TMD studies using quarkonia

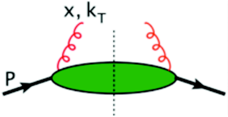
J.P. Lansberg
IPN Orsay – Paris-Sud U./Paris Saclay U. –CNRS/IN2P3
QCD Evolution 2017 workshop
May 22 – 26 – JLab, USA

Results obtained in collaboration with W. den Dunnen, M. Echevarria, T. Kasemets, C. Lorcé, C. Pisano, F. Scarpa, M. Schlegel, H.S. Shao, A. Signori

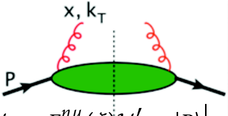
Part I

Generalities on gluon TMDs

Gluon TMDs in unpolarised protons



Gluon TMDs in unpolarised protons



- Gauge-invariant definition:

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

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

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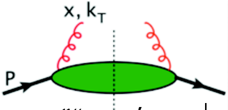

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$$\Phi_g^{\mu\nu}(x,\boldsymbol{k}_T,\zeta,\mu) = -\frac{1}{2x}\left\{g_T^{\mu\nu} f_1^g(x,k_T,\mu) - \left(\frac{k_T^\mu k_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\boldsymbol{k}_T^2}{2M_p^2}\right) h_1^{\perp g}(x,k_T,\mu)\right\} + \text{suppr.}$$

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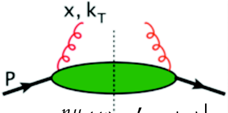

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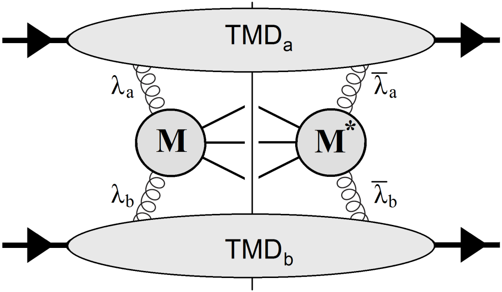
- f_1^g: TMD distribution of unpolarised gluons
- $h_1^{\perp g}$: TMD distribution of linearly polarised gluons

[Helicity-flip distribution]

gg fusion in arbitrary unpolarised process [colourless final state]

$d\sigma^{gg} \propto$



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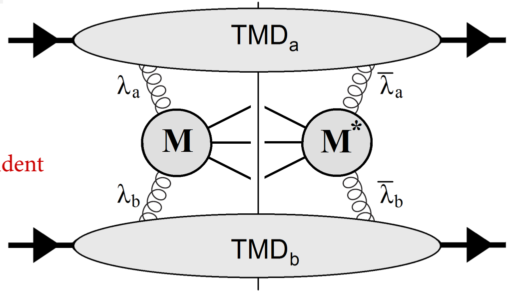
⇒ helicity non-flip, azimuthally independent



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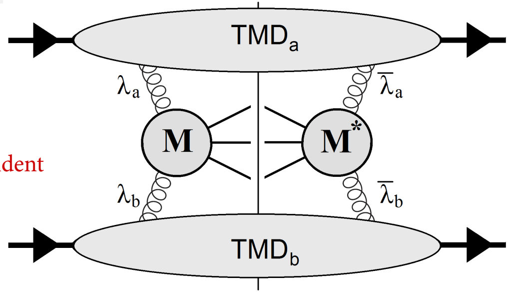

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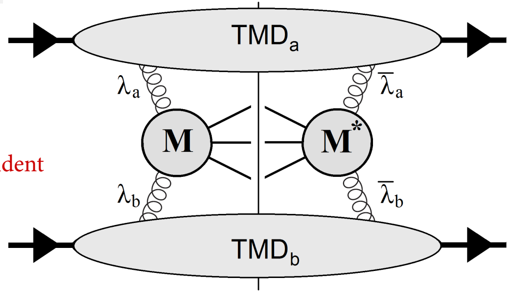

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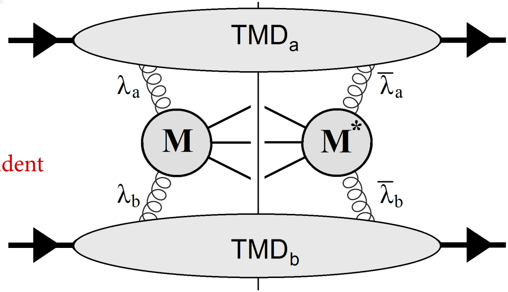

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$$+\left(\sum_{\lambda} \hat{\mathcal{M}}_{\lambda,-\lambda} \hat{\mathcal{M}}^*_{-\lambda,\lambda}\right) \mathcal{C}[w_4 \times h_1^{\perp g} h_1^{\perp g}]$$

$\Rightarrow$ double helicity flip, $\cos(4\phi)$-modulation

Part II

Quarkonium production and TMD factorisation applicability/breaking

Approaches to Quarkonium Production

See EPJC (2016) 76:107 for a recent review

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  3. Colour Octet Mechanism (encapsulated in NRQCD): higher Fock states of the mesons taken into account; $Q\bar{Q}$ can be produced in octet states with different quantum # as the meson; bleaching with semi-soft gluons ?

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3. COLOUR OCTET MECHANISM
   - one non-perturbative parameter per Fock States
   - expansion in v^2; series can be truncated
   - the phenomenology partly depends on this
   - HQSS relates some non-perturbative parameters to each others and to a specific quarkonium polarisation

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- Different independent $h_1^{\perp g}$ functions correspond to specific colour structures. Depending on the process, one extracts different combinations

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- However, if TMD factorisation holds for H^0+jet as conjectured by D. Boer-C. Pisano, there should be no issue for $\mathcal{Q}+\gamma$, $\mathcal{Q}+Z$ or $\mathcal{Q}+\gamma^\star$

D. Boer, C. Pisano PRD 91 (2015) 074024

Part III

Quarkonia and gluon TMDs at hadron colliders

$2 \to 2$ vs $2 \to 1$ processes

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- $2 \to 1$ process :
- Hard scale can only 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" ($q_T \ll Q$) virtually as wide as we wish
- Hard scale $Q^2 = (p_1 + p_2)^2$ can be tuned to study the QCD evolution of the TMDs
- Drawback : yield can be populated by Double Parton Scatterings (DPS)

J.P.L., H.S. Shao JHEP 1610 (2016) 153, NPB 900 (2015) 273, PLB 751 (2015) 479

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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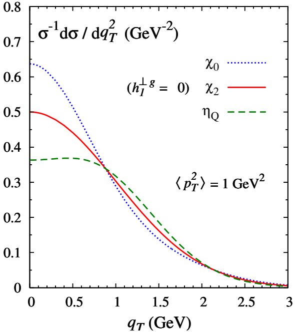

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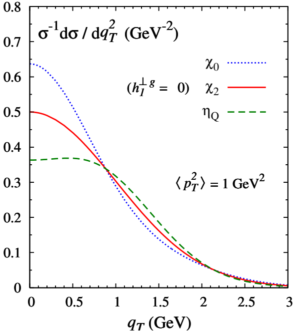

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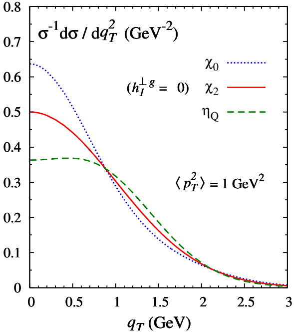
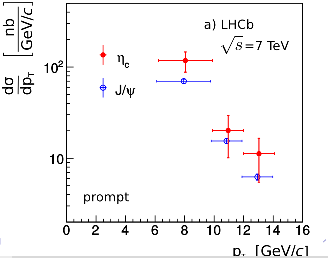
- Cannot tune Q: $Q \simeq m_Q$
- Low P_T: Experimentally very difficult

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** : factorisation holds

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*

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

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

CrossMark

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
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$\rightarrow$ **Low q_T χ_c data exist: empirical check of TMD factorisation possible**

First phenomenological study of η_c production with TMDs

M.G. Echevarria, T. Kasemets, JPL, C. Pisano, A. Signori - in preparation

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See A. Signori's talk at UCLA, May 2017; J.C. Collins *et al.* **PRD94 (2016) 034014**

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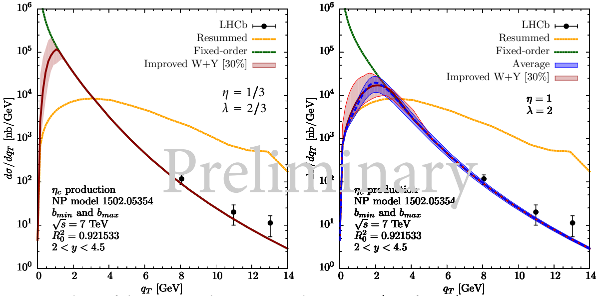


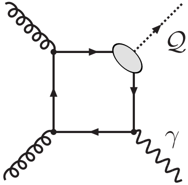
Nota: the (default) parameter values of the improved $W + Y$ matching, $\eta = 1/3$ & $\lambda = 2/3$, seem not compatible with our matching. Too early to draw conclusions, though.

Part IV

Going further with associated-quarkonium production

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

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



- Unique candidate to pin down the gluon TMDs

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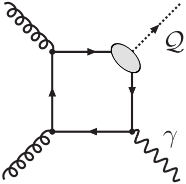

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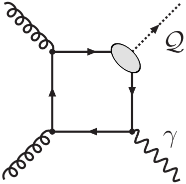

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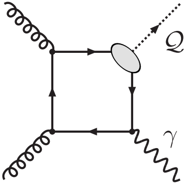

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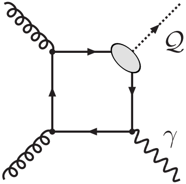

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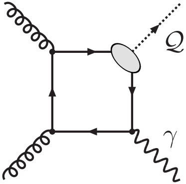

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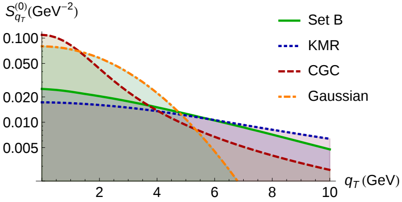
  - $\mathcal{S}_{q_T}^{(0)} = \frac{\mathcal{C}[f_1^g f_1^g]}{\int dq_T^2\, \mathcal{C}[f_1^g f_1^g]}$: does not involve $h_1^{\perp g}$ [not always the case]
  - $\mathcal{S}_{q_T}^{(2)} = \frac{F_3\, \mathcal{C}[w_2^{fh} f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2]}{2F_1 \int dq_T^2\, \mathcal{C}[f_1^g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

$\mathcal{S}_{q_T}^{(2)}, \mathcal{S}_{q_T}^{(4)} \neq 0 \Rightarrow$ 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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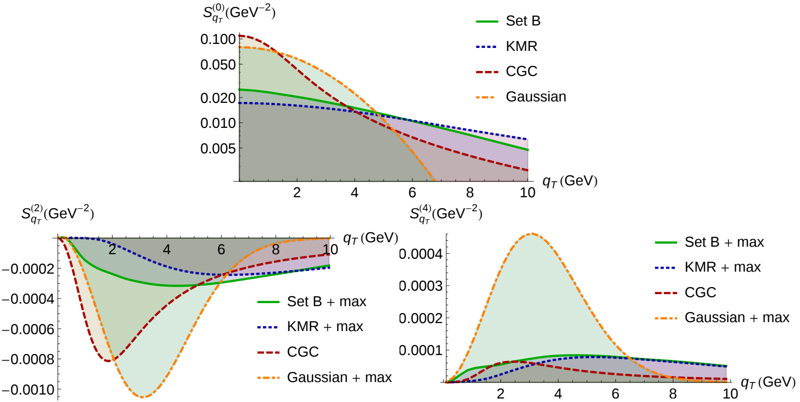

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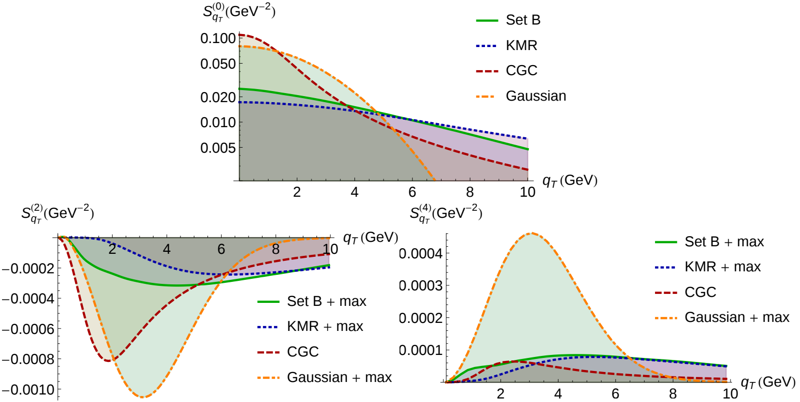

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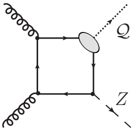
- $\mathcal{S}^{(4)}_{q_T}$: $\int dq_T \mathcal{S}^{(4)}_{q_T}$ should be measurable [$\mathcal{O}(1-2\%)$: ok with 2000 events]
- $\mathcal{S}^{(2)}_{q_T}$: slightly larger than $\mathcal{S}^{(4)}_{q_T}$

Extending to $J/\psi/\Upsilon + Z$

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

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



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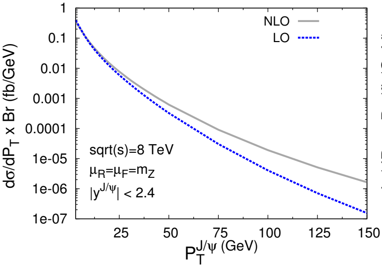

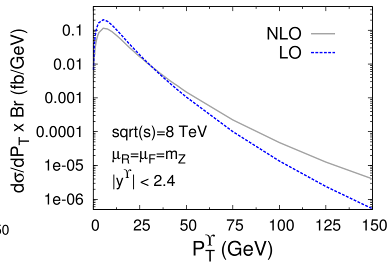

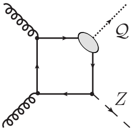

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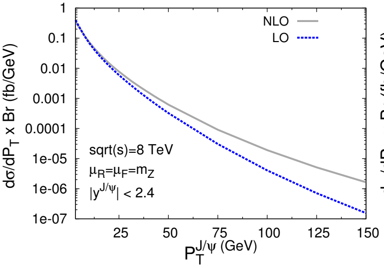

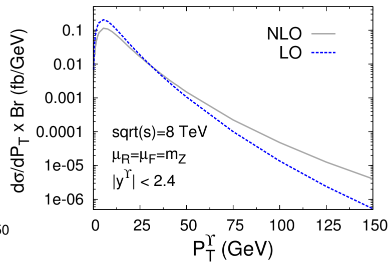

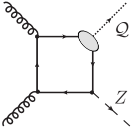

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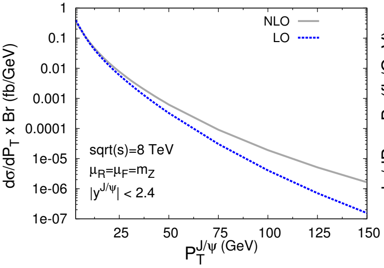

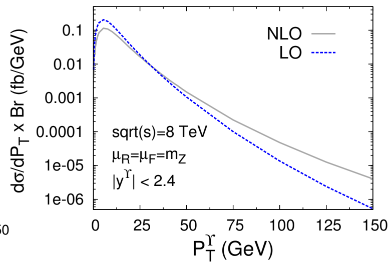

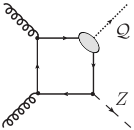

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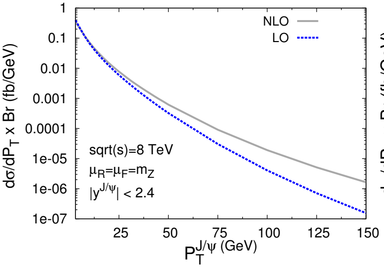

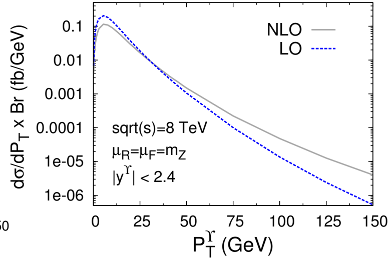

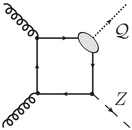

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- First measurement of $J/\psi + Z$ by ATLAS; large DPS yield : unequal p_T cuts ?

ATLAS EPJC 75 (2015) 229 ; J.P.L., H.S. Shao JHEP 1610 (2016) 153

$\Upsilon + Z$ & $\Upsilon + \gamma^\star$ @$\sqrt{s} = 14$ TeV

JPL, C. Pisano, M. Schlegel, NPB 920 (2017) 192

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JPL, C. Pisano, M. Schlegel, NPB 920 (2017) 192

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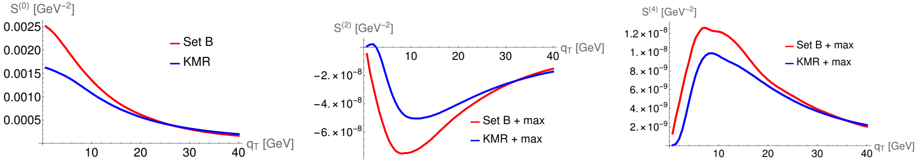

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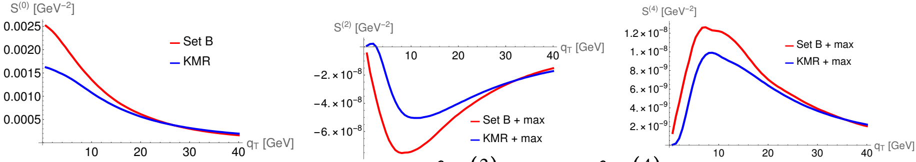
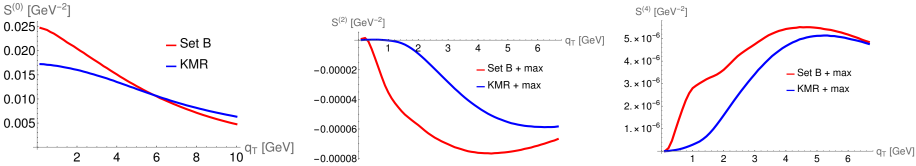


- $Q = 20$ GeV & dilepton mass [5:7] GeV $[\int \mathcal{S}^{(2)} \sim 0.5\%; \int \mathcal{S}^{(4)} \sim 0.05\%]$



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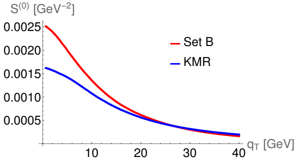

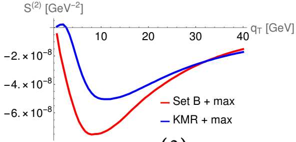

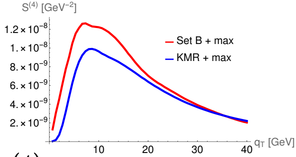

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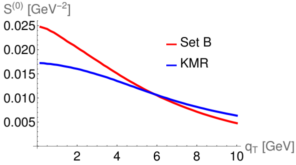
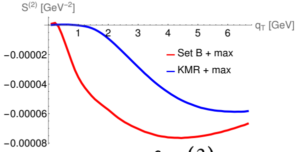
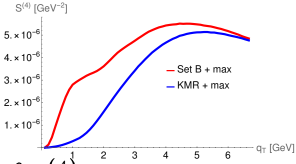
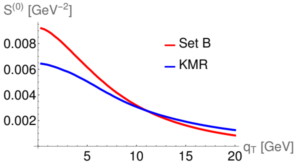
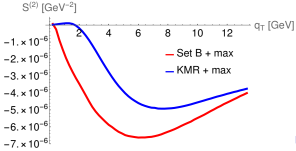


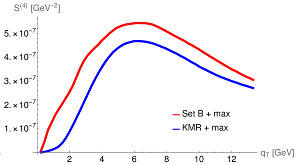




- $Q = 40$ GeV & dilepton mass [20:25] GeV [$\int \mathcal{S}^{(2)} \sim 0.15\%$; $\int \mathcal{S}^{(4)} \sim 0.01\%$]







Part V

The case of quarkonium pair production

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

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- J/ψ are much easier to detect. Already studied by LHCb, CMS & ATLAS at the LHC and D0 at the Tevatron

LHCb PLB 707 (2012) 52; CMS JHEP 1409 (2014) 094; ATLAS EPJC 77 (2017) 76; D0 PRD 90 (2014) 111101

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J.P.L., H.S. Shao NPB 900 (2015) 273

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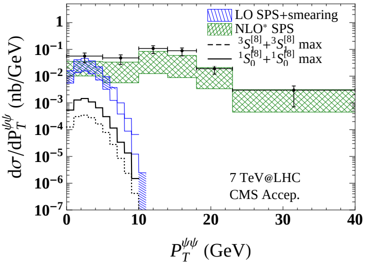
J.P.L., H.S. Shao NPB 900 (2015) 273

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

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

- No final state gluon needed for the Born contribution: pure colourless final state

JPL, H.S. Shao PRL 111, 122001 (2013)



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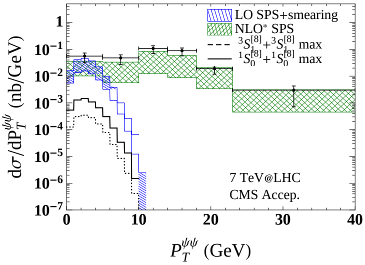
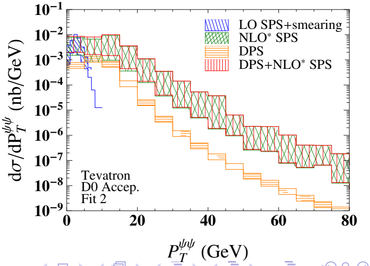
- At low $P_T^{\psi\psi}$, small DPS effects, otherwise required by the CMS & ATLAS data at large Δy





$J/\psi + J/\psi$ and the gluon TMDs

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- All allowed terms are nonzero (unlike $J/\psi + \gamma$ ($A^h = 0$))

$$d\sigma \propto A^f\, \mathcal{C}[f_1^g f_1^g] + A^h\, \mathcal{C}[w_0^{hh}\, h_1^{\perp g} h_1^{\perp g}]$$

$$+ B\left[\mathcal{C}[w_2^{fh}\, f_1^g h_1^{\perp g}] + \mathcal{C}[w_2^{hf}\, h_1^{\perp g} f_1^g]\right]\cos(2\phi) + C\,\mathcal{C}[w_4^{hh}\, h_1^{\perp g} h_1^{\perp g}]\cos(4\phi)$$

- The expressions for A-D are tractable (a little too long though to be shown in an useful manner)

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

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

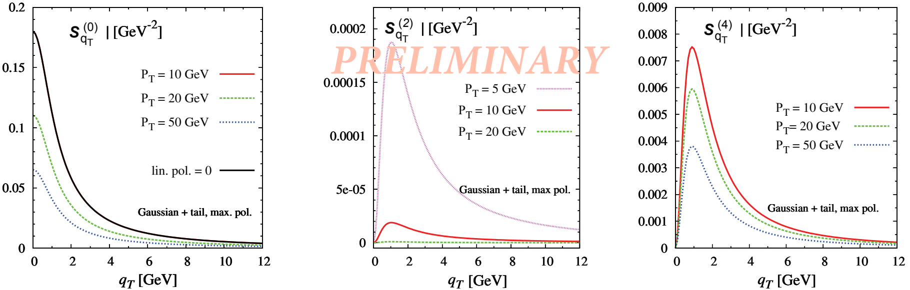
$J/\psi + J/\psi$ azimuthal effects

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

- Using a simple model (+ positivity bound) :

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

- 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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- $J/\psi + \gamma$ STSA study might also be possible with STAR in very favourable conditions

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

Part VI

Backup

$\Upsilon + \gamma$ already measured ?

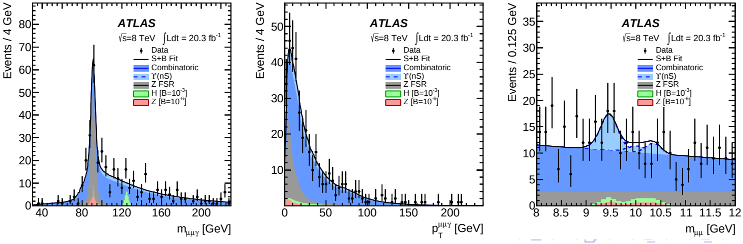
PRL **114,** 121801 (2015) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2015

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

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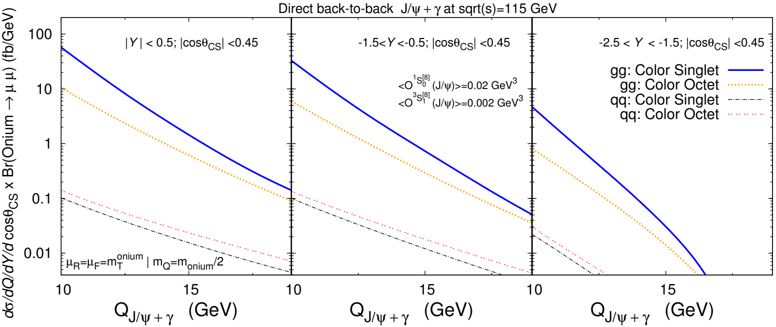

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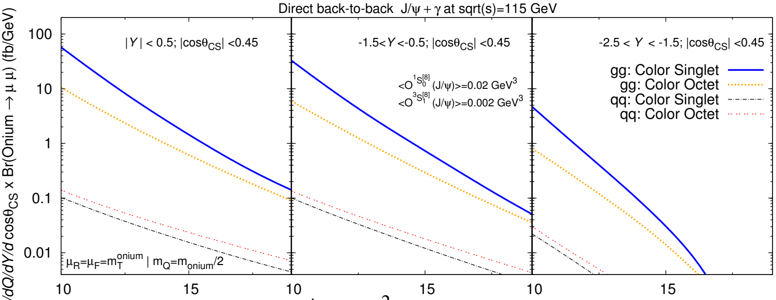
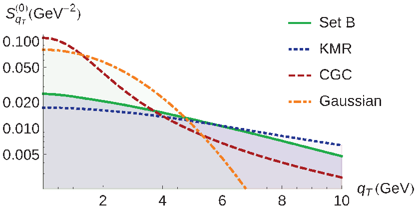


At $Y_{(cms)} \simeq -2$, $x_2 \simeq 10/115 \times e^2 \simeq 0.65$. Yet, $g - g > q - \bar{q}$!

$S_{q_T}^{(0)}$: *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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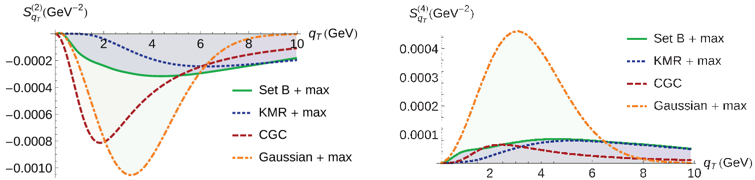

$h_1^{\perp g}$: predictions only in the CGC: in the other models saturated to its upper bound

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

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

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

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