Hadron Structure from the Drell-Yan Process

- Probing Hadron Structure with Drell-Yan
- Proton induced Drell-Yan
- Pion induced DY
- DY with polarized protons
- Future Experiments

Many thanks for their input to Caroline Riedl, and Jen-Chieh Peng

Matthias Grosse Perdekamp, UIUC
Probing the Quark Structure of Hadrons with Electro Weak Probes

**DIS**

\[ \text{DF} \otimes \text{FF} \]

**Drell-Yan (DY)**

\[ \text{DF} \otimes \text{DF} \]

mapping of valence quarks

mapping of sea quarks

\[ H \rightarrow l \otimes l' \]

\[ H_1 \rightarrow l^+ \otimes h_2 \]

\[ H_2 \rightarrow l^- \otimes h_1 \]

\[ l \rightarrow l' \]

\[ l^+ \rightarrow h_1 \]

\[ l^- \rightarrow h_2 \]
Both DIS and Drell-Yan processes are tools for probing the quark and anti-quark structure of hadrons. The data stretch over a wide range in $Q^2$ and test evolution.
Lepton-pair production provides unique information on parton distributions

\[ p + W \rightarrow \mu^+ \mu^- X \]
800 GeV/c

\[ \pi^- + W \rightarrow \mu^+ \mu^- X \]
194 GeV/c

\[ \bar{p} + p \rightarrow l^+ l^- X \]
1.8 TeV

Probe antiquark distribution in nucleon
Probe antiquark distribution in pion
Probes antiquark distributions in antiproton

Unique features of D-Y: antiquarks, unstable hadrons
DY $p_T$ Dependence for Different $Q^2$

Important input for the phenomenology of transverse momentum dependent quark distributions (TMDs) and their evolution.
Hadron Structure Explored
Through Drell-Yan Scattering

• Cleanest hard hadron-hadron scattering process

• But: experimentally challenging: small cross section.
Continuum varies as $\frac{d\sigma}{dm_{\mu\mu}} \approx 10^{-32} \cdot \frac{cm^2}{GeV^2}$

• Important role in studying quark structure in hadrons: - nucleons
  - Parton Distribution Functions (PDFs) in nuclei
  - PDFs in mesons

• Provides access to transverse-momentum dependent PDFs (TMDs)

• Interesting current focus: DY experiments with polarized protons
  ➔ complete understanding of the origin of large single transverse spin asymmetries in SIDIS and pp

Milestone: measurement of sign switch between DY and SIDS for Sivers asymmetry

Fermilab E866/NuSea

only few high-x partons to reach high mass
Typical Fixed Target Muon Drell-Yan Experiment

Omega @ CERN (1980)

39.5 GeV beam
93.9% $\pi$, 3.4% $K^-$, 2.7% anti-$p$
74.6% $\pi^+$, 3.4% $K^+$, 22.0% $p$

Cherenkov counters to identify beam particles
Absorber for beam & secondaries

Magnetic spectrometer with muon trigger

Selected Past Drell-Yan Experiments

Meson-Induced Drell-Yan

- **CERN Omega**
  - $\pi^\pm, K^\pm, p^\pm$
  - Cu/W
  - 40 GeV

- **CERN NA3**
  - $\pi^- p/Pt$
  - 150, 200, 280 GeV

- **CERN NA10**
  - $\pi^- C/Cu/W$
  - 200, 280 GeV

- **CERN NA51**
  - pp & pd
  - 450 GeV

- **Brookhaven AGS**
  - p-U
  - 29 GeV

- **FNAL CIP**
  - $\pi^\pm$
  - Be/Cu/W
  - 80, 225, 252 GeV

- **FNAL E605**
  - p-Cu
  - 252 GeV

- **FNAL E615**
  - $\pi^-W$

- **FNAL E772**
  - pd

- **FNAL E789**
  - p-p/Be/Cu/Au

- **FNAL E866 (NuSea)**
  - pp & pd
  - 800 GeV

First measurement: Observation of Massive Muon Pairs in Hadron Collisions

Nuclear Dependence of Drell-Yan and Quarkonium Production

First dbar/ubar measurement

Determination of anti-d / anti-u Ratio of the Proton via Drell-Yan

**Hadron Structure from Drell-Yan**

Spin 2014, PKU, October 19, 2014
Proton Induced DY as Probe of Sea Quark Distributions

Fixed target experiment
example: Fermilab di-muon spectrometer [E866]

selects

\[ X_{\text{Feynman}} = x_{\text{beam}} - x_{\text{target}} \gtrsim 0 \]

large \( x_{\text{beam}} \) (quark) in valence region
small \( x_{\text{target}} \) (anti-quark) in sea region

target-proton

\[ \sum e^2 [\bar{q}_t(x_t)q_b(x_b) + \bar{q}_b(x_b)q_t(x_t)] \]

suppressed

\[ \frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_bx_t s} \times \]

scaling analog to DIS

\[ \frac{m_{\mu\mu}}{s} = x_b x_t \]
Pion-Induced Drell-Yan Probes Valence Quark Distribution in Target:

- Proton-induced DY needs to generate the di-lepton from sea-quark object with small x.
- Valence anti-u quark in the pion: allows to create large-mass dileptons with valence u-quark in the target!
- Pions are complementary probe to probe - valence structure  
  - nuclear effects at high x  
  - meson structure – not accessible in DIS
- Flavor dependence: meson quark composition pics specific q-flavor in the target

Recent review: arXiv:1306.3971
W.-C. Chang and D. Dutta,
The pionic Drell-Yan process: a brief survey
E866 Isospin Symmetry
Broken in the Anti-Quark Sea

- Inclusion of E866 $\sigma^{pd}/\sigma^{pp}$ into global fits: dramatic impact of sea-quark dis. from QCD analysis of hard scattering data!

- Origin of sea quarks? $g \rightarrow q\bar{q}$ should naively give symmetric $q\bar{q}$.

- Non-perturbative contributions to sea-quark distributions:
  - meson-cloud model
  - chiral perturbation theory
  - intrinsic quark sea

Current Fermilab E906/SeaQuest

Will extend sea-quark measurements to larger x by using 120 GeV protons from Fermilab Main Injector.
Nuclear Effects in Nucleon Structure

EMC effect in DIS 1983, EMC at CERN

- Modification of parton distributions in nuclei?
- $F_2$ in DIS: charge-weighted sum of quarks and anti-quarks. Are there nuclear effects for sea quarks?
- Drell-Yan!

Geesaman, Saito, Thomas, The Nuclear EMC Effect
Flavor-Dependent EMC Effect in Pion-Induced DY

- Flavor-dependent modification of quark distributions in the nuclear medium?
- Distinguish between different nuclear models
- **Cloet, Bentz, Thomas (CBT) model:**
  - isospin dependence of nuclear forces affects u- and d-quarks differently

\[
\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}
\]

**flavor-independent EMC effect**

**flavor-dependent EMC effect**

Dutta, Peng, Cloet, Gaskell, arXiv:1007.3916

Experimental possibilities in p-Pb at LHC ?!
Drell-Yan at Highest-Energy $pp(\bar{p})$ Colliders

Di-muon production: $pp(\bar{p}) \to \mu^+\mu^-X$

- LHC & Tevatron: Drell-Yan widely explored
- Major background in searches.
- Constraints for PDFs
- Probe for new physics/precision test of SM: measurement of $A_{FB}$

Search for $Higgs \to \tau\tau \to \mu\mu$
Impact of Charged Current Ratio on PDFs

\[ A(\eta) = \frac{d\sigma/d\eta(W^+) - d\sigma/d\eta(W^-)}{d\sigma/d\eta(W^+) + d\sigma/d\eta(W^-)} \]

Input for constraining u/d and anti-quark distributions in PDF fits
Measurement of Forward-Backward Asymmetry in DY in CMS

\[ A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \]

Weak mixing angle from multi-variant analysis of DY production vs m, y, cosθ to 0.1%:

\[ \sin^2 \theta_{\text{eff}} = 0.2287 \pm 0.0020 \text{ (stat.)} \pm 0.0025 \text{ (syst.)} \]

Angular Dependence of the (Spin-Integrated) DY Cross Section

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

Drell-Yan in collinear (k_T=0) \( q\bar{q} \) annihilation

\[ (1+\cos^2\theta) + k_T + \text{higher O}(\alpha_S) : \]

\[ \frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin(2\theta) \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos(2\phi) \]

Lam-Tung relation

\[ 1 - \lambda = 2\nu \]

C.S. Lam and W.K. Tung, PRD 18 (1978) 2447

- Reflects spin-\( \frac{1}{2} \) nature of quarks (DIS-Callan-Gross-like)
- Widely insensitive to QCD corrections
- “unique opportunity to test the QCD-improved quark-parton model”
Lam-Tung in Proton- and Pion-Induced DY

- **Proton-induced Drell-Yan (E866)**
  - consistent with LT-relation
  - no \( \cos(2\Phi) \) dependence
  - no \( p_T \) dependence

- **Pion-induced Drell-Yan (NA10, E615)**
  - violates LT-relation
    - (independent of nucleus - no nuclear effect)
  - large \( \cos(2\Phi) \) dependence
  - strong with \( p_T \)

- **Explanations**
  - Boer-Mulders (BM) TMD \( \Rightarrow \) quark transverse spin correlated with quark transverse momentum ?
  - higher twist
  - spin effects in QCD vaccum

- **Pionic DY probes BM (valence), target=proton**
- **Protonic DY probes BM (sea), target=proton**
  - BM (sea) small compared to BM (valence)

- Drell-Yan may be sensitive to **spin-transverse momentum correlations**!
TMDs in Spin-Dependent Drell-Yan

Correlations between transverse nucleon spin, quark spin and quark transverse momentum

- Are Sivers function and Boer-Mulders universal? 
  - Observed to be clearly different from zero in SIDIS.
  - Expect sign switch of these time-reversal-odd TMDs in DY wrt SIDIS: fundamental QCD prediction due to gauge invariance

- Experimental verification: crucial test of non-perturbative QCD and TMD physics 
  - origin of large SSAs?
  - validity of QCD factorization?
Sign Change of Sivers- and Boer-Mulders Functions Between SIDIS and DY

Direction of the gauge-link integrals of $k_T$ dep. pdfs is process-dependent and changes its sign between SIDIS and DY.

Sivers

$$f_1^T(x, k_T)_{SIDIS} = -f_1^T(x, k_T)_{DY}$$

Boer-Mulders

$$h_1^T(x, k_T)_{SIDIS} = -h_1^T(x, k_T)_{DY}$$

Sign reversal between polarized SIDIS and Drell-Yan is to be tested!

TEST proposed process dependence of TMD pdfs!

Predictions for the size of asymmetries depend on $Q^2$ of the experiment and knowledge of TMD evolution.
Proposed future Polarized Drell-Yan Experiments

proton-proton
- SeaQuest (Fermilab)
- RHIC (Brookhaven)
- J-PARC (KEK)
- IHEP (Protvino)
- JINR (Dubna)

anti(p)-proton
- FAIR (GSI)

pion-nucleon
- COMPASS (CERN)
$A_N$ for direct-photon, DY, $W$ and $Z^0$ from STAR at RHIC

From A. Vossen’s talk at Transversity 2014
STAR $A_N(W^+)$: 2011 data vs 2016 Projections

From A. Vossen’s talk at Transversity 2014
The COMPASS Spectrometer

Secondary hadron beam from SPS

two stage spectrometer to cover a large kinematic range

- m/h beam: 160/190 GeV
- high beam intensity
- large angular acceptance
- broad kinematical range
Kinematics $4 < M_{uu} < 9 \text{ GeV/c}^2$ at COMPASS

Acceptance is largest where Sivers expected to be largest

Valence range ($x \sim 0.1$) for both quarks ($u$-$\bar{u}$ annihilation)

$P_T$ dimuon is about $1\text{ GeV/c}$ where TMD effects are dominant
COMPASS DY Statistical Precision

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

Details will be given in presentation by Bakur Parsamyan, Parallel VIII, Friday at 11am

Additional info on DY with unpolarized targets in COMPASS will be given by Wen-Chen Chang, Parallel, VIII, Friday at 11.40
Summary

Large body of Drell-Yan data available constraining:
- nucleon and meson pdfs
- flavor dependence
- nuclear effects in hadron structure
- TMD evolution through $p_T$ dependence
- spin – $k_T$ correlations in hadrons

Future experiments are being prepared with polarized Targets and polarized beams to study single transverse spin asymmetries and the related spin dependent TMD distribution functions of the hadron