Systematic Study of Dimuon Azimuthal Angle Reconstruction in SpinQuest

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Sivers Asymmetry in SpinQuest Drell-Yan

- The Sivers asymmetry arises from a correlation between the intrinsic transverse momentum $\vec{\boldsymbol{k}}_{\boldsymbol{T}}$ of the parton, and the spin $\vec{\boldsymbol{S}}$ and momentum $\vec{\boldsymbol{p}}$ of the parent nucleon.

$$\vec{\boldsymbol{S}} \cdot \left(\vec{\boldsymbol{k}}_{\boldsymbol{T}} \times \vec{\boldsymbol{p}}\right)$$

- $\vec{\boldsymbol{k}}_{\boldsymbol{T}}$ can't be measured directly but the virtual photon transverse momentum $\vec{\boldsymbol{q}}_{\boldsymbol{T}} = \vec{\boldsymbol{k}}_{\boldsymbol{T}}^{\boldsymbol{q}} + \vec{\boldsymbol{k}}_{\boldsymbol{T}}^{\bar{\boldsymbol{q}}}$ can be.
- If the spin is transverse to the beam direction, then:

$$\vec{\boldsymbol{S}}_{\perp} \cdot (\vec{\boldsymbol{q}}_{\boldsymbol{T}} \times \vec{\boldsymbol{p}}) = \left(\vec{\boldsymbol{S}}_{\perp} \times \vec{\boldsymbol{q}}_{\boldsymbol{T}}\right) \cdot \vec{\boldsymbol{p}} = \boldsymbol{S}_{\perp} \boldsymbol{q}_{\boldsymbol{T}} \boldsymbol{p} \, \boldsymbol{sin}(\boldsymbol{\phi}_{\boldsymbol{T}} - \boldsymbol{\phi}_{\boldsymbol{q}_{\boldsymbol{T}}})$$

- If the $\vec{k}_T^{\bar{q}}$ of the anti-quark in the polarized target proton is correlated to the spin, then it will create the azimuthal **asymmetry**

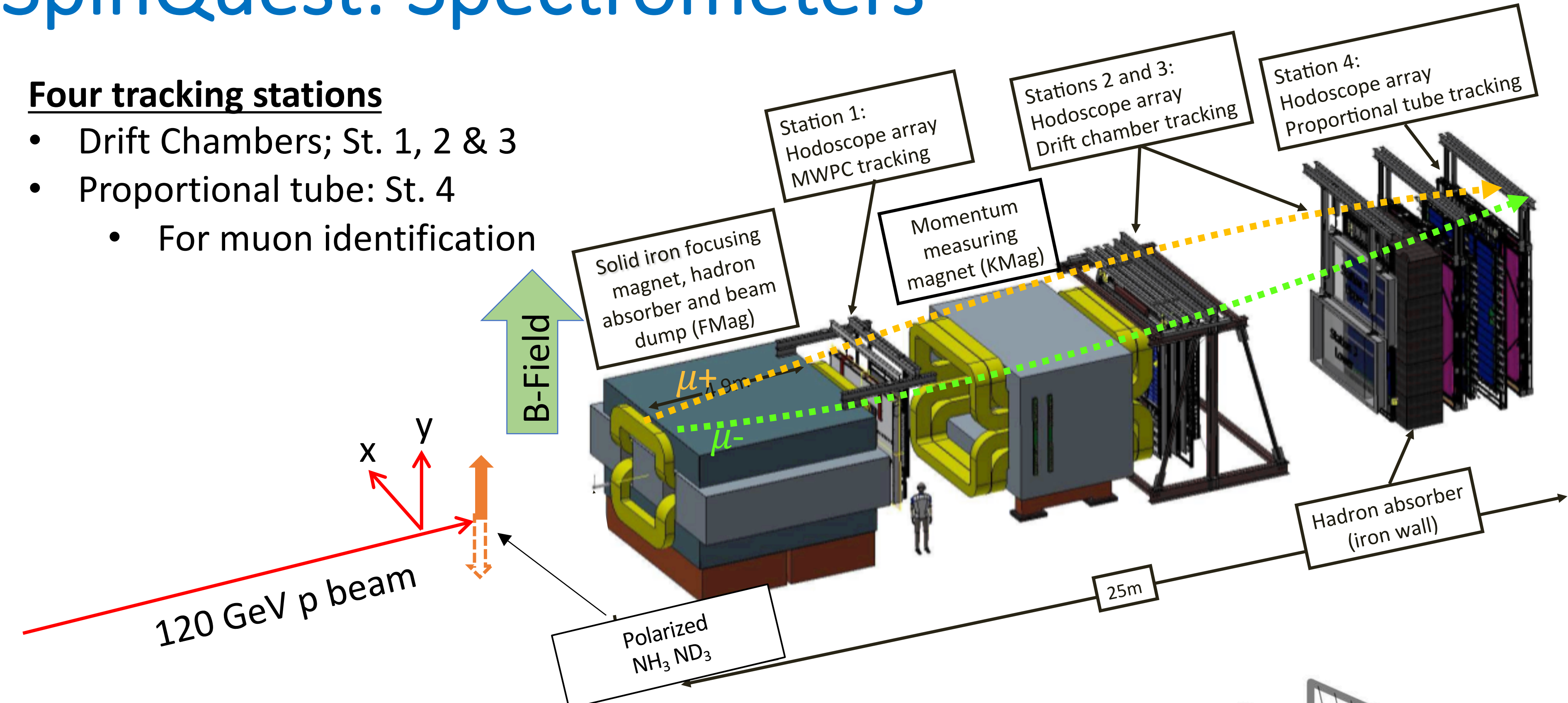
Thus, it is very important to reconstruct the ϕ_{q_T} distribution to extract the Sivers asymmetry

ϕ_{q_T} = Azimuth angle of $\vec{q}_T$ in detector rest frame
ϕ_T = Azimuth angle of target spin direction

More details in Forhad's talk

SpinQuest: Spectrometers

C.A. Aidala et al., Nu In, volume **930**, 49 (2019)

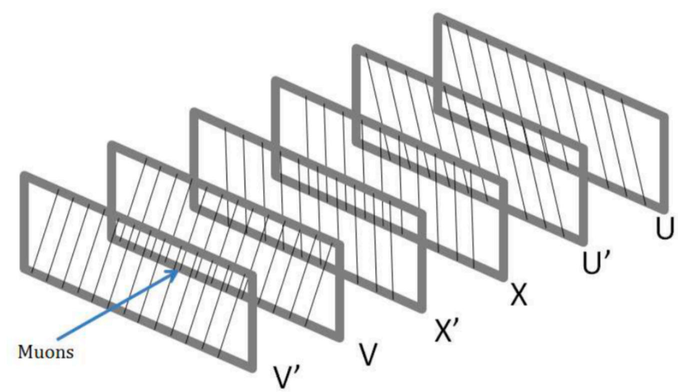


Four tracking stations

- Drift Chambers; St. 1, 2 & 3
- Proportional tube: St. 4
  - For muon identification

Drift Chambers

- x-, y- positions of muon track
- Principle: Ionization Chamber
- 6 planes of wires in each station



Rough structure of Drift Chamber

Reconstructing Azimuthal Asymmetry

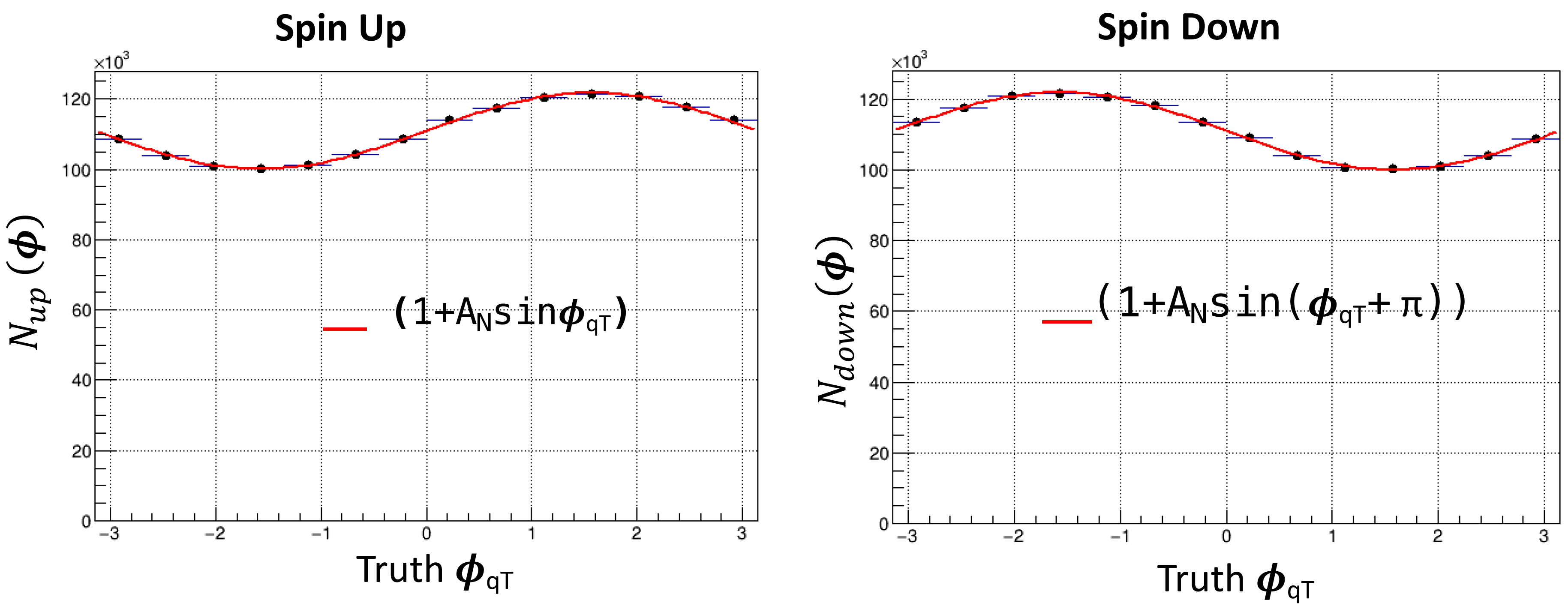
Precise extraction of the Sivers asymmetry largely depends on how well the azimuthal angle, $\boldsymbol{\phi}_{qT}$, of the dimuon can be reconstructed

Strategy

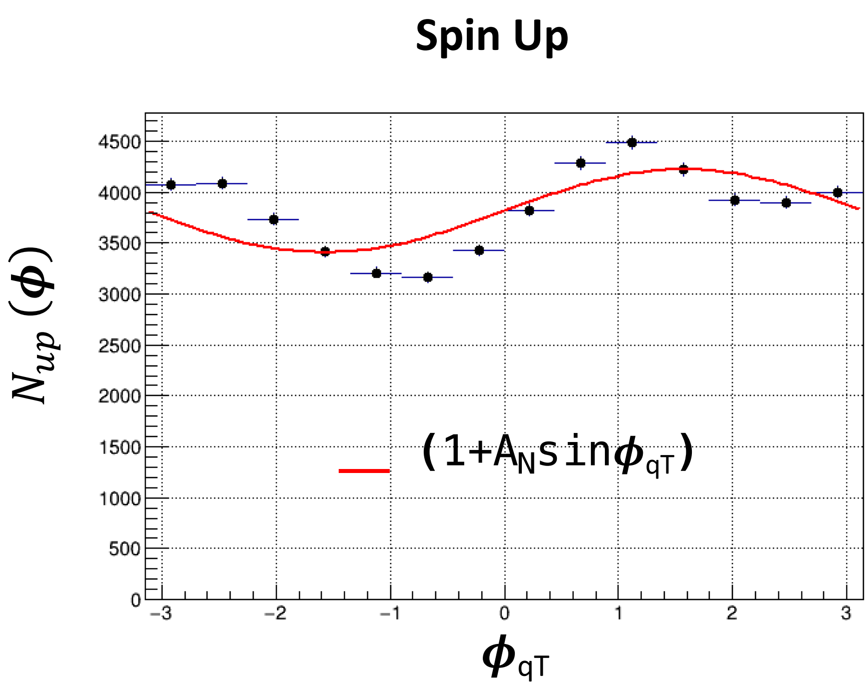
- Generate known asymmetry (spin up and spin down) in dimuon azimuthal distribution in the truth level
- Reconstruct dimuon azimuthal distribution after full detector simulation
- Unfold the measured azimuthal distribution
  - Response matrix with separate set of unpolarized MC simulation.
- Use ratio method for extracting the asymmetry from unfolded dimuon azimuthal distribution

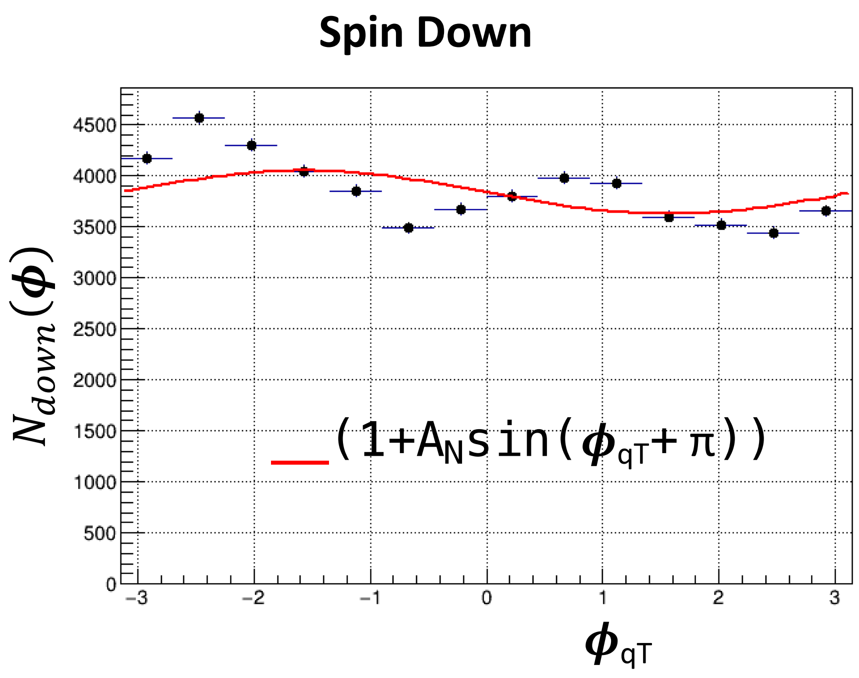
Generated Asymmetry

- Introduced asymmetry of $\boldsymbol{A_N}$ **= 0.1** in the azimuthal distribution of dimuon at generator level
- Spin Up set: azimuthal distribution of $[1+A_N*\sin(\phi_{qT})]$
- Spin Down set: azimuthal distribution of $[1+A_N*\sin(\phi_{qT}+\pi)]$



Reconstructed Azimuthal Distribution



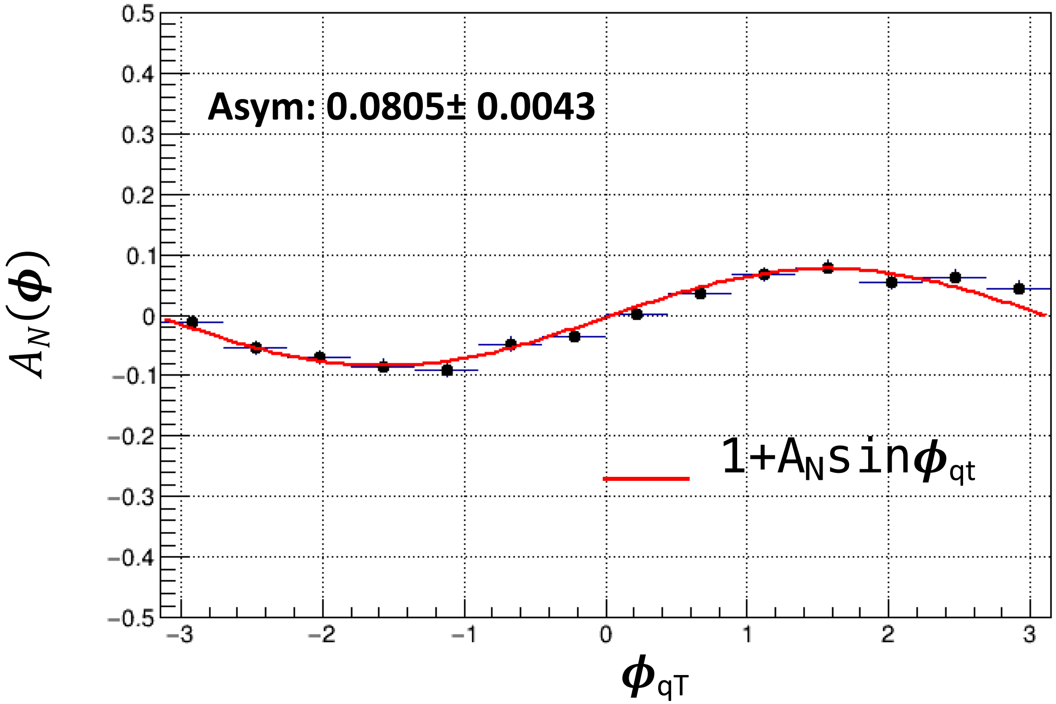


- Azimuthal distribution is distorted by detector acceptance (which has an approximately cos2ϕ_{qT} shape) and by smearing in reconstruction

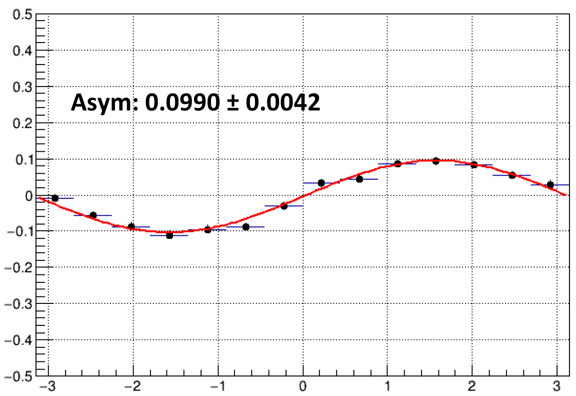
Reconstructed Phi (ϕ_{qT}) Asymmetry

$$A_N(\phi) = \frac{N_{up}(\phi) - N_{down}(\phi)}{N_{up}(\phi) + N_{down}(\phi)}$$

Measured



Truth



- Ratio method cancel out the various effects including acceptance, but the smearing doesn't.
- Magnitude of extracted asymmetry is lower than the generated one.
- We will unfold the smearing effects to restore the original asymmetry

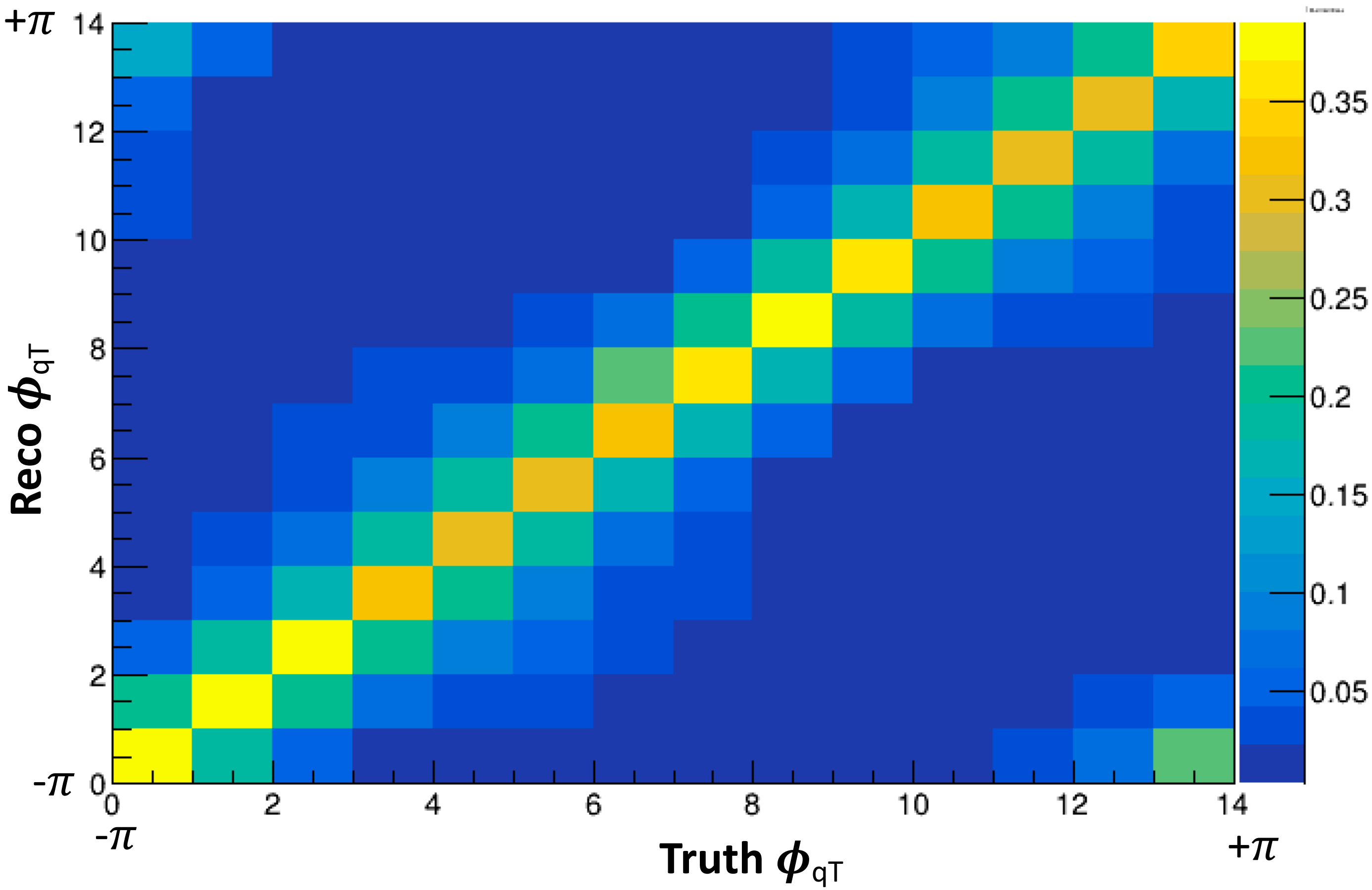
Unfolding Method

- Method to remove the known effects of systematic biases, measurement resolution to determine the "true" distribution
- **Response Matrix (R):** Maps the "true" distribution on to the measured one
  - For 1-D case, $R_{ij} = p(r \in (\Delta r)_i | t \in (\Delta t)_j)$;the conditional probability that a selected event, generated in a bin *i*, is reconstructed in a bin *j*.
  - **M = RT + β** (Matrix form, **β** background), **M**: Measured and **T**: Truth vector
  - The response matrix is usually determined using Monte Carlo simulation (*training*), with the true values coming from the generator output.
- The unfolding procedure reconstructs the true ***T*** distribution from the measured ***M*** distribution using the Response matrix **R**

$$\mathbf{T = R^{-1}M}$$

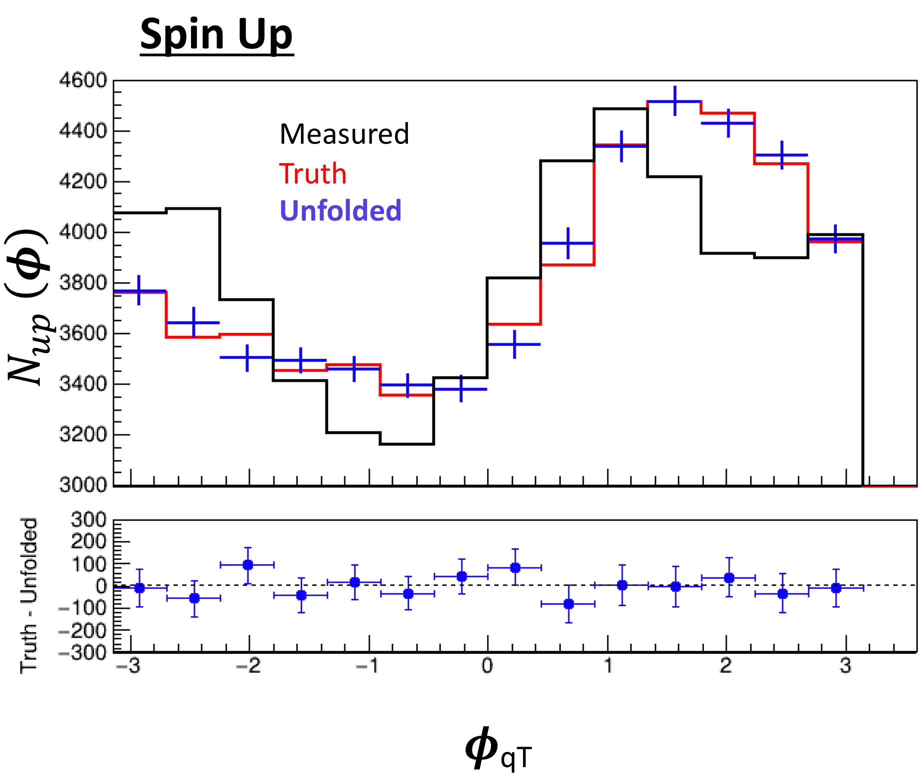
Response Matrix

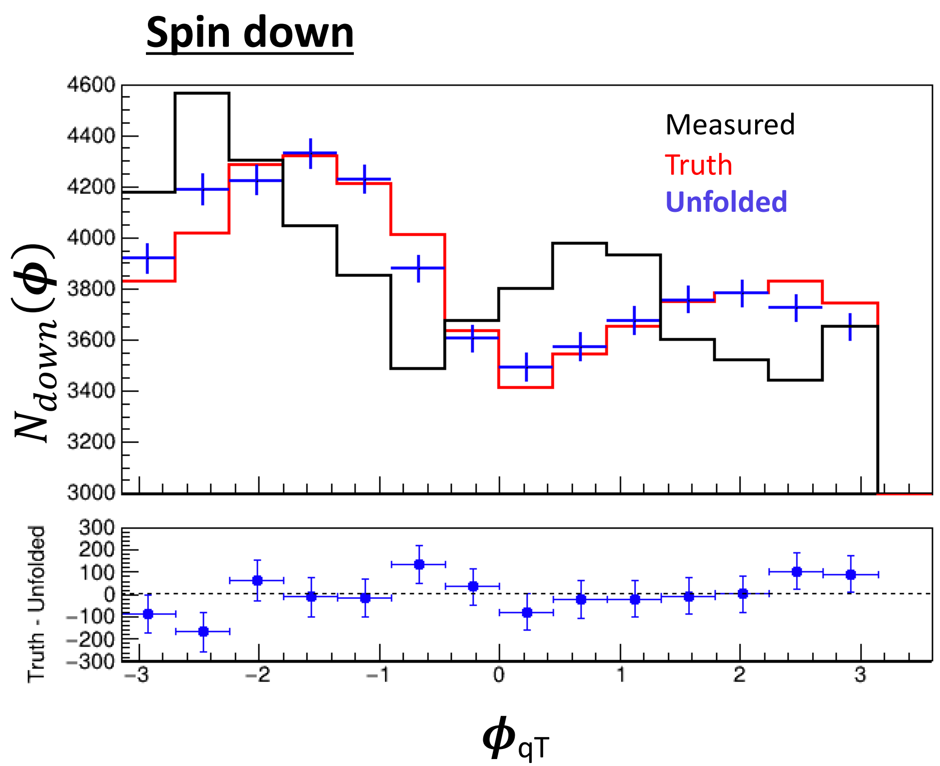
$R_{ij} = p(r \in (\Delta r)_i | t \in (\Delta t)_j)$;the conditional probability that a selected event, generated in a bin i, is reconstructed in a bin j.



Separate MC runs without any asymmetry ~11M events

Dimuon Azimuthal Distribution

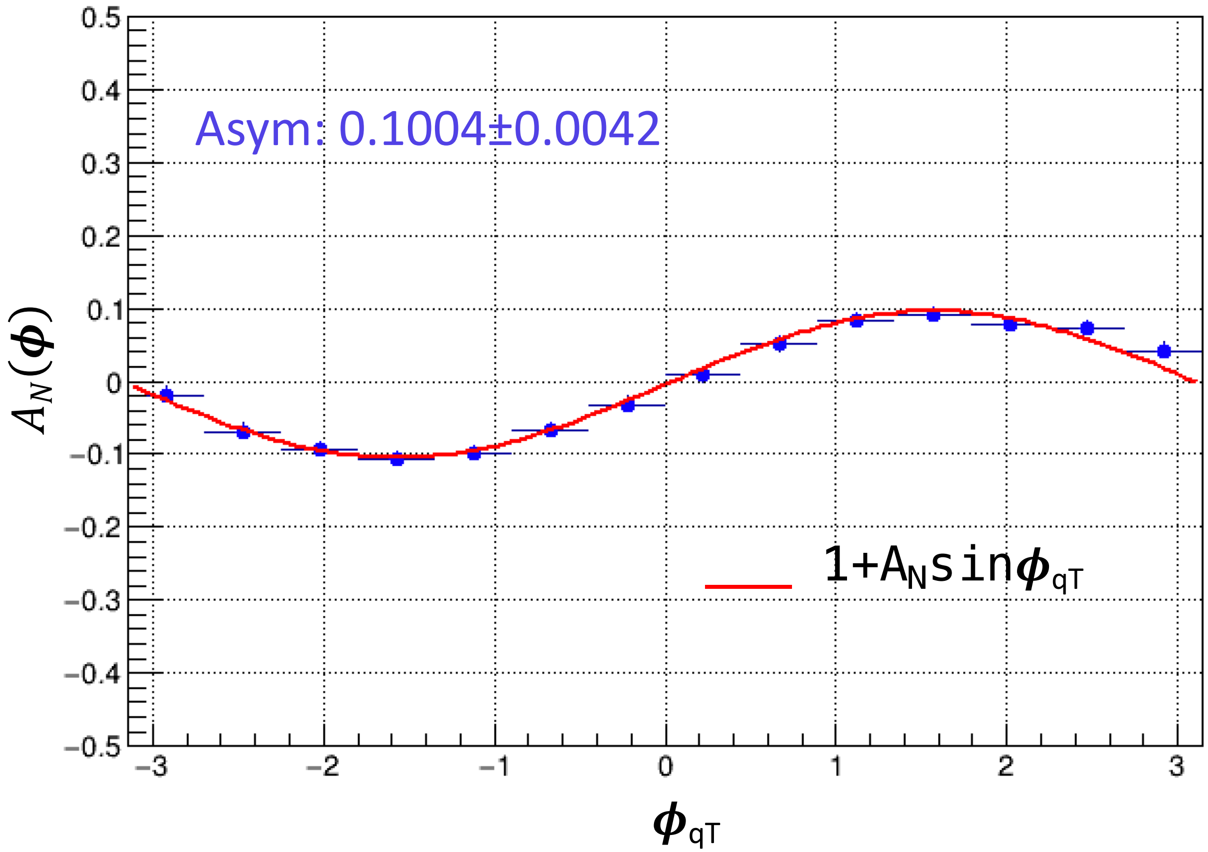




- **Iterative Bayesian** method of unfolding is used with **RooUnfold** software *arXiv:1105.1160*
- The unfolded distribution agrees with the truth distribution within the statistical uncertainties

Unfolded Asymmetry

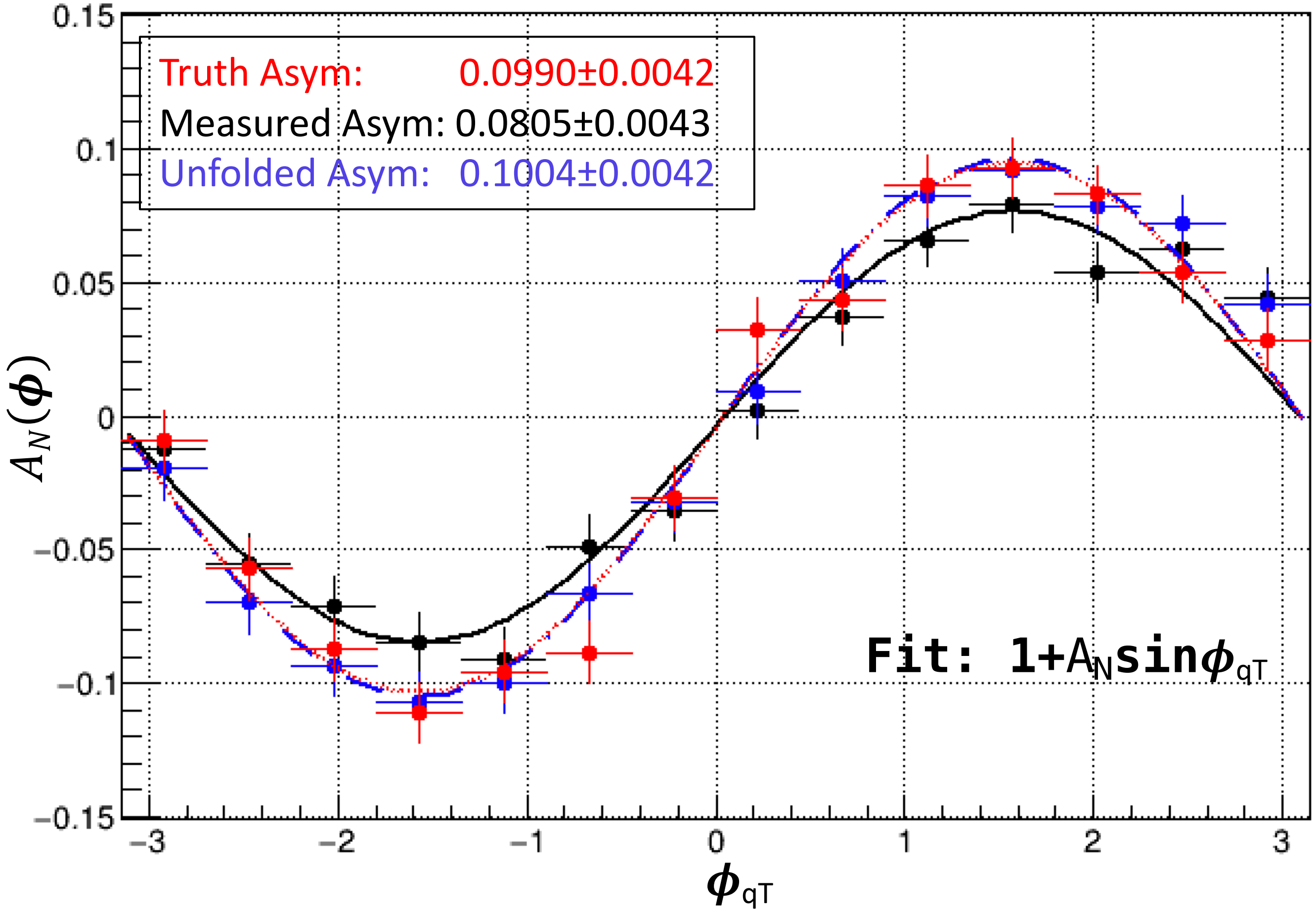
$$A_N(\boldsymbol{\phi}) = \frac{N_{up}(\boldsymbol{\phi}) - N_{down}(\boldsymbol{\phi})}{N_{up}(\boldsymbol{\phi}) + N_{down}(\boldsymbol{\phi})}$$



Original asymmetry restored from unfolded distribution

Asymmetry

$$A_N(\boldsymbol{\phi}) = \frac{N_{up}\,(\boldsymbol{\phi}) - N_{down}(\boldsymbol{\phi})}{N_{up}\,(\boldsymbol{\phi}) + N_{down}(\boldsymbol{\phi})}$$



Summary and Outlook

- Systematic study of dimuon azimuthal angle ($\boldsymbol{\phi}_{qT}$) reconstruction
- Iterative Bayesian method with RooUnfold software is used for unfolding the measured azimuthal distribution
- Asymmetries are calculated with ratio method using the measured, truth and unfolded azimuthal distribution

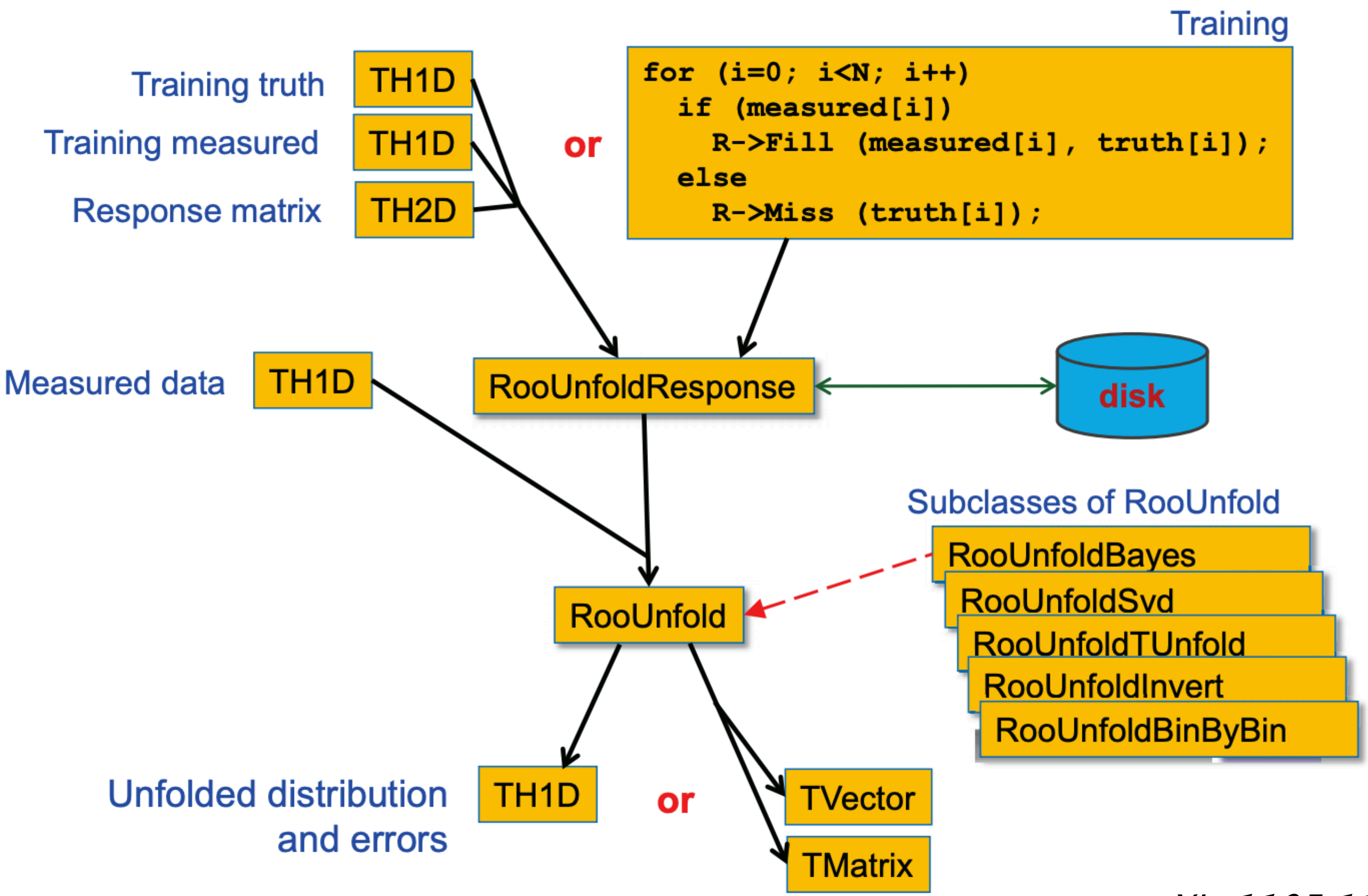
Azimuthal Distribution	**Asymmetry** $A_N(\phi) = \frac{N_{up}(\phi) - N_{down}(\phi)}{N_{up}(\phi) + N_{down}(\phi)}$
Truth (Generated MC)	0.0990 ± 0.0042
Measured	0.0805 ± 0.0043
Unfolded (Iterative Bayesian)	0.1004 ± 0.0042

- Unfolded azimuthal distribution using Iterative Bayesian method restored the generated truth
- **Work in Progress:**
  - Include systematic errors
  - Study other unfolding methods

RooUnfold

- Framework for unfolding using ROOT classes
- Methods available:
  - **Unregularized**
    1. matrix inversion (RooUnfoldInvert)
    2. using bin-by-bin correction factors, with no inter-bin migration (RooUnfoldBinbyBin)
  - **Regularized**
    1. Iterative Bayes method (RooUnfoldByes)
    2. Iterative, Dynamically Stabilized (IDS) unfolding (RooUnfoldIds)
    3. Singular Value Decomposition (SVD) method (RooUnfoldSVD)
    4. TUnfold (RooUnfoldTUnfold)

RooUnfold classes



arXiv:1105.1160

Forhad's slide

Sivers Effect in the Nucleon

Reasons for the Asymmetry

Phys. Rev. D **70**, 117504 (2004)
Phys. Rev. D **67**, 074010 (2003)

The number density of unpolarized quarks in a transversely polarized proton:

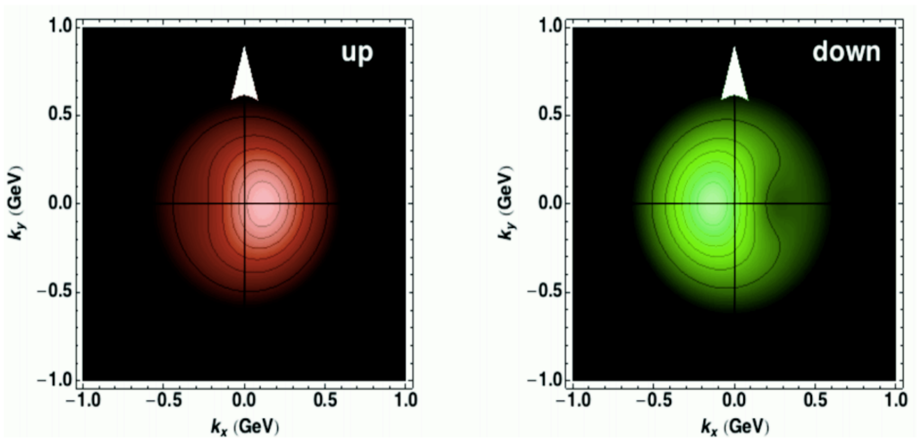
$$f_{q/p^{\uparrow}}(x_B, \vec{k}_T) = f_1^q(x_b, k_T^2) - f_{1T}^{\perp q}(x_B, k_T^2)\frac{(\hat{P} \times \vec{k}_T) \cdot \vec{S}}{m_p}$$

Gives correlation between $\vec{k}_T$ and $\vec{S}$

The $\vec{k}_T$ distribution of quarks in a transversely polarized proton can be **asymmetric** and known as "**Sivers effect**".

f_1^q = Unpolarized quark density.
$f_{1T}^{\perp q}(x_B, \vec{k}_T)$ = *Sivers function.*
$\vec{S}$ = Spin polarization vector.
$\vec{P}$ = Three momentum of the proton.
$\vec{k}_T$ = Intrinsic transverse momentum of unpolarized quarks.

Sivers Effect: Intrinsic k_T imbalance leads to the asymmetry



Source: A. Bacchetta et al. Il Nuovo Saggiatore

Forhad's slide

Sea-quark Sivers Asymmetry from Polarized Drell-Yan

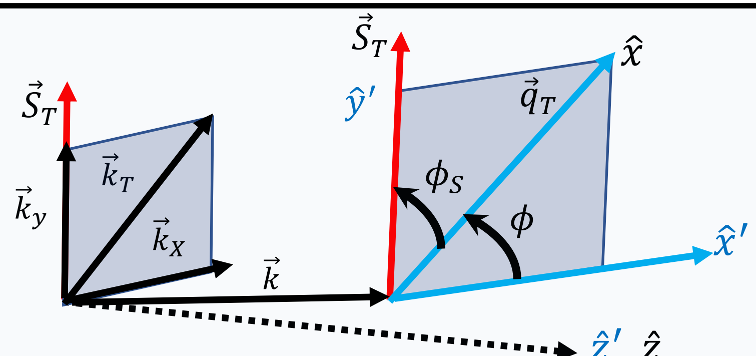
The Drell-Yan cross section in terms of Sivers asymmetry:

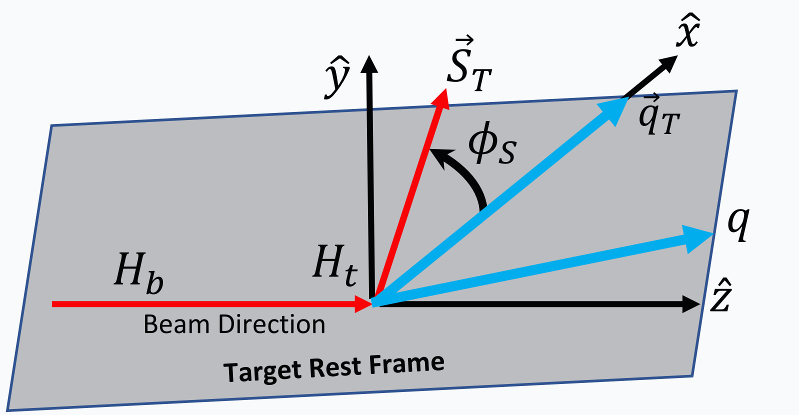
$$\sigma_{DY}^{\uparrow\downarrow} = \frac{d\,\sigma^{LO}}{d^4q\ \ d\phi_S} \propto 1 \pm |S_T|\ \ sin\,\phi_S\ \ A_T^{\sin\phi_S}$$

Phys. Rev. D 79, 034005 (2009),
PRL 119, 112002 (2017)

$$A(\phi_S) = \frac{1}{|S_T|}\ \frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}} = \ \sin\phi_S\ \ A_T^{\sin\phi_S}$$

$\vec{S}_T$= Target spin vector
$\hat{x}, \hat{y}, \hat{z},$ is target rest frame = TF; $\hat{x} = \hat{q}_T, \hat{y} = \hat{z}\times\hat{q}_T$
$\hat{x}', \hat{y}', \hat{z}'$ is detector rest frame = DF
$\vec{q}_T$= Dimuon's transverse momentum
$\vec{k}_T$= Quark's transverse momentum





1. $\sigma_{DY}^{\uparrow\downarrow}$ is the Drell-Yan cross section and $A_T^{\sin\phi_S}$ is the Sivers asymmetry .
2. Azimuthal angle ϕ_S in TF and ϕ in DF can be written as $\phi_S = \left(\frac{\pi}{2} - \phi\right)$.