T-odd Transverse Momentum Distributions in Quark Models and the Role of the Coupling Constant.

> Seminar at the C.N. Yang Institute for Theoretical Physics Stony Brook University, NY, USA February 27, 2012

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# Outline

- Hadron Structure
- T-odd Transverse Momentum Distributions
  - Final State Interactions: Sivers & Boer-Mulders functions
  - Evaluation in Models for Hadron Structure
- Rôle of the Coupling Constant
  - The Hadronic Scale: non-perturbative qualitative analysis
  - $\sim$  Final State Interactions and  $\alpha_s$
- $\sim$  Towards a quantitative analysis :  $\alpha$ s from hadronic phenomenology

Hadron Structure

### Hadron Structure

Hadron ⇔ Constituent quarks ⇔ Current quarks



#### Nonperturbative vs. Perturbative QCD

Evolution in Q<sup>2</sup>

### Hard Probes and Factorization

Small size configuration  $\Rightarrow$  Hard Probes  $\Rightarrow$  Hard processes

**Deep Inelastic Scattering** 





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### Nonperturbative aspects of QCD

with d.o.f relevant at intermediate energies

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#### Nonperturbative aspects of QCD with d.o.f relevant at intermediate energies

First Principles based effective theories → Lattice QCD

• observables calculated on the Lattice, e.g. form factors, spin densities, ...

• Effective theories and *Model Calculations* 

- observables calculated in models for hadron structure
- dynamics of proton and pion

Parameterization thanks to extraction from data

links observables and experimental data

#### Experimental measurements

the real world ...

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Spectator Models Constituent Quark Models Bag Model Chiral Quark-Soliton Model

. . .

# T-odd TMDs:

Hadronic model calculations

### Prototype Process : Semi-Inclusive Deep Inelastic Scattering



SIDIS:  $I(I) + N(P) \rightarrow I(I') + h(P_h) + X$ 

 $Q^2, P \cdot q, P \cdot P_h, P_h \cdot q \rightarrow \infty$  and x, z finite

#### Factorization

$$P_h$$
  $P_h$   $P_h$ 

$$W^{\mu
u} \propto \sum_{q} e_{q}^{2} \int d^{4}p d^{4}k \,\Phi(k,P,S) \gamma^{\mu} \Delta(p,P_{h}) \gamma^{\nu}$$

- $\Phi(k, P, S) \Rightarrow Parton Distribution Functions$
- $\Delta(p, P_h) \Rightarrow$  Fragmentation Functions
- Nonperturbative Objects

### Some Asymmetries in SIDIS

Nonperturbative effects of the intrinsic transverse momentum  $k_T$  of the quarks inside the nucleon may induce significant hadron azimuthal asymmetries.

Cahn ; Mulders & Tangermans

Azimuthal Asymmetries for unpolarized target in SIDIS

 $\sim$  e.g. A(**φ**<sub>h</sub>) ⇒ ⟨cos**φ**<sub>h</sub>⟩, ⟨cos2**φ**<sub>h</sub>⟩

Single Spin Asymmetries for transversly polarized target in SIDIS

• e.g.  $A(\boldsymbol{\phi}_h, \boldsymbol{\phi}_S) \Rightarrow \langle \sin(\boldsymbol{\phi}_h - \boldsymbol{\phi}_S) \rangle, \langle \sin(\boldsymbol{\phi}_h + \boldsymbol{\phi}_S) \rangle$ 



- $\phi_h$  = angle between leptonic and hadronic planes
- $\phi_S$  = angle between leptonic plane and transverse spin of the target
- Trento Convention [PRD70, 117504]

### Transverse Momentum Dependent PDFs

Hadronic matrix elements to f(x, k<sub>T</sub>)

Number of independent structure functions

Number of Lorentz scalars +hermiticity+parity invariance+Time-reversal invariance

∜



e.g. Sivers & Boer-Mulders functions

[Sivers, PRD41]; Boer & Mulders PRD57.]

(p,S)

• Existence of **Final State Interactions** at leading-order

[Brodsky, Hwang & Schmidt, PLB 530 ]; Belitsky, Ji & Yuan NPB 656.]

(p,S)



The gauge link:

0th order, No gauge link  $\longrightarrow$  T-odd fct = 0 Existence of leading-twist FSI  $\longrightarrow$  T-odd fct  $\neq$  0

### T-odd TMDs

#### The Sivers function

Distribution of unpolarized quarks inside a transversely polarized proton

$$\begin{aligned} \mathbf{f}_{1\mathsf{T}}^{\perp\mathcal{Q}}(\mathbf{x},\mathbf{k}_{\mathsf{T}}) &= \mathbf{f}_{\mathsf{q}/\mathsf{p}\uparrow}^{\mathcal{Q}}(\mathbf{x},\tilde{\mathbf{k}}_{\mathsf{T}},\mathsf{S}) - \mathbf{f}_{\mathsf{q}/\mathsf{p}\downarrow}^{\mathcal{Q}}(\mathbf{x},\tilde{\mathbf{k}}_{\mathsf{T}},\mathsf{S}) \\ &= -\frac{M}{2k_{x}}\int \frac{d\xi^{-}d^{2}\vec{\xi}_{T}}{(2\pi)^{3}}e^{-i(x\xi^{-}P^{+}-\vec{\xi}_{T}\cdot\vec{k}_{T})} \\ &\frac{1}{2}\sum_{S_{y}=-1,1}S_{y}\langle P,S_{y}|\bar{\psi}_{\mathcal{Q}}(0,\xi^{-},\vec{\xi}_{T})\mathcal{L}_{\vec{\xi}_{T}}^{\dagger}(\infty,\xi^{-})\gamma^{+}\mathcal{L}_{0}(\infty,0)\psi_{\mathcal{Q}}(0,0,0)|P,S_{y}\rangle \end{aligned}$$

#### The Boer-Mulders function

Distribution of transversely polarized quarks inside a unpolarized proton

$$\begin{split} \mathbf{h}_{1}^{\perp \mathcal{Q}}(\mathbf{x}, \mathbf{k}_{T}) &= \mathbf{f}_{\mathbf{q}\uparrow/\mathbf{p}}^{\mathcal{Q}}(\mathbf{x}, \tilde{\mathbf{k}}_{T}, \mathbf{S}) - \mathbf{f}_{\mathbf{q}\downarrow/\mathbf{p}}^{\mathcal{Q}}(\mathbf{x}, \tilde{\mathbf{k}}_{T}, \mathbf{S}) \\ &= -\frac{M}{2k_{x}} \int \frac{d\xi^{-} d^{2} \vec{\xi}_{T}}{(2\pi)^{3}} e^{-i(x\xi^{-}P^{+} - \vec{\xi}_{T} \cdot \vec{k}_{T})} \\ &\frac{1}{2} \sum_{S_{\tau}=-1,1} \langle P, S_{z} | \bar{\psi}_{\mathcal{Q}}(0, \xi^{-}, \vec{\xi}_{T}) \mathcal{L}_{\vec{\xi}_{T}}^{\dagger}(\infty, \xi^{-}) \gamma^{+} \gamma^{2} \gamma_{5} \mathcal{L}_{0}(\infty, 0) \psi_{\mathcal{Q}}(0, 0, 0) | P, S_{z} \rangle \end{split}$$

#### Twofold problem :

- + FSI mimicked by a one-gluon-exchange
  - gluon propagator
- Explicit dependence on the coupling constant
  - directly affected by the value of  $\alpha_s$

#### Models using 'perturbative' gluons :

- MIT bag model calculation
  - ➡ F. Yuan, PLB 575; AC, Vento & Scopetta, PRD79 074001; PRD80 074032
  - perturbative QCD governs the dynamics inside the confining region
- NR Constituent Quark Model
  - ➡ AC, Vento & Scopetta, PRD78 034002; PRD80 074032
- Other model calculations:
  - 🕈 Gamberg & Schlegel, PLB685 95; Pasquini & Yuan, PRD81 114013; Bacchetta, Conti & Radici, PRD78 074010 ; ...



### Two Quark Models Approaches

#### I. Constituent Quark Model

**NR** reduction of the interaction - up to  $O\left(\frac{k^2}{m^2}\right)$ -

Use of free spinors  $\longrightarrow$ 



 $f_{1T}^{\perp Q}, h_1^{\perp Q} \neq 0$  comes from Interference of the lower and upper components in the four-spinors of the free quark states The interaction is to be calculated between proton states in a CQM  $\Rightarrow$  e.g., Harmonic Oscillator  $|N\rangle = a|^2 S_{1/2}\rangle_S$  $\Rightarrow$  SU(6) symmetry for the proton

II. MIT Bag Model

Bag wave function  $\longrightarrow$ 

 $arphi_m(ec{k}) \propto egin{pmatrix} t_0(ec{k}ec{)}\chi_m \ ec{\sigma}\cdot\hat{k}\,t_1(ec{k}ec{)}\chi_m \end{pmatrix}$ 

 $f_{1T}^{\perp Q}, h_1^{\perp Q} \neq 0$  comes from the Interference of the lower and upper components in the **bag w.f.** 

The interaction is to be calculated between proton states, we choose  $\Rightarrow$  SU(6) symmetry for the proton

### The Sivers function in the MIT bag model







AC, Vento & Scopetta, PRD79 074001; PRD80 074032

#### Sivers function:



- 3-body calculation
- No proportionality u and d distribution
- Small Violation of the Burkardt SR

$$\frac{\langle k_x^u \rangle + \langle k_x^d \rangle}{\langle k_x^u \rangle - \langle k_x^d \rangle} \simeq 0.02$$

#### MIT Bag Model

[A.C., Scopetta and Vento, PRD 79]

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- $\blacktriangleright$  No proportionality u and d distribution
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### Comparison of T-odd functions in Hadre nic Models

NR CQM





d ----

$$f_{1T}^{\perp(1)q}(x) = \int d^2 \vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x, k_T)$$

Sivers function Boer-Mulders function

### The QCD evolution problem

→ MIT bag result with  $\mu_0^2$  specific to model and MSTW2008 conventions for  $\Lambda_{QCD}$  [AC, Vento & Scopetta, PRD79 074001]

Torino fit with QCD evolution with MSTW2008 conventions for  $\Lambda_{QCD}$  [Aybat, Collins, Qiu & Rogers, 1110.6428 [hep-ph]]



Ok for this particular value of x: interplay (x, k<sub>T</sub>) Tricky to evolve downwards in energy Error propagation

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# The Hadronic Scale:

non-perturbative qualitative analysis

### Hadronic Physics at Intermediate Energies: Hadronic Models

Nonperturbative vs. Perturbative QCD

**Models of Hadron Structure** 

**Renormalization Group Eqs.** 

QCD matrix element  $\rightarrow$  associated scale  $\mu_0^2$ 

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**Matrix Elements** 

- calculated in hadronic model
- $\sim$  at scale  $\mu_0^2$
- switch on QCD evolution

... till Ok Bjorken scaling/experiments

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#### **Matrix Elements**

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Suppose there exists a scale at which there is no sea and no gluon:

$$\left\langle \left( u_v + d_v \right) \left( \mu_0^2 \right) \right\rangle_{n=2} = 1$$
 momentum sum rule

QCD evolution introduces gluons and sea quarks:

e.g. CTEQ parameterization PRD51 :

$$\langle (u_v + d_v) \left( Q^2 = 10 \,\mathrm{GeV}^2 \right) \rangle_{n=2} = 0.36$$

Parisi & Petronzio, Phys. Lett. B 62 (1976) 331 Stratmann, Z.Phys. C 60 (1993) 763 Traini et al, Nucl. Phys. A 614, 472 (1997)

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#### Evolve downward high energy data until $2^{nd}$ moment=1 Find $\mu_0^2$

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Models scenarios in MSbar scheme

- ∞ quark model
  - ∞ μ<sub>0</sub><sup>2</sup>=0.1GeV<sup>2</sup>
  - $\sim \Lambda_{LO}=.27 \text{ GeV}; \Lambda_{NLO}=.2 \text{ GeV}$
  - $\sim \alpha_{sLO} = 4\pi \times .32$ ;  $\alpha_{sNLO} = 4\pi \times .13$
- ∞ partonic scenario
  - ∞ μ<sub>0</sub><sup>2</sup>=0.2GeV<sup>2</sup>





- ----- IK at µ0<sup>2</sup>
- ----- LO evolution to  $Q^2=10 \text{ GeV}^2$
- ----- NLO evolution to  $Q^2=10 \text{ GeV}^2$
- ..... CTEQ parametrization

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### 'Perturbative' Coupling Constant

$$\frac{d \, a(Q^2)}{d(\ln Q^2)} = \beta_{N^m LO}(\alpha) = \sum_{k=0}^m a^{k+2} \beta_k$$

 $\overline{MS}$  scheme

 $a=\alpha_s/4\pi$ 

LO exact perturbative solution  $\Lambda{=}250~\text{MeV}$ 

NLO exact perturbative solution  $\Lambda$ =250 MeV

NNLO exact perturbative solution  $\Lambda$ =250 MeV



Hadronic scale

### Infrared Freezing of as

#### Non-perturbative approaches:

- Importance of finite couplings
- ✤ Taming the Landau pole

#### e.g. :

Cornwall, Phys.Rev.D26, 1453 (1982) Mattingly & Stevenson, Phys.Rev.D49, 437 (1994) Dokshitzer, Marchesini & Webber, Nucl.Phys.B469 (1996) 93 Cornwall & Papavassiliou, Phys.Rev.Lett.79, 1209 (1997) Fischer, J. Phys. G32, R 253 (2006) Alkofer & von Smekal, Phys. Rept. 353, 281 (2001) Aguilar, Mihara & Natale, Phys. Rev.D 65, 054011 (2002) Aguilar, Binosi & Papavassiliou, JHEP 1007, 002 (2010)



Deur, A. et al. Phys.Lett. B650 (2007) 244-248

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#### 1<sup>st</sup> step: Qualitative analysis

Implications of IR finite as in hadronic physics

### NP Gluon Propagator: Gluon Mass as IR Regulator

Solving the Schwinger-Dyson eqs ...

$$\Delta^{-1}(Q^2) = Q^2 + m^2(Q^2)$$

J. M. Cornwall, Phys. Rev. D26, 1453 (1982)A. C. Aguilar and J. Papavassiliou, JHEP0612, 012 (2006)

$$m^{2}(Q^{2}) = m_{0}^{2} \left[ \ln \left( \frac{Q^{2} + \rho m_{0}^{2}}{\Lambda^{2}} \right) / \ln \left( \frac{\rho m_{0}^{2}}{\Lambda^{2}} \right) \right]^{-1-\gamma}$$

 $m_0 \sim \Lambda - 2\Lambda$ 

effective gluon mass
phenomenological estimates



Aguilar & Papavassiliou, Phys.Rev.D83:014013,2011 Bogolubsky, Proc. Sci., LAT2007 (2007) 290

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Solution free of Landau pole

Freezes in the IR



Aguilar & Papavassiliou, Phys.Rev.D83:014013,2011 Bogolubsky, Proc. Sci., LAT2007 (2007) 290

### NP Momentum-dependence of the Coupling Constant

$$\frac{\alpha_{\rm NP}(Q^2)}{4\pi} = \left[\beta_0 \ln\left(\frac{Q^2 + \rho m^2(Q^2)}{\Lambda^2}\right)\right]^{-1}$$



LO perturbative evolution  $\Lambda{=}250~{\rm MeV}$  ;  $\overline{MS}$  scheme

Low mass scenario NP coupling constant  $_{m_0=250~MeV}$  ;  $\Lambda{=}250~MeV$  ;  $\rho{=}1.5$ 

High mass scenario NP coupling constant  $m_0=500$  MeV ;  $\Lambda=250$  MeV ;  $\rho=2$ .

Hadronic scale

### Perturbative vs. NP 'evolution': Fixing the hadronic scale

2nd moment of  $f_1$ 

$$\langle q_v(Q^2) \rangle_n = \langle q_v(\mu_0^2) \rangle_n \left(\frac{\alpha(Q^2)}{\alpha(\mu_0^2)}\right)^{d_{NS}^n}$$

LO perturbative evolution  $\Lambda{=}250~{\rm MeV}$  ;  $\overline{MS}$  scheme

Low mass scenario NP coupling constant  $m_0=250$  MeV ;  $\Lambda=250$  MeV ;  $\rho=1.5$ 

High mass scenario NP coupling constant  $m_0{=}500~\text{MeV}$  ;  $\Lambda{=}250~\text{MeV}$  ;  $\rho{=}2.$ 



There exist scenarios that give results in agreement with the perturbative approach

# Final State Interactions and $\alpha_s$

### Back to T-odd TMDs

#### The Sivers function $f_{1T}^{\perp Q}(x, k_T)$

 $\Rightarrow$  Distribution of **unpolarized quarks** inside a **transversely polarized proton** 



#### The Boer-Mulders functions $h_1^{\perp Q}(x, k_T)$

 $\Rightarrow$  Distribution of transversely polarized quarks inside a unpolarized proton



Matrix element of low twist operator

$$f_{1T}^{\perp q}(x,k_{T}) = -\frac{M}{2k_{x}} \int \frac{d\xi^{-} d^{2} \vec{\xi}_{T}}{(2\pi)^{3}} e^{-i(xp^{+}\xi^{-} - \vec{k}_{T} \cdot \vec{\xi}_{T})} \\ \times \frac{1}{2} \sum_{S_{y}=-1,1} S_{y} \langle PS_{y} | \overline{\psi}_{q}(\xi^{-}, \vec{\xi}_{T} (\mathcal{L}_{\vec{\xi}_{T}}^{\dagger}(\infty,\xi^{-}))\gamma^{+} \mathcal{L}_{0}(\infty,0)\psi_{q}(0,0) | PS_{y} \rangle + \text{h.c.}$$

Importance of gauge link

$$\mathcal{L}_{\vec{\xi}_T}(\infty,\xi^-) = \mathcal{P}\exp\left(-ig \int_{\xi^-}^{\infty} A^+(\eta^-,\vec{\xi}_T) \, d\eta^-\right)$$

- holds in covariant gauges
- process dependent

#### Twofold problem :

- ✤ FSI mimicked by a one-gluon-exchange
  - gluon propagator
- Explicit dependence on the coupling constant
  - relevance of NP scheme for model calculations



#### Twofold problem :

FSI mimicked by a one-gluon-exchange

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attempt to go beyond the perturbative OGE approximation

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#### Example :

- MIT bag model calculation
  - perturbative QCD governs the dynamics inside the confining region
  - no need for NP gluon propagator
  - $\rightarrow$  NP scheme  $\rightarrow$  change of hadronic scale
- Other model calculations? e.g. L. Gamberg and M. Schlegel, Phys. Lett. B 685 (2010) 95

### Sivers & Boer-Mulders functions



$$0.1 < \frac{\alpha_s(\mu_0^2)}{4\pi} < 0.3$$





### Sivers & Boer-Mulders functions



## Towards a quantitative analysis :

 $\alpha_s$  from hadronic phenomenology

### (pre) Conclusions

Physical picture for the helicity-flip at the quark level

- - Analysis of the Sivers & Boer-Mulders functions in a 3-body model
  - Ingredients: wave functions and non-relativistic reduction of the interaction.
  - **Results:** Correct sign ; Ok Burkardt sum rule

#### T-odd functions in the MIT bag model

- Analysis of the Sivers & Boer-Mulders functions in a 1-body model
- Ingredients: bag wave function and SU(6) proton state.
- **Results:** Correct sign ; Ok Burkardt sum rule

## Conclusions

- $\sim$  Low hadronic scale validated by IR behavior of  $\alpha_s$
- Good description of perturbative dynamics by 'standard scheme': now supported by NP scheme
- Set of parameters needs to be pushed towards 'pure valence's hadronic scale:
   NP scheme favors scenarios valence quarks + sea + gluons
- Quantitative analysis:
   would depend on HOW the IR freezing is obtained.
- ✓ Impact on Phenomenology:
   Value of coupling constant → *theoretical errorban∂* NP gluon propagator
   QCD evolution equations at low Q<sup>2</sup>?

Great deal of improvements is needed here!

### Extraction of $\alpha s$ at low energy

Polarized scattering from both proton and neutron

Deur et al. Phys.Lett. B650 (2007) 244-248

Natale, PoS QCD-TNT09 (2009) 031

Bjorken Sum Rule from JLab & GDH Sum Rule at  $Q^2=0$  GeV<sup>2</sup>

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#### Bjorken Sum Rule from JLab & GDH Sum Rule at Q<sup>2</sup>=0 GeV<sup>2</sup>

Solution → Deep Inelastic Scattering (DIS) at large Bjorken-x & parton-hadron duality

Liuti, [arXiv:1101.5303 [hep-ph]].

Semi-Inclusive DIS & Extraction of T-odd TMDs from SSAs

A.C., Vento & Scopetta, Eur. Phys. J. A47, 49 (2011)

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Joint analysis: Chen, Courtoy, Deur, Liuti & Vento, work in progress

Do not quench your inspiration and your imagination ; do not become the slave of your model.

Vincent Van Gogh