Exploring Proton Structure with Drell-Yan Scattering

Hadron Physics Seminar

Darmstadt, December 13, 2017

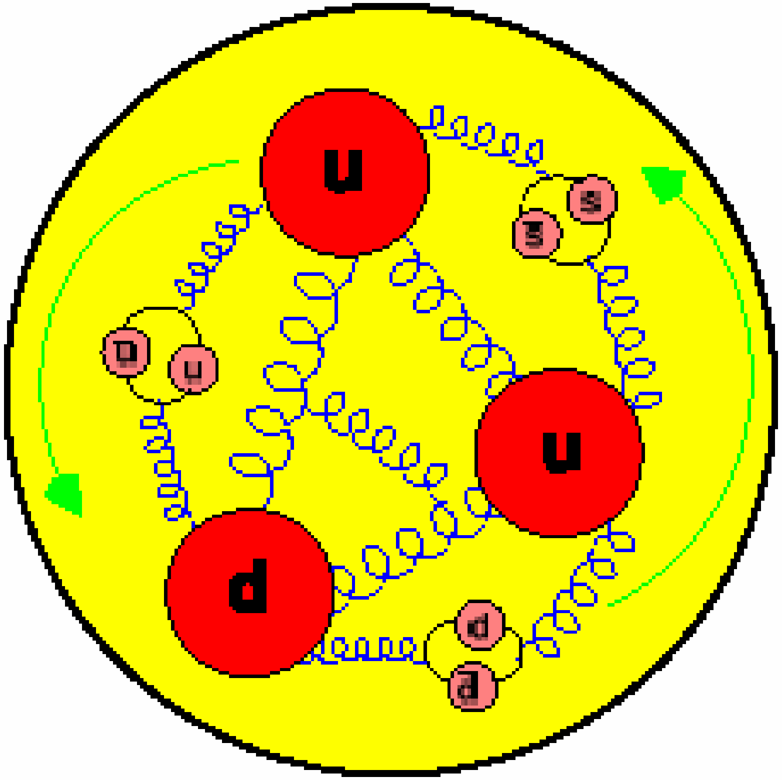
M. Grosse Perdekamp, University of Illinois

Overview

- **Exploring Proton Structure**
  - Drell Yan vs Deep Inelastic Scattering
- **Quark and Gluon Structure of the Proton**
  - Momentum distributions
  - Spin (helicity) distributions
- **Transverse momentum dependent proton structure**
  - A challenge to QCD?
  - Drell-Yan measurements
- **Meson Structure from Drell-Yan**

Motivation: **The Proton as QCD Laboratory**

The proton is the fundamental bound state of QCD; Quarks and gluons are the Constituents:

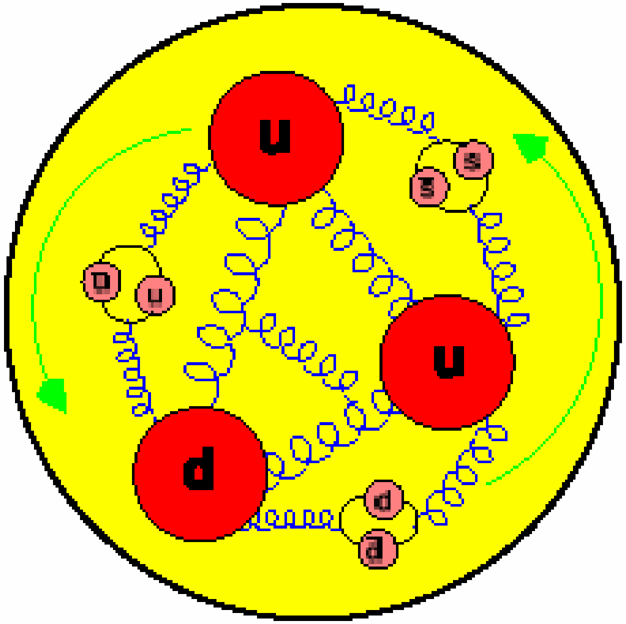


Can we understand the wave function of the proton from first principles QCD ?

Present (modest) status:

Description of proton in hard scattering processes with parton distribution functions.

Proton Structure: Momentum Distributions



Constituents:

quarks = u, d, s and gluons

$q(x) = \text{quark momentum distribution}$

$\bar{q}(x) = \text{anti-quark momentum distribution}$

$G(x) = \text{gluon momentum distribution}$

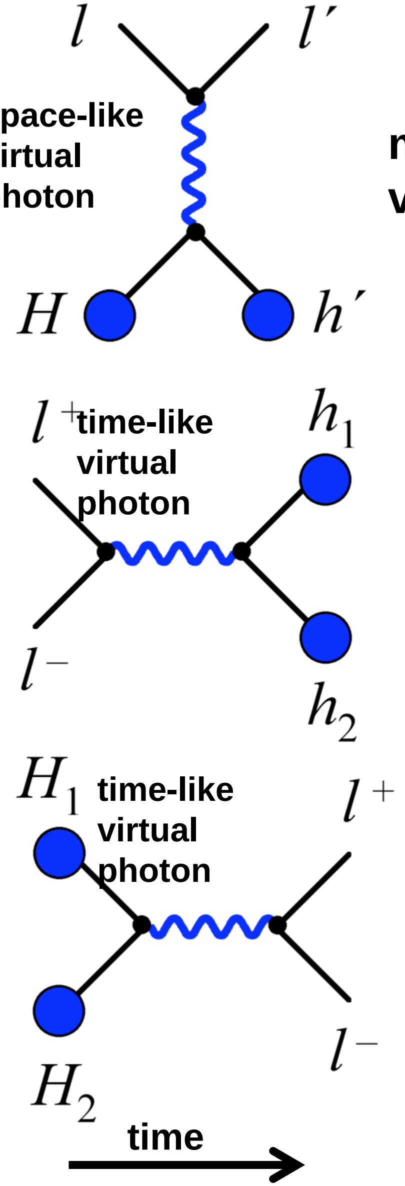
$$x = \frac{p_{quark}}{p_{proton}}$$

small x ~ sea quarks, gluons

medium - high x valence quarks

Probing the Quark Structure of Hadrons

DF ⊗ FF



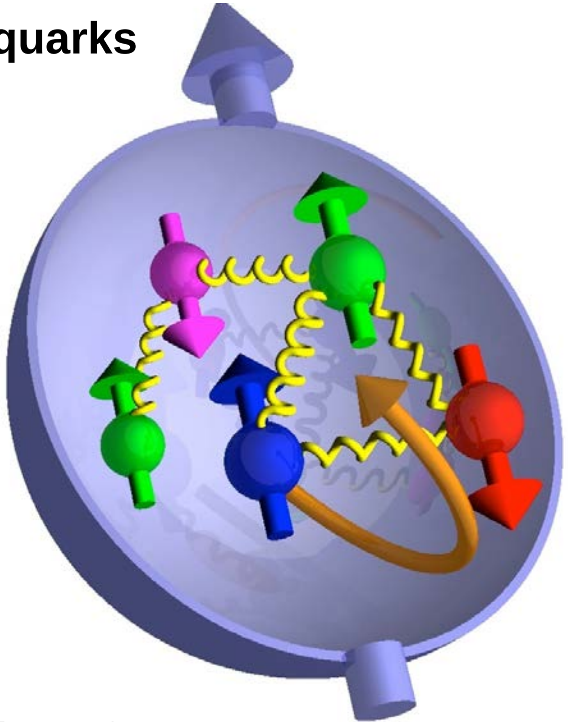
electron-electron collisions

FF ⊗ FF

Drell-Yan (DY)

DF ⊗ DF

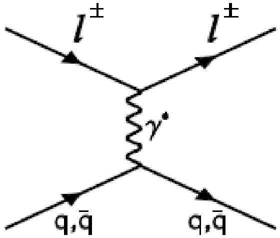
mapping of valence quarks

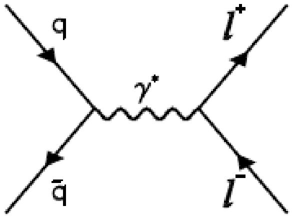


mapping of sea quarks

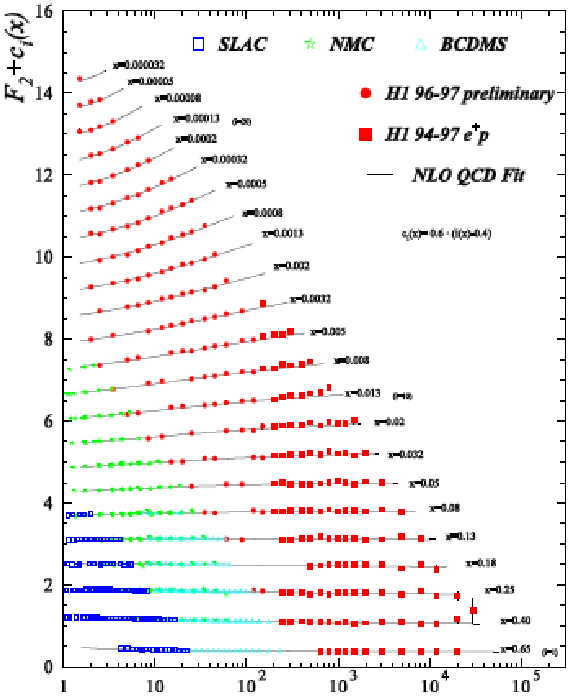
CTEQ Fits to DIS and Drell-Yan *CTEQ Phys.Rev. D 93, 033006 (2016)*

DIS

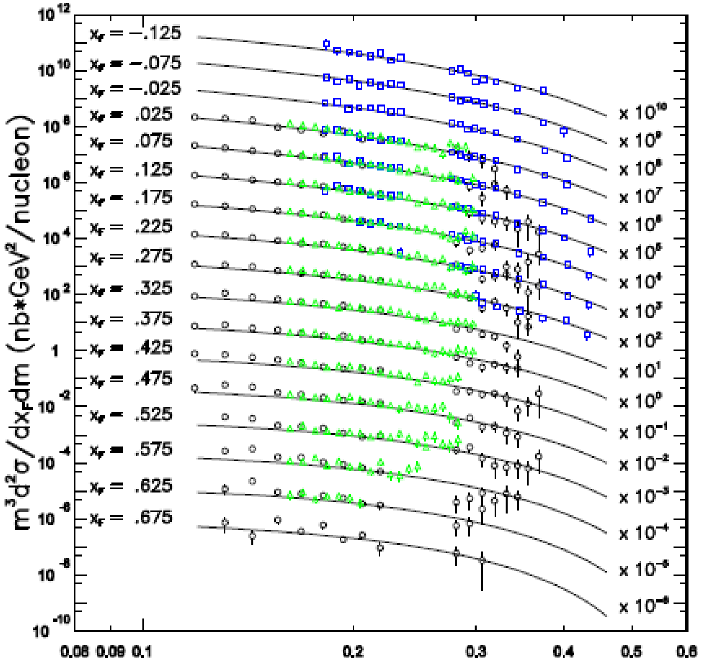




Drell-Yan



$p\,A \rightarrow \mu^+\mu^-\,X$

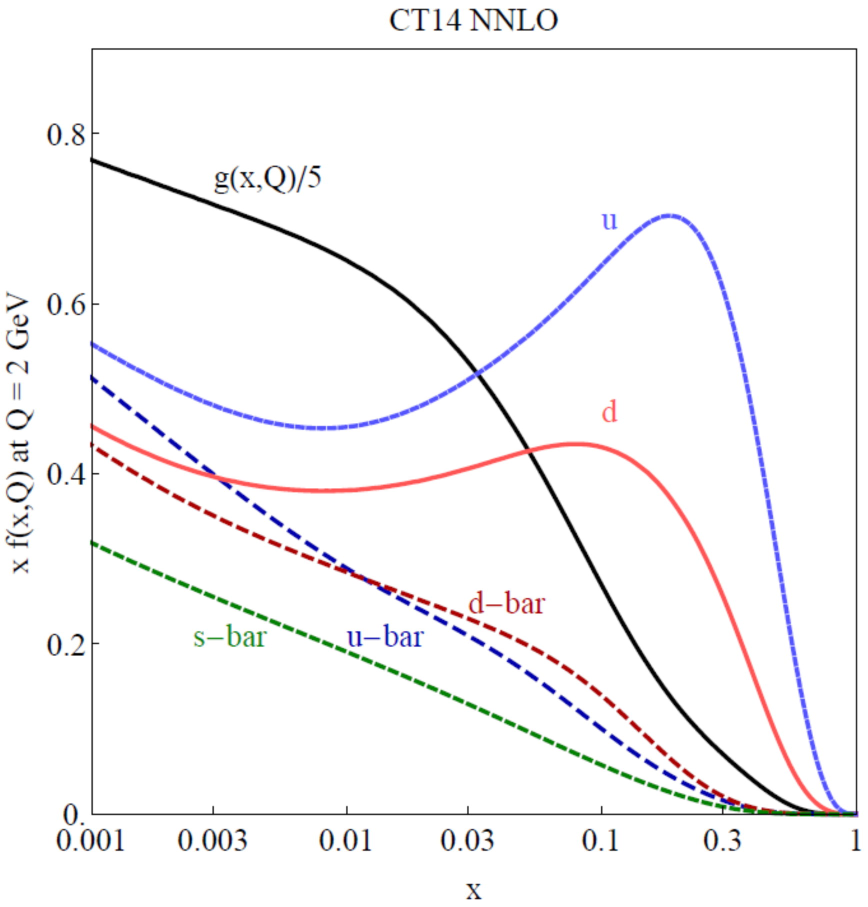


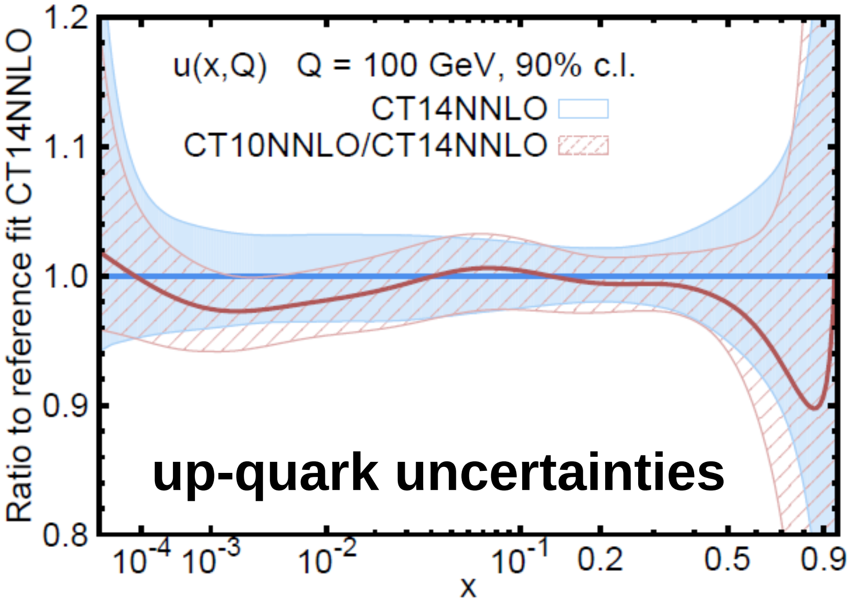
Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

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.

Quark and Gluon Momentum Distributions from CTEQ

CTEQ [Phys. Rev. D 93, 033006 (2016)]



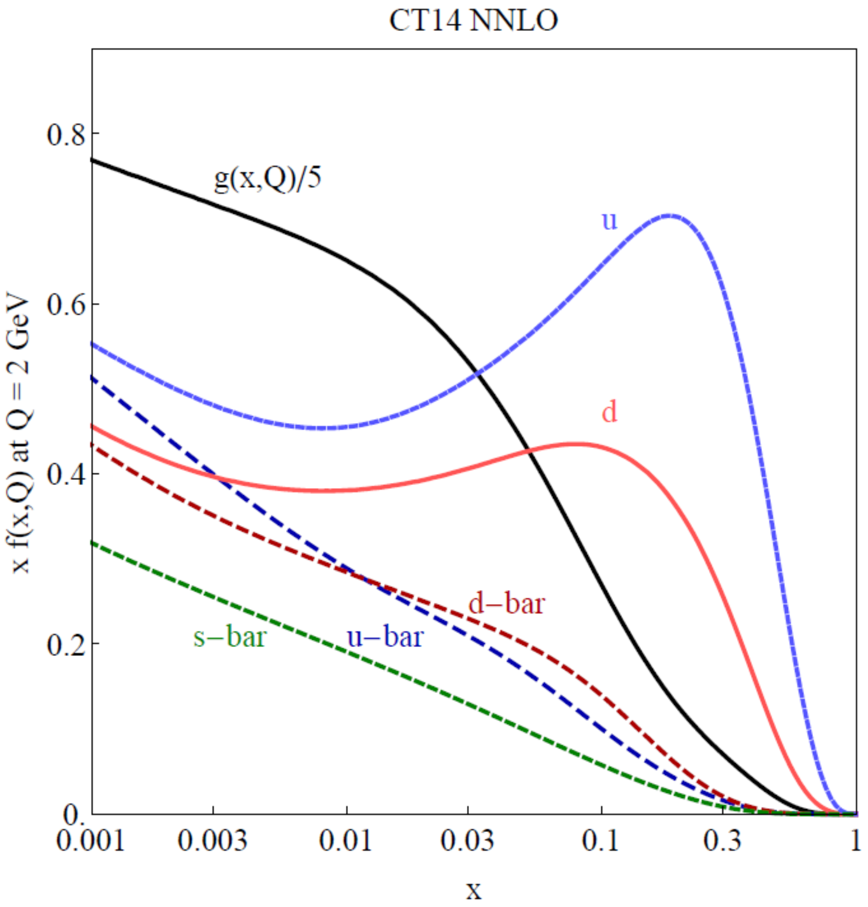


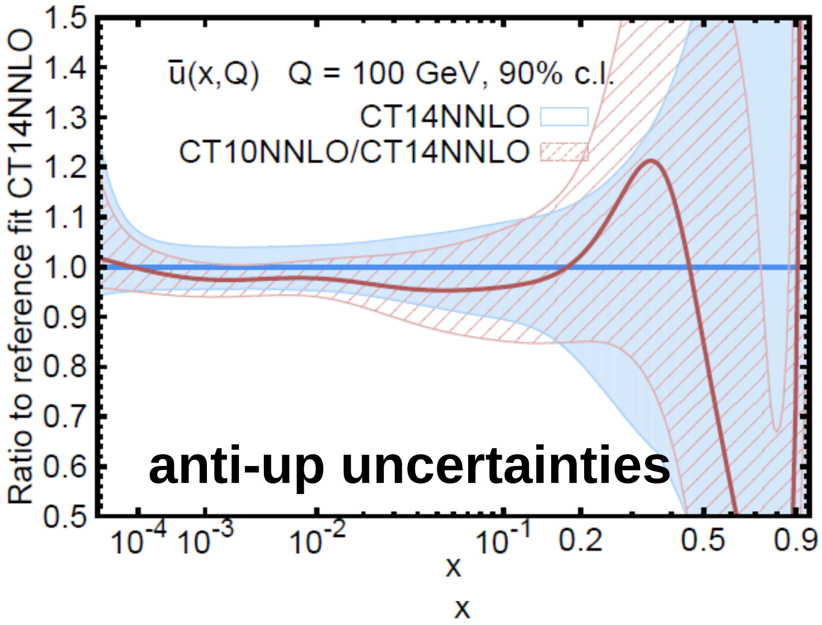
up-quark uncertainties

for example: ***$d(x,Q^2 = 2\ GeV^2)$***
is the number density for down quarks

Quark and Gluon Momentum Distributions from CTEQ

CTEQ Phys. Rev. D 93, 033006 (2016)



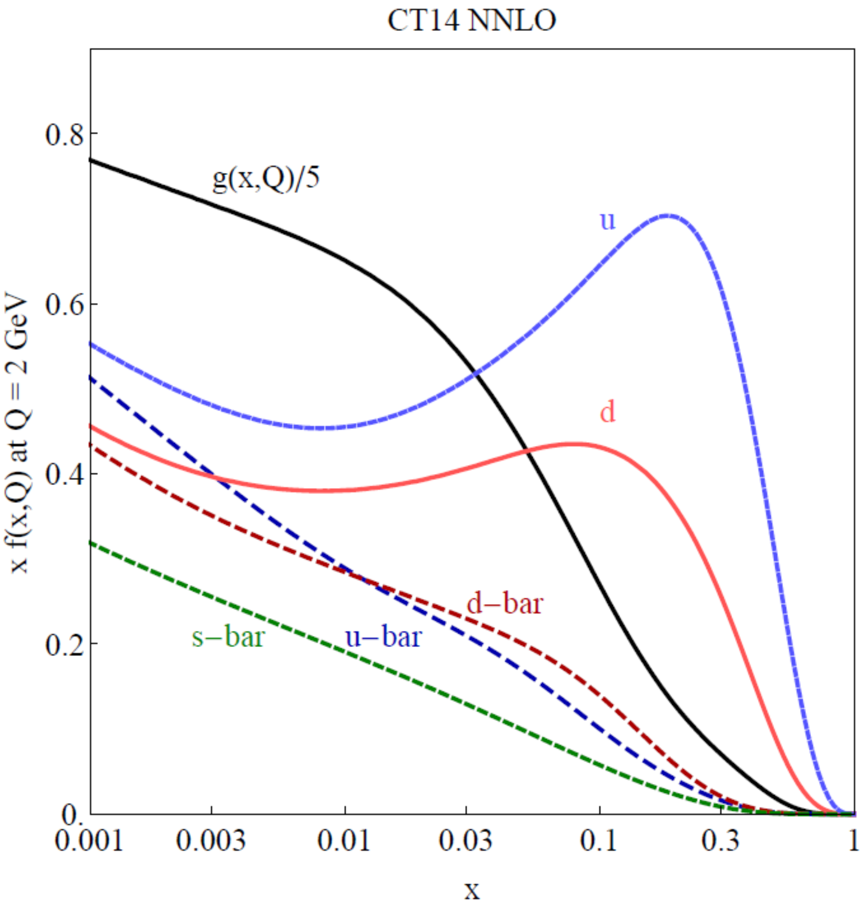


anti-up uncertainties

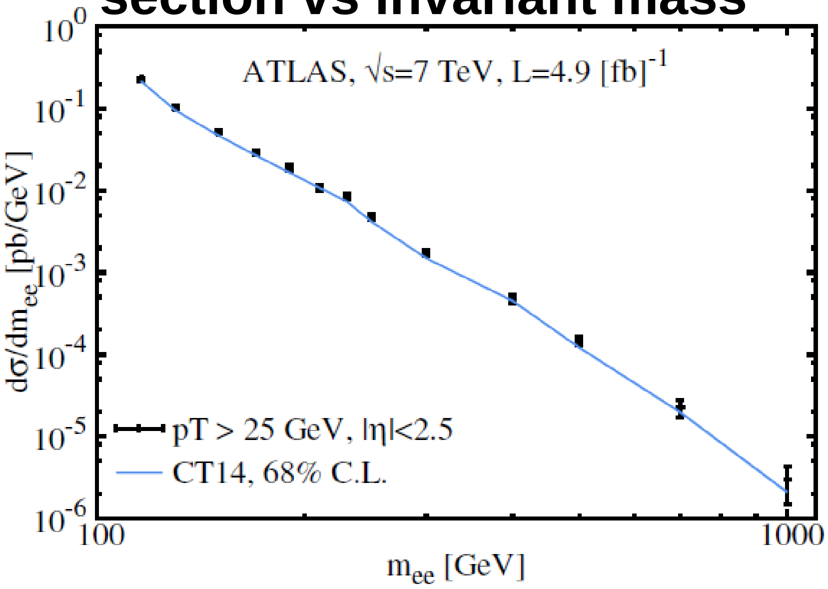
for example: $d(x,Q^2 = 2\ GeV^2)$
is the number density for down quarks

Quark and Gluon Momentum Distributions from CTEQ

CTEQ Phys. Rev. D 93, 033006 (2016)



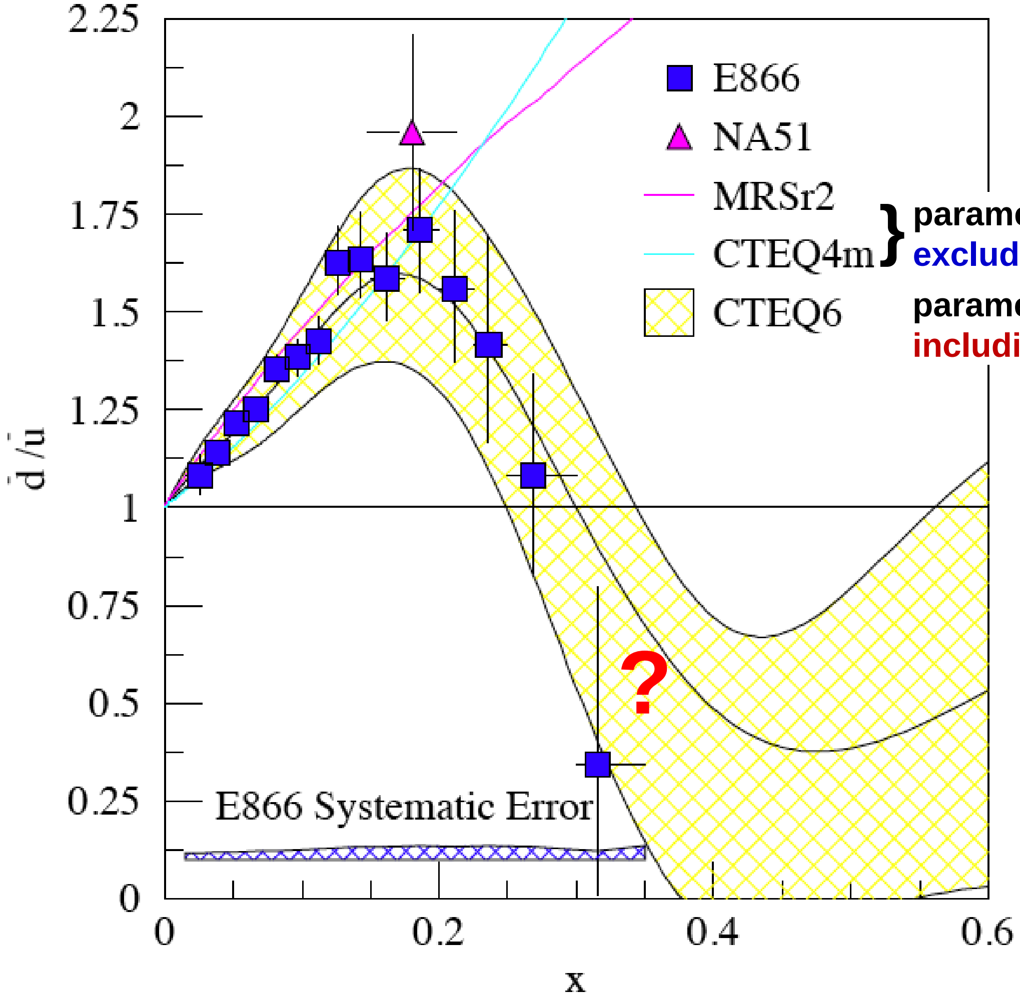
ATLAS Drell-Yan cross section vs invariant mass



for example: $d(x,Q^2 = 2\ \mathrm{GeV}^2)$
is the number density for down quarks

E866: Isospin Broken in the Anti-Quark Sea

Fermilab E866/NuSea 1998



} **parameterizations excluding E866 data**

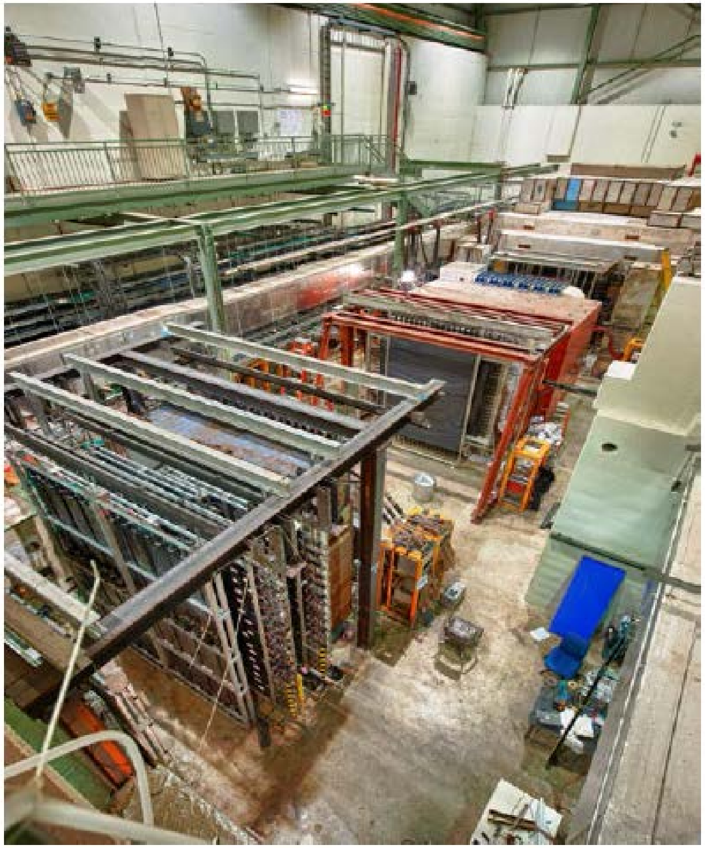
parameterization including E866 data

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

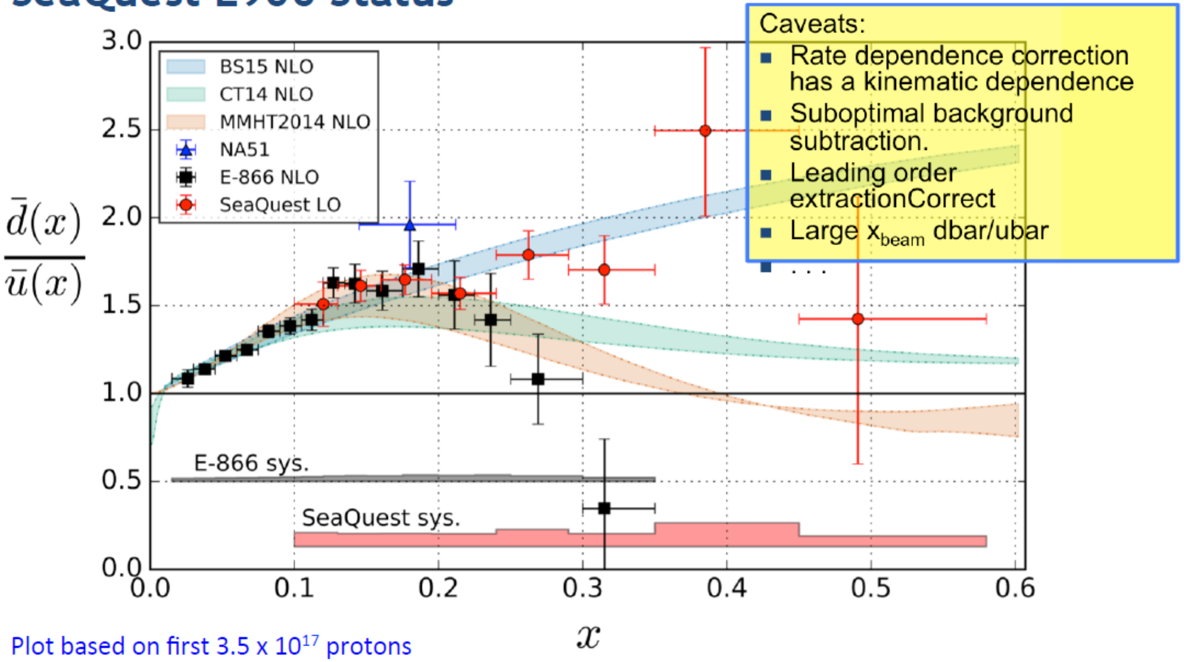
- Origin of sea quarks?
  $g \to q\bar{q}$ should naively give symmetric $q\,\bar{q}$.
- Non-perturbative contributions to sea-quark distributions:
  - meson-cloud model
  - chiral perturbation theory

Current Fermilab E906/SeaQuest

extending sea-quark measurements to larger x by using 120 GeV protons from Fermilab Main Injector.



SeaQuest E906 Status



Caveats:

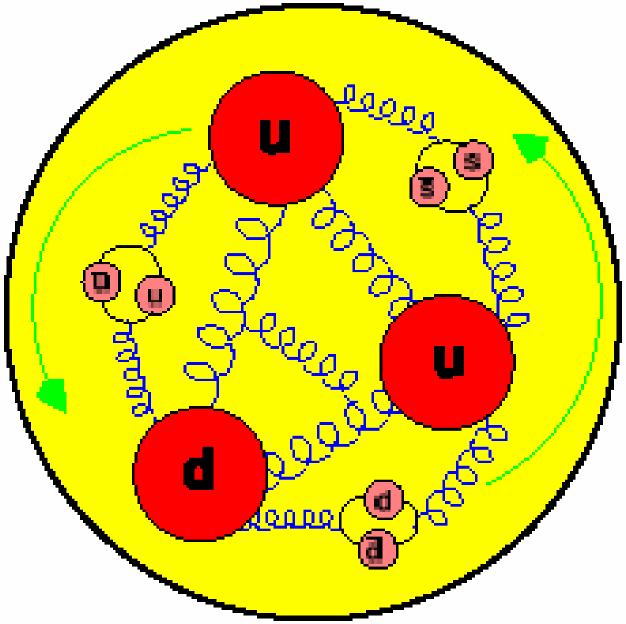
- Rate dependence correction has a kinematic dependence
- Suboptimal background subtraction.
- Leading order extractionCorrect
- Large x_{beam} dbar/ubar
- . . .

Plot based on first 3.5 x 10^{17} protons

25% of total expected beam current

from Paul Reimer's ECT talk, 10-2017

Proton Structure: Spin (Helicity) Distributions



$$x = \frac{p_{quark}}{p_{proton}}$$

Constituents:

quarks = u, d, s and gluons

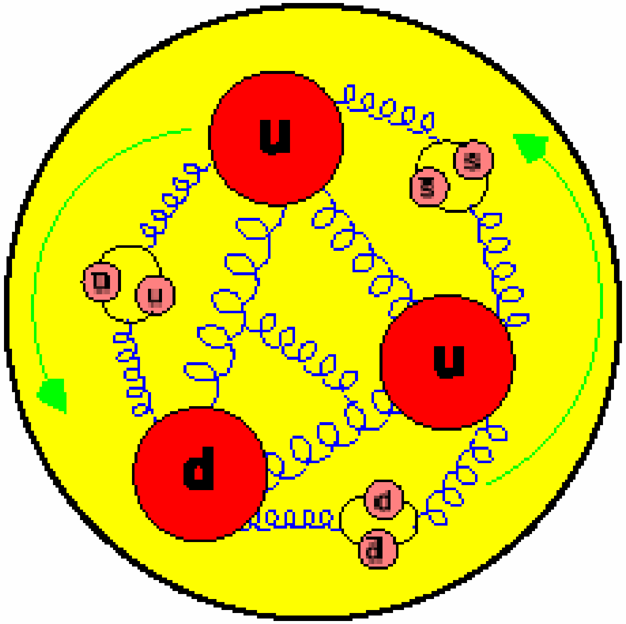
$\Rightarrow$ Total Quark Spin :

$$\Delta\Sigma = \sum_{q,\bar{q}} \int_{x=0}^{x=1} \Delta q(\mathrm{x})$$

$\Rightarrow$ Total Gluon Spin :

$$\Delta G = \int_{x=0}^{x=1} \Delta G(\mathrm{x})$$

Proton Structure: Helicity Sumrule



$$x = \frac{p_{quark}}{p_{proton}}$$

De-composition of the Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

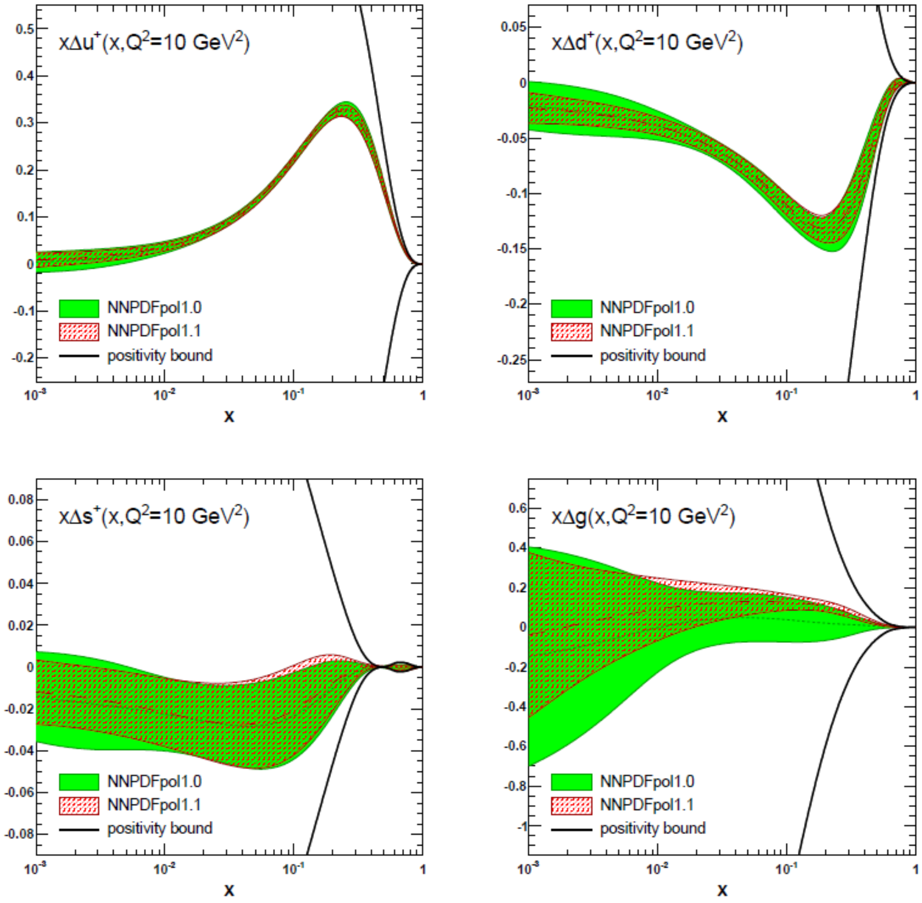
Quark Spin

Orbital Angular momentum

Gluon Spin

Quark and Gluon Helicity Distributions from NNPDF

E. Nocera et. Al. Nucl.Phys. B887 (2014) 276-308



For example:

$$\Delta^+ u\left(x, Q_0^2 = 10 GeV^2\right) = \Delta u\left(x, Q_0^2\right) + \Delta\bar{u}\left(x, Q_0^2\right)$$

Up and down quark helicity distributions are known. Still large uncertainties for gluon and anti-quarks.

RHIC: evidence for non-zero gluon spin contribution!

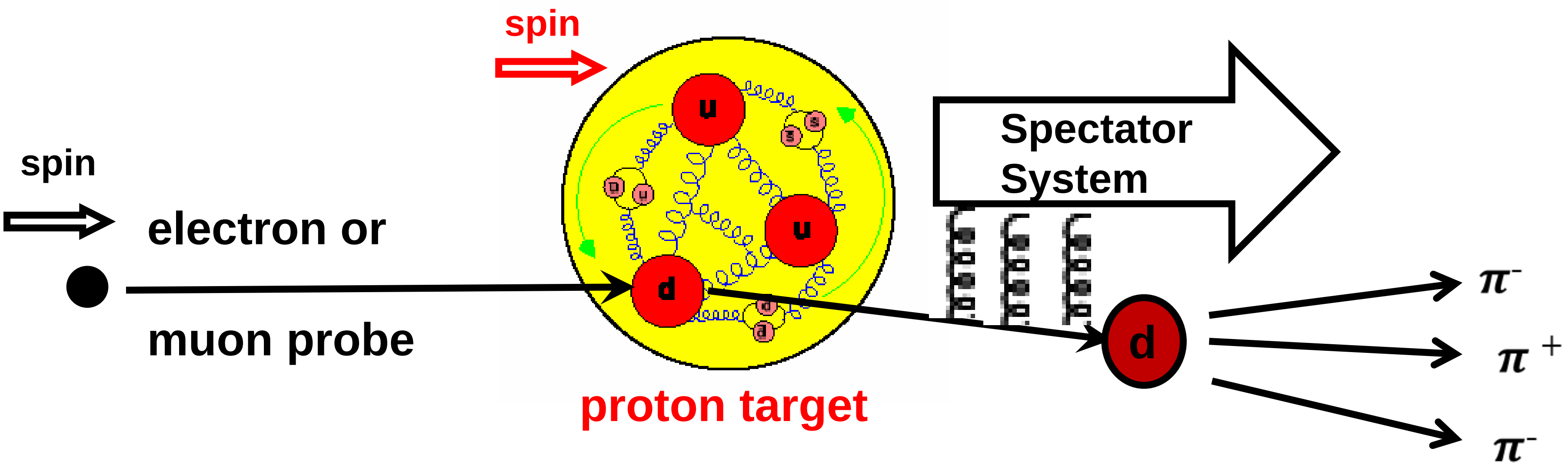
Transverse degrees of freedom:

Transverse proton/quark spin

Intrinsic transverse momentum of quarks k_T

Transverse momentum in hadron fragmentation p_T

Quark Helicity Distributions from Deep Inelastic Lepton-Nucleon Scattering



spin

electron or

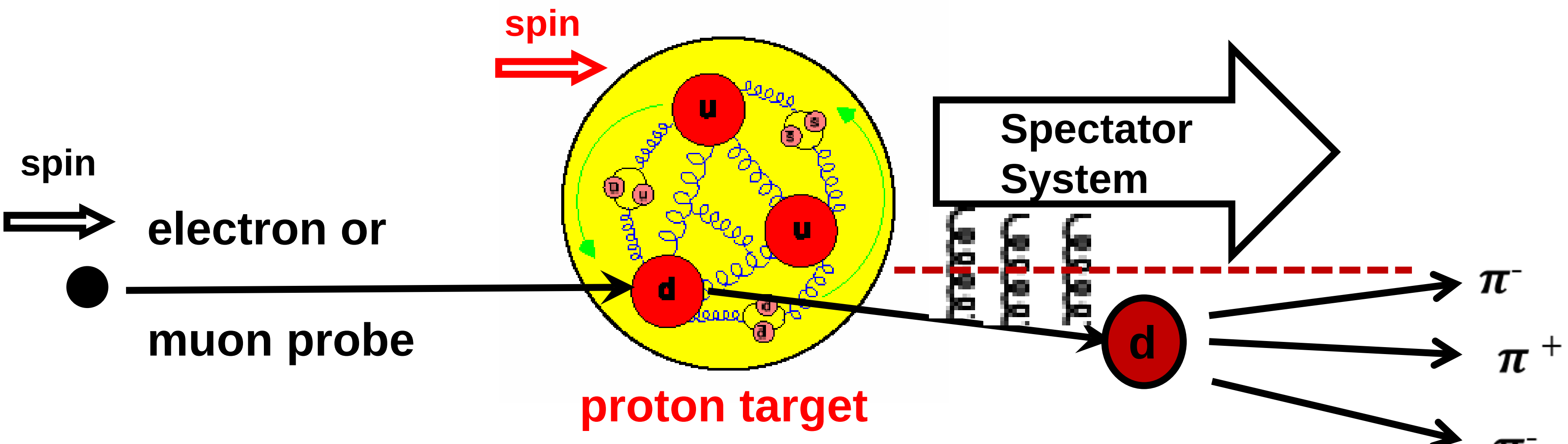
muon probe

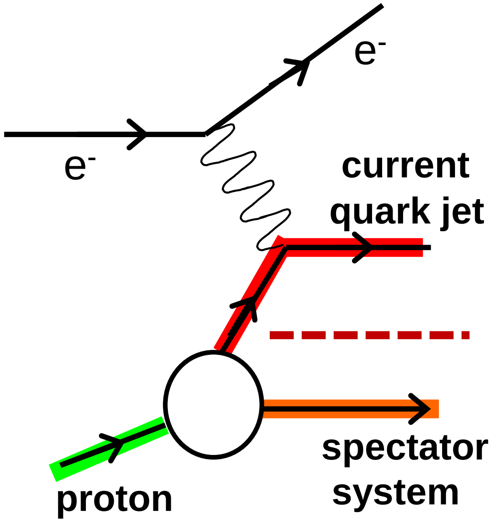
proton target

Spectator System

Magnetic Spectrometer eg. COMPASS to measure Momentum of final state Leptons and hadrons

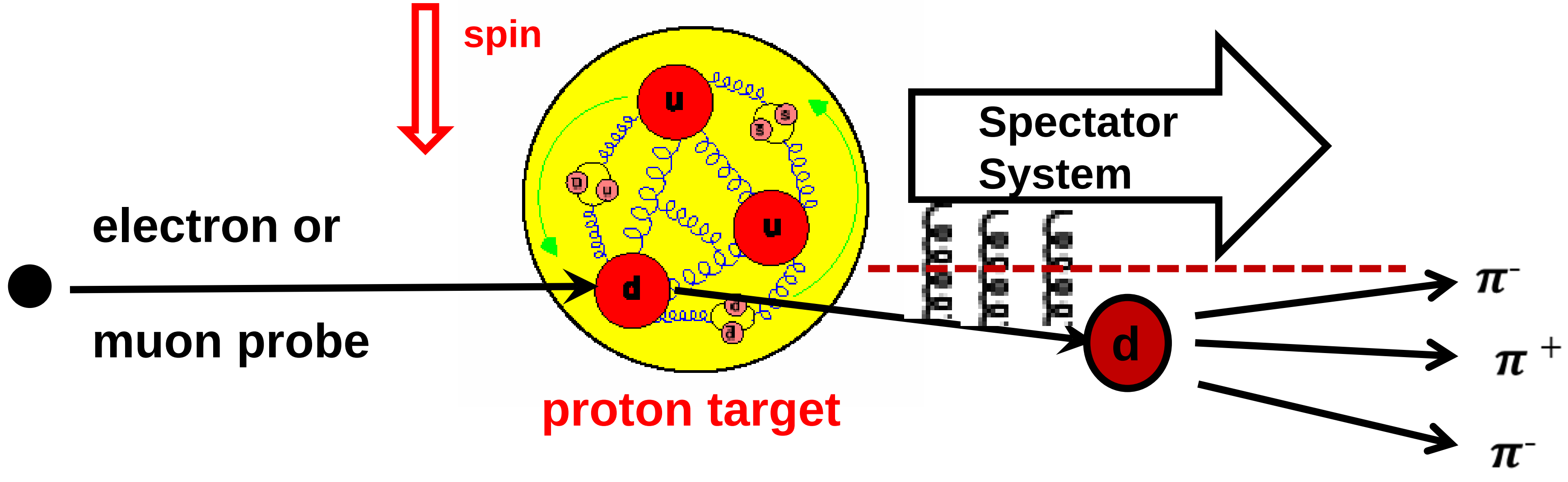
Quark Helicity Distributions from Deep Inelastic Lepton-Nucleon Scattering





factorize processes in the high energy lepton-quark scattering from target related processes

How is Transverse Spin Different?



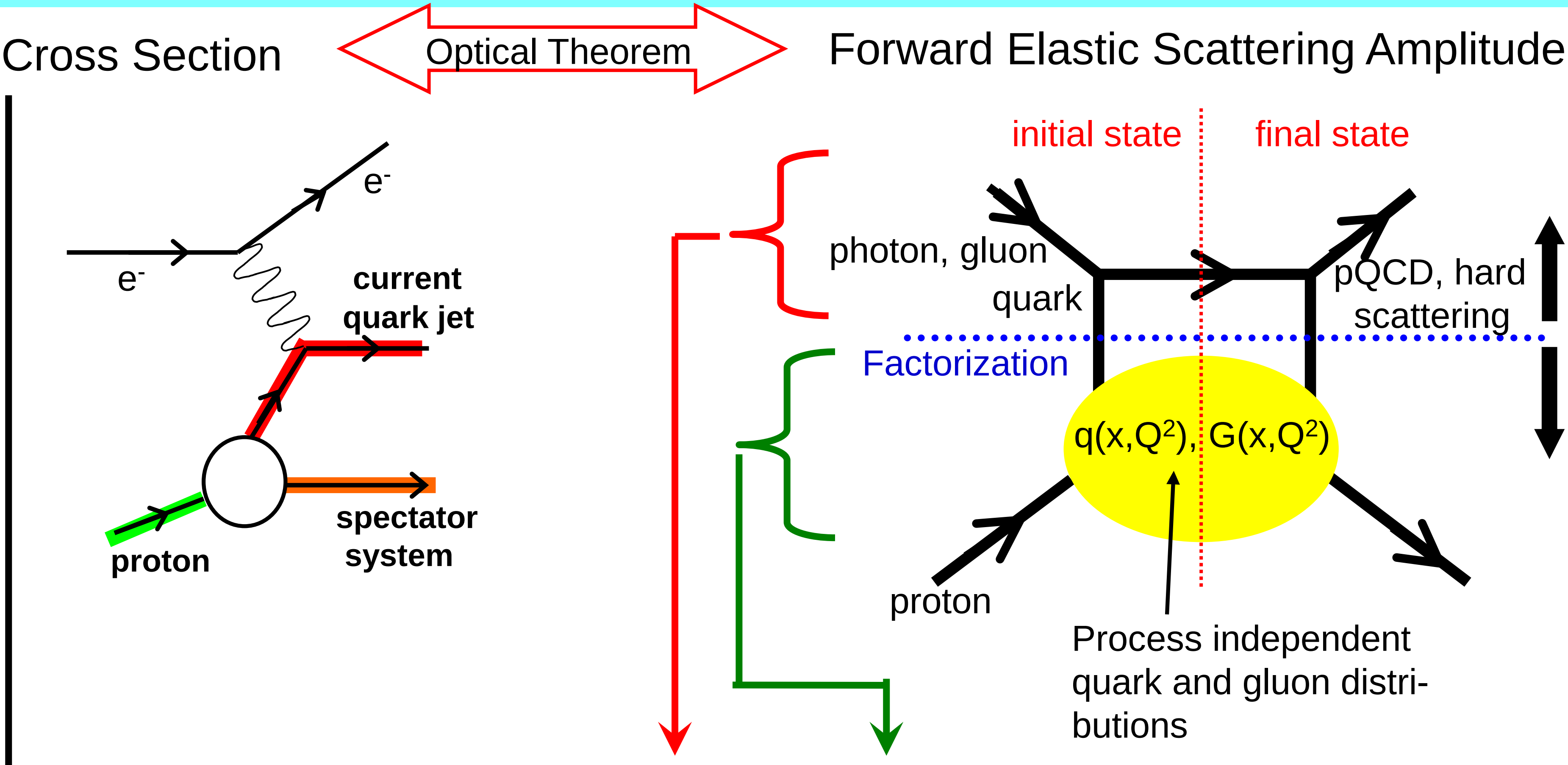
Are the quark distributions changed by a spin rotation?

At high probe energy: yes!

boosts and rotations do not commute!

Optical Theorem in Hard Scattering

Cross Section ⟺ Optical Theorem ⟺ Forward Elastic Scattering Amplitude



Process independent quark and gluon distributions

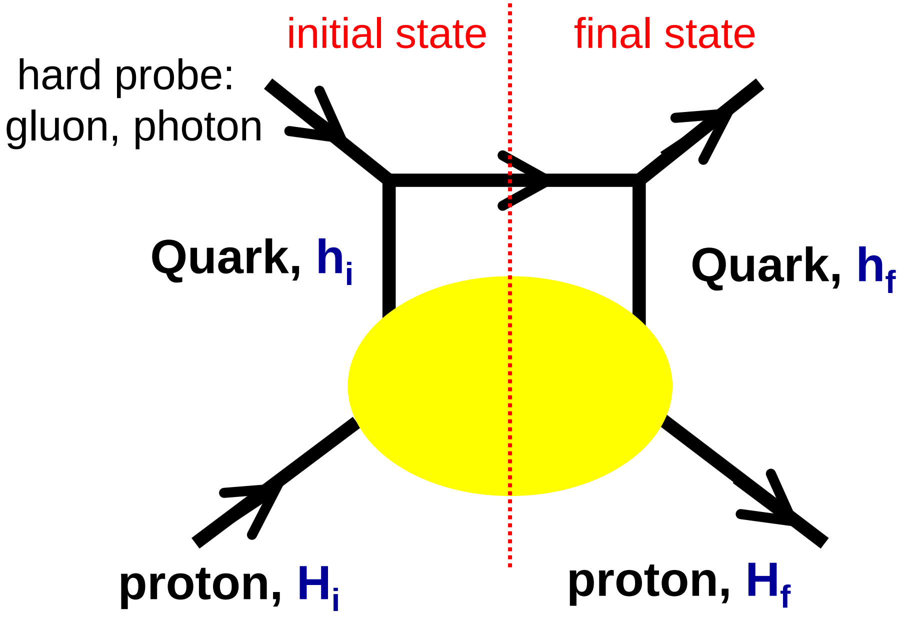
$$\sigma \sim \sum_{\mu\ldots\nu} \frac{1}{Q^{-t/2}} \boxed{C_{t=d-n_{\mu\ldots\nu}}(Q^2)} \boxed{\langle p \,|\, O^{\mu\ldots\nu} \,|\, p \rangle}$$

Wilson coefficients   Operator matrix element

Operator product expansion in twist parameter t, t=d-$n_{u..v}$

Helicity Amplitudes in Hard Scattering

Forward Scattering Amplitude



h: quark helicity
H: proton helicity
} In initial and final state

H_i	h_i		H_f	h_f	
$\frac{1}{2}$	$\frac{1}{2}$	$\rightarrow$	$\frac{1}{2}$	$\frac{1}{2}$	Helicity is conserved
$\frac{1}{2}$	$-\frac{1}{2}$	$\rightarrow$	$\frac{1}{2}$	$-\frac{1}{2}$	

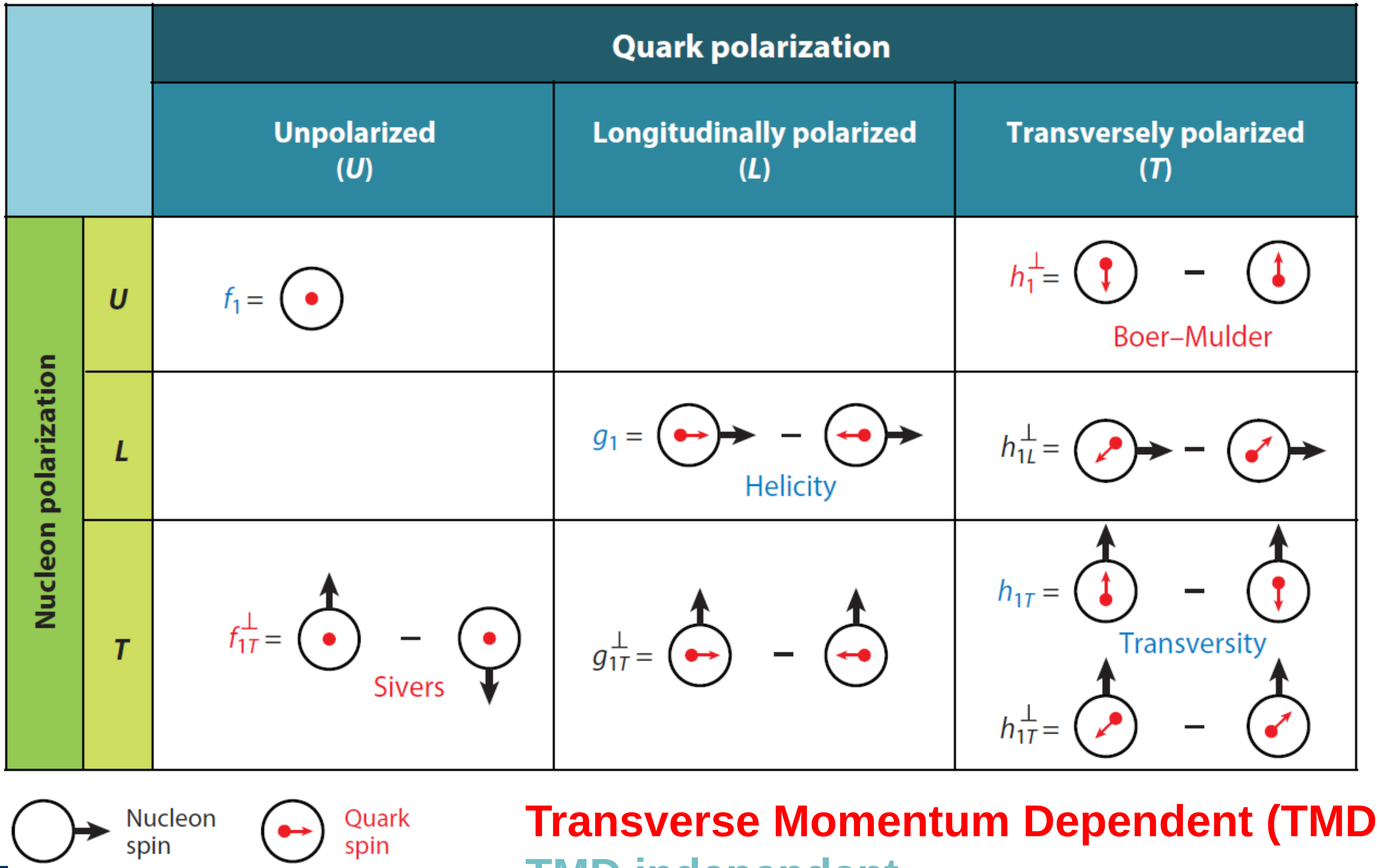
$\Rightarrow q(x,Q^2)\,,\, F_{1,2}(x,Q^2)$ helicity average

$\Delta q(x,Q^2),\, g_1\,(x,Q^2)$ helicity difference

H_i	h_i		H_f	h_f	
$\frac{1}{2}$	$-\frac{1}{2}$	$\rightarrow$	$-\frac{1}{2}$	$\frac{1}{2}$	helicity flip

$\Rightarrow \delta q(x,Q^2)$ transverse spin distributions for quarks: transversity

Decomposition of Helicity Flip Amplitudes at Leading Twist



		Quark polarization		
		Unpolarized (*U*)	**Longitudinally polarized (*L*)**	**Transversely polarized (*T*)**
Nucleon polarization	***U***	$f_1 =$		$h_1^\perp =$ − Boer–Mulder
	L		$g_1 =$ − Helicity	$h_{1L}^\perp =$ −
	T	$f_{1T}^\perp =$ − Sivers	$g_{1T}^\perp =$ −	$h_{1T} =$ − Transversity $h_{1T}^\perp =$ −

Transverse Momentum Dependent (TMD)

TMD independent

Proton Transverse Spin Structure: Transversity, Sivers and Boer-Mulders

Transversity : **correlation between transverse proton spin and quark spin** $h_{1T}(x,k_\perp^2)$ **or** $\delta q(x)$

S_p– S_q – coupling ?

Sivers : **correlation between transverse proton spin and quark transverse momentum** $\bar{f}_{1T}^{\perp q}(x,k_\perp^2)$

S_p-- L_q– coupling ?

Boer/Mulders: **correlation between transverse quark spin and quark transverse momentum** $h_1^{\perp q}(x,k_\perp^2)$

S_q-- L_q– coupling ?

Insight in spin-orbit structure of quarks in the proton …

First Experiment: Single Transverse Spin Asymmetries (SSA) in Hadron-Hadron Collisions

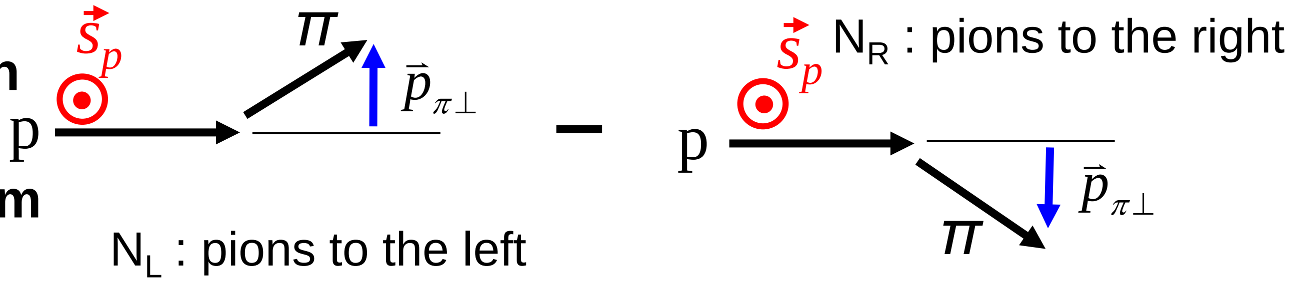
Single Transverse Spin Asymmetries (SSA) A_N in Polarized Proton-Proton Scattering

Example:
Inclusive π production in polarized p-p

$$p + p^{\uparrow} \longrightarrow \pi + X$$

one proton
is polarized!

Correlation proton spin
S_p vs $p_{\pi\perp}$
π transverse momentum



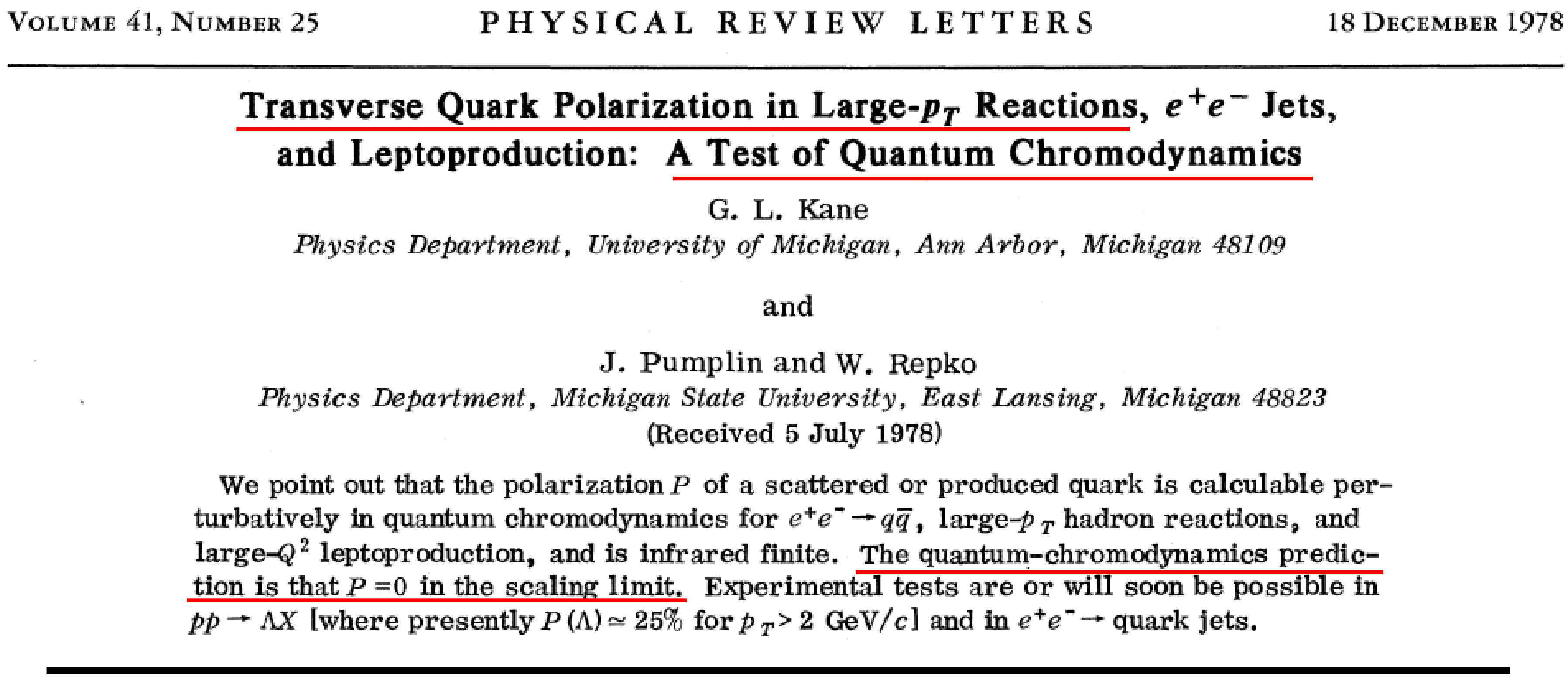
N_L : pions to the left

N_R : pions to the right

Single transverse spin asymmetries A_N

$$A_N = \frac{N_L - N_R}{N_L + N_R} \neq 0 \ ?$$

For High Energy Reactions: $A_N \rightarrow 0$
QCD Test ! (Kane, Pumplin, Repko, 1978)



VOLUME 41, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1978

Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

G. L. Kane
Physics Department, University of Michigan, Ann Arbor, Michigan 48109

and

J. Pumplin and W. Repko
Physics Department, Michigan State University, East Lansing, Michigan 48823

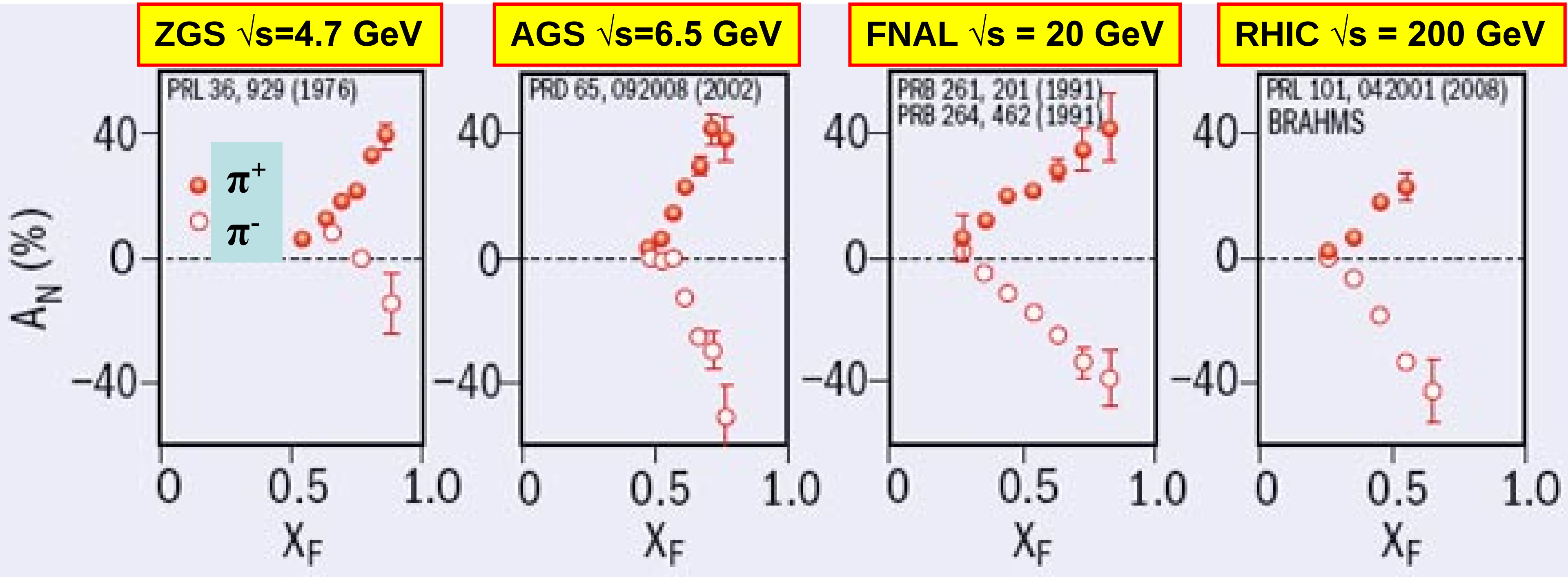
(Received 5 July 1978)

We point out that the polarization P of a scattered or produced quark is calculable perturbatively in quantum chromodynamics for $e^+e^- \rightarrow q\bar{q}$, large-$p_T$ hadron reactions, and large-Q^2 leptoproduction, and is infrared finite. The quantum-chromodynamics prediction is that $P=0$ in the scaling limit. Experimental tests are or will soon be possible in $pp \rightarrow \Lambda X$ [where presently $P(\Lambda) \simeq 25\%$ for $p_T > 2$ GeV/c] and in $e^+e^- \rightarrow$ quark jets.

$$A_N \propto \frac{\alpha_s m_q}{\sqrt{s}} \quad \text{example, m}_\text{q} = 3MeV, \sqrt{s} = 20\,GeV, A_N \approx 10^{-4}$$

Experiment: Large SSA Observed over Large Range of Scales !

Experiment: $A_N >> 10^{-4}$ for 4 GeV < $\sqrt{s}$ < 200 GeV for charged pions !



ZGS $\sqrt{s}$=4.7 GeV

AGS $\sqrt{s}$=6.5 GeV

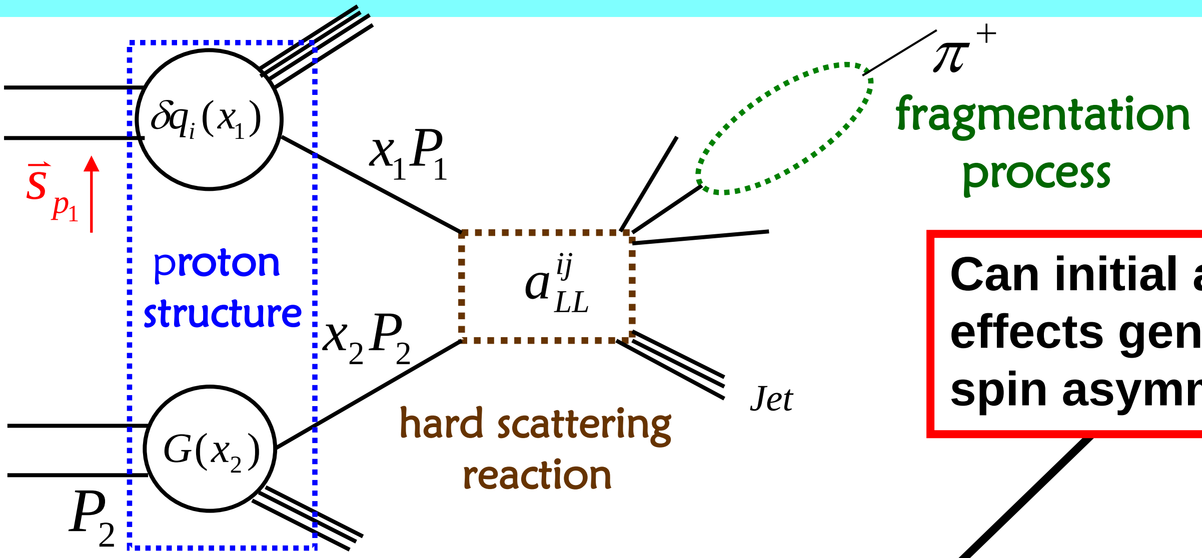
FNAL $\sqrt{s}$ = 20 GeV

RHIC $\sqrt{s}$ = 200 GeV

Soft effects due to QCD dynamics in hadrons remain relevant up to scales where pQCD can be used to describe the scattering process!

from Christine Aidala, Spin 2008 and Don Crabb & Alan Krisch in then Spin 2008 Summary, CERN Courier, 6-2009

Origin of Large SSA → Inspect Factorized Components of Cross Section



Can initial and/or final state effects generate large transverse spin asymmetries? (A_N ~10^{-1})

pQCD

$$\frac{d^3\sigma^\uparrow(pp^\uparrow \to \pi^+ X)}{dx_1 dx_2 dz} \propto q_i^\uparrow(x_1, k_{q,T}) \cdot G(x_2) \times \frac{d^3\hat{\sigma}^\uparrow(q_i q_j \to q_k q_l)}{dx_1 dx_2} \times FF_{q_{k,l}}(z, p_{h,T})$$

Initial state – proton structure

Kane, Pumplin, Repko → a_{LL}~10^{-4}

Final state – hadron fragmentation

Transverse Spin in QCD: Two Solutions

(I) “Transversity” quark-distributions and Collins fragmentation

Correlation between proton- und quark-spi and spin dependent fragmentation

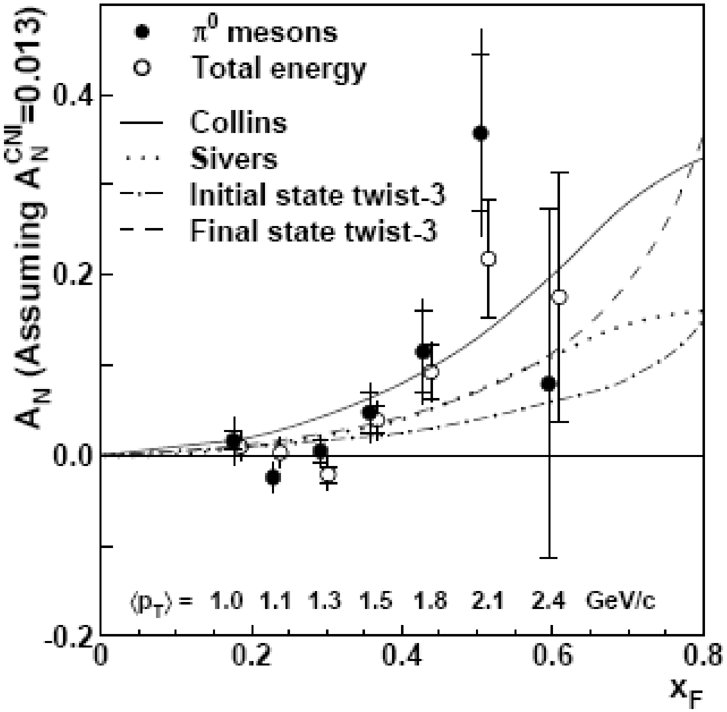
$$\propto \underbrace{\delta q(x)}_{\text{Quark transverse spin distribution}} \cdot \underbrace{H_1^{\perp}(z_2, p_T^2)}_{\text{Collins FF}}$$

(II) Sivers quark-distribution⁺

Correlation between proton-spin and transverse quark momentum

$$\propto \underbrace{\bar{f}_{1T}^{\perp q}(x, k_\perp^2)}_{\text{Sivers distribution}} \cdot D_q^h(z)$$

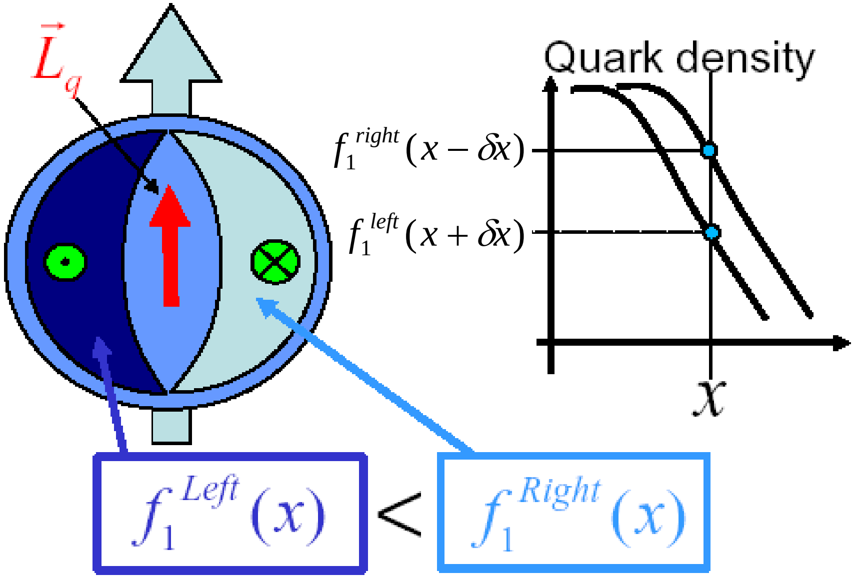
STAR, PRL-92:171801, 2004



Sivers: Connection to Orbital Angular Momentum?

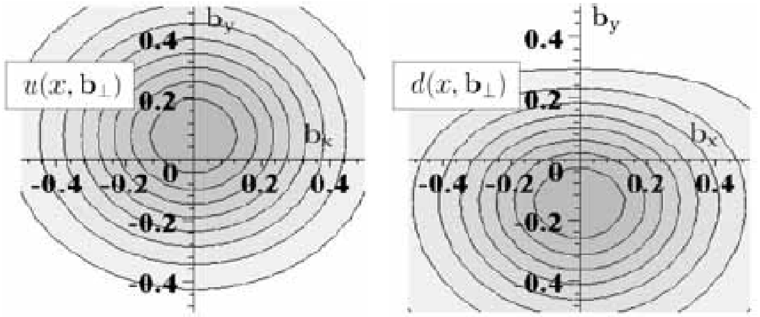
Semi-classical picture :

If quarks have L_q , probability to find quark which carries momentum fraction of "x" is different between left & right sides in the nucleon (viewed from virtual photon).



$$\boxed{f_1^{Left}(x)} < \boxed{f_1^{Right}(x)}$$

***x_q* is blue/red shifted!**



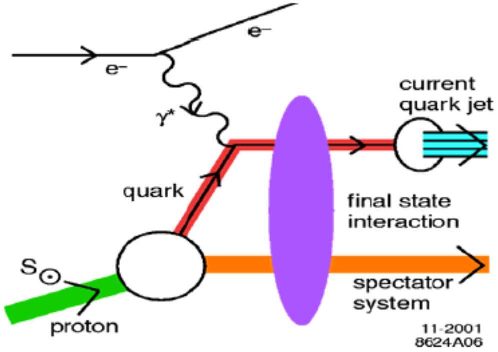
M. Burkardt
(Nucl.Phys. A735 (2004) 185-199)

➔ Sivers function can be viewed an impact-parameter dependent PDF.

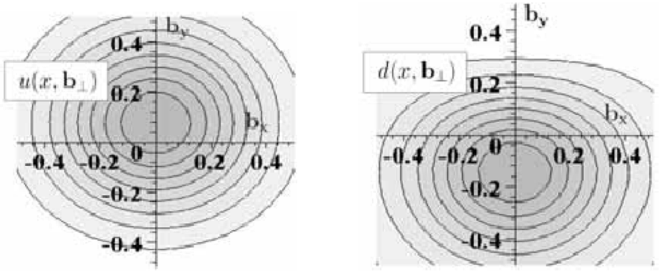
from Matthias Burkhardt

Sivers Effect: Final State Interaction

Sivers effect is an interference with a final state interaction of quark with spectator system.

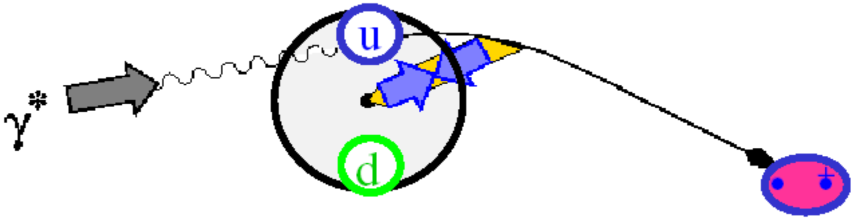


(Int.J.Mod.Phys.A18:1327-1334,2003)



(Nucl.Phys. A735 (2004) 185-199)

Can be understood as soft-gluon exchange in final state.

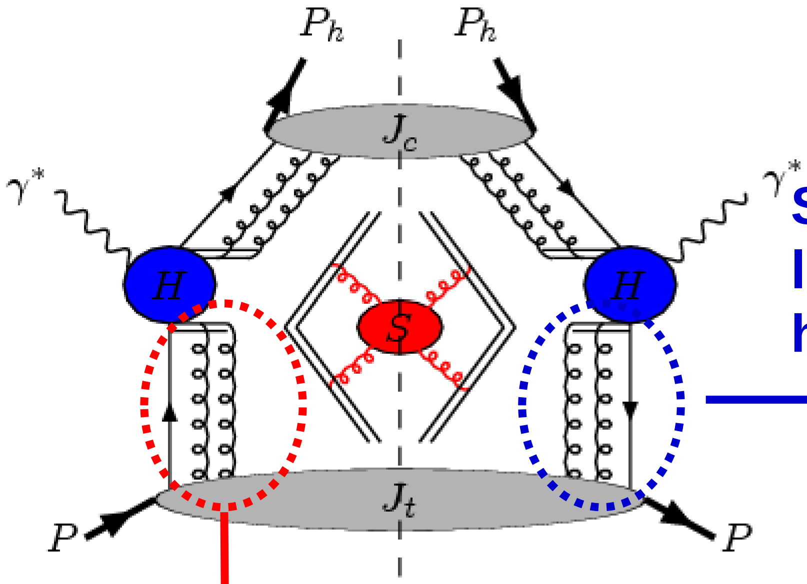


Final state soft gluons ?

What happens to factorization and universality ?

→Gauge link formalism, process dependence of Sivers effect!

Theoretical Description:
Include soft Gluon Exchange in the Initial and Final State of Hard Scattering Processes



Sum final state gluon exchange: gauge link and insert gauge link integral in hard scattering matrix element

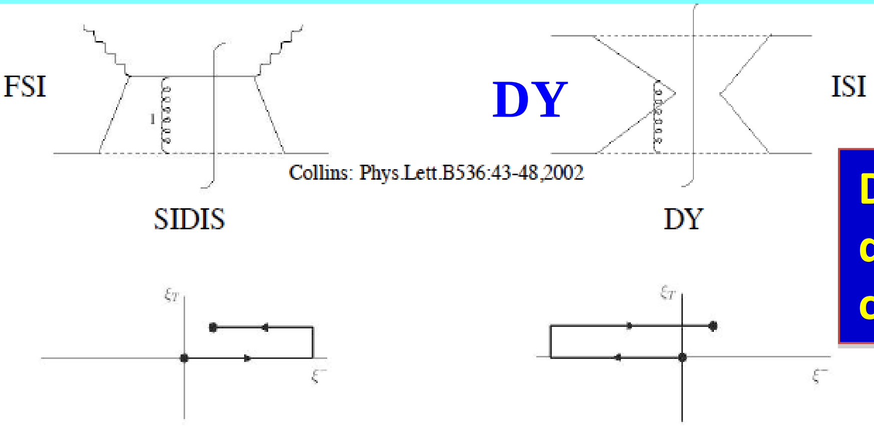
$$\sigma \sim \sum_{\mu\ldots\nu} \frac{1}{Q^{-t/2}} C_{t=d-n_{\mu\ldots\nu}}(Q^2)\left\langle p \,|\, O^{\mu\ldots\nu} \,|\, p \right\rangle$$

Sum initial state gluon exchange: gauge link and insert gauge link in hard scattering matrix element

Sign Change of Sivers- and Boer-Mulders Functions Between SIDIS and DY

SIDIS

DY



Collins: Phys.Lett.B536:43-48,2002

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

Sivers $f_{1T}^{\perp}(x,\mathbf{k}_T)\Big|_{SIDIS} = -f_{1T}^{\perp}(x,\mathbf{k}_T)\Big|_{DY}$

Boer-Mulders $h_{1}^{\perp}(x,\mathbf{k}_T)\Big|_{SIDIS} = -h_{1}^{\perp}(x,\mathbf{k}_T)\Big|_{DY}$

Need to confirm sign reversal in polarized Drell-Yan!

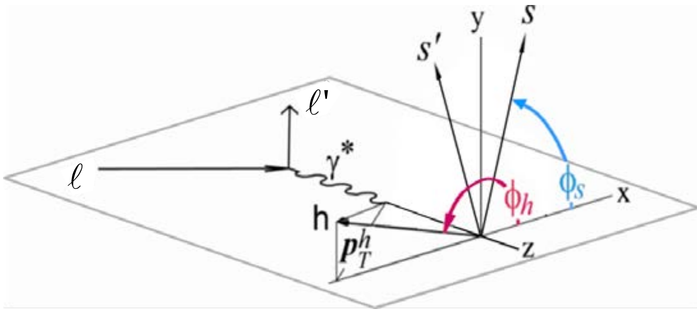
NSAC performance Milestone HP13

TEST "modified" universality of TMD pdfs!

TMD Modulations in the SIDIS and Drell-Yan Cross Sections

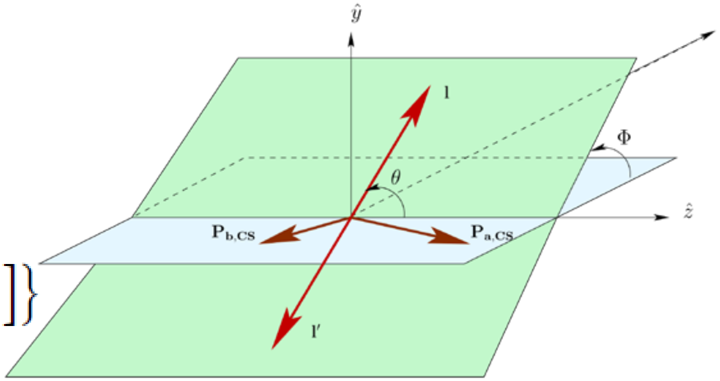
SIDIS:

$$\frac{d\sigma}{dx\,dy\,dz\,d\psi\,d\phi_h\,dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\sigma_U\Big\{1+\varepsilon\cos(2\phi_h)A_{UU}^{\cos(2\phi_h)}$$
$$+S_T\Big[\sin(\phi_h-\phi_S)A_{UT}^{\sin(\phi_h-\phi_S)}+\varepsilon\sin(\phi_h+\phi_S)A_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+\varepsilon\sin(3\phi_h-\phi_S)A_{UT}^{\sin(3\phi_h-\phi_S)}\Big]$$
$$+S_T P_l\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)A_{LT}^{\cos(\phi_h-\phi_S)}\Big]\Big\}$$



DY:

$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha^2}{\Phi q^2}\hat{\sigma}_U\Big\{\Big(1+\cos^2(\theta)+\sin^2(\theta)A_{UU}^{\cos(2\phi)}\cos(2\phi)\Big)$$
$$+S_T\Big[(1+\cos(\theta))A_{UT}^{\sin(\phi_S)}\sin(\phi_S)$$
$$+\sin^2(\theta)\Big(A_{UT}^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)+A_{UT}^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\Big)\Big]\Big\}$$



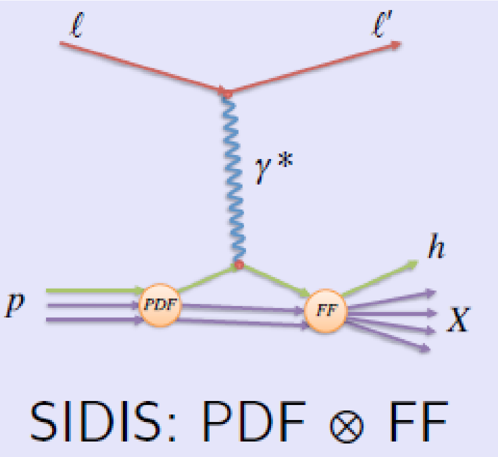
Modulation Amplitudes vs TMDs

SIDIS:

$$A_{UU}^{\cos(2\phi_h)} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$$

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

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



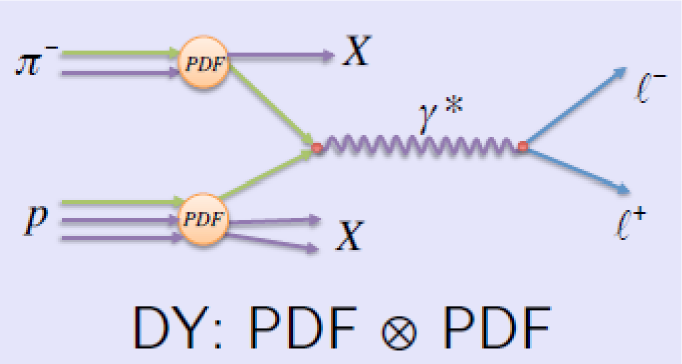
SIDIS: PDF ⊗ FF

DY:

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

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

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



DY: PDF ⊗ PDF

Avoids dependence on FFs !

COMPASS: TMD Observables

COMPASS at CERN: unique capability of measuring TMD observables with lepton beams (SIDIS) and hadron beams (Drell-Yan)

Transverse Momentum Dependent PDFs

Single Spin Asymmetries in SIDIS from COMPASS

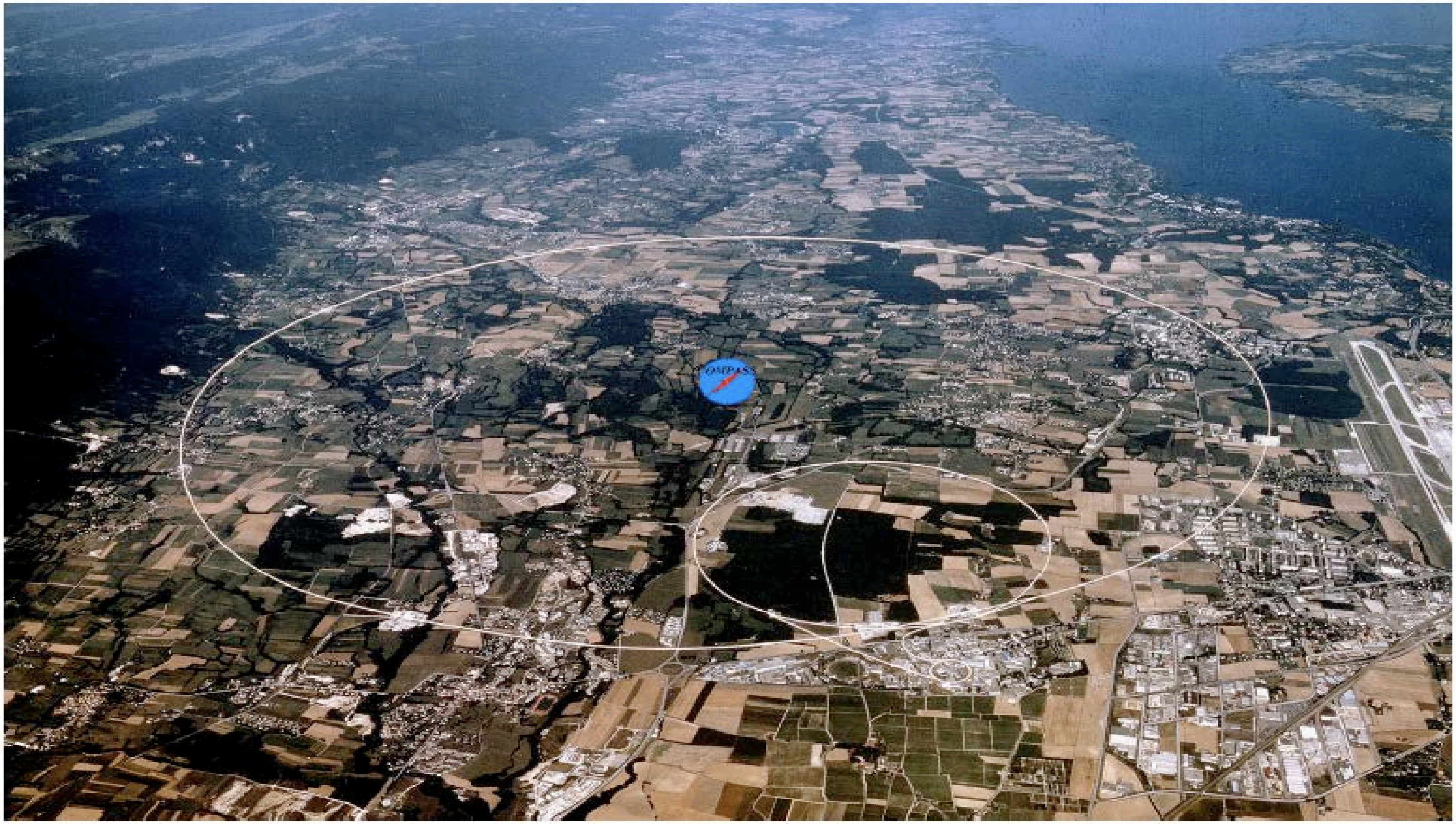
Constraining Boer Mulders-, Sivers- and Transversity-distributions

Drell-Yan at COMPASS

- **Set-up**
- **Data taking in 2014 and 2015**
- **Plans for 2018**
- **First Steps towards the future: COMPASS 2020**

COMPASS at the CERN SPS

COmmon Muon Proton Apparatus for Structure and Spectroscopy

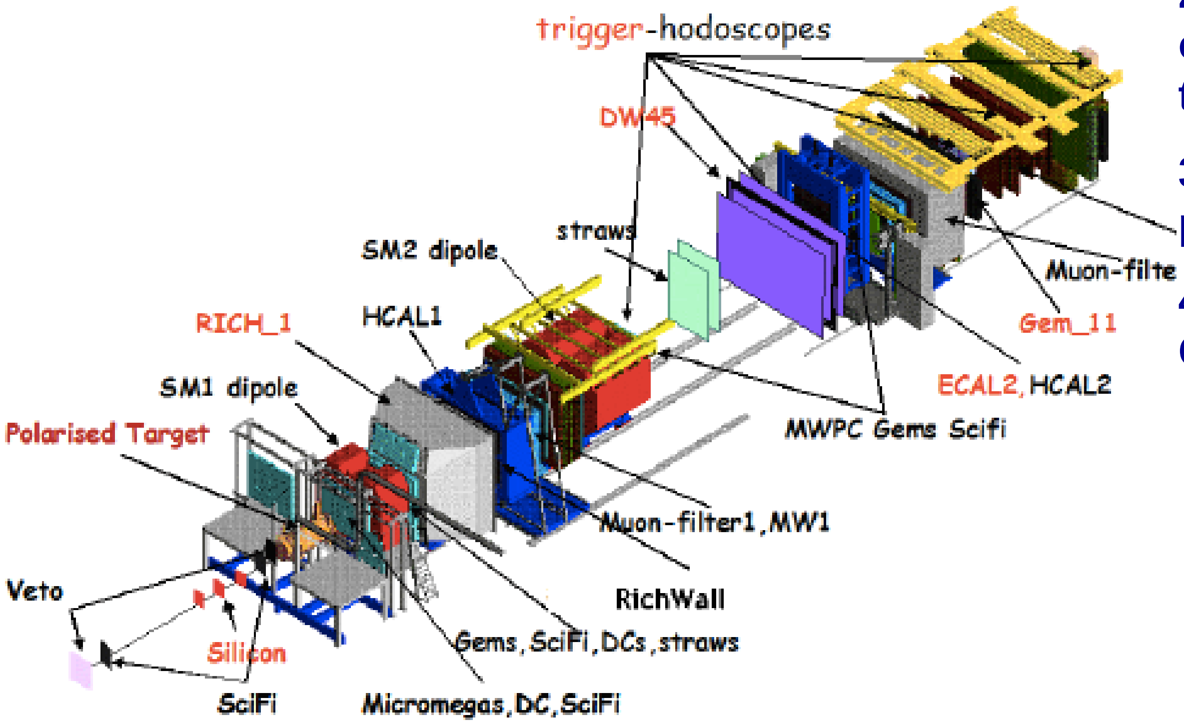


COMPASS – Important Instrumentation Features

Two stage large acceptance spectrometers with high rate capability:

❶ Large Angle Spectrometer (LAS)

❷ Small Angle Spectrometer (SAS)



1.Muon, electron or hadron secondary beams with the momentum range 20-250 GeV and intensities up to 10^8 particles per second.

2. Solid state polarized targets, NH_3 or ^{6}LiD, as well as liquid hydrogen target and nuclear targets.

3.Powerful tracking system – 350 planes.

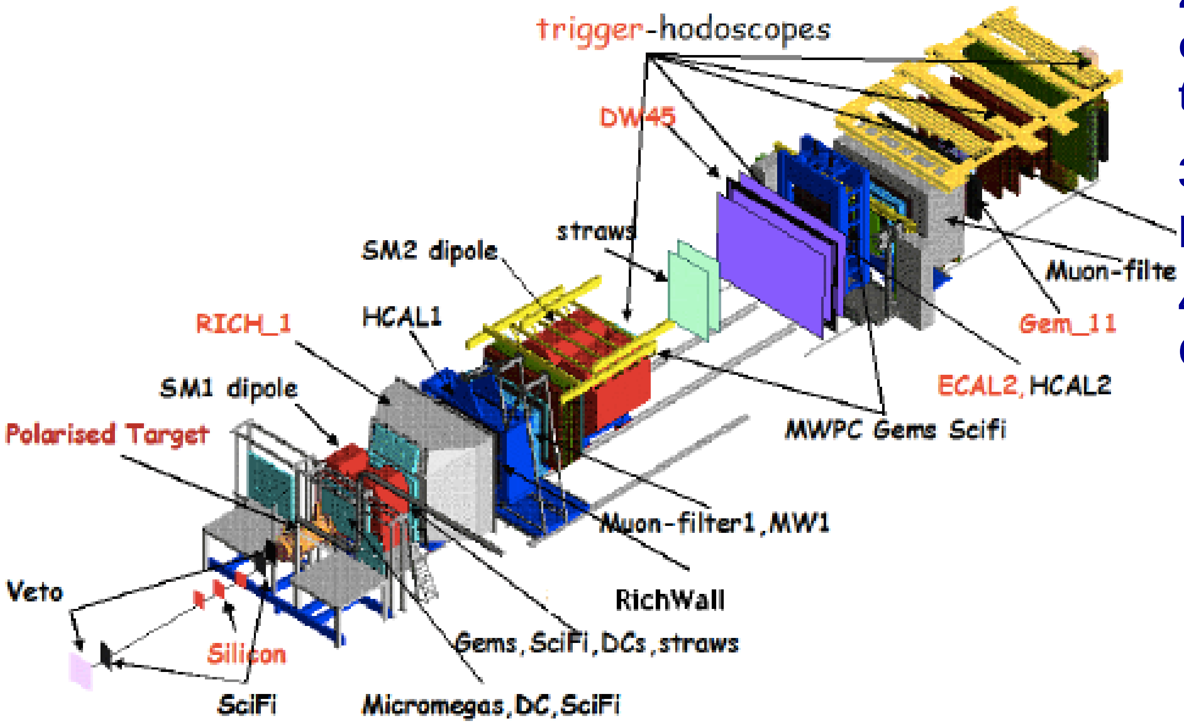
4. Versatile PID – RICH, Muon Walls, Calorimeters.

RHIC based hadron ID

COMPASS – Important Instrumentation Features

Two stage large acceptance spectrometers with high rate capability:

1. Large Angle Spectrometer (LAS)
2. Small Angle Spectrometer (SAS)



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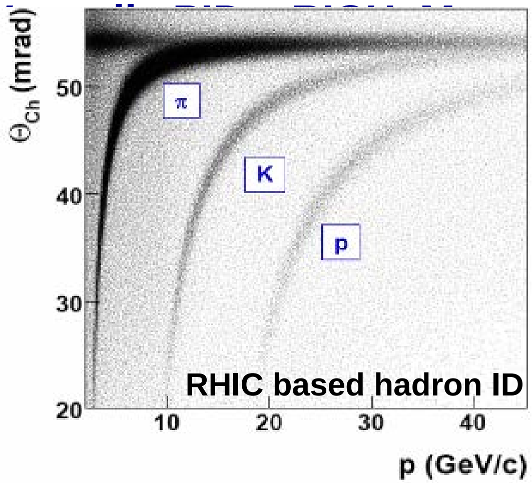
3.Powerful tracking system – 350 planes.

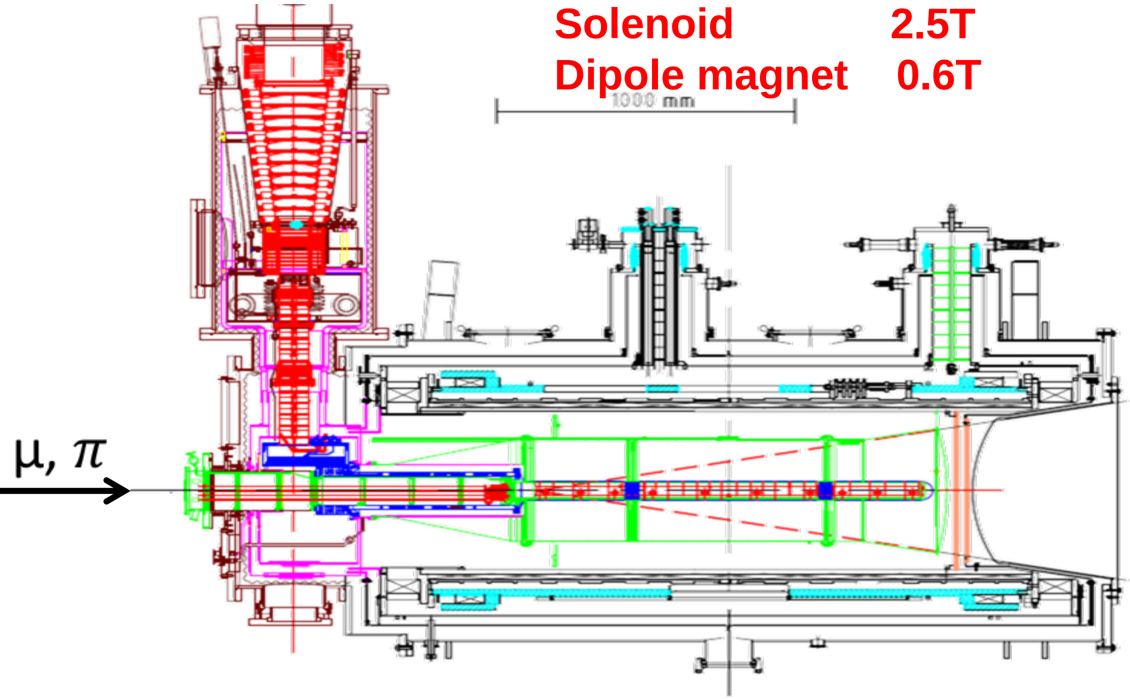
4. V … Walls, Cal



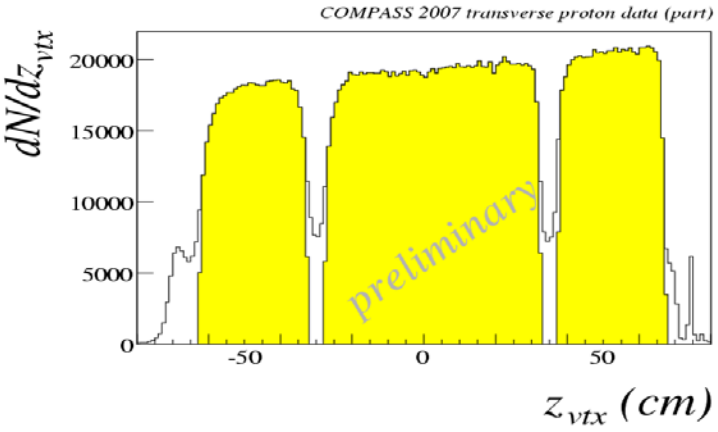
COMPASS – Important Instrumentation Features

^{3}He – ^{4}He dilution refrigerator (T~50mK)

Solenoid	2.5T
Dipole magnet	0.6T



Vertex distribution for SIDIS

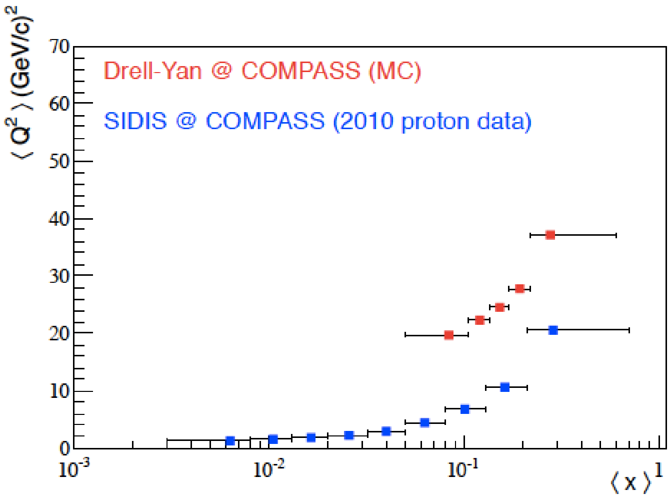


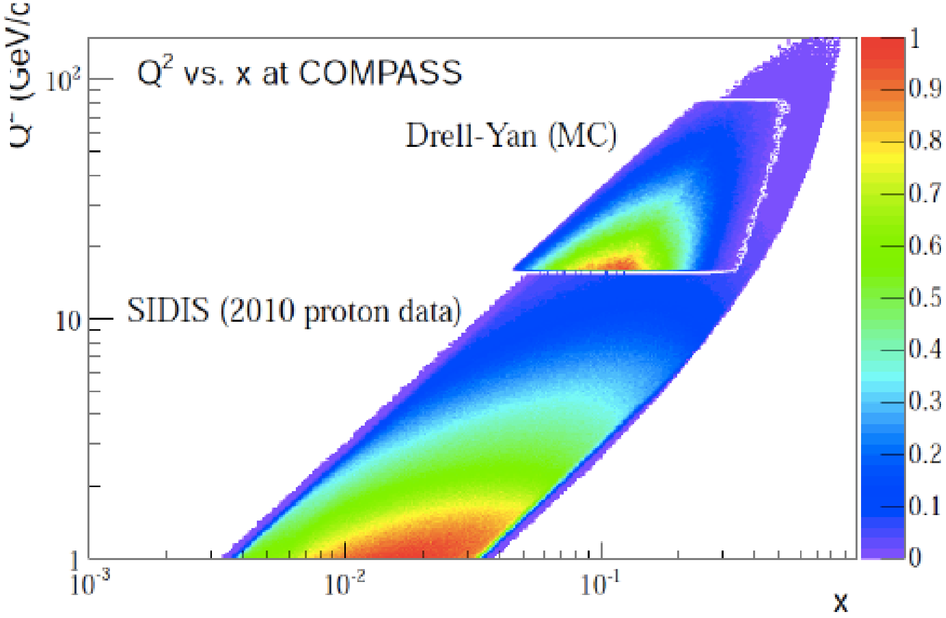
Opposite polarization in different target segments reversed frequently

	d (^{6}LiD)	p (NH_3)
Polarization	50%	90%
Dilution factor	40%	16%

Kinematic Coverage: SIDIS vs Drell-Yan

The phase space for Drell-Yan and SIDIS processes partially overlap in the x-Q^2 plane

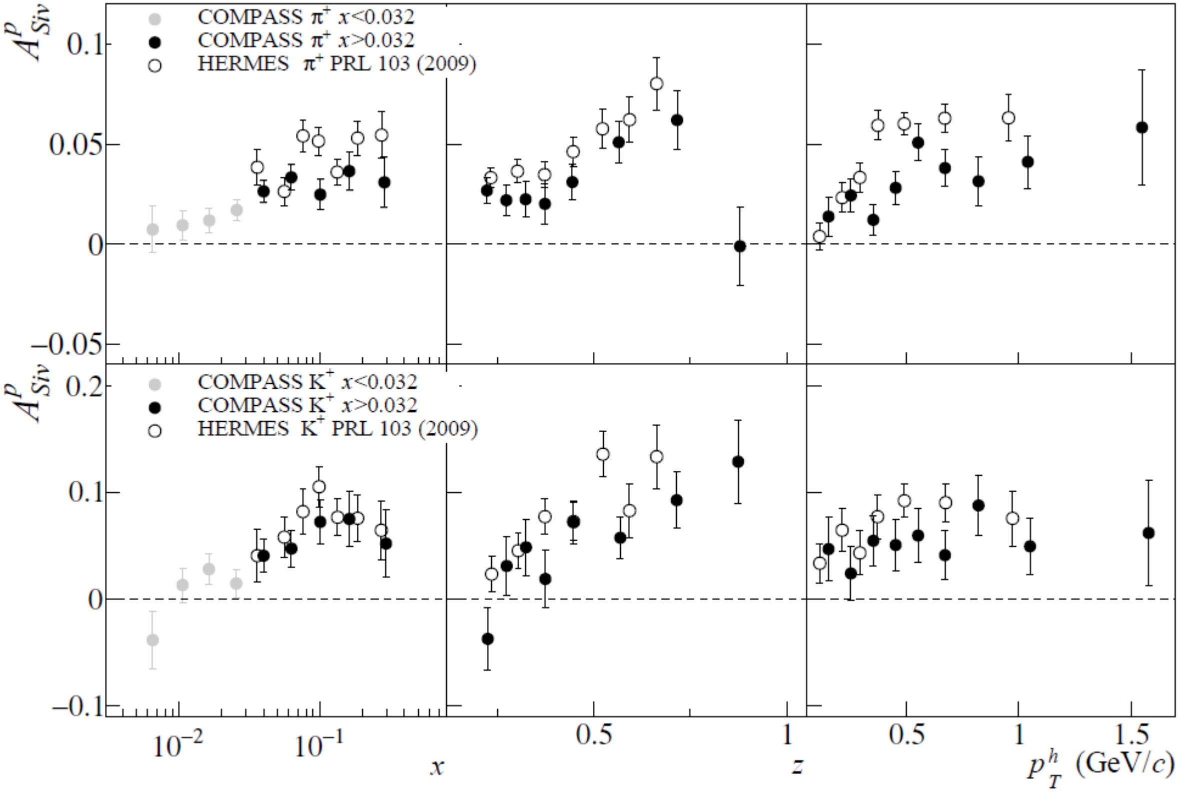




In the region of overlap in x, the average Q^2 in Drell-Yan is about two times larger compared to SIDIS

COMPASS and HERMES Sivers Asymmetries for π^+ vs K^+

COMPASS Phys.Lett. B744:250(2015)



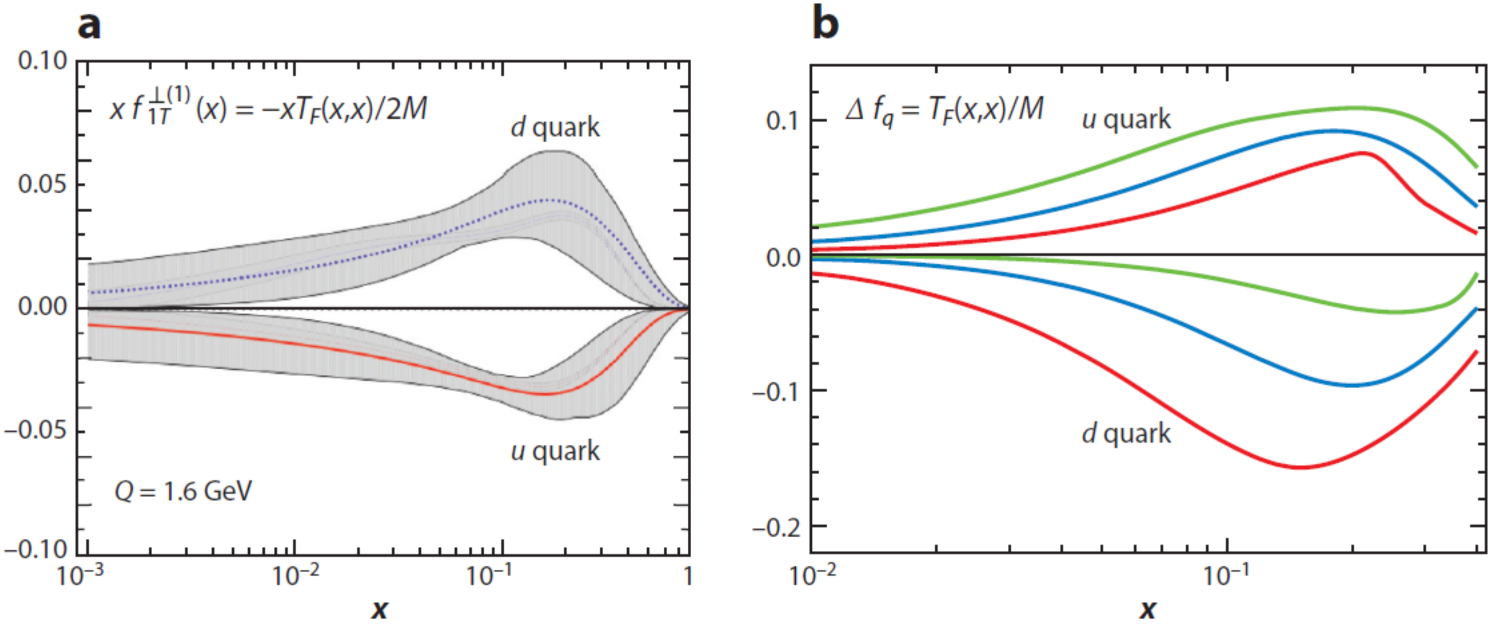
Combined 2007 and 2010 COMPASS proton data samples analyzed.

Sivers – Global Analysis of HERMES & COMPASS Data

Anselmino M, et al. arXiv:1107.4446 [hep-ph] (2011) Sun P, Yuan F. *Phys. Rev. D* 88:114012 (2013)

Leading order analysis

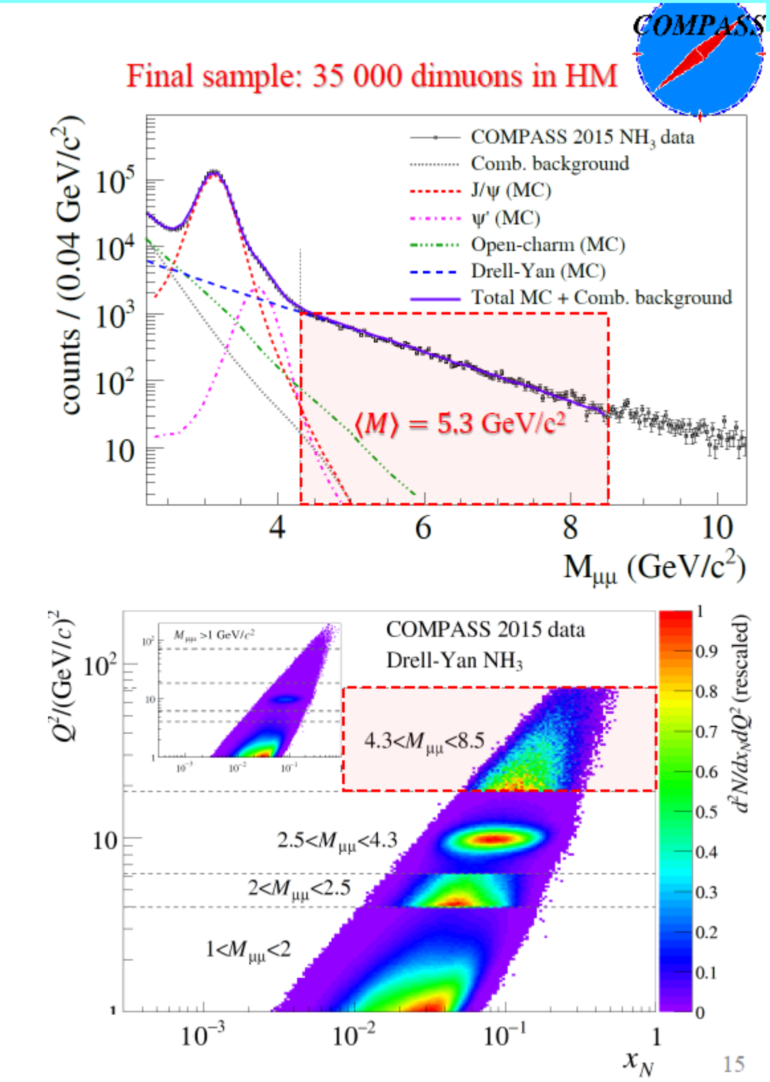
Full QCD analysis including TMD evolution



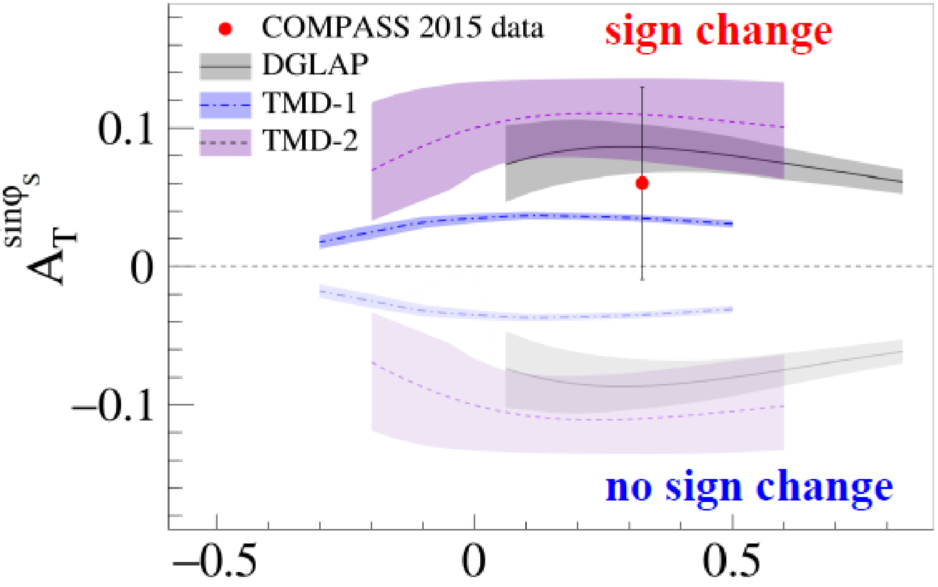
Still significant errors, no data for x>0.35

Sign Change ➔ COMPASS Drell-Yan (NSAC Milestone …)

Sivers Result from 35,000 Dimuons

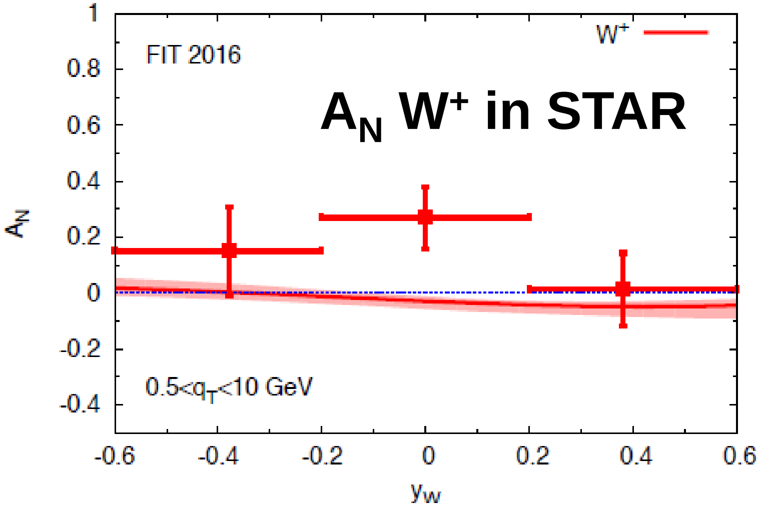


Released by
Barkur Parsamyan at DIS 2017
and Marcia Quaresma at IWHSS 2017
PRL 119, 112002 (2017)

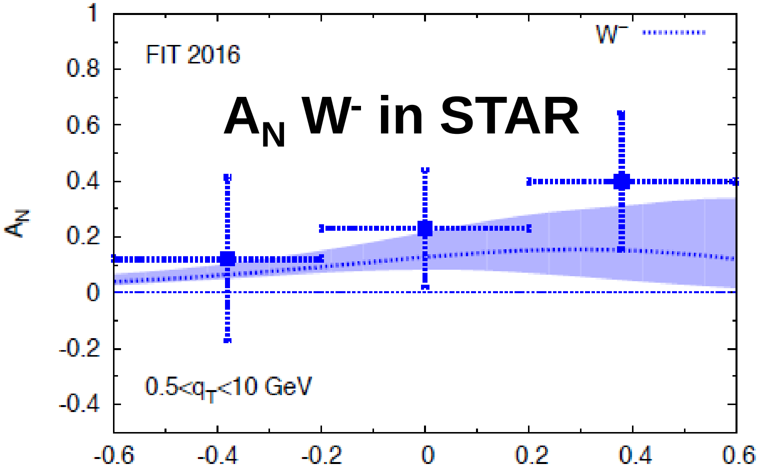


First Results on Sign Change in DY: A_N for W-Production in STAR

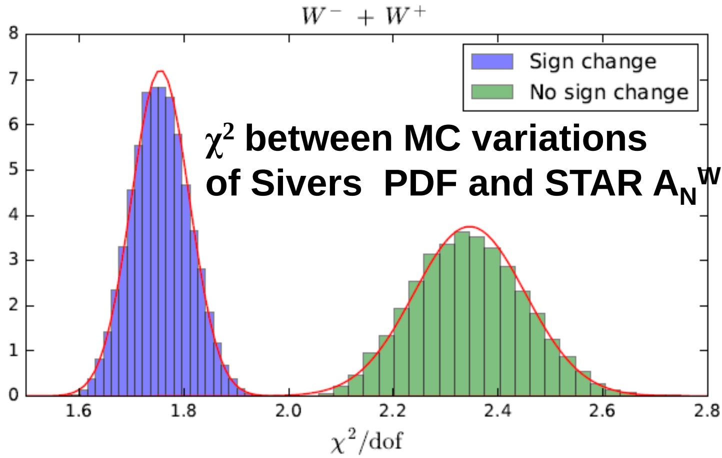
Comparison of A_N^W to Sivers from SIDIS by Anselmino, Boglione, D’Alesio, Murgia, JHEP 1704 (2017) 046



A_N W^+ in STAR



A_N W^- in STAR



χ^2 between MC variations of Sivers PDF and STAR A_N^W.

$A_N^{W+/-}$ slightly better compatible with sign change

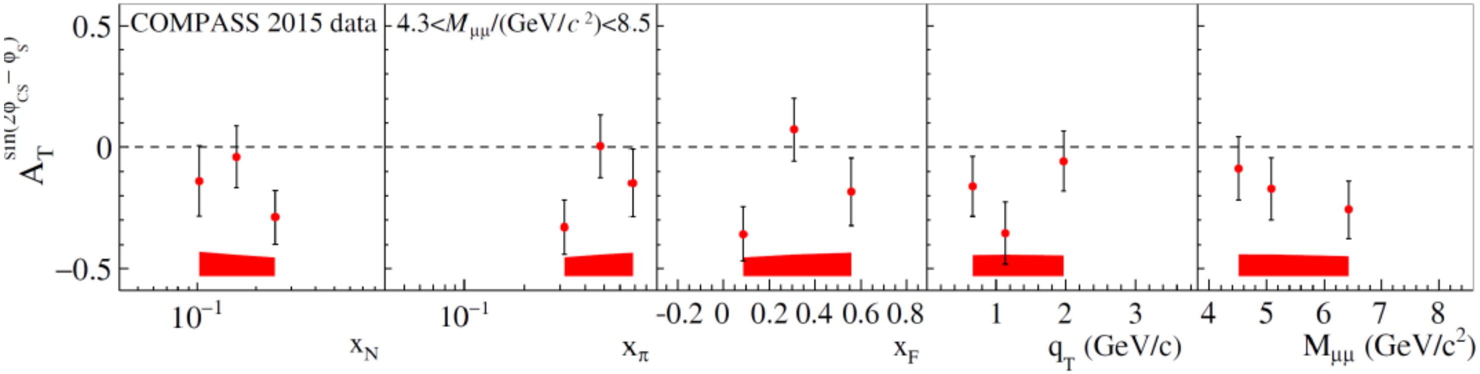
COMPASS Transversity Asymmetry

$$\frac{d\sigma}{d\Omega} \propto 1 + \ldots + S_T \left[D_{\left[\sin^2\theta_{CS}\right]} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) + \ldots \right]$$

Transversity DY TSA

$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{q}$

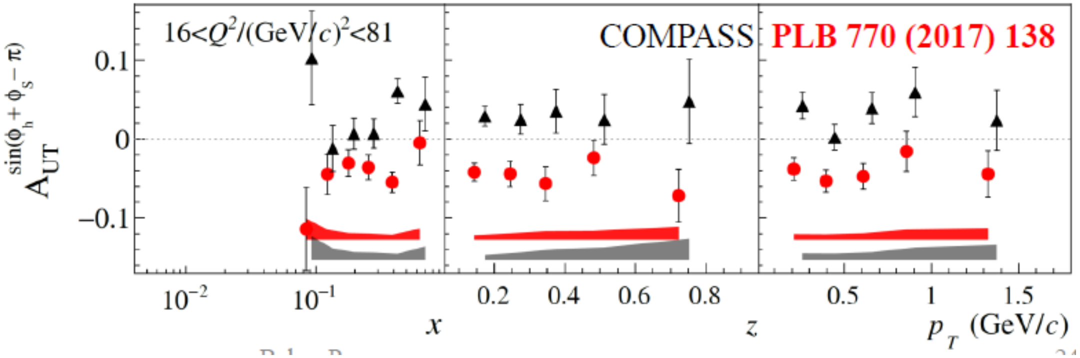
COMPASS PRL 119, 112002 (2017)



Collins SIDIS TSA

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

SIDIS in Drell-Yan *high-mass* range



Active & Future Experimental Facilities: with Drell-Yan Experiments

BNL

RHIC is running with STAR remaining as active experiment.

FNAL

E906 running: SeaQuest

COMPASS

Drell-Yan: 2014, 2015 & 208 + future with RF separated beams

JPARC

Drell-Yan physics proposals pending.

Drell-Yan + J/ψ in preparation

GSI

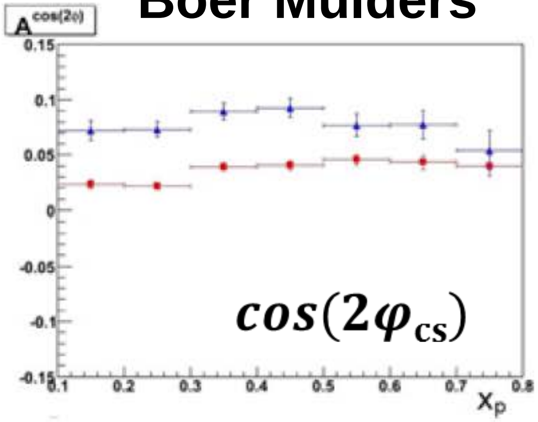
Drell-Yan physics in PANDA

TMD Drell-Yan Asymmetries with PANDA

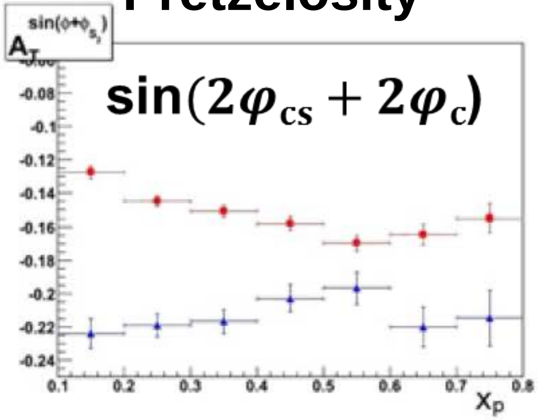
From M. Destefanis, EPJ 73,

Projections for 5 months of PANDA: $\bar{p} + p \rightarrow \mu + \mu + X$

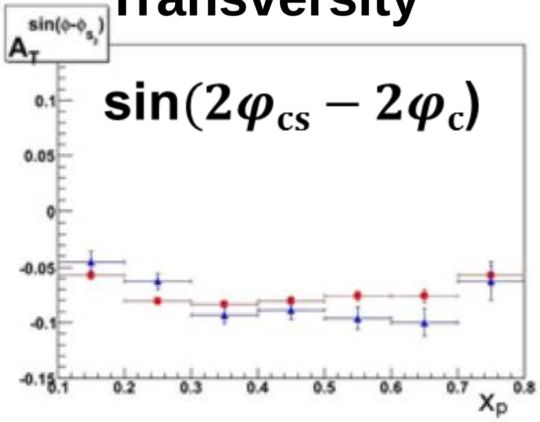
Boer Mulders



Pretzelosity



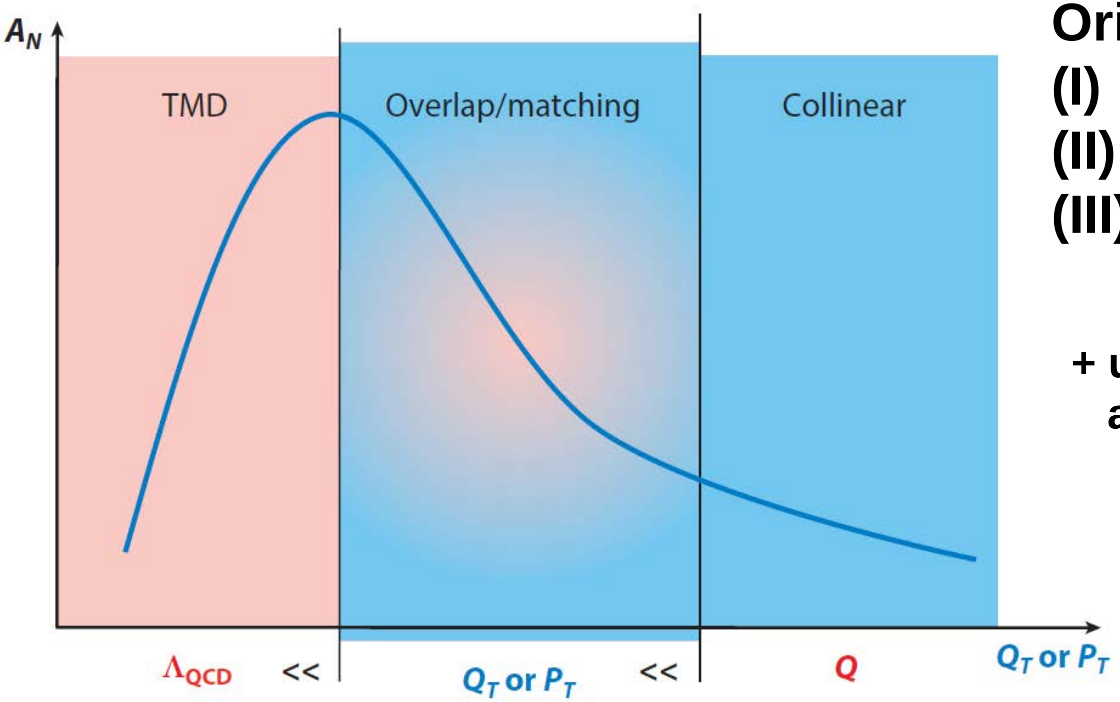
Transversity



Two bins of q_T: $1<q_T< 2$ GeV
$2<q_T< 3$ GeV

➔ Precision measurement of Boer Mulders, Transversity, Sivers asymmetries without FFs !
➔ Testing q_T dependence!

Test Unified Picture:
TMD (Sivers & Collins) vs Collinear at Twist 3



Origin of TSA

(I) Transversity

(II) Sivers

(III) Initial or final state twist-3$^+$

Qiu/Sterman and Koike

+ unified picture: Ji, Qiu, Vogelsang and Yuan in PRL-97:082002, 2006

Use TMD description (Sivers & Collins) if $p_T << Q$

Use collinear description at Twist 3 if p_T ~< Q

Unpolarized Cross Section: Precision Measurement of the Lam-Tung Relation ➔ Boer Mulders

$$\frac{dN}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2(\theta)+\mu\sin(2\theta)\cos(\phi)+\frac{\nu}{2}\sin^2(\theta)\cos(2\phi)\right)$$

In naive Drell-Yan model, no k_T and no QCD processes involving gluons:

$$\lambda = 1,\ \ \mu = 0,\ \ \nu = 0$$

The Lam-Tung relation, derived from the fermionic nature of quarks, predicts:

$$1 - \lambda - 2\nu = 0$$

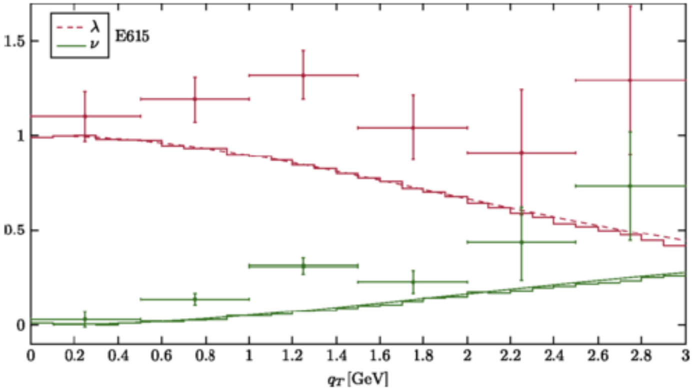
Analog of DIS Callan-Gross relation for Drell-Yan

C.S. Lam and W.K. Tung, Phys. Rev. D 18, 2447 (1978)

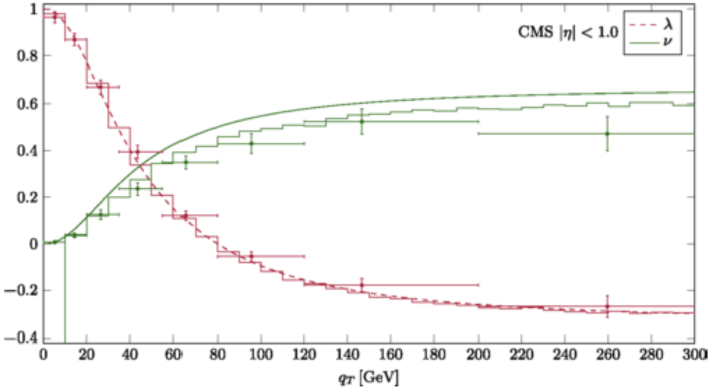
Discussion of Lam-Tung Relation from Vincent Andrieux, UIUC

Precision Measurement of the Lam-Tung Relation ➔ Boer Mulders

E615 PRD 39, 92 (1989)



CMS PLB 750, 154 (2015)

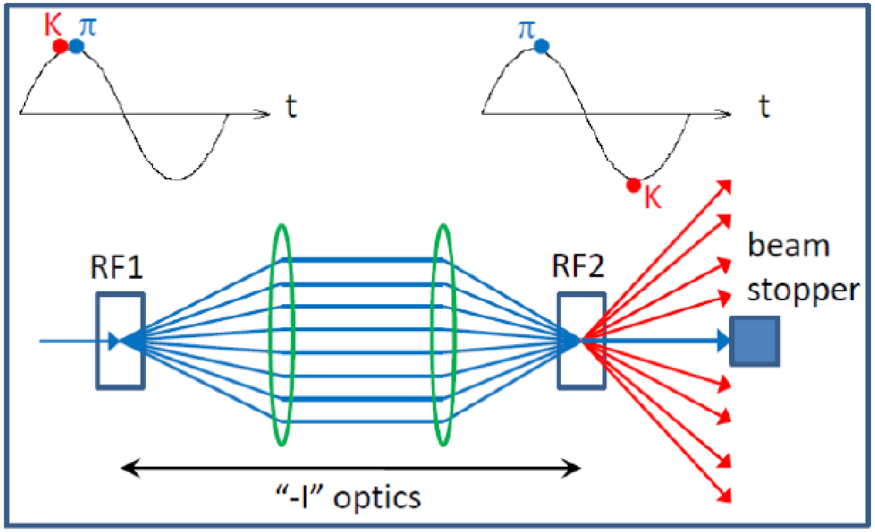


- Recent evidence in terms of QCD: radiative effects describe well data at large q_T
  - J.-C. Peng *et al.* PLB 758, 384 (2016)
  - M. Lambertsen and W. Vogelsang PRD93, 114013 (2016)
- Boer Mulders expected at low q_T $\rightarrow$ fixed target regime
- To single out Boer Mulders effects very precise data are necessary

PANDA, RF separated beams at CERN?

Drell-Yan with RF Separated Kaon and Anti-Proton Beams at CERN

- Deflection with 2 cavities
- Relative phase = 0 → dump
- Deflection of wanted particle given by $\Delta\phi \approx \frac{\pi f L}{c} \frac{m_w^2 - m_u^2}{p^2}$



To keep good separation, L should increase as p^2 → limits the beam momentum

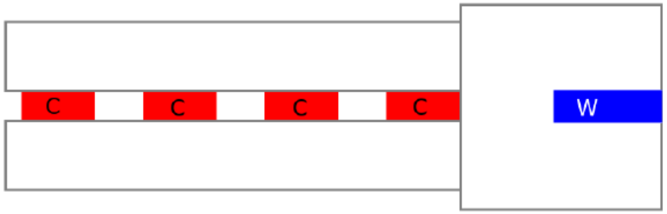
- Kaon With the current RP limits, for total beam flux of 7×10^7 particles/s:
  $I_{K^-} \sim 2\times10^7/s$ at 100 GeV
  $I_{K^+} \sim 2\times10^7/s$ at 100 GeV
- High intensity antiproton beam:
  $\sim 5 \times 10^7$ with current RP

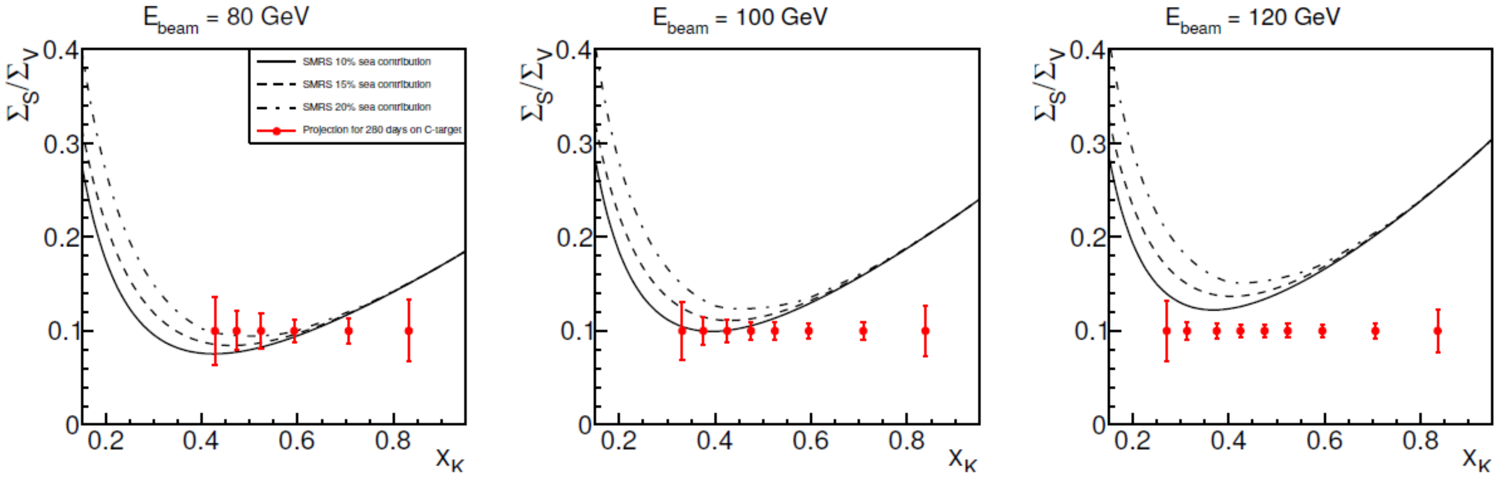
Discussion of RF upgrade from Vincent Andrieux, UIUC

Kaon Structure: Flavor Separation

- Dense & not too long for counting rate and acceptance considerations
- Isoscalar for sea-valence separation: J.T. Londergan *et al.*, PLB 380 (1996)
  - $\Sigma_S = \sigma_{DY}^{K^+D}$: Sensitive to valence and sea terms
  - $\Sigma_V = \sigma_{DY}^{K^-D} - \sigma_{DY}^{K^+D} = \frac{4}{9}\bar{u}_v^{K^-}(u_v^p + d_v^p)$: only valence sensitive
- Low A to minimize nuclear effect: Carbon target

First measurement of kaon sea!





Anti-Proton Beams for COMPASS

(1) measure Sivers asymmetries without uncertainty from pion pdf

(2) use transversity modulation, $\sin(2\phi_{CS}-\phi_S)$ for Boer Mulders measurement (less QCD radiative effects):

➔ extract transversity from SIDIS and e^+e^- measurements
➔ measure Drell Yan $A^{\sin(2\phi CS-\phi S)}$
➔ combine with SIDIS transversity to
obtain proton Boer Mulders

Summary

Several experiments with complementary kinematics

- J-PARC π, K, $\bar{p}$ beams up to 20 GeV
- PANDA at FAIR $\bar{p}$ beam up to 15 GeV
- E906 (FNAL) proton at 120 GeV dedicated to sea quarks in proton
- SPASCHARM? at IHEP 40-70 GeV proton, secondary hadron beams, tertiary pol. $\bar{p}$ beam

Will cleanly measure TSAs and for the first time kaon structure

- Kaon structure including valence sea separation
- Test of Lam Tung relation
- Model free TSA in DY with antiproton beam