COLOR CONFINEMENT VORTICES and the PION TORNADO

den sivers
Portland Phys. Inst.

I. COLOR CONFINEMENT in 3+1 dim CHROMOSTATICS

Gauss's Law

boundaries

Yang-Mills Maxwell equations

GAUGE CONNECTION gradients

Domain walls - Topological

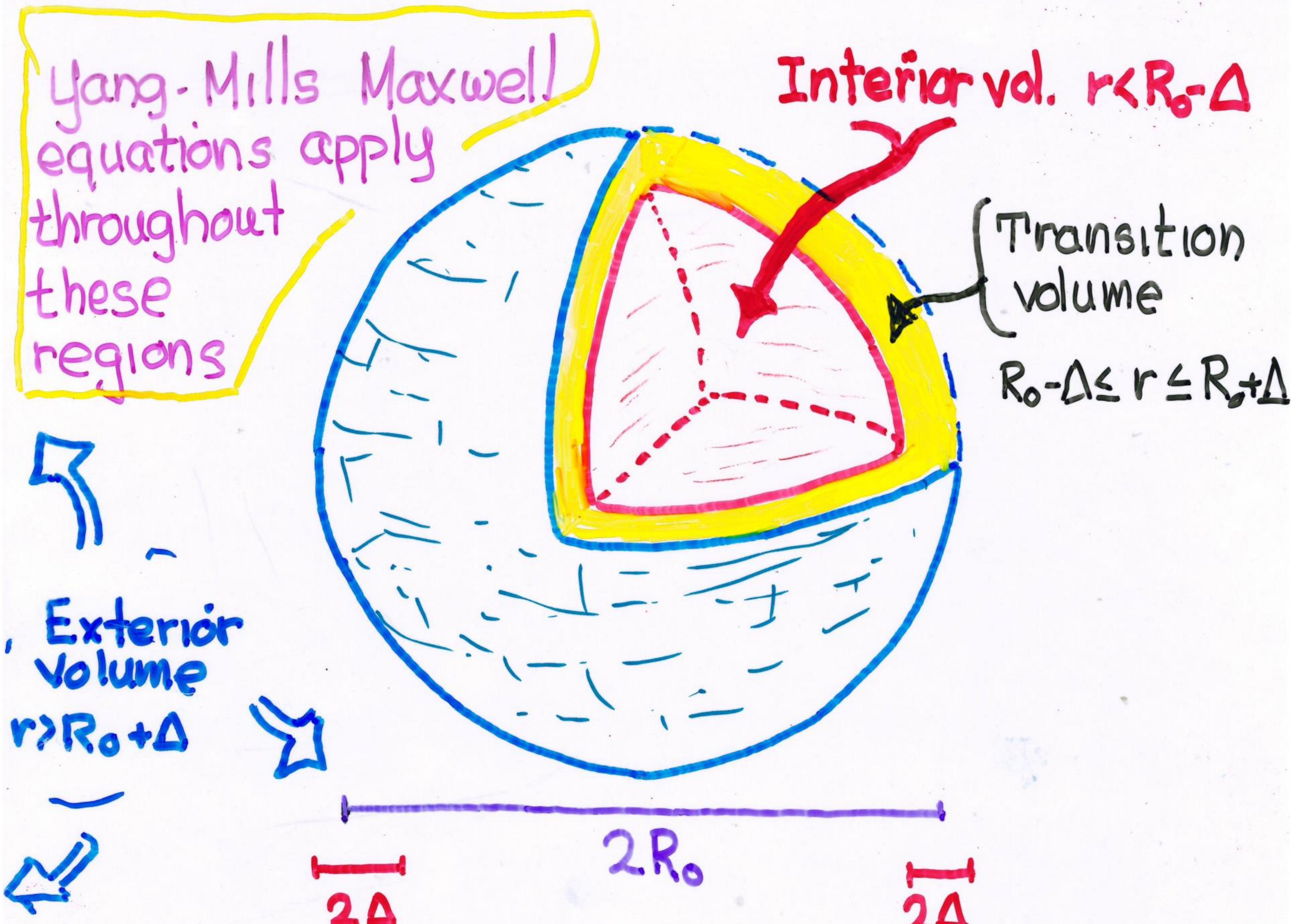
$\{E_i^a B_i^a \neq 0\}$

The Strong Conjecture

The confinement mechanism for QCD involves a domain wall of topological (CP-odd) charge separating the interior volume of hadrons from an exterior volume.

This conjecture provides a specific starting point for the study of color confinement.

There is a \$50K prize for disproving the conjecture


Yang-Mills Maxwell equations apply throughout these regions
Interior vol. $r<R_0-\Delta$
Transition volume
$R_0-\Delta\leq r\leq R_0+\Delta$
Exterior volume
$r>R_0+\Delta$
$2R_0$
2Δ
2Δ

TOPOLOGICAL CHARGE

CP-odd condensate $E_i^a B_i^a(r,t)$

forms in regions with different values of constant $a(r,t)$ as a consequence of Yang-Mills Maxwell equations $-E_L + \frac{\partial}{\partial r}(a r E_S) + \frac{\partial}{\partial t}(a r B_A) = g^2 r^2 E_i^a B_i^a$

- not a conserved charge

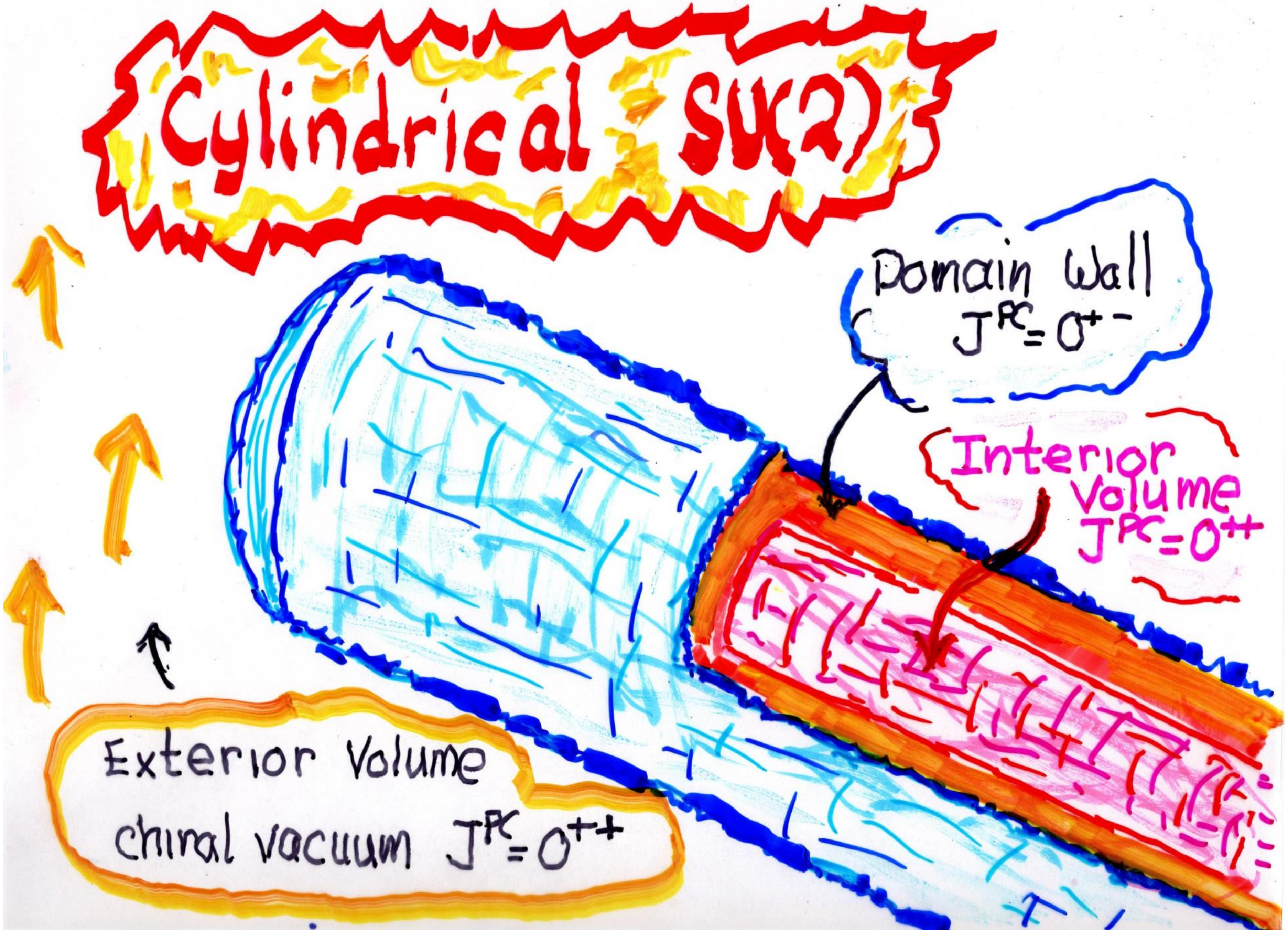
Disappears after EW hadronic decays (ex. $\pi^0 \to \gamma\gamma$)

Instantons & Merons ..

Classification of condensates in SU(2) chromostatics with spherical symmetry

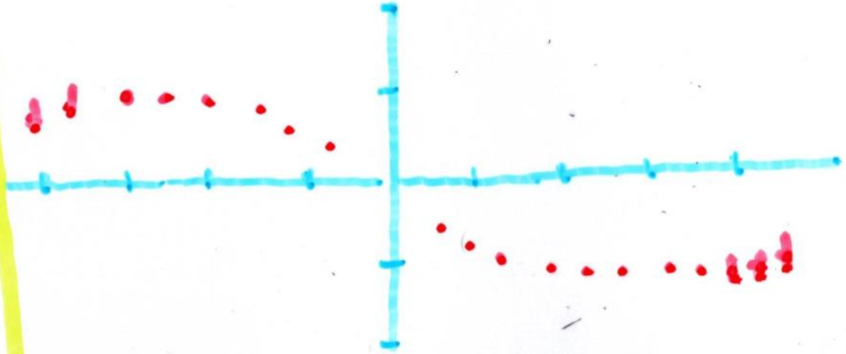
$a(r) = \pm 1$	$E_i^a E_i^a \neq 0$	$B_i^a B_i^a = 0$		color electric
$a(r) = \pm 1$	$E_i^a E_i^a = 0$	$B_i^a B_i^a \neq 0$		color magnetic
$a(r) = \pm 1$	$E_i^a E_i^a \neq 0$	$B_i^a B_i^a \neq 0$		color glass
$a(r) = \pm 1$	$E_i^a E_i^a = 0$	$B_i^a B_i^a = 0$		sterile vacuum
$a(r) = 0$	$E_i^a E_i^a = 0$	$B_L B_L = (\pm)^2 \frac{1}{r^4}$		't Hooft Polyakov
$a(r) = C \neq \pm 1, 0$	$E_i^a E_i^a \neq 0$	$B_i^a B_i^a \neq 0$	$E_i^a B_i^a \neq 0$	topological or dyonic

a domain wall is a region where $a'(r) \neq 0$ that separates other condensates and also carries topological charge



Cylindrical SU(2)
Domain Wall
$J^{PC} = 0^{+-}$
Interior Volume
$J^{PC} = 0^{++}$
Exterior Volume
chiral vacuum $J^{PC} = 0^{++}$

M. Engelhardt, B. Musch, J Negele, A. Shafer



u-quark Boer-Mulders spin-directed momentum shif in a pion

Strong Evidence of large-scale

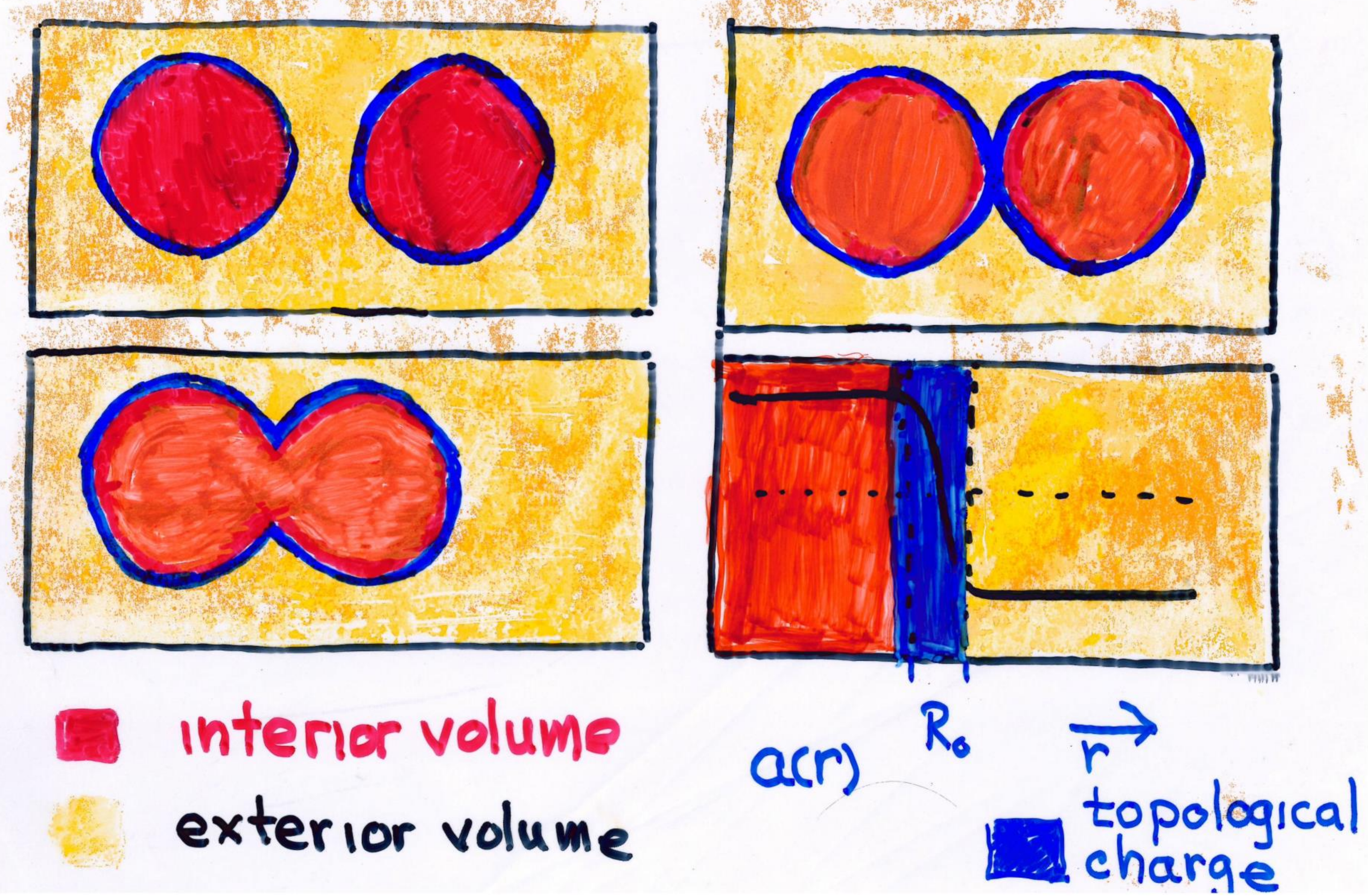
Chiral Structure

$^3P_0$ $\bar{q}q$ pairs

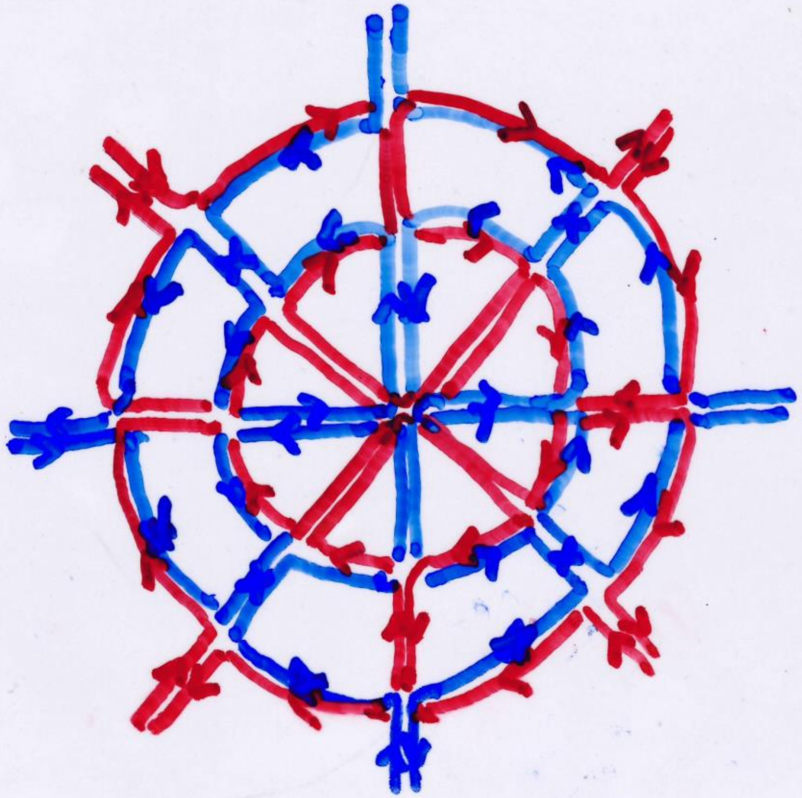
$\langle 2 \Sigma \vec{L}\cdot\vec{S} \rangle = -0.65 \pm 0.10$

M. Engelhardt
QCD Evolution 2021

Domain Zones

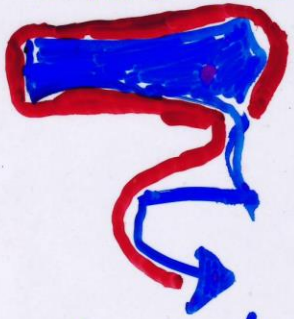


Here is the sketch showing the chiral nature covariant Derivatives generate



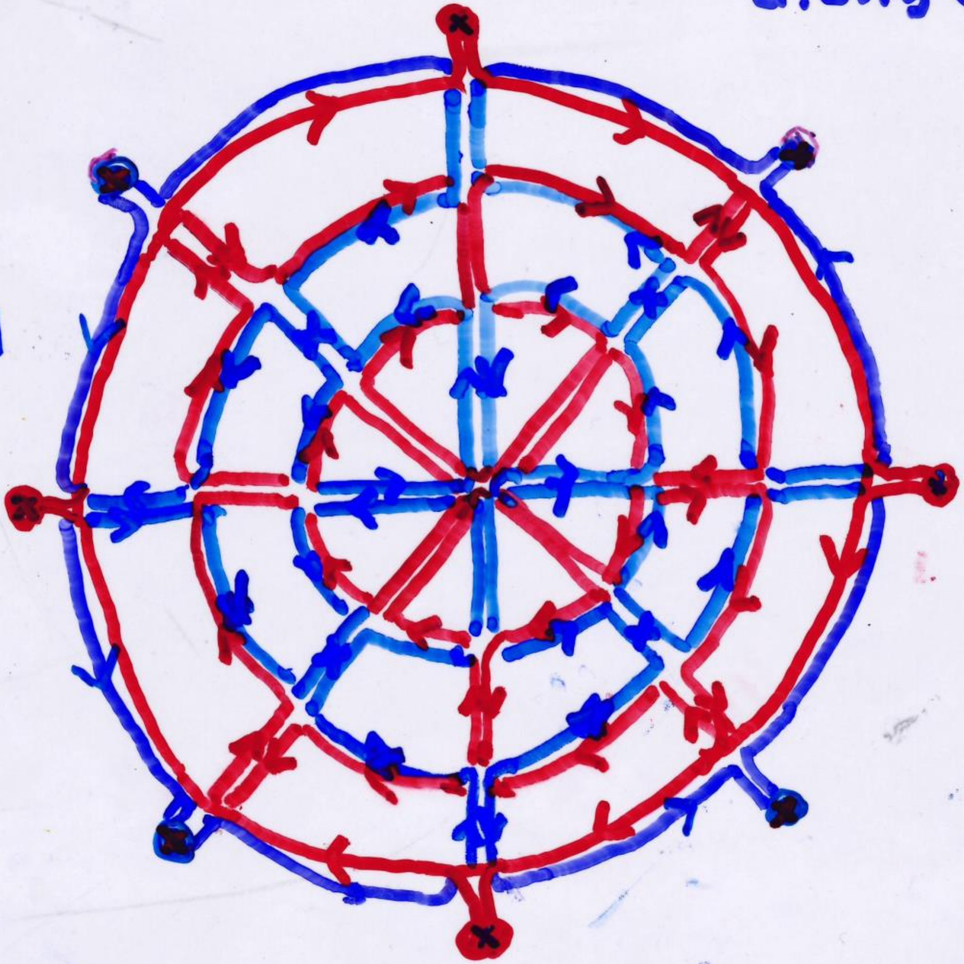
Let's compare putting on another layer with $a=1$ with two alternatives

Here is another layer with $a(r)=1$ with ends tied off by a distributed $SU(2)$ color source along each diagonal



a standard nontopological sol'n to Yang-Mills Maxwel

$a=1$



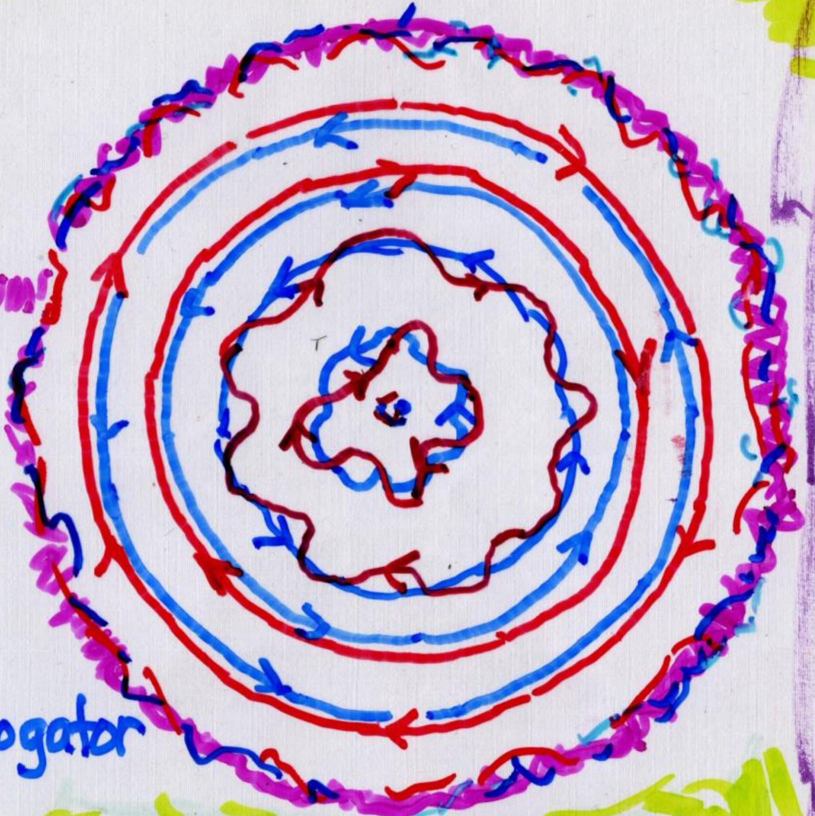
the exterior volume is a sterile vacuum condensate with the same chirality $a=1$ as outer

Leinweber & Collaborators

dynamical fermions increas density of color vortices in vacuum!

pure gauge 3277± 156

full qcd 5923± 259



Improves fit for confining potential & Landau gauge propogator

$^3P_0$ $q\bar{q}$ pairs

$J^{PC} = 0^{++}$

Chromostatics

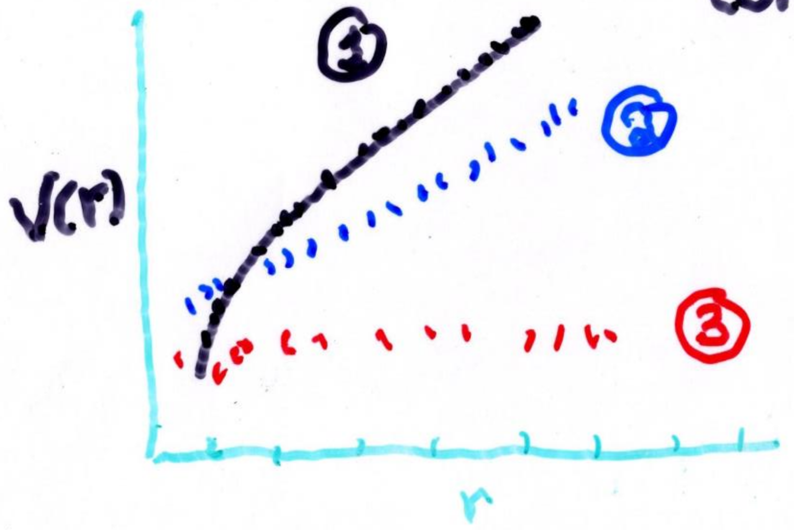
Interior Volume of hadron one chiral adiabatic vortex

$J^{PC} = 0^{++}$

Using the "maximal center gauge" it is possible to generate monte carlo gauge configurations with or without color vortices

1. regular
2. vortices only
3. vortices removed

Cornell Potential $V(r) = -\frac{\alpha}{r} + a_c + \sigma r$



Bowman et al
PR D84 034501 (2011)

Correlations in transverse-spin asymmetries

Connecting the SIDIS Target and Current Fragmentation Regions

Gary Goldstein
Simonetta Liuti
Dennis Sivers

$e p^{\uparrow} \to e' \pi^{+} p X$

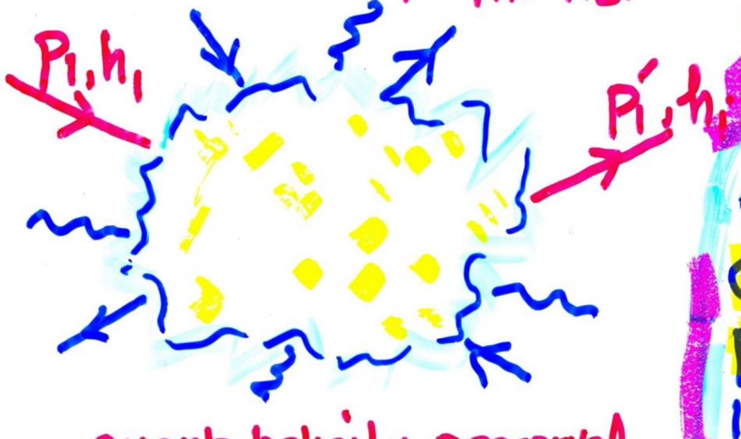
QUANTUM ENTANGLEMENT IN TRANSVERSE SPIN ASYMMETRY

I. Introduction to KPR factorization

Kane, Pumplin & Repko PRL 41, 1689 (1978)

$$A_N\Big|_{qq^{\uparrow}\Rightarrow qX} = \left[\frac{d\sigma(qq^{\uparrow}\Rightarrow q) - d\sigma(qq^{\downarrow}\Rightarrow q)}{d\sigma(qq^{\uparrow}\Rightarrow q) + d\sigma(qq^{\downarrow}\Rightarrow q)}\right] = \alpha_s(Q^2)\frac{m_q}{\sqrt{s}}\, f(\theta_{cm})() + \dots$$

where $f(\theta_{cm}) = \frac{p_{TN}}{(\mu^2 + p_{TN}^2 + p_{TS}^2)^{1/2}}$ $\quad f(\theta_{cm})$ vanishes at $\theta_{cm}=0$

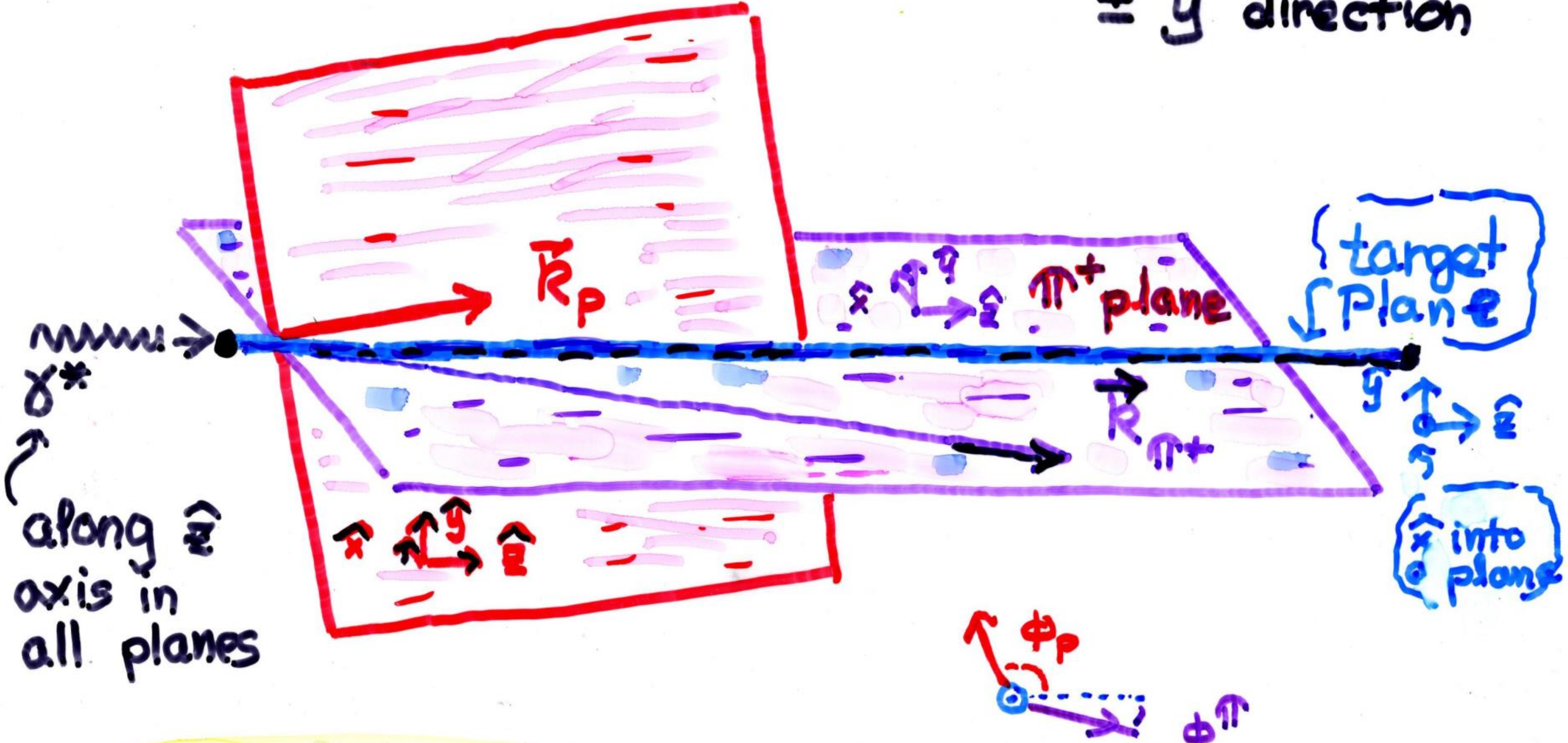


quark helicity preserved $O(m_q/\sqrt{s})$

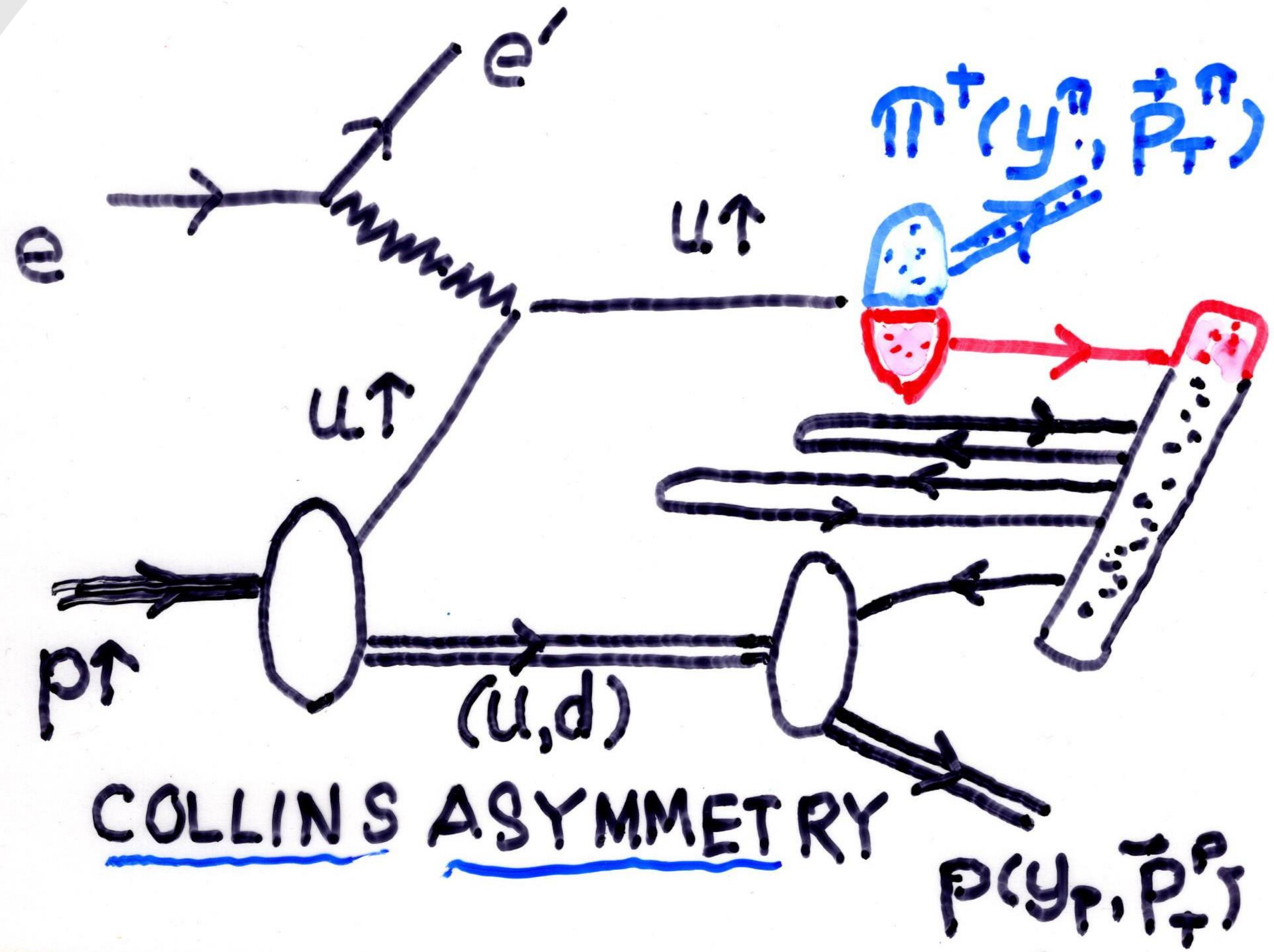
quark helicity conservation in QCD pert. theory implies an additional symmetry in pqcd that is <u>broken</u> in the full theory

Lab frame scattering planes $\gamma^* p\uparrow \Rightarrow \pi^+ p X$

target polarization
$\pm y$ direction

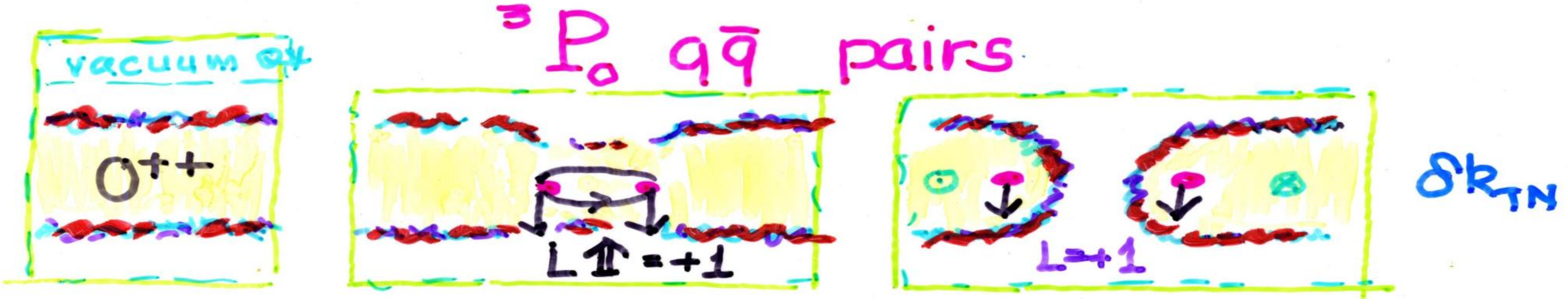


assume proton & π^+ product of rank-1 fragmentation functions


e
e'
u↑
u↑
$\pi^+(y^\pi, \vec{p}_T^{\,\pi})$
p↑
(u,d)
$P(y_P, \vec{P}_T^{\,P})$
COLLINS ASYMMETRY

SPIN-DIRECTED momentum transfers

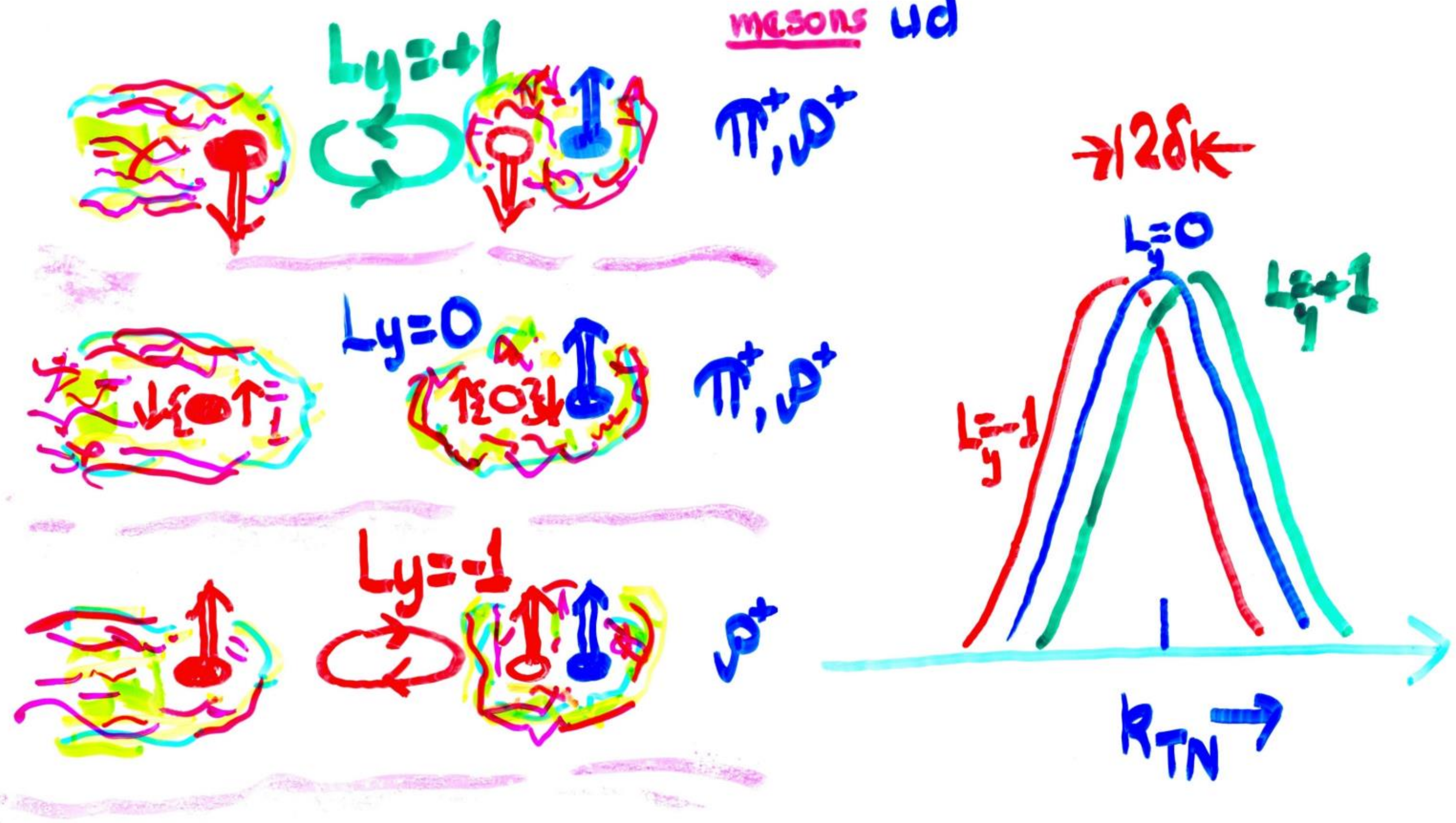
δk_{TN} generated in fragmentation process



combine with flux rupture to produce
Collins and polarizing fragmentation functions

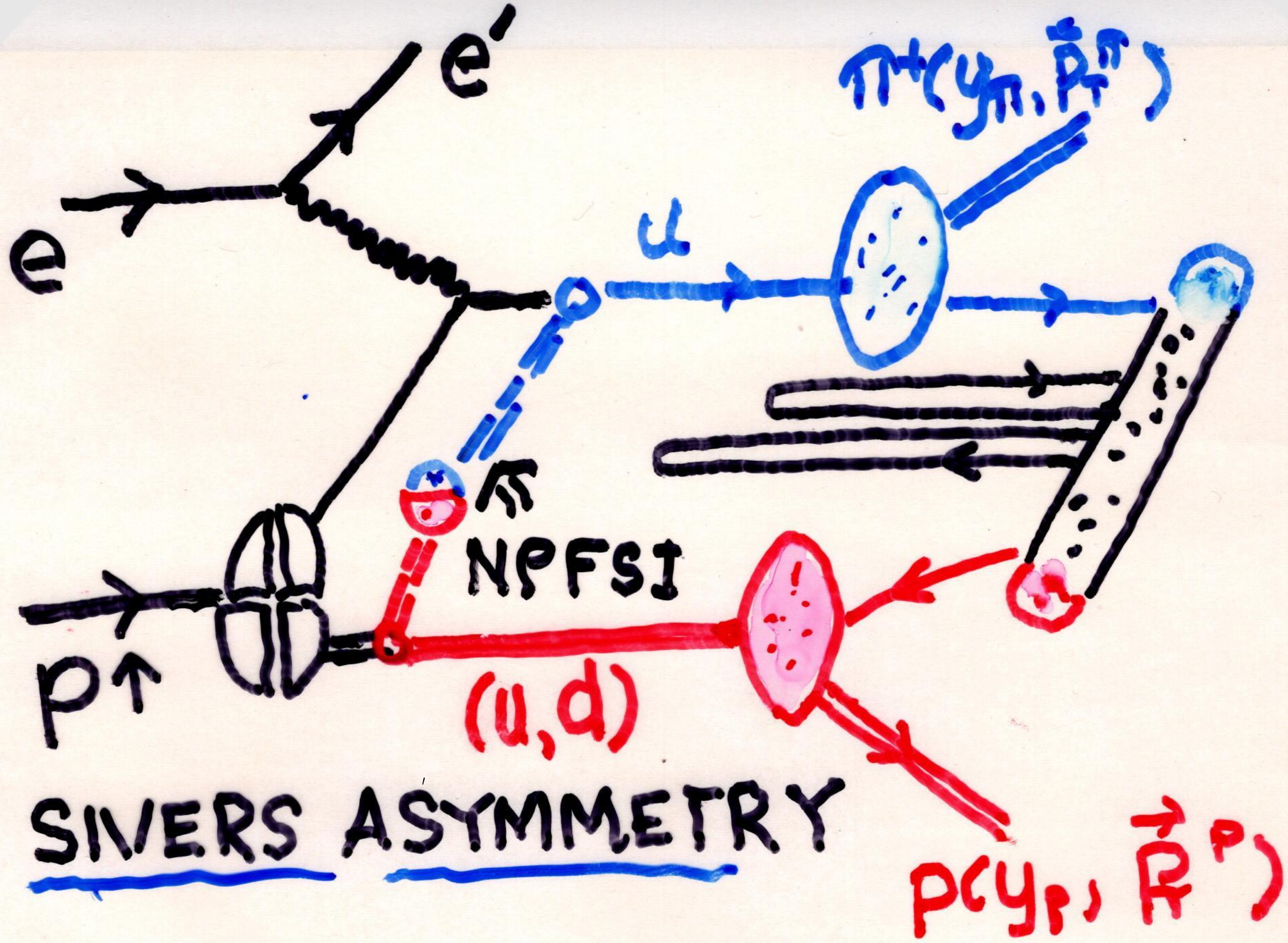
2-particle correlations short-range in rapidity

Jaffe, Bacchetta, Radici, D'Alesio ---
2-particle fragmentation fcns



Partial Wave Expansion Separates Spin-Directed Momentum transfer in fragmentation Process

$\delta = 0.2$ GeV/c



e'
e
$\pi^+(y_\pi, \vec{R}^\pi)$
u
NPFSI
P↑
(u,d)
$p(y_p, \vec{R}^p)$
SIVERS ASYMMETRY

Non-Perturbative Final-State Interactions

orbital angular momentum $\langle 2\vec{L}\cdot\vec{S}\rangle = -0.65 \pm 0.1$ (Engelhardt)

SIDIS for proton polarized $+\hat{y}$ direction

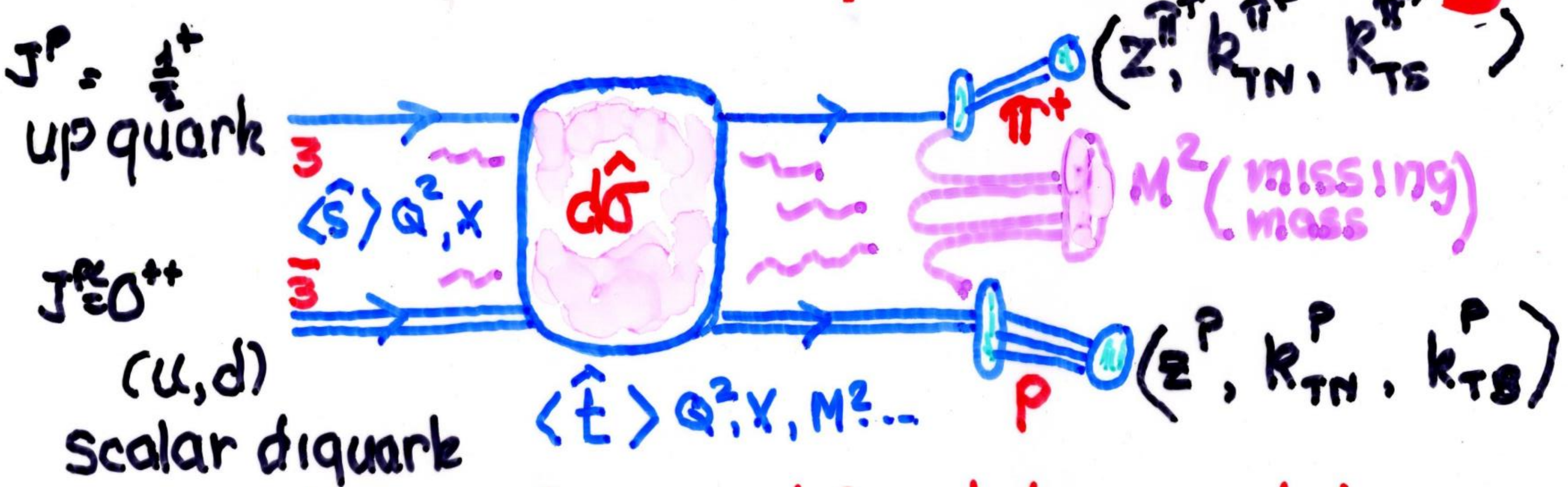
$$\boxed{\delta k_{TN}^{proton} = -\eta\, \delta k_{TN}^{\pi^+}}$$

ordinary entanglement

proton in target fragmentation

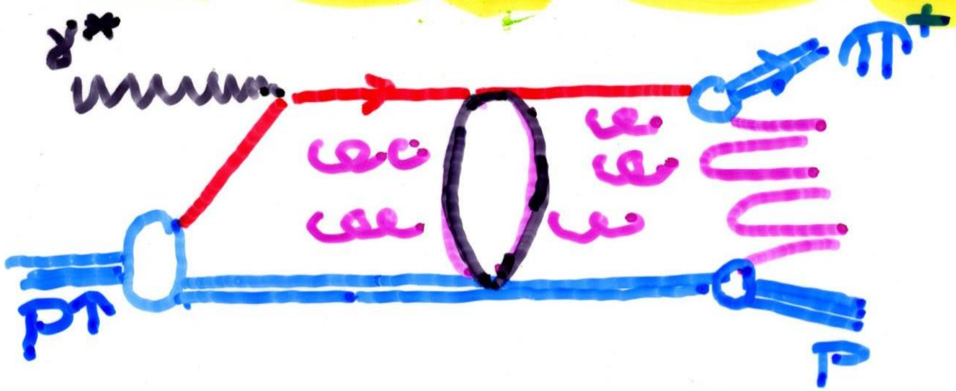
π^+ in current fragmentation

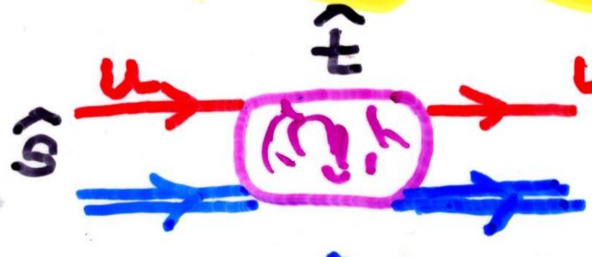
Examine non-perturbative Quark Diquark Scattering



exchange kinematics determined by measuring $\delta k_{TN}^{\pi^+}$ and δk_{TN}^{p} involved in spin asymmetry

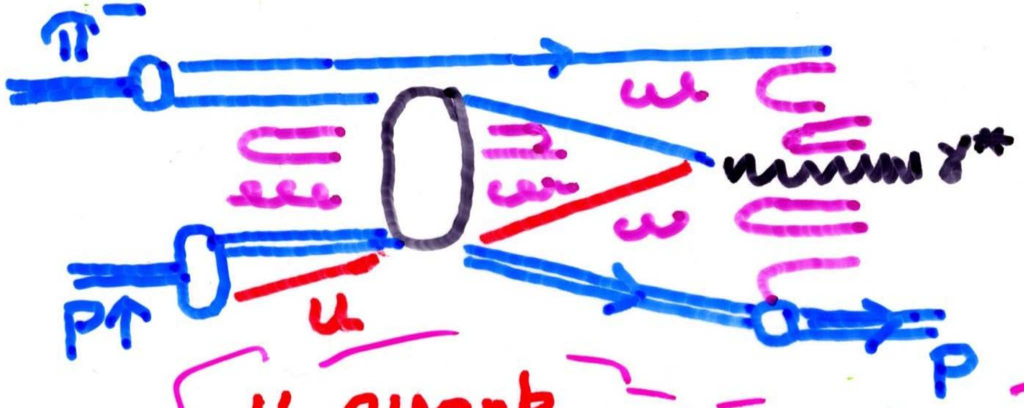
COLLINS CONJUGATION

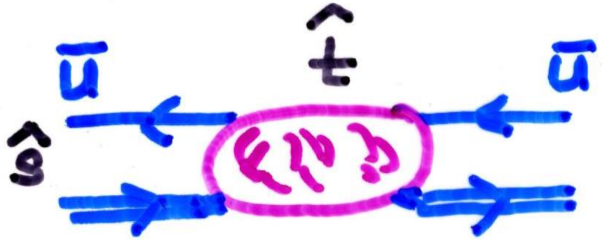




attractive

$u(u,d) \Rightarrow u(u,d)$





repulsive

$\bar{u}(u,d) \Rightarrow \bar{u}(u,d)$

u quark not involved
"not deflected"

$\bar{u}$ quark from π^-
"deflected"

Two Hadron TMD fracture functions in SIDIS

IV. extend the fracture function formalism Trentadue Veneziano

$M^{q}_{(h_1, h_2)/N}(x, Q^2; (y^{h_1}, \vec{k}_T^{h_1}) (y^{h_2}, \vec{k}_T^{h_2}))$ 1-jet

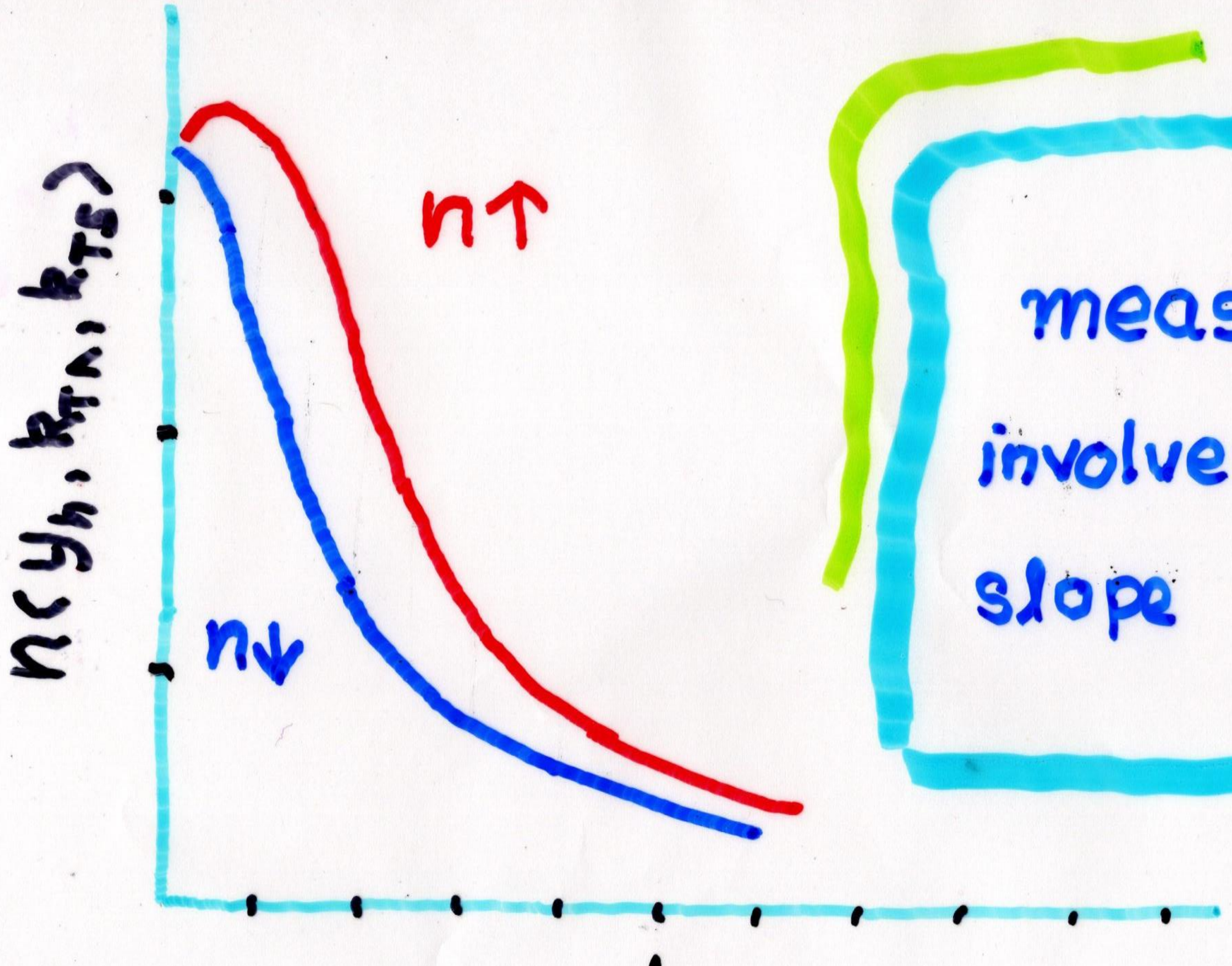
conjoint probabilities

$\Delta^N M^{u}_{(\pi^+, p)/p\uparrow} = M^{u}_{(\pi^+, p)/p\uparrow} - M^{u}_{(\pi^+, p)/p\downarrow}$

$\Delta^N M^{u}_{(\pi^+, p/p\uparrow}(x, Q^2; (y^{\pi^+}, k_{TN}^{\pi^+}, k_{TS}^{\pi^+}); (y^{p}, k_{TN}^{p}, k_{TS}^{p}))$

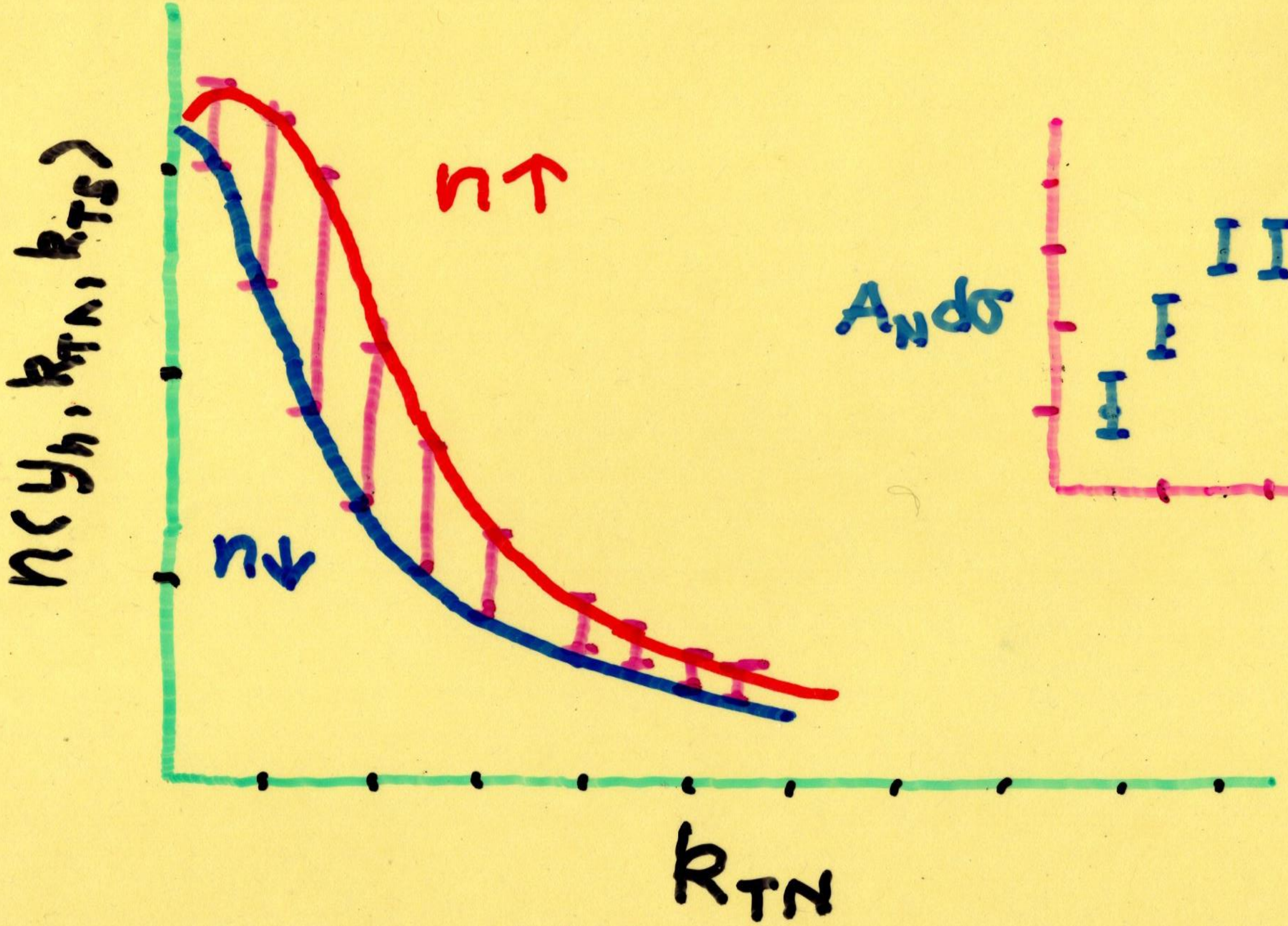
TRANSVERSE SPIN ASYMMETRY

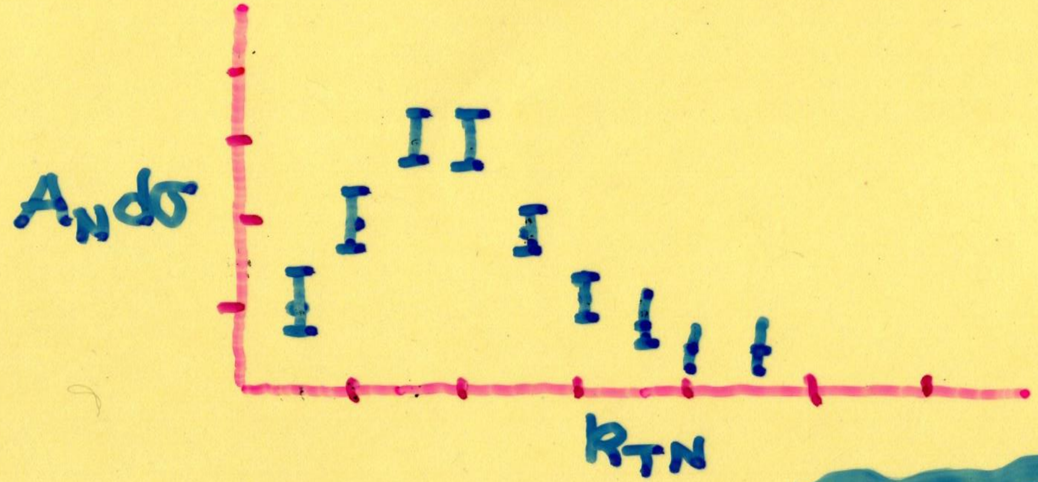
III HOW to MEASURE δk_{TN}



measuring δk_{TN} involves A_N and the slope $\frac{\partial}{\partial k_{TN}} d\sigma$

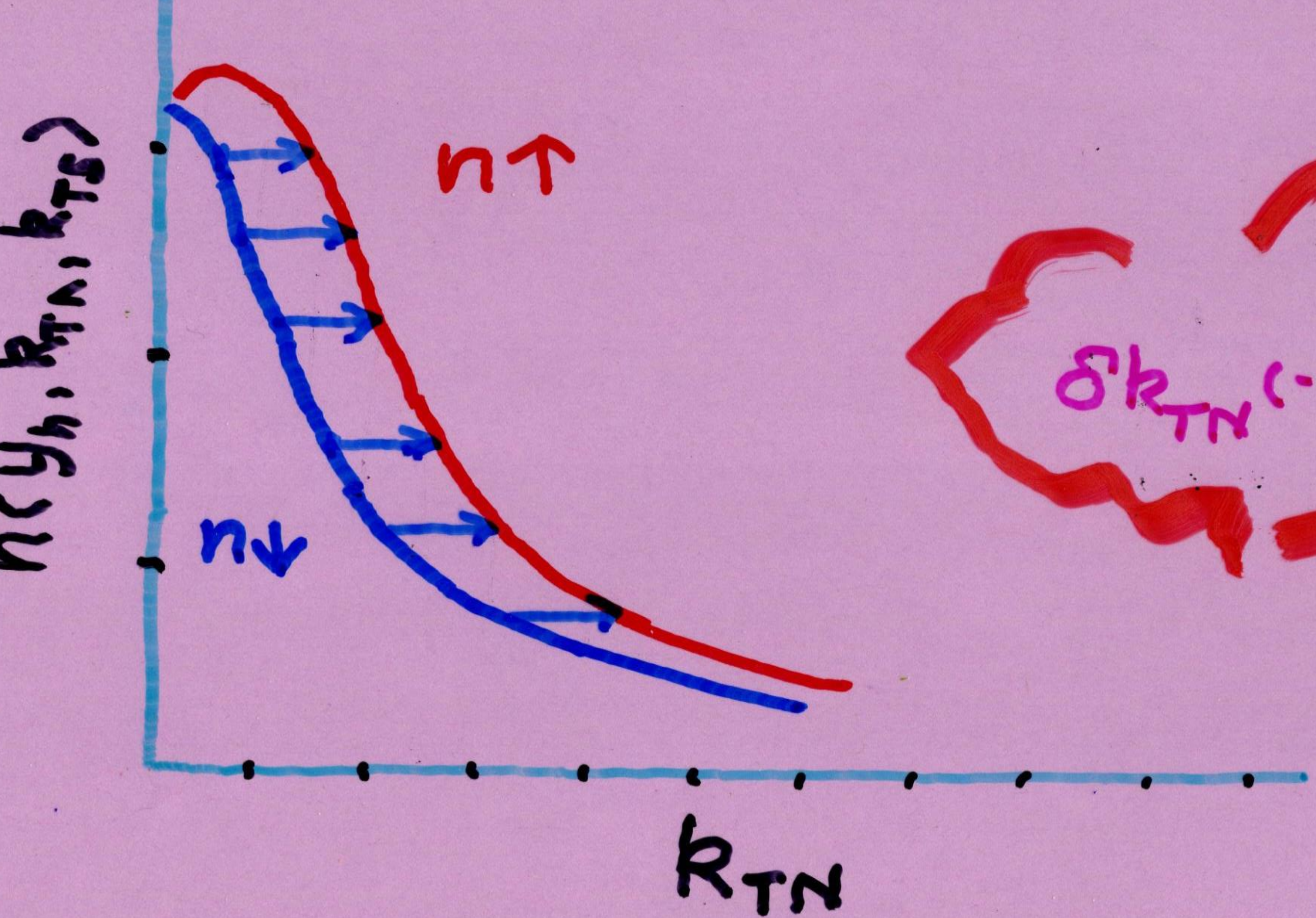
III HOW to MEASURE δR_{TN}





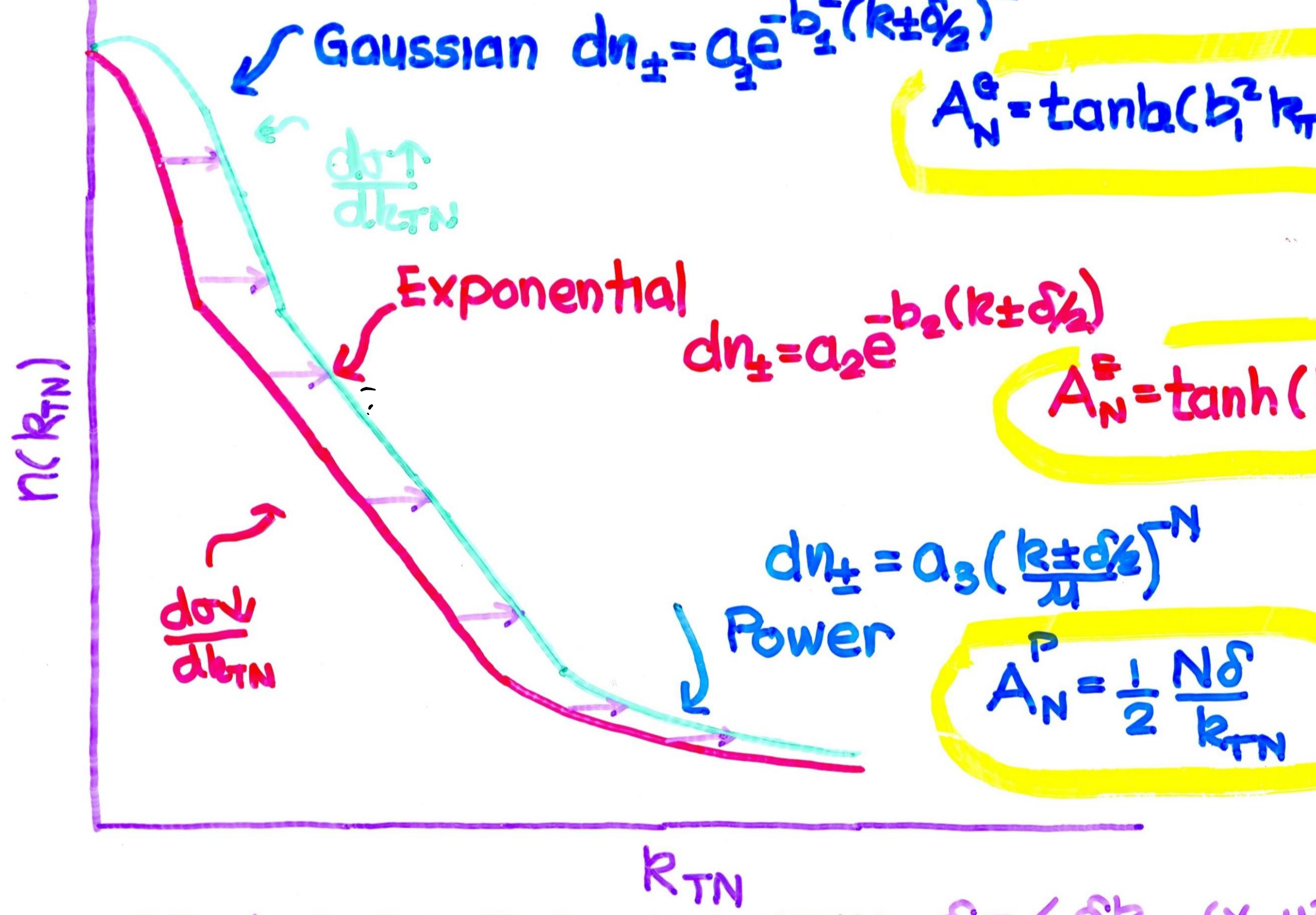
$A_N d\sigma = (n\uparrow - n\downarrow)$ at fixed k_{TN}

III HOW to MEASURE δk_{TN}



$$\delta k_{TN}(\cdots) = A_N\, d\sigma \Big/ \frac{\partial}{\partial k_{TN}}(n\uparrow + n\downarrow)$$

at fixed n



SPIN-DIRECTED MOMENTUM $\delta = \langle \delta k_{TN}(x, M$

Experimental Evidence of $ep^{\uparrow} = e\pi^{+}p$ transverse spin asymmetry correlations should already exist in CLAS-12 data from Jefferson Lab.

A range of similar correlation measurements should be a part of any program to study QCD at EIC

Two-Hadron TMD Fracture Functions in SIDIS

extend the fracture function formalism Trentadue Veneziano
conjoint probabilitie instead of number densities

$$M^{q}_{(h_1,h_2)/p}\left[x, Q^2; (z^{h_1}, \vec{k}_T^{h_1}), (z^{h_2}, \vec{k}_T^{h_2})\right]$$ 1-jet fracture function

transverse-spin asymmetry

$$\Delta^N M^{u}_{(\pi^+,p)/p\uparrow} \equiv M^{u}_{(\pi^+,p)/p\uparrow} - M^{u}_{(\pi^+,p)/p\downarrow}$$

$$= \Delta^N M^{u}_{(\pi^+,p)/p\uparrow}\left[x, Q^2; (z^{\pi^+}, k_{TN}^{\pi^+}, k_{TS}^{\pi^+})(z^{p}, k_{TN}^{p}, k_{TS}^{p})\right]$$

assume π^+, p 1st-rank fragmentation products

Diquarks and Diquark Fragmentation

$[q,q]$ $J^P = 0^+$ $\bar{3}$ color $[u,d]$ $[d,s]$ $[s,u]$ $\bar{3}_{\text{flavor } SU(3)}$

$\{q,q\}\uparrow$ $J^P = 1^+$ $\bar{3}$ color $\{u,u\}$ $\{u,d\}$ $\{d,d\}$ $\{u,s\}$ $\{d,s\}$ $\{s,s\}$ $6_{\text{flavor } SU(3)}$

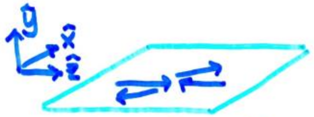
gluonic radiation $[q,q] \Rightarrow [q,q]_6^- G$ $\{q,q\} \Rightarrow \{q,q\}_6^-$

changes parity and color of diquarks but <u>not</u> flavor or symmetry

changes of flavor or symmetry require mesonic degrees of freedom

$\{q_i, q_j\}\uparrow \Rightarrow [q_i, q_l](\bar{q}_l\, q_j)$ $[q_i, q_j](q_k \bar{q}_l) \Rightarrow \{q_i, q_k\}\uparrow (q_j \bar{q}_l)$

that are incorporated into <u>fragmentation process</u>



FINITE SYMMETRIES

	T	C	P	(CPT)	Θ	A_τ	$A_>$	A_c
Σ_x	−	+	−	+	−	+	−	+
Σ_y	+	+	+	+	−	−	−	−
Σ_z	+	−	−	+	−	+	+	−
					$(^*P)^*$	ΘP	$A_\tau T$	$A_\tau C$

$*$ HODGE DUAL OPERATOR

$P:(V,A)=(-V,A)$

$*:(V,A)=(\tilde{A},\tilde{V})$

$P^*:(V,A)=(\tilde{A},-\tilde{V})$

$^*P^*:(V,A)=(V,-A)$

$\Theta = {}^*P^*$ "Snake Operator"

Changes sign of spins without changing momenta

$A_\tau:(\hat{P},\hat{\sigma})=(-\hat{P},-\hat{\sigma})$

$\boxed{\Theta = PA_\tau = - \text{ for } \underline{\text{all}} \text{ single-spin observables}}$

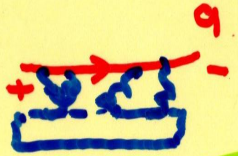
QUANTUM ENTANGLEMENT
IN TRANSVERSE SPIN ASYMMETRY

Transverse Spin Asymmetries

delineate the boundary

pqcd

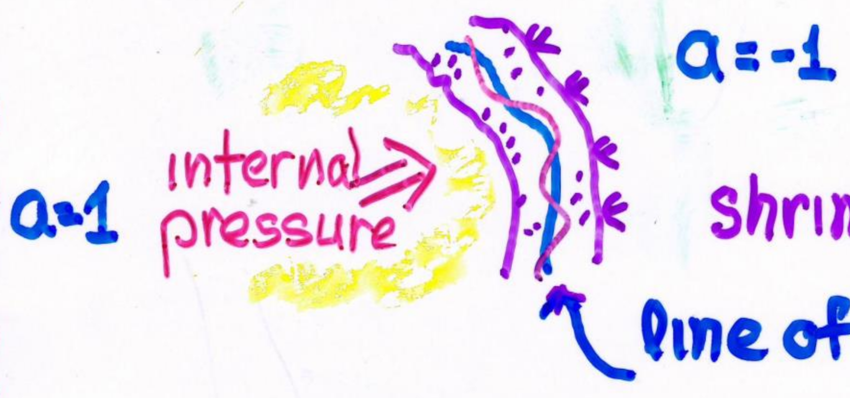
npqcd

in pqcd Im  $= 0 \quad \lim m_q \to 0$

However there are nonperbative dynamical mechanisms in the full theory that combine orbital angular momentum and hadronic-scale coherence

$^3P_0$ $q\bar{q}$ pairs

The color-glass/sterile vacuum "kink" soliton with $\Delta a = \pm 2$ is also a topologically stable solution to SU(N) field equations



Confines Abelian Gluons - adjoint charge

replaces dual superconducting "QCD vacuum" condensate with a dual insulator

Translates to cylindrical symmetry - QCD jets & Collins functions

not yet studied extensively

II. Lattice Studies of Color Vortices

Lattice QCD most important tool for understanding color confinement

Jeff Greensite An Intro. to the Confinement Problem

Detailed Calculations Hadron spectra & parton distributions

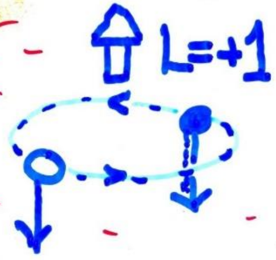
Engelhardt & Collaborators
Leinweber & Collaborators

Role of Color Vortices in the Confinement mechanism Emergent Structures

The Straw that Stirs the Drink

Jet rupture

Collins fcn's
&
Polarizing fragmentation



virtual
$^3P_0$ $(\bar{q}q)$
Pairs
0^{++}

$N\pi \rightleftarrows N^*$
$N\pi \rightleftarrows \Delta$

$Q \rightleftarrows Q'\pi$

P-wave Saturation

Baryon Structure

Streater Wightman Axioms

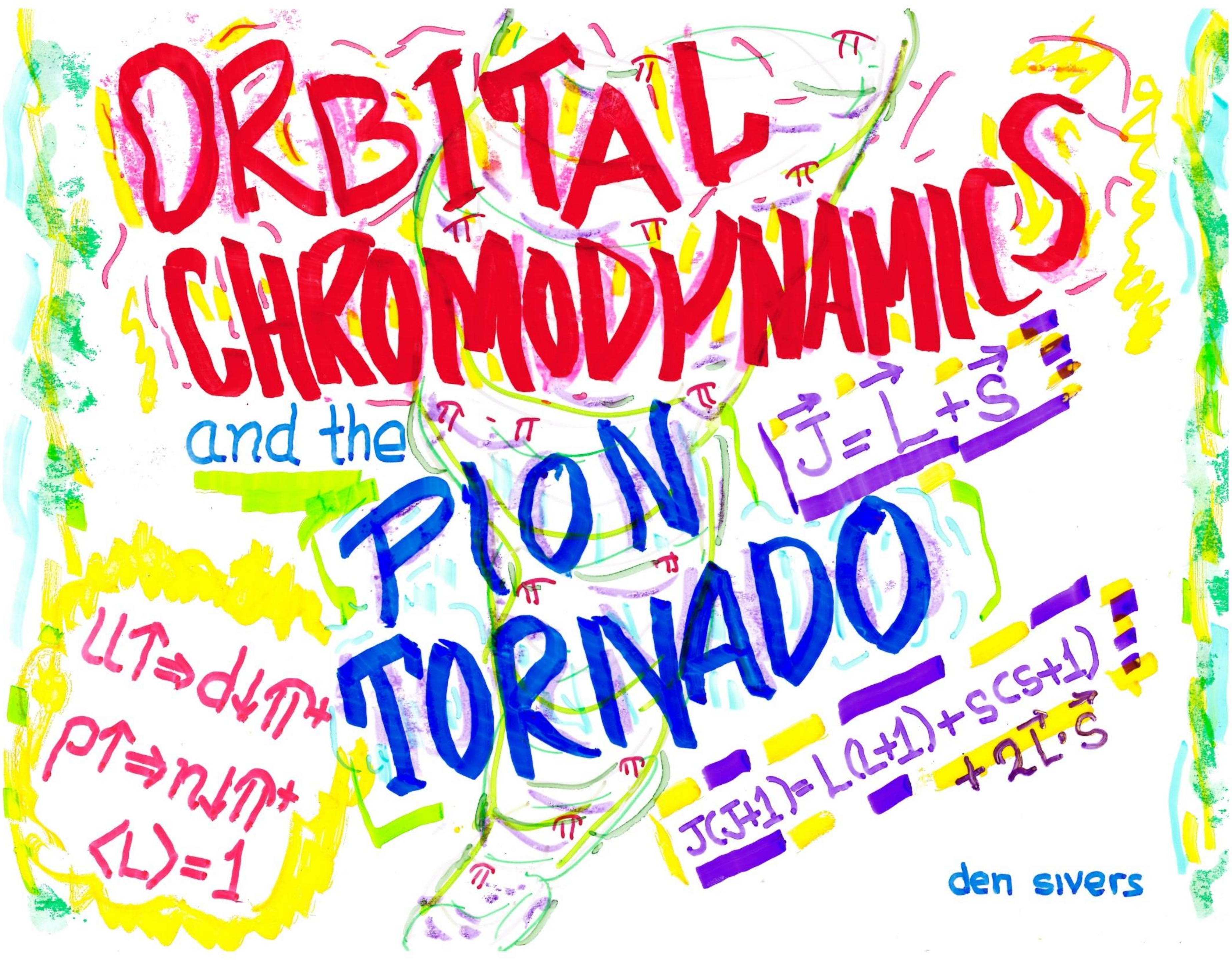
Gauge theories &
Cluster Decomposition

non-Abelian gauge theories accomodate:

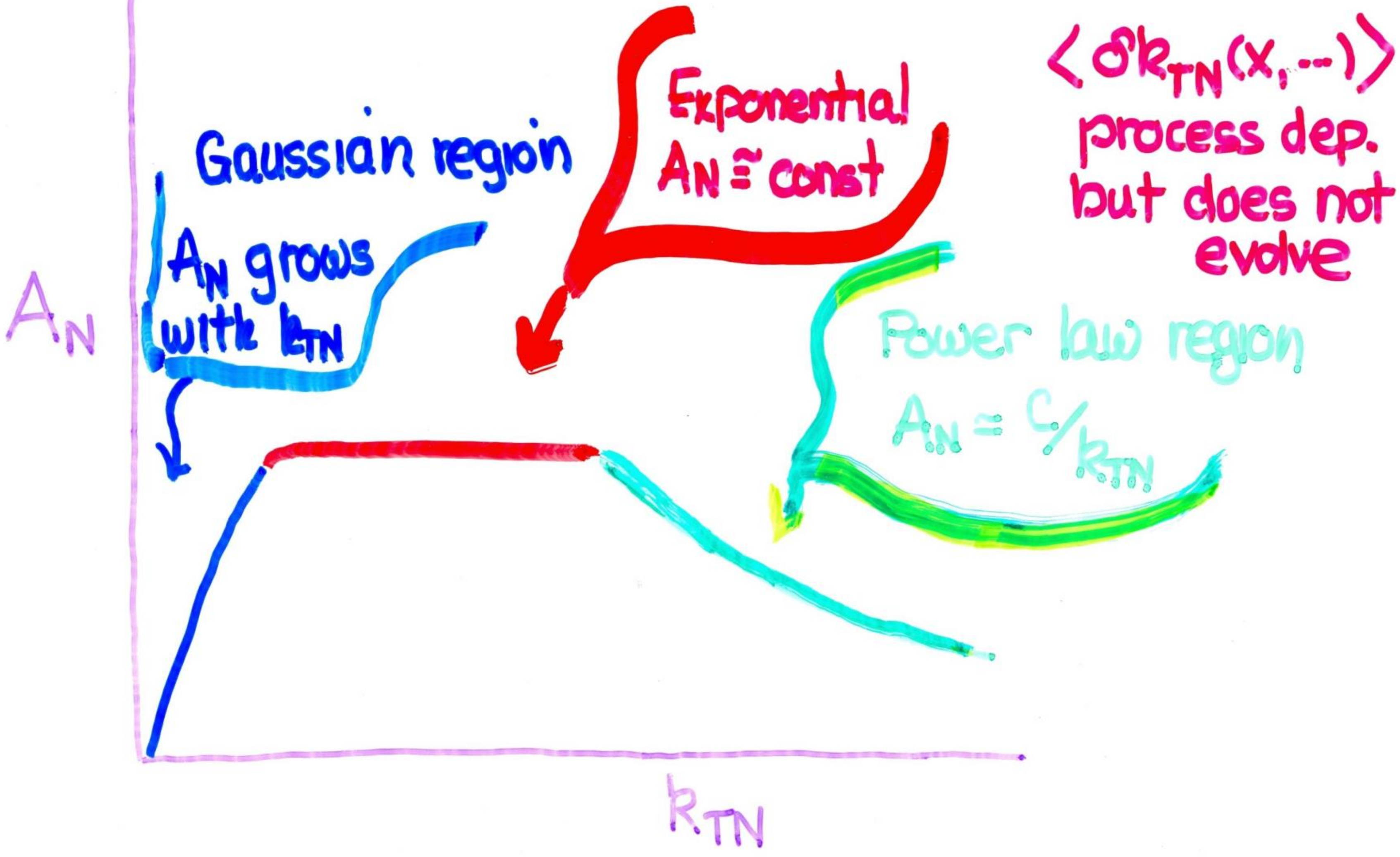
(A) area law for Wilson loops

(B) emergent structures such as topological domain walls

local fields $\nRightarrow$ non-local correlations


ORBITAL CHROMODYNAMICS
and the
PION TORNADO
$\vec{J} = \vec{L} + \vec{S}$
$u\uparrow \Rightarrow d\downarrow \pi^+$
$p\uparrow \Rightarrow n\downarrow \pi^+$
$\langle L \rangle = 1$
$J(J+1) = L(L+1) + S(S+1) + 2\vec{L}\cdot\vec{S}$
den sivers

A_N changes dramatically in response to QCD evolution in shape of $d\sigma/dk_{TN}$



(In valence SIDIS diquark participates **both** in $\langle L_y\rangle_q$ **and** in the FSI that generates $\langle \delta k_{TN}\rangle_q$)

This leads to $\langle \delta k_{TN}(x;\mu^2)\rangle_{[ud]} = -\eta(x)\langle \delta k_{TN}(x;\mu^2)\rangle_u$

with $(\eta < 1)$

and the expectation

$$A_N(ep\uparrow\to e'pX) \simeq A_N(ep\uparrow\to e'nX) \simeq A_N(ep\uparrow\to e'\Lambda X)$$
$$\simeq -e^{-\sigma} A_N(ep\uparrow\to e'\pi^+X)$$

opposite sign

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changes of flavor or symmetry require mesonic degrees of freedom

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that are incorporated into <u>fragmentation process</u>

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$= \Delta^N M^{u}_{(\pi^+,p)/p\uparrow}[x, Q^2; (z^{\pi^+}, k_{TN}^{\pi^+}, k_{TS}^{\pi^+})(z^p, k_{TN}^p, k_{TS}^p)]$

assume π^+, p 1st-rank fragmentation products

Constituent Quark
$J^P = 1/2^+$ not Dirac Fermion
$G \neq 0$ (spin/orbit structure)
....

Fundamental charge
3,3

o dirac antifermion (hole)

3 color

$\bar{3}$ color

Scalar diquark
[,] antisymmetric in flavor
$J^P = 0^+$

• dirac fermion

$\bar{3}$ color

axial vector diquark
{,} symmetric in flavor
$J^P = 1^+$ spin/orbit structure

OUTLINE

I. KPR Factorization & nonperturbative QCD

II. spin-directed momentum transfers at $m_q \to 0$

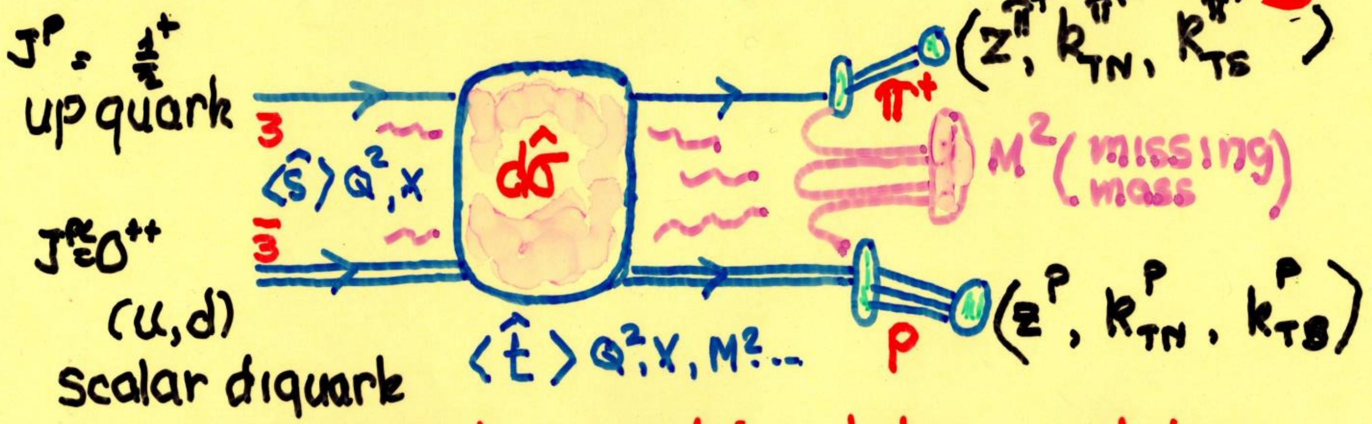
a) ${}^3P_0$ pairs & flux rupture

b) nonperturbative final-state interactions

III. How to measure δk_{TN}

IV. Transverse-spin asymmetries & 2-hadron fracture functions in $ep\uparrow \to ep\pi^+X$

Examine non-perturbative Quark Diquark Scattering



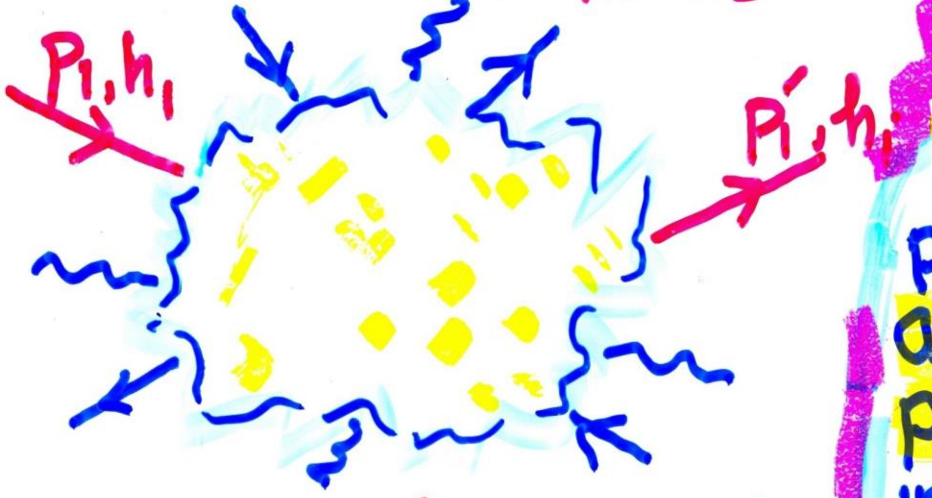
exchange kinematics determined by measuring $\delta k_{TN}^{\pi^+}$ and δk_{TN}^{p} involved in spin asymmetry

I. Introduction to KPR factorization

Kane, Pumplin & Repko PRL 41, 1689 (1978)

$$A_N\Big|_{qq^\uparrow \Rightarrow qX} = \left[\frac{d\sigma(qq^\uparrow \Rightarrow q) - d\sigma(qq^\downarrow \Rightarrow q)}{d\sigma(qq^\uparrow \Rightarrow q) + d\sigma(qq^\downarrow \Rightarrow q)}\right] = \alpha_s(Q^2)\frac{m_q}{\sqrt{s}}\, f(\theta_{cm})() + \dots$$

where $f(\theta_{cm}) = \dfrac{p_{TN}}{(\mu^2 + p_{TN}^2 + p_{TS}^2)^{1/2}}\, \mathcal{F}(\theta_{cm})$ vanishes at $\theta_{cm} = 0$



quark helicity preserved
$O(m_q/\sqrt{s})$

quark helicity conservation in QCD pert. theory implies an additional symmetry in pqcd that is <u>broken</u> in the full theory


FRACTURED
COLLINS
HEPPELMAN
LADINSKY


FRACTURED
ORBITAL DSTN.

Non-Perturbative Final-State Interactions

orbital angular momentum $\langle 2\vec{L}\cdot\vec{S}\rangle = -0.65 \pm 0.1$ (Engelhardt)

SIDIS for proton polarized $+\hat{y}$ direction

$$\delta k_{TN}^{proton} = -\eta\, \delta k_{TN}^{\pi^+}$$

ordinary entanglement

proton in target fragmentation
π^+ in current fragmentation

Diquarks and Diquark Fragmentation

$[q,q]$ $J^P = 0^+$ $\bar{3}$ color $[u,d]$ $[d,s]$ $[s,u]$ $\bar{3}_{\text{flavor } SU(3)}$

$\{q,q\}\uparrow$ $J^P = 1^+$ $\bar{3}$ color $\{u,u\}$ $\{u,d\}$ $\{d,d\}$ $\{u,s\}$ $\{d,s\}$ $\{s,s\}$ 6 flavor SU(3)

gluonic radiation $[q,q] \Rightarrow [q,q]^-_6\, G$ $\{q,q\} \Rightarrow \{q,q\}^-_6$

changes parity and color of diquarks but not flavor or symmetry

changes of flavor or symmetry require mesonic degrees of freedom

$\{q_i,q_j\}\uparrow \Rightarrow [q_i,q_l](\bar{q}_l\, q_j)$ $[q_i,q_j](q_k\bar{q}_l) \Rightarrow \{q_i,q_k\}\uparrow(q_j\bar{q}_l)$

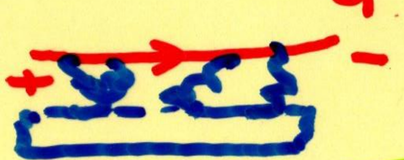
that are incorporated into fragmentation process

Transverse Spin Asymmetries

delineate the boundary

pqcd

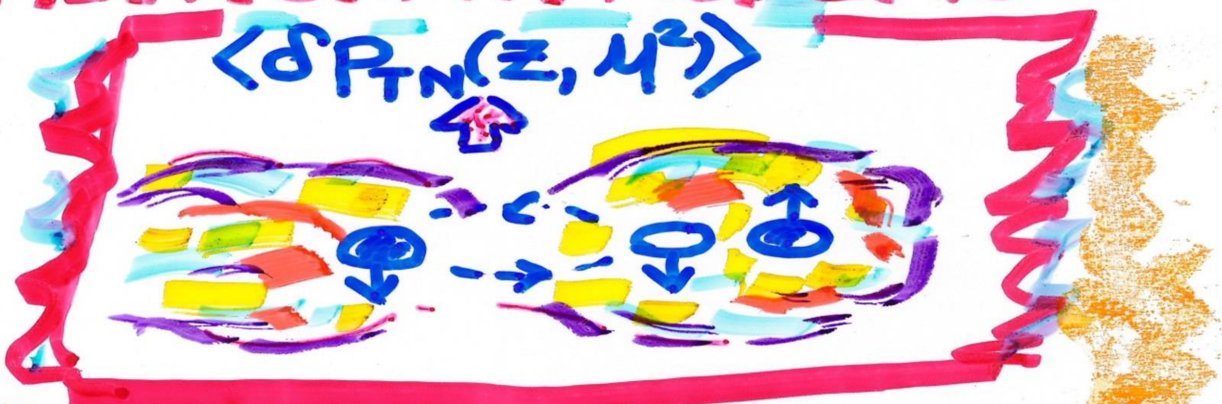
npqcd

in pqcd Im  $= 0$ lim $m_q \to 0$

However there are nonperbative dynamical mechanisms in the full theory that combine orbital angular momentum and hadronic-scale coherence

$^3P_0$ $q\bar{q}$ pairs

QUANTUM ORBITAL DYNAMICS & SPIN-DIRECTD MOMENTUM TRANSFERS



from CONFINED non-Abelian SYSTEMS

Group Hadronic Physics
2014 - Baltimore

d. sivers

The Isospin dependence of

$A_N(ep\uparrow \Rightarrow e'\Sigma^+ X)$: $A_N(ep\uparrow \Rightarrow e'\Sigma^0 X)$

should prove to be very interesting

The fractured Boer-Mulders effect presents a unique opportunity to confirm that a polarization asymmetry can be generated by dynamical effects within proton

$P_{BM}(ep \Rightarrow e'\Lambda^0\uparrow X) \cong 0$ $P_{BM}(ep \Rightarrow e'\Sigma^{+/0}\uparrow X)$ large and negative !!

$P_{BM}(ep \Rightarrow e'p\uparrow X)$
$P_{BM}(ep \Rightarrow e'n\uparrow X)$ } can be measured by rescattering on a carbon polarimeter

The orbital dst'ns for quarks measured in SIDIS require <u>both</u> $\langle L\rangle_q \neq 0$ <u>and</u> final-state interactions involving the target remnants

The fraction of the spin-directed momentum transfer of the struck quark that is transmitted to the appropriate diquark

$$\langle \delta k_{TN}(x,\mu^2)\rangle^{(0)}_{\{ud\}} + \langle \delta k_{TN}(x,\mu^2)\rangle^{(0)}_{[ud]} = -2\,\eta_u(x)\,\langle \delta k_{TN}(x,\mu^2)\rangle^{(0)}_{u}$$

$$\langle \delta k_{TN}(x,\mu^2)\rangle^{(0)}_{\{uu\}} = -\eta_d(x)\,\langle \delta k_{TN}(x,\mu^2)\rangle^{(0)}_{d}$$

$$0 < \eta_u, \eta_d < 1$$

measures the binding of the quark-diquark system to the remaining constituents

The experimental evidence for HT processes in

$\frac{E\,d\sigma}{d^3p}(pp \Rightarrow \pi X)$

$$\frac{E\,d\sigma}{d^3p}(pp \Rightarrow \pi X) = \frac{1}{\pi}\sum_{abcd}\int dx_a\, dx_b\, \frac{dz_c}{z_c^2}\, G_{a/p}(x_a;\mu^2)\, G_{b/p}(x_b;\mu^2)\, D_{\pi/c}(z_c;\mu^2) \left[\hat{s}\frac{d\sigma}{d\hat{t}}(ab \Rightarrow cd)\right] \delta(\hat{s}+\hat{t}+\hat{u}+m_1^2)$$

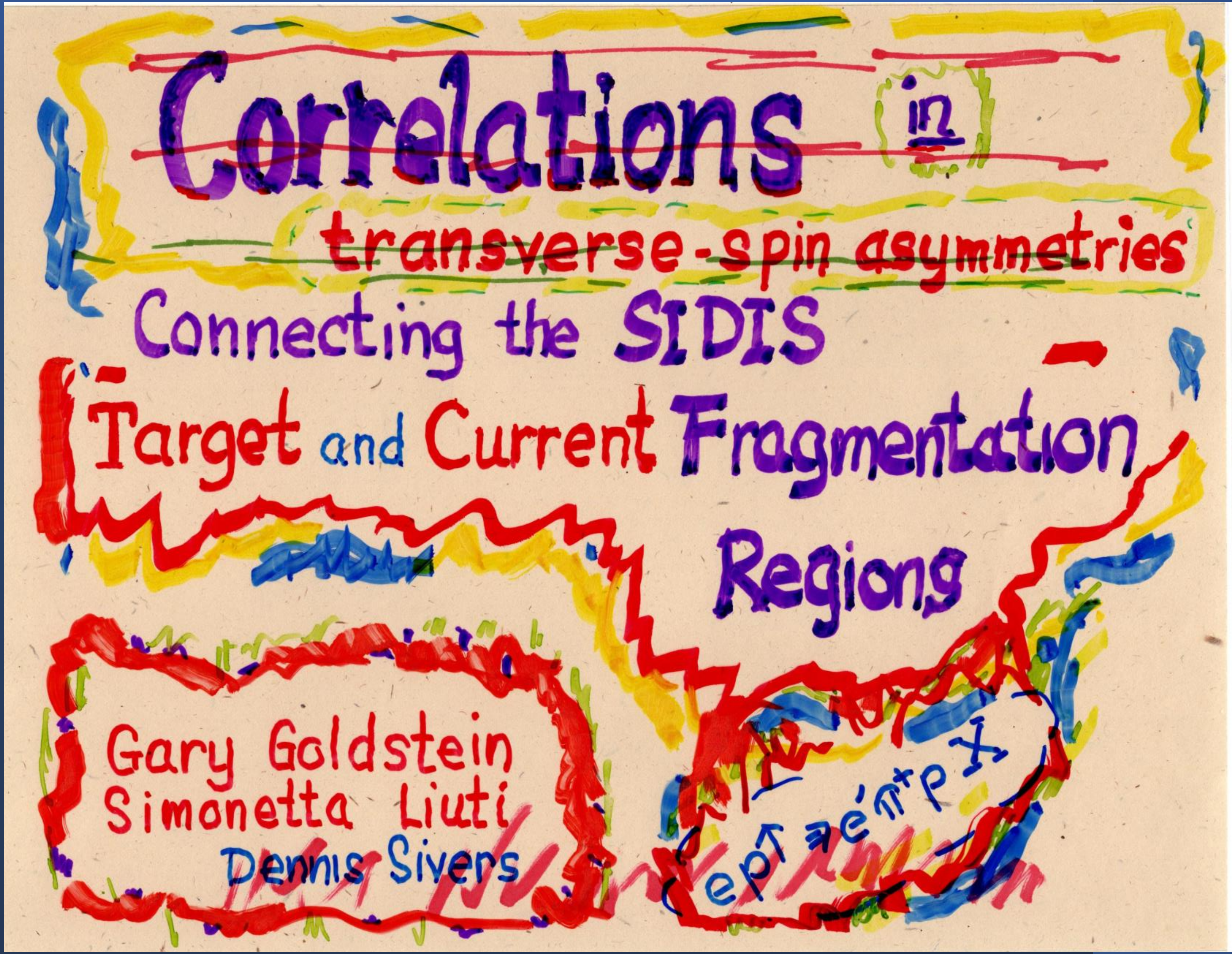
should include contributions from

$Gq = \pi q \quad \pi q \Rightarrow Gq \quad G\pi \Rightarrow q\bar{q} \quad q\bar{q} = G\pi \quad \pi q \Rightarrow \pi q$ in addition to the leading-order QCD processes

This observation has implications for

$$A_N \frac{d\sigma}{d^3p}(pp^\uparrow \Rightarrow \pi X)\Big|_{\text{ORBITAL}} = \frac{1}{\pi}\sum_{abcd}\int dx_a\, d^2k_a\, dx_b\, d^2k_b\, \frac{dz_c}{z_c^2}\, d^2p_{\pi c}\, \Delta^N G_{a/p^\uparrow}(x_a, k_{T\perp}^a, k_{T\parallel}^a; \mu^2)\, G_{b/p}(x_b, k_{Tb}^2; \mu^2)\, D_{\pi/c}(z_c, p_{\pi c}^2; \mu^2) \left[\hat{s}\frac{d\sigma}{d\hat{t}}(ab \Rightarrow cd)\right] \delta(\hat{s}+\hat{t}+\hat{u}+m_1^2)$$

(also for the Collins, Heppelman, Ladinski contribution)


Correlations in
transverse-spin asymmetries
Connecting the SIDIS
Target and Current Fragmentation
Regions
Gary Goldstein
Simonetta Liuti
Dennis Sivers
$ep^{\uparrow} \to e' \pi^{+} p X$

OUTLINE

I. KPR Factorization & nonperturbative QCD

II. spin-directed momentum transfers at $m_q \to 0$

a) $^3P_0$ pairs & flux rupture

b) nonperturbative final-state interactions

III. How to measure δk_{TN}

IV. Transverse-spin asymmetries & 2-hadron fracture functions in $ep\uparrow \to e p \pi^+ X$

To appreciate the value of KPR factorization it is appropriate to incorporate the power of superselection rules and idempotent projection operators in QFT and quantum mechanics

all single-spin asymmetries

$$A(\vec{\sigma}) = [N(\vec{\sigma}) - N(-\vec{\sigma})] / [N(\vec{\sigma}) + N(-\vec{\sigma})]$$

$\vec{k}_i$: 3 vectors

$\vec{\sigma}_j$ = axial 3 vectors

are odd under an operator Θ

$$\boxed{\Theta\{\vec{k}_i ; \vec{\sigma}_j\}\Theta^{-1} = \{\vec{k}_i ; -\vec{\sigma}_j\}}$$

Θ serves as a 3-D Hodge dual of the parity operator

$$\boxed{P\{\vec{k}_i ; \vec{\sigma}_j\}P^{-1} = \{-\vec{k}_i ; \vec{\sigma}_j\}}$$

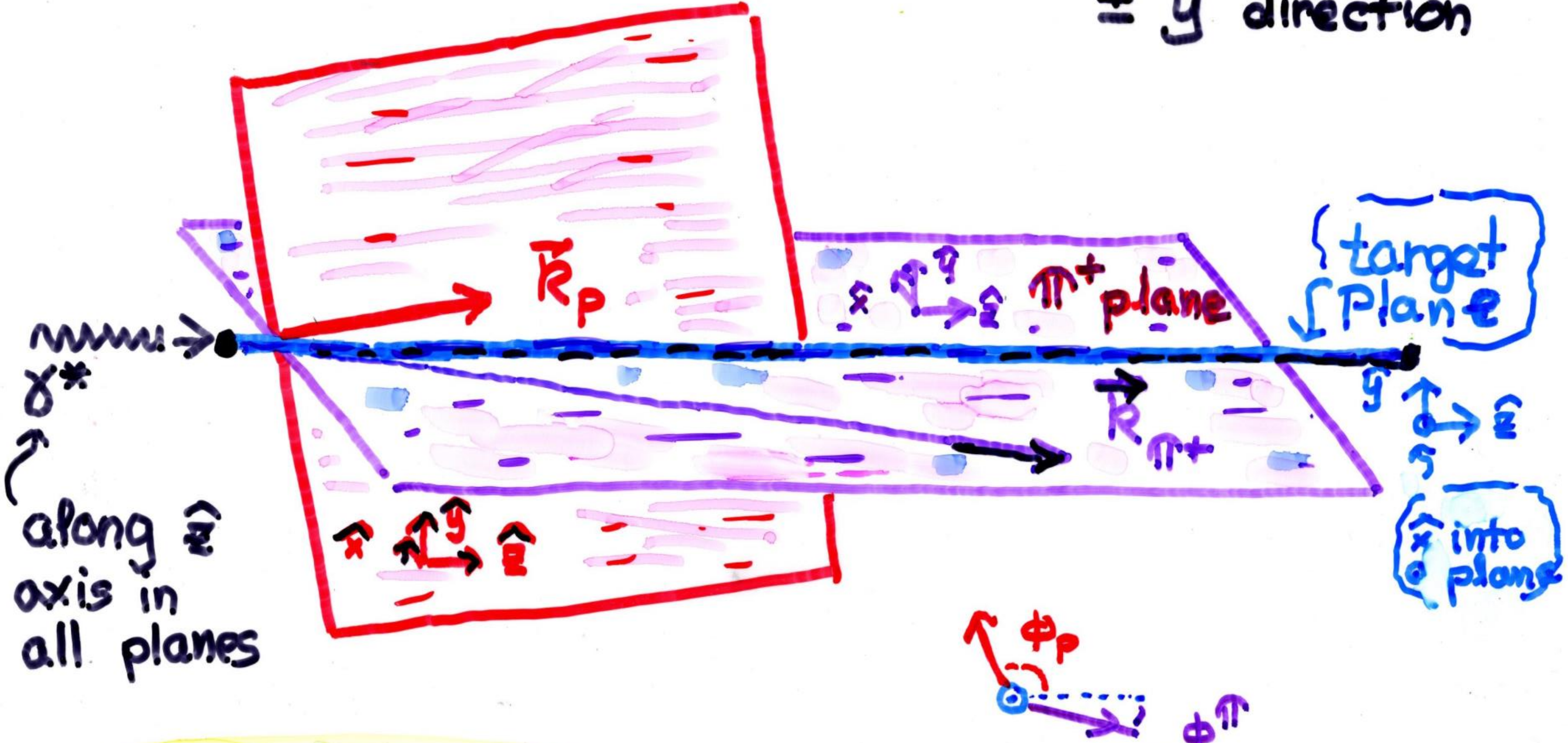
the product $A_\tau = P\Theta$ has the action

$$\boxed{A_\tau\{\vec{k}_i ; \vec{\sigma}_j\}A_\tau^{-1} = \{-\vec{k}_i ; -\vec{\sigma}_j\}}$$

A_τ "naive time reflection" (Jaffe, 1994 ; Sivers, 1994)

Lab frame scattering planes $\gamma^* p\uparrow \Rightarrow \pi^+ p X$

target polarization
$\pm y$ direction



assume proton & π^+ product of rank-1 fragmentation functions

Only one class of spherically-symmetric chromostatic condensates is compatible with the interior of a confined Lorentz-invariant structure - a color-glass condensate with

$a(r) = \pm 1$ for $r < R_0 - \Delta$

$L(0^{++}) = E_i^a E_i^a - B_i^a B_i^a \geq 0$ $\qquad L(0^{-+}) = 2 E_i^a B_i^a = 0$

for $a(r) = +1$ there are two solitons to consider

't Hooft-Polyakov $\quad a(r) = a_{tP}(z) = \frac{1}{2}[1 - \tanh(\overset{\kappa z}{z})]$

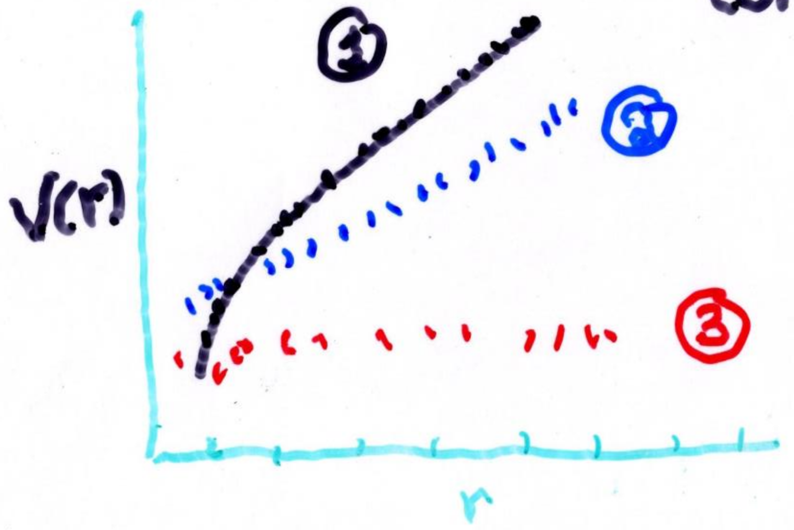
chiral transition $\quad a(r) = a_{CT}(z) = -\tanh(\kappa z)$

where $z = \left(\frac{r - R_0}{\Delta}\right)$ $\qquad \frac{\kappa}{\Delta} \gg 1$

Using the "maximal center gauge" it is possible to generate monte carlo gauge configurations with or without color vortices

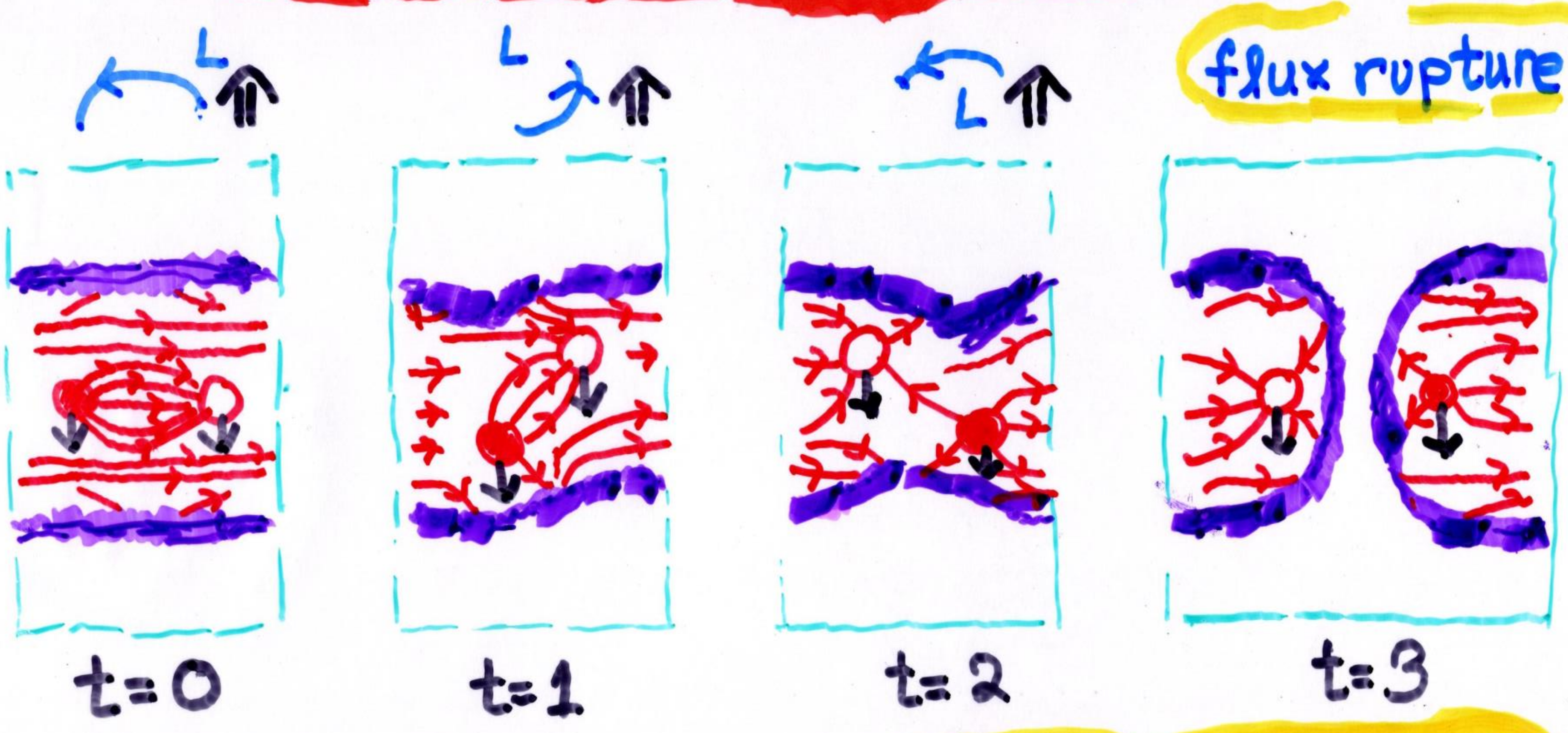
1. regular
2. vortices only
3. vortices removed

Cornell Potential $V(r) = \frac{-\alpha}{r} + a_c + \sigma r$



Bowman et al
PR D84 034501 (2011)

$^3P_0$ $J^{PC} = 0^{++}$ $q\bar{q}$ Pairs



δR_{TN}

generate flux rupture with spin-oriented momentum transfer

Extension to SU(3)

The dimensional compression shown here is not unique to the gauge group SU(2) but can be extended to any SU(N). One possible extension to SU(3)

$$|\hat{r}_a\rangle^{(3)} = |\hat{Z}_3, \hat{Z}_8\rangle \qquad \text{abelian projections}$$

$$\frac{a(r,t)}{r}\, e^{S}_{ia}(\omega^3(r,t), \omega^8(r,t)) = \partial_i \Theta^{ab} |\hat{r}_b\rangle$$

$$\frac{a(r,t)}{r}\, e^{A}_{ia}(\omega^3(r,t), \omega^8(r,t)) = -i\left[|\hat{r}_b\rangle, \partial_i \Theta^{bc} |\hat{r}_c\rangle\right]_a$$

$$i = 1,2,3 \qquad a,b,c = 1 \cdots 8$$

Transverse Fields Carry SU(3) color
(1,2 4,5 , 6,7)

Matthias Burkardt

Nucl Phys (2004)
Phys Rev (2005)

nonperturbative fsi deflects scattered quark - attractive confining force ($\delta k_{TN}, \delta L_y$)

two particle fracture functions provide access to internal dynamical mechanisms

beyond static structures

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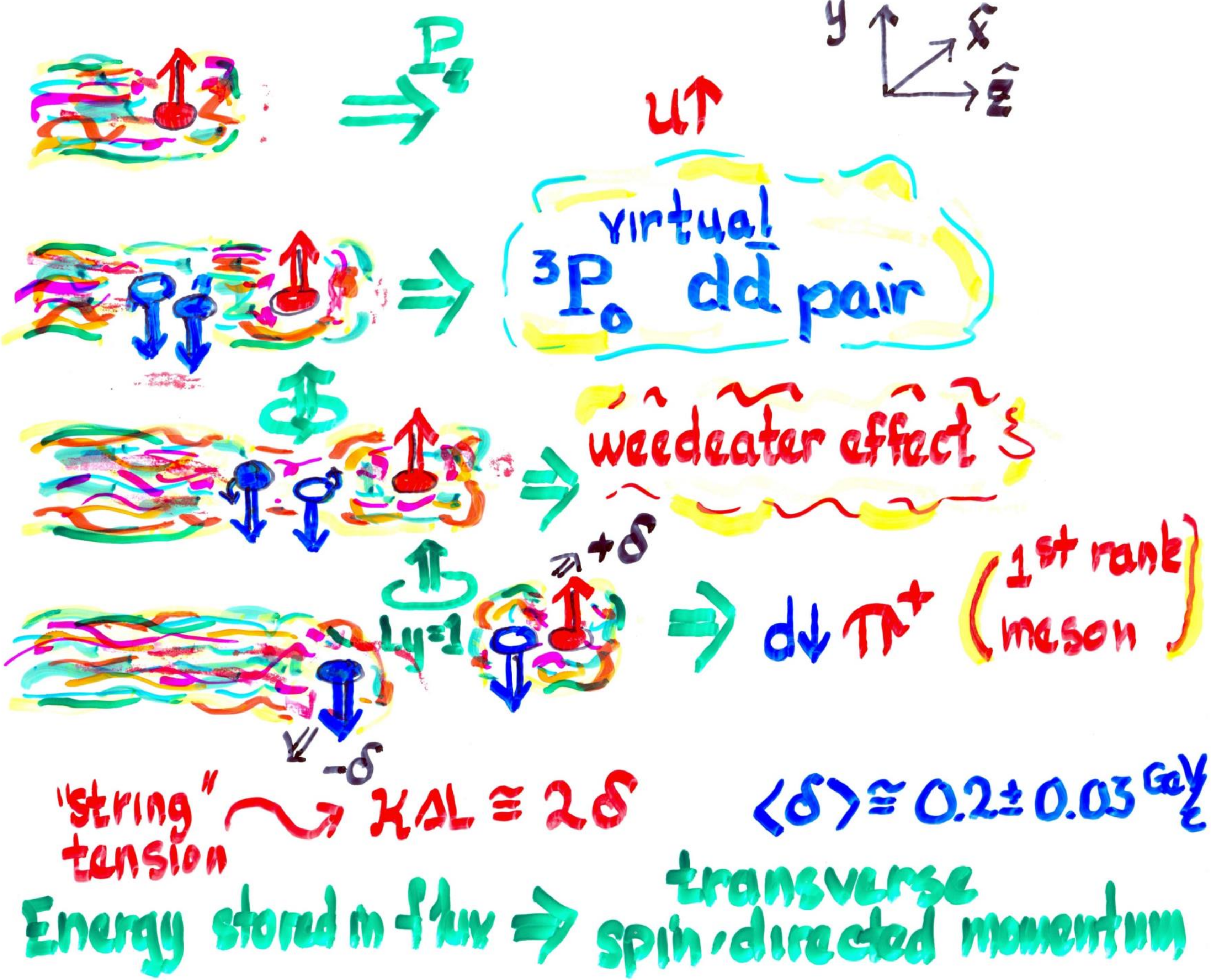
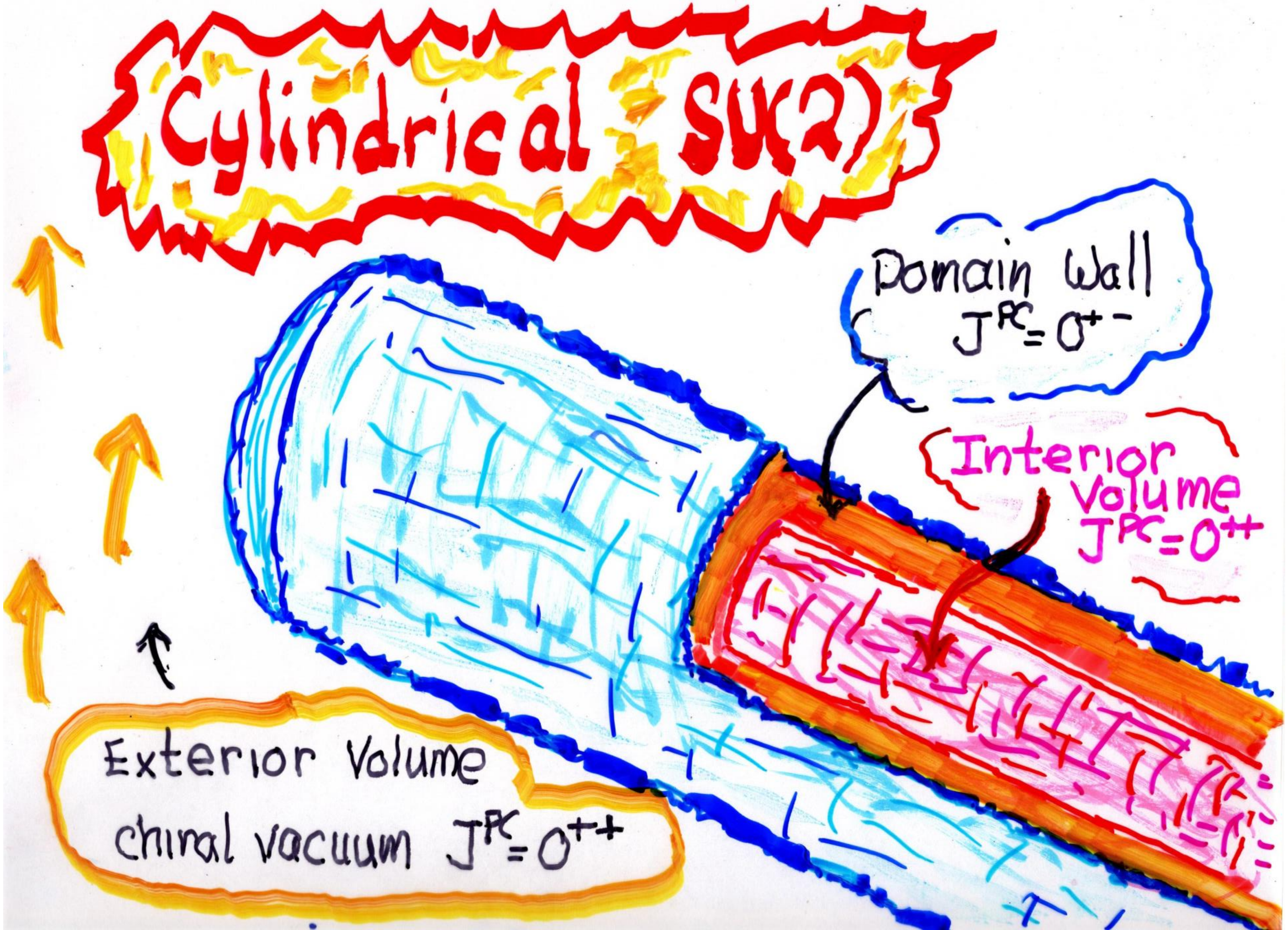
scattering amplitudes



ŷ x̂ ẑ
P_z
u↑
virtual
$^3P_0$ $d\bar{d}$ pair
weedeater effect
+δ
Ly=1
d↓ π^+ (1st rank meson)
−δ
"string" tension ⇝ $\kappa\Delta L \cong 2\delta$
$\langle\delta\rangle \cong 0.2 \pm 0.03$ GeV/c
Energy stored in flux ⇒ transverse spin-directed momentum



Cylindrical SU(2)
Domain Wall
$J^{PC} = 0^{+-}$
Interior Volume
$J^{PC} = 0^{++}$
Exterior Volume
chiral vacuum $J^{PC} = 0^{++}$

Classification of condensates in su(2) chromostatics with spherical symmetry

$a(r) = \pm 1$	$E_i^a E_i^a \neq 0$	$B_i^a B_i^a = 0$		color electric
$a(r) = \pm 1$	$E_i^a E_i^a = 0$	$B_i^a B_i^a \neq 0$		color magnetic
$a(r) = \pm 1$	$E_i^a E_i^a \neq 0$	$B_i^a B_i^a \neq 0$		color glass
$a(r) = \pm 1$	$E_i^a E_i^a = 0$	$B_i^a B_i^a = 0$		sterile vacuum
$a(r) = 0$	$E_i^a E_i^a = 0$	$B_L B_L = \pm \frac{1}{r^4}$		't Hooft Polyakov
$a(r) = C \neq \cancel{1}, 0$	$E_i^a E_i^a \neq 0$	$B_i^a B_i^a \neq 0$	$E_i^a B_i^a \neq 0$	topological or dyonic

a domain wall is a region where $a'(r) \neq 0$ that separates other condensates and also carries topological charge

Experimental Evidence of $ep^{\uparrow} = e\pi^{+}p$ transverse spin asymmetry correlations should already exist in CLAS-12 data from Jefferson Lab.

A range of similar correlation measurements should be a part of any program to study QCD at EIC