CONFINEMENT

dynamic symmetry breaking

and

TRANSVERSE SPIN

TOMOGRAPHY of HADRONS and JETS

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PROGRESSION

I. Nonperturbative QCD and physics beyond the standard model

confinement & spin-orbit dynamics

II. Yang-Mills-Maxwell's eq'ns. (SU(2) ⊂ SU(3))

topological confinement and CP-odd

III. Transverse single-spin asymmetries & non-perturbative spin-directed momentum transfers

$\langle \delta k_{TN}(x, \mu^2) \rangle$ hadron distributions

$\langle \delta p_{TN}(z, \mu^2) \rangle$ jet fragmentation

I, Nonperturbative QCD and beyond SM physics

precision calculations require understanding of confinement and orbital structure in hadrons and jets

Confinement and the Dynamical Breaking of Chiral Symmetry

Topological Confinement and the Pion Tornado

QCD: non PERTURBATIVE TOOLS

1. Lattice gauge theory simulations
   Wilson α_s large $\Rightarrow$ $V_{q\bar{q}}(r) = \sigma r + \cdots$
   for massive quarks
   necessary but not sufficient for confinement

2. Effective Field Thys. (EFT's)
   Massive Quark EFT, Soft-collinear EFT, chiral EFT
   ...

3. Schwinger-Dyson Eq.'ns
   $\Rightarrow$ analytic properties of quark, gluon dressed propogators

4. Classical non-Abelian Field Eqn's
   topological properties of confined systems

All these techniques supplement PQCD help form models that can be experimentally tested

- Spectroscopy, Amplitude analysis

One type of experiment:

semi-inclusive deep inelastic lepton scattering (SIDIS)

Can be analyzed in terms of transverse-momentum-dependent dst'ns & fragmentation fcn's (TMD's)

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A. The Yang-Mills Millenium Prize*

(* Clay Mathematics Institute .. \$1G each)

posed by A. Jaffe & E. Witten (2000)

$$S^{G}_{YM} = \frac{1}{4g^2}\int \mathrm{Tr}\, F \wedge {}^*F$$

* Hodge Dual

G compact group

F curvature, $F = dA + A \wedge A$, of G-bundle connection A.

Prove ∃ QFT in 4-dim. Space time

1.) "mass gap", $\Delta > 0$

2.) confinement (quarks & gluons)

3.) chiral symmetry breaking

These 3 requirements for solution recognize that "hadronic" sector different from perturbative sector

QCD $\neq$ PQCD

SU(3) - G

Infrared "Slavery"

While the mathematics is hard (M.Douglas - Clay.org) nature has solved the physics problem.

Transverse spin observables (everything at Transversity 2011) pierce to the meat of the question

"What distinguishes QCD from PQCD?"

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QCD ≠ PQCD

SU(3) - G

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"Constituents" in QCD (degrees of freedom in hadrons & jets) forged from nonlinear dymamics from the "partons" of PQCD (quarks & gluons)

EMERGENT STRUCTURES

- Constituent Quarks
- Diquarks
- Field·Strength Densities
- Topologically·Structured condensates
  (dyons, merons, instantons, ...?)
- Virtual baryons, mesons
  (π, σ, N ... Chiral Pert Thy)

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Connection to transverse spin SSA's

quark mass terms in QCD Lagrangian

$$\mathcal{L}_q = i(\bar{q}_L \not{D}_m q_L + \bar{q}_R \not{D} q_R) - m_q(\bar{q}_R q_L + \bar{q}_L q_R)$$

n_f massless flavors $\Rightarrow$ $SU(n_f)_L \otimes SU(n_f)_R \otimes U(1)_L \otimes U(1)_R$

$m_u = 1.9 \pm 0.2$ MeV , $m_d = 4.6 \pm 0.3$ MeV $m_s = 88 \pm 5$ MeV

Kane, Pumplin, Repko $\quad A_N d\sigma(q q\uparrow \to q q) = \alpha_s \frac{m_q}{Q} f_{cm}(\theta)$

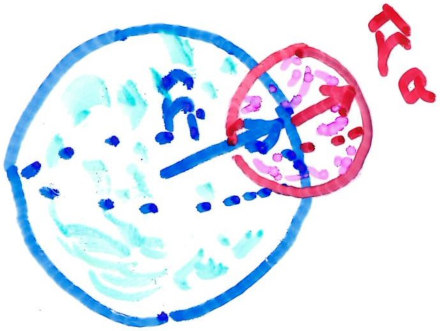
would imply very small A_χ-odd observables. ("T" odd)

These symmetries **broken** by boundary conditions (confinement) .. constituent structure .. and spin/orbit dynamics of interactions for const. basis. (1.)-(3.) KPR factorization

II - FIELD STRENGTH DESCRIPTION of CONFINED nonABELIAN CHARGES

Confining boundary conditions
& topological charge

Field-Strength Description of non-Abelian Sperically Symmetric Confined Systems



$$gA^a_0(r,t) = A_0(r,t)\,\hat{r}_a$$

$$gA^a_i(r,t) \quad A_1(r,t)\,\rho_{ia} + \frac{\alpha(r,t)}{r}\sin\omega(r,t)\,\delta^T_{ia} + \frac{\alpha(r,t)\cos\omega(r,t) - 1}{r}\,\epsilon^T_{ia}$$

$$\rho_{ia} = \hat{r}_i\hat{r}_a$$

$$\delta^T_{ia} = (\hat{\theta}_i\hat{\theta}_a + \hat{\phi}_i\hat{\phi}_a)$$

$$\epsilon^T_{ia} = (\hat{\phi}_i\hat{\theta}_a - \hat{\theta}_i\hat{\phi}_a)$$

$$\rho_{ia}\,\rho_{ia} = 1$$

$$\delta^T_{ia}\,\delta^T_{ia} = 2$$

$$\epsilon^T_{ia}\,\epsilon^T_{ia} = 2$$

$i = 1\text{-}3$

$a = 1\text{-}3$ SU(2)

[gauge rotating basis]

$\omega = \omega(r,t)$
$\alpha = \alpha(r,t)$

$$D^{ab}_i\hat{r}_b = \frac{\alpha}{r}\,\epsilon^S_{ia}(\omega)$$

$$= \frac{\alpha}{r}\left[\delta^T_{ia}\cos(\omega) - \epsilon^T_{ia}\sin(\omega)\right]$$

$$-i[\hat{r}, D_i\hat{r}] = \frac{\alpha}{r}\,\epsilon^A_{ia}(\omega)$$

$$= \frac{\alpha}{r}\left[\delta^T_{ia}\sin(\omega) + \epsilon^T_{ia}\cos(\omega)\right]$$

$$D^{ab}_i = \partial_i\delta^{ab} + g\epsilon^{abc}A^c_i \qquad (SU(2)$$

[Extension to SU(3)]

off-diagonal gluons carry charge

a=1-3 SU(2) $\Rightarrow$ a=1-8 SU(3)

$\hat{z}_a \Rightarrow \hat{z}|h\rangle_a \qquad |h\rangle_a = (h_3, h_8)$

t_3, t_8 diagonal $\qquad t_1 - t_2,\ t_4 - t_5 \Rightarrow$ 3 SU(2) subgroups

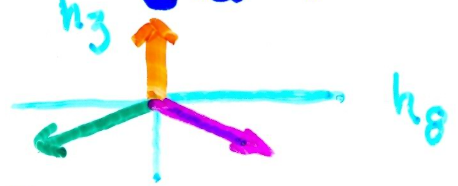
O(ry) G(yb) P(br) with ± charge

$[t_3, Q_O^{\pm}] = \pm Q_O^{\pm} \qquad [t_3, Q_G^{\pm}] = \mp\frac{1}{2} Q_G^{\pm} \qquad [t_3, Q_P^{\pm}] = \mp\frac{1}{2} Q_P^{\pm}$

$[t_8, Q_O] = 0 \qquad [t_8, Q_G^{\pm}] = \mp\frac{\sqrt{3}}{2} Q_G^{\pm} \qquad [t_8, Q_P^{\pm}] = \pm\frac{\sqrt{3}}{2} Q_P^{\pm}$

a = (1,2) $\qquad$ a = (4,5) $\qquad$ a = (6,7)

$\xi_{ia} \Rightarrow \xi_{i\bar{a}} \hat{z}_i \hat{z} |h\rangle_a \qquad e^{\pm}_{ia}(\omega) \Rightarrow e^{\pm}_{ia}\left(\sum_c \omega_a |w_c\rangle\right)$



$|w_O\rangle = (1,0) \qquad |w_G\rangle = \left(-\frac{1}{2}, -\frac{\sqrt{3}}{2}\right)$

$|w_P\rangle = \left(-\frac{1}{2}, +\frac{\sqrt{3}}{2}\right)$

$\sum_c |w_c\rangle = (0,0)$

"Hawser Laid"

Expressing gE_i^a and gB_i^a with $\varepsilon_{ia}^{AS}(\omega)$

$$gE_i^a = E_L \rho_{ia} + E_S \varepsilon_{ia}^S(\omega) + E_A \varepsilon_{ia}^A(\omega)$$

$$gB_i^a = B_L \rho_{ia} + B_S \varepsilon_{ia}^S(\omega) + B_A \varepsilon_{ia}^A(\omega)$$

with Field Strengths

$$E_L = \frac{\partial A_1}{\partial t} - \frac{\partial A_0}{\partial r} \qquad B_L = \frac{(a^2-1)}{r^2}$$

$$E_S = -\frac{(K_1 + A_0)}{ar} \qquad B_S = \frac{\partial a/\partial r}{ar}$$

$$E_A = \frac{\partial a/\partial t}{r} \qquad B_A = \frac{K_0 - A_1}{ar}$$

topological current

$$K_0 = (a^2-1)A_1 - a^2\partial \omega/\partial r$$

$$K_1 = (a^2-1)A_0 - a^2\partial \omega/\partial t$$

$$\partial^\mu K_\mu = g^2 r^2 E_i B_i$$

E_i^a B_i^a Gauge Covariant

Gauge & Spinor Fields with Spherical Symmetry

$$\int d^4x\,(\mathcal{L}_g) \Rightarrow 4\pi \int dr\,dt\,(r^2 L_g^{(2)}) \qquad r^2 L_g^{(2)} = r^2(FF) + 2D^\ell \phi D_\ell \phi^* + \frac{(\phi^2 - 1)}{r^2}$$

$$\int d^4x\,(\mathcal{L}_f) \Rightarrow 4\pi \int dr\,dt\,(r^2 L_f^{(2)}) \qquad r^2 L_f^{(2)} = \bar\Psi\,(D^\ell \gamma_\ell^{(2)} + e\,\phi\,\gamma_{(2)}^5 + h.c.)\,\Psi$$

confining boundary conditions

Interior $r < R_0 - \Delta$

$$\begin{pmatrix} \langle \frac{\alpha_s}{\pi} GG \rangle_I \neq 0 \\ \langle \bar\Psi \Psi \rangle_I \neq 0 \\ \langle \bar\Psi \gamma^\mu \Psi \rangle_I \neq 0 \end{pmatrix}$$

Exterior $r > R_0 + \Delta$

$$\begin{pmatrix} \langle \frac{\alpha_s}{\pi} GG \rangle_E = 0 \\ \langle \bar\Psi \Psi \rangle_E = 0 \\ \langle \bar\Psi \gamma^\mu \Psi \rangle_E = 0 \end{pmatrix}$$

Adler Bell Jackiw

$$\left[\; 4\pi r^2\, \bar\Psi \gamma^\mu \gamma^5 \Psi = (Q_0^5,\, Q_1^5\, \hat r) \qquad \partial^\ell Q_\ell^5 = \alpha_s r^2\, {}^*GG \;\right]$$

Gauge & Spinor Fields with Spherical Symmetry

$$\int d^4x\,(\mathcal{L}_g) \Rightarrow 4\pi \int dr\,dt\,(r^2 L_g^{(2)}) \qquad r^2 L_g^{(2)} = r^2(FF) + 2D^\rho \phi D_\rho \phi^* + \frac{(\phi^2 - 1)}{r^2}$$

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SU(2) Yang-Mills-Maxwell Eq'ns

$$-\frac{\partial}{\partial r}(r^2 E_L) + 2arE_S = J_0(r,t)$$

$$-\frac{\partial}{\partial t}(r^2 E_L) + 2arB_A = J_1(r,t)$$

$$-\frac{\partial}{\partial t}(arE_S) + \frac{\partial}{\partial r}(arB_A) = ar\,j_S(r,t)$$

$$a\,\Box_{(2)}a + r^2(E_S^2 - B_A^2) + \frac{a^2(a^2-1)}{r^2} = ar\,j_A(r,t)$$

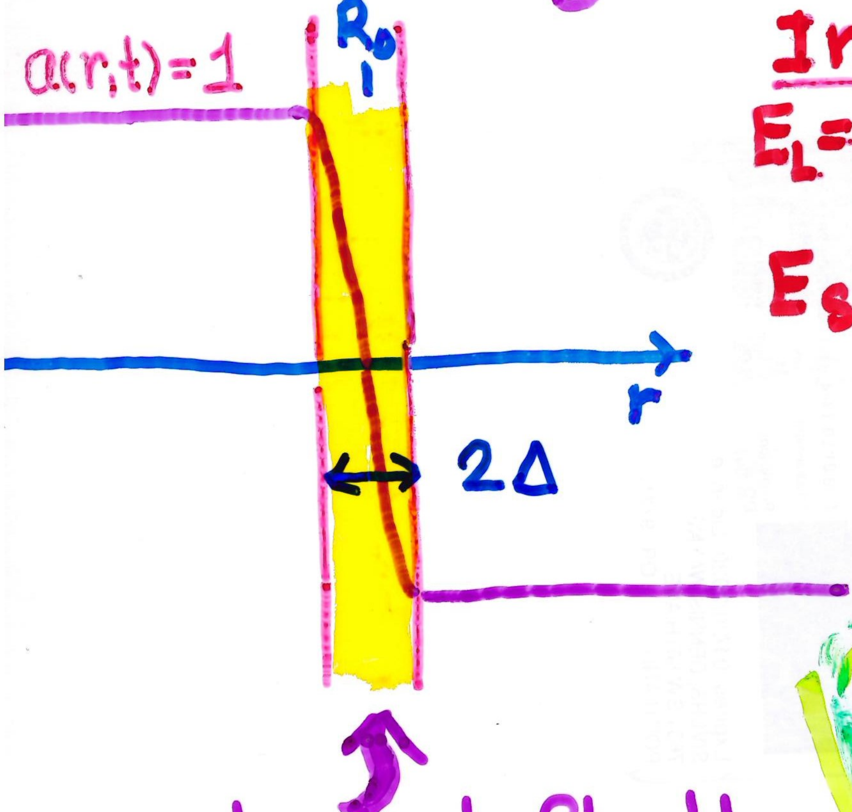
Yang-Mills Bianchi constraints give

$$\frac{\partial}{\partial r}(arE_A) - \frac{\partial}{\partial t}(arB_S) = 0$$

$$-E_L + \frac{\partial}{\partial r}(arE_S) + \frac{\partial}{\partial t}(arB_A) = \partial^\ell K_\ell = g^2 r^2 E_i^a B_i^a$$

color-current conservation $\boxed{\partial^\ell J_\ell(r,t) = 2ar\,j_S(r,t)}$

Confining Boundary Conditions



Interior $r < R_0 - \Delta$ $\quad a(r,t) = 1$

$E_L = \frac{\partial A_0}{\partial r} - \frac{\partial A_1}{\partial t}$ $\quad B_L = E_A = B_S = 0$

$E_S = (K_1 - A_0)/r$ $\quad B_A = (K_0 + A_1)/r$

$J^a_\mu(r) \neq 0$ $\quad J^{PC} = 0^{++}$

$\langle | E^a_i E^a_i | \rangle \geq 0$ $\quad \langle | B^a_i B^a_i | \rangle \geq 0$

External "Vacuum" $r > R_0 + \Delta$

$a(r,t) = -1$ $\quad \cos\omega(r,t) = -1$ $\quad A_0 = A_1 = 0$

$E^a_i = 0$ $\quad B^a_i = 0$

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

Topological Shell

$J^{PC} = 0^{-+}$ CP odd

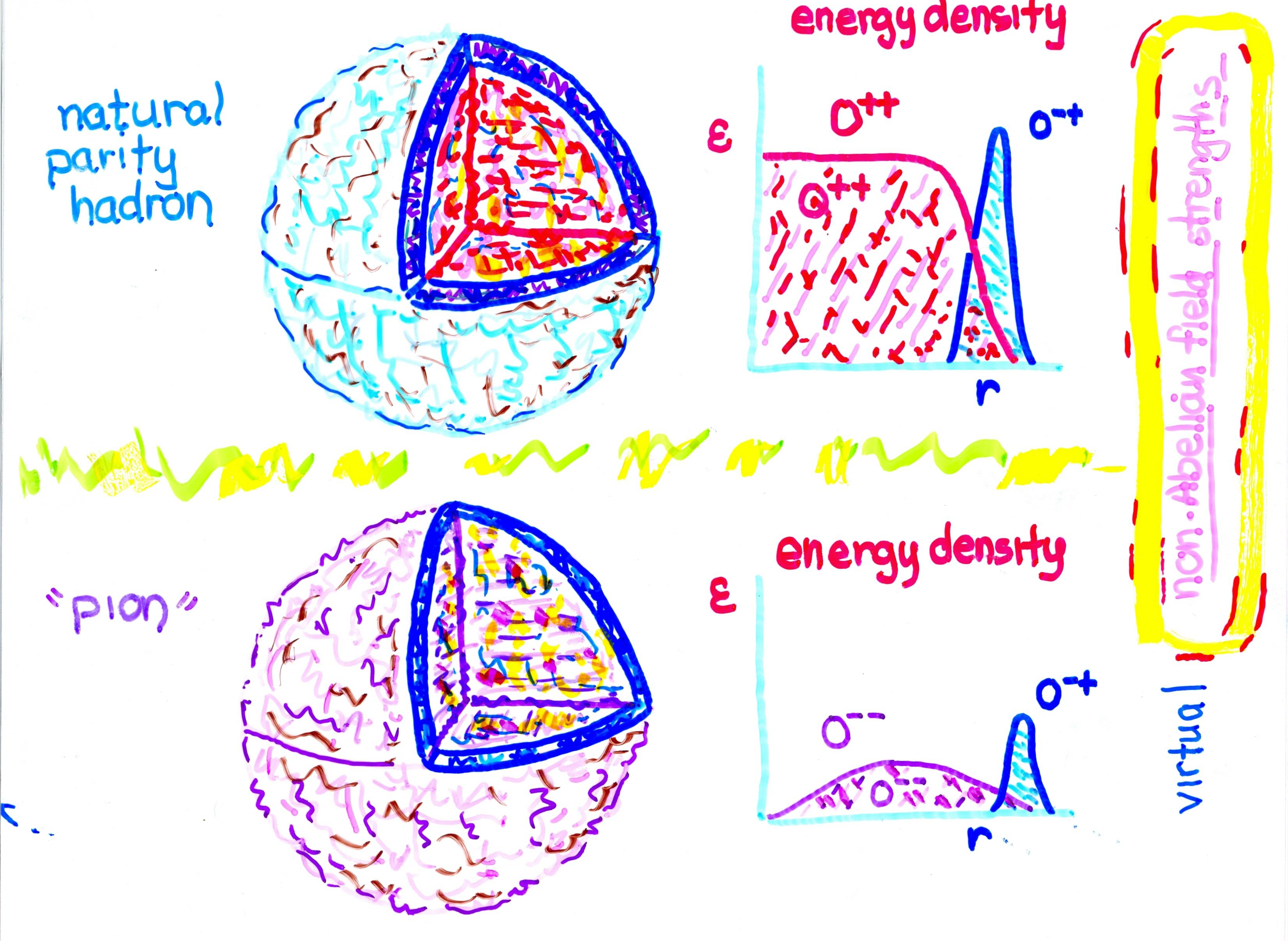
Topological Charges $\langle | E^a_i B^a_i | \rangle \neq 0$

Dyonic Charges at $r = R_0$

The Non-Abelian Maxwell's Eq'ns of QCD

with spherical symmetry and confining boundary conditions provide solutions that display the phenomenological content of MIT bag model - Chiral quark soliton & cloudy bag models ... +...

the "dual-Meissner-effect" approact to confinement can be replaced by a "dual topological insulator" picture



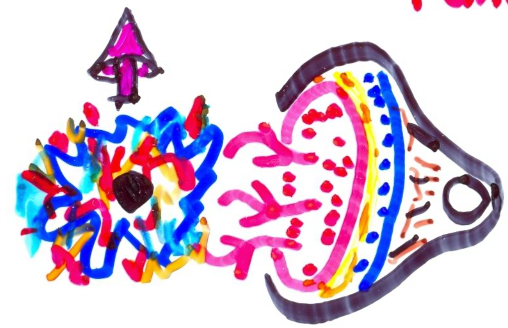
natural parity hadron
energy density
ε
0++
0-+
r
non-Abelian field strengths
virtual
"pion"
energy density
ε
0--
0-+
r

Constituent Quark

$J^P = \frac{1}{2}^+$ not Dirac Fermion

$G \neq 0$ (spin/orbit structure)

....



Fundamental charge
$3, \bar{3}$

o dirac antifermion (hole)

3 color

$\bar{3}$ color

Scalar diquark

[,] antisymmetric in flavor

$J^P = 0^+$

● dirac fermion

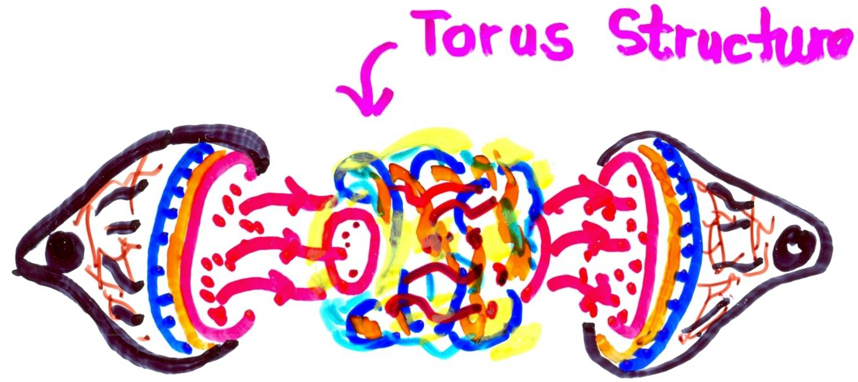
$\bar{3}$ color

axial vector diquark

{,} symmetric in flavor

$J^P = 1^+$ spin/orbit structure

adjoint charges: 8

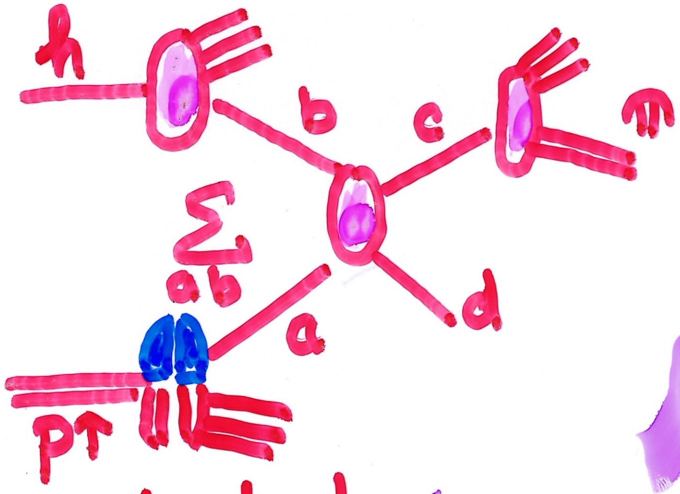


8 color	8 color
$d^{abc}(E_i^b E_i^c - B_i^b B_i^c)$ $J^{PC} = 0^{++}$	$d^{abc} E_i^b B_i^c$ $J^{PC} = 0^{-+}$
$f^{abc}(E_i^b E_i^c - B_i^b B_i^c)$ $J^{PC} = 0^{+-}$	$f^{abc} E_i^b B_i^c$ $J^{PC} = 0^{--}$

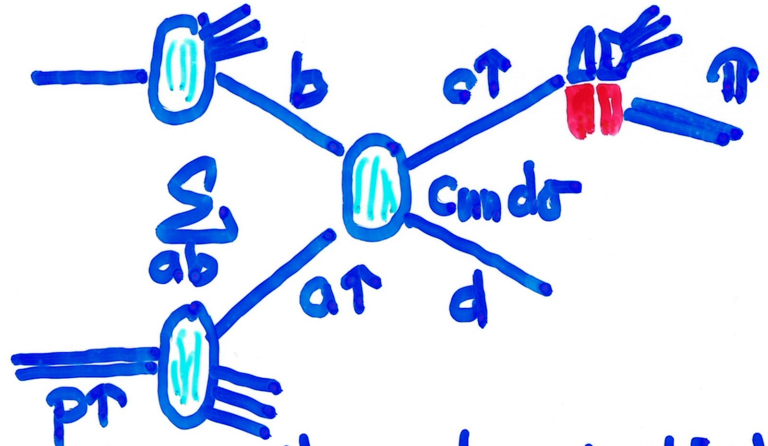
How about $J^{PC} = 1^{-+}, 1^{--}; 1^{+-}, 1^{++}$ (Poynting vector)?

These sketches done in maximally Abelian coordinate gauge T_3, T_8 diagonal along $\hat{z}$-axis

off-diagonal fields carry $r\bar{y}$-$y\bar{b}$-$b\bar{r}$ charges



orbital



Collins, Heppelman, Ladinsky

$$A_N\left[E\,d\sigma(hp^\uparrow\to\pi X)\right]_{orb} = \frac{1}{\pi}\int d^2k_T^a\,dx^a \int d^2k_T^b\,dx^b$$
$$\int d^2p_T^c\,\frac{dz_c}{z_c^2}\,\Delta^N G_{a/p^\uparrow}(x_a, k_{TN}^a, k_{TS}^a)$$
$$G_{b/h}(x_b, k_T^{2b}; M^2)\, D_{\pi/c}(z_c, p_T^2; M^2)$$
$$\hat{s}\left[\frac{d\sigma}{dt}(ab\to cd)\right]\delta(\hat{s}+\hat{t}+\hat{u})$$

$$A_N\left[E\,d\sigma(hp^\uparrow\to\pi X)\right]_{CHL} = \frac{1}{\pi}\int d^2k_T^a\,dx^a \int d^2k_T^b\,dx^b$$
$$\int d^2p_T^c\,\frac{dz_c}{z_c^2}\quad \Delta_S^T G_{a\uparrow/p\uparrow}(x_a, k_{Ta}^2; M^2)$$
$$G_{b/h}(x_b, k_T^{2b}; M^2)\,\Delta^N D_{\pi/c\uparrow}(z_c, p_{TN}^c, p_{TS}^c; M^2)$$
$$\hat{s}\left[c_{nn}\frac{d\sigma}{dt}(a^\uparrow b\to c^\uparrow d)\right]\delta(\hat{s}+\hat{t}+\hat{u})$$

two different contributions to $A_N d\sigma(pp^\uparrow\to\pi X)$

CONCENTRATE ON SPIN-DIRECTED MOMENTUM TRANSFERS

$$\int\cdots\int_{-\infty}^{+\infty} dk^{a}_{TN}\, \Delta^{N} G_{OAP}(x_a, k^{a}_{TN}) \left[\frac{d\sigma}{dt}(s, t(k^{a}_{TN}))\right] R_{orb}(x_a, x_b \ldots)$$

$$\int\cdots\int_{-\infty}^{+\infty} dp^{c}_{TN}\, \Delta^{N} D_{TT/C\uparrow}(z_c, p^{c}_{TN}) \left[C_{NN} \frac{d\sigma}{dt}(s, t(p^{c}_{TN}))\right] R_{CNL}(x_a, x_b, x \ldots)$$

[APPLY TAYLOR SERIES $\langle \delta k^{a}_{TN} \rangle \langle \delta p^{c}_{TN} \rangle \ll M^2$]

$$\Delta^{N} G_{OAP}(x^{a}, k^{a}_{TN} \ldots) = \langle \delta k^{a}_{TN} \rangle \frac{\partial}{\partial k^{a}_{TN}} G_{OAP}(x_a, k^{a}_{TN})$$

$$\Delta^{N} D_{TT/C\uparrow}(z^{c}, p^{c}_{TN}) = \langle \delta p^{c}_{TN} \rangle \frac{\partial}{\partial p^{c}_{TN}} D_{TT/C}(z_c, p^{c}_{TN})$$

[INTEGRATE by PARTS k^{a}_{TN} . p^{c}_{TN}]

$$\langle \delta k^{a}_{TN} \rangle \int_{-\infty}^{+\infty} dk^{a}_{TN} \frac{\partial}{\partial k^{a}_{TN}} G(x, k^{a}_{TN}) \left[\frac{d\sigma}{dt}(s, t(k))\right] R_{orb}(\ldots)$$

$$= \langle \delta k_{TN} \rangle \ldots \cancel{G}^{\,0}\, d\sigma\, R \Big|_{-\infty}^{+\infty} +$$

$$-\langle \delta k^{a}_{TN} \rangle \int_{-\infty}^{+\infty} dk_{TN}\, G_{OAP}(x_a, k_{TN}) \frac{\partial t}{\partial k^{a}_{TN}} \frac{\partial}{\partial t} \left[\frac{d\sigma}{dt}(s, t(k))\right] R_{orb}(x_a, x_b, z_c \ldots)$$

$$\langle \delta p^{c}_{TN} \rangle \int_{-\infty}^{+\infty} dp^{c}_{TN} \frac{\partial}{\partial p^{c}_{TN}} D(z_c, p^{c}_{TN}) \left[C_{NN} \frac{d\sigma}{dt}(s, t(p^{c}_{TN}))\right] R_{CNL}$$

$$= \langle \delta p^{c}_{TN} \rangle\, \cancel{D}^{\,0}\, C_{NN}\, d\sigma\, R \Big|_{-\infty}^{+\infty}$$

$$-\langle \delta p^{c}_{TN} \rangle \int_{-\infty}^{+\infty} dp^{c}_{TN}\, D_{TT/C}(z_c, p^{c}_{TN}) \frac{\partial t}{\partial p^{c}_{TN}} \frac{\partial}{\partial t} \left[C_{NN} \frac{d\sigma}{dt}(s, t(p^{c}_{TN}))\right] R_{CNL}(x_a, x_b, z_c \ldots)$$

$$\partial/\partial k^{a}_{TN}\; t = -2k^{a}_{TN} \qquad \partial/\partial p^{c}_{TN} = -2p^{c}_{TN}$$

$$A_N\left[E\frac{d\sigma}{d^3p}(\vec{p}p^\uparrow \to \pi X)\right]_{orb} = \sum_{ab\to cd} \frac{2\langle \delta k^a_{TN}\rangle}{\pi} \int d^2k^a_T\, dx_a \int d^2k^b_T\, dx_b \int d^2p^c_T \frac{dz_c}{z_c^2}$$

$$G_{a/p}(x_a, k^2_{Ta}; M^2)\, G_{b/\pi}(x_b, k^2_{Tb}; M^2)\, D_{\pi/c}(z_c, p^2_{Tc}; M^2)$$

$$\hat{s}\left[k_{TN}(\hat{t}) \frac{\partial}{\partial t} \frac{d\sigma}{dt}(\hat{s},\hat{t}) \right] \delta(\hat{s}+\hat{t}+\hat{u})$$

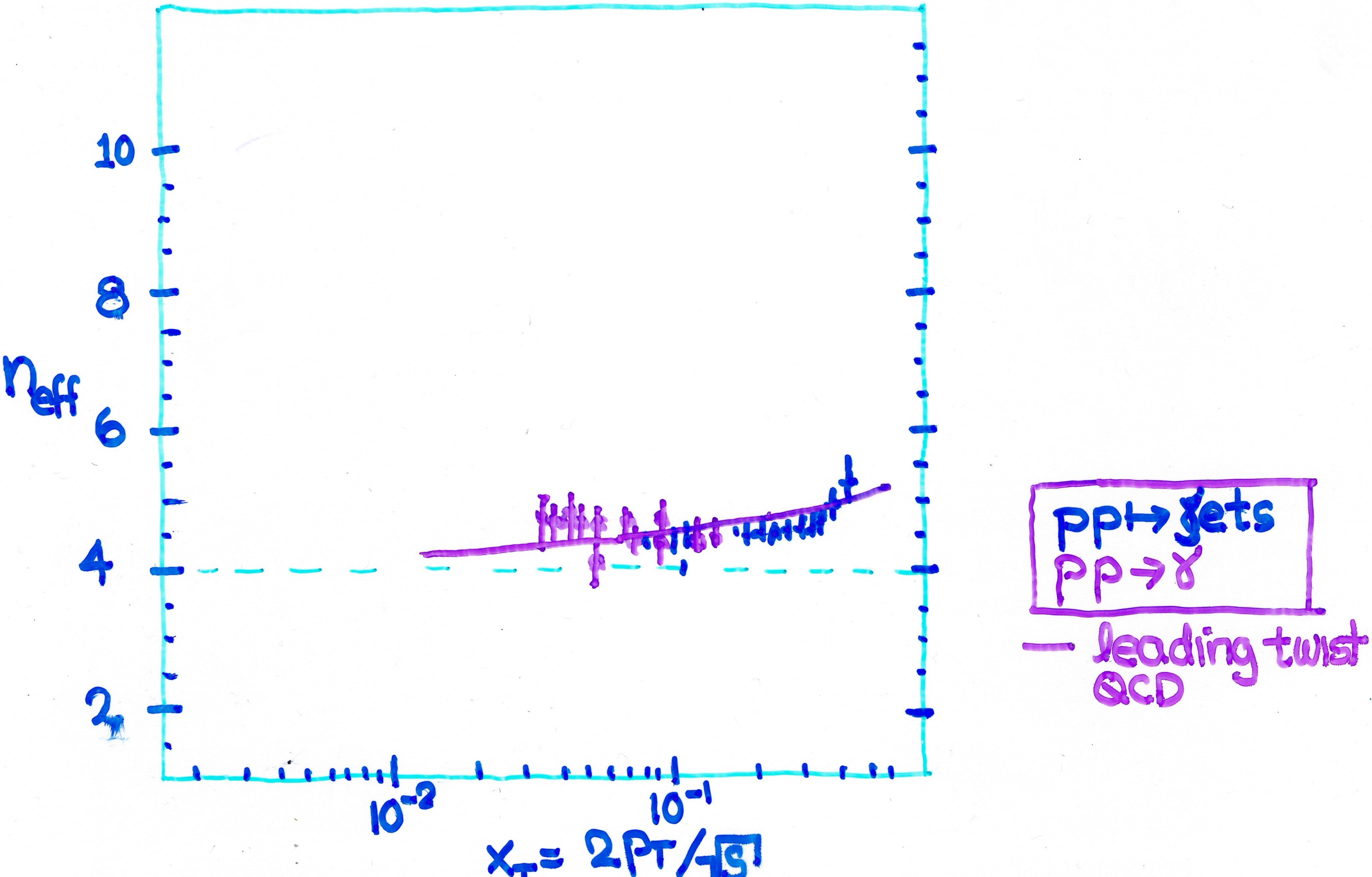
integrate over $d^2k_{Ta}\, d^2k_{Tb}$ and d^2p_{Tc}

$$\sum_{ab\to cd} \frac{2\langle \delta k^a_{TN}\rangle}{\pi} \int dx_a\, dx_b \frac{dz_c}{z_c^2}\; G_{a/p}(x_a, M^2)\, G_{b/\pi}(x_b, M^2)\, D_{\pi/c}(z_c, M^2)\Big]$$

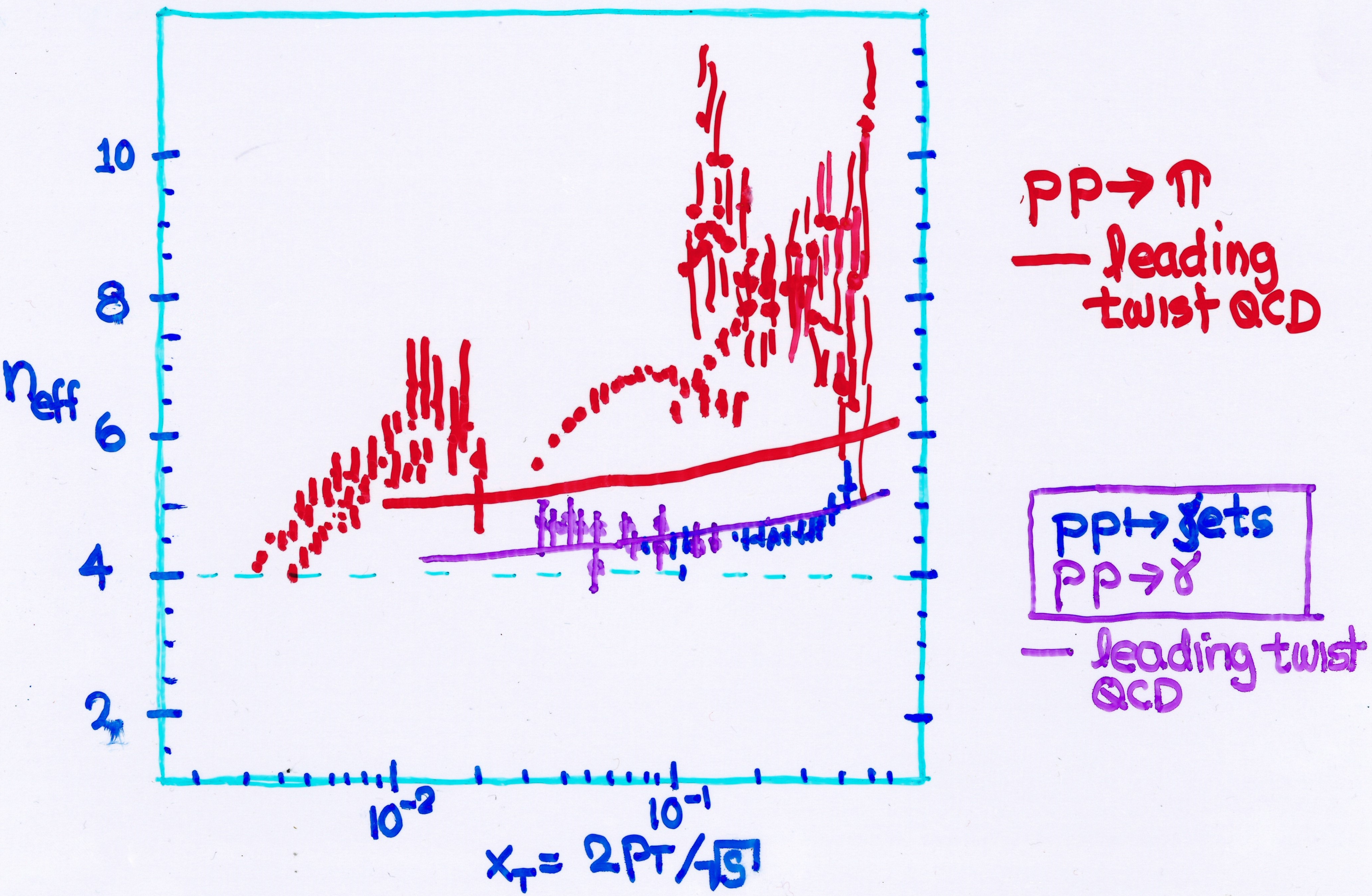
$$\hat{s}\left[p_{TN}(t) \frac{\partial}{\partial t} \frac{d\sigma}{dt}(ab\to cd)\right] \delta(\hat{s}+\hat{t}+\hat{u})\left(1+\mathcal{O}\left(\frac{\langle k_T^2\rangle}{p_T^2}\cdots\right)\right)$$

for large p_T detected pion

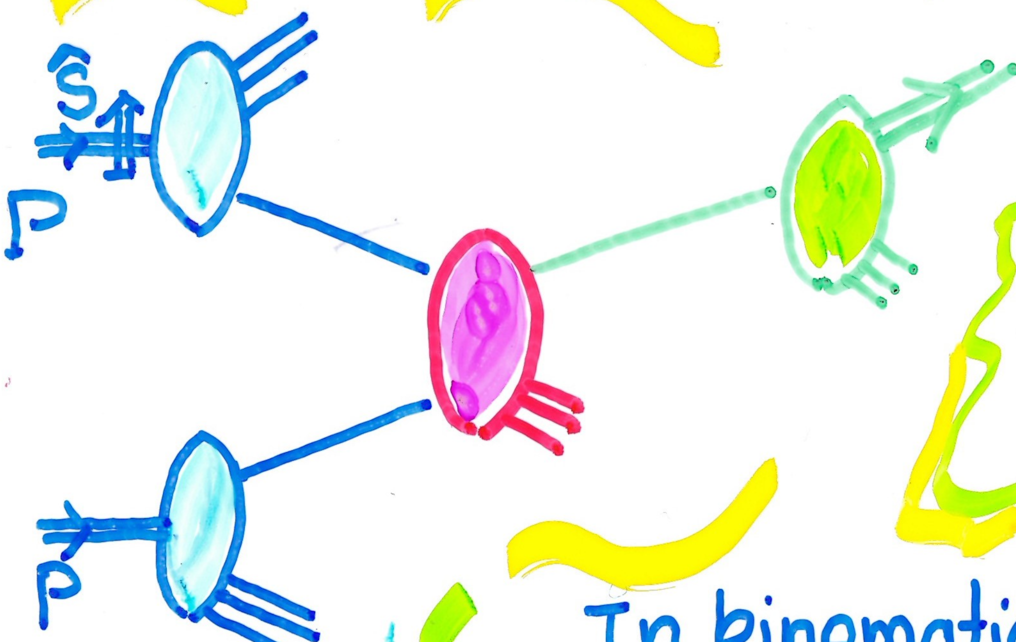
The pseudo-observables $\langle \delta k^a_{TN}\rangle, \langle \delta p^c_{TN}\rangle \cdots$ normalize single-spin observables from spin-orbit dynamics both in TMD formalism and in collinear twist formalism.



10
8
6
4
2
n_{eff}
10^{-2}
10^{-1}
$x_T = 2P_T/\sqrt{s}$
pp→ jets
pp→ γ
leading twist QCD



10
8
6
4
2
n_{eff}
10^{-2}
10^{-1}
$x_T = 2p_T/\sqrt{s}$
pp → π
— leading twist QCD
pp → jets
pp → γ
— leading twist QCD



$h = \pi^{\pm} \pi^{0} K^{\pm} K^{0} \eta \cdots$

Hard scattering
$p^{\uparrow} p \to h\, X$

In kinematic regimes where $A_N d\sigma$ measured it is **not** appropriate to assume leading-twist QCD processes dominate meson production

Sivers, Brodsky, Blankenbecler - Phys. Rep (CIM)

Berger, Gottschalk, Sivers Phys Rev D23

$d\sigma(Gq \Rightarrow \pi q) + d\sigma(\bar{q}q \to \pi G) \geq d\sigma(qG \to qG) + d\sigma(qq \to qq)$

$x_T \geq 0.3 \quad p_T \leq 6$ GeV/c

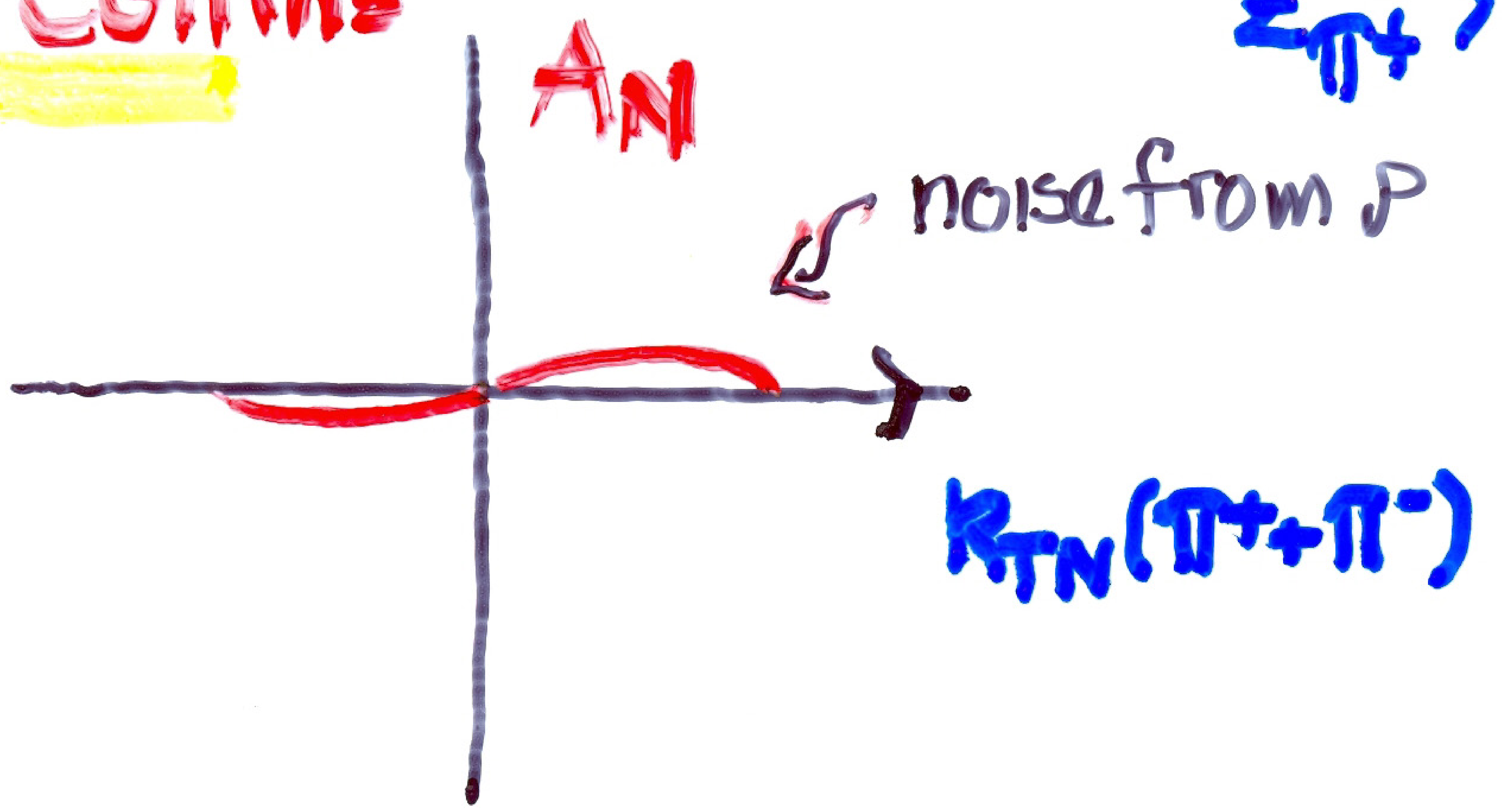
This agrees with $\langle N_{eff} \rangle$ analyses (Brodsky + collaborators)

Fragmentation Dynamics & separation of Collins-Happelman mech. from Orbital dstn's.

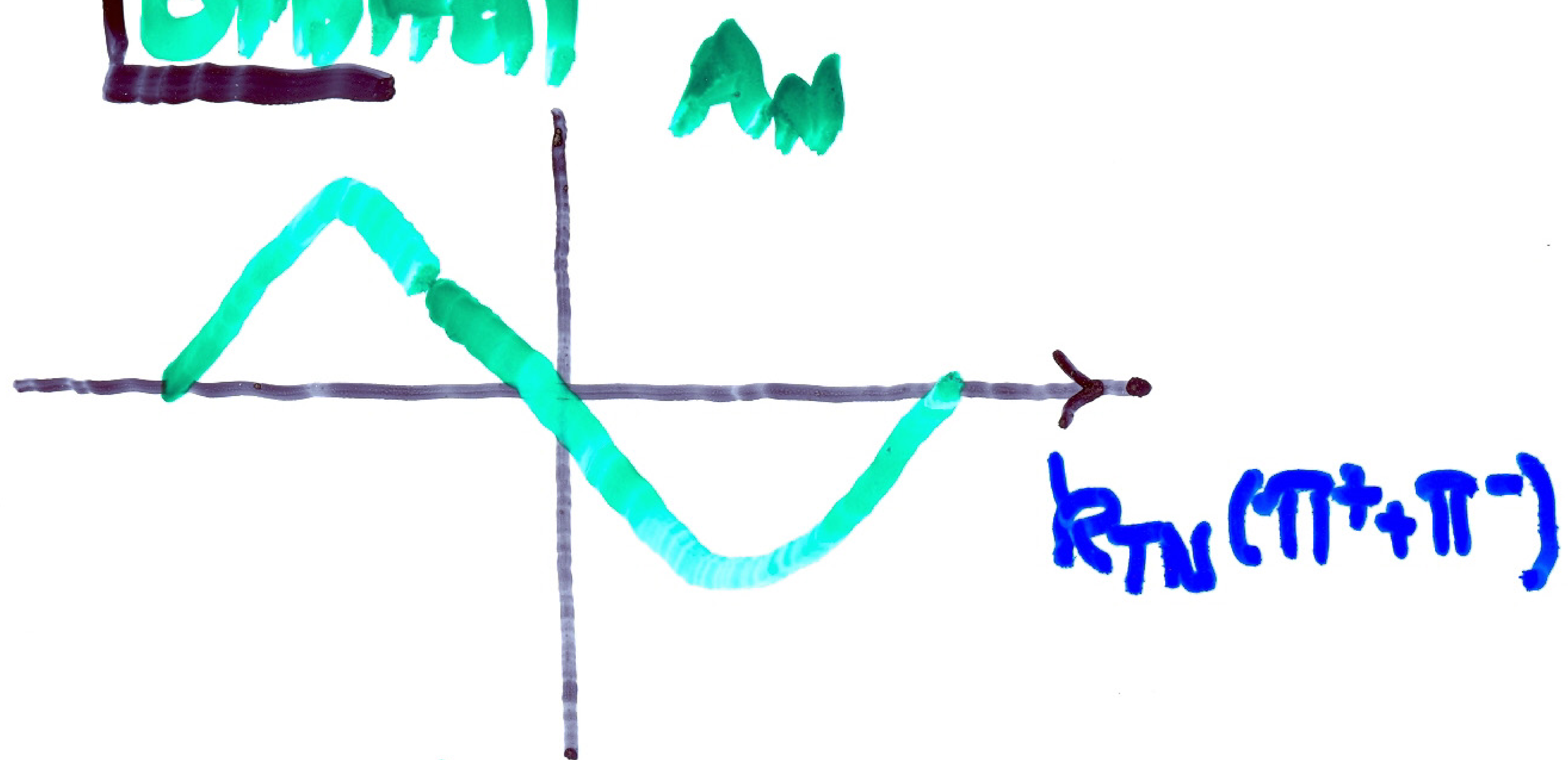
$\pi^+\pi^-$ correlations in hadron-hadron

$z_{\pi^+} > z_{\pi^-}$

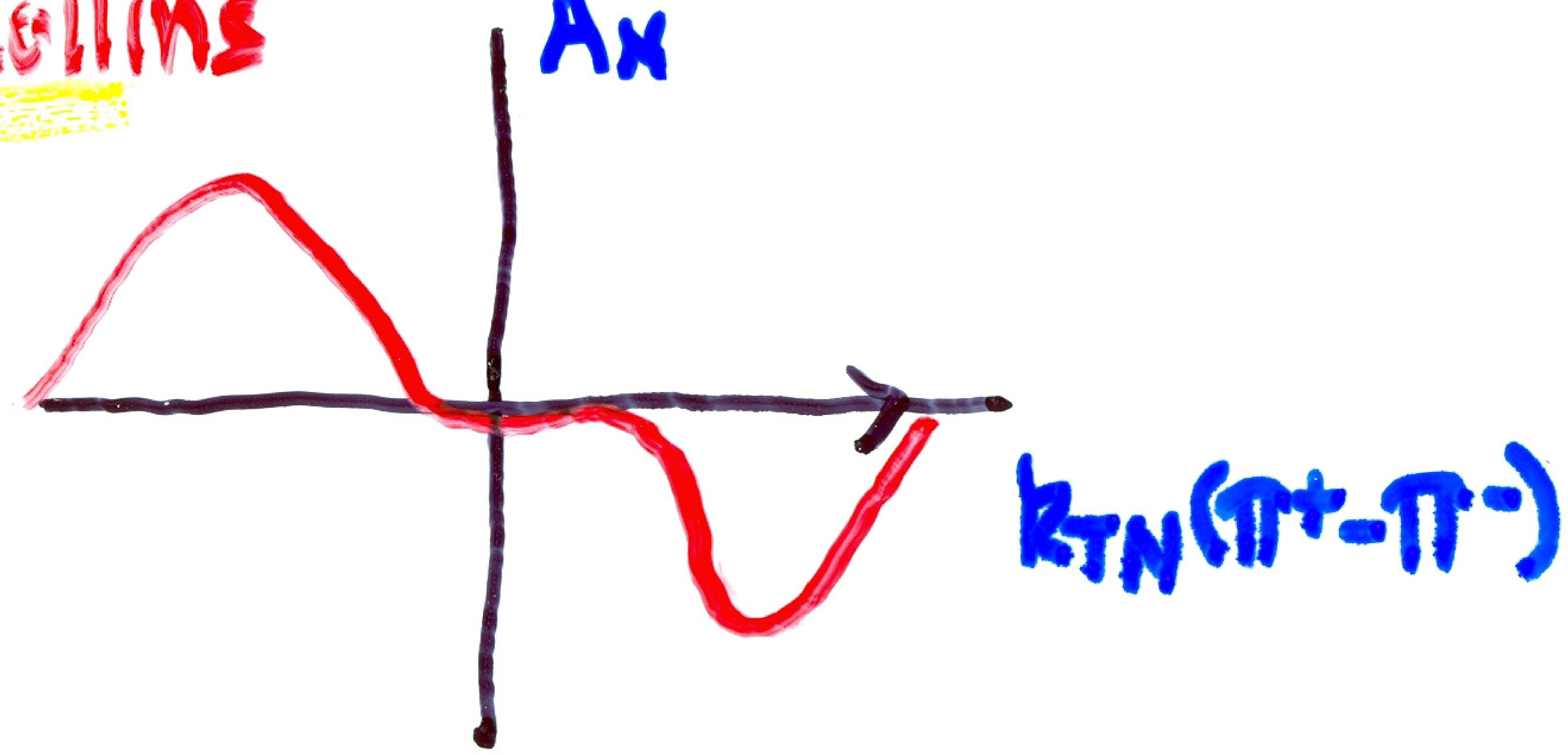
Collins



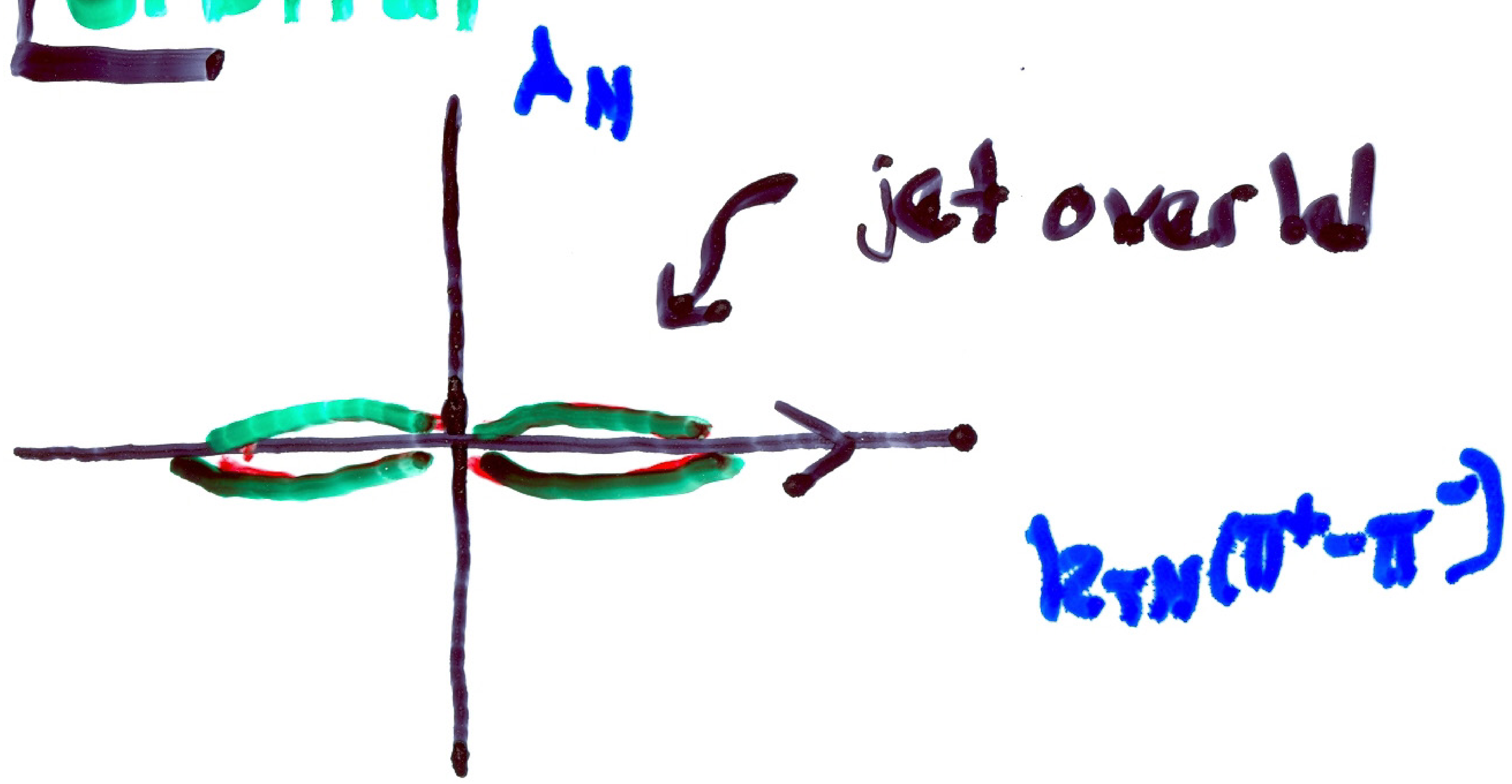
Orbital



Collins



Orbital



depends <u>only</u> on properties of fragmentation