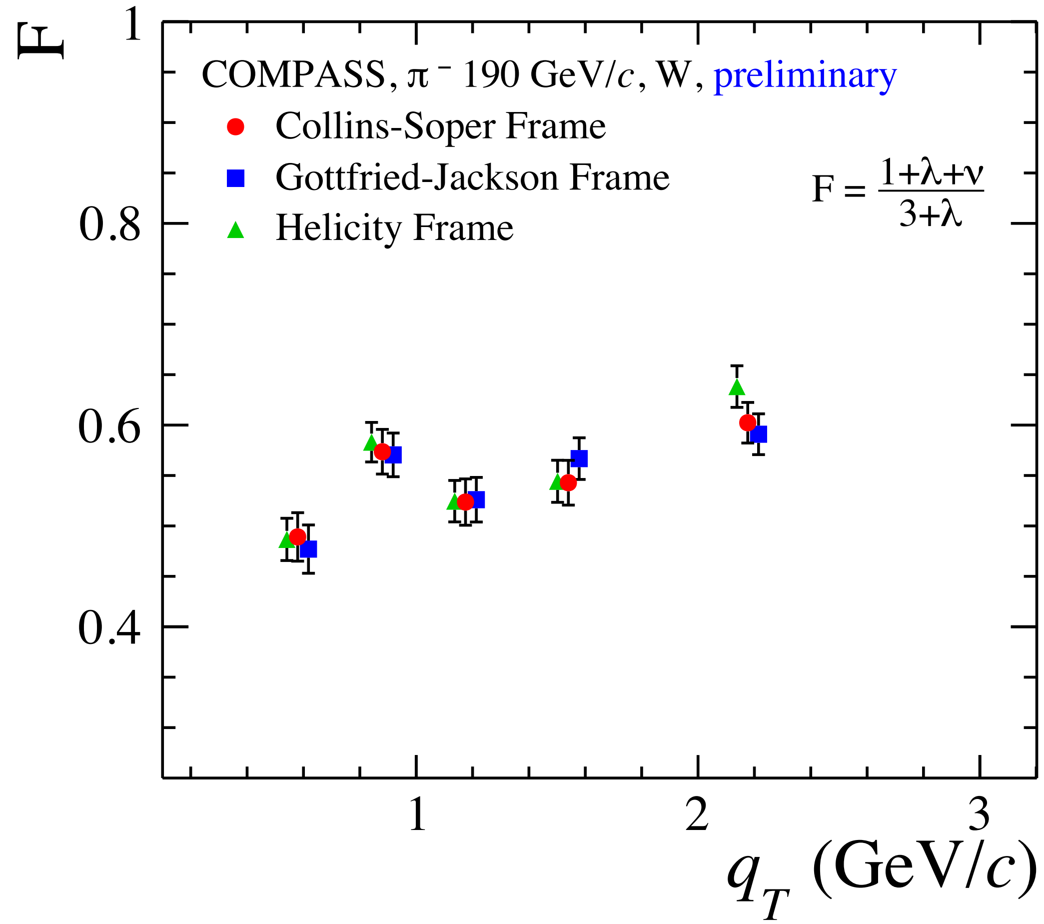
P. Faccioli, C. Lourenco, J. Seixas, H. Wohri, Phys. Rev. D 83 (2011) 056008.

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

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

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





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