Accessing gluon TMDs with quarkonium production

J.P. Lansberg
IPN Orsay – Paris-Sud U. –CNRS/IN2P3
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Results obtained in collaboration with W. den Dunnen, M. Echevarria, C. Lorcé, C. Pisano, A. Signori, F. Scarpa, M. Schlegel, H.S. Shao

Part I

Generalities on gluon TMDs

Beyond collinear factorisation

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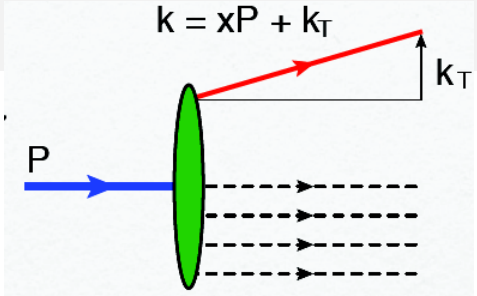

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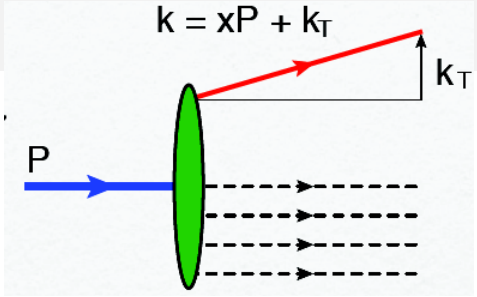

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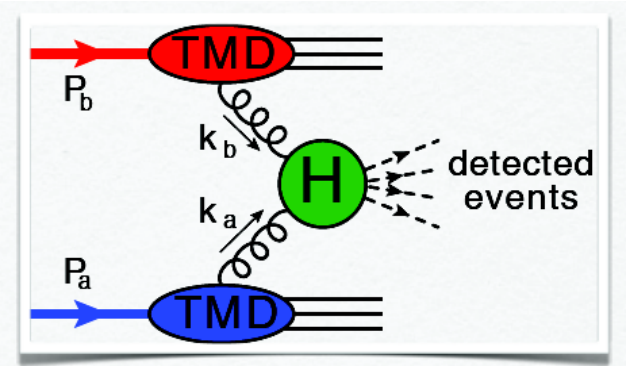

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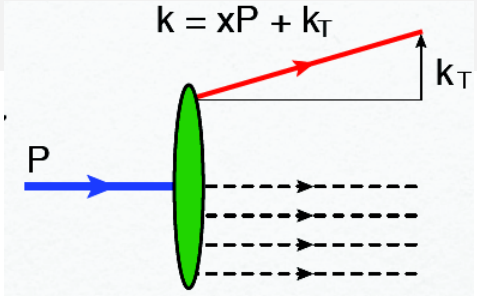

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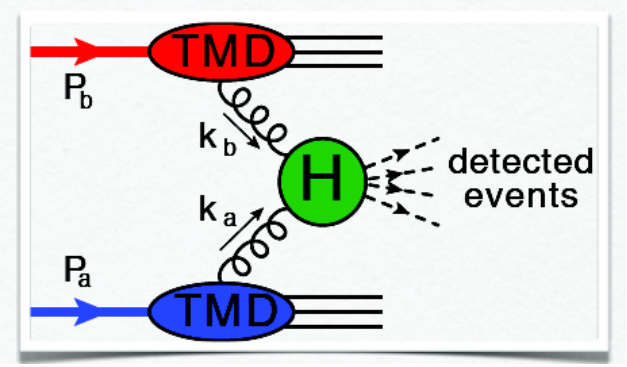

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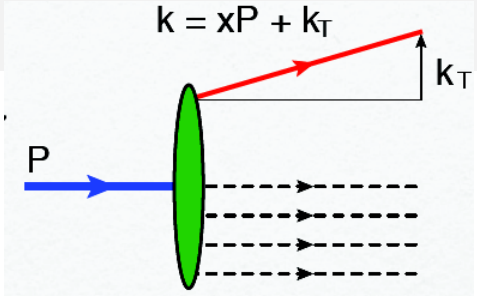

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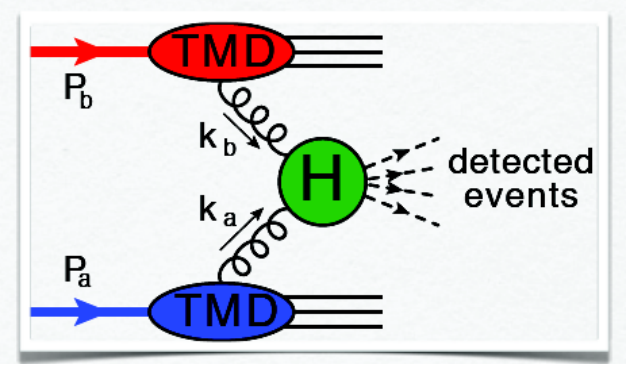

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$$d\sigma = \frac{(2\pi)^4}{8s^2} \int d^2\boldsymbol{k}_{1T} d^2\boldsymbol{k}_{2T} \delta^2(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{q}_T) H_{\mu\rho} (H_{\nu\sigma})^* \times$$

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

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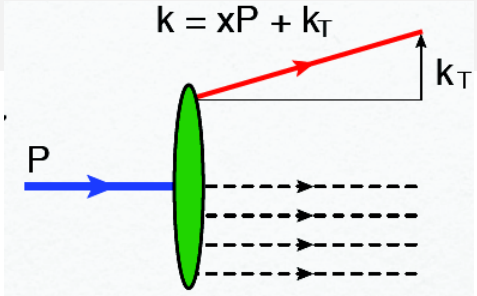

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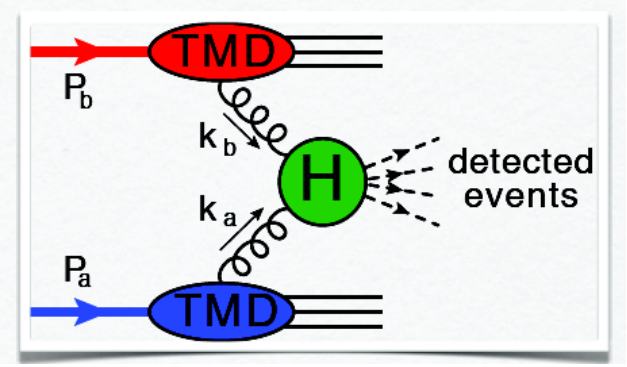

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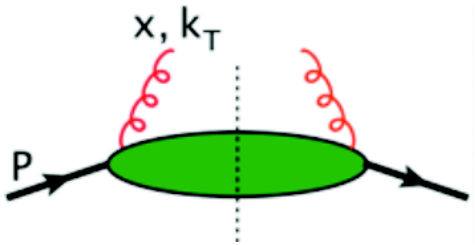
- Should work for SIDIS + pp reactions with colour singlet final states

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

Gluon TMDs in unpolarised protons



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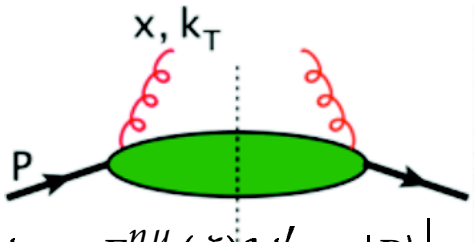

- Gauge-invariant definition:

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

- $\mathcal{U}$ and $\mathcal{U}'$ are process dependent gauge links

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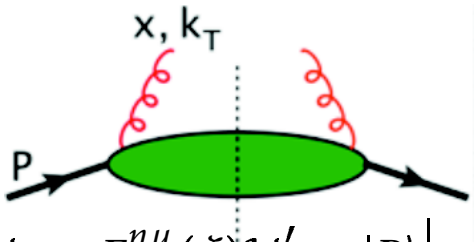

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P. J. Mulders, J. Rodrigues, PRD 63 (2001) 094021

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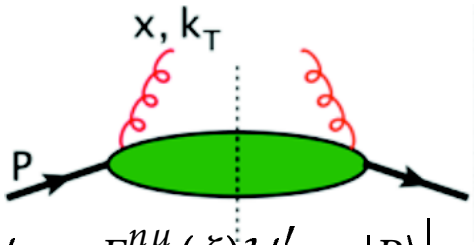

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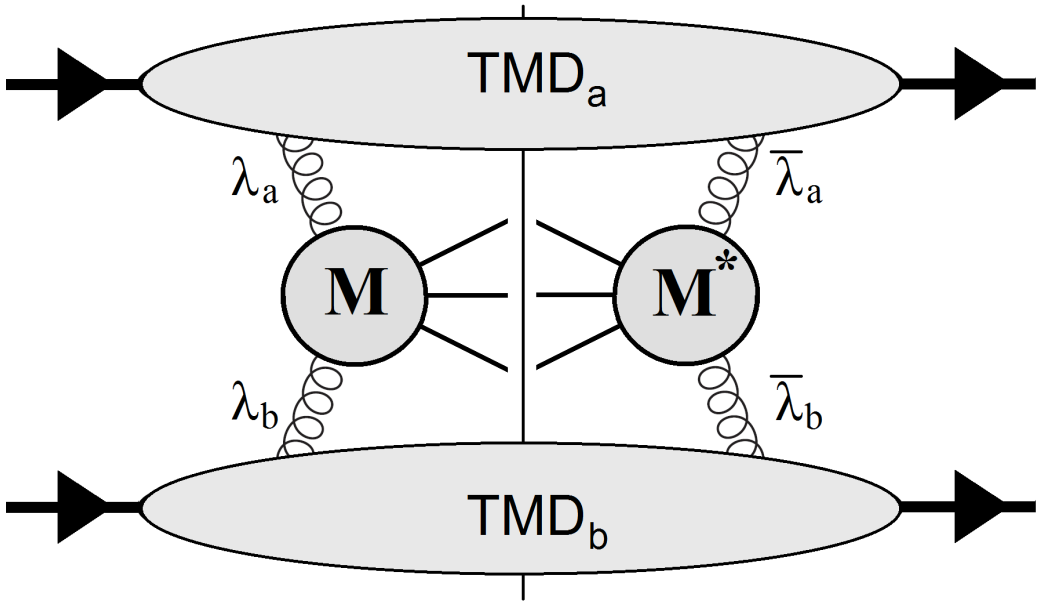
- f_1^g: TMD distribution of unpolarised gluons
- $h_1^{\perp g}$: TMD distribution of linearly polarised gluons

[Helicity-flip distribution]

gg fusion in arbitrary process (colourless final state)

$d\sigma^{gg} \propto$



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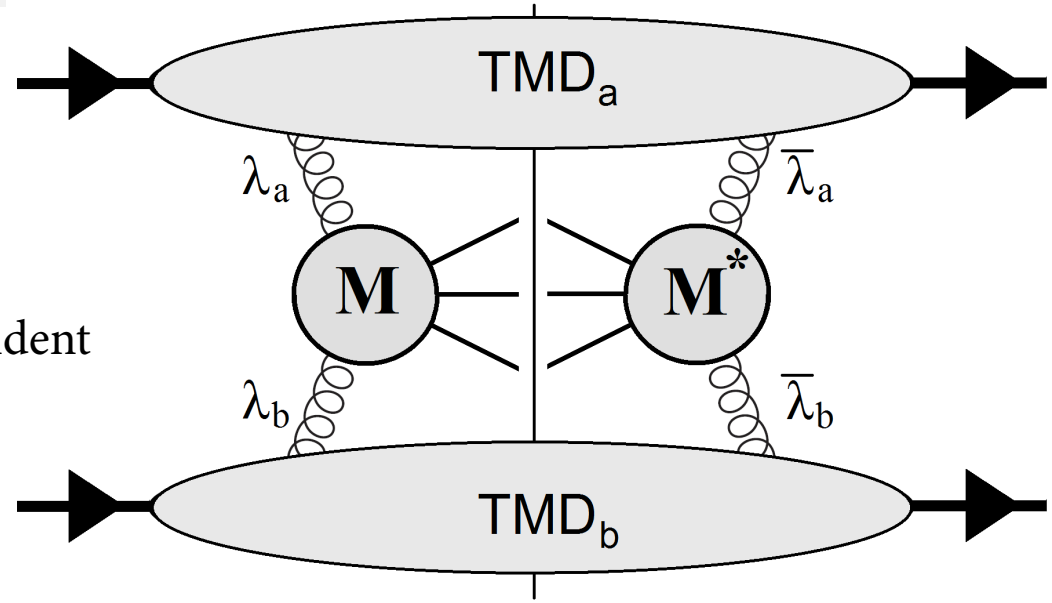
$\Rightarrow$ helicity non-flip, azimuthally independent



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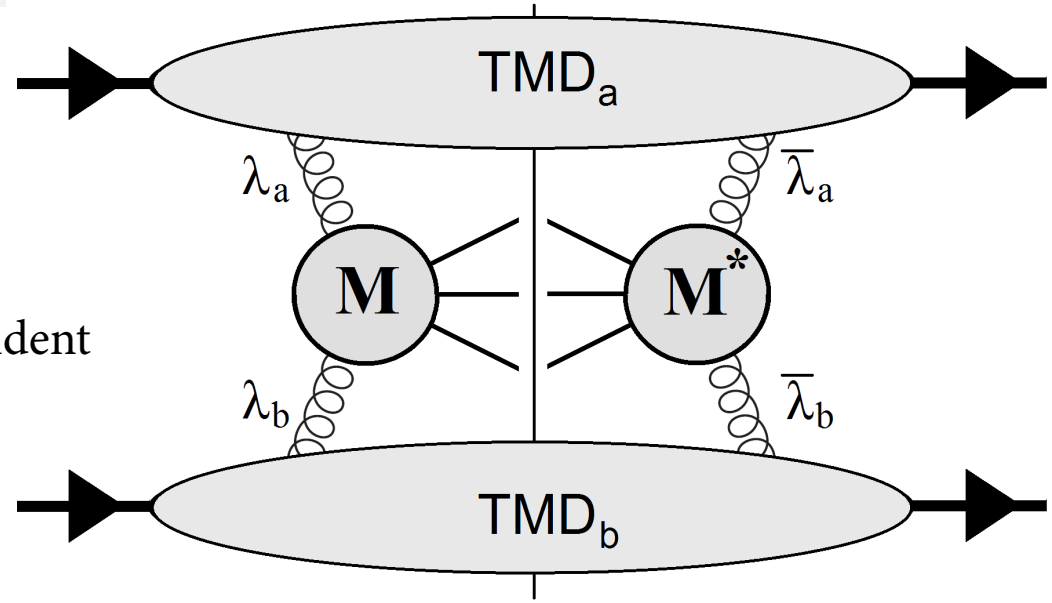

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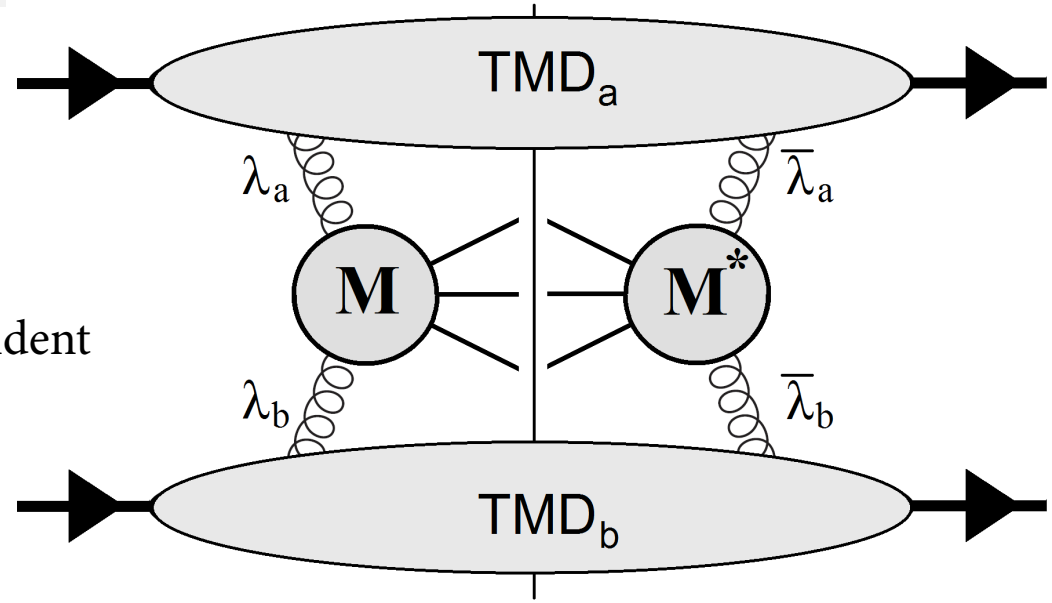

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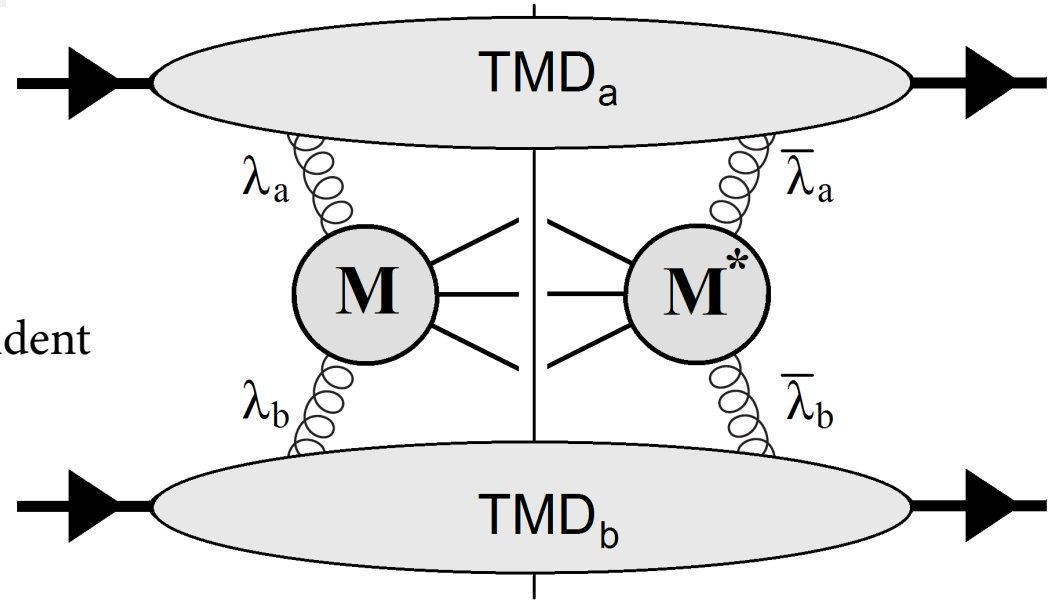

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Visualisation of $h_1^{\perp g}$

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

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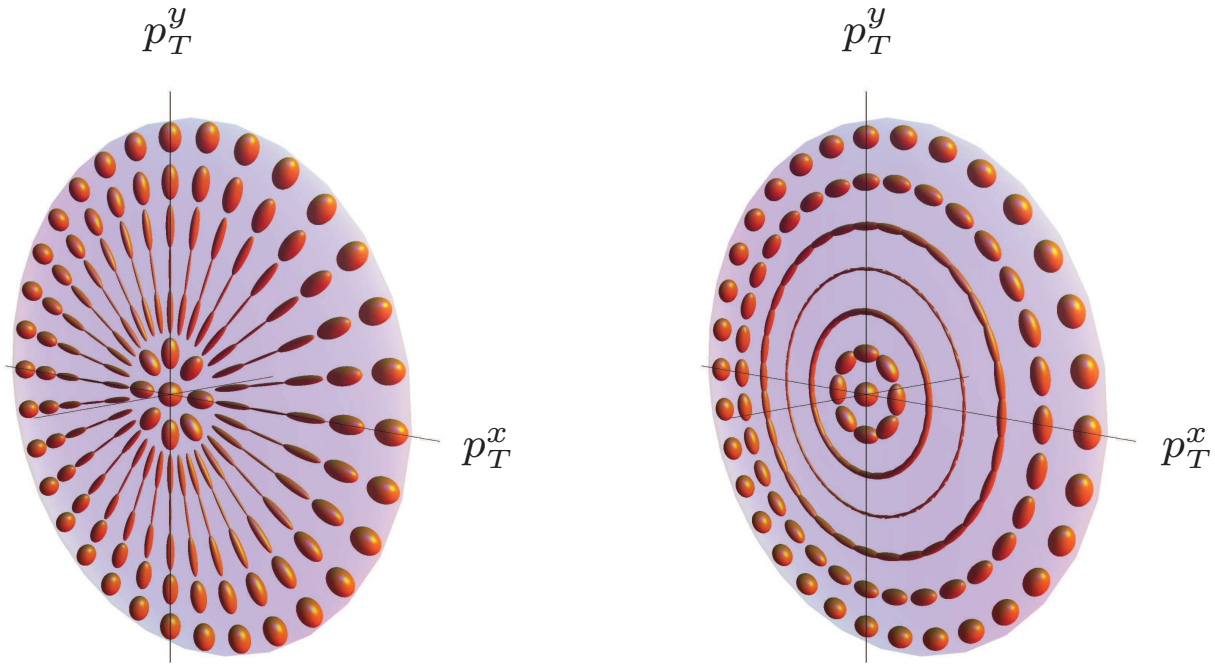

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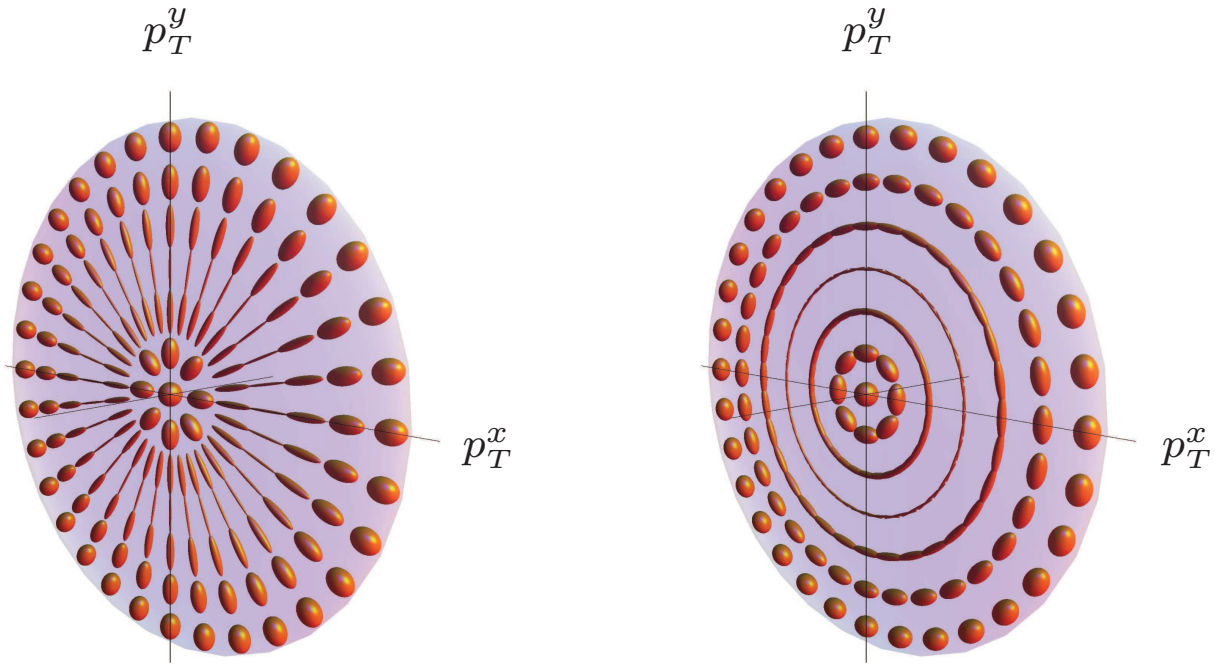

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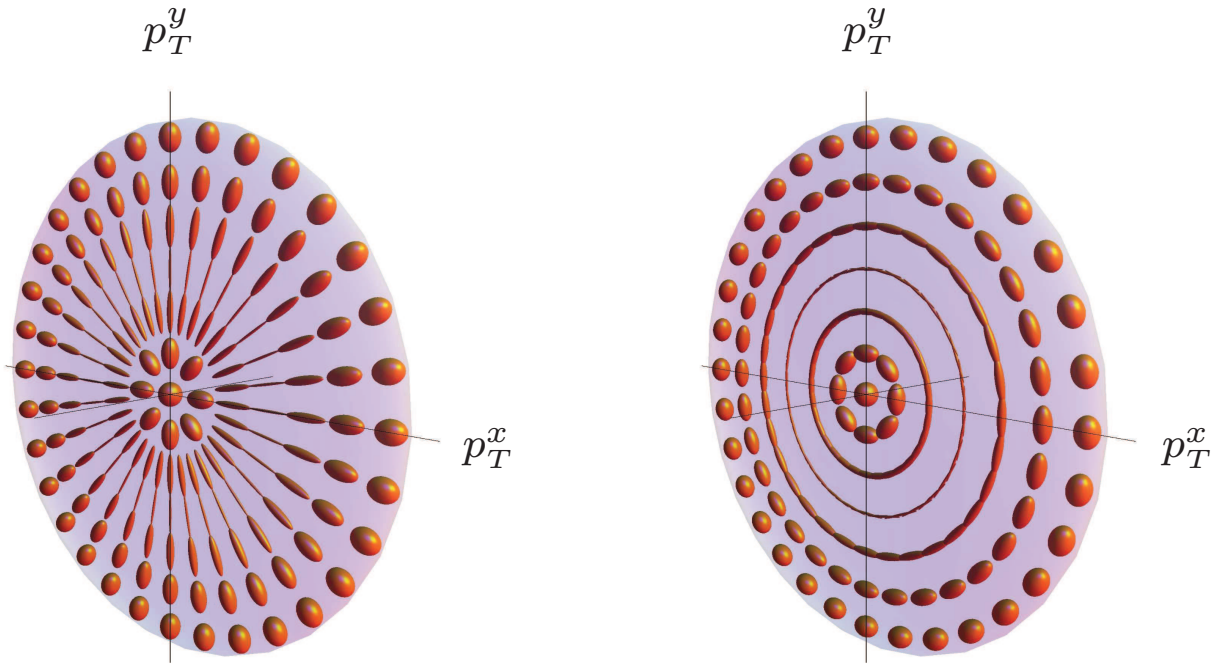

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- This bound is saturated by a number of models

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- CS vs. CO contributions should be analysed case by case

[reactions and kinematics]

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  - Hard scale has to be the particle mass : $Q^2 = M^2$
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- Back-to-back (low q_T) $2 \to 2$ process :
  - Produced particles can each have a large $\vec{p}_T$ adding up to make a small $\vec{q}_T$ for the pair. One can impose $\vec{p}_T$ large enough for the particle to be detectable
  - This renders the TMD "region" ($q_T \ll Q$) as wide as we wish
  - Hard scale $Q^2 = (k_1 + k_2)^2$ can be tuned to study the
  QCD evolution of the TMDs

Part II

Ideas to extract gluon TMDs at colliders

Di-photon

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

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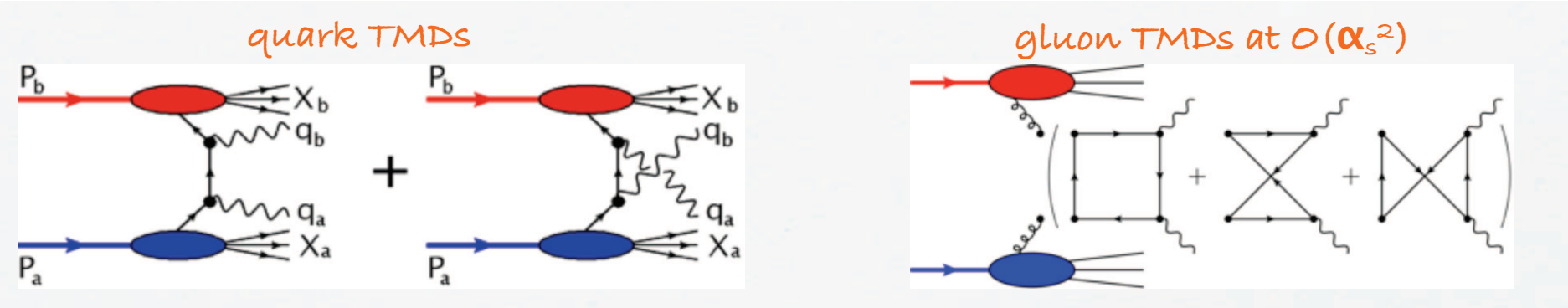

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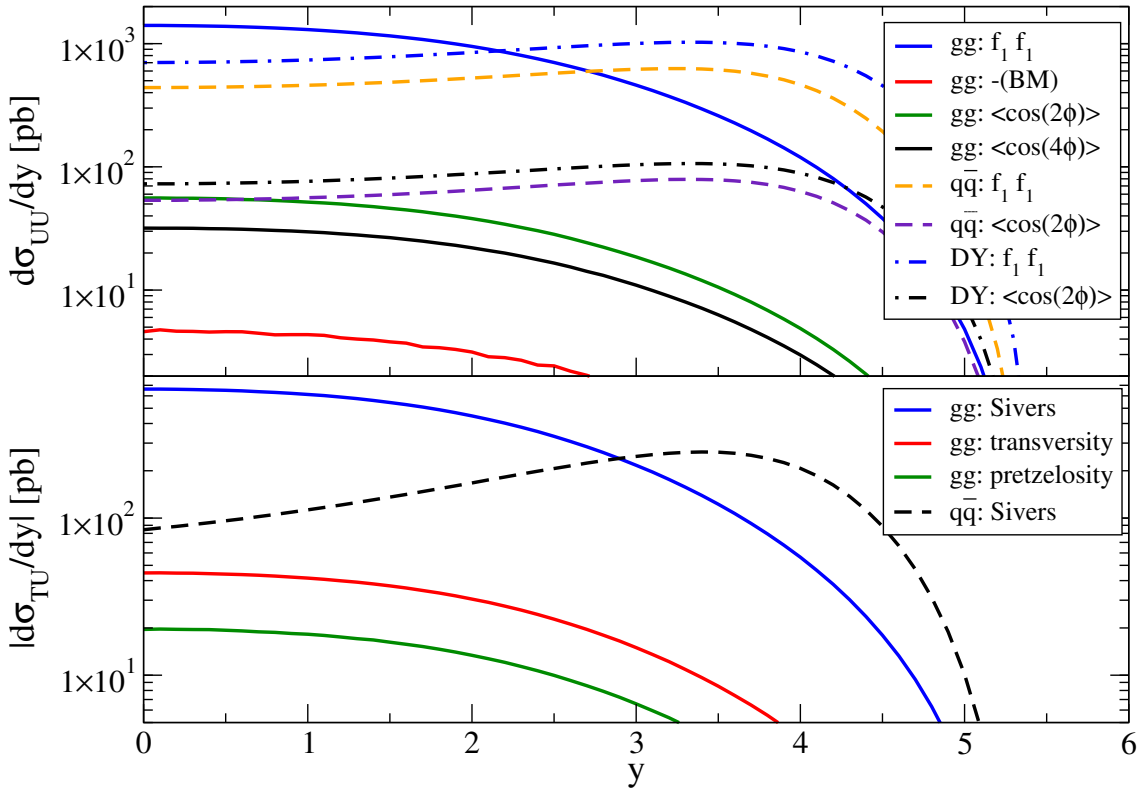

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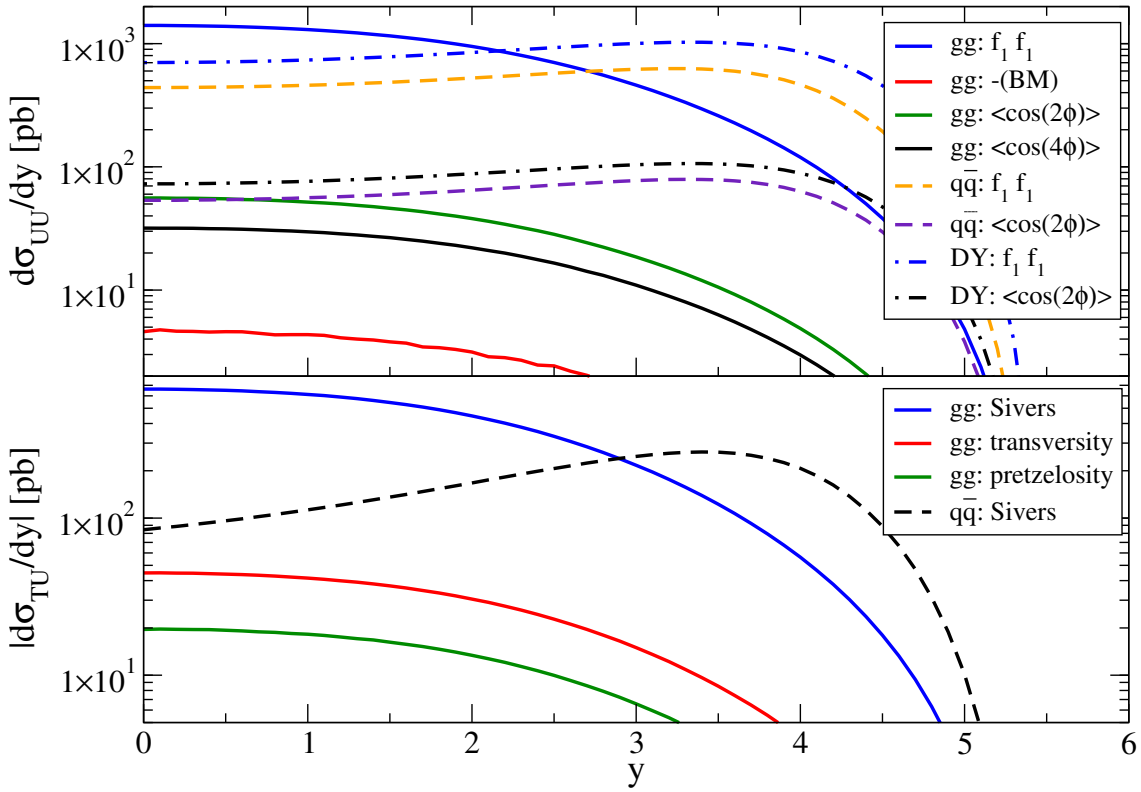

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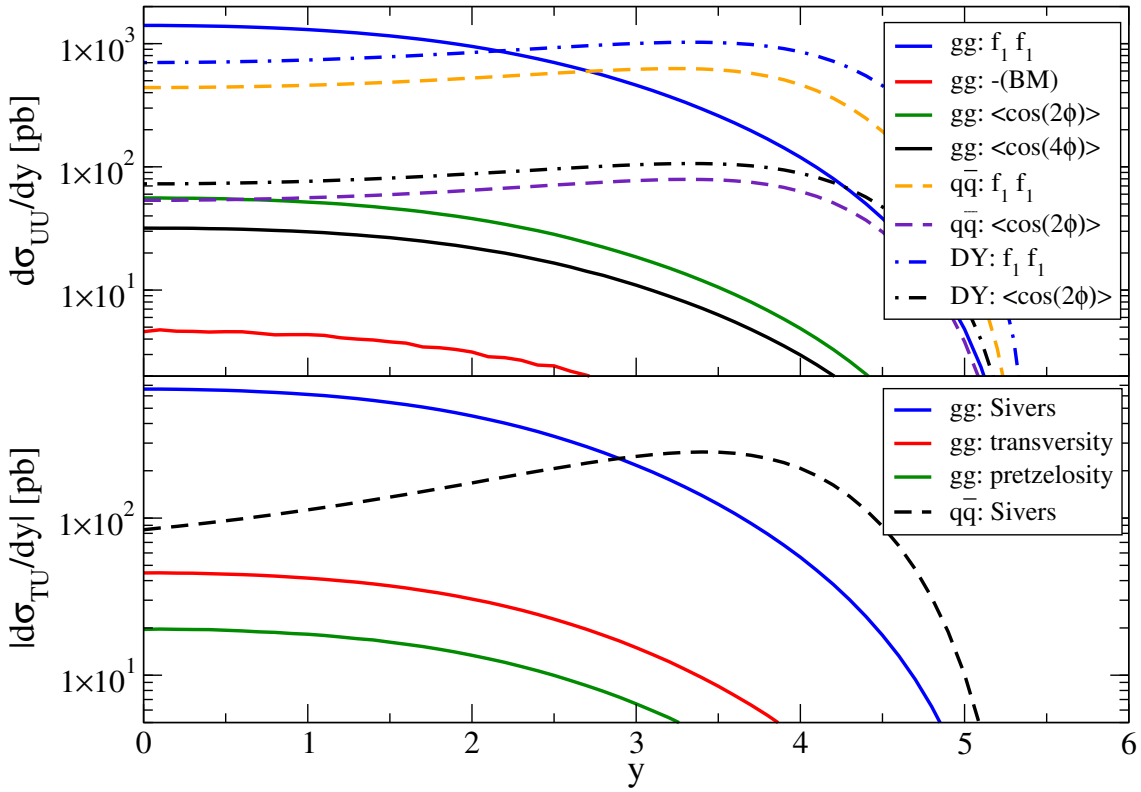

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- Huge background from $\pi^0 \rightarrow$ isolation cuts are needed

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

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- In general, heavy-flavor prod. selects out gg channels

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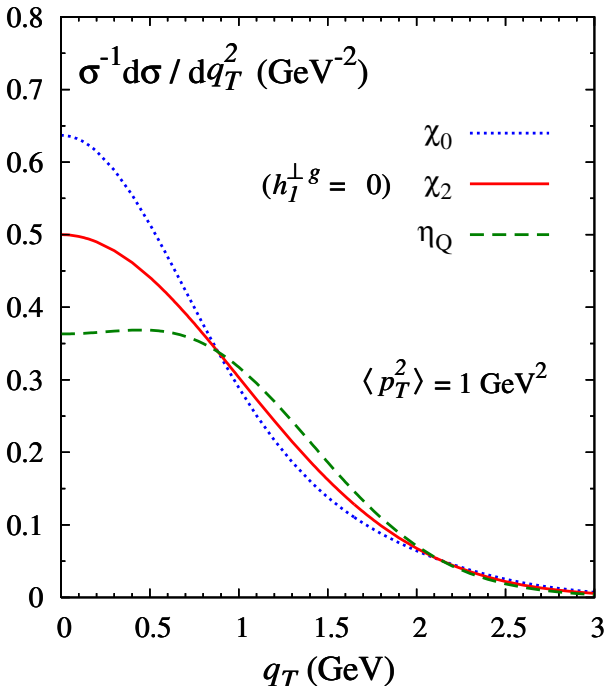

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$$\frac{1}{\sigma}\frac{d\sigma(\eta_Q)}{d\mathbf{q}_T^2} \propto 1 - R(\mathbf{q}_T^2) \;\&\; \frac{1}{\sigma}\frac{d\sigma(\chi_{Q,0})}{d\mathbf{q}_T^2} \propto 1 + R(\mathbf{q}_T^2)$$

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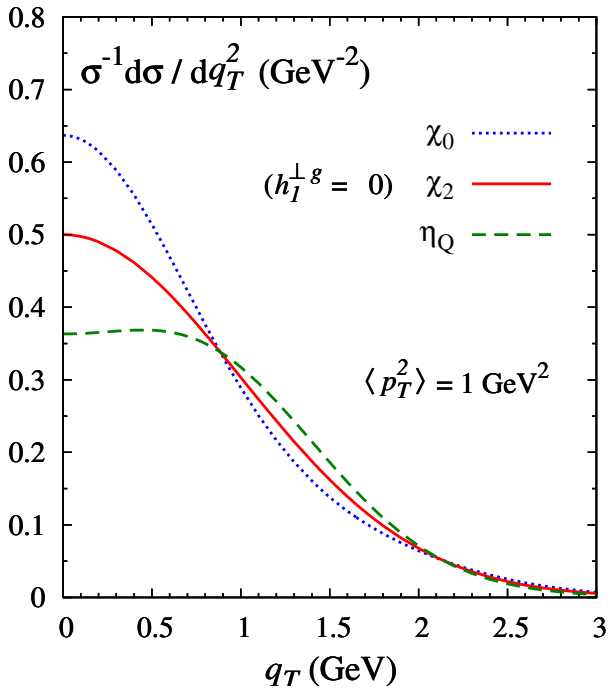

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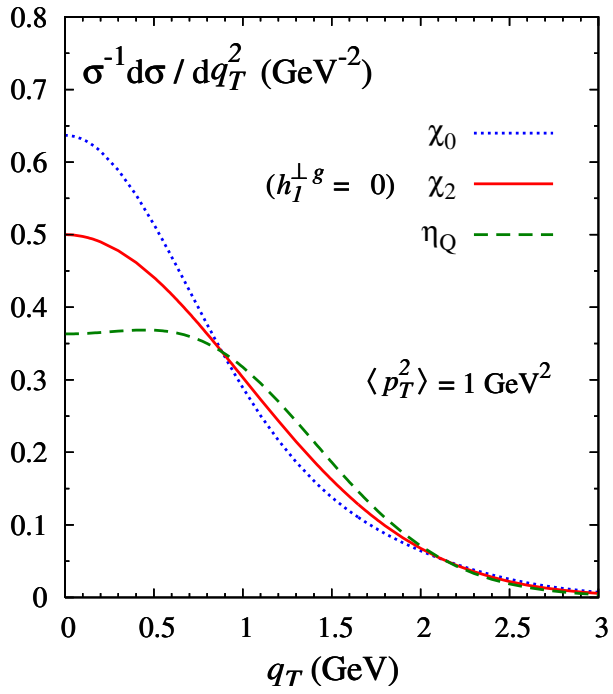

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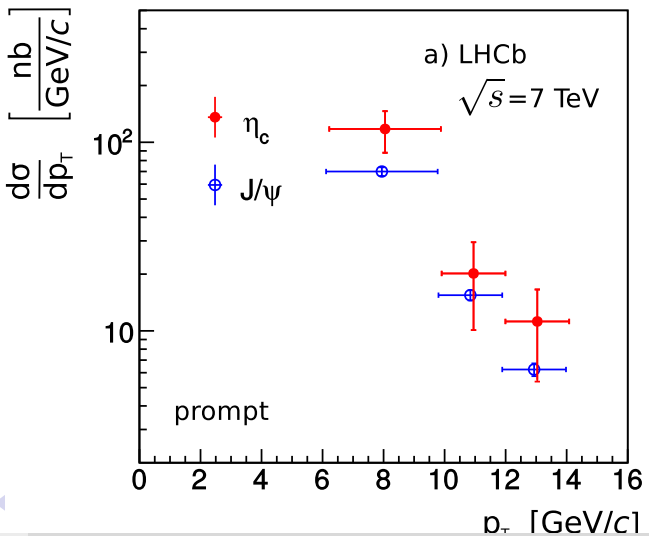
- Cannot tune Q: $Q \simeq m_{\mathcal{Q}}$
- Low P_T: Experimentally very difficult

First η_c production study at collider ever, only released in 2014

for $P_T^{\eta_c} > 6$ GeV **LHCb, EPJC75 (2015) 311**



Low P_T quarkonia and TMDs II

- η_c **production at one-loop** : everything works fine

PHYSICAL REVIEW D **88**, 014027 (2013)

Transverse momentum dependent factorization for quarkonium production at low transverse momentum

J. P. Ma,[1,2] J. X. Wang,[3] and S. Zhao[1]
[1]*Institute of Theoretical Physics, Academia Sinica, P.O. Box 2735, Beijing 100190, China*
[2]*Center for High-Energy Physics, Peking University, Beijing 100871, China*
[3]*Institute of High Energy Physics, Academia Sinica, P.O. Box 918(4), Beijing 100049, China*

Pheno at NLO: M. Echevarria, T. Kasemets, JPL, C. Pisano, A. Signori, work in progress

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- $\chi_{c0,2}$ factorisation issue ? $\leftrightarrow$ Colour Octet - Colour Singlet mixing

Physics Letters B 737 (2014) 103–108

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Breakdown of QCD factorization for P-wave quarkonium production at low transverse momentum

J.P. Ma [a,b,*], J.X. Wang [c], S. Zhao [a]

[a] *State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Academia Sinica, P.O. Box 2735, Beijing 100190, China*
[b] *Center for High-Energy Physics, Peking University, Beijing 100871, China*
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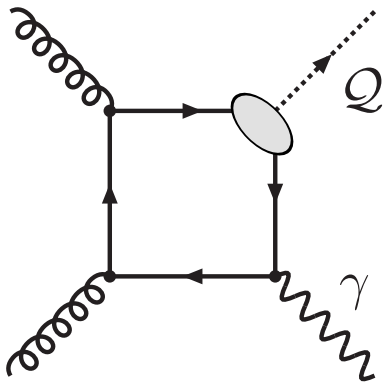
Part III

Going further with associated-quarkonium production

$\mathcal{Q} + \gamma$ at low $P_T^{\psi-\gamma}$

- Unique candidate to pin down the gluon TMDs



$\mathcal{Q} + \gamma$ at low $P_T^{\psi-\gamma}$

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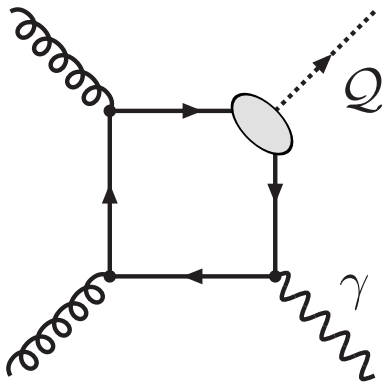
  - Hard scale $M_{\psi-\gamma}$ (or $Q_{\psi-\gamma}$) can be tuned



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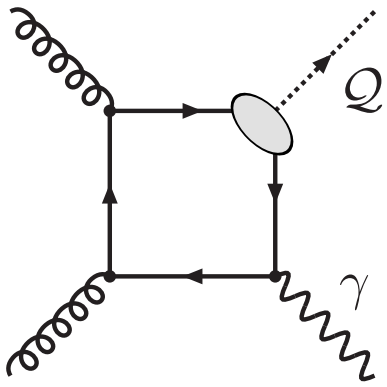

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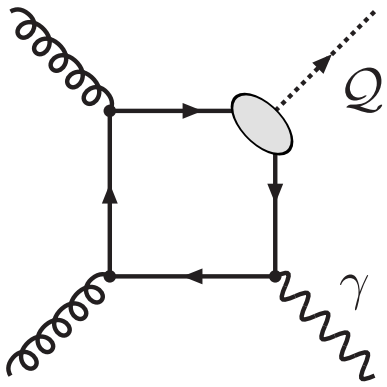

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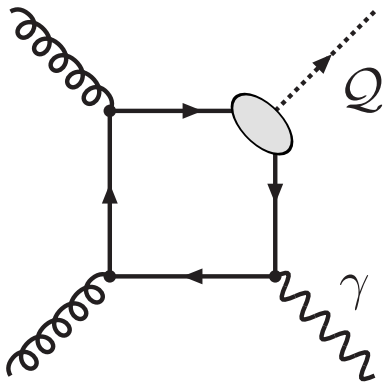

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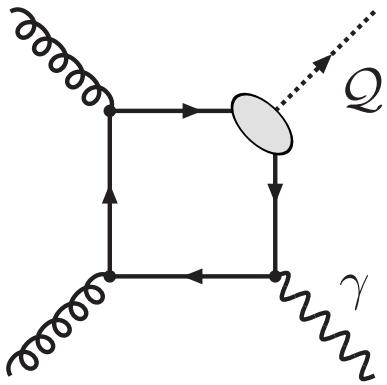

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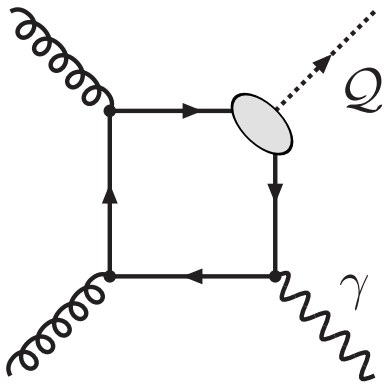

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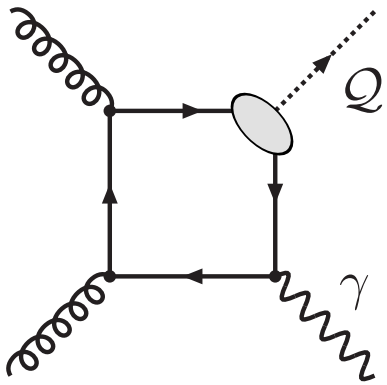

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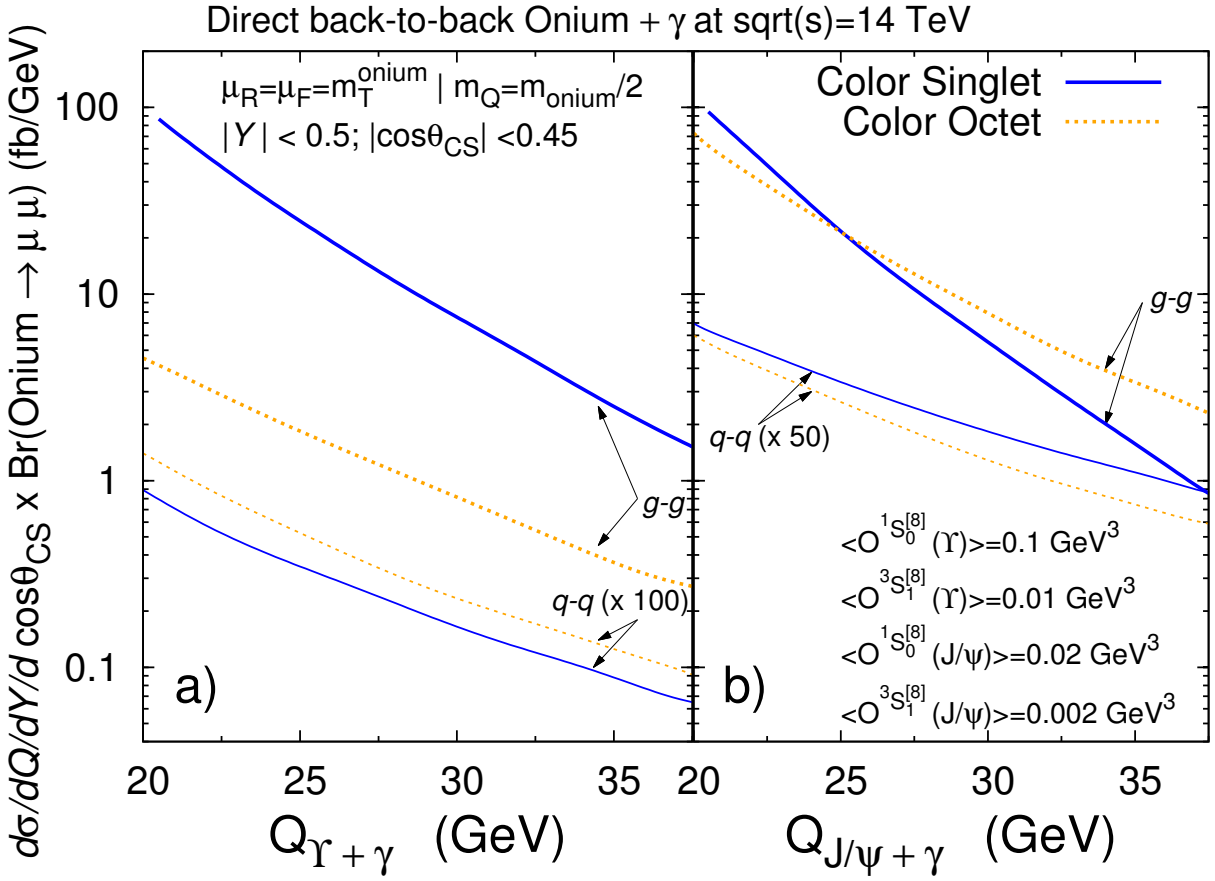
  - TMD factorisation could still hold with CO contributions owing to the presence of the final-state γ

See Higgs+jet: D. Boer, C. Pisano, PRD 91 (2015) 7 074024

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

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



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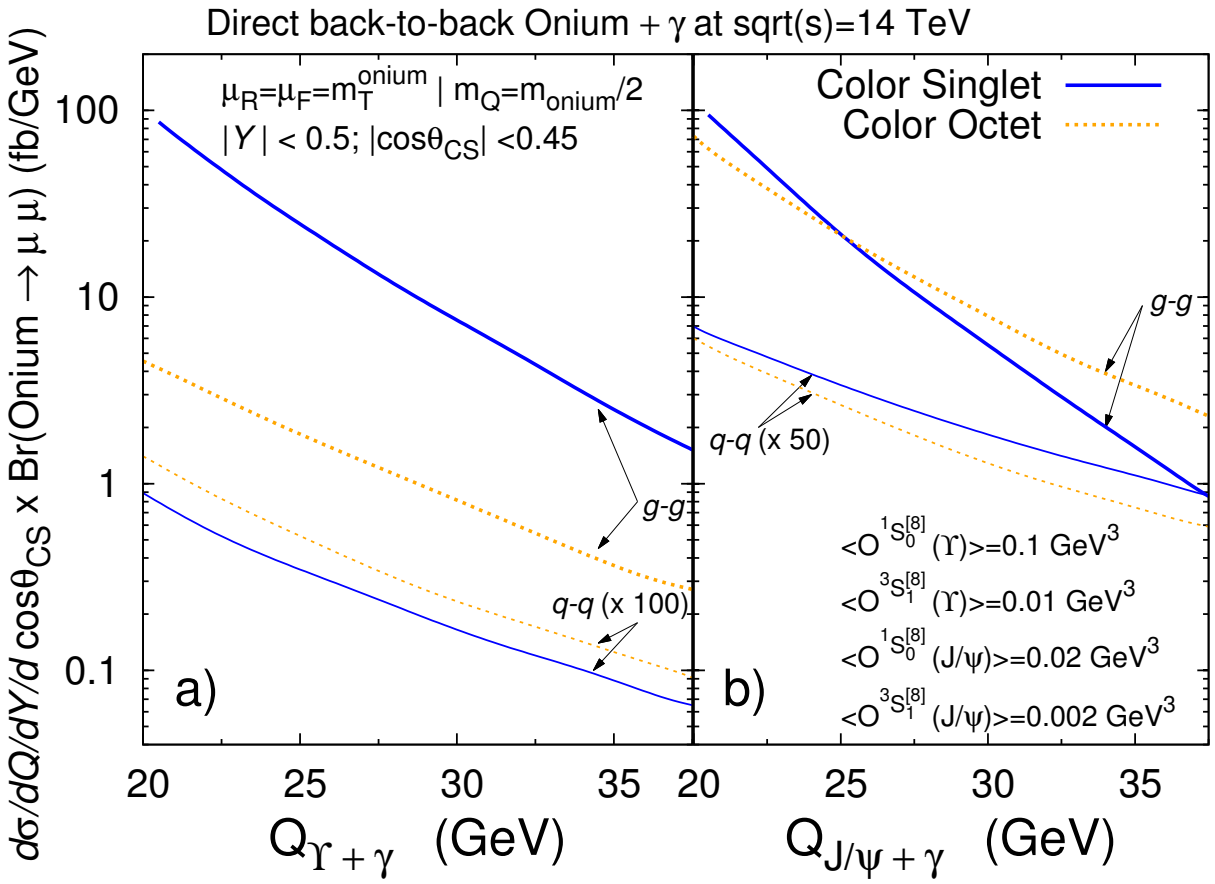

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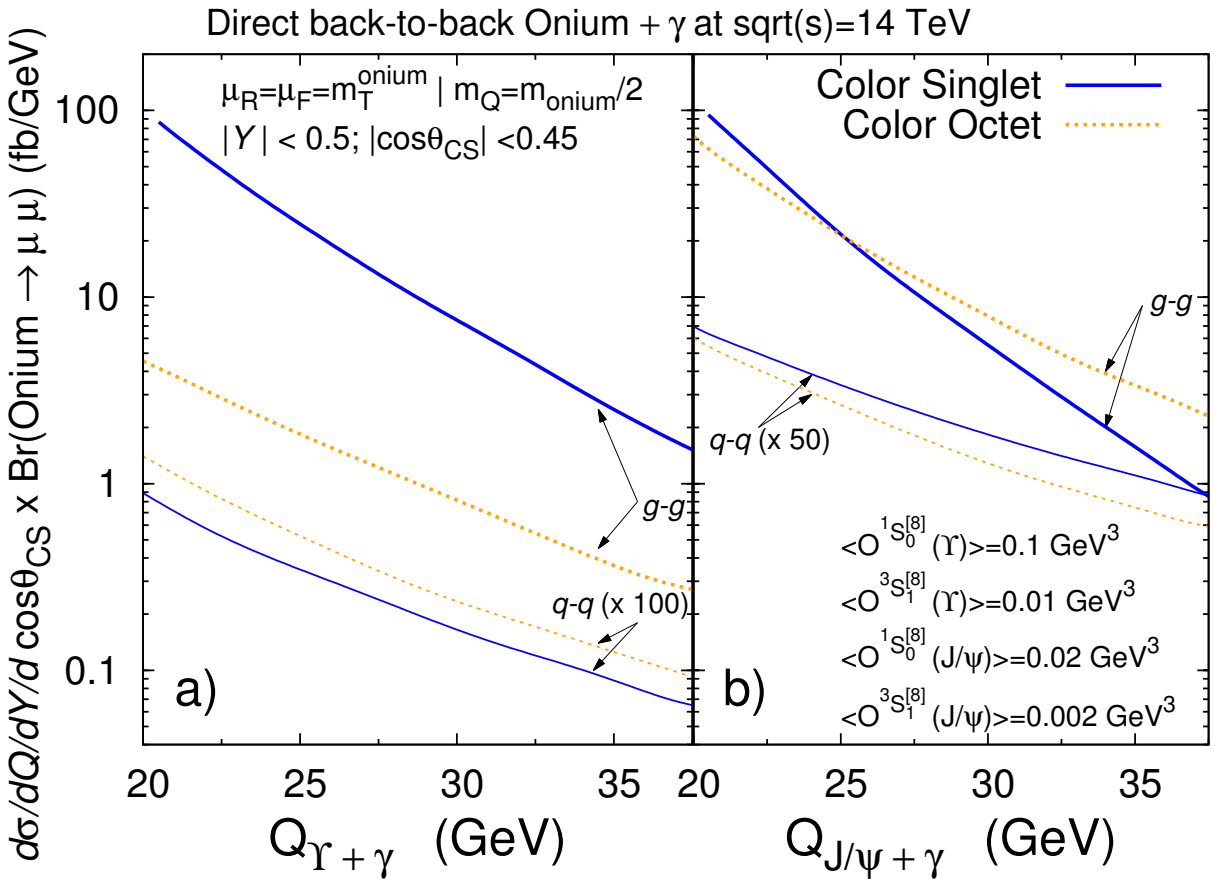

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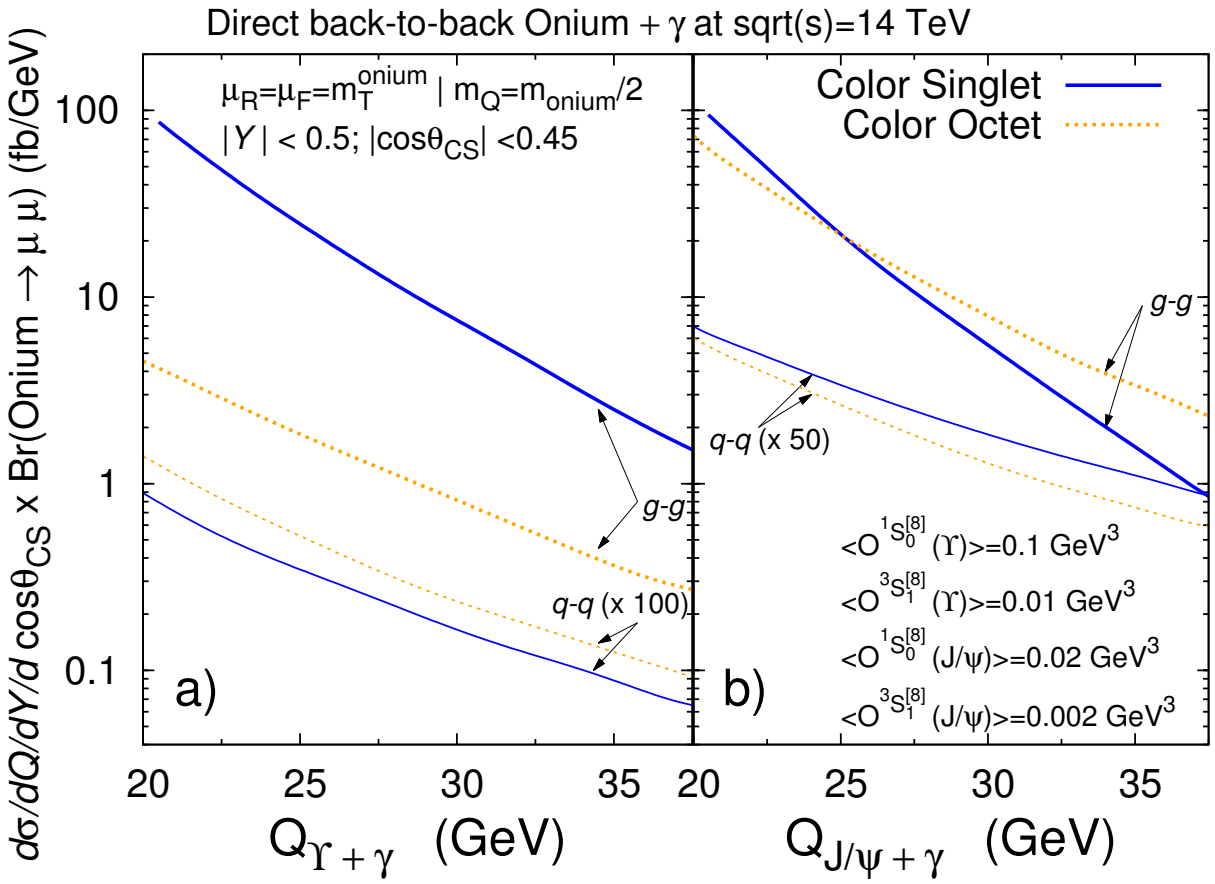

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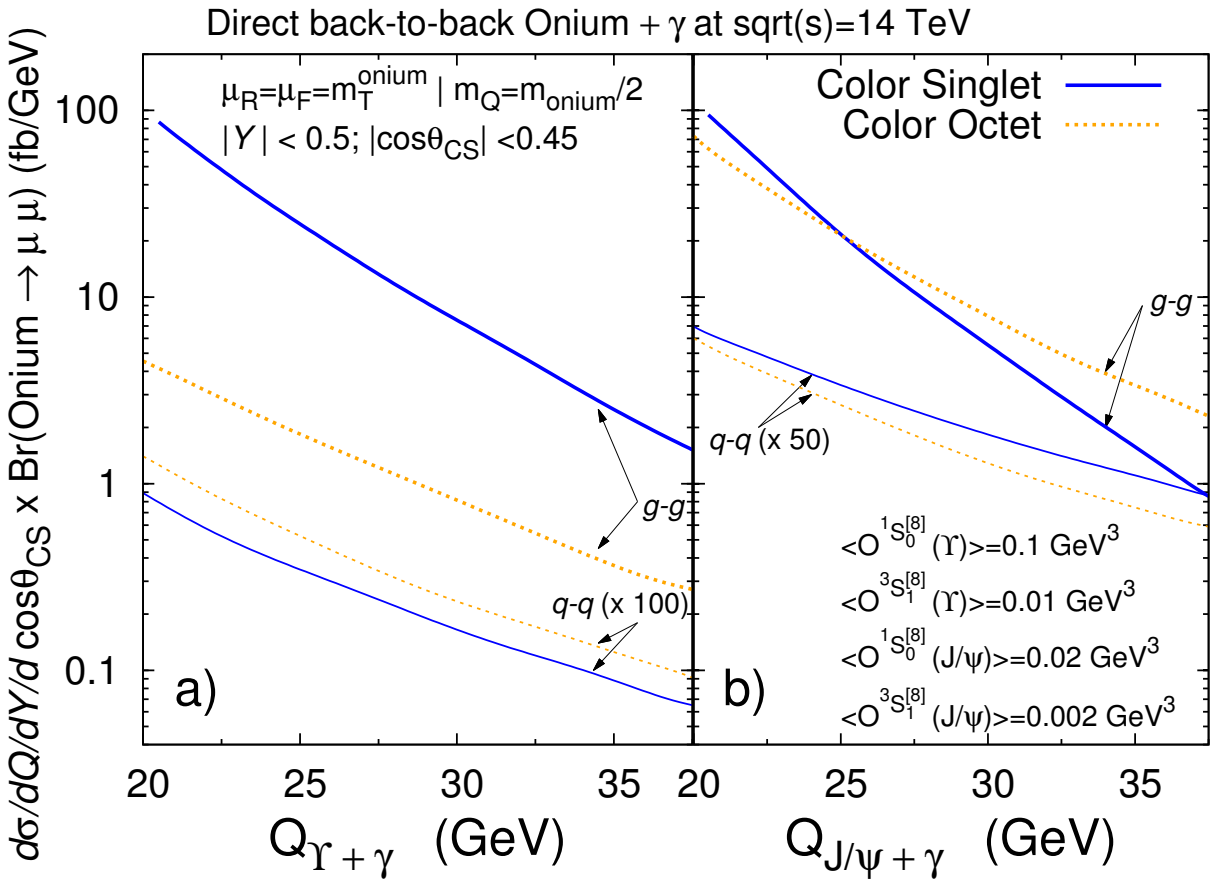

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- With the $\mathcal{L} \simeq 20$ fb^{-1} of pp data on tape, one expects up to 2000 events

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

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

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

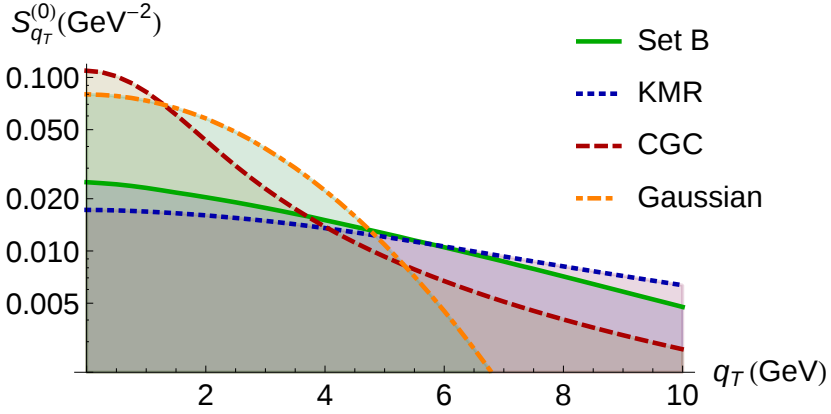
$$\frac{d\sigma}{dQdYd^2\boldsymbol{q}_T d\Omega} = \frac{C_0(Q^2-M_Q^2)}{sQ^3D}\left\{F_1\mathcal{C}\left[f_1^g f_1^g\right] + F_3\cos(2\phi_{CS})\mathcal{C}\left[w^{fh}f_1^g h_1^{\perp g} + x_1\leftrightarrow x_2\right] + F_4\cos(4\phi_{CS})\mathcal{C}\left[w_4^{hh}h_1^{\perp g}h_1^{\perp g}\right]\right\}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

- 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 $h_1^{\perp g}$ $(F_2=0)$ [not always the case]
  - $\mathcal{S}_{q_T}^{(2)} = \frac{F_3\,\mathcal{C}[w_2^{fh}f_1^g h_1^{\perp g}+x_1\leftrightarrow x_2]}{2F_1\int dq_T^2\,\mathcal{C}[f_1^g f_1^g]}$
  - $\mathcal{S}_{q_T}^{(4)} = \frac{F_4\,\mathcal{C}[w_4^{hh}h_1^{\perp g}h_1^{\perp g}]}{2F_1\int dq_T^2\,\mathcal{C}[f_1^g f_1^g]}$

$\boxed{\mathcal{S}_{q_T}^{(2)},\mathcal{S}_{q_T}^{(4)} \neq 0 \Rightarrow \text{nonzero gluon polarisation in unpolarised protons !}}$

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.

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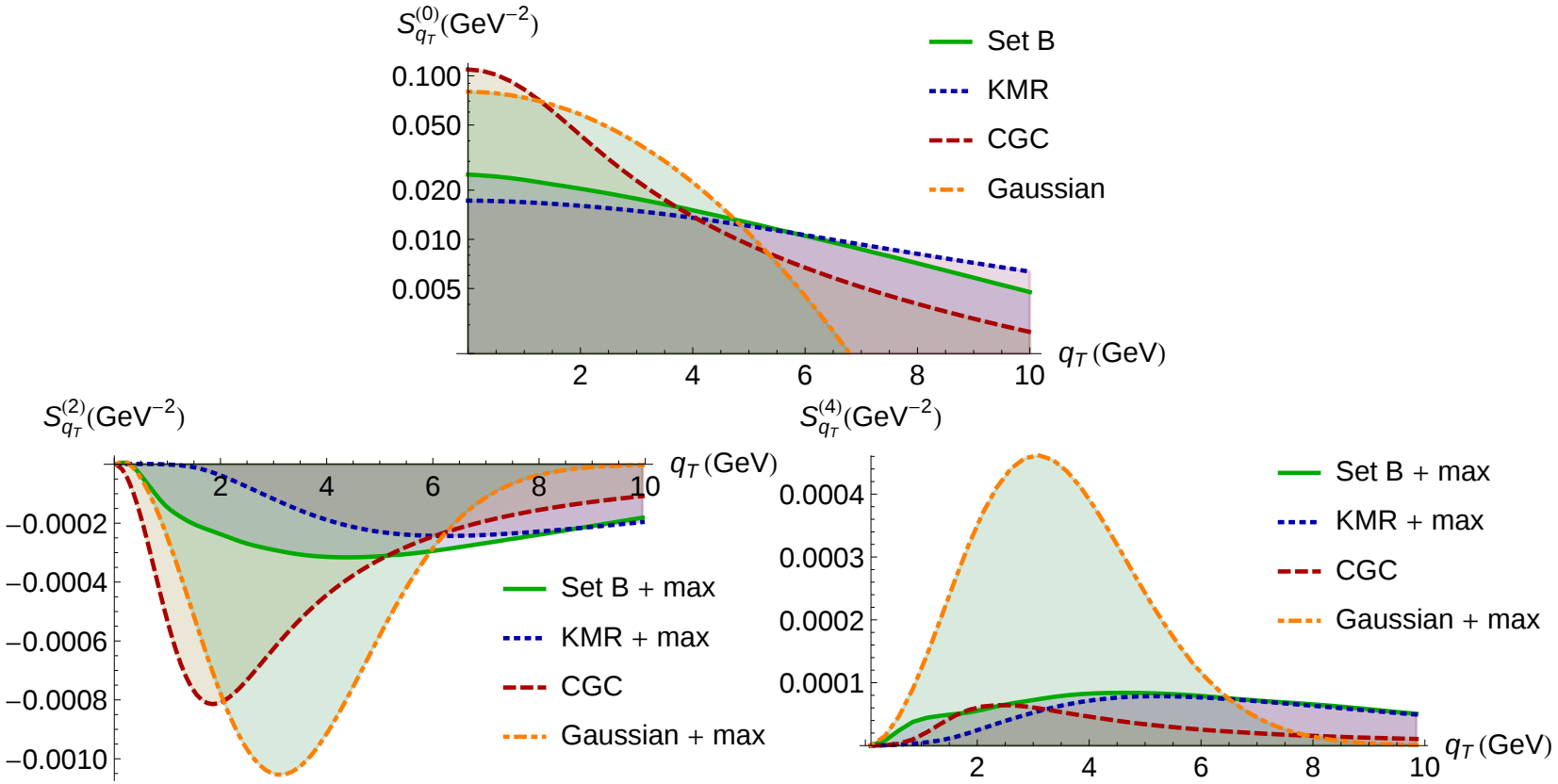

- $\mathcal{S}^{(0)}_{q_T}$: $f_1^g(x, k_T)$ from the q_T-dependence of the yield.
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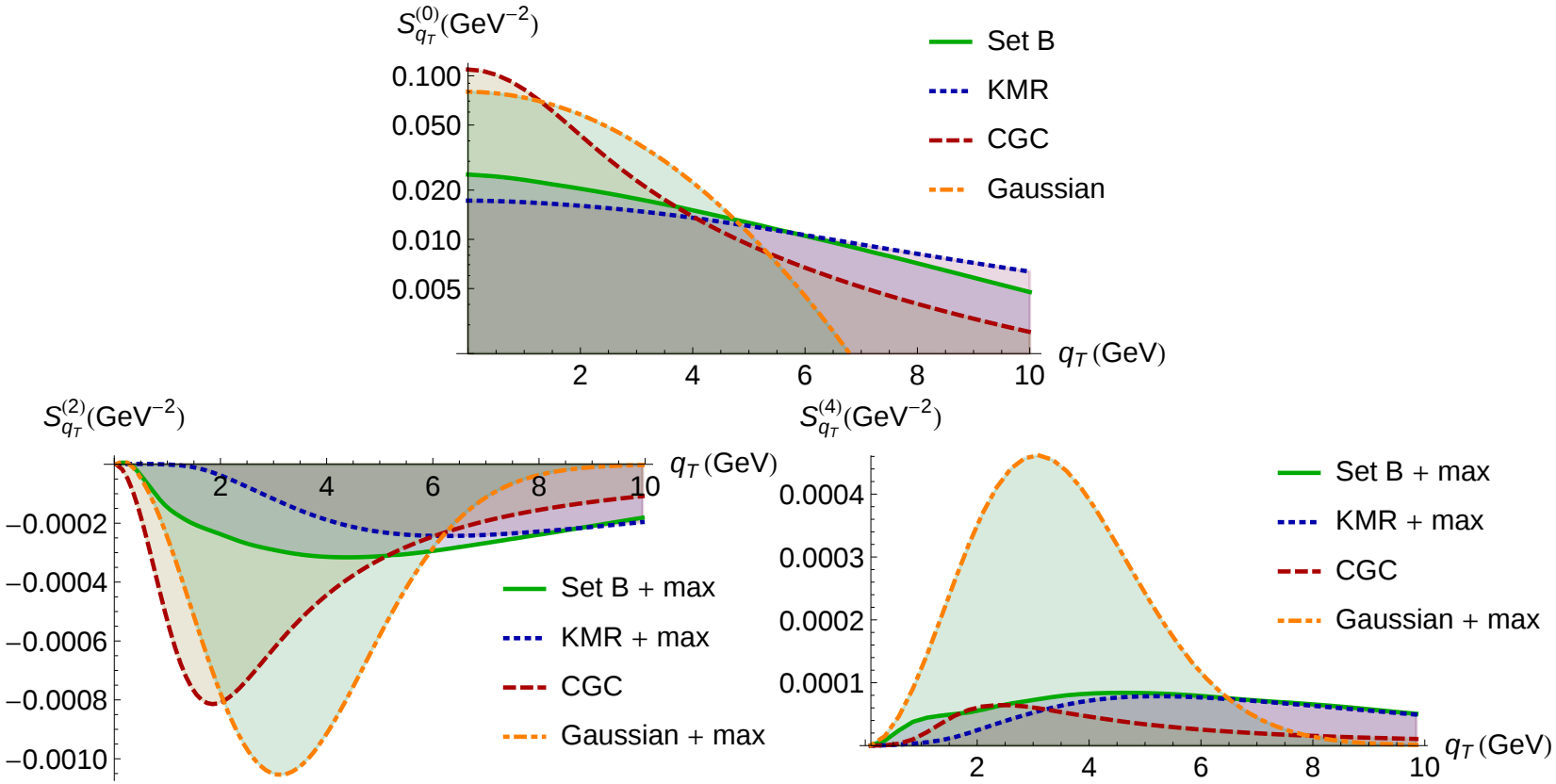

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- $\mathcal{S}^{(2)}_{q_T}$: slightly larger than $\mathcal{S}^{(4)}_{q_T}$

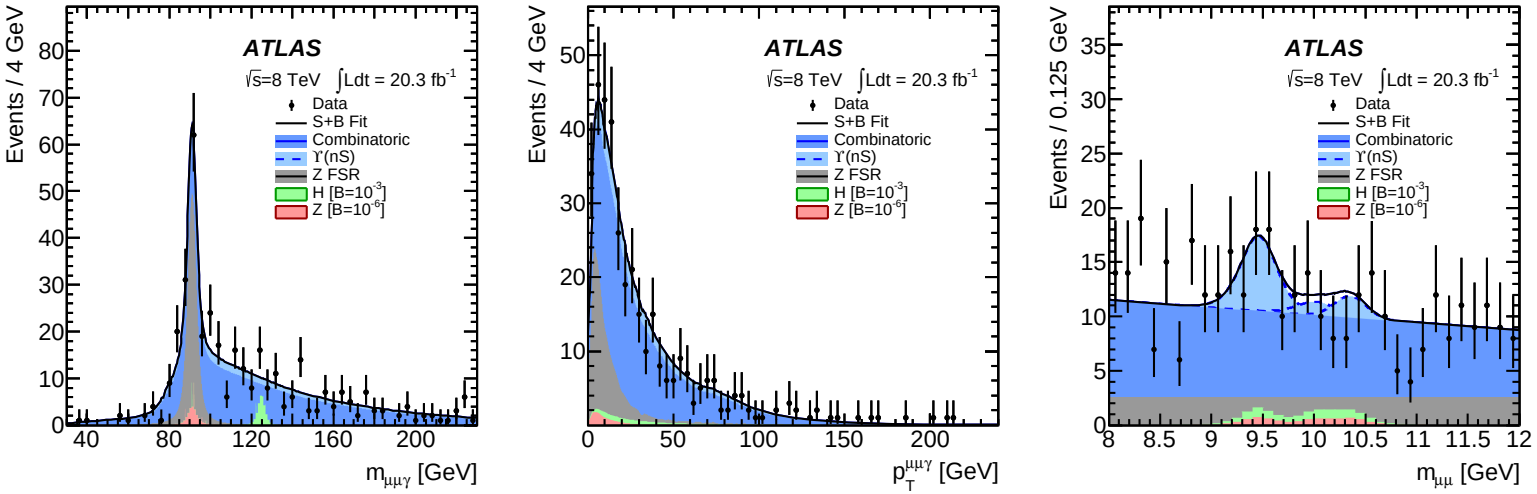
Already measured ?

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.



Same at AFTER@LHC

AFTER@LHC : a fixed-target experiment using the LHC beams

- $\sqrt{2 \times m_N \times E_p} \overset{7\,TeV}{=} 115$ GeV

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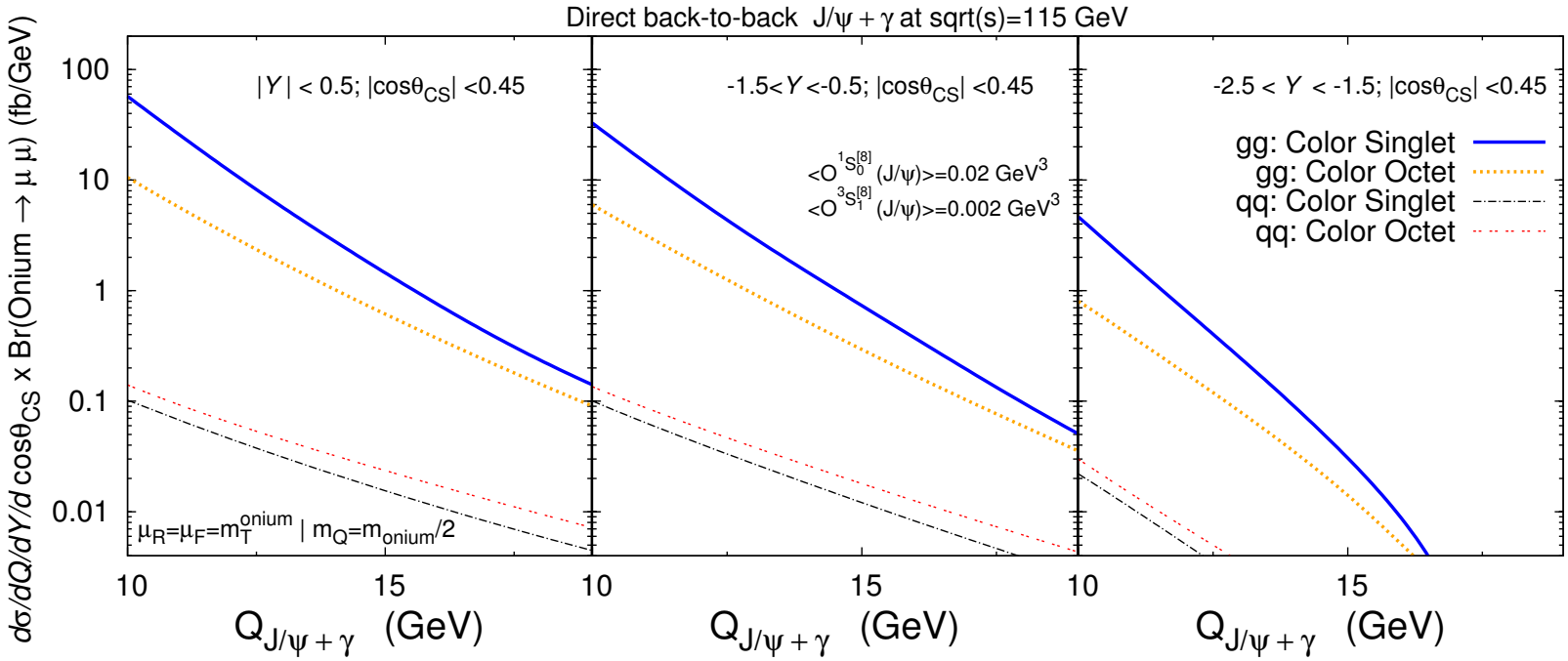

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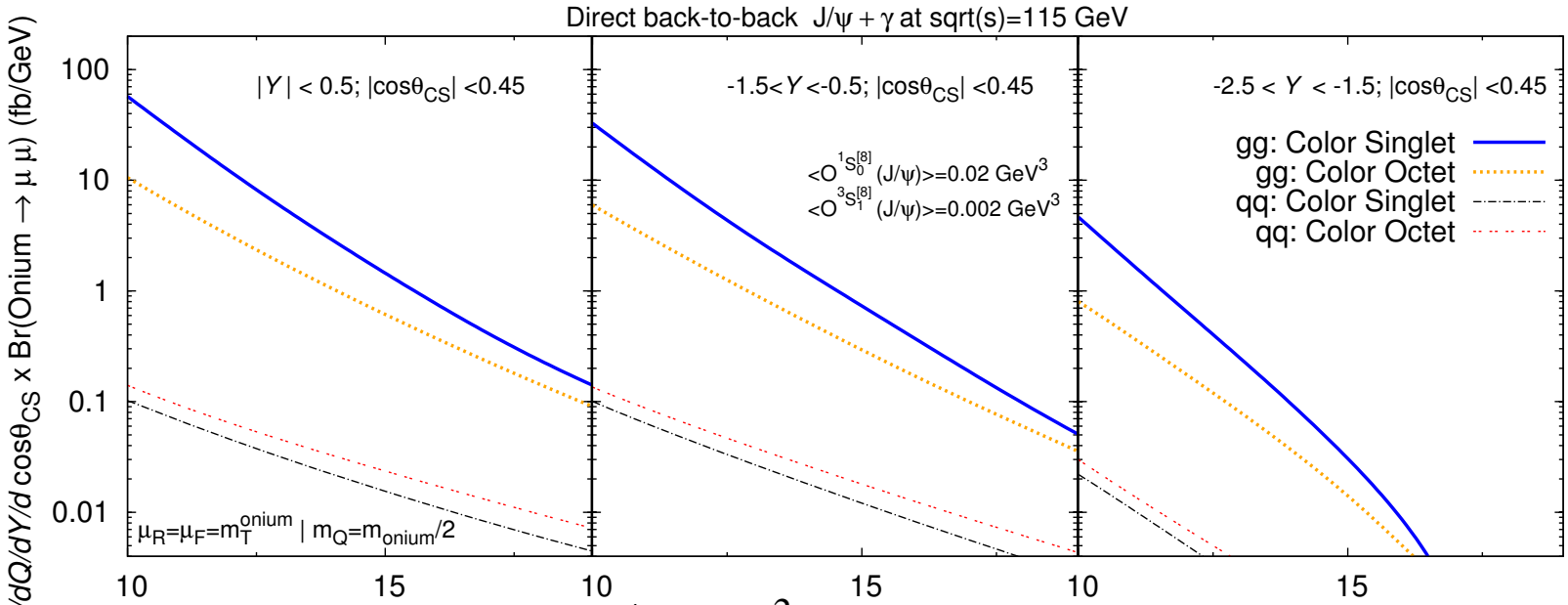
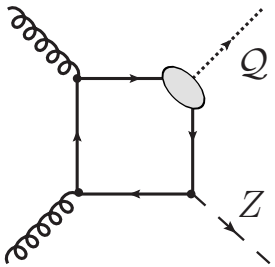


At $Y_{(\rm cms)} \simeq -2$, $x_2 \simeq 10/115 \times e^2 \simeq 0.65$. Yet, $g - g > q - \bar{q}$!

$\Upsilon + Z$ 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]



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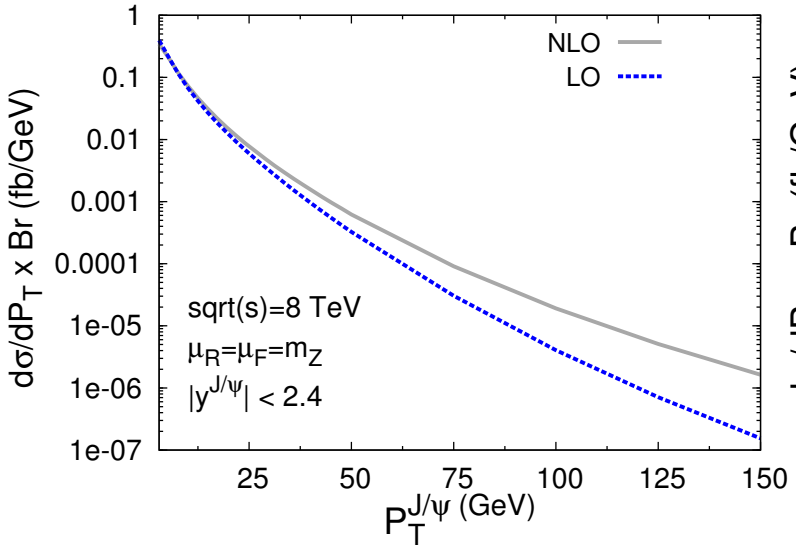

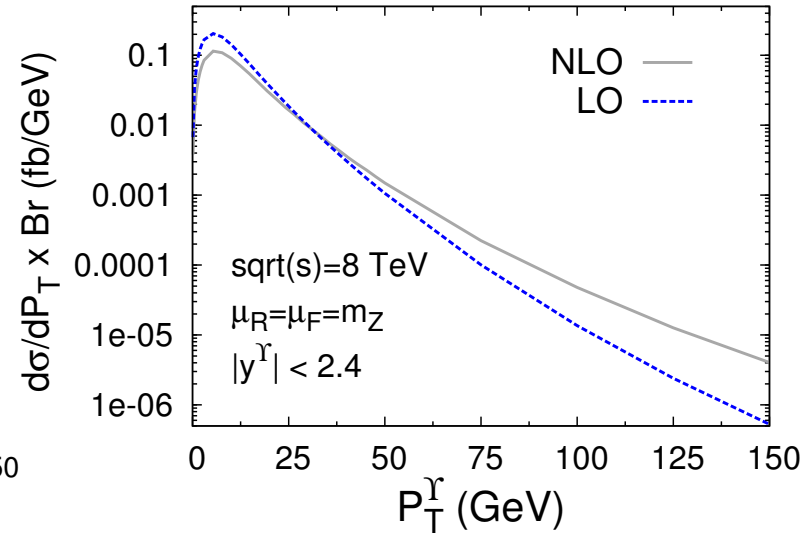

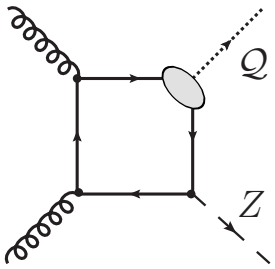

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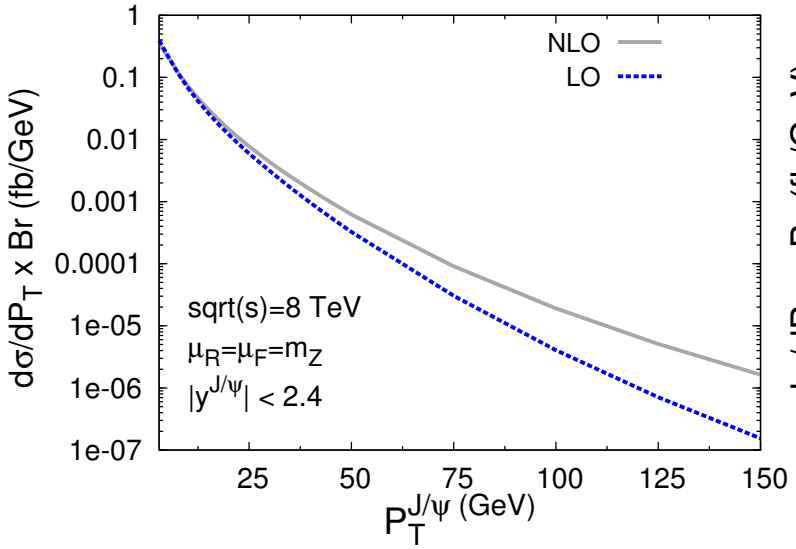

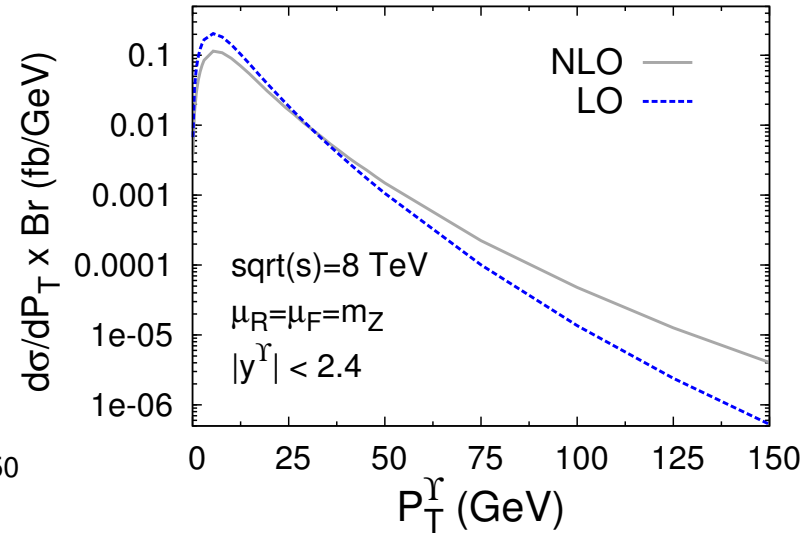

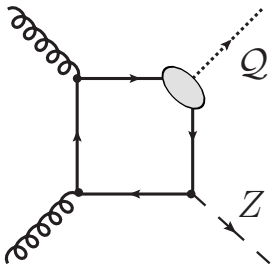

- Potential probe of gluon TMDs as well

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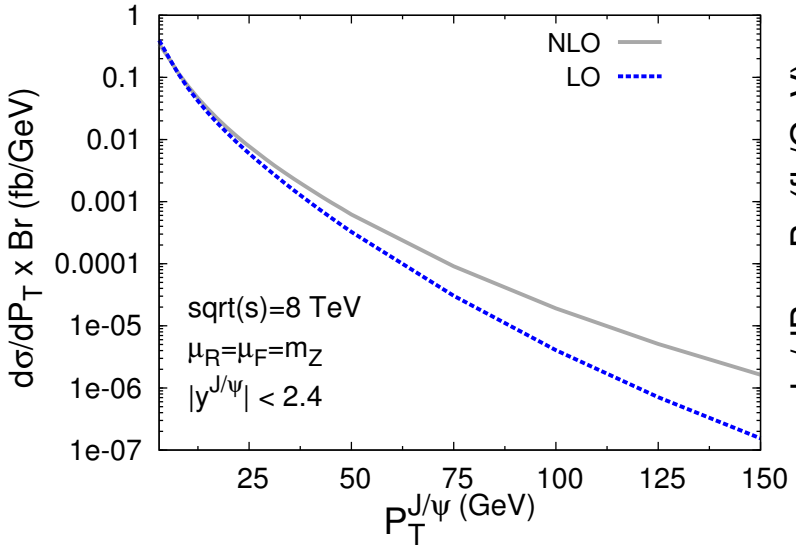
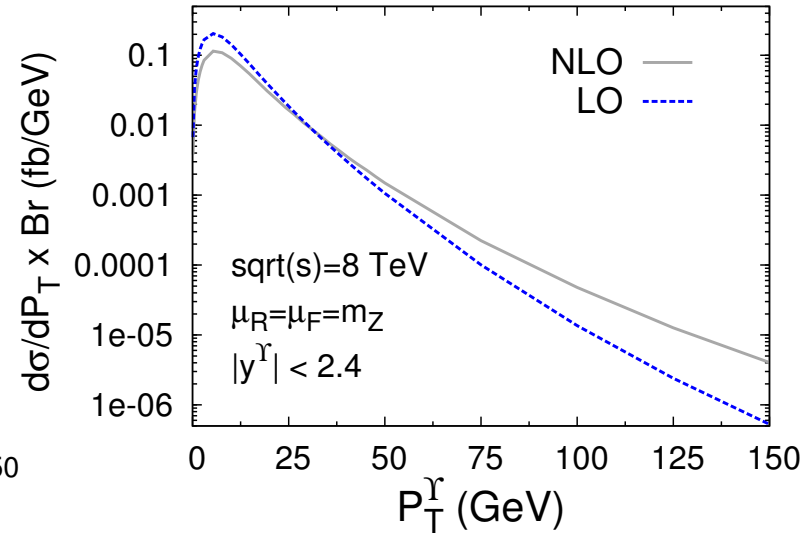
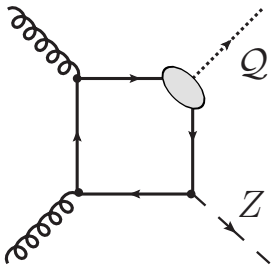




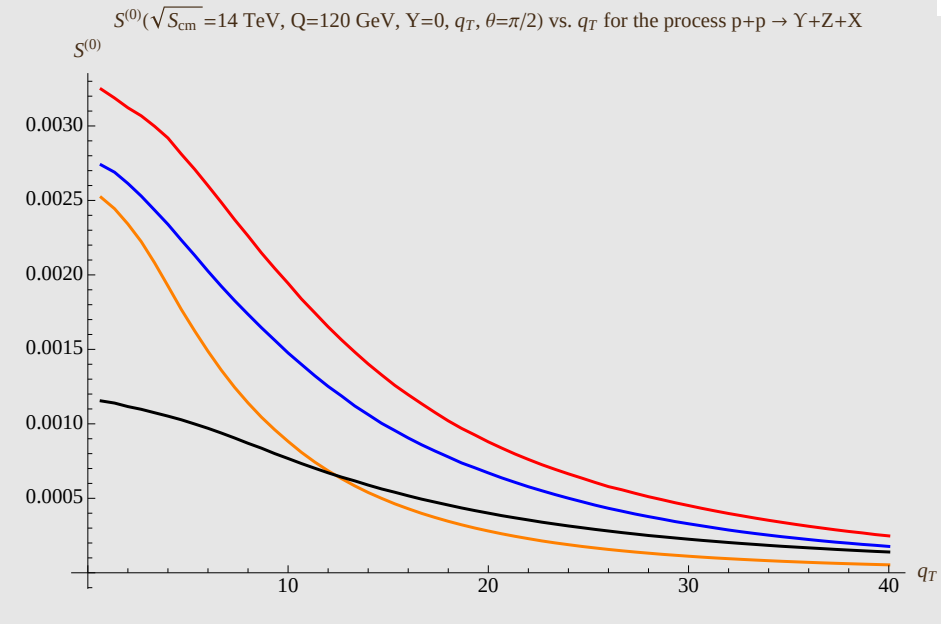


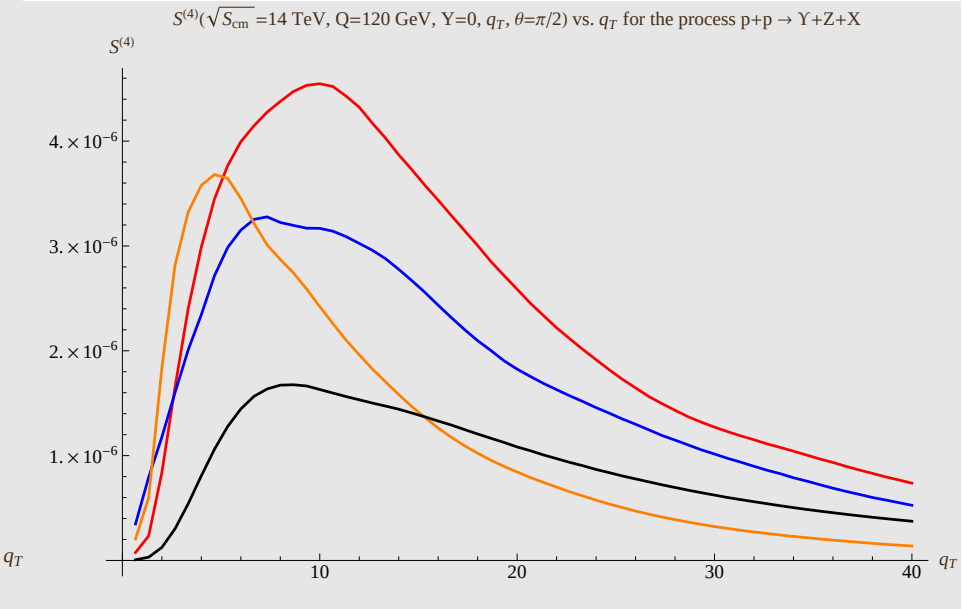
- Potential probe of gluon TMDs as well
- Rate clearly smaller than $\mathcal{Q} + \gamma$ even at low P_T

$\Upsilon + Z$ and TMDs

JPL, C. Pisano, M. Schlegel

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





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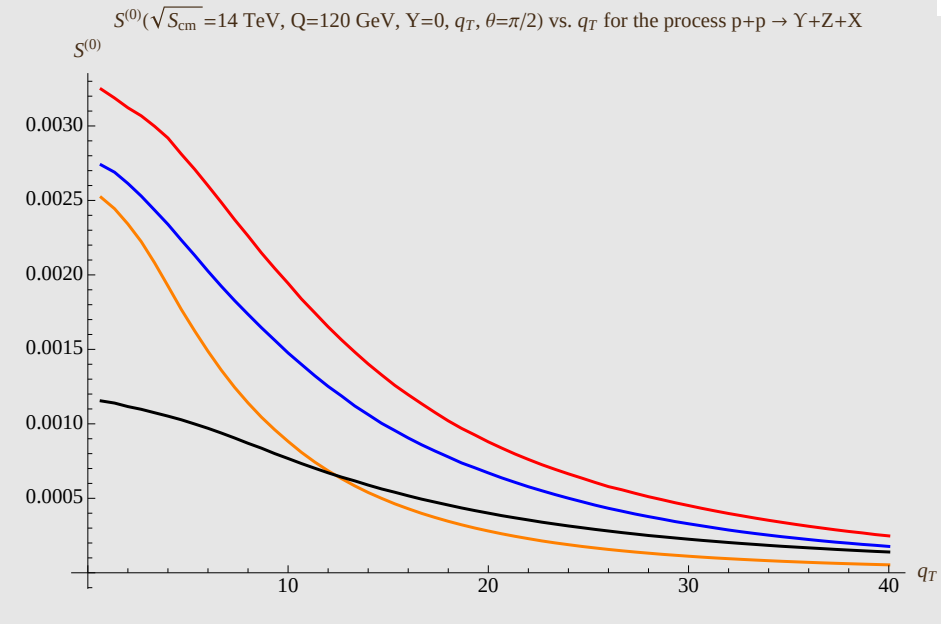

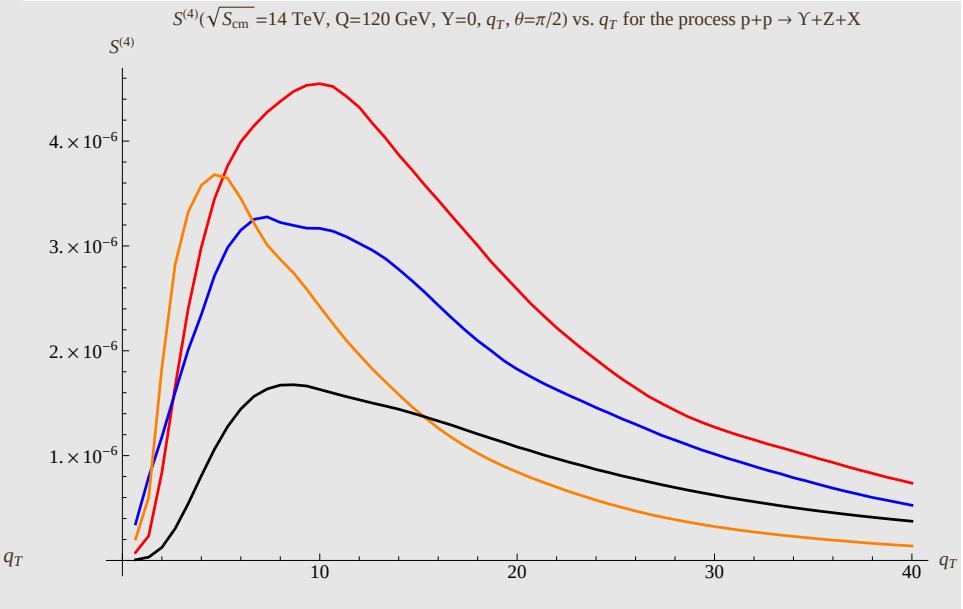

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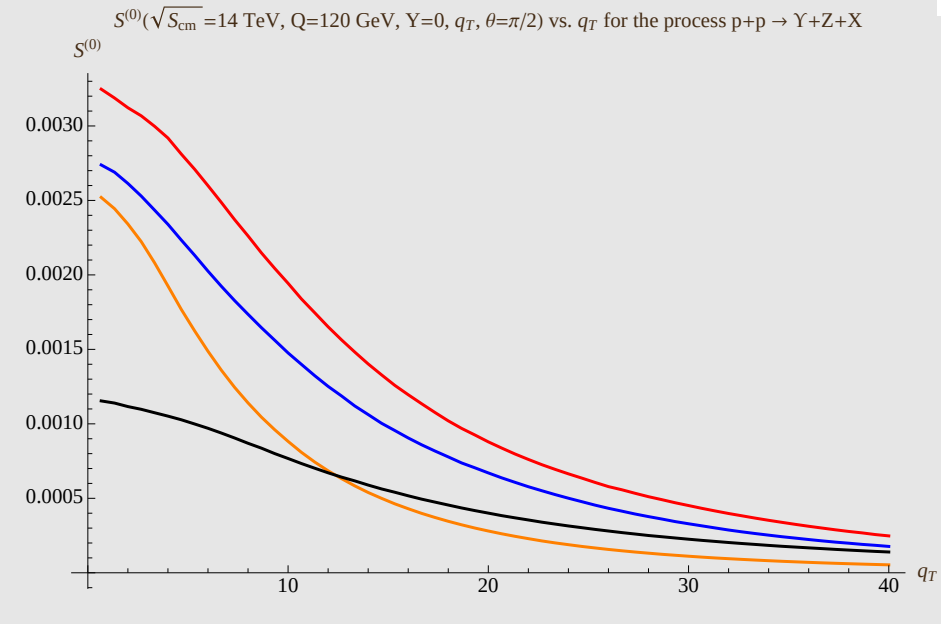

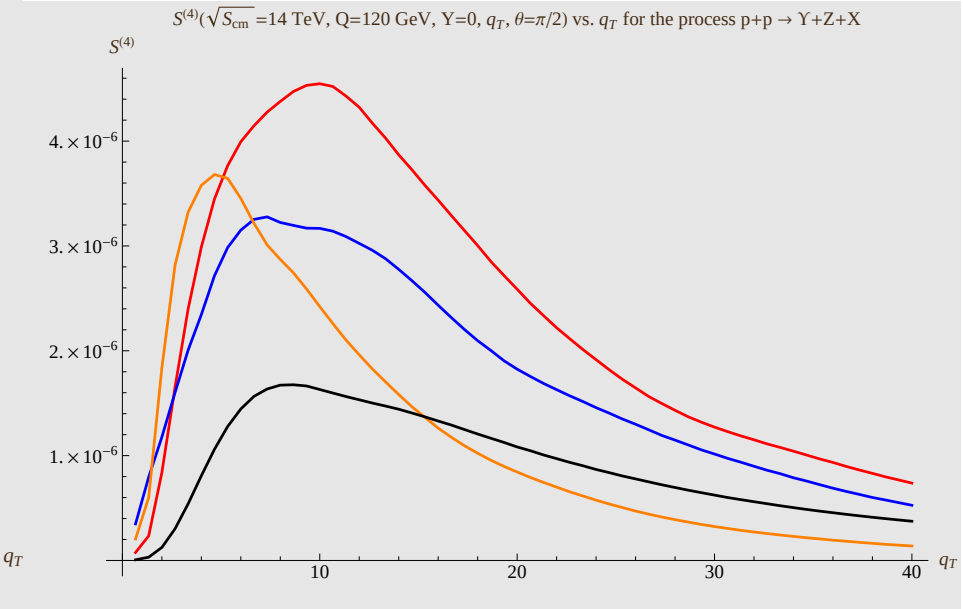

- $\mathcal{S}_{q_T}^{(n)}$ smaller than for $\mathcal{Q} + \gamma$ [one can integrate up to larger q_T, though]
- Naturally large Q: interest to study the scale evolution ?

Part IV

The case of quarkonium pair production

$\eta_c + \eta_c$ at low $P_T^{\eta_c \eta_c}$

G.P. Zhang, Phys.Rev. D 90 (2014) 9 094011

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- No reason for significant CO contribution and no final state gluon needed

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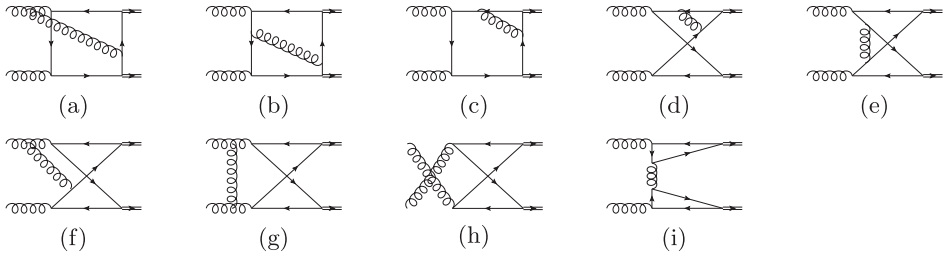

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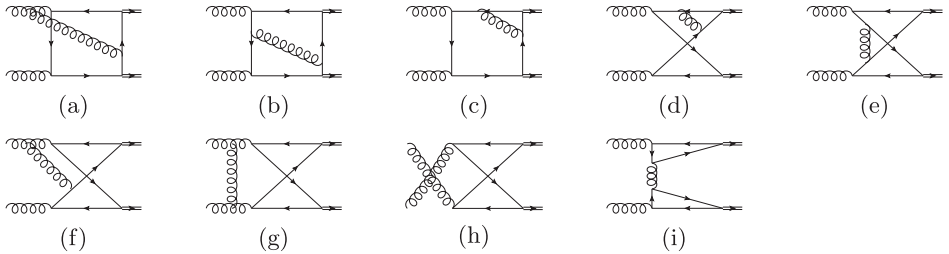

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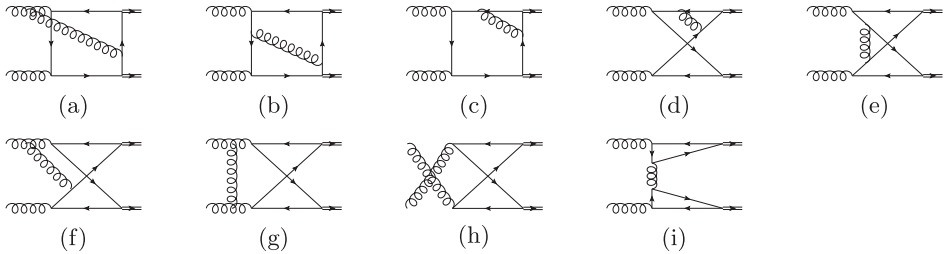

- For $J/\psi + \eta_c$, a final state gluon is needed **JPL, H.S. Shao PRL 111, 122001 (2013)**
- All 4 possible terms are nonzero:

$$\frac{d\sigma}{dy dQ d^2q_\perp d\Omega} = \frac{\pi^2 \alpha_s^4 \langle \mathcal{O}_1^\eta(^1S_0)\rangle^2 \rho}{N_c^2(N_c^2-1)M_\eta^6 SQ} \int_\perp \Big(B_1[f_{1A}^g f_{1B}^g] + B_2 \cos 2\phi \left[\frac{w_b}{2m_B^2} f_{1A}^g h_{1B}^{\perp g} + \frac{w_a}{2m_A^2} h_{1A}^{\perp g} f_{1B}^g\right] + B_3 \left[\frac{C_1+C_3}{4m_A^2 m_B^2} h_{1A}^{\perp g} h_{1B}^{\perp g}\right] + B_4 \cos 4\phi \left[\frac{C_1-C_3}{4m_A^2 m_B^2} h_{1A}^{\perp g} h_{1B}^{\perp g}\right] \Big),$$

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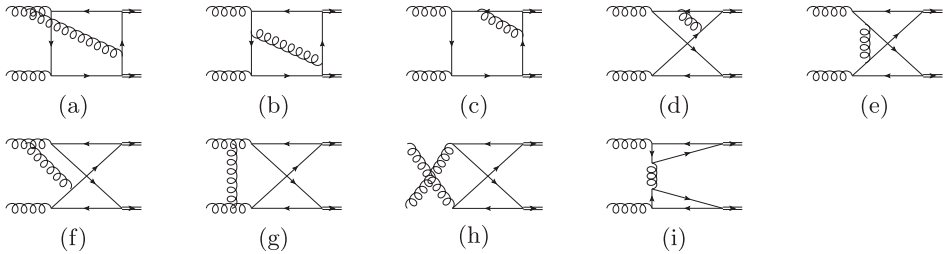

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TABLE I. The weighted differential cross sections obtained from the Gaussian model at $\sqrt{S} = 7$ TeV and $y = 0$, as defined in Eq. (20). In the calculation, we choose $\alpha_s = 0.15$, $M_\eta = 3.0$ GeV and ignore all scale dependence.

	Q(GeV) $\in$ (6.0, 10.0)	(10.0, 15.0)	(15.0, 20.0)	(20.0, 40.0)
$\langle 1\rangle(pb)$	2.3×10^4	1.7×10^3	1.8×10^2	1.3×10^2
$\lvert\langle\cos 2\phi\rangle\rvert(pb)$	2.4×10^3	4.6×10^2	0.72×10^2	0.63×10^2
$\langle\cos 4\phi\rangle(pb)$	0.20×10^2	9.1	2.5	3.3

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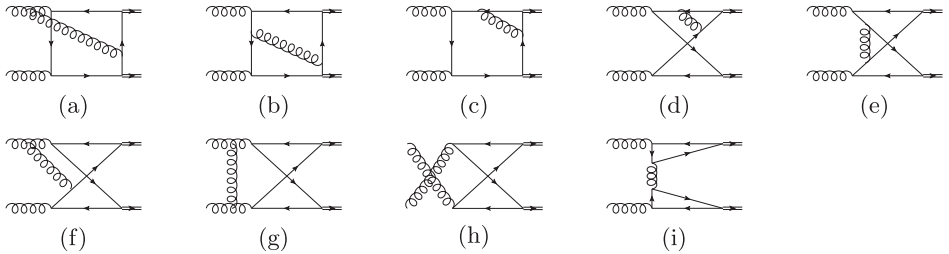

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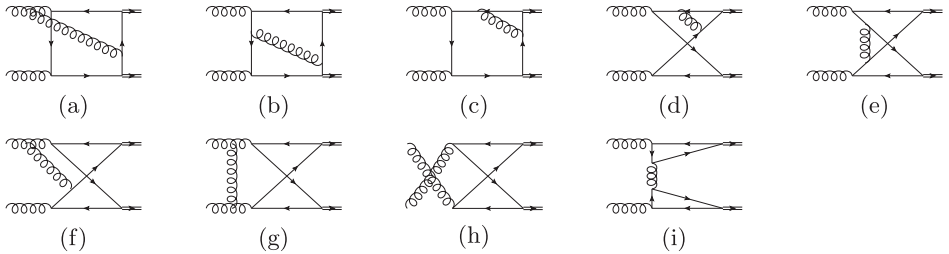
TABLE I. The weighted differential cross sections obtained from the Gaussian model at $\sqrt{S} = 7$ TeV and $y = 0$, as defined in Eq. (20). In the calculation, we choose $\alpha_s = 0.15$, $M_\eta = 3.0$ GeV and ignore all scale dependence.

	Q(GeV) $\in$ (6.0, 10.0)	(10.0, 15.0)	(15.0, 20.0)	(20.0, 40.0)
$\langle 1\rangle(pb)$	2.3×10^4	1.7×10^3	1.8×10^2	1.3×10^2
$\lvert\langle\cos 2\phi\rangle\rvert(pb)$	2.4×10^3	4.6×10^2	0.72×10^2	0.63×10^2
$\langle\cos 4\phi\rangle(pb)$	0.20×10^2	9.1	2.5	3.3

- At $\sqrt{s} = 14$ TeV, cross-sections will increase by a 2 factor ($\langle 1\rangle \sim \sigma$)

$\eta_c + \eta_c$ at low $P_T^{\eta_c\eta_c}$

- Theoretically, the simplest; **G.P. Zhang, Phys.Rev. D 90 (2014) 9 094011**
- At high energies, the $q\bar{q}$ contribution is negligible;
- No reason for significant CO contribution and no final state gluon needed



- For $J/\psi + \eta_c$, a final state gluon is needed **JPL, H.S. Shao PRL 111, 122001 (2013)**
- All 4 possible terms are nonzero:
- Expected (weighted) cross sections

$$\frac{d\sigma}{dy dQ d^2q_\perp d\Omega} = \frac{\pi^2\alpha_s^4\langle\mathcal{O}_1^\eta(^1S_0)\rangle^2\rho}{N_c^2(N_c^2-1)M_\eta^6 SQ}\int_\perp\Bigg(B_1[f_{1A}^g f_{1B}^g] + B_2\cos 2\phi\left[\frac{w_b}{2m_B^2}f_{1A}^g h_{1B}^{\perp g} + \frac{w_a}{2m_A^2}h_{1A}^{\perp g} f_{1B}^g\right] + B_3\left[\frac{C_1+C_3}{4m_A^2 m_B^2}h_{1A}^{\perp g}h_{1B}^{\perp g}\right] + B_4\cos 4\phi\left[\frac{C_1-C_3}{4m_A^2 m_B^2}h_{1A}^{\perp g}h_{1B}^{\perp g}\right]\Bigg),$$

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- At $\sqrt{s} = 14$ TeV, cross-sections will increase by a 2 factor ($\langle 1\rangle \sim \sigma$)
- $\langle 1, \cos 2\phi\rangle \times Br^2(\eta_c \to p\bar{p}) \simeq 1 - 50$ fb [observable at LHC Run II?]

$J/\psi + J/\psi$ at low $P_T^{\psi\psi}$

JPL, H.S. Shao PLB 751 (2015) 479

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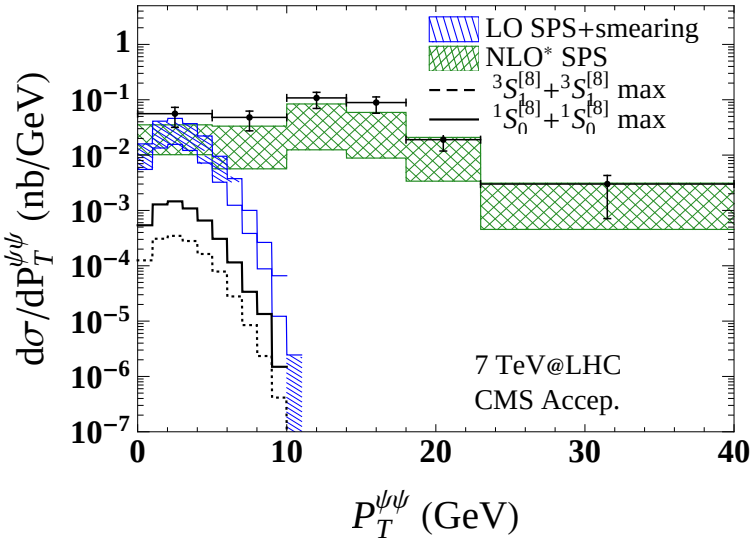
- Negligible CO contributions, in particular at low $P_T^{\psi\psi}$ [black/dashed curves vs. blue]



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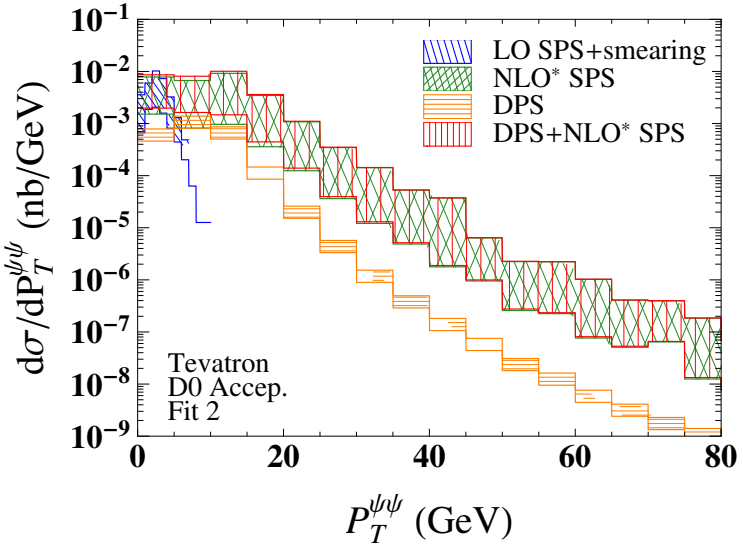
- At low $P_T^{\psi\psi}$, smaller DPS effects, otherwise needed to explain CMS data at large Δy



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- For individual $P_T^\psi \gg M_\psi$, one has

$$A^f \sim 1\,;\; A^h \sim (M_\psi/P_T^\psi)^4\,;\; B \sim (M_\psi/P_T^\psi)^2\,;\; C \sim 1$$

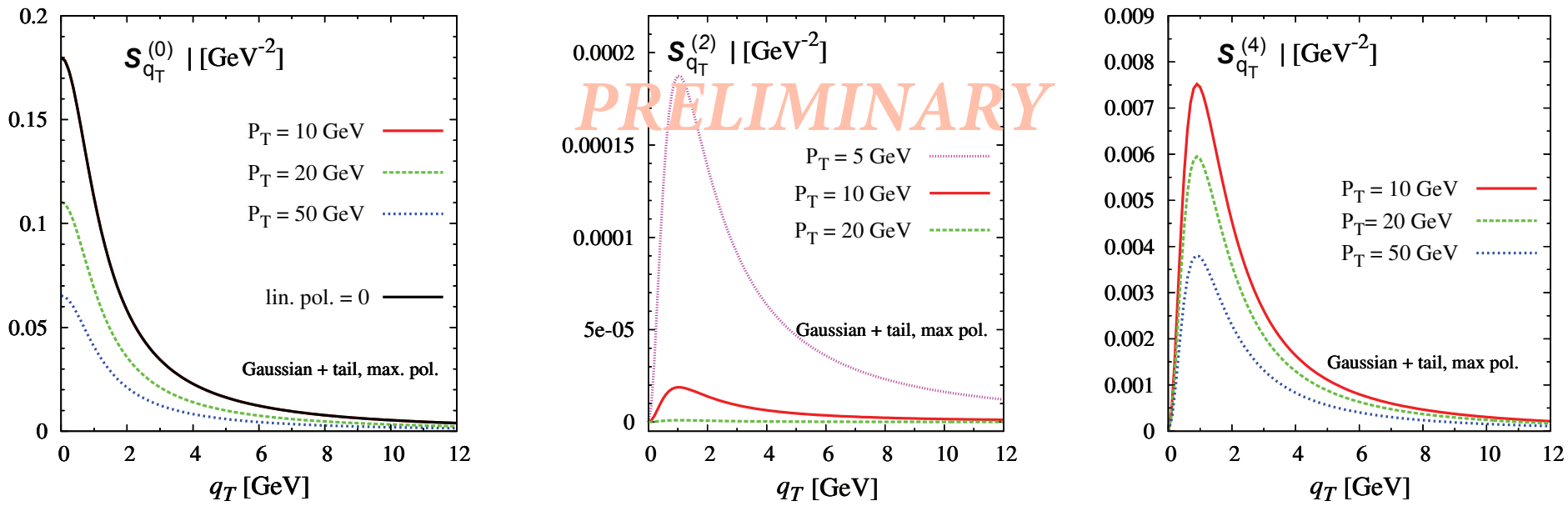
$J/\psi + J/\psi$ azimuthal effects

JPL, C. Pisano, F. Scarpa, work in progress

- Using a simple model (+ positivity bound) :

$$f_1^g(x, k_T) = \frac{1}{\pi\beta} e^{-\frac{k_T^2}{\beta}} f_1^g(x) \qquad \text{with } \beta = \langle k_T^2 \rangle$$

- One gets for $\mathcal{S}_{q_T}^{(n)}$



- it seems that $\mathcal{S}_{q_T}^{(4)} \gg \mathcal{S}_{q_T}^{(2)}$

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  with A Fixed-Target Experiment at the LHC: AFTER@LHC
- $J/\psi + \gamma$ SSA might also be possible with STAR in very favourable conditions

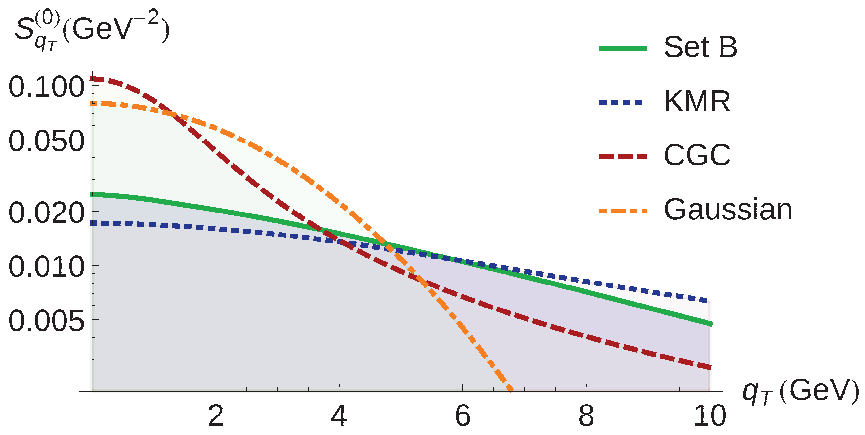
JPL, C. Pisano, M. Schlegel, in progress

Part V

Backup

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

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



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

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

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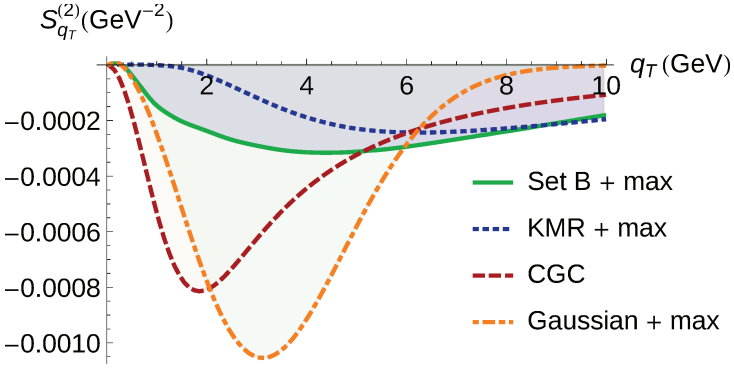

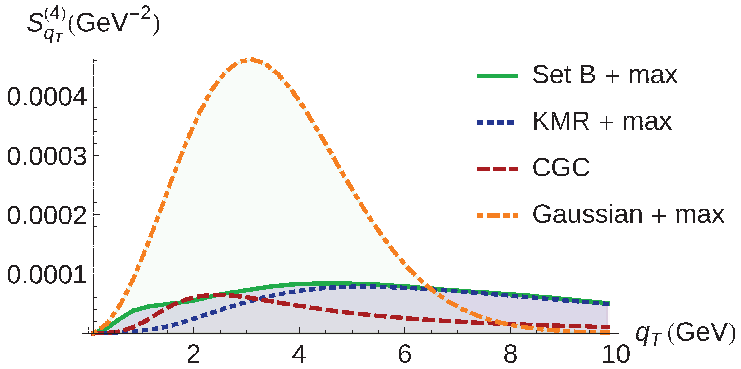

$h_1^{\perp g}$: predictions only in the CGC: in the other models saturated to its upper bound

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

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

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

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