Gluon TMDs and Quarkonium Production in Unpolarised and Polarised Proton-Proton Collisions

J.P. Lansberg
IPN Orsay – Paris-Sud U. –CNRS/IN2P3

October 20-24, 2014 – Beijing, China

Collaboration with W. den Dunnen, C. Lorcé, C. Pisano, M. Schlegel, H.S. Shao

Part I

Generalities on gluon TMDs

Gluon distributions

Gluon distributions

- Experimental and theoretical investigations of gluons inside hadrons focused so far on their longitudinal momentum and helicity distributions:

Gluon distributions

- Experimental and theoretical investigations of gluons inside hadrons focused so far on their longitudinal momentum and helicity distributions:
  - $g(x, \mu_F)$: unpolarised gluons with a collinear momentum fraction x in unpolarised nucleons
  - $\Delta g(x, \mu_F)$: circularly polarised gluons with a collinear momentum fraction x in polarised nucleons

Gluon distributions

- Experimental and theoretical investigations of gluons inside hadrons focused so far on their longitudinal momentum and helicity distributions:
  - $g(x, \mu_F)$: unpolarised gluons with a collinear momentum fraction x in unpolarised nucleons
  - $\Delta g(x, \mu_F)$: circularly polarised gluons with a collinear momentum fraction x in polarised nucleons
- Gluon Transverse Momentum Dependent pdfs (TMDs) can be nonzero

Gluon distributions

- Experimental and theoretical investigations of gluons inside hadrons focused so far on their longitudinal momentum and helicity distributions:
  - $g(x, \mu_F)$: unpolarised gluons with a collinear momentum fraction x in unpolarised nucleons
  - $\Delta g(x, \mu_F)$: circularly polarised gluons with a collinear momentum fraction x in polarised nucleons
- Gluon Transverse Momentum Dependent pdfs (TMDs) can be nonzero
- Example: for nonzero k_T, the gluons can be polarised even if the nucleons are unpolarised ($h_1^{\perp g}$ vs. Δg)

Gluon distributions

- Experimental and theoretical investigations of gluons inside hadrons focused so far on their longitudinal momentum and helicity distributions:
  - $g(x, \mu_F)$: unpolarised gluons with a collinear momentum fraction x in unpolarised nucleons
  - $\Delta g(x, \mu_F)$: circularly polarised gluons with a collinear momentum fraction x in polarised nucleons
- Gluon Transverse Momentum Dependent pdfs (TMDs) can be nonzero
- Example: for nonzero k_T, the gluons can be polarised even if the nucleons are unpolarised ($h_1^{\perp g}$ vs. Δg)
- Nontrivial property that received much more attention in the quark sector: $\rightarrow$ Boer-Mulders effect

Gluon distributions

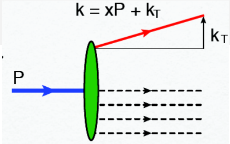
- Experimental and theoretical investigations of gluons inside hadrons focused so far on their longitudinal momentum and helicity distributions:
  - $g(x, \mu_F)$: unpolarised gluons with a collinear momentum fraction x in unpolarised nucleons
  - $\Delta g(x, \mu_F)$: circularly polarised gluons with a collinear momentum fraction x in polarised nucleons
- Gluon Transverse Momentum Dependent pdfs (TMDs) can be nonzero
- Example: for nonzero k_T, the gluons can be polarised even if the nucleons are unpolarised ($h_1^{\perp g}$ vs. Δg)
- Nontrivial property that received much more attention in the quark sector: $\rightarrow$ Boer-Mulders effect
- Once $h_1^{\perp g}$ is known, polarised processes in high-energy hadron-hadron collisions (dominated by gg fusion) become accessible even with unpolarised hadron beams !

Gluon distributions

- Experimental and theoretical investigations of gluons inside hadrons focused so far on their longitudinal momentum and helicity distributions:
  - $g(x, \mu_F)$: unpolarised gluons with a collinear momentum fraction x in unpolarised nucleons
  - $\Delta g(x, \mu_F)$: circularly polarised gluons with a collinear momentum fraction x in polarised nucleons
- Gluon Transverse Momentum Dependent pdfs (TMDs) can be nonzero
- Example: for nonzero k_T, the gluons can be polarised even if the nucleons are unpolarised ($h_1^{\perp g}$ vs. Δg)
- Nontrivial property that received much more attention in the quark sector: $\rightarrow$ Boer-Mulders effect
- Once $h_1^{\perp g}$ is known, polarised processes in high-energy hadron-hadron collisions (dominated by gg fusion) become accessible even with unpolarised hadron beams !
- Prime example: the LHC !

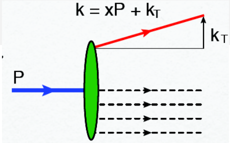
Beyond collinear factorisation

Beyond collinear factorisation



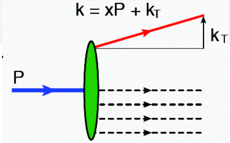
- Observed final-state q_T from
  "intrinsic" k_T from initial partons

Beyond collinear factorisation



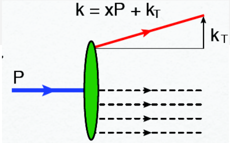
- Observed final-state q_T from
  "intrinsic" k_T from initial partons
- Novel kind of factorisation w.r.t. the collinear one

Beyond collinear factorisation

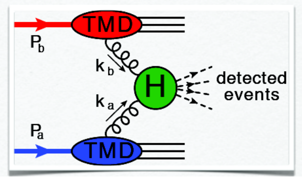


- Observed final-state q_T from
  "intrinsic" k_T from initial partons
- Novel kind of factorisation w.r.t. the collinear one
- Additional degree of freedom of the partonic motion

Beyond collinear factorisation



- Observed final-state q_T from
  "intrinsic" k_T from initial partons
- Novel kind of factorisation w.r.t. the collinear one
- Additional degree of freedom of the partonic motion
- TMD factorisation from gluon-gluon process : $q_T \ll Q$

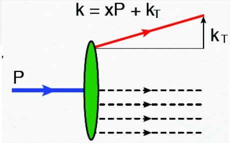


H is free of q_T

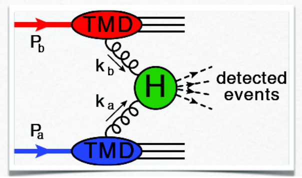
$$d\sigma = \frac{(2\pi)^4}{8s^2} \int d^2\boldsymbol{k}_{1T} d^2\boldsymbol{k}_{2T} \delta^2(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{q}_T) H_{\mu\rho} (H_{\nu\sigma})^* \times$$

$$\Phi_g^{\mu\nu}(x_1, \boldsymbol{k}_{1T}, \zeta_1, \mu)\, \Phi_g^{\rho\sigma}(x_2, \boldsymbol{k}_{2T}, \zeta_2, \mu) d\mathcal{R} + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

Beyond collinear factorisation



- Observed final-state q_T from
  "intrinsic" k_T from initial partons
- Novel kind of factorisation w.r.t. the collinear one
- Additional degree of freedom of the partonic motion
- TMD factorisation from gluon-gluon process : $q_T \ll Q$



H is free of q_T

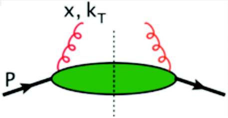
$$d\sigma = \frac{(2\pi)^4}{8s^2} \int d^2\boldsymbol{k}_{1T} d^2\boldsymbol{k}_{2T} \delta^2(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{q}_T) H_{\mu\rho} (H_{\nu\sigma})^* \times$$

$$\Phi_g^{\mu\nu}(x_1, \boldsymbol{k}_{1T}, \zeta_1, \mu)\, \Phi_g^{\rho\sigma}(x_2, \boldsymbol{k}_{2T}, \zeta_2, \mu) d\mathcal{R} + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

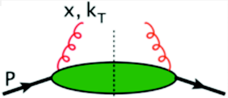
- Proven for SIDIS + *pp* reactions with colour singlet final states

Collins; Ji, Ma, Qiu; Rogers, Mulders, ...

Gluon TMDs in unpolarised protons



Gluon TMDs in unpolarised protons

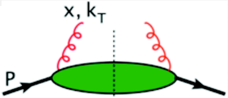


- Gauge-invariant definition:

$$\Phi_g^{\mu\nu}(x, \boldsymbol{k}_T, \zeta, \mu) \equiv \int \frac{\mathrm{d}(\xi\cdot P)\,\mathrm{d}^2\xi_T}{(xP\cdot n)^2(2\pi)^3}\, e^{i(xP+k_T)\cdot\xi} \langle P|F_a^{n\nu}(0)\left(\mathcal{U}_{[0,\xi]}^{n[-]}\right)_{ab} F_b^{n\mu}(\xi)|P\rangle\Big|_{\xi\cdot P'=0}$$

- the gauge link $\mathcal{U}_{[0,\xi]}^{n[-]}$ renders the matrix element gauge invariant and runs from 0 to ξ via $-\infty$ along the n direction.

Gluon TMDs in unpolarised protons



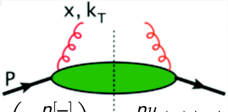
- Gauge-invariant definition:

$$\Phi_g^{\mu\nu}(x, \boldsymbol{k}_T, \zeta, \mu) \equiv \int \frac{\mathrm{d}(\xi\cdot P)\, \mathrm{d}^2\xi_T}{(xP\cdot n)^2(2\pi)^3}\, e^{i(xP+k_T)\cdot\xi} \langle P| F_a^{n\nu}(0) \left(\mathcal{U}_{[0,\xi]}^{n[-]}\right)_{ab} F_b^{n\mu}(\xi)|P\rangle\Big|_{\xi\cdot P'=0}$$

- the gauge link $\mathcal{U}_{[0,\xi]}^{n[-]}$ renders the matrix element gauge invariant and runs from 0 to ξ via $-\infty$ along the n direction.
- Parametrisation: **P. J. Mulders, J. Rodrigues, PRD 63 (2001) 094021**

$$\Phi_g^{\mu\nu}(x, \boldsymbol{k}_T, \zeta, \mu) = -\frac{1}{2x}\left\{ g_T^{\mu\nu} f_1^g(x, k_T, \mu) - \left(\frac{k_T^\mu k_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\boldsymbol{k}_T^2}{2M_p^2}\right) h_1^{\perp\, g}(x, k_T, \mu)\right\} + \text{suppr.}$$

Gluon TMDs in unpolarised protons



- Gauge-invariant definition:

$$\Phi_g^{\mu\nu}(x, \boldsymbol{k}_T, \zeta, \mu) \equiv \int \frac{\mathrm{d}(\xi\cdot P)\,\mathrm{d}^2\xi_T}{(xP\cdot n)^2(2\pi)^3}\, e^{i(xP+k_T)\cdot\xi} \langle P|F_a^{n\nu}(0)\left(\mathcal{U}^{n[-]}_{[0,\xi]}\right)_{ab} F_b^{n\mu}(\xi)|P\rangle\Big|_{\xi\cdot P'=0}$$

- the gauge link $\mathcal{U}^{n[-]}_{[0,\xi]}$ renders the matrix element gauge invariant and runs from 0 to ξ via $-\infty$ along the n direction.

- Parametrisation: **P. J. Mulders, J. Rodrigues, PRD 63 (2001) 094021**

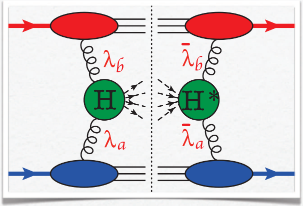
$$\Phi_g^{\mu\nu}(x, \boldsymbol{k}_T, \zeta, \mu) = -\frac{1}{2x}\left\{ g_T^{\mu\nu} f_1^g(x, k_T, \mu) - \left(\frac{k_T^\mu k_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\boldsymbol{k}_T^2}{2M_p^2}\right) h_1^{\perp\, g}(x, k_T, \mu)\right\} + \text{suppr.}$$

- f_1^g: TMD distribution of unpolarised gluons
- $h_1^{\perp\, g}$: TMD distribution of linearly polarised gluons

[Helicity-flip distribution]

gg fusion in arbitrary process (colourless final state)

illustrative: helicity space (helicity amplitudes)
→ fully diff. cross section: 4 structures



$$d\sigma^{gg}(q_T \ll Q) \propto$$

$$\Big(\sum_{\lambda_a,\lambda_b} H_{\lambda_a\lambda_b}\, H^*_{\lambda_a\lambda_b}\Big)\, \mathcal{C}[f_1^g\, f_1^g]$$

↘ F_1 → helicity non-flip, azimuthally indep., survives q_T - integration

$$+\Big(\sum_{\lambda} H_{\lambda,\lambda}\, H^*_{-\lambda,-\lambda}\Big)\, \mathcal{C}[w_2\, h_1^{g\perp}\, h_1^{\perp g}]$$

↘ F_2 → double helicity flip, azimuthally independent

$$+\Big(\sum_{\lambda_a,\lambda_b} H_{\lambda_a,\lambda_b}\, H^*_{-\lambda_a,\lambda_b}\Big)\, \mathcal{C}[w_3\, f_1^g\, h_1^{\perp g}] + \{a \leftrightarrow b\}$$

↘ F_3 → single helicity flip, cos (2ϕ) [sin (2ϕ)]- modulation

$$+\Big(\sum_{\lambda} H_{\lambda,-\lambda}\, H^*_{-\lambda,\lambda}\Big)\, \mathcal{C}[w_4\, h_1^{\perp g}\, h_1^{\perp g}]$$

↘ F_4 → double helicity flip, cos (4ϕ) [sin (4ϕ)]- modulation

Slide borrowed from M. Schlegel

Visualisation of $h_1^{\perp g}$

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

Visualisation of $h_1^{\perp g}$

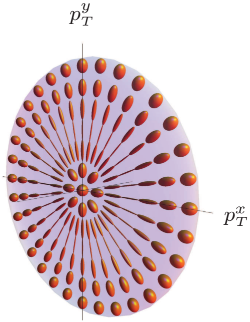
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

- Gaussian form for $h_1^{\perp g}$ [left: $h_1^{\perp g} > 0$; right: $h_1^{\perp g} < 0$]

Visualisation of $h_1^{\perp g}$

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

- Gaussian form for $h_1^{\perp g}$ [left: $h_1^{\perp g} > 0$; right: $h_1^{\perp g} < 0$]

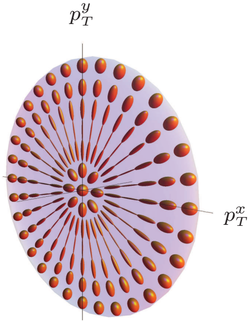


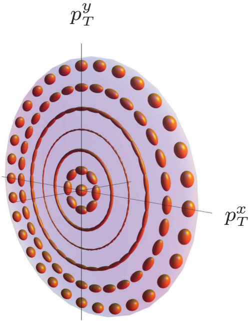
- The ellipsoid axis lengths are proportional to the probability of finding a gluon with a linear polarization in that direction

Visualisation of $h_1^{\perp g}$

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

- Gaussian form for $h_1^{\perp g}$ [left: $h_1^{\perp g} > 0$; right: $h_1^{\perp g} < 0$]



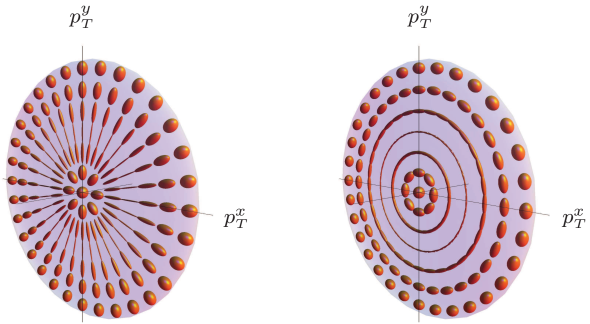


- The ellipsoid axis lengths are proportional to the probability of finding a gluon with a linear polarization in that direction
- A single constraint: a positivity bound $|h_1^{\perp g}| \leq 2M_p^2/\vec{p}_T^2 f_1^g$

Visualisation of $h_1^{\perp g}$

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

- Gaussian form for $h_1^{\perp g}$ [left: $h_1^{\perp g} > 0$; right: $h_1^{\perp g} < 0$]



- The ellipsoid axis lengths are proportional to the probability of finding a gluon with a linear polarization in that direction
- A single constraint: a positivity bound $|h_1^{\perp g}| \leq 2M_p^2/\vec{p}_T^2 f_1^g$
- This bound is saturated by a number of models

Part II

Ideas to extract gluon TMDs at colliders

Di-photon

J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)

Di-photon

J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)

- Beside being the QCD background for H^0 studies in the $\gamma\gamma$ channel, $pp \to \gamma\gamma X$ is an interesting process to study gluon TMDs

Di-photon

J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)

- Beside being the QCD background for H^0 studies in the $\gamma\gamma$ channel, $pp \to \gamma\gamma X$ is an interesting process to study gluon TMDs
- Only colour-singlet particles in the final state

(also true for ZZ and γZ)

Di-photon

J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)

- Beside being the QCD background for H^0 studies in the $\gamma\gamma$ channel, $pp \to \gamma\gamma X$ is an interesting process to study gluon TMDs
- Only colour-singlet particles in the final state

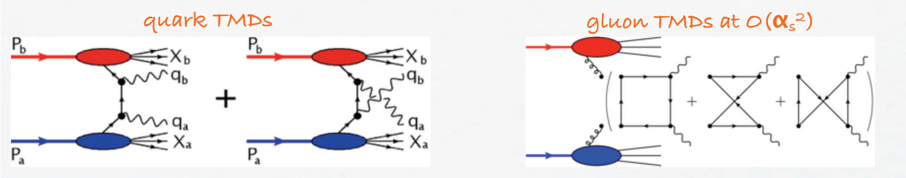
  (also true for ZZ and γZ)
- But contaminations from the $q\bar{q}$ channel (particularly at RHIC)

Di-photon

J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)

- Beside being the QCD background for H^0 studies in the $\gamma\gamma$ channel, $pp \to \gamma\gamma X$ is an interesting process to study gluon TMDs
- Only colour-singlet particles in the final state

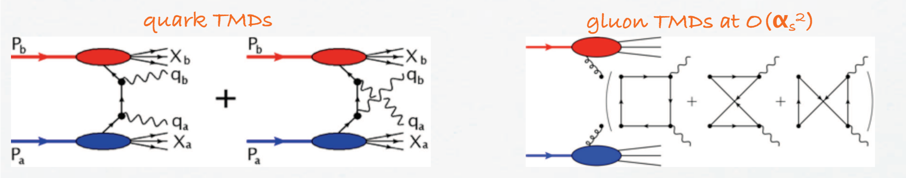
  (also true for ZZ and γZ)
- But contaminations from the $q\bar{q}$ channel (particularly at RHIC)



Di-photon

J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)

- Beside being the QCD background for H^0 studies in the $\gamma\gamma$ channel, $pp \to \gamma\gamma X$ is an interesting process to study gluon TMDs
- Only colour-singlet particles in the final state (also true for ZZ and γZ)
- But contaminations from the $q\bar{q}$ channel (particularly at RHIC)

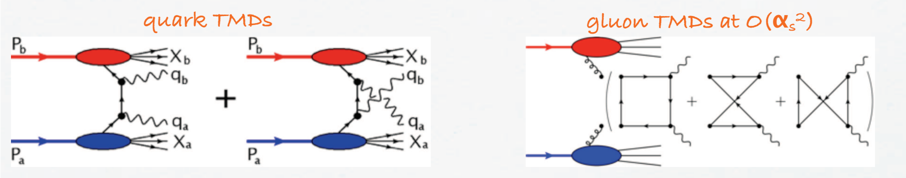


- Only F_4 (*i.e.* the $\cos(4\phi)$ modulation) is purely gluonic

Di-photon

J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)

- Beside being the QCD background for H^0 studies in the $\gamma\gamma$ channel, $pp \to \gamma\gamma X$ is an interesting process to study gluon TMDs
- Only colour-singlet particles in the final state
  (also true for ZZ and γZ)
- But contaminations from the $q\bar{q}$ channel (particularly at RHIC)



- Only F_4 (*i.e.* the $\cos(4\phi)$ modulation) is purely gluonic
- Huge background from π^0 $\to$ isolation cuts are needed

Low P_T quarkonia and TMDs

Low P_T quarkonia and TMDs

PHYSICAL REVIEW D **86,** 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer*
Theory Group, KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands

Cristian Pisano†
Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy

Low P_T quarkonia and TMDs

PHYSICAL REVIEW D **86,** 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer*
Theory Group, KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands

Cristian Pisano†
Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy

- Low P_T C-even quarkonium production is a good probe of $h_1^{\perp g}$

Low P_T quarkonia and TMDs

PHYSICAL REVIEW D **86,** 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer*

Theory Group, KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands

Cristian Pisano†

Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy

- Low P_T C-even quarkonium production is a good probe of $h_1^{\perp g}$

Low P_T quarkonia and TMDs

PHYSICAL REVIEW D **86,** 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

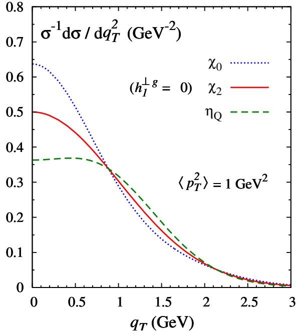
Daniël Boer*
Theory Group, KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands

Cristian Pisano†
Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy

- Low P_T C-even quarkonium production is a good probe of $h_1^{\perp g}$
- Affect the low P_T spectra:

$$\frac{1}{\sigma}\frac{d\sigma(\eta_Q)}{d\mathbf{q}_T^2} \propto 1 - R(\mathbf{q}_T^2) \;\&\; \frac{1}{\sigma}\frac{d\sigma(\chi_{Q,0})}{d\mathbf{q}_T^2} \propto 1 + R(\mathbf{q}_T^2)$$

(R involves $f_1^g(x, k_T, \mu)$ and $h_1^{\perp g}(x, k_T, \mu)$)



Low P_T quarkonia and TMDs

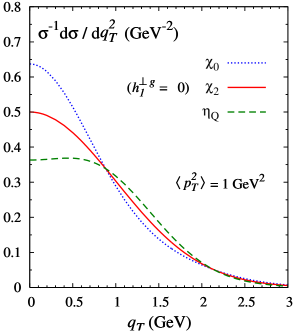
PHYSICAL REVIEW D **86,** 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer*
Theory Group, KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands

Cristian Pisano†
Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy

- Low P_T C-even quarkonium production is a good probe of $h_1^{\perp g}$
- Affect the low P_T spectra:
  $\frac{1}{\sigma}\frac{d\sigma(\eta_Q)}{d\mathbf{q}_T^2} \propto 1 - R(\mathbf{q}_T^2)$ & $\frac{1}{\sigma}\frac{d\sigma(\chi_{Q,0})}{d\mathbf{q}_T^2} \propto 1 + R(\mathbf{q}_T^2)$
  (R involves $f_1^g(x, k_T, \mu)$ and $h_1^{\perp g}(x, k_T, \mu)$)
- η_c **production at one-loop** **J.P. Ma, J.X. Wang, S. Zhao, PRD88 (2013) 1, 014027.**

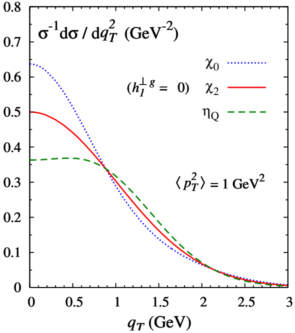


Low P_T quarkonia and TMDs

PHYSICAL REVIEW D **86**, 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer*
Theory Group, KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands
Cristian Pisano†
Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy



- Low P_T C-even quarkonium production is a good probe of $h_1^{\perp g}$
- Affect the low P_T spectra:
  $$\frac{1}{\sigma}\frac{d\sigma(\eta_Q)}{d\mathbf{q}_T^2} \propto 1 - R(\mathbf{q}_T^2) \;\&\; \frac{1}{\sigma}\frac{d\sigma(\chi_{Q,0})}{d\mathbf{q}_T^2} \propto 1 + R(\mathbf{q}_T^2)$$
  (R involves $f_1^g(x, k_T, \mu)$ and $h_1^{\perp g}(x, k_T, \mu)$)
- η_c **production at one-loop** **J.P. Ma, J.X. Wang, S. Zhao, PRD88 (2013) 1, 014027.**
- $\chi_{c0,2}$ factorisation issue ? $\leftrightarrow$ CO-CS mixing

  J.P. Ma, J.X. Wang, S. Zhao, PLB737 (2014) 103-108

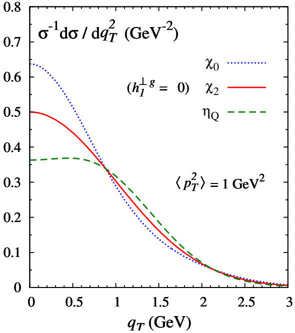
Low P_T quarkonia and TMDs

PHYSICAL REVIEW D **86,** 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer*
Theory Group, KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands

Cristian Pisano†
Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy



- Low P_T C-even quarkonium production is a good probe of $h_1^{\perp g}$
- Affect the low P_T spectra:

$$\frac{1}{\sigma}\frac{d\sigma(\eta_Q)}{d\mathbf{q}_T^2} \propto 1 - R(\mathbf{q}_T^2) \;\&\; \frac{1}{\sigma}\frac{d\sigma(\chi_{Q,0})}{d\mathbf{q}_T^2} \propto 1 + R(\mathbf{q}_T^2)$$

  (R involves $f_1^g(x, k_T, \mu)$ and $h_1^{\perp g}(x, k_T, \mu)$)
- η_c **production at one-loop** J.P. Ma, J.X. Wang, S. Zhao, PRD88 (2013) 1, 014027.
- $\chi_{c0,2}$ factorisation issue ? $\leftrightarrow$ CO-CS mixing

  J.P. Ma, J.X. Wang, S. Zhao, PLB737 (2014) 103-108
- Cannot tune Q: $Q \simeq m_{\mathcal{Q}}$

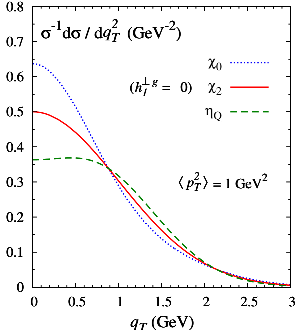
Low P_T quarkonia and TMDs

PHYSICAL REVIEW D **86,** 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer*
Theory Group, KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands

Cristian Pisano†
Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy



- Low P_T C-even quarkonium production is a good probe of $h_1^{\perp g}$
- Affect the low P_T spectra:

$$\frac{1}{\sigma}\frac{d\sigma(\eta_Q)}{d\mathbf{q}_T^2} \propto 1 - R(\mathbf{q}_T^2) \;\&\; \frac{1}{\sigma}\frac{d\sigma(\chi_{Q,0})}{d\mathbf{q}_T^2} \propto 1 + R(\mathbf{q}_T^2)$$

  (R involves $f_1^g(x, k_T, \mu)$ and $h_1^{\perp g}(x, k_T, \mu)$)

- η_c **production at one-loop** **J.P. Ma, J.X. Wang, S. Zhao, PRD88 (2013) 1, 014027.**
- $\chi_{c0,2}$ factorisation issue ? $\leftrightarrow$ CO-CS mixing

  J.P. Ma, J.X. Wang, S. Zhao, PLB737 (2014) 103-108

- Cannot tune Q: $Q \simeq m_Q$
- Experimentally very difficult

First η_c production study at collider ever, only released last month for $P_T^{\eta_c} > 6$ GeV **LHCb, 1409.3612**

Part III

Quarkonium + photon

$\mathcal{Q} +$ isolated γ: interesting but ...

- At high energy, 2 gluons in the initial states: no quark

$\mathcal{Q}$ + isolated γ: interesting but ...

- At high energy, 2 gluons in the initial states: no quark
- The photon needs to be emitted by the heavy-quark loop

$\mathcal{Q}+$ isolated γ: interesting but ...

- At high energy, 2 gluons in the initial states: no quark
- The photon needs to be emitted by the heavy-quark loop
- Consequence: gluon fragmentation associated with $C=+1$ octet [$^1S_0^{[8]}$ & $^3P_J^{[8]}$] **instead** of $C=-1$ octet [$^3S_1^{[8]}$] for the inclusive case

$\mathcal{Q}+$ isolated γ: interesting but ...

- At high energy, 2 gluons in the initial states: no quark
- The photon needs to be emitted by the heavy-quark loop
- Consequence: gluon fragmentation associated with $C=+1$ octet $[{}^1S_0^{[8]}$ & ${}^3P_J^{[8]}]$
  instead of $C=-1$ octet $[{}^3S_1^{[8]}]$ for the inclusive case
- CS rate at NLO $\simeq$ conservative (high) expectation from CO

R.Li and J.X. Wang, PLB 672,51,2009

$\mathcal{Q}$ + isolated γ: interesting but ...

- At high energy, 2 gluons in the initial states: no quark
- The photon needs to be emitted by the heavy-quark loop
- Consequence: gluon fragmentation associated with $C = +1$ octet $[{}^1S_0^{[8]}$ & ${}^3P_J^{[8]}]$ **instead** of $C = -1$ octet $[{}^3S_1^{[8]}]$ for the inclusive case
- CS rate at NLO $\simeq$ conservative (high) expectation from CO

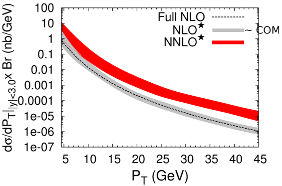
  R.Li and J.X. Wang, PLB 672,51,2009
- CO rates may be clearly lower if ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ are indeed suppressed (at NLO)

$\mathcal{Q}$ + isolated γ: interesting but ...

- At high energy, 2 gluons in the initial states: no quark
- The photon needs to be emitted by the heavy-quark loop
- Consequence: gluon fragmentation associated with $C = +1$ octet $[{}^1S_0^{[8]}$ & ${}^3P_J^{[8]}]$ **instead** of $C = -1$ octet $[{}^3S_1^{[8]}]$ for the inclusive case
- CS rate at NLO $\simeq$ conservative (high) expectation from CO

R.Li and J.X. Wang, PLB 672,51,2009

- CO rates may be clearly lower if ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ are indeed suppressed (at NLO)
- At NNLO*, CS rate clearly above (high) expectation from CO

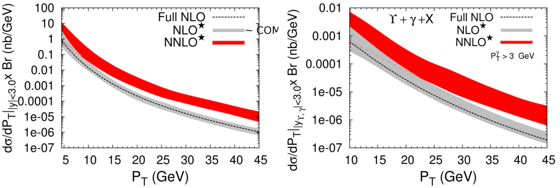


$\mathcal{Q}$ + isolated γ: interesting but ...

- At high energy, 2 gluons in the initial states: no quark
- The photon needs to be emitted by the heavy-quark loop
- Consequence: gluon fragmentation associated with $C = +1$ octet $[{}^1S_0^{[8]}$ & ${}^3P_J^{[8]}]$ **instead** of $C = -1$ octet $[{}^3S_1^{[8]}]$ for the inclusive case
- CS rate at NLO $\simeq$ conservative (high) expectation from CO

R.Li and J.X. Wang, PLB 672,51,2009

- CO rates may be clearly lower if ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ are indeed suppressed (at NLO)
- At NNLO*, CS rate clearly above (high) expectation from CO



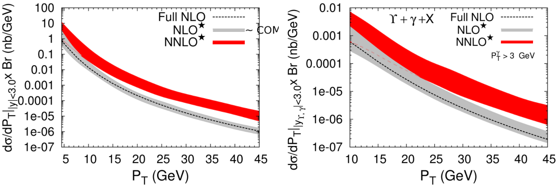
JPL, PLB 679,340,2009.

$\mathcal{Q}+$ isolated γ: interesting but ...

- At high energy, 2 gluons in the initial states: no quark
- The photon needs to be emitted by the heavy-quark loop
- Consequence: gluon fragmentation associated with $C=+1$ octet $[{}^1S_0^{[8]}$ & ${}^3P_J^{[8]}]$ **instead** of $C=-1$ octet $[{}^3S_1^{[8]}]$ for the inclusive case
- CS rate at NLO $\simeq$ conservative (high) expectation from CO

R.Li and J.X. Wang, PLB 672,51,2009

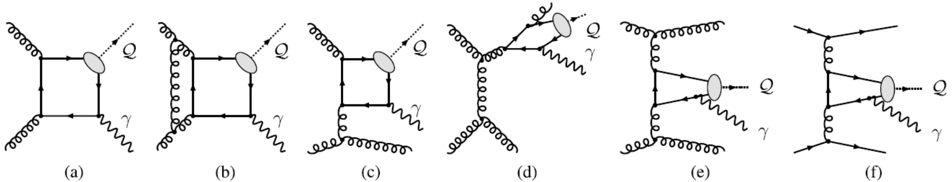
- CO rates may be clearly lower if ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$ are indeed suppressed (at NLO)
- At NNLO*, CS rate clearly above (high) expectation from CO



JPL, PLB 679,340,2009.

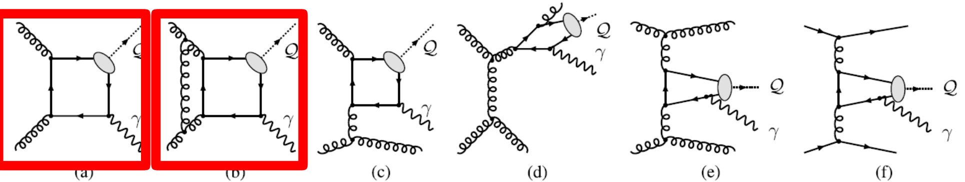
- All this is certainly interesting but TMD factorisation is most likely not applicable because of colour in the final state (either COM or gluons)

$\mathcal{Q}+\gamma$: **back-to-back** and both isolated



Representative diagrams contributing to the hadroproduction of a $\mathcal{Q}$ in association with a photon at orders $\alpha_S^2\alpha$ (a), $\alpha_S^3\alpha$ (b, c), $\alpha_S^4\alpha$ (d, e, f).

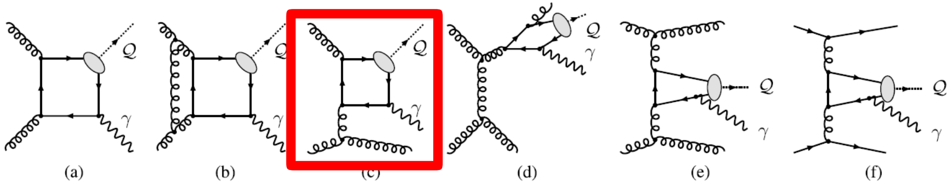
$\mathcal{Q} + \gamma$: **back-to-back** and both isolated



Representative diagrams contributing to the hadroproduction of a $\mathcal{Q}$ in association with a photon at orders $\alpha_S^2\alpha$ (a), $\alpha_S^3\alpha$ (b, c), $\alpha_S^4\alpha$ (d, e, f).

- Born (LO) + loop: $2 \to 2$ contributions (a)-(b) fall like P_T^{-8}

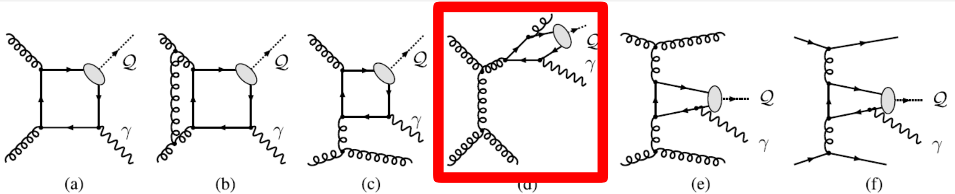
$\mathcal{Q}+\gamma$: **back-to-back** and both isolated



Representative diagrams contributing to the hadroproduction of a $\mathcal{Q}$ in association with a photon at orders $\alpha_S^2\alpha$ (a), $\alpha_S^3\alpha$ (b, c), $\alpha_S^4\alpha$ (d, e, f).

- Born (LO) + loop: $2 \to 2$ contributions (a)-(b) fall like P_T^{-8}
- At NLO: topologies like (c) contribute at mid P_T : P_T^{-6}

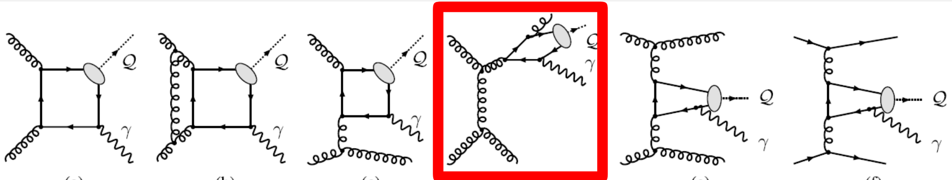
$\mathcal{Q}+\gamma$: **back-to-back** and both isolated



Representative diagrams contributing to the hadroproduction of a $\mathcal{Q}$ in association with a photon at orders $\alpha_S^2\alpha$ (a), $\alpha_S^3\alpha$ (b, c), $\alpha_S^4\alpha$ (d, e, f).

- Born (LO) + loop: $2 \rightarrow 2$ contributions (a)-(b) fall like P_T^{-8}
- At NLO: topologies like (c) contribute at mid P_T : P_T^{-6}
- At NNLO: topologies like (d) dominate at very large P_T : P_T^{-4}

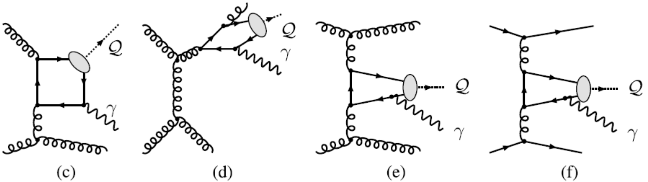
$\mathcal{Q} + \gamma$: **back-to-back** and both isolated



Representative diagrams contributing to the hadroproduction of a $\mathcal{Q}$ in association with a photon at orders $\alpha_S^2\alpha$ (a), $\alpha_S^3\alpha$ (b, c), $\alpha_S^4\alpha$ (d, e, f).

- Born (LO) + loop: $2 \to 2$ contributions (a)-(b) fall like P_T^{-8}
- At NLO: topologies like (c) contribute at mid P_T : P_T^{-6}
- At NNLO: topologies like (d) dominate at very large P_T : P_T^{-4}
- COM contributions similar to (d):
  Instead of a 'hard' gluon, there would be multiple soft gluons.

$\mathcal{Q}+\gamma$: **back-to-back** and both isolated



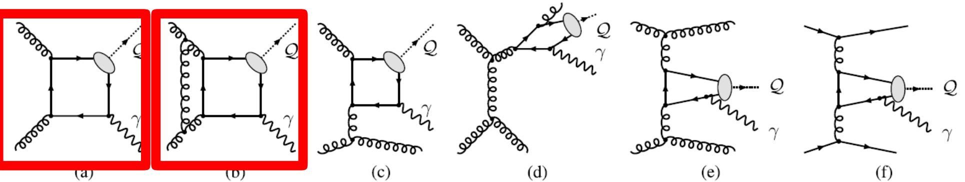
Representative diagrams contributing to the hadroproduction of a $\mathcal{Q}$ in association with a photon at orders $\alpha_S^2\alpha$ (a), $\alpha_S^3\alpha$ (b, c), $\alpha_S^4\alpha$ (d, e, f).

- Born (LO) + loop: $2 \to 2$ contributions (a)-(b) fall like P_T^{-8}
- At NLO: topologies like (c) contribute at mid P_T : P_T^{-6}
- At NNLO: topologies like (d) dominate at very large P_T : P_T^{-4}
- COM contributions similar to (d):

  Instead of a 'hard' gluon, there would be multiple soft gluons.
- (c)-(f): parton [$\to$ some hadrons] in the central region;

  for (d), hadrons near the $\mathcal{Q}$

$\mathcal{Q} + \gamma$: **back-to-back** and both isolated



Representative diagrams contributing to the hadroproduction of a $\mathcal{Q}$ in association with a photon at orders $\alpha_S^2\alpha$ (a), $\alpha_S^3\alpha$ (b, c), $\alpha_S^4\alpha$ (d, e, f).

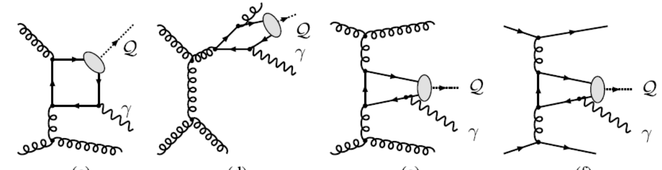
- Born (LO) + loop: $2 \to 2$ contributions (a)-(b) fall like P_T^{-8}
- At NLO: topologies like (c) contribute at mid P_T : P_T^{-6}
- At NNLO: topologies like (d) dominate at very large P_T : P_T^{-4}
- COM contributions similar to (d):

  Instead of a 'hard' gluon, there would be multiple soft gluons.
- (c)-(f): parton [$\to$ some hadrons] in the central region;

  for (d), hadrons near the $\mathcal{Q}$
- $2 \to 2$ topologies contribute to $\Delta\phi_{\mathcal{Q}-\gamma} = \pi$ (back-to-back) ;

  smearing effect small for $P_T \gg \langle k_T \rangle$

$\mathcal{Q}+\gamma$: **back-to-back** and both isolated

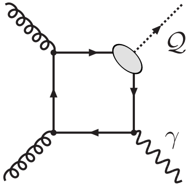


Representative diagrams contributing to the hadroproduction of a $\mathcal{Q}$ in association with a photon at orders $\alpha_S^2\alpha$ (a), $\alpha_S^3\alpha$ (b, c), $\alpha_S^4\alpha$ (d, e, f).

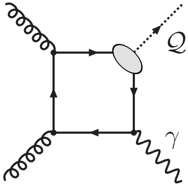
- Born (LO) + loop: $2 \to 2$ contributions (a)-(b) fall like P_T^{-8}
- At NLO: topologies like (c) contribute at mid P_T : P_T^{-6}
- At NNLO: topologies like (d) dominate at very large P_T : P_T^{-4}
- COM contributions similar to (d):
  Instead of a 'hard' gluon, there would be multiple soft gluons.
- (c)-(f): parton [$\to$ some hadrons] in the central region;
  for (d), hadrons near the $\mathcal{Q}$
- $2 \to 2$ topologies contribute to $\Delta\phi_{\mathcal{Q}-\gamma} = \pi$ (back-to-back) ;
  smearing effect small for $P_T \gg \langle k_T \rangle$
- (c)-(f) populate $\Delta\phi_{\mathcal{Q}-\gamma} < \pi$ [even $\Delta\phi \to 0$ for (c) and (d) at large P_T]

$\mathcal{Q} + \gamma$: back-to-back and both isolated

- The studies is of an isolated quarkonium back-to-back with an (isolated) photon selects the Born contributions to $\mathcal{Q} + \gamma$

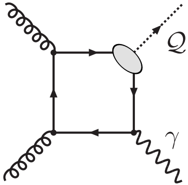


$\mathcal{Q}+\gamma$: back-to-back and both isolated



- The studies is of an isolated quarkonium back-to-back with an (isolated) photon selects the Born contributions to $\mathcal{Q}+\gamma$
- The "back-to-back" requirement also limits the DPS contributions
  [a priori evenly distributed in $\Delta\phi$]

$\mathcal{Q} + \gamma$: back-to-back and both isolated

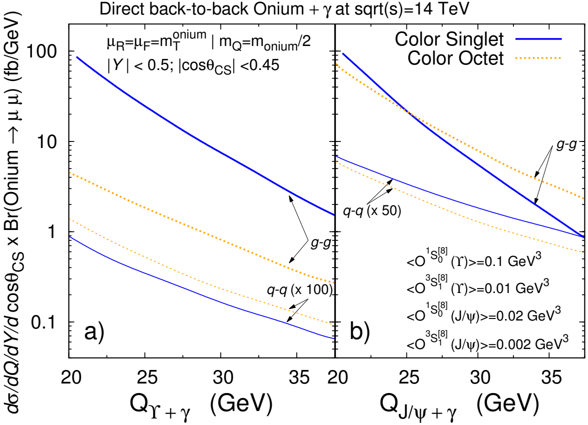


- The studies is of an isolated quarkonium back-to-back with an (isolated) photon selects the Born contributions to $\mathcal{Q} + \gamma$
- The “back-to-back” requirement also limits the DPS contributions

  [a priori evenly distributed in $\Delta\phi$]
- Unique candidate to pin down the gluon TMDs
  - gluon sensitive process
  - colourless final state (virtue of isolation): TMD factorisation applicable
  - small sensitivity to QCD corrections (most of them in the TMD evolution)

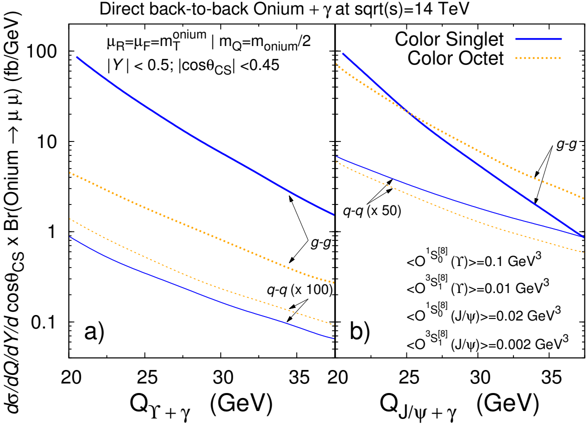
Expected rates for back-to-back $\mathcal{Q} + \gamma$

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



Expected rates for back-to-back $\mathcal{Q} + \gamma$

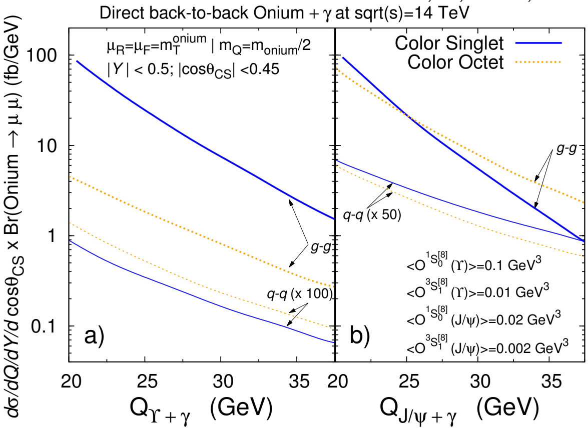
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



- $q\bar{q}$ contribution negligible;

Expected rates for back-to-back $\mathcal{Q} + \gamma$

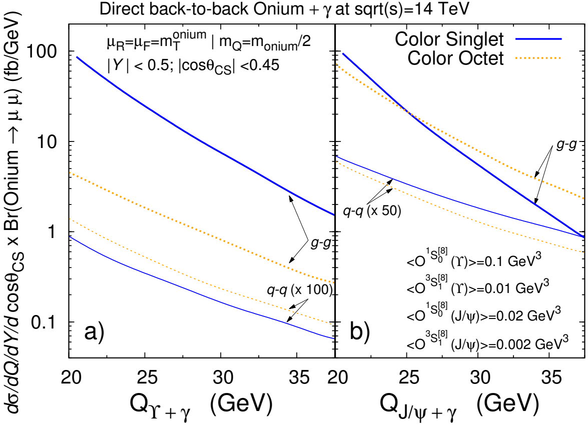
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



- $q\bar{q}$ contribution negligible;
- CO (orange) smaller than CS (blue): isolation not needed for Υ

Expected rates for back-to-back $\mathcal{Q} + \gamma$

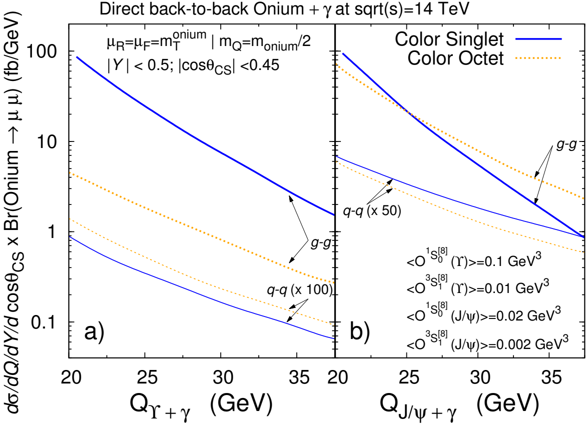
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



- $q\bar{q}$ contribution negligible;
- CO (orange) smaller than CS (blue): isolation not needed for Υ
- At 14 TeV, $\sigma(J/\psi|\Upsilon+\gamma, Q > 20\text{GeV}) \simeq$ 100fb; about half at 7 TeV

Expected rates for back-to-back $\mathcal{Q} + \gamma$

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



- $q\bar{q}$ contribution negligible;
- CO (orange) smaller than CS (blue): isolation not needed for Υ
- At 14 TeV, $\sigma(J/\psi|\Upsilon + \gamma, Q > 20\text{GeV}) \simeq$ 100fb; about half at 7 TeV
- With the $\mathcal{L} \simeq 20$ fb^{-1} of *pp* data on tape, one expects up to 2000 events

back-to-back $\mathcal{Q} + \gamma$ and the gluon TMDs

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

- The $\boldsymbol{q}_T$-differential cross section involves $f_1^g(x, \boldsymbol{k}_T, \mu_F)$ and $h_1^{\perp g}(x, \boldsymbol{k}_T, \mu_F)$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q\mathrm{d}Y\mathrm{d}^2\boldsymbol{q}_T\mathrm{d}\Omega} = \frac{C_0(Q^2 - M_{\mathcal{Q}}^2)}{s\,Q^3 D}\left\{F_1\,\mathcal{C}\left[f_1^g f_1^g\right] + F_3\cos(2\phi_{CS})\mathcal{C}\left[w_3 f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2\right] + F_4\cos(4\phi_{CS})\,\mathcal{C}\left[w_4 h_1^{\perp g} h_1^{\perp g}\right]\right\} + \mathcal{O}\left(\frac{\boldsymbol{q}_T^2}{Q^2}\right)$$

back-to-back $\mathcal{Q}+\gamma$ and the gluon TMDs

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

- The $\boldsymbol{q}_T$-differential cross section involves $f_1^g(x, \boldsymbol{k}_T, \mu_F)$ and $h_1^{\perp g}(x, \boldsymbol{k}_T, \mu_F)$

$$\frac{d\sigma}{dQ dY d^2\boldsymbol{q}_T d\Omega} = \frac{C_0(Q^2 - M_{\mathcal{Q}}^2)}{s\,Q^3 D}\left\{F_1\,\mathcal{C}\left[f_1^g f_1^g\right] + F_3\cos(2\phi_{CS})\mathcal{C}\left[w_3 f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2\right] + F_4\cos(4\phi_{CS})\,\mathcal{C}\left[w_4 h_1^{\perp g} h_1^{\perp g}\right]\right\} + \mathcal{O}\left(\frac{\boldsymbol{q}_T^2}{Q^2}\right)$$

- We define: $\mathcal{S}_{q_T}^{(n)} = \left(\frac{d\sigma}{dQ dY d\cos\theta_{CS}}\right)^{-1}\int d\phi_{CS}\pi\cos(n\phi_{CS})\frac{d\sigma}{dQ dY d^2\boldsymbol{q}_T d\Omega}$

back-to-back $\mathcal{Q}+\gamma$ and the gluon TMDs

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

- The $\boldsymbol{q}_T$-differential cross section involves $f_1^g(x, \boldsymbol{k}_T, \mu_F)$ and $h_1^{\perp g}(x, \boldsymbol{k}_T, \mu_F)$

$$\frac{d\sigma}{dQdYd^2\boldsymbol{q}_Td\Omega} = \frac{C_0(Q^2-M_{\mathcal{Q}}^2)}{s\,Q^3 D}\left\{F_1\,\mathcal{C}\left[f_1^g f_1^g\right] + F_3\cos(2\phi_{CS})\mathcal{C}\left[w_3 f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2\right] + F_4\cos(4\phi_{CS})\,\mathcal{C}\left[w_4 h_1^{\perp g} h_1^{\perp g}\right]\right\} + \mathcal{O}\left(\frac{\boldsymbol{q}_T^2}{Q^2}\right)$$

- We define: $\mathcal{S}_{q_T}^{(n)} = \left(\frac{d\sigma}{dQdYd\cos\theta_{CS}}\right)^{-1}\int d\phi_{CS}\pi\cos(n\phi_{CS})\frac{d\sigma}{dQdYd^2\boldsymbol{q}_Td\Omega}$
  - $\mathcal{S}_{q_T}^{(0)} = \frac{\mathcal{C}[f_1^g f_1^g]}{\int dq_T^2\,\mathcal{C}[f_1^g f_1^g]}$: does not involve $h_1^{\perp g}$ [not always the case]

back-to-back $\mathcal{Q}+\gamma$ and the gluon TMDs

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

- The $\boldsymbol{q}_T$-differential cross section involves $f_1^g(x, \boldsymbol{k}_T, \mu_F)$ and $h_1^{\perp g}(x, \boldsymbol{k}_T, \mu_F)$

$$\frac{d\sigma}{dQ\,dY\,d^2\boldsymbol{q}_T\,d\Omega} = \frac{C_0(Q^2 - M_{\mathcal{Q}}^2)}{s\,Q^3 D}\left\{F_1\,\mathcal{C}\left[f_1^g f_1^g\right] + F_3\cos(2\phi_{CS})\,\mathcal{C}\left[w_3 f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2\right] + F_4\cos(4\phi_{CS})\,\mathcal{C}\left[w_4 h_1^{\perp g} h_1^{\perp g}\right]\right\} + \mathcal{O}\left(\frac{\boldsymbol{q}_T^2}{Q^2}\right)$$

- We define: $\mathcal{S}_{q_T}^{(n)} = \left(\frac{d\sigma}{dQ\,dY\,d\cos\theta_{CS}}\right)^{-1}\int d\phi_{CS}\,\pi\,\cos(n\phi_{CS})\,\frac{d\sigma}{dQ\,dY\,d^2\boldsymbol{q}_T\,d\Omega}$
  - $\mathcal{S}_{q_T}^{(0)} = \frac{\mathcal{C}[f_1^g f_1^g]}{\int dq_T^2\,\mathcal{C}[f_1^g f_1^g]}$: does not involve $h_1^{\perp g}$ [not always the case]
  - $\mathcal{S}_{q_T}^{(4)} = \frac{F_4\,\mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}]}{2F_1 \int dq_T^2\,\mathcal{C}[f_1^g f_1^g]}$:

$\mathcal{S}_{q_T}^{(4)} \neq 0 \Rightarrow$ nonzero gluon polarisation in unpolarised protons !

back-to-back $\mathcal{Q} + \gamma$ and the gluon TMDs

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

- The $\boldsymbol{q}_T$-differential cross section involves $f_1^g(x, \boldsymbol{k}_T, \mu_F)$ and $h_1^{\perp g}(x, \boldsymbol{k}_T, \mu_F)$

$$\frac{d\sigma}{dQ dY d^2\boldsymbol{q}_T d\Omega} = \frac{C_0(Q^2 - M_{\mathcal{Q}}^2)}{s\, Q^3 D} \left\{ F_1\, \mathcal{C}\left[f_1^g f_1^g\right] + F_3 \cos(2\phi_{CS}) \mathcal{C}\left[w_3 f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2\right] + F_4 \cos(4\phi_{CS})\, \mathcal{C}\left[w_4 h_1^{\perp g} h_1^{\perp g}\right] \right\} + \mathcal{O}\left(\frac{\boldsymbol{q}_T^2}{Q^2}\right)$$

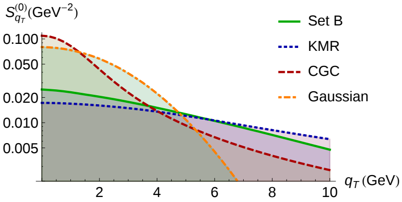
- We define: $\mathcal{S}_{q_T}^{(n)} = \left(\frac{d\sigma}{dQ dY d\cos\theta_{CS}}\right)^{-1} \int d\phi_{CS} \pi \cos(n\phi_{CS}) \frac{d\sigma}{dQ dY d^2\boldsymbol{q}_T d\Omega}$
  - $\mathcal{S}_{q_T}^{(0)} = \frac{\mathcal{C}[f_1^g f_1^g]}{\int dq_T^2\, \mathcal{C}[f_1^g f_1^g]}$: does not involve $h_1^{\perp g}$ [not always the case]
  - $\mathcal{S}_{q_T}^{(4)} = \frac{F_4\, \mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}]}{2F_1 \int dq_T^2\, \mathcal{C}[f_1^g f_1^g]}$:

  $\mathcal{S}_{q_T}^{(4)} \neq 0 \Rightarrow$ nonzero gluon polarisation in unpolarised protons !

  - $\mathcal{S}_{q_T}^{(4)} = \frac{F_4\, \mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}]}{2F_1 \int dq_T^2\, \mathcal{C}[f_1^g f_1^g]}$

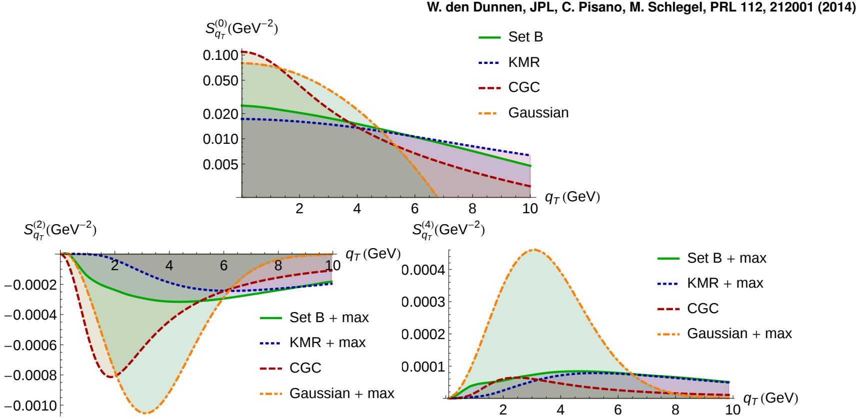
Results with UGDs as Ansätze for TMDs

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



- $\mathcal{S}^{(0)}_{q_T}$: $f_1^g(x, k_T)$ from the q_T-dependence of the yield.

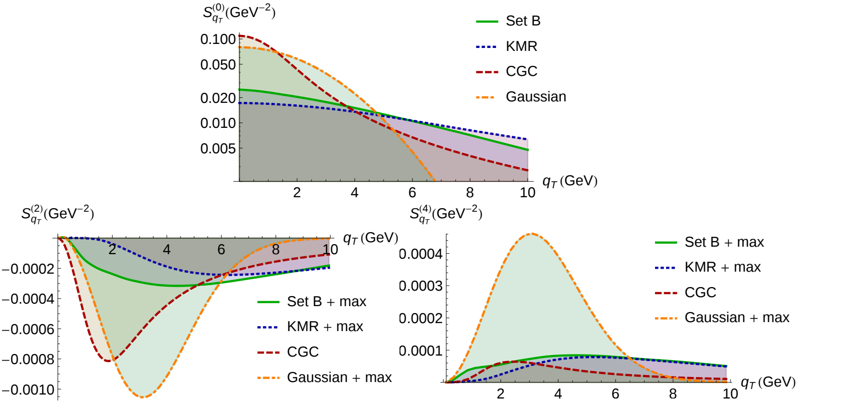
Results with UGDs as Ansätze for TMDs



- $\mathcal{S}^{(0)}_{q_T}$: $f_1^g(x, k_T)$ from the q_T-dependence of the yield.
- $\mathcal{S}^{(4)}_{q_T}$: $\int dq_T \mathcal{S}^{(4)}_{q_T}$ should be measurable [$\mathcal{O}(1-2\%)$: ok with 2000 events]

Results with UGDs as Ansätze for TMDs

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



- $\mathcal{S}^{(0)}_{q_T}$: $f_1^g(x, k_T)$ from the q_T-dependence of the yield.
- $\mathcal{S}^{(4)}_{q_T}$: $\int dq_T \mathcal{S}^{(4)}_{q_T}$ should be measurable [$\mathcal{O}(1-2\%)$: ok with 2000 events]
- $\mathcal{S}^{(2)}_{q_T}$: slightly larger than $\mathcal{S}^{(4)}_{q_T}$

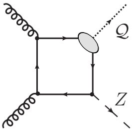
Part IV

Quarkonium + Z boson

$\Upsilon + Z$ cross sections

B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115

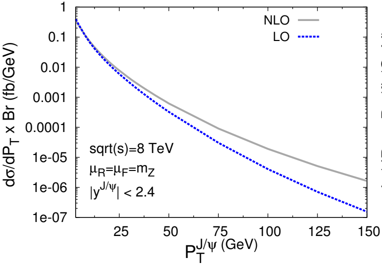
- Rates similar for $\Upsilon + Z$ and $J/\psi + Z$ [Same for $\mathcal{Q} + \gamma$ for $Q \gtrsim$ 20 GeV]

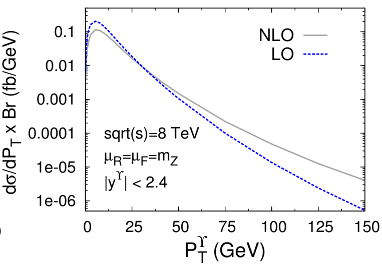


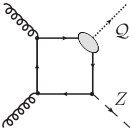
$\Upsilon + Z$ cross sections

B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115

- Rates similar for $\Upsilon + Z$ and $J/\psi + Z$ [Same for $\mathcal{Q} + \gamma$ for $Q \gtrsim 20$ GeV]



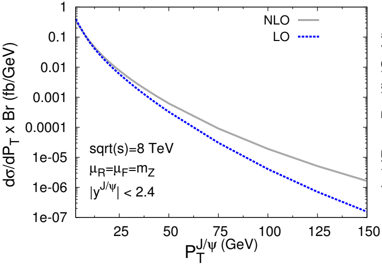


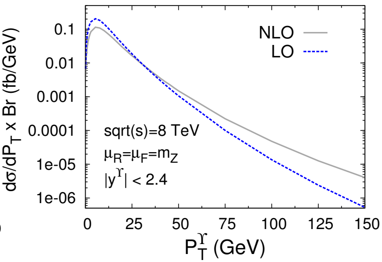


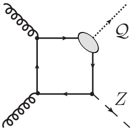
$\Upsilon + Z$ cross sections

B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115

- Rates similar for $\Upsilon + Z$ and $J/\psi + Z$ [Same for $\mathcal{Q} + \gamma$ for $Q \gtrsim 20$ GeV]





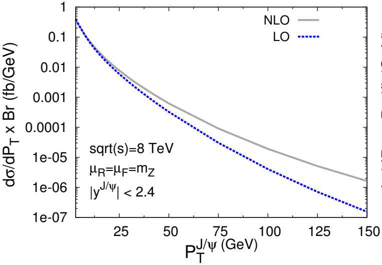


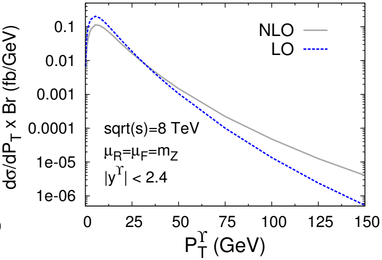
- Potential probe of gluon TMDs as well

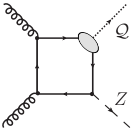
$\Upsilon + Z$ cross sections

B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115

- Rates similar for $\Upsilon + Z$ and $J/\psi + Z$ [Same for $\mathcal{Q} + \gamma$ for $Q \gtrsim$ 20 GeV]





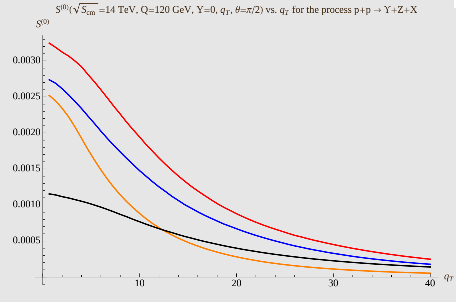


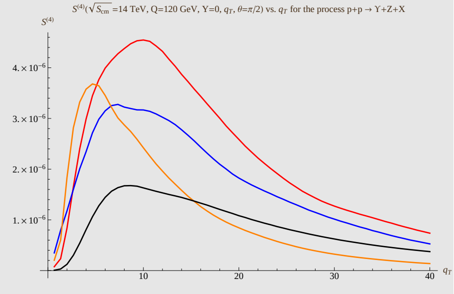
- Potential probe of gluon TMDs as well
- Rate clearly smaller than $\mathcal{Q} + \gamma$ even at low P_T

$\Upsilon + Z$ and TMDs

W. den Dunnen, JPL, C. Pisano, M. Schlegel, on-going work

- $\Upsilon + Z$ @$\sqrt{s} = 14$ TeV;
- $Q = 120$ GeV, $Y = 0$, $\theta = \pi/2$

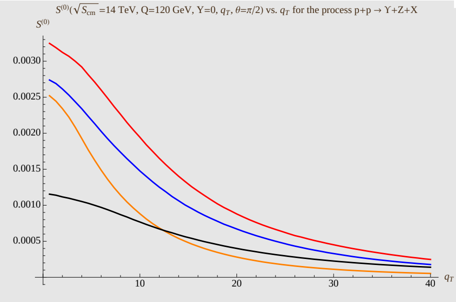


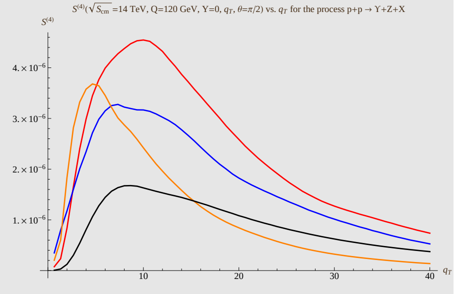


$\Upsilon + Z$ and TMDs

W. den Dunnen, JPL, C. Pisano, M. Schlegel, on-going work

- $\Upsilon + Z$ @$\sqrt{s} = 14$ TeV;
- $Q = 120$ GeV, $Y = 0$, $\theta = \pi/2$



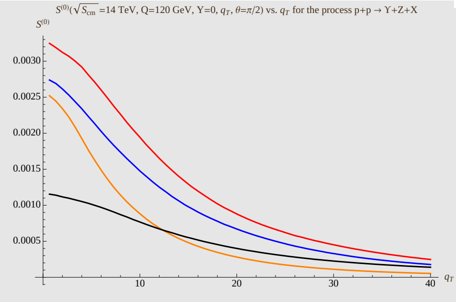


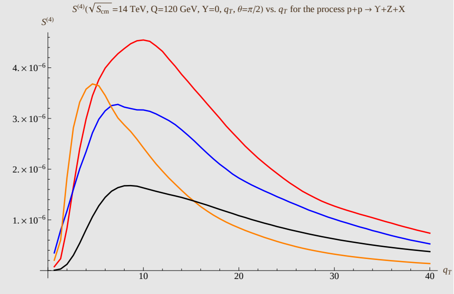
- $\mathcal{S}_{q_T}^{(n)}$ smaller than for $\mathcal{Q} + \gamma$ [one can integrate up to larger q_T, though]

$\Upsilon + Z$ and TMDs

W. den Dunnen, JPL, C. Pisano, M. Schlegel, on-going work

- $\Upsilon + Z$ @$\sqrt{s} = 14$ TeV;
- $Q = 120$ GeV, $Y = 0$, $\theta = \pi/2$





- $\mathcal{S}_{q_T}^{(n)}$ smaller than for $\mathcal{Q} + \gamma$ [one can integrate up to larger q_T, though]
- Naturally large Q: interest to study the scale evolution ?

Conclusions and Outlooks

- TMD studies in the gluon sector are very promising

Conclusions and Outlooks

- TMD studies in the gluon sector are very promising
- With lepton beams, only possible at an EIC

Conclusions and Outlooks

- TMD studies in the gluon sector are very promising
- With lepton beams, only possible at an EIC
- If we don't want to wait for 10 years, LHC can help, right now !

Conclusions and Outlooks

- TMD studies in the gluon sector are very promising
- With lepton beams, only possible at an EIC
- If we don't want to wait for 10 years, LHC can help, right now !
- Low P_T η_c production [below $M_{\eta_c}/2$] is highly challenging,
  probably impossible with the current detectors

Conclusions and Outlooks

- TMD studies in the gluon sector are very promising
- With lepton beams, only possible at an EIC
- If we don't want to wait for 10 years, LHC can help, right now !
- Low P_T η_c production [below $M_{\eta_c}/2$] is highly challenging,
  probably impossible with the current detectors
- Di-photon production is perhaps more tractable
  but very challenging where the rates are high

Conclusions and Outlooks

- TMD studies in the gluon sector are very promising
- With lepton beams, only possible at an EIC
- If we don't want to wait for 10 years, LHC can help, right now !
- Low P_T η_c production [below $M_{\eta_c}/2$] is highly challenging, probably impossible with the current detectors
- Di-photon production is perhaps more tractable but very challenging where the rates are high
- Back-to-back $J/\psi + \gamma$ and $\Upsilon + \gamma$ is certainly at reach
  - Already a couple of thousand events on tapes
  - $f_1^g(x, k_T, \mu)$ and $h_1^{\perp g}(x, k_T, \mu)$ can be determined separately
  - Q can even be tuned $\rightarrow$ gluon TMD evolution

Conclusions and Outlooks

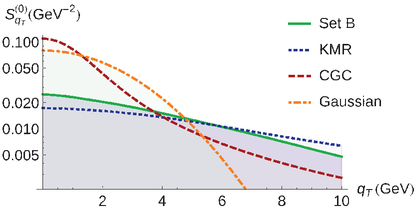
- TMD studies in the gluon sector are very promising
- With lepton beams, only possible at an EIC
- If we don't want to wait for 10 years, LHC can help, right now !
- Low P_T η_c production [below $M_{\eta_c}/2$] is highly challenging, probably impossible with the current detectors
- Di-photon production is perhaps more tractable but very challenging where the rates are high
- Back-to-back $J/\psi + \gamma$ and $\Upsilon + \gamma$ is certainly at reach
  - Already a couple of thousand events on tapes
  - $f_1^g(x, k_T, \mu)$ and $h_1^{\perp g}(x, k_T, \mu)$ can be determined separately
  - Q can even be tuned $\rightarrow$ gluon TMD evolution
- Low P_T onium and SSA of onium+photon studies could be done with A Fixed-Target Experiment at the LHC: AFTER@LHC [see talk by L. Massacrier on Friday, S11, 9h35]

Part V

Backup

$\mathcal{S}^{(0)}_{q_T}$: Model predictions for $\Upsilon + \gamma$ production at $\sqrt{s} = 14$ TeV

Q = 20 GeV, $\qquad Y = 0, \qquad \theta_{CS} = \pi/2$

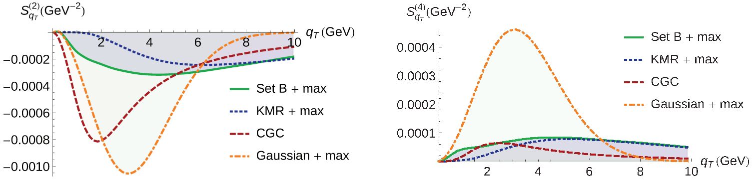


Models for f_1^g: assumed to be the same as for Unintegrated Gluon Distributions

- Set B: B0 solution to CCFM equation with input based on HERA data
  Jung et *al.*, EPJC 70 (2010) 1237
- KMR: Formalism embodies both DGLAP and BFKL evolution equations
  Kimber, Martin, Ryskin, PRD 63 (2010) 114027
- CGC: Color Glass Condensate Model
  Dominguez, Qiu, Xiao, Yuan, PRD 85 (2012) 045003
  Metz, Zhou, PRD 84 (2011) 051503

$\mathcal{S}^{(2,4)}_{q_T}$: *Model predictions for* $\Upsilon + \gamma$ *production at* $\sqrt{s} = 14$ *TeV*

Q = 20 GeV, $Y = 0$, $\theta_{CS} = \pi/2$



$h_1^{\perp g}$: predictions only in the CGC: in the other models saturated to its upper bound

$\mathcal{S}^{(2,4)}_{q_T}$ smaller than $\mathcal{S}^{(0)}_{q_T}$: can be integrated up to $q_T = 10$ GeV

$$2.0\%\ (\mathrm{KMR}) < \quad |\int \mathrm{d}q_T^2 \mathcal{S}^{(2)}_{q_T}| \quad < 2.9\%\ (\mathrm{Gauss})$$

$$0.3\%\ (\mathrm{CGC}) < \quad \int \mathrm{d}q_T^2\ \mathcal{S}^{(4)}_{q_T} \quad < 1.2\%\ (\mathrm{Gauss})$$

Possible determination of the shape of f_1^g and verification of a non-zero $h_1^{\perp g}$

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$q\bar{q}' \to \gamma^\star W \stackrel{^3S_1^{[1]}}{\to} J/\psi W$ and $q\bar{q}' \to g^\star W \stackrel{^3S_1^{[8]}}{\to} J/\psi W$ are very similar

why ?

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$q\bar{q}' \to \gamma^\star W \overset{^3S_1^{[1]}}{\to} J/\psi W$ and $q\bar{q}' \to g^\star W \overset{^3S_1^{[8]}}{\to} J/\psi W$ are very similar

why ?

Let us simplify and look at $\boxed{q\bar{q}' \to \gamma^\star \overset{^3S_1^{[1]}}{\to} J/\psi \text{ vs. } q\bar{q}' \to g^\star \overset{^3S_1^{[8]}}{\to} J/\psi}$

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$q\bar{q}' \to \gamma^\star W \stackrel{^3S_1^{[1]}}{\to} J/\psi W$ and $q\bar{q}' \to g^\star W \stackrel{^3S_1^{[8]}}{\to} J/\psi W$ are very similar

why ?

Let us simplify and look at $\boxed{q\bar{q}' \to \gamma^\star \stackrel{^3S_1^{[1]}}{\to} J/\psi \text{ vs. } q\bar{q}' \to g^\star \stackrel{^3S_1^{[8]}}{\to} J/\psi}$

The cross sections are well-known:

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$q\bar{q}' \to \gamma^\star W \overset{^3S_1^{[1]}}{\to} J/\psi W$ and $q\bar{q}' \to g^\star W \overset{^3S_1^{[8]}}{\to} J/\psi W$ are very similar

why ?

Let us simplify and look at $\boxed{q\bar{q}' \to \gamma^\star \overset{^3S_1^{[1]}}{\to} J/\psi \text{ vs. } q\bar{q}' \to g^\star \overset{^3S_1^{[8]}}{\to} J/\psi}$

The cross sections are well-known:

- CSM: $\hat{\sigma}^{[1]}_{via\ \gamma^\star} = \frac{(4\pi\alpha)^2 e_q^2 e_Q^2}{M_{\mathcal{Q}}^3 s}\,\delta\left(x_1 x_2 - M_{\mathcal{Q}}^2/s\right)|R(0)|^2$

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$q\bar{q}' \to \gamma^\star W \overset{^3S_1^{[1]}}{\to} J/\psi W$ and $q\bar{q}' \to g^\star W \overset{^3S_1^{[8]}}{\to} J/\psi W$ are very similar

why ?

Let us simplify and look at $\boxed{q\bar{q}' \to \gamma^\star \overset{^3S_1^{[1]}}{\to} J/\psi \text{ vs. } q\bar{q}' \to g^\star \overset{^3S_1^{[8]}}{\to} J/\psi}$

The cross sections are well-known:

- CSM: $\hat{\sigma}^{[1]}_{via\ \gamma^\star} = \frac{(4\pi\alpha)^2 e_q^2 e_Q^2}{M_\mathcal{Q}^3 s}\, \delta\left(x_1 x_2 - M_\mathcal{Q}^2/s\right) |R(0)|^2$
- COM: $\hat{\sigma}^{[8]}_{via\ g^\star} = \frac{(4\pi\alpha_S)^2 \pi}{27 M_\mathcal{Q}^3 s}\, \delta\left(x_1 x_2 - M_\mathcal{Q}^2/s\right) \langle \mathcal{O}_\mathcal{Q}(\,^3S_1^{[8]}) \rangle$

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$q\bar{q}' \to \gamma^\star W \overset{^3S_1^{[1]}}{\to} J/\psi W$ and $q\bar{q}' \to g^\star W \overset{^3S_1^{[8]}}{\to} J/\psi W$ are very similar

why ?

Let us simplify and look at $\boxed{q\bar{q}' \to \gamma^\star \overset{^3S_1^{[1]}}{\to} J/\psi \text{ vs. } q\bar{q}' \to g^\star \overset{^3S_1^{[8]}}{\to} J/\psi}$

The cross sections are well-known:

- CSM: $\hat{\sigma}^{[1]}_{via\ \gamma^\star} = \frac{(4\pi\alpha)^2 e_q^2 e_Q^2}{M_\mathcal{Q}^3 s}\,\delta\left(x_1 x_2 - M_\mathcal{Q}^2/s\right)|R(0)|^2$
- COM: $\hat{\sigma}^{[8]}_{via\ g^\star} = \frac{(4\pi\alpha_S)^2\pi}{27 M_\mathcal{Q}^3 s}\,\delta\left(x_1 x_2 - M_\mathcal{Q}^2/s\right)\langle\mathcal{O}_\mathcal{Q}(\,^3S_1^{[8]})\rangle$
- The ratio gives: $\frac{\hat{\sigma}^{[1]}_{via\ \gamma^\star}}{\hat{\sigma}^{[8]}_{via\ g^\star}} = \frac{6\alpha^2 e_q^2 e_Q^2\langle\mathcal{O}_\mathcal{Q}(\,^3S_1^{[1]})\rangle}{\alpha_S^2\langle\mathcal{O}_\mathcal{Q}(\,^3S_1^{[8]})\rangle}$

$\langle O_\mathcal{Q}(^3S_1^{[1]})\rangle = 2N_c(2J+1)\frac{|R(0)|^2}{4\pi}$

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$q\bar{q}' \to \gamma^\star W \overset{^3S_1^{[1]}}{\to} J/\psi W$ and $q\bar{q}' \to g^\star W \overset{^3S_1^{[8]}}{\to} J/\psi W$ are very similar

why ?

Let us simplify and look at $\boxed{q\bar{q}' \to \gamma^\star \overset{^3S_1^{[1]}}{\to} J/\psi \text{ vs. } q\bar{q}' \to g^\star \overset{^3S_1^{[8]}}{\to} J/\psi}$

The cross sections are well-known:

- CSM: $\hat{\sigma}^{[1]}_{via\ \gamma^\star} = \frac{(4\pi\alpha)^2 e_q^2 e_Q^2}{M_\mathcal{Q}^3 s} \delta\left(x_1 x_2 - M_\mathcal{Q}^2/s\right) |R(0)|^2$
- COM: $\hat{\sigma}^{[8]}_{via\ g^\star} = \frac{(4\pi\alpha_S)^2 \pi}{27 M_\mathcal{Q}^3 s} \delta\left(x_1 x_2 - M_\mathcal{Q}^2/s\right) \langle \mathcal{O}_\mathcal{Q}(^3S_1^{[8]})\rangle$
- The ratio gives: $\frac{\hat{\sigma}^{[1]}_{via\ \gamma^\star}}{\hat{\sigma}^{[8]}_{via\ g^\star}} = \frac{6\alpha^2 e_q^2 e_Q^2 \langle \mathcal{O}_\mathcal{Q}(^3S_1^{[1]})\rangle}{\alpha_S^2 \langle \mathcal{O}_\mathcal{Q}(^3S_1^{[8]})\rangle}$ $\quad \langle O_\mathcal{Q}(^3S_1^{[1]})\rangle = 2N_c(2J+1)\frac{|R(0)|^2}{4\pi}$
- Colour factor: $2N_c$

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$$\frac{\hat{\sigma}^{[1]}_{via\ \gamma^\star}}{\hat{\sigma}^{[8]}_{via\ g^\star}} = \frac{6\alpha^2 e_q^2 e_Q^2 \langle \mathcal{O}_{\mathcal{Q}}({}^3S_1^{[1]})\rangle}{\alpha_S^2 \langle \mathcal{O}_{\mathcal{Q}}({}^3S_1^{[8]})\rangle}$$

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$$\frac{\hat{\sigma}^{[1]}_{via\ \gamma^\star}}{\hat{\sigma}^{[8]}_{via\ g^\star}} = \frac{6\alpha^2 e_q^2 e_Q^2 \langle \mathcal{O}_{\mathcal{Q}}(\,^3S_1^{[1]})\rangle}{\alpha_S^2 \langle \mathcal{O}_{\mathcal{Q}}(\,^3S_1^{[8]})\rangle}$$

- The ratio depends on the initial quark, q, on α_s at $\mu_R \simeq m_{\mathcal{Q}}$ and on the ratio of the non-perturbative coefficients.

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$$\frac{\hat{\sigma}^{[1]}_{via\ \gamma^\star}}{\hat{\sigma}^{[8]}_{via\ g^\star}} = \frac{6\alpha^2 e_q^2 e_Q^2 \langle \mathcal{O}_\mathcal{Q}({}^3S_1^{[1]})\rangle}{\alpha_S^2 \langle \mathcal{O}_\mathcal{Q}({}^3S_1^{[8]})\rangle}$$

- The ratio depends on the initial quark, q, on α_s at $\mu_R \simeq m_\mathcal{Q}$ and on the ratio of the non-perturbative coefficients.
- For J/ψ production in $u\bar{u}$ fusion and for $\langle O_{J/\psi}({}^3S_1^{[8]})\rangle = 2.2 \times 10^{-3}$ GeV^3, the ratio CSM vs. COM is **2/3**

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$$\frac{\hat{\sigma}^{[1]}_{via\ \gamma^\star}}{\hat{\sigma}^{[8]}_{via\ g^\star}} = \frac{6\alpha^2 e_q^2 e_Q^2 \langle \mathcal{O}_\mathcal{Q}(\,^3S_1^{[1]})\rangle}{\alpha_S^2 \langle \mathcal{O}_\mathcal{Q}(\,^3S_1^{[8]})\rangle}$$

- The ratio depends on the initial quark, q, on α_s at $\mu_R \simeq m_\mathcal{Q}$ and on the ratio of the non-perturbative coefficients.
- For J/ψ production in $u\bar{u}$ fusion and for $\langle O_{J/\psi}(^3S_1^{[8]})\rangle = 2.2 \times 10^{-3}$ GeV^3, the ratio CSM vs. COM is **2/3**
- For Υ production, it is about the same

(e_Q smaller but α_s also smaller and $|R(0)|^2$ larger)

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$$\frac{\hat{\sigma}^{[1]}_{via\ \gamma^\star}}{\hat{\sigma}^{[8]}_{via\ g^\star}} = \frac{6\alpha^2 e_q^2 e_Q^2 \langle \mathcal{O}_\mathcal{Q}(\,^3S_1^{[1]})\rangle}{\alpha_S^2 \langle \mathcal{O}_\mathcal{Q}(\,^3S_1^{[8]})\rangle}$$

- The ratio depends on the initial quark, q, on α_s at $\mu_R \simeq m_\mathcal{Q}$ and on the ratio of the non-perturbative coefficients.
- For J/ψ production in $u\bar{u}$ fusion and for $\langle O_{J/\psi}(^3S_1^{[8]})\rangle = 2.2 \times 10^{-3}$ GeV^3, the ratio CSM vs. COM is **2/3**
- For Υ production, it is about the same
  (e_Q smaller but α_s also smaller and $|R(0)|^2$ larger)
- If we add the W emission, the charge factor changes and $\mu_R : \mathcal{O}(m_\mathcal{Q}) \to \mathcal{O}(m_W)$

$\rightarrow$ This explains our results for $J/\psi + W$

Discussion: CSM via $\gamma^\star$ vs. COM via $g^\star$

$$\frac{\hat{\sigma}^{[1]}_{via\ \gamma^\star}}{\hat{\sigma}^{[8]}_{via\ g^\star}} = \frac{6\alpha^2 e_q^2 e_Q^2 \langle \mathcal{O}_\mathcal{Q}(\,^3S_1^{[1]})\rangle}{\alpha_S^2 \langle \mathcal{O}_\mathcal{Q}(\,^3S_1^{[8]})\rangle}$$

- The ratio depends on the initial quark, q, on α_s at $\mu_R \simeq m_\mathcal{Q}$ and on the ratio of the non-perturbative coefficients.
- For J/ψ production in $u\bar{u}$ fusion and for $\langle O_{J/\psi}(^3S_1^{[8]})\rangle = 2.2 \times 10^{-3}$ GeV^3, the ratio CSM vs. COM is **2/3**
- For Υ production, it is about the same

  (e_Q smaller but α_s also smaller and $|R(0)|^2$ larger)
- If we add the W emission, the charge factor changes and $\mu_R : \mathcal{O}(m_\mathcal{Q}) \to \mathcal{O}(m_W)$

  $\to$ This explains our results for $J/\psi + W$
- General conclusion:

For production processes involving light quarks, the CSM via off-shell photon competes with the COM via off-shell gluon