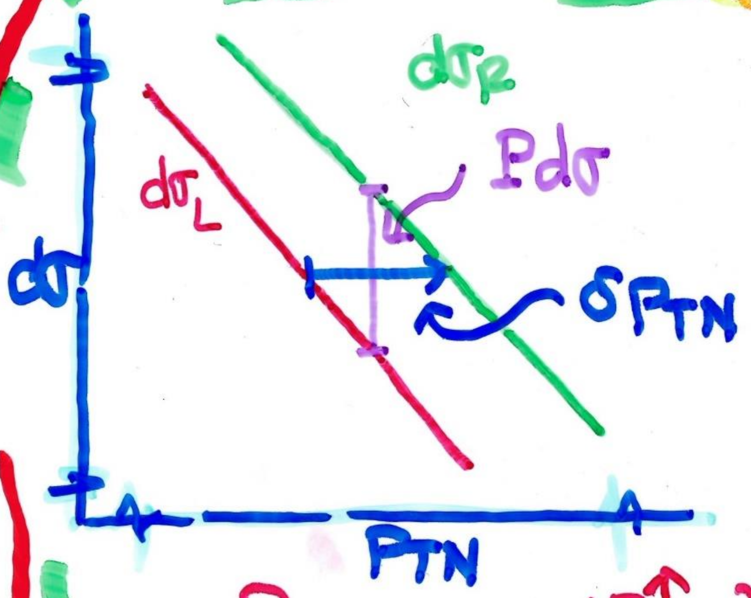
SPIN-DIRECTED momentum transfers in SIDIS baryon production

$A_N \, d\sigma(ep^{\uparrow} \Rightarrow e'Bx)$



$P d\sigma(ep \Rightarrow e'B^{\uparrow}x)$

advanced tools for the study of spin-orbit dynamics in nucleons & QCD jets

POETIC6 15

I. Baryon production in SIDIS

valence DIS selects quark-diquark basis for nucleon structure

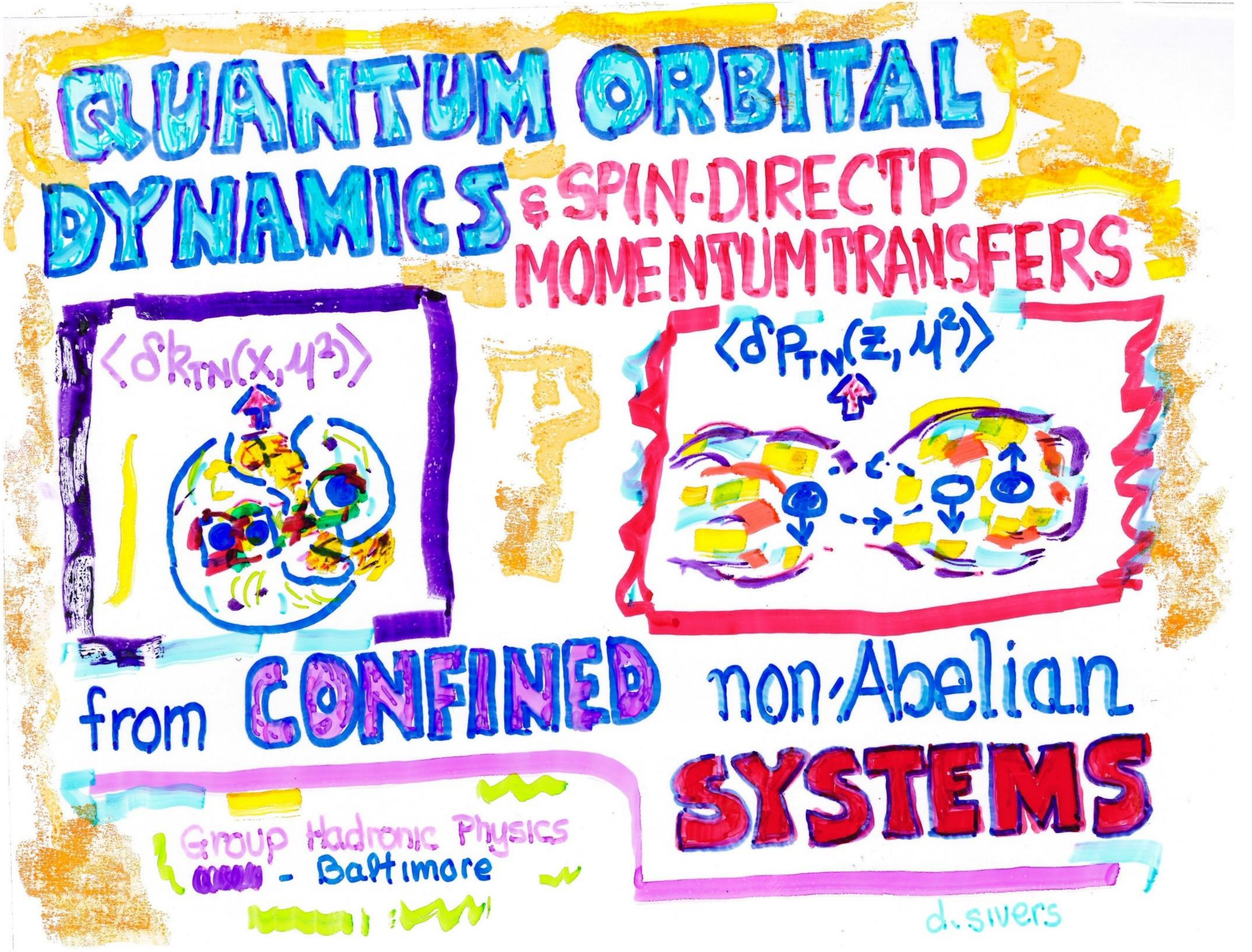
II. Fracture(d) functions & diquark fragmentation

III. Spin-directed momentum parameterization of single-spin asymmetries

IV. $\langle \delta k_{TN}(x,\mu^2) \rangle_{(qq)} = -\eta^q_{(qq)}(x) \langle \delta k_{TN}(x,\mu^2) \rangle_q$

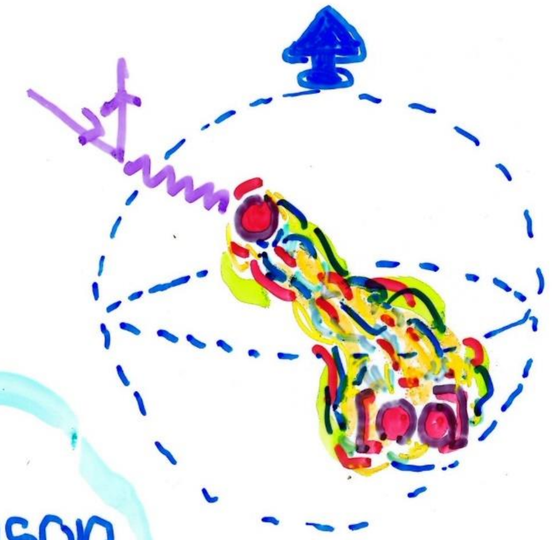
orbital dst'ns & Boer-Mulders functions for (qq)

V. Diquark fragmentation rank by rank Collins & polarizing fragmentation

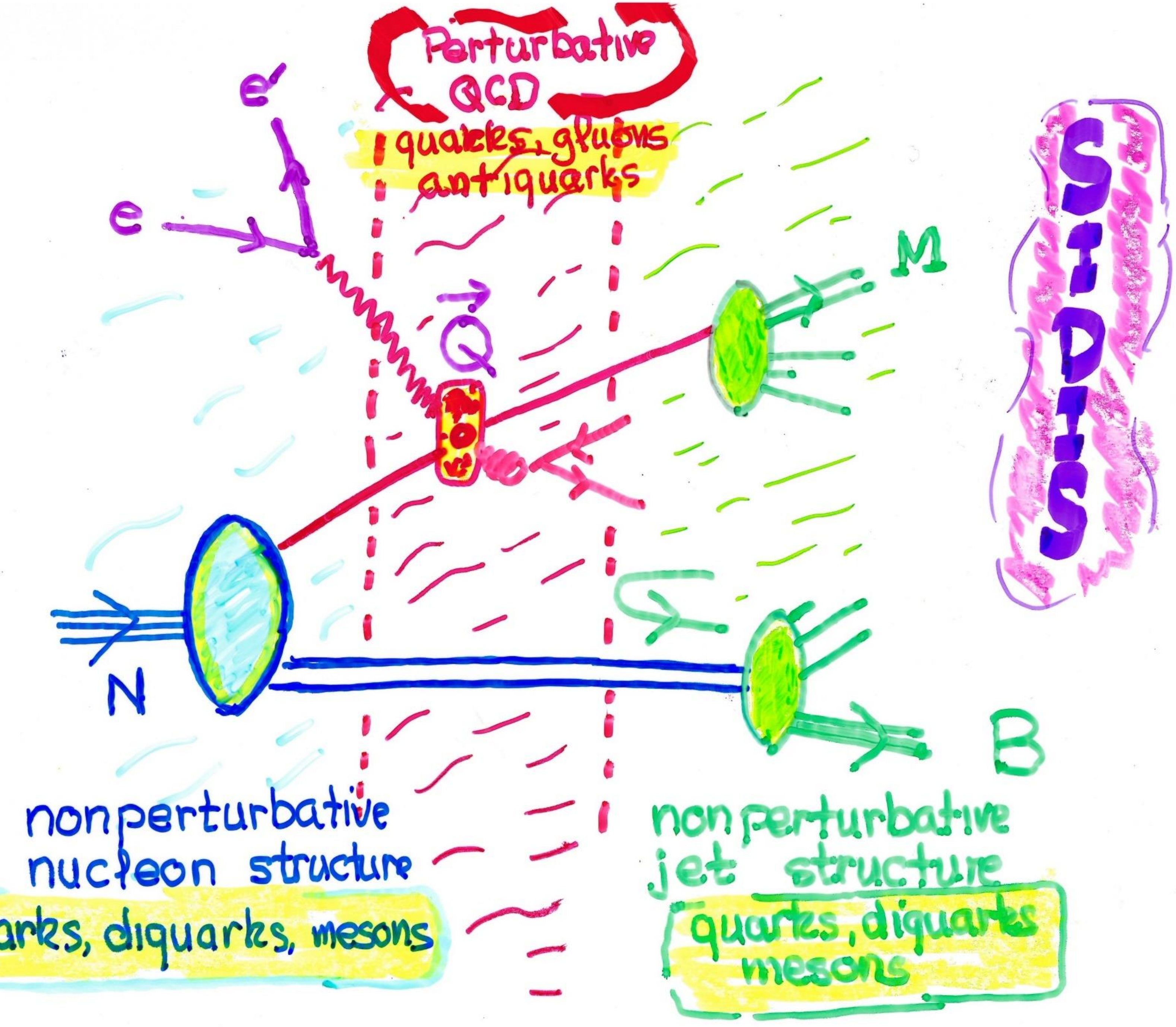

QUANTUM ORBITAL
DYNAMICS
& SPIN-DIRECTD
MOMENTUM TRANSFERS
⟨δk_TN(x, μ²)⟩
⟨δp_TN(z, μ²)⟩
from CONFINED non-Abelian
SYSTEMS
Group Hadronic Physics
[redacted] - Baltimore
d. sivers

I. Baryon Spin Asymmetries in SIDIS

Instrumenting "target fragmentation" region at an EIC (or at JLAB) provides new tools to study QCD

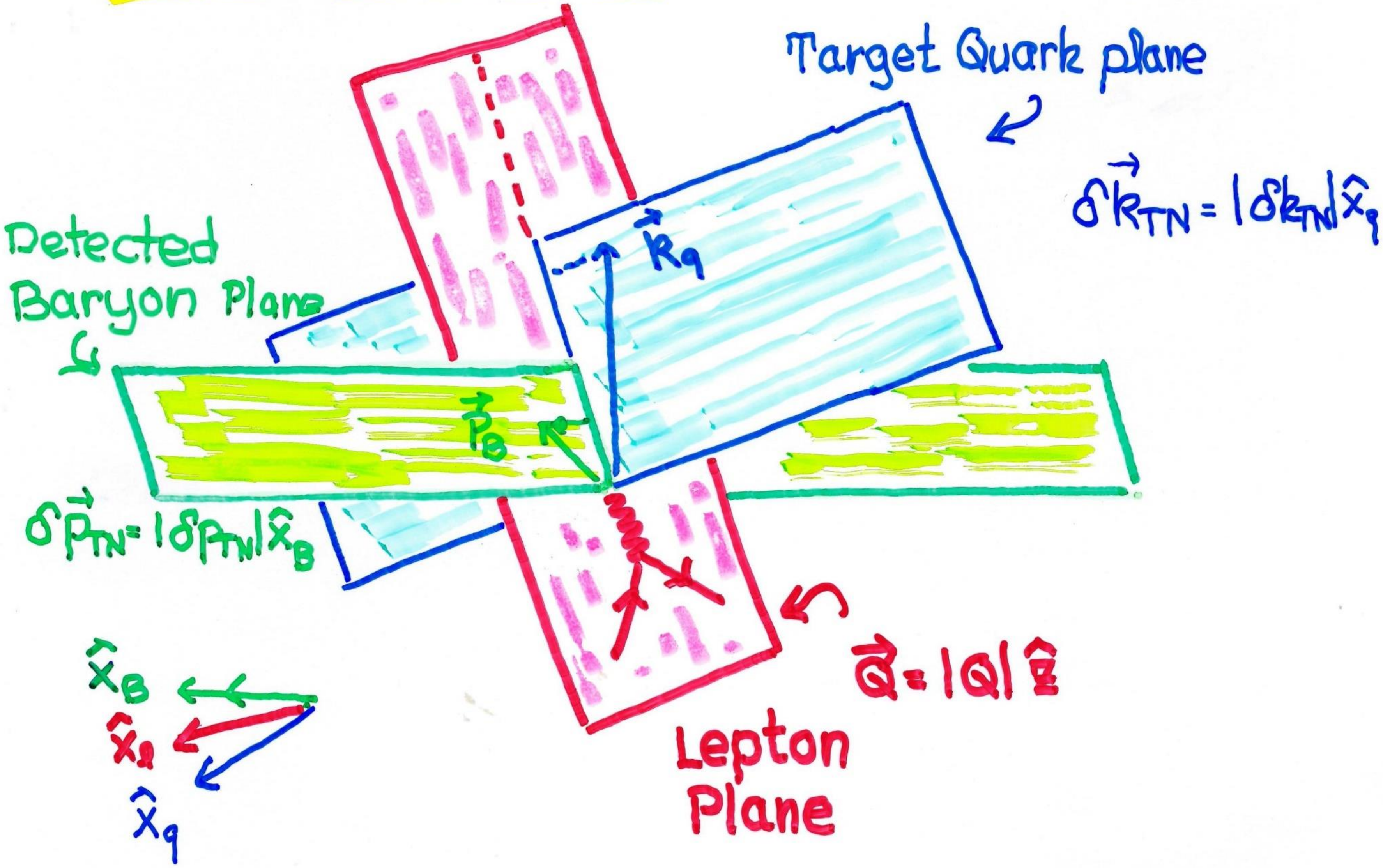


valence DIS projects on quark - diquark - meson basis for nucleon structure



Perturbative
QCD
quarks, gluons
antiquarks
e'
e
$\vec{Q}$
M
N
B
SIDIS
nonperturbative
nucleon structure
quarks, diquarks, mesons
nonperturbative
jet structure
quarks, diquarks
mesons

3 independent planes w/ shared z-axis



As in quark fragmentation, asymmetries in baryon production from diquark fragmentation in SIDIS can be identified with internal dynamics of target nucleon $\langle \delta k_{TN} \rangle$ or dynamics within the fragmenting jet $\langle \delta p_{TN} \rangle$

target nucleon $\langle \delta k_{TN}(x,\mu^2) \rangle \neq 0$	odd $\phi_{\ell T}$ even $\phi_{\ell B}$	A_N fractured orbital P fractured B-M
fragmenting jet $\langle \delta p_{TN}(z,\mu^2) \rangle \neq 0$	even $\phi_{\ell T}$ odd $\phi_{\ell B}$	A_N fractured CHL P polarizing fractured

ALL FOUR CAN BE MEASURED SYSTEMATICALLY!

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

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

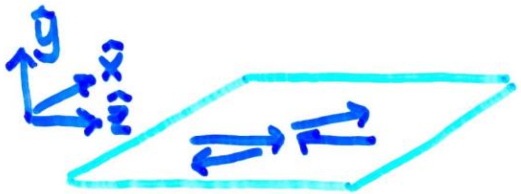
Θ serves as a 3-D Hodge dual of the parity operator

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

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

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

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



FINITE SYMMETRIES

	T	C	P	(CPT)	Θ	A_τ	A_ν	A_C
Σ_x	−	+	−	+	−	+	−	+
Σ_y	+	+	+	+	−	−	−	−
Σ_z	+	−	−	+	−	+	+	−
					$(*P)*$	OP	$A_\tau T$	$A_\tau C$

* 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

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

$\Theta = PA_\tau = -$ for all single spin observables

Classification Theorem

all single-spin observables **odd** under

$\mathcal{O} = \mathcal{P} A_\tau$, this means

1) odd $\mathcal{P}$ even A_τ (weak interactions)
2) even $\mathcal{P}$ odd A_τ (spin-orbit dynamics)

$$k_{TN} = \vec{k}_T \cdot (\hat{\sigma} \times \hat{p}) \qquad A_\tau : k_{TN} = -k_{TN}$$

a spin-directed momentum that defines transverse single-spin observables

$$\mathcal{P}_A^{\pm} = \left(\frac{1 \pm A_\tau}{2}\right)$$

superselection projection for amplitudes, cross sections

$\mathcal{P}_A^-$ diagonalizes spin density matrix in $\hat{\Sigma}_y$ basis

II Transverse-Momentum Dependent Fracture(d) Functions

L. Trentadue
G. Veneziano (1994)

There is more to be learned from a Deep-inelastic scattering event than can be found in the quark fragmentation region.

The Complete Event !!

II. TMD Fractured Functions in SIDIS

TMD "effective" diquark distributions

diquark orbital dst'ns

fractured Boer-Mulders

measure $\langle \delta k_{TN}(x,\mu^2)\rangle_{(qq)}$

TMD diquark fragmentation functions

polarizing fractured functions

fractured Collins
Heppelman - Ladinsky

measure $\langle \delta P_{TN}(z,\mu^2)\rangle_B$

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

$\{q_i,q_j\}\uparrow \Rightarrow [q_i,q_\ell](\bar{q}_\ell\, q_j)$ $[q_i,q_j](q_k\bar{q}_\ell) \Rightarrow \{q_i,q_k\}\uparrow(q_j\bar{q}_\ell)$

that are incorporated into __fragmentation process__

$M^q_{h,p}(x, \vec{k}_T ; z, \vec{p}_T ; \mu^2)$ is the fracture function that gives the conjoint probability for a SIDIS process from a proton target (4 mom p_μ) with a quark jet given by $x_{bj} = \frac{Q^2}{2p \cdot q}$, $\vec{k}_T$ and a detected hadron with $z_F = \frac{p \cdot p_h}{p \cdot q}$, $\vec{p}_T$

($\vec{k}_T$, $\vec{p}_T$ transverse to $\vec{Q} = |Q| \hat{e}_z$)

$M^q_{h,p}$ can be construed as the probability density for an effective structure function of a virtual hadronic system $\bar{p}h$ or as the probability density characterizing the fragmentation of a target remnant with QN $(p\bar{q})$

Valence SIDIS selects a quark-diquark meson basis for characterizing proton & jet structure

Fracture functions & the full power of SIDIS

$A_N d\sigma(ep\uparrow \Rightarrow e' m X)$ $m = \pi^{\pm}\ \pi^0\ K^{\pm}\ K^0\ \bar{K}_0\ \eta \cdots \rho\ \omega$ — Quark fragmentation

orbital dstn's — Collins fcn's

basic studies in transverse spin

nucleon structure — QCD jet structure

$A_N d\sigma(ep\uparrow \Rightarrow e' B X)$ $B = p, n, \Lambda, \Sigma, \Delta, \Sigma^* \cdots$ — Diquark fragmentation

fractured orbital dstn's — fractured Collins Heppelman Ladinski

$P d\sigma(ep \Rightarrow e' B\uparrow X)$ $B\uparrow = \Lambda\uparrow\ \Sigma\uparrow$ $(p\uparrow, n\uparrow \cdots)$

fractured Boer-Mulders — Polarizing fractured fncn's

refined studies in transverse spin

nucleon diquark structure — QCD jet structure

Combinations provide comprehensive tools for studies of nonperturbative QCD dynamics

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 <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>

III. $\delta_{k_{TN}}$ & $\delta_{p_{TN}}$: The direct connection between A_τ-odd TMD's and A_τ-odd higher-twist operators.

Since nonperturbative spin-directed momentum transfers generate SSA's, there is a clear tie between the A_τ-odd TMD's and the A_τ-odd higher-twist operators used within collinear factorization formalism

$$\delta k^i_{TN}(x, \mu^2) \qquad \delta p^i_{TN}(z, \mu^2)$$

A semiclassical excursion in contemplation of transvesee single-spin asymmetries

spin-directed momentum transfers provide important insight into nonperturbative dynamic structure of both hadrons ($\langle \delta k_{TN}(x,\mu^2) \rangle$) and QCD jets ($\langle \delta P_{TN}(z,\mu^2) \rangle$)

These observables unify many different processes involving different kinematic regions

production asymmetries A_N

polarization asymmetries P

TMD formalism

higher-twist collinear formalism

current fragmentation

target fragmentation

mid-rapidity production

Transverse spin-directed momentum transfers

$\vec{S} = \frac{1}{2}\hbar$

$\vec{S} = -\frac{1}{2}\hbar$ $\quad \Delta S = \hbar$

$$P_{TN} = \vec{P}_T \cdot (\hat{S} \times \hat{Q})$$

where $\vec{Q}$ large momentum scale in a hard-scattering process

encode important dynamical aspects of the chiral dynamics of light quarks in <u>confined</u> QCD systems (hadrons or QCD jets)

They are prohibited as $m_q \to 0$ in perturbative QCD by a superselection rule

$$\Pi^{\pm}_{A\tau} = \left(\frac{1 \pm A\tau}{2}\right)$$

idempotent projection operators

SPIN-ORBIT DYNAMICS

LATTICE QCD SIMULATIONS

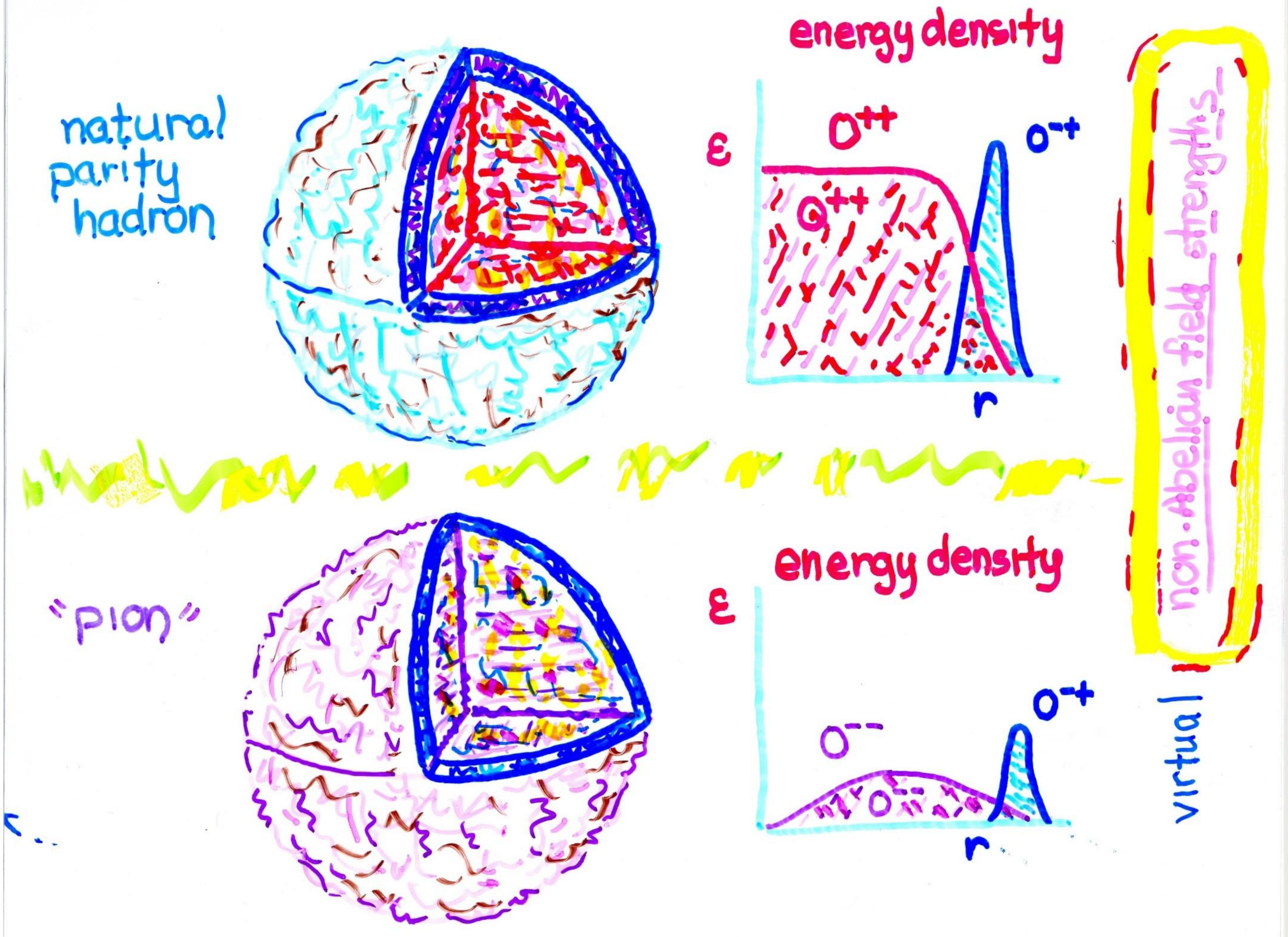
SEMICLASSICAL FIELD EQUATIONS
(QCD MAXWELL'S EQ'S)

Confined QCD systems have significant intrinsic structure that necessarily leads to

NON-PERTURBATIVE $\vec{L}\cdot\vec{S}$

$\langle \delta k_{TN} \rangle$
virtual fluctuations within hadrons

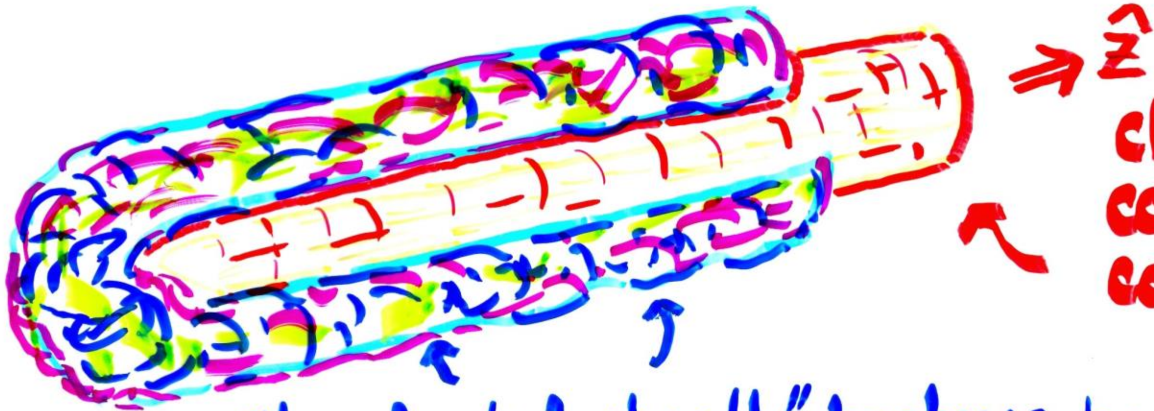
$\langle \delta p_{TN} \rangle$
flux rupture in QCD jets


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

Non-Abelian Flux vs String

$ep \to qX$ monojet

flux

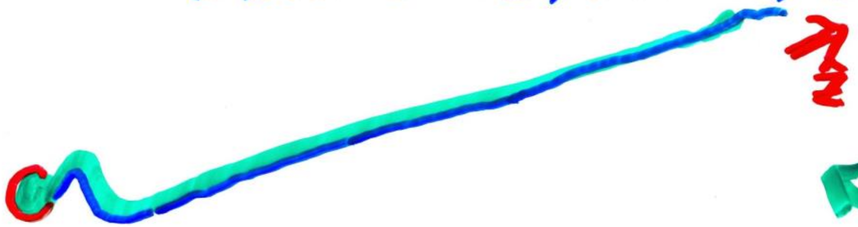


chromoelectric core gives linear confining potential

"topological sheath" bestows hadronic properties (Adler zeros, soft π, χPT dynamics)

v.

string



no transverse dimensional -or internal structure

String (Algebraic) confinement

Nambu, Artru Mennesier action, yo-yo modes

using the projection op.'s $\Pi_A^{\pm}$

$$M = (\Pi_A^+ + \Pi_A^-) M = M^+ + M^-$$

$$\frac{d\sigma\uparrow}{dk_{TN}\, dk_{TS}} = K(|M^+|^2 + |M^-|^2) \qquad \frac{d\sigma\downarrow}{dk_{TN}\, dk_{TS}} = K(|M^+|^2 - |M^-|^2)$$

$$d\sigma_0 = \frac{1}{2}(d\sigma\uparrow + d\sigma\downarrow) = K|M^+|^2 \qquad A_N = \frac{d\sigma\uparrow - d\sigma\downarrow}{d\sigma\uparrow + d\sigma\uparrow} = \frac{|M^-|^2}{|M^+|^2}$$

$$\int d\sigma\uparrow \cdot k_{TN} = \int |M^-|^2 \cdot k_{TN} = \frac{1}{2}\langle \delta k_{TN}\rangle$$
$$\int d\sigma\downarrow \cdot k_{TN} = -\int |M^-|^2 \cdot k_{TN} = -\frac{1}{2}\langle \delta k_{TN}\rangle$$

$\Rightarrow$ $\frac{d\sigma\uparrow}{dk_{TN}}$ peaks at $\frac{1}{2}\langle \delta_{kTN}\rangle$

$\frac{d\sigma\downarrow}{dk_{TN}}$ peaks at $-\frac{1}{2}\langle \delta_{kTN}\rangle$

$$\int dk_{TS} \frac{d\sigma\uparrow}{dk_{TS}\, dk_{TN}} = f\left(k_{TN} - \frac{1}{2}\langle \delta k_{TN}\rangle\right)\left[1 + O\left(\frac{\langle \delta\rangle^2}{m_p^2}\right) + \cdot\right]$$

$$\int dk_{TS} \frac{d\sigma\downarrow}{dk_{TS}\, dk_{TN}} = f\left(k_{TN} + \frac{1}{2}\langle \delta k_{TN}\rangle\right)\left[1 + O\left(\frac{\langle \delta\rangle^2}{m_p^2}\right) + \cdots\right]$$

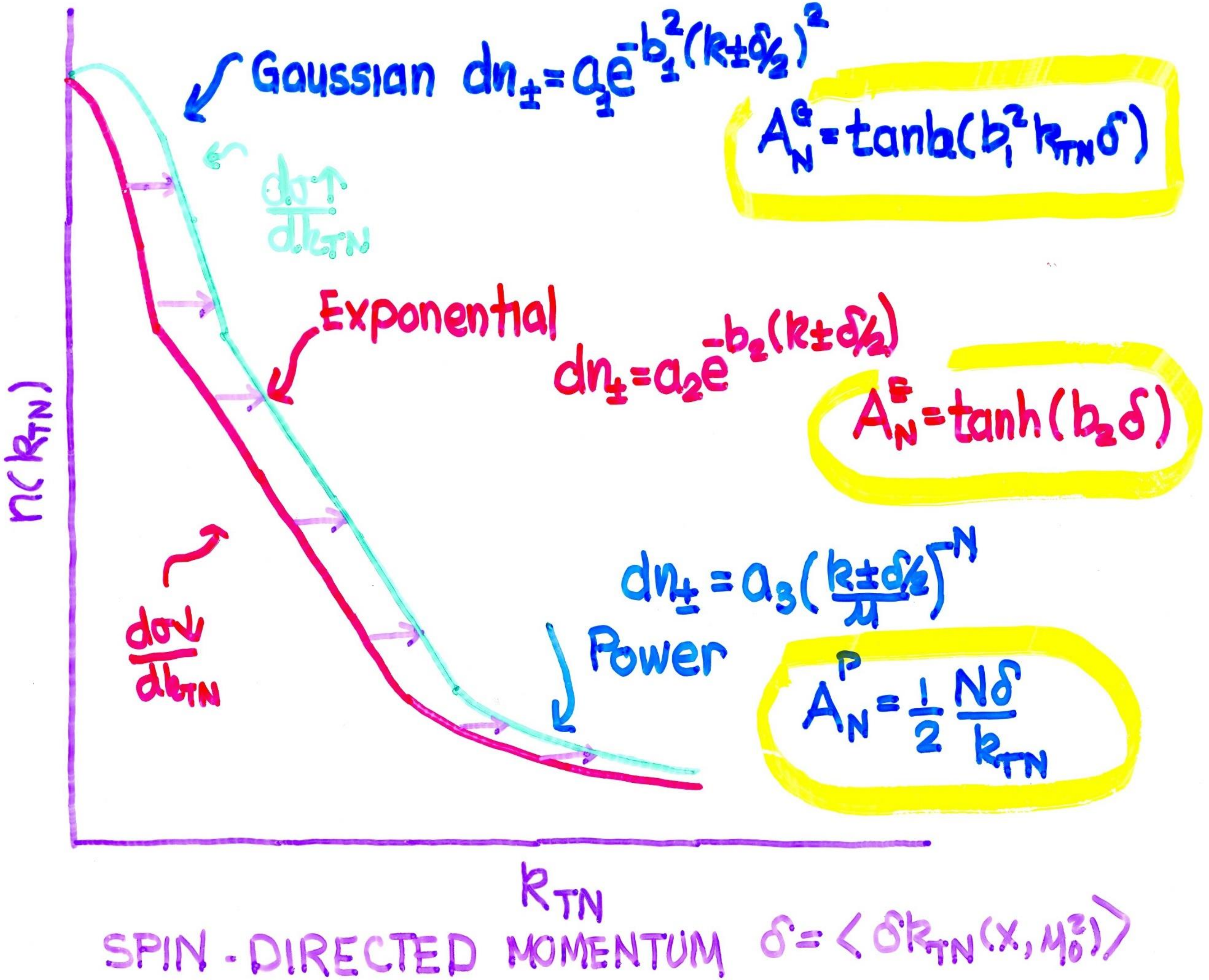
f sharply peaked at f(0)

1 unit of $\hbar$

$1\,\text{fm} \cong \frac{1}{0.2}\frac{1}{\text{GeV}}$

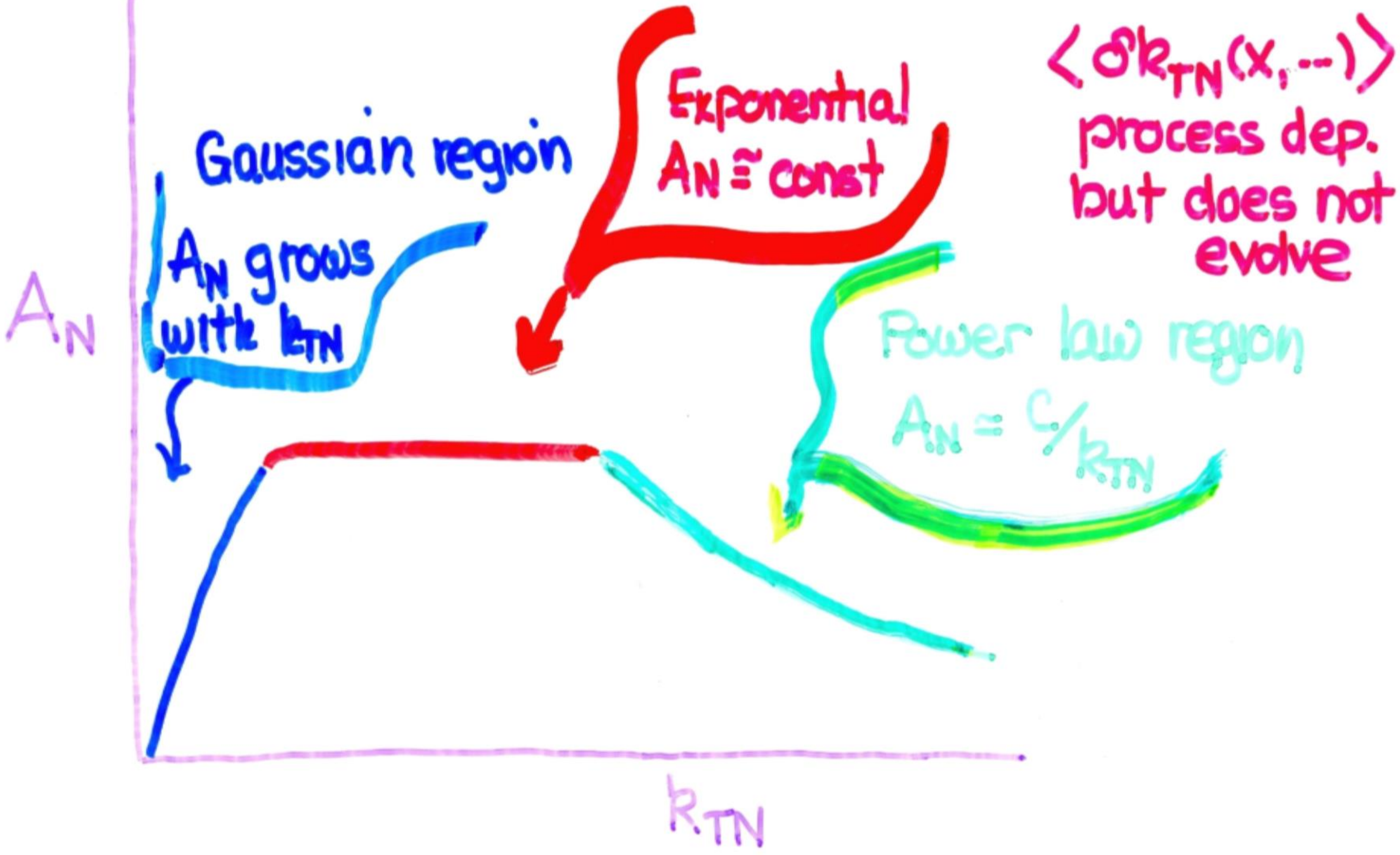
spin-orbit dynamics at hadronic scale

$\Rightarrow \delta_{kTN}$ shift

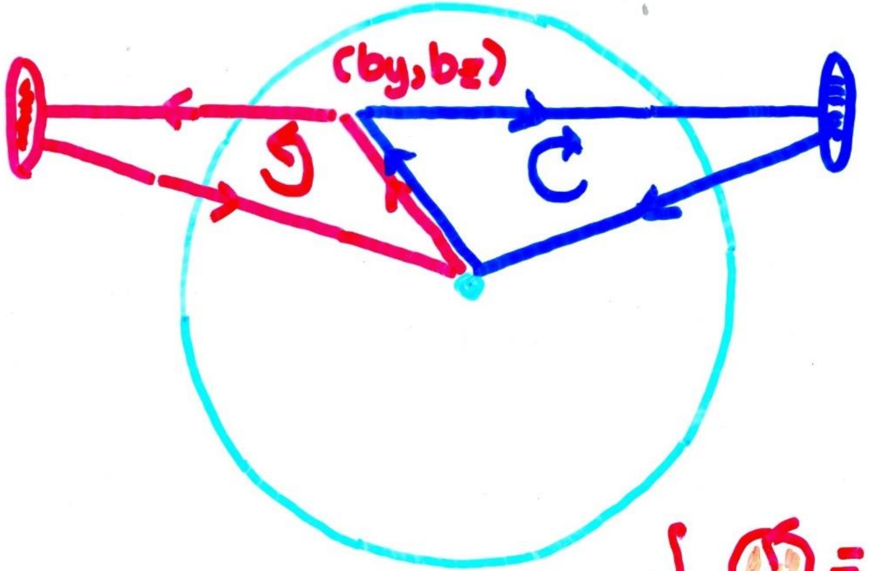


Gaussian $dn_{\pm} = a_1 e^{-b_1^2 (k \pm \delta/2)^2}$
$A_N^G = \tanh(b_1^2 k_{TN} \delta)$
$\frac{d\sigma\uparrow}{dk_{TN}}$
Exponential
$dn_{\pm} = a_2 e^{-b_2 (k \pm \delta/2)}$
$A_N^E = \tanh(b_2 \delta)$
$dn_{\pm} = a_3 \left(\frac{k \pm \delta/2}{\mu}\right)^{-N}$
Power
$A_N^P = \frac{1}{2} \frac{N\delta}{k_{TN}}$
$\frac{d\sigma\downarrow}{dk_{TN}}$
$n(k_{TN})$
k_{TN}
SPIN-DIRECTED MOMENTUM $\delta = \langle \delta k_{TN}(x, M_0^2) \rangle$

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



Wilson loops DY and SIDIS



most conveniently evaluated in radial coordinate gauge
$\vec{A}^a \cdot \hat{r} = 0$
radial lines vanish and only horizontal lines survive

$\int$ ↺ $= \longleftarrow (b_y, b_z)$ $\quad \Delta k_{TN}(b_y, b_z)$

$\int$ ↻ $\quad (b_y, b_z) \longrightarrow$ $\quad \Delta k_{TN}(b_y, b_z)$

Integrating over $b_z \in S$

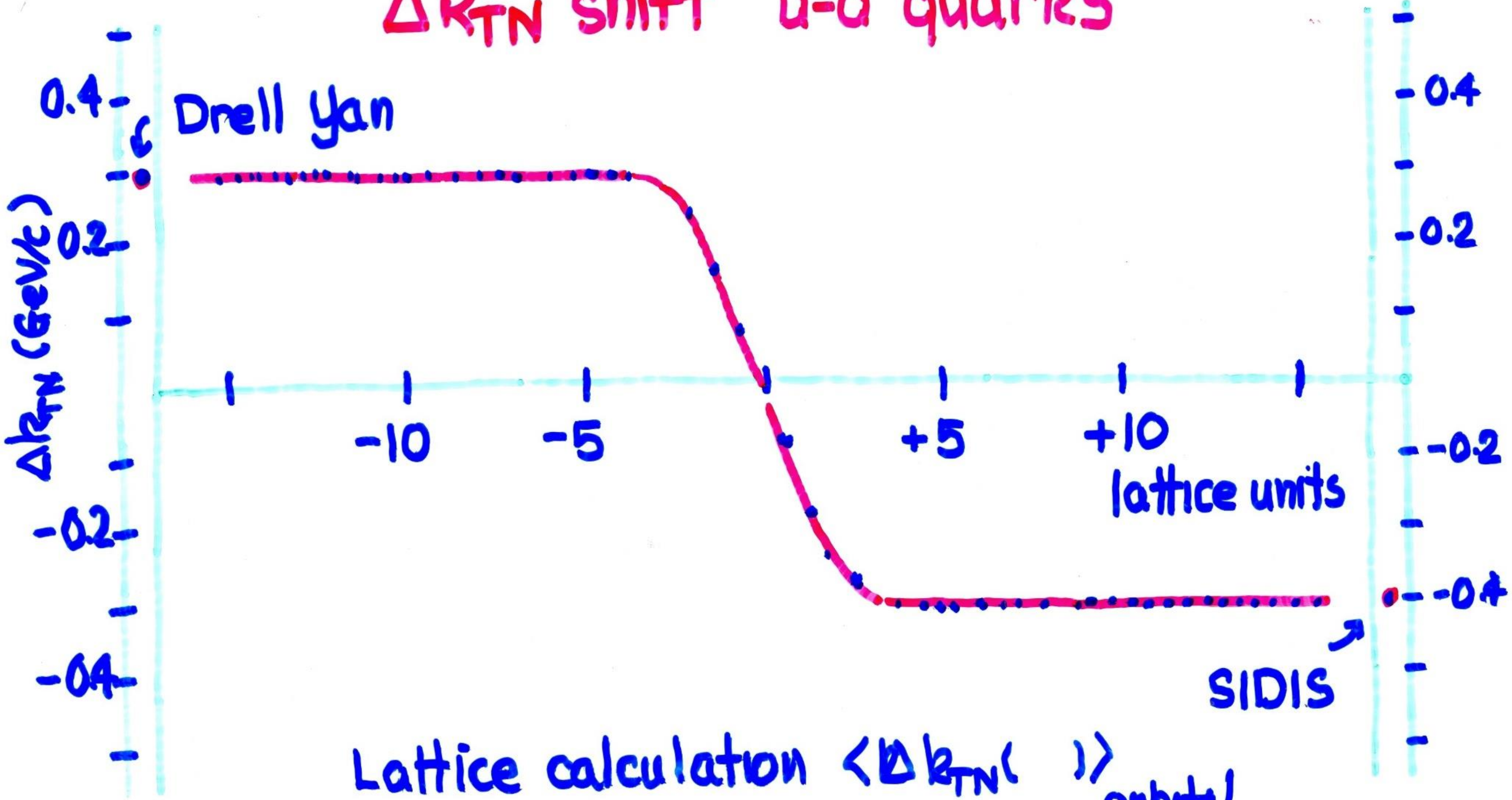
$$0 = \int db_z \{ \Delta k_{TN}(b_y, b_z) + \Delta k_{TN}(b_y, b_z) \}$$

$$\Delta k_{TN}(b_y)\Big|_{DY} = - \Delta k_{TN}(b_y)\Big|_{SIDIS}$$

B. Musch, P. Hagler, M. Engelhardt, J.W. Nagle & A. Shäfer

Phys. Rev D85, 094510 (2012) arXiv: 1111.4249 [hep.lat]

Δk_{TN} shift u-d quarks



Lattice calculation $\langle \Delta k_{TN} (\quad) \rangle_{orbital}$

IV- Spin-Orbit Correlations for Diquarks

Baryon spin asymmetries

fractured orbital dstn $A_N d\sigma(e p^{\uparrow} \to e' B X)$

$P d\sigma(e p \to e' B^{\uparrow} X)$ fractured Boer-Mulders

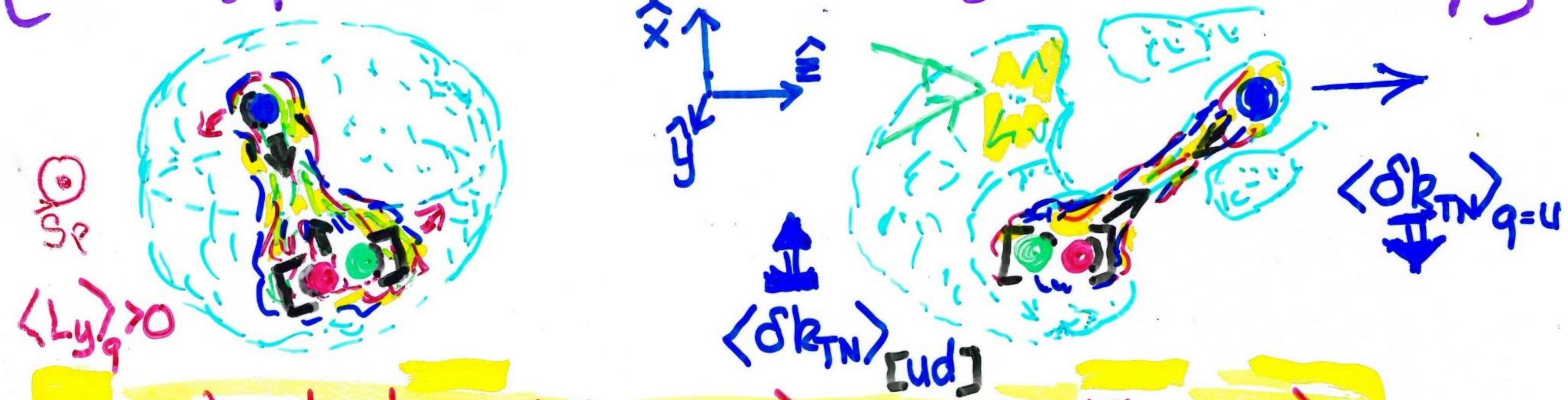
Diquark TMD's

non-perturbative QCD


FRACTURED
ORBITAL DSTN.


FRACTURED
BOER-MULDERS

(In valence SIDIS diquark participates <u>both</u> in $\langle L_y \rangle_q$ <u>and</u> 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

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

$P_{BM}(ep \Rightarrow e' \Lambda^0 \uparrow X) \simeq 0$ $P_{BM}(ep \Rightarrow e' \Sigma^{+/0} \uparrow X)$ 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 **both** $\langle L \rangle_q \neq 0$ **and** 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

V. Diquark Fragmentation v. Quark Fragmentation

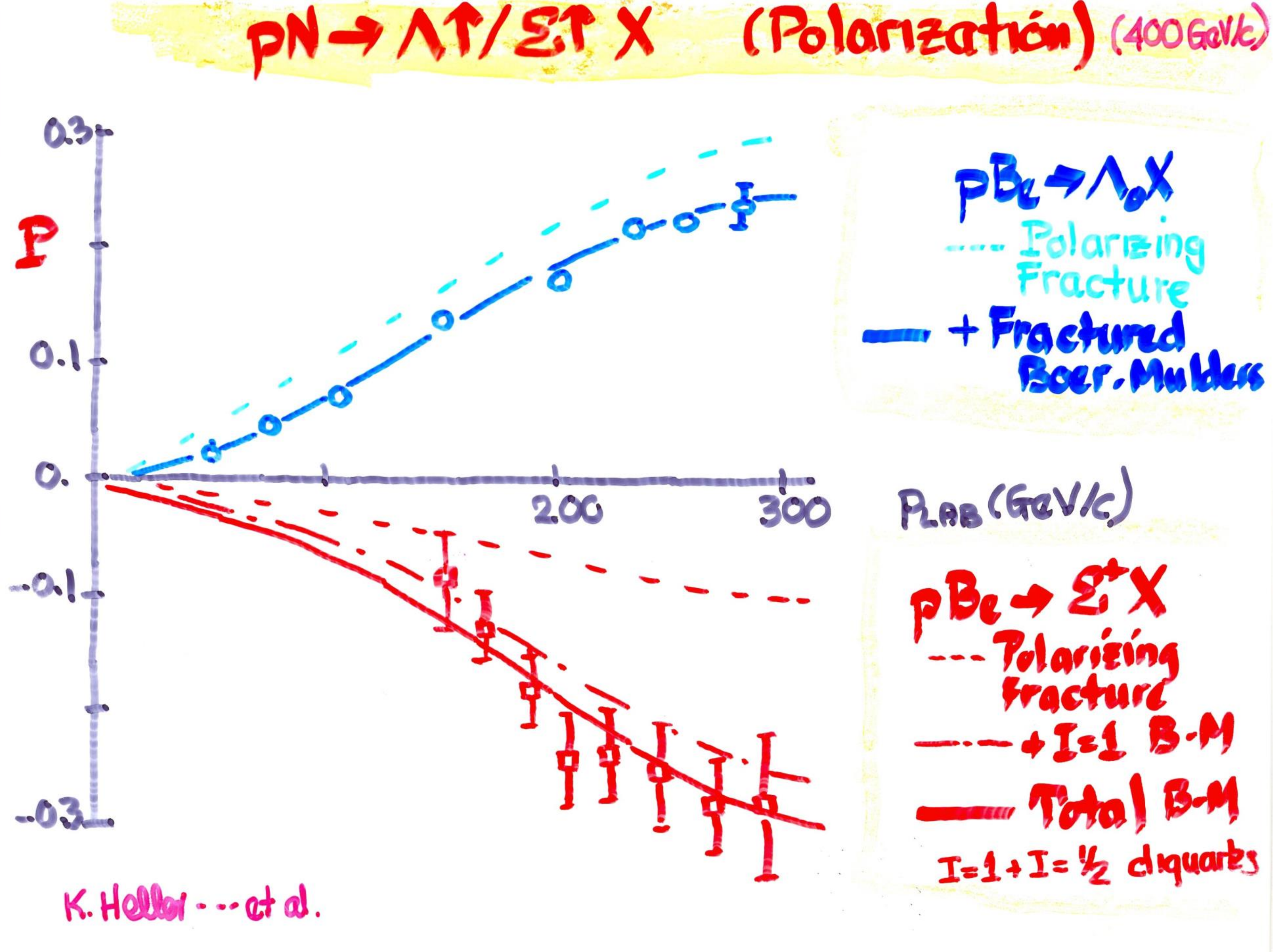
What can baryon spin asymmetries tell us about nonperturbative QCD?

Polarizing fractured functions

Fractured Collins-Heppelman-Ladinsky

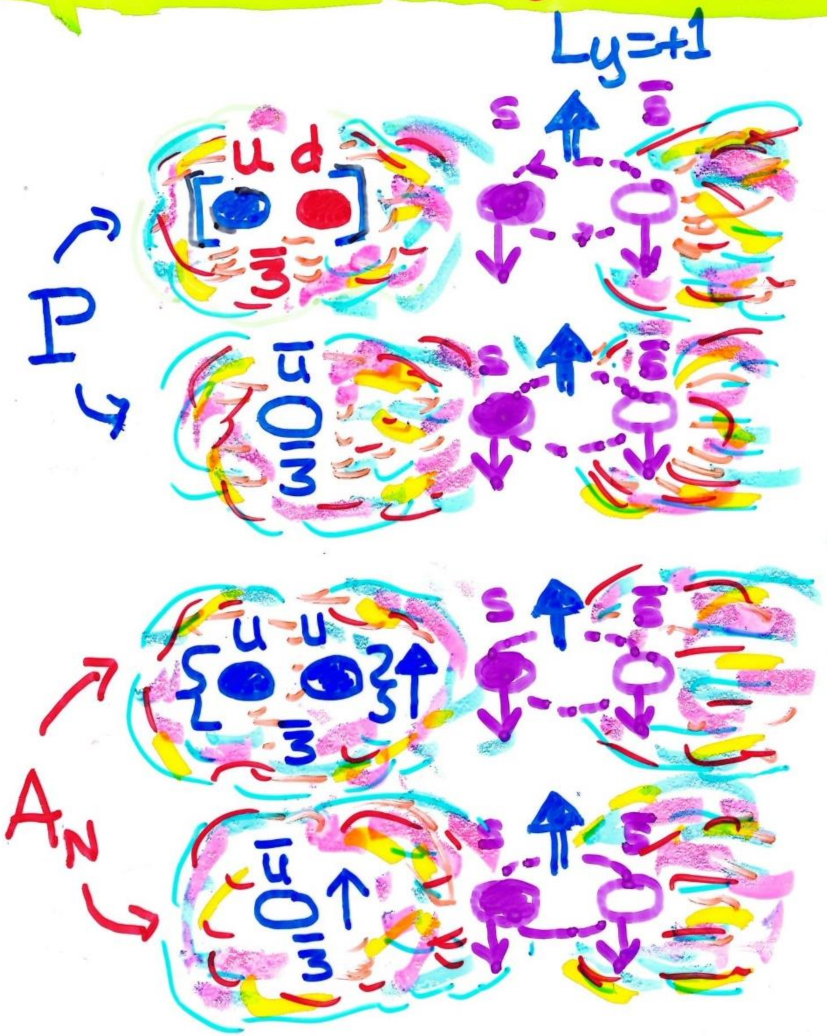

FRACTURED
COLLINS
HEPPELMAN
LADINSKY


POLARIZING
FRACTURED fcn



pN → Λ↑/Σ↑ X (Polarización) (400 GeV/c)
P
0.3
0.1
0.
-0.1
-0.3
200
300
P_{LAB} (GeV/c)
pBe → Λ_0X
Polarizing Fracture
+ Fractured Boer. Mulders
pBe → Σ^+X
Polarizing fracture
+ I=1 B-M
Total B-M
I=1 + I=½ diquarks
K. Heller ... et al.

Fragmentation of a diquark to a baryon very like rank-1 fragmentation of an antiquark to a meson!



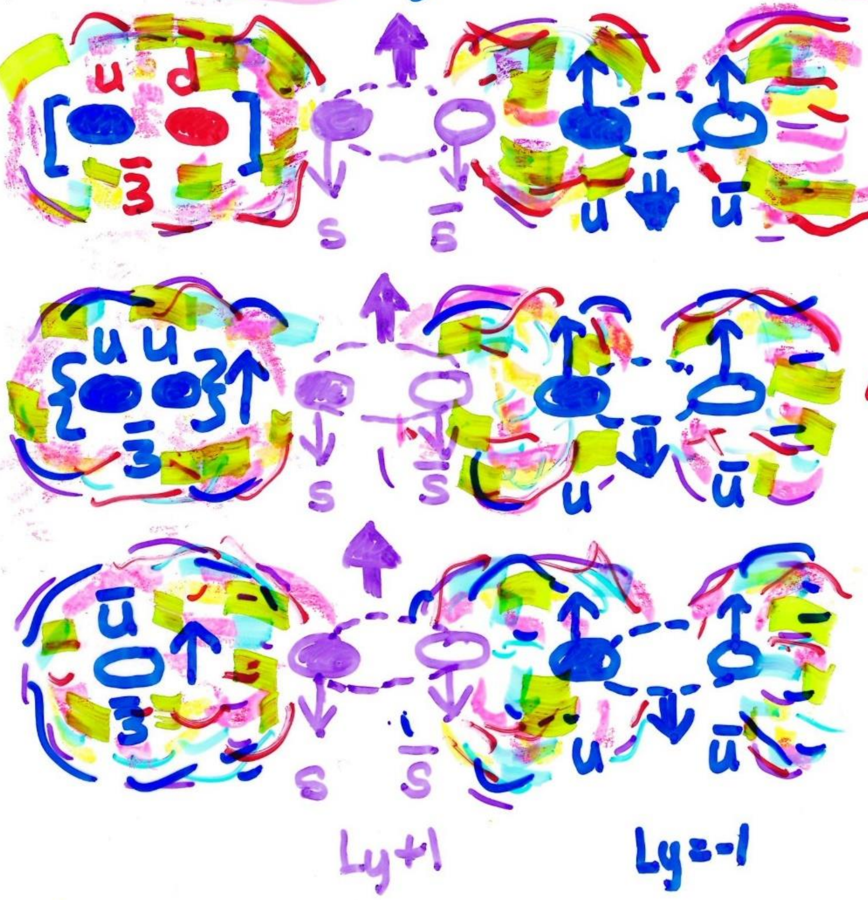
$\Delta D^{(1)}_{\Lambda\uparrow/[u,d]}(z)$ — Polarizing fractured fcn.

$\Delta D^{(1)}_{K^{*}\uparrow/\bar{u}}(z)$ — Polarizing fragmentation fcn

$\Delta D^{(1)}_{\Sigma^{+}/\{uu\}\uparrow}(z)$ — fractured Collins Heppelman Ladinsky

$\Delta D^{(1)}_{K^{-}/\bar{u}\uparrow}(z)$ — Collins function

The dynamical spin information extends to rank-2 fragmentation functions



$\Delta D^{(2)}_{K^-/[ud]:(\Lambda\uparrow)}(z)$ — polarization of $\Lambda\uparrow$ marker for rank(2) asymmetry

$\Delta D^{(2)}_{K^+/\{uu\}\uparrow:\Sigma^+}(z)$ — Isospin of Σ provides marker for rank(2) asymmetry

$\Delta D^{(2)}_{K^+/\bar{u}:K^-}(z)$ — Rank 2 Collins selected by flavor

{ $+\delta$ rank 1 -2δ rank 2 }

{ ΔP_{TN} by rank }