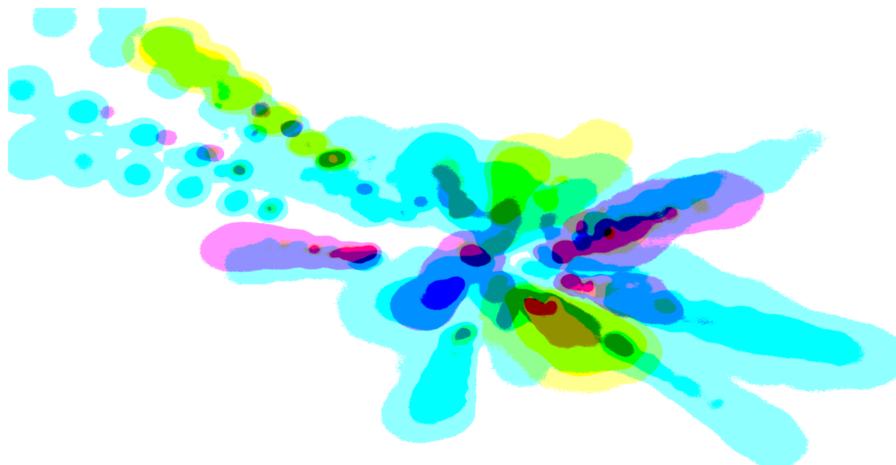
Separating fact from fantasy*: The chiral anomaly and the proton spin puzzle



Raju Venugopalan

(BNL)

CFNS seminar, August 20, 2020

Separating fact from fantasy*: The chiral anomaly and the proton spin puzzle

R. L. Jaffe

A. Manohar

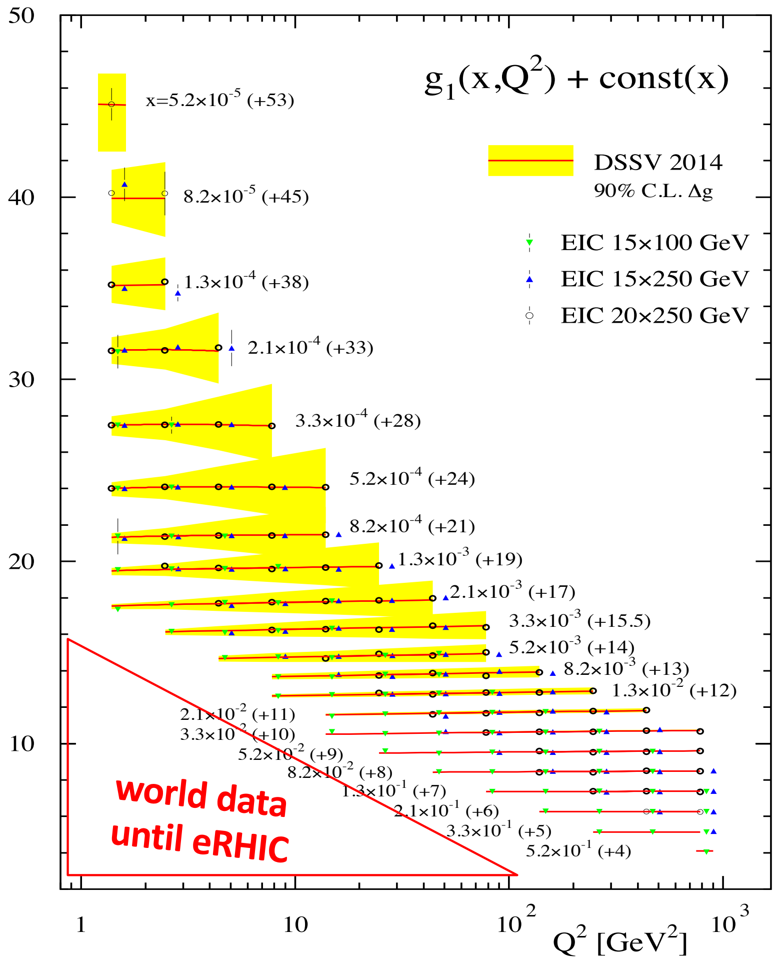
30th anniversary of their seminal paper which strongly inspired the work reported here:

The G(1) Problem: Fact and Fantasy on the Spin of the Proton.
Nucl. Phys., B337:509–546, 1990

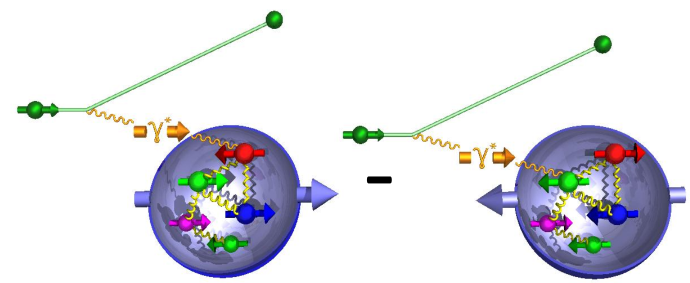
Work* in collaboration with Andrey Tarasov (The OSU and CFNS)

* https://arxiv.org/abs/2008.08104
and two follow-up papers in preparation

Resolving the proton's spin puzzle: the g_1 structure function

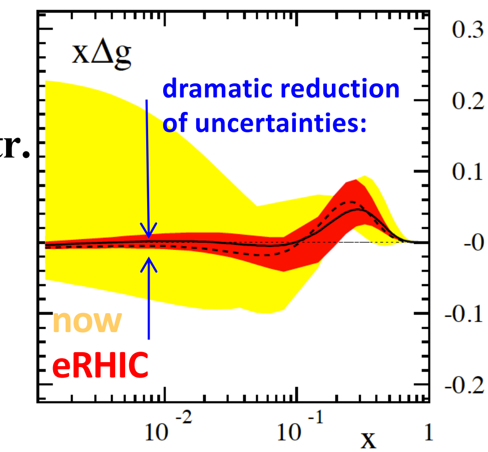


g_1 extracted from longitudinal spin asymmetry

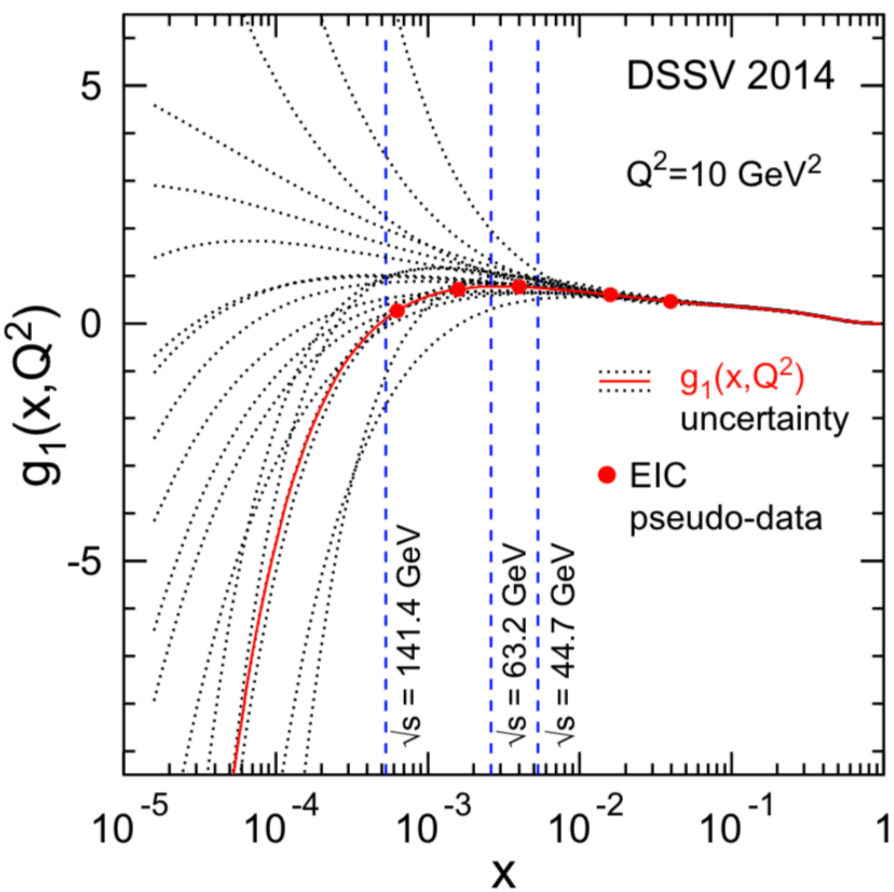


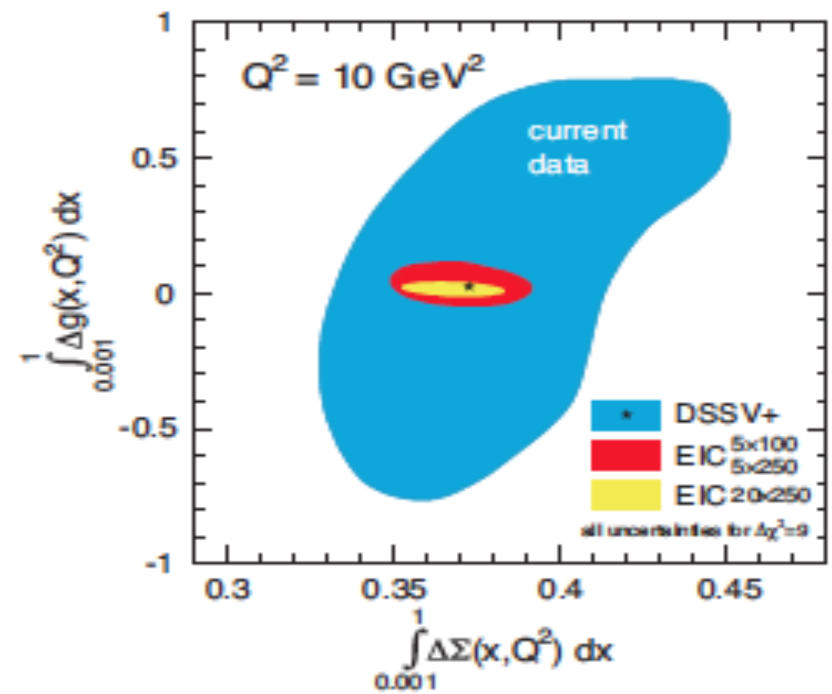
$$\Delta\Sigma(Q^2) \propto \int_0^1 dx\, g_1(x,Q^2) \rightarrow \text{quark contribution}$$

$$\frac{dg_1}{d\log(Q^2)} \overset{?}{\sim} -\Delta g(x,Q^2) \rightarrow \textbf{gluon contr.}$$



Resolving the proton's spin puzzle: the g_1 structure function



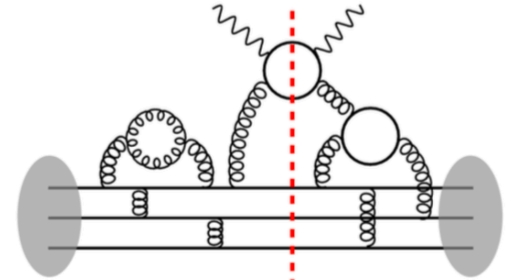


Aschenauer et al., arXiv:1708.01527
Rep. Prog. Phys. 82, 024301 (2019)

Iso-singlet axial vector current and topology of the QCD vacuum

Reviews:
S. D. Bass, RMP, hep-ph/0411005
G. M. Shore, hep-ph/0701171

g_1 structure function: formal definitions



Hadron tensor $W^{\mu\nu}$ = $\mathrm{Im}\,\frac{i}{\pi}\int d^4\mathbf{x}\, e^{i\mathbf{q}\cdot\mathbf{x}}\langle P,S|\mathbb{T}\,\hat{j}^\mu(\mathbf{x})\hat{j}^\nu(0)|P,S\rangle$

with $j^\mu = \sum_f e_f\bar{\psi}_f\gamma^\mu\psi_f$

Most generally, $g_1(x,Q^2) = \frac{1}{8\lambda}\epsilon_T^{\mu\nu}\tilde{W}_{\mu\nu}(q,P,S)$

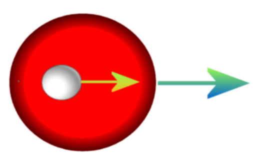
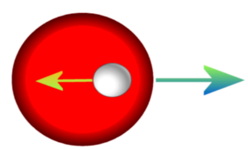
where $\widetilde{W}^{\mu\nu}$ is the antisymmetric part of $W^{\mu\nu}$

$S^\mu = \frac{2\lambda}{m_P}P^\mu$ and $\lambda = \pm 1/2$

Generalized parton model ("leading twist"): $g_1(x_B,Q^2) = \frac{1}{2}\sum_f e_f^2\left(\Delta q_f(x_B,Q^2) + \Delta\bar{q}_f(x_B,Q^2)\right)$

Where the quark helicity pdf is defined to be

$$\Delta q(x) = \frac{1}{4\pi}\int dy^-\, \mathrm{e}^{-iy^- xP^+}\,\langle P,S\,|\,\bar{\psi}\left(0,y^-,\mathbf{0}_\perp\right)\,\gamma^+\gamma_5\,\psi(0)\,|\,P,S\,\rangle$$

$\Delta q(x) =$  $-$ 

Iso-singlet axial vector current

In general, the first moment of g_1: $$\int_0^1 g_1(x,Q^2) = \frac{1}{18}\left(\underbrace{3F+D}+2\,\Sigma(Q^2)\right)$$

Combination of triplet axial vector current (gives g_A) measured in β decay and octet axial vector current measured in hyperon decays

with the iso-singlet quark helicity given by $$\Delta\Sigma(Q^2) \;=\; \sum_q^{N_f}\int_0^1 dx\left(\Delta q(x,Q^2)+\Delta\bar{q}(x,Q^2)\right)$$

In the parton model picture, this mixes, under evolution, with other isospin blind moment $\Delta G = \int_0^1 dx\,\Delta g(x,Q^2)$

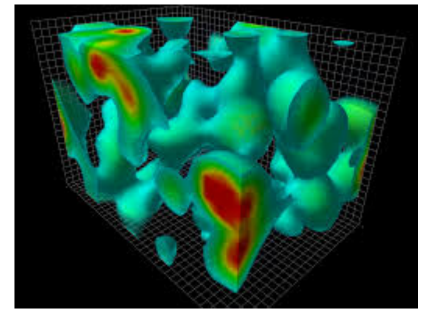
$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix} = \begin{pmatrix}\Delta P_{\Sigma\Sigma} & 2N_f\Delta P_{qG}\\ \Delta P_{Gq} & \Delta P_{GG}\end{pmatrix}\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix}$$

Splitting functions known to high loop order

Moch, Rogal, Vermaseren, Vogt
Talk by Vogelsang at POETIC IX, LBNL; DeFlorian, Vogelsang (2019)

Iso-singlet axial vector current and the chiral anomaly

$$S^\mu \, \Delta\Sigma \; = \; \langle P,S \,|\, \bar{\psi}\, \gamma^\mu \gamma_5 \, \psi \,|\, P,S \rangle \; \equiv \; \langle P,S \,|\, j_5^\mu \,|\, P,S \rangle$$



$U_A(1)$ violation from the chiral anomaly:

$$\partial_\mu J_5^\mu = 2n_f \partial_\mu K^\mu + \sum_{i=1}^{n_f} 2 i m_i \bar{q}_i \gamma_5 q_i$$

where the Chern-Simons current

$$K_\mu = \frac{g^2}{32\pi^2} \epsilon_{\mu\nu\rho\sigma} \left[A_a^\nu \left(\partial^\rho A_a^\sigma - \frac{1}{3} g f_{abc} A_b^\rho A_c^\sigma \right) \right]$$

For massless quarks, conserve $J_5^\mu - 2\, n_f K^\mu$ $\longrightarrow \propto$ $\Delta\Gamma(Q^2) = -\dfrac{\alpha_s(Q^2)}{2\pi} N_f \Delta g(Q^2)$

So then the "real" $\Delta\Sigma$ is

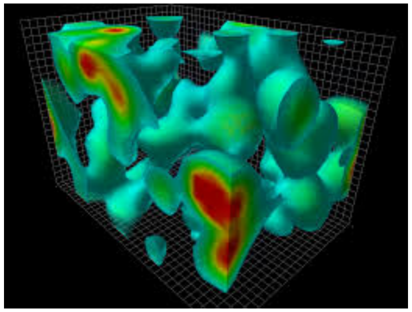
$$\Sigma(Q^2) = \tilde{\Sigma}(Q^2) - \frac{\alpha_s(Q^2)}{2\pi} N_f \Delta g(Q^2)$$

offering a possible explanation of empirical small $\Delta\Sigma$ (in addition to flavor SU(3) violation)…

ca., 1988
Efremov, Teryaev
Altarelli, Ross
Carlitz, Collins, Mueller

Iso-singlet axial vector current and the chiral anomaly

$$S^\mu\,\Delta\Sigma \;=\; \langle P,S\,|\,\bar\psi\,\gamma^\mu\gamma_5\,\psi\,|\,P,S\rangle \;\equiv\; \langle P,S\,|\,j_5^\mu\,|\,P,S\rangle$$



$U_A(1)$ violation from the anomaly:

$$\partial_\mu J_5^\mu = 2n_f\partial_\mu K^\mu + \sum_{i=1}^{n_f} 2im_i\bar q_i\gamma_5 q_i$$

where the Chern-Simons current $K_\mu = \frac{g^2}{32\pi^2}\epsilon_{\mu\nu\rho\sigma}\left[A_a^\nu\left(\partial^\rho A_a^\sigma - \frac{1}{3}g f_{abc}A_b^\rho A_c^\sigma\right)\right]$

But, identification of CS charge with ΔG is intrinsically ambiguous
… *the latter is gauge invariant, the former is not*

Jaffe, Manohar (1990)

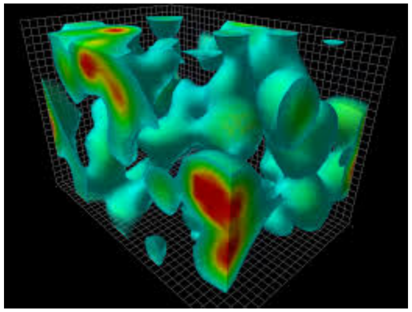
$$K_\mu \to K_\mu \;+\; i\frac{g}{8\pi^2}\epsilon_{\mu\nu\alpha\beta}\partial^\nu\left(U^\dagger\partial^\alpha U A^\beta\right)$$
$$+\;\frac{1}{24\pi^2}\epsilon_{\mu\nu\alpha\beta}\left[(U^\dagger\partial^\nu U)(U^\dagger\partial^\alpha U)(U^\dagger\partial^\beta U)\right]$$

"Large gauge transformation"
- deep consequence of topology

R. Jaffe: "Identification of K^μ with ΔG
a source of much confusion
in the literature (Varenna lectures, 2007)"

Iso-singlet axial vector current and the chiral anomaly

However, identifying CS − charge with ΔG "works" remarkably well ...
(Vogelsang, POETIC IX)



$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta\Sigma\\ \Delta\Gamma\end{pmatrix} = \begin{pmatrix}\Delta P_{\Sigma\Sigma}(a_s) & 0\\ -\frac{1}{2N_f}\Delta P_{\Sigma\Sigma}(a_s) & 0\end{pmatrix}\begin{pmatrix}\Delta\Sigma\\ \Delta\Gamma\end{pmatrix}$$

$\propto \Delta G$

NNLO splitting function computations confirm this

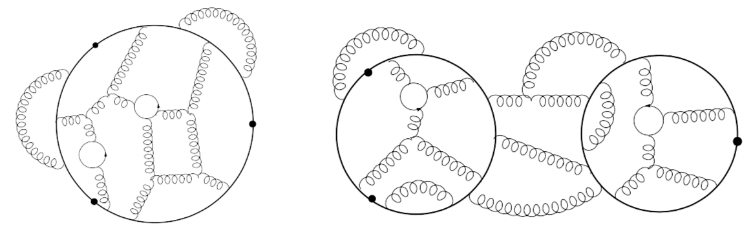
At LO, Altarelli, Lampe (1990)
NNLO: Vogt, Moch, Rogal, Vermaseren, arXiv:0807.1238

This suggests that $\Delta\Sigma$ only mixes with itself; likewise ΔG as defined, only depends on $\Delta\Sigma$ with the same splitting function

We will discuss later the deeper physics behind these expressions and their relation to the topology of the QCD vacuum

Alternative picture: topological charge screening of spin

Shore, Veneziano, PLB (1990); NPB (1992)
Narison, Shore, Veneziano, hep-ph/9812333



Anomalous chiral Ward identities and extended PCAC from $U_A(1)$ breaking – physics of the η' from mixing of a "primordial massless η' and topological charge

Example: Witten-Veneziano formula $m^2_{\eta'} = \frac{2\,n_f}{f^2_\pi}\chi_{\rm YM}(0) + O((\frac{n_f}{N_c})^2)$

where the topological susceptibility $\chi_{\rm YM}(p^2) = i\int dx\, e^{iP\cdot x}\langle 0|T(Q(x)Q(0)|0\rangle$

with $Q(x) = \frac{\alpha_S}{8\pi}{\rm Tr}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)$

In this picture,

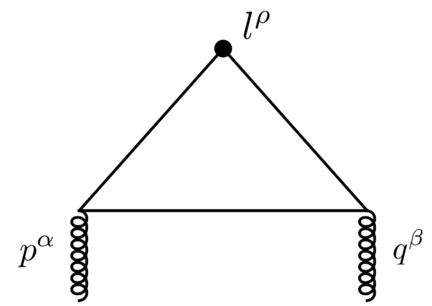
$$\Sigma(Q^2) = \frac{1}{3m_N}\Delta C_1^S(\alpha_S)\left(g_{QNN}\chi(0) + g_{\eta' NN}\sqrt{\chi'(0)}\right)$$

In chiral limit $\chi(0) \to 0$, $\Delta\Sigma$ "controlled" by the slope χ' at p^2=0 – estimated to be small by Veneziano et al.

What about dynamics – can we reconcile this picture with the perturbative one ?

Perturbative & nonperturbative interplay: The triangle graph

The key role of the $U_A(1)$ anomaly is seen from the structure of the triangle graph
In the off-forward ($l^\mu \to 0$, $t = l^2 \to 0$) matrix element of $< P',S|\, J^5_\mu|P, S >$



$$\langle P', S|J^\mu_5|P, S\rangle = G_A(t)S_\mu + l \cdot S\, l_\mu G_P(t)$$

The computation of this has an infrared pole proportional to $\frac{l^\mu}{l^2} F\tilde{F}$

Jaffe. Manohar (1990)

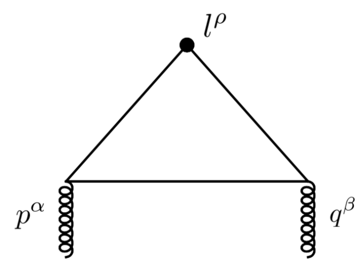
The perturbative/nonperturbative interplay gives a highly non-trivial result:

$$\langle P', S|J^\mu_5|P, S\rangle \to \frac{l \cdot S\, l^\mu}{l^2}\kappa(t) + \left(S^\mu - \frac{l \cdot S\, l^\mu}{l^2}\right)\lambda(t)$$

The infrared pole in $G_A(t)$ must be canceled by a pole in $G_P(t)$ – the corresponding Wess-Zumino-Witten term for the η'

For that to hold, one must have $\kappa(0) = \lambda(0) \propto F\tilde{F}$ the topological charge density

Perturbative & nonperturbative interplay: The triangle graph



with the (manifestly) gauge invariant result for the forward matrix element

$$\Sigma(Q^2) = \frac{n_f\,\alpha_s}{2\pi\,M_N} \lim_{l_\mu \to 0} \langle P', S| \frac{1}{il \cdot s} \mathrm{Tr}\left(F\tilde{F}\right)(0)|P, S\rangle$$

Suprisingly (since known to Jaffe+Manohar & Veneziano et al) not addressed in a lot of the "pQCD" literature
It is however deeply profound since it is intimately tied to the mechanism whereby the η' gets its mass

This result, generalization to $g_1(x,Q^2)$, and the interplay with non-perturbative physics can be explored efficiently in a worldline framework

Thinking properly about anomalies with worldlines

Review: Schubert, Phys. Repts. (2001)
N. Mueller, RV: 1701.03331.1702.01233,1901.10492
Tarasov, RV: 1903.11624 and in preparation

The worldline formulation of QFT is equivalent to the string amplitude formalism of Bern and Kosower, as shown by Strassler

Bern,Kosower, NPB 379 (1992) 145;
Bern, TASI lectures, hep-ph/9304249
Strassler, NPB 385 (1992) 145

World-line formalism: vector and axial vector fields

$$S[A, A_5] = \int d^4x\, \bar{\psi}\, (i\not\partial + \not A + \gamma_5 \not A_5)\, \psi$$

One loop effective action $\Gamma[A, A_5] = \log\det(\chi)$ with $\chi = i\not\partial + \not A + \gamma_5 \not A_5$

$$\Gamma[A, A_5] = \Gamma_R + i\Gamma_I$$

Phase of the determinant..
An elegant way to represent the chiral anomaly which Fundamentally arises from non-invariance of path integral measure under a chiral rotation

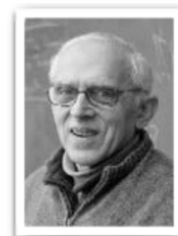
Remarkably, this phase can be re-expressed in a form that is nearly identical to Γ_R !

Useful mnemonic: *Odd* powers of γ_5 contribute to Γ_I and *Even* powers to Γ_R

D'Hoker, Gagne, hep-ph/9512080
See also Mondragon, Nellen, Schmidt, Schubert, hep-th/9502125

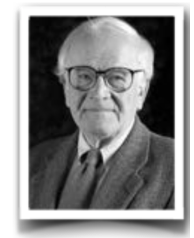
The triangle anomaly in the worldline formalism

Tarasov, RV



Steven Adler

John S. Bell



Roman Jackiw

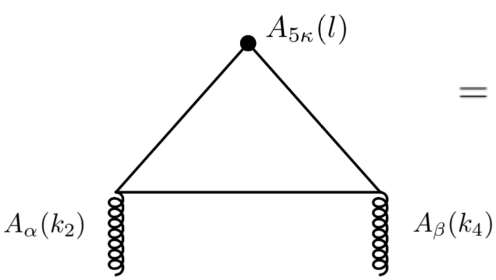
Point particle Bose and Grassmann path integrals

$$\Gamma[A, A_5] = -\frac{1}{2}\mathrm{Tr}_c \int_0^\infty \frac{dT}{T} \int \mathcal{D}x \int_{AP} \mathcal{D}\psi$$

$$\times \exp\Big\{ - \int_0^T d\tau \Big(\frac{1}{4}\dot{x}^2 + \frac{1}{2}\psi_\mu\dot{\psi}^\mu + ig\dot{x}^\mu A_\mu - ig\psi^\mu\psi^\nu F_{\mu\nu} - 2i\psi_5\dot{x}^\mu\psi_\mu\psi_\nu A_5^\nu + i\psi_5\partial_\mu A_5^\mu + (D-2)A_5^2\Big)\Big\}$$

Wilson line — Spin precession — Axial vector couplings

$$\langle P', S|J_5^\kappa|P, S\rangle = \int d^4y \frac{\partial}{\partial A_{5\kappa}(y)}\Gamma[A, A_5]\Big|_{A_5=0} e^{ily} \equiv \Gamma_5^\kappa[l]$$

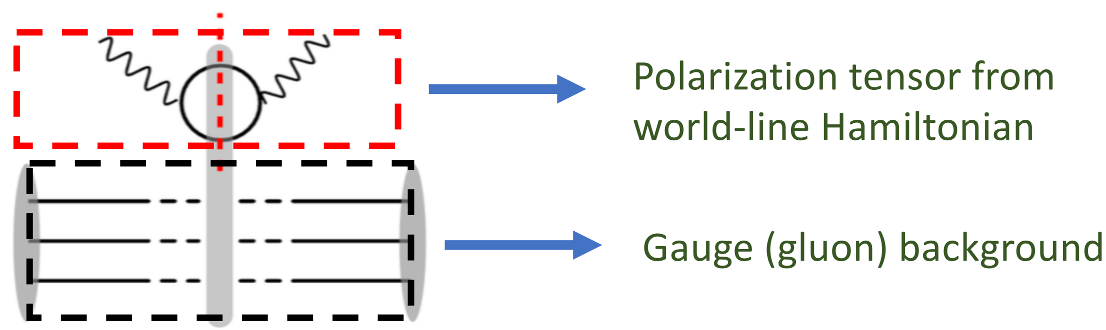


$$= \frac{1}{4\pi^2}\frac{l^\kappa}{l^2}\int \frac{d^4k_2}{(2\pi)^4}\int \frac{d^4k_4}{(2\pi)^4}\, \mathrm{Tr}_c F_{\alpha\beta}(k_2)\tilde{F}^{\alpha\beta}(k_4)\,(2\pi)^4\delta^4(l+k_2+k_4)$$

Famous infrared pole of anomaly

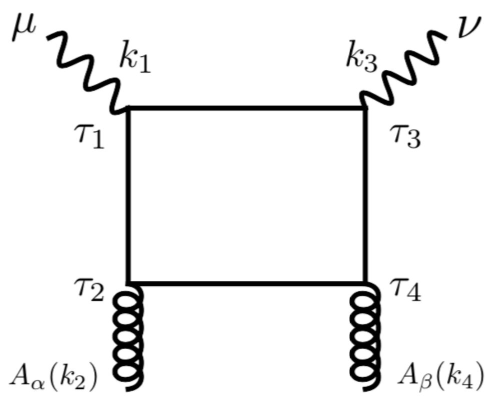
William A. Bardeen

Polarized DIS in the worldline formalism



The box diagram for polarized DIS ($g_1(x,Q^2)$)

DIS with worldlines,
Tarasov, RV (2019)



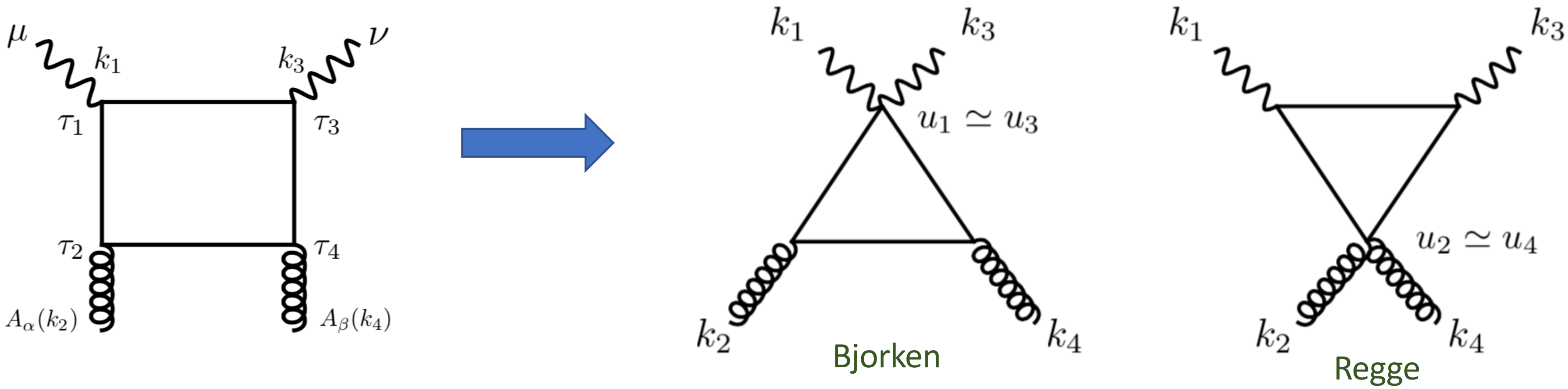
$$\Gamma_A^{\mu\nu}[k_1,k_3] = \int \frac{d^4k_2}{(2\pi)^4} \int \frac{d^4k_4}{(2\pi)^4}\, \Gamma_A^{\mu\nu\alpha\beta}[k_1,k_3,k_2,k_4]\ \mathrm{Tr_c}(\tilde{A}_\alpha(k_2)\tilde{A}_\beta(k_4))$$

Polarization tensor
(antisymmetric piece)

Box diagram

We can compute the box explicitly in both the Bjorken limit of QCD ($Q^2 \to \infty, s \to \infty, x = \text{fixed}$) and the Regge limit ($x \to 0, s \to \infty, Q^2 = \text{fixed}$). The latter result is new

Finding triangles in boxes in Bjorken and Regge asymptotics



Remarkably, $g_1(x_B, Q^2)$ has the same structure in both limits, dominated by the triangle anomaly !

$$S^\mu g_1(x_B, Q^2)\Big|_{Q^2\to\infty} = \sum_f e_f^2 \frac{\alpha_s}{i\pi M_N} \int_{x_B}^1 \frac{dx}{x}\left(1-\frac{x_B}{x}\right)\int \frac{d\xi}{2\pi} e^{-i\xi x} \lim_{l_\mu\to 0}\frac{l^\mu}{l^2}\langle P', S|\mathrm{Tr}_c F_{\alpha\beta}(\xi n)\tilde{F}^{\alpha\beta}(0)|P,S\rangle \quad + \text{non-pole } \frac{\Lambda^2{}_{QCD}}{Q^2}$$

$$S^\mu g_1(x_B, Q^2)|_{x_B\to 0} = \sum_f e_f^2 \frac{\alpha_s}{i\pi M_N} \int_{x_B}^1 \frac{dx}{x}\int \frac{d\xi}{2\pi} e^{-i\xi x} \lim_{l_\mu\to 0}\frac{l^\mu}{l^2}\langle P', S|\mathrm{Tr}_c F_{\alpha\beta}(\xi n)\tilde{F}^{\alpha\beta}(0)|P,S\rangle \quad + \text{non-pole } \frac{Q_S{}^2}{M^2} \ll 1$$

Hence g_1 is topological in both asymptotic limits of QCD…its relation to $\Delta g(x, Q^2)$ is unclear

The r.h.s in the previous expressions is infrared divergent – how is this cured to give a finite result?

The role of pseudoscalar fields in resolving the $U_A(1)$ problem

We **did not** previously write down the most general form of the **imaginary part** of the worldline effective action :

D'Hoker, Gagne,hep-th/9508131

$$W_{\Im}[\Phi, \Pi, A] = \frac{1}{8}\int_{-1}^{1} d\alpha \int_0^\infty dT\, \mathcal{N} \int \mathcal{D}x\mathcal{D}\psi\, \mathrm{Tr}_c\, \mathcal{J}(0)\, \mathcal{P}e^{-\int_0^T d\tau \mathcal{L}_\alpha}$$

with $\mathcal{L}_\alpha = \frac{\dot{x}^2}{2\mathcal{E}} + \frac{1}{2}\psi_A\dot{\psi}_A - i\dot{x}\cdot A + \frac{i}{2}\mathcal{E}\psi_\mu F_{\mu\nu}\psi_\nu + \frac{1}{2}\mathcal{E}\alpha^2\Phi^2 + \frac{1}{2}\mathcal{E}\Pi^2$

$$+ i\,\varepsilon\,\psi_\mu\psi_5 D_\mu\Pi + \alpha\,\varepsilon\,\psi_5\psi_6[\Pi, \Phi]$$

where Φ is the chiral condensate

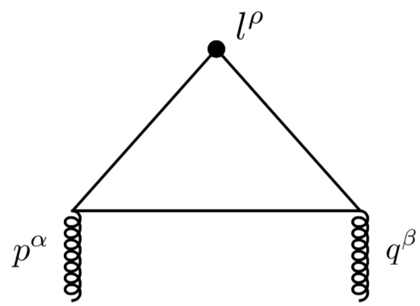
and $\mathcal{J}(0) \propto \psi_5\psi_6\{\Pi, \Phi\}$

Expanding out the worldline Lagrangian, the first nontrivial contribution to W_I is the Wess-Zumino-Witten term !

$$W_{\Im}[\Pi^5] = -\frac{i}{5}\int_{p^1,\ldots,p^5} (2\pi)^4\delta^{(4)}(p^1+\cdots+p^5)\,(-4im)\,\mathrm{Tr}_c(\tilde{\Pi}_1\cdots\tilde{\Pi}_5)\varepsilon_{\mu_1\cdots\mu_4}p^1_{\mu_1}\cdots p^4_{\mu_4}I'(p^i)$$

The role of pseudoscalar fields in resolving the $U_A(1)$ problem

Tarasov, RV, in preparation

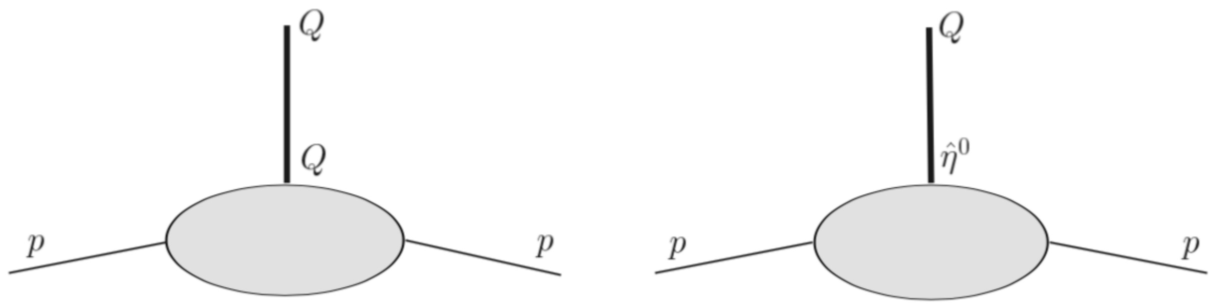


The WZW term has a contribution $\propto$ $\eta' \, F\tilde{F}$ (Leutwyler (1996); Herrara-Sikody et al (1997); Leutwyler-Kaiser (2000))

The zero mode part of it exactly cancels the $\frac{l^\mu}{l^2}$ *"perturbative" contribution to the anomaly*

$$g_1(x_B, Q^2) \to \frac{\alpha_S}{8\pi} \lim_{l_\mu \to 0} \langle P', S| \frac{1}{il \cdot s} \mathrm{Tr}\left(F\tilde{F}\right)(0)|P, S\rangle$$

Conjecture: "Axion-like" effective action for polarized DIS



$$\Delta\Sigma(Q^2) \;=\; \frac{2}{3}\frac{1}{2m_N}\Delta C_1^S(\alpha_s)\left(\langle 0|T\;Q\;Q|0\rangle\; g_{QNN} \;+\; \langle 0|T\;Q\;\hat{\eta}^0|0\rangle\; g_{\hat{\eta}^0 NN}\right)$$

$$\approx \mathbf{0} \qquad\qquad \chi'(p^2=0)$$

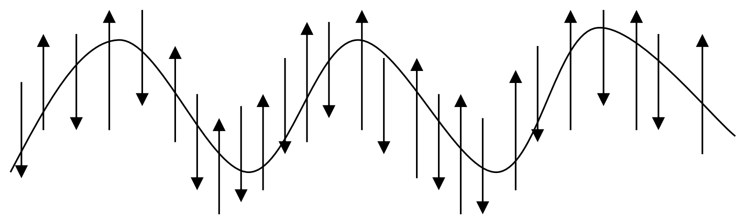
Narison, Shore and Veneziano (see hep-ph/0701171) argue that the result is dominated by the derivative of the topological susceptibility (χ'), which they compute (using QCD sum rules) to be in agreement with the HERMES and COMPASS data

g_1 can also in principle be computed on the lattice (Kei-Fei Liu et al) though computing Off-forward matrix elements of non-local operators is

Emergent ”axion” effective action for polarized DIS at small x

Tarasov, RV: in preparation

Conjecture: “Axion-like” effective action for Regge limit



If we now assume (at small x), the background field couples to a large # of quark and gluon world-line trajectories, one can construct the *effective action for an ensemble of spinning, colored partons at a given x<< 1*:

$$g_1(x,Q^2) \propto \int [D\rho] W_Y^P[\rho] \int [D\psi] \tilde{W}_P^{P,S}[\psi]$$

Density matrix: coupling of charge and topological charge to nucleon

$$\times \int [dA] \int d^4X\, \omega(X) \exp\left(iS_{\rm YM}[A] + \frac{i}{N_c} {\rm Tr}_c \left(\rho\, U_{-\infty,\infty}\right)\right)$$

Color charge current

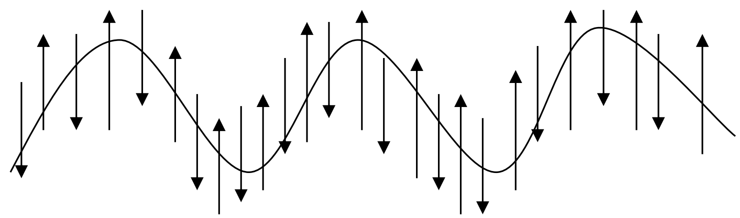
$$\times \exp\left(\int d^4X \left(-\frac{\omega^2}{2\,\chi_{\rm YM}} - \sqrt{\frac{N_f}{2}}\omega\,\psi + \frac{1}{2}F^2\psi\partial^2\psi\right)\right)$$

Topological current

Topological susceptibility: $\chi_{\rm YM} = \int d^4X \langle \omega(X)\omega(0)\rangle_A$

$\omega(X)$ *is the topological charge density*, $F\,\psi$ *is the* η' field and F is the η' decay constant

Conjecture: "Axion-like" effective action for Regge limit



The term $\exp\left(\int d^4X\left(-\frac{\omega^2}{2\,\chi_{\rm YM}}-\sqrt{\frac{N_f}{2}}\omega\,\psi+\frac{1}{2}F^2\psi\partial^2\psi\right)\right)$

can be rewritten as the "Veneziano effective action" of a glueball and η' field

$$\exp\left(-\int d^4X\left(-\frac{G^2}{2\chi_{\rm YM}}+\frac{1}{2}\eta'\left(\partial^2+m_{\eta'}^2\right)\eta'\right)\right)$$

ChPT formulation for the nonet, Herrera-Siklody et al, hep-ph/9610549

with $m_{\eta'}$ given by the Witten-Veneziano formula $m_{\eta'}^2=\frac{2N_f\,\chi_{\rm YM}}{F^2}$

or equivalently as $\exp\left(\int d^4X\left(F^2\psi\partial^2\psi+(\psi+\theta)\,\omega+\chi_{\rm YM}\,(\psi+\theta)^2\right)\right)$

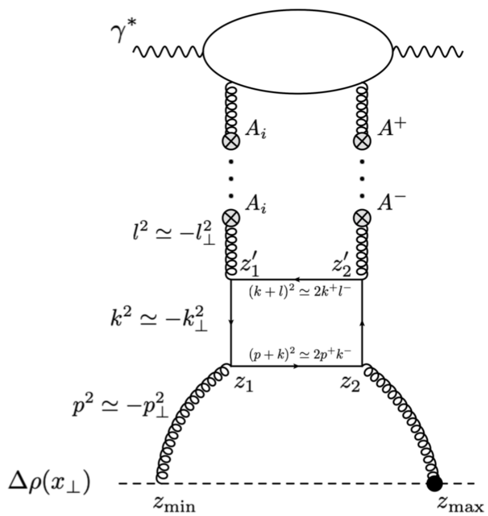
Spin diffusion to small x

A lot of impressive work on perturbative computations of g_1 at small x…

Kirschner Lipatov (1980's); Bartels, Ermolaev, Ryskin (1990's); Kovchegov, Pitonyak, Sievert (2015-), Kovchegov,Cougoulic (2019); Boussarie, Hatta, Yuan (2019)

Can we reconcile this work with the dynamics of the chiral anomaly at small x ?

QCD evolution to small x

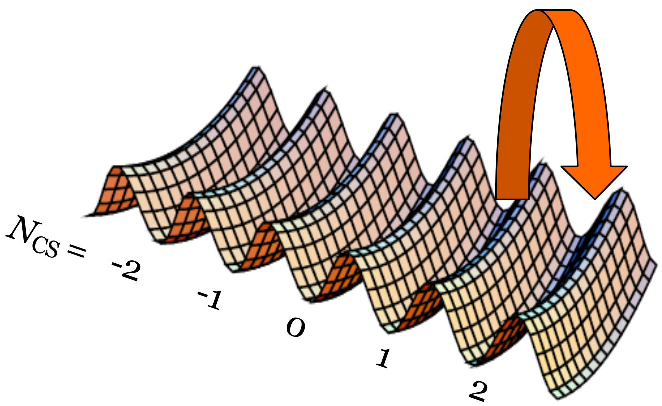


After smearing of the shockwave target in x^-,
the effective action reproduces itself (in a double log approximation)

– renormalizing the "axion effective action" at small x, one should recover
the triangle structure in the "box diagram"

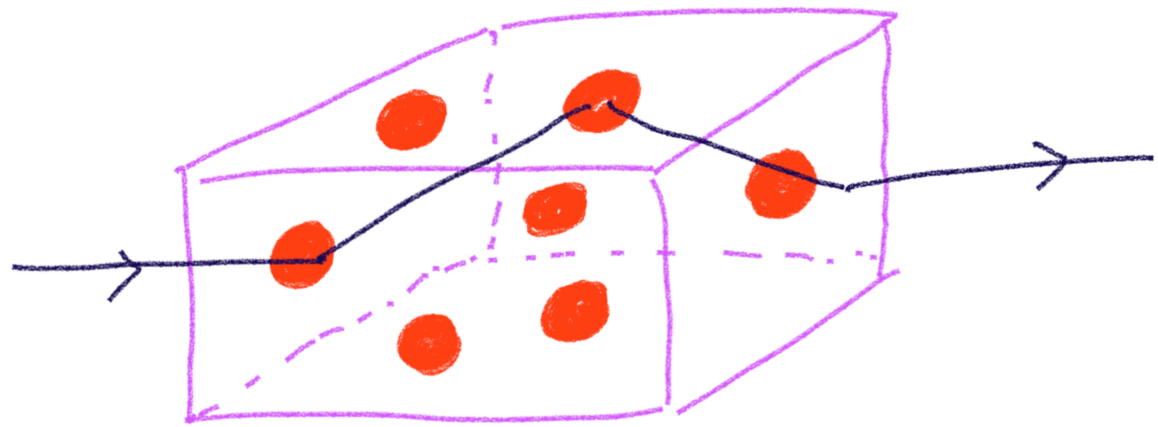
Fascinating interplay between gluon saturation (controlled by the saturation scale Q_S)
and spin diffusion (controlled by the topological charge density ω)

Spin diffusion via sphaleron transitions in topologically disordered media



Over the barrier (sphaleron) transitions between different
topological sectors of QCD vacuum…characterized by integer valued Chern-Simons #
--analogous to proposed mechanism for Electroweak Baryogenesis

Spin diffusion via sphaleron transitions in topologically disordered media



● Dense gluon blob of size $1/\sqrt{\sigma}$ given by $\Gamma^{Y}_{sphaleron} = \# \sigma^2$ & carrying topological charge

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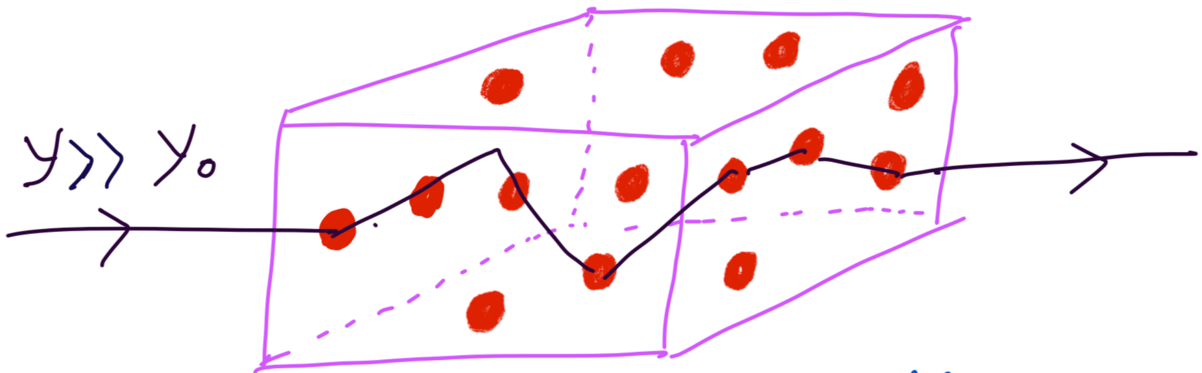
Helicity flip for massless quarks given by $nL - nR = 2\, N_f\, \nu$

where $\Gamma^{Y}_{sphaleron} \propto \langle \nu^2 \rangle$

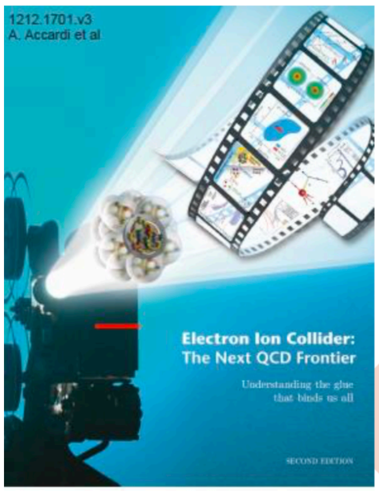
Spin diffusion via sphaleron transitions in topologically disordered media



As x decreases ($y \gg y_0$), the blobs become smaller ($Q_s(y) > Q_s(y_0)$) and denser with more topological charge

Helicity flip for massless quarks given by $nL - nR = 2\, N_f\, \nu$
where $\Gamma^{Y}_{\text{sphaleron}} \propto \langle \nu^2 \rangle$

Outlook: these ideas can be tested at the EIC !



White paper
arXiv:1212.1701

Conformal Anomaly

Chiral Anomaly

Origin of nucleon mass

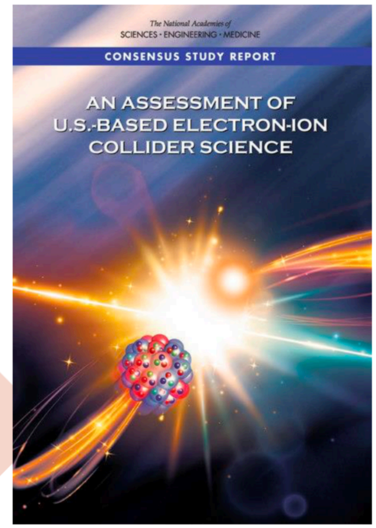
Origin of nucleon spin

Gluon saturation

Nucleon tomography

Color Glass Condensate

Confined many-body parton dynamics



NAS report
July 2018

Precision probes of the strong interplay between perturbative many-body parton dynamics and non-perturbative structure (“the ether”) of the QCD vacuum