

# Gluon TMDs and Quarkonium Production in Unpolarised (and Polarised) Proton-Proton Collisions

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IPN Orsay – Paris-Sud U. –CNRS/IN2P3



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Collaboration with W. den Dunnen, C. Lorcé, C. Pisano, M. Schlegel, H.S. Shao  
+ newcomers M. Echevarria, A. Signori

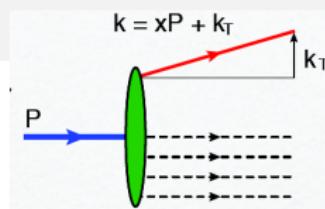
# Part I

## Generalities on gluon TMDs

# Beyond collinear factorisation

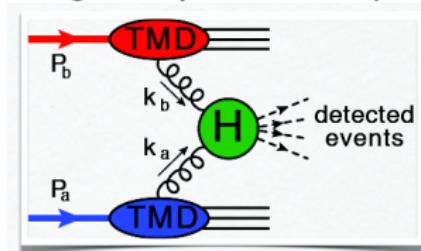
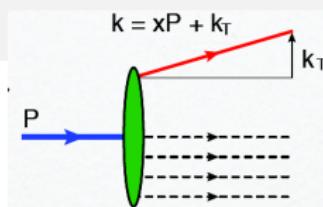
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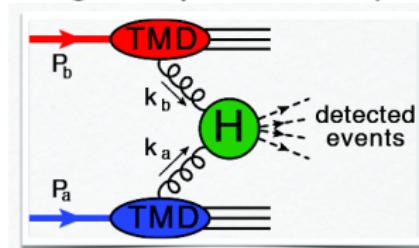
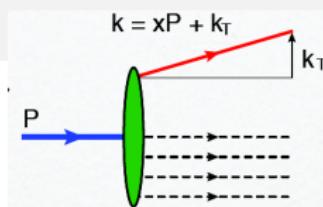
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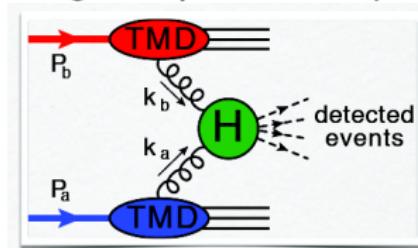
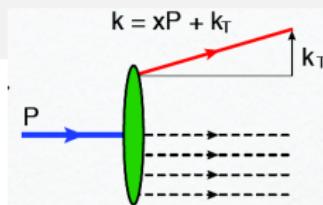
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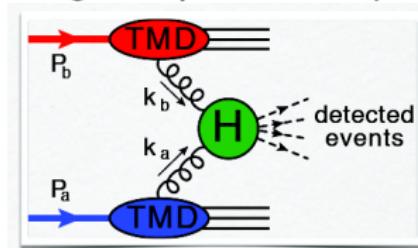
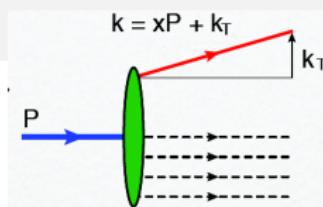


**H is free of  $q_T$**

$$\begin{aligned} d\sigma = & \frac{(2\pi)^4}{8s^2} \int d^2\mathbf{k}_{1T} d^2\mathbf{k}_{2T} \delta^2(\mathbf{k}_{1T} + \mathbf{k}_{2T} - \mathbf{q}_T) H_{\mu\rho} (H_{\nu\sigma})^* \times \\ & \Phi_g^{\mu\nu}(x_1, \mathbf{k}_{1T}, \zeta_1, \mu) \Phi_g^{\rho\sigma}(x_2, \mathbf{k}_{2T}, \zeta_2, \mu) d\mathcal{R} + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right) \end{aligned}$$

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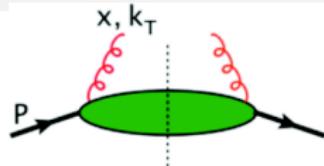
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- Should work for SIDIS +  $pp$  reactions with colour singlet final states

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

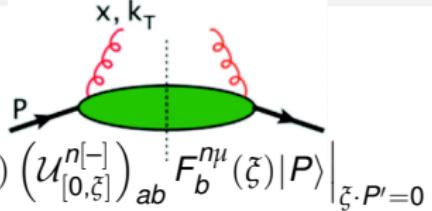
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- Gauge-invariant definition:

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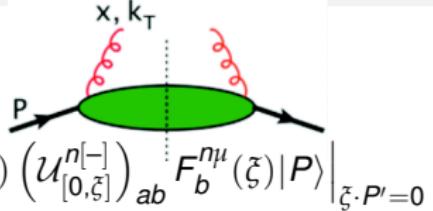


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- Parametrisation:

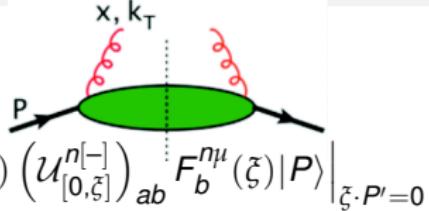
P. J. Mulders, J. Rodrigues, PRD 63 (2001) 094021

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

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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)

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

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

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

$\rightarrow F_1 \rightarrow$  helicity non-flip, azimuthally indep., survives qT-integration

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

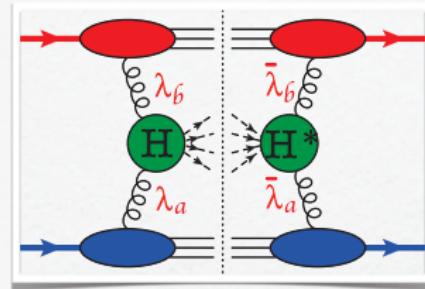
$\rightarrow F_2 \rightarrow$  double helicity flip, azimuthally independent

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

$\rightarrow F_3 \rightarrow$  single helicity flip,  $\cos(2\phi)$  [ $\sin(2\phi)$ ] - modulation

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

$\rightarrow F_4 \rightarrow$  double helicity flip,  $\cos(4\phi) [\sin(4\phi)]$ - modulation



## 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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- Only colour-singlet particles in the final state  
(also true for  $Z Z$  and  $\gamma Z$ )

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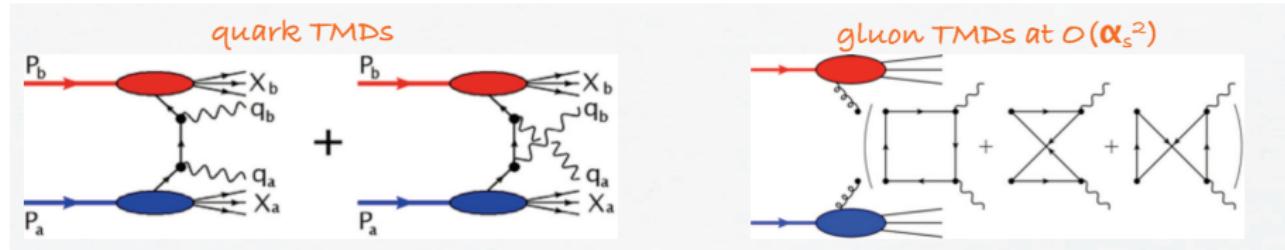
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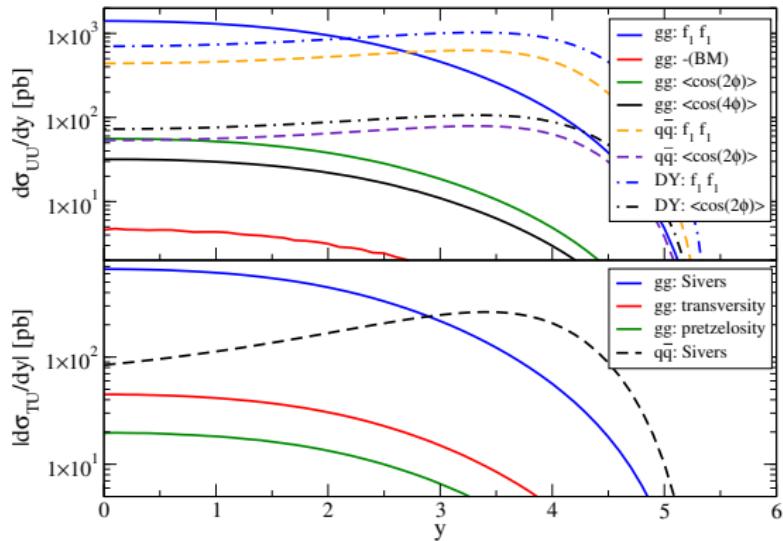
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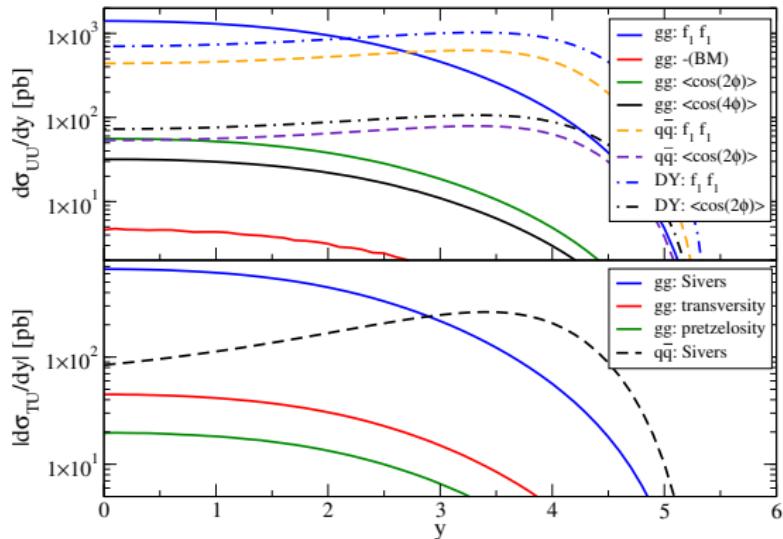
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for  $p_T^\gamma \geq 1 \text{ GeV}$ ,  $4 \leq Q^2 \leq 30 \text{ GeV}$ ,  $0 \leq q_T \leq 1 \text{ GeV}$



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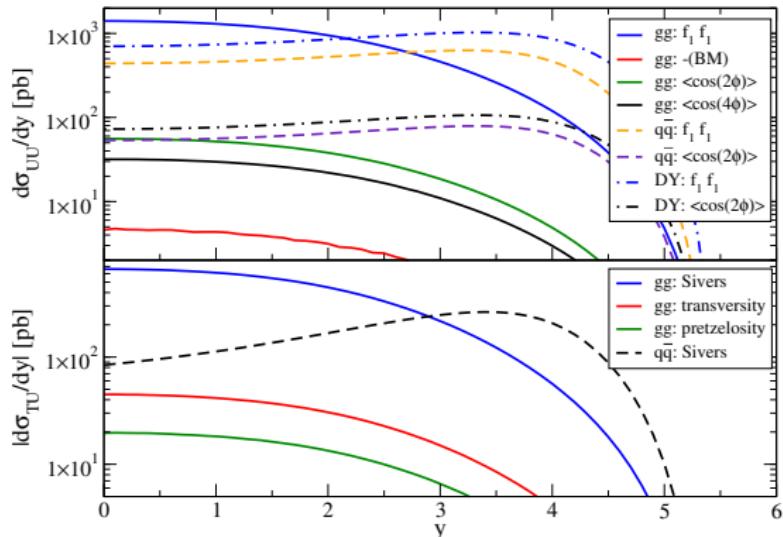


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- Huge background from  $\pi^0 \rightarrow$  isolation cuts are needed

# Low $P_T$ quarkonia and TMDs

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PHYSICAL REVIEW D 86, 094007 (2012)

## Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

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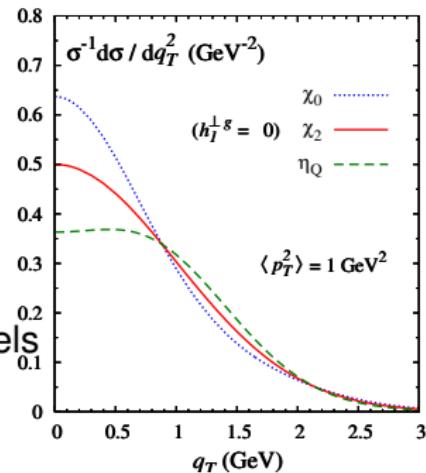
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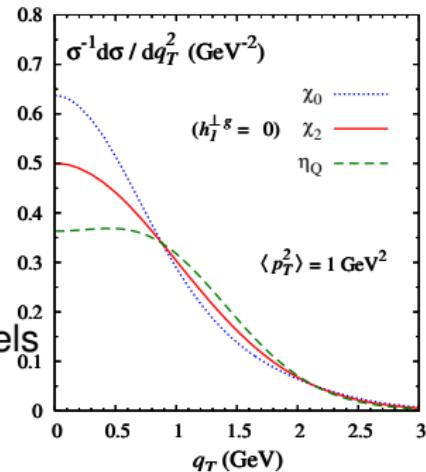
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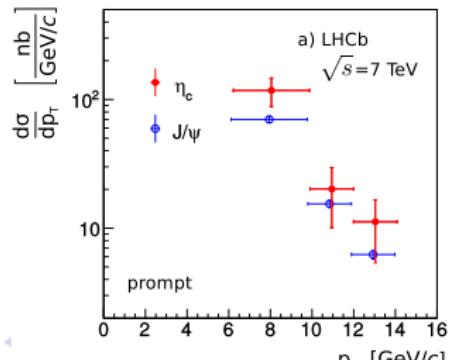
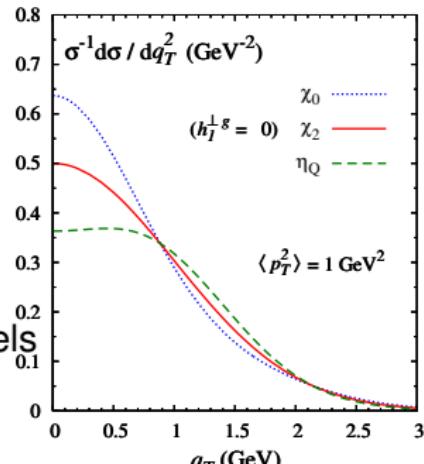
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- Cannot tune  $Q$ :  $Q \simeq m_Q$
- Low  $P_T$ : Experimentally very difficult  
First  $\eta_c$  production study at collider ever, only released last September for  $P_T^{\eta c} > 6$  GeV LHCb, 1409.3612



# Low $P_T$ quarkonia and TMDs II

## • $\eta_c$ production at one-loop

PHYSICAL REVIEW D 88, 014027 (2013)

### Transverse momentum dependent factorization for quarkonium production at low transverse momentum

J. P. Ma,<sup>1,2</sup> J. X. Wang,<sup>3</sup> and S. Zhao<sup>1</sup>

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## • $\chi_{c0,2}$ factorisation issue ? $\leftrightarrow$ Colour Octet - Colour Singlet mixing $\leftrightarrow$ how about $v^2$ Colour Singlet corrections ?

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



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## Part III

### Quarkonium + photon

# $Q +$ isolated $\gamma$ : interesting but ...

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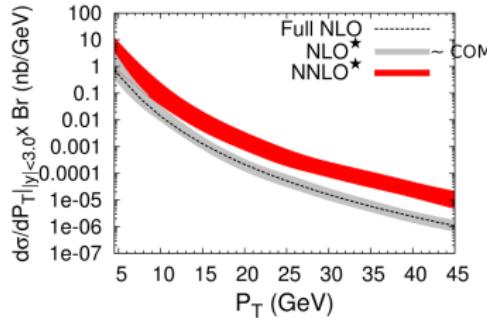
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R.Li and J.X. Wang, PLB 672,51,2009

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- CS rate at NLO  $\simeq$  conservative (high) expectation from CO
- At NNLO\*, CS rate clearly above (high) expectation from CO

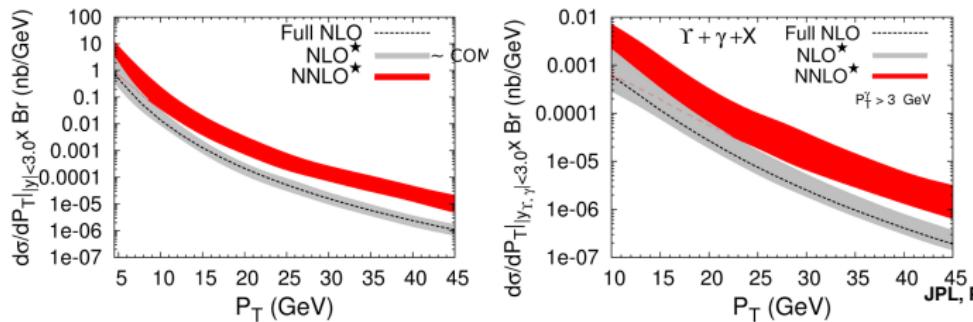
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R.Li and J.X. Wang, PLB 672,51,2009

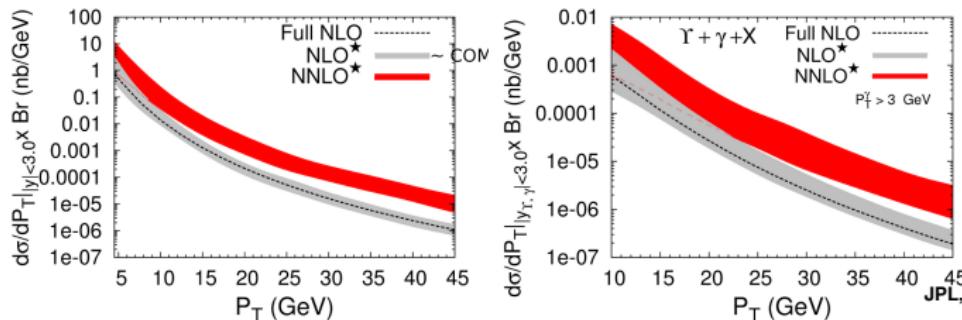


JPL, PLB 679,340,2009.

# $\mathcal{Q} + \text{isolated } \gamma$ : interesting but ...

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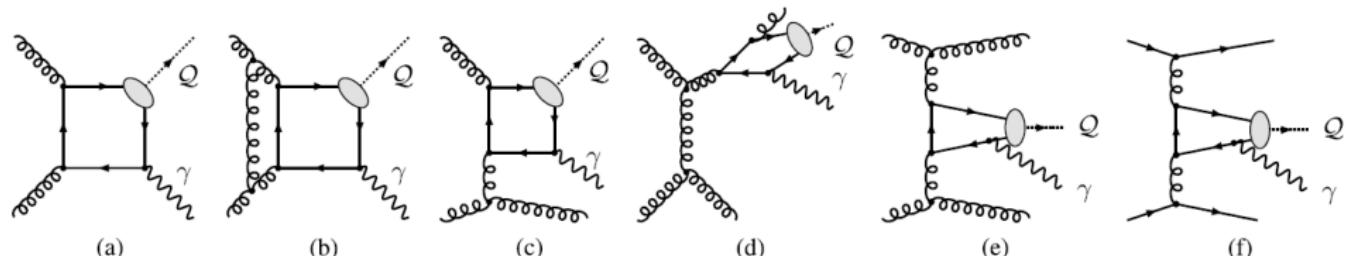
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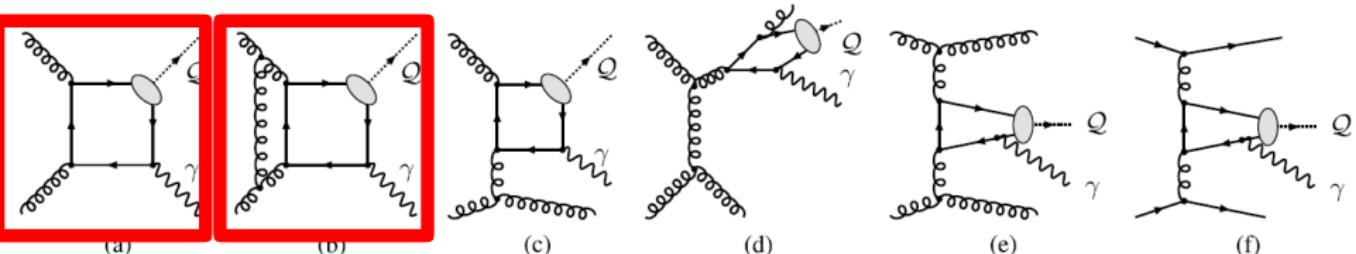
- All this is certainly interesting but TMD factorisation is most likely not applicable because of colour in the final state (either COM or gluons)

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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).

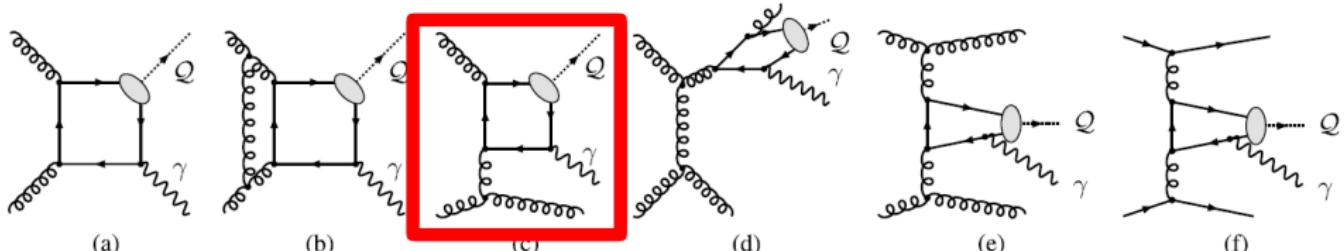
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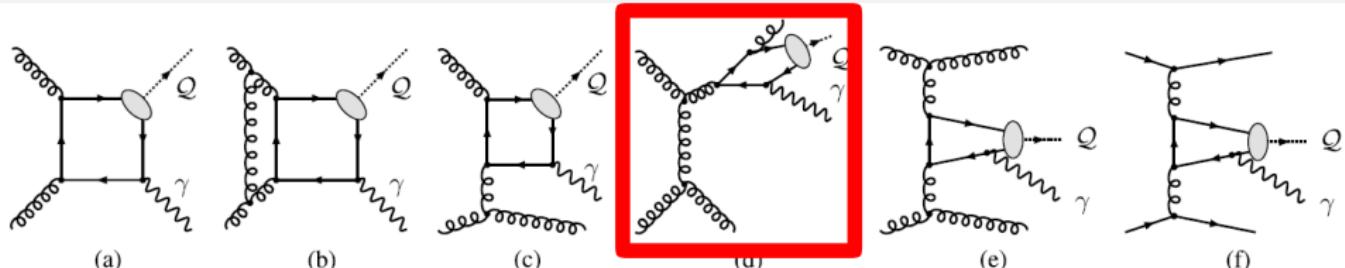
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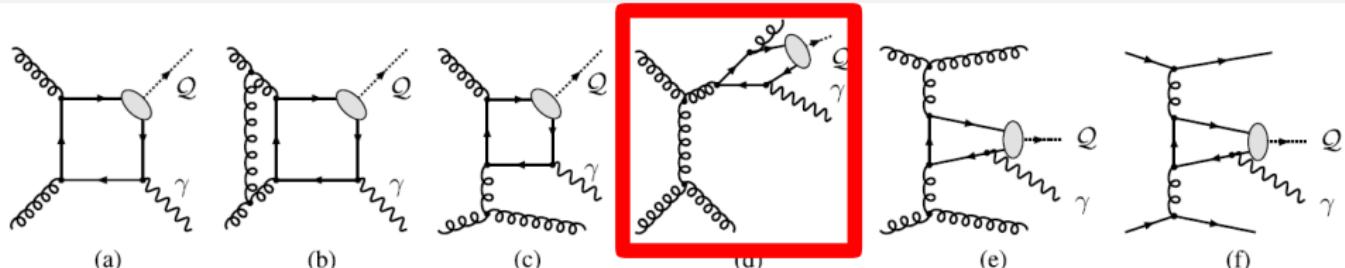
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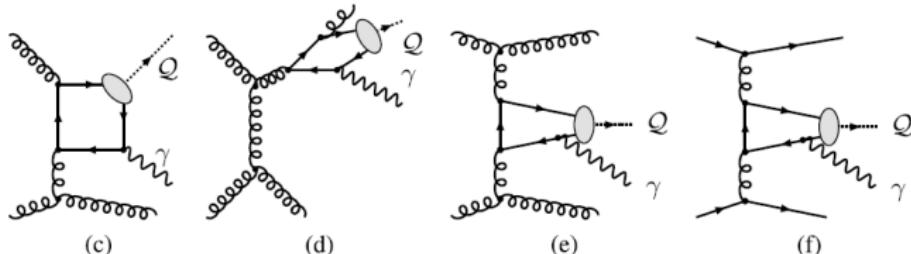


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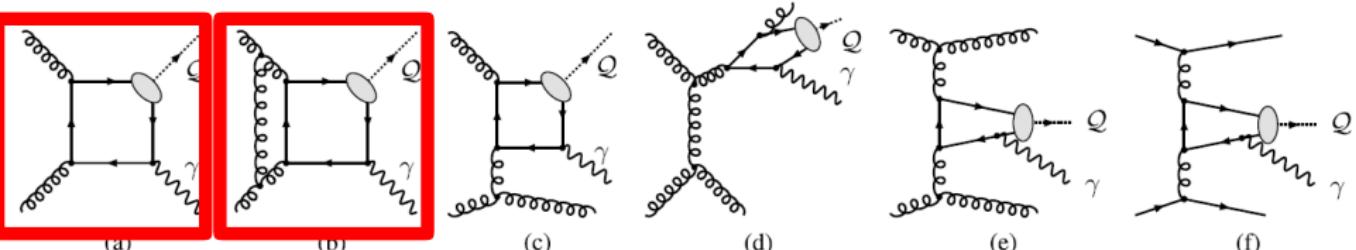
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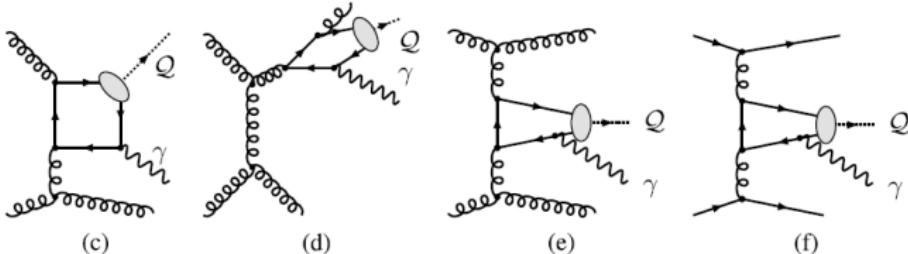
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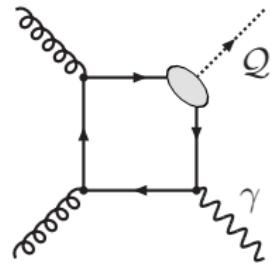


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- (c)-(f) populate  $\Delta\phi_{\mathcal{Q}-\gamma} < \pi$  [even  $\Delta\phi \rightarrow 0$  for (c) and (d) at large  $P_T$ ]

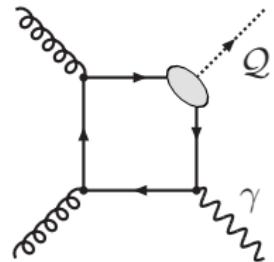
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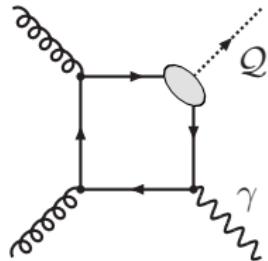
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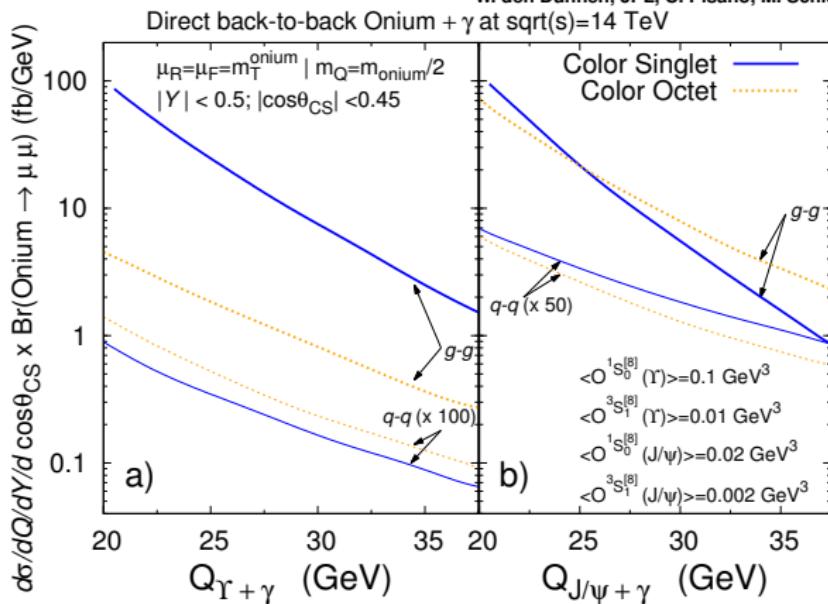
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- Unique candidate to pin down the gluon TMDs
  - **gluon** sensitive process
  - **colourless** final state (virtue of isolation): **TMD factorisation applicable**
  - small sensitivity to QCD corrections (most of them in the TMD evolution)



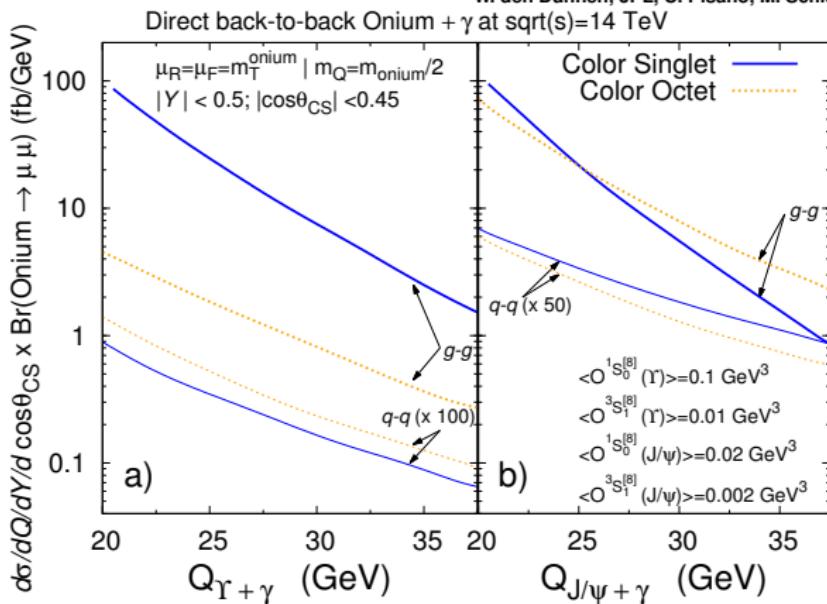
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W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



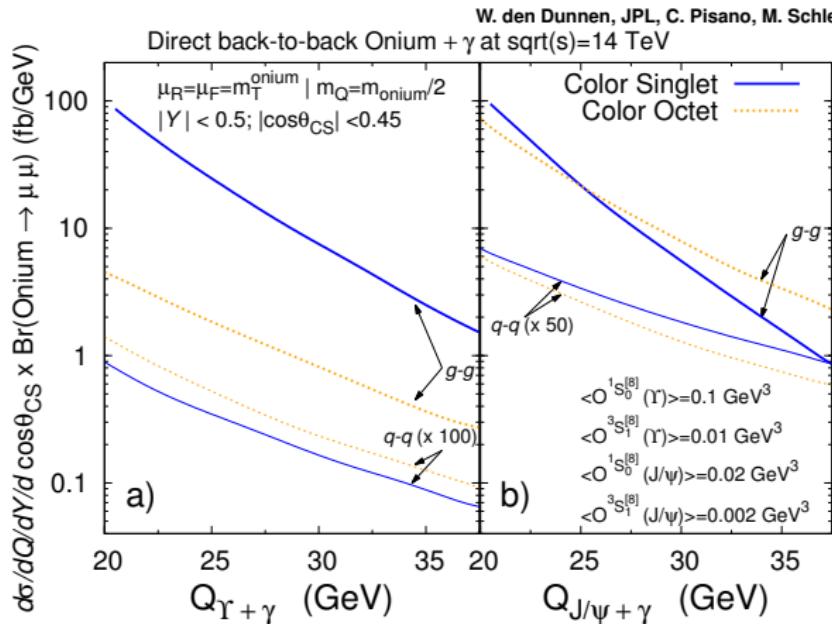
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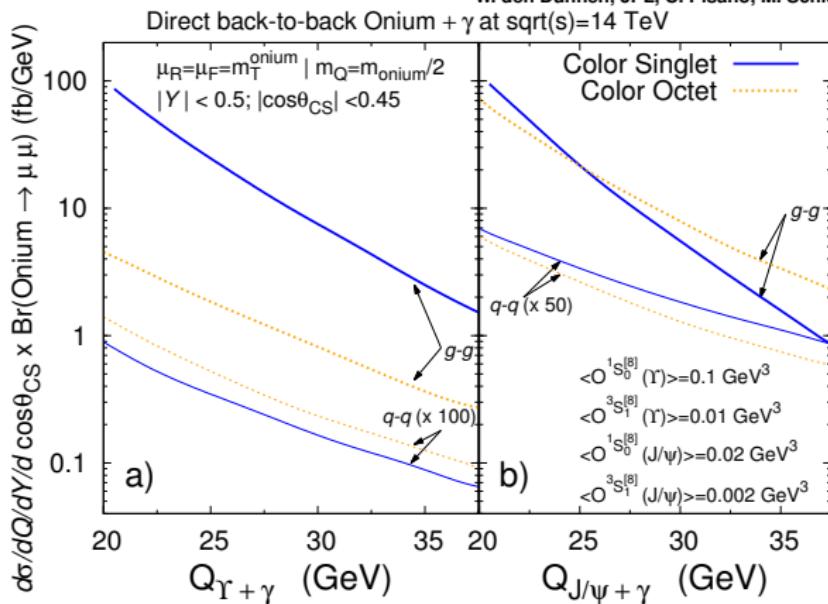
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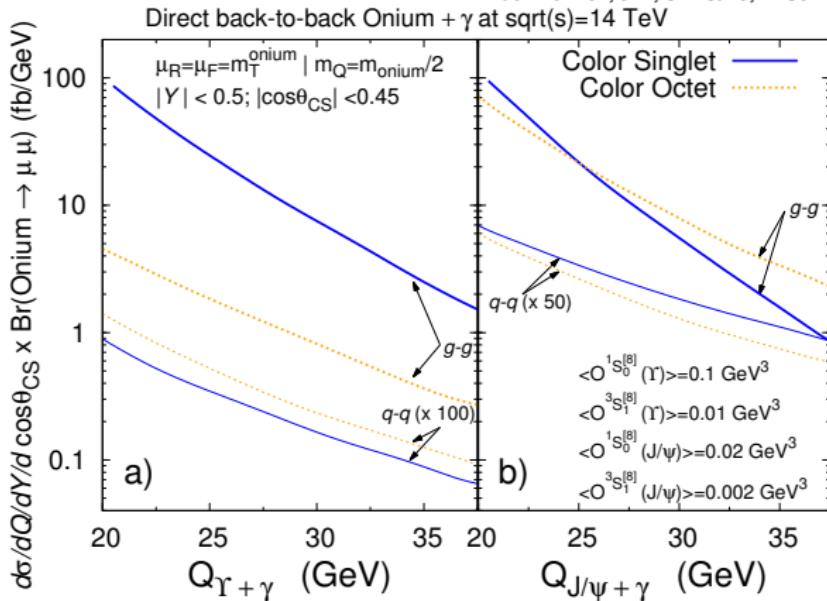
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W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

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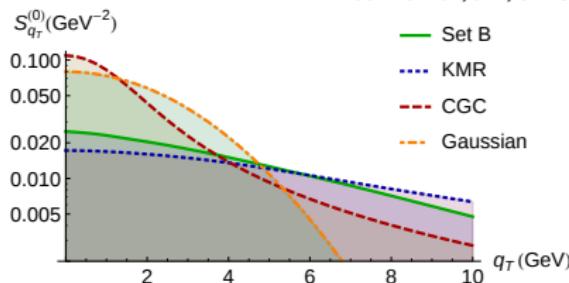
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$S_{q_T}^{(2)}, S_{q_T}^{(4)} \neq 0 \Rightarrow$  nonzero gluon polarisation in unpolarised protons !

# Results with UGDs as Ansätze for TMDs

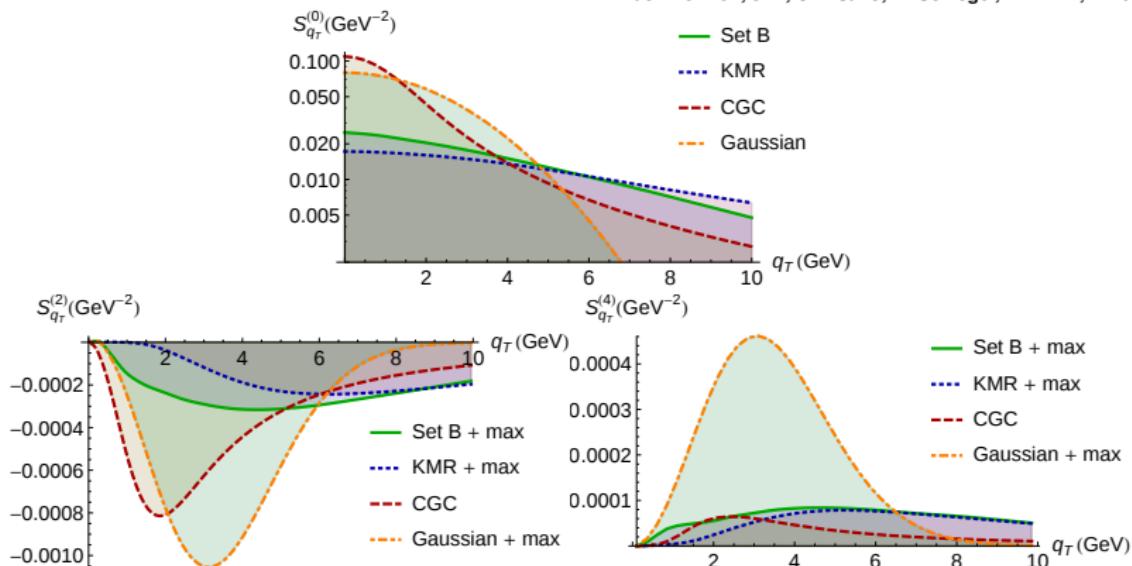
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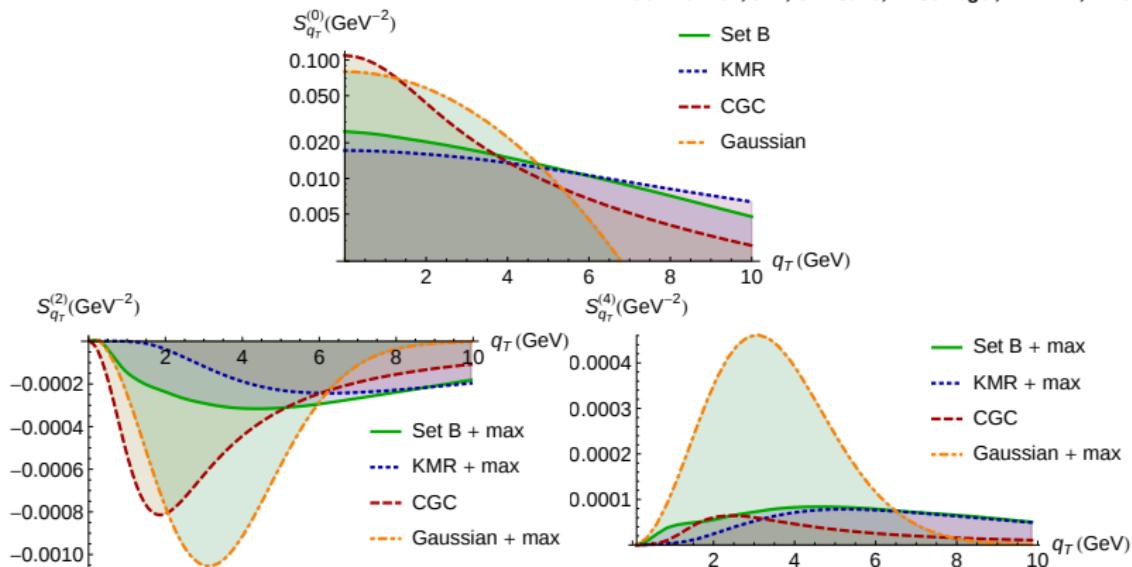
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- $S_{q_T}^{(2)}$  : slightly larger than  $S_{q_T}^{(4)}$

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- $\sqrt{2 \times m_N \times E_p} \stackrel{7\text{TeV}}{=} 115 \text{ GeV}$

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down to  $x_F \rightarrow -1$  for  $Q \gtrsim 5 \text{ GeV}$

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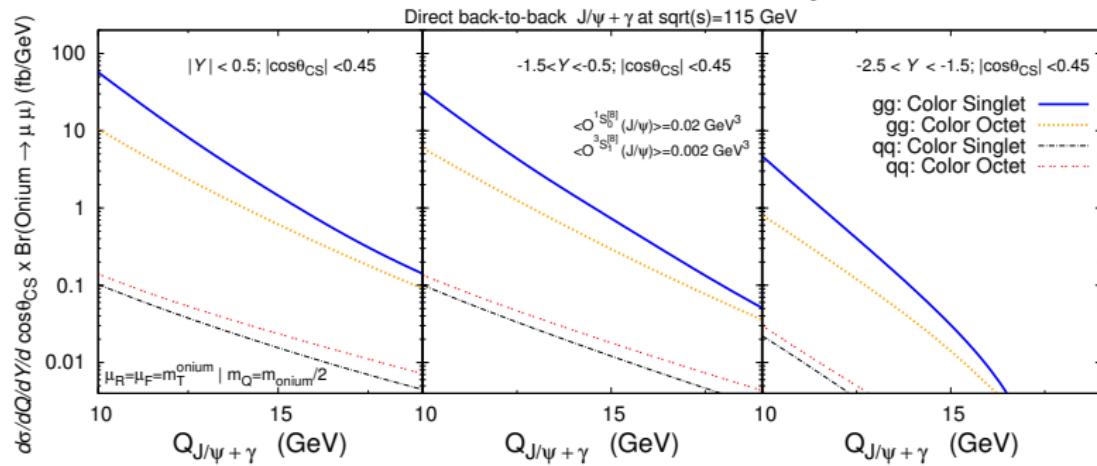
AFTER@LHC : a fixed-target experiment using the LHC beams

- $\sqrt{2 \times m_N \times E_p} \stackrel{7\text{TeV}}{=} 115 \text{ GeV}$
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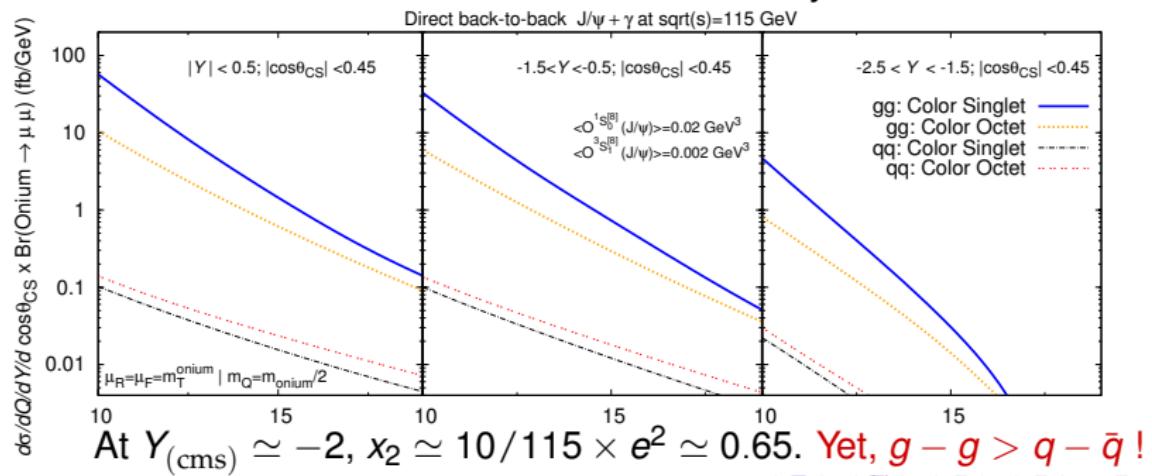
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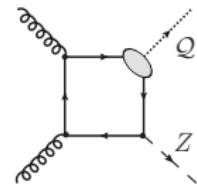
## Part IV

### Quarkonium + Z boson

# $\Upsilon + Z$ cross sections

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

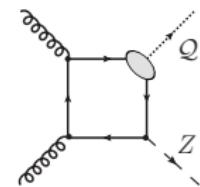
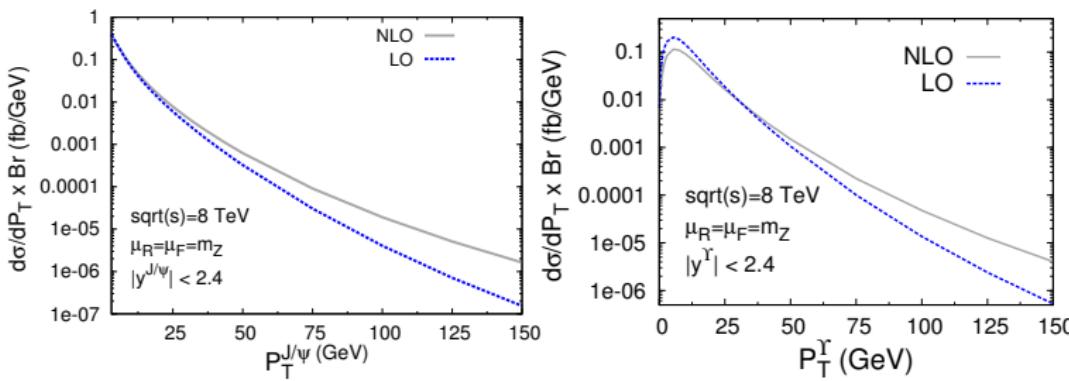
- Rates similar for  $\Upsilon + Z$  and  $J/\psi + Z$  [Same for  $Q + \gamma$  for  $Q \gtrsim 20$  GeV]



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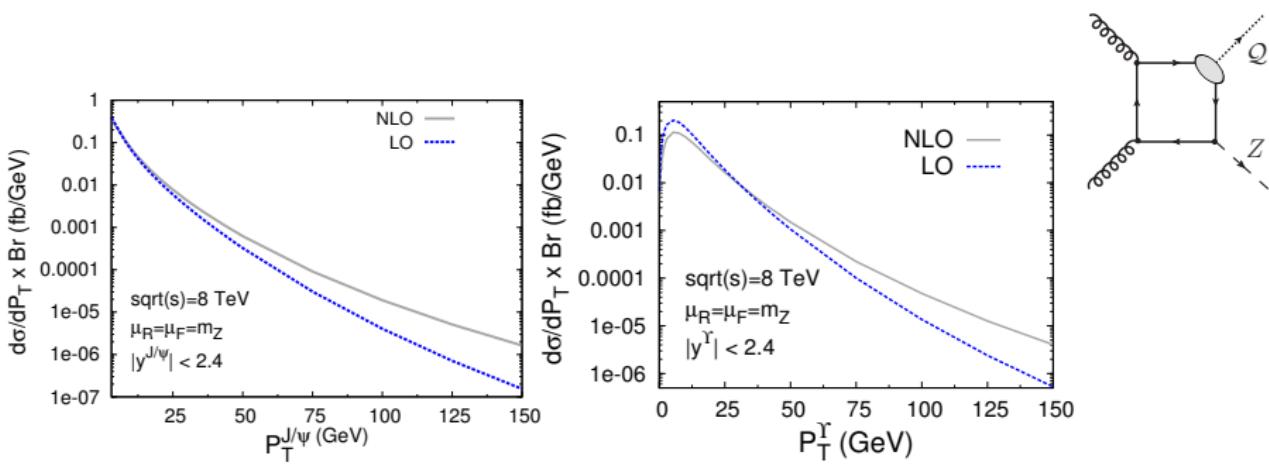
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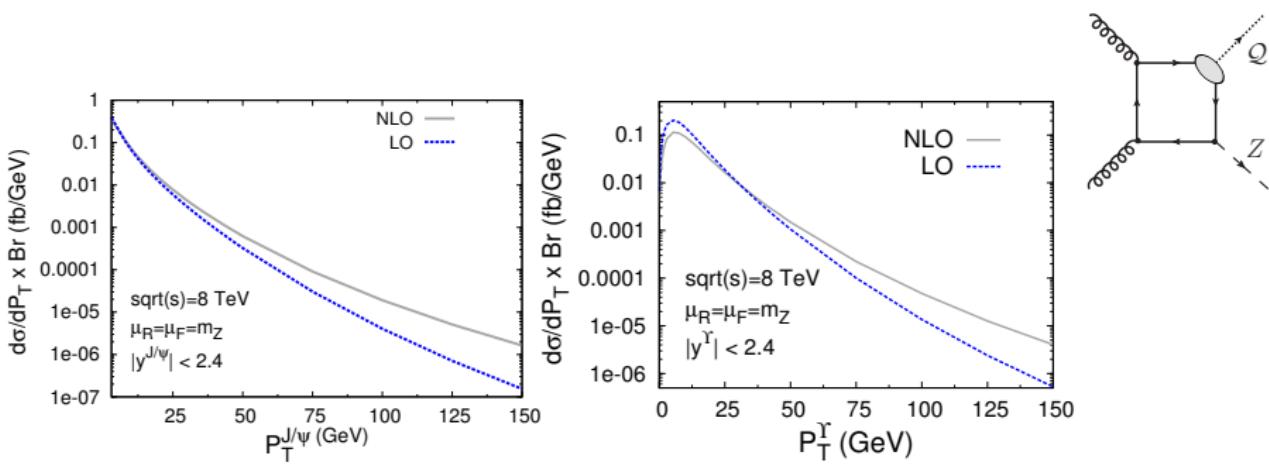


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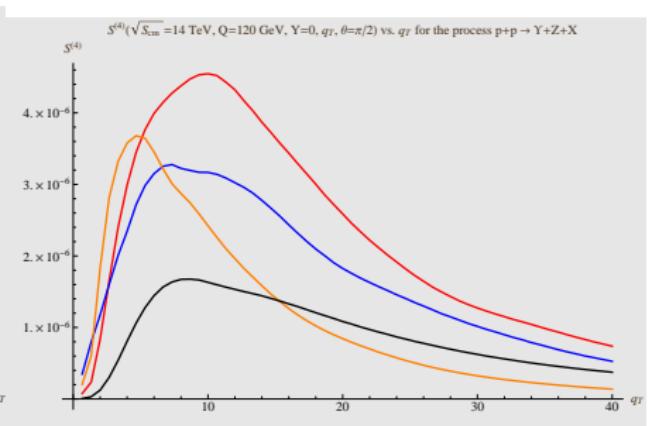
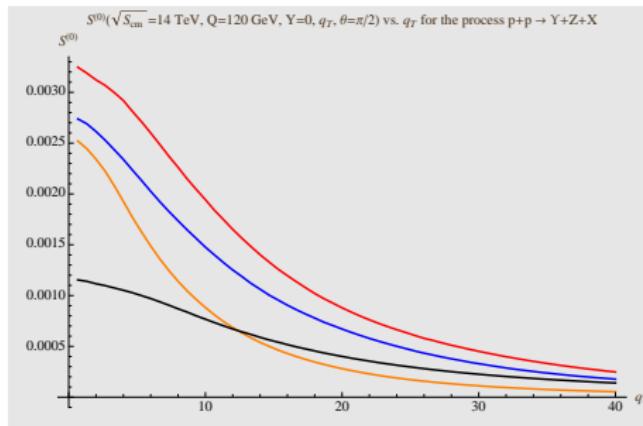


- Potential probe of gluon TMDs as well
- Rate clearly smaller than  $Q + \gamma$  even at low  $P_T$

# $\Upsilon + Z$ and TMDs

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

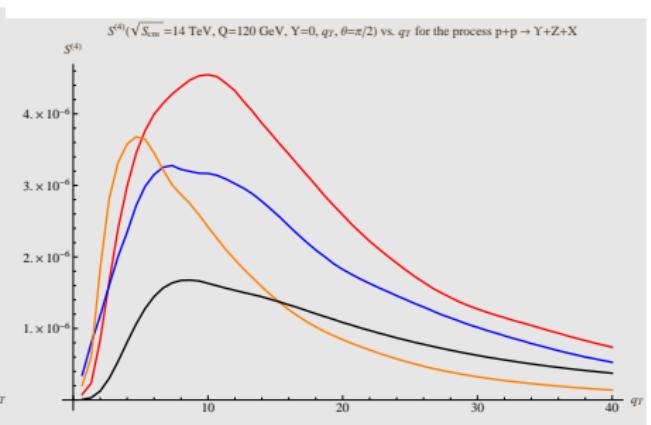
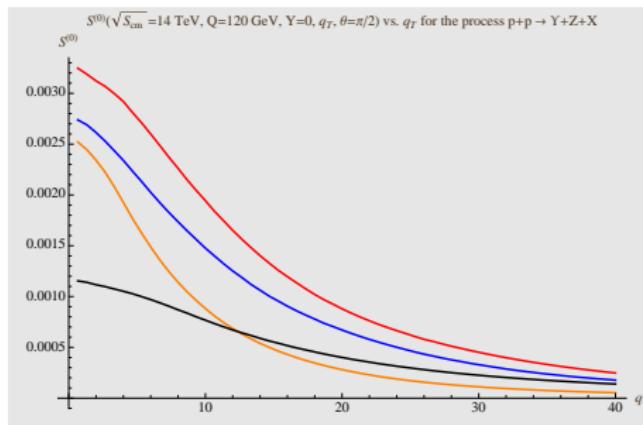
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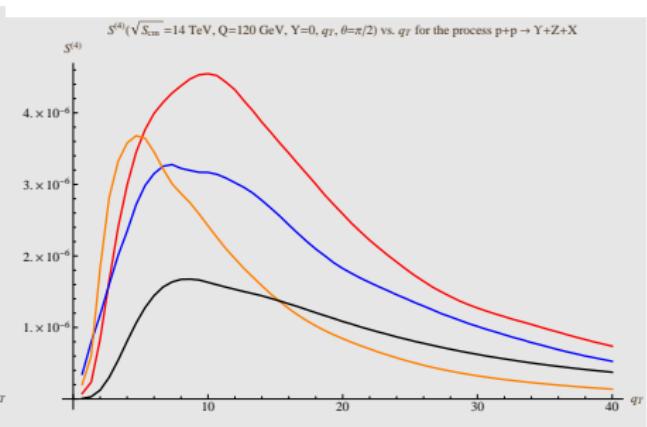
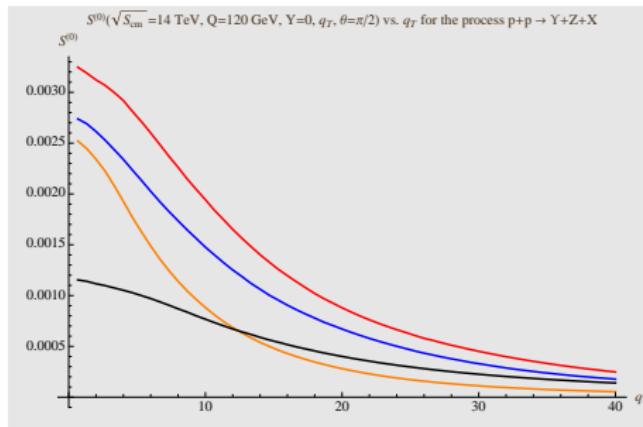


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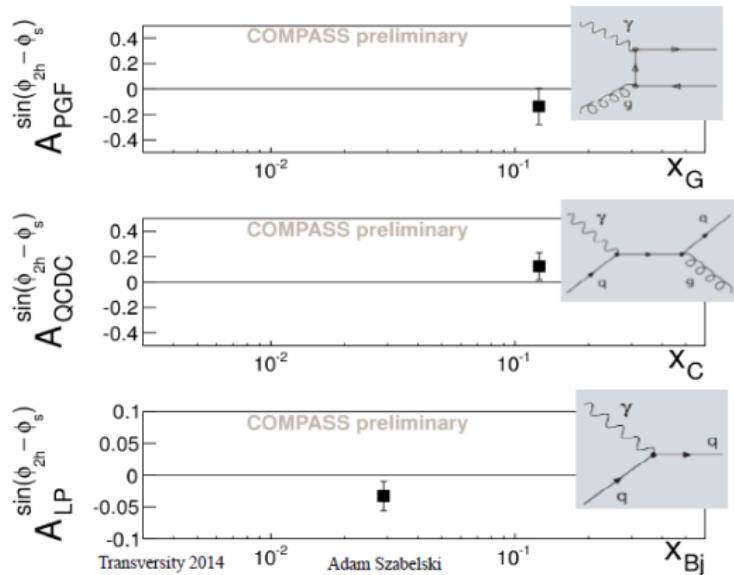


- $S_{q_T}^{(n)}$  smaller than for  $Q + \gamma$  [one can integrate up to larger  $q_T$ , though]
- Naturally large  $Q$ : interest to study the scale evolution ?

## Part V

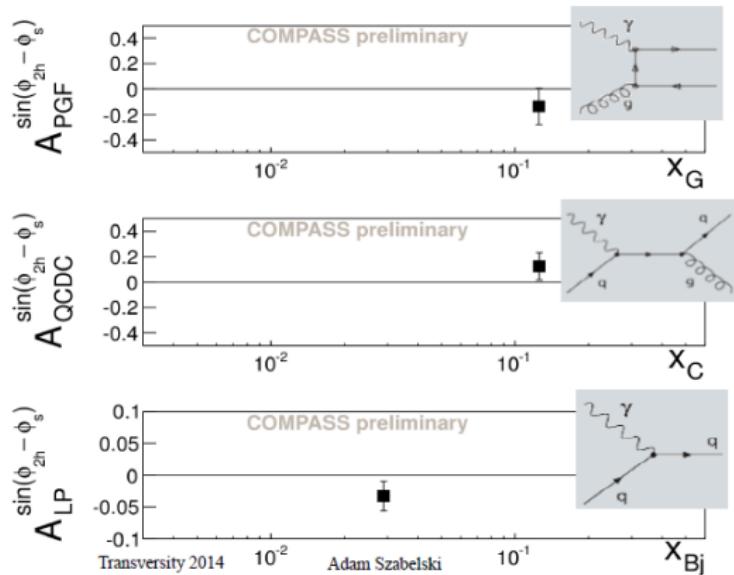
# On the smallness of the gluon Sivers effect

# High $P_T$ hadron-pair SSA in $\mu p$ collisions



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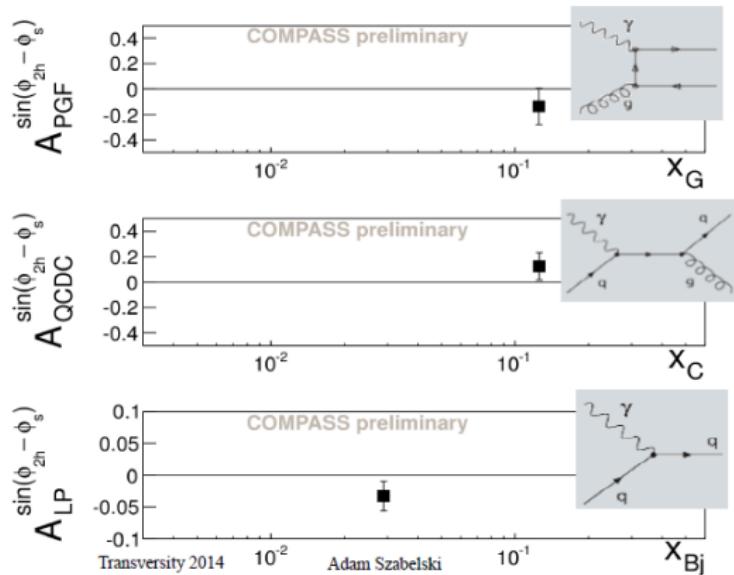
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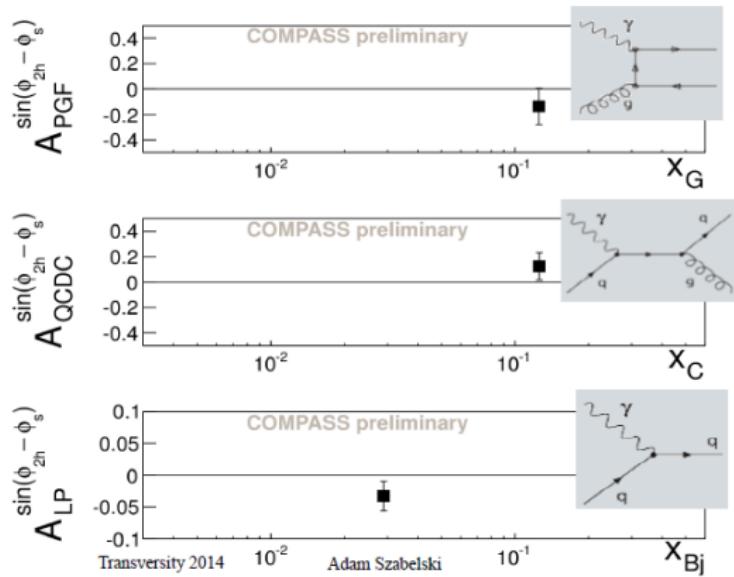
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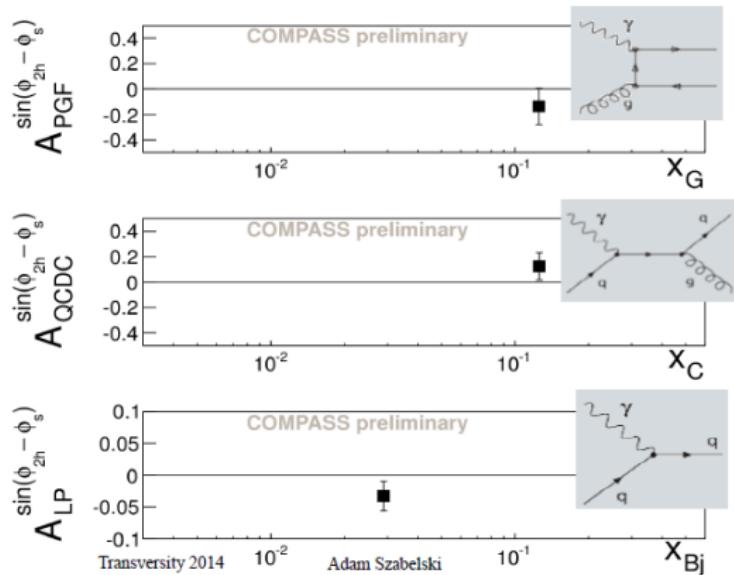
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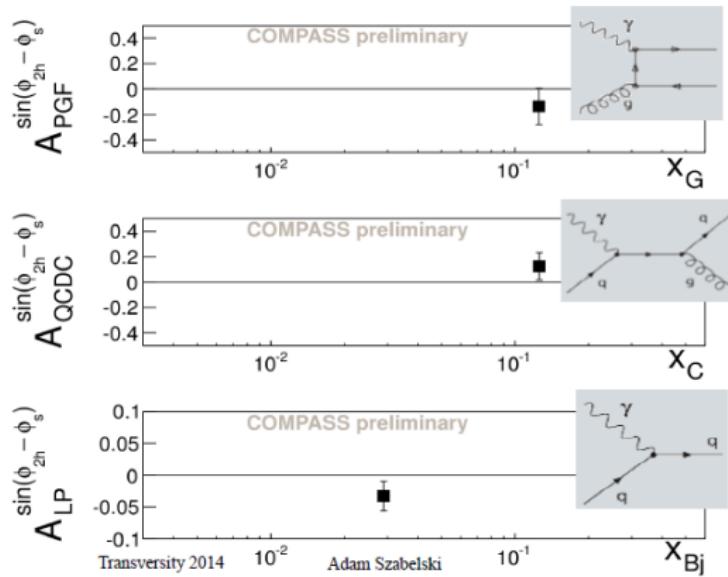
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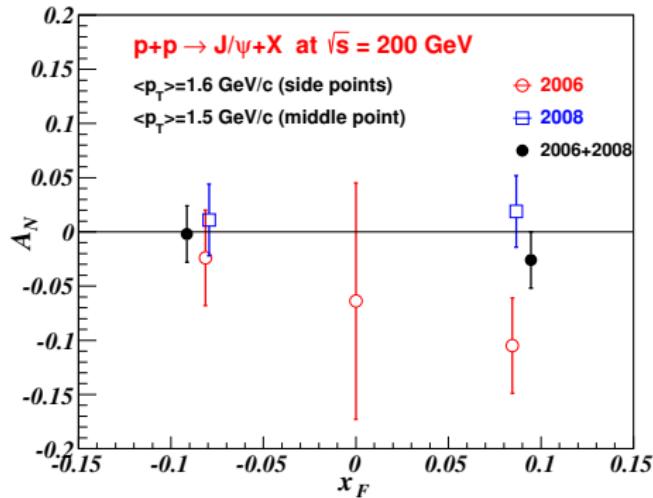


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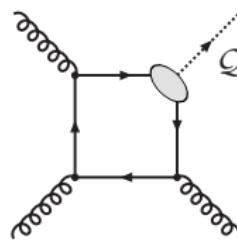
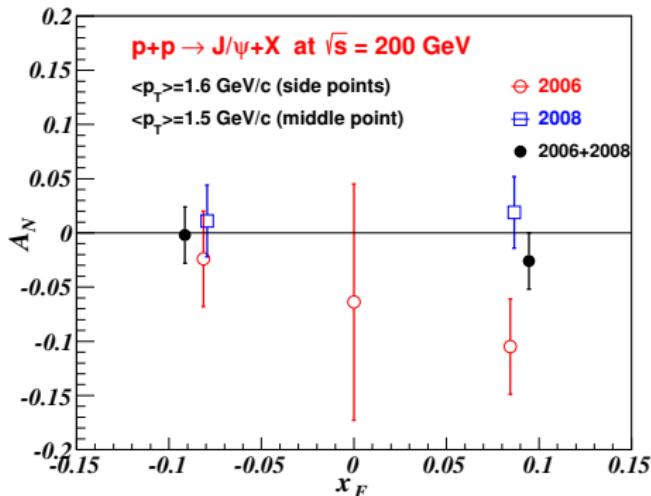
# $J/\psi$ SSA in $pp$ collisions

PHENIX Coll. PRD 86 (2012) 099904



# $J/\psi$ SSA in $pp$ collisions

PHENIX Coll. PRD 86 (2012) 099904



- hadron–hadron process with colour in the final state  
→ connection to the Sivers function is less obvious
- Probably excludes large asymmetry, but
- Difficult to draw further conclusion

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- Back-to-back  $J/\psi + \gamma$  and  $\Upsilon + \gamma$  is certainly at reach
  - Already a couple of thousand events on tapes
  - $f_1^g(x, k_T, \mu)$  and  $h_1^{\perp g}(x, k_T, \mu)$  can be determined separately
  - $Q$  can even be tuned → gluon TMD evolution

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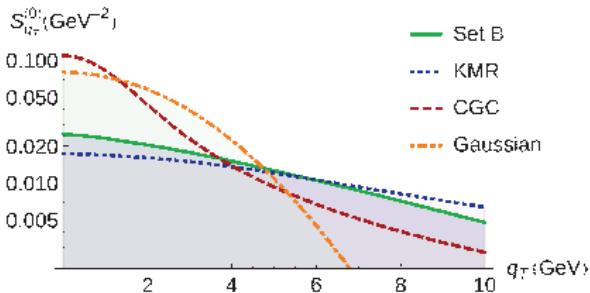
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- Low  $P_T$  onium and SSA of onium+photon studies could be done  
with A Fixed-Target Experiment at the LHC: AFTER@LHC

# Part VI

## Backup

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

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

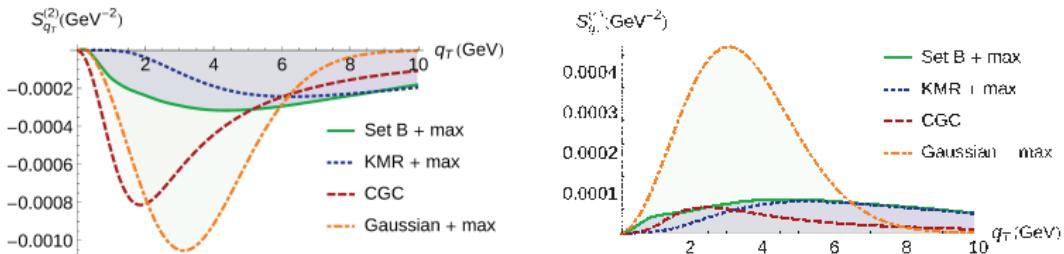


Models for  $f_1^g$ : assumed to be the same as for Unintegrated Gluon Distributions

- 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

## $\mathcal{S}_{q_T}^{(2,4)}$ : 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

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

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

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

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$q\bar{q}' \rightarrow \gamma^* W \xrightarrow{^3S_1^{[1]}} J/\psi W$  and  $q\bar{q}' \rightarrow g^* W \xrightarrow{^3S_1^{[8]}} J/\psi W$  are very similar  
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- Colour factor:  $2N_c$

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- For  $Y$  production, it is about the **same**  
 $(e_Q$  smaller but  $\alpha_s$  also smaller and  $|R(0)|^2$  larger)

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

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- For  $J/\psi$  production in  $u\bar{u}$  fusion and for  $\langle \mathcal{O}_{J/\psi}({}^3S_1^{[8]}) \rangle = 2.2 \times 10^{-3} \text{ GeV}^3$ , the ratio CSM vs. COM is **2/3**
- For  $Y$  production, it is about the **same**  
 $(e_Q$  smaller but  $\alpha_s$  also smaller and  $|R(0)|^2$  larger)
- If we add the  $W$  emission, the charge factor changes and  
 $\mu_R : \mathcal{O}(m_Q) \rightarrow \mathcal{O}(m_W)$   
→ This explains our results for  $J/\psi + W$

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

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→ 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