TMDs, a 3D look at the proton

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2015
3D proton structure @ Nikhef

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Postdocs and visitors

PhD students
Why the proton ..?

- building blocks of our world:
  ~ **99.97% of the mass** of the world we live in is accounted by protons+neutrons

- **connection** between chemistry, atomic/nuclear physics and the elementary building blocks of Nature

- **field theory**: subtle role in canceling some of the divergencies of the theory

**HOW CAN WE DESCRIBE IT?**
The quest for the structure
quantum field theory:
Quantum Chromodynamics

Quarks & gluons
Observing protons

$$\psi_i(\xi) |P, S\rangle$$

**extraction** of a quark from the proton
Observing protons

how can we define distribution functions?

\[ \Phi_{ij}(k; P, S) \sim \text{F.T.} \langle P, S| \bar{\psi}_j(0) \ U_{[0,\xi]} \psi_i(\xi) \ |P, S\rangle_{LF} \]

Dirac matrix, parametrized in terms of quark distribution functions
Quarks in 1D - PDFs

3 parton distribution functions (PDFs)

not computable in pert. theory

Proton and quark spin configuration:

unpolarized longitudinal transverse

level of knowledge: very good getting better basic

{ $f_1(x)$, $g_1(x)$, $h_1(x)$ }
Quarks in 3D - TMDs

8 transverse-momentum-dependent parton distribution functions (TMD PDFs)

\[ f_1^q (x, k_T) \]

\textit{richer than 1D PDFs}

\textbf{for LHC}

<table>
<thead>
<tr>
<th>nucleon pol.</th>
<th>( U )</th>
<th>( L )</th>
<th>( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U )</td>
<td>( f_1 )</td>
<td></td>
<td>( h_1^{\perp} )</td>
</tr>
<tr>
<td>( L )</td>
<td></td>
<td>( g_{1L} )</td>
<td>( h_{1L}^{\perp} )</td>
</tr>
<tr>
<td>( T )</td>
<td>( f_{1T}^{\perp} )</td>
<td>( g_{1T} )</td>
<td>( h_1, h_{1T}^{\perp} )</td>
</tr>
</tbody>
</table>

extraction of a quark not collinear with the proton

\textbf{partly not computable}

\textbf{Twist-2 TMDs}
Gluons in 3D - TMDs

8 transverse-momentum-dependent parton distribution functions (TMD PDFs)

- Extraction of a gluon not collinear with the proton

partly not computable

for LHC

<table>
<thead>
<tr>
<th>LEADING TWIST</th>
<th>GLUONS</th>
<th>unpolarized</th>
<th>circular</th>
<th>linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$f_1^g$</td>
<td></td>
<td></td>
<td>$h_{1g}^g$</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td>$g_{1L}^g$</td>
<td></td>
<td>$h_{1L}^g$</td>
</tr>
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<td>T</td>
<td>$f_{1T}^g$</td>
<td>$g_{1T}^g$</td>
<td></td>
<td>$h_{1T}^g, h_{1L}^g$</td>
</tr>
</tbody>
</table>

Mulders, Rodriguez PRD 63 (2001)
Phenomenology of TMDs @ the LHC

useful references (Xmas reading):

AS et al. - 10.5506/APhysPolB.46.2501

Echevarria, Kasemets, Mulders, Pisano
10.1007/JHEP07(2015)158

AS, Bacchetta, Radici, Schnell
10.1007/JHEP11(2013)194

Bacchetta, Echevarria, Mulders, Radici, AS
10.1007/JHEP11(2015)076
TMDs - a physical picture

intrinsic transverse momentum

\[ |k_\perp| \sim \Lambda_{QCD} \]
TMDs - a physical picture

-intrinsic
transverse
momentum

soft and collinear
 gluon radiation

\[ |k_\perp| \sim \Lambda_{\text{QCD}} \quad |k_\perp| \ll Q \]
TMDs - a physical picture

- intrinsic transverse momentum
- soft and collinear gluon radiation
- hard gluon radiation

\[ |k_\perp| \sim \Lambda_{\text{QCD}} \quad |k_\perp| \ll Q \quad |k_\perp| \sim Q \]

courtesy A. Bacchetta
TMDs - from low to high momenta

TMDs generate the $q_T$ dep. of cross sections: but how in practice?

**intrinsic** momentum + **soft/coll.** gluon radiation

**matching**

**hard** gluon radiation

$vrije Universiteit amsterdam$

$pp \rightarrow Z X \ (ECM = 1.8 \ TeV)$

$y = 0$

$q_T, \text{GeV}$

$\frac{d\sigma}{dydq_T}, \text{pb}$
**Gluons @ the LHC**

**Higgs** production

\[ P_A + P_B \rightarrow h(q_T) + X \]

\[ m_h = 125 \text{ GeV} \]

**quarkonium** production

\[ P_A + P_B \rightarrow \eta_b(q_T) + X \]

\[ m_{\eta_b} = 9.39 \text{ GeV} \]
Gluons @ the LHC

**Higgs production**

\[ P_A + P_B \rightarrow h(q_T) + X \]

\[ m_h = 125 \text{ GeV} \]

\[ \frac{d\sigma}{dq_T} \sim \Phi_A^U \Phi_B^U |\mathcal{M}|^2 \]

\[ \sim C[ f_{1g/A} f_{1g/B} ] \quad \text{unpolarized gluons} \]

**Quarkonium production**

\[ P_A + P_B \rightarrow \eta_b(q_T) + X \]

\[ m_{\eta_b} = 9.39 \text{ GeV} \]

\[ \sim C[ h_{1g/A} h_{1g/B} ] \quad \text{lin. polarized gluons} \]
Linearly polarized vs unpolarized

\[ \mathcal{R}(q_T; Q) = \frac{C[ h_1^{g/A} h_1^{g/B} ]}{C[ f_1^{g/A} f_1^{g/B} ]} \]

quarkonium - low energy
higgs - high energy

\[ b_c = 1.5 \text{ GeV}^{-1} \]
\[ \lambda_Q = 0.01 \]
\[ \lambda_f = 0.01 \]
\[ \lambda_h = 0.01 \]
\[ x_A = x_B = Q/\sqrt{s} \]
\[ \sqrt{s} = 8 \text{ TeV} \]
Linearily polarized vs unpolarized

Nonperturbative physics enhanced at low $Q$

$Q = 9.39$ GeV
$Q = 125$ GeV

$b_c = 1.5$ GeV$^{-1}$
$\lambda_Q = 0.01$
$\lambda_f = 0.01$
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$x_A = x_B = Q/\sqrt{s}$
$\sqrt{s} = 8$ TeV

$Q = 9.39$ GeV
$Q = 125$ GeV

$b_c = 1.5$ GeV$^{-1}$
$\lambda_Q = 1$
$\lambda_f = 0.01$
$\lambda_h = 1$
$x_A = x_B = Q/\sqrt{s}$
$\sqrt{s} = 8$ TeV
Linearly polarized vs unpolarized

lin. pol. gluons: 10% - 70% at low $Q$
Linearily polarized vs unpolarized

lin. pol. gluons:
1% - 9% at high Q

\[ Q = 9.39 \text{ GeV} \]
\[ Q = 125 \text{ GeV} \]
\[ b_c = 1.5 \text{ GeV}^{-1} \]
\[ \lambda_Q = 0.01 \]
\[ \lambda_f = 0.01 \]
\[ \lambda_h = 0.01 \]
\[ x_A = x_B = Q/\sqrt{s} \]
\[ \sqrt{s} = 8 \text{ TeV} \]
Gluons @ the LHC - take home

Lin. polarized gluons are not negligible when studying TMD observables!

puzzling interplay: the proton structure manifests in different ways

ITS PHENOMENOLOGY IS NOT UNIQUE
Quarks @ the LHC

\[
\begin{align*}
Z & \rightarrow \bar{u} u \\
W^+ & \rightarrow \bar{d} u
\end{align*}
\]
Quarks @ the LHC

\[
\frac{d\sigma}{dq_T} \sim \Phi_A^U \Phi_B^U |\mathcal{M}|^2
\]

\[
\sim C[ f_{1q/A}^q f_{1q/B}^q ] \pm C[ h_{1q/A}^{q} h_{1q/B}^{q} ]
\]

unpolarized quarks

transv. polarized quarks
Quarks @ the LHC

\[
\frac{d\sigma}{dq_T} \sim \Phi^U_A \Phi^U_B |\mathcal{M}|^2
\]

\[
\sim C \left[ f_{1q/A}^q f_{1q/B}^q \right] \quad \text{unpolarized quarks}
\]

\[
\pm C \left[ h_{1q/A}^{\perp q} h_{1q/B}^{\perp q} \right] \quad \text{transv. polarized quarks}
\]

no sufficient knowledge
Quarks @ the LHC

\[ \frac{d\sigma}{dq_T} \sim \Phi_A^U \Phi_B^U |M|^2 \]

\[ \sim C[ f_{q/A}^q f_{q/B}^q ] \pm C[ h_{q/A}^q h_{q/B}^q ] \]

unpolarized quarks

transv. polarized quarks

focus on the

flavor structure

of the NP part

no sufficient knowledge

Preliminary
Conclusions

1) We are opening a window on the structure of the proton in 3D momentum space

2) It's an interesting endeavor, with very close connections between theory and experiments - also with the LHC

3) Questions? Interested? Come to the 3rd floor!
Backup slides
The quest for the structure

Electron-proton deep inelastic scattering (MIT/SLAC -1960) to test the inner structure of the proton

scattering techniques

what happened ..?
The quest for the structure

Experimental data are compatible with elastic scattering off pointlike, free, spin $\frac{1}{2}$ particles

The partons
[Feynman, Bjorken]
Experimental data are compatible with elastic scattering off pointlike, free, spin $\frac{1}{2}$ particles.

The partons [Feynman, Bjorken]

Quantum Chromodynamics: they are the physical degrees of freedom of the theory at high-energies.

Quarks & gluons
“freedom” in the perturbative part leads to different descriptions of the NP part (the core of proton structure) especially important for hadron structure studies.
REMEMBER:

dependence on non-perturbative parameters vanishes in the limit
\[ \frac{Q}{\Lambda_{QCD}} \rightarrow \infty \] (Parisi, Petronzio 1979).

If we want to explore effects at low qT we should look at relatively low Q values.

BUT not too low: problems with factorization and/or pollution from higher twist effects

At medium values of Q we could appreciate and extract the low qT effects applying TMD evolution properly

“in medio stat virtus”
The Sivers effect

Interaction between spin of the proton and OAM of the quark
interaction between spin of the proton and OAM of the quark
Estimated **impact of flavor dependent intrinsic transverse momentum** on electron-positron annihilation into two hadrons.
Gluon correlator

\[ \Phi^{\mu\nu}(k; P, S) \sim \text{F.T.} \langle P, S \mid F^{\mu+}(0) \ U_{[0,\xi]} \ F^{\nu\mu}(\xi) \ U_{[\xi,0]}' \mid P, S \rangle_{LF} \]

This is a Lorentz matrix, parametrized in terms of gluon distributions.