Review of Drell-Yan Experiments

- Highlights from proton-induced DY
- Pion-induced DY
- Spin-dependent DY
- Future experiments

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International Workshop on Hadron Structure and Spectroscopy
Appetizer: Drell-Yan at highest-energy pp(-) collider

Di-muon production: pp(-)→μ+μ- X

- LHC and Tevatron: Drell-Yan widely explored
  - Major background in searches.
  - Probe for new physics, e.g. through angular dependences (A_{FB}).
  - Constraints on PDFs, e.g. s(x) in W- and Z-production.

- Studies of proton structure:
  - Dilepton-p_T  \uparrow  \sqrt{s}
  - Q^2-evolution of Sivers effect
  - Cannot probe valence quarks.

- Need more than “Physics at the Terascale”
Probing the partonic structure of hadrons

**DIS**

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

**Drell-Yan (DY)**

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

**Caveat:** factorization applies

**Assumption:**

Caveat: might break down @ high-x

**Probe universality**
Hadron structure explored through DY scattering

- Cleanest hard hadron-hadron scattering process

- But: experimentally challenging: small cross section.
  Continuum varies as $\frac{d\sigma}{dm_{\mu\mu}} \approx \frac{10^{-32}}{m_{\mu\mu}^5} \cdot \text{cm}^2/\text{GeV}^2$

- Crucial role in studying quark structure in hadrons:
  - nucleons
  - nuclei
  - mesons

- Spin-orbit correlations,
  TMDs = transverse-momentum dependent PDFs

- Add polarization to our DY experiments to cover the missing spin program:
  spin-dependent TMDs in Drell-Yan

**Milestone will be measurement of Sivers-function sign switch (?) in polarized Drell-Yan**
Drell-Yan as selective probe of sea distributions

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

favors $x_{\text{Feynman}} (= x_{\text{beam}} - x_{\text{target}}) \approx 0$
large $x_{\text{beam}}$ (quark) in valence region
small $x_{\text{target}}$ (anti-quark) in sea region

dipole spectrometer & forward boost of dileptons

(proton-induced Drell-Yan)

dipole spectrometer & forward boost of dileptons

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t s} \times$$
$$\sum e^2[\bar{q}_t(x_t)q_b(x_b) + \bar{q}_b(x_b)q_t(x_t)]$$
suppressed

$$\frac{m_{\mu\mu}}{s} = x_b x_t$$
scaling analog to DIS

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What about pion-induced Drell-Yan?

- Valence anti-u quark in the pion: allows to create large-mass dileptons. Proton-induced DY needs to generate the dilepton from sea-quark object with small $x$.

- Pions as alternative probe to test
  - nuclear models
  - meson structure – not accessible in DIS
  - “subtleties of partonic structure”

- Flavor dependence: pion (or meson in general) is specific $qq\bar{q}$ compound

Recent review: arXiv:1306.3971
W.-C. Chang and D. Dutta,
The pionic Drell-Yan process: a brief survey
Selected Drell-Yan experiments of the past

meson-induced Drell-Yan

1970
Brookhaven
AGS
p-U
29 GeV

1979
FNAL
CIP
\( \pi^\pm \)
Be/Cu/W
80, 225, 252 GeV

1980
FNAL
CERN
Omega
\( \pi^\pm, K^\pm, p^\pm \)
Cu/W
40 GeV

1981
FNAL
CERN
NA3
\( \pi^- p/\text{Pt} \)
150, 200, 280 GeV
p-Cu

1985
FNAL
CERN
NA10
\( \pi^- C/\text{Cu/W} \)
200, 280 GeV

1986
FNAL
E772
pd

1988
FNAL
E789
pp & pd
800 GeV

1991
FNAL
E866
(Cu/W)

1994
FNAL
E866
(NuSea)

1996

First dbar/ubar measurement

First measurement:
Observation of Massive Muon Pairs in Hadron Collisions

Nuclear Dependence of Drell-Yan and Quarkonium Production

Search for Two-Body Decays of Heavy Quark Mesons

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

Heavy material to absorb secondaries

Magnetic spectrometer with muon trigger

Isospin symmetry violation in the anti-quark sea

- Inclusion of $\sigma_{pd}/\sigma_{pp}$ into global fits: change of perception of sea-quark distributions in the nucleon

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

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

Nucleons in nuclei

EMC effect in DIS

- Modification of parton distributions in nuclei?
- Can the nucleus be described in terms of quarks and gluons only?
- Explanation of EMC effect: nuclear pions?
- \( F_2 \) in DIS: charge-weighted sum of quarks and anti-quarks. What about the sea quarks?

Geesaman, Saito, Thomas, The Nuclear EMC Effect

EMC effect in Drell-Yan

- DY: no excess pions.
  Traditional meson-exchange model?
- Contemporary models:
  large effects for anti-quarks as x increases.
- Needs more statistics to confirm
  (e.g. Fermilab E906/SeaQuest)

\[
\frac{\sigma_{pA}}{\sigma_{pd}} \approx \frac{\overline{u}_A(x)}{\overline{u}_N(x)}
\]

EMC effect in DIS

\[
Q^2 = 5 \text{ GeV}^2
\]

\[
Q^2 = 50 \text{ GeV}^2
\]

E772: PRL 64 (1990) 2479
E866: PRL 83 (1999) 2304
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:
  isovector mean field in a N≠Z nucleus affects u- and d-quarks differently

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

Dutta, Peng, Cloet, Gaskell, arXiv:1007.3916
Flavor-dependent EMC effect in pion-induced DY

\[
\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)} \quad \frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}
\]

Important new information from COMPASS-II Drell-Yan data with pion beams

160 GeV pion beam @Q^2=25 GeV^2
Pion-induced exclusive Drell-Yan \( \pi^- N \rightarrow N' \mu^- \mu^+ \)

**DVCS**

![Diagram of DVCS](image)

- **Hard exclusive pion production (DVMP)**
  - **Space-like**
  - **Time-like**

- Preferred @lower beam energy to enhance exclusive cross section


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@larger momentum transfer to the target: involves TDA = nucleon-to-pion Transition Distribution Amplitude
Angular dependence of the (spin-integrated) DY cross section

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

(1+\cos^2\theta) “naive DY”
+ k_T + 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

- Basic derivation from structure-function formalism
- 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 $p_T$

- The **Boer-Mulders (BM) TMD** enters the stage:
  correlation between
  - quark transverse spin &
  - quark transverse momentum

- **Pionic DY probes BM (valence), target=proton**
  - BM (sea) small compared to BM (valence)
  - from Drell-Yan, we can learn something about spin-orbit correlations!

Spin-orbit correlations from Drell-Yan?

- **Boer and Mulders 1998**: distribution function of the unpolarized nucleon with intrinsic $k_T$ dependence.
  - Describes correlation between quark transverse spin and momentum.
  - Induces $\cos(2\Phi)$ modulation of the DY cross section.

- **Other theoretical interpretations**:
  - QCD higher-twist effect causes change of virtual-photon polarization from transversely ($\lambda=1$) to longitudinally ($\lambda=-1$) polarized for $x_\pi \rightarrow 1$?
    - Data taken at different $\sqrt{s}$: pion: 11 GeV and 16 GeV; proton: 39 GeV.
    - Such effect should be seen in E906/SeaQuest data.
  - Spin correlations between annihilating quark and anti-quark?
  - Glauber gluons, QCD instantons, ... 

More measurements in wider kinematic range, and kaon/anti-proton beams will help to differentiate the interpretations.
The missing spin program: TMDs in spin-dependent Drell-Yan

- 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 \( \text{DY} \) wrt \( \text{SIDIS} \): 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?

\[ S^N \quad s^q \quad k^q \]

\( N \) nucleon transverse spin
\( q \) quark transverse spin
\( k \) quark transverse momentum

Transversity

Manifest as ISR
Manifest as FSR

More details on TMDs in G. Schnell’s talk
Theoretical overview in M. Radici’s talk @ this workshop
Future Drell-Yan experiments

- Programs for future Drell-Yan measurements:
  - nucleon-nucleon at
    - SeaQuest (Fermilab)
    - RHIC (Brookhaven)
    - J-PARC (KEK)
    - IHEP (Protvino)
    - JINR (Dubna)
  - anti(p)-nucleon at
    - FAIR (GSI)
  - pion-nucleon at
    - COMPASS (CERN)

Only existing meson plan!

- Past measurements exclusively considered the unpolarized cross section, future ones also aim for polarization measurements.
  - transversely polarized DY: spin-dependent TMDs
  - longitudinally polarized DY: quark helicity

More details on FAIR in K. Peter’s talk @ this workshop
More details on JINR in I. Savin’s and A. Nagaytsev’s talk

The RHIC Spin program, arXiv:1304.0079
Fermilab E906/SeaQuest

- Unpolarized proton-induced Drell-Yan
  - Significant increase in physics reach: high-x structure of the proton
  - Extend sea-quark measurements to larger x by using 120 GeV protons from Fermilab Main Injector.
  - Will start physics run in the nearest future.

- Probed physics:
  - What is dbar / ubar?
  - What are the origins of the sea quarks?
  - How are quark spin and orbital motion correlated?
  - Where are the nuclear pions?
  - Is anti-shadowing a valence effect?
  - Do colored partons lose energy in cold nuclear matter?

- Polarized SeaQuest: plans to polarize the proton beam and maybe even the target.

Click: Opportunities for polarized physics at Fermilab, workshop May 20-22, 2013
Key elements:
1. Transversely polarized NH$_3$ target
2. Tracking system
   (Large and Small Angle Spectrometer)
3. Muon trigger
4. RICH-I, calorimetry
5. Hadron absorber

More details on COMPASS-II in A. Ferrero’s talk @ this workshop

adapted from O. Denisov
COMPASS-II DY will probe the valence-quark region, where the Sivers function has its largest magnitude.

\[ \pi p \rightarrow \mu^+ \mu^- X: \text{sensitivity to } u \text{-quark Sivers function} \]

**DY** with trans. pol. NH3 target:
- a) Sivers \( \sin(\Phi_S) \): magnitude and sign
- b) Pretzelosity \( \sin(2\Phi + \Phi_S) \)
- c) Transversity \( \sin(2\Phi - \Phi_S) \)

**DY** with unpolarized NH3 target:
- d) Boer-Mulders \( \cos(2\Phi) \)

**DY SSA with trans. pol. NH3 target:**
low-mass dimuon events to study a)-d)

**Projection:** 2 years running and 140 days pa, about 230k DY events above J/Psi threshold

Optimal conditions for the observation of **Sivers sign-switch**: kinematic overlap between SIDIS and DY.
Drell-Yan at COMPASS-II

Possible additional physics with approved measurements:

- Modification of the $\lambda$, $\mu$, $\nu$ parameters as $x \to 1$ (existing data are for $\lambda$ only).
  
- Violation of the Lam-Tung relation as $x \to 1$.

- Dependence of $<p_T>$ on the kinematic variables (e.g. $x$)

- $x$-dependence of the valence-quark distribution of pions.

- Low-mass, high $p_T$ DY events as alternative for direct-photon production.

+ if a solid nuclear target is placed in the beam:

  - Quark energy loss in nuclei.

  - Test of flavor-dependent EMC effect.

  - Nuclear-dependence of the Boer-Mulders function.

New measurements using liquid hydrogen and liquid deuterium targets:

- Measure $d/u$ ratios at large-$x$.

- Determine pion valence quark distributions.

- Test charge-symmetry-breaking of parton distributions in nucleons.

- Measure $d\bar{u}/u\bar{d}$ at large-$x$ using $(\pi^+ + d) / (\pi^+ + p)$ DY ratios.

In this region, DY is related to high $p_T$ direct photon production by the electromagnetic coupling $\alpha$ multiplied by a factor that is essentially a measure of the virtuality of the intermediate photon.


based on priv. comm. with Jen-Chieh Peng, 2011 / 2013
Summary

Drell-Yan: explore the flavor and spin structure of nucleons and nuclei

- Pion-induced Drell-Yan provides important additional information compared to the proton-induced case.
- To cover the full Drell-Yan program: need
  - proton, anti-proton and meson beams
  - unpolarized H, D & nuclear targets
  - polarized targets and / or desirably polarized beams

This review would not have been possible without material from Wen-Chen Chang, Jen-Chieh Peng, Paul Reimer, Wolfgang Lorenzon, Markus Diefenthaler, Oleg Denisov, and others.

Thank you!
Nucleon Tomography in DIS

Correlation between spin and transverse momentum?

Transverse Momentum dependent PDFs

TMDs $f(x, k_\perp)$

$k_\perp$-integration

semi-inclusive measurements

inclusive measurements

Correlation between longitudinal momentum and transverse position?

Generalized Parton Distributions

GPDs $H(x, b_\perp)$

$\leftrightarrow$ FT $\leftrightarrow H(x, \xi, t)$

$x = 0$, $t = 0$

exclusive measurements

PDFs $q(x)$, 1D:

Parton Distribution Functions

Courtesy A. Bacchetta (Università di Pavia)
Transverse-Momentum Dependent PDFs (TMDs)

Distribution Functions (DF)

<table>
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<tr>
<th>nucleon</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
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<td>$g_1$</td>
<td>$h_{1\perp}$</td>
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<td>Number Density</td>
<td>Helicity</td>
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<tr>
<td></td>
<td>Sivers</td>
<td>Worm-gear</td>
<td>Transversity</td>
</tr>
</tbody>
</table>

Diagonal ‘survives’ integration over transverse momentum $k_T$.

“Collinear analysis”

Fragmentation Function (FF)

$\sigma^{ep \to ehX} = \sum_q (\text{FF} \otimes \text{DF})$

TMDs depend on the longitudinal and transverse momentum of a parton inside a hadron.

Describe strength of various spin-spin or spin-orbit correlations of the parton-hadron system.