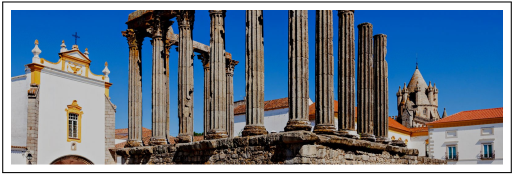
Partons and QCD from COMPASS at LIP

Ana S. Nunes (LIP-Lisbon)



Jornadas do LIP 2018, 16-18 February 2018, Évora

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

CERN/FIS-NUC/0017/2015, CERN/FIS-PAR/007/2017

Members of the COMPASS group at LIP

Senior:

Catarina Quintans
Group leader &
DY subgroup coordinator

Post-docs:

Marcin Stolarski
gluon polarisation &
had. multiplicities

Celso Franco
DY vertex detector &
machine learning

Ana Sofia Nunes
g_1^p at low Q^2,
had. multiplicities &
DCS

Engineer:

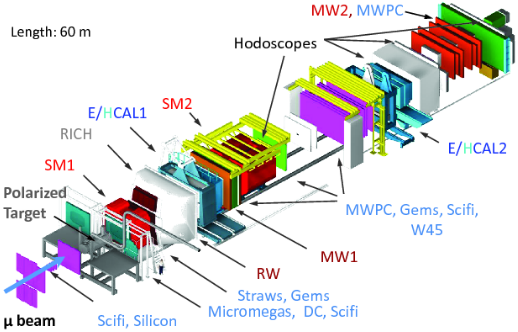
Christophe Pires
DCS

COMPASS @ CERN

[**CO**mmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy]

- Ground level **fixed target experiment** at the SPS using a tertiary **muon beam** ($\mu^{\pm}$) or a secondary **hadron beam** ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$)
- Collaboration of around 220 members from 13 countries and 24 institutions

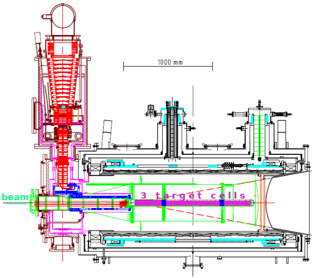
COMPASS spectrometer

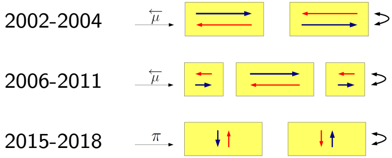


- 160/200 GeV μ^+ (or μ^-) naturally **polarised beams** or 190 GeV **hadron beams** (positive or negative)
- **^{6}LiD** or N**H_3**, 1.2 m long, 2 or 3 cells, longitudinally or transversely **polarised target**, or 4 m long **liquid hydrogen** target

- Large acceptance, two staged spectrometer
- Tracking ($\sim$350 detector planes)
- Particle identification: muon walls, RICH, calorimetry
- Hodoscope-based trigger (for scattered muon or dimuon)

Polarised target





^{6}**LiD** (2002-2006): $f \sim 40\%$, $P_{\text{target}} \sim 50\%$

NH_3 (2007-2018): $f \sim 16\%$, $P_{\text{target}} \sim 85\%$

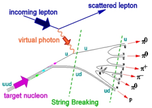
$$\mathbf{N}^{\leftrightarrows,\leftleftarrows} = \mathbf{a}\phi\mathbf{n}\bar{\sigma}(\mathbf{1} \pm \mathbf{P}_{\text{beam}}\mathbf{P}_{\text{target}}\mathbf{fDA}_{||})$$

Cancellation of $a\phi n\bar{\sigma}$ via:

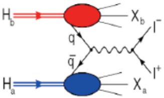
- *Flux cancellation:*
  - beam or extrapolation must cross all the target cells
- *Acceptance cancellation:*
  - 3 (2) target cells
  - polarisation rotation every 24 hours (1 week)
  - grouping of runs in ∼48 h long configurations (2 weeks)
  - reversal of “microwave setting” at least once per year (longitudinal polarisation)

COMPASS data-taking with a polarised target or beam

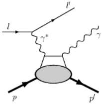
Processes:



DIS: $\mu^+ p \to \mu^+ X$



DY: $\pi^- p \to \mu^+ \mu^- X$



DVCS: $\mu^\pm p \to \mu^\pm p \gamma$

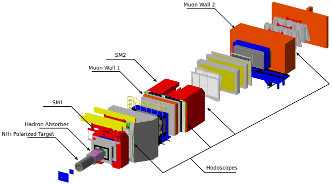
Year	Beam		Target			LIP analyses (2016/17)
	Particles	Energy (GeV)	Material	Cells	Magnetic field (T)	
2002	muons	160	^{6}LiD	2	long. ± 2.5; transv. 0.42	✓
2003	muons	160	^{6}LiD	2	long. ± 2.5; transv. 0.42	✓
2004	muons	160	^{6}LiD	2	long. ± 2.5; transv. 0.42	✓
2006	muons	160	^{6}LiD	3	long. ± 1.0	✓
2007	muons	160	NH_3	3	long. ± 1.0; transv. 0.63	✓
2010	muons	160	NH_3	3	transv. 0.63	✓
2011	muons	200	NH_3	3	long. ± 2.5	✓
2012$^{(*)}$	muons	160	H_2	1	0.0	
2014$^{(*)}$	hadrons	190	NH_3	2	0.0	
2015	hadrons	190	NH_3	2	transv. 0.63	✓
2016	muons	160	H_2	1	0.0	
2017	muons	160	H_2	1	0.0	
2018	hadrons	190	NH_3	2	transv. 0.63	

$^{(*)}$ Tests.

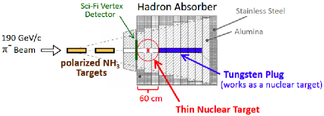
COMPASS papers with LIP analysis contributions (2016-)

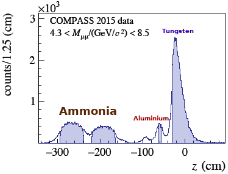
1. *First measurement of transverse-spin-dependent azimuthal asymmetries in the Drell-Yan process*, PRL 119 (2017) 112002
2. *Sivers asymmetry extracted in SIDIS at the hard scale of the Drell-Yan process at COMPASS*, PLB 770 (2017) 138
3. *First measurement of the Sivers asymmetry for gluons from SIDIS data*, PLB 772 (2017) 854
4. *Leading-order determination of the gluon polarisation from semi-inclusive deep inelastic scattering data*, EPJC 77 (2017) 209
5. *Multiplicities of charged pions and unidentified charged hadrons from deep-inelastic scattering of muons off an isoscalar target*, PLB 764 (2017) 001
6. *Multiplicities of charged kaons from deep-inelastic muon scattering off an isoscalar target*, PLB 767 (2017) 133
7. *Transverse-momentum-dependent multiplicities of charged hadrons in muon-deuteron deep inelastic scattering*, PRD 97 (2018) 032006
8. *Longitudinal double-spin asymmetry A_1^p and spin dependent structure function g_1^p of the proton at small values of x and Q^2*, hep-ex/1710.01014, accepted by PLB
9. *K^- over K^+ multiplicity ratio for kaons produced in DIS with a large fraction of the virtual-photon energy*, hep-ex/1802.02739, submitted to PLB

Highlight: pioneering polarised Drell-Yan measurement



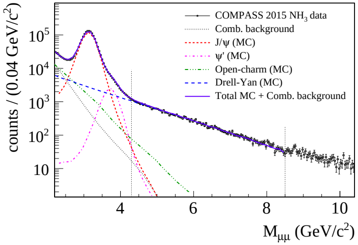
- MC studies for the optimisation of the setup done at LIP
  - hadron absorber
  - symmetrised hodoscope-based dimuon trigger
- Tests in 2009 (without absorber) and 2012 (with simpler hadron absorber)
- **Data-taking in 2015** (to be continued in 2018)
- Analysis in record time, **publication in September 2017**

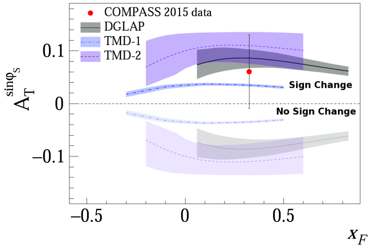




↪ contributions of M. Quaresma, C. Quintans, L. Silva, C. Franco

Polarised Drell-Yan results



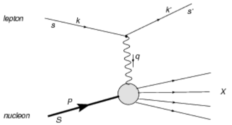


[COMPASS, PRL 119 (2017) 112002]

- Transversely polarised ammonia target
- Drell-Yan: dimuon events with invariant mass $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$
- Sign of the Sivers asymmetry **consistent with fundamental QCD prediction**:
  - Sivers TMD PDF extracted from DY and from SIDIS have **opposite sign**

↪ contributions of M. Quaresma, C. Quintans, L. Silva, C. Franco

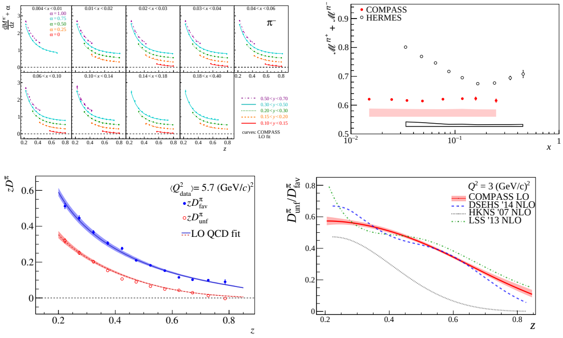
Hadron multiplicity results: pions



$$k_\mu = (E_\mu, \mathbf{k}_\mu)$$
$$k'_\mu = (E'_\mu, \mathbf{k}'_\mu)$$
$$P = (M, 0)$$
$$q = k_\mu - k'_\mu = (\nu, \mathbf{q})$$
$$Q^2 = -q^2$$
$$\nu = P \cdot q/M = E_\mu - E'_\mu$$
$$W^2 = M^2 + 2M\nu - Q^2$$
$$x = Q^2/(2M\nu)$$
$$y = \nu/E_\mu$$
$$z = E_h/(E_\mu - E_{\mu'})$$

Multiplicities & fragmentation functions

$$\frac{dM^h(x, z, Q^2)}{dz} \overset{=}{\text{at LO}} \frac{\sum_q e_q^2 f_q(x, Q^2) \mathbf{D_q^h(z, Q^2)}}{\sum_q e_q^2 f_q(x, Q^2)}$$



[COMPASS, PLB 764 (2017) 001]

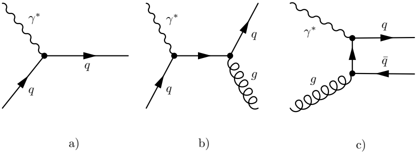
- $M^h(x, y, z)$: # of hadrons produced per DIS event
- Several hundred data points of $M^h(x, y, z)$
- **Tension with HERMES results** (also for kaons)
- Disagreement with a previous fit (HKNS'07 NLO)

$\hookrightarrow$ contributions of M. Stolarski

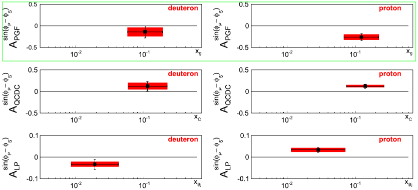
Gluon Sivers results

- **Sivers function:** describes correlation between transverse spin of a nucleon and transverse momentum of its partons
- **Photon-gluon fusion (PGF)** contribution enhanced requiring **2 high-p_T hadrons**
- Using MC and a Neural Network, the contribution from the processes of PGF, QCD Compton and leading order virtual-photon absorption are evaluated and the Sivers function is evaluated for the 3 processes
- **Negative values for the gluon Sivers asymmetry found**

Photon-nucleon processes:



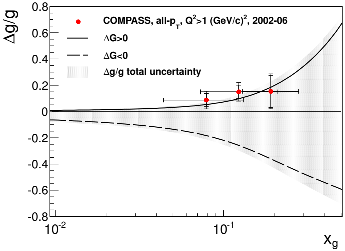
Leading process | QCD Compton | Photon-**gluon** fusion

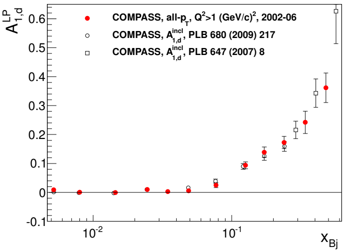


[COMPASS, PLB 772 (2017) 854]

↪ contributions of L. Silva, M. Stolarski

Gluon polarisation in the nucleon with all-p_T hadrons



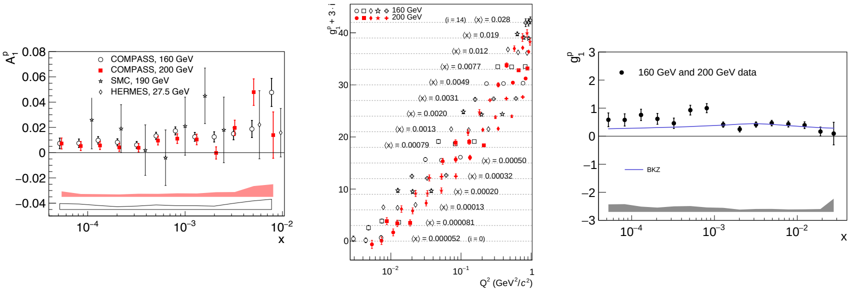


[COMPASS, EPJC 77 (2017) 209]

- Improved statistical and systematic errors with respect to the high-p_T hadron pair analysis (by factors 1.6 and 1.8 respectively)
- A_1^d obtained independently, consistent with extractions with other methods
- **World's most precise** $\langle \Delta g/g \rangle$ extracted in LO
- Positive solution of ΔG favoured

↪ contributions of M. Stolarski

g_1^p at low Q^2 results



[COMPASS, hep-ex/1710.01014]

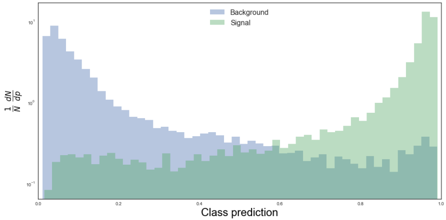
- Virtual-photon-proton spin asymmetry A_1^p and spin-dependent structure function g_1^p extracted for $Q^2 < 1$ $(\mathrm{GeV}/c)^2$ and $4 \times 10^{-5} < x < 4 \times 10^{-2}$
  - as functions of x, ν, (x, Q^2), (ν, Q^2), (x, ν), $(Q^2\ x)$
- **Spin effects observed for the first time at such low values of x**
- No big dependence with the studied variables observed in the 2D analyses
- Agreement with phenomenological models

↪ contributions of A.S. Nunes, M. Stolarski

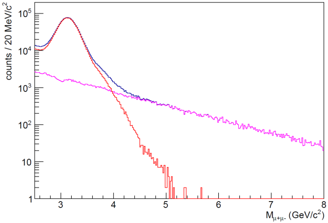
Machine learning techniques for the DY analysis

(Very preliminary!)

- Goal: assign DY probabilities to dimuons that survive analysis cuts for $M_{\mu\mu} > 2.5$ GeV/c^2
- Two-step method for separation of Drell-Yan from ψ, ψ', open charm, comb. bkg.:
  1. Clusterise the data in a multidimensional space using a **self-organizing map** (SOM) algorithm as an unsupervided learning tool
  2. Train a **deep neural network** (DNN) using 2 data clusters from (1) as learning samples, to obtain DY probabilities
- Implementation using PCA (**primary component analysis**) from the python library scikit-learn to decorrelate the training variables, and **Keras** for the DNN



(validation sample)



↪ contributions of C. Franco

Future

2018 polarised Drell-Yan programme:

- **Improved statistical errors** of azimuthal asymmetries for TMDs extraction

Near future analyses:

- **2018 Drell-Yan** data quality checks (Catarina Quintans)
- Drell-Yan event selection using **Machine Learning/Neural Network** techniques (Celso Franco)
- Study of the J/ψ production mechanism (Celso Franco)
- **Hadron multiplicities** in muon-proton deep inelastic scattering: unidentified, pions, kaons (Marcin Stolarski, Ana Sofia Nunes)

Future measurements:

- **Addendum to the COMPASS proposal presented** to the SPSC:
    - **SIDIS with a transversely deuteron polarised target** in 2021, to improve statistics and do flavour separation: transverse spin asymmetries of d-quarks versus u-quarks, proposed to SPSC
- **New Letter of Intent** being prepared for 2021+:
    - Unpolarized pion-induced Drell-Yan on light isoscalar target – precise measurement of the pion structure
    - **Drell-Yan measurements and hadron spectroscopy** with RF separated beams of high intensity: kaon and antiproton beams
    - **Proton radius** via $\mu - p$ elastic scattering

Summary and outlook

- Since 2016, 7 COMPASS **papers** with analyses done at LIP were published, 1 more just accepted, 1 more recently submitted
- **DIS data taken in 2016 and 2017** to be produced soon $\hookrightarrow$ will be analysed at LIP
- Optimizations for the 2014-2015 DY data analyses and preparation of the **DY 2018 Run** under the **coordination** of Catarina Quintans
- **Machine learning** methods for process separation pioneered for the COMPASS DY data by Celso Franco
- **DCS** accompanying the data-taking in every campaign $\hookrightarrow$ See Christophe Pires' talk

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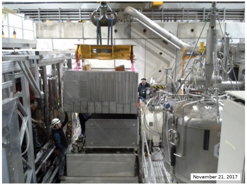

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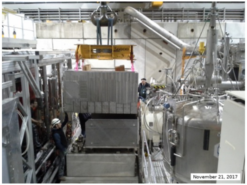
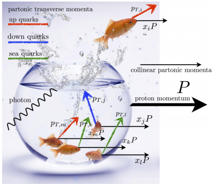




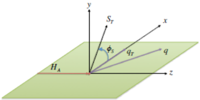
BACKUP

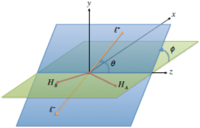
DY and SIDIS cross sections in terms of asymmetries

DY:

$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U \Big\{ \Big(1 + D_{[\sin^2(\theta)]} A_{UU}^{\cos(2\phi)} \cos(2\phi)\Big) + |\vec{S}_T| \Big[A_{UT}^{\sin(\phi_S)} \sin(\phi_S)$$

$$+ D_{[\sin^2(\theta)]} \Big(A_{UT}^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) + A_{UT}^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) \Big) \Big] \Big\}$$





SIDIS:

$$\frac{d\sigma}{dx\,dy\,dz\,d\psi\,d\phi_h\,dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1 + \frac{\gamma^2}{2x}\right)(F_{UU,T} + \varepsilon F_{UU,L}) \times$$

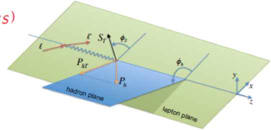
$$\Big\{ 1 + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi_h) A_{UU}^{\cos(\phi_h)} + \varepsilon\cos(2\phi_h) A_{UU}^{\cos(2\phi_h)} + P_l\sqrt{2\varepsilon(1-\varepsilon)}\sin(\phi_h) A_{LU}^{\sin(\phi_h)}$$

$$+ S_T \Big[\sin(\phi_h - \phi_S) A_{UT}^{\sin(\phi_h-\phi_S)} + \varepsilon\sin(\phi_h+\phi_S) A_{UT}^{\sin(\phi_h+\phi_S-\pi)} + \varepsilon\sin(3\phi_h-\phi_S) A_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_S) A_{UT}^{\sin(\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S) A_{UT}^{\sin(2\phi_h-\phi_S)} \Big]$$

$$+ S_T P_l \Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S) A_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos(\phi_S) A_{LT}^{\cos(\phi_S)}$$

$$+ \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S) A_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\}$$



DY asymmetries and TMD PDFs

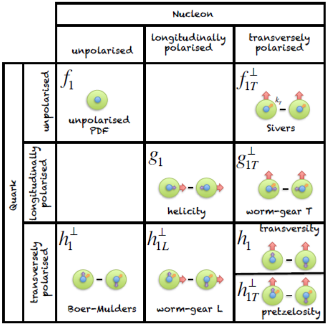
DY:

$$A_{UU}^{\cos(2\phi_{CS})} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q} \quad \text{Boer-Mulders}$$

$$A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q} \quad \text{Sivers}$$

$$A_{UT}^{\sin(2\phi_{CS}-\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q} \quad \text{Transversity}$$

$$A_{UT}^{\sin(2\phi_{CS}+\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q} \quad \text{pretzelosity}$$



SIDIS:

$$A_{UU}^{\cos(\phi_h)} \propto Q^{-1}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots\right)$$

$$A_{UU}^{\cos(2\phi_h)} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1}\left(f_1^q \otimes D_{1q}^h + \ldots\right)$$

$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_S)} \propto Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

$$A_{UT}^{\sin(2\phi_h-\phi_S)} \propto Q^{-1}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

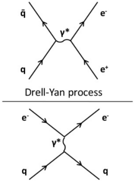
$$A_{LT}^{\cos(\phi_S)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$$

$$A_{LT}^{\cos(2\phi_h-\phi_S)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$$

Sign change SIDIS-DY

Why Drell-Yan Spin Asymmetries?

- The Drell-Yan process is the annihilation of a quark-antiquark pair into a virtual photon, which splits into a lepton-antilepton pair.
- A closely related process is called Deep-Inelastic Scattering, in which a lepton electromagnetically strikes a quark inside a hadron.
- The leading-order amplitudes of these processes are equal in magnitude, as they are related by crossing symmetry.

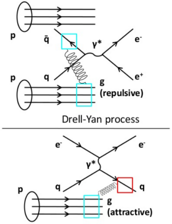


Drell-Yan process

Deep-Inelastic Scattering

Why Drell-Yan Spin Asymmetries?

- Next-to-leading order effects break the symmetry.
- Strong-force effects between the quark or antiquark and the remaining proton fragments are predicted to be equal in magnitude and opposite in sign.
- The Sivers function, which relates the transverse momentum of quarks and gluons within a proton with the transverse spin of the proton, predicts that this will result in opposite spin asymmetries for Drell-Yan and semi-inclusive Deep-Inelastic Scattering processes.
- Testing this prediction is so important that it has been made a milestone for the DOE hadronic physics program.

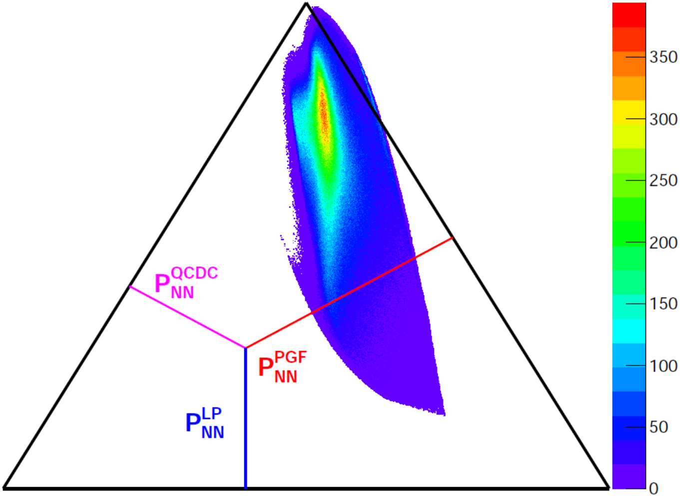


Drell-Yan process

Deep-Inelastic Scattering

(slides by J. Phybus *et. al.*)

NN output for Gluon Sivers analysis



Programs in Letter of Intent

R=RICH-1 & if possible, RICH-0
C=CEDARs

Program	[GeV]	Rate [/s]	[kHz]	Beam	Target	Hardware additions	R	C
Proton radius	100	$4 \cdot 10^6$	100	muon	high-pr. H2	active TPC, SciFi trigger, silicon veto		
GPD E	160	10^7	10	muon	NH3↑	recoil silicon, modified PT magnet		
Anti-matter	190	$5 \cdot 10^5$	25	proton	LH2, LHe	recoil TOF	×	×
Spectroscopy $\overline{p}$	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	target spectrometer: tracking, calorimetry	×	×
Drell-Yan conv	190	$6.8 \cdot 10^7$	25	$\pi^\pm$	C/W	vertex detector		×
Drell-Yan RF	~100	10^8	25-50	$K^\pm, \overline{p}$	6LiD↑, C/W	"active absorber", vertex detector		×
Primakoff	~100	$5 \cdot 10^6$	> 10	K^-	Ni		×	×
Prompt photon	100	$5 \cdot 10^6$	10-100	K^+	LH2	hodoscope		×
Spectroscopy K^-	50-100	$3.7 \cdot 10^6$	25	K^-	LH2	recoil TOF	×	×

C.Riedl, Report from TC 19 January 25, 2018