Measurement of Angular Distributions of Drell-Yan Dimuons in p + p Interactions at 800 GeV/c

L.Y. Zhu et al., Physical Review Letters 102, 182001 (2009)

LIST OF CONTENTS

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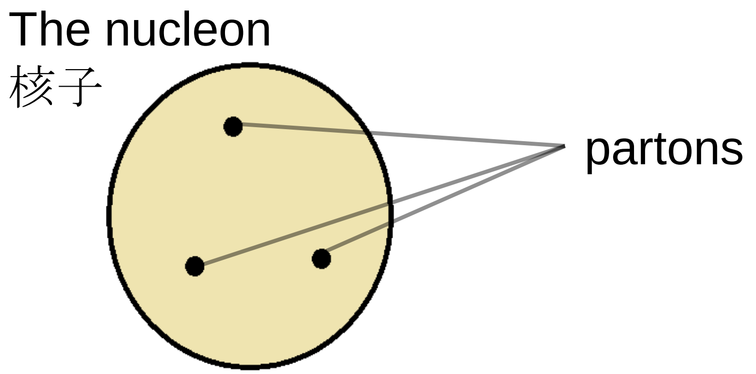
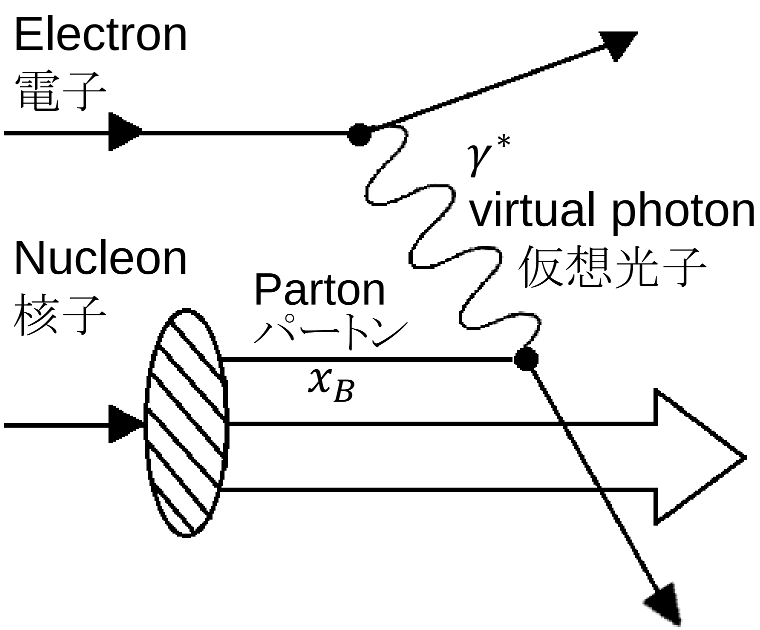
1. Purpose of Experiment

- The purpose of the experiment is to understand the **3-D structure of the nucleon** using parton distribution functions (PDFs).
- Partons are point-like particles in the nucleon.
- Parton distribution functions describe the momentum distribution of partons inside the nucleon.



2. Parton Distribution Functions (PDFs) and Drell-Yan Process

2.1 Parton Distribution Functions（パートン分布関数）



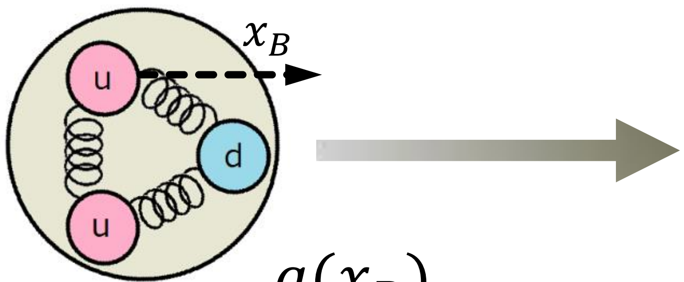
- Charged partons are identified with quarks today.
- Neutral partons are identified with gluons.

In a lepton-nucleon scattering,

- PDFs are denoted as $q(x_B)$, where x_B is the momentum fraction of the parton (0< x_B<1).
- $q(x_B)$ is the momentum distribution of the parton.
  ⇒describes the motion of a parton inside the nucleon.

2.2 Longitudinal Momentum Dependent PDFs and Transverse Momentum Dependent (TMD) PDFs (縦方向, 横方向運動量依存パートン分布関数)

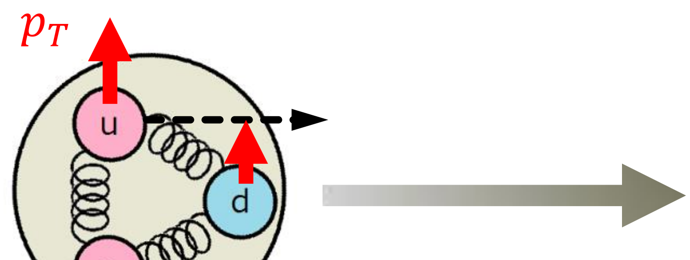
Original PDFs



$q(x_B)$

- In the scattering, only the momentum along the beam direction is considered.
- Longitudinal momentum dependent PDF

TMD PDFs



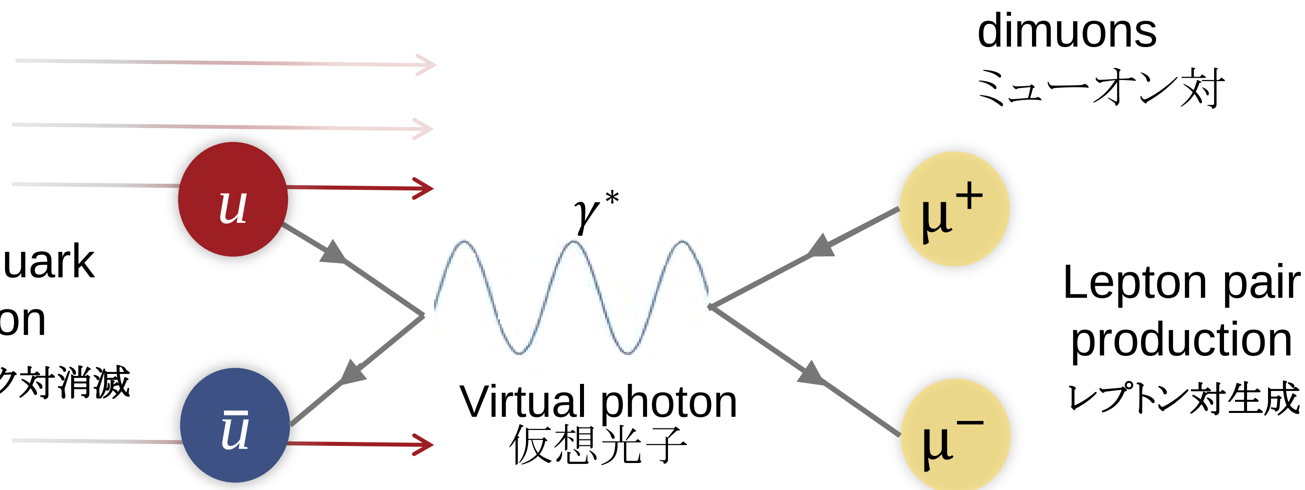
$q(x_B, \underline{\underline{p_T}})$

- But recent studies show the need to include the transverse momentum (90 degrees from beam direction).
- Expresses 3-D structure of the nucleon

2.3 Drell-Yan Process (ドレル・ヤン反応)

The partons (quarks) can be studied through the Drell-Yan process.

Quark-antiquark Annihilation
クォーク・反クォーク対消滅



The process gives complete kinematic information of the quark and antiquark.

For example, transverse momentum of muon pairs is equal to transverse momentum of quark-antiquark pair.

$$p_{T\,quark} + p_{T\,antiquark} = p_{T\mu+} + p_{T\mu-}$$

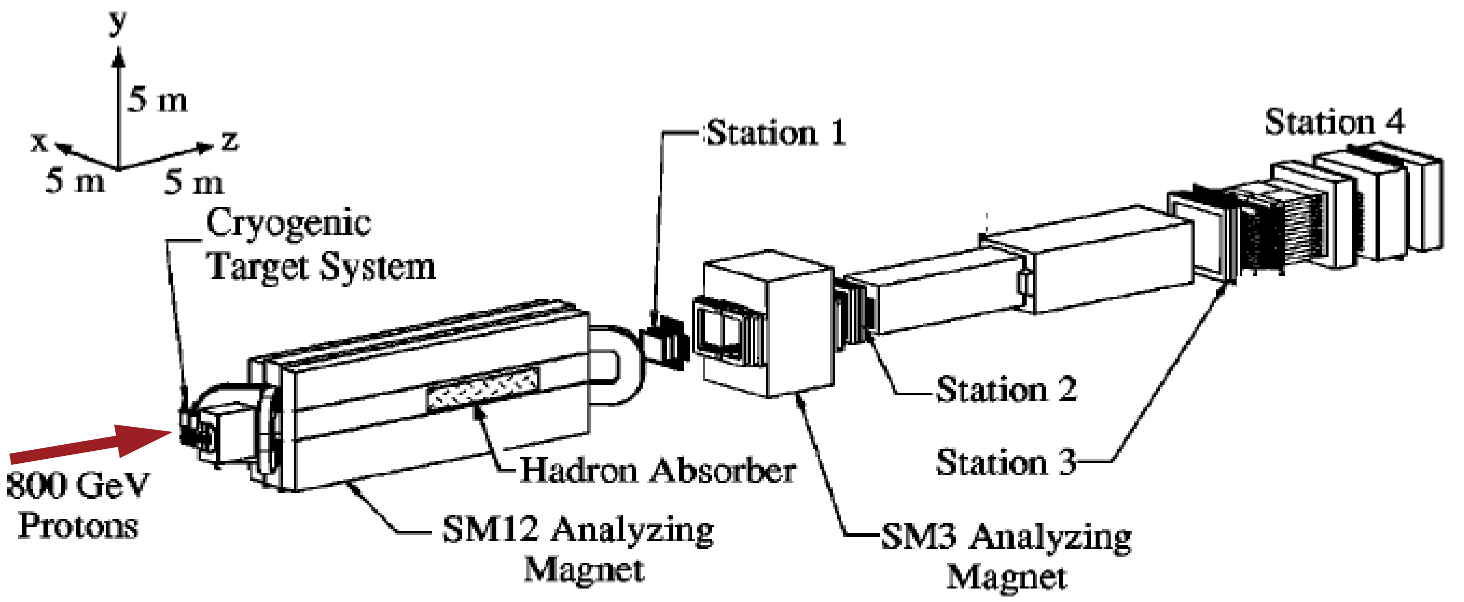
3. The Experiment

3.1 E866/NuSea Experiment

- Fermi National Accelerator Laboratory (FNAL) in USA in 2007 using the Tevatron accelerator
- 800 GeV/c proton beam was extracted to a fixed hydrogen target
- Drell-Yan process in p-p reaction was measured
- Transverse momentum and angular distribution were measured
- Used these measurements to extract TMD PDF

FNAL Tevatron and extracted beam

3.2 The Spectrometer



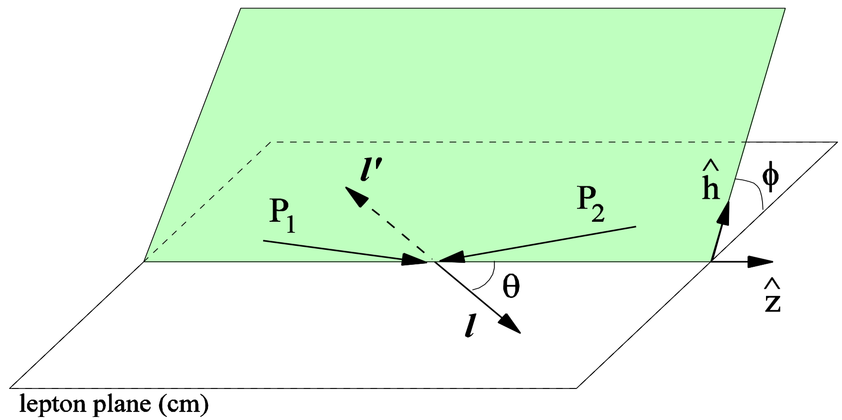
- SM12: select a particular range of the dimuon mass
- SM3: determine momenta of muons
- Station 1 ~ Station 4: track the dimuons and measure the angular distribution

3.3 Angular Distribution (角度分布) in Drell-Yan Process

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\varphi + \frac{\nu}{2} \sin^2\theta \cos 2\varphi$$

Transverse momenta of partons cause these terms.

If no transverse momentum exists, then $\lambda = 1,\ \mu = \nu = 0$



For example, in an e^+e^- collider,

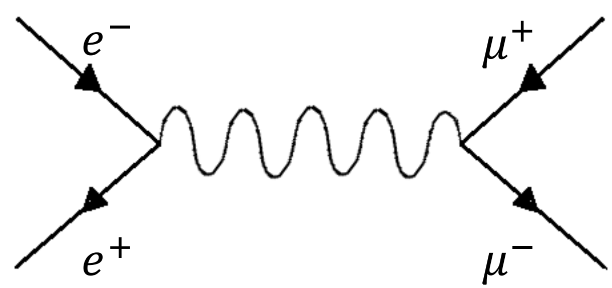
$$e^+e^- \to \gamma^* \to \mu^-\mu^+$$

$$\frac{d\sigma}{d\Omega} \propto 1 + \cos^2\theta$$

θ: Angle between e^- and μ^-

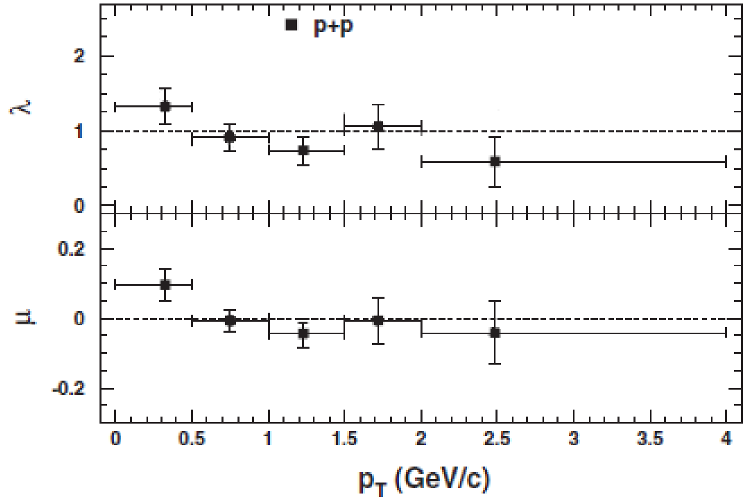
⇒No internal structure

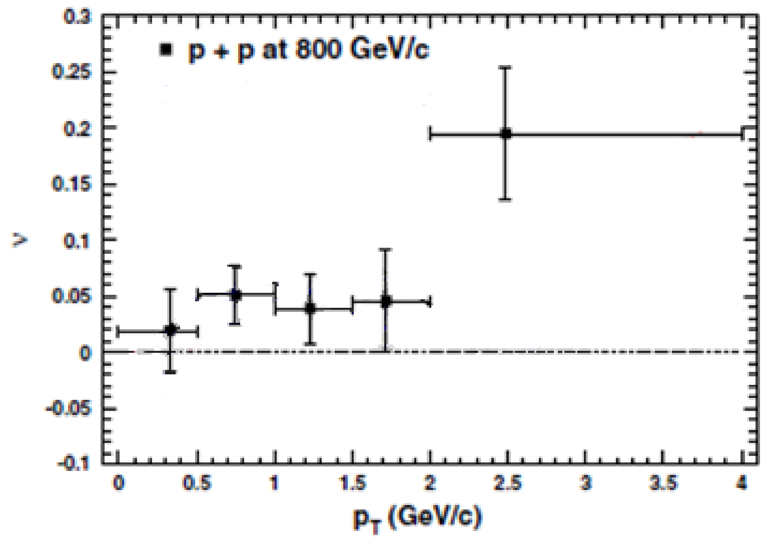
⇒No transverse momentum



4. RESULTS

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin2\theta \cos\varphi + \frac{\nu}{2} \sin^2\theta \cos2\varphi$$



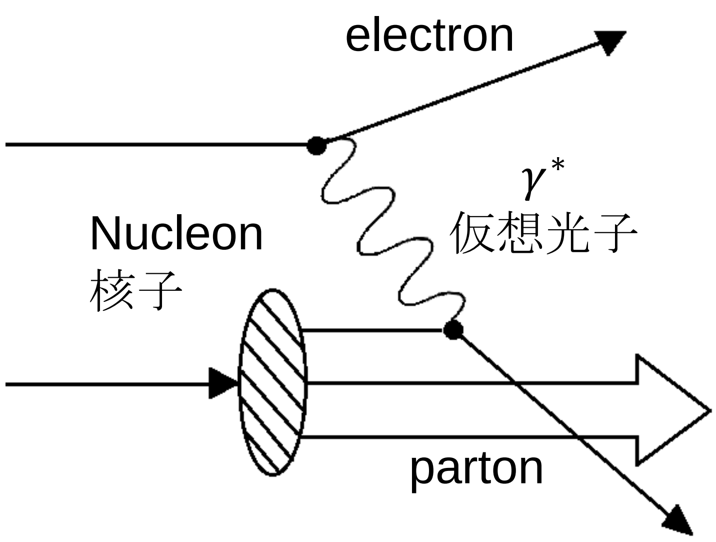


- λ is around 1
- μ is almost zero except for the first point
- Non-zero ν was observed. This is the effect of non-zero transverse momentum.
- The result on ν is useful information for TMD PDF.
- However, higher order QCD effects need to be taken into account before TMD PDF is extracted.

5. SUMMARY

- Parton distribution functions show the structure of nucleons.
- Drell-Yan Process is a good method to study quarks and antiquarks in the nucleon.
- The purpose of E866/NuSea is to study the effects of transverse motion of partons.
- Protons of 800 GeV/c, from Tevatron was extracted from to the proton target.
- A non-zero ν parameter was observed. This is the effect of non-zero transverse momentum.
- In order to extract transverse momentum dependent (TMD) PDF, higher order QCD effects need to be evaluated theoretically.

APPENDIX A: Parton Distribution Functions



Parton distribution functions (PDFs) show the probability of finding a parton with a certain momentum

$$q(x_B)$$

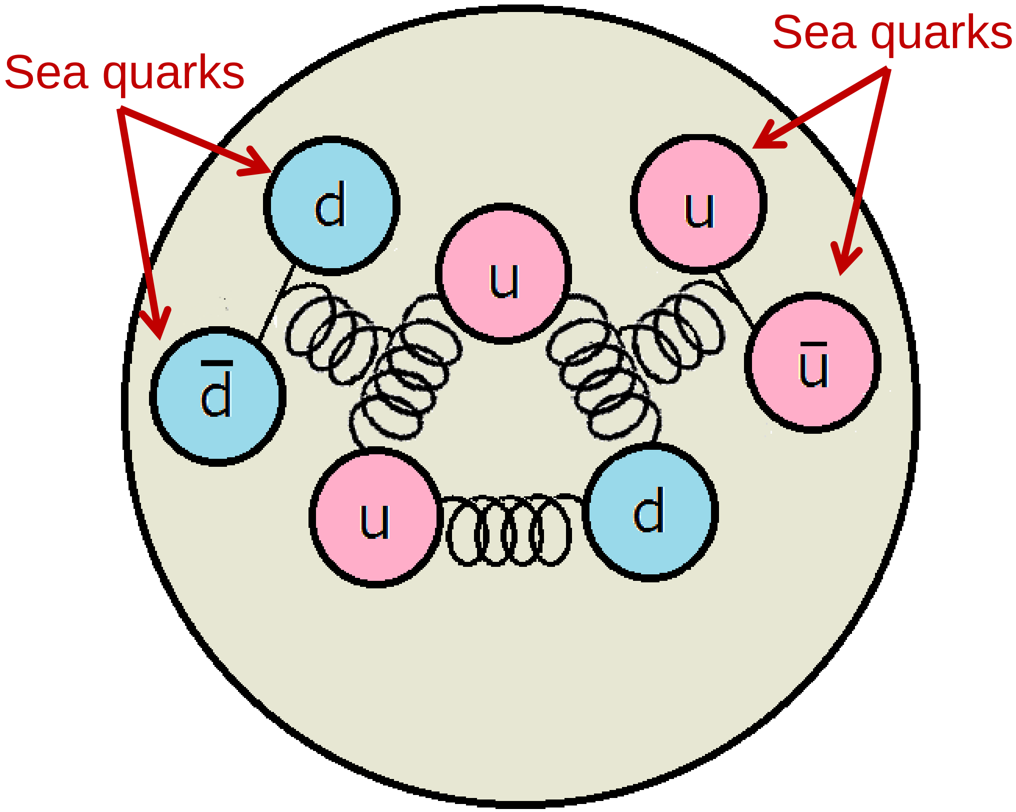
The momentum is shown using Bjorken-x (x_B)

Bjorken-x is:

$$x_B = \frac{\boldsymbol{momentum\ of\ parton}}{\boldsymbol{momentum\ of\ nucleon}}$$

So for example, in a proton, PDF of up quark has a peak around $x_B = {}^{1}/_{3}$

APPENDIX B: Sea Quarks



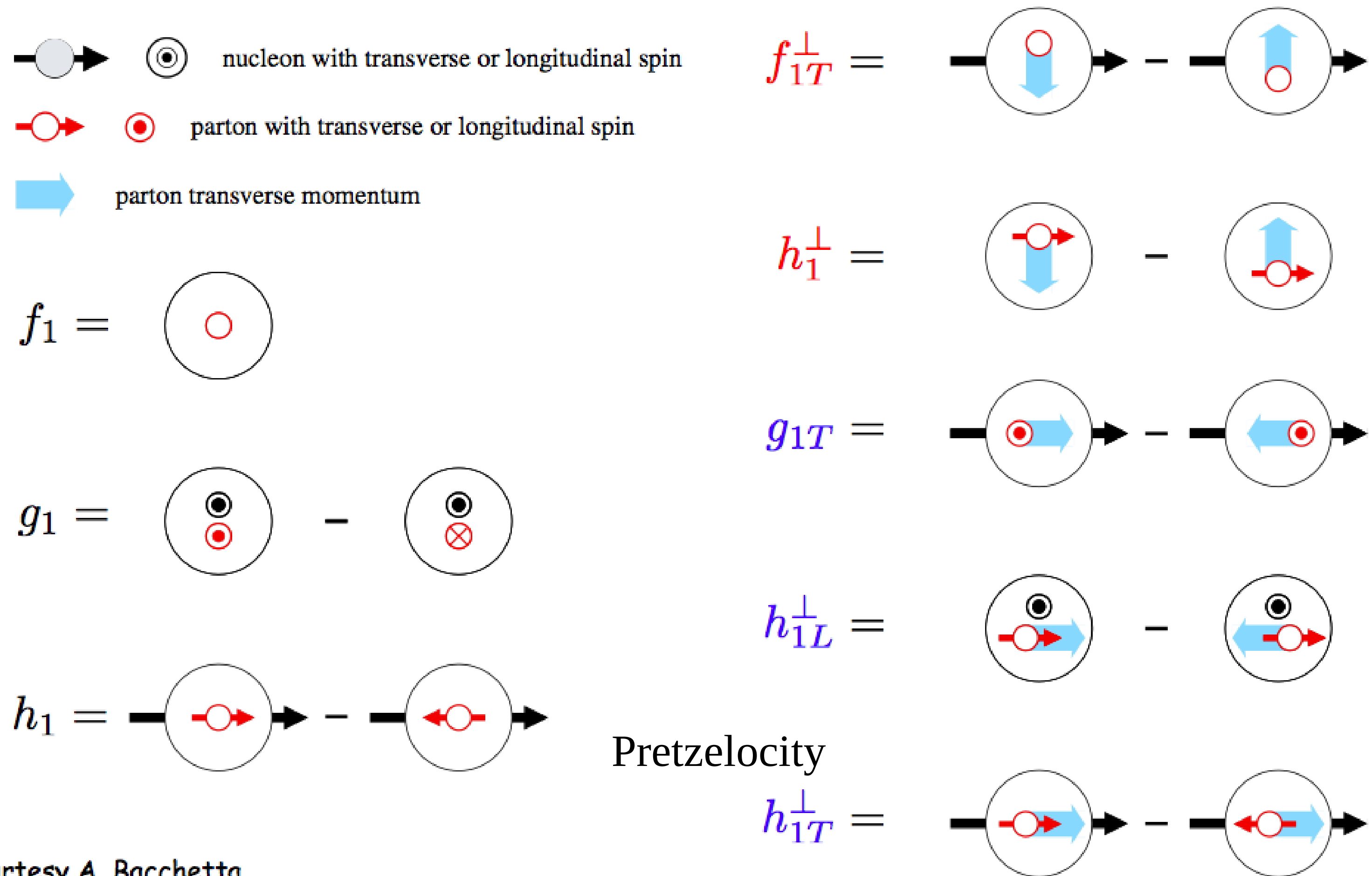
Gluons separate into a quark-antiquark pair.

These are called sea quarks.

In the Drell-Yan Process, the antiquark comes from the sea quark.

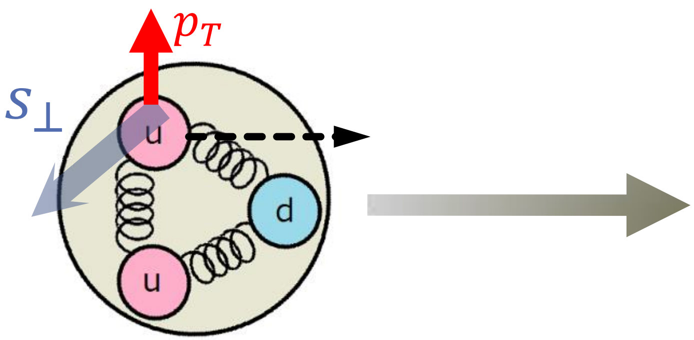
APPENDIX C: TMD PDFs

Proton goes out of the screen/ photon goes into the screen



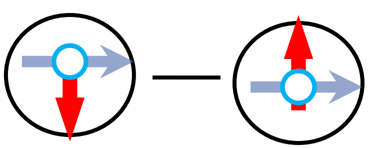
courtesy A. Bacchetta

APPENDIX D: Boer-Mulders Functions

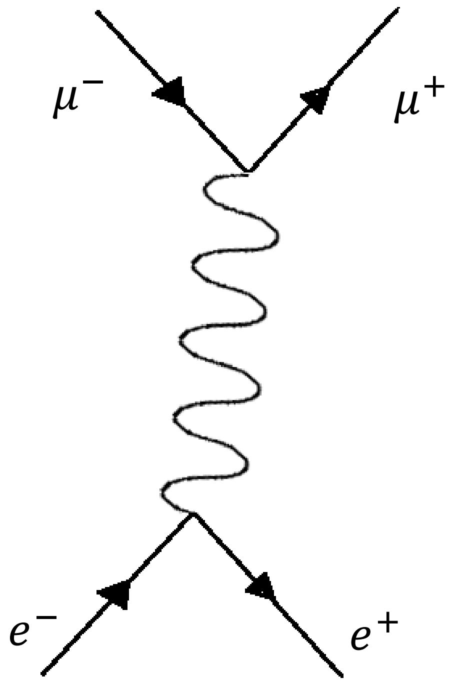


$$h_1^{\perp}(x_B, p_T^{\,2})$$

- Shows the correlation between transverse momentum and transverse spin of
  - A polarized quark in an
  - Unpolarized nucleon
- Shows the likelihood of finding a parton in a certain spin direction

$h_1^{\perp}(x_B, p_T^{\,2}) =$ 

APPENDIX E: Electron-Positron Scattering



$$\frac{d\boldsymbol{\sigma}}{d\boldsymbol{\Omega}} = \frac{4\pi\alpha^2}{3s}\left[\frac{3}{16\pi}(1 + cos^2\theta)\right]$$

APPENDIX F: Dilepton Mass

Mass setting	Mass regions accepted
low	4.0 to 8.8 GeV/c^2
intermediate	4.3 to 8.8 GeV/c^2 and >10.8 GeV/c^2
high	4.5 to 9.0 GeV/c^2 and >10.7 GeV/c^2

SM12, and SM3 selected a particular range of dilepton mass.

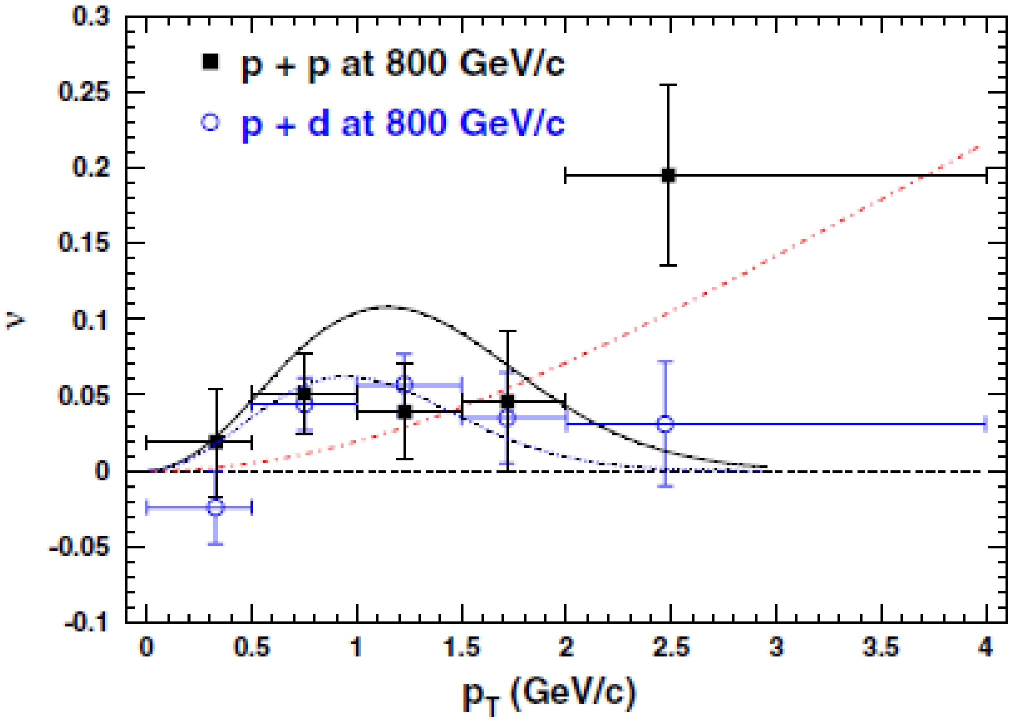
The dilepton mass is invariant mass.

$$m_0{}^2c^2 = \left(\frac{E}{c}\right)^2 - |\boldsymbol{p}|^2$$

For this experiment, the "high mass" and "low mass" settings were used.

Dimuon events with $m_{\mu\mu}$< 4.5 GeV/c^2 and 9.0 < $m_{\mu\mu}$ <10.7 GeV/c^2 were rejected.
This is to eliminate the J/Ψ and Υ resonance peak.

APPENDIX G: Contribution of QCD



$$\nu = \frac{Q^2{}_\perp / Q^2}{1 + \frac{3}{2} Q^2{}_\perp / Q^2}$$

Red line shows the QCD effects.

The QCD effects have a greater contribution in high-p_T regions, while Boer-Mulders effects have a greater contribution in low-p_T regions.

Therefore, higher-order QCD effects must be taken into account to reliably extract the Boer-Mulders.