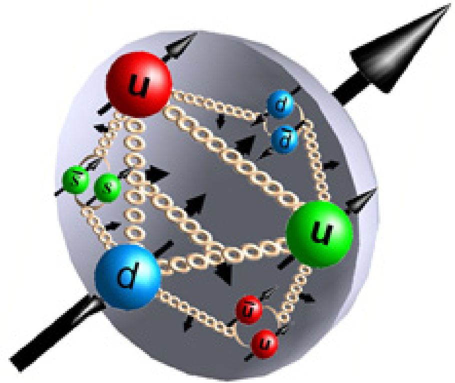
# Exploring the Three-Dimensional Structure of the Nucleon with Quantum Chromodynamics

Cristian Pisano



Fundamental .be Interactions

IAP

The Summer Solstice Meeting of the Fundamental Interactions and IAP Network

Brussels, 19 June 2015

Particle Physics Group
University of Antwerp

fwo
Fonds Wetenschappelijk Onderzoek Vlaanderen
Opening new horizons

# Outline

- Hadronic collisions at high energy in QCD
- Transverse momentum dependent parton distributions
- Linear polarization of gluons inside protons at the LHC:
  - Inclusive $H$-boson production
  - Inclusive heavy quarkonium production
  - $H$+jet production
- Conclusions

# QCD Description of Proton-Proton Collisions

**Scattering processes at high energy scales $Q \gg M_p$ (proton mass) provide important information on the internal structure of hadrons**

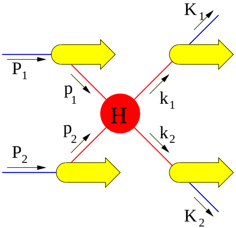
**Study based on fundamental properties and concepts of QCD**

- Confinement: fundamental building blocks of QCD–quarks and gluons (partons)–do not exist as free particles
- Running coupling: the strong coupling $\alpha_s$ changes with the characteristic energy
- Asymptotic freedom: at small distance the quarks and gluons are (almost) free particles: perturbative approach is applicable

# Factorization Theorems

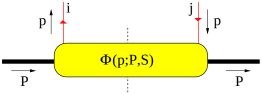
Enable the separation of large (essentially nonperturbative) and small-distance (perturbative hard scattering matrix elements) contributions

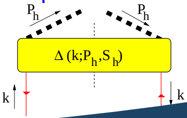
Cross section for the process $A(P_1) + B(P_2) \to C(K_1) + D(K_2) + X$:




$$\sigma \sim \Phi_a \otimes \Phi_b \otimes |H_{ab\to cd}|^2 \otimes \Delta_c \otimes \Delta_d$$

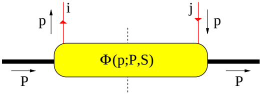
- $H$ : calculable partonic subprocess $a(p_1) + b(p_2) \to c(k_1) + d(k_2)$
- Parton correlators $\Phi$ and $\Delta$ describe soft parton $\leftrightarrow$ hadron transitions



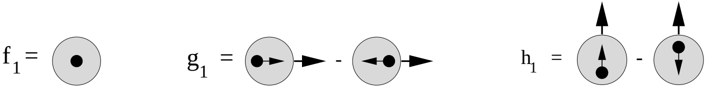



# Collinear Factorization

- It describes **inclusive processes**: one or less hadron detected; e.g., DIS, electron-positron annihilation into hadrons
- Correlator parametrized in terms of Parton Distribution Functions (PDFs): depend on long. momentum fraction $x$ and a hard scale

$A(P) \to a(p) + X$: 

$\sim \quad f_1, \quad g_1, \quad h_1$




unpolarized helicity transversity

- **Longitudinal** momenta of the partons are intrinsic, **Transverse** momenta can be created by perturbative radiation (parton showers)

# TMD Factorization

**The one-dimensional picture of the proton provided by PDFs is not always satisfactory: a more complete description involving also transverse degrees of freedom (in spin and momentum) is nedeed**

- **Transverse momentum dependent (TMD) factorization:** describes **Semi-inclusive processes**: two or more hadrons in the initial or final state detected; e.g. **Drell-Yan, SIDIS, hadron-hadron to jets, *H*-boson and heavy-flavor production**

- **It provides a** unifying QCD-based framework with both mechanisms of the **transverse-momentum** creation taken into account: intrinsic (essentially non-perturbative) and perturbative radiation

- TMD-PDFs depend also on the partonic transverse momentum $\boldsymbol{p}_T$:

$$f_1^g(x) \longrightarrow f_1^g(x, \boldsymbol{p}_T^2), \ \ldots$$

# TMD-PDFs (or TMDs)

**Our research is focussed on the QCD study of the three-dimensional PDFs, which contain information about the intrinsic longitudinal and two-dimensional transverse momenta of quarks and gluons**

**The are 16 TMDs (many more than collinear PDFs!):**
**more detailed information on the intrinsic structure of the proton**

quark pol. / nucleon pol.

| nucleon pol. \ quark pol. | U | L | T | |
|---|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ | |
| L | | $g_1$ | $h_{1L}^\perp$ | |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$ | $h_{1T}^\perp$ |

gluon pol. / nucleon pol.

| nucleon pol. \ gluon pol. | U | L | linear |
|---|---|---|---|
| U | $f_1^g$ | | $h_1^{\perp g}$ |
| L | | $g_{1L}^g$ | $h_{1L}^{\perp g}$ |
| T | $f_{1T}^{\perp g}$ | $g_{1T}^g$ | $h_1^g$, $h_{1T}^{\perp g}$ |

# Properties of (TMD-)PDFs

Both collinear and TMD-PDFs must be

- gauge-invariant
- universal
- renormalizable

Other important features:

- Wilson lines: save gauge invariance; jeopardise universality; complicate renormalizability
- Factorisation scale is arbitrary: transition from one scale to another (different experiments have different characteristic scales) by means of evolution equations
- TMD Evolution: differs from DGLAP, BFKL, CCFM; development of dedicated Monte-Carlo needed [in progress]

# Experimental facilities

**TMDs are, or will be, under active experimental investigation at**

- COMPASS (CERN): $\mu p$ collisions with polarized protons
- RHIC (BNL): *pp* collisions (both proton can be polarized)
- Jefferson Lab (USA): *ep* scattering;
  one third of approved experiments for 12 GeV Upgrade are devoted to the 3D structure of the nucleon (TMDs and GPDs)
- Electron-Ion Collider (USA): large-$x$ regime, high luminosity, broad TMD program; spin effects

**In the TMD approach, partons can be polarized even if the parent hadron is unpolarized**

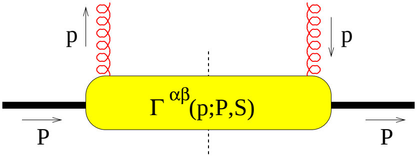
- **Even the LHC can be viewed as polarized gluon collider**

  (e.g. $H$-boson and heavy quark production in unp. *pp* collisions, test resummation algorithms)

# Gluon correlator

The gluon correlator describes the hadron → gluon transition

Gluon momentum $p = x\,P + p_T + p^-\,n,$ with $n^2{=}0$ and $n{\cdot}P{=}1$
transverse projector: $g_T^{\alpha\beta} \equiv g^{\alpha\beta} - P^\alpha n^\beta - n^\alpha P^\beta$




Definition for an unpolarized hadron, in terms of QCD operators on the light front (LF) $\xi \cdot n = 0$ [$U$, $U'$: process dependent Wilson lines]:

$$\Phi_g^{\mu\nu}(x, \boldsymbol{p}_T) \equiv \Gamma^{\mu\nu} = \frac{n_\rho\, n_\sigma}{(p{\cdot}n)^2} \int \frac{\mathrm{d}(\xi{\cdot}P)\,\mathrm{d}^2\xi_T}{(2\pi)^3}\; e^{ip\cdot\xi}\,\langle P|\,\mathrm{Tr}\big[\,F^{\mu\rho}(0)\,U_{[0,\xi]}\,F^{\nu\sigma}(\xi)\,U'_{[\xi,0]}\,\big]\,|P\rangle\,\big]_{\mathrm{LF}}$$

Mulders, Rodrigues, PRD 63 (2001) 094021

# Gluon correlator

At "Leading Twist" and omitting Wilson lines:

$$\Phi_g^{\mu\nu}(x,p_T;P) = \frac{1}{2x}\left\{ -g_T^{\mu\nu}\, f_1^g + \left(\frac{p_T^\mu p_T^\nu}{M_h^2} + g_T^{\mu\nu}\frac{\boldsymbol{p}_T^2}{2M_h^2}\right) h_1^{\perp\, g}\right\}$$

- $f_1^g(x,\boldsymbol{p}_T^2)$ unpolarized TMD gluon distribution; $p_T^2 = -\boldsymbol{p}_T^2$
- $h_1^{\perp\, g}(x,\boldsymbol{p}_T^2)$ distribution of linearly pol. gluons in an unp. hadron

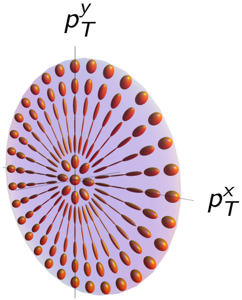
Mulders, Rodrigues, PRD 63 (2001) 094021

$h_1^{\perp\, g}$ is a $T$-even, helicity-flip distribution, and a rank-2 tensor in $p_T$

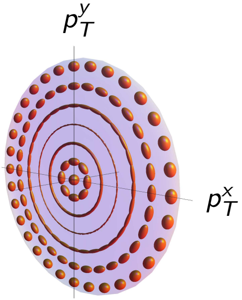
$h_1^{\perp g}(x,\boldsymbol{p}_T^2) \neq 0$ in the absence of ISI or FSI, but, as any TMD, it will receive contributions from ISI/FSI $\longrightarrow$ it can be nonuniversal

# Visualization of the gluon polarization

Transverse momentum plane. $h_1^{\perp g}$ is taken to be a Gaussian




$h_1^{\perp g} > 0$




$h_1^{\perp g} < 0$

The ellipsoid axis lengths are proportional to the probability of finding a gluon with a linear polarization in that direction

# The function $h_1^{\perp\, g}$: phenomenology

No experimental studies of the function $h_1^{\perp\, g}$ have been performed

- Measurements of the $\cos 2\phi$ azimuthal asymmetries in heavy quark and jet pair production in $e\, p$ collisions (EIC, LHeC)

$$\mathcal{A}_{2\phi} \quad \sim \quad \cos 2\phi \; h_1^{\perp\, g}$$

Boer, Brodsky, Mulders, CP, PRL 106 (2011) 132001
CP, Boer, Brodsky, Mulders, Buffing, JHEP 1310 (2013) 024

- Asymmetries in $p\, p \to \gamma\, \gamma\, X$ or $p\, p \to J/\psi\, \gamma\, X$ (RHIC, LHC)

$$\mathcal{A}_{2\phi} \quad \sim \quad \cos 2\phi \; f_1^g \otimes h_1^{\perp\, g}$$

$$\mathcal{A}_{4\phi} \quad \sim \quad \cos 4\phi \; h_1^{\perp\, g} \otimes h_1^{\perp\, g}$$

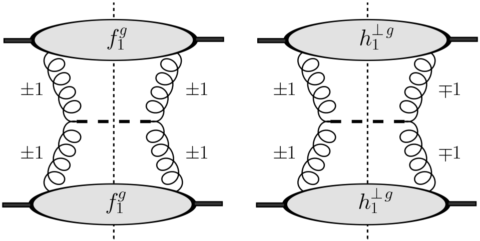
Qiu, Schlegel, Vogelsang, PRL 107 (2011) 062001
den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014) 212001

# $h_1^{\perp\, g}$ in $pp \to H\, X$

$H$ boson production happens mainly via $gg \to H$

Pol. gluons affect the $H$ transverse spectrum at NNLO pQCD

Catani, Grazzini, NPB 845 (2011) 297




The nonperturbative distribution can be present at tree level and would contribute to $H$ production at low $q_T$

Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012) 032002
Echevarria, Kasemets, Mulders, CP, arXiv:1502.05354

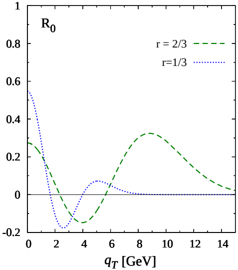
## Transverse spectrum of the $H$ boson

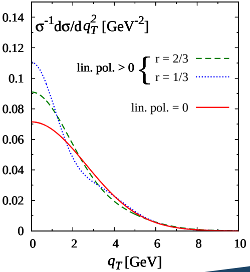
$$\frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{q}_T^2} \propto 1 + R_0(\boldsymbol{q}_T^2) \qquad R_0 = \frac{h_1^{\perp g} \otimes h_1^{\perp g}}{f_1^g \otimes f_1^g} \qquad |h_1^{\perp g}(x, \boldsymbol{p}_T^2)| \leq \frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x, \boldsymbol{p}_T^2)$$

Gaussian model for both $f_1^g$ and $h_1^{\perp g}$:

$$f_1^g(x, \boldsymbol{p}_T^2) = \frac{f_1^g(x)}{\pi \langle p_T^2 \rangle} \exp\left(-\frac{\boldsymbol{p}_T^2}{\langle p_T^2 \rangle}\right)$$

$$h_1^{\perp g}(x, \boldsymbol{p}_T^2) = \frac{M^2 f_1^g(x)}{\pi \langle p_T^2 \rangle^2} \frac{2(1-r)}{r} \exp\left(1 - \frac{1}{r}\frac{\boldsymbol{p}_T^2}{\langle p_T^2 \rangle}\right) \qquad 0 < r < 1$$



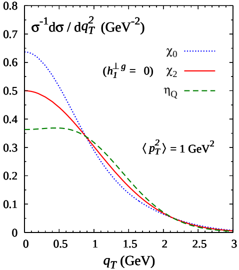

$$\langle p_T^2 \rangle = 7 \ \mathrm{GeV}^2$$

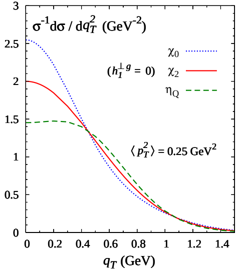
## Transverse spectra of $C$-even quarkonia $\eta_Q$ and $\chi_Q$ $(Q = c, b)$

$$\frac{1}{\sigma(\eta_Q)}\frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto 1 - R_0(\boldsymbol{q}_T^2) \qquad \text{[pseudoscalar]}$$

$$\frac{1}{\sigma(\chi_Q)}\frac{d\sigma(\chi_{Q0})}{d\boldsymbol{q}_T^2} \propto 1 + R_0(\boldsymbol{q}_T^2) \qquad \text{[scalar]}$$

Boer, CP, PRD 86 (2012) 094007




Effects of $h_1^{\perp g}$ on higher angular momentum states are suppressed

# $H$+jet production

Motivations: azimuthal asymmetries can be defined [$\neq pp \to HX$]
study of the TMD evolution by tuning the hard scale
Nonuniversality and factorization breaking effects

Boer, CP, PRD 91 (2015) 074024

## TMD Master Formula

$$d\sigma = \frac{1}{2s}\frac{\mathrm{d}^3\boldsymbol{K}_H}{(2\pi)^3\,2K_H^0}\frac{\mathrm{d}^3\boldsymbol{K}_\mathrm{j}}{(2\pi)^3\,2K_\mathrm{j}^0}\sum_{a,b,c}\int \mathrm{d}x_a\,\mathrm{d}x_b\,\mathrm{d}^2\boldsymbol{p}_{aT}\,\mathrm{d}^2\boldsymbol{p}_{bT}\,(2\pi)^4$$
$$\times\,\delta^4(p_a+p_b-q)\,\mathrm{Tr}\left\{\Phi_a(x_a,\boldsymbol{p}_{aT})\Phi_b(x_b,\boldsymbol{p}_{bT})\left|\mathcal{M}^{ab\to Hc}\right|^2\right\}$$

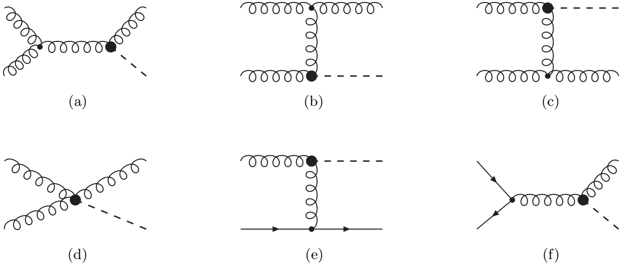
$H$ boson and jet almost back to back in the $\perp$ plane: $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

$$\boldsymbol{q}_T = \boldsymbol{K}_{HT} + \boldsymbol{K}_{\mathrm{j}T}, \qquad \boldsymbol{K}_\perp = (\boldsymbol{K}_{HT} - \boldsymbol{K}_{\mathrm{j}T})/2$$

# Feynman diagrams

At LO in pQCD the partonic subprocesses that contribute are

$$g\,g \to H\,g \qquad g\,q \to H\,q \qquad q\,\bar{q} \to H\,g$$




Quark masses taken to be zero, except for $M_t \to \infty$

Kauffman, Desai, Risal, PRD 55 (1997) 4005

No indications that TMD factorization can be broken due to color entanglement

Rogers, Mulders, PRD 81 (2010) 094006

# Angular structure of the cross section

Focus on $gg \to Hg$ (dominant at the LHC). In the hadronic c.m.s.:

$$\boldsymbol{q}_T = |\boldsymbol{q}_T|(\cos\phi_T, \sin\phi_T) \quad \boldsymbol{K}_\perp = |\boldsymbol{K}_\perp|(\cos\phi_\perp, \sin\phi_\perp) \quad \phi \equiv \phi_T - \phi_\perp$$

$$\mathrm{d}\sigma \equiv \frac{\mathrm{d}\sigma}{\mathrm{d}y_H\,\mathrm{d}y_\mathrm{j}\,\mathrm{d}^2\boldsymbol{K}_\perp\,\mathrm{d}^2\boldsymbol{q}_T} \qquad \frac{\mathrm{d}\sigma}{\sigma} \equiv \frac{\mathrm{d}\sigma}{\int_0^{q_{T\mathrm{max}}^2}\mathrm{d}\boldsymbol{q}_T^2\int_0^{2\pi}\mathrm{d}\phi\,\mathrm{d}\sigma}$$

## Normalized cross section for $p\,p \to H\,\mathrm{jet}\,X$

$$\frac{\mathrm{d}\sigma}{\sigma} = \frac{1}{2\pi}\,\sigma_0(\boldsymbol{q}_T^2)\left[1 + R_0(\boldsymbol{q}_T^2) + R_2(\boldsymbol{q}_T^2)\cos 2\phi + R_4(\boldsymbol{q}_T^2)\cos 4\phi\right]$$

$$\sigma_0(\boldsymbol{q}_T^2) \equiv \frac{f_1^g \otimes f_1^g}{\int_0^{q_{T\mathrm{max}}^2}\mathrm{d}\boldsymbol{q}_T^2\; f_1^g \otimes f_1^g}$$

# TMD observables

The three contributions can be isolated by defining the observables

$$\langle \cos n\phi \rangle_{q_T} \equiv \frac{\int_0^{2\pi} \mathrm{d}\phi \, \cos n\,\phi \, \mathrm{d}\sigma}{\mathrm{d}\sigma} \qquad (n = 0, 2, 4)$$

such that

$$\langle \cos n\phi \rangle = \int_0^{q^2_{T\max}} \mathrm{d}\boldsymbol{q}_T^2 \, \langle \cos n\phi \rangle_{q_T}$$

$$\frac{1}{\sigma} \frac{\mathrm{d}\sigma}{\mathrm{d}^2 q_T} \equiv \langle 1 \rangle_{q_T} \quad \Longrightarrow \quad 1 + R_0 \propto f_1^g \otimes f_1^g + h_1^{\perp g} \otimes h_1^{\perp g}$$

$$\langle \cos 2\phi \rangle_{q_T} \quad \Longrightarrow \quad R_2 \propto f_1^g \otimes h_1^{\perp g}$$

$$\langle \cos 4\phi \rangle_{q_T} \quad \Longrightarrow \quad R_4 \propto h_1^{\perp g} \otimes h_1^{\perp g}$$

# Models for the TMD gluon distributions

## $f_1^g$: Gaussian + tail

$$f_1^g(x, \boldsymbol{p}_T^2) = f_1^g(x)\,\frac{R^2}{2\,\pi}\,\frac{1}{1+\boldsymbol{p}_T^2\,R^2} \qquad R = 2\ \mathrm{GeV}^{-1}$$

## $h_1^{\perp\,g}$: Maximal polarization and Gaussian + tail

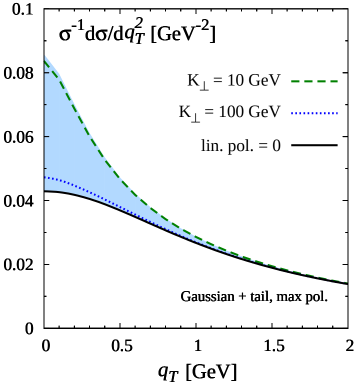
$$h_1^{\perp\,g}(x, \boldsymbol{p}_T^2) = \frac{2M_p^2}{\boldsymbol{p}_T^2}\,f_1^g(x, \boldsymbol{p}_T^2) \qquad [max\ pol.]$$

$$h_1^{\perp\,g}(x, \boldsymbol{p}_T^2) = 2\,f_1^g(x)\,\frac{M_p^2 R_h^4}{2\,\pi}\,\frac{1}{(1+\boldsymbol{p}_T^2 R_h^2)^2} \qquad R_h = \frac{3}{2}\,R$$

Boer, den Dunnen, NPB 886 (2014) 421

# $q_T$-distribution

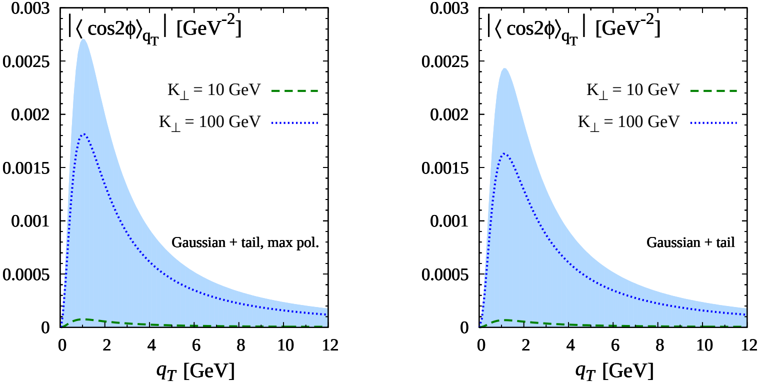
Configuration in which the $H$ and the jet have same rapidities




Effects largest at small $q_T$ (hard to measure), but model dependent!

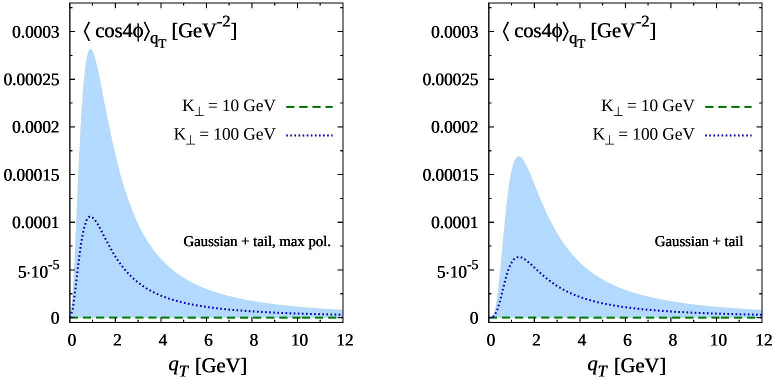
# Azimuthal $\cos 2\phi$ asymmetries

Sensitive to the sign of $h_1^{\perp g}$: $\langle \cos 2\phi \rangle_{q_T} < 0 \implies h_1^{\perp g} > 0$



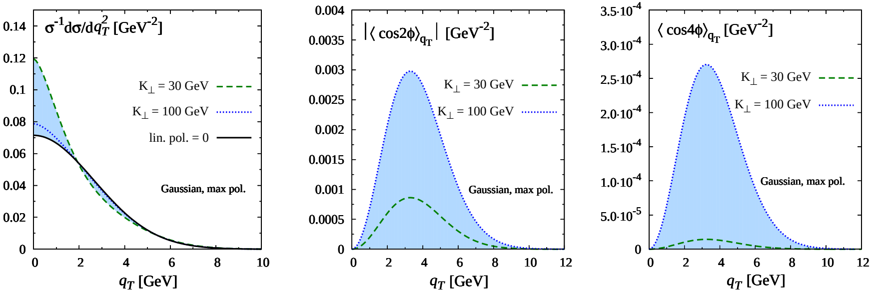

$q_{T\max} = M_H/2$ $\langle \cos 2\phi \rangle \approx 12\%$ at $K_\perp = 100$ GeV

# Azimuthal $\cos 4\phi$ asymmetries




$q_{T\mathrm{max}} = M_H/2$ $\langle \cos 4\phi \rangle \approx 0.1 - 0.2\%$ at $K_\perp = 100$ GeV

# Gaussian model for the unpolarized TMDs




$q_{T\mathrm{max}} = K_\perp/2$ , $\langle \cos 2\phi \rangle \approx 9\%$, $\langle \cos 4\phi \rangle \approx 0.4\%$ at $K_\perp = 100$ GeV

# Conclusions

- $h_1^{\perp\,g}$ leads to a modulation of the angular independent transverse momentum distribution of scalar $(H, \chi_{c0}, \chi_{b0})$ and pseudoscalar $(\eta_c, \eta_b)$ particles

- $h_1^{\perp\,g}$ produces a modulation of the transverse spectrum of the $H$+jet pair and to azimuthal asymmetries in $pp \to H\,\mathrm{jet}\,X$

- First determination of $h_1^{\perp g}$ and $f_1^g$ could come from $J/\psi(\Upsilon) + \gamma$ production at the running experiments at the LHC.

  den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014) 212001

- $H$ and quarkonium production can be used to extract gluon TMDs and to study their process and scale dependences

# QCD Theory in UAntwerpen

**Regular Workshops** 'Resummation, Evolution, Factorization' organized in collaboration with groups in **DESY, Amsterdam, Oxford, Groningen**:

- International Workshop REF2015, 02 - 08 Nov 2015, DESY, Hamburg, **Germany** *[planned]*
- International Meeting preREF2015, 01 - 03 Jun 2015, Amsterdam, **The Netherlands**
- International Workshop REF2014, 08 - 11 Dec 2014, Antwerp, **Belgium**
- TMD/uPDF Workshop, 23 - 24 Jun 2014, Antwerp, **Belgium**

# QCD Theory in UAntwerpen

## Books

- **I.O. Cherednikov, P. Tales, F.F. Van der Veken**
  *"Parton Densities in Quantum Chromodynamics"*
  **De Gruyter** Stud. Math. Phys., Berlin (2016) [in progress]
- **I.O. Cherednikov, T. Mertens, F.F. Van der Veken**
  *"Wilson Lines in Quantum Field Theory"*
  **De Gruyter** Stud. Math. Phys., Berlin (2014)

## PhD Projects

- **Pieter Taels** [in progress, scheduled to 2017]
- **Frederik Van der Veken –** *"Wilson lines: Applications in QCD"* [defended in 2014]
- **Tom Mertens –** *"Wilson loops: Mathematical foundations with applications in QCD"* [defended in 2014]

**MSc and BSc projects; regular articles; etc.**