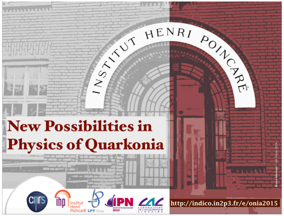
Theoretical motivations to study $J/\psi + \gamma$ & $\Upsilon + \gamma$ production at the LHC: from H^0 to $h_1^{\perp g}$ and vice et versa

J.P. Lansberg

IPN Orsay – Paris-Sud U. –CNRS/IN2P3



September 24-25, 2015 – IHP Paris

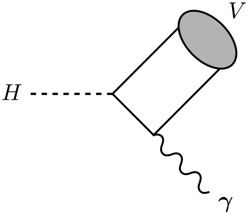
Part I

BEH boson decay to $^3S_1(Q\bar{Q}) + \gamma$ *

*Mostly taken from G. Bodwin's talk at the QWG 2014 at CERN

Measuring the $Hc\bar{c}$ Coupling

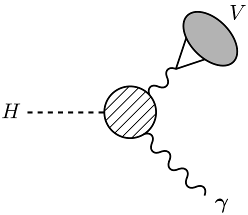
- Higgs couplings to vector bosons, τ leptons, and b quarks have been measured.
- The coupling to t quarks is known implicitly from loop contributions to decay processes.
- However, the couplings to first- and second-generation quarks are *terra incognita*.
- One could hope to measure the $Hc\bar{c}$ coupling in direct decays to $J/\psi + \gamma$:



- The channel $J/\psi \to \ell^+\ell^-$, when combined with the m_H and $m_{J/\psi}$ mass constraints, provides a clean experimental signal.

Slide borrowed from G. Bodwin

- The direct amplitude was computed many years ago.
  (Keung, PRD 27, 2762 (1983))
  - It is proportional to the $H\bar{c}c$ coupling.
  - But, the corresponding decay width is far too small to be observed at the LHC.
- However, there is also a (newly identified) indirect process for producing a vector quarkonium plus a photon:



Dominated by t quarks and W bosons in the loop.

Slide borrowed from G. Bodwin

- For J/ψ, the indirect amplitude is about an order of magnitude larger than the direct amplitude.
- The interference between the direct and indirect amplitudes is large enough to be measured at the LHC.
- Requires knowing the theoretical prediction for the indirect amplitude with good precision.

Slide borrowed from G. Bodwin

$$\underline{\Gamma[H \to J/\psi + \gamma]}$$

- Parametrize deviations from the standard-model $Hc\bar{c}$ coupling with a factor κ_c:

$$g_{Hc\bar{c}} = \kappa_c \, g_{Hc\bar{c}}^{\mathrm{SM}} \, .$$

- Then, the decay rate is

$$\Gamma[H \to J/\psi + \gamma] = \left| \sqrt{\Gamma_{\mathrm{indirect}}^{\mathrm{SM}}} - \kappa_c \sqrt{\Gamma_{\mathrm{direct}}^{\mathrm{SM}}} \right|^2 .$$

- The indirect and direct amplitudes interfere destructively (aside from a small phase (0.005) that we neglect).
- The rate depends on both the magnitude and the phase of $g_{Hc\bar{c}}$.

Slide borrowed from G. Bodwin

Indirect Amplitude

- It is essential to predict the indirect amplitude very precisely in order to measure the direct amplitude.
- Can be computed from $H \to \gamma\gamma^*$, followed by $\gamma^* \to J/\psi$.
- $H \to \gamma\gamma^*$ can be approximated by $H \to \gamma\gamma$, up to corrections of order $m_{J/\psi}^2/m_H^2$.
  - The amplitude for $H \to \gamma\gamma$ has been computed to high precision.
    (Dittmaier *et al.*, arXiv:1101.0593, arXiv:1201.3084)
- Extract the amplitude for $\gamma^* \to J/\psi$ from the measured rate for $J/\psi \to \ell^+\ell^-$.
  - Both amplitudes are proportional to the coupling of the J/ψ to the EM current.
  - This approach effectively includes QCD and relativistic corrections to all orders—greatly reducing uncertainties.

Slide borrowed from G. Bodwin

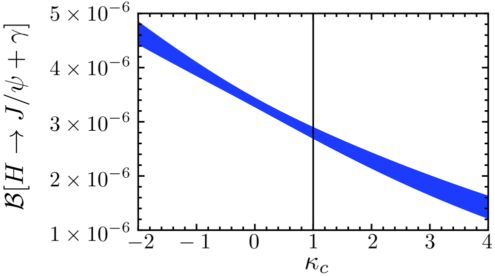
Numerical Results for $H \to J/\psi + \gamma$

$$g_{Hc\bar{c}} = \kappa_c \, g^{\rm SM}_{Hc\bar{c}}$$

$$\Gamma[H \to J/\psi + \gamma] = |(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c|^2 \times 10^{-10}\ \text{GeV}.$$

$$\Gamma_{\rm SM}[H \to J/\psi+\gamma] = 1.17^{+0.05}_{-0.05}\times 10^{-8}\ \text{GeV}. \qquad \mathcal{B}_{\rm SM}[H \to J/\psi+\gamma] = 2.79^{+0.16}_{-0.15}\times 10^{-6}.$$

- The width is sensitive to deviations from the Standard Model value of the $H\bar{c}c$ coupling:



- $+42\%$ for $\kappa_c = -1$.
- $+20\%$ for $\kappa_c = 0$.
- -18% for $\kappa_c = 2$.
- Interference allows us to determine the sign of κ_c.

Slide borrowed from G. Bodwin

Numerical results for $H \to \Upsilon(nS) + \gamma$

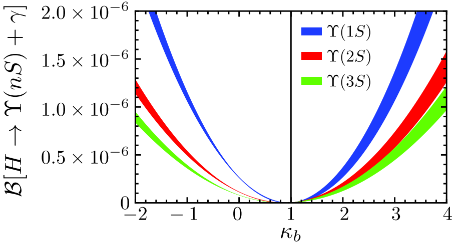
- We do the same calculation for the $\Upsilon(nS)$ states.

$$g_{Hb\bar{b}} = \kappa_b \, g^{\mathrm{SM}}_{Hb\bar{b}}$$

$$\Gamma[H \to \Upsilon(1S) + \gamma] = |(3.33 \pm 0.03) - (3.49 \pm 0.15)\kappa_b|^2 \times 10^{-10}\ \mathrm{GeV}.$$

$$\Gamma_{\mathrm{SM}}[H \to \Upsilon(1S) + \gamma] = 2.56^{+7.30}_{-2.56} \times 10^{-12}\ \mathrm{GeV}.$$
$$\mathcal{B}_{\mathrm{SM}}[H \to \Upsilon(1S) + \gamma] = 6.11^{+17.41}_{-6.11} \times 10^{-10}.$$

- In the SM, the $\Upsilon(1S)$ direct and indirect amplitudes cancel at the 5% level.



- The SM rates are probably unobservable at the LHC.
- However, there is a dramatic sensitivity to deviations from the SM coupling.

Slide borrowed from G. Bodwin

ATLAS search

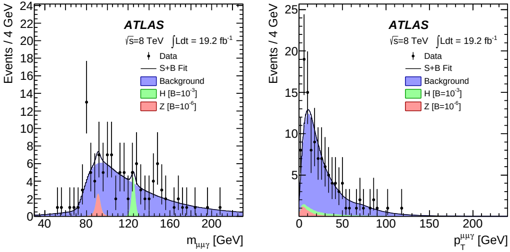
See Talk by Kostas yesterday

PRL **114,** 121801 (2015) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2015

Search for Higgs and Z Boson Decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS Detector

G. Aad *et al.*[*]
(ATLAS Collaboration)
(Received 15 January 2015; published 26 March 2015)

A search for the decays of the Higgs and Z bosons to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$) is performed with pp collision data samples corresponding to integrated luminosities of up to 20.3 fb^{-1} collected at $\sqrt{s} = 8$ TeV with the ATLAS detector at the CERN Large Hadron Collider. No significant excess of events is observed above expected backgrounds and 95% C.L. upper limits are placed on the branching fractions. In the $J/\psi\gamma$ final state the limits are 1.5×10^{-3} and 2.6×10^{-6} for the Higgs and Z boson decays, respectively, while in the $\Upsilon(1S, 2S, 3S)\gamma$ final states the limits are $(1.3, 1.9, 1.3) \times 10^{-3}$ and $(3.4, 6.5, 5.4) \times 10^{-6}$, respectively.



ATLAS search

See Talk by Kostas yesterday

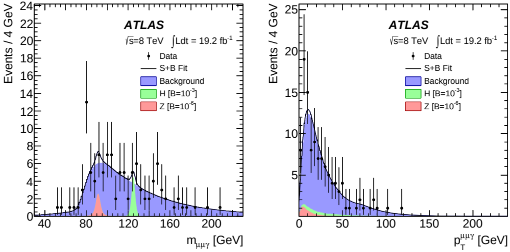
PRL **114,** 121801 (2015) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2015

Search for Higgs and Z Boson Decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS Detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 15 January 2015; published 26 March 2015)

A search for the decays of the Higgs and Z bosons to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$) is performed with pp collision data samples corresponding to integrated luminosities of up to 20.3 fb^{-1} collected at $\sqrt{s} = 8$ TeV with the ATLAS detector at the CERN Large Hadron Collider. No significant excess of events is observed above expected backgrounds and 95% C.L. upper limits are placed on the branching fractions. In the $J/\psi\gamma$ final state the limits are 1.5×10^{-3} and 2.6×10^{-6} for the Higgs and Z boson decays, respectively, while in the $\Upsilon(1S, 2S, 3S)\gamma$ final states the limits are $(1.3, 1.9, 1.3) \times 10^{-3}$ and $(3.4, 6.5, 5.4) \times 10^{-6}$, respectively.



The (acceptance and efficiency) corrected background (modulo isolation cuts) can be extremely useful for QCD ⇒ see Part IV

Part II

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

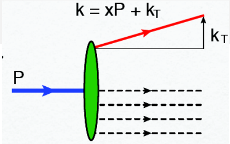
- Experimental and theoretical investigations of gluons inside hadrons focused so far on their longitudinal momentum and helicity distributions:
  - $g(x, \mu_F)$: unpolarised gluons with a collinear momentum fraction x in unpolarised nucleons
  - $\Delta g(x, \mu_F)$: circularly polarised gluons with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

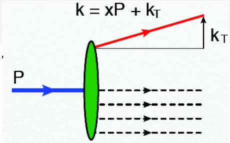
Beyond collinear factorisation

Beyond collinear factorisation



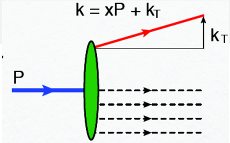
- Observed final-state q_T from
  "intrinsic" k_T from initial partons

Beyond collinear factorisation



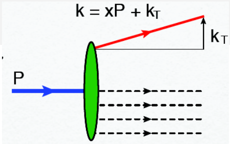
- Observed final-state q_T from
  "intrinsic" k_T from initial partons
- Novel kind of factorisation w.r.t. the collinear one

Beyond collinear factorisation

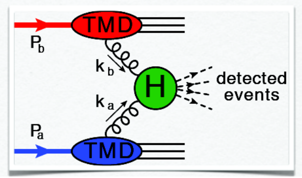


- Observed final-state q_T from
  "intrinsic" k_T from initial partons
- Novel kind of factorisation w.r.t. the collinear one
- Additional degree of freedom of the partonic motion

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 : $q_T \ll Q$

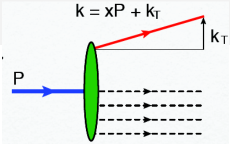


H is free of q_T

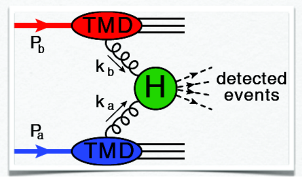
$$d\sigma = \frac{(2\pi)^4}{8s^2}\int d^2\boldsymbol{k}_{1T} d^2\boldsymbol{k}_{2T}\delta^2(\boldsymbol{k}_{1T}+\boldsymbol{k}_{2T}-\boldsymbol{q}_T)H_{\mu\rho}\left(H_{\nu\sigma}\right)^* \times$$

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

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

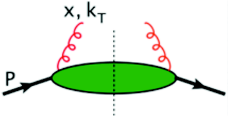
$$d\sigma = \frac{(2\pi)^4}{8s^2} \int d^2\boldsymbol{k}_{1T} d^2\boldsymbol{k}_{2T} \delta^2(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{q}_T) H_{\mu\rho} (H_{\nu\sigma})^* \times$$

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

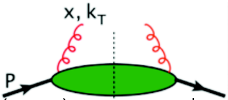
- Proven for SIDIS + pp reactions with colour singlet final states

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

Gluon TMDs in unpolarised protons



Gluon TMDs in unpolarised protons

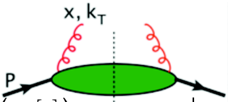


- Gauge-invariant definition:

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

- 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.

Gluon TMDs in unpolarised protons



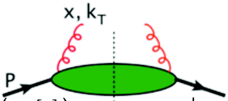
- Gauge-invariant definition:

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

- 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**

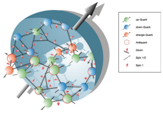
$$\Phi_g^{\mu\nu}(x, \boldsymbol{k}_T, \zeta, \mu) = -\frac{1}{2x}\left\{g_T^{\mu\nu} f_1^g(x, k_T, \mu) - \left(\frac{k_T^\mu k_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\boldsymbol{k}_T^2}{2M_p^2}\right) h_1^{\perp g}(x, k_T, \mu)\right\} + \text{suppr.}$$

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

[Helicity-flip distribution]

Gluon TMDs in general

$$\Phi_g^{[U,U']\mu\nu} \sim \mathrm{FT}\ \langle P,S|F^{n\mu}(0)\ U_{[0,\zeta]}F^{n\nu}(\zeta)\ U'_{[\zeta,0]}\underline{|P,S\rangle}|_{LF}$$



proton = **rich** structure

hermiticity, parity, time-reversal invariance

LEADING TWIST

GLUONS	*unpolarized*	*circular*	*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	$h_{1T}^g,\ h_{1T}^{\perp g}$

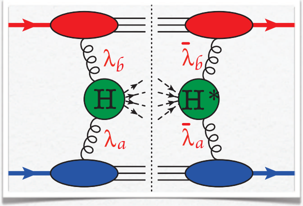
Mulders, Rodriguez PRD 63 (2001)

A. Signori, talk at LC 2015

gg fusion in arbitrary process (colourless final state)

illustrative: helicity space (helicity amplitudes)

→ fully diff. cross section: 4 structures



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

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

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

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

↘ F_2 → double helicity flip, azimuthally independent

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

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

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

↘ 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 $h_1^{\perp g}$

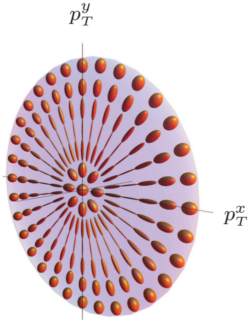
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

- 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: $h_1^{\perp g} < 0$]

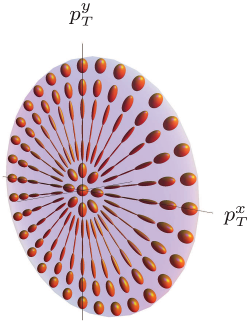


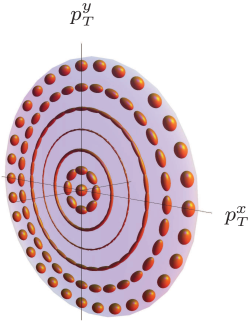
- The ellipsoid axis lengths are proportional to the probability of finding a gluon with a linear polarization in that direction

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: $h_1^{\perp g} < 0$]



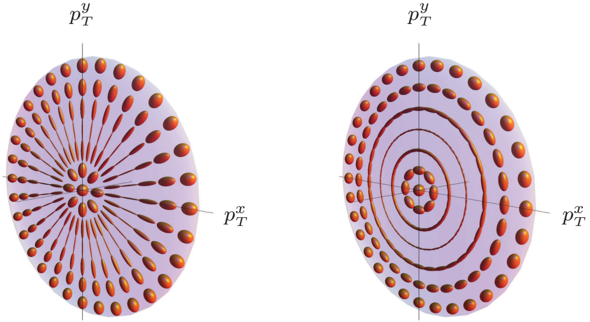


- The ellipsoid axis lengths are proportional to the probability of finding a gluon with a linear polarization in that direction
- A single constraint: a positivity bound $|h_1^{\perp g}| \leq 2M_p^2/\vec{p}_T^{\,2} f_1^g$

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 III

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

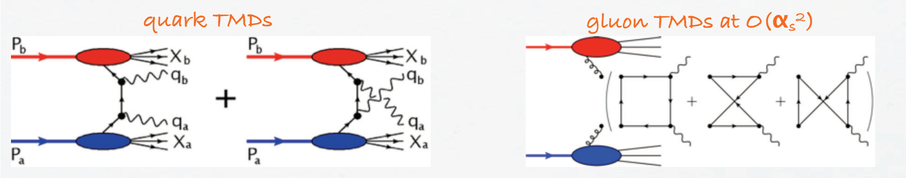
  (also true for ZZ and γZ)
- But contaminations from the $q\bar{q}$ channel (particularly at RHIC)

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)

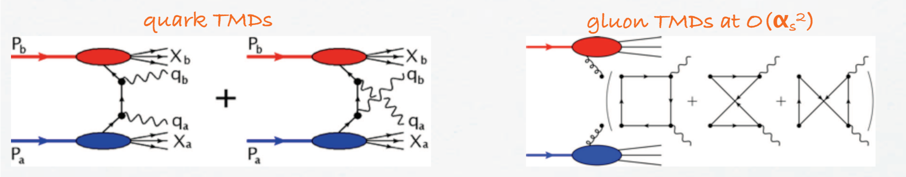


Di-photon

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)



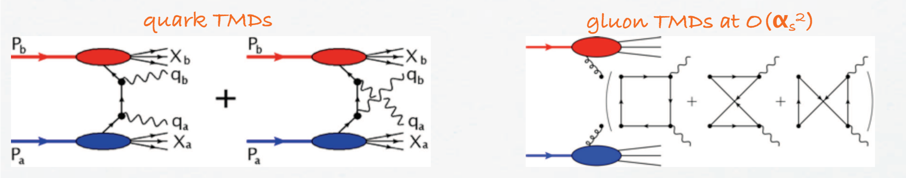
- Only F_4 (*i.e.* the $\cos(4\phi)$ modulation) is purely gluonic

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 → 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)

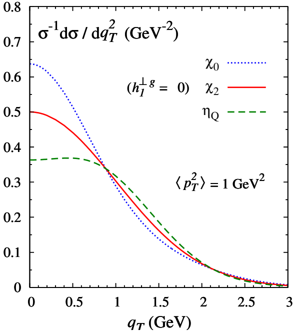
Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

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

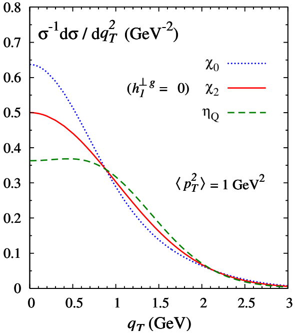
PHYSICAL REVIEW D **86,** 094007 (2012)

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)

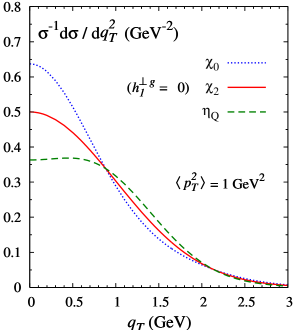
Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

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

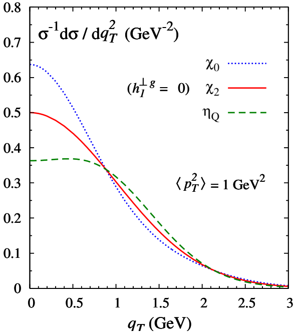
Low P_T quarkonia and TMDs

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: $Q \simeq m_{\mathcal{Q}}$

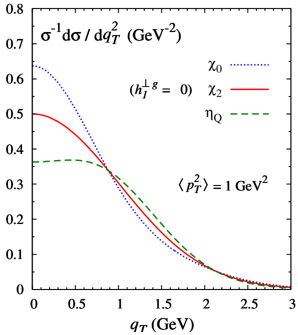
Low P_T quarkonia and TMDs

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

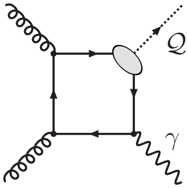
  J.P. Ma, J.X. Wang, S. Zhao, PLB737 (2014) 103-108
- Cannot tune Q: $Q \simeq m_{\mathcal{Q}}$
- Experimentally very difficult

First η_c production study at collider ever, only released last month for $P_T^{\eta_c} > 6$ GeV **LHCb, Eur.Phys.J. C75 (2015) 7, 311**

Part IV

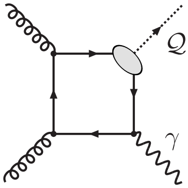
Quarkonium + photon

$\mathcal{Q} + \gamma$: 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 $\mathcal{Q} + \gamma$

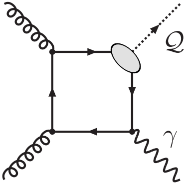
$\mathcal{Q} + \gamma$: back-to-back and both isolated



- 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

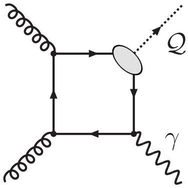


- The studies is of an isolated quarkonium back-to-back with an (isolated) photon selects the Born contributions to $\mathcal{Q} + \gamma$
- The "back-to-back" requirement also limits the DPS contributions

  [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)

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



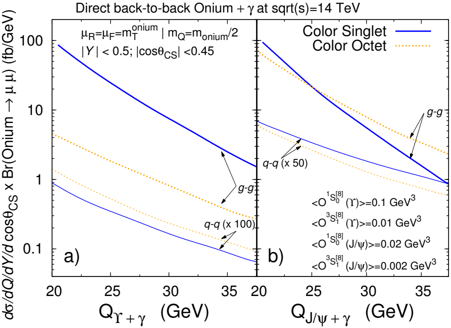
- The studies is of an isolated quarkonium back-to-back with an (isolated) photon selects the Born contributions to $\mathcal{Q} + \gamma$
- The "back-to-back" requirement also limits the DPS contributions

  [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)

[Nota: Since our analysis, it has been argued that TMD factorisation could still hold with CO contributions owing to the presence of the final-state photon **D. Boer, C. Pisano, Phys.Rev. D91 (2015) 7, 074024**]

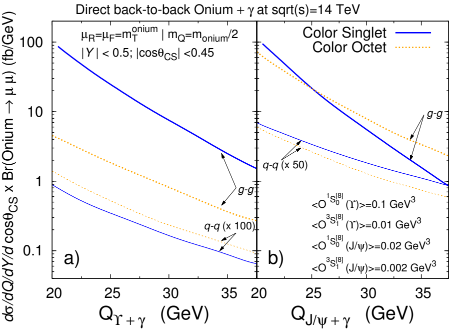
Expected rates for back-to-back $\mathcal{Q} + \gamma$

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



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

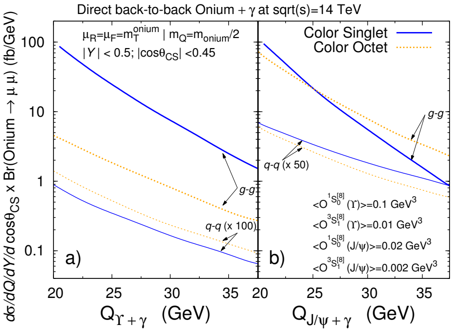
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



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

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

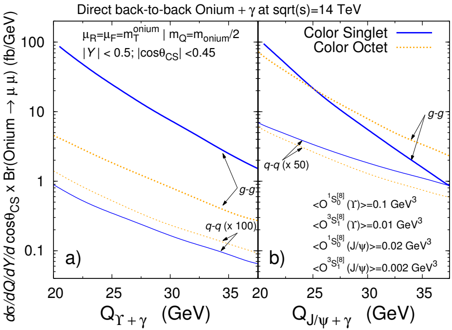
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



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

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

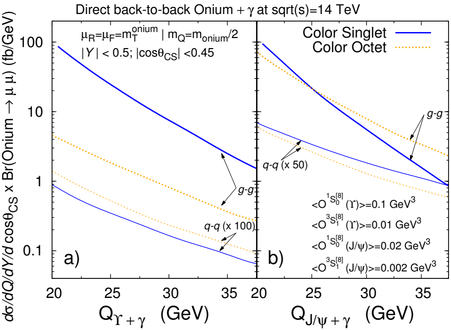
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



- $q\bar{q}$ 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 $\mathcal{Q} + \gamma$

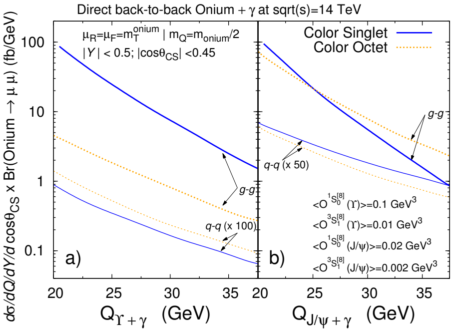
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



- $q\bar{q}$ 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

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

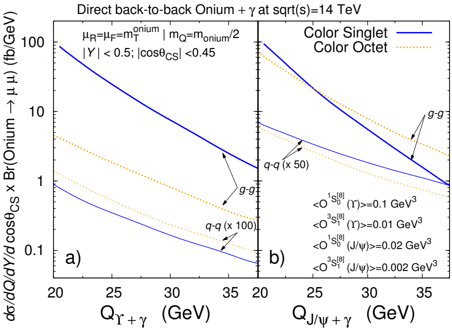
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



- $q\bar{q}$ 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
- The ATLAS search looked at much larger Q + isolation of the leading μ
  $\leftrightarrow$ CO contributions suppressed by this isolation ?

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
- The ATLAS search looked at much larger Q + isolation of the leading μ
  $\leftrightarrow$ CO contributions suppressed by this isolation ?
- With a couple of refinements, their background is maybe what we look for !

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 $h_1^{\perp g}(x, \boldsymbol{k}_T, \mu_F)$

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

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 $h_1^{\perp g}(x,\boldsymbol{k}_T,\mu_F)$

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

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

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 $h_1^{\perp g}(x,\boldsymbol{k}_T,\mu_F)$

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

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

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 $h_1^{\perp g}(x, \boldsymbol{k}_T, \mu_F)$

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

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

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

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 $h_1^{\perp g}(x, \boldsymbol{k}_T, \mu_F)$

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

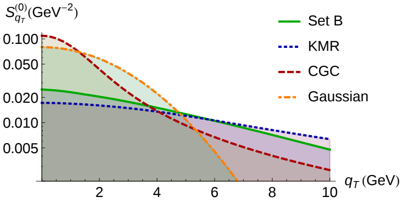
- We define: $\mathcal{S}_{q_T}^{(n)} = \left(\frac{d\sigma}{dQdYd\cos\theta_{CS}}\right)^{-1} \int d\phi_{CS}\,\pi\,\cos(n\phi_{CS})\,\frac{d\sigma}{dQdYd^2\boldsymbol{q}_T d\Omega}$
  - $\mathcal{S}_{q_T}^{(0)} = \frac{\mathcal{C}[f_1^g f_1^g]}{\int dq_T^2\,\mathcal{C}[f_1^g f_1^g]}$: does not involve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

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

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

Results with UGDs as Ansätze for TMDs

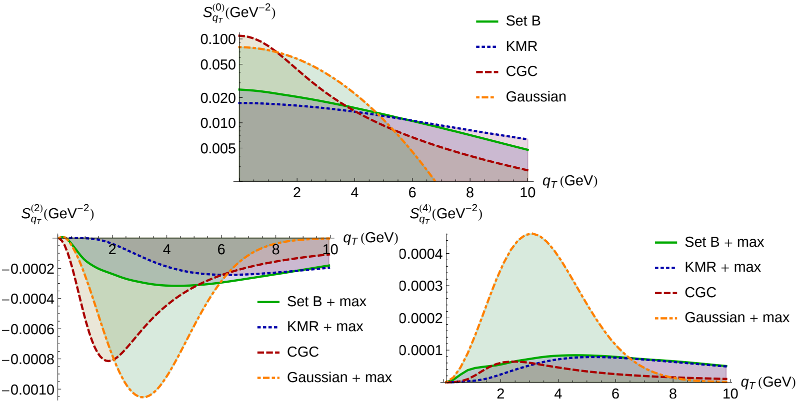
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



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

Results with UGDs as Ansätze for TMDs

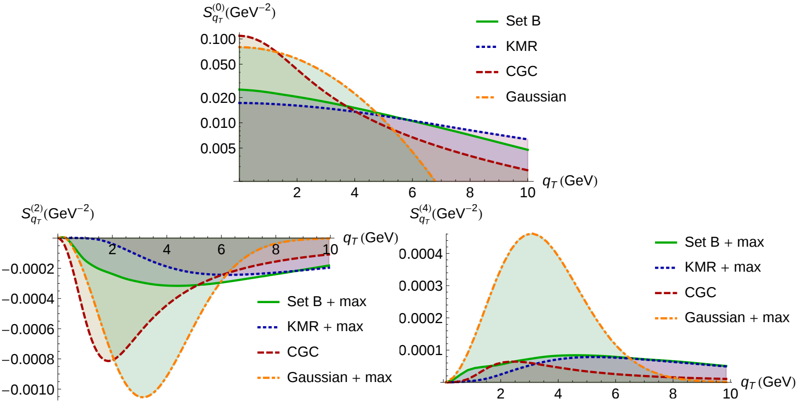
W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



- $\mathcal{S}^{(0)}_{q_T}$: $f_1^g(x, k_T)$ 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]

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 $\mathcal{S}^{(4)}_{q_T}$

Conclusions and Outlooks

- $H^0 \to \mathcal{Q} + \gamma$ to probe $H \to c\bar{c}$ and $H \to b\bar{b}$

Conclusions and Outlooks

- $H^0 \to \mathcal{Q} + \gamma$ to probe $H \to c\bar{c}$ and $H \to b\bar{b}$
- But a QED contribution à la VMD complexifies the case

Conclusions and Outlooks

- $H^0 \to \mathcal{Q} + \gamma$ to probe $H \to c\bar{c}$ and $H \to b\bar{b}$
- But a QED contribution à la VMD complexifies the case
- The ATLAS search paves the way for more studies
- Similar final-state studies, but non-resonnant, are golden paths for the extraction of the distribution of linearly polarised gluon in unpolarised proton at the LHC

Conclusions and Outlooks

- $H^0 \to \mathcal{Q} + \gamma$ to probe $H \to c\bar{c}$ and $H \to b\bar{b}$
- But a QED contribution à la VMD complexifies the case
- The ATLAS search paves the way for more studies
- Similar final-state studies, but non-resonnant, are golden paths for the extraction of the distribution of linearly polarised gluon in unpolarised proton at the LHC
- A side effect of such investigations could be to make a case for isolated-quarkonium-production studies to verify the CSM (i.e. LO v^2 NRQCD) predictions !!!

Conclusions and Outlooks

- $H^0 \to \mathcal{Q} + \gamma$ to probe $H \to c\bar{c}$ and $H \to b\bar{b}$
- But a QED contribution à la VMD complexifies the case
- The ATLAS search paves the way for more studies
- Similar final-state studies, but non-resonnant, are golden paths for the extraction of the distribution of linearly polarised gluon in unpolarised proton at the LHC
- A side effect of such investigations could be to make a case for isolated-quarkonium-production studies to verify the CSM (i.e. LO v^2 NRQCD) predictions !!!
- With lepton beams, $h_1^{\perp g}$ extraction is only possible at an EIC

Conclusions and Outlooks

- $H^0 \to \mathcal{Q} + \gamma$ to probe $H \to c\bar{c}$ and $H \to b\bar{b}$
- But a QED contribution à la VMD complexifies the case
- The ATLAS search paves the way for more studies
- Similar final-state studies, but non-resonnant, are golden paths for the extraction of the distribution of linearly polarised gluon in unpolarised proton at the LHC
- A side effect of such investigations could be to make a case for isolated-quarkonium-production studies to verify the CSM (i.e. LO v^2 NRQCD) predictions !!!
- With lepton beams, $h_1^{\perp g}$ extraction is only possible at an EIC
- Low P_T η_c production [below $M_{\eta_c}/2$] is highly challenging, probably impossible with the current detectors

Conclusions and Outlooks

- $H^0 \to \mathcal{Q} + \gamma$ to probe $H \to c\bar{c}$ and $H \to b\bar{b}$
- But a QED contribution à la VMD complexifies the case
- The ATLAS search paves the way for more studies
- Similar final-state studies, but non-resonnant, are golden paths for the extraction of the distribution of linearly polarised gluon in unpolarised proton at the LHC
- A side effect of such investigations could be to make a case for isolated-quarkonium-production studies to verify the CSM (i.e. LO v^2 NRQCD) predictions !!!
- With lepton beams, $h_1^{\perp g}$ extraction is only possible at an EIC
- Low P_T η_c production [below $M_{\eta_c}/2$] is highly challenging, probably impossible with the current detectors
- Nota: the nonperturbative inputs of the TMD formalism are similar for η_Q and H^0 production via the evolution of the TMDs

Conclusions and Outlooks

- $H^0 \to \mathcal{Q} + \gamma$ to probe $H \to c\bar{c}$ and $H \to b\bar{b}$
- But a QED contribution à la VMD complexifies the case
- The ATLAS search paves the way for more studies
- Similar final-state studies, but non-resonnant, are golden paths for the extraction of the distribution of linearly polarised gluon in unpolarised proton at the LHC
- A side effect of such investigations could be to make a case for isolated-quarkonium-production studies to verify the CSM (i.e. LO v^2 NRQCD) predictions !!!
- With lepton beams, $h_1^{\perp g}$ extraction is only possible at an EIC
- Low P_T η_c production [below $M_{\eta_c}/2$] is highly challenging, probably impossible with the current detectors
- Nota: the nonperturbative inputs of the TMD formalism are similar for η_Q and H^0 production via the evolution of the TMDs
- Di-photon production is perhaps more tractable but very challenging where the rates are high

Part V

Backup

$\mathcal{Q}$ + 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 ...

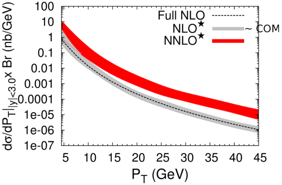
- At high energy, 2 gluons in the initial states: no quark
- The photon needs to be emitted by the heavy-quark loop
- Consequence: gluon fragmentation associated with $C = +1$ octet $[{}^1S_0^{[8]}$ & ${}^3P_J^{[8]}]$ **instead** of $C = -1$ octet $[{}^3S_1^{[8]}]$ for the inclusive case
- CS rate at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

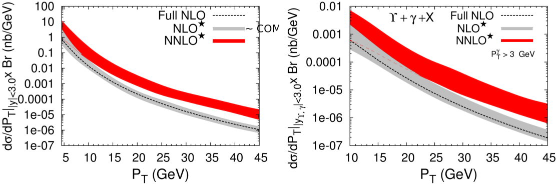
- At high energy, 2 gluons in the initial states: no quark
- The photon needs to be emitted by the heavy-quark loop
- Consequence: gluon fragmentation associated with $C = +1$ octet $[{}^1S_0^{[8]}$ & ${}^3P_J^{[8]}]$ **instead** of $C = -1$ octet $[{}^3S_1^{[8]}]$ for the inclusive case
- CS rate at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

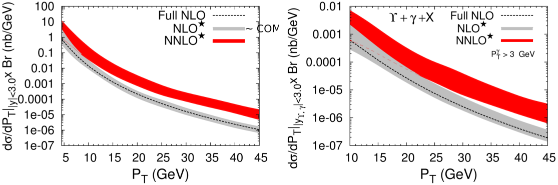
- At high energy, 2 gluons in the initial states: no quark
- The photon needs to be emitted by the heavy-quark loop
- Consequence: gluon fragmentation associated with $C = +1$ octet $[{}^1S_0^{[8]}$ & ${}^3P_J^{[8]}]$ **instead** of $C = -1$ octet $[{}^3S_1^{[8]}]$ for the inclusive case
- CS rate at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

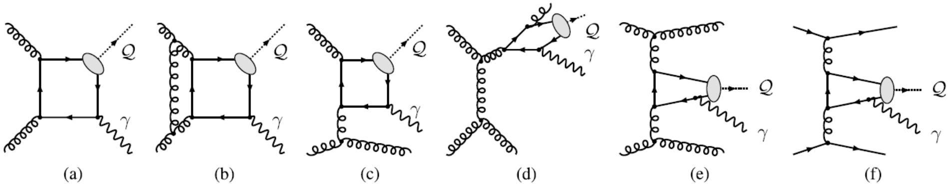
- At NNLO*, CS rate clearly above (high) expectation from CO



JPL, PLB 679,340,2009.

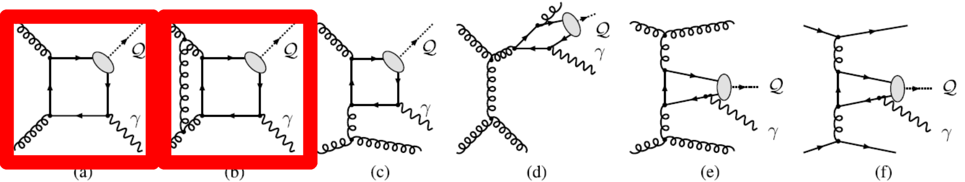
- All this is certainly interesting but TMD factorisation is most likely not applicable because of colour in the final state (either COM or gluons)

$\mathcal{Q} + \gamma$: **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).

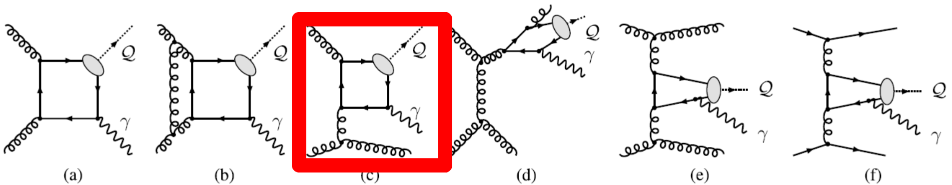
$\mathcal{Q} + \gamma$: **back-to-back** and both isolated



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}

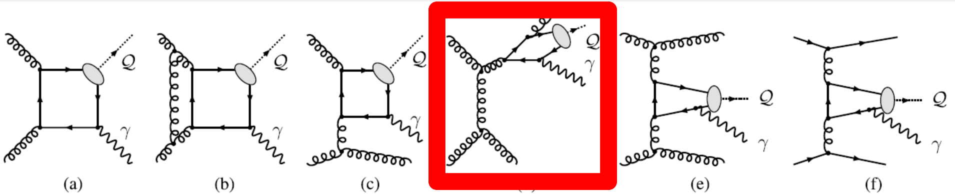
$\mathcal{Q}+\gamma$: **back-to-back** and both isolated



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}

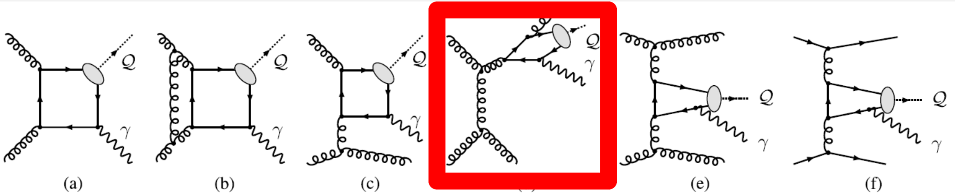
$\mathcal{Q} + \gamma$: **back-to-back** and both isolated



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: $2 \to 2$ 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}

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

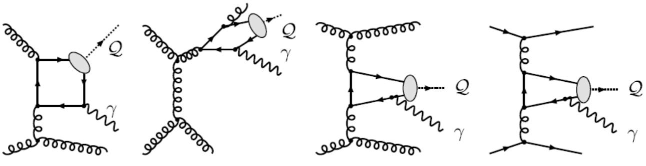


Representative diagrams contributing to the hadroproduction of a $\mathcal{Q}$ in association with a photon at orders $\alpha_S^2\alpha$ (a), $\alpha_S^3\alpha$ (b, c), $\alpha_S^4\alpha$ (d, e, f).

- 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



(c) (d) (e) (f)

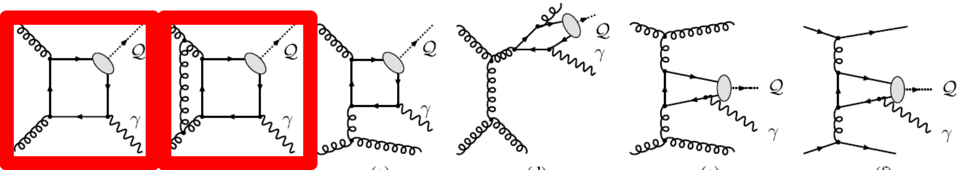
Representative diagrams contributing to the hadroproduction of a $\mathcal{Q}$ in association with a photon at orders $\alpha_S^2\alpha$ (a), $\alpha_S^3\alpha$ (b, c), $\alpha_S^4\alpha$ (d, e, f).

- 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).

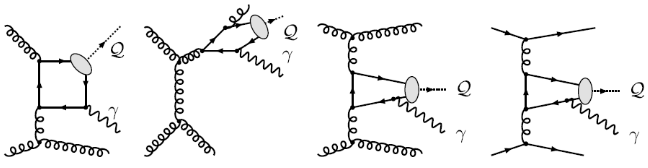
- Born (LO) + loop: $2 \to 2$ contributions (a)-(b) fall like P_T^{-8}
- At NLO: topologies like (c) contribute at mid P_T : P_T^{-6}
- At NNLO: topologies like (d) dominate at very large P_T : P_T^{-4}
- COM contributions similar to (d):

  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



(c) (d) (e) (f)

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 [→ some hadrons] in the central region;

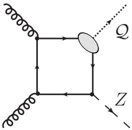
  for (d), hadrons near the $\mathcal{Q}$
- $2 \to 2$ topologies contribute to $\Delta\phi_{\mathcal{Q}-\gamma} = \pi$ (back-to-back) ;

  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]

$\Upsilon + Z$ cross sections

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

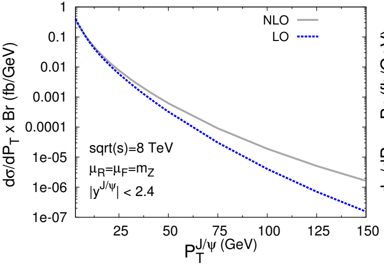
- Rates similar for $\Upsilon + Z$ and $J/\psi + Z$ [Same for $\mathcal{Q} + \gamma$ for $Q \gtrsim 20$ GeV]

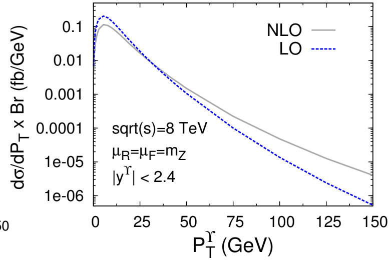


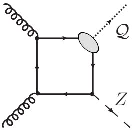
$\Upsilon + Z$ cross sections

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]



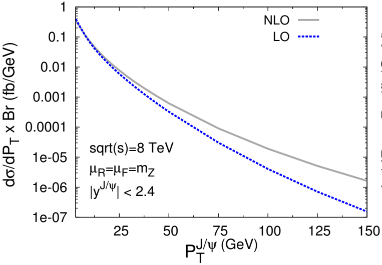


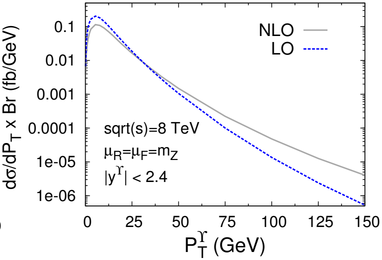


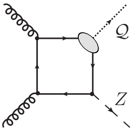
$\Upsilon + Z$ cross sections

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]





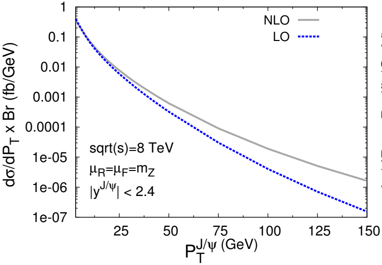


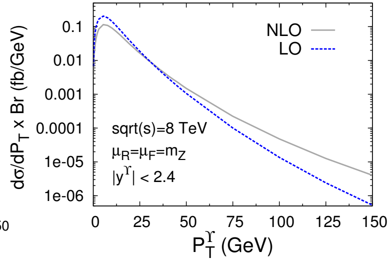
- Potential probe of gluon TMDs as well

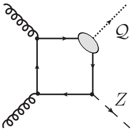
$\Upsilon + Z$ cross sections

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]





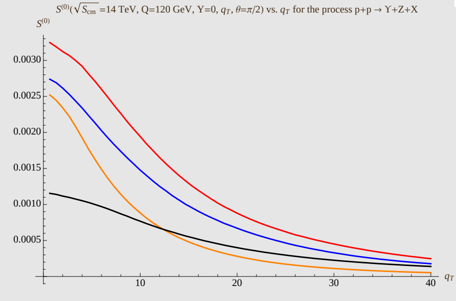


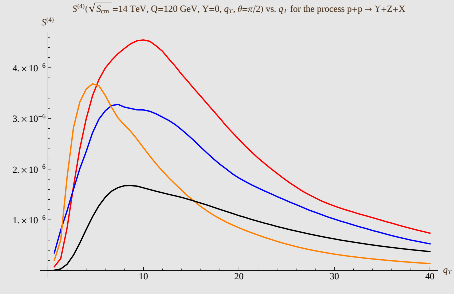
- Potential probe of gluon TMDs as well
- Rate clearly smaller than $\mathcal{Q} + \gamma$ even at low P_T

$\Upsilon + Z$ and TMDs

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

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

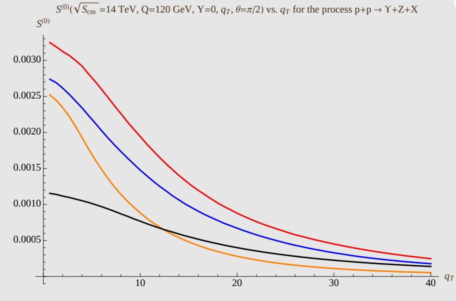


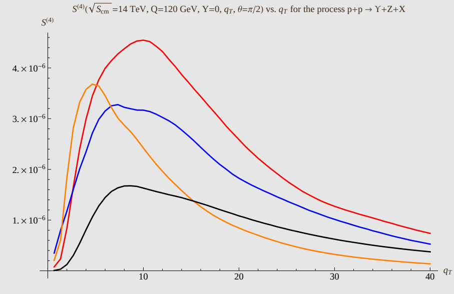


$\Upsilon + Z$ and TMDs

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

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



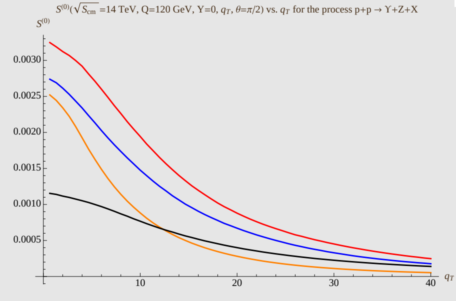


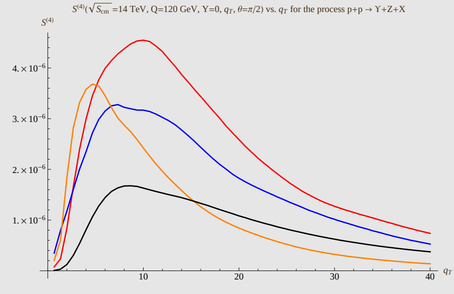
- $\mathcal{S}^{(n)}_{q_T}$ smaller than for $\mathcal{Q} + \gamma$ [one can integrate up to larger q_T, though]

$\Upsilon + Z$ and TMDs

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

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

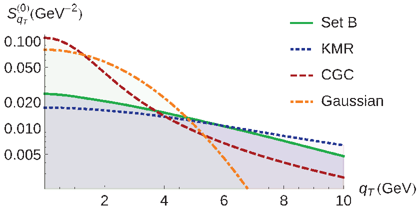




- $\mathcal{S}^{(n)}_{q_T}$ smaller than for $\mathcal{Q} + \gamma$ [one can integrate up to larger q_T, though]
- Naturally large Q: interest to study the scale evolution ?

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

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

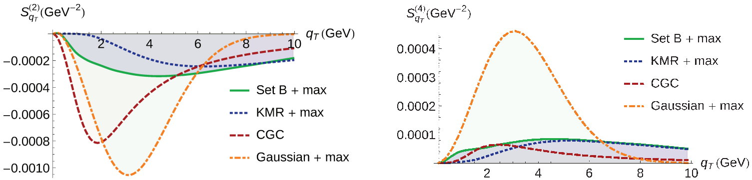


Models for f_1^g: assumed to be the same as for Unintegrated Gluon Distributions

- 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, $\quad Y = 0, \quad \theta_{CS} = \pi/2$



$h_1^{\perp g}$: 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

$$2.0\% \text{ (KMR)} < \quad |\int \mathrm{d}q_T^2 \mathcal{S}^{(2)}_{q_T}| \quad < 2.9\% \text{ (Gauss)}$$
$$0.3\% \text{ (CGC)} < \quad \int \mathrm{d}q_T^2\, \mathcal{S}^{(4)}_{q_T} \quad < 1.2\% \text{ (Gauss)}$$

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 $g^\star$

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

why ?

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

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

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

why ?

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

The cross sections are well-known:

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

$q\bar{q}' \to \gamma^\star W \stackrel{^3S_1^{[1]}}{\to} J/\psi W$ 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:

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

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: $\hat{\sigma}^{[1]}_{via\ \gamma^\star} = \frac{(4\pi\alpha)^2 e_q^2 e_Q^2}{M_\mathcal{Q}^3\, s}\,\delta\left(x_1x_2 - M_\mathcal{Q}^2/s\right)|R(0)|^2$
- COM: $\hat{\sigma}^{[8]}_{via\ g^\star} = \frac{(4\pi\alpha_S)^2\pi}{27 M_\mathcal{Q}^3\, s}\,\delta\left(x_1x_2 - M_\mathcal{Q}^2/s\right)\langle\mathcal{O}_\mathcal{Q}(^3S_1^{[8]})\rangle$
- 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 $\mu_R : \mathcal{O}(m_\mathcal{Q}) \to \mathcal{O}(m_W)$

$\to$ 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